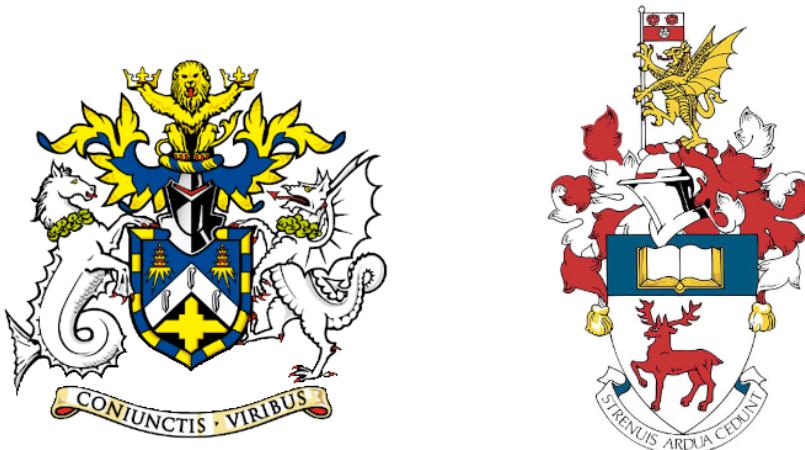


<sup>1</sup> ADVANCING NEUTRINO  
<sup>2</sup> DETECTION AND TRIGGERING IN  
<sup>3</sup> DUNE



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<sup>6</sup> Submitted in partial fulfillment of the requirements  
<sup>7</sup> of the Degree of Doctor of Philosophy

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<sup>12</sup> December 2024



13

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# Abstract

31

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*¡Oh memoria, enemiga mortal de mi descanso!*

---

*El ingenioso hidalgo don Quijote de la Mancha*

MIGUEL DE CERVANTES SAAVEDRA



## Acknowledgements

34 Work in progress ...



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## List of Abbreviations

<b>ADC</b>	Analog to Digital Converter.
<b>ALEPH</b>	Apparatus for LEP PHysics.
<b>ALICE</b>	A Large Ion Collider Experiment.
<b>BDT</b>	Boosted Decision Tree.
<b>CC</b>	Charged Current.
<b>DM</b>	Dark Matter.
<b>DUNE</b>	Deep Underground Neutrino Experiment.
<b>ECal</b>	Electromagnetic Calorimeter.
<b>FD</b>	Far Detector.
<b>FHC</b>	Forward Horn Current.
<b>HPgTPC</b>	High Pressure gaseous Time Projection Chamber.
<b>LBL</b>	Long BaseLine.
<b>MuID</b>	Muon IDentification system.
<b>NC</b>	Neutral Current.
<b>ND</b>	Near Detector.
<b>ND-GAr</b>	Near Detector Gaseous Argon.
<b>ND-LAr</b>	Near Detector Liquid Argon.
<b>PDG</b>	Particle Data Group.
<b>RHC</b>	Reverse Horn Current.



1

546

## Introduction

547



# Neutrino physics

550        *Little particles of inspiration sleet through the universe all the time traveling  
551        through the densest matter in the same way that a neutrino passes through a  
552        candyfloss haystack, and most of them miss.*

553

– Terry Pratchett, *Sourcery*

554        Ever since they were postulated in 1930 by Wolfgang Pauli to explain the continuous  
555         $\beta$  decay spectrum [15] and later found by F. Reines and C. Cowan at the Savannah  
556        River reactor in 1953 [16], neutrinos have had a special place among all other elementary  
557        particles. They provide a unique way to probe a wide range of quite different physics,  
558        from nuclear physics to cosmology, from astrophysics to colliders. Moreover, there is  
559        compelling evidence to believe that the study of neutrinos may be key to unveil different  
560        aspects of physics beyond the SM, difficult to test elsewhere.

561        In this Chapter, I will review the basics of neutrino physics, from its role within the  
562        SM to the main open questions related to the neutrino sector, paying special attention  
563        to the phenomenology of neutrino oscillations.

## 564        2.1 Neutrinos in the SM

565        The SM of fundamental interactions was initially proposed in 1967 by S. Glashow, S.  
566        Weinberg and A. Salam[17–19]. This theoretical framework describes the dynamics  
567        of leptons and quarks, by introducing a collection of mediating gauge vector bosons  
568        and one scalar particle, known as the Higgs boson. It assumes that the local  $SU(3) \times$

## CHAPTER 2. NEUTRINO PHYSICS

569  $SU(2)_L \times U(1)_Y$  gauge symmetry is an internal symmetry of the system, with  $SU(3)$   
570 describing quantum chromodynamics, and  $SU(2)_L \times U(1)_Y$  being the gauge groups of  
571 the electroweak sector. For a detailed overview of the SM of electroweak interactions,  
572 see Ref. [20].

573 In the SM, neutrinos appear in three flavours, namely  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ . These are  
574 associated with the corresponding charged leptons,  $e$ ,  $\mu$ , and  $\tau$ . Neutrinos exist only  
575 as left-handed particles, grouped in doublets with the charged leptons, while the later  
576 come in both chirality states:

$$\begin{pmatrix} \nu_e \\ e_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_\mu \\ \mu_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_\tau \\ \tau_L^- \end{pmatrix}, \quad e_R^-, \quad \mu_R^-, \quad \tau_R^-. \quad (2.1)$$

577 Similarly, quarks also exist in both chirality states, and are grouped as:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} s_L \\ c_L \end{pmatrix}, \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}, \quad u_R, \quad d_R, \quad s_R, \quad c_R, \quad t_R, \quad b_R. \quad (2.2)$$

578 The fact that there are no right-handed neutrino fields implies that neutrinos are  
579 strictly massless within the SM. This restriction follows from the experimental observation  
580 that all neutrinos produced via weak interactions are pure left-handed helicity states  
581 (and similarly antineutrinos are pure right-handed states). The hypothetical existence  
582 of right-handed neutrinos could be indirectly inferred from the observation of non-zero  
583 neutrino masses, nevertheless the existence of neutrino masses is not a sufficient condition  
584 for the existence of such fields.

585 Left and right-handed fermions transform differently under  $SU(2)_L \times U(1)_Y$  rotations,  
586 as the right-handed particles are singlets under  $SU(2)_L$ . Applying a local transformation,  
587 they change as:

$$\begin{aligned} \psi_L &\longrightarrow e^{-iY\beta(x)/2} e^{-iT_a\alpha_a(x)} \psi_L, \\ \psi_R &\longrightarrow e^{-iY\beta(x)/2} \psi_R, \end{aligned} \quad (2.3)$$

588 where  $Y/2$  and  $T_a$  are the generators of  $SU(2)_L$  and  $U(1)_Y$ , respectively, and  $\beta(x)$  and

## 2.1. NEUTRINOS IN THE SM

**Table 2.1:** Values of  $T_3$  and  $Y/2$  assigned to the first generation of fermions.

	$e_L$	$\nu_e$	$e_R$	$u_L$	$d_L$	$u_R$	$d_R$
$T_3$	-1/2	1/2	0	1/2	-1/2	0	0
$Y/2$	-1/2	-1/2	-1	1/6	1/6	2/3	-1/3

589  $\alpha_a(x)$  are the parameters of the rotation.

590 The values of the quantum numbers  $Y/2$  and  $T_3$ , the third component of the weak  
 591 isospin, have to be assigned to the different particles. The values of  $T_3$  follow from the  
 592 commutation relations of the generators of SU(2). After the spontaneous symmetry  
 593 breaking  $SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$ , one finds the relation which determines the electric  
 594 charge:

$$Q = T_3 + \frac{Y}{2}, \quad (2.4)$$

595 Setting the electric charge to  $-1$  for electrons, we can find the values of the hypercharge  
 596 for the rest of the fermions. The resulting values for the first generation of leptons and  
 597 quarks are shown in Tab. 2.1.

598 It is clear that the free Lagrangian of the theory is not be invariant under the gauge  
 599 transformations, as the kinetic terms contain derivatives. Therefore, to make it invariant,  
 600 one needs to introduce a set of gauge bosons. They appear in the so-called covariant  
 601 derivative, which replaces the common derivative and transforms in the same way as the  
 602 fermion fields under local rotations. This constrain fixes completely the transformations  
 603 of the spin-1 fields. For left and right-handed particles, the covariant derivatives are  
 604 given by:

$$\begin{aligned} D_\mu \psi_L &= \left( \partial_\mu + ig' \frac{Y}{2} B_\mu + ig T_a W_\mu^a \right) \psi_L, \\ D_\mu \psi_R &= \left( \partial_\mu + ig' \frac{Y}{2} B_\mu \right) \psi_R, \end{aligned} \quad (2.5)$$

605 where  $W_\mu^i$ ,  $i = 1, 2, 3$  and  $B_\mu$  are the gauge bosons for the  $SU(2)_L$  and  $U(1)_Y$  factors,  
 606 respectively, and  $g$  and  $g'$  are the corresponding gauge couplings. It can be shown that  
 607 these fields transform in the adjoint representation of the gauge group.

## CHAPTER 2. NEUTRINO PHYSICS

**Table 2.2:** Neutral current couplings.

	$u$	$d$	$\nu_e$	$e$
$2v_f$	$1 - \frac{8}{3}\sin^2\theta_W$	$-1 + \frac{4}{3}\sin^2\theta_W$	1	$-1 + 4\sin^2\theta_W$
$2a_f$	1	-1	1	-1

So far, the theory only contains massless particles, as adding bare mass terms to the Lagrangian would spoil the gauge symmetry. Therefore, the mass terms need to be induced by a spontaneous violation of the symmetries. In the SM, the responsible for this is the Higgs mechanism. The Higgs doublet is coupled to the gauge bosons through the covariant derivative, and to the fermions through the Yukawa couplings. Upon spontaneous symmetry breaking, the vacuum expectation value of the Higgs field generate the mass terms of the particles.

In order to obtain the physical intermediate vector boson states, we need to perform the following redefinitions:

$$\begin{aligned} A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu, \\ Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu, \\ W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2), \end{aligned} \tag{2.6}$$

where  $A_\mu$  is the photon field, and  $Z_\mu$  and  $W_\mu^\pm$  are the neutral and the charged weak boson fields, respectively. The Weinberg angle,  $\theta_W$ , relates the weak coupling constants and the electric charge:

$$e = g' \cos \theta_W = g \sin \theta_W. \tag{2.7}$$

At this point, the interacting part of the electroweak Lagrangian can be re-written as the sum of three contributions: the electromagnetic (EM), charged-current (CC) and neutral-current (NC) components:

$$\begin{aligned} \mathcal{L}_{\text{EW}}^{\text{int}} &= \mathcal{L}_{\text{EM}} + \mathcal{L}_{\text{CC}} + \mathcal{L}_{\text{NC}} \\ &= -e A_\mu J_{\text{EM}}^\mu - \frac{g}{2\sqrt{2}} (W_\mu^+ J_{\text{CC}}^\mu + \text{h.c.}) - \frac{g}{2\cos\theta_W} Z_\mu J_{\text{NC}}^\mu, \end{aligned} \tag{2.8}$$

## 2.2. TROUBLE IN THE NEUTRINO SECTOR

623 with the currents defined as:

$$\begin{aligned}
 J_{\text{EM}}^\mu &= \sum_f Q_f \bar{f} \gamma^\mu f, \\
 J_{\text{CC}}^\mu &= \sum_\ell \bar{\nu}_\ell \gamma^\mu (1 - \gamma_5) \ell + \sum_f \bar{u}_f \gamma^\mu (1 - \gamma_5) d_f, \\
 J_{\text{NC}}^\mu &= \sum_f \bar{f} \gamma^\mu (v_f - a_f \gamma_5) f,
 \end{aligned} \tag{2.9}$$

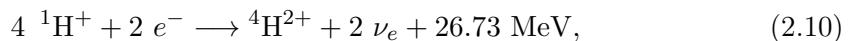
624 where  $f$  denotes any SM fermion,  $\ell$  and  $\nu_\ell$  a charged lepton and a neutrino of any flavour,  
 625 and  $u_f$  and  $d_f$  an up-like and a down-like quarks of any flavour. For the NC case, the  
 626 values of the  $v_f$  and  $a_f$  couplings are given in Tab. 2.2.

627 As seen in Eq. (5.8), in the electroweak theory neutrinos are coupled to the  $Z$  boson  
 628 in a universal way. Therefore, by measuring the so-called invisible decay width of the  $Z$   
 629 boson we have an estimate of the number of light (i.e. lighter than the  $Z$  boson) neutrino  
 630 flavours. This number was measured by LEP in a combined analysis of  $e^+ e^- \rightarrow \mu^+ \mu^-$   
 631 and  $e^+ e^- \rightarrow$  hadrons to be  $N_\nu = 2.9840 \pm 0.0082$  [21].

## 632 2.2 Trouble in the neutrino sector

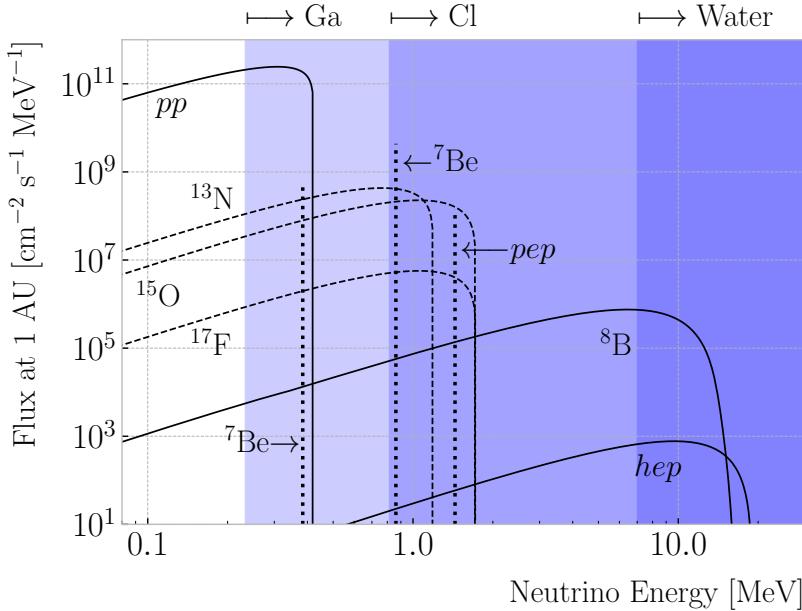
### 633 2.2.1 The solar neutrino problem

634 Neutrinos are produced everywhere in vast amounts. One of the most prominent sources  
 635 of neutrinos in our vicinity is our Sun. The Sun is powered mainly by two nuclear fusion  
 636 reactions, the p – p chain and the CNO cycle. In both cases, the overall reaction is:



637 where part of the released energy is lost to the neutrinos. The electron neutrinos  
 638 produced are often labelled after the processes that generate them. Figure 2.1 shows the  
 639 solar neutrino flux as a function of the neutrino energy, broken down by the production  
 640 process.

## CHAPTER 2. NEUTRINO PHYSICS



**Figure 2.1:** Solar neutrino fluxes for the solar model BS05(OP). The detection thresholds for Gallium, Chlorine and water-based experiments are also shown. Figure adapted from Ref. [1].

In the late 1960s, the Brookhaven Solar Neutrino Experiment, led by R. Davis, started

data taking with the goal of measuring the solar neutrino flux [22]. The experiment

used a tank containing  $380 \text{ m}^3$  of tetrachloroethene ( $\text{C}_2\text{Cl}_4$ ), a liquid commonly used

in dry-cleaning, located 1.5 km underground in the Homestake mine, in Lead, South

Dakota. The incoming neutrinos would get captured following the reaction:

$$\nu_e + {}^{37}\text{Cl} \longrightarrow {}^{37}\text{Ar} + e^-, \quad (2.11)$$

therefore allowing to measure the neutrino flux by counting the  ${}^{37}\text{Ar}$  isotopes. The

threshold for this reaction is 0.814 MeV, just below the 0.862 MeV line from the  ${}^7\text{Be}$

ground state transition.

The results of the experiment were compared to the theoretical predictions made by

J. Bahcall [23]. During its operation from 1968 to 2002, the experiment observed a solar

$\nu_e$  flux that was approximately a third of the total prediction [24].

In the early 1990s, the SAGE [25] and GALLEX [26] experiments started operations.

## 2.2. TROUBLE IN THE NEUTRINO SECTOR

653 The detection principle used for both experiments was similar to that of the Homestake  
 654 experiment, but using  $^{71}\text{Ga}$  instead of  $\text{C}_2\text{Cl}_4$ . With a detection threshold of 0.233 MeV,  
 655 the Gallium-based experiments were able to observe the  $pp$  neutrino flux. Both  
 656 experiments measured a solar electron neutrino flux that was a factor of two lower  
 657 than the predictions, demonstrating that this deficit was energy-dependent.

658 In the early 2000s, the SNO experiment put an end to the solar neutrino puzzle  
 659 [27, 28]. Thanks to its directionality capabilities, being a Cherenkov light detector, as  
 660 well as to its heavy water target, SNO measured the total solar neutrino flux through  
 661 the NC process:

$$\nu_\alpha + d \longrightarrow n + p + \nu_\alpha, \quad (2.12)$$

662 where  $\alpha = e, \mu, \tau$ . This measurement agreed with the solar model predictions. Then,  
 663 measuring the CC reaction:

$$\nu_e + d \longrightarrow p + p + e^-, \quad (2.13)$$

664 they were able to establish that the  $\nu_\mu$  and  $\nu_\tau$  solar fluxes are in fact non-zero, revealing  
 665 that electron neutrinos were transitioning into different flavours.

### 666 2.2.2 The atmospheric neutrino problem

667 When cosmic-rays interact with the atoms in the upper atmosphere, a plethora of  
 668 hadrons, mainly  $\pi$  and  $K$  mesons, are produced. In particular, for the charged pions,  
 669 we have the following decay chain dominates:

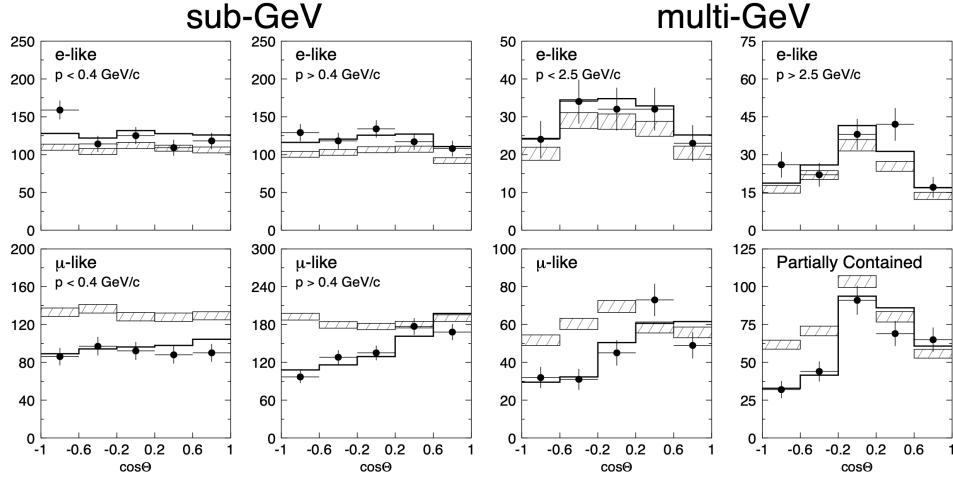
$$\begin{aligned} \pi^+ &\longrightarrow \mu^+ + \nu_\mu, \\ \mu^+ &\longrightarrow e^+ + \bar{\nu}_\mu + \nu_e, \end{aligned} \quad (2.14)$$

670 and similar for the antiparticles. For neutrino energies  $< 1$  GeV, the ratio:

$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)}, \quad (2.15)$$

671 of produced neutrinos and antineutrinos is, in good approximation, equal to two [29].

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**Figure 2.2:** Zenith angle distributions for the selected  $\nu_e$  (top row) and  $\nu_\mu$  (bottom row) events in the SK detector. The hatched region corresponds to the expectation in the case of no oscillations, whereas the solid line indicates the best-fit in the case of  $\nu_\mu \rightarrow \nu_\tau$  oscillations. Figure taken from Ref. [34].

672 During the 1980s, several proton decay experiments, like Kamiokande [30], IMB [31],

673 MACRO [32], and Soudan-2 [33], measured the flux of atmospheric neutrinos. This was  
674 an important part of their research programme, as the atmospheric neutrinos constitute  
675 their main background. All these experiments reported an atmospheric neutrino ratio  
676 lower than the predictions.

677 A few years before the SNO discovery, in 1998, Super-Kamiokande (SK) collaboration

678 measured the atmospheric  $\nu_e$  and  $\nu_\mu$  spectra as a function of the zenith angle [34].  
679 Upward-going particles have negative zenith angle,  $\cos \Theta < 0$ , indicating that they  
680 entered from the bottom of the detector. These upward-going neutrinos had to travel  
681 through the Earth in order to reach the detector, allowing SK to probe a broad range  
682 of baselines. Figure 2.2 shows the reported distributions (black dots), compared to the  
683 no oscillations prediction (hatched region). This measurement confirmed that muon  
684 neutrinos transition to other flavours, and that this phenomenon depends both on the  
685 energy and the path length of the neutrino.

686 The SK and SNO findings provided definitive evidence for the existence of neutrino

687 oscillations, and therefore non-zero neutrino masses. This constitutes one of the  
688 groundbreaking discoveries of modern physics and has acted as driving force for beyond

## 2.3. MASSIVE NEUTRINOS

the Standard Model (BSM) physics. The minimal extension of the SM we can do to address these phenomena is introducing different masses for at least two of the neutrinos. This way, we are left with three neutrino mass eigenstates  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$ , with masses  $m_1$ ,  $m_2$ , and  $m_3$  respectively, which in general will not coincide with the flavour eigenstates,  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$ .

### 2.3 Massive neutrinos

The existence of neutrino oscillations imply that neutrinos are massive particles. However, as we have seen before, within the SM neutrinos are massless, as they do not have a mass term in the Lagrangian. If one wants to give neutrinos a mass, the particle content of the SM needs to be expanded.

A way of generating massive neutrinos while maintaining gauge invariance is by introducing an arbitrary number of sterile neutrinos  $N_i$ ,  $i = 1, \dots, m$ . These allow for two different types of neutrino mass terms:

$$-\mathcal{L}_{M_\nu} = \sum_{i=1}^m \sum_{j=1}^3 M_D^{ij} \bar{N}_i \nu_{Lj} + \frac{1}{2} \sum_{i=1}^m \sum_{j=1}^m M_N^{ij} \bar{N}_i N_j^c + \text{h.c.}, \quad (2.16)$$

where  $M_D$  is a complex  $m \times 3$  matrix and  $M_N$  a complex and symmetric  $m \times m$  matrix. The first term, often referred to as the Dirac mass term, arises from the corresponding Yukawa interaction after the spontaneous electroweak symmetry breaking, similar to the other fermions. The second term, called the Majorana mass term, is allowed in the Lagrangian, as it is a singlet of the gauge group. However, it violates lepton number conservation by two units.

If one imposes lepton number symmetry conservation, the Majorana term must banish,  $M_N = 0$ . In this case, if  $m = 3$  we can identify the sterile neutrinos as the right-handed component of the neutrino field. The Dirac mass matrix can be diagonalised using two unitary matrices,  $V_R^\nu$  and  $V_L^\nu$ , as:

$$M_D = V_R^\nu \text{ diag}(m_1, m_2, m_3) V_L^{\nu\dagger}, \quad (2.17)$$

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712 where  $m_i$ ,  $i = 1, 2, 3$  are the masses of the three neutrino mass eigenstates.

713 The neutrino mass term can be written in term of the resulting eigenstates as:

$$-\mathcal{L}_{M_\nu} = \sum_{i=1}^3 m_i \bar{\nu}_{Di} \nu_{Di}, \quad (2.18)$$

714 with:

$$\nu_{Di} = \left( V_L^{\nu\dagger} \nu_L \right)_i + \left( V_R^{\nu\dagger} N \right)_i. \quad (2.19)$$

715 In this scenario, both the low energy particle budget and the symmetries of the SM  
 716 have to be modified. Moreover, the masses of the neutrinos are generated exclusively  
 717 through the Higgs mechanism, which does not explain why they are much smaller than  
 718 those of the charged leptons.

719 Going back to the general case, we can re-write Eq. (2.16) in matrix form as:

$$-\mathcal{L}_{M_\nu} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c & \bar{N} \end{pmatrix} \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N^c \end{pmatrix} + \text{h.c.} = \bar{\nu}^c M_\nu \nu + \text{h.c.}, \quad (2.20)$$

720 with  $\nu = (\nu_L, N^c)^T$  being a  $(3+m)$ -dimensional vector grouping the active and the  
 721 sterile neutrinos. The matrix  $M_\nu$ , which is a complex  $(3+m) \times (3+m)$  symmetric  
 722 matrix, can be diagonalised by means of a unitary matrix  $V^\nu$ , yielding:

$$M_\nu = V^\nu \text{ diag}(m_1, m_2, \dots, m_{3+m}) V^{\nu T}. \quad (2.21)$$

723 Using this eigendecomposition, the neutrino mass term can be expressed as:

$$-\mathcal{L}_{M_\nu} = \frac{1}{2} \sum_{i=1}^{3+m} m_i \bar{\nu}_{Mi} \nu_{Mi}, \quad (2.22)$$

724 where the states  $\nu_{Mi}$ , commonly referred to as Majorana neutrinos, are defined as:

$$\nu_{Mi} = \left( V^{\nu\dagger} \nu \right)_i + \left( V^{\nu\dagger} \nu \right)_i^c, \quad (2.23)$$

725 in such a way that the Majorana condition,  $\nu_M^c = \nu_M$ , holds true.

## 2.4. NEUTRINO OSCILLATION FORMALISM

726 As a consequence of the Majorana condition, the neutrino and the antineutrino states  
 727 can be described in terms of a single field. As opposed to the charged leptons, which  
 728 need to be represented by a four-component or Dirac spinor, the Majorana neutrino is  
 729 described by a two-component or Weyl spinor.

730 If the eigenvalues of the Majorana mass matrix,  $M_N$ , are much larger than the  
 731 electroweak symmetry breaking scale, the diagonalisation of  $M_\nu$  leads to 3 light and  $m$   
 732 heavy neutrino states:

$$-\mathcal{L}_{M_\nu} = \frac{1}{2}\bar{\nu}_l M_l \nu_l + \frac{1}{2}\bar{\nu}_h M_h \nu_h, \quad (2.24)$$

733 where the two mass matrices are given by:

$$\begin{aligned} M_l &\simeq -V_l^T M_D^T M_N^{-1} M_D V_l, \\ M_h &\simeq V_h^T M_N V_h, \end{aligned} \quad (2.25)$$

734 with  $V_l$  and  $V_h$  two unitary matrices.

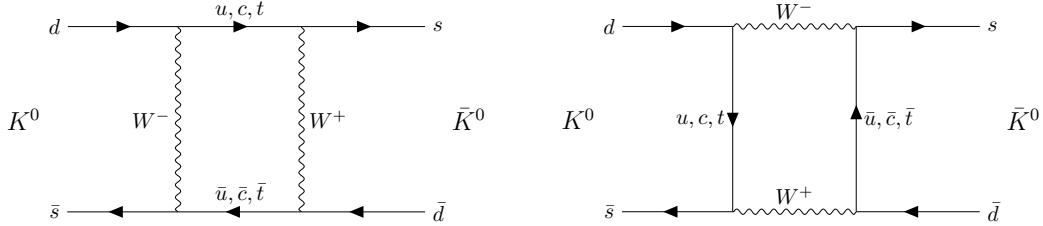
735 This scenario represents the so-called see-saw mechanism [35–39]. The name comes  
 736 from the fact that the masses of the heavy states are proportional to  $M_N$ , whereas for  
 737 the light states they are proportional to  $M_N^{-1}$ . While both the heavy and the light  
 738 neutrinos are Majorana particles, it can be shown that the heavy states are mainly  
 739 right-handed, whereas the light ones are mostly left-handed.

## 740 2.4 Neutrino oscillation formalism

741 Neutrino oscillations were first proposed in 1958 by B. Pontecorvo [40], inspired by the  
 742 neutral kaon oscillation phenomenon [41]. Neutral kaons,  $K^0$  and  $\bar{K}^0$ , have opposite  
 743 strangeness ( $\pm 1$ ) and are produced in strong processes. It was observed that, when  
 744 having a beam initially pure of neutral kaons of one type, these would transition into  
 745 their antiparticles while propagating. Because the weak interaction does not conserve  
 746 strangeness, neutral kaons can change their identity via the processes shown in Fig. 2.3.

747 The mixing considered initially by Pontecorvo was between the neutrino and the

## CHAPTER 2. NEUTRINO PHYSICS



**Figure 2.3:**  $K^0 \rightleftharpoons \bar{K}^0$  mixing through  $W^\pm$  exchange.

748 antineutrino states, as only one neutrino flavour was known at the time. After the  
 749 discovery of the muon neutrino, the mixing between flavours was also explored [42].

750 In the general case, we have 3 active and  $m$  sterile neutrinos, resulting in  $3 + m$   
 751 neutrino mass eigenstates. Working in the mass basis, the leptonic charged-current  
 752 Lagrangian can be written as:

$$-\mathcal{L}_{CC}^{lep} = \frac{g}{\sqrt{2}} (\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L) \gamma^\mu U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \vdots \\ \nu_{3+m} \end{pmatrix} W_\mu^+ + \text{h.c.}, \quad (2.26)$$

753 where  $U$  is a  $3 \times (3 + m)$  matrix which obeys  $UU^\dagger = I_{3 \times 3}$ , but in general will not be  
 754 unitary,  $U^\dagger U \neq I_{(3+m) \times (3+m)}$ .

755 The leptonic mixing matrix,  $U$ , establishes how the neutrino mass states couple to  
 756 the charged leptons. In general, a complex  $n \times n$  matrix can be fully specified by  $2n^2$  real  
 757 parameters. If the matrix is unitary, then the number of independent parameters reduces  
 758 to  $n^2$ , as one has to impose  $n$  normalisation and  $n(n - 1)$  orthogonality constraints.  
 759 In our case, we can further reduce the number of parameters by performing a phase  
 760 redefinition of the charged lepton fields, without affecting the physics. This is not true  
 761 for the neutrinos. As they may be their own antiparticles, one is not allowed to remove  
 762 any physically relevant phases. If we consider  $n$  generations of leptons, the total number  
 763 of parameters in the mixing matrix is  $n^2 - n$ . Out of these, half of them are mixing  
 764 angles, while the other half are complex phase factors.

765 Considering the extended SM without any additional sterile neutrino states, the  
 766 resulting  $3 \times 3$  mixing matrix is unitary. This matrix, often called the Pontecorvo-Maki-

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767 Nakagawa-Sakata (PMNS) matrix [43, 44], relates the set of active neutrinos and the  
768 three mass eigenstates as:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad (2.27)$$

769 where the Greek index  $\alpha$  denotes the flavour  $\{e, \mu, \tau\}$  and the Latin index  $i$  the mass state  
770  $\{1, 2, 3\}$ . This leptonic mixing matrix may be parametrized in terms of 6 parameters, 3  
771 of which are mixing angles  $\theta_{12}$ ,  $\theta_{13}$  and  $\theta_{23}$ , one CP-violating phase  $\delta_{CP}$  and 2 Majorana  
772 phases  $\alpha$  and  $\beta$ :

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}, \quad (2.28)$$

773 where  $c_{ij} \equiv \cos \theta_{ij}$  and  $s_{ij} \equiv \sin \theta_{ij}$ . This matrix is analogous to the Cabibbo-Kobayashi-  
774 Maskawa (CKM) matrix in the quark sector. If neutrinos are Dirac fermions, we can  
775 drop the Majorana phases in the PMNS matrix, as in this case we can perform the  
776 phase redefinitions. However, these phases play no role on the neutrino oscillation  
777 phenomenology.

778 In the case that additional sterile neutrinos states are present, the full leptonic mixing  
779 matrix would not be unitary in general. For instance, in the see-saw scenario, the  $3 \times 3$   
780 submatrix for the three light Majorana neutrinos is not unitary. However, the deviations  
781 from unitarity are of the order  $\mathcal{O}(M_D/M_N)$ , and therefore expected to be negligible.

### 782 2.4.1 Oscillations in vacuum

783 Consider the case where a neutrino of flavour  $\alpha$  is produced at  $t = 0$ , and then it  
784 propagates through vacuum. Such a state will evolve in time according to the relation:

$$|\nu_\alpha(\vec{x}, t)\rangle = \sum_{i=1}^3 U_{\alpha i}^* e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} |\nu_i(\vec{x} = \vec{0}, t = 0)\rangle, \quad (2.29)$$

785 in the plane wave approximation, as the mass eigenstates are also eigenstates of the free  
786 Hamiltonian.

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787 This way, the probability for the neutrino to transition from flavour  $\alpha$  to flavour  $\beta$

788 will be given by:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(\vec{x}, t) \rangle|^2 = \left| \sum_{i=1}^3 \sum_{j=1}^3 U_{\alpha i}^* U_{\beta j} e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \langle \nu_j | \nu_i \rangle \right|^2 \\ = \left| \sum_{i=1}^3 U_{\alpha i}^* U_{\beta i} e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \right|^2, \quad (2.30)$$

789 where we have used the orthogonality relation  $\langle \nu_i | \nu_j \rangle = \delta_{ij}$ . A usual approximation to

790 take at this point is to consider ultra-relativistic neutrinos, i.e.  $p_i \simeq E$ , so we can write

791 the dispersion relations as:

$$E_i = \sqrt{p_i^2 + m_i^2} \approx E + \frac{m_i^2}{2E}. \quad (2.31)$$

792 In the end, assuming  $t \approx L$  where  $L$  is the distance between the production and the

793 detection points, the probability for the  $\nu_\alpha \rightarrow \nu_\beta$  transition becomes:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j} e^{-i \frac{\Delta m_{ij}^2}{2E} L} \\ = \delta_{\alpha\beta} - 4 \sum_{i < j} \Re [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left( \frac{\Delta m_{ij}^2}{4E} L \right) \\ + 2 \sum_{i < j} \Im [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin \left( \frac{\Delta m_{ij}^2}{2E} L \right), \quad (2.32)$$

794 where  $\Delta m_{ij}^2$  is the difference of the squared masses of the  $j$ th and  $i$ th neutrino mass

795 eigenvalues. At this point, it is usual to write the phase responsible for the oscillations

796 as:

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{4E} L \simeq 1.27 \frac{\Delta m_{ij}^2}{(\text{eV}^2)} \frac{L}{(\text{km})} \frac{(\text{GeV})}{E}. \quad (2.33)$$

797 Notice that, in the case of antineutrinos, the only difference would be the sign of the

798 last term in the oscillation probability. As the process  $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$  is the CP-mirror image

799 of  $\nu_\alpha \rightarrow \nu_\beta$ , the differences between their oscillation probabilities would be a measure of

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800 CP symmetry violation:

$$\begin{aligned} A_{CP}^{\alpha\beta} &= P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \\ &= 4 \sum_{i<j} \Im \left[ U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right] \sin 2\Delta_{ij}. \end{aligned} \quad (2.34)$$

801 Assuming that CPT invariance holds, then the following relation must be true:

$$P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha), \quad (2.35)$$

802 as these two process are related by the CPT symmetry. From the definition of probability,  
803 we also must have:

$$\sum_\beta P(\nu_\alpha \rightarrow \nu_\beta) = \sum_\beta P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = 1, \quad (2.36)$$

804 where the sum includes all flavours, including  $\alpha$ . From these two constraints, one can  
805 probe that:

$$A_{CP}^{\alpha\beta} = -A_{CP}^{\beta\alpha}, \quad (2.37)$$

806 and in particular:

$$A_{CP}^{\alpha\alpha} = 0. \quad (2.38)$$

807 A direct consequence of this last relation is that there are no observable CP-violating  
808 effects in the so-called disappearance experiments. One needs to perform appearance  
809 experiments, where the flavour detected is different from the original flavour, in order  
810 to measure the CP asymmetry. Neutrino experiments often report the amount of CP-  
811 violation through the Jarlskog invariant. In terms of the parametrisation typically used  
812 to write the PMNS matrix, it is given by:

$$J = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta_{CP}. \quad (2.39)$$

813 The Jarlskog invariant can be used to compare the amount of CP-violation in the lepton  
814 and the quark sectors, where  $J = 3.12^{+0.13}_{-0.12} \times 10^{-5}$  in the latter [45].

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### 2.4.2 Oscillations in matter

When neutrinos propagate through matter, their oscillation can be affected in mainly two ways. First, neutrinos can inelastically scatter with nuclei, thus destroying the coherent propagation of their quantum state. Nevertheless, in most cases this effect is negligible (even in very dense mediums like the core of the Sun). Second, neutrinos can also experience coherent or forward scatterings, that can affect their oscillation but not lose the coherent propagation of the state.

The first proposed model to account for neutrino oscillations in matter was proposed by Mikhaev, Smirnov and Wolfenstein (MSW) [46]. It relies on the fact that, as the only charged lepton present in ordinary matter is the electron, electron neutrinos can undergo both charged and neutral-current interactions with matter whereas for muon and tau neutrinos just neutral currents are possible.

An illustrative way to introduce the MSW mechanism is by considering the two flavours case. It can be shown that the evolution of the two flavour eigenstates in vacuum is given by the following time-dependent Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = H_V \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \quad (2.40)$$

with a vacuum Hamiltonian given by:

$$H_V = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}, \quad (2.41)$$

where  $\Delta m^2$  is the mass splitting between the two neutrino states and  $\theta$  the only mixing angle. For simplicity, I omit the terms of the Hamiltonian that are proportional to the identity, as they do not affect the oscillation phenomenology.

The NC contribution to the matter potential is identical for all the flavours, and has the form:

$$V_{NC} = -\frac{G_F}{\sqrt{2}} N_n(x), \quad (2.42)$$

## 2.4. NEUTRINO OSCILLATION FORMALISM

836 where  $G_F$  is the Fermi constant and  $N_n(x)$  the local neutron density. Because it is  
 837 common to all flavours, I do not take it into account in the effective Hamiltonian, as it  
 838 would appear as a term proportional to the identity. The CC component only affects  
 839 the electron neutrino (and antineutrino). It can be written as:

$$V_{\text{CC}} = \pm \sqrt{2} G_F N_e(x), \quad (2.43)$$

840 with  $N_e(x)$  being the local electron density in the material. In the end, the effective  
 841 Hamiltonian which describes the propagation of the flavour eigenstates in matter only  
 842 contains an extra  $\nu_e - \nu_e$  element:

$$H_M = H_V + \begin{pmatrix} V_{\text{CC}} & 0 \\ 0 & 0 \end{pmatrix}. \quad (2.44)$$

843 The solution to the Schrödinger equation greatly simplifies if one considers the case  
 844 of a constant matter density. In that case, the effective Hamiltonian can be diagonalised,  
 845 obtaining the effective neutrino mass eigenstates in matter. It can be re-written in the  
 846 same form as the vacuum Hamiltonian:

$$H_M = \frac{\Delta m_m^2}{4E} \begin{pmatrix} -\cos 2\theta_m & \sin 2\theta_m \\ \sin 2\theta_m & \cos 2\theta_m \end{pmatrix}, \quad (2.45)$$

847 where the effective mass splitting and the effective mixing angle are given by:

$$\begin{aligned} \Delta m_m^2 &= \lambda \Delta m_m^2, \\ \sin 2\theta_m &= \frac{\sin 2\theta_m}{\lambda} \end{aligned} \quad (2.46)$$

848 with:

$$\begin{aligned} \lambda &= \sqrt{(\cos 2\theta - A)^2 + \sin^2 2\theta}, \\ A &= \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}. \end{aligned} \quad (2.47)$$

849 In terms of the effective matter oscillation parameters, the transition probability

## CHAPTER 2. NEUTRINO PHYSICS

850  $\nu_e \rightarrow \nu_\mu$  (in the two flavour approximation) reads:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_m \sin^2 \left( \frac{\Delta m_m^2}{2E} L \right) \quad (2.48)$$

851 From this last equation one can see that, when  $\cos 2\theta = A > 0$  the oscillations are  
852 greatly enhanced. This effect is known as the MSW resonance. For the neutrinos, this  
853 resonant condition is only satisfied if  $\Delta m^2 > 0$  (the opposite is true for antineutrinos).  
854 This is can be exploited by long baseline experiments, which can gain sensitivity to the  
855 neutrino mass hierarchy through matter effects.

### 856 2.4.3 Current status of neutrino oscillations

857 A wide range of neutrino experiments provide experimental input to the neutrino  
858 oscillation framework, both using natural or synthetic neutrino sources. The results  
859 from one of the neutrino global fit analyses, shown in Tab. 2.3<sup>1</sup>, summarise well our  
860 current understanding of the different oscillation parameters.

861 **Solar neutrino experiments** detect neutrinos produced in thermonuclear reactions  
862 inside the Sun, mainly from the so-called *pp* chain and the CNO cycle. These neutrinos  
863 have a typical energy in the range from 0.1 to 20 MeV. These experiments (Homestake  
864 [47], GALLEX [26], SAGE [25], Borexino [48], Super-Kamiokande [49] and SNO [50])  
865 provide the best sensitivities to  $\theta_{12}$  and  $\Delta m_{21}^2$ .

866 **Atmospheric neutrino experiments** detect the neutrino flux produced when  
867 cosmic rays scatter with particles in Earth's atmosphere. These collisions generate particle  
868 showers that eventually produce electron and muon neutrinos (and antineutrinos). Their  
869 energies range from few MeV to about  $10^9$  GeV. Experiments, like Super-Kamiokande  
870 [51] and IceCube [52] use atmospheric neutrinos to measure oscillations and are specially  
871 sensitive to  $\theta_{23}$  and  $\Delta m_{32}^2$ .

872 **Reactor neutrino experiments** look for the  $\bar{\nu}_e$  spectrum produced by nuclear  
873 reactors, with energies in the MeV scale. Depending on the distance to the source,

<sup>1</sup>These are the results reported during M. Tórtola's talk at Neutrino 2024 (see this link). I need to keep an eye and see if they publish these or other updated results in the near future.

## 2.5. OPEN QUESTIONS IN THE NEUTRINO SECTOR

**Table 2.3:** Summary of neutrino oscillation parameters determined in the Neutrino Global Fit of 2020 [14].

Parameter	Best fit $\pm 1\sigma$	$3\sigma$ range
$\Delta m_{21}^2$ [eV $^2 \times 10^{-5}$ ]	$7.55^{+0.22}_{-0.20}$	6.98 – 8.19
$ \Delta m_{31}^2 $ [eV $^2 \times 10^{-3}$ ] (NO)	$2.51^{+0.02}_{-0.03}$	2.43 – 2.58
$ \Delta m_{31}^2 $ [eV $^2 \times 10^{-3}$ ] (IO)	$2.41^{+0.03}_{-0.02}$	2.34 – 2.49
$\sin^2 \theta_{12}/10^{-1}$	$3.04 \pm 0.16$	2.57 – 3.55
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23 – 6.04
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27 – 6.03
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03 – 2.38
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04 – 2.38
$\delta_{CP}/\pi$ (NO)	$1.12^{+0.16}_{-0.12}$	0.76 – 2.00
$\delta_{CP}/\pi$ (IO)	$1.50^{+0.13}_{-0.14}$	1.11 – 1.87

874 long-baseline experiments like KamLAND [53] are sensitive to the solar mass splitting  
875  $\Delta m_{21}^2$  whereas much shorter baseline experiment such as RENO [54] or DayaBay [55]  
876 measure  $\theta_{13}$  and  $\Delta m_{31}^2$ .

877 **Accelerator experiments** measure neutrino fluxes generated in particle accelerators.  
878 Usually mesons are produced in the accelerator to be focused into a beam, then some  
879 decay to muon neutrinos and the rest are absorbed by a target. Depending on the  
880 configuration one can obtain a beam made of mostly neutrinos or antineutrinos. The  
881 typical energies of these neutrinos are in the GeV range. Experiments such as NOvA  
882 [56], T2K [57], MINOS [58], OPERA [59] and K2K [60] (and in the future DUNE [61])  
883 are primarily sensitive to  $\theta_{13}$ ,  $\theta_{23}$  and  $\Delta m_{32}^2$ . Also, in the coming years DUNE [61] and  
884 Hyper-Kamiokande [62] will be sensitive to  $\delta_{CP}$ .

885 **2.5 Open questions in the neutrino sector**

886 A crucial question that remains open these days, and is of vital importance for oscillation  
887 phenomena, is whether the mass eigenvalue  $\nu_3$  is the heaviest (what we call normal  
888 ordering) or the lightest (referred to as inverted ordering) of the mass eigenstates. In

## CHAPTER 2. NEUTRINO PHYSICS

other words, this means that we do not know the sign of  $\Delta m_{32}^2$ , so we can either have  $m_1 < m_2 < m_3$  (NO) or  $m_3 < m_1 < m_2$  (IO).

Another big puzzle is related to the value of  $\delta_{CP}$ . Nowadays it is poorly constrained, with all values between  $\pi$  and  $2\pi$  being consistent with data. A prospective measurement different from  $\delta_{CP} = 0, \pi$  will predict CP-violation in the leptonic sector, and thus contribute along with the one measured in the quark sector to the total amount of CP-violation. Although it is true that these two contributions by themselves are not enough to explain the matter anti-matter asymmetry in our universe, the amount of CP-violation in the leptonic sector can be key to explain such imbalance.

Both of these questions, because of their nature, could be understood thanks to future oscillation experiments.

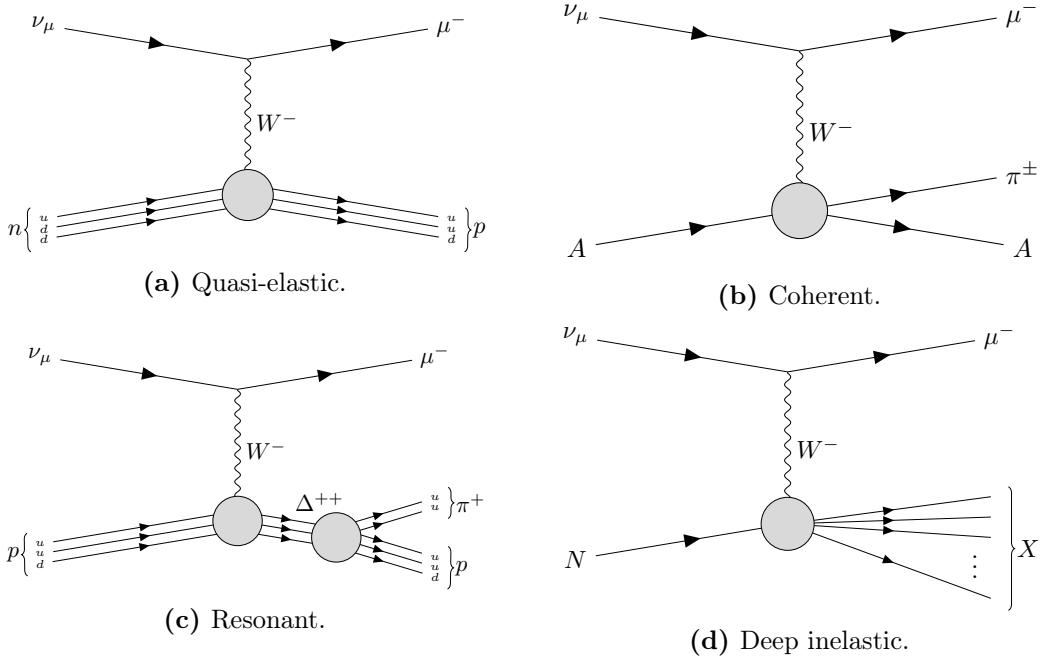
Notwithstanding, there are other mysteries that can not be unveiled just by conducting oscillation experiments, as certain quantities do not influence these phenomena. Among these there is the question of the absolute values of the neutrino masses. Depending on the value of the lightest of the neutrino masses we can have different mass spectra, from hierarchical  $m_1 \ll m_2 < m_3$  (NO) or  $m_3 \ll m_1 < m_2$  (IO) to quasi-degenerate  $m_1 \simeq m_2 \simeq m_3$ .

Other open question concerns the nature itself of the neutrinos. If neutrinos are Dirac particles then their mass term can be generated through the usual Higgs mechanism by adding right-handed neutrino fields. However, if they are Majorana particles and therefore their own antiparticles, there is no need to add extra fields to have the mass term in the Lagrangian. Experiments like SuperNEMO [63], SNO+ [64] and NEXT [65], which search for neutrino-less double beta decay, will be able to determine whether neutrinos are Dirac or Majorana.

## 2.6 Neutrino interactions

The study of neutrino-nucleus interactions is of great importance for long baseline neutrino oscillation experiments. The interaction model provides a mapping between

## 2.6. NEUTRINO INTERACTIONS

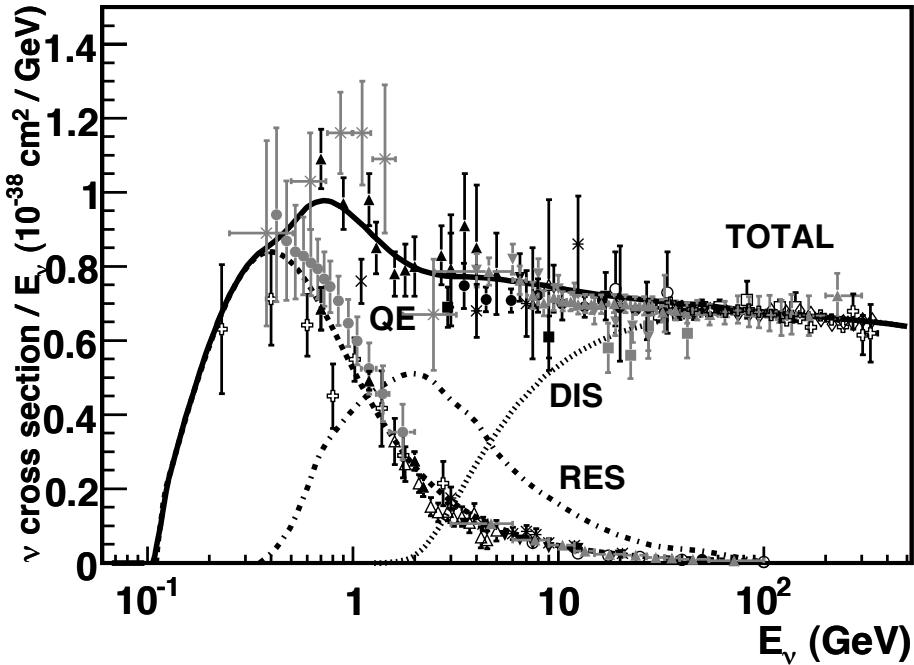


**Figure 2.4:** Feynman diagrams of the four most relevant CC interactions to long baseline neutrino oscillation experiments.

the energy of the incoming neutrino and the final state particles after the interaction.  
 Because in this kind of experiments neutrinos are obtained as secondary decay products of mesons, typically charged pions and kaons, their energies are not known a priori. Not only that, but the kinematics of the interacting nucleon are also unknown. Therefore, we rely on the neutrino interaction models to provide this relation between the observables in the detector and the true kinematics of the neutrino. Interaction modelling is expected to be the one of the leading sources of systematic uncertainties in the next generation of long baseline experiments [66–68].

In the case of neutrino interactions with nuclei, at the energies relevant for long baseline oscillation experiments, around the GeV-scale, the process is dominated by the interaction between the neutrino and a single nucleon within the nuclear medium. Figure 2.4 shows examples of the four most common neutrino CC interactions. In this diagrams  $A$  indicated that the interaction happened with the nucleus as a whole, whereas  $N$  denotes a single nucleon.

At low energies, below 1 GeV, quasi-elastic (QE) interactions dominate. In a CCQE

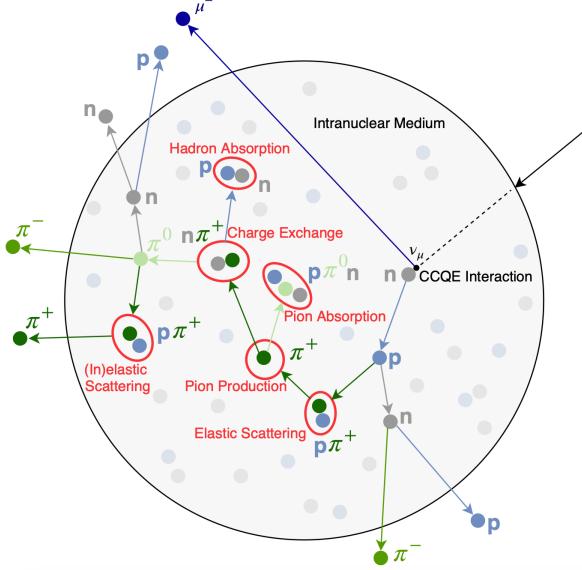


**Figure 2.5:** Total  $\nu_\mu$  CC cross section per nucleon as a function of the neutrino energy. The contributions from the different channels are shown. Figure taken from Ref. [69].

931 interaction a neutrino (antineutrino) interacts with a neutron (proton), converting it into  
 932 a proton (neutron) which is then ejected from the nucleus together with the resulting  
 933 charged lepton. At energies above 1 GeV the neutrino is able to excite the nucleon  
 934 into a baryonic resonance, which promptly decays into a nucleon and a pion. These are  
 935 the so-called resonant (RES) interactions. Neutrinos also interact with entire nucleus  
 936 coherently, in the process known as coherent (COH) interaction. This kind of reactions  
 937 also produce a single pion in the final state. At high neutrino energies, above 5 GeV,  
 938 deep inelastic scattering (DIS) takes place. In these processes, the neutrino interacts  
 939 with a single quark within the nucleon, breaking the nucleon and producing a hadronic  
 940 shower.

941 Figure 2.5 shows a compilation of measurements of the total  $\nu_\mu$  CC cross section  
 942 (see Ref. [69] for the details of the different experimental results). Also shown are the  
 943 contributions from the different interaction modes. The contribution of the CCCOH  
 944 interaction is omitted, as it is negligible compared to the others. This shows how the

## 2.6. NEUTRINO INTERACTIONS



**Figure 2.6:** Schematic representation of a  $\nu_\mu$  CCQE interaction with a neutron inside a nucleus. The reaction produces a muon and a proton, which travel through the nuclear medium. The outgoing proton undergoes various kinds of hadronic FSIs on its way out. Figure taken from Ref. [70].

interaction model needs to accurately predict the neutrino-nucleon cross section for the different interaction modes across a broad energy range, to obtain the correct relative contributions.

Nuclear effects alter the neutrino cross section, as well as the multiplicities of the final state particles. Therefore, the interaction models need to account for the effects introduced by the nuclei. There are several models available to describe the initial state of the nucleus, like the relativistic Fermi gas model [71], spectral functions [72] or the random phase approximation [73]. The other main effect that interaction models have to deal with are the so-called final state interactions (FSI). These are the interactions of the particles produced in the neutrino-nucleon scattering as they travel through the nuclear medium. Typically, the lepton exits the nucleus without interacting. However, hadrons tend to get scattered, absorbed or re-emitted. These effects are usually described by means of intra-nuclear cascade models [74]. Figure 2.6 illustrates the effects of FSI on the observable particle content in the detector after a  $\nu_\mu$  CCQE interaction.

There exists a rich experimental programme dedicated to the measurement of neutrino

## CHAPTER 2. NEUTRINO PHYSICS

960 cross sections. The list of such experiments in the recent years include MiniBooNE  
961 [75], MINERvA [76], MicroBooNE [77] and SBND [78]. Additionally, thanks to their  
962 near detectors, long baseline experiments can perform cross section measurements.  
963 Some recent examples are NOvA [79] or T2K [80]. Future oscillation experiments  
964 will greatly benefit from these measurements, as the measurement of the oscillation  
965 parameters depends on the cross section modelling. However, there are alternative  
966 data-driven approaches to extract the oscillation probabilities without relying on a  
967 neutrino interaction model, which are planned to be explored in the next generation of  
968 experiments [81, 82].

970

# The Deep Underground Neutrino 971 Experiment

972 The Deep Underground Neutrino Experiment (DUNE) is a next generation long-baseline  
973 neutrino experiment [83]. It will aim to address several questions in neutrino physics,  
974 study neutrinos from astrophysical sources and search for beyond the standard model  
975 physics.

976 This chapter reviews the main goals of the DUNE experiment, the design of the far  
977 detector modules and their data acquisition (DAQ) system, and the role that the near  
978 detector plays in the physics program of DUNE.

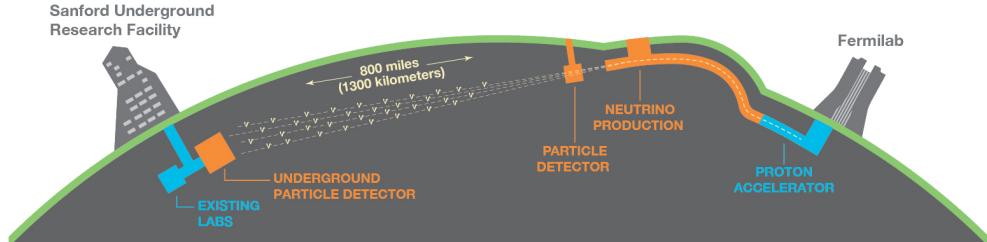
## 979 3.1 Overview

980 The main physics goals of DUNE are:

- 981 • measure the neutrino mass hierarchy, the amount of CP violation in the leptonic  
982 sector and the  $\theta_{23}$  octant,
- 983 • detect rare low energy neutrino events, like neutrinos from supernova bursts, and
- 984 • search for proton decay and other beyond the standard model phenomena.

985 The design of DUNE has been tailored with these goals in mind. It will consist  
986 of two neutrino detectors. A near detector (ND) complex will be placed at Fermilab,  
987 574 m downstream of the neutrino production point, whereas a larger far detector

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



**Figure 3.1:** Schematic diagram of the DUNE experiment and the LBNF beamline [83].

988 (FD) will be built in the Sandford Underground Research Facility (SURF), South  
 989 Dakota, approximately 1300 km away. Figure 3.1 shows a simplified view of the various  
 990 components of DUNE (not to scale).

991 The beam neutrinos will be provided by the Long-Baseline Neutrino Facility (LBNF)  
 992 beamline, the multi-megawatt wide-band neutrino beam planned for Fermilab. It will  
 993 produce neutrinos travelling in the direction of SURF, with the capability to switch  
 994 between neutrino and antineutrino mode.

995 Before arriving to the FD, the neutrino beam meets the ND complex, which serves  
 996 as the experiment's control. The design of the DUNE ND is mainly driven by the  
 997 needs of the oscillation physics program, as its main role is to measure the unoscillated  
 998 neutrino energy spectra. From these we can predict the unoscillated spectra at the FD,  
 999 which can be compared to the spectra measured at the FD to extract the oscillation  
 1000 parameters. Additionally, the ND has a physics programme of its own, including cross  
 1001 section measurements and BSM physics searches.

1002 The technology chosen for the FD modules of DUNE is the liquid Argon time  
 1003 projection chamber (LArTPC). Its four modules will record neutrino interactions from  
 1004 the accelerator-produced beam arriving at predictable times. As it also aims at recording  
 1005 rare and low energy events, like supernovae and solar neutrinos, the FD requires trigger  
 1006 schemes which can deal with both kinds of physics, and also maximum uptime.

1007 DUNE is planned to be built using a staged approach consisting on two phases,  
 1008 which are summarised in Tab. 3.1. Phase I consists of a FD with 50% of the total

### 3.2. PHYSICS GOALS OF DUNE

**Table 3.1:** Summary of the two-phased plan for DUNE. Adapted from Ref. [84].

Parameter	Phase I	Phase II	Benefit
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	2.4 MW	FD statistics
ND config.	ND-LAr, TMS, SAND	ND-LAr, ND-GAr, SAND	Systematic constraints

**Table 3.2:** Exposure and time required to achieve the different physics milestones of the two phases. The predictions assume a Phase II staging scenario where FD modules 3 and 4 are deployed in years 4 and 6 and both the beam and ND are upgraded after 6 years. Adapted from Ref. [84].

Stage	Physics milestone	Exposure (kt-MW-years)	Years (staged)
Phase I	$5\sigma$ MO ( $\delta_{CP} = -\pi/2$ )	16	1-2
	$5\sigma$ MO (100% of the $\delta_{CP}$ values)	66	3-5
	$3\sigma$ CPV ( $\delta_{CP} = -\pi/2$ )	100	4-6
Phase II	$5\sigma$ CPV ( $\delta_{CP} = -\pi/2$ )	334	7-8
	$\delta_{CP}$ resolution of 10 degrees ( $\delta_{CP} = 0$ )	400	8-9
	$5\sigma$ CPV (50% of the $\delta_{CP}$ values)	646	11
	$3\sigma$ CPV (75% of the $\delta_{CP}$ values)	936	14
	$\sin^2(2\theta_{13})$ resolution of 0.004	1079	16

1009 fiducial mass, a reduced version of the ND complex and a 1.2 MW proton beam. It will  
 1010 be sufficient to achieve some early physics goals, like the determination of the neutrino  
 1011 mass ordering. For its Phase II, DUNE will feature the full four FD modules, a more  
 1012 capable ND and a 2.4 MW proton beam. The physics milestones for the two phases are  
 1013 given in Tab. 3.2, in a staging scenario which assumes that Phase II is completed after  
 1014 6 years of operation.

1015 A summary of the DUNE science program can be found in the DUNE FD Technical  
 1016 Design Report (TDR) Volume I [83]. For a detailed discussion on the two-phased  
 1017 approach the reader is referred to the DUNE Snowmass 2021 report [84].

### 1018 3.2 Physics goals of DUNE

1019 As noted in the literature (see for instance Ref. [14] for a review), the parameter space of  
 1020 the neutrino oscillation phenomena within the three-flavour picture is quite constrained

### CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

1021 by current experimental data. However, there are still crucial open questions, like the  
1022 mass ordering, the value of  $\delta_{CP}$  or the  $\theta_{23}$  octant. One of the main goals of DUNE is to  
1023 determine precisely the values of these parameters [85].

1024 To address these questions DUNE can look to the subdominant oscillation channel  
1025  $\nu_\mu \rightarrow \nu_e$  ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ ) and study the energy dependence of the  $\nu_e$  ( $\bar{\nu}_e$ ) appearance probability.  
1026 When we focus on the antineutrino channel  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  there is a change in the sign of  $\delta_{CP}$ ,  
1027 thus introducing CP-violation. Moreover, due to the fact that there are no positrons in  
1028 the composition of Earth, there is a sign difference for the matter effect contribution  
1029 when looking to the antineutrino channel. This asymmetry is proportional to the baseline  
1030 length  $L$  and is sensitive to the sign of  $\Delta m_{31}^2$ , and thus to the neutrino mass ordering.

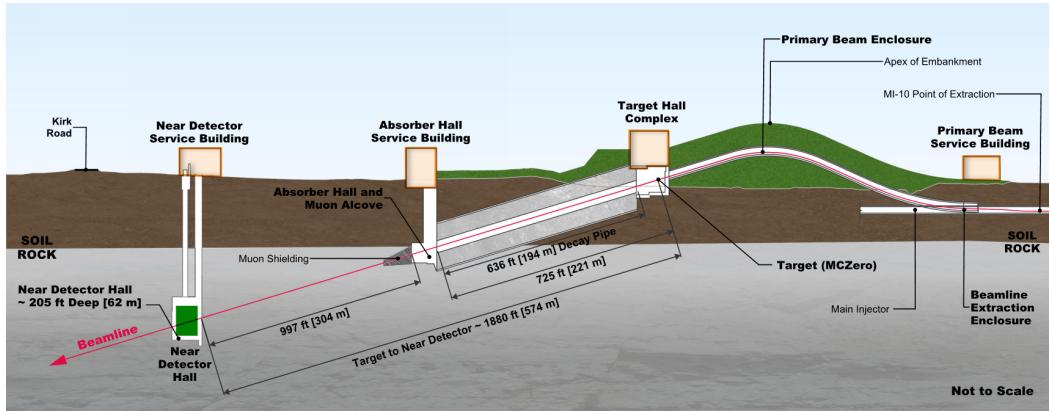
1031 Another of the main physics goals of DUNE is the search for baryon-number violating  
1032 processes. Specifically, it will try to answer the question of whether protons are stable  
1033 or not. There is no symmetry argument that forbids protons from decaying, but its  
1034 apparent stability seems to suggest that baryon number is conserved [86]. However,  
1035 proton decay is a usual feature of grand-unified theories, where electromagnetic, weak  
1036 and strong interactions are unified above a certain energy scale [87].

1037 As the energy deposition scale for this kind of searches is nearly the same as the one  
1038 for long-baseline neutrino oscillations, DUNE will be able to look for them. It has several  
1039 advantages over other experiments, such as excellent imaging and particle identification,  
1040 which can be translated to lower backgrounds.

1041 The last of the main objectives of DUNE is the detection of neutrinos originated in  
1042 supernovae explosions, what is called a supernova neutrino burst (SNB). These neutrinos  
1043 carry with them information about the core-collapse process, from the progenitor to the  
1044 explosion and the remnant; but also may have information about new exotic physics. So  
1045 far, the only neutrino events ever recorded from such a process were a few dozens of  $\bar{\nu}_e$   
1046 events from the 1987A supernova located in the Magellanic Cloud, 50 kpc away from  
1047 Earth [88, 89].

1048 DUNE aims to collect SNB events. Although these are quite rare, as the expected  
1049 supernovae explosion events are about one every few decades for our galaxy and

### 3.3. LBNF BEAMLINE



**Figure 3.2:** Schematic longitudinal section of the LBNF beamline at Fermilab (not to scale). Figure taken from Ref. [90].

1050 Andromeda, the long lifetime of the experiment (around a few decades as well) makes it  
 1051 reasonable to expect some. Nowadays the main sensitivity to SNB of most experiments  
 1052 is to the  $\bar{\nu}_e$  through inverse beta decay. One of the advantages of DUNE is its expected  
 1053 sensitivity to  $\nu_e$ , since the dominant channel will be  $\nu_e$  CC scattering.

1054 Moreover, due to the stringent requirements that the main physics goals set for  
 1055 DUNE, it will allow also to perform searches for all kind of BSM physics. Among  
 1056 others, DUNE will be able to look for: active-sterile neutrino mixing, non-unitarity of  
 1057 the PMNS matrix, non-standard interactions, Lorentz and CPT violations, neutrino  
 1058 trident production, light-mass DM, boosted DM and heavy neutral leptons. The reader  
 1059 is referred to the DUNE FD TDR Volume II [85] for a full discussion of the physics  
 1060 scope of DUNE.

### 1061 3.3 LBNF beamline

1062 The LBNF project is responsible for producing the neutrino beam for the DUNE detectors.  
 1063 A detailed discussion of the LBNF program can be found in the DUNE/LBNF CDR  
 1064 Volume III [90].

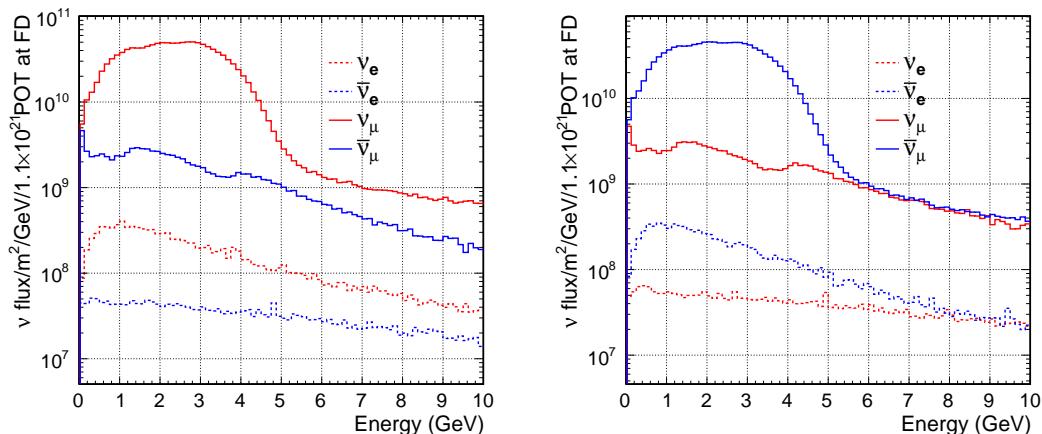
1065 A schematic diagram of the longitudinal section of the LBNF beamline is shown in  
 1066 Fig. 3.2. First, a beam of 60 – 120 GeV protons is extracted from the Fermilab Main  
 1067 Injector. This beam is aimed towards the target area, where it collides with a cylindrical

### CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

graphite target to produce pions and kaons.

The diffuse, secondary beam of particles is focused by a pair of magnetic horns. These select the positively charged particles when operated in Forward Horn Current (FHC) mode, or the negatively charged ones when the current is reversed, also known as Reverse Horn Current (RHC) mode. The focused secondary beam then enters a 194 m decay pipe where the pions and kaons will predominantly produce  $\mu^+\nu_\mu$  pairs when in FHC mode (or  $\mu^-\bar{\nu}_\mu$  in RHC mode).

At the end of the decay pipe a hadron absorber removes the undecayed hadrons and muons from the beam, which reduces the  $\nu_e$  ( $\bar{\nu}_e$ ) and  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) contamination coming from the  $\mu^+$  ( $\mu^-$ ) decays. The resulting neutrino flux at the FD is shown in Fig. 3.3, both for FHC (left) and RHC (right) modes. These predictions show the intrinsic  $\nu_e$  contamination and wrong sign component from wrong sign and neutral meson decays, as well as muons decaying before reaching the absorber.

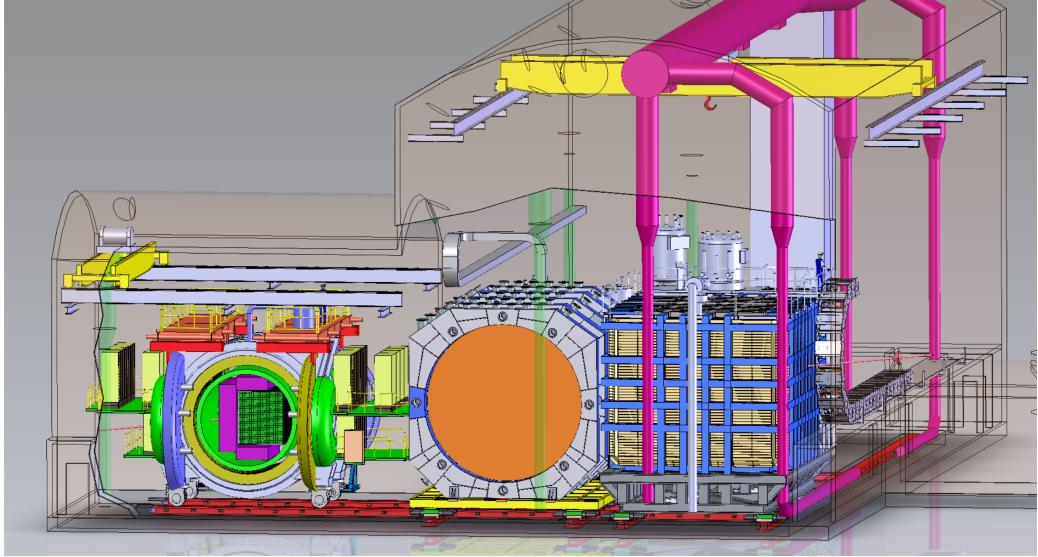


**Figure 3.3:** Predicted neutrino fluxes at the FD in FHC mode (left panel) and RHC mode (right panel). Figures taken from Ref. [85].

### 3.4 Near Detector

To estimate the oscillation parameters we measure the neutrino energy spectra at the FD. This reconstructed energy arises from a convolution of the neutrino flux, cross section, detector response and the oscillation probability. Using theoretical and empirical models

### 3.4. NEAR DETECTOR



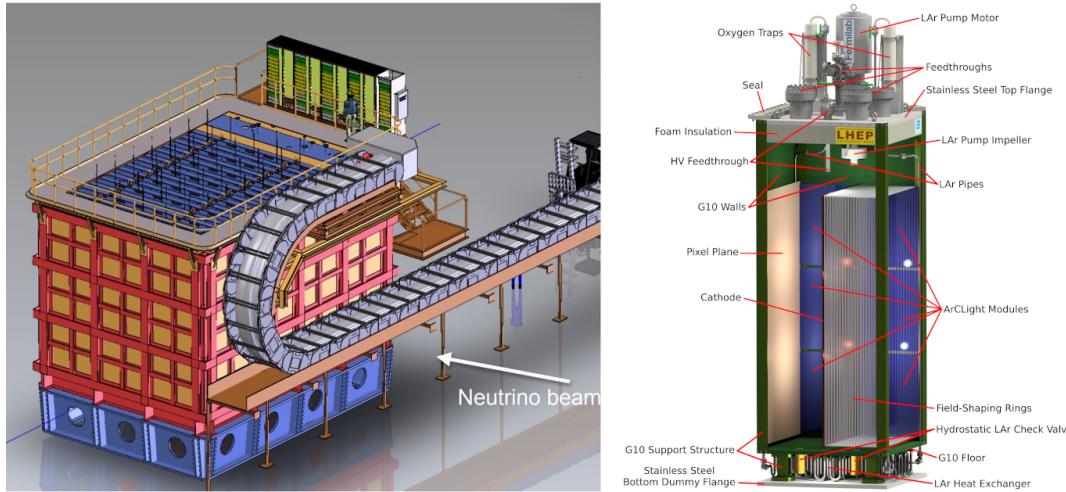
**Figure 3.4:** Representation of the ND hall in Phase II, showing the different subcomponents. From right to left, in the direction of the beam, we have ND-LAr, ND-GAr and SAND. Figure taken from Ref. [91].

1085 to account for the other effects, one can extract the oscillation probability using the  
 1086 measurement. However, these models have associated a number of uncertainties that  
 1087 are then propagated to the oscillation parameters.

1088 One of the main roles of the ND is to measure the neutrino interaction rates before  
 1089 the oscillation effects become relevant, i.e. close to the production point. By measuring  
 1090 the  $\nu_\mu$  and  $\nu_e$  energy spectra, and that of their corresponding antineutrinos, at the ND  
 1091 we can constrain the model uncertainties. A complete cancellation of the uncertainties  
 1092 when taking the ratio between the FD and ND measurements is not possible, as that  
 1093 would require both detectors to have identical designs and the neutrino fluxes to be  
 1094 the same. Because of the distance, the flux probed by the FD will have a different  
 1095 energy and flavour composition than that at the ND, as neutrinos oscillate and the beam  
 1096 spreads. The differences in the flux also determine the design of the detectors, therefore  
 1097 the ND is limited in its capability to match the FD design.

1098 Nevertheless, having a highly capable ND, DUNE can minimise the systematic  
 1099 uncertainties affecting the observed neutrino energy. The ND data can be used to  
 1100 tune the model parameters by comparison with the prediction. Then, one uses the

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



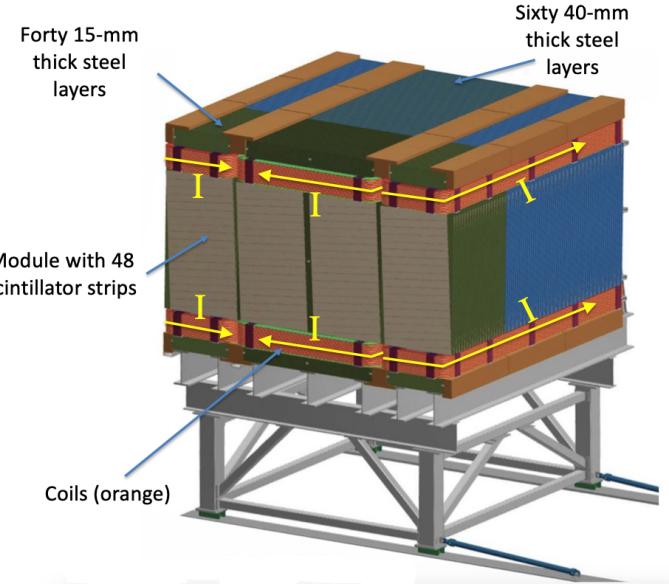
**Figure 3.5:** Schematic representation of the external components of ND-LAr, including the cryostat and the PRISM movable system (left) and detailed drawing of one ArgonCube module (right). Figure adapted from Ref. [83].

1101 tuned model to predict the unoscillated FD spectra. Comparing the prediction with the  
 1102 measured spectra it is possible to extract the oscillation parameters.

1103 Additionally, the ND will have a physics program of its own. In particular, it will  
 1104 measure neutrino cross sections that will then be used to constrain the model used in  
 1105 the long-baseline oscillation analysis. It will also be used to search for BSM phenomena  
 1106 such as heavy neutral leptons, dark photons, millicharged particles, etc.

1107 The DUNE ND can be divided in three main components, a LArTPC known as ND-  
 1108 LAr, a magnetised muon spectrometer, which will be the Temporary Muon Spectrometer  
 1109 (TMS) in Phase I and ND-GAr in Phase II, and the System for on-Axis Neutrino  
 1110 Detection (SAND). The layout of the Phase II DUNE ND can be seen in Fig. 3.4. The  
 1111 first two components of the ND will be able to move off-axis, in what is called the  
 1112 Precision Reaction-Independent Spectrum Measurement (PRISM) concept. More details  
 1113 on the purpose and design of the ND can be found in the DUNE ND Conceptual Design  
 1114 Report (CDR) [91].

### 3.4. NEAR DETECTOR



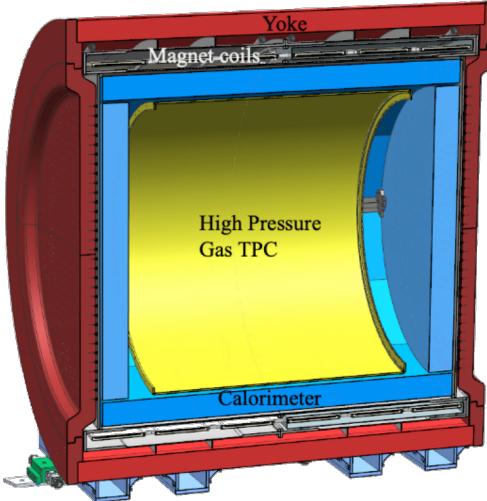
**Figure 3.6:** Schematic view of the TMS detector, highlighting its main parts. Figure adapted from Ref. [83].

#### 3.4.1 ND-LAr

ND-LAr is a LArTPC, as the ND needs a LAr component to reduce cross section and detector systematic uncertainties in the oscillation analysis. However, its design differs significantly from those proposed for the FD modules. Because of the high event rates at the ND, approximately 55 neutrino interaction events per  $10 \mu\text{s}$  spill, ND-LAr will be built in a modular way. Each of the modules, based on the ArgonCube technology, is a fully instrumented, optically isolated TPC with a pixelated readout. The pixelisation allows for a fully 3D reconstruction and the optical isolation reduces the problems due to overlapping interactions. Figure 3.5 shows a representation of the external parts of ND-LAr (left) and a detailed diagram of an ArgonCube module (right).

With a fiducial mass of 67 t and dimensions  $7 \text{ m} (\text{w}) \times 3 \text{ m} (\text{h}) \times 5 \text{ m} (\text{l})$ , ND-LAr will be able to provide high statistics and contain the hadronic systems from the beam neutrino interactions, but muons with a momentum higher than 0.7 GeV will exit the detector.

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



**Figure 3.7:** Cross section of the ND-GAr geometry, showing the HPgTPC, ECal and magnet. Figure adapted from Ref. [92].

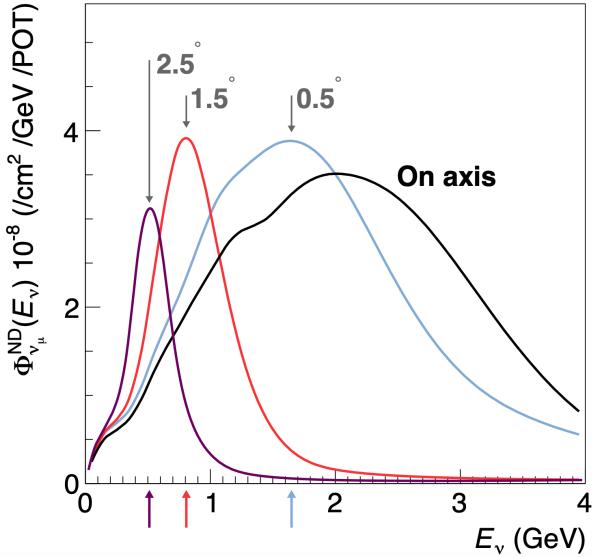
### <sup>1129</sup> 3.4.2 TMS/ND-GAr

<sup>1130</sup> To accurately estimate the neutrino energy, the momentum of the outgoing muons needs  
<sup>1131</sup> to be determined. That is the reason why a muon spectrometer is needed downstream  
<sup>1132</sup> of ND-LAr.

<sup>1133</sup> In Phase I that role will be fulfilled by TMS. It is a magnetised sampling calorimeter,  
<sup>1134</sup> with alternating steel and plastic scintillator layers. Figure 3.6 shows a schematic view  
<sup>1135</sup> of the TMS detector. The magnetic field allows a precise measurement of the sign of the  
<sup>1136</sup> muon, so one can distinguish between neutrino and antineutrino interactions.

<sup>1137</sup> After the Phase II upgrade, TMS will be replaced with a more capable near detector.  
<sup>1138</sup> The current technology considered is ND-GAr. This detector is a magnetised, high-  
<sup>1139</sup> pressure GAr TPC (often denoted as HPgTPC) surrounded by an electromagnetic  
<sup>1140</sup> calorimeter (ECal) and a muon tagger. A cross section of its geometry can be seen  
<sup>1141</sup> in Fig. 3.7. ND-GAr will be able to measure the momenta of the outgoing muons  
<sup>1142</sup> while also detect neutrino interactions inside the GAr volume. This allows ND-GAr  
<sup>1143</sup> to constrain the systematic uncertainties even further, as it will be able to accurately  
<sup>1144</sup> measure neutrino interactions at low energies thanks to the lower tracking thresholds of  
<sup>1145</sup> GAr.

### 3.4. NEAR DETECTOR



**Figure 3.8:** Predicted beam muon neutrino flux at the ND location for different off-axis positions. Figure taken from Ref. [91].

#### 1146 3.4.3 PRISM

1147 In general, the observed peak neutrino energy of a neutrino beam decreases as the  
 1148 observation angle with respect to the beam direction increases. This feature has been  
 1149 used in other long-baseline neutrino experiments, like T2K ( $2.5^\circ$  off-axis) and NOvA  
 1150 ( $0.8^\circ$  off-axis), to achieve narrower energy distributions. The DUNE PRISM concept  
 1151 exploits this effect using a movable ND. Within PRISM both ND-LAr and the muon  
 1152 spectrometer (TMS in Phase I and ND-GAr in Phase II) can be moved up to  $3.2^\circ$   
 1153 off-axis, equivalent to move the detectors 30.5 m laterally through the ND hall.

1154 This allows to record additional data samples with different energy compositions.  
 1155 Figure 3.8 compares the on-axis muon neutrino flux at the ND with the fluxes at different  
 1156 off-axis positions. As the off-axis position increases the neutrino flux becomes closer to  
 1157 a monoenergetic beam with a lower peak energy. These samples can be used to perform  
 1158 a data-driven determination of the relation between true and reconstructed neutrino  
 1159 energy, to reduce the dependence on the interaction model. The off-axis samples are  
 1160 linearly combined to produce a narrow Gaussian energy distribution centered on a target  
 1161 true energy. From the combination coefficients one can build a sample of reconstructed

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

1162 neutrino events that will determine the energy mapping.

1163 The PRISM samples will be used to form a flux at the ND location similar in shape  
1164 to the oscillated flux measured by the FD. This method can be used to extract the  
1165 oscillation parameters with minimal input from the neutrino interaction model.

### 1166 3.4.4 SAND

1167 The role of SAND is to monitor the beam stability by measuring the on-axis neutrino  
1168 energy spectra. As the PRISM program requires that ND-LAr and its downstream  
1169 muon spectrometer spend about half of the time in off-axis positions, it is not possible  
1170 to monitor the stability with the movable detectors. Moreover, for the success of PRISM  
1171 it is essential to have a stable beam configuration, or, at least, a quick assessment and  
1172 modeling of the distortions.

1173 The SAND detector is magnetised, and features an inner low density tracker, a LAr  
1174 target with optical readout and surrounding sampling calorimeter.

## 1175 3.5 A More Capable Near Detector

1176 In DUNE Phase II, a more capable near detector is needed to achieve the ultimate physics  
1177 goals of the experiments. The current leading proposal for this detector is ND-GAr.  
1178 As mentioned previously, it will fulfill the role of TMS, measuring the momentum and  
1179 sign of the charged particles exiting ND-LAr. Additionally, it will be able to measure  
1180 neutrino interactions inside the HPgTPC, achieving lower energy thresholds than those  
1181 of the ND and FD LArTPCs. By doing so ND-GAr will allow to constrain the relevant  
1182 systematic uncertainties for the LBL analysis even further. A detailed discussion on the  
1183 requirements, design, performance and physics of ND-GAr can be found in the DUNE  
1184 ND CDR [91] and the ND-GAr white paper [93].

### 3.5. A MORE CAPABLE NEAR DETECTOR

#### 1185 3.5.1 Requirements

1186 The primary requirement for ND-GAr is to measure the momentum and charge of  
1187 muons from  $\nu_\mu$  and  $\bar{\nu}_\mu$  CC interactions in ND-LAr, in order to measure their energy  
1188 spectrum. To achieve the sensitivity to the neutrino oscillation parameters described  
1189 in the DUNE FD TDR Volume II [85], ND-GAr should be able to constrain the muon  
1190 energy within a 1% uncertainty or better. The main constraint will come from the  
1191 calibration of the magnetic field, which will be performed using neutral kaon decays in  
1192 the HPgTPC.

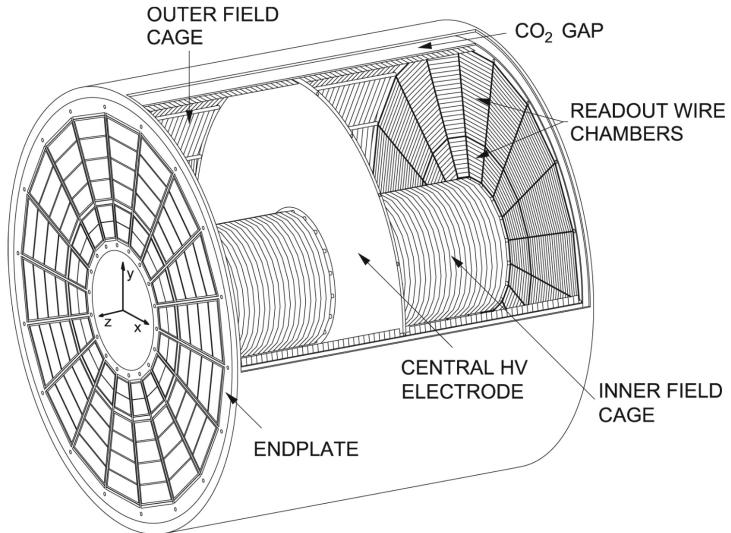
1193 Another requirement for ND-GAr is the precise measurement of neutrino interactions  
1194 on argon for the energies relevant to the neutrino oscillation program. The goal is to  
1195 constrain the cross section systematic uncertainties in the regions of phase space that  
1196 are not accessible to ND-LAr. This requires the kinematic acceptance for muons in  
1197 ND-GAr to exceed that of ND-LAr, being comparable to the one observed in the FD.

1198 ND-GAr should also be able to help establishing the relationship between true and  
1199 reconstructed energy from neutrino interactions on argon with low thresholds, being  
1200 sensitive to particles that are not observed or may be misidentified in ND-LAr. In  
1201 particular, ND-GAr needs to have low tracking thresholds in order to measure the  
1202 spectrum of pions and protons produced in final-state interactions (FSI). It also must  
1203 be able to accurately measure the pion multiplicity in 1, 2 and 3 pions final states, to  
1204 inform the pion mass correction in the LArTPCs.

#### 1205 3.5.2 Reference design

1206 The final design of ND-GAr is still under preparation. However, a preliminary baseline  
1207 design was in place at the time of the ND CDR. This section summarises the main  
1208 features of that design, as it is also the one used for the default geometry in our simulation.  
1209 A DUNE Phase II white paper, discussing the different options under consideration for  
1210 the ND-GAr design, is in progress.

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



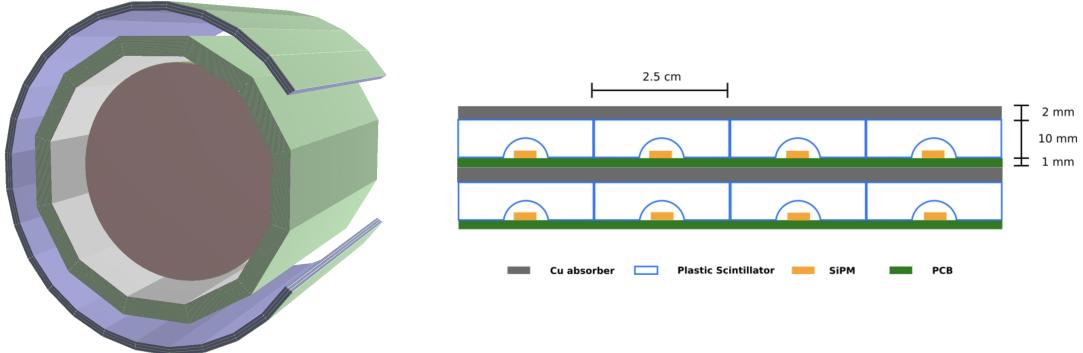
**Figure 3.9:** Diagram of the ALICE TPC, showing the two drift chambers, inner and outer field cages and readout chambers. Figure taken from Ref. [91].

### 1211 HPgTPC

1212 The reference design for the ND-GAr HPgTPC follow closely that of the ALICE TPC.  
 1213 It is a cylinder with a central high-voltage cathode, generating the electric field for  
 1214 the two drift volumes, with a maximum drift distance of 2.5 m each. The anodes will  
 1215 be instrumented with charge readout chambers. The original design repurposed the  
 1216 multi-wire proportional readout chambers (MWPCs) of ALICE, however some of the  
 1217 current R&D efforts focus on a gas electron multiplier (GEM) [94] option instead. Figure  
 1218 3.9 shows a schematic diagram of the ALICE TPC design. The basic ND-GAr geometry  
 1219 will resemble this, except for the inner field cage.

1220 It will use a 90:10 molar fraction Ar:CH<sub>4</sub> mixture at 10 bar. With this baseline gas  
 1221 mixture light collection is not possible, as the quenching gas absorbs most of the VUV  
 1222 photons. Additional R&D efforts are underway, to understand if different mixtures allow  
 1223 for the light signal to be used to provide a  $t_0$  while maintaining stable charge gain.

### 3.5. A MORE CAPABLE NEAR DETECTOR



**Figure 3.10:** View of the 12-sided ECal barrel and outer muon tagger geometries (left) and layout of the ECal tile layers for the 2 mm Cu, 10 mm scintillator option (right). Figure adapted from Ref. [91].

#### 1224    ECal

1225    The main role of the ND-GAr ECal is the calorimetric measurement of the electron  
 1226    energies and the reconstruction of photons, in particular those from neutral pion decays.  
 1227    Also, the ECal is able to provide a  $t_0$  timestamp for neutrino interactions, by associating  
 1228    its activity to the tracks in the HPgTPC. The ECal will also be able to perform  
 1229    neutron reconstruction using time of flight and reject external backgrounds, thanks to  
 1230    its sub-nanosecond time resolution.

1231       The ECal design features three independent subdetectors, two end caps at each side  
 1232    and a barrel surrounding the HPgTPC. Each of the detectors is divided in modules,  
 1233    which combine alternating layers of plastic scintillator and absorber material readout  
 1234    by SiPMs. The inner scintillator layers consist of  $2.5 \times 2.5 \text{ cm}^2$  high-granularity tiles,  
 1235    whereas the outer ones are made out of 4 cm wide cross-strips spanning the whole  
 1236    module length. The current barrel geometry consists of 8 tile layers and 34 strip layers,  
 1237    while the end caps feature 6 and 36 respectively. The thickness of the scintillator layers  
 1238    is 7 mm and 5 mm for the Pb absorber layers. The 12-sided geometry of the ECal barrel  
 1239    (left) and the layout of the tile layers (left)<sup>1</sup> can be seen in Fig. 3.10.

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<sup>1</sup>The figure shows the layout of the tile layers for a previous design with 2 mm Cu absorber and 10 mm plastic scintillator, as mentioned in the text the current choice is 5 mm Pb absorber and 7 mm scintillator.

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

### 1240 Magnet

1241 The ND-GAr magnet design, know as the Solenoid with Partial Yoke (SPY), consists of  
1242 two coupled solenoids with an iron return yoke. The idea behind the design is to have a  
1243 solenoid as thin as possible, as well as a return yoke mass distribution that minimises  
1244 the material budget between ND-LAr and ND-GAr. The magnet needs to provide a  
1245 0.5 T field in the direction perpendicular to the beam, parallel to the drift electric field.  
1246 It needs to host the pressure vessel and the surrounding ECal, which points to a inner  
1247 diameter of  $\sim 6.4$  m.

1248 The solenoid is a single layer coil, based on niobium titanium superconducting  
1249 Rutherford cable. The total length of the coil is 7.5 m. The bobbin will be split in four  
1250 segments grouped in pairs with two identical cryostats, connected in series. The iron  
1251 yoke features an aperture in the upstream side to allow the muons coming from ND-LAr.  
1252 Still, its material will be enough to reduce the magnetic field reaching SAND, and also  
1253 stop the charged pions produced inside the HPgTPC.

### 1254 Muon system

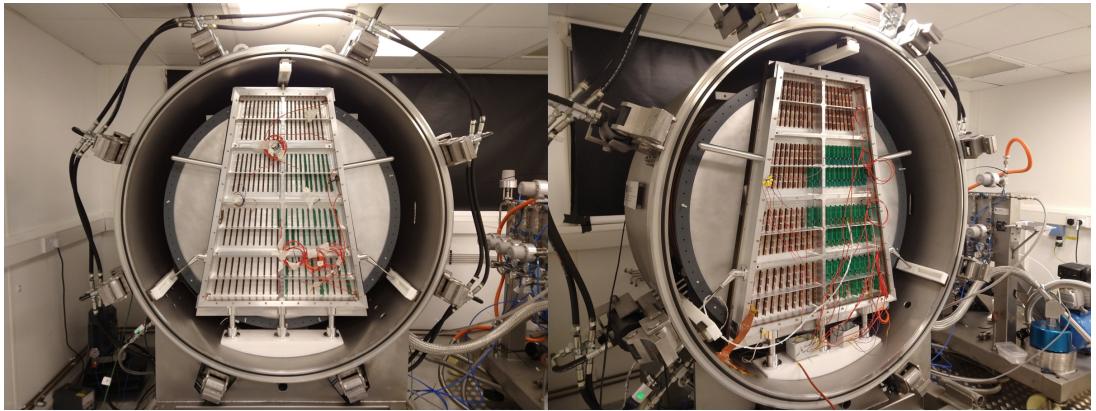
1255 The design of the ND-GAr muon system is still in a preliminary stage. Its role is to  
1256 distinguish between muons and pions punching through the ECal. This is especially  
1257 important for wrong-sign determination, to separate these from neutral current events.

1258 In its current form, the muon system consists of three layers of longitudinal sampling  
1259 structures. It alternates 10 cm Fe absorber slabs with 2 cm plastic scintillator strips.  
1260 The transverse granularity required is still under study.

### 1261 3.5.3 R&D efforts

1262 There are several ND-GAr-related prototypes, mostly focused on the TPC charge  
1263 readout and electronics. The priority is to test the full readout chain, in a high-pressure  
1264 environment, using a gas mixture with high argon fraction. A detailed summary of these  
1265 can be found in the DUNE Phase II white paper [92].

### 3.5. A MORE CAPABLE NEAR DETECTOR



**Figure 3.11:** Photographs of the TOAD pressure vessel at RHUL. The TPC is mounted inside the vessel, and the OROC is supported by an aluminium frame. Figure taken from Ref. [95].

#### **1266 Multi-Wire Proportional Chambers**

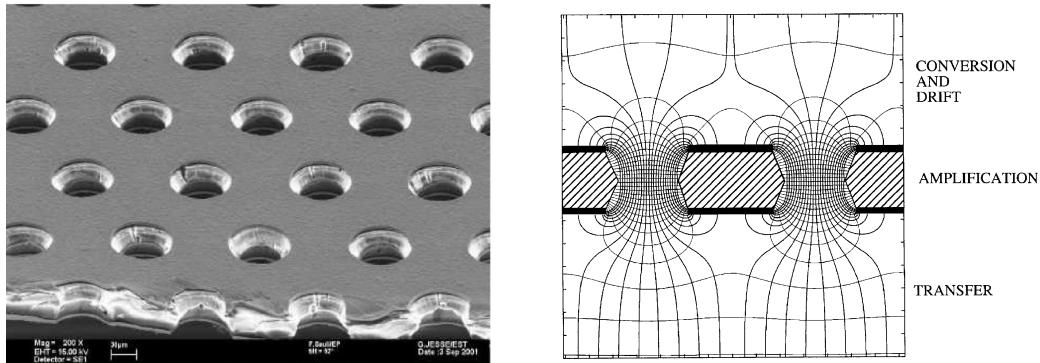
1267 As mentioned before, the original ND-GAr design repurposes the MWPCs of the ALICE  
1268 TPC, which became available after the recent upgrade [96]. These were operated using  
1269 a 90:10:5 Ne:CO<sub>2</sub>:N<sub>2</sub> gas mixture at 1 atm. Therefore, their performance needed to be  
1270 studied in an argon gas environment at high pressure.

1271 The Gas-argon Operation of ALICE TPC (GOAT) test stand tested the ALICE  
1272 readout chambers at high pressure. In particular, it used one of the previously operated  
1273 ALICE inner MWPCs, also known as IROCs, in a pressure vessel rated to 10 atm. It  
1274 measured the gas gain at various pressure points, voltages and gas mixtures.

1275 The Test stand of an Overpressure Argon Detector (TOAD) tested an ALICE outer  
1276 MWPC, also known as OROC, up to 5 atm. During its time at RHUL, it was used to  
1277 study the achievable gas gain of the OROC [95]. At the moment, it is being commissioned  
1278 at Fermilab for a full detector test of the readout electronics and the DAQ.

1279 Figure 3.11 shows the interior of the TOAD pressure vessel. The TPC is mounted  
1280 inside the vessel on three rails. The back of the OROC, supported by an aluminium  
1281 frame, can be seen at the front.

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



**Figure 3.12:** Left panel: electron microscope image of a  $50\ \mu\text{m}$  thick GEM electrode, with hole pitch and diameter of  $140$  and  $70\ \mu\text{m}$ , respectively. Right panel: Schematics of a GEM electrode cross section, showing the electric field lines around the holes. Figures taken from Ref. [97].

### 1282 Gas Electron Multiplier

1283 An alternative to the MWPC option is the use of GEMs. These are a type of micro-patter  
 1284 detector, where the ionisation electrons passing through the holes in the GEM layers  
 1285 are accelerated by a high intensity electric field. The acceleration causes the electrons  
 1286 to ionise the medium, resulting in an avalanche which increase the signal exponentially  
 1287 [94]. GEMs are used in numerous experiments that need a high spatial resolution, like  
 1288 ALICE [98] and CMS [99] after their upgrades.

1289 Figure 3.12 (left panel) shows an electron microscope picture of a  $50\ \mu\text{m}$  thick GEM  
 1290 electrode, with a pitch between neighbouring holes of  $140\ \mu\text{m}$  and a hole diameter of  
 1291  $70\ \mu\text{m}$ . A schematic representation of the cross section of a GEM layer is shown in Fig.  
 1292 3.12 (left panel).

1293 The Gaseous Argon T0 (GAT0<sup>2</sup>) prototype studies the use of thick GEMs made out  
 1294 of glass to achieve optical imaging of the primary ionisation. Using a 10 atm pressure  
 1295 vessel, the goal is to study different argon-based mixtures that allow for a precise  $t_0$   
 1296 determination.

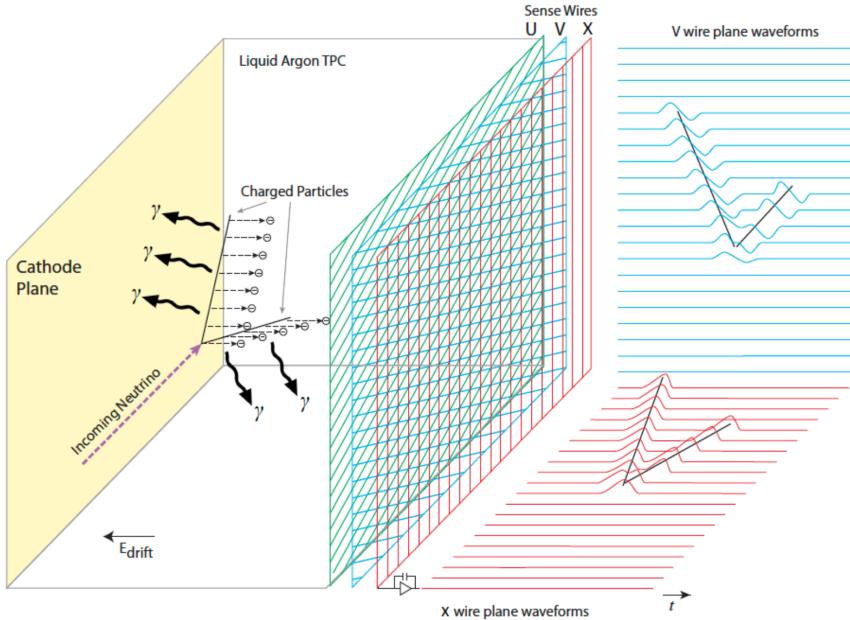
1297 The GEM Over-pressurized with Reference Gases (GORG<sup>3</sup>) test stand is currently  
 1298 testing a GEM-based charge readout, using a triple-GEM stack.

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<sup>2</sup>Spanish for cat.

<sup>3</sup>Persian for wolf.

### 3.6. FAR DETECTOR



**Figure 3.13:** Schematic diagram showing the operating principle of a LArTPC with wire readout. Figure taken from Ref. [83].

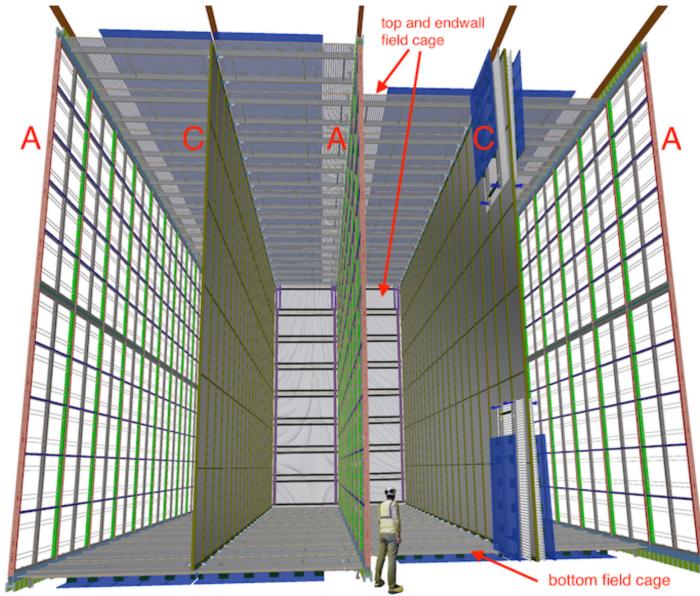
## 1299 3.6 Far Detector

1300 The DUNE FD complex will sit 1300 km away from the beam target and 1.5 km  
 1301 underground at SURF, South Dakota. Two caverns will host the four FD modules, two  
 1302 of them per cavern, each embedded in cryostats of dimensions 18.9 m (w)  $\times$  17.8 m (h)  $\times$   
 1303 65.8 m (l). A central, smaller cavern will host the cryogenic system.

1304 Three out of the four modules will be liquid argon (LAr) time projection chamber  
 1305 detectors, often refer to as LArTPCs, with a LAr fiducial mass of at least 10 kt each.  
 1306 The first and second FD modules, FD-1 and FD-2, will use a Horizontal Drift (HD)  
 1307 technology, whereas the third module, FD-3, will have a Vertical Drift (VD) direction.  
 1308 The technology for the fourth module is still to be decided,

1309 For each event, with energies ranging from a few MeV to several GeV, these detectors  
 1310 collect both the scintillation light and the ionisation electrons created when the charged  
 1311 particles produced in neutrino-nucleus interactions ionise the argon nuclei. In both HD  
 1312 and VD designs the characteristic 128 nm scintillation light of argon is collected by a  
 1313 photon detection system (PDS). This light will indicate the time at which electrons

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



**Figure 3.14:** Proposed design for the FD-1 and FD-2 modules following the HD principle. Figure taken from Ref. [83].

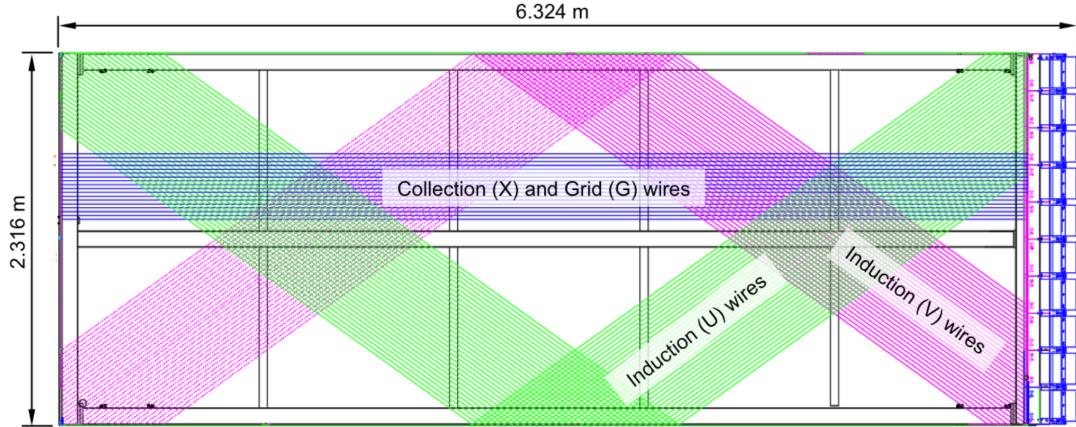
1314 start to drift, thus enabling reconstruction over the drift coordinate when compared  
 1315 to the time when the first ionisation electron arrives to the anode. Reconstruction of  
 1316 the topology in the transverse direction is achieved using the charge readout. Fig. 3.13  
 1317 illustrates the detection principle described, for the case of a HD detector with a wire  
 1318 readout.

### 1319 3.6.1 Horizontal Drift

1320 The HD design the ionisation electrons produced as charged particles traverse the LAr  
 1321 drift horizontally towards the anode planes, due to the effect of an electric field. These  
 1322 anode planes are made out of three layers of wire readout. This design, previously  
 1323 known as single-phase (SP), was tested by the ProtoDUNE-SP detector at CERN. The  
 1324 prototype collected data from a hadron beam and cosmic rays, providing high-quality  
 1325 data sets for calibration and performance studies.

1326 Each FD HD detector module is divided in four drift regions, with a maximum drift  
 1327 length of 3.5 m, by alternating anode and cathode walls. The surrounding field cage  
 1328 ensures the uniformity of the 500 V/cm horizontal electric field across the drift volumes.

### 3.6. FAR DETECTOR



**Figure 3.15:** Schematic representation of an APA. The black lines represent the APA steel frame. The green and magenta lines correspond to the direction of the U and V induction wires respectively. The blue lines indicate the direction of the X collection wires and the wire shielding G. Figure taken from Ref. [83].

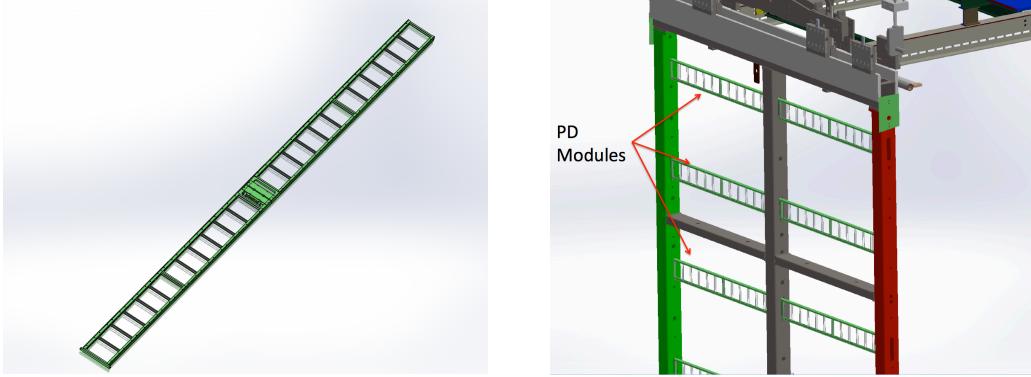
1329 The three anode walls, which constitute the charge readout of the detector, are built by  
 1330 stacking anode plane assemblies (APAs), 2 high times 25 wide. The design of the HD  
 1331 modules is shown in Fig. 3.14.

1332 Each APA is made of 2560 active wires arranged in three layers, plus an extra grid  
 1333 layer, wrapped around a metal frame. The two induction wire planes, U and V, sit at  
 1334  $\pm 35.7^\circ$  to the vertical on each side of the APA. The collection and shielding plane wires,  
 1335 X and G, run parallel to the vertical direction. The ionisation electrons drift past the  
 1336 induction planes, generating bipolar signals on those wires, and are collected by the  
 1337 collection plane, producing a monopolar positive signal. The spacing between the wires  
 1338 is  $\sim 5$  mm, and it defines the spatial resolution of the APA.

1339 The front-end readout electronics, or cold electronics as they are immerse in the LAr,  
 1340 are attached to the top of the up APAs and the bottom of the down APAs. Mounted on  
 1341 the front-end mother boards we have a series of ASICs that digitize the signals from the  
 1342 collection and induction planes. Each wire signal goes to a charge-sensitive amplifier,  
 1343 then there is a pulse-shaping circuit and this is followed by the analogue-to-digital  
 1344 converter. This part of the process happens inside the LAr to minimise the number of  
 1345 cables penetrating the cryostat. The digitised signals come out finally via a series of

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- 1346 high-speed serial links to the warm interface boards (WIBs), from where the data is sent  
1347 to the back-end DAQ through optical fibers.



**Figure 3.16:** A PDS module containing 24 X-ARAPUCAs (left) and the location of the modules on the APAs (right). Figure taken from Ref. [83].

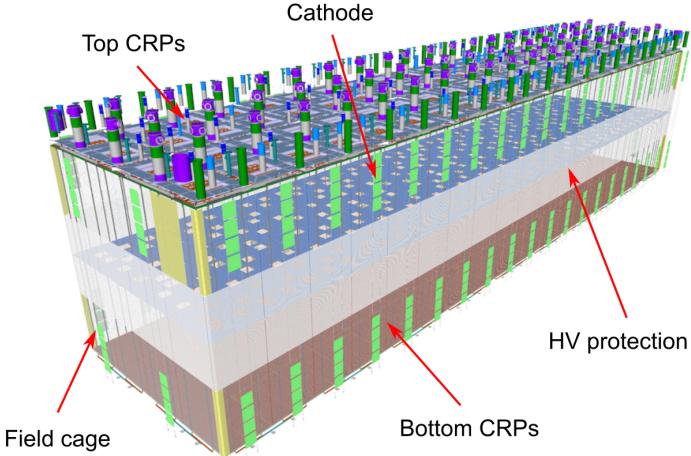
1348 The PDS uses modules of X-ARAPUCA devices, mounted on the APA frames  
1349 between the wire planes. Each X-ARAPUCA consists of layers of dichroic filter and  
1350 wavelength-shifter. They shift the VUV scintillation light into the visible spectrum,  
1351 sending then the visible photons to silicon photomultiplier (SiPM) devices. The PDS  
1352 modules are 209 cm × 12 cm × 2 cm bars, containing 24 X-ARAPUCAs. There are 10  
1353 of these PDS modules per APA. Fig. 3.16 shows a PDS module (left) and the placement  
1354 of the modules on the APAs (right).

### 1355 3.6.2 Vertical Drift

1356 In the VD case the ionisation electrons will drift vertically until they meet a printed  
1357 circuit board-based (PCB) readout plane. It is based on the original dual-phase (DP)  
1358 design deployed at CERN, known as ProtoDUNE-DP, used a vertical drift design with  
1359 an additional amplification of the ionization electrons using a gaseous argon (GAr) layer  
1360 above the liquid phase. The VD module incorporates the positive features of the DP  
1361 design without the complications of having the LAr-GAr interface.

1362 The current design of the FD VD module counts with two drift chambers with a  
1363 maximum drift distance of 6.5 cm. A cathode plane splits the detector volume along the  
1364 drift direction while the two anode planes are connected to the bottom and top walls

### 3.6. FAR DETECTOR



**Figure 3.17:** Proposed design for the FD-3 module following the VD principle. Figure adapted from Ref. [100].

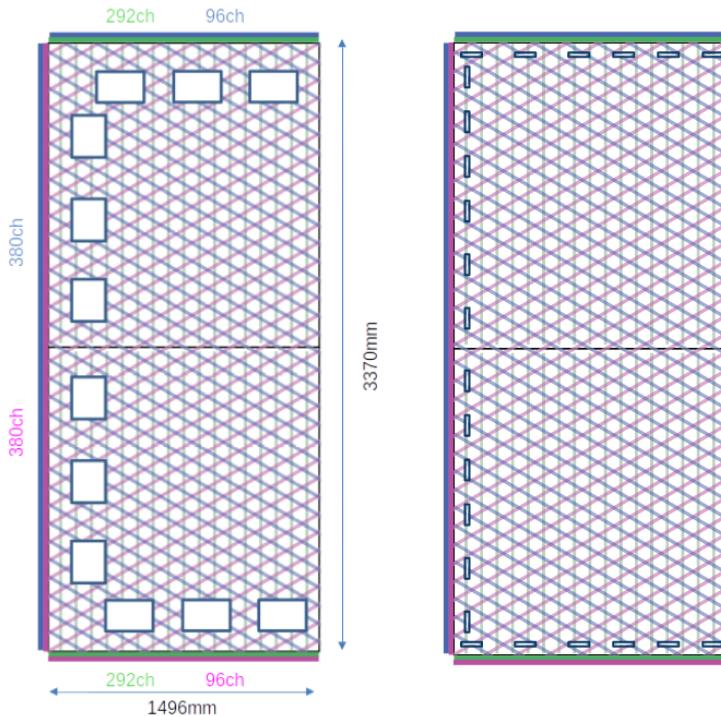
1365 of the detector. The layout of the VD module is shown in Fig. 3.17. Compared with  
 1366 the HD design, the VD option offers a slightly larger instrumented volume and a more  
 1367 cost-effective solution for the charge readout.

1368 As in the HD design, each drift volume features a 500 V/cm electric field and a  
 1369 field cage that ensures its uniformity. The anode planes are arrays of 3.4 m × 3 m  
 1370 charge-readout planes (CRPs). These are formed by a pair of charge-readout units  
 1371 (CRUs), which are built from two double-sided perforated PCBs, with their perforations  
 1372 aligned. The perforations allow the drift electrons to pass between the layers.

1373 The PCB face opposite to the cathode has a copper guard plane which acts as  
 1374 shielding, while its reverse face is etched with electrode strips forming the first induction  
 1375 plane. The outer PCB has electrode strips on both faces, the ones facing the inner PCB  
 1376 form the second induction plane while the outermost ones form the collection plane. Fig.  
 1377 3.18 shows the layout of the electrode strips for the top (left) and bottom (right) CRUs.  
 1378 The magenta and blue lines represent the first and second induction planes respectively,  
 1379 and the green lines correspond to the collection plane.

1380 The PDS in the VD module will use the same X-ARAPUCA technology developed  
 1381 for the HD design. The plan is to place the PDS modules on the cryostat walls and on

## CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT



**Figure 3.18:** Schematic representation of the electrode strip configuration for a top (left) and bottom (right) CRU. Figure taken from Ref. [100].

1382 the cathode, in order to maximise the photon yield.

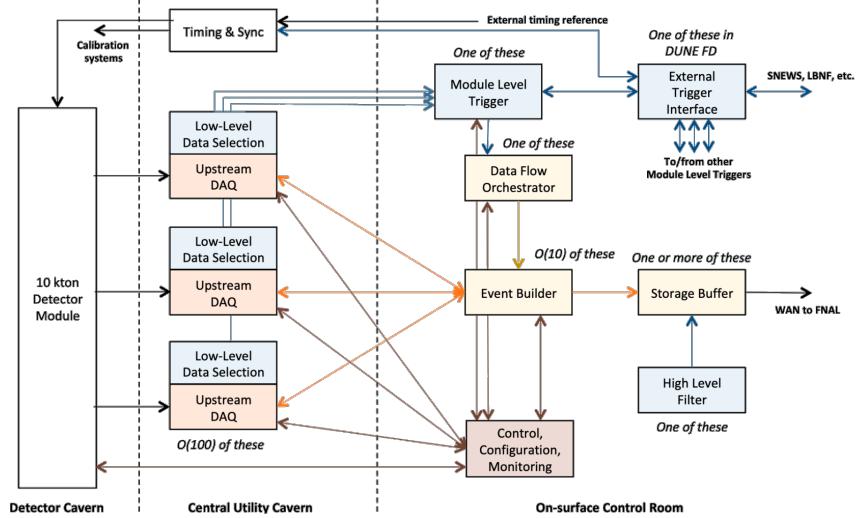
### 1383 3.6.3 FD Data Acquisition System

1384 The data acquisition (DAQ) system receives, processes and stores data from the detector  
1385 modules. In the case of DUNE the DAQ architecture is designed to work for all FD  
1386 modules interchangeably, except some aspects of the upstream part which may depend  
1387 on the specific module technology.

1388 The enormous sample rate and the number of channels in TPC and PD readouts  
1389 will produce a very large volume of data. These pose really strong requirements and  
1390 challenges to the DUNE FD DAQ architecture. It will be required to read out data of  
1391 the order of ten thousand or more channels at rates of a few MHz. To cope with the  
1392 huge data volume, segmented readouts and compression algorithms are used to reduce  
1393 the data rate to manageable levels.

1394 The DAQ system of the DUNE FD is composed of five different subsystems. The

### 3.6. FAR DETECTOR



**Figure 3.19:** Detailed diagram of the DUNE FD DAQ system. Figure taken from Ref. [101].

1395 first one is the upstream DAQ, which receives the raw data from the detector, buffers it  
 1396 and perform some low-level pre-processing. The minimally processed data is then fed  
 1397 into a hierarchical data selection system, which then performs a module level trigger  
 1398 decision. In case of a positive decision a trigger command is produced and executed by  
 1399 the data flow orchestrator, located in the back-end (BE) DAQ subsystem. Subsequently  
 1400 the DAQ BE retrieves the relevant data from the buffers located in the upstream DAQ,  
 1401 adds all the data into a cohesive record and saves it to permanent storage. Watching  
 1402 over all the other subsystems we also have the control, configuration and monitoring  
 1403 subsystem and the time and synchronization subsystem. Figure 3.19 shows a schematic  
 1404 diagram of the DAQ system, showing the different subsystems and their relations.

1405 A notorious challenge for the DUNE DAQ system comes from its broad physics  
 1406 goals. We must be prepared to process events spanning a wide range of time windows  
 1407 (from 5 ms in the case of beam and cosmic neutrinos and nucleon decay to 100 s in the  
 1408 case of SNBs) and therefore this requires a continuous readout of the detector modules.  
 1409 Moreover, because of the off-beam measurements we need to ensure the capabilities  
 1410 of online data processing and self-triggering. Having this into account, together with  
 1411 the technical constraints, the DUNE FD DAQ faces a series of challenges: it needs to

### CHAPTER 3. THE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- 1412 be fault tolerant and redundant to reduce downtime, accommodate new components
- 1413 while it keeps serving the operational modules, have large upstream buffers to handle
- 1414 SNB physics, be able to support a wide range of readout windows and last reduce the
- 1415 throughput of data to permanent storage to be at most 30 PB/year.

# 4

1416

1417

## Matched Filter approach to Trigger

1418

## Primitives

### 1419 4.1 Motivation

1420 The filter implemented in the firmware of the upstream DUNE FD DAQ is a 32nd-order  
1421 low-pass finite impulse-response (FIR) filter. The output of such filter for a discrete  
1422 system can be written as:

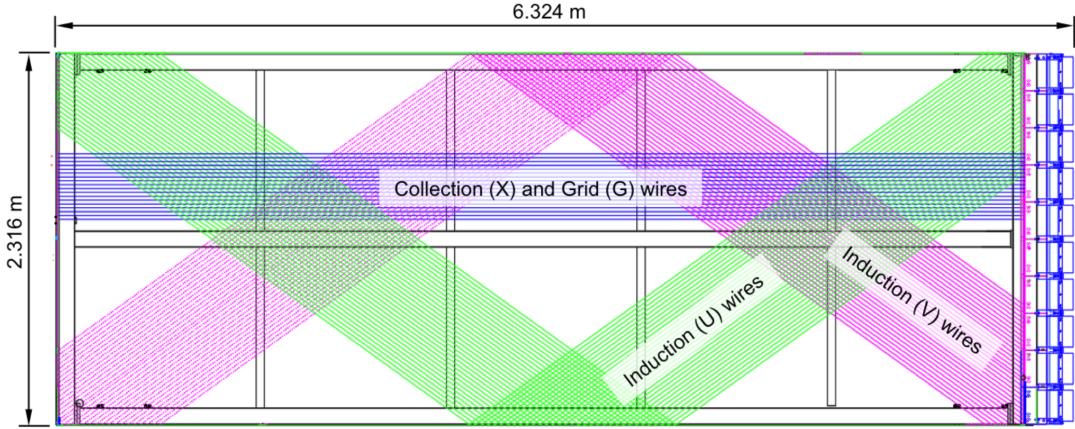
$$y[i] = \sum_{j=0}^N h[j]x[i-j], \quad (4.1)$$

1423 where  $N$  is the order of the filter,  $y$  is the output sequence,  $x$  is the input sequence and  $h$   
1424 is the set of coefficients of the filter. The current implementation within `dtp-firmware`  
1425 [102] uses a set of 16 non-zero integer coefficients.

1426 Filtering is a vital step in the hit finder chain. It helps to suppress the noise and  
1427 enhance the signal peaks with respect to the noiseless baseline. A good filtering strategy  
1428 allows us to use lower thresholds when forming the trigger primitives (TPs) and thus  
1429 increasing the sensitivity of our detector to low energy physics events. In such events,  
1430 the hits produced by the ionisation electrons tend to have lower amplitudes than those  
1431 of interest to the baseline physics programme of the DUNE experiment.

1432 This is particularly important for the induction planes. In general, signal peaks in  
1433 the induction wires have smaller amplitude than the ones in the induction plane. This,  
1434 together with the fact that the pulse shapes are bipolar, reduces our capacity to detect

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES



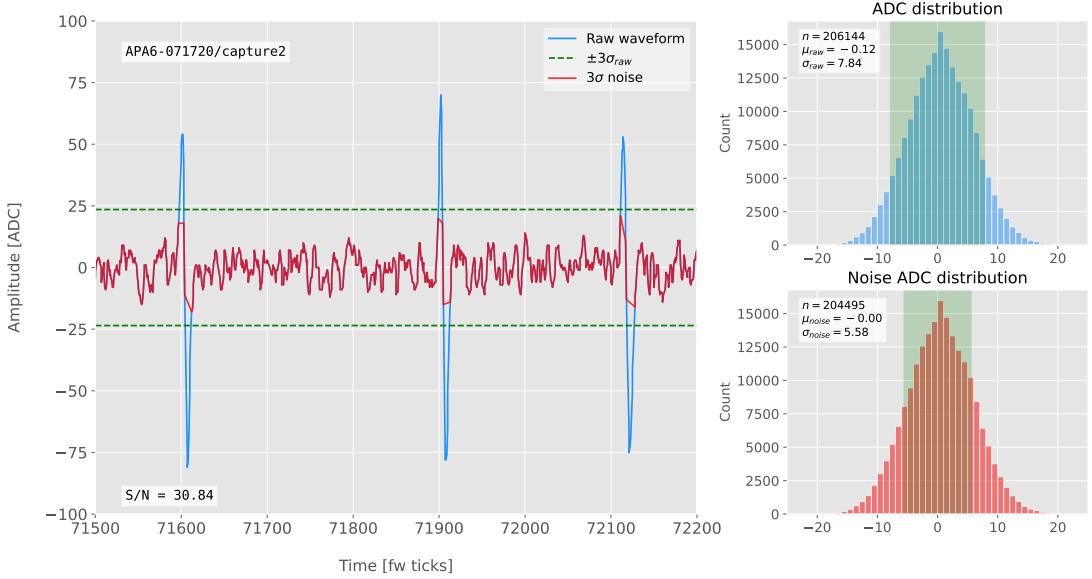
**Figure 4.1:** Schematic representation of an APA. The black lines represent the APA steel frame. The green and magenta lines correspond to the direction of the U and V induction wires respectively. The blue lines indicate the direction of the X collection wires and the wire shielding G.

the hits on these channels. The inefficiency of detecting TPs in the induction planes (denoted as U and V planes) lead trigger algorithms to focus mainly on the TPs from the collection plane (so-called X plane). As a result, the possibility of making trigger decisions based on the coincidence of TPs across the three wire planes remains nowadays unexploited in DUNE. Fig. 4.1 shows a schematic view of an anode plane assembly (APA), with the different wire plane orientations highlighted.

A possible improvement of the current hit finder chain could require optimising the existing or choosing a new filter implementation. A filter strategy which improves the induction signals may be able to enhance the detection efficiency of TPs from the induction planes and ideally make it comparable to that of the collection plane.

The goal is to implement a better finite-impulse response filter design and to evaluate its performance relative to the current filter. To do so, we need to take into account the limitations of the firmware: the FIR filter shall have maximum 32 coefficients (so-called taps) whose values are 12-bit unsigned integers. Although it is technically possible to include non-integer coefficients, it would be a technical challenge as we have 40 FIR instances per APA, as there are 4 FIR per optical link and 10 optical links per APA. With these restrictions, the task is to provide a set of 32 coefficients which yield an

## 4.2. SIGNAL-TO-NOISE RATIO DEFINITION



**Figure 4.2:** Left panel: Zoomed unfiltered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44` (blue line). The green dashed lines mark the region  $\pm 3\sigma_{\text{raw}}$ . The resulting noise waveform is also shown (red line). Top right panel: ADC distribution for channel 7840, where the green shaded region represents  $\pm \sigma_{\text{raw}}$ . Bottom right panel: noise ADC distribution for channel 7840, where the green shaded region represents  $\pm \sigma_{\text{noise}}$ .

1452 optimal filter performance for the induction wires.

## 1453 4.2 Signal-to-noise ratio definition

1454 I introduce the signal to noise ratio (S/N) as a measure of the FIR filter performance  
 1455 and demonstrate how to extract its value for a set of ProtoDUNE-SP data. The S/N  
 1456 metrics allow us to compare different filter implementations and serve as a basis for more  
 1457 detailed studies presented later in this document. Specifically, I use the ADC capture  
 1458 `felix-2020-07-17-21:31:44` (data capture taken for firmware validation purposes). I  
 1459 defined S/N as the height of the signal peaks relative to the size of the noise peaks.  
 1460 To quantify this quantity channel by channel one first need to estimate the standard  
 1461 deviation of the ADC data for each channel,  $\sigma_{\text{ADC}}$ . Then, I define the corresponding  
 1462 noise waveform to be the ADC values in the range  $\pm 3\sigma_{\text{ADC}}$ . From this new noise data  
 1463 one can estimate again the mean and standard deviation,  $\mu_{\text{noise}}$  and  $\sigma_{\text{noise}}$ , so I can

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES

1464 write the S/N for any given channel as:

$$S/N = \frac{\max[ADC] - \mu_{noise}}{\sigma_{noise}}, \quad (4.2)$$

1465 where  $\max[ADC]$  is simply the maximum ADC value found in the corresponding channel.

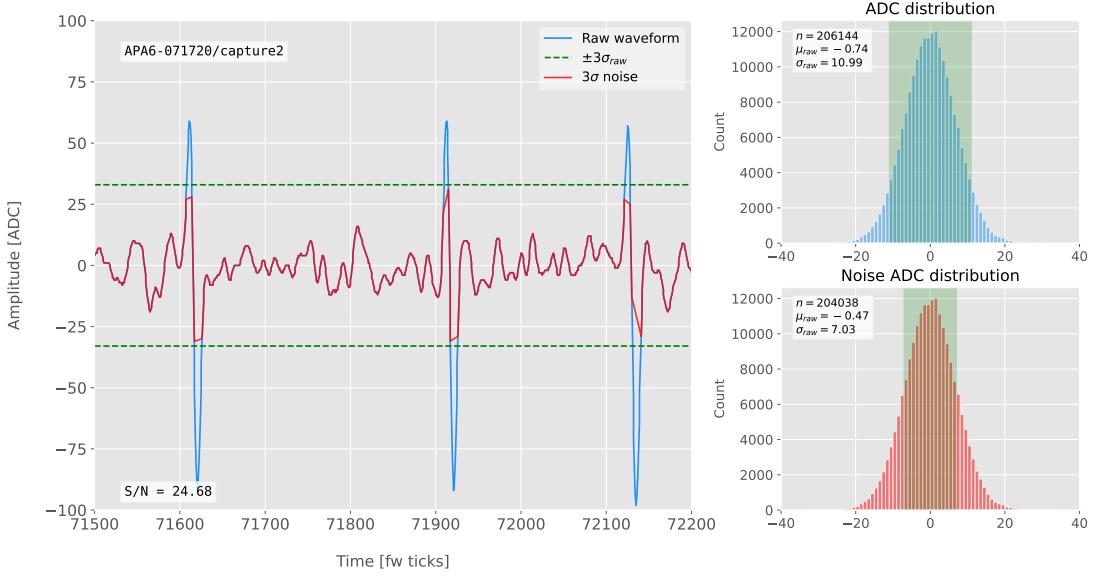
1466 One can apply this definition of the S/N with a waveform from one of the channels  
1467 of the data capture<sup>1</sup>. Fig. 4.2 shows a zoomed region of the waveform corresponding to  
1468 channel 7840 (blue line), where one can clearly see three signal peaks and continuous  
1469 additive noise (we actually see 6 peaks, 3 positive and 3 negative, but, because by design  
1470 for induction channels the expected signal pulse shapes are bipolar, I treat them as a  
1471 collection of 3 individual signal peaks). I estimated the standard deviation of this raw  
1472 waveform to be  $\sigma_{raw} = 7.84$  ADC, so I am able to define the noise waveform (red line)  
1473 as the ADC values in the range  $\pm 23.52$  ADC. This way one obtains  $\mu_{noise} = 0$  and  
1474  $\sigma_{noise} = 5.58$  ADC, which gives  $S/N = 30.84$ .

1475 We can repeat this calculation now for the corresponding filtered waveform (using the  
1476 current firmware FIR filter). In Fig. 4.3 I plotted the same time window for the filtered  
1477 waveform from channel 7840 (blue line). In this case, the standard deviation of the  
1478 waveform is larger than before, giving  $\sigma_{raw} = 10.99$  ADC. The resulting noise waveform  
1479 (red line) results from selection the ADC values in the range  $\pm 32.91$  ADC, giving now  
1480  $\mu_{noise} = -0.47$  ADC and  $\sigma_{noise} = 7.03$  ADC. Finally, one obtains  $S/N = 24.68$ . Notice  
1481 that the value of S/N decreases after the filtering. Clearly, one can see that the noise  
1482 baseline has increased by a factor of 1.35 when we applied the FIR filter and at the same  
1483 time the amplitude of the signal peaks has remained almost unchanged, leading to this  
1484 poorer S/N value.

---

<sup>1</sup>All the original work was done within the `dtp-simulation` package [103], which offers a variety of tools to read raw data and emulate the TPG block (pedestal subtraction, filtering and hit finder). However, the results shown in this report were re-worked later using the C++ based `dtpemulator` package [104]. Its main purpose is the emulation of the TPG block and, in the same way as its predecessor, it has been cross-checked against the current firmware implementation.

### 4.3. LOW-PASS FIR FILTER DESIGN



**Figure 4.3:** Left panel: Zoomed filtered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44` (blue line). The filter used was the current implementation of the low-pass FIR filter in `dtp-firmware`. The green dashed lines mark the region  $\pm 3\sigma_{\text{raw}}$ . The resulting noise waveform is also shown (red line). Top right panel: ADC distribution for channel 7840 after filtering, where the green shaded region represents  $\pm \sigma_{\text{raw}}$ . Bottom right panel: noise ADC distribution for channel 7840 after filtering, where the green shaded region represents  $\pm \sigma_{\text{noise}}$

## 1485 4.3 Low-pass FIR filter design

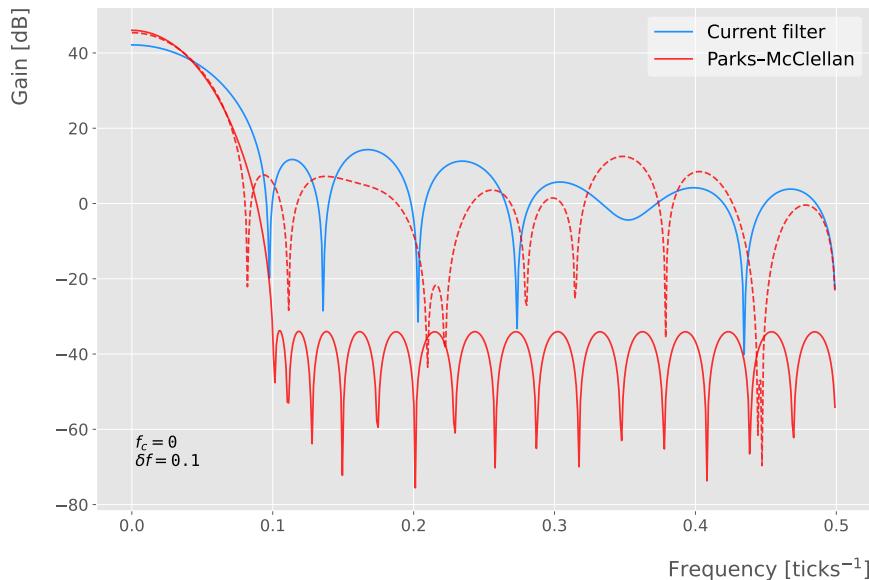
1486 In general, when one uses a method to optimize the frequency response of a digital filter,  
 1487 such as the Parks-McClellan algorithm, one finds a set of  $N$  real coefficients that give  
 1488 the best response for the specified pass-band and order of the filter [105].

1489 In our case, as the sampling frequency is defined as  $1 \text{ ticks}^{-1}$ , the Nyquist frequency  
 1490 will simply be  $1/2 \text{ ticks}^{-1}$ . The current implementation of the filter seems to have as  
 1491 pass-band the range  $[0, 0.1] \text{ ticks}^{-1}$ . This can be seen in Fig. 4.4, where I show the  
 1492 power spectrum, in decibels, of such filter implementation (blue solid line). For instance,  
 1493 the Park-McClellan algorithm finds the optimal Chebyshev FIR filter taking as input  
 1494 the boundaries of the target pass-band and stop-band, which can be written in the form:

$$\left\{ \begin{array}{l} [0, f_c] \\ [f_c + \delta f, f_N] \end{array} \right. , \quad (4.3)$$

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES

where  $f_c$  is the cut-off frequency,  $\delta f$  is the transition width and  $f_N$  is the aforementioned Nyquist frequency. A similar behaviour to the one in the current filter can be obtained by setting  $f_c = 0$  and  $\delta f = 0.1 \text{ ticks}^{-1}$ . The response of the resulting filter is also shown in Fig. 4.4 (blue solid line). Notice that the suppression of the stop-band is enhanced for this optimal filter. For comparison I included the power response of the filter obtained by taking the integer part of the coefficients resulting from the Parks-McClellan method (red dashed line). One can see that it does not suppress that much the stop-band, in a similar way to the current implementation of the filter.

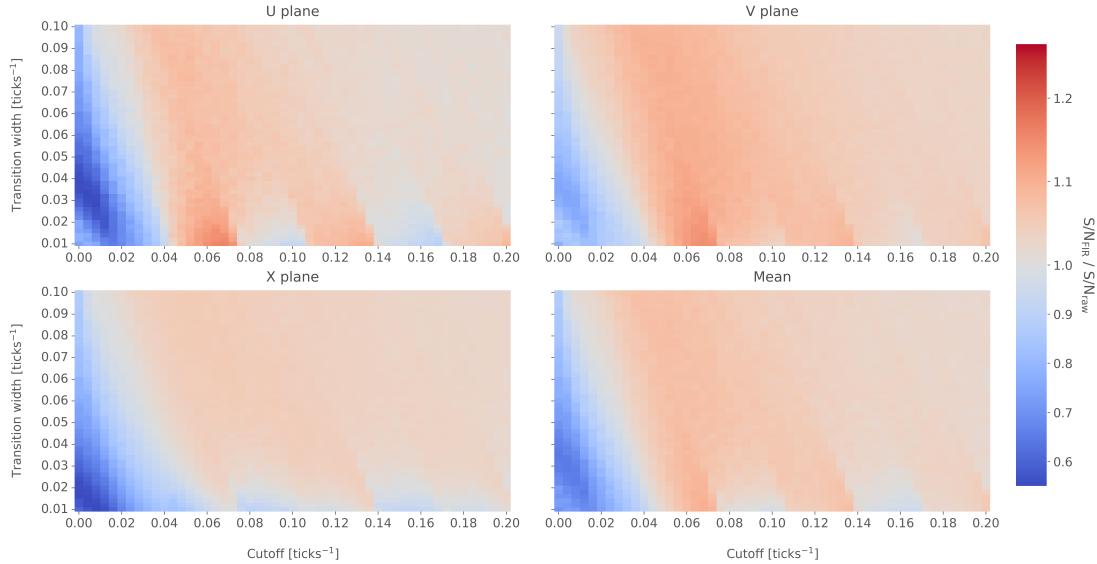


**Figure 4.4:** Power spectrum in decibels for the current implementation of the low-pass FIR filter in `dtp-firmware` (blue line), compared to the response of an optimal filter obtained using the Parks-McClellan algorithm for the same pass-band (red line). Also for comparison I include the spectrum of the optimal filter when taking only the integer part of the coefficients (red dashed line).

At this point, I tried to improve the performance of the FIR filter using the Parks-McClellan method, i.e. maximize the overall S/N, using the available data captures. I did so by varying the values of the two quantities that parametrize the pass-band and stop-band, the cut-off frequency  $f_c$  and the transition width  $\delta f$ .

Fig. 4.5 shows the average relative change in the S/N (i.e. the ratio between the value of the S/N after and before the filtering) for capture `felix-2020-07-17-21:31:44`,

### 4.3. LOW-PASS FIR FILTER DESIGN

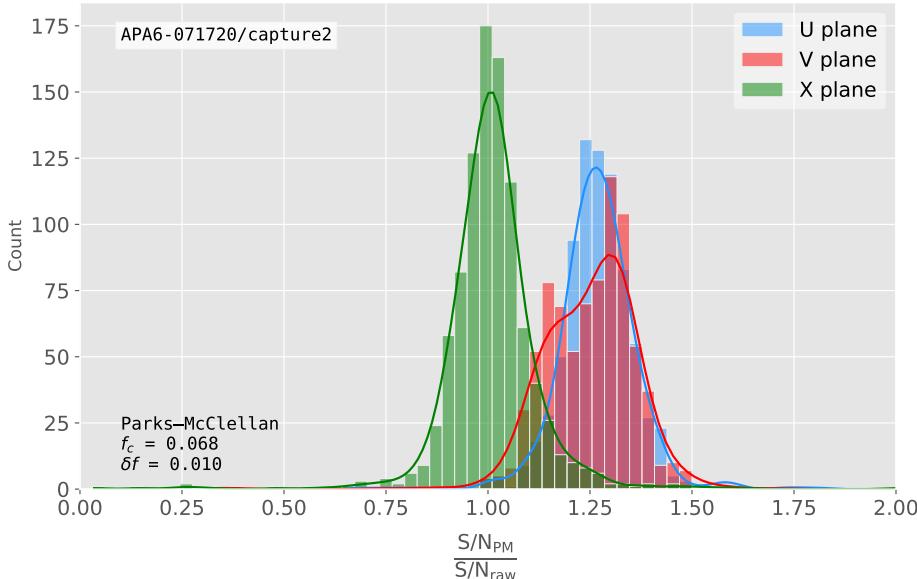


**Figure 4.5:** Relative change in the S/N for the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44`, using different values of the cutoff frequency  $f_c$  and the transition width  $\delta f$ . The optimal Chebyshev filters were applied using just the integer part of the coefficients given by the Parks-McClellan algorithm.

when using filters designed with the Parks-McClellan algorithm for the specified values of the cut-off frequency  $f_c$  and the transition width  $\delta f$ , restricted to integer values for the filter coefficients. One can clearly distinguish different regions where we get an improvement of up to a factor of 1.35 for the U plane. For large values of  $f_c + \delta f$  the ratio tends to 1, as expected (in that limit the width of the stop-band goes to 0, meaning that no frequencies are filtered out and thus the waveform remains the same).

Using the configuration which gives the best mean performance for the three planes (see bottom right panel of Fig. 4.5), i.e.  $f_c = 0.068 \text{ ticks}^{-1}$  and  $\delta f = 0.010 \text{ ticks}^{-1}$ , we can see how such filter affects the different channels. Fig. 4.6 shows the distribution of the S/N improvement values for all the channels in the raw ADC capture `felix-2020-07-17-21:31:44`, separated by wire plane, after the optimal Chebyshev filter was applied. One can see that there is a clear improvement for both U and V induction wire planes, obtaining a mean change of 1.25 and 1.30 for them respectively. However, in the case of the collection plane X the mean of this distribution is roughly 1, meaning that a good fraction of channels in that plane get a slightly worse S/N after the

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES



**Figure 4.6:** Distribution of the relative change of the S/N on the different wire planes from the ProtoDUNE-SP raw data capture *felix-2020-07-17-21:31:44* after the optimal Chebyshev filter was applied. The filter was computed with the Parks-McClellan algorithm using a cutoff of  $f_c = 0.068 \text{ ticks}^{-1}$  and a transition width  $\delta f = 0.010 \text{ ticks}^{-1}$ .

filter is applied. In any case, this is not a big issue as the S/N for collection channels is usually much higher than the one for induction channels.

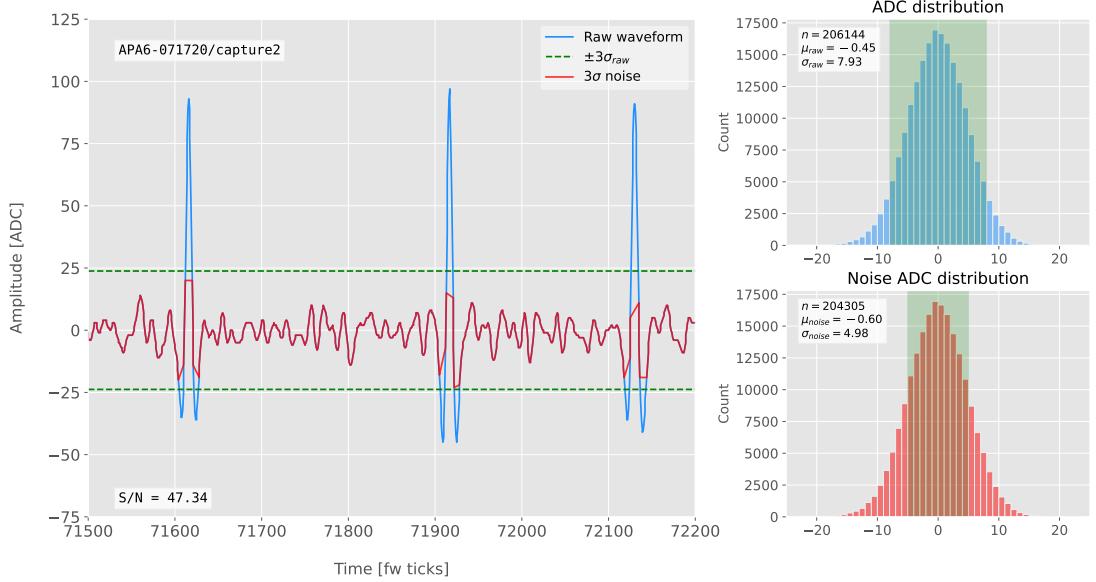
The results I obtained optimising the low pass filter with the Parks-McClellan method are promising. Nonetheless, the improvement found is rather marginal so I wondered if there could be an alternative approach to the filtering problem which yields better outputs. At this point, I found a possible alternative in matched filters. By construction, this kind of filters offer the best improvement on the S/N.

## 4.4 Matched filters

In the context of signal processing, a matched filter is the optimal linear filter for maximising the signal-to-noise ratio (S/N) in the presence of additive noise, obtained by convolving a conjugated time-reversed known template with an unknown signal to detect the presence of the template in the signal [106].

Given a known signal sequence  $s(t)$  and another (a priori unknown) noise sequence

#### 4.4. MATCHED FILTERS



**Figure 4.7:** Left panel: Zoomed match filtered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture felix-2020-07-17-21:31:44 (blue line). The filter used was directly extracted from the data, being the 32 values around the first peak in the original waveform. The green dashed lines mark the region  $\pm 3\sigma_{\text{raw}}$ . The resulting noise waveform is also shown (red line). Top right panel: ADC distribution for channel 7840 after match filtering, where the green shaded region represents  $\pm \sigma_{\text{raw}}$ . Bottom right panel: noise ADC distribution for channel 7840 after match filtering, where the green shaded region represents  $\pm \sigma_{\text{noise}}$

1537  $n(t)$ , the input signal can be written as:

$$x(t) = s(t) + n(t). \quad (4.4)$$

1538 Now, considering a linear time-invariant filter, whose impulse-response function I  
1539 will refer to as  $h(t)$ , one can write the output signal as:

$$\begin{aligned} y(t) &= x(t) * h(t) \\ &= (s(t) + n(t)) * h(t) \\ &= y_s(t) + y_n(t), \end{aligned} \quad (4.5)$$

1540 where  $y_s(t)$  and  $y_n(t)$  are simply the outputs of the filter due to the signal and the noise  
1541 components respectively.

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES

1542 The goal of the matched filter is to detect the presence of the signal  $s(t)$  in the input  
 1543 sample  $x(t)$  at a certain time  $t_0$ , which effectively means we need to maximise the S/N.  
 1544 This way, what one wants is to have a filter which gives a much bigger output when the  
 1545 known signal is present than when it is not. Putting it in other words, the instantaneous  
 1546 power of the signal output  $y_s(t)$  should be much larger than the average power of the  
 1547 noise output  $y_n(t)$  at some time  $t_0$ .

1548 For the case of the filtered signal, one can easily re-write it as an inverse Fourier  
 1549 transform:

$$y_s(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega H(\omega)S(\omega)e^{i\omega t}, \quad (4.6)$$

1550 where  $H(\omega)$  and  $S(\omega)$  are the Fourier transforms of the impulse-response function (i.e.  
 1551 the transfer function of the filter) and of the input signal, respectively.

1552 Now focusing on the noise, we can use the Wiener-Khinchin theorem [107] to write  
 1553 the mean power of the noise after filtering as:

$$E|y_n(t)|^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega |H(\omega)|^2 S_n(\omega), \quad (4.7)$$

1554 where  $S_n(\omega)$  is the power spectral density of the noise.

1555 Having these, one can write the instantaneous S/N at time  $t_0$  as:

$$\begin{aligned} \left( \frac{S}{N} \right)_{t_0} &= \frac{|y_s|^2}{E|y_n(t)|^2} \\ &= \frac{1}{2\pi} \frac{\left| \int_{-\infty}^{\infty} d\omega H(\omega)S(\omega)e^{i\omega t_0} \right|^2}{\int_{-\infty}^{\infty} d\omega |H(\omega)|^2 S_n(\omega)}. \end{aligned} \quad (4.8)$$

1556 Once we have this expression, we need to find the upper limit of it to determine what  
 1557 would be the optimal choice for the transfer function. One can use the Cauchy-Schwarz  
 1558 inequality, which in the present case takes the form:

$$\left| \int_{-\infty}^{\infty} dx f(x)g(x) \right|^2 \leq \int_{-\infty}^{\infty} dx |f(x)|^2 + \int_{-\infty}^{\infty} dx |g(x)|^2, \quad (4.9)$$

#### 4.4. MATCHED FILTERS

1559 for any two analytical functions  $f(x)$  and  $g(x)$ . One can prove that making the choice:

$$\begin{aligned} f(x) &= H(\omega) \sqrt{S_n(\omega)} e^{i\omega t_0}, \\ g(x) &= \frac{S(\omega)}{\sqrt{S_n(\omega)}}, \end{aligned} \quad (4.10)$$

1560 leads to the following upper bound for the S/N:

$$\left( \frac{S}{N} \right)_{t_0} \leq \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \frac{|S(\omega)|^2}{S_n(\omega)}. \quad (4.11)$$

1561 From Eqs. (4.8), (4.9) and (4.10) one can also derive the form of the transfer function  
1562 such that the upper bound is exactly reached [108]:

$$H(\omega) \propto \frac{S^*(\omega) e^{-i\omega t_0}}{S_n(\omega)}. \quad (4.12)$$

1563 From this last expression we can clearly see the way the matched filter acts. As the  
1564 transfer function is proportional to the Fourier transform of the signal it will try to only  
1565 pick the frequencies present in the signal [109].

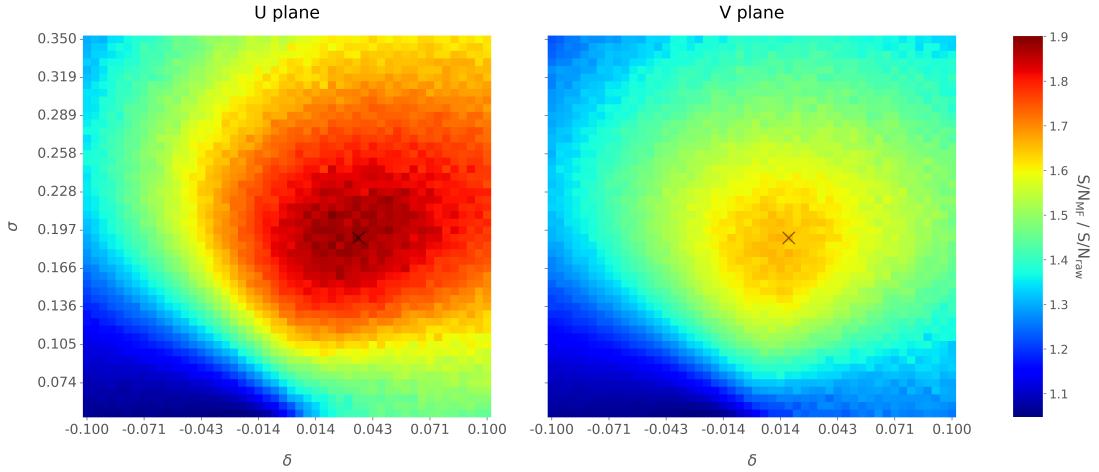
1566 The matched filter transfer function can be greatly simplified if the input noise is  
1567 Gaussian. In that case, the power spectral density of the noise is a constant, so it can be  
1568 re-absorbed in the overall normalisation of the transfer function. Moreover, considering  
1569 that the input signal is a real function, one can simply set  $S^*(\omega) = S(-\omega)$ , which gives:

$$H(\omega) \propto S(-\omega) e^{-i\omega t_0}. \quad (4.13)$$

1570 For a discrete signal, one can think of the input and impulse-response sequences as  
1571 vectors of  $\mathbb{R}^N$ . Then, the matched filter tries to maximise the inner product of the signal  
1572 and the filter while minimising the output due to the noise by choosing a filter vector  
1573 orthogonal to the later. In the case of additive noise, that leads to the impulse-response  
1574 vector:

$$h = \frac{1}{\sqrt{s^\dagger R_n^{-1} s}} R_n^{-1} s, \quad (4.14)$$

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**Figure 4.8:** Relative improvement in the S/N for the raw data capture `felix-2020-07-17-21:31:44`, using the matched filter following the parametrisation in Eq. (4.17). The black crosses in both panels denote the location of the maximum ratio value.

where  $s$  is a reversed signal template sequence of length  $N$  equal to the order of the filter and  $R_n$  is the covariance matrix associated with the noise sequence  $n$ . For the Gaussian noise case, the covariance matrix is simply the unit matrix, so the above expression simplifies again to:

$$h = \frac{s}{|s|}. \quad (4.15)$$

For this first stage of the study, I use a definition of the S/N per channel given by:

$$\text{S/N} = \frac{\max [ADC] - \mu_{noise}}{\sigma_{noise}}, \quad (4.16)$$

where the subscript *noise* refers to a subset of the data obtained by only taking into account waveform values within a  $\pm 3\sigma$  range around the mean of the data and  $\max [ADC]$  is the maximum of the original waveform. This definition is further discussed in App. 4.2, where I also show examples of its application to raw data and to a waveform filtered with the current low-pass FIR filter.

To test whether this choice of filter is appropriate one needs to choose a signal template. As an example of how a matched filter would affect our signal, I simply took the filter coefficients to be the 32 ADC values around a signal peak present in the data.

#### 4.4. MATCHED FILTERS

1588 In Fig. 4.7 (left panel) I plotted a zoomed region for channel 7840 in the raw data capture  
1589 `felix-2020-07-17-21:31:44`, after applying the matched filter described before (blue  
1590 line). When compared to the raw and FIR filtered case (see App. 4.2), after applying  
1591 the match filter the standard deviation of the noise waveform (red line) decreases and at  
1592 the same time the signal peaks are enhanced. This leads to an improvement of the S/N  
1593 by a factor of 1.92 when compared to the raw waveform.

1594 In order to obtain the matched filter that is more suitable for our data, I explored  
1595 different configurations of signal templates. In order to perform this exploration, I  
1596 parametrised the signal using the bipolar function:

$$f(x) = -A(x + \delta) e^{-x^2/\sigma^2}, \quad (4.17)$$

1597 where the parameter  $\delta$  controls the asymmetry between the positive and negative peaks  
1598 and  $\sigma$  controls their width. The amplitude parameter  $A$  is set such that it keeps the  
1599 height of the biggest peak to be less than 200 ADC in absolute value.

1600 As this parametrisation is only adequate for bipolar signals I will focus exclusively  
1601 on the induction channels. Also, the optimal configurations I found for the U and V  
1602 plane will be kept separate, i.e. I will have two sets of coefficients that will be applied to  
1603 either the U and V planes of wires. I do so as I found this was the choice giving the  
1604 best performance. Even so, as I will discuss, the differences are not very pronounced. In  
1605 case it is not technically possible to separate channels in the firmware according to the  
1606 wire plane they come from and use different sets of filter coefficients for them, we can  
1607 just find a common unique set of coefficients. In such case, I do not expect our results  
1608 to change dramatically.

1609 In Fig. 4.8 I present the results of our parameter scan, for channels in the induction  
1610 planes U (left panel) and V (right panel). For each configuration of  $\sigma$  and  $\delta$  the resulting  
1611 matched filter was applied to all channels in the corresponding plane within the data  
1612 capture `felix-2020-07-17-21:31:44`, the S/N improvement was computed with respect  
1613 to the raw waveforms and then the S/N mean value was kept as a score for such filter.

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES

1614 One can see that the improvement obtained for the U plane is in general higher than the  
1615 one for the V plane. In any case, I got substantially higher ratios than the ones obtained  
1616 for the low-pass FIR filters. For the optimal configurations I attained improvements up  
1617 to a factor of 1.85 for the U plane and 1.65 for the V plane.

1618 The sets of optimal matched filter coefficients were obtained for the parameters  
1619  $\delta = 0.035$ ,  $\sigma = 0.191$  for the U plane and  $\delta = 0.018$ ,  $\sigma = 0.191$  for the V plane. I  
1620 show these two sets of coefficients in Fig. 4.9 (left panel). Also in Fig. 4.9 (right  
1621 panel) I plot the distribution of the S/N improvement after the optimal match filters  
1622 for the U and V were applied to the corresponding channels in the raw data capture  
1623 `felix-2020-07-17-21:31:44`. As mentioned before, the mean improvement achieved  
1624 for the U plane channels is slightly bigger than the one for the V channels. Note, however,  
1625 that the spread of the distribution for the V plane is also smaller than the one for the U  
1626 plane.

1627 I also performed a similar scan for the case of a low-pass FIR filter using the Parks-  
1628 McClellan algorithm. In that case, the parameters to check were the cutoff frequency  
1629 and the transition width of the filter. A summary of the results is given in App. 4.3.

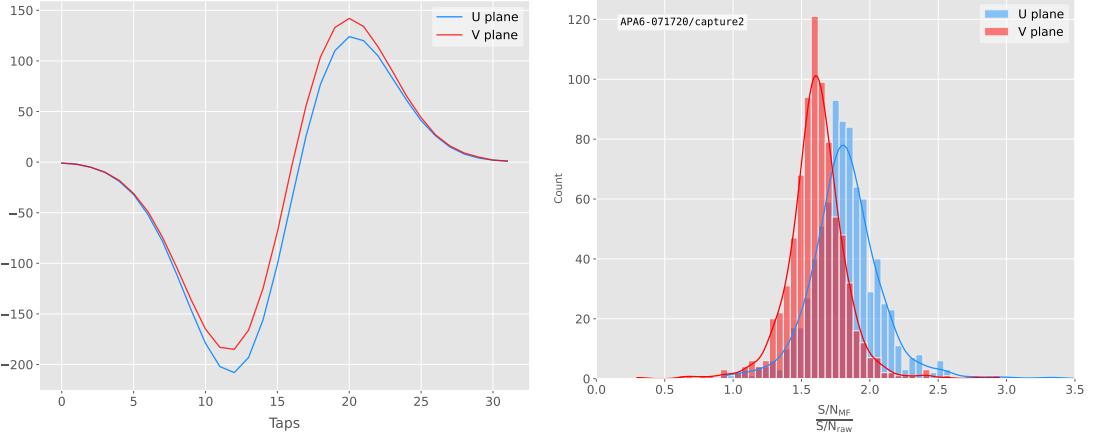
1630 Overall, one can see that the improvements on the S/N are much more significant in  
1631 the case of the matched filter than it is for the low-pass FIR filters. The analysis of this  
1632 and other raw data captures from ProtoDUNE-SP suggest that matched filters increase  
1633 the S/N of induction channels by a factor of 1.5 more than the optimal low-pass FIR  
1634 filters.

1635 Although these results are by themselves great points in favour of the matched  
1636 filter, more studies are needed to completely assess the robustness of this approach. I  
1637 proceeded then to test the matched filter with simulated data samples.

### 1638 4.5 Using simulated samples

1639 In order to further test the matched filter, the next step was to generate and process  
1640 data samples using *LArSoft* [110]. In this way, one can control the particle content of

## 4.5. USING SIMULATED SAMPLES



**Figure 4.9:** Left panel: Optimal matched filter coefficients for the  $U$  (blue line) and  $V$  (red line) planes. The filters were computed with our parametrisation in Eq. (4.17) for the parameter values  $\delta = 0.035$ ,  $\sigma = 0.191$  and  $\delta = 0.018$ ,  $\sigma = 0.191$  respectively. Right panel: Distribution of the relative change of the  $S/N$  on the two induction wire planes from the ProtoDUNE-SP raw data capture *felix-2020-07-17-21:31:44* after their respective optimal matched filters were applied.

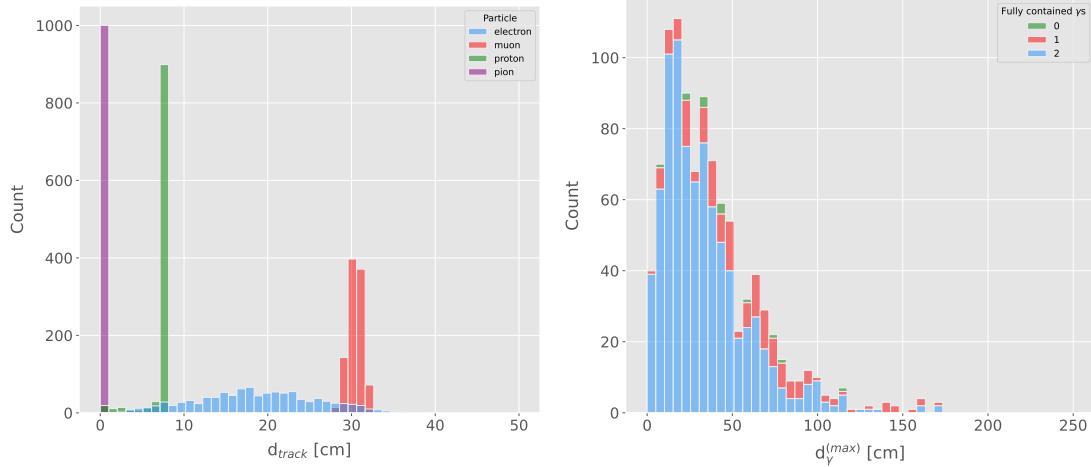
1641 the samples, the orientation of the tracks and their energy, and therefore see how the  
1642 matched filter behaves in various situations.

1643 To begin with, I prepared different monoenergetic and isotropic samples containing  
1644 a single particle per event. Each sample contains a different particle species, namely  
1645 electrons, muons, protons and neutral pions all with a kinetic energy of  $E_k = 100$  MeV.  
1646 I chose these because of the fairly different topologies they generate in the liquid argon,  
1647 ranging from shower-like to track-like. The procedure I followed to generate the samples  
1648 and process them is discussed in detail in App. ??.

1649 These were generated with the single particle gun and the Geant4 stage of the  
1650 *LArSoft* simulation [110] was performed with the standard configuration for the DUNE  
1651 FD 10kt module.

1652 For simplicity, I restricted the particles to start drifting in a single TPC volume  
1653 (in this case TPC 0), so I can focus exclusively on the signals coming from one APA.  
1654 The chosen kinetic energy for all the particles in my first trial is  $E_k = 100$  MeV, so a  
1655 necessary check is to see if all our tracks will be typically contained in one TPC volume.  
1656 Fig. 4.10 (left panel) shows the distributions of the track lengths in the liquid argon

## CHAPTER 4. MATCHED FILTER APPROACH TO TRIGGER PRIMITIVES



**Figure 4.10:** Left panel: distributions of the particles track length in the liquid argon for the generated  $E_k = 100$  MeV monoenergetic samples, electrons (blue), muons (red), protons (green) and neutral pions (purple). Right panel: distribution of the length of the longest photon in the neutral pion sample after the decay process  $\pi^0 \rightarrow \gamma\gamma$ .

of all generated particles with  $E_k = 100$  MeV. One can see that, in the case of the track-like particles (i.e. muons and protons), their length distributions are quite sharp and centered at relatively low distances (30 and 8 cm, respectively). For electrons, the distribution is quite broad but it does not extend past  $\sim 30$  cm. The case of neutral pions can be misleading, as they decay promptly the track length associated with the true Monte Carlo particle is always  $< 1$  cm. In Fig. 4.10 (right panel) I show the effective length distribution of the longest photon after the pion decays as  $\pi^0 \rightarrow \gamma\gamma$ , highlighting the number of fully contained photons in the TPC volume per event (either zero, one or both). One can see that the vast majority of events has both photons contained and that just a negligible number of them has none of them contained in the TPC volume. In any case, for the sake of caution, I will only keep the pion events with both photons contained.

Once I have prepared a sample at the Geant4 level, I need to process it through the detector simulation. In order to make adequate estimations of the noise levels and run the filtering and hit finder as I did with the ProtoDUNE data, one needs to turn off the default zero-suppression of the waveforms produced by the simulation. At this first stage I am only concerned with the waveforms with the noise added, so I keep the noise

## 4.5. USING SIMULATED SAMPLES

addition option as true in the configuration. However, for studies related to the hit finder performance one will also need to store the noiseless waveforms in order to retrieve the truth information of the hits. I will discuss this approach next.

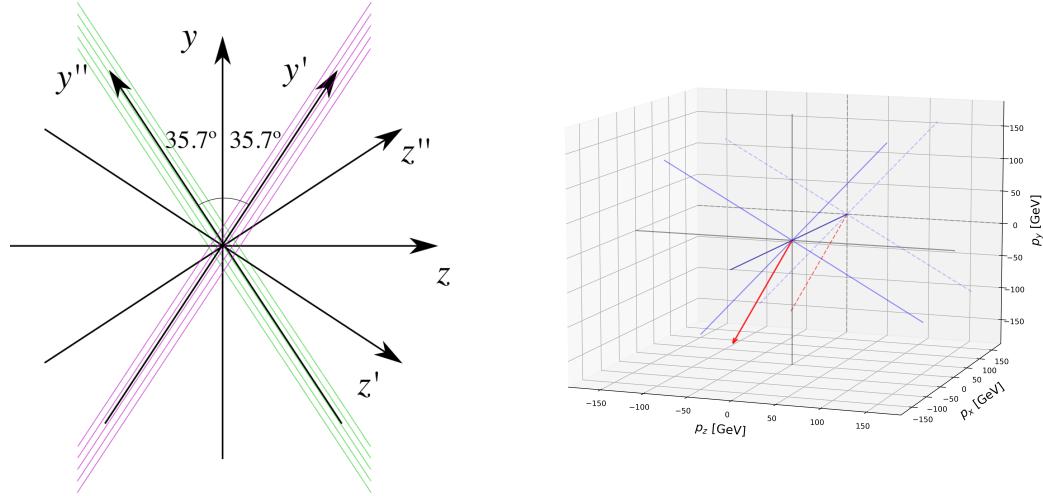
After the detector simulation stage, one needs to extract the no zero-suppressed noisy waveforms, along with their offline channel numbers, and store them in a certain format to be analysed later. To reduce the amount of data that will go for processing, I used the information from the Geant4 step of the simulation to select only the active channels, i.e. the channels where some ionisation electrons arrive. Moreover, as said previously, I only extract the waveforms from APA 0 and exclusively the ones coming from induction channels. The resulting ROOT file contains a tree with two branches, one containing the waveforms for each event and channel and the other with the corresponding offline channel numbers.

Finally, to extract the truth values for the orientation of the tracks and the energies of the particles I used a modified analysis module. This gives a ROOT file with a single tree, containing several branches with different information such as the components of the initial momentum of the particles, initial and final  $xyz$  location, track length, etc.

For the analysis of the resulting waveforms and truth values I used a custom set of Python libraries (available at [??]). Among other functionalities, these enable the user to read the ROOT files, export the raw data as pandas objects, apply the filters and compute the S/N of both the raw and filtered signals. So far, the default configuration for the filtering uses the set of optimal matched filter coefficients that I found using the ProtoDUNE data samples.

Additionally, for the analysis of the samples it was necessary to use two different reference frames, to study separately the signals coming from the U and V induction wire planes. As I am focussing on a single APA, the U and V wires have a different orientation in the  $yz$  plane. In the case of U wires, these are tilted  $35.7^\circ$  clockwise from the vertical ( $y$  direction), whereas the V wires are at the same angle but in the counter clockwise direction. Because of this, the best option is to deal with two new coordinate systems rotated by  $\pm 35.7^\circ$  along the  $x$  axis, so the new  $y'$  and  $y''$  directions are aligned with the

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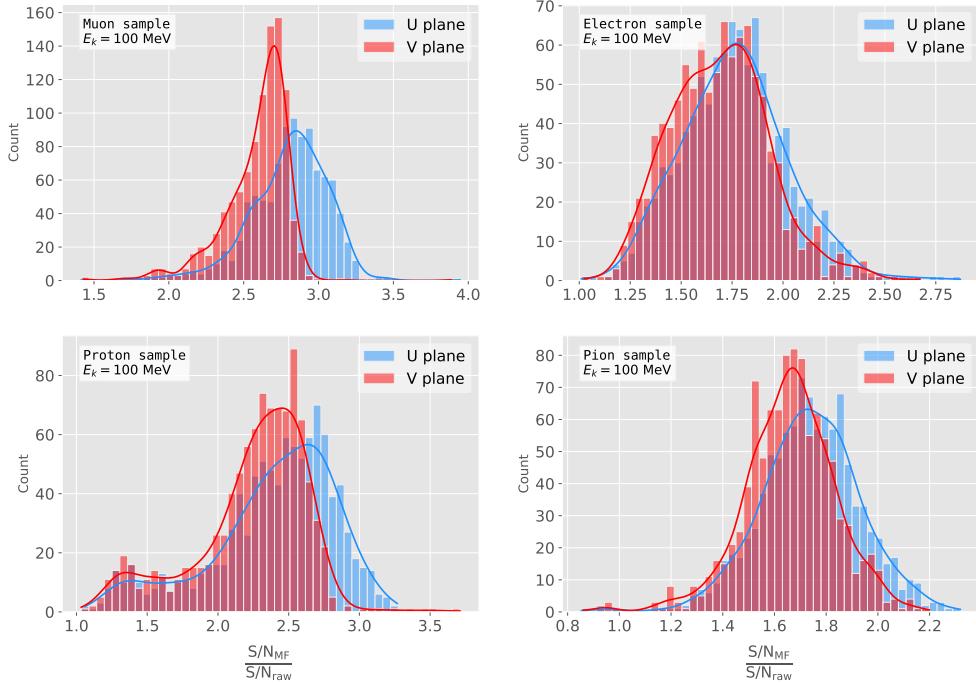


**Figure 4.11:** Left panel: schematic representation of the two new rotated reference frames used in this analysis (denoted as prime and double prime), viewed from the  $yz$  plane. The magenta stack of lines represent the wires in the  $U$  plane, whereas the green lines correspond to the wires in the  $V$  plane. Right panel: 3D representation of the momentum of one of the generated monoenergetic muons (red arrow) in the original reference frame (black lines), along with the new reference frame used for the  $U$  plane waveforms (blue lines). In the  $yz$  plane I added the projection of these three.

1703 U and V induction wires. Fig. 4.11 (left panel) shows a schematic representation of  
 1704 the original reference frame together with the two rotated ones (denoted by primed and  
 1705 double primed). This way, one can easily understand how parallel was a track to the  
 1706 wires in the two induction planes. Fig. 4.11 (right panel) shows a 3D representation of  
 1707 the momentum of a track (red arrow) in the original reference frame (black lines), along  
 1708 with the new reference frame for  $U$  wires (blue lines). I added the projection in the  $yz$   
 1709 plane of this three, to show the usefulness of the new reference frame to tell whether a  
 1710 track is parallel or normal to the wires in the induction plane.

1711 Fig. 4.12 shows the distribution of the average S/N improvement per event when one  
 1712 applies the optimal matched filters. I produced separate distributions for the channels  
 1713 in the  $U$  (red) and  $V$  (blue) induction wire planes. Notice that the S/N distributions  
 1714 for the track-like particles, i.e. muons (top left panel) and protons (bottom left panel),  
 1715 have significantly larger mean values than the distributions of the shower like particles,  
 1716 i.e. electrons (top right panel) and neutral pions (bottom right panel). An important

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**Figure 4.12:** Distributions of the mean  $S/N$  improvement per event for the corresponding sample after applying the matched filters. Here I separated the change in the U plane (blue) and the V plane (red) channels. From top left to the right: muon, electron, proton and neutral pion. All the events have a fixed kinetic energy of  $E_k = 100 \text{ MeV}$ .

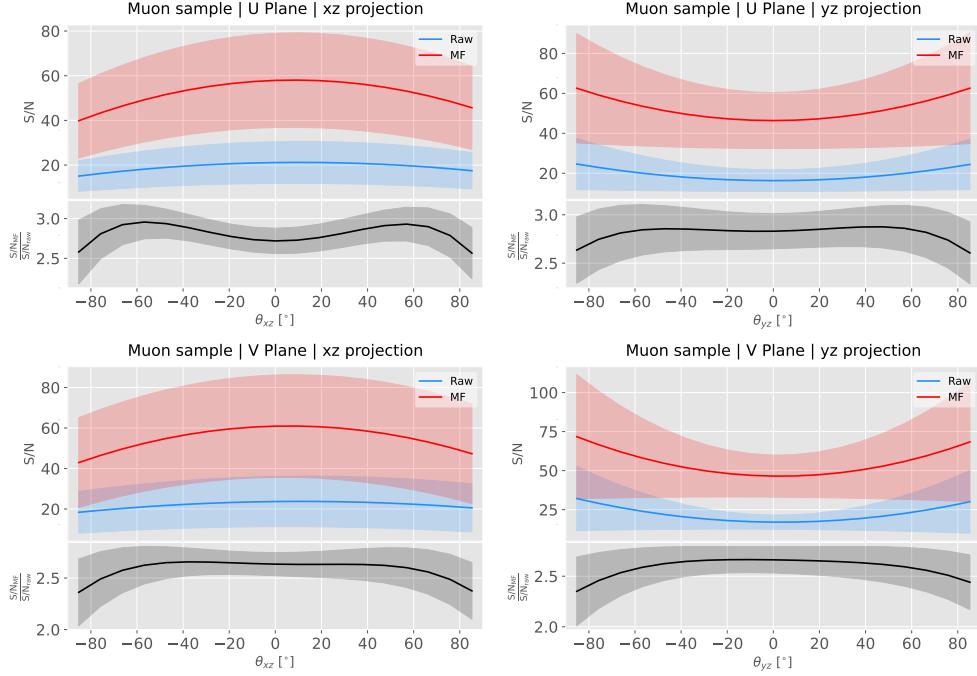
difference between these results and the ones seen before for ProtoDUNE data is that, overall, the improvements that I get for simulated data are bigger. This could be due either to the default noise model used in the *LArSoft* simulation or to the simulated hits having higher energy than the ones in the recorded data. Nonetheless, the concluding message is that the previously optimised matched filters give an overall significant improvement of the S/N for the different samples.

About the convention I followed for the plots and results, in the case of the raw and filtered S/N of each event in the sample I simply took the average of the quantities over all the active channels in the event. That is, if a certain event has  $N_{chan}$  active channels these two quantities are computed as:

$$(S/N_{fir})_{event} = \frac{\sum_{i=0}^{N_{chan}} (S/N_{fir})_i}{N_{chan}}, \quad (4.18)$$

$$(S/N_{raw})_{event} = \frac{\sum_{i=0}^{N_{chan}} (S/N_{raw})_i}{N_{chan}}.$$

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**Figure 4.13:** Angular dependence of the mean S/N and the S/N improvement, for the different monoenergetic samples considered (from top to bottom: electrons, muons, protons and neutral pions). The two columns on the left represent the values for the U plane waveforms. The top subplots show the mean S/N for raw (green) and filtered (red) waveforms whereas the bottom subplots depict the averaged S/N improvement (black).

1727 However, for the ratio of the raw and filtered S/N (what I called the S/N improvement)  
 1728 per event I am not just taking the ratio of the previous two quantities but computing  
 1729 the average of the individual ratios per channel in the event:

$$\left( \frac{S/N_{fir}}{S/N_{raw}} \right)_{event} = \frac{\sum_{i=0}^{N_{chan}} \left( \frac{S/N_{fir}}{S/N_{raw}} \right)_i}{N_{chan}}, \quad (4.19)$$

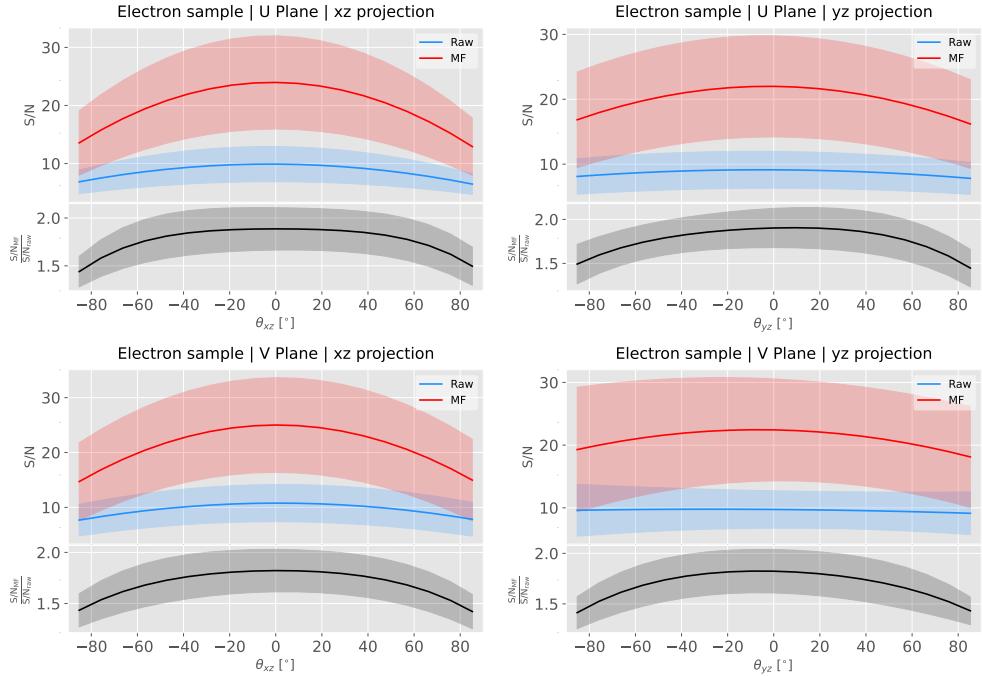
1730 and so:

$$\left( \frac{S/N_{fir}}{S/N_{raw}} \right)_{event} \neq \frac{(S/N_{fir})_{event}}{(S/N_{raw})_{event}}. \quad (4.20)$$

### 1731 4.5.1 Angular dependence

1732 Having these monoenergetic samples, one can also study the angular dependence of the  
 1733 performance of the matched filter. This is an important point, as it is a well established

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**Figure 4.14:** Angular dependence of the mean S/N and the S/N improvement, for the different monoenergetic samples considered (from top to bottom: electrons, muons, protons and neutral pions). The two columns on the left represent the values for the U plane waveforms. The top subplots show the mean S/N for raw (green) and filtered (red) waveforms whereas the bottom subplots depict the averaged S/N improvement (black).

fact that for certain configurations (an extreme case configuration being signals normal to the wire plane and perpendicular to the induction wires at the same time) the S/N is much lower than average as the corresponding waveforms are severely distorted. In this sense, I am interested to see how the matched filter behaves for these cases and how the S/N improvement on those compare to the average.

Fig. 4.13 shows the angular dependence of the S/N for the monoenergetic  $E_k = 100$  MeV isotropic muons, for the different induction wire planes and projections. The angles for each event are given by the components of the initial value of the momentum of the particles, taking the angles of the projections on the  $xz$  and  $yz$  planes with respect to the  $z$  axis (more accurately, one needs to compute these angles twice for each event, a pair for the  $xy'z'$  coordinate system and the other for the  $xy''z''$ ). The top row shows the dependence on the angles corresponding to the U plane, i.e.  $\theta_{xz'}$  and  $\theta_{y'z'}$ , whereas the bottom row shows the angular dependence viewed from the V plane,  $\theta_{xz''}$  and  $\theta_{y''z''}$ . In

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1747 each plot, the top subplot represents the mean values of the S/N for the raw (blue) and  
1748 matched filtered (red) signals, and the bottom subplot the averaged S/N improvement  
1749 (black). The solid lines represent the mean value obtained for the corresponding angular  
1750 value, whereas the semitransparent bands represent one standard deviation around the  
1751 mean at each point.

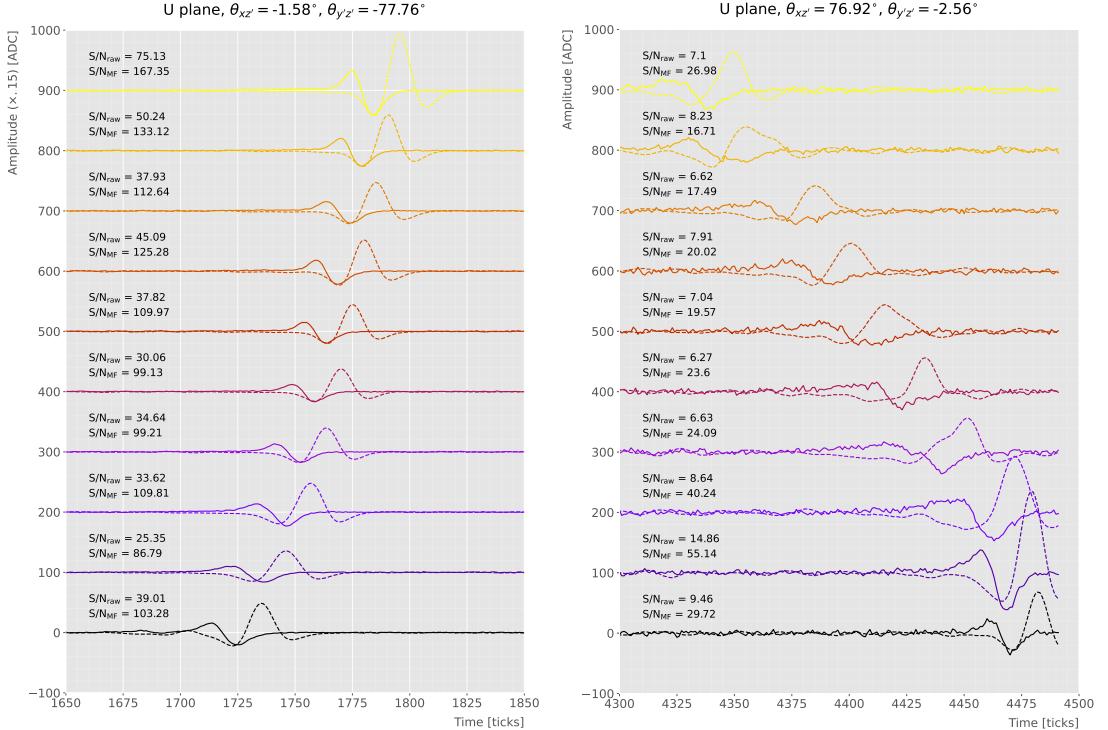
1752 As expected, the S/N is in general higher when tracks are parallel to the APA (i.e.  
1753  $\theta_{xz} \sim 0$ ) and lower when it is normal to the plane ( $\theta_{xz} \sim \pm 90^\circ$ ). In the same way, tracks  
1754 parallel to the wires ( $\theta_{yz} \sim \pm 90^\circ$ ) tend to have higher S/N than those perpendicular to  
1755 these ( $\theta_{yz} \sim \pm 0$ ).

1756 Fig. 4.14 shows the corresponding angular dependence information for the  $E_k =$   
1757 100 MeV electrons sample. Notice that, in this case, the S/N behaviour discussed above  
1758 does not hold. A possible explanation can be that, because most hits in these events  
1759 are produced by the secondary particles generated in the EM shower, the signal peaks  
1760 whose S/N ratios were computed do not correspond to the directional information of  
1761 the primary electron.

### 1762 4.5.2 Distortion and peak asymmetry

1763 As a little case of study, I selected two of the simulated  $E_k = 100$  MeV monoenergetic  
1764 muon events. With respect to the U induction plane, one is parallel to the APA (low  
1765  $\theta_{xz'}$ ) and to the wires (high  $\theta_{y'z'}$ ) and the other is normal to the APA plane (high  $\theta_{xz'}$ )  
1766 and perpendicular to the wires (low  $\theta_{y'z'}$ ). As expected from the results on the angular  
1767 dependence discussed above, the former has a higher S/N (before and after the filtering)  
1768 when compared to the latter. An interesting thing to notice about these two samples  
1769 is that, even though one has a much bigger S/N than the other, it is the one with the  
1770 smallest S/N the one that got the biggest averaged S/N improvement. In Table 4.1  
1771 I included all the relevant parameters of these two  $E_k = 100$  MeV muon events I am  
1772 considering, namely, the angles with respect to the  $xy'z'$  reference frame, the values of  
1773 the S/N, the S/N improvement and also the so-called peak asymmetry  $\Delta_{peak}$  that I will  
1774 discuss next.

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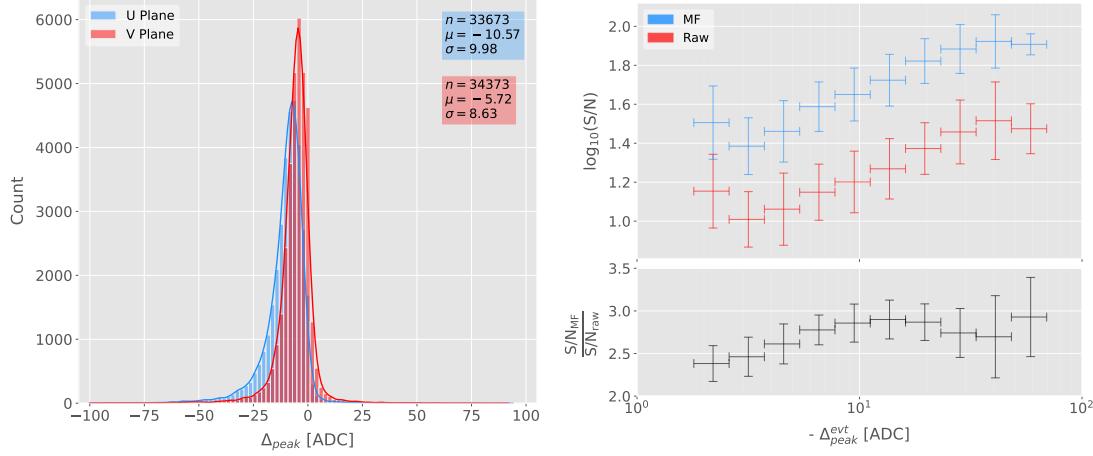
**Figure 4.15:** Selected consecutive waveforms corresponding to two monoenergetic  $E_k = 100$  MeV muon events, one is parallel to the APA and to the wires in the U plane (left panel) and the other is normal to the APA plane and perpendicular to the U plane wires (right panel). The solid lines represent the raw waveforms whereas the dashed lines correspond to the waveforms after the matched filter was applied. The waveforms on the left panel have been scaled by a factor of 0.15 to have similar amplitude to the ones on the right panel.

**Table 4.1:** Characteristic parameters of the two monoenergetic muon events selected, relative to the U plane: projected angles in the  $xz'$  and  $yz'$  planes,  $S/N$  values for the raw and filtered waveforms, mean improvement of the  $S/N$  and peak asymmetry.

	$\theta_{xz'} (\circ)$	$\theta_{yz'} (\circ)$	$S/N_{\text{raw}}$	$S/N_{\text{MF}}$	$\frac{S/N_{\text{MF}}}{S/N_{\text{raw}}}$	$\Delta_{\text{peak}} (\text{ADC})$
High ("parallel")	-1.58	-77.76	41.65	112.44	2.83	-35.73
Low ("normal")	76.92	-2.56	8.07	25.46	3.12	-10.38

1775 One can try to understand better what is going on with these two events by looking  
 1776 at the raw and filtered data from some of their active channels. Fig. 4.15 shows a  
 1777 selection of consecutive raw and filtered U plane waveforms from the event with high S/N  
 1778 (left panel) and the one with low S/N (right panel). Notice that to show both collections  
 1779 of waveforms at a similar scale I had to apply a factor of 0.15 to the waveforms with  
 1780 high S/N. Additionally, next to each waveform I included the values of the raw and

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**Figure 4.16:** Left panel: peak asymmetry distribution for the case of the monoenergetic  $E_k = 100$  MeV muon sample. Each value corresponds to a single bipolar signal peak from a channel in any event. The blue distribution represents the peaks on U plane channels, whereas the red corresponds to signal peaks in V wires. Right panel: relation between the mean peak asymmetry per event with the S/N for U channel waveforms from the  $E_k = 100$  MeV muon sample. The top subplot shows the decimal logarithm of the mean S/N for the raw (red) and the matched filtered (blue) waveforms. The bottom subplot contains the mean S/N improvement ratio after the matched filter was applied.

1781 matched filtered S/N for the corresponding channel. The first thing to notice in this plot  
 1782 is that the amplitude of the signal peaks from the normal track have a much smaller  
 1783 amplitude, and also appear quite distorted when compared to the others. On the other  
 1784 hand, although the matched filtered S/N is still smaller, the relative improvement is  
 1785 bigger than in the parallel case.

1786 A way I found to quantify the difference between the shapes within these two events  
 1787 is their different peak asymmetry. One can define the peak asymmetry as the (signed)  
 1788 difference between the positive and the negative peaks of the bipolar shape, i.e.:

$$\Delta_{peak} \equiv h_+ - h_-, \quad (4.21)$$

1789 where both heights  $h_+$  and  $h_-$  are positive defined. Fig. 4.16 (left panel) shows the  
 1790 distribution of this peak asymmetry for all the waveforms corresponding to channels  
 1791 in the U (blue) and V (red) planes for the monoenergetic muon sample. One can  
 1792 see that these distributions are clearly shifted to negative values (with mean values

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1793  $\mu_{\Delta}^U = -10.57$  ADC and  $\mu_{\Delta}^V = -5.72$  ADC respectively). It is interesting to notice  
1794 that the peak asymmetry value of the sample with high S/N sits at the left tail of the  
1795 distribution whereas the corresponding value of the sample with low S/N lies around  
1796 the mean.

1797 Now, one can try to correlate the peak asymmetry with the S/N and the S/N change  
1798 per event. Fig. 4.16 (right panel) shows the result of comparing (minus) the mean  
1799 peak asymmetry per event to the averaged raw (red) and matched filtered (blue) S/N  
1800 per event (top subplot). The horizontal lines sit at the mean value obtained in the fit  
1801 and represent the width of the  $-\Delta_{peak}$  bins used, while the vertical lines indicate one  
1802 standard deviation around that mean value. Notice that, when taking decimal logarithm  
1803 on both, there is an approximate linear relation between these quantities, except for  
1804 peak asymmetry values bigger than  $-5$  ADC where the S/N remains constant.

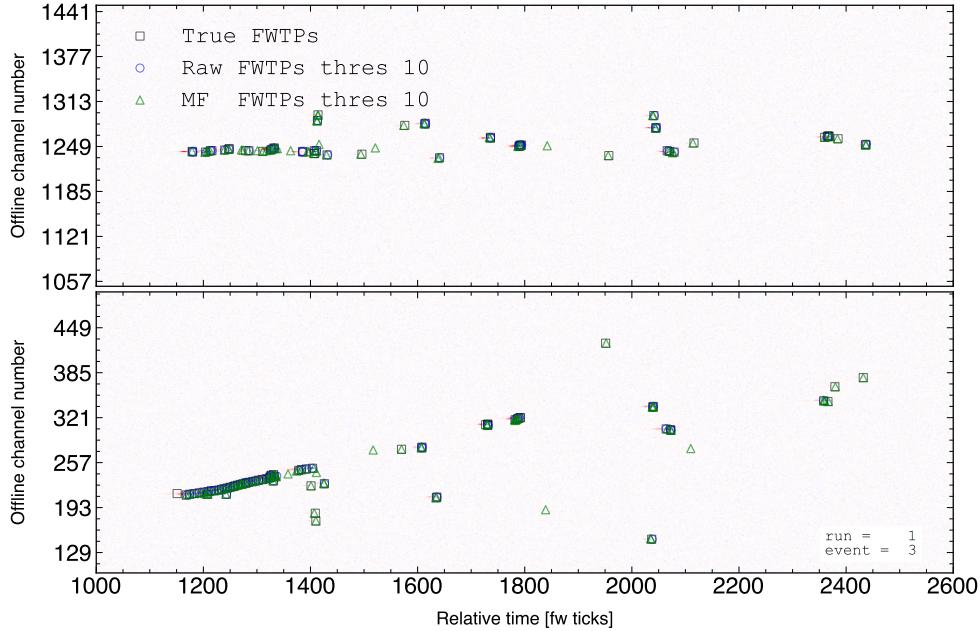
1805 Also, in the bottom subplot of Fig. 4.16 (right panel) I show the relation between  
1806 the peak asymmetry and the mean S/N improvement. In this case, one see that there is  
1807 a maximum at  $\Delta_{peak} \sim -10$  ADC. As mentioned previously, this is also the value of the  
1808 mean of the peak asymmetry distribution. In fact, it is expected that our filter favours  
1809 the signal peaks with the most common values of the peak asymmetry, as this was one  
1810 of the features I target in our filter coefficient optimisation through the parameter  $\delta$ .

1811 These results suggest that events with poorer values of the mean S/N, usually  
1812 associated to non-favourable track orientations, tend to have smaller values of the mean  
1813 peak asymmetry (in absolute value). Nonetheless, because our matched filters have  
1814 been optimised to account for these asymmetries, the improvement on the S/N for these  
1815 events is sizeable if not better than the one for events which already had a high S/N.

### 1816 4.5.3 Hit sensitivity

1817 One of the advantages of the matched filter, directly related to increasing the S/N, is  
1818 the capability of picking hits that before fell below the threshold. For instance, Fig. 4.17  
1819 shows the raw ADC data from an example event (electron,  $E_k = 100$  MeV) with the  
1820 produced true hits superimposed (black boxes), together with the hits produced by the

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**Figure 4.17:** Raw data display in the plane time (in firmware ticks) vs. offline channel number for an  $E_k = 100$  MeV electron event. The produced true hits are superimposed (black boxes) as well as the hits coming from the standard hit finder chain (blue circles) and the hit finder using the matched filter (green triangles).

standard hit finder chain (blue circles), i.e. using the current FIR filter, and the hits obtained using the matched filters (green triangles). Both the standard and the matched filter hit finders were run with a threshold of 10 ADC. Notice that the standard hits match well the true ones at the initial part of the event (where we have a track-like object), but they miss most of the hits produced by the EM shower at later times. On the other hand, the hits produced with the matched filter have a better agreement with the true hits even for the more diffuse shower activity.

Notwithstanding that now I get more hits with this combination of matched filter and low threshold as a results of the enhancement of the signal peaks relative to the noise level, it is also true that I pick some spurious hits not related to any real activity if one lowers the thresholds too much. Therefore, some optimisation of the threshold is needed. Basically one will need to make a trade-off between precision and sensitivity.

Having this in mind, I tried to compare the produced hits one gets from the standard hit finder and the ones resulting from applying the matched filter with the true hits.

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1835 By running the hit finders on our samples with different values of the threshold one  
1836 can understand, for instance, how low one can set the threshold without getting mostly  
1837 spurious hits and then evaluate the gains obtained from this.

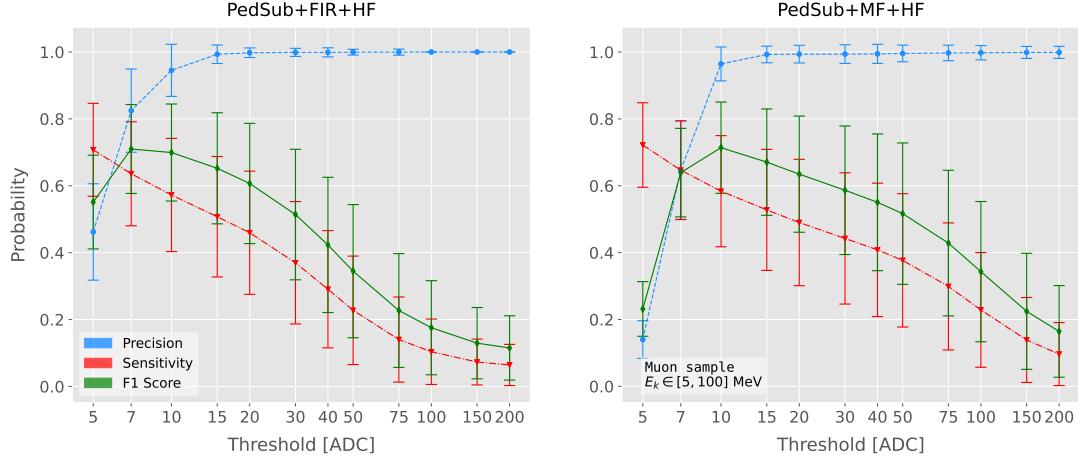
1838 Because now I am also interested in seeing how the hit sensitivity changes with the  
1839 energy, I prepared new isotropic samples with the same types of particles as before  
1840 (muons, electrons, protons and neutral pions) but with a flat kinetic energy distribution  
1841 ranging from 5 to 100 MeV.

1842 In order to estimate the hit sensitivity, given a certain sample, one needs to recover  
1843 the set of true hits to be able to compare these with the ones produced. To do so,  
1844 a modification in the procedure I was using to extract the raw waveforms is needed.  
1845 For this kind of study I run the detector simulation in two steps, first I produce the  
1846 waveforms without noise and extract them in the same format I used for the raw data,  
1847 then the noise is added and the noisy waveforms are then written to a file as well.

1848 To have a better comparison between the true hits and the ones produced from  
1849 the raw waveforms after applying the two filters, I applied also the FIR filter and the  
1850 matched filters to the noiseless waveforms and then I run the hit finder with a minimal  
1851 threshold (in this case I used 1 ADC) on these noiseless filtered waveforms. In this way  
1852 I generated two sets of true hits, I will refer to them as standard true hits (with the  
1853 current/default FIR filter) and matched filter true hits respectively. This allows a more  
1854 precise matching between the different groups of hits produced, as it will account for  
1855 any delays and distortions introduced by the FIR and the matched filters.

1856 In the case of the raw waveforms (with noise), I run the hit finder on them, with  
1857 different values of the threshold, after applying either the FIR or the matched filters. I  
1858 will name them simply standard hits and matched filter hits respectively. Then, I match  
1859 the generated hits to the true hits (the standard hits with the standard true hits and  
1860 the matched filter hits with the matched filter true hits). The matching is performed by  
1861 comparing the channel number and the timestamp of the hits. To count as a match,  
1862 I require that all hits with the same channel number and timestamp have overlapping  
1863 hit windows, i.e. the time windows between their hit end and hit start times need to

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**Figure 4.18:** Dependence of the precision (blue), sensitivity (red) and  $F_1$  (green) scores on the threshold values used in the hit finder, for the FIR (left panel) and matched filter (right panel) cases. The results were obtained after matching the hits to the true hits in the case of the isotropic muon sample with kinetic energy in the range 5 to 100 MeV, taking only into account the induction plane channels. The points represent the mean value while the error bars indicate one standard deviation around that mean value.

overlap. If more than one hit in one of the groups have hit overlap with the same hit in the other group I only count the hit with closer hit peak time value.

The generation of the samples, the procedure to produce the standard hits (with the default FIR filter) and matched filter hits and the matching of these with the true hits is described in detail in App. ??.

To quantify the performance of the two hit finder approaches, I use a classical method from statistical classification known as confusion matrix [111]. This is basically a way of sorting the outputs of a binary classifier, considering the true values of the classification and the predicted values. It divides the outputs in four categories: true positive (TP, both true and predicted values are 1), false negative (FN, true value is 1 but predicted is 0), false positive (FP, true value is 0 but predicted is 1) and true negative (TN, both true and predicted values are 0)).

The contents of the confusion matrix allow us to compute other derived scores to judge the performance of our classifiers. In this study, I will make use of three of these

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1878 metrics, namely the precision or positive predictive value:

$$\text{PPV} = \frac{\text{TP}}{\text{TP} + \text{FP}}, \quad (4.22)$$

1879 the sensitivity or true positive rate:

$$\text{TPR} = \frac{\text{TP}}{\text{TP} + \text{FN}}, \quad (4.23)$$

1880 and the  $F_1$  score [112]:

$$F_1 = \frac{2\text{TP}}{2\text{TP} + \text{FP} + \text{FN}}, \quad (4.24)$$

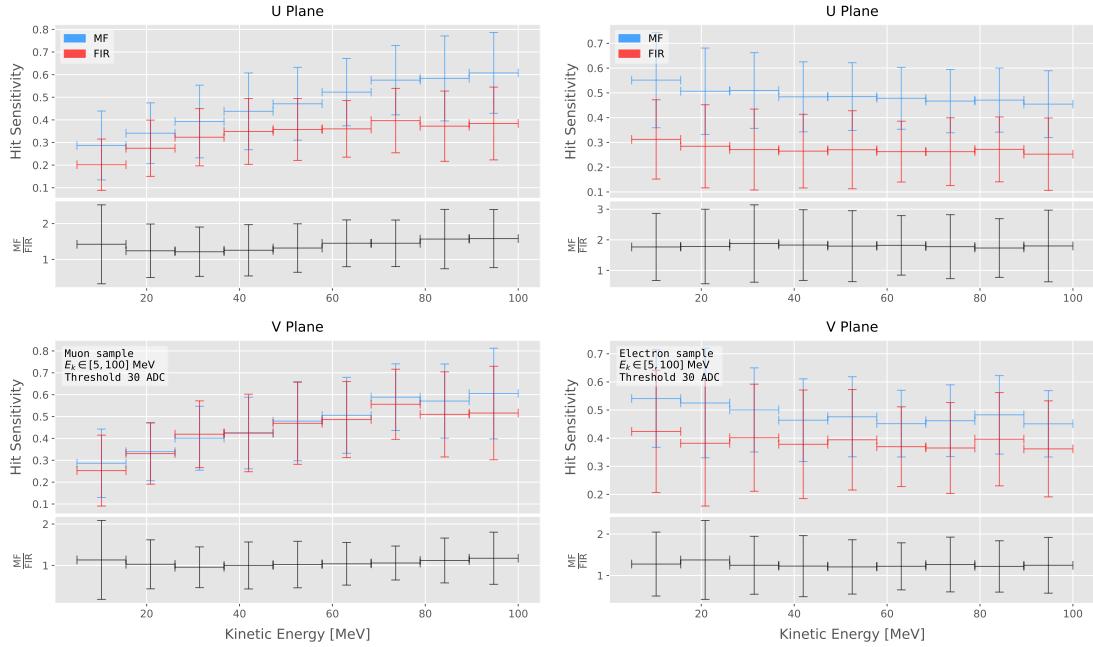
1881 which is the harmonic mean of the precision and the sensitivity.

1882 In our specific case I am not going to make use of the true negative value, as its  
1883 definition in this context can be ambiguous because one does not have clear instances in  
1884 the classification process. This way, I will only count the number of true positives as the  
1885 total amount of hits I can match between true and raw populations, the number of false  
1886 negatives will be the number of missing true hits and the false positive the number of  
1887 hits which do not match any true hit.

1888 In Fig. 4.18 I show the precision (blue), sensitivity (red) and  $F_1$  (green) scores I  
1889 obtained for different values of the threshold used in the hit finder for the case of the  
1890 muon sample. Because the matched filters are only applied to induction channels, I only  
1891 consider here hits coming from the U and V planes. The panel on the left corresponds  
1892 to the scores I got when I ran the hit finder on the FIR filtered waveforms, whereas the  
1893 right panel contains the scores for the matched filter case. The points are centered at  
1894 the threshold value used and represent the mean value obtained for each score using all  
1895 the generated events, while the error bars indicate one standard deviation around the  
1896 mean value.

1897 One can see that the precision for the matched filter case is lower when the thresholds  
1898 are very low, as the noise baseline is slightly amplified, but then rises to high values  
1899 quicker than for the FIR case. The other difference one can spot is that the sensitivity

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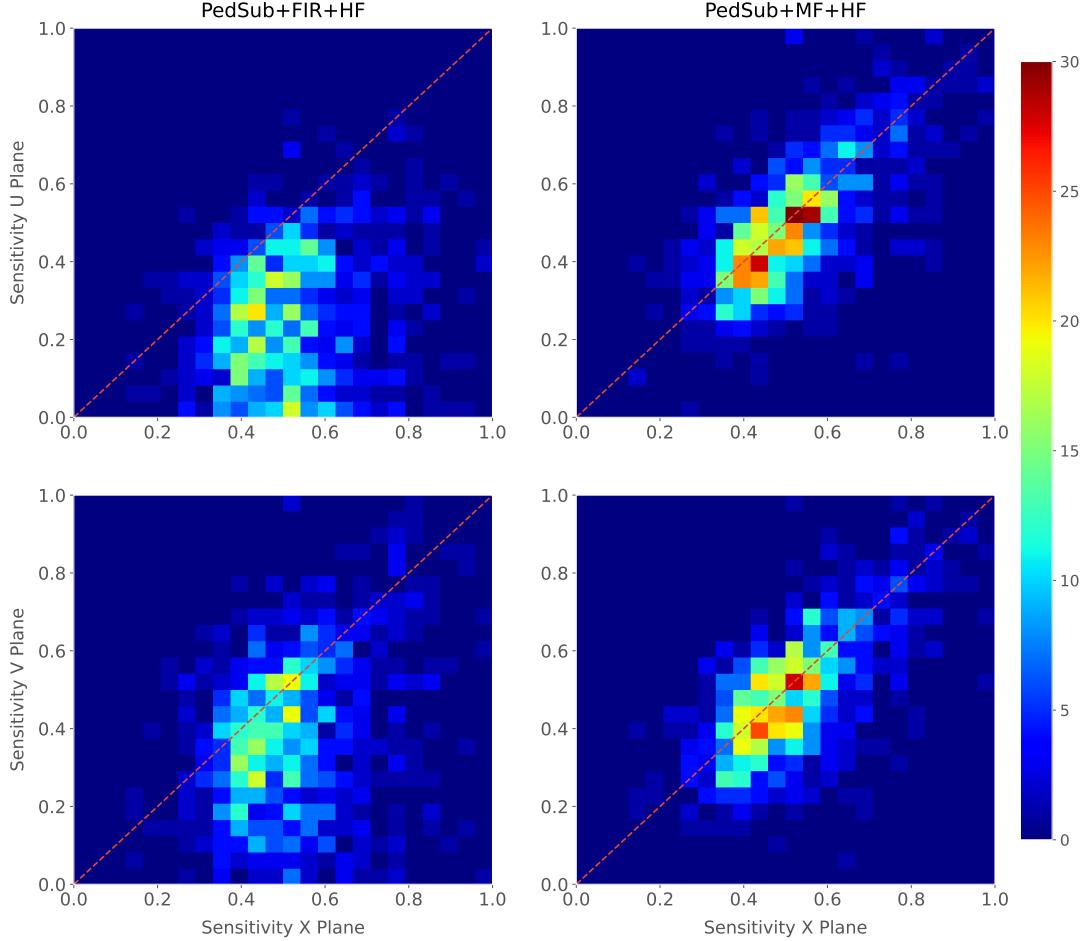


**Figure 4.19:** Dependence of the averaged hit sensitivity on the kinetic energy of the events for the matched filter (blue) and standard (red) hits, for the case of the muon (left panel) and electron (right panel) samples, separated between U (top plots) and V (bottom plots) induction wire planes. The top subplots contain the hit sensitivities for the two hit finder alternatives, while the bottom subplots show the ratio between the two. The horizontal lines sit at the mean value and represent the size of the energy bins, while the vertical error bars indicate one standard deviation around that mean value.

in the FIR case starts dropping faster at around the same threshold values where the precision stabilizes around 1, while in contrast for the matched filter this rapid decrease starts at higher threshold values. A similar scan for the same thresholds was performed for the electron sample in the same energy range, yielding similar results.

In Fig. 4.19 I show the averaged hit sensitivity versus the kinetic energy of the events, both for the matched filter hits (blue) and the standard hits (red). The left panel corresponds to the muon sample, whereas the one on the right corresponds to the electron sample, both with kinetic energies between 5 and 100 MeV. In each panel the top plot corresponds to hits in the U plane, while the bottom plot contains the same information for the V plane. Each plot contains two subplots, the one on the top shows the hit sensitivity values for the matched filter and standard hits separate, while the bottom subplot depicts the ratio between the matched filter and standard sensitivities.

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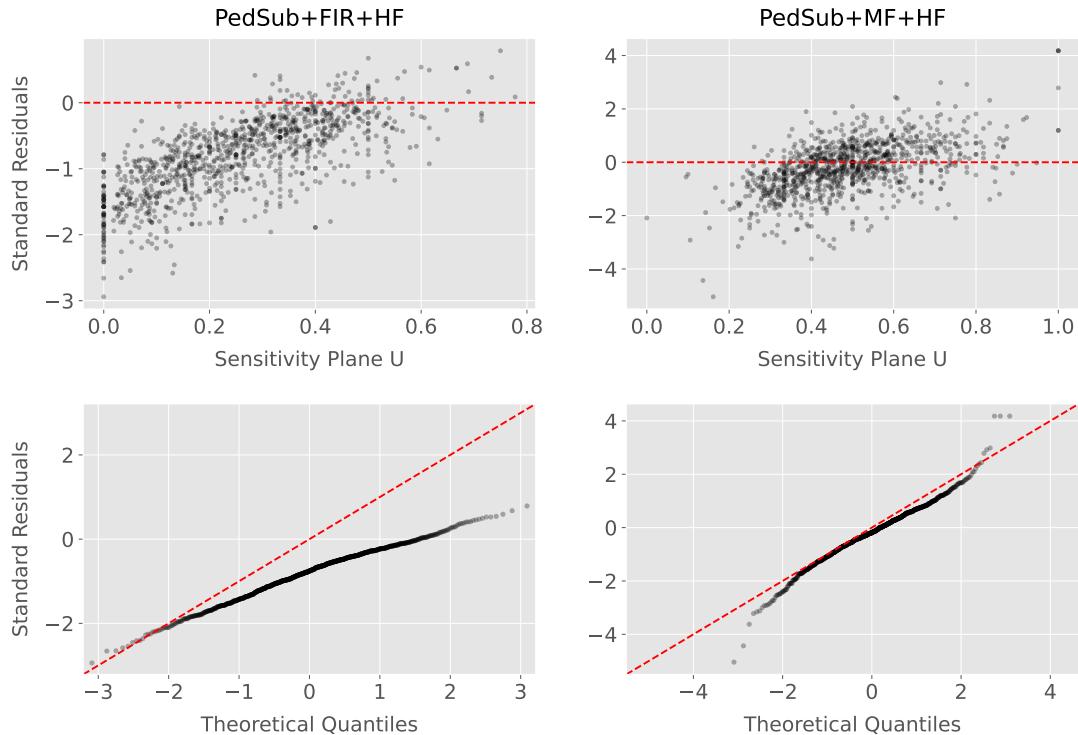


**Figure 4.20:** Distributions of the hit sensitivity in the  $U$  (top panels) and  $V$  (bottom panels) planes versus the hit sensitivity in the  $X$  plane, both for the standard hits (left panels) and the matched filter hits (right panels), in the case of the electron sample and a threshold of 30 ADC.

1912 The horizontal lines are placed at the mean value obtained in the fit and represent the  
 1913 width of the  $E_k$  bins used, while the vertical error bars indicate one standard deviation  
 1914 around that mean value. In both cases the threshold used was 30 ADC, as I required  
 1915 the precision to be higher than 0.99 for both matched filter and standard cases.

1916 One can see that, in general, the improvements are better for the  $U$  than for the  $V$   
 1917 plane. While for the  $U$  channels I achieved a mean improvement of 50% and 80% for  
 1918 muons and electrons respectively, the improvement in the  $V$  plane is stalled at 10% and  
 1919 25%. Nevertheless, if I look at the sensitivities for the matched filter hits in both planes  
 1920 one can see these have similar mean values for each energy bin, while on the contrary

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**Figure 4.21:** Top panels: standard residual plots of the hit sensitivities between the  $X$  and  $U$  planes. Bottom panels: quantile-quantile plots of the hit sensitivity standard residuals between the  $X$  and  $U$  planes. In all cases, the left panel corresponds to the standard hits while the right panel represents the matched filter case, all from the electron sample with a 30 ADC threshold.

for the standard hits the sensitivity remains relatively high for the  $V$  plane. This way, it looks there was a less significant gain because the hit sensitivity was already high.

Another interesting observation is the different behaviors for muons and electrons. While hit sensitivity for muons grows significantly with energy, in the case of electrons this slightly decreases the higher the kinetic energy of the event is. In any case, when it comes to the improvement on the sensitivities, this remains almost constant in all cases.

Furthermore, we can look at how the concurrence of hits between the different wire planes has changed. For any given event, I expect to have a similar number of hits in the three planes. As the ionisation electrons need to cross the  $U$  and  $V$  planes prior to reach the collection plane  $X$  they will induce current in those wire planes. A way to check the concurrence of hits across planes is looking at the relation between the hit sensitivities for each individual event. One cannot expect the sensitivities to be exactly equal across

## 4.5. USING SIMULATED SAMPLES

1933 planes, but ideally they should be normally distributed around the diagonal.

1934 Fig. 4.20 shows the hit sensitivity in the U (top panels) and V (bottom panels)  
1935 planes versus the hit sensitivity in the X plane, for the case of the standard hits (left  
1936 panels) and the matched filter hits (right panels). All plots were generated for the  
1937 electron sample and a threshold of 30 ADC. From these one can see a clear trend,  
1938 when I use the standard hit finder chain the sensitivities in the induction planes are  
1939 systematically lower than the hit sensitivity in the X plane, i.e. most of the points sit  
1940 below the diagonal (red dashed line). In contrast, when the matched filters are applied,  
1941 the majority of the events are distributed around the diagonal. This points out that the  
1942 concurrence of hits across planes has improved.

1943 To exemplify the improvement I obtained, one can consider the residuals of the hit  
1944 sensitivities for the X and U planes. Assuming the diagonal hypothesis, i.e. given a  
1945 dataset of the form  $(x, y)$  for any  $x$  I take the predicted  $y$  value to be equal to the value  
1946 of  $x$ , I can compute the standard residuals for the hit sensitivities in U given the ones for  
1947 X. In Fig. 4.21 (top panels) I show these standard residuals against the corresponding  
1948 values of the hit sensitivity in the U plane, for our electron sample with kinetic energy  
1949 between 5 and 100 MeV. If I compare the scatter points in the case of the standard  
1950 hits (left panel) and the matched filter hits (right panel), I see that the residuals of the  
1951 standard hit finder case follow a certain pattern and their mean deviates from 0.

1952 To see clearly if the residuals are normally distributed, in Fig. 4.21 (bottom panels)  
1953 I plot the corresponding quantile-quantile plot for both the standard (left panel) and  
1954 matched filter (right panel) standard residuals. One can clearly see that the points for  
1955 the standard case follow a strongly non-linear pattern, suggesting that the residuals  
1956 do not follow a normal distribution. In contrast, for the matched filter hits the points  
1957 conform to a roughly linear path, implying that in this case the normality condition is  
1958 fulfilled.

1959 All these results hint at the fact that the concurrence of hits across the wire planes  
1960 can be strengthened by applying the matched filters.



## 1962 DM searches with neutrinos from the Sun

### 1963 5.1 Motivation

1964 The idea of detecting neutrino signals coming from the Sun’s core to probe DM is not  
1965 new. The main focus of these searches has usually been high-energy neutrinos originated  
1966 from DM annihilations into heavy particles [113–116], although recent studies have  
1967 proposed to look at the low-energy neutrino flux arising from the decay of light mesons  
1968 at rest in the Sun [117–120] previously thought undetectable.

1969 In this chapter I try to demonstrate the capability of DUNE to constrain different  
1970 DM scenarios. I used the neutrino fluxes arising from DM annihilations in the core  
1971 of the Sun to compute the projected limits that DUNE would be able to set on the  
1972 annihilation rates in the Sun and the DM scattering cross sections.

### 1973 5.2 Gravitational capture of DM by the Sun

1974 The Sun and the centre of the Earth are possible sources of DM annihilations, specially  
1975 interesting because of their proximity. Their gravitational attraction ensured the capture  
1976 of DM from the local halo through repeated scatterings of DM particles crossing them.  
1977 Only neutrinos produced from DM annihilations can escape the dense interior of these  
1978 objects. Therefore, neutrino telescopes are the most useful experimental layouts to  
1979 pursue DM searches from their cores.

1980 The neutrino flux from DM annihilations inside the Sun depends on the DM capture

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN

1981 rate, which is proportional to the DM scattering cross section, and the annihilation rate,  
 1982 which is proportional to the velocity-averaged DM annihilation cross-section. The total  
 1983 number of DM particles inside the Sun follows the Boltzmann equation [117]:

$$\frac{dN_{DM}}{dt} = C_\odot - A_\odot N_{DM}^2, \quad (5.1)$$

1984 where  $C_\odot$  and  $A_\odot$  are the total Sun DM capture and annihilation rates respectively.  
 1985 In this expression I neglected the evaporation term, proportional to  $N_{DM}$ , which only  
 1986 contribute for  $m_{DM} \lesssim 4$  GeV [121]. As the current threshold of neutrino telescopes  
 1987 is a few GeV, this region falls below the probed range but can be important in future  
 1988 low-energy projects.

1989 This equation has an equilibrium solution:

$$N_{DM}^{eq} = \sqrt{\frac{C_\odot}{A_\odot}}, \quad (5.2)$$

1990 which represents the amount of DM inside the Sun if the capture and annihilation have  
 1991 reached equilibrium. As the Sun is approximately 4.6 Gyr old, it is usually assumed that  
 1992 equilibrium has been achieved. Therefore, the anomalous neutrino flux from the Sun  
 1993 would only depend on the DM scattering cross section, enabling us to set limits on this  
 1994 quantity. If one does not assume equilibrium, some assumptions on the DM annihilation  
 1995 cross section are necessary to extract predictions from neutrino signals.

1996 Here, I am going to consider three possible scenarios for the DM interactions: DM  
 1997 scattering off electrons, spin-dependent (SD) and spin-independent interactions off nuclei.  
 1998 For the case of these last two, the cross sections will be given in terms of the SD and  
 1999 SI elastic scattering DM cross section off protons (assuming that DM interactions off  
 2000 protons and neutrons are identical),  $\sigma_p^{\text{SD}}$  and  $\sigma_p^{\text{SI}}$ , as [2, 117]:

$$\sigma_i^{\text{SD}} = \left( \frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p} \right)^2 \frac{4(J_i + 1)}{3J_i} |\langle S_{p,i} \rangle + \langle S_{n,i} \rangle|^2 \sigma_p^{\text{SD}}, \quad (5.3)$$

$$\sigma_i^{\text{SI}} = \left( \frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p} \right)^2 A_i^2 \sigma_p^{\text{SI}}, \quad (5.4)$$

## 5.2. GRAVITATIONAL CAPTURE OF DM BY THE SUN

2001 where  $\tilde{\mu}_{A_i}$  is the reduced mass of the DM-nucleus  $i$  system,  $\tilde{\mu}_p$  is the reduced mass of  
 2002 the DM-proton system,  $A_i$  and  $J_i$  the mass number and total angular momentum of  
 2003 nucleus  $i$  and  $\langle S_{p,i} \rangle$  and  $\langle S_{n,i} \rangle$  the expectation value of the spins of protons and neutrons  
 2004 averaged over all nucleons, respectively (see Ref. [122] for a review on spin expectation  
 2005 values).

2006 Since the Sun is mainly composed of Hydrogen, the capture of DM from the halo  
 2007 is expected to occur mainly through spin-dependent scattering. However, since the  
 2008 spin-independent cross section is proportional to the square of the atomic mass, heavy  
 2009 elements can contribute to the capture rate (even though they constitute less than 2%  
 2010 of the mass of the Sun). Heavy elements can also contribute to the spin-dependent cross  
 2011 section if the DM has also momentum-dependent interactions.

2012 DM particles can get captured by the Sun if after repeated scatterings off solar  
 2013 targets their final velocity is lower than the escape velocity of the Sun. In the limit of  
 2014 weak cross sections, this capture rate can be approximately written as [2]:

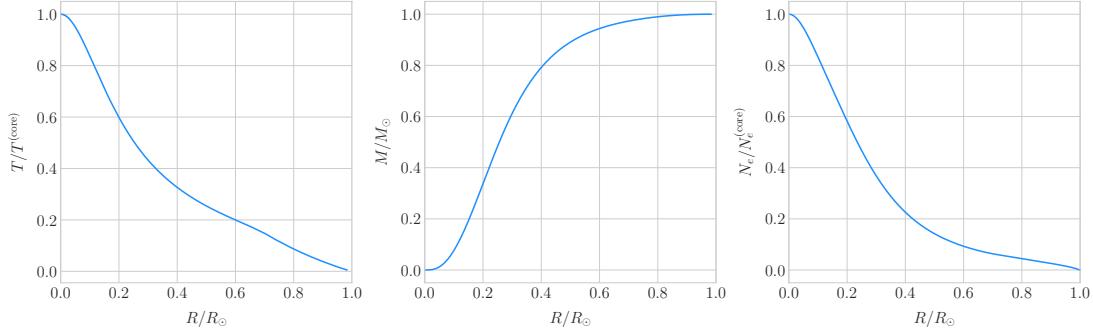
$$C_{\odot}^{\text{weak}} = \sum_i \int_0^{R_{\odot}} dr 4\pi r^2 \int_0^{\infty} du_{\chi} \frac{\rho_{\chi}}{m_{\chi}} \frac{f_{v_{\odot}}(u_{\chi})}{u_{\chi}} \omega(r) \int_0^{v_e(r)} dv R_i^-(\omega \rightarrow v) |F_i(q)|^2, \quad (5.5)$$

2015 where the summation extends over all possible nuclear targets. In this expression,  $R_{\odot}$   
 2016 is the radius of the Sun,  $\rho_{\chi}$  is the local DM density,  $m_{\chi}$  the mass of the DM particle,  
 2017  $f_{v_{\odot}}(u_{\chi})$  the DM velocity distribution seen from the Sun's reference frame,  $R_i^-(\omega \rightarrow v)$   
 2018 is the differential rate at which a DM particle with velocity  $v$  scatters a solar target of  
 2019 mass  $m_i$  to end up with a velocity  $\omega$  and  $|F_i(q)|$  is the nuclear form factor of target  $i$ .

2020 The differential scattering rate takes a rather simple form when considering velocity-  
 2021 independent and isotropic cross sections. In that case, this quantity is given by [2, 123]:

$$R_i^-(\omega \rightarrow v) = \frac{2}{\sqrt{\pi}} \frac{\mu_{i,+}^2}{\mu_i} \frac{v}{\omega} n_i(r) \sigma_i \left[ \chi(-\alpha_-, \alpha_+) + \chi(-\beta_-, \beta_+) e^{\mu_i(\omega^2 - v^2)/u_i^2(r)} \right], \quad (5.6)$$

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN



**Figure 5.1:** Input solar parameters used in our capture rate computation as functions of the Sun's radius, from left to right: temperature (with respect to the temperature at the core), mass (in solar masses) and electron number density (with respect to the electron density at the core). All quantities shown correspond to the standard solar model BS2005-OP [1].

2022 where  $\mu_i$  is the ratio between the DM mass and the mass of target  $i$ ,  $\mu_{i,\pm}$  is defined as:

$$\mu_{i,\pm} \equiv \frac{\mu_i \pm 1}{2}, \quad (5.7)$$

2023  $n_i(r)$  is the density profile of target  $i$  in the solar medium,  $u_i(r)$  is the most probable  
2024 velocity of target  $i$  given by:

$$u_i(r) = \sqrt{\frac{2T_\odot(r)}{m_i}}, \quad (5.8)$$

2025 where  $T_\odot(r)$  is the temperature of the Sun, the quantities  $\alpha_\pm$  and  $\beta_\pm$  are defined as:

$$\alpha_\pm \equiv \frac{\mu_{i,+}v \pm \mu_{i,-}\omega}{u_i(r)}, \quad (5.9)$$

$$\beta_\pm \equiv \frac{\mu_{i,-}v \pm \mu_{i,+}\omega}{u_i(r)}, \quad (5.10)$$

2026 and the function  $\chi(a, b)$  is a Gaussian integral of the form:

$$\chi(a, b) \equiv \int_a^b dx e^{-x^2}. \quad (5.11)$$

2027 Finally, if one assumes the DM halo velocity distribution in the galactic rest frame  
2028 to be a Maxwell-Boltzmann distribution, one can write the halo velocity distribution for

## 5.2. GRAVITATIONAL CAPTURE OF DM BY THE SUN

2029 an observer moving at the speed of the Sun with respect to the DM rest frame as:

$$f_{v_\odot}(u_\chi) = \sqrt{\frac{3}{2\pi}} \frac{u_\chi}{v_\odot v_d} \left( e^{-\frac{3(u_\chi - v_\odot)^2}{2v_d^2}} - e^{-\frac{3(u_\chi + v_\odot)^2}{2v_d^2}} \right), \quad (5.12)$$

2030 where:

$$\omega^2 = u_\chi^2 + v_e(r)^2, \quad (5.13)$$

2031 is the DM velocity squared,  $v_\odot$  the relative velocity of the Sun from the DM rest frame  
2032 and  $v_d \simeq \sqrt{3/2}v_\odot$  the velocity dispersion.

2033 For the case of strong scattering cross section, Eq. (5.5) ceases to be valid, as it  
2034 escalates indefinitely with the cross section. In that limit, the capture rate saturates to  
2035 the case where the probability of interaction is equal to one, which can be written as:

$$C_\odot^{\text{geom}} = \pi R_\odot^2 \left( \frac{\rho_\chi}{m_\chi} \right) \langle v \rangle \left( 1 + \frac{3}{2} \frac{v_e^2(R_\odot)}{v_d^2} \right) \xi(v_\odot, v_d), \quad (5.14)$$

2036 where  $v_d = \sqrt{8/3\pi}v_\odot$  is the mean velocity in the DM rest frame and the factor  $\xi(v_\odot, v_d)$   
2037 accounts for the suppression due to the motion of the Sun:

$$\xi(v_\odot, v_d) = \frac{v_d^2 e^{-\frac{3v_\odot^2}{2v_d^2}} + \sqrt{\frac{\pi}{6}} \frac{v_d}{v_\odot} (v_d^2 + 3v_e^2(R_\odot) + 3v_\odot^2) \operatorname{Erf} \left( \sqrt{\frac{3}{2}} \frac{v_\odot}{v_d} \right)}{2v_d^2 + 3v_e^2(R_\odot)}. \quad (5.15)$$

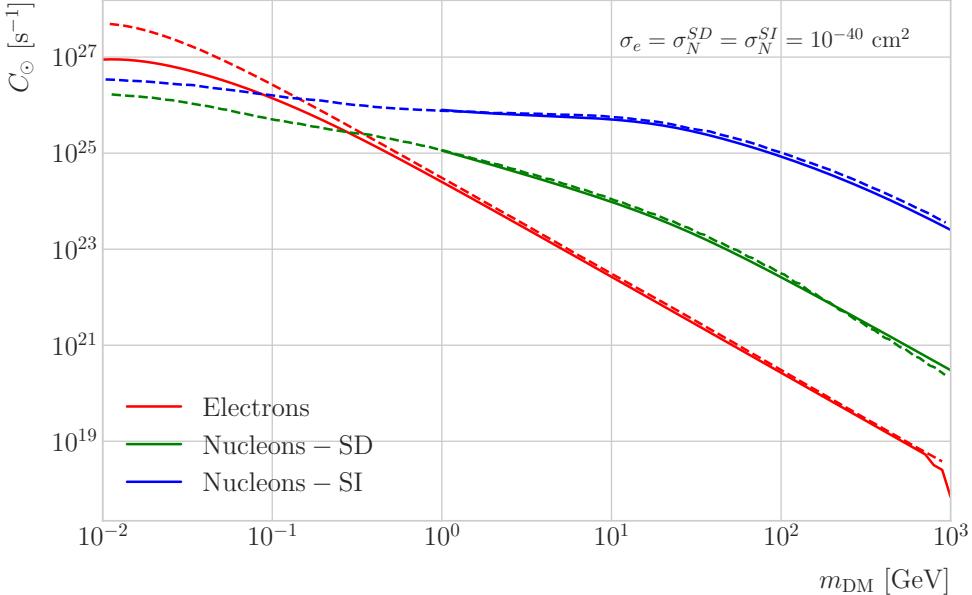
2038 Having these into account, one can write the total capture rate as a combination of  
2039 both contributions, allowing a smooth transition between the two, as:

$$C_\odot = C_\odot^{\text{weak}} \left( 1 - e^{C_\odot^{\text{geom}} / C_\odot^{\text{weak}}} \right). \quad (5.16)$$

2040 I computed the capture rate from Eq. (5.16) in the case of interactions with  
2041 electrons. To do so, I used the standard solar model BS2005-OP [1]. Fig. 5.1 shows the  
2042 three parameters from the solar model that are needed for the computation, the solar  
2043 temperature (left panel), mass (central panel) and electron density (right panel) profiles.

2044 For the case of the interactions off nuclei, the computations are more convoluted

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**Figure 5.2:** Capture rates as a function of the DM mass for the DM-electron interactions (red lines), SD DM-nucleons interactions (green lines) and SI DM-nucleons interactions (blue lines). Solid lines represent the values computed in this work while the dashed lines are the one given in Ref. [2]. All the rates are shown for a choice of scattering cross section of  $\sigma_i = 10^{-40} \text{ cm}^2$ .

as one needs to add up the contributions of the different most abundant nuclei in the Sun. Also, in contrast to the electron scenario where the form factor is trivially  $|F_e(q)|^2 = 1$ , for any nucleus  $i$  one would need to consider some appropriate nuclear density distribution (either a Gaussian approximation, a Woods-Saxon distribution, etc) which would complicate the calculations even further.

That is the reason why, at this stage of our study, I decided to take an alternative approach to the computation of the DM-nucleus capture rates. I used the **DarkSUSY** software, that allows us to compute these quantities performing a full numerical integration over the momentum transfer of the form factors. The default standard solar model used by **DarkSUSY** is BP2000<sup>1</sup> [124].

In Fig. 5.2 I show the results I obtained for the capture rates, for the case of interactions off electrons (red solid line), SD (green solid line) and SI (blue solid line)

<sup>1</sup>This is what they say in their manual, but I fear it is somewhat outdated. It appears to me this model is relatively old and do not see why they are not using others like [1]. Maybe one can double-check in the code to make sure.

## 5.2. GRAVITATIONAL CAPTURE OF DM BY THE SUN

interactions of nucleons. In all cases I used a value of the scattering cross sections of  $\sigma_i = 10^{-40} \text{ cm}^2$ . Note here one of the limitations of the **DarkSUSY** approach, one can not extend the computation below  $m_{\text{DM}} = 1 \text{ GeV}$ . Nevertheless, this is not something to worry about in this case, as I will discuss next. As a comparison, I added also the values computed in Ref. [2] (same color scheme, dashed lines). One can see there is good agreement between these and the **DarkSUSY** computation of the SD and SI interactions for  $m_{\text{DM}} \geq 1 \text{ GeV}$ . In this regime their computations also matches quite well our result for the electron capture rate. However, these start to differ significantly below  $m_{\text{DM}} = 1 \text{ GeV}$ , being their estimate up to a factor of 5 bigger than ours for low masses.

Let us comment briefly about the assumption I made before about not including an evaporation term in the Boltzmann equation. If I include this term in the equation (which will be proportional to the number of DM particles) the equilibrium solution takes the form:

$$N_{\text{DM}}^{\text{eq}} = \sqrt{\frac{C_{\odot}}{A_{\odot}}} \frac{1}{\kappa + \frac{1}{2} E_{\odot} \tau_{\text{eq}}}, \quad (5.17)$$

where  $E_{\odot}$  is the total evaporation rate,  $\tau_{\text{eq}}$  is the equilibrium time in the absence of evaporation:

$$\tau_{\text{eq}} = \frac{1}{\sqrt{C_{\odot} A_{\odot}}}, \quad (5.18)$$

and  $\kappa$  is defined as:

$$\kappa \equiv \sqrt{1 + \left( \frac{E_{\odot} \tau_{\text{eq}}}{2} \right)^2}. \quad (5.19)$$

Now, it is easy to proof that in case evaporation dominates  $\kappa \gg 1$  and therefore:

$$N_{\text{DM}}^{\text{eq}} \simeq \frac{C_{\odot}}{E_{\odot}}. \quad (5.20)$$

In contrast, if evaporation is irrelevant  $\kappa \simeq 1$  and one recovers Eq. (5.2).

In this way, one can define the evaporation mass as the mass for which the number of DM particles in equilibrium approaches Eq. (5.20) at 10% level:

$$\left| N_{\text{DM}}^{\text{eq}}(m_{\text{evap}}) - \frac{C_{\odot}(m_{\text{evap}})}{E_{\odot}(m_{\text{evap}})} \right| = 0.1 N_{\text{DM}}^{\text{eq}}(m_{\text{evap}}). \quad (5.21)$$

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN

2077 This can be regarded as the minimum testable mass one can reach using the annihilation  
2078 products of the DM in the Sun.

2079 It was reported in Ref. [2] that, in the case of both SD and SI DM interactions  
2080 off nuclei, this value ranges from 2 to 4 GeV depending on the specific scattering  
2081 cross section value, compatible with the usual assumptions in the literature. What is  
2082 interesting is the case of the electron capture. It was found that, when one applies a  
2083 cutoff in the velocity distribution of the DM trapped in the Sun slightly below the escape  
2084 velocity, the evaporation mass for the DM-electron interaction decreases remarkably. For  
2085 a moderate choice of  $v_c(r) = 0.9v_e(r)$  one gets an evaporation mass of around 200 to  
2086 600 MeV. This possibility opens a region of the parameter space that could be tested  
2087 with neutrino detectors.

### 2088 5.3 Neutrino flux from DM annihilations

2089 When WIMPs annihilate inside the Sun a flux of high-energy neutrinos is expected from  
2090 heavy quarks, gauge bosons and  $\tau^+\tau^-$  final states, which decay before losing energy in  
2091 the dense solar medium, as they will produce a continuum spectra up to  $E_\nu \sim m_\chi$  (in  
2092 the case of direct annihilation to neutrinos one would have a line at  $E_\nu = m_\chi$ ) [118].  
2093 This kind of signal has been extensively studied in the literature, allowing to put strong  
2094 limits on the SD WIMP-proton cross section for large  $m_\chi$ . However, the number of  
2095 high-energy neutrinos per WIMP annihilation is small and the spectrum depends on the  
2096 unknown final state. Moreover, background rejection is easier for large  $m_\chi$  but neutrinos  
2097 with  $E_\nu \gtrsim 100$  GeV are significantly attenuated by interactions in the Sun.

2098 Nevertheless, most WIMP annihilation final states eventually produce a low-energy  
2099 neutrino spectrum. In this case one does not just consider the more massive final states  
2100 but also annihilations into  $e^+e^-$ ,  $\mu^+\mu^-$  and light quarks [117]. In particular, light  
2101 mesons would be produced and stopped in the dense medium, thus decaying at rest and  
2102 producing a monoenergetic neutrino signal. The decay-at-rest of kaons will produce  
2103 a  $E_\nu = 236$  MeV  $\nu_\mu$  while in the case of pions one would have a  $E_\nu = 29.8$  MeV  $\nu_\mu$ .

## 5.4. COMPUTING LIMITS FROM SOLAR NEUTRINO FLUXES

2104 In practice only  $K^+$  and  $\pi^+$  contribute to these signals, as  $K^-$  and  $\pi^-$  are usually  
 2105 Coulomb-captured in an atomic orbit and get absorbed by the nucleus. There is also a  
 2106 low-energy neutrino signal coming from muon decays, which are produced in kaon or  
 2107 pion decays, leptonic decays of other hadrons and heavy leptons or even directly from  
 2108 WIMP annihilations, which can decay at rest and contribute to the previous low-energy  
 2109 neutrino flux with a well known spectrum below 52.8 MeV.

2110 These monoenergetic MeV neutrinos were previously considered undetectable but,  
 2111 due to the large yield, the known spectra and the modern advances in the detector  
 2112 technology, these low-energy neutrino flux can be a good probe of the SD WIMP-proton  
 2113 cross-section in standard solar WIMP capture scenario, as it is sensitive to low WIMP  
 2114 masses and insensitive to the particular final state. A good place to look for these signals  
 2115 are next-generation neutrino experiments such as DUNE.

### 2116 5.4 Computing limits from solar neutrino fluxes

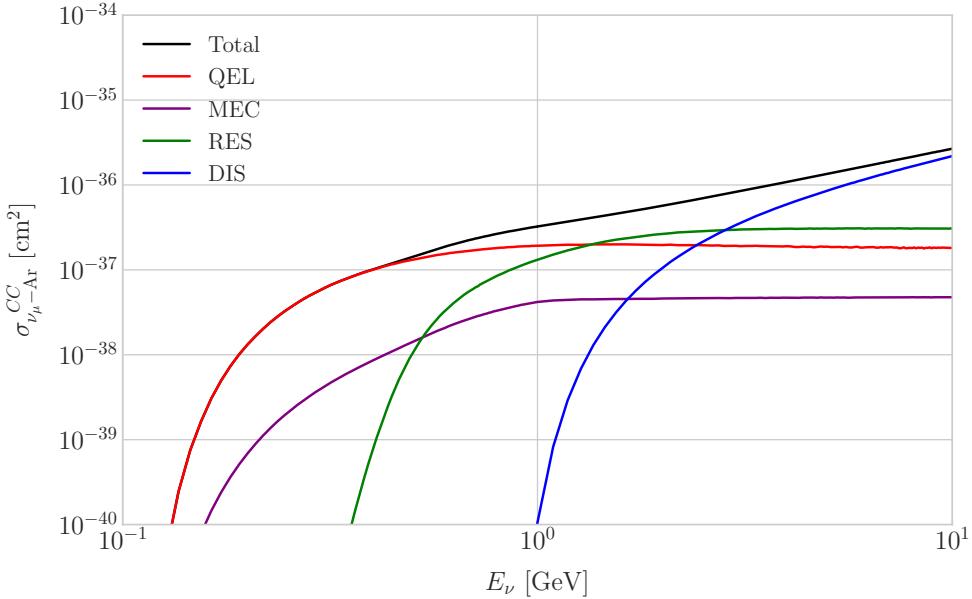
2117 In order to use the neutrino fluxes from DM annihilations in the Sun, the first thing I  
 2118 need to do is to determine the expected number of atmospheric background events, for  
 2119 a given exposure, after directionality selection has been applied. I can write this number  
 2120 as:

$$N_B = \eta_B \int d\Omega \int_{E_{min}}^{E_{max}} dE_\nu \frac{d^2\Phi_{atm}^\mu}{dE_\nu d\Omega} \times \left( A_{eff}^{(\mu)}(E_\nu) T \right), \quad (5.22)$$

2121 where  $\eta_B$  is the background efficiency,  $E_{min}$  and  $E_{max}$  the minimum and maximum  
 2122 energies to integrate over,  $d^2\Phi_{atm}^\mu/dE_\nu d\Omega$  the differential flux of atmospheric muon  
 2123 neutrinos,  $A_{eff}^{(\mu)}$  is the effective area of DUNE to muon neutrinos and  $T$  is the exposure  
 2124 time. The effective area can be expressed as the product of the neutrino-nucleus scattering  
 2125 cross section and the number of nuclei in the fiducial volume of the detector. This way  
 2126 for DUNE I can write:

$$A_{eff}^{(\mu)}(E_\nu) = (6.0 \times 10^{-10} \text{ m}^2) \left( \frac{\sigma_{\nu-\text{Ar}}^{(\mu)}(E_\nu)}{10^{-38} \text{ cm}^2} \right) \left( \frac{M_{target}}{40 \text{ kT}} \right), \quad (5.23)$$

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**Figure 5.3:** *NuWro* computed  $\nu_\mu - {}^{40}\text{Ar}$  charged-current scattering cross section as a function of the neutrino energy  $E_\mu$ . The black line shows to the total cross section, whereas the others correspond to the different contributions (in red quasi-elastic scattering, in green resonant pion exchange, in blue deep inelastic scattering and in purple meson exchange current).

where  $\sigma_{\nu_\mu-\text{Ar}}^{(\mu)}$  is the  $\nu_\mu - {}^{40}\text{Ar}$  charged-current scattering cross section. In Fig. 5.3 I show the computed value of this cross section as a function of the neutrino energy  $E_\nu$ , in the range of interest both for the atmospheric background and signal events. It was computed using the *NuWro* Monte Carlo neutrino event generator [125], including the charged-current contributions of the quasi-elastic scattering (red line), resonant pion exchange (green line), deep inelastic scattering (blue line) and meson exchange current (purple line).

The background rejection will depend on the resolution of the detector and the selection one applies on the events. A geometry argument can be used to estimate the maximum background rejection one can achieve in this case, considering one can efficiently discriminate all events coming from a direction different from that of the Sun. In that case, the optimal background efficiency will simply be the relative angular coverage of the Sun. Taking the angular diameter of the Sun as seen from the Earth to

## 5.4. COMPUTING LIMITS FROM SOLAR NEUTRINO FLUXES

2140 be  $0.5^\circ$ , I have:

$$\eta_B^{(opt)} \approx \frac{\pi \left(\frac{0.5}{2}\right)^2}{360 \times 180} \simeq 3.03 \times 10^{-6}. \quad (5.24)$$

2141 This value will give a very optimistic estimate of the number of background events.

2142 However, it can be regarded as an lower limit, as it represents the best case scenario.

2143 In Fig. 5.4 I show the fluxes of atmospheric neutrinos at the Homestake mine during  
2144 solar minimum, taken from Ref. [3]. The values are averaged over the two angular  
2145 directions. In blue I have the flux of muon neutrinos while in red I indicate the flux  
2146 of electron neutrinos. Additionally, the dashed lines correspond to both antineutrino  
2147 species.

2148 Using these values for the muon neutrino and the corresponding total CC cross  
2149 section, one can compute the number of expected background events by integrating over  
2150 the given energy range (as in this case the angular integral is trivial). As for the energy  
2151 range to integrate over, I choose the range for DUNE specified in [85],  $E_{min} = 10^{-1}$  GeV  
2152 and  $E_{max} = 10$  GeV. Taking all these into account, I found the number of background  
2153 events to be:

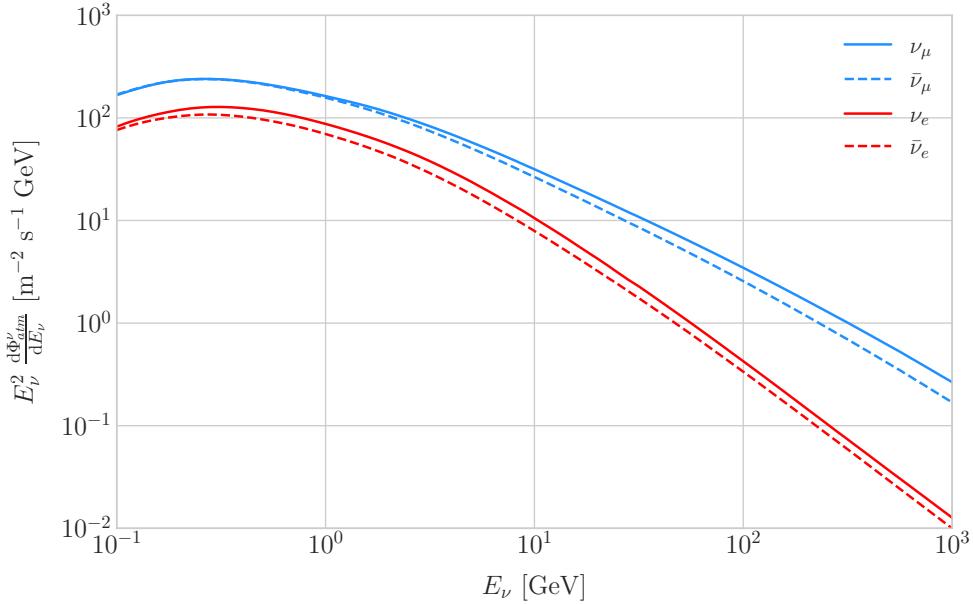
$$N_B \simeq \eta_B \times (3.827 \times 10^4) \times \left( \frac{\text{exposure}}{400 \text{ kT yr}} \right). \quad (5.25)$$

2154 In order to estimate the sensitivity of DUNE to this kind signal, one can consider a  
2155 hypothetical data set where the number of observed neutrinos is taken to be the expected  
2156 number of background events rounded to the nearest integer,  $N_{obs} = \text{round}(N_B)$  [126].  
2157 Now, if I assume that the number of signal and background events seen by DUNE are  
2158 given by Poisson distributions with means equal to the expected number of signal and  
2159 background events,  $N_S$  and  $N_B$ , one can denote by  $N_S^{90}$  to the number of expected  
2160 signal events such that the probability of having an experimental run with a number of  
2161 events greater than  $N_{obs}$  is 90%. This number can be obtained as the numerical solution  
2162 to the equation:

$$1 - \frac{\Gamma(N_{obs} + 1, N_S^{90} + N_B)}{N_{obs}!} = 0.9, \quad (5.26)$$

2163 where  $\Gamma(x, y)$  is the upper incomplete gamma function.

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**Figure 5.4:** Expected atmospheric neutrino flux as a function of the neutrino energy  $E_\nu$  at Homestake at solar minimum, taken from Ref. [3]. The blue solid (dashed) line correspond to muon neutrinos (antineutrinos) and the red solid (dashed) line correspond to electron neutrinos (antineutrinos).

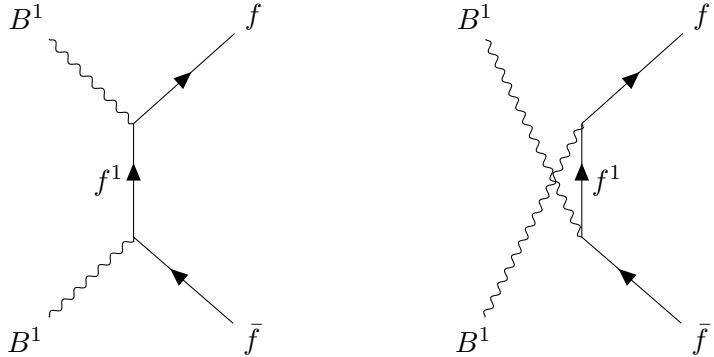
2164 The number of signal events is related to the neutrino flux from DM annihilations in  
 2165 a similar way as the background events to the atmospheric neutrino flux. In this case I  
 2166 have:

$$N_S = \eta_S \Gamma_A^{eq} \int_{z_{min}}^{z_{max}} dz \frac{dN_\nu}{dAdN_A dz} \times (A_{eff}^\mu(z)T), \quad (5.27)$$

2167 where  $\eta_S$  is the signal efficiency,  $\Gamma_A^{eq}$  is the total annihilation rate of DM particles at  
 2168 equilibrium,  $\Gamma_A^{eq} = A_\odot (N_{DM}^{eq})^2$ ,  $z_{min}$  and  $z_{max}$  the minimum and maximum relative  
 2169 energies to integrate over (in such a way that  $z_{min,max} \leq E_{min,max}/m_{DM}$  for each  $m_{DM}$ )  
 2170 and  $dN_\nu/dAdN_A dz$  the muon neutrino flux per DM annihilation in the Sun.

2171 Knowing  $N_S^{90}$  one can use the relation in Eq. (5.27) to obtain  $\Gamma_A^{eq,90}$  for different  
 2172 values of the DM mass. From there I can directly translate those values into the  
 2173 upper limits for DUNE on the DM scattering cross sections, for a given exposure. The  
 2174 relation between the annihilation rate and the DM-nucleon cross section comes from the  
 2175 equilibrium condition through the solar DM capture rate. The details of the evolution  
 2176 of the number of DM particles inside the Sun and the computation of the capture rates

## 5.5. EXAMPLE: KALUZA-KLEIN DARK MATTER



**Figure 5.5:** Feynman diagrams for  $B^1 B^1$  annihilation into SM fermions.

2177 are discussed in App. 5.2.

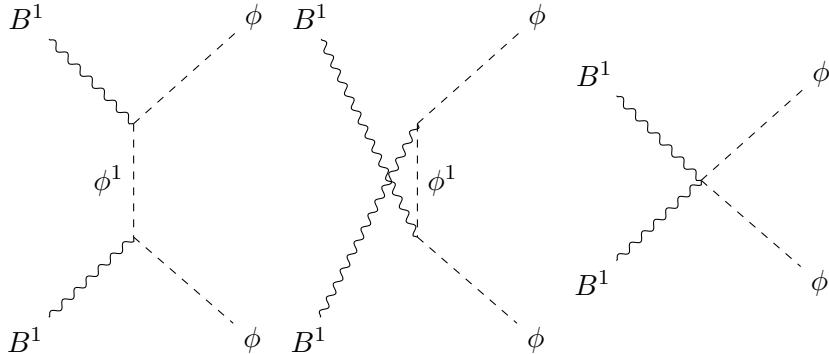
### 2178 5.5 Example: Kaluza-Klein Dark Matter

2179 Even though there are plenty of BSM theories which provide viable dark matter  
2180 candidates, Kaluza-Klein type of models [127, 128] within the universal extra dimensions  
2181 (UED) paradigm naturally predict the existence of a massive, stable particle that can  
2182 play the role of the dark matter. In the UED scenario all the SM fields can propagate  
2183 in one or more compact extra dimensions [129], as opposed to the idea of brane worlds  
2184 [130, 131], where just gravity can propagate in the bulk while SM particles live at fixed  
2185 points.

2186 Furthermore, in UED there is no violation of the translational invariance along the  
2187 extra dimensions, thus leading to degenerate KK modes masses and also the conservation  
2188 of the KK number in the effective four dimensional theory. At loop level, radiative  
2189 corrections and boundary terms shift the masses of the KK modes and break KK  
2190 number conservation into a KK parity. As a result, this theory only contains interactions  
2191 between an even number of odd KK modes and therefore the lightest among the first KK  
2192 excitations will be stable. This particle is usually denoted as the lightest Kaluza-Klein  
2193 particle (LKP) and its mass is proportional to  $1/R$ , being  $R$  the size of the extra  
2194 dimension.

2195 A viable DM candidate needs to be electrically neutral and non-baryonic, therefore

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN

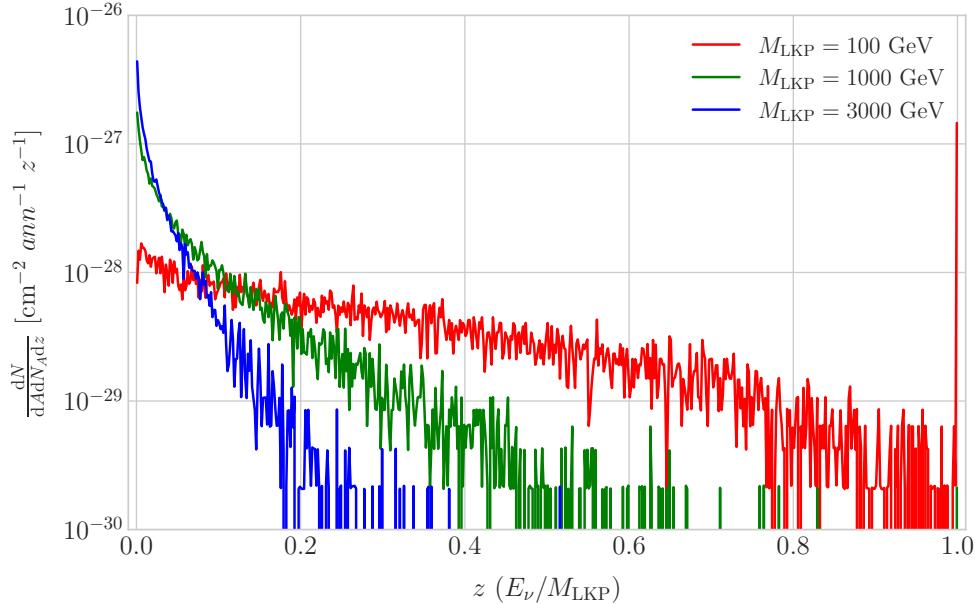


**Figure 5.6:** Feynman diagrams for  $B^1B^1$  annihilation into a Higgs boson pair.

good candidates among the first Kaluza-Klein excitations would be the KK neutral gauge bosons and the KK neutrinos [132]. Another possible candidate is the first KK excitation of the graviton, which receives negligible radiative contributions and therefore has a mass almost equal to  $1/R$ , but it has been shown that the lightest eigenstate from the mixing of the gauge mass states ( $B^1, W_3^1$ ) would be lighter, as  $B^1$  and  $W_3^1$  receive negative radiative corrections [133]. It is also understood that, when these corrections become sizeable, the eigenstates become approximately pure  $B^1$  and  $W_3^1$  states as the Weinberg mixing angle grows small with the KK number [133]. In that case, the LKP can be well-approximated as being entirely  $B^1$ .

I need to compute the neutrino flux produced by the annihilations of the LKP in the core of the Sun, taking into account their propagation in the solar medium, as well as neutrino oscillations. To this end I used `WimpSim` [134, 135] to generate one million annihilation events in the Sun over a time span of four years and propagate them to the DUNE FD location ( $44^\circ 20' \text{ N}, 103^\circ 45' \text{ W}$ ), for different values of  $M_{\text{LKP}}$ . In Fig. 5.7 I show the obtained muon neutrino spectra arriving to the detector from LKP annihilations in the Sun, per unit area and per annihilation, plotted in relative energy units for different values of the mass. As one could expect the spectra get steeper the higher is the mass, due to the absorption of high-energy neutrinos in the solar medium. Also, one can see the peak at  $z = 1$  due to the direct annihilation into neutrinos  $\chi\bar{\chi} \rightarrow \nu\bar{\nu}$ .

## 5.5. EXAMPLE: KALUZA-KLEIN DARK MATTER



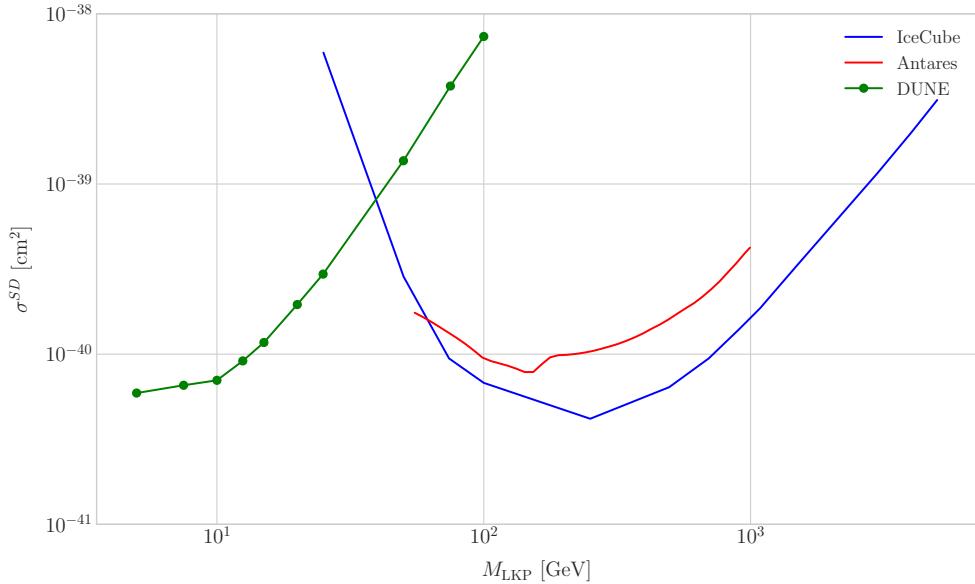
**Figure 5.7:** Computed spectra of muon neutrinos at the DUNE FD site from  $B^1$  annihilations in the Sun for three different values of  $M_{\text{LKP}}$ , plotted in relative energy units for legibility.

Now, one can estimate the sensitivity of DUNE to this particular model by using the methods I previously discussed. To begin with, I will use the optimistic estimation of the background efficiency in Eq. (5.24) to get our upper bound. Using it, one can directly compute the number of expected background events to be  $N_B = 0.1101$  for an exposure of 400 kT yr. Then, Eq. (5.26) give us a value of  $N_S^{90} = 2.20$  for the 90% exclusion number of expected signal events. By using the NuWro generated cross sections and the computed neutrino fluxes from  $B^1$  annihilations in the Sun I can estimate the limits on the SD and SI DM-nucleus cross section using the relation in Eq. (5.2) and the capture rates I computed with DarkSUSY.

In Fig. 5.8 I show the projected sensitive for DUNE on the spin-dependent  $B^1$ -proton scattering cross section versus the mass of the DM particle, for a exposure of 400 kT yr (green dots). I also include the previous results from IceCube [4] (blue line) and Antares [5] (red line). The shaded area represents the disfavoured region from combined searches for UED by ATLAS and CMS [6].

From the experimental point of view, this estimation lacked a detailed simulation of

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN



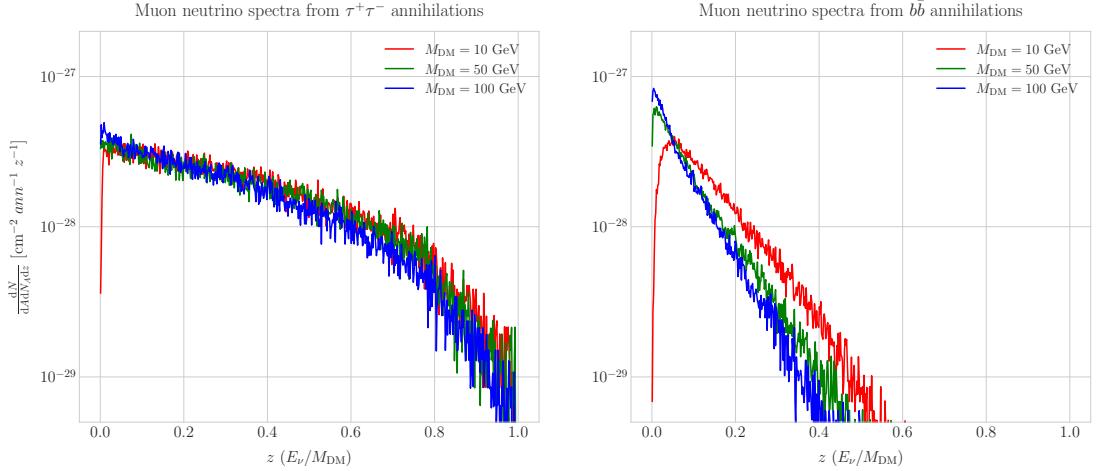
**Figure 5.8:** Projected 90% confidence level upper limit for DUNE (400 kT yr) on the spin-dependent  $B^1$ -proton scattering cross section as a function of  $M_{LKP}$  (green dots). I also show the previous limits from IceCube [4] (blue line) and Antares [5] (red line) on the LKP cross section. The shaded area represents the disfavoured region (at 95% confidence level) on the mass of the LKP from LHC data [6].

the detector response and thus this must be consider as a mere optimistic sensitivity computation. However, it shows the potential of DUNE to constrain this kind of exotic scenarios, showing the region where it will be in a position to compete with other neutrino telescopes. A more detailed analysis is needed if I am to make a realistic estimation. Even though the region of the parameter space where DUNE would be sensitive to this particular model is quite constrained by collider searches [6] and other rare decay measurements [136, 137], it still constitutes an alternative indirect probe.

## 5.6 High energy DM neutrino signals

To have better estimates on the capability of the DUNE FD to constrain the parameter space of DM using solar neutrino fluxes, I need to start accounting for the detector resolution effects and the topologies of the different signatures. As a starting point, I will focus on specific annihilation channels. For the case of DUNE, the relevant ones are mainly the hard channels  $\tau^+\tau^-$  and  $\nu\bar{\nu}$  and the soft channel  $b\bar{b}$ . These are the open

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS



**Figure 5.9:** Computed spectra of muon neutrinos at the DUNE FD site from  $\tau^+\tau^-$  (left panel) and  $b\bar{b}$  (right panel) annihilations in the Sun for the DM masses  $m_{\text{DM}} = 10 \text{ GeV}$  (red line),  $50 \text{ GeV}$  (green line) and  $100 \text{ GeV}$  (blue line), plotted in relative energy units.

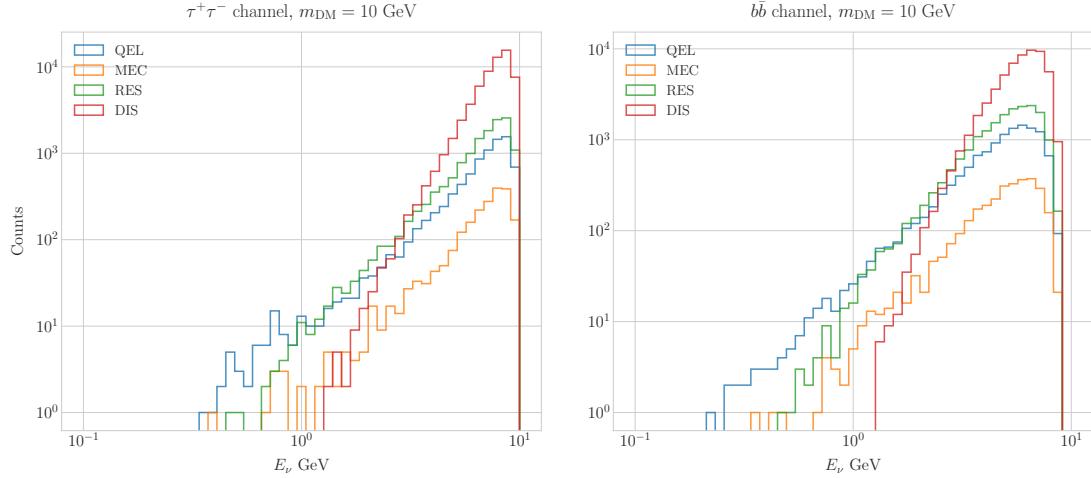
annihilation channels for relatively low mass WIMPs that will actually give neutrino fluxes. Other channels, like  $W^+W^-$  and  $ZZ$ , are open for more massive WIMPs, but those will produce usually a higher energy neutrino flux that will be out of reach for DUNE (usually the maximum neutrino energy is taken to be  $E_{\max} = 10 \text{ GeV}$ ).

In Fig. 5.9 I show the `WimpSim` [134, 135] generated muon neutrino spectra at the DUNE FD location ( $44^\circ 20' \text{ N}, 103^\circ 45' \text{ W}$ ) from  $\tau^+\tau^-$  (left panel) and  $b\bar{b}$  (right panel) annihilations in the core of the Sun, for different DM masses. Here, one can clearly see the meaning of the previous distinction between hard and soft channels. For the same DM mass value, the muon neutrino spectrum from the  $\tau^+\tau^-$  channel is more flat and reaches higher energies than the one from the  $b\bar{b}$  channel, which drops faster.

In this case, I prepared two sets of files, one for  $\tau^+\tau^-$  and the other for  $b\bar{b}$ , for DM masses in the range from 5 to 100 GeV (actually for  $b\bar{b}$  the first mass point I took is 7.5 GeV, as a WIMP with  $m_{\text{DM}} = 5 \text{ GeV}$  can not kinematically self annihilate into  $b\bar{b}$ ). Then, I prepared the `WimpSim` output fluxes in a specific way to use them as inputs to `NuWro`, which simulates the neutrino interaction with the argon.

Because `WimpSim` outputs an event list together with the fluxes, I can use the former to generate the events. The direction of these is given in terms of the azimuth and

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**Figure 5.10:** Distribution of the muon neutrino energies from the  $\tau^+\tau^-$  (left panel) and  $b\bar{b}$  (right panel) annihilation channels, for  $m_{\text{DM}} = 10$  GeV, separated by CC interaction type: QEL (blue), MEC (orange), RES (green) and DIS (red).

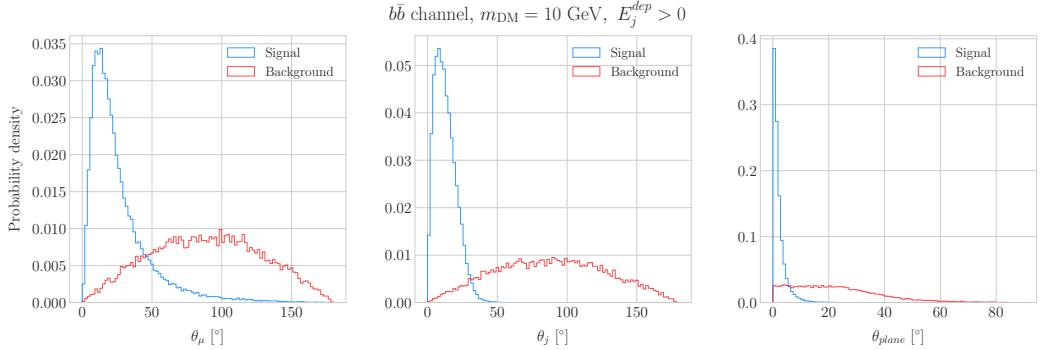
altitude angles viewed from the specified location, so first I need to convert these into the DUNE FD coordinates. Once I have done it, each event can be processed with `NuWro`. To increase the number of samples and optimise the computation time, I generate 100 interactions (i.e. `NuWro` events) for each `WimpSim` event<sup>2</sup>. I restrict the event generation to charged current interactions, but I allow all the different contributions to the CC cross section, i.e. quasielastic scattering (QEL), meson exchange current process (MEC), resonant pion production (RES) and deep inelastic scattering (DIS). I just take into account the CC contribution because I am only interested in final states with charged leptons, as we have better chances of reconstructing the kinematics of CC events.

For the atmospheric fluxes I follow a similar procedure, only that this time I do not have a set of events but the fluxes binned in azimuth and altitude angles. This way, I transform these to DUNE coordinates and process the fluxes for each bin separated with `NuWro`.

At this point, I have two sets of events with different energies and final states. In Fig. 5.10 one can see the distribution of the muon neutrino energies for the case

<sup>2</sup>This also solves a problem related with the generation of the neutrino interactions in `NuWro`, as if you only produce one event each time you launch `NuWro` it will always produce an interaction of the dominant interaction type for that particular energy.

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS



**Figure 5.11:** Distributions of  $\theta_\mu$  (left panel),  $\theta_j$  (central panel) and  $\theta_{\text{plane}}$  (right panel) for the  $b\bar{b}$  sample with  $m_{\text{DM}} = 10$  GeV (blue) and the atmospheric background (red).

2276  $m_{\text{DM}} = 10$  GeV, both for the  $\tau^+\tau^-$  (left panel) and  $b\bar{b}$  (right panel) channels, separated  
2277 by interaction. One can clearly see that there are different energy regimes where the  
2278 primary interaction type is different. This leads to a plurality of event topologies,  
2279 therefore making it difficult to implement a general approach to the selection of events  
2280 in detriment of the background. As a way to proceed, I decided to split our samples,  
2281 based on the different interaction modes and contents of the final state, into a CC DIS  
2282 sample and a single proton CC QEL sample.

2283 **5.6.1 DIS events**

2284 To begin with, I consider the high energy part of the spectrum. In this region DIS events  
2285 dominate, i.e. interactions of the form  $\nu_\mu + q_d(\bar{q}_u) \rightarrow \mu^- + q_u(\bar{q}_d)$ . Therefore, our final  
2286 estates will contain a muon and a hadronic jet from the fragmentation of the outgoing  
2287 quark. As all these events have  $E_\nu \gtrsim 1$  GeV the momentum transfer to the remnant  
2288 nucleus is negligible, for this reason the neutrino energy can be effectively reconstructed  
2289 just taking into account the momenta of the muon and the jet. This technique was  
2290 successfully used in Ref. [138] to select monoenergetic DM solar neutrino events from  
2291  $\nu\bar{\nu}$  annihilation channels.

2292 Using momentum conservation one sees that the plane generated by the momenta  
2293 of the muon and the jet needs to also contain the momentum of the neutrino. As we  
2294 are interested in neutrinos coming from the Sun, the momentum of the neutrino can be

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regarded as known beforehand. This will allow us to define the angle of the outgoing muon and jet with respect to the incoming neutrino. Moreover, one can also use that information to reject poorly reconstructed jets, checking for deviations of these from the momentum conservation plane.

To account for the limited angular resolution of the detector, I smeared the momenta of the muons and hadrons. In a liquid argon TPC muons are expected to be tracked with high precision, therefore I take the associated angular resolution to be  $1^\circ$ . In the case of jets, it is expected that for the hadrons dominating the cascade a detector like DUNE has an angular resolution between  $1^\circ$  to  $5^\circ$  [85], so I take the latter, more conservative, estimate.

As a first selection step, I will just take into account particles with kinetic energies above the detection threshold of DUNE. For muons and photons the specified threshold energy is 30 MeV, for charged pions 100 MeV and for other hadrons 50 MeV [85]. This way, if the outgoing muon in a certain event has an energy lower than the required threshold I will drop such event. For the case of hadrons and photons, I will only require to have at least one particle above the energy threshold, so then one can compute the jet momentum using the (smeared) momenta of the  $N$  particles above threshold as:

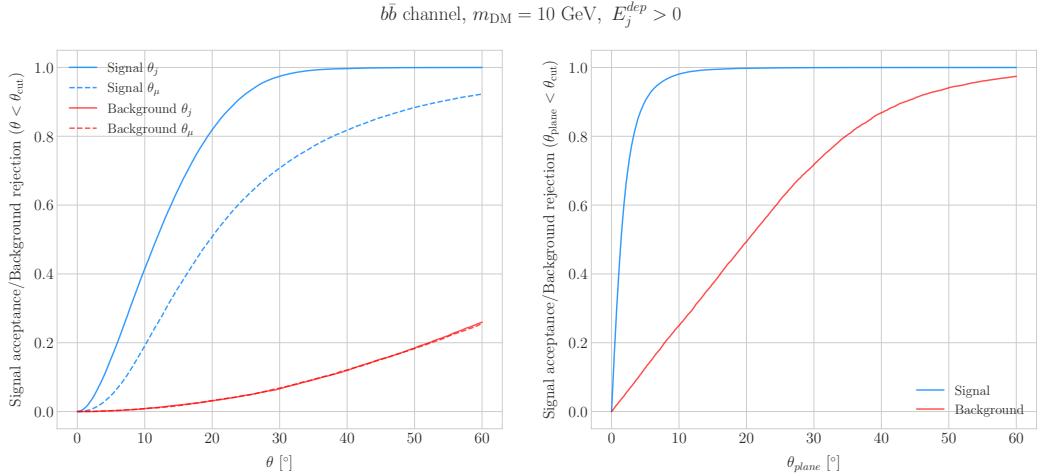
$$\vec{p}_j = \sum_{i=1}^N \vec{p}_i. \quad (5.28)$$

Additionally, I will also define an estimation of the deposited hadronic energy as:

$$E_j^{dep} = m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}} + \sum_{i=1}^N \sqrt{|\vec{p}_i|^2 + m_i^2}. \quad (5.29)$$

This quantity is useful to select events with enough hadronic visible energy in the detector. For events where most of the hadronic energy is scattered across plenty of hadrons with individual energies below the detection threshold, this estimation will give  $E_j^{dep} \leq 0$ . In these cases it could be expected that the jet momentum is poorly reconstructed, and therefore I require events to pass the cut  $E_j^{dep} > 0$ .

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS



**Figure 5.12:** Left panel: signal efficiencies (blue lines) and background rejections (red lines) for events passing the cuts  $\theta < \theta_{cut}$  for the jet (solid lines) and muon (dashed lines) angles. Right panel: signal efficiency (blue line) and background rejection (red line) for events passing the cut  $\theta_{plane} < \theta_{cut}$  for the momentum conservation plane deviation.

2318 For the events I can compute the angles for the muon and jet with respect to the  
 2319 incoming neutrino as:

$$\cos \theta_\mu = \hat{p}_\nu \cdot \hat{p}_\mu, \quad (5.30)$$

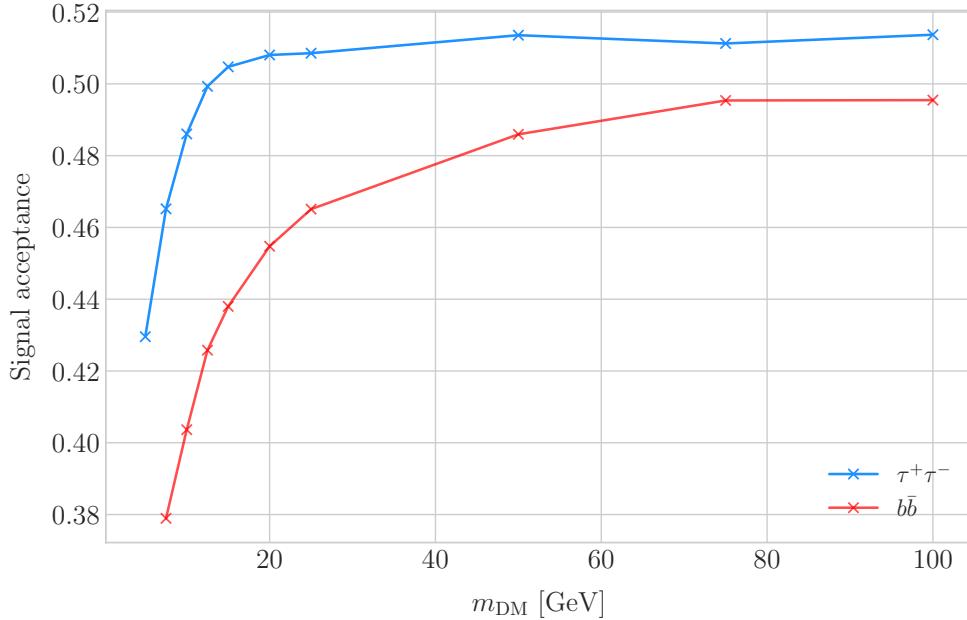
$$\cos \theta_j = \hat{p}_\nu \cdot \hat{p}_j, \quad (5.31)$$

2320 and the deviation from the momentum conservation plane as:

$$\sin \theta_{plane} = \left| \frac{\hat{p}_\mu \times \hat{p}_\nu}{|\hat{p}_\mu \times \hat{p}_\nu|} \cdot \hat{p}_j \right|. \quad (5.32)$$

2321 In Fig. 5.11 I show some distributions of these quantities for the case of the  $b\bar{b}$  sample  
 2322 with  $m_{DM} = 10$  GeV (blue histograms) and for the atmospheric backgrounds (red).  
 2323 In order to select the atmospheric events I followed the same criteria as for the signal  
 2324 events. However, because in the signal case I used the true direction of the neutrino  
 2325 as input, as it should be that of the Sun at that time and therefore known, in the  
 2326 atmospheric case I used a set of solar positions as our ansatz for the neutrino direction.  
 2327 From the distributions, one can see that the muon and the jet for the signal events are

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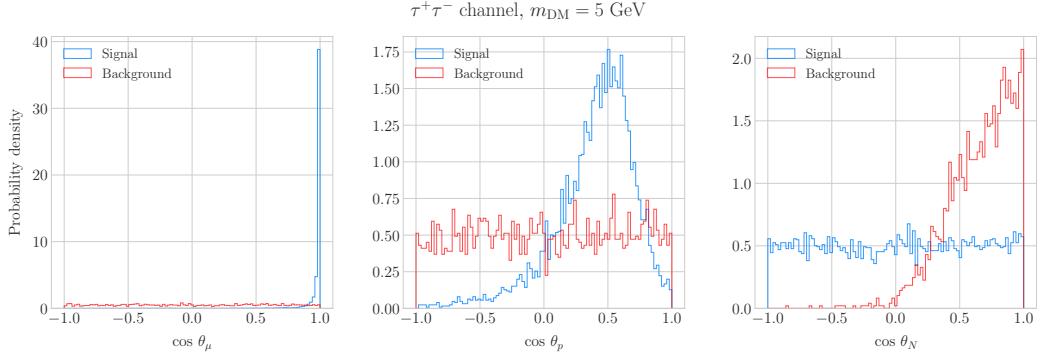
**Figure 5.13:** Signal efficiencies for the  $\tau^+\tau^-$  (blue line) and  $b\bar{b}$  (red line) DIS samples as functions of the DM mass,  $m_{\text{DM}}$ , obtained by applying the optimal angular cuts  $\theta_\mu < 27^\circ$ ,  $4^\circ < \theta_j < 26^\circ$  and  $\theta_{\text{plane}} < 3.5^\circ$ .

predominantly forward and also that the deviations from the momentum conservation plane are peaked at zero, as one should expect.

Now, I can start applying cuts to maximise our signal selection efficiency while at the same time I try to minimise the amount of atmospheric background events passing the selection. To this end, I will need to find some lower and upper cuts for  $\theta_j$  and  $\theta_\mu$  and an upper bound for  $\theta_{\text{plane}}$ . In Fig. 5.12 I show how upper bound cuts in the different angular variables affect the signal efficiency (blue lines) and the background rejection (red lines). Notice that the signal efficiency behaves in a quite different way when I apply cuts in the jet and the muon angles. On the contrary, the cuts on both variables have a similar effect on the background rejection.

In order to obtain the optimal set of cuts, I perform a multidimensional scan. I do this separately for the  $\tau^+\tau^-$  and the  $b\bar{b}$  samples. For each case, I scan the possible cuts for each mass point and then I take the mean value of the signal efficiency for each configuration, to get the mean efficiency for each set of cuts. I do a similar scan for the atmospheric sample independently. Then, I take the sets of cuts such that

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS



**Figure 5.14:** Distributions of  $\cos \theta_\mu$  (left panel),  $\cos \theta_p$  (central panel) and  $\cos \theta_N$  (right panel) for the  $\tau^+\tau^-$  QEL sample with  $m_{\text{DM}} = 5 \text{ GeV}$  (blue) and the atmospheric background (red).

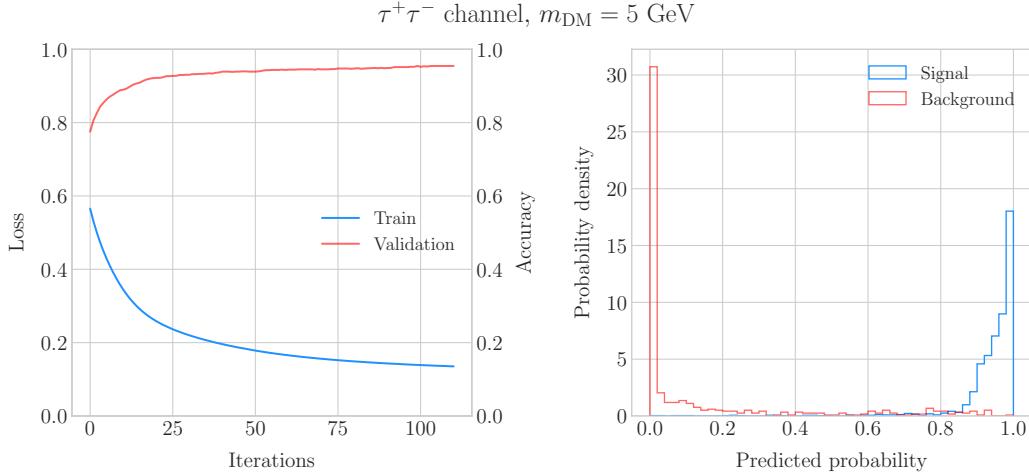
the background rejection achieved is greater than 99.8% and search for the one which maximises the  $\tau^+\tau^-$  and  $b\bar{b}$  sample mean efficiencies. I found that with the cuts  $\theta_\mu < 27^\circ$ ,  $4^\circ < \theta_j < 26^\circ$  and  $\theta_{\text{plane}} < 3.5^\circ$  I get a background rejection of 99.80% while achieving a 49.40% and 44.92% mean signal efficiencies for the  $\tau^+\tau^-$  and  $b\bar{b}$  signals respectively.

In Fig. 5.13 I show the signal efficiencies as a function of the DM mass for the  $\tau^+\tau^-$  (blue line) and the  $b\bar{b}$  (red line) DIS events, after applying the cuts discussed above, as well as the energy threshold and hadronic visible energy selections. One can see that the efficiency grows with the mass, as annihilations of more massive DM particles will produce a neutrino spectrum centered at higher energies, where DIS events dominate. Notice also that the efficiency is higher for the  $\tau^+\tau^-$  case at every mass point, as in general this channel produces neutrinos at higher energies than the corresponding  $b\bar{b}$  channel.

### 5.6.2 Single proton QEL events

Now, one can try to explore the low energy tail of the neutrino energy distributions. This regime is dominated by the QEL interactions, i.e. events of the type  $\nu_\mu + n \rightarrow \mu^- + p$ . In this case, as the typical energies are  $E_\nu \lesssim 1 \text{ GeV}$ , the momentum transfer to the remnant nucleus is sizeable. Therefore, I can not make the approximation I did before and assume that the momentum of the muon and the proton will give an adequate

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**Figure 5.15:** Left panel: value of the loss function for the training sample (blue line) and accuracy for the validation sample (red line) versus the number of iterations for the MLP classifier training. Right panel: distributions of the predicted probabilities assigned by the MLP classifier to the test sample for the  $\tau^+\tau^-$  QEL signal with  $m_{\text{DM}} = 5 \text{ GeV}$  (blue) and the atmospheric background (red).

2361 estimation of the reconstructed neutrino energy.

2362 In any case, as before, I can take the direction of the incoming neutrino as known.

2363 That way, one can estimate the energy of the neutrino as:

$$E_\nu^{reco} = E_\mu + E_p + m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}}, \quad (5.33)$$

2364 and using momentum conservation I can write the momentum of the remnant nucleus

2365 as:

$$\vec{p}_N = \hat{p}_\nu (E_\mu + E_p + m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}}) - \vec{p}_\mu - \vec{p}_p. \quad (5.34)$$

2366 As in the previous case, I need to drop the events where the muon or the proton fall  
 2367 below the kinetic energy detection threshold [85]. Also, I again apply a smearing to the  
 2368 momenta of the particles, a 1% for muons and 5% for protons.

2369 Having done that, one can compute the following angular variables for our selected  
 2370 events:

$$\cos \theta_\mu = \hat{p}_\nu \cdot \hat{p}_\mu, \quad (5.35)$$

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS

$$\cos \theta_p = \hat{p}_\nu \cdot \hat{p}_p, \quad (5.36)$$

$$\cos \theta_N = \hat{p}_\nu \cdot \hat{p}_N. \quad (5.37)$$

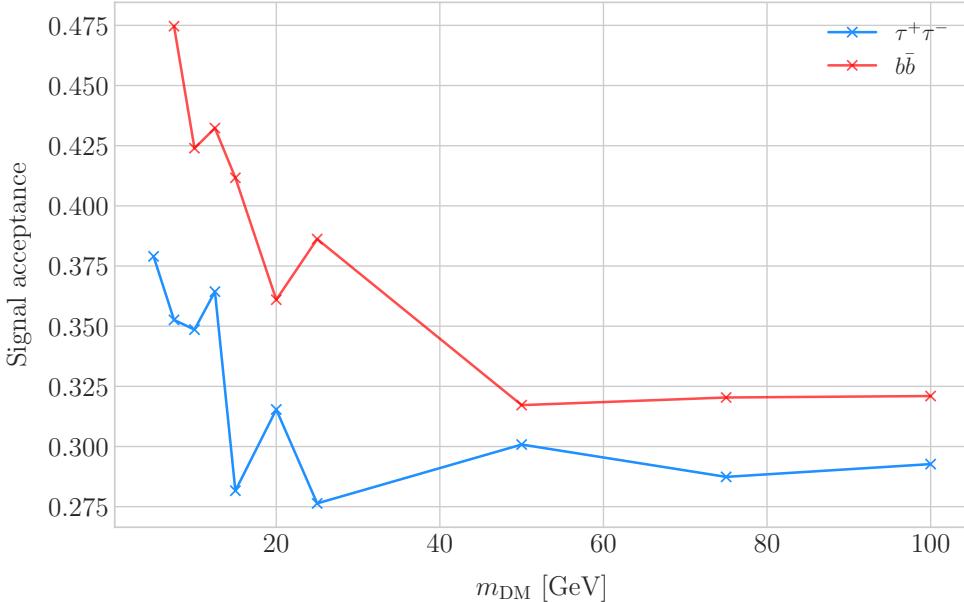
2371 Fig. 5.14 shows the distributions of these angular variables for the  $\tau^+\tau^-$  QEL  
 2372 sample with  $m_{\text{DM}} = 5$  GeV (blue) and the atmospheric background (red). Again, for  
 2373 the atmospheric events I used a random solar position as the ansatz for the incoming  
 2374 neutrino direction. Notice that now, opposed to the DIS case where the signal had very  
 2375 sharp distributions for the variables considered, the shapes of the angular distributions  
 2376 for signal and background are not that much different.

2377 This effectively means that the usual approach of applying simple angular cuts would  
 2378 not work as well as in the previous situation. Therefore, as a possible solution, I tried to  
 2379 use a multilayer perceptron (MLP) classifier to separate between signal and background  
 2380 events. Thus, the power of the hypothesis test will serve as an estimate of the signal  
 2381 efficiency, and in the same way one can take the size of the test to be our background  
 2382 rejection.

2383 For each DM mass value and channel, as well as for the background sample, I divide  
 2384 our events into training, validation and test samples. The input variables for the classifier  
 2385 were the reconstructed neutrino energy from Eq. (5.33) and the angular variables defined  
 2386 in Eqs. (5.35 - 5.37). I used the MLP classifier implemented in **scikit-learn** [139], with  
 2387 a total of five hidden layers, the rectified linear unit activation function and adaptive  
 2388 learning rate. In order to account for fluctuations due to artifacts in the training process I  
 2389 repeated the training a thousand times for each sample, redefining each time the training,  
 2390 validation and test subsets, so one can take as our signal efficiency and background  
 2391 rejection the mean values of the powers and sizes of the tests.

2392 The results of one of these training processes for the  $\tau^+\tau^-$  QEL signal with  $m_{\text{DM}} =$   
 2393 5 GeV is shown in Fig. 5.15. On the left panel I show the loss function values (blue) and  
 2394 accuracy (red) at each iteration for the training and the validation samples respectively.  
 2395 The training stops either when the maximum number of iterations is reached (1000 in  
 2396 this case) or when the accuracy for the validation sample reaches a certain tolerance

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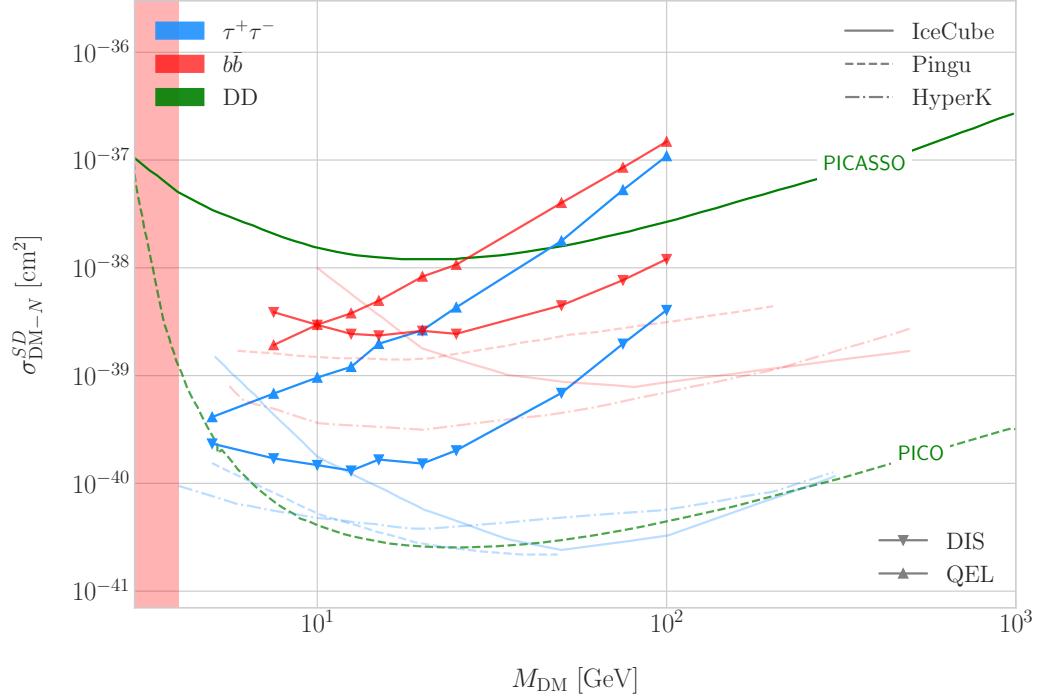


**Figure 5.16:** Signal efficiencies for the  $\tau^+\tau^-$  (blue line) and  $b\bar{b}$  (red line) single proton QEL samples as functions of the DM mass,  $m_{\text{DM}}$ , obtained by requiring a minimum predicted probability from the MLP classifier of 0.97 in order to achieve a background rejection greater than 99.8%.

2397 (I chose  $10^{-4}$  as our tolerance). On the right panel I have the distributions for the  
 2398 predicted probability by the model, separated in true signal (blue) and background  
 2399 (red) events, for the test sample. One can see that both populations are well separated,  
 2400 obtaining a power of 44.97% and a size of 0.17% when I require a predicted probability  
 2401 greater than 0.97.

2402 Applying this criteria for each sample, I obtain the mean signal efficiencies shown in  
 2403 Fig. 5.16. Notice that the efficiencies for the channel  $\tau^+\tau^-$  (blue line) are consistently  
 2404 lower than the ones for the  $b\bar{b}$  channel (red line). This can be due to the fact that, for  
 2405 each DM mass point, the neutrino spectrum coming from the  $b\bar{b}$  annihilation channel is  
 2406 centered at lower energies when compared to the  $\tau^+\tau^-$  spectrum. This directly translates  
 2407 into more low energy neutrinos undergoing QEL interactions, which give signals that  
 2408 can be easily separated from the atmospheric background. This explanation also help us  
 2409 understand why in both cases the signal acceptance drops when the DM mass increases.  
 2410 In all cases, the background rejection took values between 99.8% to 99.9%. I will assume

## 5.6. HIGH ENERGY DM NEUTRINO SIGNALS



**Figure 5.17:** Projected 90% confidence level upper limit for DUNE (400 kT yr) on the spin-dependent DM-nucleon scattering cross section as a function of  $m_{\text{DM}}$ , for the annihilation channels  $\tau^+\tau^-$  (blue) and  $b\bar{b}$  (red) separated by interaction type (up triangles denote DIS interactions whereas down triangles represent QEL interactions). I also show the previous limits from IceCube [7] (solid lines) and the projected sensitivities for Pingu [8] (dashed lines) and Hyper-Kamiokande [9] (dash-dotted lines), as well as the direct detection limits from PICASSO [10] (solid green line) and PICO-60 C<sub>3</sub>F<sub>8</sub> [11] (dashed green line).

2411 a 99.8% background rejection value in all cases to keep our estimation conservative.

2412 **5.6.3 Results**

2413 In order to estimate the DM-nucleon cross section sensitivities in the present case I need  
 2414 again to compute the expected number of background events. As I am now separating  
 2415 events by interaction type Eq. (5.25) does not hold anymore, as in that case I integrated  
 2416 over the total neutrino-argon cross section. In this instance, the expected background  
 2417 events for DIS events is approximately given by:

$$N_B^{DIS} \simeq \eta_B^{DIS} \times (4.655 \times 10^3) \times \left( \frac{\text{exposure}}{400 \text{ kT yr}} \right), \quad (5.38)$$

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN

2418 whereas for QEL events we have:

$$N_B^{QEL} \simeq \eta_B^{QEL} \times (2.248 \times 10^4) \times \left( \frac{\text{exposure}}{400 \text{ kT yr}} \right). \quad (5.39)$$

2419 Now, using these together with Eqs. (5.26) and (5.27) one can obtain the 90% C.L.  
2420 upper limit on the total annihilation rate at equilibrium for both kind of events. Then,  
2421 applying the computed DM-nucleons capture rates I can translate these into limits on  
2422 the DM-nucleon cross section by means of Eqs. (5.2), (5.5) and (5.6).

2423 Fig. 5.17 shows the obtained limits on the SD DM-nucleon cross section for DUNE,  
2424 using the DIS (up triangles) and QEL (down triangles) events both for the  $\tau^+\tau^-$  (blue)  
2425 and the  $b\bar{b}$  (red) samples, for an exposure of 400 kT yr. I also include the corresponding  
2426 current limits from IceCube [7] (solid lines), as well as the projected sensitivities of  
2427 Pingu [8] (dashed lines) and Hyper-Kamiokande [9] (dash-dotted lines). For comparison,  
2428 I also show the reported direct detection limits from PICASSO [10] (solid green line)  
2429 and PICO-60  $C_3F_8$  [11] (dashed green line).

2430 Notice that, for most of the mass range, the limits one can set by using the DIS  
2431 events are stronger than those of the QEL interactions, except for the low mass part  
2432 of both the  $\tau^+\tau^-$  and the  $b\bar{b}$  curves where the QEL events dominate. In general, the  
2433 expected sensitivity of DUNE for DM masses  $\lesssim 25$  GeV surpasses the stronger current  
2434 indirect limits. However, experiments like Hyper-Kamiokande are foreseen to have an  
2435 overall better sensitivity in this kind of searches, as they have a bigger active volume  
2436 and accept a broader energy range.

2437 A pending question is what happens when we add the RES and MEC charged-current  
2438 interaction contributions. In that case it would probably be more convenient to split  
2439 the samples by final state interaction topologies. Also, another necessary improvement  
2440 would be adding a full detector simulation and reconstructions. This will also require  
2441 considering the effect of poorly reconstructed events or final states containing neutral  
2442 particles such that they mimic the desired topology at the reconstruction level.

## 5.7. EXAMPLE: LEPTOPHILIC DARK MATTER

### **2443 5.7 Example: Leptophilic Dark Matter**

**2444** In general, the capture rate of DM particles by the Sun via interactions with electrons is  
**2445** several orders of magnitude smaller than the capture via DM-nucleus scattering. Thus,  
**2446** it would be sub-leading even when nucleon capture is loop suppressed. As I showed in  
**2447** Fig. 5.2, the capture rate via scattering off electrons only surpasses the capture rates  
**2448** via DM-nucleons interactions for DM masses  $\lesssim 100 - 500$  MeV.

**2449** However, if one considers a model where DM-nucleon interactions are forbidden even  
**2450** at loop level, then electron interactions will be the sole contributor to DM capture in  
**2451** the Sun. One can describe such scenario where the DM particles couple to leptons but  
**2452** not to the quark sector using effective operators.

**2453** In general, assuming that the DM particle is a Dirac fermion, the dimension six  
**2454** operators describing the interaction between two DM particles and two leptons can be  
**2455** written as:

$$\mathcal{L}_{eff} = G \sum_i (\bar{\chi} \Gamma^i \chi) (\bar{\ell} \Gamma^i \ell), \quad (5.40)$$

**2456** where  $G = 1/\Lambda^2$  is the effective coupling strength,  $\Lambda$  the cut-off of the effective field  
**2457** theory and  $\ell$  denotes any lepton. In principle, one should consider all the possible  
**2458** Lorentz structures  $\Gamma_f^i$  in order to have a complete set of effective operators.

**2459** However, some combinations will induce interactions with nucleons at loop level.  
**2460** As we are specifically interested in interactions which forbid any communication with  
**2461** the quark sector, I will not consider those [140]. In addition, some of the effective  
**2462** operators give rise to velocity-suppressed scattering cross sections between DM particles  
**2463** and leptons. I will also neglect those, as the suppression goes with the square of the DM  
**2464** halo velocity which in units of the speed of light is  $\sim 10^{-6}$ .

**2465** This way, the only Lorentz tensor structure that do not induce interactions with  
**2466** quarks at loop level and gives a contribution to the scattering cross section that is not  
**2467** velocity suppress is the axial-axial interaction. The effective Lagrangian is then given

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN

2468 by:

$$\mathcal{L}_{eff} = \frac{c_A^\chi c_A^\ell}{\Lambda^2} (\bar{\chi} \gamma^\mu \gamma^5 \chi) (\bar{\ell} \gamma_\mu \gamma^5 \ell), \quad (5.41)$$

2469 where  $c_A^\chi$  and  $c_A^\ell$  are the couplings for the different species. As the DM coupling appears  
 2470 as a common factor for any lepton choice, I will redefine the corresponding coupling  $c_A^\ell$   
 2471 to absorb  $c_A^\chi$ . Also, for simplicity, I will assume that the couplings between the DM  
 2472 particles and the leptons are flavour independent, i.e. I have just two couplings,  $c_A^e$  for  
 2473 charged leptons and  $c_A^v$  for neutrinos.

2474 In the case of a scalar DM particle, the lowest order effective interaction with  
 2475 leptons happens through a dimension five operator, generating scalar and pseudoscalar  
 2476 interactions. However, the former induces interactions with quarks at two loop level  
 2477 whereas the latter gives a velocity suppressed scattering cross section.

2478 From the effective Lagrangian in Eq. (5.41) it can be shown that the axial-axial  
 2479 contribution to the scattering cross section for the fermionic DM and a charged lepton  
 2480 is given by:

$$\sigma_{DM-e}^{AA} = 3 (c_A^e)^2 \frac{m_e^2}{\pi \Lambda^4}. \quad (5.42)$$

2481 If the DM interacts exclusively with fermions, then the only annihilation channels  
 2482 that will give us a measurable neutrino flux coming out of the Sun are  $\tau^+ \tau^-$  and  $\nu \bar{\nu}$ . The  
 2483 former channel, already explored previously in the more mainstream scenario of the DM  
 2484 capture via scattering off nucleons, is open only for  $m_{DM} > m_\tau \simeq 1776.86 \pm 0.12$  MeV  
 2485 [141], a mass region where the solar DM capture by electrons is at least one order of  
 2486 magnitude smaller than the capture via interactions with nucleons. On the contrary, the  
 2487 latter allows us to explore a region where the capture rate via scattering off electrons  
 2488 dominates over the rest.

2489 One downside of focusing in such low mass range is that it falls below the usual  
 2490 limit of  $m_{evap} \sim 4$  GeV usually explored in the literature. The pretext to explore this  
 2491 region is the result discussed previously reported in Ref. [2], where DM evaporation in  
 2492 the Sun for the case of capture via electron scattering could be negligible for masses  
 2493 as low as  $m_{evap} \sim 200$  MeV. This result is quite sensitive to the high velocity tail of

## 5.7. EXAMPLE: LEPTOPHILIC DARK MATTER

2494 the DM velocity distribution in equilibrium inside the Sun, and therefore full numerical  
 2495 simulations would be needed to asses the impact of this effect. However, this falls out of  
 2496 the scope of our work.

2497 In this case, as I have an specific realisation of the interaction between the DM  
 2498 and leptons, one can estimate the relic density of our DM for different values of the  
 2499 couplings and the effective field theory scale  $\Lambda$ . The first step to do so is compute the  
 2500 self-annihilation cross section. Because I consider cold relics, at the freeze-out time our  
 2501 DM particles were non-relativistic and so one can expand the annihilation cross section  
 2502 in terms of the relative velocity  $v$  between two annihilating DM particles as [142]:

$$\sigma_{ann}^{AA}|v| \approx \frac{1}{2\pi\Lambda^4} \sum_{\ell} \left(c_A^{\ell}\right)^2 m_{\chi}^2 \sqrt{1 - \frac{m_{\ell}^2}{m_{\chi}^2} \left[ \frac{m_{\ell}^2}{m_{\chi}^2} + \frac{1}{12} \left(2 - \frac{m_{\ell}^2}{m_{\chi}^2}\right) v^2 \right]}, \quad (5.43)$$

2503 where the sum includes all the possible lepton final states with mass  $m_{\ell}$ .

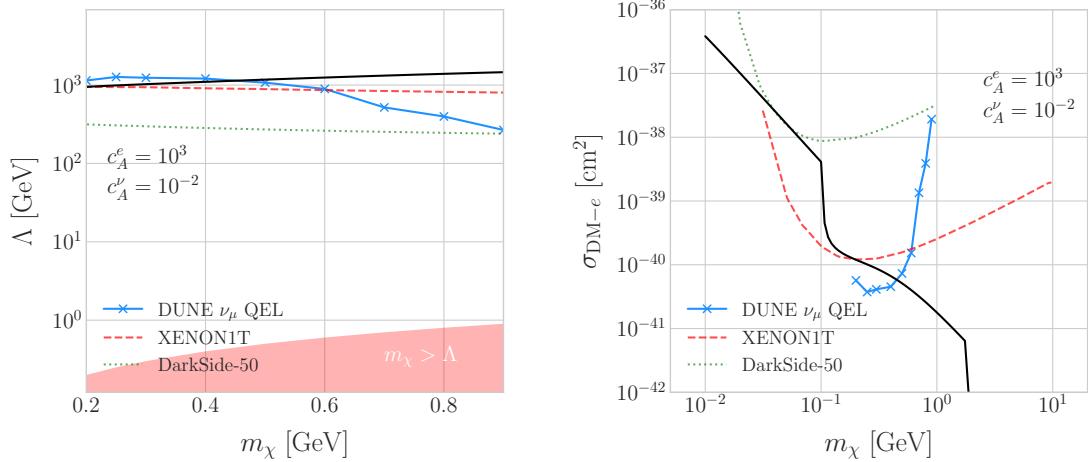
2504 Solving the Boltzmann equation for the evolution of the DM density gives as a  
 2505 solution a relic density of:

$$\Omega_{\chi} h^2 \approx \frac{(1.04 \times 10^9) x_F}{M_{Pl} \sqrt{g_*} (a + 3b/x_F)}, \quad (5.44)$$

2506 where  $x_F = m_{\chi}/T_F$  being  $T_F$  the freeze-out temperature,  $g_*$  the number of relativistic  
 2507 degrees of freedom at freeze-out and  $a$  and  $b$  the terms in the annihilation cross section  
 2508 expansion  $\sigma_{ann}|v| \approx a + bv^2 + \mathcal{O}(v^4)$ . Using the current best fit for the relic DM density  
 2509  $\Omega_{\chi} h^2 = 0.1198 \pm 0.0012$  [143] one can use these relations to compute the required  
 2510 effective theory scale  $\Lambda$  at which the correct density is achieved for any combinations of  
 2511  $m_{\chi}$  and  $c_A^{\ell}$ .

2512 As discussed before, in the low DM mass region QEL interactions dominate. Moreover,  
 2513 if I focus on direct annihilation to neutrinos, the energy of the muon neutrino flux is  
 2514 known as it must be equal to the mass of the DM particle,  $E_{\nu} = m_{\chi}$ . That way, now  
 2515 I do not need to use Eq. (5.33) in order to estimate the momentum transfer to the

## CHAPTER 5. DM SEARCHES WITH NEUTRINOS FROM THE SUN



**Figure 5.18:** Left panel: Projected 90% confidence level sensitivity of DUNE (400 kT yr) to the scale  $\Lambda$  of an EFT containing only leptophilic DM axial-axial interactions (blue line). Right panel: . In both cases the corresponding limits from DarkSide-50 [12] (dotted green line) and XENON1T [13] (dashed red line) are also shown, together with the configurations for which the correct relic density is achieved (black line), all for the coupling values  $c_A^e = 10^3$  and  $c_A^\nu = 10^{-2}$ .

2516 remnant nucleus, I can simply take:

$$\vec{p}_N = \hat{p}_\nu m_\chi - \vec{p}_\mu - \vec{p}_p. \quad (5.45)$$

2517 To estimate the signal efficiency and background rejection for this case I used again  
 2518 the MLP classifier from `scikit-learn`, using the same specifications as before. The  
 2519 only difference now is that I add also the reconstructed neutrino energy as one of the  
 2520 features to train the classifier with, because the characteristic monoenergetic flux for  
 2521 each  $m_\chi$  value will help to distinguish between signal and background events.

2522 In this case, for masses below  $\sim 500$  MeV I obtain a signal efficiency close to unity  
 2523 while keeping a background rejection of 99.9%. For bigger values of the mass, the signal  
 2524 efficiency drops significantly if I require to keep the background acceptance under 0.01%.  
 2525 However, because this kind of search is dominated by the background, sacrificing the  
 2526 signal acceptance to keep the background rejection to a minimum enhances the reach  
 2527 of the analysis. This way, for DM masses of the order of  $m_\chi \sim 1$  GeV I end up with  
 2528 efficiencies as low as 1%.

## 5.7. EXAMPLE: LEPTOPHILIC DARK MATTER

Now, estimating the number of background events using Eq. (5.39) one can go on and apply Eqs. (5.26) and (5.27) together with Eq. (5.42) to derive the sensitivity of DUNE to this kind of model. Fig. 5.18 (left panel) shows the potential reach of DUNE to constrain the EFT scale  $\Lambda$  this model containing only leptophilic DM axial-axial interactions (blue line), for a choice of couplings  $c_A^e = 10^3$  and  $c_A^\nu = 10^{-2}$ . I also included the current limits on the DM-electron scattering cross section from DarkSide-50 [12] (dotted green line) and XENON1T [13] (dashed red line), reworked with Eq. (5.42) to show their implications for the EFT scale. The values of  $\Lambda$  for which the correct DM relic density value is achieved for each mass are also shown (black line). This tells us that, for that specific choice of couplings, DUNE would be sensitive to DM configurations allowed by the relic density constraint up to a mass of  $m_\chi \sim 400$  MeV.

In Fig. 5.18 (right panel) I show the same upper limits but for the DM-electron scattering cross section. From this view one can see that DUNE would be able to offer complementary information to the low energy DM-electron interaction searches performed by direct detection experiments, in a slightly higher mass range.

With the present example, although it focuses on a very specific realisation of the DM interactions, I show the potential of DUNE to constrain exotic DM scenarios. Thanks to its low backgrounds and superb angular resolution DUNE will be able to help with the systematic searches for dark sectors physics.



## Particle ID in ND-GAr

2550 ND-GAr is a magnetised, high-pressure gaseous argon TPC (HPgTPC), surrounded by  
2551 an electromagnetic calorimeter (ECal) and a muon detector (commonly refer to as  $\mu$ ID).  
2552 A detailed discussion on the requirements, design, performance and physics of ND-GAr  
2553 can be found in the DUNE ND CDR [91] and the ND-GAr whitepaper (cite).

2554 In DUNE Phase II ND-GAr will fulfill the role of TMS, measuring the momentum  
2555 and sign of the charged particles exiting ND-LAr. Additionally, it will be able to measure  
2556 neutrino interactions inside the HPgTPC, achieving lower energy thresholds than those  
2557 of the ND and FD LArTPCs. By doing so ND-GAr will allow to constrain the relevant  
2558 systematic uncertainties for the LBL analysis even further.

2559 The goal of the present chapter is to review the requirements that the physics program  
2560 of DUNE impose on ND-GAr, present the current status of its design and describe the  
2561 GArSoft package, its simulation and reconstruction software.

2562 As decided during the DUNE Phase II workshop in June 2023 [reference], we want  
2563 to build ND-GAr physics case by showing:

- 2564 • That ND-GAr can constrain systematic uncertainties that ND-LAr might miss.
- 2565 • The impact on the neutrino oscillation results if such systematic uncertainties are  
2566 missed.
- 2567 • That ND-GAr is necessary to reach DUNE's main physics goals.

2568 This way, the design of ND-GAr will be physics driven.

## CHAPTER 6. PARTICLE ID IN ND-GAr

2569 In order to study the effects of final state interactions (FSI) in CC interactions,  
2570 ND-GAr should be able to measure the spectrum of protons and charged pions at low  
2571 energies. ND-GAr also needs to be able to measure the pion multiplicity, specially for  
2572 energies above 100 MeV as at these energies the pions shower in the LAr, to inform the  
2573 pion mass correction in the ND and FD LArTPCs.

2574 In order to correctly identify electrons, muons, pions, kaons and protons ND-GAr  
2575 can use a combination of:  $dE/dx$  measurements in the HPgTPC,  $E_{ECAL}/p$  using the  
2576 ECAL total energy and the momentum obtained from magnetic spectroscopy in the  
2577 HPgTPC and penetration information through the ECAL and muon tagger.

### 2578 6.1 GArSoft

2579 GArSoft is a software package developed for the simulation and reconstruction of events  
2580 in ND-GAr. It is inspired by the LArSoft toolkit used for the simulation of LArTPC  
2581 experiments, like the DUNE FD modules. It is based on `art`, the framework for event  
2582 processing in particle physics experiments [144]. Other of its main dependencies are  
2583 `ROOT`, `NuTools`, `GENIE` and `Geant4`. It allows the user to run all the steps of a generation-  
2584 simulation-reconstruction workflow using FHiCL configuration files.

#### 2585 6.1.1 Event generation

2586 The standard generator FHiCLs in GArSoft run the event generation and particle  
2587 propagation simulation (i.e. Geant4) in the same job by default. However, it is possible  
2588 to split them up if needed. The current version of GArSoft provides five different event  
2589 generators, each of them producing `simb::MCTruth` products defined in `NuTools`. The  
2590 available modules are:

- 2591 • **SingleGen**: particle gun generator. It produces the specified particles with a given  
2592 distribution of momenta, initial positions and angles.
- 2593 • **TextGen**: text file generator. The input file must follow the `hepevt` format<sup>1</sup>, the

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<sup>1</sup>In brief, each event contains at least two lines. The first line contains two entries, the event number

## 6.1. GARSOFT

2594 module simply copies this to `simb::MCTruth` data products.

2595 • **GENIEGen**: GENIE neutrino event generator. The module runs the neutrino-nucleus  
2596 interaction generator using the options specified in the driver FHiCL file (flux file,  
2597 flavour composition, number of interactions per event,  $t_0$  distribution, ...). Current  
2598 default version is v3\_04\_00.

2599 • **RadioGen**: radiological generator. It produces a set list of particles to model  
2600 radiological decays. Not tested.

2601 • **CRYGen**: cosmic ray generator. The module runs the CRY event generator with a  
2602 configuration specified in the FHiCL file (latitude and altitude of detector, energy  
2603 threshold, ...). Not tested.

2604 The module **GArG4** searches for all the generated `simb::MCTruth` data products, using  
2605 them as inputs to the Geant4 simulation with the specified detector geometry. A constant  
2606 0.5 T magnetic field along the drift coordinate is assumed. The main outputs of this step  
2607 are `simb::MCParticle` objects for the generated Geant4 particles, `gar::EnergyDeposit`  
2608 data products for the energy deposits in the HPgTPC and `gar::CaloDeposit` data  
2609 products for the energy deposits in the ECal and muon system.

### 2610 6.1.2 Detector simulation

2611 The standard detector simulation step in GArSoft is all run with a single FHiCL, but  
2612 the different modules can be run independently as well. First the `IonizationReadout`  
2613 module simulates the charge readout of the HPgTPC, and later the `SiPMReadout` module  
2614 runs twice, once for the ECal and then for the muon system, with different configurations.

2615 The `IonizationAndScintillation` module collects all the `gar::EnergyDeposit`  
2616 data products, to compute the equivalent number of ionization electrons for each energy

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and the number of particles in the event. Each following line contains 15 entries to describe each particle. The entries are: status code, pdg code for the particle, entry of the first mother for this particle, entry of the second mother for this particle, entry of the first daughter for this particle, entry of the second daughter for this particle, x component of the particle momentum, y component of the particle momentum, z component of the particle momentum, energy of the particle, mass of the particle, x component of the particle initial position, y component of the particle initial position, z component of the particle initial position and time of the particle production.

## CHAPTER 6. PARTICLE ID IN ND-GAr

deposit. The `ElectronDriftAlg` module simulates the electron diffusion numerically both in the longitudinal and transverse directions and applies an electron lifetime correction factor. The induced charge on the nearest and neighbouring readout pads is modeled using the provided pad response functions. The digitisation of the data is then simulated with the `TPCReadoutSimAlg` module. By default, the ADC sampling rate used is 50.505 MHz. The resulting raw waveforms for each channel are stored with zero-suppression, in order to save memory and CPU time. The algorithms keep blocks of ADC values above a certain threshold, plus some adjustable additional early and late tick counts. The results of these three steps are `gar::raw::RawDigit` data products.

For the ECal and the muon system the `SiPMReadout` module calls either the `ECALReadoutSimStandardAlg` or `MuIDReadoutSimStandardAlg` modules. These take all the `gar::CaloDeposit` data products in the corresponding detector and do the digitisation depending on whether the hit was in a tile or strip layer. They include single photon statistics, electronic noise, SiPM saturation and time smearing. The resulting objects are `gar::raw::CaloRawDigit` data products.

### 6.1.3 Reconstruction

The reconstruction in GArSoft is also run as a single job by default. It first runs the hit finding, clustering, track fitting and vertex identification in the HPgTPC, followed by the hit finding and clustering in the ECal and muon system. After those it produces the associations between the associations between the tracks and the ECal clusters.

Focusing first on the HPgTPC reconstruction, the `CompressedHitFinder` module takes the zero-suppressed ADCs from the `gar::raw::RawDigit` data products. The reconstructed hits largely correspond to the above threshold blocks, however the hit finder identifies waveforms with more than one maximum, diving them in multiple hits if they dip below a certain threshold. The data products produced are of the form `gar::rec::Hit`. These are the inputs to the clustering of hits in the `TPCHitCluster` module. Hits close in space and time are merged, and the resulting centroids are found. This module outputs `gar::rec::TPCClusters` objects and associations to the input

## 6.1. GARSOFT

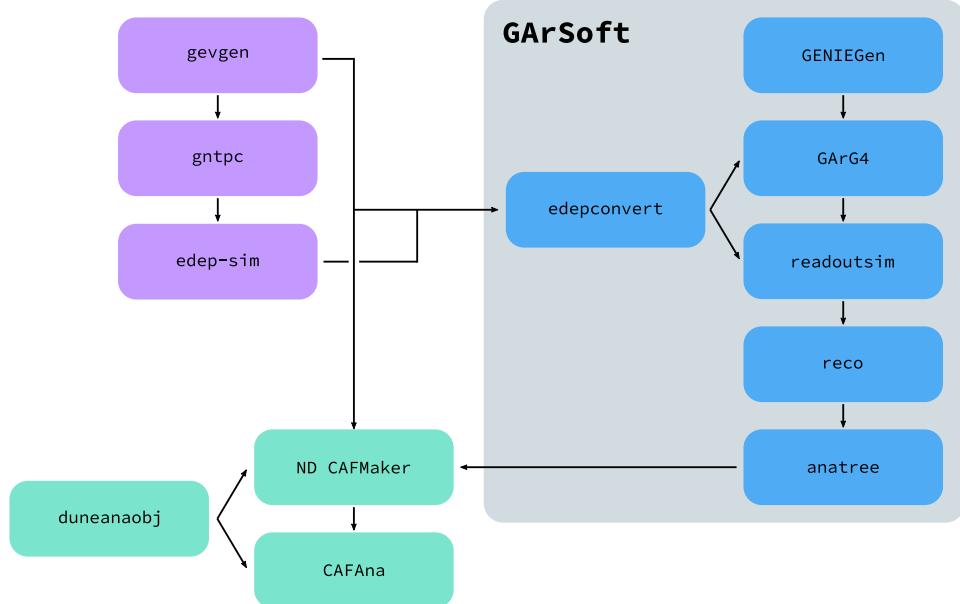
2645 hits.

2646 The following step prior to the track fitting is pattern recognition. The module  
2647 called `tpcvechitfinder2` uses the `gar::rec::TPCClusters` data products to find track  
2648 segments, typically called vector hits. They are identified by performing linear 2D fits  
2649 to the positions of the clusters in a 10 cm radius, one fit for each coordinate pair. A  
2650 3D fit defines the line segment of the vector hit, using as independent variable the one  
2651 whose sum of (absolute value) slopes in the 2D fits is the smallest. The clusters are  
2652 merged to a given vector hit if they are less than 2 cm away from the line segment. The  
2653 outputs are `gar::rec::VecHit` data products, as well as associations to the clusters. The  
2654 `tpcpatrec2` module takes the `gar::rec::VecHit` objects to form the track candidates.  
2655 The vector hits are merged together if their direction matches, their centers are within  
2656 60 cm and their direction vectors point roughly to their respective centers. Once  
2657 the clusters of vector hits are formed they are used to make a first estimation of the  
2658 track parameters, simply taking three clusters along the track. The module produces  
2659 `gar::rec::Track` data products and associations between these tracks and the clusters  
2660 and vector hits.

2661 The track is fitted by means of a Kalman filter in the `tpctrackfit2` module, using  
2662 the position along the drift direction as the independent variable. Two different fits are  
2663 performed per track, a forward and a backwards fit, each starting from one of the track  
2664 ends. The Kalman filter state vector ( $y, z, R, \phi, \tan\lambda$ ) is estimated at each point along  
2665 the track using a Bayesian update. The track parameters reported in the forward and  
2666 backwards fits are the ones computed at the opposite end where the fit started. The  
2667 main outputs of the track fit are the `gar::rec::Track` objects. Additionally, the module  
2668 stores the fitted 3D positions along the track in the `gar::rec::TrackTrajectory` data  
2669 products and the total charge and step sizes for each point also get stored in the form of  
2670 `gar::rec::TrackIonization` objects.

2671 After the tracking step, the `vertexfinder1` module looks at the reconstructed  
2672 `gar::rec::Track` products, creating vertex candidates with the track ends that are  
2673 within 12 cm of each other. The vertices are then fitted using linear extrapolations from

## CHAPTER 6. PARTICLE ID IN ND-GAr



**Figure 6.1:** Schematic diagram showing the different modules involved in the ND-GAr production.

2674 the different track ends associated. The results are `gar::rec::Vertex` data products,  
 2675 and associations to the tracks and corresponding track ends.

2676 For the ECal and muon tagger, the `SiPMHitFinder` module runs twice with different  
 2677 configurations, adapted to the particular capabilities of both. The module simply takes  
 2678 the `gar::raw::CaloRawDigit` products, applies a calibration factor to convert the ADC  
 2679 counts to MeV and for the strip layer hits it calculates the position along the strip using  
 2680 the times recorded of both SiPMs. This module produces `gar::rec::CaloHit` data  
 2681 products. Next, these objects are used as inputs to the `CaloClustering` module. It  
 2682 merges the hits based on a simple nearest neighbours (NN) algorithm. For the resulting  
 2683 clusters it also computes the total energy and position of the centroid. The results are  
 2684 stored as `gar::rec::Cluster` data products, with associations to the hits.

2685 The last step in the reconstruction is associating the reconstructed tracks in the  
 2686 HPgTPC to the clusters formed in the ECal and muon system. The `TPCECALAssociation`  
 2687 module checks first the position of the track end points, considering only the points  
 2688 that are at least 215 cm away from the cathode or have a radial distance to the center

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC

2689 greater than 230 cm. The candidates are propagated up to the radial position, in the  
2690 case of clusters in the barrel, or the drift coordinate position, for the end cap cluster, of  
2691 the different clusters in the collection using the track parameters computed at the end  
2692 point. The end point is associated to the cluster if certain proximity criteria are met.  
2693 This module creates associations between the tracks, the end points and the clusters.  
2694 The criteria for the associations are slightly different for the ECal and the muon tagger.

### 2695 6.2 $dE/dx$ measurement in the TPC

2696 Among the parameters extracted from the track fitting, ionisation is particularly useful  
2697 for particle identification, as it is a function of the particle velocity. Although for the  
2698 case of relativistic particles this dependence is not very strong, measuring the track on  
2699 a large number of points may allow us to estimate the amount of ionisation accuratel.  
2700 This, paired with a measurement of the momentum, may allow us to identify the particle  
2701 type.

2702 The first calculation of the energy loss per unit length of relativistic particles using a  
2703 quantum-mechanical treatment is due to Bethe [145]. Using this approach, the mean  
2704 ionisation rate of a charged particle traveling through a material medium is (using  
2705 natural units  $G = \hbar = c = 1$ ):

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi Ne^4}{m_e \beta^2} z^2 \left( \log \frac{2m_e \beta^2 \gamma^2}{I} - \beta^2 \right), \quad (6.1)$$

2706 where  $N$  is the number density of electrons in the medium,  $e$  the elementary charge,  $m_e$   
2707 is the electron mass,  $z$  the charge of the particle in units of  $e$ ,  $\beta$  is the velocity of the  
2708 particle,  $\gamma = (1 - \beta^2)^{-1}$  and  $I$  denotes the effective ionisation potential averaged over  
2709 all electrons. This relation is known as the Bethe-Bloch formula.

2710 From Eq. (6.1) one can see that the ionisation loss does not depend explicitly on  
2711 the mass of the charged particle, that for non-relativistic velocities it falls as  $\beta^{-2}$ , then  
2712 goes through a minimum and increases as the logarithm of  $\gamma$ . This behaviour at high  
2713 velocities is commonly known as the relativistic rise. The physical origin of this effect

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2714 is partly due to the fact that the transverse electromagnetic field of the particle is  
2715 proportional to  $\gamma$ , therefore as it increases so does the cross section.

2716 It was later understood that the relativistic rise could not grow indefinitely with  $\gamma$ .  
2717 A way to add this feature in the Bethe-Bloch formula is by introducing the so-called  
2718 density effect term. It accounts for the polarisation effect of the atoms in the medium,  
2719 which effectively shield the electromagnetic field of the charged particle halting any  
2720 further increase of the energy loss [146]. Denoting the correction as  $\delta(\beta)$ , one can rewrite  
2721 Eq. (6.1) as:

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi Ne^4}{m_e \beta^2} z^2 \left( \log \frac{2m_e \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\beta)}{2} \right). \quad (6.2)$$

2722 In general, the form of  $\delta(\beta)$  depends on the medium and its state of aggregation,  
2723 involving the usage of tabulated parameters and implicit relations [147].

2724 Another standard method to compute the amount of ionisation a charged particle  
2725 produces is the so-called photo-absorption ionisation (PAI) model proposed by Allison  
2726 and Cobb [148]. Within their approach, the mean ionisation is evaluated using a  
2727 semiclassical calculation in which one characterises the continuum material medium by  
2728 means of a complex dielectric constant  $\epsilon(k, \omega)$ . However, in order to model the dielectric  
2729 constant they rely on the quantum-mechanical picture of photon absorption and collision.  
2730 Therefore, in the PAI model the computation of the ionisation loss involves a numerical  
2731 integration of the measured photo-absorption cross-section for the relevant material.

2732 In a particle physics experiment, the typical way of determining the energy loss  
2733 per unit length as a function of the particle velocity is studying identified particles  
2734 over a range of momenta. Once we have established this relation we can use it for  
2735 other, unknown particles. In this sense, it makes sense to have a regular mathematical  
2736 expression for this relation that one can use.

2737 It happens that neither the Bethe-Bloch theory nor the PAI model from Allison and  
2738 Cobb offer a close mathematical form for the ionisation curve. This is the reason why a  
2739 full parametrisation of the ionisation curves can be useful. A parametrisation originally  
2740 proposed for the ALEPH TPC [149] and later used by the ALICE TPC [150] group that

## 6.2. dE/dx MEASUREMENT IN THE TPC

2741 manages to capture the features of the ionisation energy loss is:

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left( P_2 - \beta^{P_4} - \log \left[ P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right] \right), \quad (6.3)$$

2742 where  $P_i$  are five free parameters. Hereafter, we will refer to Eq. (6.3) as the ALEPH

2743 dE/dx parametrisation.

### 2744 6.2.1 Energy calibration

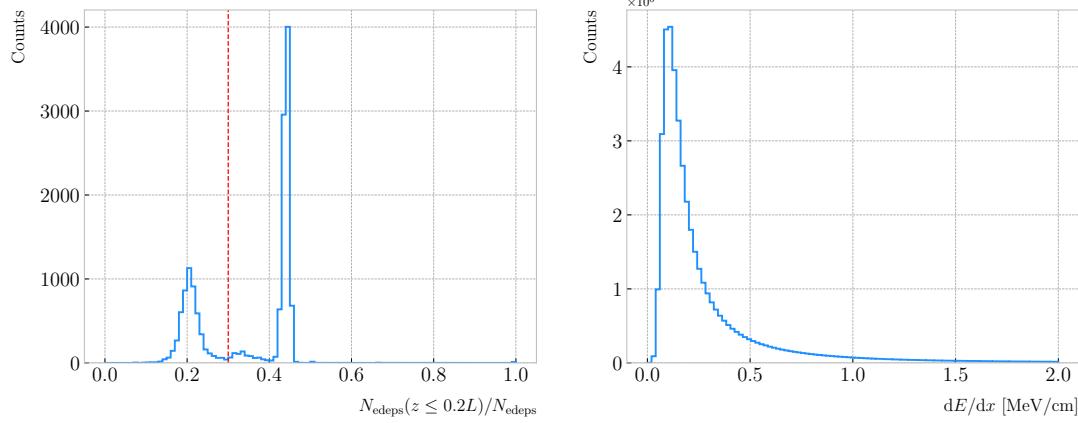
2745 In order to obtain the amount of energy loss by a charged particle due to ionisation  
2746 in our TPC we need to determine the conversion between the charge deposited in our  
2747 readout planes and the actual energy depositions. This procedure is known as energy  
2748 calibration.

2749 In a general, the first step of the calibration involves a non-uniformity correction,  
2750 to make sure that the detector response is uniform throughout the TPC. These are  
2751 typically divided into three categories, non-uniformities in the transverse  $YZ$  plane,  
2752 non-uniformities along the drift direction  $X$  and variations of the detector response  
2753 over time (would not apply to us as the detector is not built yet). These would correct  
2754 for effects such as electron diffusion and attenuation, space charge effects or channel  
2755 misconfiguration. However, because at the moment I am only interested in making sure  
2756 we recover a sensible result from our simulation, I will not apply uniformity corrections  
2757 to our charge deposits.

2758 Other effects, like electron-ion recombination or ADC saturation, lead to a non-linear  
2759 relation between the observed charge and the deposited energy in the detector, with the  
2760 observed readout charge saturating at high ionisation energies. In this case, because we  
2761 are dealing with gaseous argon and therefore recombination is not as important as in  
2762 liquid, we do not simulate recombination effects in the TPC. Even so, the simulation of  
2763 the electronic response will still introduce charge saturation, and one needs to correct  
2764 for it in order to obtain the exact amount of energy loss due to ionisation.

2765 By default, the track fitting algorithm in GArSoft provides a `TrackIonization`

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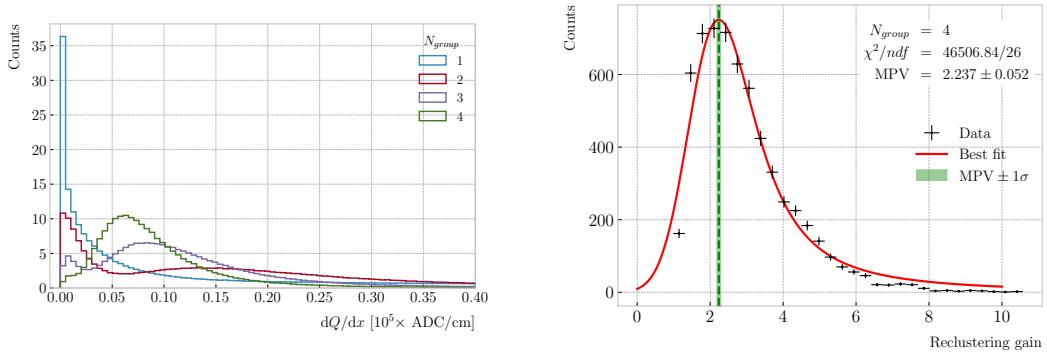
**Figure 6.2:** Left panel: distribution of the fraction of Geant4-level energy deposits per track with residual range less than 20% of the total track length, for the isotropic proton sample. Right panel: distribution of the ionisation per unit length of the energy deposits in the proton sample after removing the tracks with less than 30% of their energy deposits in the last 20% of the track.

object associated to each reconstructed track. It contains two collections of charge deposits, one for each fitting direction, consisting on pairs of charge values ( $dQ$ , in ADC) and step sizes ( $dx$ , in cm).

In order to estimate the ionisation loss in the ND-GAr TPC, I have used an MC sample consisting of single, isotropic protons propagating in the TPC. The starting points of the protons were sampled inside a  $50 \times 50 \times 25$  cm box centered at  $(100, -150, 1250)$ , and their momenta are uniformly distributed in the range  $0.25 - 1.75$  GeV. I ran the simulated sample through GArSoft's default detector simulation and reconstruction, and then a custom analyser module that extracts the ionisation data together with other reconstructed track information from the Kalman fit.

For studying the energy loss of the protons I select the reconstructed tracks that range out (i.e. slow down to rest) inside the TPC. A characteristic feature of the energy loss profile of any stopping ionising particle is the so-called Bragg peak, a pronounced peak that occurs immediately before the particle comes to rest. From Eq. (6.1) we can see that this behaviour is expected, as the energy loss for non-relativistic particles is inversely proportional to  $\beta^2$ . In data, a way of identifying the Bragg peak, and thus select the stopping particles, is checking the number of energy deposits towards the

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**Figure 6.3:** Left panel: distribution of the reconstructed ionisation charge per unit length for our MC stopping proton sample. The different colors indicate how many consecutive  $dQ/dx$  pairs were grouped together. Right panel: distribution of the median change in  $dQ/dx$  per track after  $N_{group} = 4$  clusters were reclustered together.

end of the track. In this case, I count the fraction of the Geant4 simulated energy deposits with a residual range value (the distance from a given energy deposit to the last deposit in the track trajectory) less than a 20% of the corresponding track length<sup>2</sup>. The distribution of this fraction of energy deposits for our proton sample is shown in Fig. 6.2 (left panel). We can clearly see two well separated peaks in this distribution, one centered at 0.2 and another, narrower, one centered at a higher value. The first one corresponds to non-stopping protons, as in that case the number of energy deposits towards the end of the track is uniformly distributed due to the absence of the Bragg peak. In that way, I apply a cut in this distribution, requiring that at least 30% of the simulated energy deposits sit in the last 20% of the tracks, to ensure that the Bragg peak is present.

Figure 6.2 (right panel) shows the distribution of the energy loss per unit length for the Geant4 simulated energy deposits of the selected stopping protons. We can see that it follows the expected shape of a Landau distribution, which describes the fluctuations of the ionisation energy losses [151]. This distribution has a characteristic asymmetric PDF, with a long right tail that translates into a high probability for high-energy ionisation losses. The origin of these fluctuations is mainly the possibility of transferring a high

<sup>2</sup>As we are applying this selection at the Geant4 level we could have simply selected the stopping protons using the `EndProcess` labels from the simulation. However, the Bragg peak identification method displayed here could serve as a starting point for a selection of stopping protons in real data.

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2800 enough energy to an electron, so it becomes a ionising particle itself.

2801 Now, from the point of view of the reconstruction, the objects that we have available  
 2802 to extract the ionisation information for the different reconstructed tracks are the  
 2803 collections of  $dQ$  and  $dx$  pairs, as stated before. The  $dQ$  values come from adding up  
 2804 the amplitude of all the reconstructed hits in a cluster, which is the input object to the  
 2805 Kalman fit.

2806 Figure 6.3 (left panel) shows the distribution of the ionisation charge deposits  
 2807 per unit length for the track in the stopping proton sample (blue line). As one can  
 2808 notice, this distribution does not resemble the expected shape of the Landau PDF. This  
 2809 distribution peaks sharply at 0 and has a heavy tailed behaviour. Notice, however, how  
 2810 the distribution changes its shape as we group together  $N_{group}$  consecutive charge deposit  
 2811 pairs (red, purple and green lines). The distribution in the  $N_{group} = 4$  case already has  
 2812 a shape which resembles that of the Geant4-level ionisation per unit length, so I will  
 2813 proceed using this amount of reclustering for the reconstruction-level depositions.

2814 An extra factor I need to account for, when reclustering is applied, is how the overall  
 2815  $dQ/dx$  per track changes. To do so, we can look at the ratio between the median  $dQ/dx$   
 2816 after and before the reclustering. Figure 6.3 (right panel) shows the median enhancement  
 2817 in  $dQ/dx$  per track for the stopping proton sample in the case  $N_{group} = 4$ . Fitting a  
 2818 Landau distribution convolved with a Gaussian<sup>3</sup>, I estimate the most probable value of  
 2819 this ratio to be  $G_{group} = 2.24 \pm 0.05$ .

2820 At this point, I am left with determining the conversion between the charge deposits  
 2821 per unit length  $dQ/dx$  and the energy deposits per unit length  $dE/dx$ . To this end, we  
 2822 need a way of comparing the two. I can use the residual range  $z$  to get a prediction of  
 2823 the most probable  $dE/dx$  by using the following empirical parametrisation [152]:

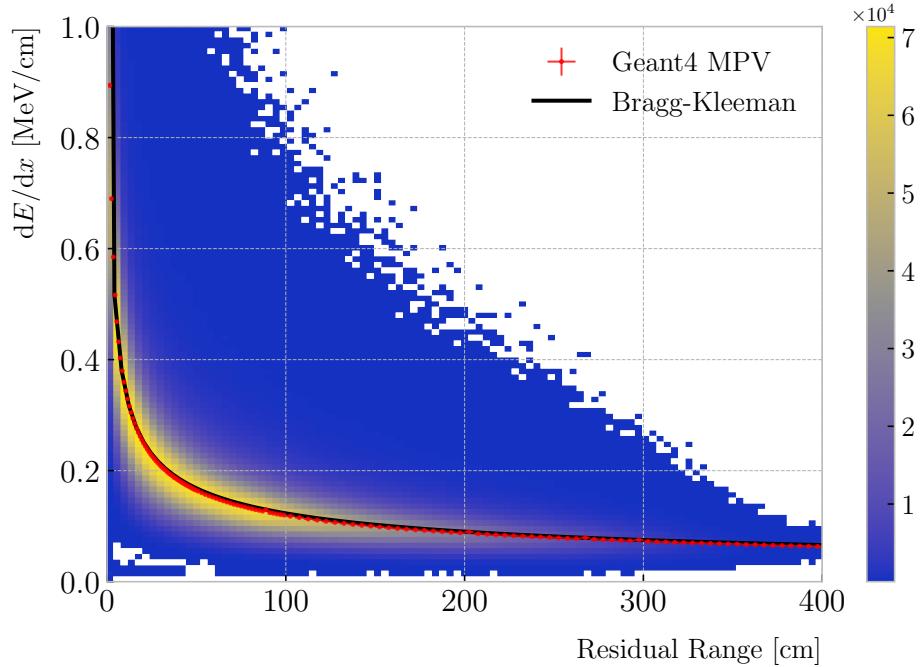
$$\frac{dE}{dx}(z) = \frac{z^{\frac{1}{p}-1}}{p\Lambda^{\frac{1}{p}}}, \quad (6.4)$$

2824 which is quoted in the literature as the Bragg-Kleeman formula. In order to obtain the

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<sup>3</sup>In the literature, this distribution is often referred to as Landau+Gaussian or langau. In the following, I will use LanGauss to refer to such PDF.

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC

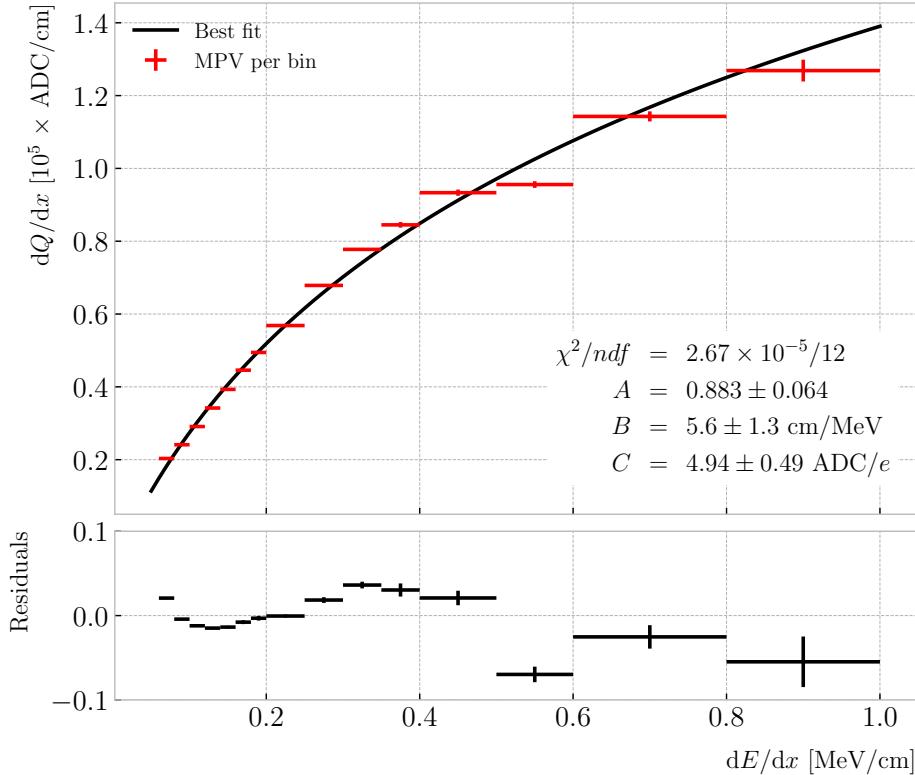


**Figure 6.4:** Distribution of the Geant4-simulated energy losses per unit length versus residual range for the stopping proton sample. The overlaid points represent the fitted most probable value of the  $dE/dx$  distribution in each residual range bin, whereas the curve is their best fit to the Bragg-Kleeman formula from Eq. (6.4).

2825  $p$  and  $\Lambda$  parameters I perform a fit using the energy losses and the residual ranges given  
 2826 by the Geant4 stage of our proton sample.

2827 Within our simulation, the residual range is sampled with a maximum size of  
 2828 5 mm. Therefore, to perform the fit to the Bragg-Kleeman formula, we can use a  
 2829 fine-grained residual range binning. For each of the residual range bins I extract the  
 2830  $dE/dx$  distribution and fit it to a LanGauss distribution, to obtain the value of the  
 2831 most probable  $dE/dx$  in the bin together with a statistical uncertainty. I then fit Eq.  
 2832 (6.4) to these most probable values and the centres of the residual range bins. This  
 2833 procedure is depicted in Fig. 6.4, where I show the distribution of the energy loss per  
 2834 unit length versus the residual range, together with the most probable  $dE/dx$  values  
 2835 and their uncertainty in each bin (red points) and the curve with the best fit of the  
 2836 Bragg-Kleeman relation to those values (black line). The best fit is obtained for the

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**Figure 6.5:** Fitted most probable  $dQ/dx$  values for each  $dE/dx$  bin (red points), obtained from the stopping proton sample. The overlaid curve (black line) represents the best fit to the logarithmic calibration function from Eq. (6.5).

2837 parameter values  $p = 1.8192 \pm 0.0005$  and  $\Lambda = 0.3497 \pm 0.0008 \text{ cm/MeV}^{p4}$ .

2838 Having an analytical expression that relates the residual range to  $dE/dx$ , I can take  
 2839 our reconstruction-level residual ranges from the stopping proton sample and compute  
 2840 the most probable energy loss associated.

2841 In order to parametrise the charge saturation, we can use the following logarithmic  
 2842 function inspired by the modified box model for recombination:

$$\frac{dE}{dx} = \frac{e^{\frac{dQ}{dx} B \frac{W_{ion}}{G_{group} C}} - A}{B}, \quad (6.5)$$

2843 where  $A$  and  $B$  are the calibration parameters we need to determine,  $W_{ion}$  is the average  
 2844 energy to produce an electron-ion pair,  $G_{group}$  is the gain from the reclustering discussed

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<sup>4</sup>These strange units for  $\Lambda$  come from dimensional analysis, just to keep the Bragg-Kleeman formula (6.4) consistent.

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC

**Table 6.1:** Calibration parameters obtained from the fit of the ND-GAr simulated stopping proton sample to the calibration function from Eq. (6.5). The fits were performed for the 10, 12, and 16-bit ADC limits.

	$\chi^2/ndf$	Best fit $\pm 1\sigma$		
		$A$	$B$ (cm/MeV)	$C$ (ADC/e)
10-bit	$1.83 \times 10^{-6}/12$	$-9.3 \pm 3.9$	$270 \pm 69$	$27.1 \pm 5.4$
12-bit	$2.67 \times 10^{-5}/12$	$0.883 \pm 0.064$	$5.6 \pm 1.3$	$4.94 \pm 0.49$
16-bit	$1.44 \times 10^{-5}/12$	$0.949 \pm 0.024$	$3.53 \pm 0.58$	$4.52 \pm 0.29$

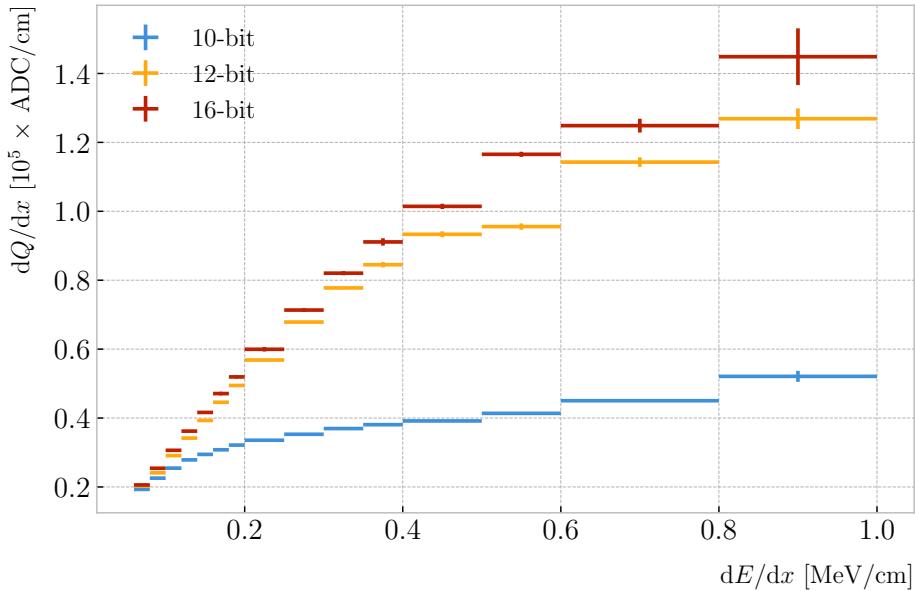
above and  $C$  is the calibration constant to convert number of electrons to ADC counts, commonly refer to as gain (also to be obtained in the fit). In this case, I use a value for the electron-ion production energy of  $W_{ion} = 26.4$  eV [153]. This value, used in our simulation as well, was measured for gaseous argon in normal conditions, and therefore should be checked in the future to describe correctly the high-pressure argon-CH<sub>4</sub> mixture of ND-GAr.

For the calibration fit I follow a procedure similar to the previous one for Eq. (6.4). Binning the  $dE/dx$  range, I fit a LanGauss distribution to the corresponding  $dQ/dx$  distribution to obtain the most probable value. The resulting data points (red bars) are shown in Fig. 6.5 (top panel), the horizontal error bars depict the width of the  $dE/dx$  bin whereas the vertical bars represent the error associated to the most probable value estimation. A fit to the logarithmic function in Eq. (6.5) is also shown (black line). For this I weighted the data points using the inverse of their relative error, obtaining a reduced chi-square value of  $\chi^2/ndf = 2.22 \times 10^{-6}$ . The best fit parameters I found from this fit are  $A = 0.883 \pm 0.064$ ,  $B = 5.6 \pm 1.3$  cm/MeV and  $C = 4.94 \pm 0.49$  ADC/e. Figure 6.5 (bottom panel) shows the residuals between the data points and the fit.

The value for the gain I obtained from the fit is in reasonable agreement with our expectation. This value is set in GArSoft to 5 ADC/e by default.

One interesting thing to check is what induces this non-linear relation between charge and energy. The only effects that modify the amount of electrons reaching the readout planes in the simulation are the transverse diffusion and the finite electron lifetime. Once the electrons reach the readout chambers, the pad response functions are applied,

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**Figure 6.6:** Fitted most probable  $dQ/dx$  values for each  $dE/dx$  bin for three different ADC bit limits, 10 (blue points), 12 (default, yellow points) and 16-bit (red points).

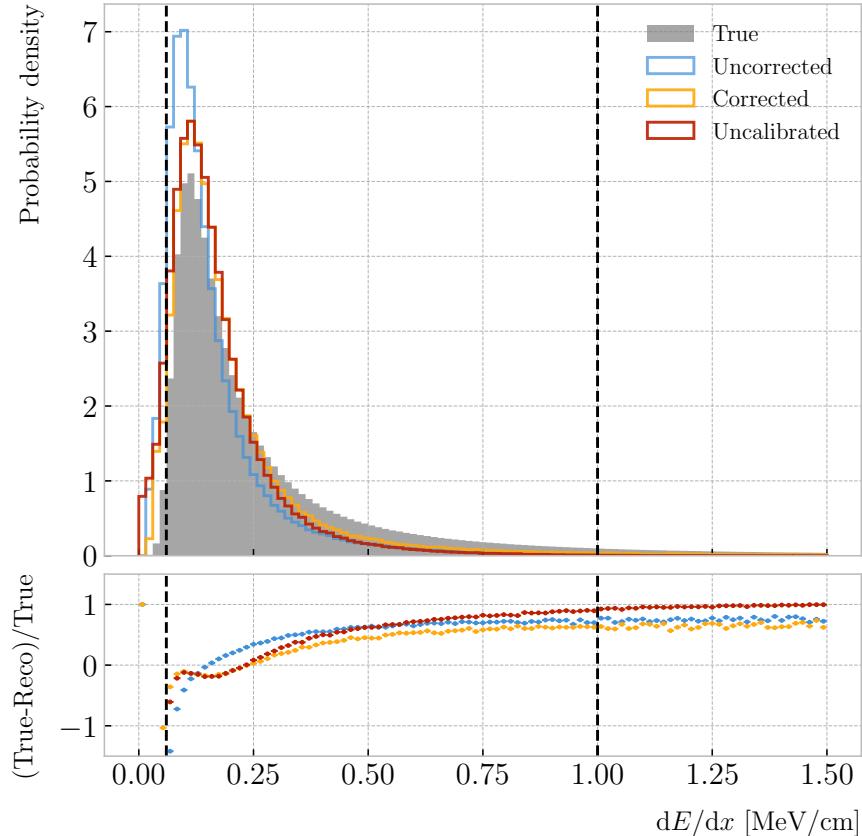
2867 together with an electrons-to-ADC conversion and the ADC saturation limit.

2868 By default, GArSot applies a 12-bit ADC limit, which can be changed in the  
 2869 simulation configuration. However, it can only be increased up to 16-bit, as we represent  
 2870 the ADC collection as a `std::vector<short>`. This way, I tried to change the saturation  
 2871 parameter to see how it affects the relation between reconstructed charge and energy.  
 2872 Figure 6.6 shows a comparison between the most probable  $dQ/dx$  for 10, 12 and 16-  
 2873 bit ADC limits. As expected, the lower the limit is the sooner the charge saturates.  
 2874 For higher ADC limits the relation between energy and charge remains linear up to  
 2875 higher  $dE/dx$  values, but even for the 16-bit limit the saturation is noticeable for values  
 2876  $\gtrsim 0.5$  MeV/cm.

2877 Table 6.1 shows the results of fitting the samples with 10 and 16-bits ADC limits to  
 2878 the calibration function from Eq. (6.5), using the weights based on their relative error  
 2879 as described previously. One interesting feature to notice is how different the best fit  
 2880 points look for the 10-bit ADC saturation when compared to the other two, which are  
 2881 consistent with each other.

2882 At this point we can compare the  $dE/dx$  distribution one gets from Geant4, i.e. the

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC



**Figure 6.7:** Top panel: area normalised  $dE/dx$  distributions for the true (solid grey) and the reconstructed energy deposits in the stopping proton sample, both after applying the calibration (blue) and the calibration and the normalisation correction (yellow). Also shown is the distribution obtained by applying a correction factor to the  $dQ/dx$  values but not the calibration (red). Bottom panel: fractional residuals for the uncorrected (blue), corrected (yellow) and uncalibrated (red) samples.

2883 true energy loss distribution, and the distribution I found by applying the calibration  
 2884 function to our collection of reconstructed  $dQ/dx$  values. Figure 6.7 (top panel) shows  
 2885 the true (solid grey) and reconstructed (blue, labeled as uncorrected) distributions  
 2886 together. The dashed vertical lines indicate the region of validity of the calibration fit, i.e.  
 2887 the left and right edges of the first and last  $dE/dx$  bin respectively. Notice that these  
 2888 histograms are area-normalised, as the total number of true energy deposits is much  
 2889 higher than the number of reconstructed charge deposits. This is due to a combination  
 2890 of effects, like the finite spatial resolution of the detector, the hit clustering used in the  
 2891 track fitting and the reclustering we have applied here.

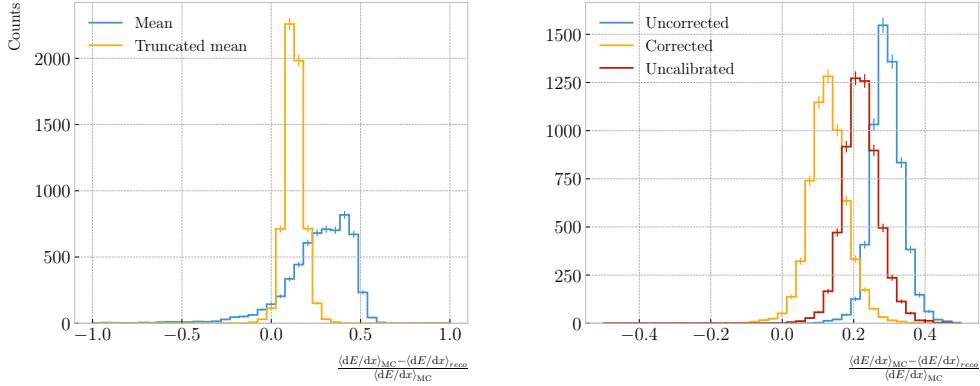
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2892 The two distributions are significantly different. That can be seen clearly when  
2893 looking at the fractional residuals, shown in Fig. 6.7 (bottom panel). In particular,  
2894 the position of the peak is off, which could bias the mean energy loss predictions. It  
2895 seems like the difference between these may be due to an overall scaling factor. One  
2896 possibility is to scale the most probable value of the reconstructed distribution to  
2897 the most probable value predicted by Geant4. I do this by fitting both distributions  
2898 using a LanGauss function, obtaining  $dE/dx_{MPV, true} = 0.1145 \pm 0.0005$  MeV/cm and  
2899  $dE/dx_{MPV, reco} = 0.0928 \pm 0.0005$  MeV/cm for the true and reconstructed most probable  
2900 values respectively. These can be translated into an scaling factor  $S = 0.579 \pm 0.006$ .

2901 The result of applying the scaling correction can be seen in Fig. 6.7 (top panel).  
2902 The corrected  $dE/dx$  distribution (yellow, labeled as corrected) peaks around the same  
2903 value the true distribution does, as expected. Moreover, the high energy region is also  
2904 slightly better described. For low ionisations, below the lower limit of the calibration  
2905 fit, the differences between true and reconstructed are still significant. This low energy  
2906 excess may be migration of some events from the peak region. The overall effect of the  
2907 correction can be seen in the fractional residual plot in Fig. 6.7 (bottom panel).

2908 One can also check what happens if instead of applying the logarithmic calibration we  
2909 simply scale the  $dQ/dx$  distribution (post reclustering) to have the same most probable  
2910 value as the true  $dE/dx$  distribution. In this case, following an analogous procedure to the  
2911 one described earlier, I found the scaling factor  $S_{uncalibrated} = 0.414 \pm 0.002$  MeV/ADC<sup>5</sup>.  
2912 The resulting distribution (red, labeled as uncalibrated) is also shown in in Fig. 6.7 (top  
2913 panel). The behaviour of the new distribution is similar to the corrected case at low  
2914 energy losses, around the peak of the true distribution, but it is worse at describing the  
2915 high energy tail. This is expected, it is in the high ionisation regime where saturation  
2916 effects apply and therefore calibration is needed.

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**Figure 6.8:** Left panel: fractional residuals between the true and the corrected  $dE/dx$  means (blue) and the 60% truncated means (yellow), for each event in the stopping proton sample. Right panel: fractional residuals between the true and the uncorrected (blue), corrected (yellow) and uncalibrated (red)  $dE/dx$  60% truncated means, for each event in the stopping proton sample.

### 2917 6.2.2 Truncated $dE/dx$ mean

2918 Once we have a collection of  $dE/dx$  values for each reconstructed track, we can compute  
 2919 the corresponding most probable ionisation loss per unit length of the particle. This  
 2920 is the value predicted by the Bethe-Bloch or the PAI models, and together with a  
 2921 measurement of the momentum it allows for particle identification.

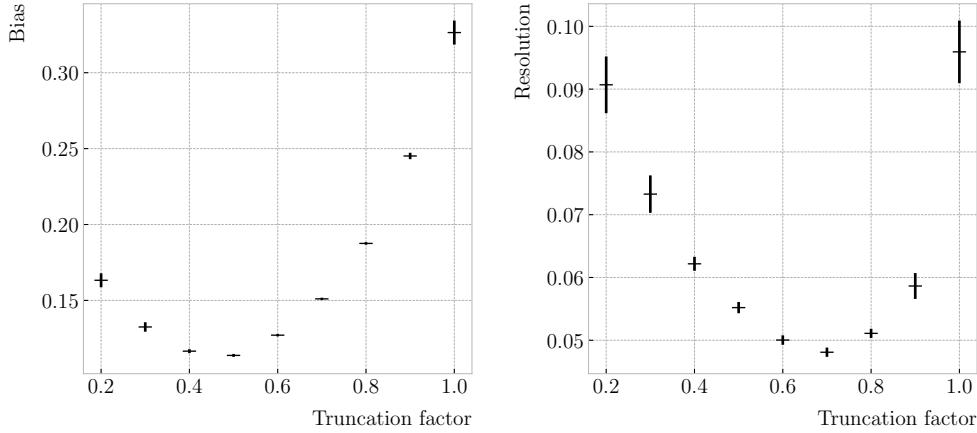
2922 However, estimating the most probable  $dE/dx$  value for each reconstructed track  
 2923 is not a trivial task. As mentioned before, the  $dE/dx$  distributions follow Landau-like  
 2924 distributions. Therefore, one should perform e.g. a LanGauss fit to correctly estimate  
 2925 the most probable values. Automating this kind of fits is often problematic, as they  
 2926 usually incur in convergence problems. Moreover, the reconstructed  $dE/dx$  distributions  
 2927 we obtain tend to have relatively small statistics, which may also produce poor fits. In  
 2928 practice, doing these unsupervised fits may degrade our performance, and a more robust  
 2929 method is preferred.

2930 A possibility could be taking the mean of the reconstructed  $dE/dx$  distribution for  
 2931 each particle. The problem with this approach is that the high energy Landau tail,  
 2932 combined with our limited statistics, can induce large fluctuations in the computation

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<sup>5</sup>Notice that now the scaling factor is not dimensionless, as it acts more like a conversion factor here.

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**Figure 6.9:** Estimated values of the mean  $dE/dx$  bias (left panel) and resolution (right panel) obtained using the corrected data from the stopping proton sample, for different values of the truncation factor.

of the mean. Imagine you have two protons with the same kinetic energy, but due to reconstruction problems in one case you did not get as many charge deposits reconstructed in its high ionisation loss region. If you do not remove the tails the computed  $dE/dx$  means will be significantly different.

In order to avoid those fluctuations, one can compute the mean of a truncated  $dE/dx$  distribution instead. By keeping only a given fraction of the lowest energy deposits we obtain an estimate of the mean energy loss that is more resilient to reconstruction inefficiencies and statistical effects. Figure 6.8 (left panel) shows a comparison between the  $\langle dE/dx \rangle$  computed by taking the mean of the full distribution (blue line) and the 60% lowest energy clusters (yellow line), for the stopping proton sample. The fractional residuals are computed for each proton, taking the corresponding means using their collections of true and reconstructed energy deposits. One can see that using the simple mean translates into a high bias and uncertainty in the  $\langle dE/dx \rangle$  estimation, whereas applying the truncation reduces both significantly.

Additionally, I performed a comparison between the 60% truncated mean  $dE/dx$  obtained using the different calibration methods discussed earlier, namely the uncorrected (blue), corrected (yellow) and uncalibrated (red) distributions. The results are shown in Fig. 6.8 (right panel). While the widths of these distributions are similar, the bias

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC

2951 obtained for the corrected sample, i.e. calibration function and correction factor applied,  
 2952 is a factor of  $\sim 2$  lower than in the uncalibrated case and almost three times smaller  
 2953 than for the uncorrected sample.

2954 The next step is to optimise the level of truncation we are going to apply to our  
 2955 data. To do so, I used different truncation factors, i.e. the percentage of energy-ordered  
 2956 reconstructed energy deposits we keep to compute the mean, on the corrected  $dE/dx$   
 2957 sample of the stopping protons. Then, following the same procedure of computing the  
 2958 fractional residuals as before, I fitted the resulting histograms using a double Gaussian  
 2959 function. This is simply the sum of two Gaussian functions of the type:

$$g(x; \mu, \sigma, A) = A e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \quad (6.6)$$

2960 I do not add the classical normalisation factor of the Gaussian,  $1/\sqrt{2\pi}\sigma$ , therefore  
 2961 the amplitude  $A$  simply represents the maximum of the function. One of the two  
 2962 Gaussian functions describes the core part of the distribution, while the other captures  
 2963 the behaviour of the tails.

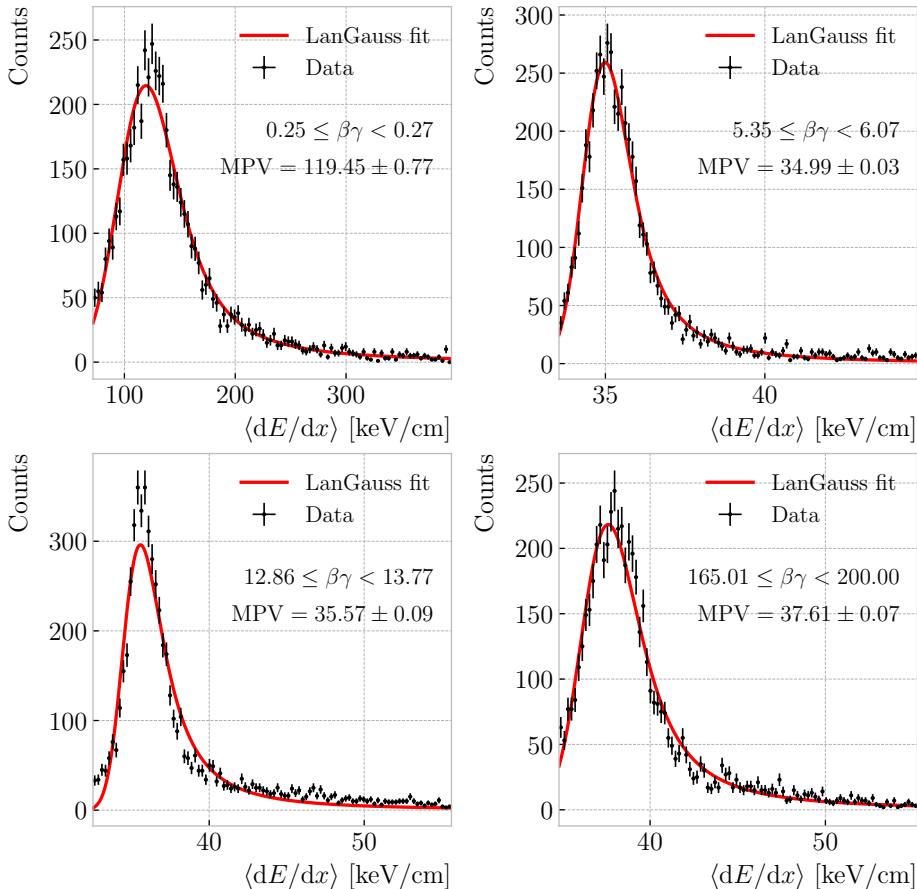
2964 For each truncation factor, I look at the bias and the resolution I obtain. I define  
 2965 these as the weighted means of the corresponding parameters in the fits:

$$\bar{x} = \frac{A_{core} x_{core} + A_{tail} x_{tail}}{A_{core} + A_{tail}}, \quad (6.7)$$

2966 where  $A_{core}$  and  $A_{tail}$  are the amplitudes of the core and tail distributions respectively  
 2967 and  $x$  is either the mean  $\mu$  or the width  $\sigma$  of said distributions.

2968 Figure 6.9 shows the bias (left panel) and the resolution (right panel) I obtained  
 2969 for the stopping proton sample, using different values of the truncation. From these, it  
 2970 can be seen that a truncation factor of 50% minimises the bias in the estimation, while  
 2971 70% gives the best resolution. That way, I settled on the intermediate value of 60%  
 2972 truncation, which yields a  $\langle dE/dx \rangle$  resolution of  $5.00 \pm 0.08$  % for stopping protons.

## CHAPTER 6. PARTICLE ID IN ND-GAr



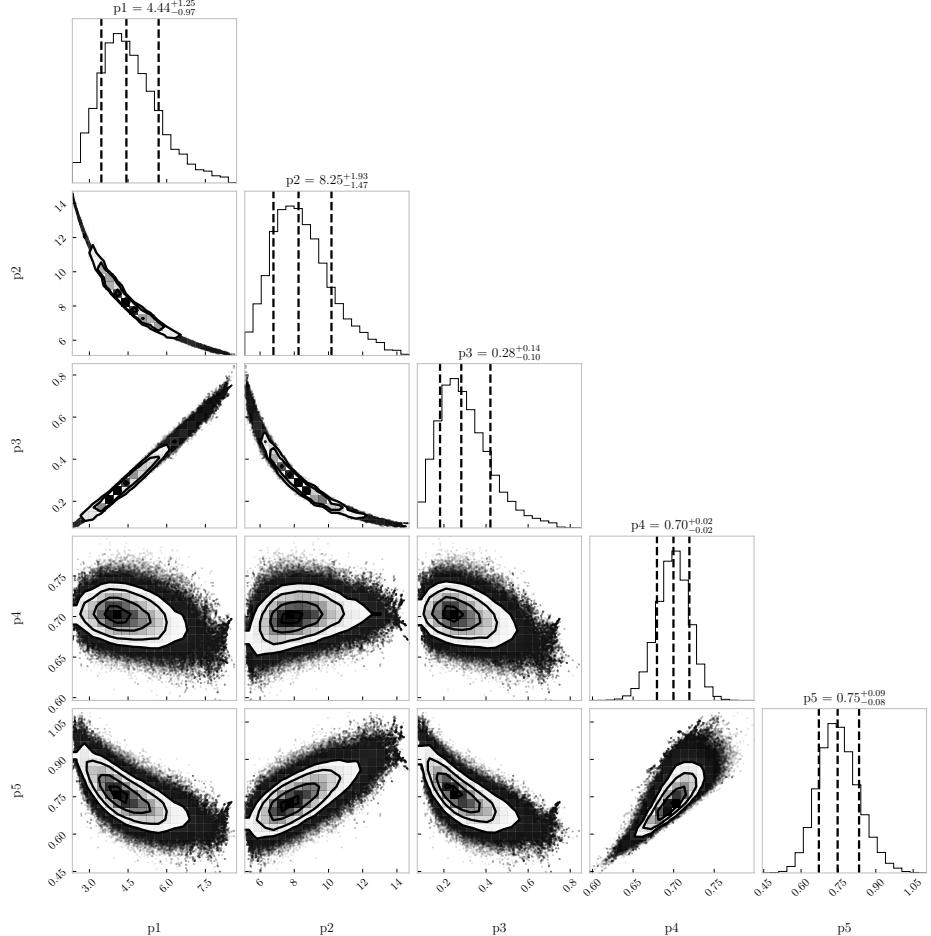
**Figure 6.10:** Examples of the truncated mean  $dE/dx$  LanGauss fits for various  $\beta\gamma$  bins, from a simulated FHC neutrino sample.

### 2973 6.2.3 Mean $dE/dx$ parametrisation

2974 Now that we have a way to estimate the mean energy loss of a particle in the HPgTPC,  
 2975 we can determine the value of the free parameters in the ALEPH formula, Eq. (6.3).  
 2976 For this, I used a sample of  $10^5$  reconstructed FHC neutrino events inside ND-GAr. In  
 2977 this case I cannot use the stopping proton sample, as we need to cover the full kinematic  
 2978 range of interest for the neutrino interactions in our detector.

2979 The original data does not contain an estimation of the velocity of the tracks, instead  
 2980 the tracks have a value for the reconstructed momentum and the associated PDG code  
 2981 of the Geant4-level particle that created the track. Therefore, one can select some of the  
 2982 particles in the data, in this case I selected electrons, muons, pions and protons, and

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC



**Figure 6.11:** Resulting one and two dimensional projections of the posterior probability distributions of the ALEPH  $\langle dE/dx \rangle$  parameters obtained by fitting the 60% truncated mean  $dE/dx$  values from a FHC neutrino sample in ND-GAr. The vertical dashed lines in the 1D distributions represent the 16th, 50th and 84th percentiles.

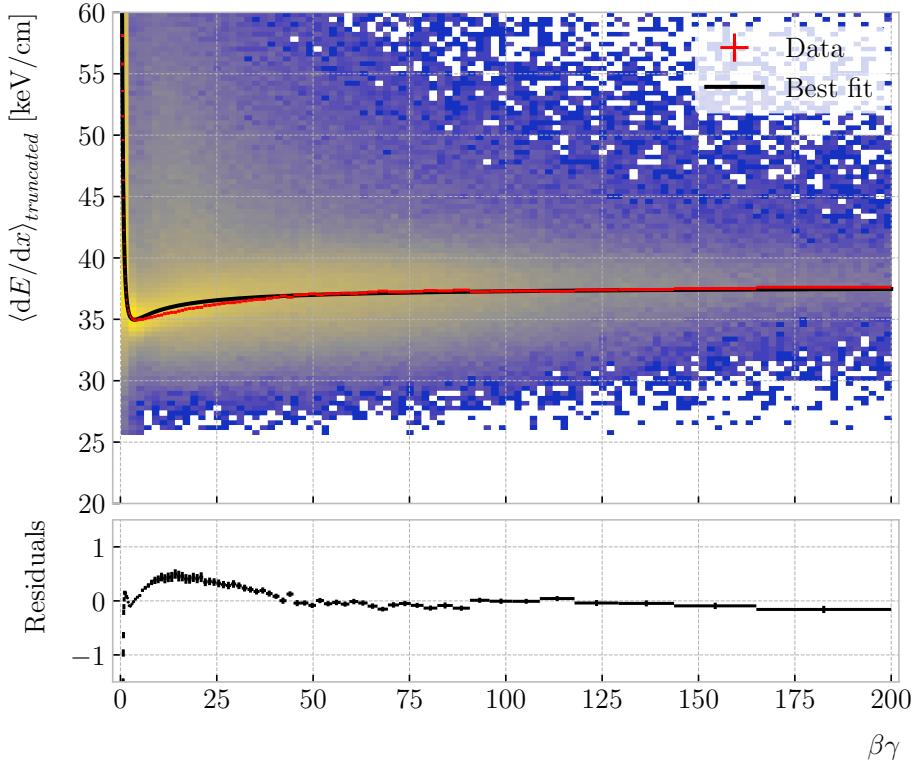
2983 compute  $\beta$  and  $\gamma$  using the reconstructed momentum and their mass. In terms of  $\beta\gamma$   
 2984 the mean  $dE/dx$  does not depend on the particle species, so one can consider all the  
 2985 dataset as a whole. For this fit, I will express  $\beta$  in terms of the  $\beta\gamma$  product as:

$$\beta = \frac{\beta\gamma}{\sqrt{1 + (\beta\gamma)^2}}, \quad (6.8)$$

2986 which can be easily proven from the definition of  $\gamma$ .

2987 Next, I bin the data in  $\beta\gamma$ . I chose a fine binning so as to capture the different  
 2988 features of the ionisation curve. Instead of fixing the bin width, I select them so each one

## CHAPTER 6. PARTICLE ID IN ND-GAr

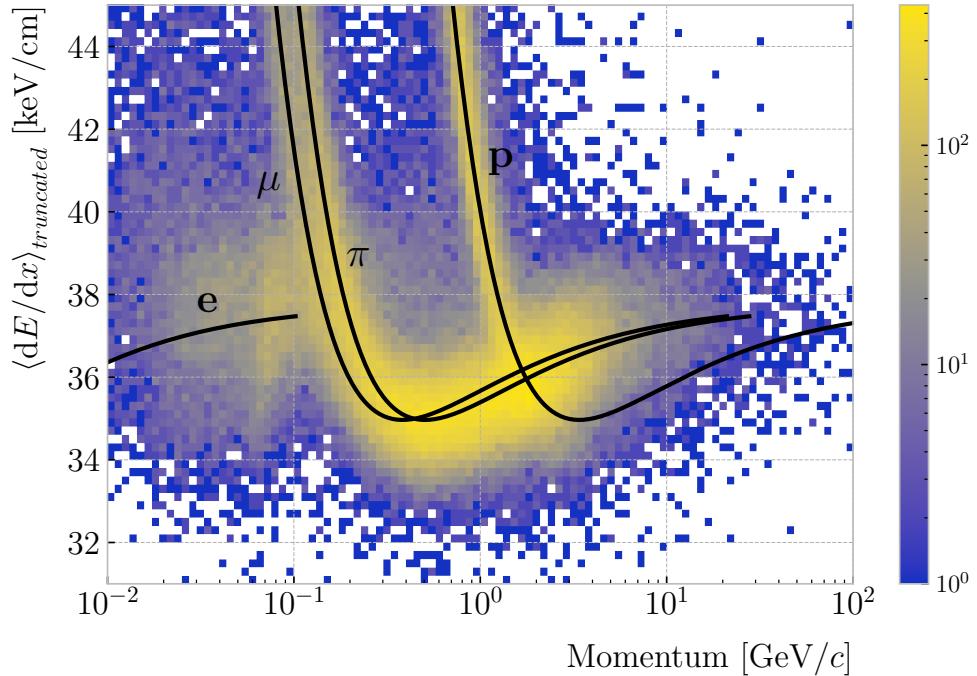


**Figure 6.12:** Truncated mean  $dE/dx$  obtained for the FHC neutrino sample as a function of the  $\beta\gamma$  product (upper panel). Also shown are the fitted most probable values for each  $\beta\gamma$  bin (red points) and the best fit obtained using the ALEPH parametrisation (black line). The residuals resulting from the fit are shown in the lower panel.

2989 has approximately the same statistics. Then, for each  $\beta\gamma$  slice, I compute the median  
 2990 and the interquartile range (IQR) of the  $\langle dE/dx \rangle$  distribution. Using these, I make a  
 2991 histogram in the range [median – IQR, median + 5 IQR], which I fit to a LanGauss  
 2992 function in order to extract the MPV. Using this range accounts for the asymmetric  
 2993 nature of the distributions, while also helps avoiding a second, lower maximum present  
 2994 at low  $\beta\gamma$ , probably a result of reconstruction failures.

2995 A few examples of these fits are shown in Fig. 6.10. The chosen values of  $\beta\gamma$  sit in  
 2996 very distinct points along the  $\langle dE/dx \rangle$  curve, going from the high ionisation region at  
 2997 low velocities (top left panel), to the minimum point (top right panel), the beginning of  
 2998 the relativistic rise (bottom left panel), and the plateau produced by the density effect  
 2999 (bottom right panel).

## 6.2. $dE/dx$ MEASUREMENT IN THE TPC

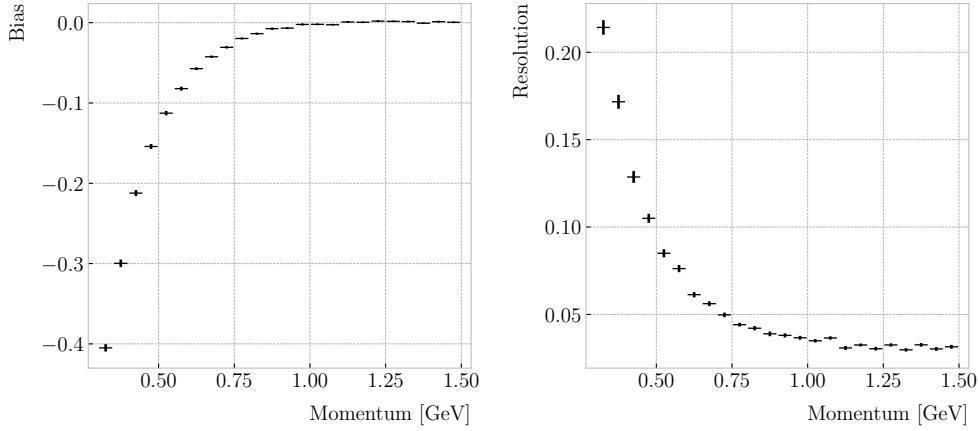


**Figure 6.13:** Distribution of the 60% truncated mean  $dE/dx$  versus reconstructed momentum for the FHC neutrino sample. The black lines indicate the predictions of the ALEPH parametrisation for electrons, muons, charged pions and protons.

3000 I used the resulting most probable  $\langle dE/dx \rangle$  values and the centres of the  $\beta\gamma$  bins as  
 3001 the points to fit to the ALEPH formula. For this particular fit I used the least-squares  
 3002 method to get a first estimation of the ALEPH parameters. Applying some uniform  
 3003 priors, I then used these values as the starting point of a 100000 steps MCMC. Figure 6.11  
 3004 shows the posterior probability distributions I obtain for each parameter. The reported  
 3005 best fit points are based on the 16th, 50th, and 84th percentiles in the marginalised  
 3006 distributions.

3007 The resulting fit (black line), compared to the data points (red points) and the  
 3008 underlying distribution is shown in Fig. 6.12 (top panel). The overall fit is good, with a  
 3009 reduced chi-squared of  $\chi^2/ndf = 1.02$ . However, there are some regions where the fit  
 3010 does not describe the data correctly, like the very low  $\beta\gamma$  regime, where the fit severely  
 3011 underestimates for energy losses  $\gtrsim 50$  keV/cm, and the start of the relativistic raise,  
 3012 where we have a slight overestimation. This is a result of those points having a larger  
 3013 uncertainty when compared to the ones around the dip or the plateau areas. These

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**Figure 6.14:** Estimated values of the mean  $dE/dx$  bias (left panel) and resolution (right panel) obtained for the true protons in a FHC neutrino sample.

3014 differences can be better seen in the residual plot, Fig. 6.12 (bottom panel).

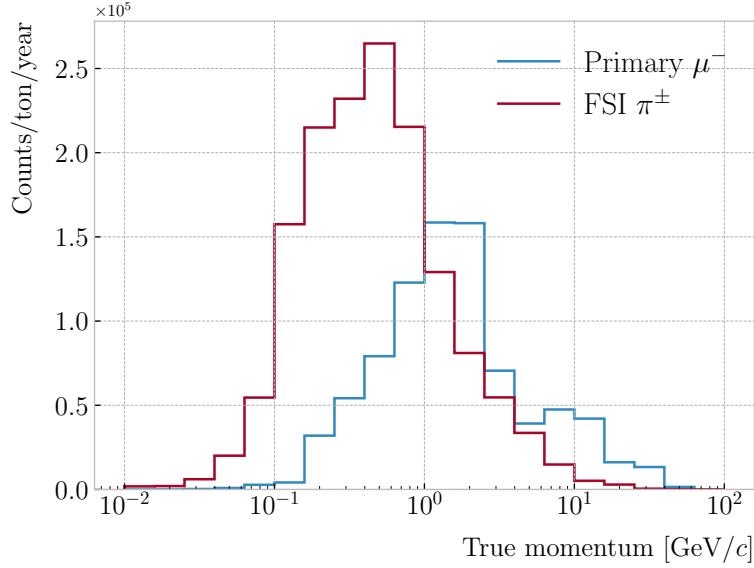
### 3015 6.2.4 Particle identification

## 3016 6.3 Muon and pion separation in the ECal and MuID

3017 As it could be seen from Fig. 6.13, it is not possible to separate muons and charged pions  
3018 in the HPgTPC using  $dE/dx$  for momenta  $\gtrsim 300 \text{ MeV}/c$ . In ND-GAr, approximately  
3019 70% of the interactions in FHC mode will be  $\nu_\mu$  CC (compared to the 47% of  $\bar{\nu}_\mu$  CC  
3020 interactions when operating in RHC mode), while 24% are neutral currents. Out of  
3021 these, around 53% and 47% of them will produce at least one charged pion in the final  
3022 state, respectively. Figure 6.15 shows a comparison between the spectra of the primary  
3023 muons and the charged pions for  $\nu_\mu$  CC interactions in ND-GAr producing one or more  
3024 charged pions. From this, one can see that (i) the majority of muons and charged pions  
3025 are not going to be distinguishable with a  $\langle dE/dx \rangle$  measurement, and that (ii) particle  
3026 identification is necessary both to classify correctly the  $\nu_\mu$  CC events and identify the  
3027 primary muon within them.

3028 ND-GAr features two other subdetectors which can provide additional information  
3029 for this task, namely the ECal and MuID. The current ECal design, described in (ref  
3030 section), consists of 42 layers, made of 5 mm of Pb, 7 mm of plastic scintillator and a

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID



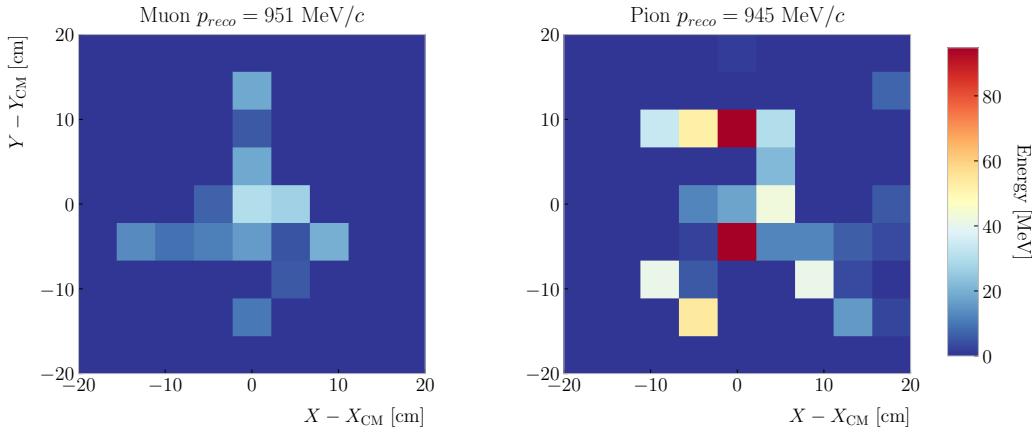
**Figure 6.15:** True momentum distribution for the primary muon in  $\nu_\mu$  CC  $N\pi^\pm$  interactions inside the fiducial volume of ND-GAr (blue line), compared to the post FSI charged pion spectrum (red line).

3031 1 mm PCB board. The total thickness of this calorimeter is 1.66 nuclear interaction  
 3032 lengths or 1.39 pion interaction lengths. The Muid design is in a more conceptual  
 3033 stage, however it is envisioned to feature layers with 10 cm of Fe and 2 cm of plastic  
 3034 scintillator<sup>6</sup>. With its three layers, it will have a thickness of 1.87 or 1.53 nuclear or pion  
 3035 interaction lengths, respectively.

3036 Because pion showers are dominated by inelastic nuclear interactions, the signatures  
 3037 of these particles in the calorimeter will look significantly different from those of muons.  
 3038 Although our ECal is not thick enough to fully contain the hadronic showers of the  
 3039 charged pions at their typical energies in FHC neutrino interactions, they can still be  
 3040 used to understand whether the original particle was more hadron-like or MIP-like. In  
 3041 Fig. 6.16 I show two examples of energy distributions created by a muon (left panel)  
 3042 and a charged pion (right panel) of similar momenta interacting in the ECal. These  
 3043 figures represent the transverse development of the interactions. For each of them, I  
 3044 computed the principal component and centre of mass of the interaction, projecting

<sup>6</sup>It is not mentioned anywhere, but I assume that there should also be another layer of PCB board of 1 mm. However, in this case its contribution to the total thickness of the sampling calorimeter would be negligible.

## CHAPTER 6. PARTICLE ID IN ND-GAr



**Figure 6.16:** Distributions of energy deposits in the ECal for a muon (left panel) and a charged pion (right panel) with similar momenta. The energy is projected onto the plane perpendicular to the principal component of the hits, and the positions are relative to the center of the interaction.

3045 the position of the hits onto the plane perpendicular to that direction, and taking the  
 3046 distances relative to the centre. It can be seen that the muon follows an almost MIP-like  
 3047 behaviour, being the central bin in the histogram the one with the highest deposited  
 3048 energy. On the other hand, the pion not only deposits more energy overall, but also this  
 3049 energy is more spread-out among the different hits. It is this kind of information that  
 3050 would allow us to tell apart muons from pions.

3051 This way, I identify three main action points that need to be addressed if one wants  
 3052 to use these detectors to distinguish between muons and charged pions. These are:

- 3053 1. the way we make the associations between tracks in the HPgTPC to the activities  
 3054 (what in GArSoft we call clusters) in the ECal and the MuID,
- 3055 2. what variables or features one can extract from the calorimeters that encapsulate  
 3056 the information we are interested about,
- 3057 3. and how to carry out the classification problem.

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID

#### 3058 6.3.1 Track-ECal matching

3059 One of the main players in the muon and pion separation is the way we associate clusters  
3060 in the ECal to reconstructed tracks in the TPC. Missing some associations or making  
3061 wrong ones can bias the ECal quantities that we can use for classifying particles. The  
3062 current algorithm in GArSoft provides precise associations, i.e. most of the associations  
3063 that it produces are correct, but it appears to miss an important number of associations  
3064 (at least when using the default configuration).

3065 The current TPC track-ECal cluster association algorithm is divided in four parts.  
3066 It first checks whether the track end point fulfils certain conditions to be extrapolated.  
3067 There are two cut values in this step, one for the drift direction and other radial.

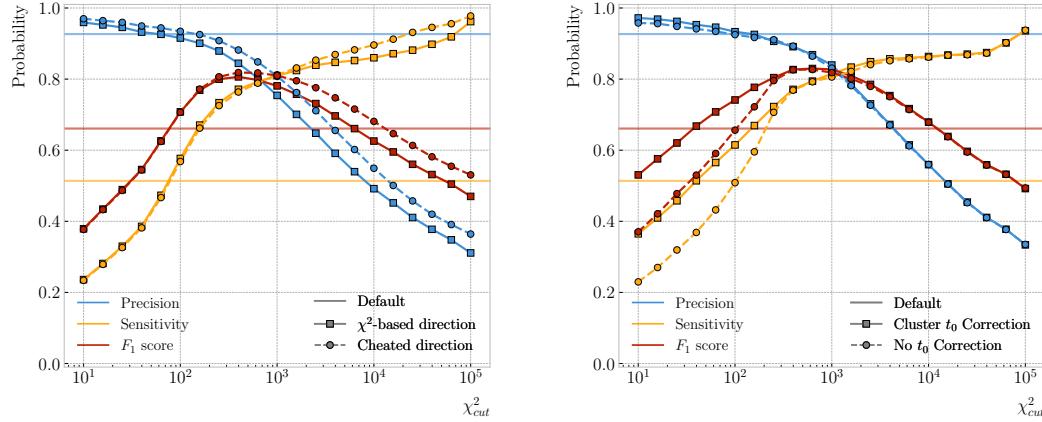
3068 If the point can be extrapolated, the code computes the coordinates of the centre  
3069 of curvature using the Kalman fit estimates at the track end ( $y$ ,  $z$ ,  $1/R$ ,  $\phi$ ,  $\tan\lambda$ ). It  
3070 then compares the distance between this and the cluster in the  $(z, y)$  plane with  $R$ . This  
3071 introduces another cut in the perpendicular direction.

3072 The next step is different for clusters in the barrel or in one of the end caps. If it  
3073 is a barrel cluster the algorithm extrapolates the track up to the radial distance of the  
3074 cluster. There are three possible outcomes, the extrapolated helix can cut the cylinder  
3075 of radius  $r_{clus}$  two, one or zero times. I get the cut point that is closer to the cluster and  
3076 check that it is either in the barrel or the end caps. Computing the difference between  
3077 the  $x$  coordinates of the cluster and the extrapolated point, the module checks that this  
3078 is not greater than a certain cut. If the cluster is in an end cap, I propagate the track  
3079 up to the  $x$  position of the cluster. Then, the algorithm computes the angle in the  $(z, y)$   
3080 plane between the centre of curvature and the cluster,  $\alpha$ , and the centre of curvature  
3081 and the propagated point,  $\alpha'$ . A cut is applied to the quantity  $(\alpha - \alpha')R$ .

3082 If the cluster contains more than a certain number  $N$  of hits, I apply an extra cut to  
3083 the dot product of the direction of the track at the propagated  $x$  value and the cluster  
3084 direction.

3085 The code makes sure to only associate one end of the track (if any) to a cluster.

## CHAPTER 6. PARTICLE ID IN ND-GAr



**Figure 6.17:** Left panel: comparison between the precision (blue), sensitivity (yellow) and  $F_1$  score (red) obtained for the default (horizontal lines) and new algorithms, both with the  $\chi^2$ -based direction estimator (squares) and cheating the directions (circles), for different values of the  $\chi^2$  cut. Right panel: comparison of the performance of the new algorithm when applying the cluster  $t_0$  correction (squares) and when (circles).

3086 However, it can associate more than one track to the same cluster. This makes sense,  
3087 as different particles can contribute to the same cluster in the ECal, but it makes it  
3088 difficult to quantify the relative contributions of the tracks to a certain cluster.

3089 As a way of comparing the performance of this algorithm, a new, simpler association  
3090 module was written. The goal was to have a simple and robust algorithm, which depends  
3091 on as few parameters as possible and that can produce a one-to-one matching between  
3092 tracks and ECal clusters.

3093 For each reconstructed track, the new algorithms applies the same procedure to the  
3094 forward and the backward fits irrespective of their end point positions. It first gets the  
3095 Kalman fit parameters at the corresponding end point together with the  $X$  position,  $x_0$ ,  
3096 ( $y_0$ ,  $z_0$ ,  $1/R$ ,  $\phi_0$ ,  $\tan\lambda$ ).

3097 For each ECal cluster, I compute the radial distance to the centre of the TPC and  
3098 find the  $\phi$  value in the range  $[\phi_0, \phi_0 + \text{sign}(R)\phi_{max}]$  that makes the propagated helix  
3099 intersect with the circle defined with such radius. The  $(x, y, z)$  position of the helix for  
3100 the  $\phi$  value found (if any) is then computed. In case there are two intersections, I keep  
3101 the one that minimises the distance between  $(y, z)$  and  $(y_c, z_c)$ .

3102 I then calculate  $\chi^2$  value based on the Euclidean distance between the propagated

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID

3103 point and the cluster:

$$\chi^2/ndf = \frac{\sum_{n=0}^2 (x^{(n)} - x_c^{(n)})^2}{3}. \quad (6.9)$$

3104 If there was no intersection I store a  $-1$  instead. In the end, for each reconstructed track  
3105 in the event one ends up with two collections of  $\chi^2$  values, one for each ECal cluster  
3106 and fit directions.

3107 The current code only supports having ECal clusters associated to one end of each  
3108 track. We have two options to decide what track end to keep. The first one tries to  
3109 cheat the selection, looking at the distance between the two track ends and the true  
3110 start position of the associated MC particle. The second one keeps the track end with  
3111 more  $\chi^2$  entries below the cut.

3112 This feature of only considering one track end limits the algorithm, making it not  
3113 suitable for reconstructing events with particles originating outside the TPC. However,  
3114 as for the moment the main concern of the group is the study of neutrino interactions  
3115 off the gaseous argon, this is an acceptable assumption.

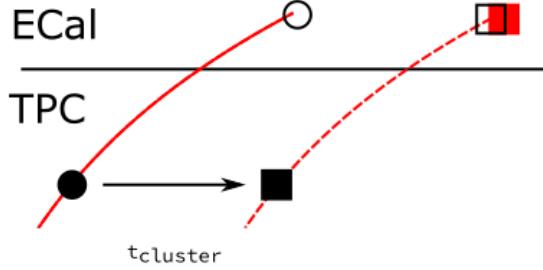
3116 In order to associate a cluster to a track, I take all clusters with a  $\chi^2$  value in the  
3117 range  $[0, \chi_{cut}^2]$ . If a cluster has been assigned to more than one track we leave it with  
3118 the one with the lowest  $\chi^2$ .

3119 This default behaviour of the algorithm can be modified to associate more than one  
3120 track to each cluster. Not only that, but the  $\chi^2$  values can be used to assign relative  
3121 weights to the different contributions.

3122 To evaluate the performance of the association method, I use a binary classification  
3123 approach. In this case, I check the leading MC Track IDs associated to the reconstructed  
3124 tracks and ECal clusters. I count an association as true positive (TP) if both Track  
3125 IDs coincide. An association is considered false positive (FP) when the Track IDs are  
3126 different. If a cluster has not been associated to any track but it shares the Track ID  
3127 with a reconstructed track it is counted as a false negative (FN).

3128 For the testing, I used a sample of 10000 FHC neutrino events inside the HPgTPC.  
3129 Figure 6.17 (left panel) shows the precision (blue line), sensitivity (yellow line), and  $F_1$

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**Figure 6.18:** Schematics of a possible option to deal with track-ECal associations in non-zero  $t_0$  neutrino interaction events, trying to correct for the drift direction uncertainty in a cluster-by-cluster basis using the cluster time,  $t_{cluster}$ .

score (red line) I obtained for different values of  $\chi^2_{cut}$ . For comparison, the same metrics computed for the default algorithm with the current configuration are also shown (dashed lines). In the case of the new algorithm, I used both the  $\chi^2$ -based method to estimate the track direction described earlier (square markers) and the cheated direction from the Geant-level information (circle markers). For either of these we achieve similar values of the precision compared to the old code, while having a considerably higher sensitivity. It can be seen that cheating the direction of the tracks only makes a difference at high  $\chi^2_{cut}$ , past the optimal value of the cut around the  $F_1$  score maximum. Therefore, I set the  $\chi^2$  method as the default.

One of the possible weak points of this approach is that it relies on the position along the drift direction to make the decisions. Within the current ND-GAr design implemented in GArSoft, the timing information is provided by the ECal. That effectively means that prior to make the track-ECal associations the reconstructed  $x$  positions of the track trajectories differ from the simulated ones by an amount:

$$x_{reco}^{(n)} - x_{sim}^{(n)} = v_{drift} t_0, \quad (6.10)$$

where  $v_{drift}$  is the mean drift velocity in our medium and the initial time is in the range  $t_0 \in [0, t_{spill}]$  where  $t_{spill}$  is the spill length. For a 10  $\mu\text{s}$  spill this translates into a maximum 30 cm uncertainty on the drift direction position.

The current default in GArSoft sets  $t_0 = 0$ , but the functionality to randomly sample

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID

3148 this within the spill time is in place. Therefore, we need to understand what is the impact  
3149 of a non-zero  $t_0$  on the associations algorithm and foresee possible ways of minimising a  
3150 loss in performance.

3151 Figure 6.18 represents a possible option to tackle the association problem when  
3152 having events with a non-zero initial time  $t_0$ . The black and white circles represent the  
3153 original points, whereas the squares indicate the corrected positions. The end points of  
3154 the track and the propagated points up to the cluster radius are indicated using filled  
3155 and unfilled markers respectively. The red square represents the position of the cluster.

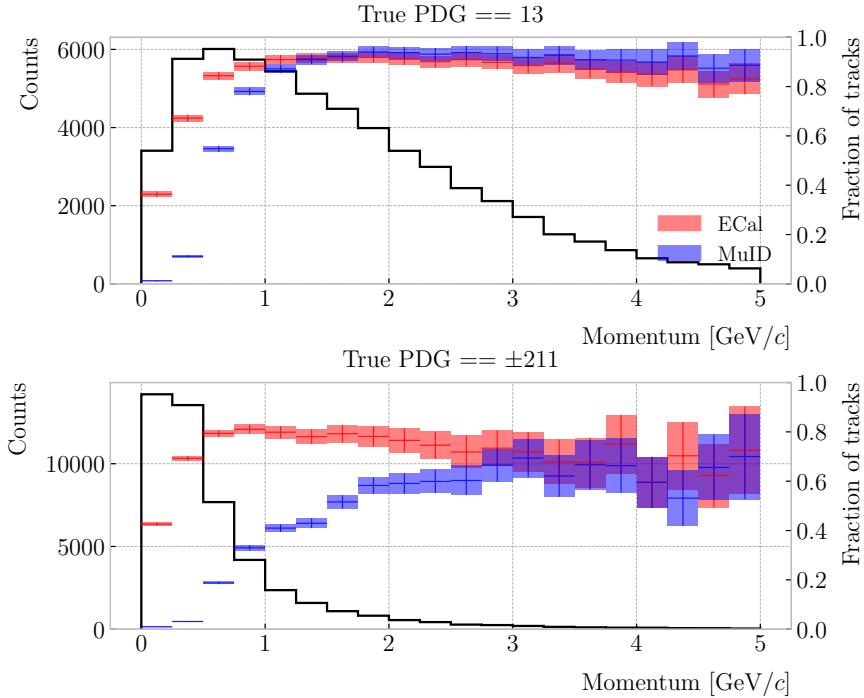
3156 Here I try to correct for the drift coordinate position using the time associated to the  
3157 cluster. Assuming that the drift time is much larger than the propagation time,  $t_{cluster}$   
3158 could be used as a good estimation of the  $t_0$ . An alternative can be using the earliest  
3159 time associated to a hit in said cluster. Doing this for each cluster before computing  
3160 the  $\chi^2$  value could be used as an alternative to knowing the specific value of the  $t_0$ , as  
3161 when the association is correct this will provide the right correction but its impact is  
3162 small enough to not change the position significantly in the case the cluster does not  
3163 correspond to a given track.

3164 I tested the effect of this correction again using a sample of 10000 FHC neutrino  
3165 events. Figure 6.17 (right panel) shows the precision (blue line), sensitivity (yellow line),  
3166 and  $F_1$  score (red line) for the case the cluster  $t_0$  correction is applied (square markers)  
3167 and for the no correction case (circle markers), as a function of  $\chi^2_{cut}$ . In this case, the  
3168 differences are particularly notorious at low values of the cut. It makes sense, as the  $t_0$   
3169 effect becomes subdominant when the distance we consider grows large. Overall, the  
3170 correction increases the sensitivity while keeping the precision almost unchanged. As a  
3171 result, I apply the  $t_0$  correction to the generated samples as the default.

#### 3172 6.3.2 Classification strategy

3173 The problem of the muon and charged pion separation has to be viewed in the broader  
3174 context of the particle identification in our detector. Focusing on the beam neutrino  
3175 interactions, it is clear that we are going to have muons and pions spanning a broad

## CHAPTER 6. PARTICLE ID IN ND-GAr

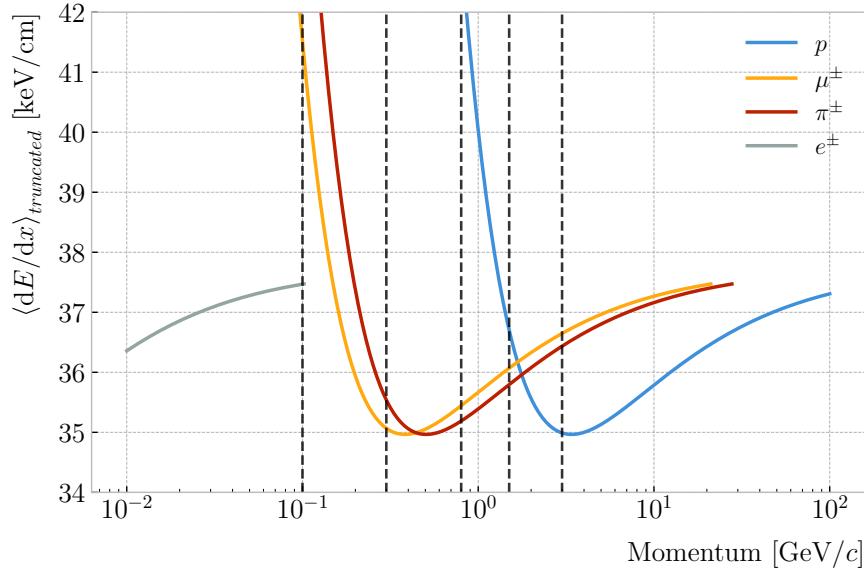


**Figure 6.19:** Momentum distribution for the reconstructed muons (top panel) and charged pions (bottom panel) in a FHC neutrino sample, together with the fraction of them reaching the ECal (red) and MuID (blue). Each entry corresponds to a reconstructed track, backtracked to a true muon or pion which has not produced any other reconstructed track.

3176 momentum range. Not only that, but we will also have other particles with similar  
 3177 characteristics that will make the classification even more challenging. Therefore, we are  
 3178 presented with a task that will depend heavily on the kinematic range we are looking at  
 3179 each time, as both the available information and the possible impurities of other particle  
 3180 species vary.

3181 For instance, distinguishing muons from pions could be difficult at low momenta, as  
 3182 a great number of them do not reach the ECal. Therefore, we could think of tailoring a  
 3183 version of the classification for that particular case, which could be complemented with  
 3184 a  $dE/dx$  measurement. Likewise, for momenta  $\gtrsim 1$  GeV muons and pions reach the  
 3185 calorimeters efficiently, but so do protons. Because of this, one can try to train another  
 3186 classifier for this energy range, and rely on other methods to remove as many of the  
 3187 protons as possible.

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**Figure 6.20:** Predicted truncated mean  $dE/dx$  versus momentum, for electrons, muons, charged pions and protons, obtained using the ALEPH parametrisation. The vertical dashed lines represent the boundaries of the six regions used for the muon and pion classification training.

3188     Figure 6.19 shows the momentum distribution of the reconstructed muons (top) and  
 3189     pions (bottom) in a FHC sample. It also contains the fraction of particles reaching the  
 3190     ECal (red) and MuID (blue), for the different momentum bins. In Fig. 6.20 I show the  
 3191     mean  $dE/dx$  of different particles as a function of the momentum, computed using the  
 3192     ALEPH parametrisation with the best fit parameters found in Subsec. 6.2.2.

3193     Using these two figures as references, I decided to approach the classification by  
 3194     dividing the problem into six different momentum regions. A summary of these can be  
 3195     found in Tab. 6.2. The basic idea is to exploit all the information that is available in  
 3196     each region and . For the problem at hand, I prepared separated samples of isotropic  
 3197     single muons and pions, with momenta uniformly distributed along the corresponding  
 3198     momentum range. Each sample contains 50000 events of the corresponding particle  
 3199     species. I did not generate samples for the first region, as it is assumed that the separation  
 3200     can be achieved using  $dE/dx$  only. For the last region, I generated particles up to a  
 3201     momentum of 10  $\text{GeV}/c$ , as that is well above the typical energies of muons and pions  
 3202     from FHC neutrino interactions in ND-GAr.

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**Table 6.2:** Momentum ranges and description of the PID approach assumed for the muon and pion classification task.

Momentum range	Description
$< 0.1 \text{ GeV}/c$	All tracks can be separated with $dE/dx$
$[0.1, 0.3) \text{ GeV}/c$	Use ECal for reaching muons and pions, $dE/dx$ for the rest
$[0.3, 0.8) \text{ GeV}/c$	Use ECal for muons and pions, $dE/dx$ for protons
$[0.8, 1.5) \text{ GeV}/c$	Use ECal and MuID for muons and pions, $dE/dx$ for protons
$[1.5, 3.0) \text{ GeV}/c$	Use ECal and MuID for muons and pions, ToF for protons
$\geq 3.0 \text{ GeV}/c$	Use ECal and MuID for muons and pions, $dE/dx$ and ToF for protons

3203     Additionally, I prepared another sample of 100000 FHC neutrino events. For each  
 3204    interaction, I select the reconstructed particles which were backtracked to true muons or  
 3205    charged pions. I use this dataset to perform validation checks, to see how the models  
 3206    trained with the single particle data generalise to a more realistic scenario.

3207     To tackle this classification problem, I make use of Boosted Decision Trees (BDT). A  
 3208    decision tree uses a flowchart-like structure to make decisions based on some input data.  
 3209    It starts from a root node, which represents the complete dataset, and then it splits  
 3210    this based on the variable or feature which gives the best separation between classes,  
 3211    creating two new nodes. The process repeats for each node until it reaches a certain  
 3212    limit, like a maximum number of splits or some tolerance criteria. The last set of nodes  
 3213    are often called leave nodes, and represent the final prediction of the classifier.

3214     Boosting refers to a family of methods to combine the predictions from multiple  
 3215    classifiers, following a sequential approach where each new model learns from the errors  
 3216    of the previous one. The process starts with a simple decision tree, which is used to  
 3217    make predictions on the training data. Then, the data points misclassified by the first  
 3218    model are assigned higher weights, and another decision tree is trained on the data with  
 3219    adjusted weights. The predictions of the two trees are then combined, and the cycle  
 3220    repeats for a predefined number of iterations. Gradient boosting uses the direction of  
 3221    the steepest error descent to guide the learning process and improve the accuracy with  
 3222    each iteration.

### 6.3. MUON AND PION SEPARATION IN THE ECal AND MuID

#### 3223 6.3.3 Feature selection and importance

3224 Using the reconstructed tracks as a starting point, I compute a number of ECal and  
3225 MuID variables for each of them. As there can be more than one cluster associated to a  
3226 track, what I do is collect all associated clusters and compute these variables from the  
3227 complete collection of associated hits. For the MuID, because it only features three layers  
3228 and typically there will be less hits, I also allow single hits to be associated with tracks<sup>7</sup>.  
3229 I can roughly divide the variables in three types: energy-related, geometry-related and  
3230 statistical. In the following, I briefly describe the variables related exclusively to the  
3231 ECal:

##### 3232 • Energy-related ECal

- 3233 – ECal total energy (ClusterTotalEnergy): sum of the energy of all the ECal  
3234 hits.
- 3235 – Mean ECal hit energy (HitMeanEnergy): mean of the hit energy distribution.
- 3236 – Standard deviation ECal hit energy (HitStdEnergy): standard deviation of  
3237 the hit energy distribution.
- 3238 – Maximum ECal hit energy (HitMaxEnergy): maximum of the hit energy  
3239 distribution.

##### 3240 • Geometry-related ECal

- 3241 – Mean distance hit-to-cluster (DistHitClusterMean): mean of the distance  
3242 distribution between the hits and the corresponding cluster's main axis.
- 3243 – RMS distance hit-to-cluster (DistHitClusterRMS): root mean square of the  
3244 distance distribution between the hits and the corresponding cluster's main  
3245 axis.

---

<sup>7</sup>At the reconstruction level what happens is that non-clustered hits are put into single hit clusters, instead of being thrown away. This is necessary to keep the consistency of the track-cluster association code.

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- 3246        – Maximum distance hit-to-centre (DistHitCenterMax): maximum of the  
3247                  distance distribution between the hits and the centre of the TPC.  
  
3248        – Time-of-Flight velocity (TOFVelocity): slope obtained when fitting a straight  
3249                  line to the hit time versus hit distance to the centre (i.e.  $d = v \times t$ ).

### 3250        • Energy and geometry ECal

- 3251        – Radius 90% energy (Radius90E): distance in the hit-to-cluster distribution  
3252                  for which 90% of the total energy is contained in the hits that are closer to  
3253                  the axis (i.e. radius that contains 90% of the energy).

### 3254        • Statistical ECal

- 3255        – Number of hits (NHits): total number of hits associated to the track.  
3256        – Number of layers with hits (NLayers): not really a count of all layers with  
3257                  hits but the difference between the last and the first layer with hits.

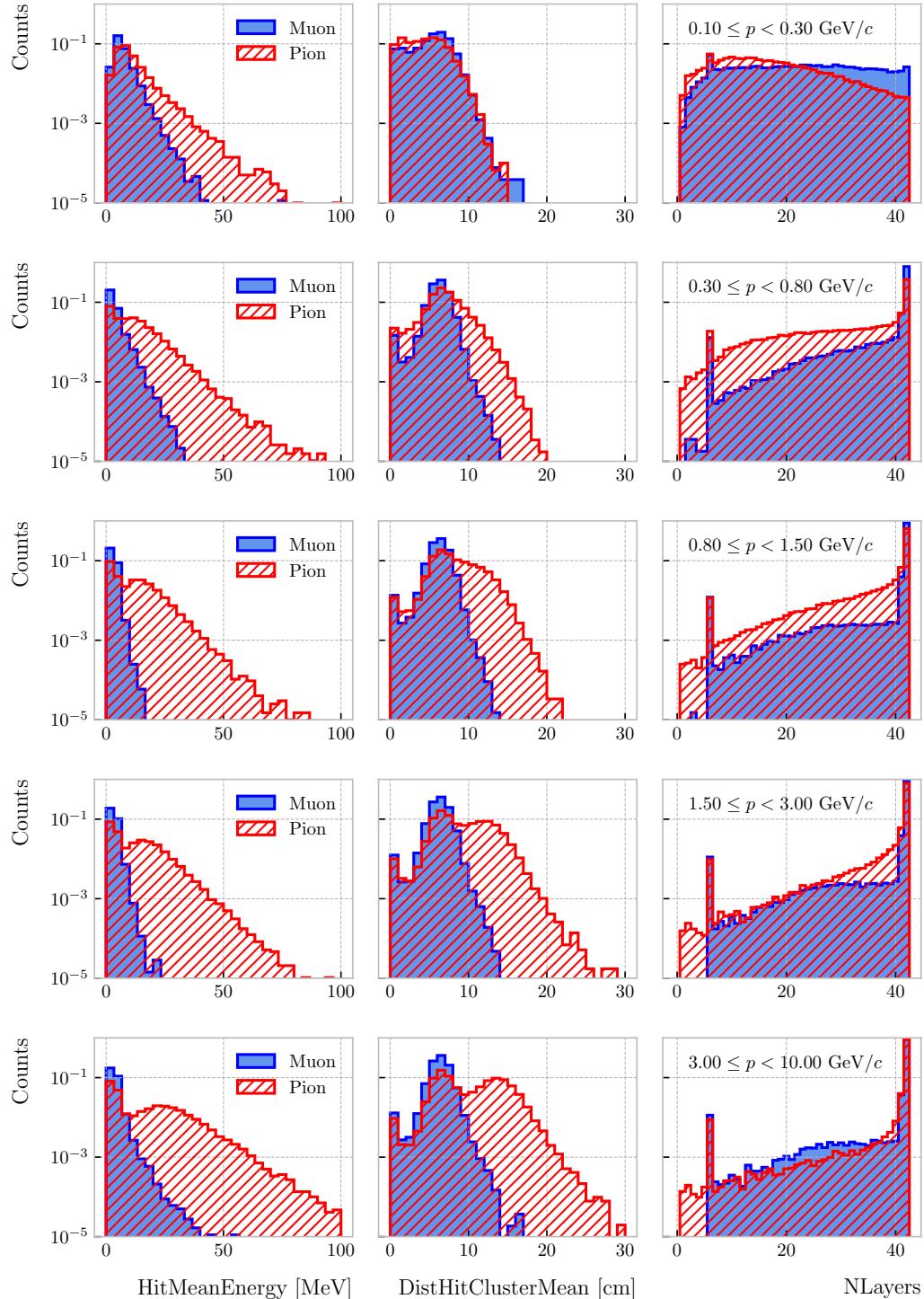
3258        Figure 6.21 shows the distributions of three different ECal variables, separating true  
3259                  muons (blue) and charged pions (red), for the five momentum ranges considered. I chose  
3260                  to show one feature from each category, namely the mean energy per hit (left column),  
3261                  the mean distance between the hits and the centre of the cluster (middle column), and  
3262                  the number of ECal layers with hits (right column). These give an idea of the separating  
3263                  power of the different features, and how it changes considerably with the energy. In  
3264                  the number of layers with hits distributions, the peak at 6 is due to the fact that the  
3265                  first six ECal layers sit inside the pressure vessel<sup>8</sup>. Therefore, some of the particles get  
3266                  stopped crossing it, never making it to the seventh layer.

3267        In the case of the MuID, because at low momenta a significant fraction of the particles  
3268                  do not make it past the ECal, I only consider the information coming from this detector  
3269                  for momenta  $\geq 0.8$  GeV/c, i.e. for the last three momentum regions. The variables I  
3270                  extract from it are the following:

---

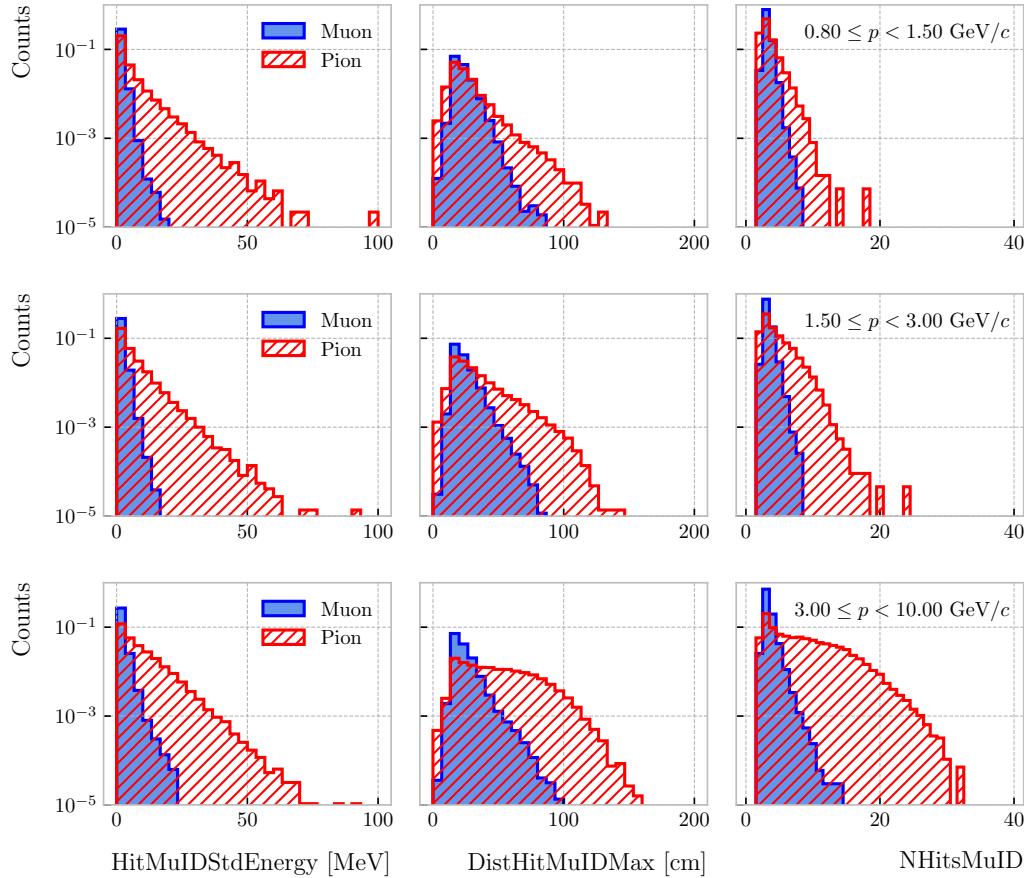
<sup>8</sup>Note to self: check this. I thought the ECal barrel had 8 layers of tiles, and that all of them were inside the pressure vessel.

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID



**Figure 6.21:** Example ECal feature distributions for muons (blue) and charged pions (red) in the five different momentum ranges considered (from top to bottom, in ascending momentum order). From left to right: mean hit energy, mean distance hit-to-cluster, and number of layers with hits.

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**Figure 6.22:** Example MuID feature distributions for muons (blue) and charged pions (red) in the three different momentum ranges considered (from top to bottom, in ascending momentum order). From left to right: standard deviation hit energy, maximum distance hit-to-hit, and number of hits.

### • Energy-related MuID

- 3271 – MuID total energy (ClusterMuIDTotalEnergy): sum of the energy of all the
- 3272        MuID hits.
- 3273
- 3274 – Mean MuID hit energy (HitMuIDMeanEnergy): mean of the MuID hit energy
- 3275        distribution.
- 3276
- 3277 – Standard deviation MuID hit energy (HitMuIDStdEnergy): standard deviation
- 3278        of the MuID hit energy distribution.
- 3279
- 3278 – Maximum MuID hit energy (HitMuIDMaxEnergy): maximum of the MuID
- 3279        hit energy distribution.

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID

3280        • **Geometry-related MuID**

- 3281            – Maximum distance MuID hit-to-hit (DistHitMuIDMax): maximum distance  
3282              between pairs of MuID hits (not sure this is a good variable, distribution  
3283              looks nuts).
- 3284            – Maximum distance MuID hit-to-centre (DistHitCenterMuIDMax): maximum  
3285              of the distance distribution between the MuID hits and the centre of the  
3286              TPC.

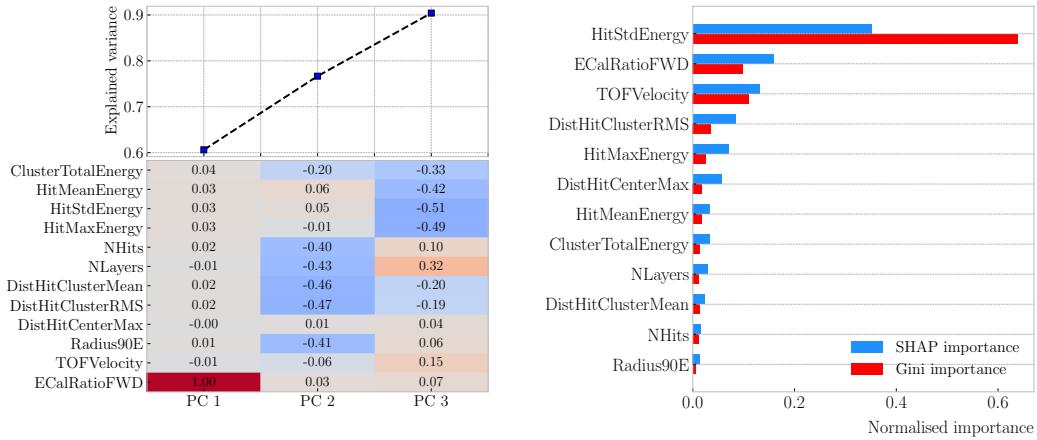
3287        • **Statistical MuID**

- 3288            – Number of hits (NHitsMuID): total number of MuID hits associated to the  
3289              track.
- 3290            – Number of layers with hits (NLayersMuID): not really a count of all layers  
3291              with MuID hits but the difference between the last and the first layer with  
3292              MuIDhits.

3293        Figure 6.22 shows the distributions of three different MuID variables, separating true  
3294        muons (blue) and charged pions (red), for the three momentum ranges which use the  
3295        muon tagger information. In this case I decided to standard deviation of the MuID hit  
3296        energy distribution (left column), the maximum distance between the MuID hit pairs  
3297        (middle column), and the number of MuID hits (right column). These variables are used  
3298        together with the ECAL features at high momenta, providing additional disambiguation  
3299        power.

3300        Once our features have been defined, one can do some exploratory analysis to  
3301        understand how well the variables describe the target class, and avoid the black-box  
3302        approach by what features are most relevant for the learning process. This way, I  
3303        performed a feature analysis for each of the momentum ranges I divided this classification  
3304        problem into. It follows three steps: first a principal component analysis (PCA), followed  
3305        by a feature importance study using Gini and Shapley values, and finally a feature  
3306        permutation importance analysis.

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**Figure 6.23:** Left panel: cumulative explained variance for the first three principal components (top panel) and contribution of the different features to the principal axes in feature space (bottom panel). Right panel: Shapley (blue) and Gini (red) feature importances for the different input features. Both figures correspond to the samples in the momentum range  $0.3 \leq p < 0.8 \text{ GeV}/c$ .

The PCA is useful to understand the variance of the feature space. It is an unsupervised machine learning technique that allows the user to perform a dimensionality reduction. It uses a singular value decomposition of the input features to project them into a lower dimensional space. The idea is to find the matrix  $\mathbf{C}_m$ , whose columns are the first  $m$  orthonormal eigenvectors of the input covariance matrix. Consider the  $n \times p$  real matrix of input data  $\mathbf{X}$ , where  $n$  is the number of samples and  $p$  the number of features. If  $\mathbf{X}$  is centred, i.e. the means of its columns are equal to zero, we can write the covariance matrix of  $\mathbf{X}$  as  $\mathbf{C} = \mathbf{X}^\top \mathbf{X} / (n - 1)$ . This matrix can be diagonalised, yielding:

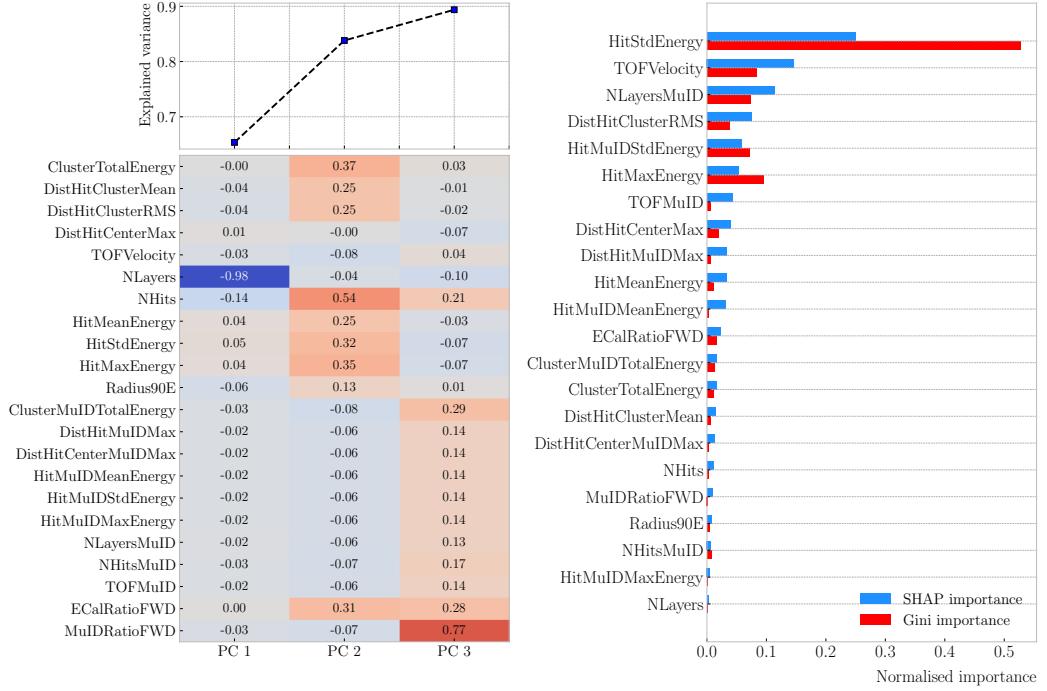
$$\mathbf{C} = \mathbf{V} \mathbf{L} \mathbf{V}^\top, \quad (6.11)$$

where  $\mathbf{V}$  is a matrix of eigenvectors and  $\mathbf{L}$  a diagonal matrix with eigenvalues  $\lambda_i$ . Then, performing SVD on  $\mathbf{X}$  gives us:

$$\mathbf{X} = \mathbf{U} \mathbf{S} \mathbf{W}^\top, \quad (6.12)$$

where  $\mathbf{U}$  is a unitary matrix, whose columns are called left singular vectors,  $\mathbf{S}$  is a diagonal matrix of single values  $s_i$ , and  $\mathbf{W}$  is another unitary matrix, its columns known

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID



**Figure 6.24:** Left panel: cumulative explained variance for the first three principal components (top panel) and contribution of the different features to the principal axes in feature space (bottom panel). Right panel: Shapley (blue) and Gini (red) feature importances for the different input features. Both figures correspond to the samples in the momentum range  $0.8 \leq p < 1.5$  GeV/c.

as right singular vectors. This way, we can write:

$$\mathbf{C} = \mathbf{W}\mathbf{S}\mathbf{U}^\top\mathbf{U}\mathbf{S}\mathbf{W}^\top/(n-1) = \mathbf{W}\frac{\mathbf{S}^2}{n-1}\mathbf{W}^\top. \quad (6.13)$$

meaning that the right singular vectors are also the eigenvectors of the covariance matrix.

The SVD can be computed numerically following an iterative approach.

This way, taking an input data vector  $X \in \mathbb{R}^n$ , the resulting feature vector  $Y \in \mathbb{R}^m$

is given by:

$$Y = \mathbf{C}_m^\top X. \quad (6.14)$$

The new features capture most of the variance of the original sample, while being lower

dimensional, as  $m < n$ .

Before applying the PCA reduction one needs to centre and scale the input data.

## CHAPTER 6. PARTICLE ID IN ND-GAR

3327 Centring is necessary when using SVD to obtain the eigenvectors of the covariance  
3328 matrix, as only in that case we can do the identification with the right singular vectors  
3329 from the input data. Scaling is needed when variables are on different scales, as some  
3330 can then dominate the PCA procedure.

3331 I used the PCA module of `scikit-learn`, together with the `RobustScaler`, which  
3332 centres the data and scales it based on the interquartile range. In Fig. 6.23 (left panel)  
3333 and Fig. 6.24 (left panel) I show the results I obtained from the PCA for the momentum  
3334 ranges  $0.3 \leq p < 0.8 \text{ GeV}/c$  and  $0.8 \leq p < 1.5 \text{ GeV}/c$ , respectively. Notice that in  
3335 the second case the number of features increases considerably, as this is the first region  
3336 which uses the MuID variables. I found that, in all the cases, adding a fourth PC does  
3337 not add additional information. As it can be seen in the top panels of the figures, the  
3338 cumulative explained variance is already over 80% with three PCs.

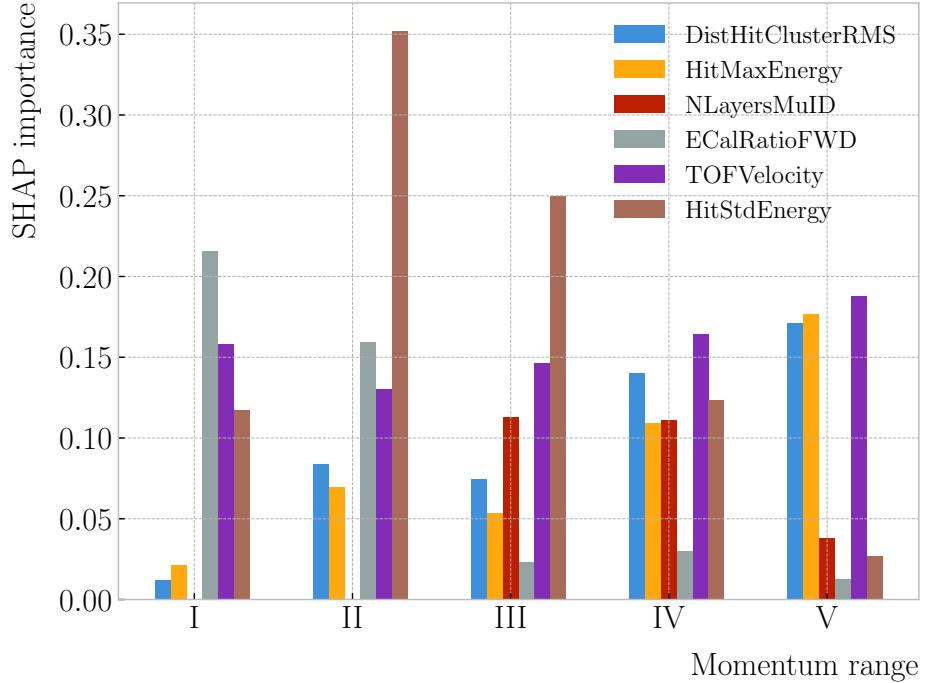
3339 The bottom panels show the contribution of the variables to the principal axes. For  
3340 the two first momentum regions, I observe a tendency of the energy-related and the  
3341 geometry-related ECal variables to be clustered together. For the other ranges, when  
3342 I include the MuID variables, there seems to be a division between ECal and MuID  
3343 variables. For these, it seems like the number of ECal layers with hits also plays an  
3344 important role.

3345 The next step in the analysis is to quantify the importance of the features based on  
3346 two additional metrics, namely the Gini and the Shapley values. The Gini importance,  
3347 often called mean decrease impurity, is based on how much a feature contributes to the  
3348 purity improvement at the splits in each decision tree. The purity is measured in terms  
3349 of the Gini impurity index, defined as:

$$I_G = 1 - \sum_i f_i, \quad (6.15)$$

3350 where  $f_i$  is the fractional abundance of the  $i$ -th class. Then, for each split one can

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**Figure 6.25:** Evolution of the SHAP importance for the top six most important features across all five momentum ranges.

3351 compute the weighted decrease in impurity as:

$$\Delta_G = \frac{N_t}{N} \left( I_G - \frac{N_t^R}{N_t} I_G^R - \frac{N_t^L}{N_t} I_G^L \right), \quad (6.16)$$

3352 where  $N$  represents the total number of samples,  $N_t$  the number of samples at the current  
 3353 node,  $N_t^R$  and  $N_t^L$  the number of samples in the right and left children respectively,  
 3354  $I_G$  is the Gini impurity at the current node, and  $I_G^R$  and  $I_G^L$  the Gini impurities of the  
 3355 resulting right and left children.

3356 For each decision tree, one will have a normalised vector with the accumulated  
 3357 decrease in Gini impurity for each feature. In the case of a BDT, the feature importances  
 3358 are simply the mean for all the estimators in the ensemble<sup>9</sup>.

3359 The concept of Shapley values originated in the context of game theory, and it  
 3360 measures the marginal contribution of a feature in enhancing the accuracy of a classifier.

---

<sup>9</sup>Note to self: this appears not to be the case. If you get the `feature_importance` for each tree in the BDT and take the average, the result is not the same to be one reported in the `feature_importance` attribute of the BDT.

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3361 Take  $F$  to be the set of all features in a problem, and  $S \subseteq F$  the subset of features. To  
 3362 compute the Shapley value of the  $i$ -th feature, one has to train a model with that feature  
 3363 present,  $f_{S \cup \{i\}}$ , and another model trained without it,  $f_S$ . This has to be repeated for  
 3364 all possible combinations of subsets  $S \subset F \setminus \{i\}$ , and evaluating the models predictions  
 3365 on the appropriate sets of data  $x_S$ . This way, the Shapley value results:

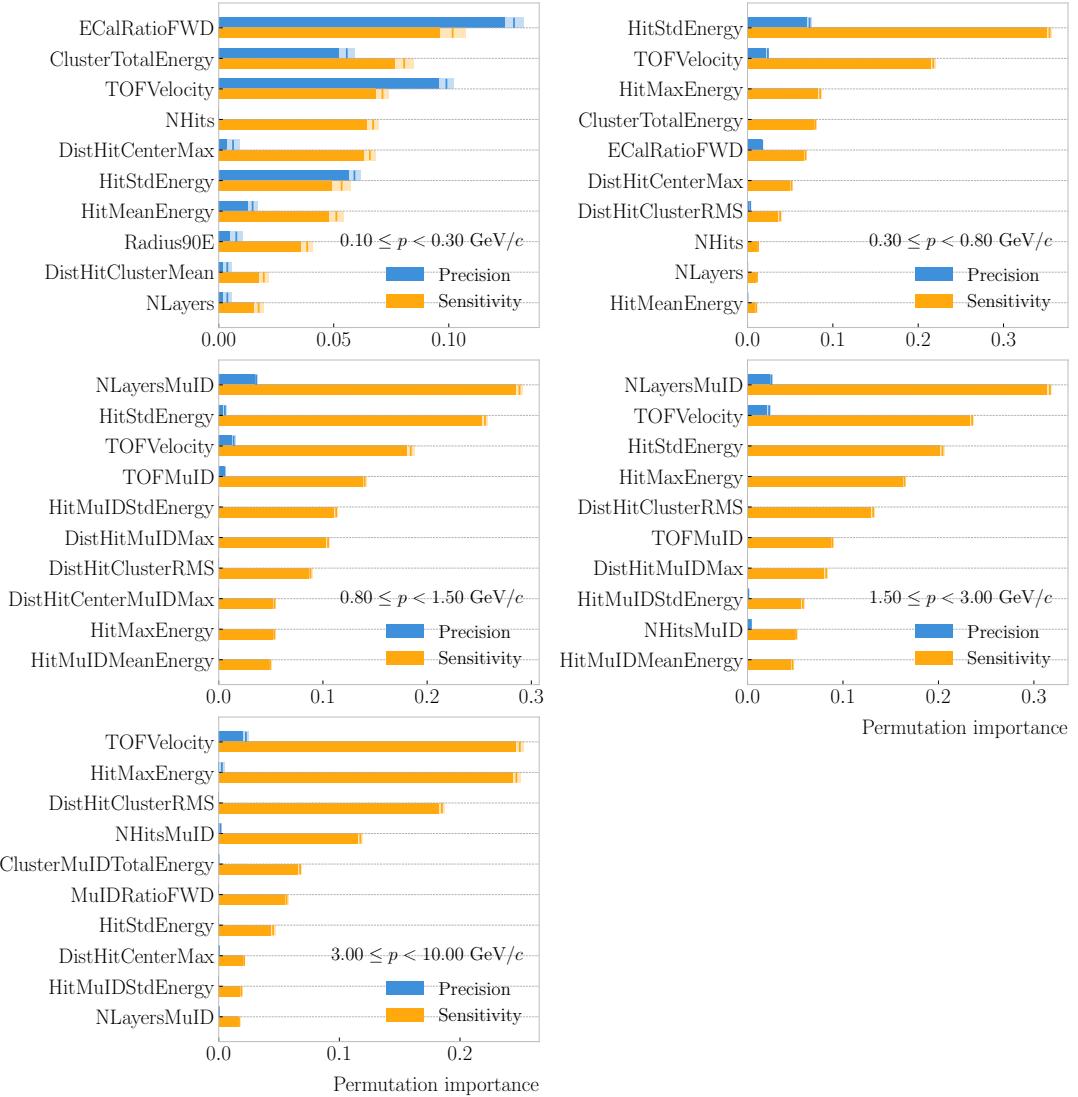
$$\varphi_i = \sum_{S \subset F \setminus \{i\}} \frac{|S|! (|F| - |S| - 1)!}{|F|!} [f_{S \cup \{i\}}(x_{S \cup \{i\}}) - f_S(x_S)]. \quad (6.17)$$

3366 I trained the `GradientBoostingClassifier` from `scikit-learn` with the default  
 3367 configuration in order to evaluate both the Gini and Shapley importances. The Gini  
 3368 scores are automatically computed by `scikit-learn`, using the training data. For the  
 3369 Shapley importance, I used the implementation from the `SHAP` package, computing  
 3370 it using the test sample. The results can be seen in Fig. 6.23 (right panel) and  
 3371 Fig. 6.24 (right panel), again for the momentum ranges  $0.3 \leq p < 0.8 \text{ GeV}/c$  and  
 3372  $0.8 \leq p < 1.5 \text{ GeV}/c$ . The length of the bars denote either the SHAP (blue) or the Gini  
 3373 (red) importance of the feature. One interesting thing to notice is that, when looking at  
 3374 the Gini importance, there is always one feature that dominates over the rest. This is  
 3375 not the case for the SHAP importance, where importances tend to be more balanced.

3376 Across all momentum ranges, I observe that the most important features are. For  
 3377 the five momentum ranges considered, only six variables sit in the top five at least once.  
 3378 Figure 6.25 shows the evolution of the SHAP importance of these six features. It is  
 3379 interesting to see that the time-of-flight variable keeps its importance almost unchanged  
 3380 for all momenta. Also, it looks like the ECal energy ratio gets less relevant the higher the  
 3381 momentum is, but the RMS of the hit-to-cluster distance distribution and the maximum  
 3382 ECal hit energy become more important in the last momentum ranges.

3383 The last step in the feature selection analysis is the feature permutation. This  
 3384 technique measures the contribution of each feature to the performance of a model by  
 3385 randomly shuffling its values and checking how some scores degrade. For the present  
 3386 case, I am interested in the precision or purity, and the sensitivity or efficiency, as these

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**Figure 6.26:** Permutation importances for the ten most important features in the different momentum ranges (from left to right, top to bottom, in increasing momentum order). The bars indicate the effect that permutations of each feature have on the purity (blue) and the sensitivity (yellow), the translucent regions representing one standard deviation around the central value.

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3387 two are the most relevant metrics from a physics point of view. The `scikit-learn`  
3388 module provides the user with a method to perform the permutation scans.

3389 The results of these are shown in Fig. 6.26. For the different momentum ranges  
3390 I show the permutation importances for the ten most important features. For each  
3391 of the variables I report the effect the permutations have on the precision (blue) and  
3392 sensitivity (yellow) of the models. The bars indicate the importance value, with the  
3393 lighter part representing one standard deviation around the mean (hinted as an additional  
3394 vertical line). Something to notice is that, in the first momentum region, the feature  
3395 permutations have an effect on both the precision and the sensitivity. However, for the  
3396 rest the precision is almost unaffected, while the sensitivity changes are considerably  
3397 larger.

3398 It is also interesting to see that most of the variables identified as important here  
3399 are the same I found when looking at the Shapley values. The behaviour of these across  
3400 the momentum ranges is also similar, with the same patterns of some features being  
3401 important at low momenta and then dropping in importance for the high momentum  
3402 ranges.

3403 Wit this, I conclude the study of the features. I have prepared the training and  
3404 testing datasets and understood what features are likely to have the largest impact on  
3405 the performance of the classifiers.

### 3406 6.3.4 Hyperparameter optimisation

3407 Any BDT requires the user to specify a number of parameters that will dictate its  
3408 behaviour. They can be divided into two categories: (i) tree-specific parameters, which  
3409 affect each individual tree in the model, and (ii) boosting parameters, which control the  
3410 boosting operation in the model. The value of these so-called hyperparameters affect the  
3411 performance and predictive power of the models. Therefore, one needs to carefully select  
3412 their optimal values in order to extract as much information as possible from the data.

3413 From all the parameters used to define a tree in the `scikit-learn` implementation  
3414 of the BDT classifier, I only consider a subset of them. This is due to the fact that some

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3415 are mutually exclusive, but also because I noticed that others have little effect on the  
3416 problem at hand. Therefore, the parameters I investigate are the following:

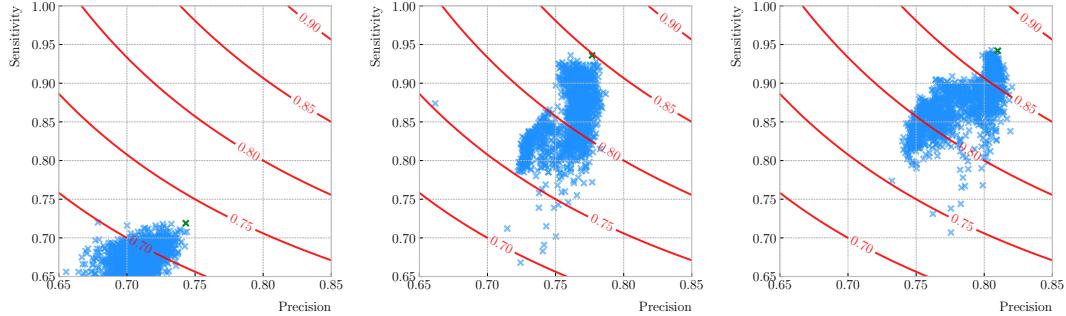
- 3417 • `min_samples_split`: defines the minimum number of samples required in a node  
3418 to be considered for splitting. Higher values prevent a model from learning relations  
3419 which might be highly specific to the particular sample, but may lead to under-fitting  
3420 if the value is too low.
- 3421 • `min_samples_leaf`: defines the minimum samples required in a leaf node. For  
3422 imbalanced problems it should take a low value, as there will not be many cases  
3423 where the minority class dominates.
- 3424 • `max_depth`: maximum depth of a tree. Useful to prevent over-fitting, as higher  
3425 depth will allow a model to learn relations specific to the training sample.

3426 In the case of the boosting parameters, the ones I look at are:

- 3427 • `learning_rate`: determines the impact of each tree on the final outcome. Low  
3428 values make the model robust to the specific characteristics of a tree, and thus  
3429 allow it to generalise well. However, that usually requires a large number of trees  
3430 to model the data properly.
- 3431 • `n_estimators`: number of sequential trees to be trained. In general, BDTs are  
3432 fairly robust at higher number of trees but it can still overfit at a point.
- 3433 • `subsample`: fraction of observations to be selected for each tree. Values slightly  
3434 less than 1 make the model robust by reducing the variance.

3435 In general, hyperparameters depend on each other. Thus, it is not possible to  
3436 optimise them independently. In the literature, we find two main strategies to explore  
3437 the hyperparameter space. We could use a grid search, in which one discretises a  
3438 portion of the space of hyperparameters and evaluates the model at each point. Another  
3439 approach is the randomised search, where a certain number of random configurations of  
3440 hyperparameters are explored.

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**Figure 6.27:** Values of the precision and sensitivity obtained for 10000 BDT hyperparameter configurations, for the momentum regions I, III and V. The red contours indicate the curves of equal  $F_1$ -score, while the green crosses are the selected configurations.

3441 In this case, I used the random search to scan the hyperparameter space. Also,  
 3442 because it is not guaranteed that a set of hyperparameters can be efficiently applied  
 3443 across different datasets, I perform the optimisation for each of the momentum ranges  
 3444 considered. Table 6.3 shows the list of hyperparameters considered, and the range within  
 3445 which I let them vary. I decided to fix the number of estimators to 400 in all cases, as  
 3446 its value is correlated with that of the learning rate.

3447 I evaluate 10000 different hyperparameter configurations for each momentum range.  
 3448 For the hyperparameter tuning, I used subsamples containing 10% of the full datasets,  
 3449 keeping the original proportions between classes, in order to reduce the computational  
 3450 load. The performance of the models was assessed using a stratified 3-fold cross-validation  
 3451 with replacement. Cross-validation involves dividing the data in a number of subsets,  
 3452 training the model using some of them, and testing it with the rest. In our case, I  
 3453 divide the data in 3 equal-sized subsets, maintaining the class proportions of the original  
 3454 dataset. Then, for 3 consecutive iterations, I train the models using 2 of the subsets  
 3455 while I compute the precision and sensitivity scores with the other. This approach  
 3456 provides a more robust estimate of the performance on unseen data.

3457 Figure 6.27 shows the results in the precision versus sensitivity plane, for the  
 3458 momentum regions I, III and V (from left to right). The contours represent the curves  
 3459 of equal  $F_1$ -score, i.e. the harmonic mean of the precision and the sensitivity. In order

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**Table 6.3:** Optimal values of the hyperparameters used by the BDT, for each momentum range.

Hyperparameter	Range	Best value				
		I	II	III	IV	V
<code>min_samples_split</code>	[0.001, 1]	0.10	0.06	0.05	0.27	0.06
<code>min_samples_leaf</code>	[0.001, 1]	0.02	0.03	0.01	0.02	0.07
<code>max_depth</code>	{2, 3, ..., 8}	8	2	4	2	7
<code>learning_rate</code>	[0.05, 1]	0.10	0.23	0.07	0.13	0.09
<code>subsample</code>	[0.01, 1]	0.75	0.65	0.79	0.86	0.95

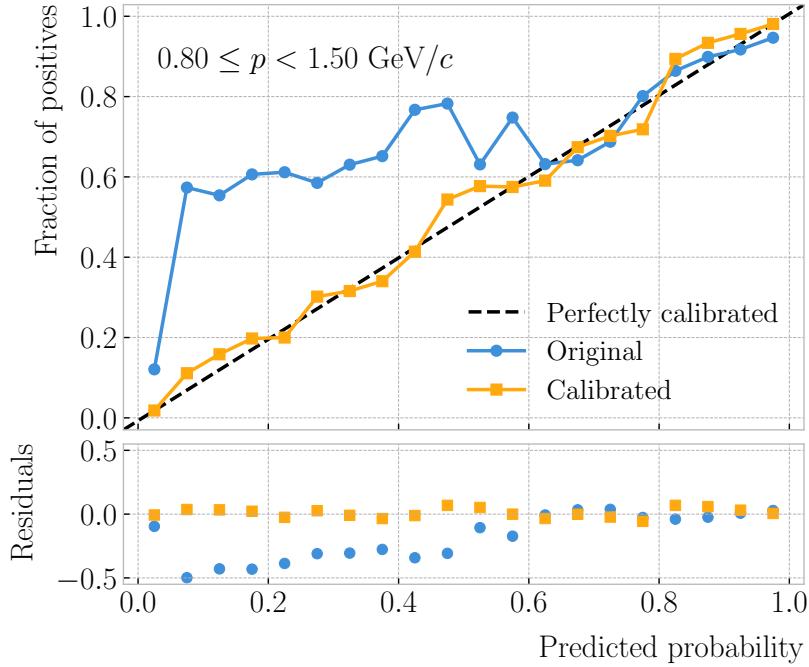
**Table 6.4:** Performance metrics of the BDTs with optimal hyperparameters, for the different momentum ranges.

Metric	Value $\pm 1\sigma$				
	I	II	III	IV	V
Accuracy	$0.779 \pm 0.003$	$0.812 \pm 0.003$	$0.846 \pm 0.002$	$0.861 \pm 0.003$	$0.874 \pm 0.002$
Precision	$0.769 \pm 0.003$	$0.752 \pm 0.005$	$0.788 \pm 0.002$	$0.805 \pm 0.003$	$0.815 \pm 0.003$
Sensitivity	$0.745 \pm 0.009$	$0.921 \pm 0.006$	$0.965 \pm 0.002$	$0.967 \pm 0.002$	$0.976 \pm 0.001$
$F_1$ -score	$0.757 \pm 0.004$	$0.828 \pm 0.003$	$0.867 \pm 0.002$	$0.879 \pm 0.002$	$0.889 \pm 0.002$
ROC AUC	$0.868 \pm 0.003$	$0.865 \pm 0.003$	$0.899 \pm 0.002$	$0.902 \pm 0.002$	$0.911 \pm 0.001$

3460 to select the optimal configurations (indicated in the plots with a green cross), I chose  
 3461 the point with the highest  $F_1$ -score.

3462 The results for the different momentum ranges are summarised in Tab. 6.3. One  
 3463 can see some consistency in hyperparameter choices, with models generally preferring  
 3464 small values for the tree-specific parameters, small learning rate, and relatively large  
 3465 subsample sizes.

3466 Now that I have obtained the optimal values of the hyperparameters, I can train  
 3467 the different BDTs. In this case I use the complete datasets, keeping 20% of the data  
 3468 for testing. Table 6.4 shows the values of the different performance metrics obtained  
 3469 using the selected hyperparameters and 5-fold cross-validation. The last row indicates  
 3470 the value of the area under the receiver operating characteristic (ROC) curve. This  
 3471 represents the sensitivity of a model as a function of the false positive rate. I have



**Figure 6.28:** Reliability diagrams for the BDT classifier used in the momentum range  $0.3 \leq p < 0.8 \text{ GeV}/c$ , both for the original (blue circles) and calibrated (yellow squares) responses. For reference, the response of a perfectly calibrated classifier is also shown (black dashed line).

3472 included it here as it is a classic model metric used in the machine learning community.

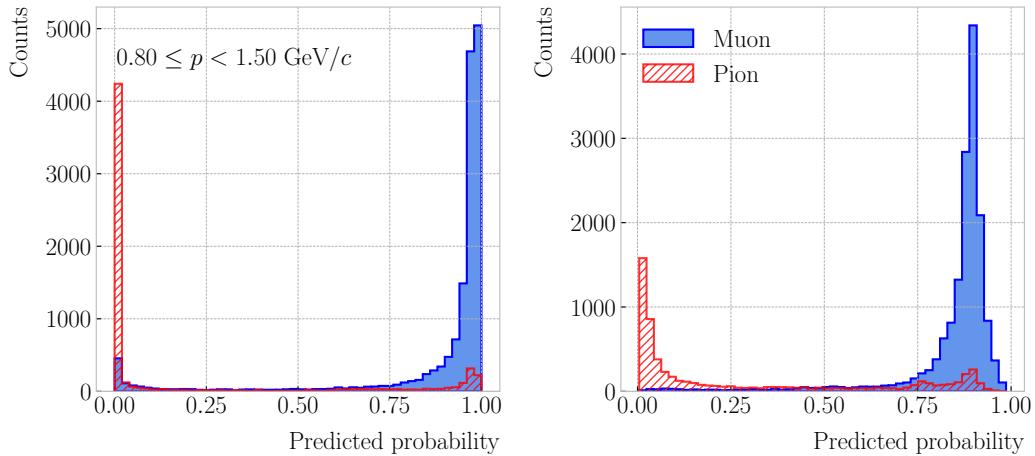
3473 Overall, there is a clear trend of models performing better at higher momentum.

### 3474 6.3.5 Probability calibration

3475 So far, the trained BDTs are able to provide predictions of the class labels. Ideally,  
3476 one would like the output of a classifier to give a confidence level about the prediction.  
3477 However, it is not straightforward to interpret the outputs of our BDTs in terms of  
3478 probabilities.

3479 A way to visualise how well the predictions of a classifier are calibrated is using  
3480 reliability diagrams [154]. They represent the probability of the positive label versus the  
3481 probability predicted by the classifier. These can be obtained by binning the predicted  
3482 probabilities, and then compute the conditional probability  $P(y_{true} = 1 | y_i \leq y_{pred} <$   
3483  $y_{i+1})$  by checking the fraction of true positive instances in each bin. The reliability

### 6.3. MUON AND PION SEPARATION IN THE ECAL AND MUID



**Figure 6.29:** Uncalibrated (left panel) and calibrated (right panel) predicted probabilities assigned by the BDT classifiers for true muons (blue) and charged pions (red) in the momentum range  $0.3 \leq p < 0.8 \text{ GeV}/c$ .

3484 diagram of a perfectly calibrated classifier would be a diagonal line.

3485 In this case, I try to correct the raw response of the classifiers by applying a sigmoid  
3486 function:

$$\sigma(x; A, B) = \frac{1}{1 + e^{Ax+B}}, \quad (6.18)$$

3487 where the parameters  $A$  and  $B$  are real numbers determined using the method of least  
3488 squares.

3489 For each classifier, I perform a grid search to obtain the optimal values of  $A$  and  $B$ .  
3490 For any pair, I compute the predicted probabilities as  $y_{pred} = \sigma(y_{raw}; A, B)$ , where  $y_{raw}$   
3491 are the raw predictions of the classifier<sup>10</sup>. Then, I calculate the corresponding reliability  
3492 curve, and take the sum of the squared residuals between it and the response of the  
3493 perfectly calibrated classifier.

3494 Figure 6.28 shows the reliability diagrams for the original (blue) and calibrated  
3495 (yellow) probability predictions of the classifier for the III momentum range,  $0.3 \leq p <$   
3496  $0.8 \text{ GeV}/c$ . The original response of the classifier is given by  $y_{pred} = \sigma(y_{raw}; -2, 0)$ ,  
3497 which is the transformation applied by `scikit-learn` to produce the probability estimate.  
3498 Notice how the calibrated prediction matches the ideal response much better than the

---

<sup>10</sup>In `scikit-learn` these correspond to the outputs of the `decision_function` method.

## CHAPTER 6. PARTICLE ID IN ND-GAr

3499 original, across all the probability range.

3500 One can also compare the responses of the uncalibrated and calibrated classifiers  
3501 broken down by true particle type, as shown in Fig. 6.29. It can be seen that the  
3502 distributions for both muons (blue) and charged pions (red) smoothen after calibration,  
3503 but still the separating power of the classifier remains unchanged.

3504 At this point, having the trained classifiers and the probability calibration parameters,  
3505 I am able to assess the performance of the classification strategy in a physics-relevant  
3506 case.

### 3507 6.3.6 Performance

## 3508 6.4 ECal time-of-flight

3509 Looking at Fig. 6.20, it is clear that for momentum values in the range  $1.0 - 3.0 \text{ GeV}/c$   
3510 it is not possible to separate pions and protons using a  $\langle dE/dx \rangle$  measurement in the  
3511 HPgTPC. However, in the previous section I assumed that protons at those energies  
3512 could be identified by other means, and therefore were not an issue for the muon and  
3513 pion discrimination.

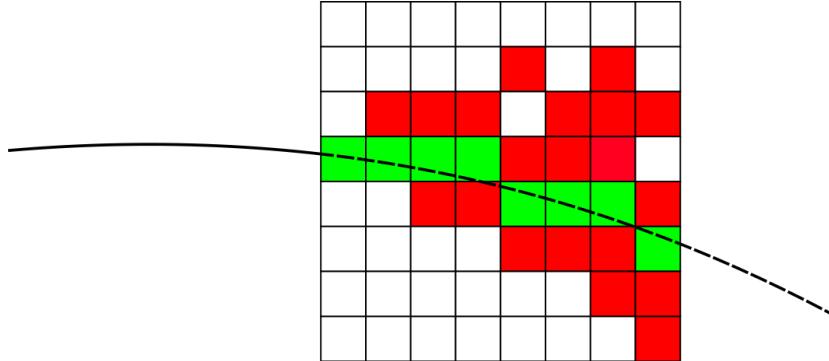
3514 Some detectors, like ALICE [155] or the ILD concept [156], complement the PID  
3515 capabilities of their gaseous trackers with time-of-flight measurements. The use of  
3516 fast timing silicon sensors, with hit time resolutions under 100 ps, would allow for the  
3517 identification of charged hadrons via a ToF measurement up to  $5.0 \text{ GeV}/c$ . In the case  
3518 of ND-GAr, one could think of using the inner layers of the ECal, the ones consisting of  
3519 high-granularity tiles, to obtain a ToF-based PID, with some inputs from the TPC.

3520 Measuring the momentum and the velocity of a charged particle allows for a  
3521 determination of the mass through the relativistic momentum formula:

$$m = \frac{p}{\beta} \sqrt{1 - \beta^2}. \quad (6.19)$$

3522 In our case, the momentum is measured in the TPC, using the curvature and the dip

## 6.4. ECAL TIME-OF-FLIGHT



**Figure 6.30:** Schematic of the hit selection used for the ToF measurement. The grid represents the layers of the inner ECAL, with coloured squares indicating the tiles with hits. Green squares indicate the selected hits.

angle of the helix inside the magnetic field. The velocity of the particle can be written as:

$$\beta = \frac{\ell_{track}}{c\tau}, \quad (6.20)$$

where  $\ell_{track}$  is the length of the track, and  $\tau$  the arrival time to the ECAL.

In GArSoft, the track length is computed at the Kalman filter stage. It is simply the sum of the line segments along the track, either in the forward or backward fit. In this case, because we are only interested in the particles that make it to the ECAL, I choose the fit direction based on the results of the track-cluster associations.

Additionally, because the last 30 cm of the TPC radius are uninstrumented<sup>11</sup>, I need to correct for the length of the tracks. Using the track fit parameters to propagate the helix to its entry point in the ECAL, one can write the total track length as:

$$\ell_{track} = \ell + \left| \frac{\phi_{EP} - \phi}{R^{-1}} \right| \sqrt{1 + \tan^2 \lambda}, \quad (6.21)$$

where  $\phi_{EP}$  is the angle of rotation at the entry point to the calorimeter, and  $\ell$ ,  $\phi$ ,  $R$  and  $\lambda$  are the track length, angle of rotation, radius of curvature and dip angle at the last point in the fit, respectively.

To test the idea of performing a ToF measurement with the inner ECAL, I generated

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<sup>11</sup>Note to self: check this number.

## CHAPTER 6. PARTICLE ID IN ND-GAr

3537 two data samples. Each consists of 10000 single particle events, either charged pions or  
3538 protons. Their momenta are uniformly distributed in the range  $0.5 - 5.0 \text{ GeV}/c$ , and  
3539 their directions are isotropic. I process each sample using different values of the time  
3540 resolution, from  $\Delta\tau = 0$ , the perfect time resolution case for comparison, to the current  
3541 nominal value of  $\Delta\tau = 0.7 \text{ ns}$ , and the worse scenario of  $\Delta\tau = 1.0 \text{ ns}$ .

### 3542 6.4.1 Arrival time estimations

3543 In the simulation, the limited time resolution of the ECal is taken into account by  
3544 applying a Gaussian smearing to the true hit times. Other effects, like the digitisation  
3545 of the signals, are not taken into account and fall beyond the scope of this study. After  
3546 the track-cluster, one ends up with a collection of ECal hits associated to each particle.  
3547 From these, the arrival time of the particle to the ECal can be extracted.

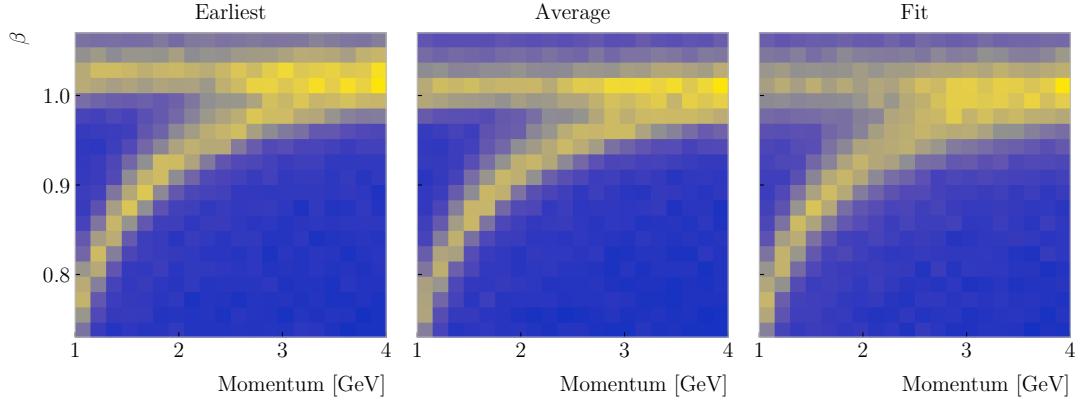
3548 The simplest possibilities are to either take the time of the earliest hit or the hit  
3549 closest to the entry point. Because these two coincide, in general, I focused only in  
3550 the earliest hit time. However, this needs to be corrected, to account for the distance  
3551 travelled from the entry point to the position of the hit:

$$\tau_{earliest} = \tau_{hit} - \frac{d_{EP-hit}}{c}, \quad (6.22)$$

3552 where  $\tau_{hit}$  is the time of the earliest hit, and  $d_{EP-hit}$  is the distance between that hit  
3553 and the entry point of the particle to the ECal. This is computed as the arc length  
3554 between the entry point and the point of the extrapolated helix up to the layer of the  
3555 hit. This way of correcting the time assumes  $c$  for the propagation of the particle, which  
3556 may lead to biased estimates.

3557 I also tried to estimate the arrival times using information from the rest of the hits.  
3558 In order to do this, as a simplifying assumption, I approximate the hadronic shower  
3559 considering only its MIP component. For each layer, I keep only the hit in the tile closest  
3560 to the point of the extrapolated track up to that layer. Figure 6.30 shows an example of  
3561 how this hit selection works. The dashed line represents the extrapolated track, while

## 6.4. ECAL TIME-OF-FLIGHT



**Figure 6.31:** Particle velocity versus momentum measured with different ECal arrival time estimations. From left to right: earliest hit time, average hit time, and fitted hit time. In all cases the time resolution is  $\Delta\tau = 0.1$  ns.

the coloured squares are the tiles containing hits. Green indicates the tiles closer to the track in each layer (in the sketch they correspond to the grid columns).

Now, I can use these collections of hits to estimate the arrival times. A possibility is to take the average of the times of the selected hits, denoted  $\tau_{average}$ . For that to work, one needs to correct these times, in a similar way as in Eq. (6.22), before taking the average. However, as before, this correction assumes that the particle travels at the speed of light inside the ECal. Another option is to perform a linear fit to the hit times and the distances to the entry point. In that case, the arrival time would be the fitted value of the intercept,  $\tau_{fit}$ . This method would not assume a speed of light propagation.

Figure 6.31 shows the velocity estimations as a function of the particle momentum, for the earliest hit time (left panel), average hit time (middle panel), and fitted hit time (right panel). The two bands correspond to the  $\pi^\pm$  and the  $p$  particles.  $\Delta\tau = 0.1$  ns. Notice how, for the earliest hit time method, the velocities are significantly biased towards larger values. For the multi-hit methods, the  $\tau_{fit}$  estimate appears to produce a larger variance than when using the  $\tau_{average}$  method.

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### 3577 6.4.2 Proton and pion separation

3578 Once we have the velocities of the particles, one can estimate their masses through  
3579 Eq. (6.19). The resulting mass spectra are shown in Fig. 6.32. I computed the masses  
3580 for the three arrival time estimates discussed above, and three different values of the  
3581 time resolution:  $\Delta\tau = 0.00$  (perfect time resolution),  $\Delta\tau = 0.10$  ns, and  $\Delta\tau = 0.70$  ns.  
3582 Although in all cases we have the same number of events, it appears as if the entries  
3583 in the histograms decrease as the time resolution increases. Sometimes, the particles  
3584 get unphysical values of  $\beta > 1$ , and in turn they do not contribute to the mass spectra.  
3585 This is more likely to happen for higher values of  $\Delta\tau$ .

3586 As noted before, the average hit time method produces the most robust estimates  
3587 when increasing  $\Delta\tau$ . Intuitively this makes sense, as by taking the mean one averages  
3588 out the effect of the Gaussian smearing. Going forward, I will use this arrival time  
3589 estimator, as it appears to be the best performing one.

3590 It is possible to use the velocity estimations to select a sample of protons. In this  
3591 case, I do so by dividing the relevant momentum range in bins of  $0.1 \text{ GeV}/c$ . For each  
3592 momentum bin, I compute the expected velocity for the protons via the inverse of Eq.  
3593 (6.19), and then take the fractional residuals of the measured velocities. Using that  
3594 distribution, I choose the cut that maximises the  $F_1$ -score of the proton selection.

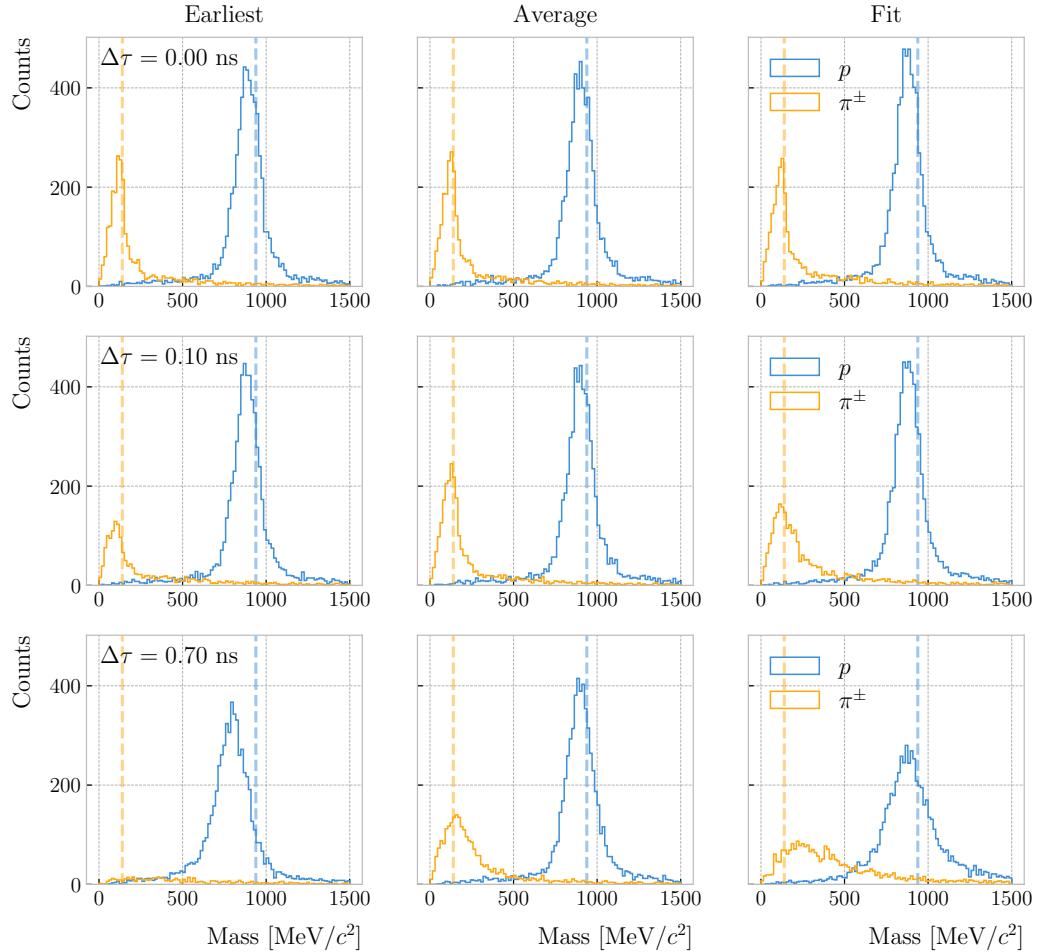
3595 The results can be seen in Fig. 6.33, for the case  $\Delta\tau = 0.10$  ns. As expected from  
3596 Fig. 6.31, the performance of the selection degrades rapidly with increasing momentum.  
3597 However, the purity is still around 75% at  $3.0 \text{ GeV}/c$ . This is likely to be sufficient, as  
3598 we do not expect protons or charged pions with higher energies from the beam neutrino  
3599 interactions.

3600 Figure 6.34

### 3601 6.5 Charged pion decay in flight

3602 As discussed previously, in GArSoft the TPC tracks are formed after a pattern recognition  
3603 algorithm and a Kalman filter are applied to the TPC clusters. These two steps can

## 6.5. CHARGED PION DECAY IN FLIGHT

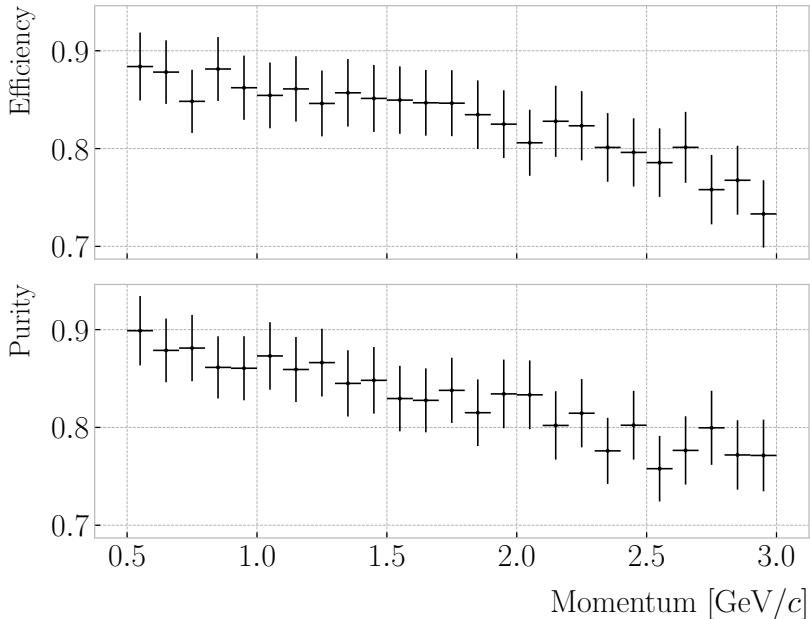


**Figure 6.32:** Mass spectra for  $p$  (blue) and  $\pi^\pm$  (yellow) particles, using different ECal time resolution values (from top to bottom, in ascending order), and arrival time estimates. From left to right: earliest hit time, average hit time, and fitted hit time. The dashed lines indicate the true masses of the particles.

3604 find discontinuities in the track candidates (e.g. due to a particle decay) when these  
 3605 so-called breakpoints are large enough. However, for some, more subtle, cases they may  
 3606 miss them and form a single reconstructed track. It has been noted in the literature  
 3607 that Kalman filters offer, as a by-product, additional information to form test statistics  
 3608 to identify these breakpoints [157, 158].

3609 Considering the mean life of the charged pion,  $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$  s, one  
 3610 can estimate that about 12% of the pions with momentum  $p \sim \mathcal{O}(500 \text{ MeV}/c)$  (roughly  
 3611 the peak of the pion momentum distribution in  $\nu_\mu$  CC interactions off argon) decay

## CHAPTER 6. PARTICLE ID IN ND-GAr



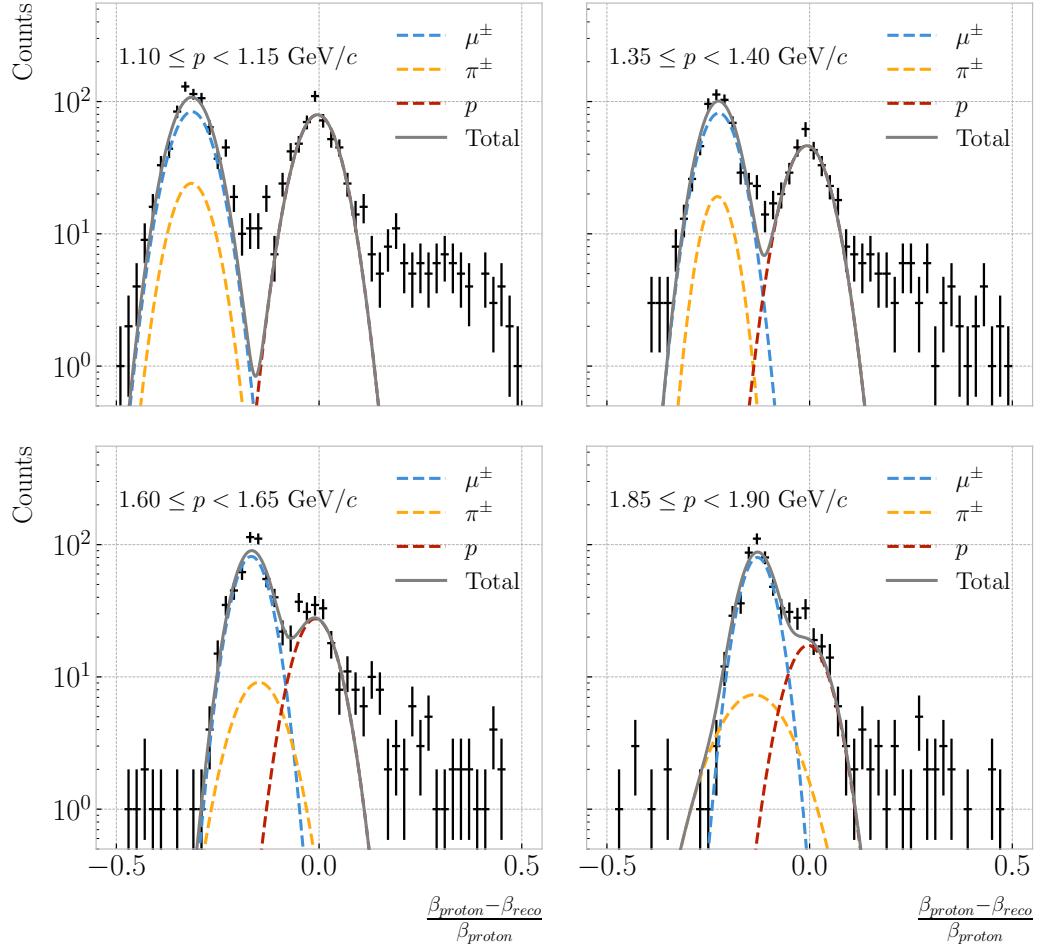
**Figure 6.33:** Efficiency (top panel) and purity (bottom panel) for the proton selection as a function of the momentum, for  $\Delta\tau = 0.10$  ns.

3612 inside the TPC. Figure 6.35 (left panel) shows the amount of charged pions decaying in  
 3613 the full TPC and fiducial volumes from an isotropic, monoenergetic sample of 100000  
 3614 negatively charged pions with  $p = 500$  MeV/ $c$ . We see that about 10% of those decayed,  
 3615 with more than half of them decaying inside the TPC fiducial volume.

3616 Figure 6.35 (right panel) shows an example event display of a charged pion (magenta  
 3617 line) decays in flight inside the TPC, but because the angle of the muon (blue line) is  
 3618 small both were reconstructed as one single track (black line). In this case, the composite  
 3619 track reaches the ECal, where it undergoes a muon-like interaction, thus being classified  
 3620 as a muon.

3621 A way to understand what decaying pion tracks were totally or partially reconstructed  
 3622 together with the daughter muon is looking at the relative energy contributions to the  
 3623 reconstructed track. In order to select a sample of such events, I require that a minimum  
 3624 50% of the total energy comes from the pion and at least 20% from the muon.

## 6.5. CHARGED PION DECAY IN FLIGHT



**Figure 6.34:** Distributions of the velocities measured by ToF with the inner ECal, for different momentum bins, in a FHC neutrino interaction sample. The Gaussian fits are performed around the maxima for each particle species.

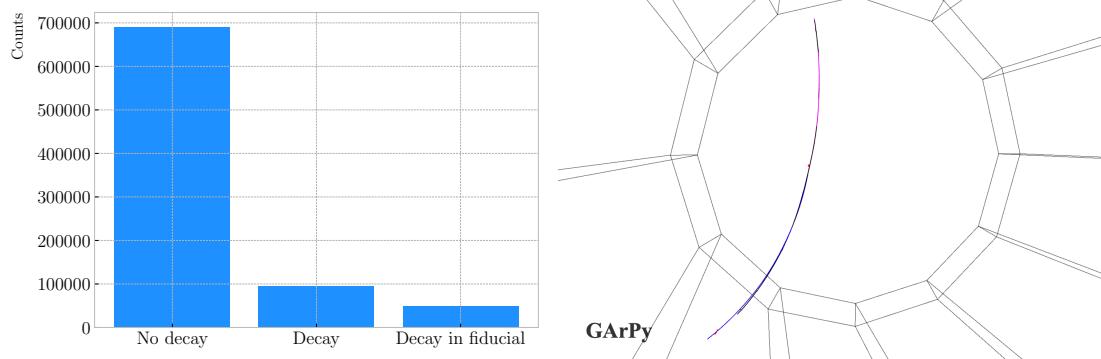
### 3625 6.5.1 Track breakpoints

3626 To identify potential decays we can use the information we obtain from the Kalman  
 3627 filter at each step of the fitted track. The simplest test we can think about is computing  
 3628 the  $\chi^2$  of the mismatch between all the parameters in the forward and the backward fits:

$$\chi_k^{2 (FB)} = (\hat{x}_k^B - \hat{x}_k^F)^T [V^{(\hat{x}_k, B)} + V^{(\hat{x}_k, F)}]^{-1} (\hat{x}_k^B - \hat{x}_k^F), \quad (6.23)$$

3629 where  $\hat{x}_k^F$ ,  $\hat{x}_k^B$  are the Kalman filter state vector estimates at step  $k$  in the forward and  
 3630 backward fits and  $V^{(\hat{x}_k, F)}$ ,  $V^{(\hat{x}_k, B)}$  the covariance matrices of  $\hat{x}_k^F$  and  $\hat{x}_k^B$  respectively.

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**Figure 6.35:** Left panel: number of non-decaying, decaying and decaying in the fiducial volume pions for a MC sample of 100000,  $p = 500$  MeV/c isotropic positively charged pions inside the TPC. Right panel: event display for a positive pion decaying inside the fiducial volume, with a single reconstructed track for the pion and muon system.

3631 Using the values of the  $\chi^2$  at measurement  $k$  for the forward and backward fits we can  
 3632 compute another  $\chi^2$  value that characterises the overall track fit:

$$\chi_{track}^2 = \chi_k^{2(F)} + \chi_k^{2(B)} + \chi_k^{2(FB)}, \quad (6.24)$$

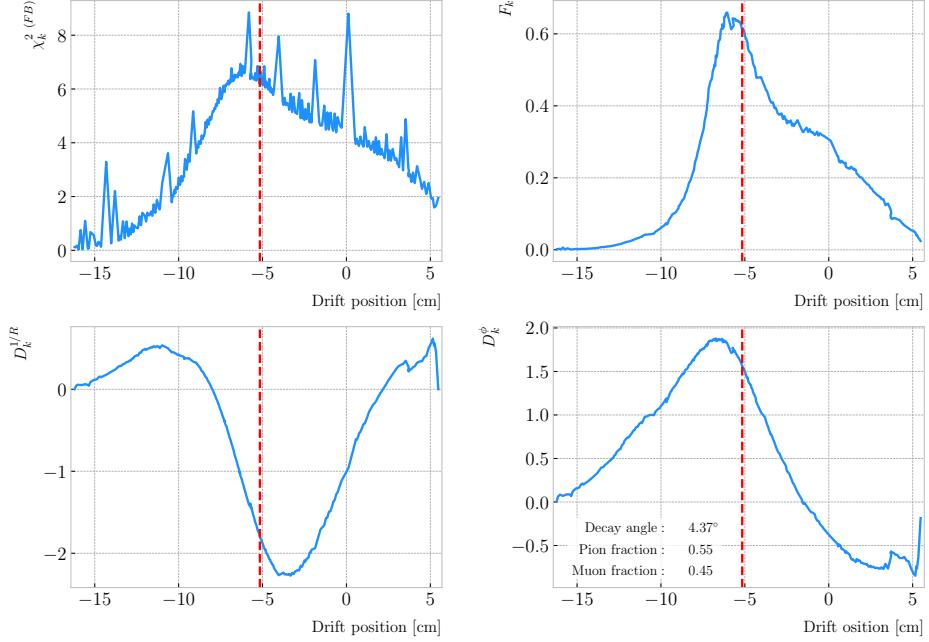
3633 which remains approximately constant for all  $k$ .

3634 An alternative approach proposed in the context of the NOMAD experiment was  
 3635 using a fit with a more elaborate breakpoint hypothesis, so we can perform a comparison  
 3636 of the  $\chi^2$  with and without breakpoints. This can be achieved by using some alternative  
 3637 parametrisation with extra parameters, which allows some of the track parameters to  
 3638 be discontinuous at certain points. A decay changes the momentum magnitude and  
 3639 direction, so we can use the new state vector:

$$\alpha = (y, z, 1/R_F, 1/R_B, \phi_F, \phi_B, \tan\lambda_F, \tan\lambda_B)^T. \quad (6.25)$$

3640 As we already have the estimates from the standard Kalman filter and their  
 3641 covariance matrices at each point, we do not need to repeat the Kalman fit for the new  
 3642 parametrisation. Instead, I can compute the values of  $\alpha$  at each point  $k$  that minimise

## 6.5. CHARGED PION DECAY IN FLIGHT



**Figure 6.36:** Values of  $\chi_k^2(FB)$  (top left panel),  $F_k$  (top right panel),  $D_k^{1/R}$  (bottom left panel) and  $D_k^\phi$  (bottom right panel) versus position along the drift direction for a reconstructed track in a positive pion decay event. The vertical red dashed line indicates the true location of the decay point.

3643 the  $\chi^2$  resulting from comparing them to  $\{\hat{x}_k^B, \hat{x}_k^F\}$ . Introducing the two  $5 \times 8$  matrices:

$$H^F = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}, \quad H^B = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad (6.26)$$

3644 we can write this as:

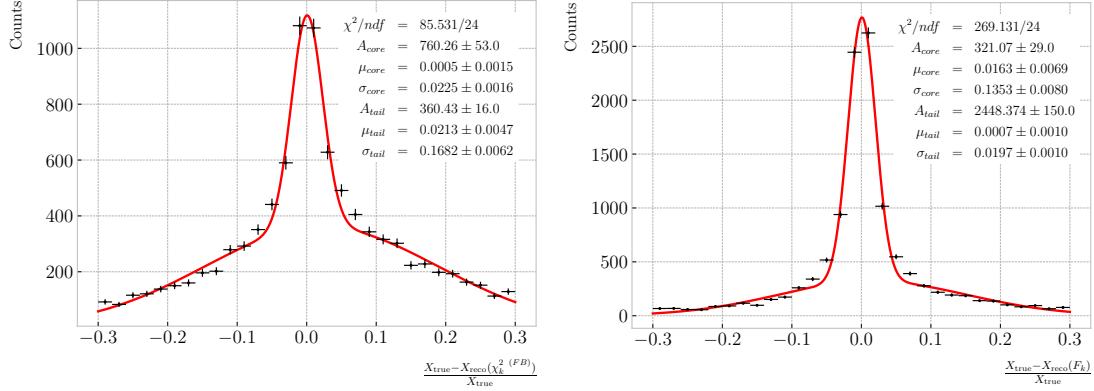
$$\begin{aligned} \chi_k^2(FB)(\alpha) &= (\hat{x}_k^F - H^F \alpha)^T \left[ V^{(\hat{x}_k, F)} \right]^{-1} (\hat{x}_k^F - H^F \alpha) \\ &\quad + (\hat{x}_k^B - H^B \alpha)^T \left[ V^{(\hat{x}_k, B)} \right]^{-1} (\hat{x}_k^B - H^B \alpha). \end{aligned} \quad (6.27)$$

3645 The minimum of  $\chi_k^2(FB)(\alpha)$  is found when the measured new state vector takes the

3646 value:

$$\hat{\alpha}_k = V^{(\hat{\alpha}_k)} H^T (V^{(\hat{x}_k)})^{-1} \hat{X}, \quad (6.28)$$

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**Figure 6.37:** Fractional residual distributions of the true and reconstructed decay position along the drift coordinate, using the position of the maximum of  $\chi_k^2(FB)$  (left panel) and  $F_k$  (right panel) as estimates of the decay position. Also shown are double Gaussian fits to these points (red lines).

where  $\hat{\mathbf{X}} = \{\hat{x}_k^B, \hat{x}_k^F\}$ ,  $V^{(\hat{x}_k)}$  is the block diagonal matrix formed by  $V^{(\hat{x}_k, F)}$  and  $V^{(\hat{x}_k, B)}$  and  $V^{(\hat{\alpha}_k)}$  is the covariance matrix of  $\hat{\alpha}_k$ , given by:

$$V^{(\hat{\alpha}_k)} = \left( H^T (V^{(\hat{x}_k)})^{-1} H \right)^{-1}. \quad (6.29)$$

From these new fit estimates we can compute the  $F$  statistic, which tells us whether the model with breakpoint provides a statistically significant better fit:

$$F_k = \left( \frac{\chi_{\text{track},k}^2 - \chi_{\text{full},k}^2}{8 - 5} \right) / \left( \frac{\chi_{\text{full},k}^2}{N - 8} \right). \quad (6.30)$$

One can also compute the signed difference of the duplicated variables divided by their standard deviation at each point. These represent how significant the discontinuity in each variable is. For any variable  $\eta$  we can write it as:

$$D_k^\eta = \frac{\hat{\eta}_k^B - \hat{\eta}_k^F}{\sqrt{\text{Var}[\hat{\eta}_k^F] + \text{Var}[\hat{\eta}_k^B] - 2\text{Cov}[\hat{\eta}_k^F, \hat{\eta}_k^B]}}. \quad (6.31)$$

In our case, the relevant ones to look at are  $D_k^{1/R}$  and  $D_k^\phi$ .

Figure 6.36 shows the values of  $\chi_k^2(FB)$ ,  $F_k$ ,  $D_k^{1/R}$  and  $D_k^\phi$  as functions of the position along the drift direction, for an example reconstructed track with 55.5% of the energy

## 6.5. CHARGED PION DECAY IN FLIGHT

3657 coming from the charged pion and 45.5% from the daughter muon. The true position of  
 3658 the decay is indicated (dashed red lines). Notice how  $\chi_k^2(FB)$  and  $F_k$ ,  $D_k^{1/R}$  reach their  
 3659 maxima near the decay point. In the former case this indicates a large forward-backward  
 3660 difference in the track fit. In the later it represents that the extended state vector  
 3661 improves the fit particularly around that point.

3662 I can estimate the decay position finding resolution by computing the difference  
 3663 between the  $X$  position of the maxima of  $\chi_k^2(FB)$  and  $F_k$  and the  $X$  position of the  
 3664 true decay. Figure 6.37 represent the the fractional residual distributions for both  
 3665 cases, from the sample of tracks containing pion decays. Fitting a double Gaussian to  
 3666 the distributions (red lines) I find a resolution of  $(3.31 \pm 0.15)\%$  and  $(6.94 \pm 0.31)\%$   
 3667 respectively.

3668 In principle, the  $F$ -statistic should follow a Fisher distribution with  $(8 - 5)$  and  
 3669  $(N - 8)$  degrees of freedom under the null hypothesis. In most of our cases  $N \sim \mathcal{O}(100)$ ,  
 3670 so the probability density functions will look very similar. In this case, it is safe to take  
 3671 the limit  $N \rightarrow \infty$  in the Fisher PDF:

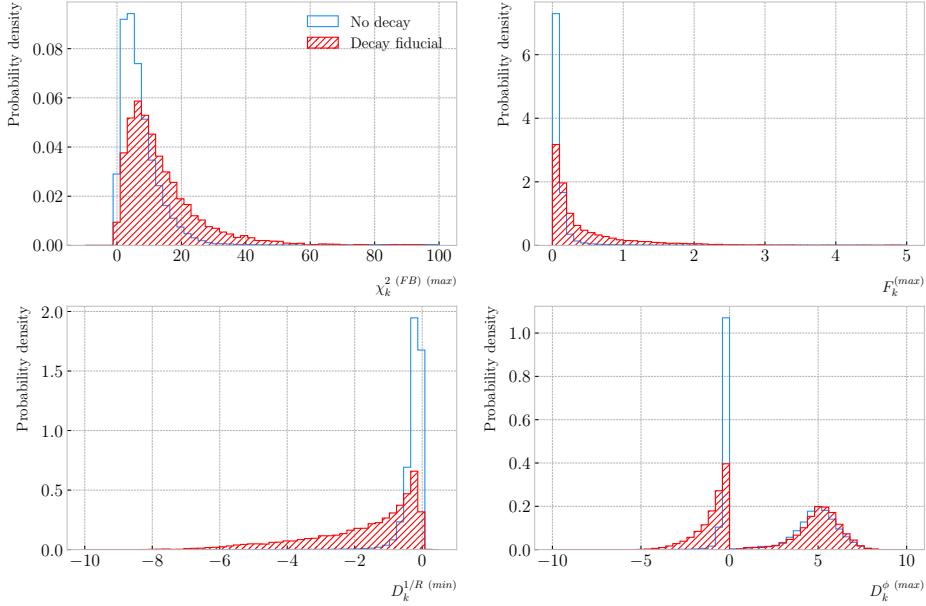
$$\begin{aligned}\tilde{f}(x; a - b) &= \lim_{N \rightarrow \infty} f(x; a - b, N - a) \\ &= \frac{2^{-\frac{a-b}{2}}}{\Gamma\left(\frac{a-b}{2}\right)} (a - b)^{\frac{a-b}{2}} x^{\frac{a-b}{2}-1} e^{-\frac{a-b}{2}x}.\end{aligned}\tag{6.32}$$

3672 In our case  $a - b = 8 - 5 = 3$ , so we would obtain a p-value of 0.05 at  $x = 2.60$ .

3673 Figure 6.38 contains the distributions of the maxima of  $\chi_k^2(FB)$ ,  $F_k$  and  $D_k^\phi$  and the  
 3674 minima of  $D_k^{1/R}$  for a sample of non-decaying pion tracks (blue) and another sample of  
 3675 reconstructed tracks containing part of the pion and the daughter muon from a decay  
 3676 inside the fiducial volume (red). Notice that, even though the values of  $F_k^{(max)}$  for the  
 3677 decay sample are typically larger than for the non-decaying one, just a small fraction of  
 3678 the events go beyond the aforementioned value of  $F = 2.60$ . Therefore, from a practical  
 3679 point of view, it is not the most efficient variable to use for selecting the decay events.

3680 However, looking at the  $D_k^{1/R \text{ (min)}}$  distribution we can see there is a big difference  
 3681 between non-decaying and decaying events in this variable. One can use a combination

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**Figure 6.38:** Distributions of the extreme values of  $\chi_k^2(FB)$  (top left panel),  $F_k$  (top right panel),  $D_k^{1/R}$  (bottom left panel) and  $D_k^\phi$  (bottom right panel) for non-decaying reconstructed pion tracks (blue) and tracks which include the decay inside the fiducial volume (red).

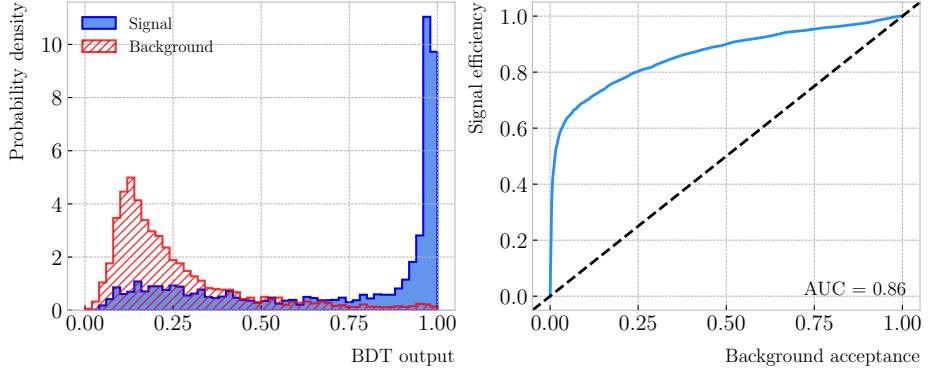
3682 of these four variables to distinguish between the pion decay events (signal) and the  
 3683 non-decaying pions (background).

3684 An approach to this classification could be using a boosted decision tree (BDT). One  
 3685 of the advantages of BDTs is that they are easy to interpret and identify the relative  
 3686 importance of the different input variables. Training a BDT with 400 estimators and a  
 3687 maximum depth of 4 I can obtain an efficient classification without overtraining. Figure  
 3688 6.39 (left panel) shows the distribution of probabilities predicted by the BDT for a test  
 3689 sample. The signal efficiency as a function of background acceptance, the so-called ROC  
 3690 curve, is shown in Fig. 6.39 (right panel). With a relative importance of 0.83, the most  
 3691 important variable turned out to be  $D_k^{1/R} \text{ (min)}$ .

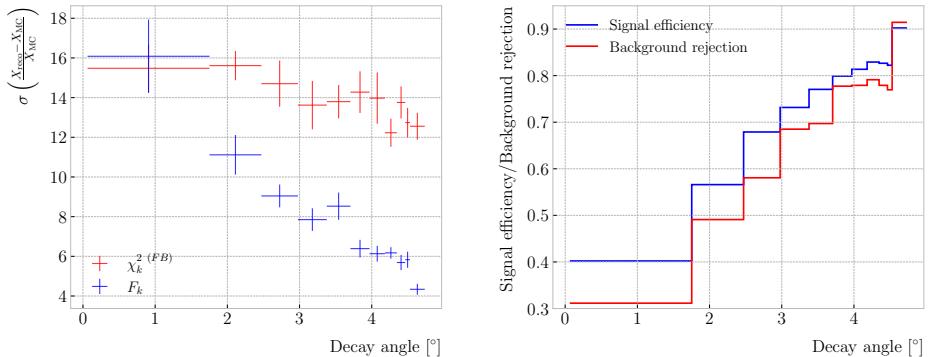
3692 One thing we can check is how the resolution to the decay and the signal efficiency in  
 3693 the classification changes with the true decay angle. Using an equal-frequency binning  
 3694 for the decay angles, we can repeat the previous steps for each bin.

3695 Figure 6.40 (left panel) shows the dependence on the decay angle of the decay finding

## 6.5. CHARGED PION DECAY IN FLIGHT



**Figure 6.39:** Left panel: distributions of the predicted probabilities assigned by the BDT classifier to a test sample of decaying pion+muon tracks (blue) and non-decaying pion tracks (red). Left: signal efficiency versus background acceptance (ROC curve) obtained from the BDT for the test sample.



**Figure 6.40:** Left panel: dependence of the decay position finding resolution on the true value of the decay angle for the  $\chi_k^2(FB)$  (red) and  $F_k$  (blue) methods. Right panel: signal efficiency (blue line) and background rejection (red line) from the BDT classifier versus true decay angle.

resolution. We can see that for the  $\chi_k^2(FB)$  maximum location method the resolution consistently lies between 12 to 16%. However, the  $F_k^{(\max)}$  approach gives a significantly better resolution for high angle values, reaching the 4 – 6% range for decay angles  $\geq 4^\circ$ .

For the classification dependence on the angle, I use the same classifier I trained before but evaluating the test sample for each individual angular bin. I compute the signal efficiency in each bin for a fixed value of the background rejection, in this case 90%. Similarly, for the background rejection estimation I use a fixed signal efficiency value of 90%. Figure 6.40 (right panel) represents the change in signal efficiency (blue)

## CHAPTER 6. PARTICLE ID IN ND-GAr

3704 and background rejection (red) with the value of the true decay angles.

### 3705 6.6 Neutral particle identification

#### 3706 6.6.1 ECal clustering

3707 Another important reconstruction item is the clustering algorithm of ECal hits in  
3708 GArSoft. The default module features a NN algorithm that treats all hits in the same  
3709 way, independently of the layer each hit comes from. However, the current ECal design  
3710 of ND-GAr has two very different types of scintillator layers. The inner layers are made  
3711 out of tiles, which provide excellent angular and timing resolutions. On the other hand,  
3712 the outer layers are cross scintillator strips. That way, an algorithm that treats hits  
3713 from both kinds of layers differently may be able to improve the current performance.

3714 Inspired by the reconstruction of T2K’s ND280 downstream ECal [159], the idea  
3715 was to put together a clustering module that first builds clusters for the different ECal  
3716 views (tiles, strips segmented in the  $X$  direction and strips segmented in  $Y$  direction),  
3717 and then tries to match them together to form the final clusters.

3718 Working on a module-by-module basis, the algorithm first separates the hits depending  
3719 on the layer type they come from. Then, it performs a NN clustering for the 3 sets of  
3720 hits separately. For the tile hits it clusters together all the hits which are in nearest-  
3721 neighbouring tiles and nearest-neighbouring layers, for strip hits it looks at nearest-  
3722 neighbouring strips and next-to-nearest-neighbouring layers (as the layers with strips  
3723 along the two directions are alternated). For strip clusters an additional cut in the  
3724 direction along the strip length is needed.

3725 After this first clustering I then apply a recursive re-clustering for each collection  
3726 of strip clusters based on a PCA method. In each case, we loop over the clusters with  
3727  $N_{hits} \geq 2$ , computing the centre of mass and three principal components. Propagating  
3728 these axes up to the layers of the rest of the clusters, we check if the propagated point  
3729 and the centre of mass of the second cluster are within next-to-nearest-neighbouring  
3730 strips. An additional cut in the direction along the strip length is also needed. Moreover,

## 6.6. NEUTRAL PARTICLE IDENTIFICATION

3731 I require that the two closest hits across the two clusters are at most in next-to-nearest-  
3732 neighbouring strips. I merge the clusters if these three conditions are satisfied. The  
3733 re-clustering is repeated until no more cluster pairs pass the cuts.

3734 The clusters in each strip view are combined if their centres of mass are close enough  
3735 and they point in the same direction. An alternative approach for the strip cluster  
3736 merging could be to compute the overlap between the ellipsoids defined by the principal  
3737 axes of the clusters, and then merge the pair if the overlap exceeds some threshold.  
3738 Further study is needed to understand if this change would have an impact in the overall  
3739 clustering performance.

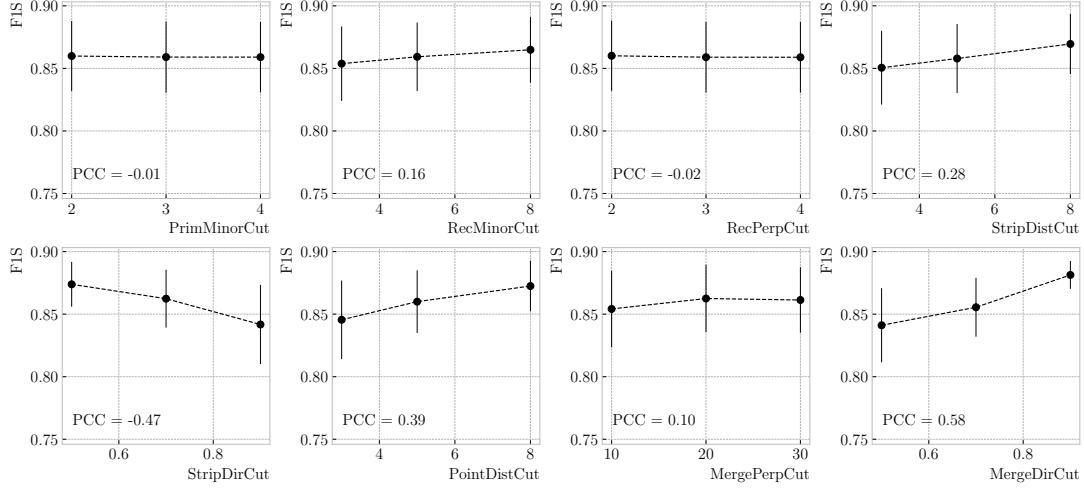
3740 To merge the tile clusters to the combined strip clusters I propagate the principal  
3741 axis of the strip cluster towards the inner layers, up to the centre of mass layer of the  
3742 tile cluster. I merge the clusters if the distance between the propagated point and the  
3743 centre of mass is below a certain cut.

3744 The last step is to check if clusters in neighbouring modules should be merged  
3745 together, both across two barrel modules, across end cap modules and between barrel  
3746 end cap modules. I check the distance between the two closest hits in the pair of clusters  
3747 and merge them if it passes this and an additional direction cut.

3748 Figure ?? presents an example of the clustering steps relevant for strip layer hits, from  
3749 the input hits (top left panel) to the NN clustering (top right panel) and re-clustering  
3750 (bottom left panel) for each strip view and the final merging strip clusters (bottom  
3751 right panel). It shows the hits from a single ECal barrel module in a  $\nu_\mu$  CC interaction  
3752 event with a neutral pion and a proton in the final state. The two clusters on the left  
3753 correspond to the photon pair from the  $\pi^0$  decay and the one on the upper right corner  
3754 is associated to the proton.

3755 This algorithm has a total number of eight free parameters that need to be optimised.  
3756 I used a sample of 1000  $\nu_\mu$  CC interactions in order to obtain the optimal configuration of  
3757 clustering parameters. This sample was generated up to the default ECal hit clustering  
3758 level, so then I could run the new clustering algorithm each time with a different  
3759 configuration of parameters. As the number of parameters is relatively large, I only

## CHAPTER 6. PARTICLE ID IN ND-GAr



**Figure 6.41:** Mean values of the  $F_1$ -score marginal distributions for the different free parameters of the new clustering algorithm, with the error bars representing one standard deviation around the mean. The  $F_1$ -score values were computed for the 6561 possible parameter configurations using 1000  $\nu_\mu$  CC interaction events.

**Table 6.5:** Summary of parameters and sampled values used in the optimisation of the clustering algorithm.

Name	Units	Sampled values	Description
PrimMinorCut	strips	2, 3, 4	Distance along strip length in NN clustering
RecMinorCut	strips	3, 5, 8	Distance between propagated point and CM along strip length in re-clustering
RecPerpCut	strips	2, 3, 4	Closest hit pair distance in re-clustering
StripDistCut	strips	3, 5, 8	Distance between CMs in strip cluster merging
StripDirCut	cos	0.5, 0.7, 0.9	Main axes direction cut in strip cluster merging
PointDistCut	tiles	3, 5, 8	Distance between propagated point and CM in strip-tile matching
MergePerpCut	cm	10, 20, 30	Closest hit pair distance in module merging
MergeDirCut	cos	0.5, 0.7, 0.9	Main axes direction cut in module merging

3760 performed a coarse-grained scan of the parameter space. Sampling each of the eight  
 3761 parameters at three different points each I obtain 6561 different configurations. These  
 3762 parameters, together with the used values, are summarised in Tab. 6.5.

3763 In order to measure the performance of the clustering, I use a binary classification  
 3764 approach. For each formed cluster, I identify the Geant4 Track ID of the matching MC  
 3765 particle and the energy fraction of each hit. Then, I assign to each cluster the Track ID  
 3766 with the highest total energy fraction. For each of the different Track IDs associated to

## 6.6. NEUTRAL PARTICLE IDENTIFICATION

3767 the clusters, I select the cluster with the highest energy (only from the hits with the  
3768 same Track ID). I identify such a cluster as the main cluster for that Track ID. I count  
3769 as true positives (TPs) the hits with the correct Track ID in each main cluster. False  
3770 positives (FPs) are the hits with the incorrect Track ID for the cluster they are in, not  
3771 only main clusters. The false negatives (FNs) are the hits with the correct Track ID in  
3772 clusters other than the main.

3773 Figure 6.41 shows the computed  $F_1$ -score values for the different cuts. In each case,  
3774 the central value represents the mean of the  $F_1$ -score distribution for the specified value  
3775 of the corresponding variable and the vertical error bar represents one standard deviation  
3776 around the mean. Also shown are the Pearson correlation coefficients of these central  
3777 values. We can see that five of the variables have a sizeable effect on the  $F_1$ -score, with  
3778 an absolute difference between the last and first values as big as 4%.

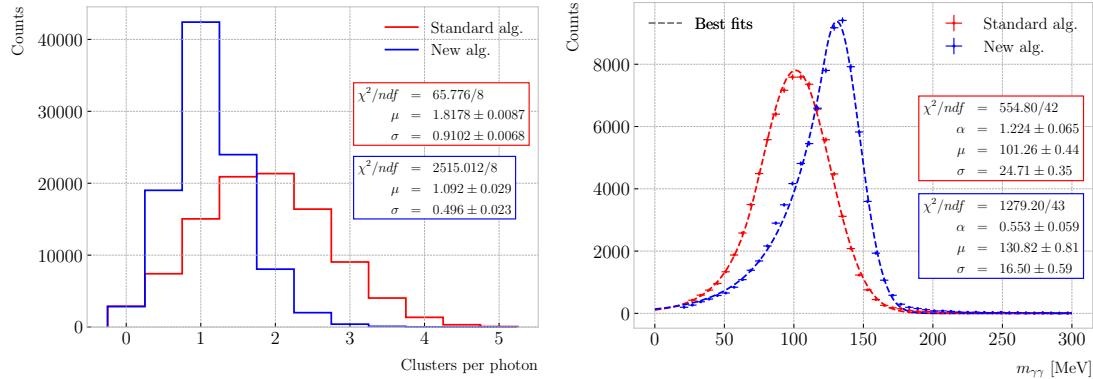
3779 The working configuration is obtained as follows. I first select all configurations  
3780 with purity  $\geq 90\%$ . Among those, I choose the combinations that yield the maximum  
3781  $F_1$ -score. If more than one configuration remains I select the one with the highest  
3782 sensitivity. Doing so, I end up with a parameter configuration with an efficiency of 88%  
3783 and a 90% purity. Compared with the default algorithm, which gives an efficiency of  
3784 76% and a purity of 91% for the same sample, I have managed to improve the efficiency  
3785 by a factor of 1.16.

### 3786 6.6.2 $\pi^0$ reconstruction

3787 One of the potential applications of the new ECal hit clustering is the reconstruction of  
3788 neutral particles, in particular pions. Neutral pions decay promptly after being produced,  
3789 through the  $\pi^0 \rightarrow \gamma\gamma$  channel ( $98.823 \pm 0.034\%$ ) of the time. The photon pair does  
3790 not leave any traces in the HPgTPC (unless one or both of them converts into an  
3791 electron-positron pair), but each of them will produce an electromagnetic shower in  
3792 the ECal.

3793 To test the potential impact of the new algorithm in  $\pi^0$  reconstruction, I generated  
3794 a MC sample of single, isotropic neutral pions inside the HPgTPC. All pions were

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**Figure 6.42:** Left panel: distributions of the number of ECal clusters per photon from  $\pi^0$  decays for the standard (red) and new (blue) clustering algorithms. Right panel: reconstructed invariant mass distributions for photon pairs from single  $\pi^0$  events using the standard (red) and new (blue) ECal clustering algorithms.

3795 generated with a momentum  $p = 500$  MeV and their initial positions were uniformly  
 3796 sampled inside a  $2 \times 2 \times 2$  m box aligned with the centre of the TPC. I ran both the  
 3797 default and the new clustering algorithms, using for the latter the optimised configuration  
 3798 discussed above.

3799 The first thing to notice is that the number of clusters produced per photon has  
 3800 decreased. Figure 6.42 (left panel) shows these distributions for the default (red) and  
 3801 new (blue) algorithms. Using a simple Gaussian fit, we see that the mean number of  
 3802 ECal clusters per photon went from  $1.82 \pm 0.01$  to  $1.09 \pm 0.03$ . This effectively means that  
 3803 with the new algorithm the ECal activity of one true particle is typically reconstructed  
 3804 as a single object. From the reconstruction point of view this can be an advantage. As  
 3805 now most of the photon energy ends up in a single ECal cluster, I can simply use cluster  
 3806 pairs to identify the  $\pi^0$  decay.

3807 In general, one calculates the invariant mass of the photon pair as:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \theta)}, \quad (6.33)$$

3808 where  $E_i$  are the energies of the photons and  $\theta$  the opening angle between them. In this  
 3809 case I can use the energies deposited in the ECal and their incident directions. This  
 3810 quantity is computed for all possible pairs of clusters, using their position together with

## 6.6. NEUTRAL PARTICLE IDENTIFICATION

3811 the true decay point. In a more realistic scenario, e.g.  $\nu_\mu$  CC interaction, one could use  
 3812 the position of the reconstructed primary vertex instead. I also tried to use the principal  
 3813 direction of the clusters, but that approach gave considerably worse results. For each  
 3814 event I only keep the pair with an invariant mass closer to the true  $\pi^0$  mass value.

3815 Figure 6.42 (right panel) shows the invariant mass distributions for the photon pairs  
 3816 we get using the default (red) and the new (blue) ECal clustering algorithms. For the fit  
 3817 I used a modified version of the Crystal Ball function [160], obtained by taking the limit  
 3818 where the parameter controlling the power-law tail goes to infinity:

$$f(x; N, \mu, \sigma, \alpha) = N \cdot \begin{cases} e^{\frac{\alpha(2x-2\mu+\alpha\sigma)}{2\sigma}}; & x \leq \mu - \alpha\sigma, \\ e^{-\frac{(x-\mu)^2}{2\sigma^2}}; & x > \mu - \alpha\sigma. \end{cases} \quad (6.34)$$

3819 Comparing the fitted mean and standard deviation values for the Gaussian cores, we  
 3820 see that the distribution for the new algorithm is a 67% narrower and also peaks much  
 3821 closer to the true  $m_{\pi^0}$  value, going from  $101.3 \pm 0.4$  MeV to  $130.8 \pm 0.6$  MeV.



3822

3823

# Event selection in ND-GAr

## 3824 7.1 Data sample

## 3825 7.2 $\nu_\mu$ CC selection

3826 In some cases, it is interesting to divide the signal events by interaction mode. I will  
 3827 distinguish between charged-current quasi-elastic (CCQE), coherent (CCCOH), resonant  
 3828 (CCRES), and deep-inelastic (CCDIS) interactions. I also use a separate category for  
 3829 the interactions not included in any of the others (CCOther).

3830 For this selection, I use the following categorisation for the background events:

3831 • Out of FV: if the true neutrino vertex lies outside the defined FV.

3832 • NC: if the event is a true neutral-current event.

3833 •  $\bar{\nu}_\mu$  CC: if the true neutrino candidate is of muon antineutrino flavour.

3834 • Other: if the event is not signal nor falls in any of the other background categories.

3835 For a particle position to lie within the FV it must satisfy:

$$\vec{x}_{\text{start}} \in \left\{ \vec{x} \in \mathbb{R}^3 \mid |x_0| \leq L_{\text{FV}} \text{ \& } \sqrt{x_1^2 + x_2^2} \leq R_{\text{FV}} \right\}, \quad (7.1)$$

## CHAPTER 7. EVENT SELECTION IN ND-GAR

**Table 7.1:** Event rates in ND-GAr.

Process	Events/ton/year	
	$1.1 \times 10^{21}$ POT/year	$1.9 \times 10^{21}$ POT/year
All $\nu_\mu$ -CC	$1.60 \times 10^6$	$2.83 \times 10^6$
CC $0\pi$	$5.28 \times 10^5$	$9.35 \times 10^5$
CC $1\pi^\pm$	$3.02 \times 10^5$	$5.34 \times 10^5$
CC $1\pi^0$	$1.65 \times 10^5$	$2.92 \times 10^5$
CC $2\pi$	$3.18 \times 10^5$	$5.63 \times 10^5$
CC $3\pi$	$1.36 \times 10^5$	$2.41 \times 10^5$
CC other	$1.52 \times 10^5$	$2.69 \times 10^5$
All $\bar{\nu}_\mu$ -CC	$7.54 \times 10^4$	$1.33 \times 10^5$
All NC	$5.50 \times 10^5$	$9.73 \times 10^5$
All $\nu_e$ -CC	$2.70 \times 10^4$	$4.78 \times 10^4$

3836 in the reference frame of the HPgTPC. For convenience, I define:

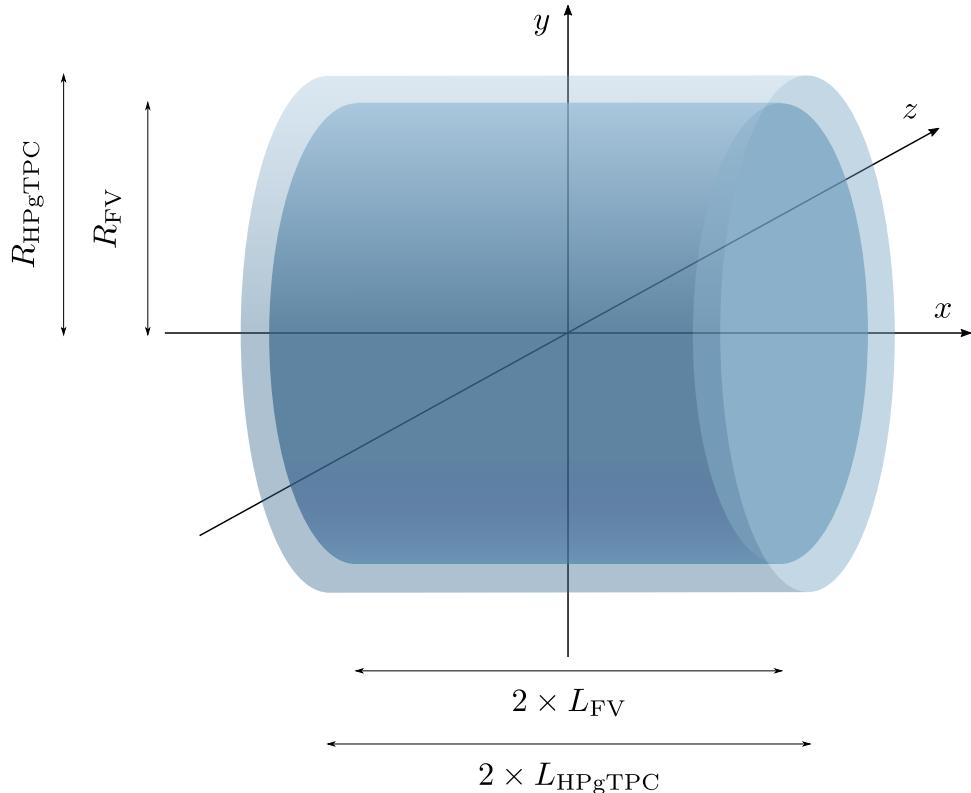
$$\begin{aligned}\Delta R_{\text{FV}} &= R_{\text{HPgTPC}} - R_{\text{FV}}, \\ \Delta L_{\text{FV}} &= L_{\text{HPgTPC}} - L_{\text{FV}},\end{aligned}\tag{7.2}$$

3837 where  $R_{\text{HPgTPC}}$  and  $L_{\text{HPgTPC}}$  refer to the radius and the half-length of the HPgTPC,  
3838 respectively.

3839 The key to the CC selection is the identification of a primary muon candidate.  
3840 Typically, this is the longest track in the event. However, sometimes protons and pions  
3841 leave tracks longer than that of the muon. This is particularly important in the GAr  
3842 medium, considerably less dense than the LAr. For this reason, the muon identification  
3843 in ND-GAr relies mainly on the capabilities of the ECal.

- 3844 1. Event contains reconstructed particles.
- 3845 2. Select particles with reconstructed negative charge,  $q_{\text{reco}} = -1$ .
- 3846 3. Select particles passing the muon score cut,  $\mu_{\text{score}} \geq \mu_{\text{score}}^{\text{cut}}$ .
- 3847 4. Keep reconstructed particle with the highest momentum,  $\max [p_{\text{reco}}]$ .

### 7.3. CHARGED PION IDENTIFICATION



**Figure 7.1:** Schematic diagram of the HPgTPC including the fiducial volume (FV). In this case the FV is given by  $\Delta L_{\text{FV}} = 30.0$  cm and  $\Delta R_{\text{FV}} = 30.0$  cm.

- 3848        5. Alternatively, keep reconstructed particle with the highest muon score,  $\max [\mu_{\text{score}}]$ .
- 3849        6. Check that the particle starts within the FV.

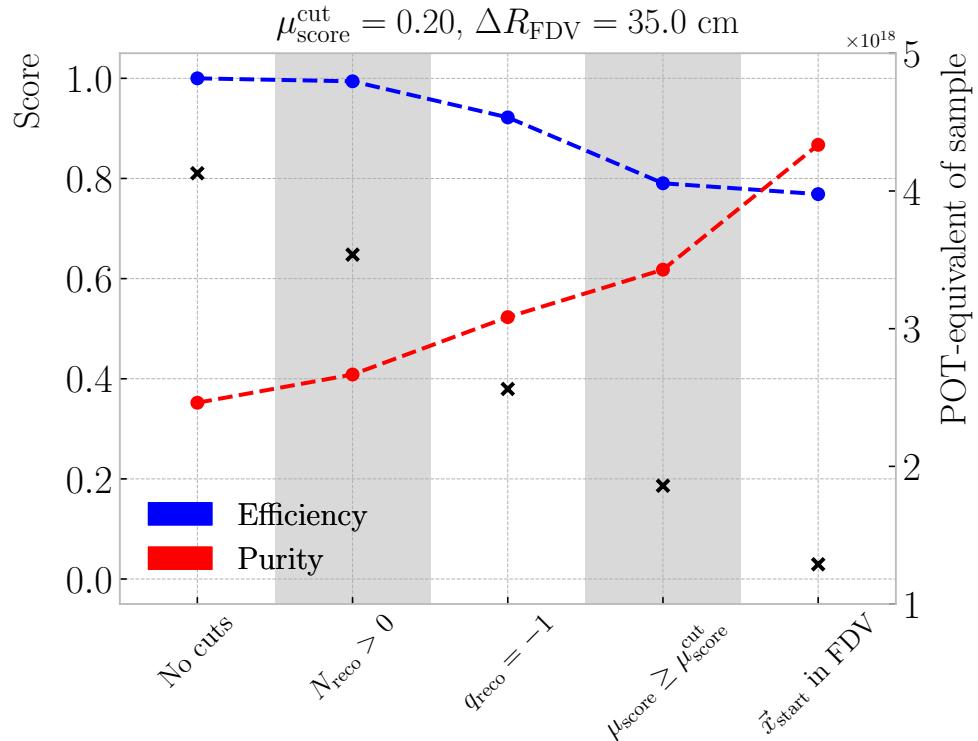
## 3850    7.3    Charged pion identification

### 3851    7.3.1    $\nu_\mu$ CC $1\pi^\pm$ selection

## CHAPTER 7. EVENT SELECTION IN ND-GAR

**Table 7.2:** Event rates in ND-GAr.

Cut #	Selection cut	Events	Passing rates
0	Total number of events (No cuts)	100000	100.00% (100.00%)
1	At least one reconstructed particle	85680	85.68% (85.68%)
2	Negatively charged particles only	62054	62.05% (72.43%)
3	$\mu_{\text{score}} > \text{threshold}$	45035	45.03% (72.57%)
4	$\vec{x}_{\text{start}}$ in FDV	31212	31.21% (69.31%)



**Figure 7.2**

8

3852

## Conclusions

3853



A

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An appendix

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