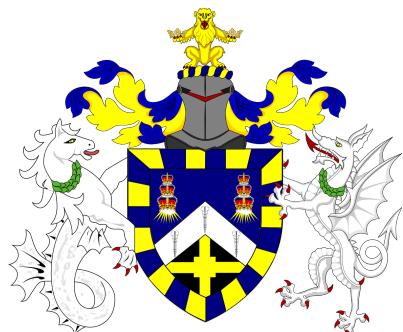


¹ ADVANCING NEUTRINO
² DETECTION AND TRIGGERING IN
³ DUNE



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⁶ Submitted in partial fulfillment of the requirements
⁷ of the Degree of Doctor of Philosophy

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¹⁰ December 2023

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²⁹ Abstract

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O time, thou must untangle this, not I.
It is too hard a knot for me to untie!

Twelfth Night

SHAKESPEARE

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³⁹ In principio fu la Maestra Manuela.

⁴⁰ A heartfelt thank you to . . . for accepting to be the referees of this thesis, and for
⁴¹ the thought-provoking discussions we shared. Their comments brought this manuscript
⁴² to a significant improvement.

⁴³ I feel privileged to have this many eminent researchers in my committee. A very big
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⁴⁵ Thank you to . . .

⁴⁶ Un ringraziamento va anche agli amici triestini di nascita, di adozione, o di passaggio,
⁴⁷ matematici, sballerine, o altro, oggi sparpagliati per il mondo a formare una famiglia
⁴⁸ grazie alla quale uno non si sente mai troppo solo e lontano da tutti. Tanto siamo
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⁴⁵⁷ Chapter 1

⁴⁵⁸ Introduction

459 **Chapter 2**

460 **Neutrino physics**

461 Ever since they were postulated in 1930 by Wolfgang Pauli to explain the continuous
462 β decay spectrum [17] and later found by Reines and Cowan at the Savannah River
463 reactor in 1953 [18], neutrinos have had a special place among all other elementary
464 particles. They provide a unique way to probe a wide range of quite different physics,
465 from nuclear physics to cosmology, from astrophysics to colliders. Moreover, there is
466 compelling evidence to believe that the study of neutrinos may be key to unveil different
467 aspects of physics beyond the SM, difficult to test elsewhere.

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

471 **2.1 Neutrinos in the SM**

472 By definition, in the SM there are no right-handed neutrino fields. A direct implication
473 of this fact is that neutrinos are strictly massless within the SM. This follows from the
474 experimental observation that all neutrinos produced via weak interactions are pure
475 left-handed helicity states (and similarly antineutrinos are pure right-handed states).
476 The hypothetical existence of right-handed neutrinos could be indirectly inferred from
477 the observation of non-zero neutrino masses, nevertheless the existence neutrino masses

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478 is not a sufficient condition for the existence of such fields.

479 In the SM neutrinos appear in three flavours, namely ν_e , ν_μ and ν_τ . These are
480 associated with the corresponding charged leptons e , μ and τ , in such a way that the
481 charged current part of the Lagrangian coupling them is diagonal. As in the electroweak
482 theory neutrinos are coupled to the Z boson in a universal way, by measuring the so-called
483 invisible decay width of the Z we have an estimate of the number of light (i.e. lighter
484 than the Z boson) neutrino flavours. This number was measured by LEP in a combined
485 analysis of $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow$ hadrons to be $N_\nu = 2.9840 \pm 0.0082$ [19].

486 2.2 Neutrino oscillations

487 The evidence for neutrino oscillation [20], and therefore the existence of non-zero neutrino
488 masses, constitutes one of the groundbreaking discoveries of modern Physics and has
489 acted as driving force for Beyond the Standard Model (BSM) Physics. The minimal
490 extension of the Standard Model (SM) we can do to address these phenomena is
491 introducing distinct masses for at least two of the neutrinos. This way, we are left with
492 three neutrino mass eigenstates ν_1 , ν_2 and ν_3 , with masses m_1 , m_2 and m_3 respectively,
493 which in general will not coincide with the flavour eigenstates ν_e , ν_μ and ν_τ .

494 The way to relate these two sets of neutrino eigenstates is via a 3×3 unitary matrix,
495 called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [21, 22], as:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad (2.1)$$

496 where the Greek index α denotes the flavour $\{e, \mu, \tau\}$ and the Latin index i the associated
497 masses $\{1, 2, 3\}$. This leptonic mixing matrix may be parametrized in terms of 6
498 parameters, 3 of which are mixing angles θ_{12} , θ_{13} and θ_{23} , one CP-violating phase δ_{CP}

2.2. Neutrino oscillations

499 and 2 Majorana phases α and β :

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}, \quad (2.2)$$

500 where $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$. This matrix is analogous to the Cabibbo-Kobayashi-
501 Maskawa (CKM) matrix in the quark sector. If neutrinos are Dirac fermions, we can
502 drop the Majorana phases in the PMNS matrix. But, in any case, these phases play no
503 role on the neutrino oscillations.

504 2.2.1 Oscillations in vacuum

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

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^3 U_{\alpha i}^* e^{-iE_i t} |\nu_i(t=0)\rangle, \quad (2.3)$$

507 as the mass eigenstates are also eigenstates of the free Hamiltonian. Now, if we express
508 the mass eigenstates as a superposition of flavour eigenstates, the last expression can be
509 rewritten as:

$$|\nu_\alpha(t)\rangle = \sum_{i=1}^3 U_{\beta i} e^{-iE_i t} U_{\alpha i}^* |\nu_\beta\rangle. \quad (2.4)$$

510 This way, the probability for the neutrino to transition from flavour α to flavour β
511 will be given by:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{i=1}^3 U_{\beta i} e^{-iE_i t} U_{\alpha i}^* \right|^2. \quad (2.5)$$

512 A usual approximation to take at this point is to consider ultra-relativistic neutrinos,
513 i.e. $E \approx |\vec{p}|$, so we can write the dispersion relations as:

$$E_i = \sqrt{p^2 + m_i^2} \approx E + \frac{m_i^2}{2E}, \quad (2.6)$$

Chapter 2. Neutrino physics

514 so we can write the oscillation probability as:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) &= \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* e^{-i \frac{\Delta m_{ij}^2}{2E} t} \\ &= \delta_{\alpha\beta} - 4 \sum_{i < j} \Re [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left(\frac{\Delta m_{ij}^2}{4E} t \right) \\ &\quad + 2 \sum_{i < j} \Im [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin \left(\frac{\Delta m_{ij}^2}{2E} t \right), \end{aligned} \quad (2.7)$$

515 where Δm_{ij}^2 is the difference of the squared masses of the j th and i th neutrino mass
 516 eigenvalues. At this point, it is usual to write the phase responsible for the oscillations
 517 as (under the approximate assumption $t \approx L$):

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{4E} L \simeq 1.27 \frac{\Delta m_{ij}^2}{(\text{eV}^2)} \frac{L}{(\text{km})} \frac{(\text{GeV})}{E}. \quad (2.8)$$

518 Notice that, in the case of antineutrinos the only difference would be the sign of the
 519 last term in the oscillation probability. This way, one can write the CP asymmetry as:

$$\begin{aligned} A_{CP}^{\alpha\beta} &= P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \\ &= 4 \sum_{i < j} \Im [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin 2\Delta_{ij}. \end{aligned} \quad (2.9)$$

520 2.2.2 Oscillations in matter

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

527 The first proposed model to account for neutrino oscillations in matter was proposed
 528 by Mikhaev, Smirnov and Wolfenstein (MSW) [23]. It relies on the fact that, as the
 529 only charged lepton present in ordinary matter is the electron, electron neutrinos can

2.2. Neutrino oscillations

530 undergo both charged and neutral-current interactions with matter whereas for muon
531 and tau neutrinos just neutral currents are possible.

532 2.2.3 Current status of neutrino oscillations

533 A wide range of neutrino experiments provide experimental input to the neutrino
534 oscillation framework, both using natural or synthetic neutrino sources. The results
535 from one of the neutrino global fit analyses, shown in Tab. 2.1¹, summarise well our
536 current understanding of the different oscillation parameters.

537 **Solar neutrino experiments** detect neutrinos produced in thermonuclear reactions
538 inside the Sun, mainly from the so-called *pp* chain and the CNO cycle. These neutrinos
539 have a typical energy in the range from 0.1 to 20 MeV. These experiments (Homestake
540 [24], GALLEX [25], SAGE [26], Borexino [27], Super-Kamiokande [28] and SNO [29])
541 provide the best sensitivities to θ_{12} and Δm_{21}^2 .

542 **Atmospheric neutrino experiments** detect the neutrino flux produced when
543 cosmic rays scatter with particles in Earth's atmosphere. These collisions generate particle
544 showers that eventually produce electron and muon neutrinos (and antineutrinos). Their
545 energies range from few MeV to about 10^9 GeV. Experiments, like Super-Kamiokande
546 [30] and IceCube [31] use atmospheric neutrinos to measure oscillations and are specially
547 sensitive to θ_{23} and Δm_{32}^2 .

548 **Reactor neutrino experiments** look for the $\bar{\nu}_e$ spectrum produced by nuclear
549 reactors, with energies in the MeV scale. Depending on the distance to the source,
550 long-baseline experiments like KamLAND [32] are sensitive to the solar mass splitting
551 Δm_{21}^2 whereas much shorter baseline experiment such as RENO [33] or DayaBay [34]
552 measure θ_{13} and Δm_{31}^2 .

553 **Accelerator experiments** measure neutrino fluxes generated in particle accelerators.
554 Usually mesons are produced in the accelerator to be focused into a beam, then some
555 decay to muon neutrinos and the rest are absorbed by a target. Depending on the

¹These 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.

Chapter 2. Neutrino physics

Table 2.1: Summary of neutrino oscillation parameters determined in the Neutrino Global Fit of 2020 [16].

Parameter	Best fit $\pm 1\sigma$	3σ range
Δm_{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 ± 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
δ_{CP}/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76 – 2.00
δ_{CP}/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11 – 1.87

556 configuration one can obtain a beam made of mostly neutrinos or antineutrinos. The
 557 typical energies of these neutrinos are in the GeV range. Experiments such as NOvA
 558 [35], T2K [36], MINOS [37], OPERA [?] and K2K [38] (and in the future DUNE [39])
 559 are primarily sensitive to θ_{13} , θ_{23} and Δm_{32}^2 . Also, in the coming years DUNE [39] and
 560 Hyper-Kamiokande [40] will be sensitive to δ_{CP} .

561 2.3 Open questions in the neutrino sector

562 A crucial question that remains open these days, and is of vital importance for oscillation
 563 phenomena, is whether the mass eigenvalue ν_3 is the heaviest (what we call normal
 564 ordering) or the lightest (referred to as inverted ordering) of the mass eigenstates. In
 565 other words, this means that we do not know the sign of Δm_{32}^2 , so we can either have
 566 $m_1 < m_2 < m_3$ (NO) or $m_3 < m_1 < m_2$ (IO).

567 Another big puzzle is related to the value of δ_{CP} . Nowadays it is poorly constrained,
 568 with all values between π and 2π being consistent with data. A prospective measurement
 569 different from $\delta_{CP} = 0, \pi$ will predict CP-violation in the leptonic sector, and thus

2.3. Open questions in the neutrino sector

570 contribute along with the one measured in the quark sector to the total amount of
571 CP-violation. Although it is true that these two contributions by themselves are not
572 enough to explain the matter anti-matter asymmetry in our universe, the amount of
573 CP-violation in the leptonic sector can be key to explain such imbalance.

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

576 Notwithstanding, there are other mysteries that can not be unveiled just by conducting
577 oscillation experiments, as certain quantities do not influence these phenomena. Among
578 these there is the question of the absolute values of the neutrino masses. Depending
579 on the value of the lightest of the neutrino masses we can have different mass spectra,
580 from hierarchical $m_1 \ll m_2 < m_3$ (NO) or $m_3 \ll m_1 < m_2$ (IO) to quasi-degenerate
581 $m_1 \simeq m_2 \simeq m_3$.

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

589 Chapter 3

590 The Deep Underground Neutrino
591 Experiment

592 The Deep Underground Neutrino Experiment (DUNE) is a next generation long-baseline
593 neutrino experiment [1]. It will aim to address several questions in neutrino physics,
594 study neutrinos from astrophysical sources and search for beyond the standard model
595 physics.

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

599 3.1 Overview

600 The main physics goals of DUNE are:

- 601 • measure the neutrino mass hierarchy, the amount of CP violation in the leptonic
602 sector and the θ_{23} octant,
- 603 • detect rare low energy neutrino events, like neutrinos from supernova bursts, and
- 604 • search for proton decay and other beyond the standard model phenomena.

Chapter 3. The Deep Underground Neutrino Experiment

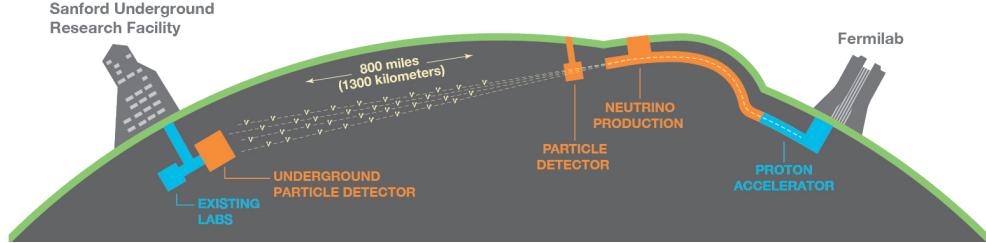


Figure 3.1: Schematic diagram of the DUNE experiment and the LBNF beamline [1].

605 The design of DUNE has bee tailored with these goals in mind. It will consist
606 of two neutrino detectors. A near detector (ND) complex will be placed in Fermilab,
607 574 m downstream of the neutrino production point, whereas a larger far detector (FD)
608 will be built in the Sandford Underground Research Facility (SURF), South Dakota,
609 approximately 1300 km away. Fig. 3.1 shows a simplified view of the various components
610 of DUNE (not to scale).

611 The beam neutrinos to be used in DUNE will be provided by the LBNF beamline,
612 the multi-megawatt wide-band neutrino beam planned for Fermilab. First, an intense
613 proton beam is extracted from the Fermilab Main Injector. Then, these protons with
614 energies between 60 GeV and 120 GeV collide with a high-power production target and
615 produce charged mesons. Two magnetic horns allow to focus the mesons and perform a
616 sign selection (thus having the capability to switch between neutrino and antineutrino
617 mode). Soon after that, the mesons decay and produce neutrinos (or antineutrinos)
618 which are then aimed to SURF.

619 Before arriving to the FD, the neutrino beam meets the ND complex, which serves as
620 the experiment's control. Its role is to measure the unoscillated neutrino energy spectra.
621 From these we can predict the unoscillated spectra at the FD, which can be compared to
622 the spectra measured at the FD in order to extract the oscillation parameters. Therefore,
623 the design of the DUNE ND is mainly driven by the needs of the oscillation physics
624 program.

625 The liquid Argon time projection chamber (LArTPC) technology has been chosen for

3.2. Physics goals of DUNE

Table 3.1: Summary of the two-phased plan for DUNE. Adapted from Ref. [41].

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

the FD modules of DUNE. Its four modules will record neutrino interactions from the accelerator-produced beam arriving at predictable times. As it also aims at recording rare events, the FD requires trigger schemes which can deal with both kinds of physics, and also maximum uptime.

DUNE is planned to be built using a staged approach consisting on two phases, which are summarised in Tab. 3.1. Phase I consists of a FD with 50% of the total fiducial mass, a reduced version of the ND complex and a 1.2 MW proton beam. It will be sufficient to achieve some early physics goals, like the determination of the neutrino mass ordering. For its Phase II, DUNE will feature the full four FD modules, a more capable ND and a 2.4 MW proton beam. The physics milestones for the two phases are given in Tab. 3.2, in a staging scenario which assumes that Phase II is completed after 6 years of operation.

A summary of the DUNE science program can be found in the DUNE FD Technical Design Report (TDR) Volume I [1]. For a detailed discussion on the two-phased approach the reader is referred to the DUNE Snowmass 2021 report [41].

3.2 Physics goals of DUNE

As noted in the literature (see for instance Ref. [16] for a review), the parameter space of the neutrino oscillation phenomena within the three-flavour picture is quite constrained by current experimental data. However, there are still crucial open questions, like the mass ordering, the value of δ_{CP} or the θ_{13} octant. One of the main goals of DUNE is to shed some light on the values of these parameters [42].

To address these questions DUNE can look to the subdominant oscillation channel

Chapter 3. The Deep Underground Neutrino Experiment

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. [41].

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

648 $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and study the energy dependence of the ν_e ($\bar{\nu}_e$) appearance probability.

649 When we focus on the antineutrino channel $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ there is a change in the sign of δ_{CP} ,
650 thus introducing CP-violation. Moreover, due to the fact that there are no positrons in
651 the composition of Earth, there is a sign difference for the matter effect contribution
652 when looking to the antineutrino channel. This asymmetry is proportional to the baseline
653 length L and is sensitive to the sign of Δ_{31} , and thus to the neutrino mass ordering.

654 Another of the main physics goals of DUNE is the search for baryon-number violating
655 processes. Specifically, it will try to answer the question of whether protons are stable
656 or not. There is no symmetry argument that forbids protons from decaying, but its
657 apparent stability seems to suggest that baryon number is conserved [43]. However,
658 proton decay is a usual feature of grand-unified theories, where electromagnetic, weak
659 and strong interactions are unified above a certain energy scale [44].

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

664 The last of the main objectives of DUNE is the detection of neutrinos originated in
665 supernovae explosions, what is called a supernova neutrino burst (SNB). These neutrinos
666 carry with them information about the core-collapse process, from the progenitor to the

3.3. Far Detector

explosion and the remnant; but also may have information about new exotic physics. So far, the only neutrino events ever recorded from such a process were a few dozens of $\bar{\nu}_e$ events from the 1987A supernova located in the Magellanic Cloud, 50 kpc away from Earth [45, 46].

DUNE aims to collect also some SNB events. Although these are quite rare, as the expected supernovae explosion events are about one every few decades for our galaxy and Andromeda, the long lifetime of the experiment (around a few decades as well) makes it reasonable to expect some. Nowadays the main sensitivity to SNB of most experiments is to the $\bar{\nu}_e$ through inverse beta decay. One of the advantages of DUNE is its expected sensitivity to ν_e , since the dominant channel will be ν_e CC scattering.

Moreover, due to the stringent requirements that the main physics goals set for DUNE, it will allow also to perform searches for all kind of BSM physics. Among others, DUNE will be able to look for: active-sterile neutrino mixing, non-unitarity of the PMNS matrix, non-standard interactions, Lorentz and CPT violations, neutrino trident production, light-mass DM, boosted DM and heavy neutral leptons. The reader is referred to the DUNE FD TDR Volume II [42] for a full discussion of the physics scope of DUNE.

3.3 Far Detector

The so-called DUNE FD complex will sit 1.5 km underground at SURF, South Dakota. Two caverns will host the four FD modules, two of them per cavern, each embedded in cryostats of dimensions 18.9 m (w) \times 17.8 m (h) \times 65.8 m (l). A central, smaller cavern will host the cryogenic system.

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

Chapter 3. The Deep Underground Neutrino Experiment

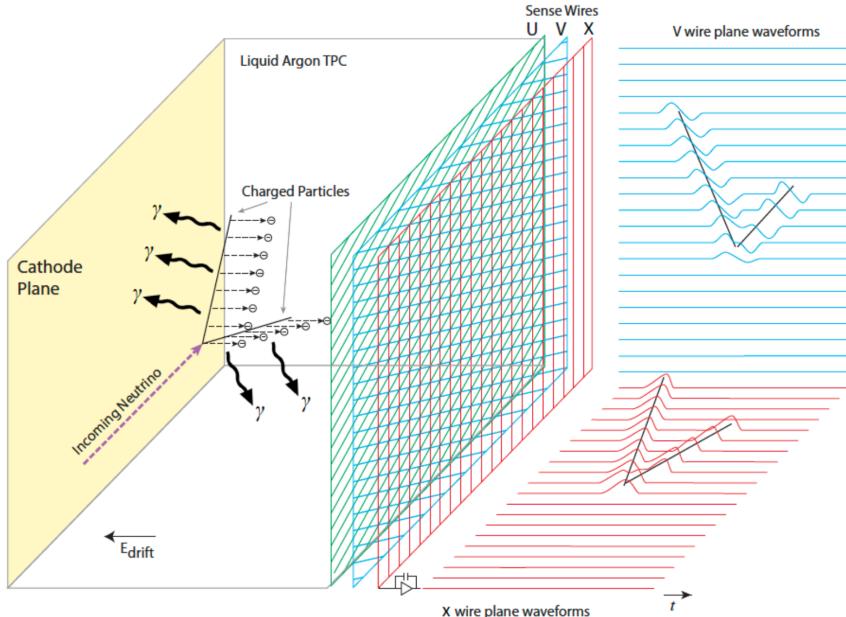


Figure 3.2: Schematic diagram showing the operating principle of a LArTPC with wire readout. Figure taken from Ref. [1].

For each event, with energies ranging from a few MeV to several GeV, these detectors collect both the scintillation light and the ionisation electrons created when the charged particles produced in neutrino-nucleus interactions ionise the argon nuclei. In both HD and VD designs the characteristic 128 nm scintillation light of argon is collected by a photon detection system (PDS). This light will indicate the time at which electrons start to drift, thus enabling reconstruction over the drift coordinate when compared to the time when the first ionisation electron arrives to the anode. Reconstruction of the topology in the transverse direction is achieved using the charge readout. Fig. 3.2 illustrates the detection principle described, for the case of a HD detector with a wire readout.

3.3.1 Horizontal Drift

Within the HD design the ionisation electrons produced as charged particles traverse the LAr drift horizontally towards the anode planes, made out of three layers of wire readout, due to the effect of an electric field. This design, previously known as single-phase (SP), was tested by the ProtoDUNE-SP detector at CERN. The prototype collected data from

3.3. Far Detector

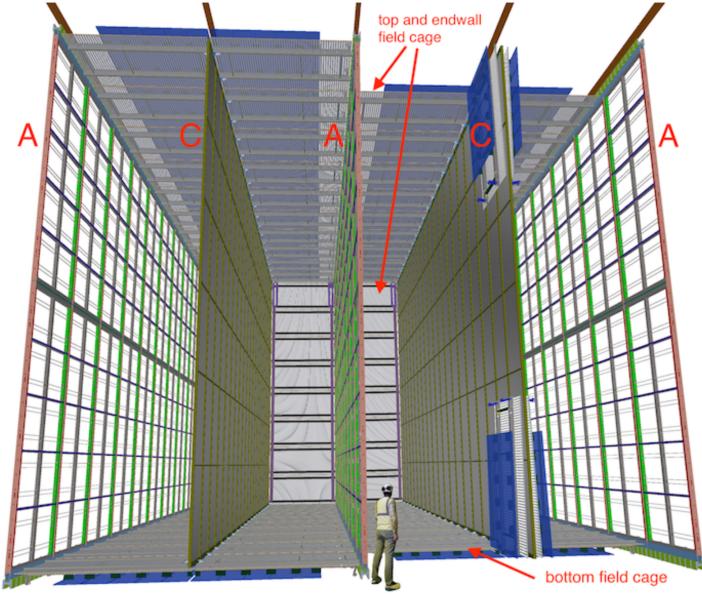


Figure 3.3: Proposed design for the FD-1 and FD-2 modules following the HD principle. Figure taken from Ref. [1].

709 a hadron beam and cosmic rays, providing high-quality data sets for calibration studies
 710 and proving the excellent performance of this design.

711 Each FD HD detector module is divided in four drift regions, with a maximum drift
 712 length of 3.5 m, by alternating anode and cathode walls. The surrounding field cage
 713 ensures the uniformity of the 500 V/cm horizontal electric field across the drift volumes.
 714 The three anode walls, which constitute the charge readout of the detector, are built by
 715 stacking anode plane assemblies (APAs), 2 high times 25 wide. The design of the HD
 716 modules is shown in Fig. 3.3.

717 Each APA is made of 2560 active wires arranged in three layers, plus an extra grid
 718 layer, wrapped around a metal frame. The two induction wire planes, U and V, sit at
 719 $\pm 35.7^\circ$ to the vertical on each side of the APA. The collection and shielding plane wires,
 720 X and G, run parallel to the vertical direction. The ionisation electrons drift past the
 721 induction planes, generating bipolar signals on those wires, and are collected by the
 722 collection plane, producing a monopolar positive signal. The spacing between the wires
 723 is ~ 5 mm, and it defines the spatial resolution of the APA.

724 The front-end readout electronics, or cold electronics as they are immerse in the LAr,

Chapter 3. The Deep Underground Neutrino Experiment

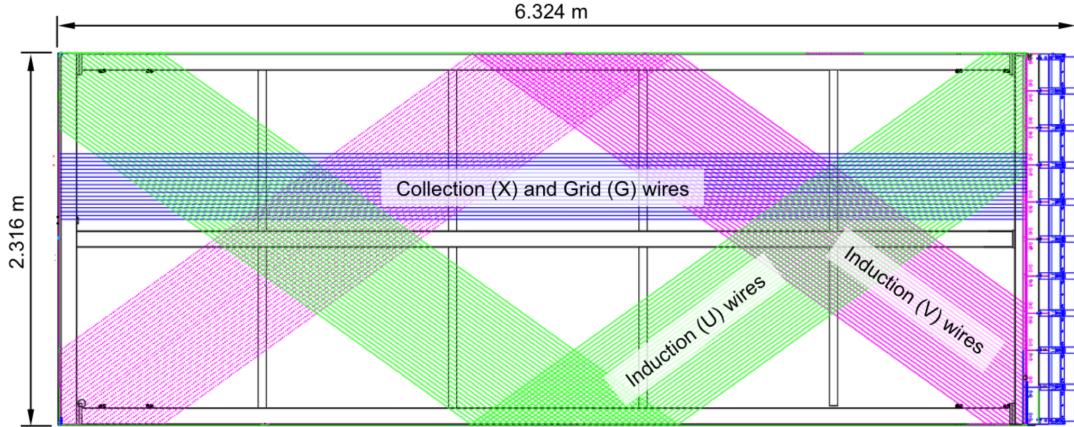


Figure 3.4: Schematic representation of an APA. The black lines represent the APA steel frame. The green and magenta lines correspond to the direction of the U and V induction wires respectively. The blue lines indicate the direction of the X collection wires and the wire shielding G. Figure taken from Ref. [1].

725 are attached to the top of the up APAs and the bottom of the down APAs. Mounted on
 726 the front-end mother boards we have a series of ASICs that digitize the signals from the
 727 collection and induction planes. Each wire signal goes to a charge-sensitive amplifier,
 728 then there is a pulse-shaping circuit and this is followed by the analogue-to-digital
 729 converter. This part of the process happens inside the LAr to minimise the number of
 730 cables penetrating the cryostat. The digitised signals come out finally via a series of
 731 high-speed serial links to the warm interface boards (WIBs), from where the data is sent
 732 to the back-end DAQ through optical fibers.

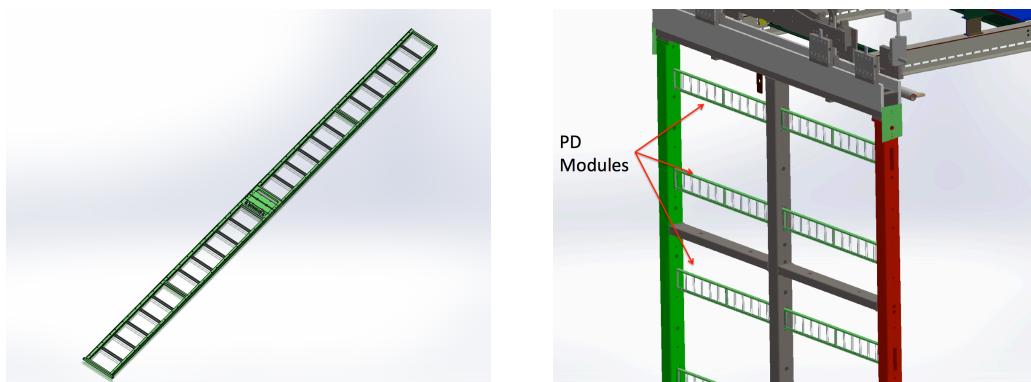


Figure 3.5: A PDS module containing 24 X-ARAPUCAs (left) and the location of the modules on the APAs (right). Figure taken from Ref. [1].

3.3. Far Detector

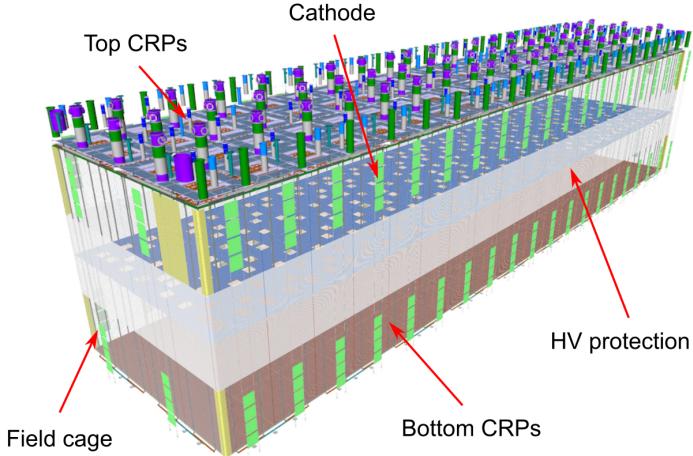


Figure 3.6: Proposed design for the FD-3 module following the VD principle. Figure adapted from Ref. [47].

The PDS uses modules of X-ARAPUCA devices, mounted on the APA frames between the wire planes. Each X-ARAPUCA consists of layers of dichroic filter and wavelength-shifter. They shift the VUV scintillation light into the visible spectrum, sending then the visible photons to silicon photomultiplier (SiPM) devices. The PDS modules are $209\text{ cm} \times 12\text{ cm} \times 2\text{ cm}$ bars, containing 24 X-ARAPUCAs. There are 10 of these PDS modules per APA. Fig. 3.5 shows a PDS module (left) and the placement of the modules on the APAs (right).

3.3.2 Vertical Drift

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

The current design of the FD VD module counts with two drift chambers with a maximum drift distance of 6.5 cm. A cathode plane splits the detector volume along the

Chapter 3. The Deep Underground Neutrino Experiment

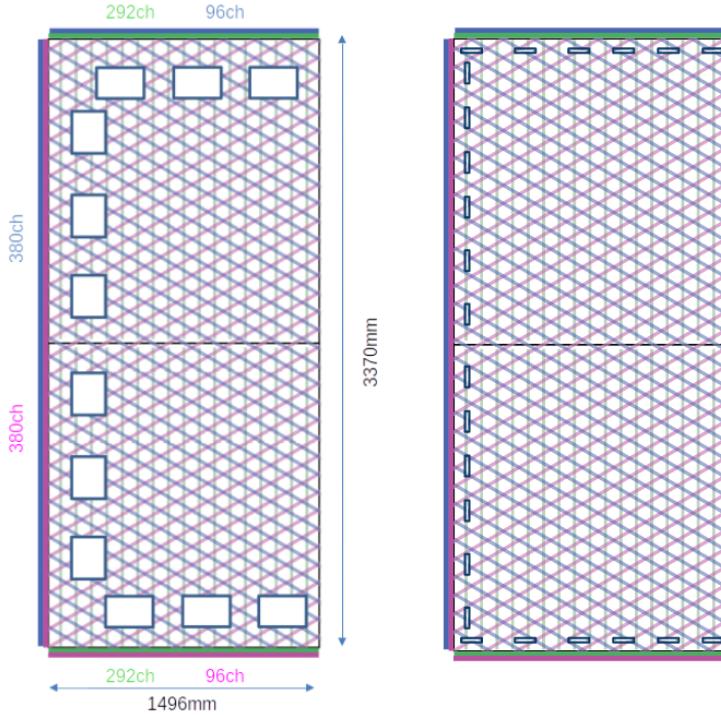


Figure 3.7: Schematic representation of the electrode strip configuration for a top (left) and bottom (right) CRU. Figure taken from Ref. [47].

drift direction while the two anode planes are connected to the bottom and top walls of the detector. The layout of the VD module is shown in Fig. 3.6. Compared with the HD design, the VD option offers a slightly larger instrumented volume and a more cost-effective solution for the charge readout.

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

The PCB face opposite to the cathode has a copper guard plane which acts as shielding, while its reverse face is etched with electrode strips forming the first induction plane. The outer PCB has electrode strips on both faces, the ones facing the inner PCB form the second induction plane while the outermost ones form the collection plane. Fig. 3.7 shows the layout of the electrode strips for the top (left) and bottom (right) CRUs.

3.3. Far Detector

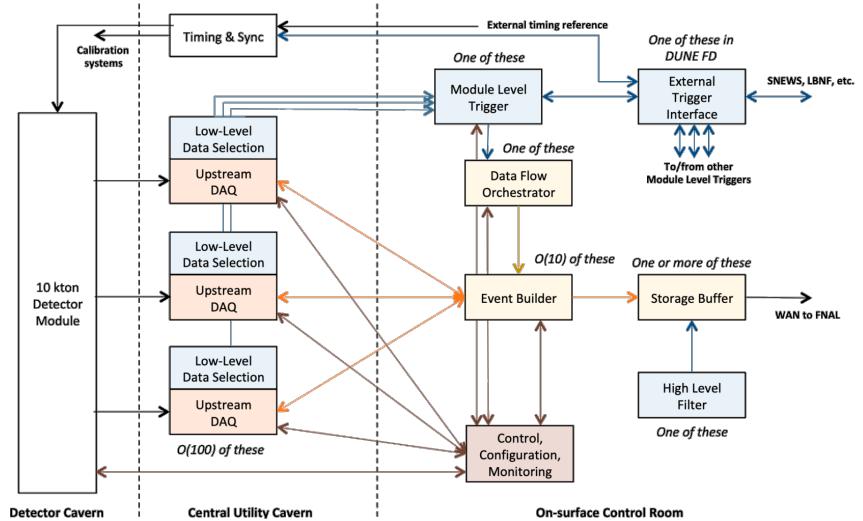


Figure 3.8: Detailed diagram of the DUNE FD DAQ system. Figure taken from Ref. [2].

763 The magenta and blue lines represent the first and second induction planes respectively,
 764 and the green lines correspond to the collection plane.

765 The PDS in the VD module will use the same X-ARAPUCA technology developed
 766 for the HD design. The plan is to place the PDS modules on the cryostat walls and on
 767 the cathode, in order to maximise the photon yield.

768 **3.3.3 FD Data Acquisition System**

769 The task of the data acquisition (DAQ) system is to receive, process and store data from
 770 the detector modules. In the case of DUNE the DAQ architecture is designed to work
 771 for all FD modules interchangeably, except some aspects of the upstream part which
 772 may depend on the specific module technology.

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

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779 The DAQ system of the DUNE FD is composed of five different subsystems. The
780 first one is the upstream DAQ, which receives the raw data from the detector, buffers it
781 and perform some low-level pre-processing. The minimally processed data is then fed
782 into a hierarchical data selection system, which then performs a module level trigger
783 decision. In case of a positive decision a trigger command is produced and executed by
784 the data flow orchestrator, located in the back-end (BE) DAQ subsystem. Subsequently
785 the DAQ BE retrieves the relevant data from the buffers located in the upstream DAQ,
786 adds all the data into a cohesive record and saves it to permanent storage. Watching
787 over all the other subsystems we also have the control, configuration and monitoring
788 subsystem and the time and synchronization subsystem. Fig. 3.8 shows a schematic
789 diagram of the DAQ system, showing the different subsystems and their relations.

790 A notorious challenge for the DUNE DAQ system comes from its broad physics
791 goals. We must be prepared to process events spanning a wide range of time windows
792 (from 5 ms in the case of beam and cosmic neutrinos and nucleon decay to 100 s in the
793 case of SNBs) and therefore this requires a continuous readout of the detector modules.
794 Moreover, because of the off-beam measurements we need to ensure the capabilities
795 of online data processing and self-triggering. Having this into account, together with
796 the technical constraints, the DUNE FD DAQ faces a series of challenges: it needs to
797 be fault tolerant and redundant to reduce downtime, accommodate new components
798 while it keeps serving the operational modules, have large upstream buffers to handle
799 SNB physics, be able to support a wide range of readout windows and last reduce the
800 throughput of data to permanent storage to be at most 30 PB/year.

801 3.4 Near Detector

802 In order to estimate the oscillation parameters we measure the neutrino energy spectra
803 at the FD. This reconstructed energy arises from a convolution of the neutrino flux, cross
804 section, detector response and the oscillation probability. Using theoretical and empirical
805 models to account for the other effects, one can extract the oscillation probability using

3.4. Near Detector

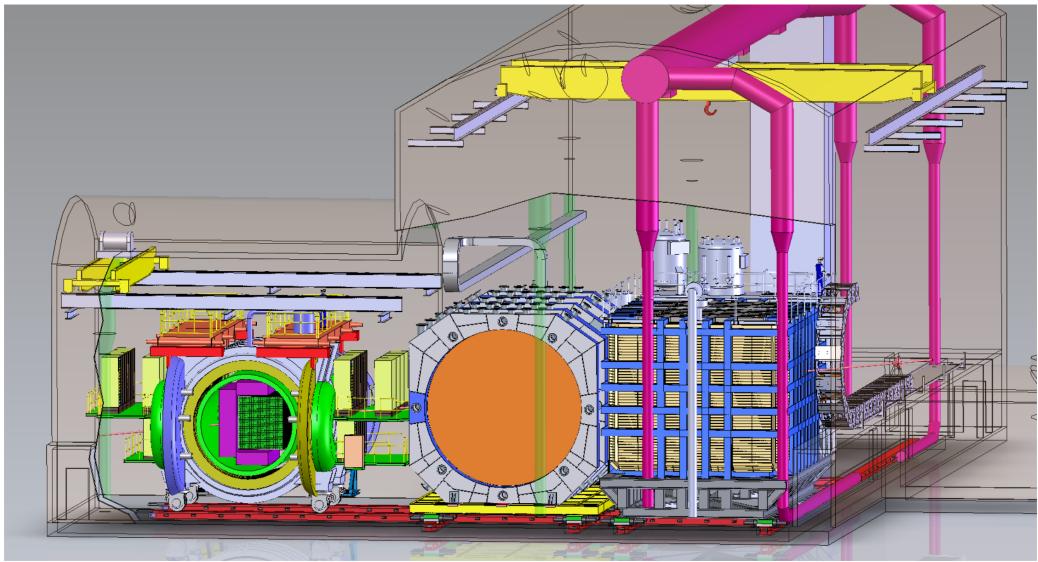


Figure 3.9: Representation of the ND hall in Phase II, showing the different subcomponents. From right to left, in the direction of the beam, we have ND-LAr, ND-GAr and SAND. Figure taken from Ref. [48].

806 the measurement. However, these models have associated a number of uncertainties that
807 are then propagated to the oscillation parameters.

808 One of the main roles of the ND is to measure the neutrino interaction rates before
809 the oscillation effects become relevant, i.e. close to the production point. By measuring
810 the ν_μ and ν_e energy spectra, and that of their corresponding antineutrinos, at the ND
811 we can constrain the model uncertainties. A complete cancellation of the uncertainties
812 when taking the ratio between the FD and ND measurements is not possible, as that
813 would require both detectors to have identical designs and the neutrino fluxes to be
814 the same. Because of the distance, the flux probed by the FD will have a different
815 energy and flavour composition than that at the ND, as neutrinos oscillate and the beam
816 spreads. The differences in the flux also determine the design of the detectors, therefore
817 the ND is limited in its capability to match the FD design.

818 Nevertheless, having a highly capable ND DUNE can minimise the systematic
819 uncertainties affecting the observed neutrino energy. The ND data can be used to
820 tune the model parameters by comparison with the prediction. Then, one uses the
821 tuned model to predict the unoscillated FD spectra. Comparing the prediction with the

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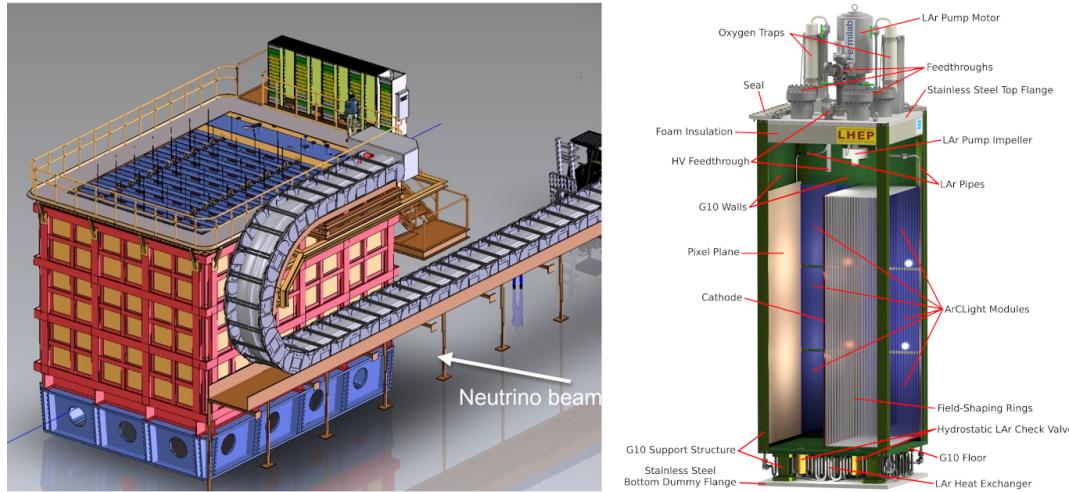


Figure 3.10: Schematic representation of the external components of ND-LAr, including the cryostat and the PRISM movable system (left) and detailed drawing of one ArgonCube module (right). Figure adapted from Ref. [1].

measured spectra it is possible to extract the oscillation parameters.

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

The DUNE ND can be divided in three main components, a LArTPC known as ND-LAr, a magnetised muon spectrometer, which will be the Temporary Muon Spectrometer (TMS) in Phase I and ND-GAr in Phase II, and the System for on-Axis Neutrino Detection (SAND). The layout of the Phase II DUNE ND can be seen in Fig. 3.9. The first two components of the ND will be able to move off-axis, in what is called the Precision Reaction-Independent Spectrum Measurement (PRISM) concept. More details on the purpose and design of the ND can be found in the DUNE ND Conceptual Design Report (CDR) [48].

3.4.1 ND-LAr

ND-LAr is a LArTPC, as the ND needs a LAr component in order to reduce cross section and detector systematic uncertainties in the oscillation analysis. However, its

3.4. Near Detector

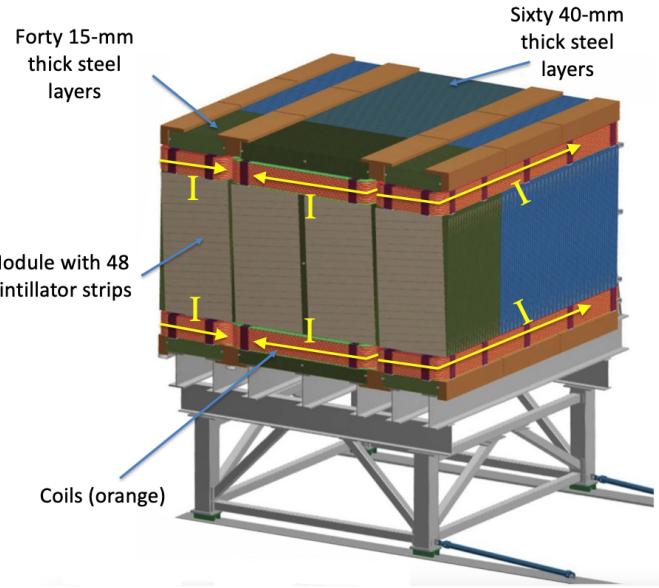


Figure 3.11: Schematic view of the TMS detector, highlighting its main parts. Figure adapted from Ref. [1].

838 design differs significantly from those proposed for the FD modules. Because of the
 839 high event rates at the ND, approximately 55 neutrino interaction events per $10 \mu\text{s}$ spill,
 840 ND-LAr will be built in a modular way. Each of the modules, based on the ArgonCube
 841 technology, is a fully instrumented, optically isolated TPC with a pixelated readout.
 842 The pixelisation allows for a fully 3D reconstruction and the optical isolation reduces
 843 the problems due to overlapping interactions. Fig. 3.10 shows a representation of the
 844 external parts of ND-LAr (left) and a detailed diagram of an ArgonCube module (right).

845 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
 846 will be able to provide high statistics and contain the hadronic systems from the beam
 847 neutrino interactions, but muons with a momentum higher than 0.7 GeV will exit the
 848 detector.

849 3.4.2 TMS/ND-GAr

850 In order to accurately estimate the neutrino energy, the momentum of the outgoing
 851 muons needs to be determined. That is the reason why a muon spectrometer is needed
 852 downstream of ND-LAr.

Chapter 3. The Deep Underground Neutrino Experiment

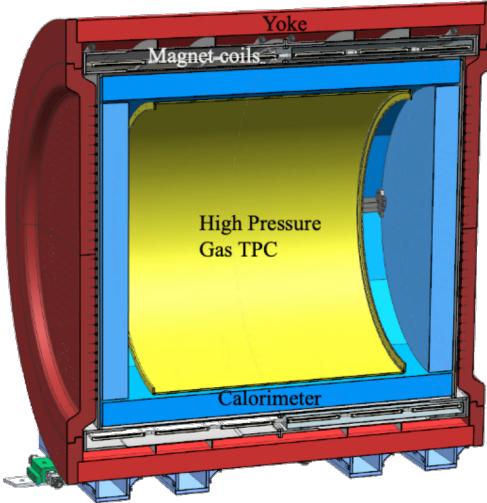


Figure 3.12: Cross section of the ND-GAr geometry, showing the HPgTPC, ECal and magnet. Figure adapted from Ref. [1].

853 In Phase I that role will be fulfilled by TMS. It is a magnetised sampling calorimeter,
854 with alternating steel and plastic scintillator layers. Fig. 3.11 shows a schematic view of
855 the TMS detector. The magnetic field allows a precise measurement of the sign of the
856 muon, so one can distinguish between neutrino and antineutrino interactions.

857 After the Phase II upgrade, TMS will be replaced with ND-GAr. This detector is
858 a magnetised, high-pressure GAr TPC (often denoted as HPgTPC) surrounded by an
859 electromagnetic calorimeter (ECal) and a muon tagger. A cross section of its geometry
860 can be seen in Fig. 3.12. ND-GAr will be able to measure the momenta of the outgoing
861 muons while also detect neutrino interactions inside the GAr volume. This allows
862 ND-GAr to constrain the systematic uncertainties even further, as it will be able to
863 accurately measure neutrino interactions at low energies thanks to the lower tracking
864 thresholds of GAr.

865 3.4.3 PRISM

866 In general, the observed peak neutrino energy of a neutrino beam decreases as the
867 observation angle with respect to the beam direction increases. This feature has been
868 used in other long-baseline neutrino experiments, like T2K (2.5° off-axis) and NOvA

3.4. Near Detector

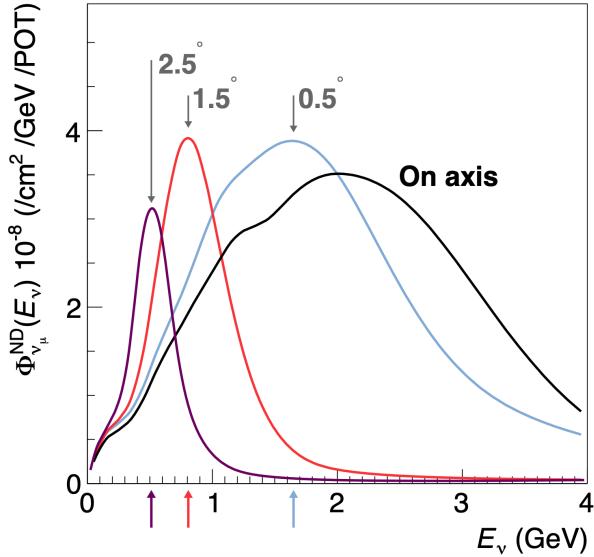


Figure 3.13: Predicted beam muon neutrino flux at the ND location for different off-axis positions. Figure taken from Ref. [48].

(0.8° off-axis), in order to achieve narrower energy distributions. The DUNE PRISM concept exploits this effect using a movable ND. Within PRISM both ND-LAr and the muon spectrometer (TMS in Phase I and ND-GAr in Phase II) can be moved up to 3.2° off-axis, equivalent to move the detectors 30.5 m laterally through the ND hall.

This allows to record additional data samples with different energy compositions. Fig. 3.13 compares the on-axis muon neutrino flux at the ND with the fluxes at different off-axis positions. As the off-axis position increases the neutrino flux becomes closer to a monoenergetic beam with a lower peak energy. These samples can be used to perform a data-driven determination of the relation between true and reconstructed neutrino energy, in order to reduce the dependence on the interaction model. The off-axis samples are linearly combined to produce a narrow Gaussian energy distribution centered on a target true energy. From the combination coefficients one can build a sample of reconstructed neutrino events that will determine the energy mapping.

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

Chapter 3. The Deep Underground Neutrino Experiment

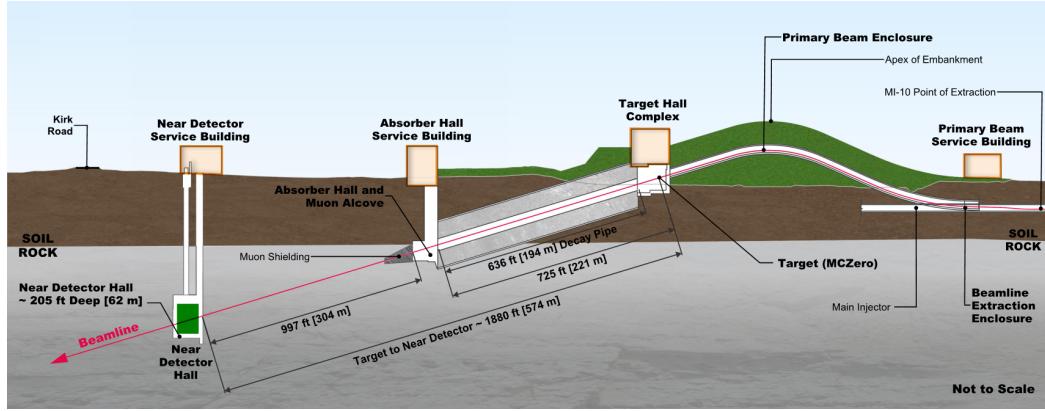


Figure 3.14: Schematic longitudinal section of the LBNF beamline at Fermilab (not to scale). Figure taken from Ref. [49].

885 3.4.4 SAND

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

892 The SAND detector is magnetised, and it counts with an inner low density tracker,
 893 a LAr target with optical readout and surrounding sampling calorimeter.

894 3.5 LBNF beamline

895 The Long-Baseline Neutrino Facility (LBNF) project is responsible for producing the
 896 neutrino beam for the DUNE detectors. A detailed discussion of the LBNF program
 897 can be found in the DUNE/LBNF CDR Volume III [49].

898 The LBNF beamline will provide a high-intensity neutrino beam within the adequate
 899 energy range in order to meet the long-baseline oscillation physics goals of DUNE. A
 900 schematic diagram of the longitudinal section of the LBNF beamline is shown in Fig.
 901 3.14. First, a beam of $60 - 120$ GeV protons is extracted from the Fermilab Main

3.5. LBNF beamline

902 Injector. This beam is aimed towards the target area, where it collides with a cylindrical
 903 graphite target to produce pions and kaons.

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

910 At the end of the decay pipe a hadron absorber removes the undecayed hadrons and
 911 muons from the beam, which reduces the ν_e ($\bar{\nu}_e$) and $\bar{\nu}_\mu$ (ν_μ) contamination coming
 912 from the μ^+ (μ^-) decays. The resulting neutrino flux at the FD is shown in Fig. 3.15,
 913 both for FHC (left) and RHC (right) modes. These predictions show the intrinsic $(\bar{\nu}_e)$
 914 contamination and wrong sign component from wrong sign and neutral meson decays,
 915 as well as muons decaying before reaching the absorber.

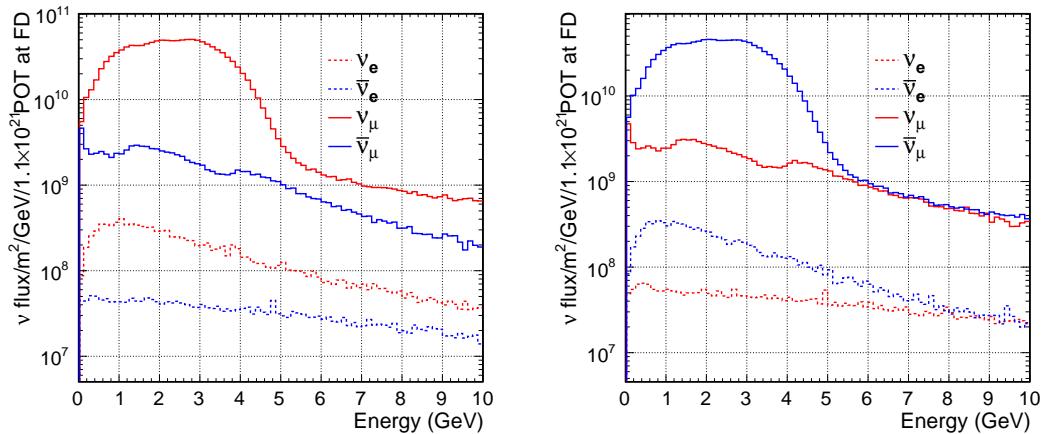


Figure 3.15: Predicted neutrino fluxes at the FD in FHC mode (left panel) and RHC mode (right panel). Figures taken from Ref. [42].

916 **Chapter 4**

917 **ND-GAr**

918 ND-GAr is a magnetised, high-pressure gaseous argon TPC (HPgTPC), surrounded by
919 an electromagnetic calorimeter (ECal) and a muon detector (commonly refer to as μ ID).
920 A detailed discussion on the requirements, design, performance and physics of ND-GAr
921 can be found in the DUNE ND CDR [48] and the ND-GAr whitepaper (cite).

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

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

930 **4.1 Requirements**

931 The primary requirement for ND-GAr is to the measure the momentum and charge of
932 muons from ν_μ and $\bar{\nu}_\mu$ CC interactions in ND-LAr, in order to measure their energy
933 spectrum. To achieve the sensitivity to the neutrino oscillation parameters described
934 in the DUNE FD TDR Volume II [42] ND-GAr should be able to constrain the muon

Chapter 4. ND-GAr

935 energy within a 1% uncertainty or better. The main constraint will come from the
936 calibration of the magnetic field, performed using neutral kaon decays in the HPgTPC.

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

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

949 4.2 Reference design

950 The final design of ND-GAr is still under preparation. However, a preliminary baseline
951 design was in place at the time of the ND CDR. This section summarises the main
952 features of that design, as it is also the one used for the default geometry in our simulation.
953 A DUNE Phase II whitepaper, discussing the different options under consideration for
954 the ND-GAr design, is in progress.

955 4.2.1 HPgTPC

956 The reference design for the ND-GAr HPgTPC follow closely that of the ALICE TPC.
957 It is a cylinder with a central high-voltage cathode, generating the electric field for
958 the two drift volumes, with a maximum drift distance of 2.5 m each. The anodes will
959 be instrumented with charge readout chambers. The original design repurposed the
960 multi-wire proportional readout chambers of ALICE, however the current R&D efforts

4.2. Reference design

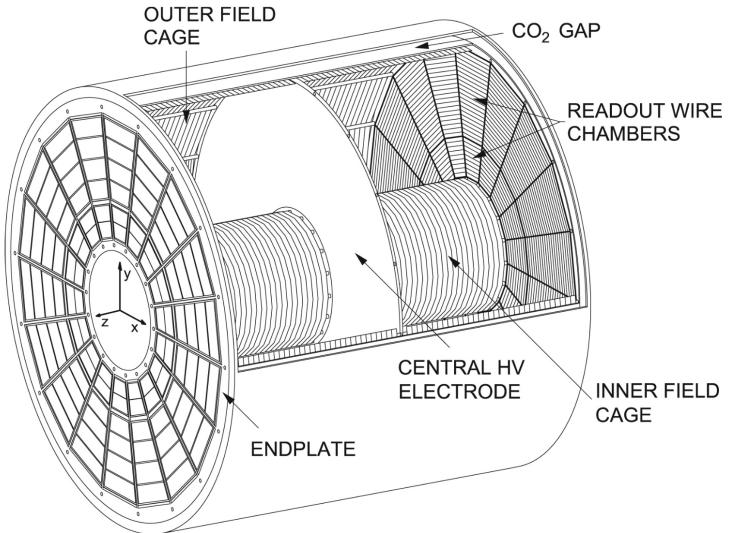


Figure 4.1: Diagram of the ALICE TPC, showing the two drift chambers, inner and outer field cages and readout chambers. Figure taken from Ref. [1].

961 focus on a gas electron multiplier option instead. Fig. 4.1 shows a schematic diagram of
 962 the ALICE TPC design. The basic ND-GAr geometry will resemble this, except for the
 963 inner field cage.

964 It will use a 90-10 molar fraction argon-CH₄ mixture at 10 bar. With this baseline
 965 gas mixture light collection is not possible, as the quenching gas absorbs most of the
 966 VUV photons. Additional R&D efforts are underway, to understand if different mixtures
 967 allow for the light signal to be used to provide a t_0 while maintaining stable charge gain.

968 **4.2.2 ECal**

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

975 The ECal design features three independent subdetectors, two end caps at each side
 976 and a barrel surrounding the HPgTPC. Each of the detectors is divided in modules,

Chapter 4. ND-GAr

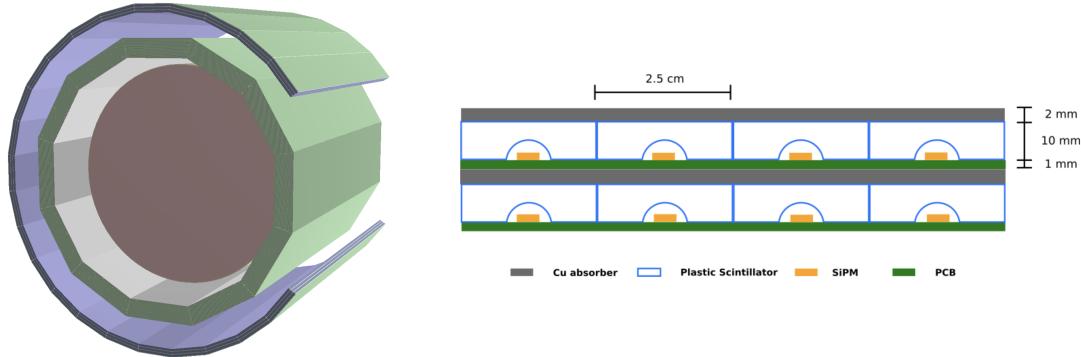


Figure 4.2: View of the 12-sided ECal barrel and outer muon tagger geometries (left) and layout of the ECal tile layers for the 2 mm Cu, 10 mm scintillator option (right). Figure adapted from Ref. [1].

which combine alternating layers of plastic scintillator and absorber material readout by SiPMs. The inner scintillator layers consist of $2.5 \times 2.5 \text{ cm}^2$ high-granularity tiles, whereas the outer ones are made out of 4 cm wide cross-strips spanning the whole module length. The current barrel geometry consists of 8 tile layers and 34 strip layers, while the end caps feature 6 and 36 respectively. The thickness of the scintillator layers is 7 mm and 5 mm for the Pb absorber layers. The 12-sided geometry of the ECal barrel (left) and the layout of the tile layers (left)¹ can be seen in Fig. 4.2.

4.2.3 Magnet

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

The solenoid is a single layer coil, based on niobium titanium superconducting

¹The 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.

4.3. GArSoft

993 Rutherford cable. The total length of the coil is 7.5 m. The bobbin will be split in four
994 segments grouped in pairs with two identical cryostats, connected in series. The iron
995 yoke features an aperture in the upstream side to allow the muons coming from ND-LAr.
996 Still, its material will be enough to reduce the magnetic field reaching SAND, and also
997 stop the charged pions produced inside the HPgTPC.

998 4.2.4 Muon system

999 The design of the ND-GAr muon system is still in a preliminary stage. Its role is to
1000 distinguish between muons and pions punching through the ECal. This is especially
1001 important for wrong-sign determination, to separate these from neutral current events.

1002 In its current form, the muon system consists of three layers of longitudinal sampling
1003 structures. It alternates 10 cm Fe absorber slabs with 2 cm plastic scintillator strips.
1004 The transverse granularity required is still under study.

1005 4.3 GArSoft

1006 GArSoft is a software package developed for the simulation and reconstruction of events
1007 in ND-GAr. It is inspired by the LArSoft toolkit used for the simulation of LArTPC
1008 experiments, like the DUNE FD modules. It is based on `art`, the framework for event
1009 processing in particle physics experiments [?]. Other of its main dependencies are `ROOT`,
1010 `NuTools`, `GENIE` and `Geant4`. It allows the user to run all the steps of a generation-
1011 simulation-reconstruction workflow using FHiCL configuration files.

1012 4.3.1 Event generation

1013 The standard generator FHiCLs in GArSoft run the event generation and particle
1014 propagation simulation (i.e. Geant4) in the same job by default. However, it is possible
1015 to split them up if needed. The current version of GArSoft provides five different event
1016 generators, each of them producing `simb::MCTruth` products defined in `NuTools`. The
1017 available modules are:

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- 1018 • **SingleGen**: particle gun generator. It produces the specified particles with a given
1019 distribution of momenta, initial positions and angles.
- 1020 • **TextGen**: text file generator. The input file must follow the `hepevt` format², the
1021 module simply copies this to `simb::MCTruth` data products.
- 1022 • **GENIEGen**: GENIE neutrino event generator. The module runs the neutrino-nucleus
1023 interaction generator using the options specified in the driver FHiCL file (flux file,
1024 flavour composition, number of interactions per event, t_0 distribution, ...). Current
1025 default version is `v3_04_00`.
- 1026 • **RadioGen**: radiological generator. It produces a set list of particles to model
1027 radiological decays. Not tested.
- 1028 • **CRYGen**: cosmic ray generator. The module runs the CRY event generator with a
1029 configuration specified in the FHiCL file (latitude and altitude of detector, energy
1030 threshold, ...). Not tested.

1031 The module `GArG4` searches for all the generated `simb::MCTruth` data products, using
1032 them as inputs to the Geant4 simulation with the specified detector geometry. A constant
1033 0.5 T magnetic field along the drift coordinate is assumed. The main outputs of this step
1034 are `simb::MCParticle` objects for the generated Geant4 particles, `gar::EnergyDeposit`
1035 data products for the energy deposits in the HPgTPC and `gar::CaloDeposit` data
1036 products for the energy deposits in the ECal and muon system.

1037 4.3.2 Detector simulation

1038 The standard detector simulation step in GArSoft is all run with a single FHiCL, but
1039 the different modules can be run independently as well. First the `IonizationReadout`

²In brief, each event contains at least two lines. The first line contains two entries, the event number 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.

4.3. GArSoft

1040 module simulates the charge readout of the HPgTPC, and later the `SiPMReadout` module
1041 runs twice, once for the ECal and then for the muon system, with different configurations.

1042 The `IonizationAndScintillation` module collects all the `gar::EnergyDeposit`
1043 data products, to compute the equivalent number of ionization electrons for each energy
1044 deposit. The `ElectronDriftAlg` module simulates the electron diffusion numerically
1045 both in the longitudinal and transverse directions and applies an electron lifetime
1046 correction factor. The induced charge on the nearest and neighbouring readout pads
1047 is modeled using the provided pad response functions. The digitisation of the data is
1048 then simulated with the `TPCReadoutSimAlg` module. By default, the ADC sampling
1049 rate used is 50.505 MHz. The resulting raw waveforms for each channel are stored with
1050 zero-suppression, in order to save memory and CPU time. The algorithms keep blocks
1051 of ADC values above a certain threshold, plus some adjustable additional early and late
1052 tick counts. The results of these three steps are `gar::raw::RawDigit` data products.

1053 For the ECal and the muon system the `SiPMReadout` module calls either the
1054 `ECALReadoutSimStandardAlg` or `MuIDReadoutSimStandardAlg` modules. These take
1055 all the `gar::CaloDeposit` data products in the corresponding detector and do the
1056 digitisation depending on whether the hit was in a tile or strip layer. They include single
1057 photon statistics, electronic noise, SiPM saturation and time smearing. The resulting
1058 objects are `gar::raw::CaloRawDigit` data products.

1059 4.3.3 Reconstruction

1060 The reconstruction in GArSoft is also run as a single job by default. It first runs the hit
1061 finding, clustering, track fitting and vertex identification in the HPgTPC, followed by
1062 the hit finding and clustering in the ECal and muon system. After those it produces the
1063 associations between the associations between the tracks and the ECal clusters.

1064 Focusing first on the HPgTPC reconstruction, the `CompressedHitFinder` module
1065 takes the zero-suppressed ADCs from the `gar::raw::RawDigit` data products. The
1066 reconstructed hits largely correspond to the above threshold blocks, however the hit
1067 finder identifies waveforms with more than one maximum, diving them in multiple hits

Chapter 4. ND-GAr

1068 if they dip below a certain threshold. The data products produced are of the form
1069 `gar::rec::Hit`. These are the inputs to the clustering of hits in the `TPCHitCluster`
1070 module. Hits close in space and time are merged, and the resulting centroids are found.
1071 This module outputs `gar::rec::TPCClusters` objects and associations to the input
1072 hits.

1073 The following step prior to the track fitting is pattern recognition. The module
1074 called `tpcvecchitfinder2` uses the `gar::rec::TPCClusters` data products to find track
1075 segments, typically called vector hits. They are identified by performing linear 2D fits
1076 to the positions of the clusters in a 10 cm radius, one fit for each coordinate pair. A
1077 3D fit defines the line segment of the vector hit, using as independent variable the one
1078 whose sum of (absolute value) slopes in the 2D fits is the smallest. The clusters are
1079 merged to a given vector hit if they are less than 2 cm away from the line segment. The
1080 outputs are `gar::rec::VecHit` data products, as well as associations to the clusters. The
1081 `tpcpatrec2` module takes the `gar::rec::VecHit` objects to form the track candidates.
1082 The vector hits are merged together if their direction matches, their centers are within
1083 60 cm and their direction vectors point roughly to their respective centers. Once
1084 the clusters of vector hits are formed they are used to make a first estimation of the
1085 track parameters, simply taking three clusters along the track. The module produces
1086 `gar::rec::Track` data products and associations between these tracks and the clusters
1087 and vector hits.

1088 The track is fitted by means of a Kalman filter in the `tpctrackfit2` module, using
1089 the position along the drift direction as the independent variable. Two different fits are
1090 performed per track, a forward and a backwards fit, each starting from one of the track
1091 ends. The Kalman filter state vector ($y, z, R, \phi, \tan\lambda$) is estimated at each point along
1092 the track using a Bayesian update. The track parameters reported in the forward and
1093 backwards fits are the ones computed at the opposite end where the fit started. The
1094 main outputs of the track fit are the `gar::rec::Track` objects. Additionally, the module
1095 stores the fitted 3D positions along the track in the `gar::rec::TrackTrajectory` data
1096 products and the total charge and step sizes for each point also get stored in the form of

4.3. GArSoft

1097 `gar::rec::TrackIonization` objects.

1098 After the tracking step, the `vertexfinder1` module looks at the reconstructed
1099 `gar::rec::Track` products, creating vertex candidates with the track ends that are
1100 within 12 cm of each other. The vertices are then fitted using linear extrapolations from
1101 the different track ends associated. The results are `gar::rec::Vertex` data products,
1102 and associations to the tracks and corresponding track ends.

1103 For the ECal and muon tagger, the `SiPMHitFinder` module runs twice with different
1104 configurations, adapted to the particular capabilities of both. The module simply takes
1105 the `gar::raw::CaloRawDigit` products, applies a calibration factor to convert the ADC
1106 counts to MeV and for the strip layer hits it calculates the position along the strip using
1107 the times recorded of both SiPMs. This module produces `gar::rec::CaloHit` data
1108 products. Next, these objects are used as inputs to the `CaloClustering` module. It
1109 merges the hits based on a simple nearest neighbours (NN) algorithm. For the resulting
1110 clusters it also computes the total energy and position of the centroid. The results are
1111 stored as `gar::rec::Cluster` data products, with associations to the hits.

1112 The last step in the reconstruction is associating the reconstructed tracks in the
1113 HPgTPC to the clusters formed in the ECal and muon system. The `TPCECALAssociation`
1114 module checks first the position of the track end points, considering only the points
1115 that are at least 215 cm away from the cathode or have a radial distance to the center
1116 greater than 230 cm. The candidates are propagated up to the radial position, in the
1117 case of clusters in the barrel, or the drift coordinate position, for the end cap cluster, of
1118 the different clusters in the collection using the track parameters computed at the end
1119 point. The end point is associated to the cluster if certain proximity criteria are met.
1120 This module creates associations between the tracks, the end points and the clusters.
1121 The criteria for the associations are slightly different for the ECal and the muon tagger.

₁₁₂₂ Chapter 5

₁₁₂₃ FWTPG offline software

1124 Chapter 6

1125 Matched Filter approach to
1126 induction wire Trigger Primitives

1127 6.1 Motivation

1128 The filter implemented in the firmware of the upstream DUNE FD DAQ is a 32nd-order
1129 low-pass finite impulse-response (FIR) filter. The output of such filter for a discrete
1130 system can be written as:

$$y[i] = \sum_{j=0}^N h[j]x[i-j], \quad (6.1)$$

1131 where N is the order of the filter, y is the output sequence, x is the input sequence and h
1132 is the set of coefficients of the filter. The current implementation within `dtp-firmware`
1133 [50] uses a set of 16 non-zero integer coefficients.

1134 Filtering is a vital step in the hit finder chain. It helps to suppress the noise and
1135 enhance the signal peaks with respect to the noiseless baseline. A good filtering strategy
1136 allows us to use lower thresholds when forming the trigger primitives (TPs) and thus
1137 increasing the sensitivity of our detector to low energy physics events. In such events,
1138 the hits produced by the ionisation electrons tend to have lower amplitudes than those
1139 of interest to the baseline physics programme of the DUNE experiment.

1140 This is particularly important for the induction planes. In general, signal peaks in

Chapter 6. Matched Filter approach to induction wire Trigger Primitives

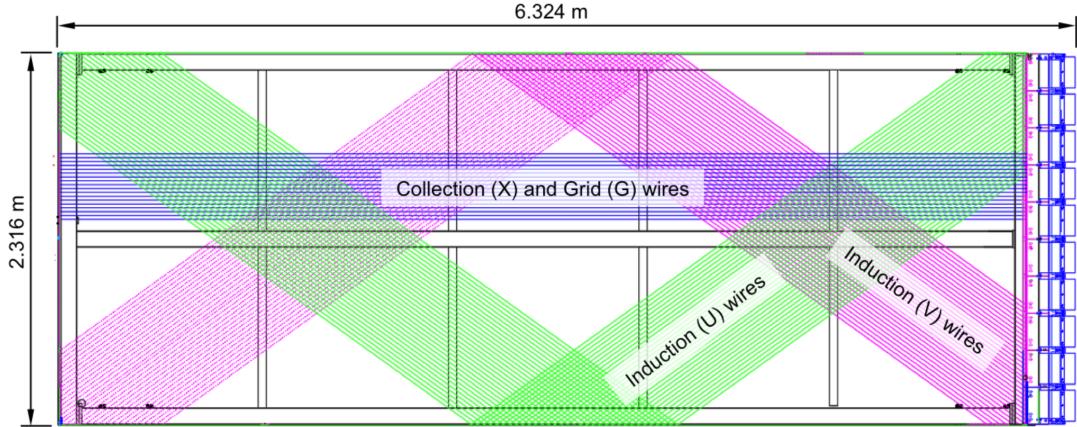


Figure 6.1: Schematic representation of an APA. The black lines represent the APA steel frame. The green and magenta lines correspond to the direction of the U and V induction wires respectively. The blue lines indicate the direction of the X collection wires and the wire shielding G.

the induction wires have smaller amplitude than the ones in the induction plane. This, together with the fact that the pulse shapes are bipolar, reduces our capacity to detect 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. 6.1 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

6.2. Signal-to-noise ratio definition

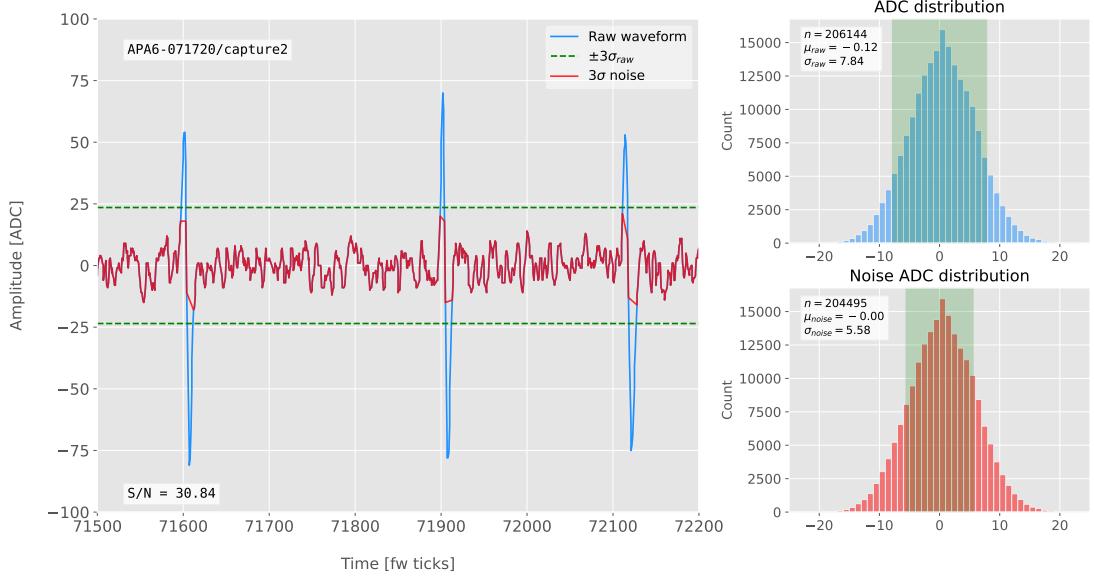


Figure 6.2: Left panel: Zoomed unfiltered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44` (blue line). The green dashed lines mark the region $\pm 3\sigma_{\text{raw}}$. The resulting noise waveform is also shown (red line). Top right panel: ADC 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 $\pm \sigma_{\text{noise}}$.

1158 instances per APA, as there are 4 FIR per optical link and 10 optical links per APA.
 1159 With these restrictions, the task is to provide a set of 32 coefficients which yield an
 1160 optimal filter performance for the induction wires.

1161 6.2 Signal-to-noise ratio definition

1162 I introduce the signal to noise ratio (S/N) as a measure of the FIR filter performance
 1163 and demonstrate how to extract its value for a set of ProtoDUNE-SP data. The S/N
 1164 metrics allow us to compare different filter implementations and serve as a basis for more
 1165 detailed studies presented later in this document. Specifically, I use the ADC capture
 1166 `felix-2020-07-17-21:31:44` (data capture taken for firmware validation purposes). I
 1167 defined S/N as the height of the signal peaks relative to the size of the noise peaks.
 1168 To quantify this quantity channel by channel one first need to estimate the standard
 1169 deviation of the ADC data for each channel, σ_{ADC} . Then, I define the corresponding

Chapter 6. Matched Filter approach to induction wire Trigger Primitives

noise waveform to be the ADC values in the range $\pm 3\sigma_{ADC}$. From this new noise data one can estimate again the mean and standard deviation, μ_{noise} and σ_{noise} , so I can write the S/N for any given channel as:

$$S/N = \frac{\max [ADC] - \mu_{noise}}{\sigma_{noise}}, \quad (6.2)$$

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

One can apply this definition of the S/N with a waveform from one of the channels of the data capture¹. Fig. 6.2 shows a zoomed region of the waveform corresponding to channel 7840 (blue line), where one can clearly see three signal peaks and continuous additive noise (we actually see 6 peaks, 3 positive and 3 negative, but, because by design for induction channels the expected signal pulse shapes are bipolar, I treat them as a collection of 3 individual signal peaks). I estimated the standard deviation of this raw waveform to be $\sigma_{raw} = 7.84$ ADC, so I am able to define the noise waveform (red line) as the ADC values in the range ± 23.52 ADC. This way one obtains $\mu_{noise} = 0$ and $\sigma_{noise} = 5.58$ ADC, which gives $S/N = 30.84$.

We can repeat this calculation now for the corresponding filtered waveform (using the current firmware FIR filter). In Fig. 6.3 I plotted the same time window for the filtered waveform from channel 7840 (blue line). In this case, the standard deviation of the waveform is larger than before, giving $\sigma_{raw} = 10.99$ ADC. The resulting noise waveform (red line) results from selection the ADC values in the range ± 32.91 ADC, giving now $\mu_{noise} = -0.47$ ADC and $\sigma_{noise} = 7.03$ ADC. Finally, one obtains $S/N = 24.68$. Notice that the value of S/N decreases after the filtering. Clearly, one can see that the noise baseline has increased by a factor of 1.35 when we applied the FIR filter and at the same time the amplitude of the signal peaks has remained almost unchanged, leading to this poorer S/N value.

¹All the original work was done within the `dtp-simulation` package [51], 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 [52]. 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.

6.3. Low-pass FIR filter design

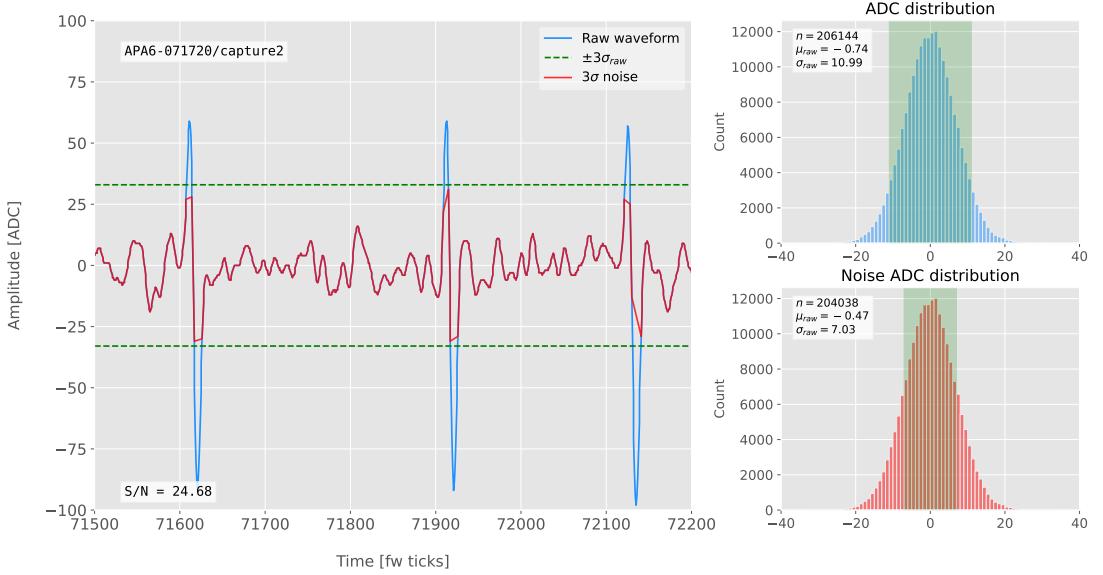


Figure 6.3: Left panel: Zoomed filtered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44` (blue line). The filter used was the current implementation of the low-pass FIR filter in `dtp-firmware`. The green dashed lines mark the region $\pm 3\sigma_{\text{raw}}$. 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 $\pm \sigma_{\text{noise}}$

1193 6.3 Low-pass FIR filter design

1194 In general, when one uses a method to optimize the frequency response of a digital filter,
 1195 such as the Parks-McClellan algorithm, one finds a set of N real coefficients that give
 1196 the best response for the specified pass-band and order of the filter [53].

1197 In our case, as the sampling frequency is defined as 1 ticks^{-1} , the Nyquist frequency
 1198 will simply be $1/2 \text{ ticks}^{-1}$. The current implementation of the filter seems to have as
 1199 pass-band the range $[0, 0.1] \text{ ticks}^{-1}$. This can be seen in Fig. 6.4, where I show the
 1200 power spectrum, in decibels, of such filter implementation (blue solid line). For instance,
 1201 the Park-McClellan algorithm finds the optimal Chebyshev FIR filter taking as input
 1202 the boundaries of the target pass-band and stop-band, which can be written in the form:

$$\left\{ \begin{array}{l} [0, f_c] \\ [f_c + \delta f, f_N] \end{array} \right. , \quad (6.3)$$

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1203 where f_c is the cut-off frequency, δf is the transition width and f_N is the aforementioned
 1204 Nyquist frequency. A similar behaviour to the one in the current filter can be obtained
 1205 by setting $f_c = 0$ and $\delta f = 0.1 \text{ ticks}^{-1}$. The response of the resulting filter is also shown
 1206 in Fig. 6.4 (blue solid line). Notice that the suppression of the stop-band is enhanced for
 1207 this optimal filter. For comparison I included the power response of the filter obtained
 1208 by taking the integer part of the coefficients resulting from the Parks-McClellan method
 1209 (red dashed line). One can see that it does not suppress that much the stop-band, in a
 1210 similar way to the current implementation of the filter.

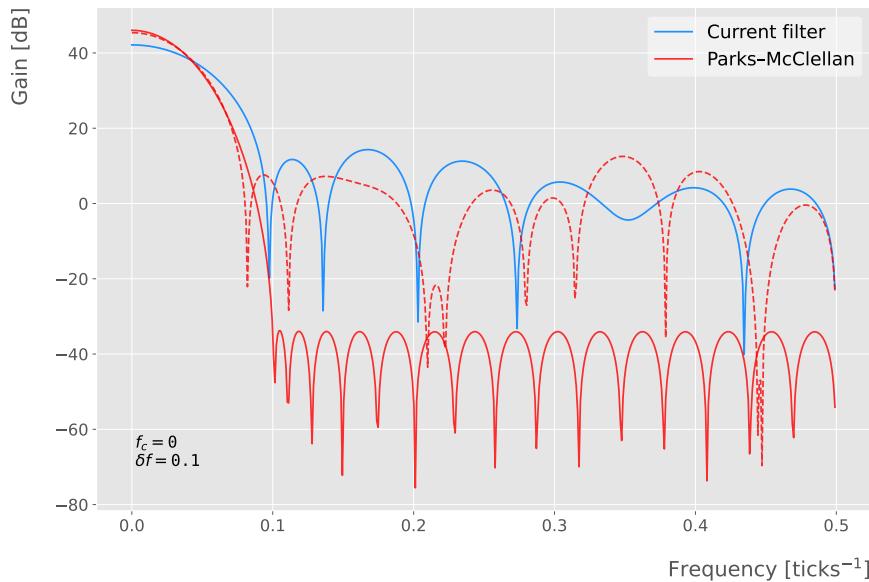


Figure 6.4: Power spectrum in decibels for the current implementation of the low-pass FIR filter in `dtp-firmware` (blue line), compared to the response of an optimal filter obtained using the Parks-McClellan algorithm for the same pass-band (red line). Also for comparison I include the spectrum of the optimal filter when taking only the integer part of the coefficients (red dashed line).

1211 At this point, I tried to improve the performance of the FIR filter using the Park-
 1212 McClellan method, i.e. maximize the overall S/N, using the available data captures. I
 1213 did so by varying the values of the two quantities that parametrize the pass-band and
 1214 stop-band, the cut-off frequency f_c and the transition width δf .

1215 Fig. 6.5 shows the average relative change in the S/N (i.e. the ratio between the
 1216 value of the S/N after and before the filtering) for capture `felix-2020-07-17-21:31:44`,

6.3. Low-pass FIR filter design

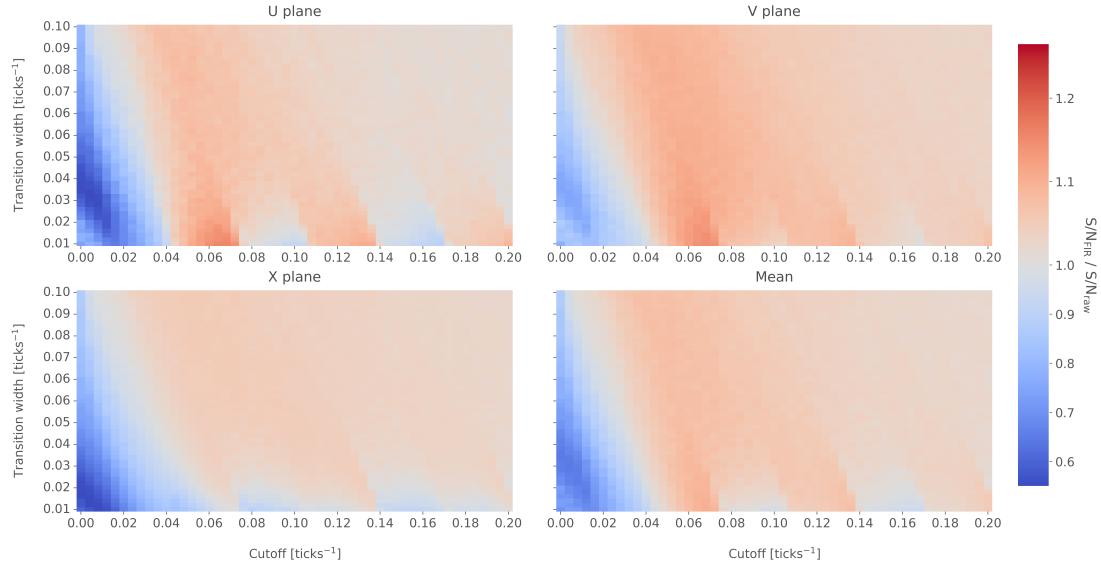


Figure 6.5: Relative change in the S/N for the ProtoDUNE-SP raw data capture `felix-2020-07-17-21:31:44`, using different values of the cutoff frequency f_c and the transition width δf . The optimal Chebyshev filters were applied using just the integer part of the coefficients given by the Parks-McClellan 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 δf , 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. 6.5), 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. 6.6 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 6. Matched Filter approach to induction wire Trigger Primitives

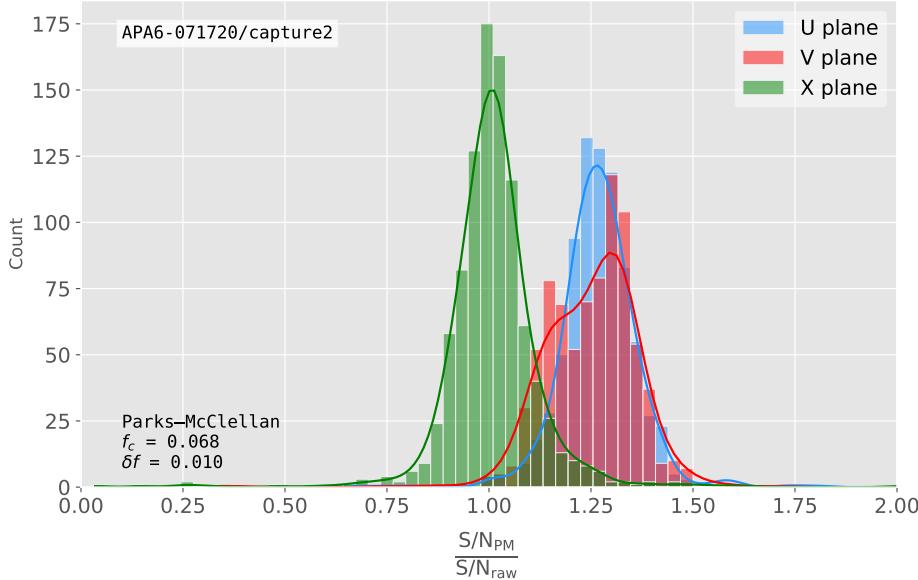


Figure 6.6: Distribution of the relative change of the S/N on the different wire planes from the ProtoDUNE-SP raw data capture *felix-2020-07-17-21:31:44* after the optimal Chebyshev filter was applied. The filter was computed with the Parks-McClellan algorithm using a cutoff of $f_c = 0.068 \text{ ticks}^{-1}$ 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.

6.4 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 [54].

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

6.4. Matched filters

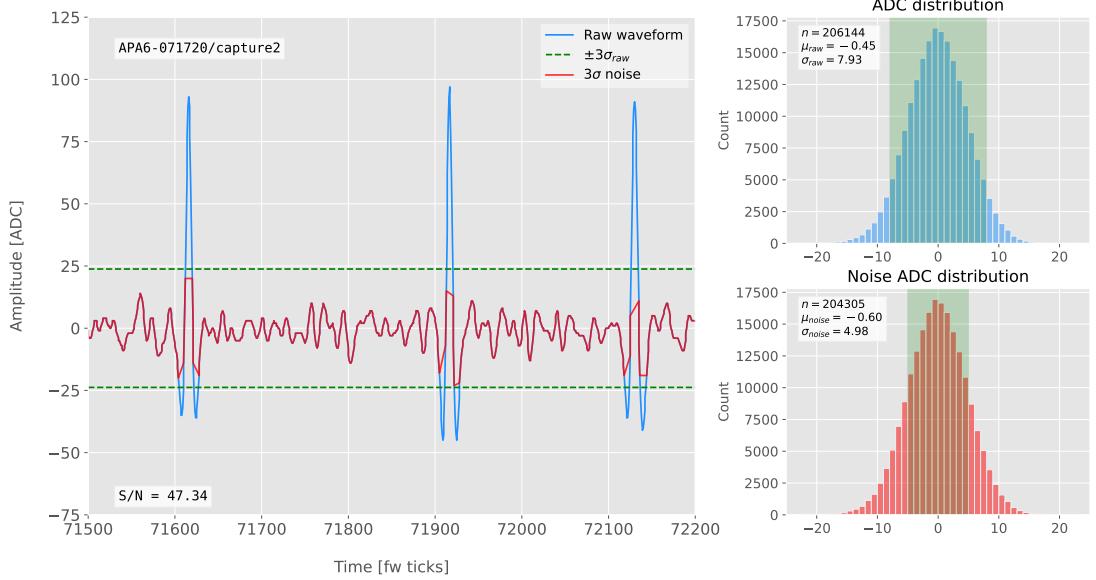


Figure 6.7: Left panel: Zoomed match filtered waveform corresponding to channel 7840 from the ProtoDUNE-SP raw data capture felix-2020-07-17-21:31:44 (blue line). The filter used was directly extracted from the data, being the 32 values around the first peak in the original waveform. The green dashed lines mark the region $\pm 3\sigma_{raw}$. 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 $\pm \sigma_{raw}$. Bottom right panel: noise ADC distribution for channel 7840 after match filtering, where the green shaded region represents $\pm \sigma_{noise}$

1245 $n(t)$, the input signal can be written as:

$$x(t) = s(t) + n(t). \quad (6.4)$$

1246 Now, considering a linear time-invariant filter, whose impulse-response function I
1247 will refer to as $h(t)$, one can write the output signal as:

$$\begin{aligned} y(t) &= x(t) * h(t) \\ &= (s(t) + n(t)) * h(t) \\ &= y_s(t) + y_n(t), \end{aligned} \quad (6.5)$$

1248 where $y_s(t)$ and $y_n(t)$ are simply the outputs of the filter due to the signal and the noise
1249 components respectively.

Chapter 6. Matched Filter approach to induction wire Trigger Primitives

1250 The goal of the matched filter is to detect the presence of the signal $s(t)$ in the input
 1251 sample $x(t)$ at a certain time t_0 , which effectively means we need to maximise the S/N.
 1252 This way, what one wants is to have a filter which gives a much bigger output when the
 1253 known signal is present than when it is not. Putting it in other words, the instantaneous
 1254 power of the signal output $y_s(t)$ should be much larger than the average power of the
 1255 noise output $y_n(t)$ at some time t_0 .

1256 For the case of the filtered signal, one can easily re-write it as an inverse Fourier
 1257 transform:

$$y_s(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega H(\omega)S(\omega)e^{i\omega t}, \quad (6.6)$$

1258 where $H(\omega)$ and $S(\omega)$ are the Fourier transforms of the impulse-response function (i.e.
 1259 the transfer function of the filter) and of the input signal, respectively.

1260 Now focusing on the noise, we can use the Wiener-Khinchin theorem [55] to write
 1261 the mean power of the noise after filtering as:

$$E|y_n(t)|^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega |H(\omega)|^2 S_n(\omega), \quad (6.7)$$

1262 where $S_n(\omega)$ is the power spectral density of the noise.

1263 Having these, one can write the instantaneous S/N at time t_0 as:

$$\begin{aligned} \left(\frac{S}{N} \right)_{t_0} &= \frac{|y_s|^2}{E|y_n(t)|^2} \\ &= \frac{1}{2\pi} \frac{\left| \int_{-\infty}^{\infty} d\omega H(\omega)S(\omega)e^{i\omega t_0} \right|^2}{\int_{-\infty}^{\infty} d\omega |H(\omega)|^2 S_n(\omega)}. \end{aligned} \quad (6.8)$$

1264 Once we have this expression, we need to find the upper limit of it to determine what
 1265 would be the optimal choice for the transfer function. One can use the Cauchy-Schwarz
 1266 inequality, which in the present case takes the form:

$$\left| \int_{-\infty}^{\infty} dx f(x)g(x) \right|^2 \leq \int_{-\infty}^{\infty} dx |f(x)|^2 + \int_{-\infty}^{\infty} dx |g(x)|^2, \quad (6.9)$$

6.4. Matched filters

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

$$\begin{aligned} f(x) &= H(\omega) \sqrt{S_n(\omega)} e^{i\omega t_0}, \\ g(x) &= \frac{S(\omega)}{\sqrt{S_n(\omega)}}, \end{aligned} \quad (6.10)$$

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

$$\left(\frac{S}{N} \right)_{t_0} \leq \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \frac{|S(\omega)|^2}{S_n(\omega)}. \quad (6.11)$$

From Eqs. (6.8), (6.9) and (6.10) one can also derive the form of the transfer function such that the upper bound is exactly reached [56]:

$$H(\omega) \propto \frac{S^*(\omega) e^{-i\omega t_0}}{S_n(\omega)}. \quad (6.12)$$

From this last expression we can clearly see the way the matched filter acts. As the transfer function is proportional to the Fourier transform of the signal it will try to only pick the frequencies present in the signal [57].

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

$$H(\omega) \propto S(-\omega) e^{-i\omega t_0}. \quad (6.13)$$

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

$$h = \frac{1}{\sqrt{s^\dagger R_n^{-1} s}} R_n^{-1} s, \quad (6.14)$$

Chapter 6. Matched Filter approach to induction wire Trigger Primitives

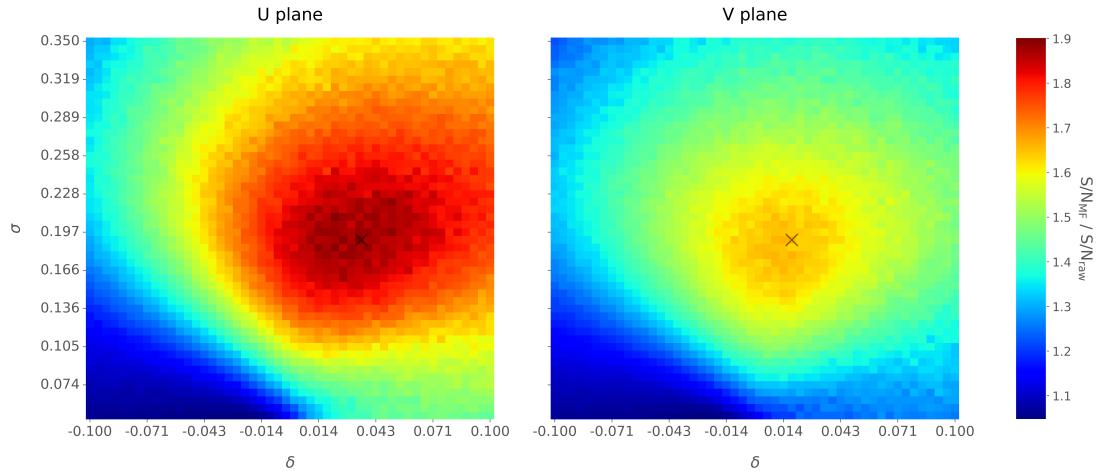


Figure 6.8: Relative improvement in the S/N for the raw data capture `felix-2020-07-17-21:31:44`, using the matched filter following the parametrisation in Eq. (6.17). The black crosses in both panels denote the location of the maximum ratio value.

1283 where s is a reversed signal template sequence of length N equal to the order of the filter
 1284 and R_n is the covariance matrix associated with the noise sequence n . For the Gaussian
 1285 noise case, the covariance matrix is simply the unit matrix, so the above expression
 1286 simplifies again to:

$$h = \frac{s}{|s|}. \quad (6.15)$$

1287 For this first stage of the study, I use a definition of the S/N per channel given by:

$$\text{S/N} = \frac{\max [ADC] - \mu_{noise}}{\sigma_{noise}}, \quad (6.16)$$

1288 where the subscript *noise* refers to a subset of the data obtained by only taking into
 1289 account waveform values within a $\pm 3\sigma$ range around the mean of the data and $\max [ADC]$
 1290 is the maximum of the original waveform. This definition is further discussed in App.
 1291 6.2, where I also show examples of its application to raw data and to a waveform filtered
 1292 with the current low-pass FIR filter.

1293 To test whether this choice of filter is appropriate one needs to choose a signal
 1294 template. As an example of how a matched filter would affect our signal, I simply took
 1295 the filter coefficients to be the 32 ADC values around a signal peak present in the data.

6.4. Matched filters

1296 In Fig. 6.7 (left panel) I plotted a zoomed region for channel 7840 in the raw data capture
1297 `felix-2020-07-17-21:31:44`, after applying the matched filter described before (blue
1298 line). When compared to the raw and FIR filtered case (see App. 6.2), after applying
1299 the match filter the standard deviation of the noise waveform (red line) decreases and at
1300 the same time the signal peaks are enhanced. This leads to an improvement of the S/N
1301 by a factor of 1.92 when compared to the raw waveform.

1302 In order to obtain the matched filter that is more suitable for our data, I explored
1303 different configurations of signal templates. In order to perform this exploration, I
1304 parametrised the signal using the bipolar function:

$$f(x) = -A(x + \delta) e^{-x^2/\sigma^2}, \quad (6.17)$$

1305 where the parameter δ controls the asymmetry between the positive and negative peaks
1306 and σ controls their width. The amplitude parameter A is set such that it keeps the
1307 height of the biggest peak to be less than 200 ADC in absolute value.

1308 As this parametrisation is only adequate for bipolar signals I will focus exclusively
1309 on the induction channels. Also, the optimal configurations I found for the U and V
1310 plane will be kept separate, i.e. I will have two sets of coefficients that will be applied to
1311 either the U and V planes of wires. I do so as I found this was the choice giving the
1312 best performance. Even so, as I will discuss, the differences are not very pronounced. In
1313 case it is not technically possible to separate channels in the firmware according to the
1314 wire plane they come from and use different sets of filter coefficients for them, we can
1315 just find a common unique set of coefficients. In such case, I do not expect our results
1316 to change dramatically.

1317 In Fig. 6.8 I present the results of our parameter scan, for channels in the induction
1318 planes U (left panel) and V (right panel). For each configuration of σ and δ the resulting
1319 matched filter was applied to all channels in the corresponding plane within the data
1320 capture `felix-2020-07-17-21:31:44`, the S/N improvement was computed with respect
1321 to the raw waveforms and then the S/N mean value was kept as a score for such filter.

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1322 One can see that the improvement obtained for the U plane is in general higher than the
1323 one for the V plane. In any case, I got substantially higher ratios than the ones obtained
1324 for the low-pass FIR filters. For the optimal configurations I attained improvements up
1325 to a factor of 1.85 for the U plane and 1.65 for the V plane.

1326 The sets of optimal matched filter coefficients were obtained for the parameters
1327 $\delta = 0.035$, $\sigma = 0.191$ for the U plane and $\delta = 0.018$, $\sigma = 0.191$ for the V plane. I
1328 show these two sets of coefficients in Fig. 6.9 (left panel). Also in Fig. 6.9 (right
1329 panel) I plot the distribution of the S/N improvement after the optimal match filters
1330 for the U and V were applied to the corresponding channels in the raw data capture
1331 `felix-2020-07-17-21:31:44`. As mentioned before, the mean improvement achieved
1332 for the U plane channels is slightly bigger than the one for the V channels. Note, however,
1333 that the spread of the distribution for the V plane is also smaller than the one for the U
1334 plane.

1335 I also performed a similar scan for the case of a low-pass FIR filter using the Parks-
1336 McClellan algorithm. In that case, the parameters to check were the cutoff frequency
1337 and the transition width of the filter. A summary of the results is given in App. 6.3.

1338 Overall, one can see that the improvements on the S/N are much more significant in
1339 the case of the matched filter than it is for the low-pass FIR filters. The analysis of this
1340 and other raw data captures from ProtoDUNE-SP suggest that matched filters increase
1341 the S/N of induction channels by a factor of 1.5 more than the optimal low-pass FIR
1342 filters.

1343 Although these results are by themselves great points in favour of the matched
1344 filter, more studies are needed to completely assess the robustness of this approach. I
1345 proceeded then to test the matched filter with simulated data samples.

1346 6.5 Using simulated samples

1347 In order to further test the matched filter, the next step was to generate and process
1348 data samples using *LArSoft* [58]. In this way, one can control the particle content of

6.5. Using simulated samples

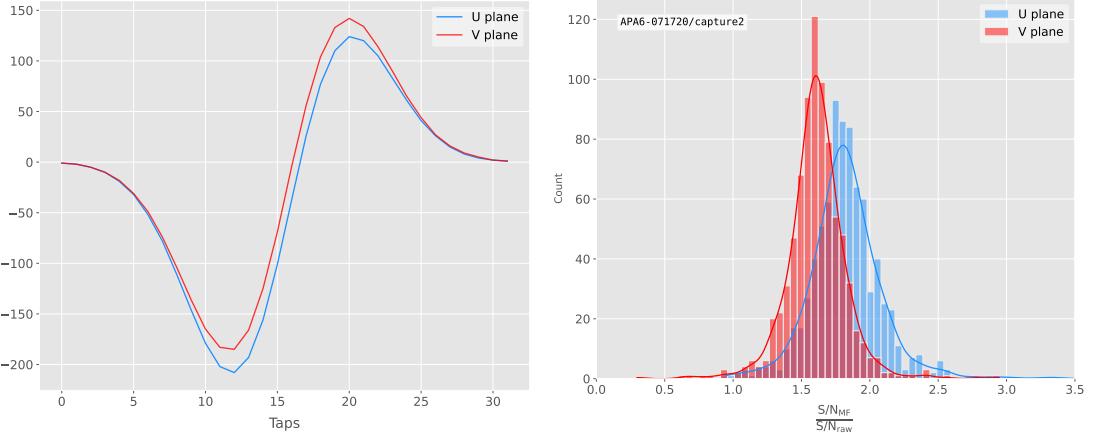


Figure 6.9: Left panel: Optimal matched filter coefficients for the U (blue line) and V (red line) planes. The filters were computed with our parametrisation in Eq. (6.17) for the parameter values $\delta = 0.035$, $\sigma = 0.191$ and $\delta = 0.018$, $\sigma = 0.191$ respectively. Right panel: Distribution 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.

1349 the samples, the orientation of the tracks and their energy, and therefore see how the
1350 matched filter behaves in various situations.

1351 To begin with, I prepared different monoenergetic and isotropic samples containing
1352 a single particle per event. Each sample contains a different particle species, namely
1353 electrons, muons, protons and neutral pions all with a kinetic energy of $E_k = 100$ MeV.
1354 I chose these because of the fairly different topologies they generate in the liquid argon,
1355 ranging from shower-like to track-like. The procedure I followed to generate the samples
1356 and process them is discussed in detail in App. ??.

1357 These were generated with the single particle gun and the Geant4 stage of the
1358 *LArSoft* simulation [58] was performed with the standard configuration for the DUNE
1359 FD 10kt module.

1360 For simplicity, I restricted the particles to start drifting in a single TPC volume
1361 (in this case TPC 0), so I can focus exclusively on the signals coming from one APA.
1362 The chosen kinetic energy for all the particles in my first trial is $E_k = 100$ MeV, so a
1363 necessary check is to see if all our tracks will be typically contained in one TPC volume.
1364 Fig. 6.10 (left panel) shows the distributions of the track lengths in the liquid argon

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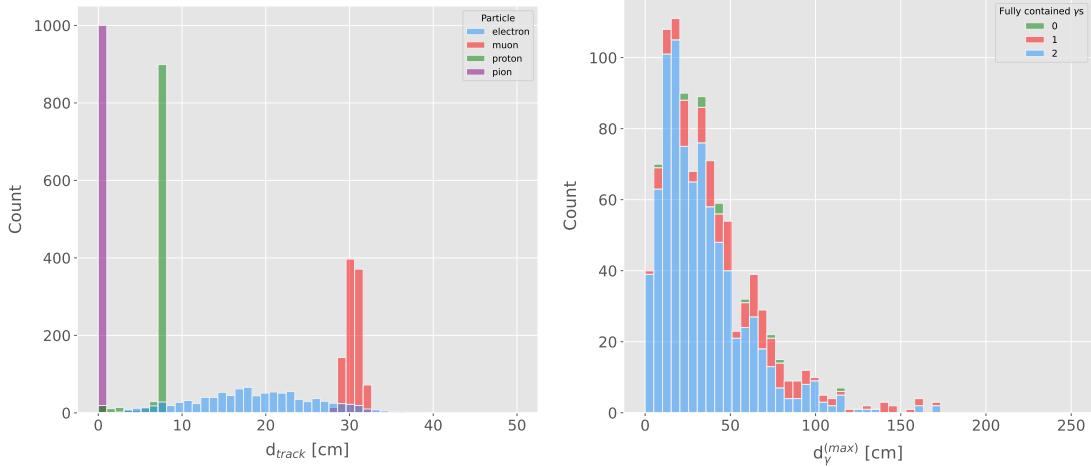


Figure 6.10: Left panel: distributions of the particles track length in the liquid argon for the generated $E_k = 100$ MeV monoenergetic samples, electrons (blue), muons (red), protons (green) and neutral pions (purple). Right panel: distribution of the length of the longest photon in the neutral pion 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 ~ 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. 6.10 (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

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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° 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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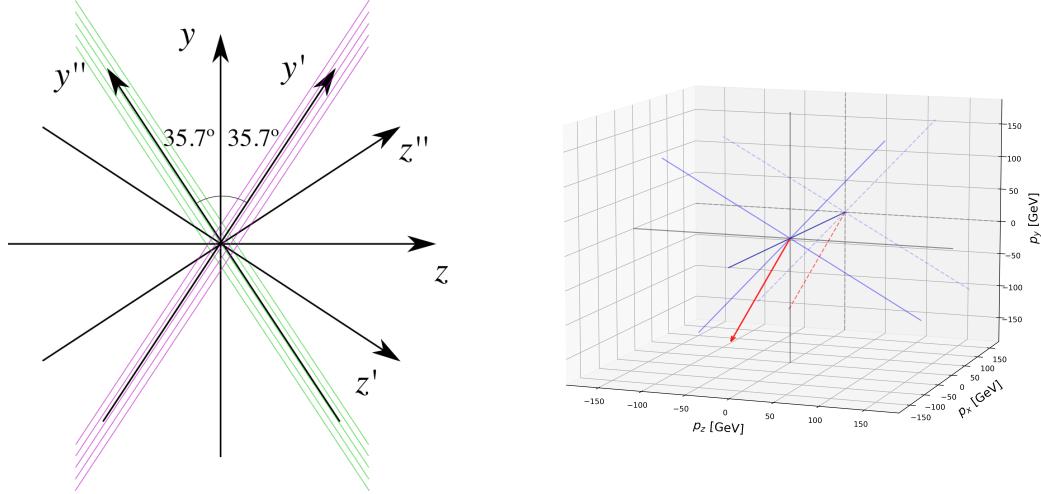


Figure 6.11: Left panel: schematic representation of the two new rotated reference frames used in this analysis (denoted as prime and double prime), viewed from the yz plane. The magenta stack of lines represent the wires in the U plane, whereas the green lines correspond to the wires in the V plane. 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.

1411 U and V induction wires. Fig. 6.11 (left panel) shows a schematic representation of
 1412 the original reference frame together with the two rotated ones (denoted by primed and
 1413 double primed). This way, one can easily understand how parallel was a track to the
 1414 wires in the two induction planes. Fig. 6.11 (right panel) shows a 3D representation of
 1415 the momentum of a track (red arrow) in the original reference frame (black lines), along
 1416 with the new reference frame for U wires (blue lines). I added the projection in the yz
 1417 plane of this three, to show the usefulness of the new reference frame to tell whether a
 1418 track is parallel or normal to the wires in the induction plane.

1419 Fig. 6.12 shows the distribution of the average S/N improvement per event when one
 1420 applies the optimal matched filters. I produced separate distributions for the channels
 1421 in the U (red) and V (blue) induction wire planes. Notice that the S/N distributions
 1422 for the track-like particles, i.e. muons (top left panel) and protons (bottom left panel),
 1423 have significantly larger mean values than the distributions of the shower like particles,
 1424 i.e. electrons (top right panel) and neutral pions (bottom right panel). An important

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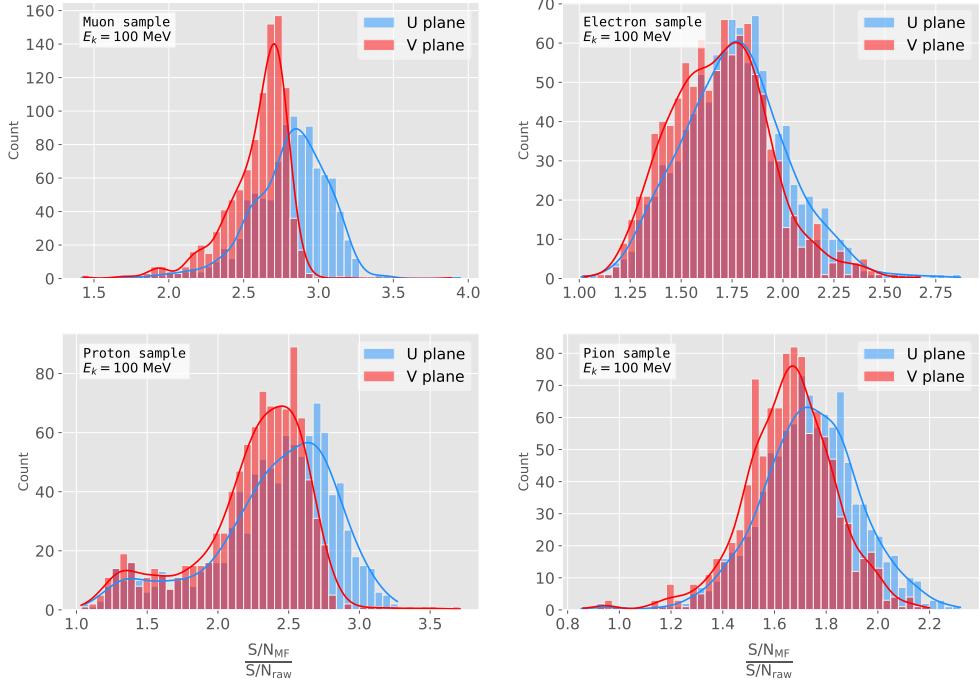


Figure 6.12: Distributions of the mean S/N improvement per event for the corresponding sample after applying the matched filters. Here I separated the change in the U plane (blue) and the V plane (red) channels. From top left to the right: muon, electron, proton and neutral pion. All the events have 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:

$$(S/N_{fir})_{event} = \frac{\sum_{i=0}^{N_{chan}} (S/N_{fir})_i}{N_{chan}}, \quad (6.18)$$

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

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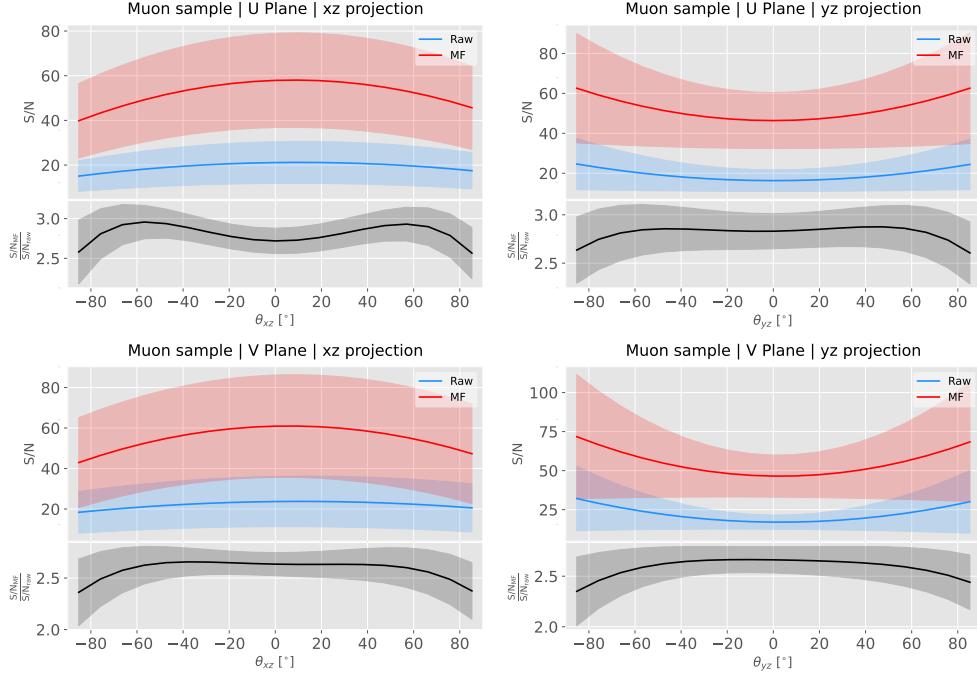


Figure 6.13: Angular dependence of the mean S/N and the S/N improvement, for the different monoenergetic samples considered (from top to bottom: electrons, muons, protons and neutral pions). The two columns on the left represent the values for the U plane waveforms. The top subplots show the mean S/N for raw (green) and filtered (red) waveforms whereas the bottom subplots depict the averaged S/N improvement (black).

1435 However, for the ratio of the raw and filtered S/N (what I called the S/N improvement)
 1436 per event I am not just taking the ratio of the previous two quantities but computing
 1437 the average of the individual ratios per channel in the event:

$$\left(\frac{S/N_{fir}}{S/N_{raw}} \right)_{event} = \frac{\sum_{i=0}^{N_{chan}} \left(\frac{S/N_{fir}}{S/N_{raw}} \right)_i}{N_{chan}}, \quad (6.19)$$

1438 and so:

$$\left(\frac{S/N_{fir}}{S/N_{raw}} \right)_{event} \neq \frac{(S/N_{fir})_{event}}{(S/N_{raw})_{event}}. \quad (6.20)$$

1439 6.5.1 Angular dependence

1440 Having these monoenergetic samples, one can also study the angular dependence of the
 1441 performance of the matched filter. This is an important point, as it is a well established
 1442 fact that for certain configurations (an extreme case configuration being signals normal

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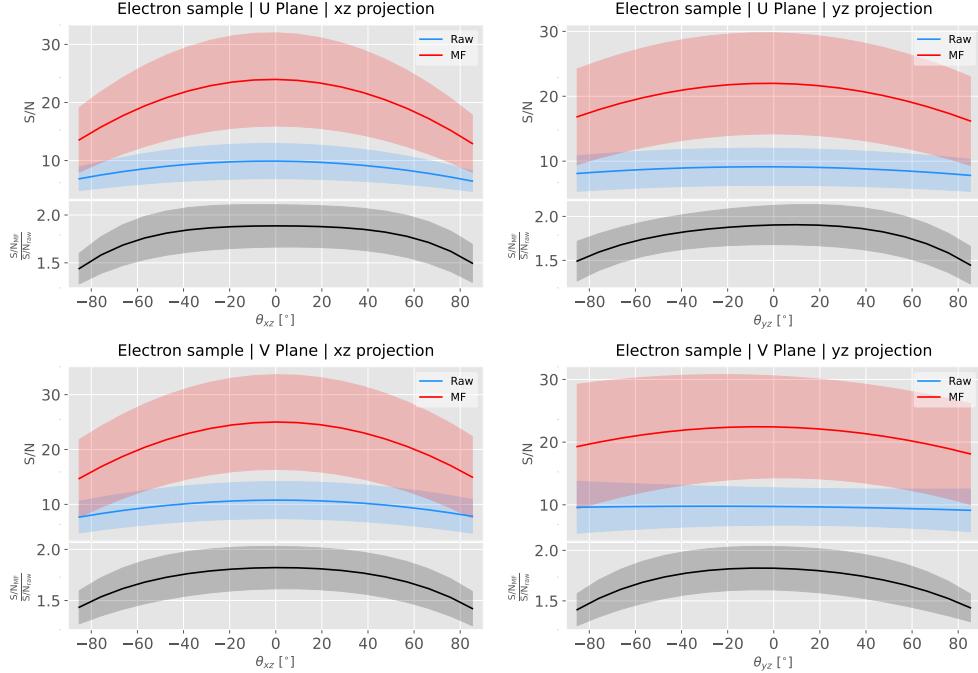


Figure 6.14: Angular dependence of the mean S/N and the S/N improvement, for the different monoenergetic samples considered (from top to bottom: electrons, muons, protons and neutral pions). The two columns on the left represent the values for the U plane waveforms. The top subplots show the mean S/N for raw (green) and filtered (red) waveforms whereas the bottom subplots depict the averaged S/N improvement (black).

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. 6.13 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 each plot, the top subplot represents the mean values of the S/N for the raw (blue) and

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1456 matched filtered (red) signals, and the bottom subplot the averaged S/N improvement
1457 (black). The solid lines represent the mean value obtained for the corresponding angular
1458 value, whereas the semitransparent bands represent one standard deviation around the
1459 mean at each point.

1460 As expected, the S/N is in general higher when tracks are parallel to the APA (i.e.
1461 $\theta_{xz} \sim 0$) and lower when it is normal to the plane ($\theta_{xz} \sim \pm 90^\circ$). In the same way, tracks
1462 parallel to the wires ($\theta_{yz} \sim \pm 90^\circ$) tend to have higher S/N than those perpendicular to
1463 these ($\theta_{yz} \sim \pm 0$).

1464 Fig. 6.14 shows the corresponding angular dependence information for the $E_k =$
1465 100 MeV electrons sample. Notice that, in this case, the S/N behaviour discussed above
1466 does not hold. A possible explanation can be that, because most hits in these events
1467 are produced by the secondary particles generated in the EM shower, the signal peaks
1468 whose S/N ratios were computed do not correspond to the directional information of
1469 the primary electron.

1470 6.5.2 Distortion and peak asymmetry

1471 As a little case of study, I selected two of the simulated $E_k = 100$ MeV monoenergetic
1472 muon events. With respect to the U induction plane, one is parallel to the APA (low
1473 $\theta_{xz'}$) and to the wires (high $\theta_{y'z'}$) and the other is normal to the APA plane (high $\theta_{xz'}$)
1474 and perpendicular to the wires (low $\theta_{y'z'}$). As expected from the results on the angular
1475 dependence discussed above, the former has a higher S/N (before and after the filtering)
1476 when compared to the latter. An interesting thing to notice about these two samples
1477 is that, even though one has a much bigger S/N than the other, it is the one with the
1478 smallest S/N the one that got the biggest averaged S/N improvement. In Table 6.1
1479 I included all the relevant parameters of these two $E_k = 100$ MeV muon events I am
1480 considering, namely, the angles with respect to the $xy'z'$ reference frame, the values of
1481 the S/N, the S/N improvement and also the so-called peak asymmetry Δ_{peak} that I will
1482 discuss next.

1483 One can try to understand better what is going on with these two events by looking

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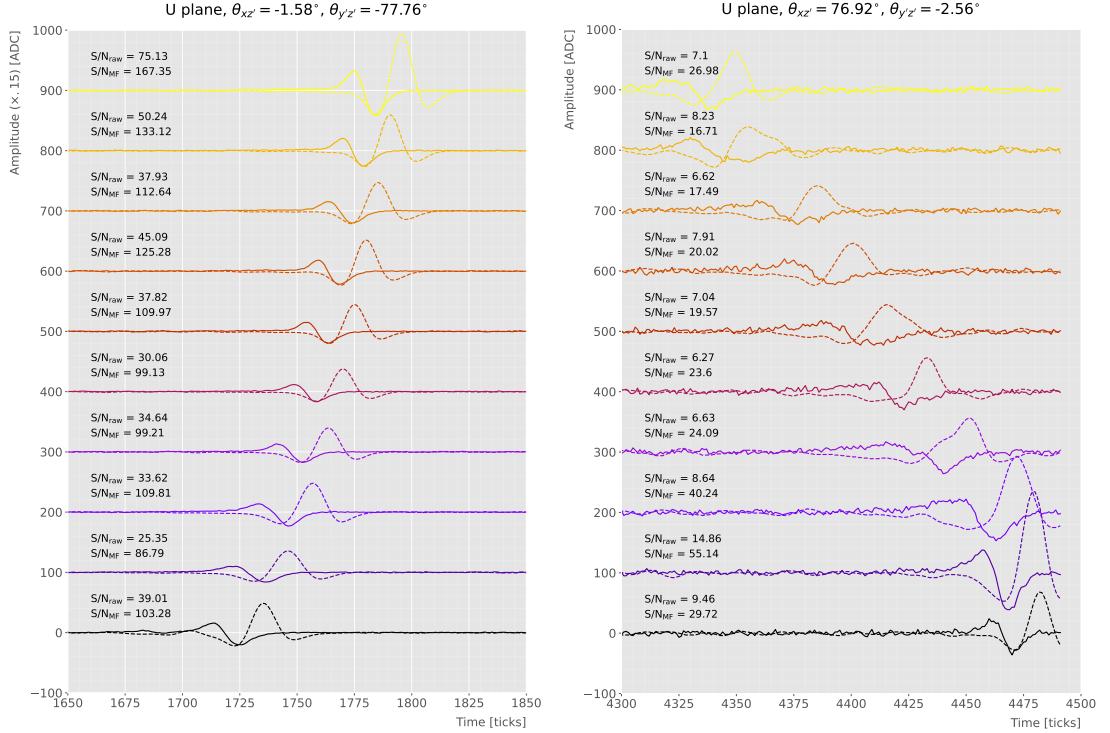


Figure 6.15: Selected consecutive waveforms corresponding to two monoenergetic $E_k = 100$ MeV muon events, one is parallel to the APA and to the wires in the U plane (left panel) and the other is normal to the APA plane and perpendicular to the U plane wires (right panel). The solid lines represent 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 6.1: Characteristic parameters of the two monoenergetic muon events selected, relative to the U plane: projected angles in the xz' and $y'z'$ planes, S/N values for the raw and filtered waveforms, mean improvement of the S/N and peak asymmetry.

	$\theta_{xz'} (\circ)$	$\theta_{y'z'} (\circ)$	S/N _{raw}	S/N _{MF}	$\frac{S/N_{MF}}{S/N_{raw}}$	Δ_{peak} (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

at the raw and filtered data from some of their active channels. Fig. 6.15 shows a selection of consecutive raw and filtered U plane waveforms from the event with high S/N (left panel) and the one with low S/N (right panel). Notice that to show both collections of waveforms at a similar scale I had to apply a factor of 0.15 to the waveforms with high S/N. Additionally, next to each waveform I included the values of the raw and

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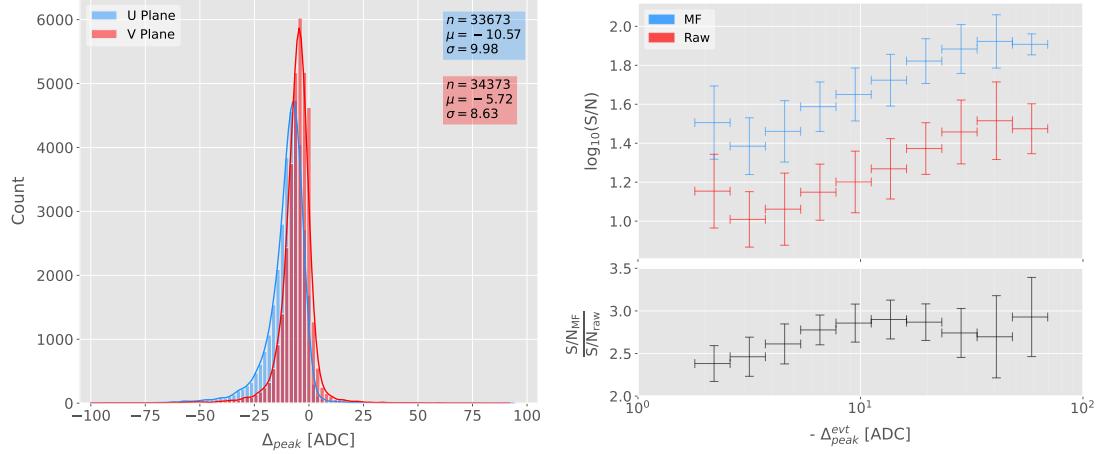


Figure 6.16: Left panel: peak asymmetry distribution for the case of the monoenergetic $E_k = 100$ MeV muon sample. Each value corresponds to a single bipolar signal peak from a channel in any event. The blue distribution represents the peaks on U plane channels, whereas the red corresponds to signal 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.

1489 matched filtered S/N for the corresponding channel. The first thing to notice in this plot
 1490 is that the amplitude of the signal peaks from the normal track have a much smaller
 1491 amplitude, and also appear quite distorted when compared to the others. On the other
 1492 hand, although the matched filtered S/N is still smaller, the relative improvement is
 1493 bigger than in the parallel case.

1494 A way I found to quantify the difference between the shapes within these two events
 1495 is their different peak asymmetry. One can define the peak asymmetry as the (signed)
 1496 difference between the positive and the negative peaks of the bipolar shape, i.e.:

$$\Delta_{peak} \equiv h_+ - h_-, \quad (6.21)$$

1497 where both heights h_+ and h_- are positive defined. Fig. 6.16 (left panel) shows the
 1498 distribution of this peak asymmetry for all the waveforms corresponding to channels
 1499 in the U (blue) and V (red) planes for the monoenergetic muon sample. One can
 1500 see that these distributions are clearly shifted to negative values (with mean values

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1501 $\mu_{\Delta}^U = -10.57$ ADC and $\mu_{\Delta}^V = -5.72$ ADC respectively). It is interesting to notice
1502 that the peak asymmetry value of the sample with high S/N sits at the left tail of the
1503 distribution whereas the corresponding value of the sample with low S/N lies around
1504 the mean.

1505 Now, one can try to correlate the peak asymmetry with the S/N and the S/N change
1506 per event. Fig. 6.16 (right panel) shows the result of comparing (minus) the mean
1507 peak asymmetry per event to the averaged raw (red) and matched filtered (blue) S/N
1508 per event (top subplot). The horizontal lines sit at the mean value obtained in the fit
1509 and represent the width of the $-\Delta_{peak}$ bins used, while the vertical lines indicate one
1510 standard deviation around that mean value. Notice that, when taking decimal logarithm
1511 on both, there is an approximate linear relation between these quantities, except for
1512 peak asymmetry values bigger than -5 ADC where the S/N remains constant.

1513 Also, in the bottom subplot of Fig. 6.16 (right panel) I show the relation between
1514 the peak asymmetry and the mean S/N improvement. In this case, one see that there is
1515 a maximum at $\Delta_{peak} \sim -10$ ADC. As mentioned previously, this is also the value of the
1516 mean of the peak asymmetry distribution. In fact, it is expected that our filter favours
1517 the signal peaks with the most common values of the peak asymmetry, as this was one
1518 of the features I target in our filter coefficient optimisation through the parameter δ .

1519 These results suggest that events with poorer values of the mean S/N, usually
1520 associated to non-favourable track orientations, tend to have smaller values of the mean
1521 peak asymmetry (in absolute value). Nonetheless, because our matched filters have
1522 been optimised to account for these asymmetries, the improvement on the S/N for these
1523 events is sizeable if not better than the one for events which already had a high S/N.

1524 6.5.3 Hit sensitivity

1525 One of the advantages of the matched filter, directly related to increasing the S/N, is
1526 the capability of picking hits that before fell below the threshold. For instance, Fig. 6.17
1527 shows the raw ADC data from an example event (electron, $E_k = 100$ MeV) with the
1528 produced true hits superimposed (black boxes), together with the hits produced by the

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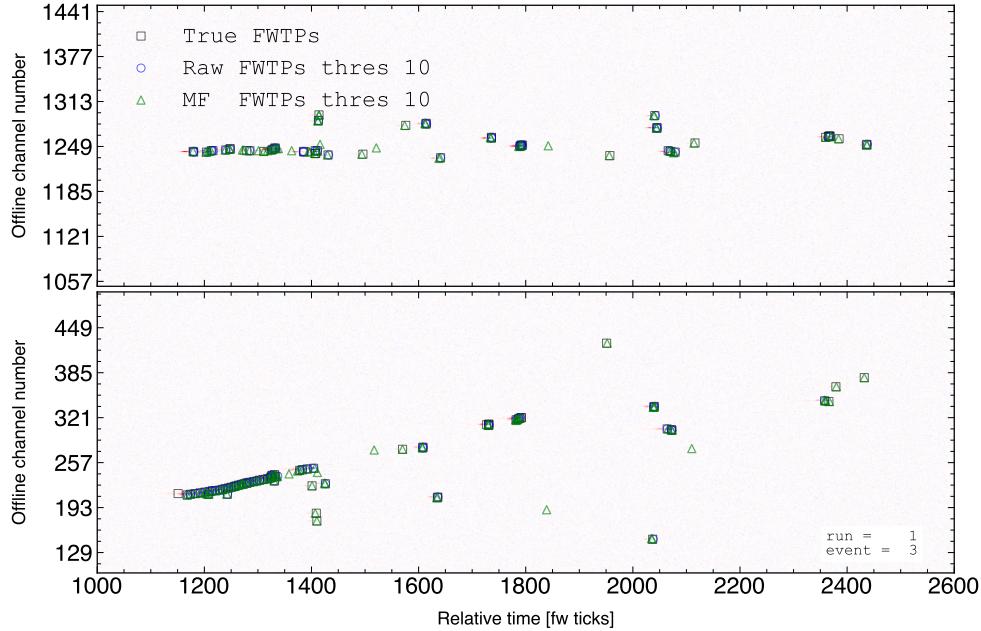


Figure 6.17: Raw data display in the plane time (in firmware ticks) vs. offline channel number for an $E_k = 100$ MeV electron event. The produced true hits are superimposed (black boxes) as well as the hits coming from the standard hit finder chain (blue circles) and the hit finder using the matched 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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1543 By running the hit finders on our samples with different values of the threshold one
1544 can understand, for instance, how low one can set the threshold without getting mostly
1545 spurious hits and then evaluate the gains obtained from this.

1546 Because now I am also interested in seeing how the hit sensitivity changes with the
1547 energy, I prepared new isotropic samples with the same types of particles as before
1548 (muons, electrons, protons and neutral pions) but with a flat kinetic energy distribution
1549 ranging from 5 to 100 MeV.

1550 In order to estimate the hit sensitivity, given a certain sample, one needs to recover
1551 the set of true hits to be able to compare these with the ones produced. To do so,
1552 a modification in the procedure I was using to extract the raw waveforms is needed.
1553 For this kind of study I run the detector simulation in two steps, first I produce the
1554 waveforms without noise and extract them in the same format I used for the raw data,
1555 then the noise is added and the noisy waveforms are then written to a file as well.

1556 To have a better comparison between the true hits and the ones produced from
1557 the raw waveforms after applying the two filters, I applied also the FIR filter and the
1558 matched filters to the noiseless waveforms and then I run the hit finder with a minimal
1559 threshold (in this case I used 1 ADC) on these noiseless filtered waveforms. In this way
1560 I generated two sets of true hits, I will refer to them as standard true hits (with the
1561 current/default FIR filter) and matched filter true hits respectively. This allows a more
1562 precise matching between the different groups of hits produced, as it will account for
1563 any delays and distortions introduced by the FIR and the matched filters.

1564 In the case of the raw waveforms (with noise), I run the hit finder on them, with
1565 different values of the threshold, after applying either the FIR or the matched filters. I
1566 will name them simply standard hits and matched filter hits respectively. Then, I match
1567 the generated hits to the true hits (the standard hits with the standard true hits and
1568 the matched filter hits with the matched filter true hits). The matching is performed by
1569 comparing the channel number and the timestamp of the hits. To count as a match,
1570 I require that all hits with the same channel number and timestamp have overlapping
1571 hit windows, i.e. the time windows between their hit end and hit start times need to

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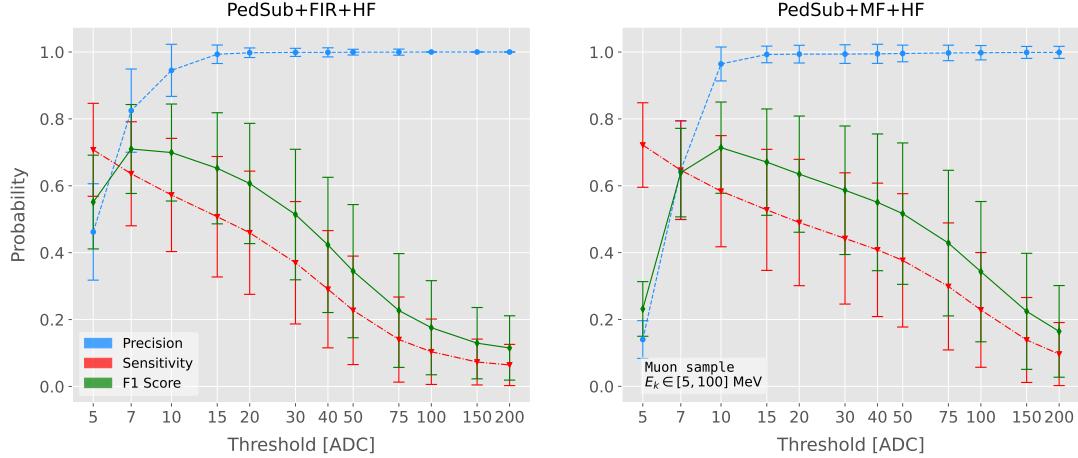


Figure 6.18: Dependence of the precision (blue), sensitivity (red) and F_1 (green) scores on the threshold values used in the hit finder, for the FIR (left panel) and matched filter (right panel) cases. The results were obtained after matching the hits to the true hits in the case of the isotropic muon 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 [59]. 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

6.5. Using simulated samples

1586 metrics, namely the precision or positive predictive value:

$$\text{PPV} = \frac{\text{TP}}{\text{TP} + \text{FP}}, \quad (6.22)$$

1587 the sensitivity or true positive rate:

$$\text{TPR} = \frac{\text{TP}}{\text{TP} + \text{FN}}, \quad (6.23)$$

1588 and the F_1 score [60]:

$$F_1 = \frac{2\text{TP}}{2\text{TP} + \text{FP} + \text{FN}}, \quad (6.24)$$

1589 which is the harmonic mean of the precision and the sensitivity.

1590 In our specific case I am not going to make use of the true negative value, as its
 1591 definition in this context can be ambiguous because one does not have clear instances in
 1592 the classification process. This way, I will only count the number of true positives as the
 1593 total amount of hits I can match between true and raw populations, the number of false
 1594 negatives will be the number of missing true hits and the false positive the number of
 1595 hits which do not match any true hit.

1596 In Fig. 6.18 I show the precision (blue), sensitivity (red) and F_1 (green) scores I
 1597 obtained for different values of the threshold used in the hit finder for the case of the
 1598 muon sample. Because the matched filters are only applied to induction channels, I only
 1599 consider here hits coming from the U and V planes. The panel on the left corresponds
 1600 to the scores I got when I ran the hit finder on the FIR filtered waveforms, whereas the
 1601 right panel contains the scores for the matched filter case. The points are centered at
 1602 the threshold value used and represent the mean value obtained for each score using all
 1603 the generated events, while the error bars indicate one standard deviation around the
 1604 mean value.

1605 One can see that the precision for the matched filter case is lower when the thresholds
 1606 are very low, as the noise baseline is slightly amplified, but then rises to high values
 1607 quicker than for the FIR case. The other difference one can spot is that the sensitivity

Chapter 6. Matched Filter approach to induction wire Trigger Primitives

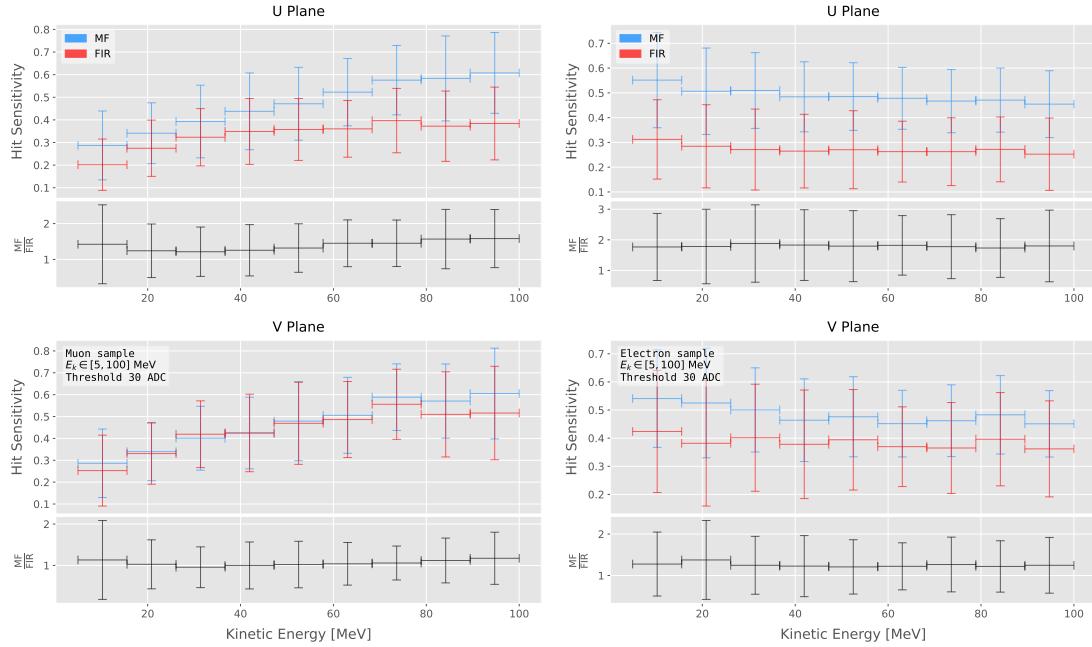


Figure 6.19: Dependence of the averaged hit sensitivity on the kinetic energy of the events for the matched filter (blue) and standard (red) hits, for the case of the muon (left panel) and electron (right panel) samples, separated between U (top plots) and V (bottom plots) induction wire planes. The 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. 6.19 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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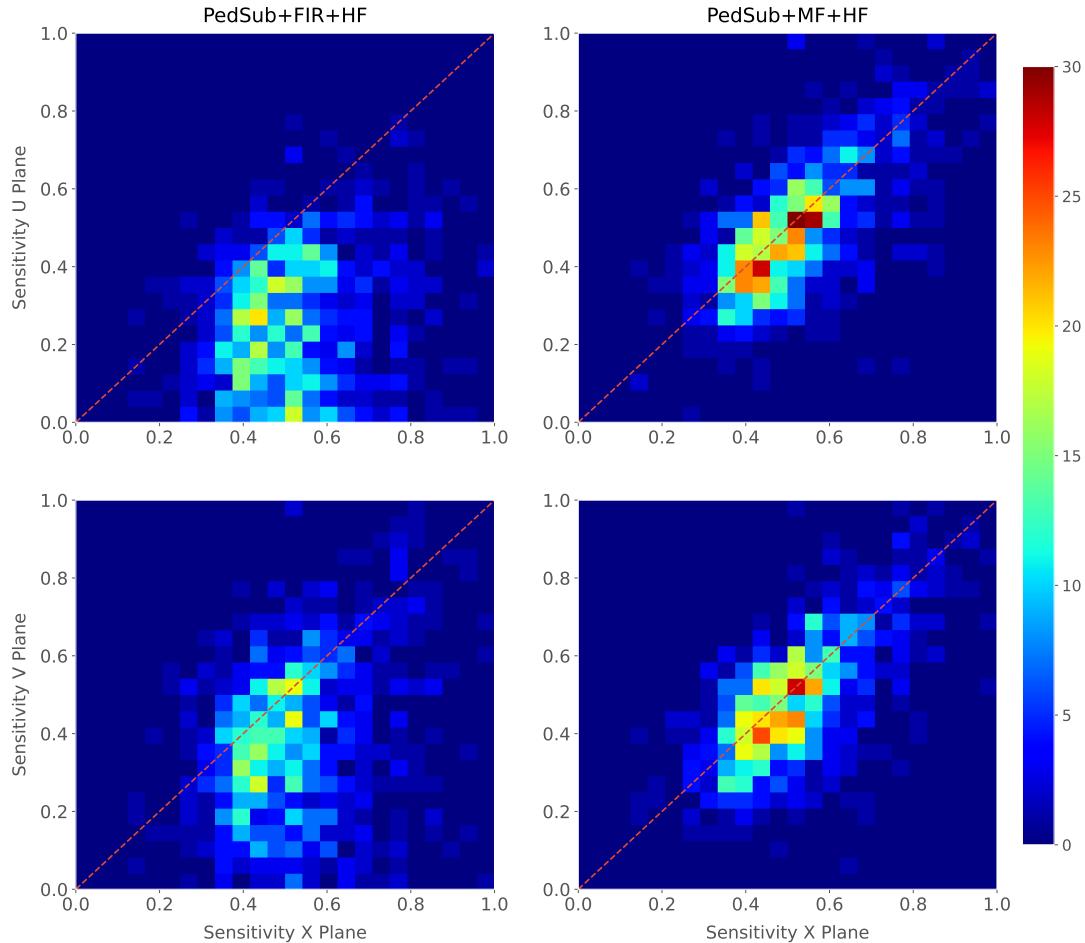


Figure 6.20: Distributions of the hit sensitivity in the U (top panels) and V (bottom panels) planes versus the hit sensitivity in the X plane, both for the standard hits (left panels) and the matched filter hits (right panels), in the case of the electron sample and a threshold of 30 ADC.

1620 The horizontal lines are placed at the mean value obtained in the fit and represent the
 1621 width of the E_k bins used, while the vertical error bars indicate one standard deviation
 1622 around that mean value. In both cases the threshold used was 30 ADC, as I required
 1623 the precision to be higher than 0.99 for both matched filter and standard cases.

1624 One can see that, in general, the improvements are better for the U than for the V
 1625 plane. While for the U channels I achieved a mean improvement of 50% and 80% for
 1626 muons and electrons respectively, the improvement in the V plane is stalled at 10% and
 1627 25%. Nevertheless, if I look at the sensitivities for the matched filter hits in both planes
 1628 one can see these have similar mean values for each energy bin, while on the contrary

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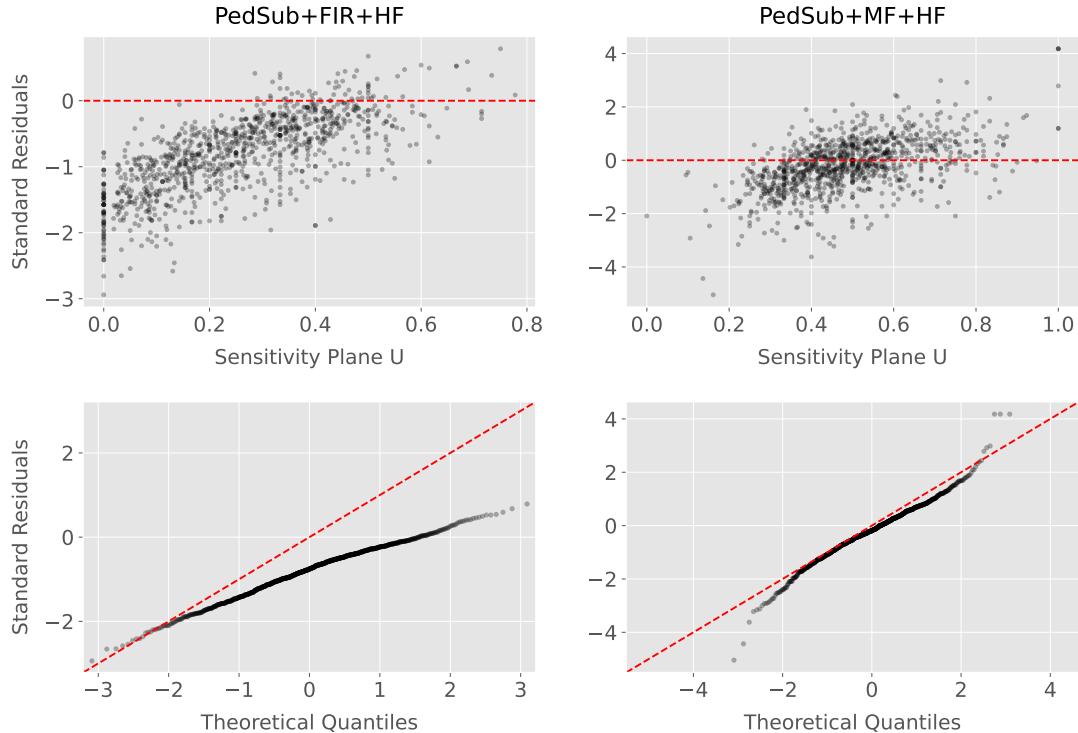


Figure 6.21: Top panels: standard residual plots of the hit sensitivities between the X and U planes. Bottom panels: quantile-quantile plots of the hit sensitivity standard residuals between the X and U planes. In all cases, the left panel corresponds to the standard hits while the right panel represents 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

6.5. Using simulated samples

1641 planes, but ideally they should be normally distributed around the diagonal.

1642 Fig. 6.20 shows the hit sensitivity in the U (top panels) and V (bottom panels)
1643 planes versus the hit sensitivity in the X plane, for the case of the standard hits (left
1644 panels) and the matched filter hits (right panels). All plots were generated for the
1645 electron sample and a threshold of 30 ADC. From these one can see a clear trend,
1646 when I use the standard hit finder chain the sensitivities in the induction planes are
1647 systematically lower than the hit sensitivity in the X plane, i.e. most of the points sit
1648 below the diagonal (red dashed line). In contrast, when the matched filters are applied,
1649 the majority of the events are distributed around the diagonal. This points out that the
1650 concurrence of hits across planes has improved.

1651 To exemplify the improvement I obtained, one can consider the residuals of the hit
1652 sensitivities for the X and U planes. Assuming the diagonal hypothesis, i.e. given a
1653 dataset of the form (x, y) for any x I take the predicted y value to be equal to the value
1654 of x , I can compute the standard residuals for the hit sensitivities in U given the ones for
1655 X. In Fig. 6.21 (top panels) I show these standard residuals against the corresponding
1656 values of the hit sensitivity in the U plane, for our electron sample with kinetic energy
1657 between 5 and 100 MeV. If I compare the scatter points in the case of the standard
1658 hits (left panel) and the matched filter hits (right panel), I see that the residuals of the
1659 standard hit finder case follow a certain pattern and their mean deviates from 0.

1660 To see clearly if the residuals are normally distributed, in Fig. 6.21 (bottom panels)
1661 I plot the corresponding quantile-quantile plot for both the standard (left panel) and
1662 matched filter (right panel) standard residuals. One can clearly see that the points for
1663 the standard case follow a strongly non-linear pattern, suggesting that the residuals
1664 do not follow a normal distribution. In contrast, for the matched filter hits the points
1665 conform to a roughly linear path, implying that in this case the normality condition is
1666 fulfilled.

1667 All these results hint at the fact that the concurrence of hits across the wire planes
1668 can be strengthened by applying the matched filters.

1669 **Chapter 7**

1670 **DM searches with neutrinos from
1671 the Sun**

1672 **7.1 Motivation**

1673 The idea of detecting neutrino signals coming from the Sun’s core to probe DM is not new.
1674 The main focus of these searches has usually been high-energy neutrinos originated from
1675 DM annihilations into heavy particles [61–64], although recent studies have proposed to
1676 look at the low-energy neutrino flux arising from the decay of light mesons at rest in the
1677 Sun [65–68] previously thought undetectable.

1678 In this chapter I try to demonstrate the capability of DUNE to constrain different
1679 DM scenarios. I used the neutrino fluxes arising from DM annihilations in the core
1680 of the Sun to compute the projected limits that DUNE would be able to set on the
1681 annihilation rates in the Sun and the DM scattering cross sections.

1682 **7.2 Gravitational capture of DM by the Sun**

1683 The Sun and the centre of the Earth are possible sources of DM annihilations, specially
1684 interesting because of their proximity. Their gravitational attraction ensured the capture
1685 of DM from the local halo through repeated scatterings of DM particles crossing them.

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1686 Only neutrinos produced from DM annihilations can escape the dense interior of these
1687 objects. Therefore, neutrino telescopes are the most useful experimental layouts to
1688 pursue DM searches from their cores.

1689 The neutrino flux from DM annihilations inside the Sun depends on the DM capture
1690 rate, which is proportional to the DM scattering cross section, and the annihilation rate,
1691 which is proportional to the velocity-averaged DM annihilation cross-section. The total
1692 number of DM particles inside the Sun follows the Boltzmann equation [65]:

$$\frac{dN_{DM}}{dt} = C_{\odot} - A_{\odot} N_{DM}^2, \quad (7.1)$$

1693 where C_{\odot} and A_{\odot} are the total Sun DM capture and annihilation rates respectively.
1694 In this expression I neglected the evaporation term, proportional to N_{DM} , which only
1695 contribute for $m_{DM} \lesssim 4$ GeV [69]. As the current threshold of neutrino telescopes is
1696 a few GeV, this region falls below the probed range but can be important in future
1697 low-energy projects.

1698 This equation has an equilibrium solution:

$$N_{DM}^{eq} = \sqrt{\frac{C_{\odot}}{A_{\odot}}}, \quad (7.2)$$

1699 which represents the amount of DM inside the Sun if the capture and annihilation have
1700 reached equilibrium. As the Sun is approximately 4.6 Gyr old, it is usually assumed that
1701 equilibrium has been achieved. Therefore, the anomalous neutrino flux from the Sun
1702 would only depend on the DM scattering cross section, enabling us to set limits on this
1703 quantity. If one does not assume equilibrium, some assumptions on the DM annihilation
1704 cross section are necessary to extract predictions from neutrino signals.

1705 Here, I am going to consider three possible scenarios for the DM interactions: DM
1706 scattering off electrons, spin-dependent (SD) and spin-independent interactions off nuclei.
1707 For the case of these last two, the cross sections will be given in terms of the SD and
1708 SI elastic scattering DM cross section off protons (assuming that DM interactions off

7.2. Gravitational capture of DM by the Sun

1709 protons and neutrons are identical), σ_p^{SD} and σ_p^{SI} , as [4, 65]:

$$\sigma_i^{\text{SD}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p} \right)^2 \frac{4(J_i + 1)}{3J_i} |\langle S_{p,i} \rangle + \langle S_{n,i} \rangle|^2 \sigma_p^{\text{SD}}, \quad (7.3)$$

$$\sigma_i^{\text{SI}} = \left(\frac{\tilde{\mu}_{A_i}}{\tilde{\mu}_p} \right)^2 A_i^2 \sigma_p^{\text{SI}}, \quad (7.4)$$

1710 where $\tilde{\mu}_{A_i}$ is the reduced mass of the DM-nucleus i system, $\tilde{\mu}_p$ is the reduced mass of
 1711 the DM-proton system, A_i and J_i the mass number and total angular momentum of
 1712 nucleus i and $\langle S_{p,i} \rangle$ and $\langle S_{n,i} \rangle$ the expectation value of the spins of protons and neutrons
 1713 averaged over all nucleons, respectively (see Ref. [70] for a review on spin expectation
 1714 values).

1715 Since the Sun is mainly composed of Hydrogen, the capture of DM from the halo
 1716 is expected to occur mainly through spin-dependent scattering. However, since the
 1717 spin-independent cross section is proportional to the square of the atomic mass, heavy
 1718 elements can contribute to the capture rate (even though they constitute less than 2%
 1719 of the mass of the Sun). Heavy elements can also contribute to the spin-dependent cross
 1720 section if the DM has also momentum-dependent interactions.

1721 DM particles can get captured by the Sun if after repeated scatterings off solar
 1722 targets their final velocity is lower than the escape velocity of the Sun. In the limit of
 1723 weak cross sections, this capture rate can be approximately written as [4]:

$$C_{\odot}^{\text{weak}} = \sum_i \int_0^{R_{\odot}} dr 4\pi r^2 \int_0^{\infty} du_{\chi} \frac{\rho_{\chi}}{m_{\chi}} \frac{f_{v_{\odot}}(u_{\chi})}{u_{\chi}} \omega(r) \int_0^{v_e(r)} dv R_i^-(\omega \rightarrow v) |F_i(q)|^2, \quad (7.5)$$

1724 where the summation extends over all possible nuclear targets. In this expression, R_{\odot}
 1725 is the radius of the Sun, ρ_{χ} is the local DM density, m_{χ} the mass of the DM particle,
 1726 $f_{v_{\odot}}(u_{\chi})$ the DM velocity distribution seen from the Sun's reference frame, $R_i^-(\omega \rightarrow v)$
 1727 is the differential rate at which a DM particle with velocity v scatters a solar target of
 1728 mass m_i to end up with a velocity ω and $|F_i(q)|$ is the nuclear form factor of target i .

1729 The differential scattering rate takes a rather simple form when considering velocity-

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1730 independent and isotropic cross sections. In that case, this quantity is given by [4, 71]:

$$R_i^-(\omega \rightarrow v) = \frac{2}{\sqrt{\pi}} \frac{\mu_{i,+}^2}{\mu_i} \frac{v}{\omega} n_i(r) \sigma_i \left[\chi(-\alpha_-, \alpha_+) + \chi(-\beta_-, \beta_+) e^{\mu_i(\omega^2 - v^2)/u_i^2(r)} \right], \quad (7.6)$$

1731 where μ_i is the ratio between the DM mass and the mass of target i , $\mu_{i,\pm}$ is defined as:

$$\mu_{i,\pm} \equiv \frac{\mu_i \pm 1}{2}, \quad (7.7)$$

1732 $n_i(r)$ is the density profile of target i in the solar medium, $u_i(r)$ is the most probable

1733 velocity of target i given by:

$$u_i(r) = \sqrt{\frac{2T_\odot(r)}{m_i}}, \quad (7.8)$$

1734 where $T_\odot(r)$ is the temperature of the Sun, the quantities α_\pm and β_\pm are defined as:

$$\alpha_\pm \equiv \frac{\mu_{i,+}v \pm \mu_{i,-}\omega}{u_i(r)}, \quad (7.9)$$

$$\beta_\pm \equiv \frac{\mu_{i,-}v \pm \mu_{i,+}\omega}{u_i(r)}, \quad (7.10)$$

1735 and the function $\chi(a, b)$ is a Gaussian integral of the form:

$$\chi(a, b) \equiv \int_a^b dx e^{-x^2}. \quad (7.11)$$

1736 Finally, if one assumes the DM halo velocity distribution in the galactic rest frame

1737 to be a Maxwell-Boltzmann distribution, one can write the halo velocity distribution for

1738 an observer moving at the speed of the Sun with respect to the DM rest frame as:

$$f_{v_\odot}(u_\chi) = \sqrt{\frac{3}{2\pi}} \frac{u_\chi}{v_\odot v_d} \left(e^{-\frac{3(u_\chi - v_\odot)^2}{2v_d^2}} - e^{-\frac{3(u_\chi + v_\odot)^2}{2v_d^2}} \right), \quad (7.12)$$

1739 where:

$$\omega^2 = u_\chi + v_e(r)^2, \quad (7.13)$$

1740 is the DM velocity squared, v_\odot the relative velocity of the Sun from the DM rest frame

7.2. Gravitational capture of DM by the Sun

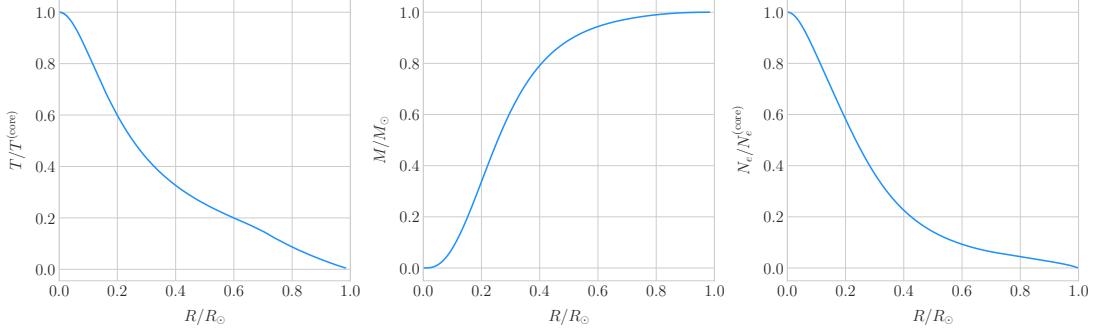


Figure 7.1: Input solar parameters used in our capture rate computation as functions of the Sun's radius, from left to right: temperature (with respect to the temperature at the core), mass (in solar masses) and electron number density (with respect to the electron density at the core). All quantities shown correspond to the standard solar model BS2005-OP [3].

1741 and $v_d \simeq \sqrt{3/2}v_\odot$ the velocity dispersion.

1742 For the case of strong scattering cross section, Eq. (7.5) ceases to be valid, as it
 1743 escalates indefinitely with the cross section. In that limit, the capture rate saturates to
 1744 the case where the probability of interaction is equal to one, which can be written as:

$$C_\odot^{\text{geom}} = \pi R_\odot^2 \left(\frac{\rho_\chi}{m_\chi} \right) \langle v \rangle \left(1 + \frac{3}{2} \frac{v_e^2(R_\odot)}{v_d^2} \right) \xi(v_\odot, v_d), \quad (7.14)$$

1745 where $v_d = \sqrt{8/3\pi}v_d$ is the mean velocity in the DM rest frame and the factor $\xi(v_\odot, v_d)$
 1746 accounts for the suppression due to the motion of the Sun:

$$\xi(v_\odot, v_d) = \frac{v_d^2 e^{-\frac{3v_\odot^2}{2v_d^2}} + \sqrt{\frac{\pi}{6}} \frac{v_d}{v_\odot} (v_d^2 + 3v_e^2(R_\odot) + 3v_\odot^2) \operatorname{Erf}\left(\sqrt{\frac{3}{2}} \frac{v_\odot}{v_d}\right)}{2v_d^2 + 3v_e^2(R_\odot)}. \quad (7.15)$$

1747 Having these into account, one can write the total capture rate as a combination of
 1748 both contributions, allowing a smooth transition between the two, as:

$$C_\odot = C_\odot^{\text{weak}} \left(1 - e^{C_\odot^{\text{geom}}/C_\odot^{\text{weak}}} \right). \quad (7.16)$$

1749 I computed the capture rate from Eq. (7.16) in the case of interactions with
 1750 electrons. To do so, I used the standard solar model BS2005-OP [3]. Fig. 7.1 shows the

Chapter 7. DM searches with neutrinos from the Sun

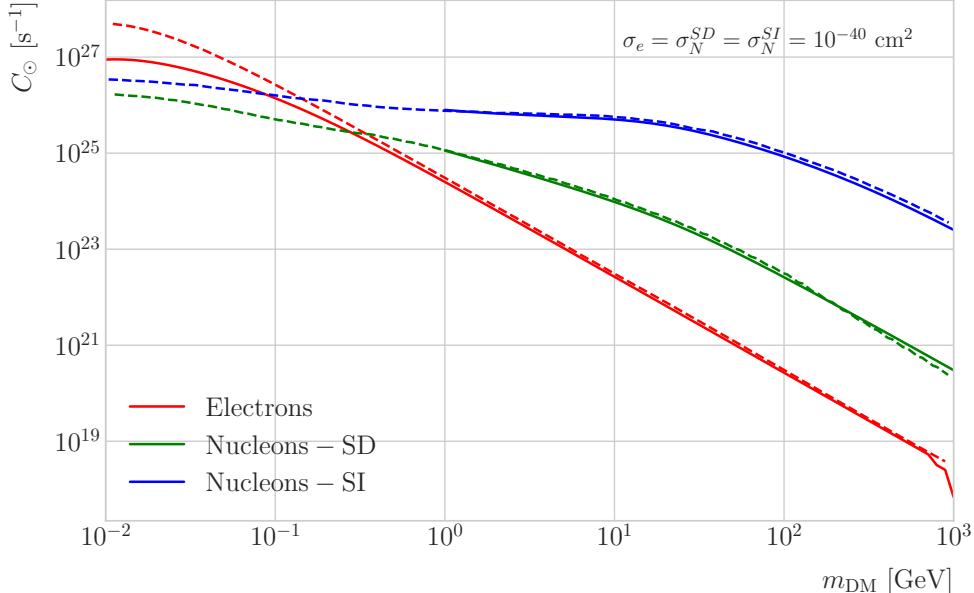


Figure 7.2: Capture rates as a function of the DM mass for the DM-electron interactions (red lines), SD DM-nucleons interactions (green lines) and SI DM-nucleons interactions (blue lines). Solid lines represent the values computed in this work while the dashed lines are the one given in Ref. [4]. All the rates are shown for a choice of scattering cross section of $\sigma_i = 10^{-40} \text{ cm}^2$.

1751 three parameters from the solar model that are needed for the computation, the solar
 1752 temperature (left panel), mass (central panel) and electron density (right panel) profiles.

1753 For the case of the interactions off nuclei, the computations are more convoluted
 1754 as one needs to add up the contributions of the different most abundant nuclei in
 1755 the Sun. Also, in contrast to the electron scenario where the form factor is trivially
 1756 $|F_e(q)|^2 = 1$, for any nucleus i one would need to consider some appropriate nuclear
 1757 density distribution (either a Gaussian approximation, a Woods-Saxon distribution, etc)
 1758 which would complicate the calculations even further.

1759 That is the reason why, at this stage of our study, I decided to take an alternative
 1760 approach to the computation of the DM-nucleus capture rates. I used the **DarkSUSY**
 1761 software, that allows us to compute these quantities performing a full numerical
 1762 integration over the momentum transfer of the form factors. The default standard
 1763 solar model used by **DarkSUSY** is BP2000¹ [72].

¹This is what they say in their manual, but I fear it is somewhat outdated. It appears to me this

7.2. Gravitational capture of DM by the Sun

1764 In Fig. 7.2 I show the results I obtained for the capture rates, for the case of
 1765 interactions off electrons (red solid line), SD (green solid line) and SI (blue solid line)
 1766 interactions of nucleons. In all cases I used a value of the scattering cross sections of
 1767 $\sigma_i = 10^{-40} \text{ cm}^2$. Note here one of the limitations of the **DarkSUSY** approach, one can
 1768 not extend the computation below $m_{\text{DM}} = 1 \text{ GeV}$. Nevertheless, this is not something
 1769 to worry about in this case, as I will discuss next. As a comparison, I added also the
 1770 values computed in Ref. [4] (same color scheme, dashed lines). One can see there is good
 1771 agreement between these and the **DarkSUSY** computation of the SD and SI interactions
 1772 for $m_{\text{DM}} \geq 1 \text{ GeV}$. In this regime their computations also matches quite well our
 1773 result for the electron capture rate. However, these start to differ significantly below
 1774 $m_{\text{DM}} = 1 \text{ GeV}$, being their estimate up to a factor of 5 bigger than ours for low masses.

1775 Let us comment briefly about the assumption I made before about not including
 1776 an evaporation term in the Boltzmann equation. If I include this term in the equation
 1777 (which will be proportional to the number of DM particles) the equilibrium solution
 1778 takes the form:

$$N_{\text{DM}}^{eq} = \sqrt{\frac{C_{\odot}}{A_{\odot}}} \frac{1}{\kappa + \frac{1}{2} E_{\odot} \tau_{eq}}, \quad (7.17)$$

1779 where E_{\odot} is the total evaporation rate, τ_{eq} is the equilibrium time in the absence of
 1780 evaporation:

$$\tau_{eq} = \frac{1}{\sqrt{C_{\odot} A_{\odot}}}, \quad (7.18)$$

1781 and κ is defined as:

$$\kappa \equiv \sqrt{1 + \left(\frac{E_{\odot} \tau_{eq}}{2} \right)^2}. \quad (7.19)$$

1782 Now, it is easy to proof that in case evaporation dominates $\kappa \gg 1$ and therefore:

$$N_{\text{DM}}^{eq} \simeq \frac{C_{\odot}}{E_{\odot}}. \quad (7.20)$$

1783 In contrast, if evaporation is irrelevant $\kappa \simeq 1$ and one recovers Eq. (7.2).

model is relatively old and do not see why they are not using others like [3]. Maybe one can double-check in the code to make sure.

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1784 In this way, one can define the evaporation mass as the mass for which the number
1785 of DM particles in equilibrium approaches Eq. (7.20) at 10% level:

$$\left| N_{DM}^{eq}(m_{\text{evap}}) - \frac{C_{\odot}(m_{\text{evap}})}{E_{\odot}(m_{\text{evap}})} \right| = 0.1 N_{DM}^{eq}(m_{\text{evap}}). \quad (7.21)$$

1786 This can be regarded as the minimum testable mass one can reach using the annihilation
1787 products of the DM in the Sun.

1788 It was reported in Ref. [4] that, in the case of both SD and SI DM interactions
1789 off nuclei, this value ranges from 2 to 4 GeV depending on the specific scattering
1790 cross section value, compatible with the usual assumptions in the literature. What is
1791 interesting is the case of the electron capture. It was found that, when one applies a
1792 cutoff in the velocity distribution of the DM trapped in the Sun slightly below the escape
1793 velocity, the evaporation mass for the DM-electron interaction decreases remarkably. For
1794 a moderate choice of $v_c(r) = 0.9v_e(r)$ one gets an evaporation mass of around 200 to
1795 600 MeV. This possibility opens a region of the parameter space that could be tested
1796 with neutrino detectors.

1797 7.3 Neutrino flux from DM annihilations

1798 When WIMPs annihilate inside the Sun a flux of high-energy neutrinos is expected from
1799 heavy quarks, gauge bosons and $\tau^+\tau^-$ final states, which decay before losing energy
1800 in the dense solar medium, as they will produce a continuum spectra up to $E_{\nu} \sim m_{\chi}$
1801 (in the case of direct annihilation to neutrinos one would have a line at $E_{\nu} = m_{\chi}$) [66].
1802 This kind of signal has been extensively studied in the literature, allowing to put strong
1803 limits on the SD WIMP-proton cross section for large m_{χ} . However, the number of
1804 high-energy neutrinos per WIMP annihilation is small and the spectrum depends on the
1805 unknown final state. Moreover, background rejection is easier for large m_{χ} but neutrinos
1806 with $E_{\nu} \gtrsim 100$ GeV are significantly attenuated by interactions in the Sun.

1807 Nevertheless, most WIMP annihilation final states eventually produce a low-energy
1808 neutrino spectrum. In this case one does not just consider the more massive final

7.4. Computing limits from solar neutrino fluxes

1809 states but also annihilations into e^+e^- , $\mu^+\mu^-$ and light quarks [65]. In particular, light
 1810 mesons would be produced and stopped in the dense medium, thus decaying at rest and
 1811 producing a monoenergetic neutrino signal. The decay-at-rest of kaons will produce
 1812 a $E_\nu = 236$ MeV ν_μ while in the case of pions one would have a $E_\nu = 29.8$ MeV ν_μ .
 1813 In practice only K^+ and π^+ contribute to these signals, as K^- and π^- are usually
 1814 Coulomb-captured in an atomic orbit and get absorbed by the nucleus. There is also a
 1815 low-energy neutrino signal coming from muon decays, which are produced in kaon or
 1816 pion decays, leptonic decays of other hadrons and heavy leptons or even directly from
 1817 WIMP annihilations, which can decay at rest and contribute to the previous low-energy
 1818 neutrino flux with a well known spectrum below 52.8 MeV.

1819 These monoenergetic MeV neutrinos were previously considered undetectable but,
 1820 due to the large yield, the known spectra and the modern advances in the detector
 1821 technology, these low-energy neutrino flux can be a good probe of the SD WIMP-proton
 1822 cross-section in standard solar WIMP capture scenario, as it is sensitive to low WIMP
 1823 masses and insensitive to the particular final state. A good place to look for these signals
 1824 are next-generation neutrino experiments such as DUNE.

1825 7.4 Computing limits from solar neutrino fluxes

1826 In order to use the neutrino fluxes from DM annihilations in the Sun, the first thing I
 1827 need to do is to determine the expected number of atmospheric background events, for
 1828 a given exposure, after directionality selection has been applied. I can write this number
 1829 as:

$$N_B = \eta_B \int d\Omega \int_{E_{min}}^{E_{max}} dE_\nu \frac{d^2\Phi_{atm}^\mu}{dE_\nu d\Omega} \times \left(A_{eff}^{(\mu)}(E_\nu) T \right), \quad (7.22)$$

1830 where η_B is the background efficiency, E_{min} and E_{max} the minimum and maximum
 1831 energies to integrate over, $d^2\Phi_{atm}^\mu/dE_\nu d\Omega$ the differential flux of atmospheric muon
 1832 neutrinos, $A_{eff}^{(\mu)}$ is the effective area of DUNE to muon neutrinos and T is the exposure
 1833 time. The effective area can be expressed as the product of the neutrino-nucleus scattering
 1834 cross section and the number of nuclei in the fiducial volume of the detector. This way

Chapter 7. DM searches with neutrinos from the Sun

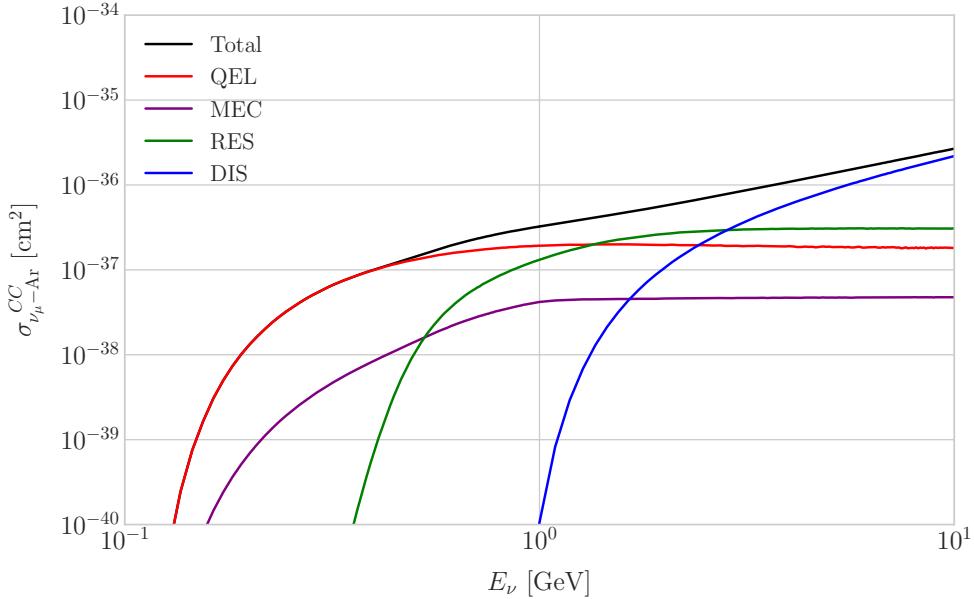


Figure 7.3: *NuWro* computed $\nu_\mu - {}^{40}\text{Ar}$ charged-current scattering cross section as a function of the neutrino energy E_μ . The black line shows to the total cross section, whereas the others correspond to the different contributions (in red quasi-elastic scattering, in green resonant pion exchange, in blue deep inelastic scattering and in purple meson exchange current).

1835 for DUNE I can write:

$$A_{eff}^{(\mu)}(E_\nu) = (6.0 \times 10^{-10} \text{ m}^2) \left(\frac{\sigma_{\nu - \text{Ar}}^{(\mu)}(E_\nu)}{10^{-38} \text{ cm}^2} \right) \left(\frac{M_{target}}{40 \text{ kT}} \right), \quad (7.23)$$

1836 where $\sigma_{\nu - \text{Ar}}^{(\mu)}$ is the $\nu_\mu - {}^{40}\text{Ar}$ charged-current scattering cross section. In Fig. 7.3 I
 1837 show the computed value of this cross section as a function of the neutrino energy E_ν ,
 1838 in the range of interest both for the atmospheric background and signal events. It was
 1839 computed using the NuWro Monte Carlo neutrino event generator [73], including the
 1840 charged-current contributions of the quasi-elastic scattering (red line), resonant pion
 1841 exchange (green line), deep inelastic scattering (blue line) and meson exchange current
 1842 (purple line).

1843 The background rejection will depend on the resolution of the detector and the
 1844 selection one applies on the events. A geometry argument can be used to estimate
 1845 the maximum background rejection one can achieve in this case, considering one can

7.4. Computing limits from solar neutrino fluxes

1846 efficiently discriminate all events coming from a direction different from that of the
 1847 Sun. In that case, the optimal background efficiency will simply be the relative angular
 1848 coverage of the Sun. Taking the angular diameter of the Sun as seen from the Earth to
 1849 be 0.5° , I have:

$$\eta_B^{(opt)} \approx \frac{\pi \left(\frac{0.5}{2}\right)^2}{360 \times 180} \simeq 3.03 \times 10^{-6}. \quad (7.24)$$

1850 This value will give a very optimistic estimate of the number of background events.
 1851 However, it can be regarded as a lower limit, as it represents the best case scenario.

1852 In Fig. 7.4 I show the fluxes of atmospheric neutrinos at the Homestake mine during
 1853 solar minimum, taken from Ref. [5]. The values are averaged over the two angular
 1854 directions. In blue I have the flux of muon neutrinos while in red I indicate the flux
 1855 of electron neutrinos. Additionally, the dashed lines correspond to both antineutrino
 1856 species.

1857 Using these values for the muon neutrino and the corresponding total CC cross
 1858 section, one can compute the number of expected background events by integrating over
 1859 the given energy range (as in this case the angular integral is trivial). As for the energy
 1860 range to integrate over, I choose the range for DUNE specified in [42], $E_{min} = 10^{-1}$ GeV
 1861 and $E_{max} = 10$ GeV. Taking all these into account, I found the number of background
 1862 events to be:

$$N_B \simeq \eta_B \times (3.827 \times 10^4) \times \left(\frac{\text{exposure}}{400 \text{ kT yr}} \right). \quad (7.25)$$

1863 In order to estimate the sensitivity of DUNE to this kind signal, one can consider a
 1864 hypothetical data set where the number of observed neutrinos is taken to be the expected
 1865 number of background events rounded to the nearest integer, $N_{obs} = \text{round}(N_B)$ [74].
 1866 Now, if I assume that the number of signal and background events seen by DUNE are
 1867 given by Poisson distributions with means equal to the expected number of signal and
 1868 background events, N_S and N_B , one can denote by N_S^{90} to the number of expected
 1869 signal events such that the probability of having an experimental run with a number of
 1870 events greater than N_{obs} is 90%. This number can be obtained as the numerical solution

Chapter 7. DM searches with neutrinos from the Sun

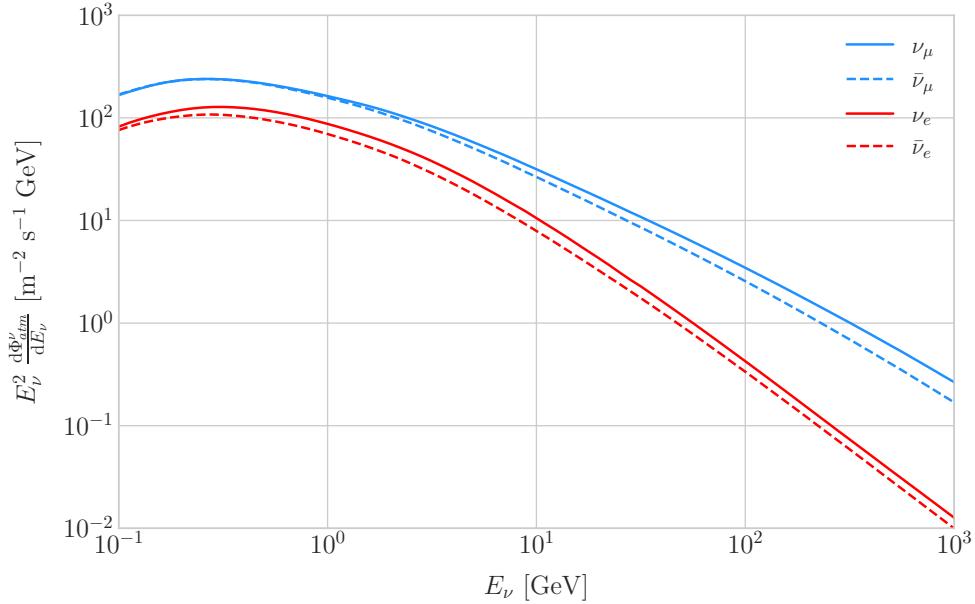


Figure 7.4: Expected atmospheric neutrino flux as a function of the neutrino energy E_ν at Homestake at solar minimum, taken from Ref. [5]. The blue solid (dashed) line correspond to muon neutrinos (antineutrinos) and the red solid (dashed) line correspond to electron neutrinos (antineutrinos).

1871 to the equation:

$$1 - \frac{\Gamma(N_{obs} + 1, N_S^{90} + N_B)}{N_{obs}!} = 0.9, \quad (7.26)$$

1872 where $\Gamma(x, y)$ is the upper incomplete gamma function.

1873 The number of signal events is related to the neutrino flux from DM annihilations in
 1874 a similar way as the background events to the atmospheric neutrino flux. In this case I
 1875 have:

$$N_S = \eta_S \Gamma_A^{eq} \int_{z_{min}}^{z_{max}} dz \frac{dN_\nu}{dAdN_A dz} \times (A_{eff}^\mu(z)T), \quad (7.27)$$

1876 where η_S is the signal efficiency, Γ_A^{eq} is the total annihilation rate of DM particles at
 1877 equilibrium, $\Gamma_A^{eq} = A_\odot (N_{DM}^{eq})^2$, z_{min} and z_{max} the minimum and maximum relative
 1878 energies to integrate over (in such a way that $z_{min,max} \leq E_{min,max}/m_{DM}$ for each m_{DM})
 1879 and $dN_\nu/dAdN_A dz$ the muon neutrino flux per DM annihilation in the Sun.

1880 Knowing N_S^{90} one can use the relation in Eq. (7.27) to obtain $\Gamma_A^{eq,90}$ for different
 1881 values of the DM mass. From there I can directly translate those values into the

7.5. Example: Kaluza-Klein Dark Matter

1882 upper limits for DUNE on the DM scattering cross sections, for a given exposure. The
1883 relation between the annihilation rate and the DM-nucleon cross section comes from the
1884 equilibrium condition through the solar DM capture rate. The details of the evolution
1885 of the number of DM particles inside the Sun and the computation of the capture rates
1886 are discussed in App. 7.2.

1887 7.5 Example: Kaluza-Klein Dark Matter

1888 Even though there are plenty of BSM theories which provide viable dark matter
1889 candidates, Kaluza-Klein type of models [75, 76] within the universal extra dimensions
1890 (UED) paradigm naturally predict the existence of a massive, stable particle that can
1891 play the role of the dark matter. In the UED scenario all the SM fields can propagate
1892 in one or more compact extra dimensions [77], as opposed to the idea of brane worlds
1893 [78, 79], where just gravity can propagate in the bulk while SM particles live at fixed
1894 points.

1895 Furthermore, in UED there is no violation of the translational invariance along the
1896 extra dimensions, thus leading to degenerate KK modes masses and also the conservation
1897 of the KK number in the effective four dimensional theory. At loop level, radiative
1898 corrections and boundary terms shift the masses of the KK modes and break KK
1899 number conservation into a KK parity. As a result, this theory only contains interactions
1900 between an even number of odd KK modes and therefore the lightest among the first KK
1901 excitations will be stable. This particle is usually denoted as the lightest Kaluza-Klein
1902 particle (LKP) and its mass is proportional to $1/R$, being R the size of the extra
1903 dimension.

1904 A viable DM candidate needs to be electrically neutral and non-baryonic, therefore
1905 good candidates among the first Kaluza-Klein excitations would be the KK neutral
1906 gauge bosons and the KK neutrinos [80]. Another possible candidate is the first KK
1907 excitation of the graviton, which receives negligible radiate contributions and therefore
1908 has a mass almost equal to $1/R$, but it has been shown that the lightest eigenstate from

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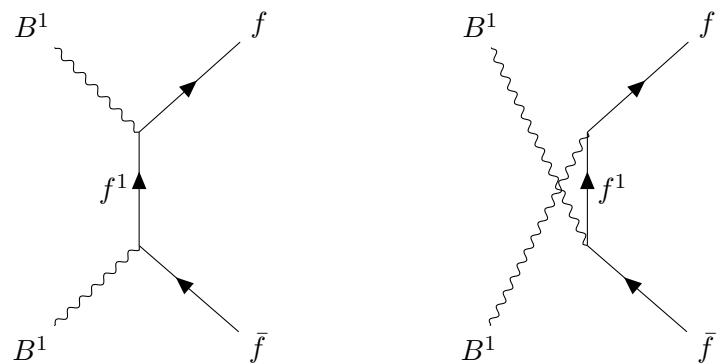


Figure 7.5: Feynman diagrams for B^1B^1 annihilation into SM fermions.

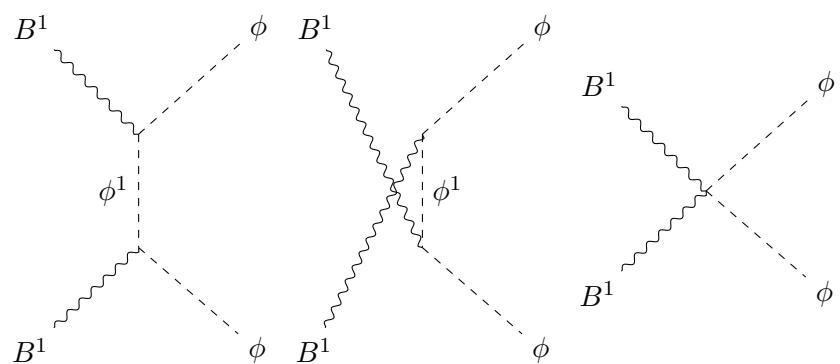


Figure 7.6: Feynman diagrams for B^1B^1 annihilation into a Higgs boson pair.

7.5. Example: Kaluza-Klein Dark Matter

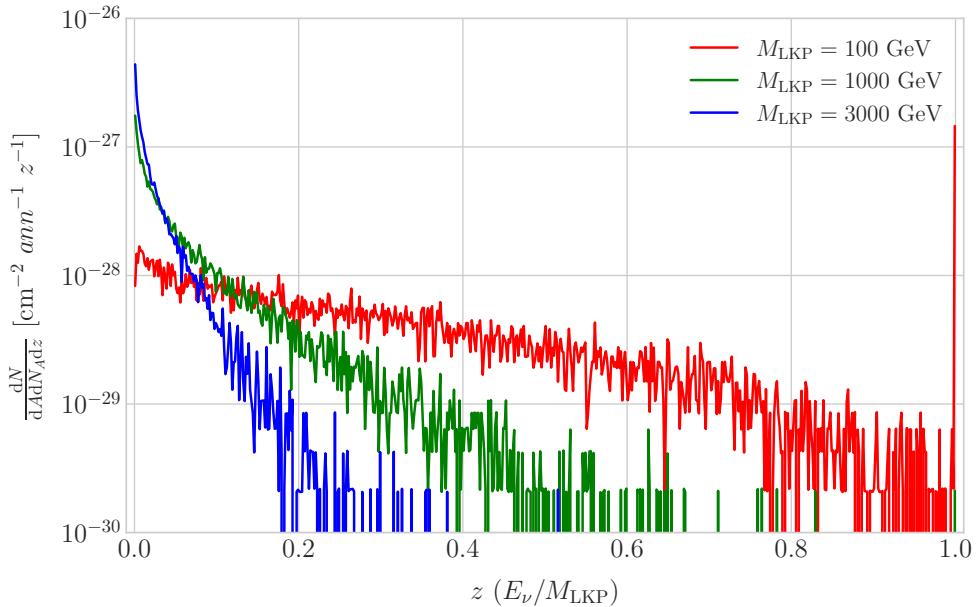


Figure 7.7: Computed spectra of muon neutrinos at the DUNE FD site from B^1 annihilations in the Sun for three different values of M_{LKP} , plotted in relative energy units for legibility.

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 [81]. 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 [81]. 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` [82, 83] 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_{LKP} . In Fig. 7.7 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 $\chi\chi \rightarrow \nu\bar{\nu}$.

Chapter 7. DM searches with neutrinos from the Sun

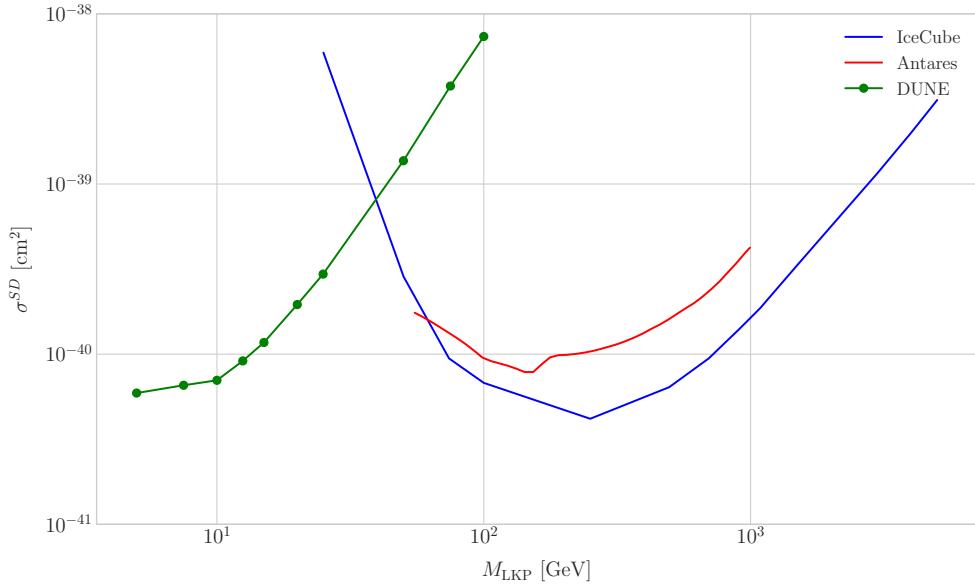


Figure 7.8: Projected 90% confidence level upper limit for DUNE (400 kT yr) on the spin-dependent B^1 -proton scattering cross section as a function of M_{LKP} (green dots). I also show the previous limits from IceCube [6] (blue line) and Antares [7] (red line) on the LKP cross section. The shaded area represents the disfavoured region (at 95% confidence level) on the mass of the LKP from LHC data [8].

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. (7.24) 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. (7.26) 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. (7.2) and the capture rates I computed with DarkSUSY.

In Fig. 7.8 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 [6] (blue line) and Antares [7] (red line). The shaded area represents the disfavoured region from combined searches for UED by ATLAS and CMS [8].

7.6. High energy DM neutrino signals

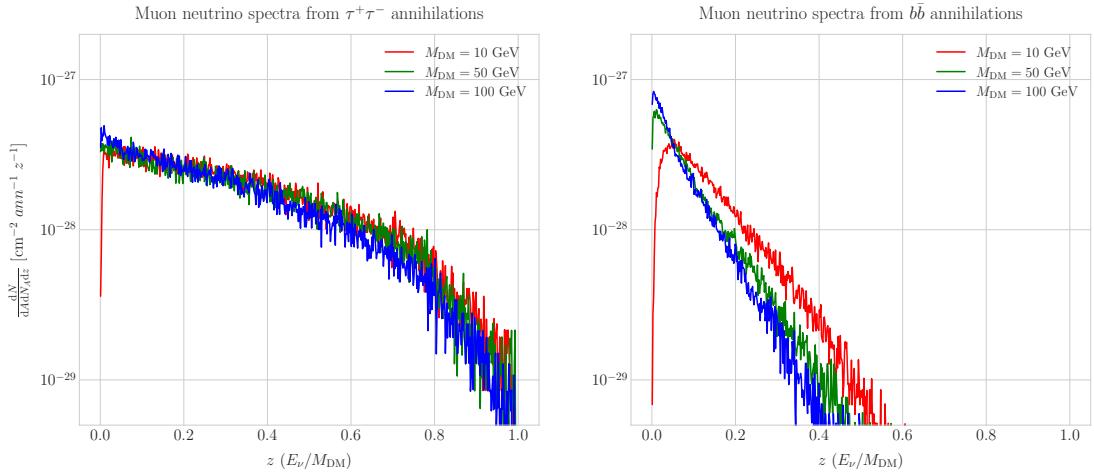


Figure 7.9: Computed spectra of muon neutrinos at the DUNE FD site from $\tau^+\tau^-$ (left panel) and $b\bar{b}$ (right panel) annihilations in the Sun for the DM masses $m_{\text{DM}} = 10 \text{ GeV}$ (red line), 50 GeV (green line) and 100 GeV (blue line), plotted in relative energy units.

From the experimental point of view, this estimation lacked a detailed simulation of 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 [8] and other rare decay measurements [84, 85], it still constitutes an alternative indirect probe.

7.6 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 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

Chapter 7. DM searches with neutrinos from the Sun

1954 those will produce usually a higher energy neutrino flux that will be out of reach for
1955 DUNE (usually the maximum neutrino energy is taken to be $E_{max} = 10$ GeV).

1956 In Fig. 7.9 I show the `WimpSim` [82, 83] generated muon neutrino spectra at the
1957 DUNE FD location ($44^\circ 20' N, 103^\circ 45' W$) from $\tau^+\tau^-$ (left panel) and $b\bar{b}$ (right panel)
1958 annihilations in the core of the Sun, for different DM masses. Here, one can clearly see
1959 the meaning of the previous distinction between hard and soft channels. For the same
1960 DM mass value, the muon neutrino spectrum from the $\tau^+\tau^-$ channel is more flat and
1961 reaches higher energies than the one from the $b\bar{b}$ channel, which drops faster.

1962 In this case, I prepared two sets of files, one for $\tau^+\tau^-$ and the other for $b\bar{b}$, for DM
1963 masses in the range from 5 to 100 GeV (actually for $b\bar{b}$ the first mass point I took is
1964 7.5 GeV, as a WIMP with $m_{DM} = 5$ GeV can not kinematically self annihilate into $b\bar{b}$).
1965 Then, I prepared the `WimpSim` output fluxes in a specific way to use them as inputs to
1966 `NuWro`, which simulates the neutrino interaction with the argon.

1967 Because `WimpSim` outputs an event list together with the fluxes, I can use the former
1968 to generate the events. The direction of these is given in terms of the azimuth and
1969 altitude angles viewed from the specified location, so first I need to convert these into the
1970 DUNE FD coordinates. Once I have done it, each event can be processed with `NuWro`.
1971 To increase the number of samples and optimise the computation time, I generate 100
1972 interactions (i.e. `NuWro` events) for each `WimpSim` event². I restrict the event generation
1973 to charged current interactions, but I allow all the different contributions to the CC
1974 cross section, i.e. quasielastic scattering (QEL), meson exchange current process (MEC),
1975 resonant pion production (RES) and deep inelastic scattering (DIS). I just take into
1976 account the CC contribution because I am only interested in final states with charged
1977 leptons, as we have better chances of reconstructing the kinematics of CC events.

1978 For the atmospheric fluxes I follow a similar procedure, only that this time I do not
1979 have a set of events but the fluxes binned in azimuth and altitude angles. This way, I
1980 transform these to DUNE coordinates and process the fluxes for each bin separated with

²This 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.

7.6. High energy DM neutrino signals

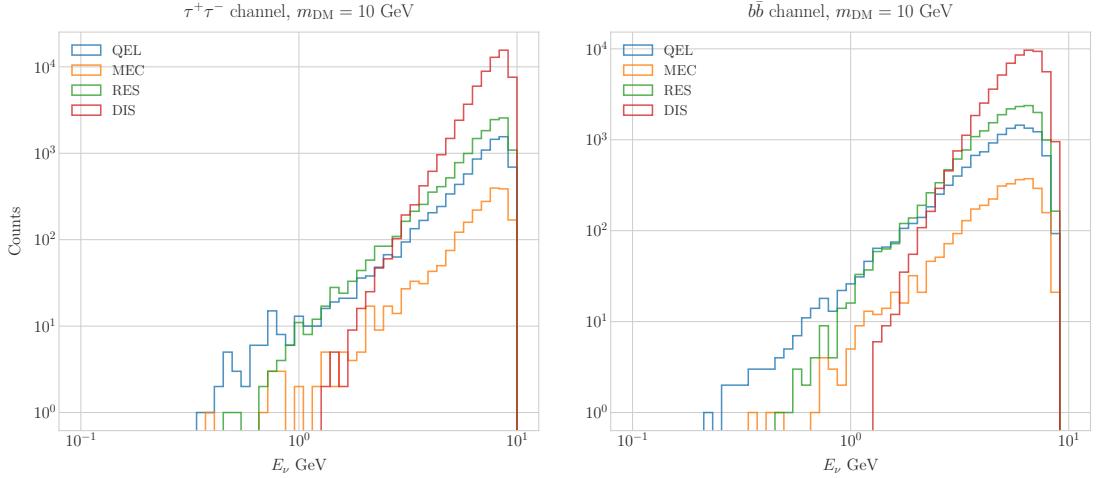


Figure 7.10: Distribution of the muon neutrino energies from the $\tau^+\tau^-$ (left panel) and $b\bar{b}$ (right panel) annihilation channels, for $m_{\text{DM}} = 10 \text{ GeV}$, separated by CC interaction type: QEL (blue), MEC (orange), RES (green) and DIS (red).

1981 NuWro.

1982 At this point, I have two sets of events with different energies and final states.
 1983 In Fig. 7.10 one can see the distribution of the muon neutrino energies for the case
 1984 $m_{\text{DM}} = 10 \text{ GeV}$, both for the $\tau^+\tau^-$ (left panel) and $b\bar{b}$ (right panel) channels, separated
 1985 by interaction. One can clearly see that there are different energy regimes where the
 1986 primary interaction type is different. This leads to a plurality of event topologies,
 1987 therefore making it difficult to implement a general approach to the selection of events
 1988 in detriment of the background. As a way to proceed, I decided to split our samples,
 1989 based on the different interaction modes and contents of the final state, into a CC DIS
 1990 sample and a single proton CC QEL sample.

1991 7.6.1 DIS events

1992 To begin with, I consider the high energy part of the spectrum. In this region DIS events
 1993 dominate, i.e. interactions of the form $\nu_\mu + q_d(\bar{q}_u) \rightarrow \mu^- + q_u(\bar{q}_d)$. Therefore, our final
 1994 estates will contain a muon and a hadronic jet from the fragmentation of the outgoing
 1995 quark. As all these events have $E_\nu \gtrsim 1 \text{ GeV}$ the momentum transfer to the remnant
 1996 nucleus is negligible, for this reason the neutrino energy can be effectively reconstructed

Chapter 7. DM searches with neutrinos from the Sun

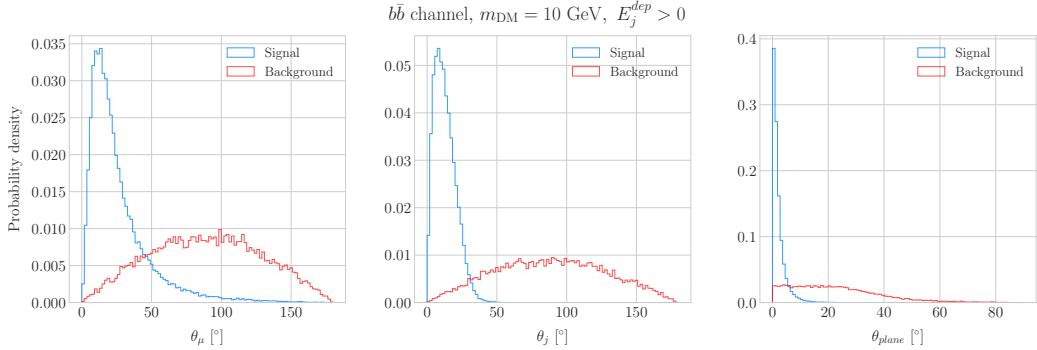


Figure 7.11: Distributions of θ_μ (left panel), θ_j (central panel) and θ_{plane} (right panel) for the $b\bar{b}$ sample with $m_{\text{DM}} = 10$ GeV (blue) and the atmospheric background (red).

1997 just taking into account the momenta of the muon and the jet. This technique was
 1998 successfully used in Ref. [86] to select monoenergetic DM solar neutrino events from $\nu\bar{\nu}$
 1999 annihilation channels.

2000 Using momentum conservation one sees that the plane generated by the momenta
 2001 of the muon and the jet needs to also contain the momentum of the neutrino. As we
 2002 are interested in neutrinos coming from the Sun, the momentum of the neutrino can be
 2003 regarded as known beforehand. This will allow us to define the angle of the outgoing
 2004 muon and jet with respect to the incoming neutrino. Moreover, one can also use that
 2005 information to reject poorly reconstructed jets, checking for deviations of these from the
 2006 momentum conservation plane.

2007 To account for the limited angular resolution of the detector, I smeared the momenta
 2008 of the muons and hadrons. In a liquid argon TPC muons are expected to be tracked with
 2009 high precision, therefore I take the associated angular resolution to be 1° . In the case of
 2010 jets, it is expected that for the hadrons dominating the cascade a detector like DUNE
 2011 has an angular resolution between 1° to 5° [42], so I take the latter, more conservative,
 2012 estimate.

2013 As a first selection step, I will just take into account particles with kinetic energies
 2014 above the detection threshold of DUNE. For muons and photons the specified threshold
 2015 energy is 30 MeV, for charged pions 100 MeV and for other hadrons 50 MeV [42]. This
 2016 way, if the outgoing muon in a certain event has an energy lower than the required

7.6. High energy DM neutrino signals

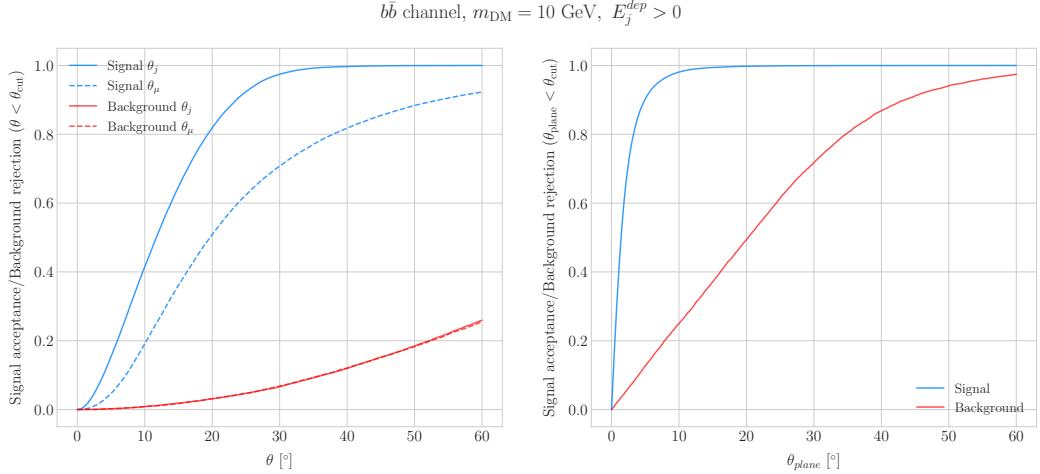


Figure 7.12: Left panel: signal efficiencies (blue lines) and background rejections (red lines) for events passing the cuts $\theta < \theta_{\text{cut}}$ for the jet (solid lines) and muon (dashed lines) angles. Right panel: signal efficiency (blue line) and background rejection (red line) for events passing the cut $\theta_{\text{plane}} < \theta_{\text{cut}}$ for the momentum conservation plane deviation.

2017 threshold I will drop such event. For the case of hadrons and photons, I will only require
 2018 to have at least one particle above the energy threshold, so then one can compute the
 2019 jet momentum using the (smeared) momenta of the N particles above threshold as:

$$\vec{p}_j = \sum_{i=1}^N \vec{p}_i. \quad (7.28)$$

2020 Additionally, I will also define an estimation of the deposited hadronic energy as:

$$E_j^{\text{dep}} = m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}} + \sum_{i=1}^N \sqrt{|\vec{p}_i|^2 + m_i^2}. \quad (7.29)$$

2021 This quantity is useful to select events with enough hadronic visible energy in the
 2022 detector. For events where most of the hadronic energy is scattered across plenty of
 2023 hadrons with individual energies below the detection threshold, this estimation will
 2024 give $E_j^{\text{dep}} \leq 0$. In these cases it could be expected that the jet momentum is poorly
 2025 reconstructed, and therefore I require events to pass the cut $E_j^{\text{dep}} > 0$.

2026 For the events I can compute the angles for the muon and jet with respect to the

Chapter 7. DM searches with neutrinos from the Sun

2027 incoming neutrino as:

$$\cos \theta_\mu = \hat{p}_\nu \cdot \hat{p}_\mu, \quad (7.30)$$

$$\cos \theta_j = \hat{p}_\nu \cdot \hat{p}_j, \quad (7.31)$$

2028 and the deviation from the momentum conservation plane as:

$$\sin \theta_{plane} = \left| \frac{\hat{p}_\mu \times \hat{p}_\nu}{|\hat{p}_\mu \times \hat{p}_\nu|} \cdot \hat{p}_j \right|. \quad (7.32)$$

2029 In Fig. 7.11 I show some distributions of these quantities for the case of the $b\bar{b}$ sample
2030 with $m_{DM} = 10$ GeV (blue histograms) and for the atmospheric backgrounds (red).
2031 In order to select the atmospheric events I followed the same criteria as for the signal
2032 events. However, because in the signal case I used the true direction of the neutrino
2033 as input, as it should be that of the Sun at that time and therefore known, in the
2034 atmospheric case I used a set of solar positions as our ansatz for the neutrino direction.
2035 From the distributions, one can see that the muon and the jet for the signal events are
2036 predominantly forward and also that the deviations from the momentum conservation
2037 plane are peaked at zero, as one should expect.

2038 Now, I can start applying cuts to maximise our signal selection efficiency while at
2039 the same time I try to minimise the amount of atmospheric background events passing
2040 the selection. To this end, I will need to find some lower and upper cuts for θ_j and
2041 θ_μ and an upper bound for θ_{plane} . In Fig. 7.12 I show how upper bound cuts in the
2042 different angular variables affect the signal efficiency (blue lines) and the background
2043 rejection (red lines). Notice that the signal efficiency behaves in a quite different way
2044 when I apply cuts in the jet and the muon angles. On the contrary, the cuts on both
2045 variables have a similar effect on the background rejection.

2046 In order to obtain the optimal set of cuts, I perform a multidimensional scan. I
2047 do this separately for the $\tau^+\tau^-$ and the $b\bar{b}$ samples. For each case, I scan the possible
2048 cuts for each mass point and then I take the mean value of the signal efficiency for

7.6. High energy DM neutrino signals

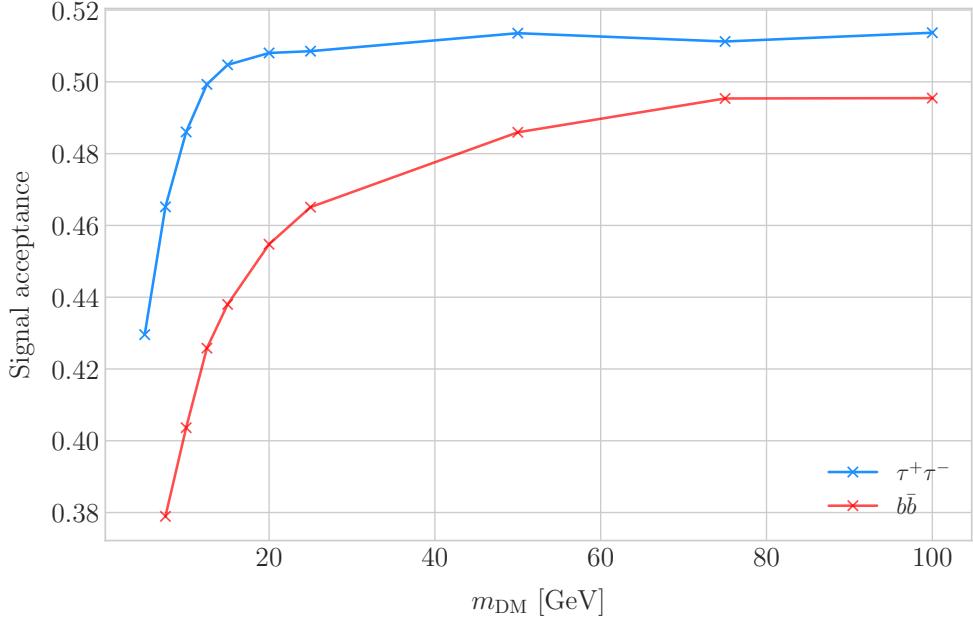


Figure 7.13: Signal efficiencies for the $\tau^+\tau^-$ (blue line) and $b\bar{b}$ (red line) DIS samples as functions of the DM mass, m_{DM} , obtained by applying the optimal angular cuts $\theta_\mu < 27^\circ$, $4^\circ < \theta_j < 26^\circ$ and $\theta_{\text{plane}} < 3.5^\circ$.

2049 each configuration, to get the mean efficiency for each set of cuts. I do a similar scan
 2050 for the atmospheric sample independently. Then, I take the sets of cuts such that
 2051 the background rejection achieved is greater than 99.8% and search for the one which
 2052 maximises the $\tau^+\tau^-$ and $b\bar{b}$ sample mean efficiencies. I found that with the cuts $\theta_\mu < 27^\circ$,
 2053 $4^\circ < \theta_j < 26^\circ$ and $\theta_{\text{plane}} < 3.5^\circ$ I get a background rejection of 99.80% while achieving
 2054 a 49.40% and 44.92% mean signal efficiencies for the $\tau^+\tau^-$ and $b\bar{b}$ signals respectively.

2055 In Fig. 7.13 I show the signal efficiencies as a function of the DM mass for the $\tau^+\tau^-$
 2056 (blue line) and the $b\bar{b}$ (red line) DIS events, after applying the cuts discussed above, as
 2057 well as the energy threshold and hadronic visible energy selections. One can see that
 2058 the efficiency grows with the mass, as annihilations of more massive DM particles will
 2059 produce a neutrino spectrum centered at higher energies, where DIS events dominate.
 2060 Notice also that the efficiency is higher for the $\tau^+\tau^-$ case at every mass point, as in
 2061 general this channel produces neutrinos at higher energies than the corresponding $b\bar{b}$
 2062 channel.

Chapter 7. DM searches with neutrinos from the Sun

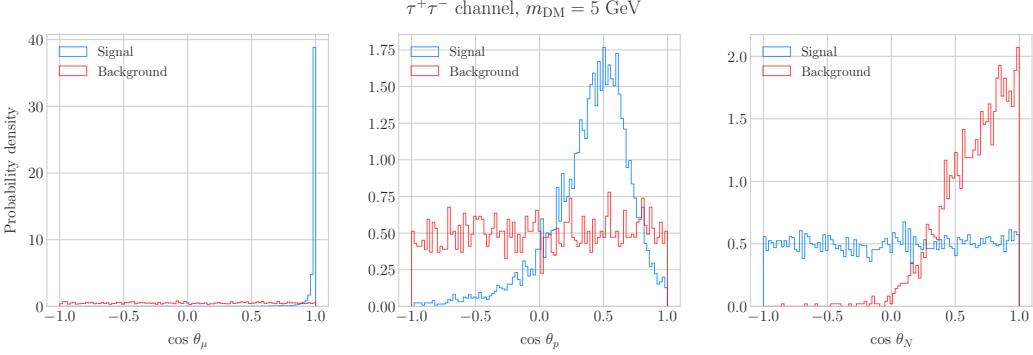


Figure 7.14: Distributions of $\cos \theta_\mu$ (left panel), $\cos \theta_p$ (central panel) and $\cos \theta_N$ (right panel) for the $\tau^+\tau^-$ QEL sample with $m_{\text{DM}} = 5 \text{ GeV}$ (blue) and the atmospheric background (red).

2063 7.6.2 Single proton QEL events

2064 Now, one can try to explore the low energy tail of the neutrino energy distributions. This
 2065 regime is dominated by the QEL interactions, i.e. events of the type $\nu_\mu + n \rightarrow \mu^- + p$.
 2066 In this case, as the typical energies are $E_\nu \lesssim 1 \text{ GeV}$, the momentum transfer to the
 2067 remnant nucleus is sizeable. Therefore, I can not make the approximation I did before
 2068 and assume that the momentum of the muon and the proton will give an adequate
 2069 estimation of the reconstructed neutrino energy.

2070 In any case, as before, I can take the direction of the incoming neutrino as known.
 2071 That way, one can estimate the energy of the neutrino as:

$$E_\nu^{reco} = E_\mu + E_p + m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}}, \quad (7.33)$$

2072 and using momentum conservation I can write the momentum of the remnant nucleus
 2073 as:

$$\vec{p}_N = \hat{p}_\nu (E_\mu + E_p + m_{^{39}\text{Ar}} - m_{^{40}\text{Ar}}) - \vec{p}_\mu - \vec{p}_p. \quad (7.34)$$

2074 As in the previous case, I need to drop the events where the muon or the proton fall
 2075 below the kinetic energy detection threshold [42]. Also, I again apply a smearing to the
 2076 momenta of the particles, a 1% for muons and 5% for protons.

2077 Having done that, one can compute the following angular variables for our selected

7.6. High energy DM neutrino signals

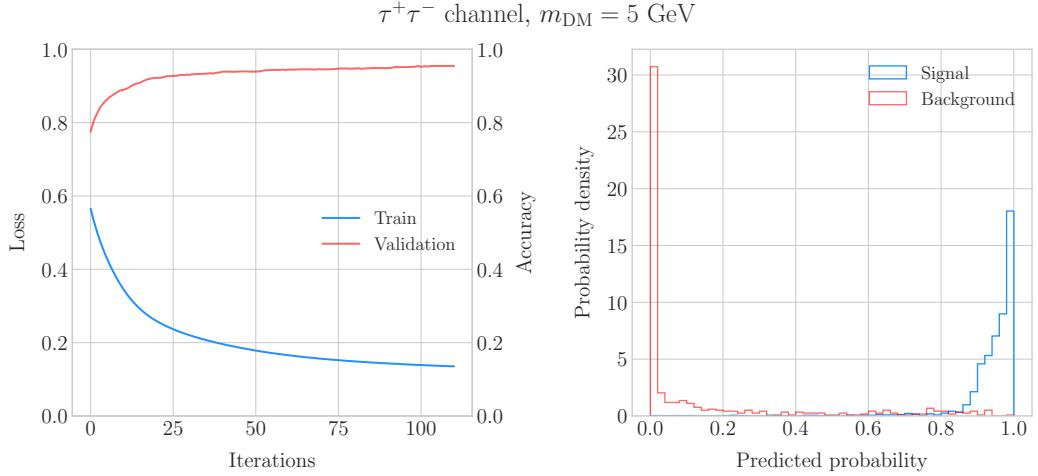


Figure 7.15: Left panel: value of the loss function for the training sample (blue line) and accuracy for the validation sample (red line) versus the number of iterations for the MLP classifier training. Right panel: distributions of the predicted probabilities assigned by the MLP classifier to the test sample for the $\tau^+\tau^-$ QEL signal with $m_{\text{DM}} = 5 \text{ GeV}$ (blue) and the atmospheric background (red).

2078 events:

$$\cos \theta_\mu = \hat{p}_\nu \cdot \hat{p}_\mu, \quad (7.35)$$

$$\cos \theta_p = \hat{p}_\nu \cdot \hat{p}_p, \quad (7.36)$$

$$\cos \theta_N = \hat{p}_\nu \cdot \hat{p}_N. \quad (7.37)$$

2079 Fig. 7.14 shows the distributions of these angular variables for the $\tau^+\tau^-$ QEL
 2080 sample with $m_{\text{DM}} = 5 \text{ GeV}$ (blue) and the atmospheric background (red). Again, for
 2081 the atmospheric events I used a random solar position as the ansatz for the incoming
 2082 neutrino direction. Notice that now, opposed to the DIS case where the signal had very
 2083 sharp distributions for the variables considered, the shapes of the angular distributions
 2084 for signal and background are not that much different.

2085 This effectively means that the usual approach of applying simple angular cuts would
 2086 not work as well as in the previous situation. Therefore, as a possible solution, I tried to
 2087 use a multilayer perceptron (MLP) classifier to separate between signal and background
 2088 events. Thus, the power of the hypothesis test will serve as an estimate of the signal

Chapter 7. DM searches with neutrinos from the Sun

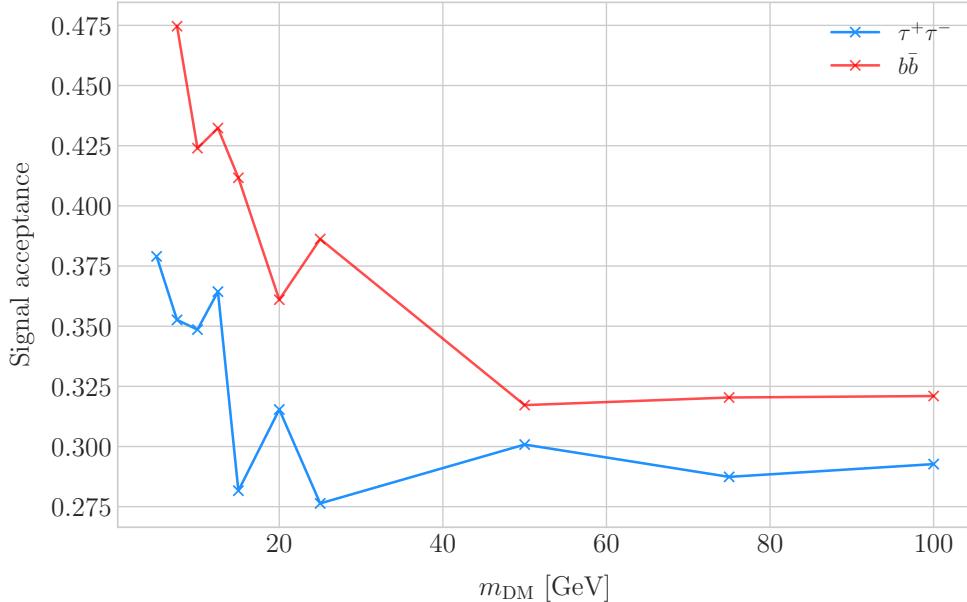


Figure 7.16: Signal efficiencies for the $\tau^+\tau^-$ (blue line) and $b\bar{b}$ (red line) single proton QEL samples as functions of the DM mass, m_{DM} , obtained by requiring a minimum predicted probability from the MLP classifier of 0.97 in order to achieve a background rejection greater than 99.8%.

efficiency, and in the same way one can take the size of the test to be our background rejection.

For each DM mass value and channel, as well as for the background sample, I divide our events into training, validation and test samples. The input variables for the classifier were the reconstructed neutrino energy from Eq. (7.33) and the angular variables defined in Eqs. (7.35 - 7.37). I used the MLP classifier implemented in `scikit-learn` [87], with a total of five hidden layers, the rectified linear unit activation function and adaptive learning rate. In order to account for fluctuations due to artifacts in the training process I repeated the training a thousand times for each sample, redefining each time the training, validation and test subsets, so one can take as our signal efficiency and background rejection the mean values of the powers and sizes of the tests.

The results of one of these training processes for the $\tau^+\tau^-$ QEL signal with $m_{\text{DM}} = 5$ GeV is shown in Fig. 7.15. On the left panel I show the loss function values (blue) and accuracy (red) at each iteration for the training and the validation samples respectively.

7.6. High energy DM neutrino signals

2103 The training stops either when the maximum number of iterations is reached (1000 in
2104 this case) or when the accuracy for the validation sample reaches a certain tolerance
2105 (I chose 10^{-4} as our tolerance). On the right panel I have the distributions for the
2106 predicted probability by the model, separated in true signal (blue) and background
2107 (red) events, for the test sample. One can see that both populations are well separated,
2108 obtaining a power of 44.97% and a size of 0.17% when I require a predicted probability
2109 greater than 0.97.

2110 Applying this criteria for each sample, I obtain the mean signal efficiencies shown in
2111 Fig. 7.16. Notice that the efficiencies for the channel $\tau^+\tau^-$ (blue line) are consistently
2112 lower than the ones for the $b\bar{b}$ channel (red line). This can be due to the fact that, for
2113 each DM mass point, the neutrino spectrum coming from the $b\bar{b}$ annihilation channel is
2114 centered at lower energies when compared to the $\tau^+\tau^-$ spectrum. This directly translates
2115 into more low energy neutrinos undergoing QEL interactions, which give signals that
2116 can be easily separated from the atmospheric background. This explanation also help us
2117 understand why in both cases the signal acceptance drops when the DM mass increases.
2118 In all cases, the background rejection took values between 99.8% to 99.9%. I will assume
2119 a 99.8% background rejection value in all cases to keep our estimation conservative.

2120 7.6.3 Results

2121 In order to estimate the DM-nucleon cross section sensitivities in the present case I need
2122 again to compute the expected number of background events. As I am now separating
2123 events by interaction type Eq. (7.25) does not hold anymore, as in that case I integrated
2124 over the total neutrino-argon cross section. In this instance, the expected background
2125 events for DIS events is approximately given by:

$$N_B^{DIS} \simeq \eta_B^{DIS} \times (4.655 \times 10^3) \times \left(\frac{\text{exposure}}{400 \text{ kT yr}} \right), \quad (7.38)$$

Chapter 7. DM searches with neutrinos from the Sun

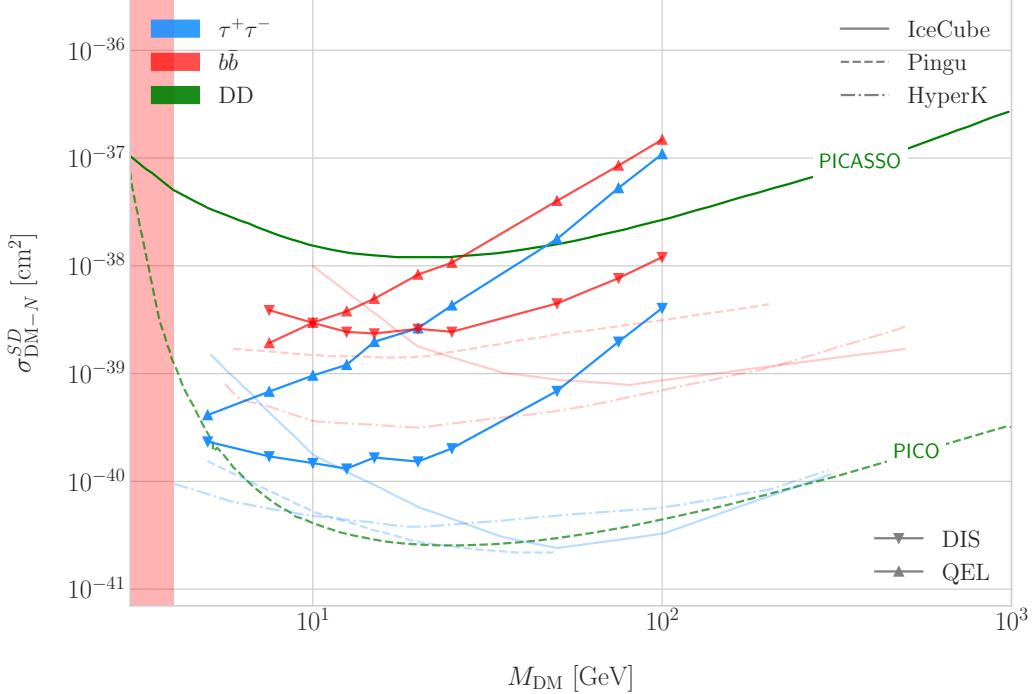


Figure 7.17: Projected 90% confidence level upper limit for DUNE (400 kT yr) on the spin-dependent DM-nucleon scattering cross section as a function of m_{DM} , for the annihilation channels $\tau^+\tau^-$ (blue) and $b\bar{b}$ (red) separated by interaction type (up triangles denote DIS interactions whereas down triangles represent QEL interactions). I also show the previous limits from IceCube [9] (solid lines) and the projected sensitivities for Pingu [10] (dashed lines) and Hyper-Kamiokande [11] (dash-dotted lines), as well as the direct detection limits from PICASSO [12] (solid green line) and PICO-60 C₃F₈ [13] (dashed green line).

2126 whereas for QEL events we have:

$$N_B^{QEL} \simeq \eta_B^{QEL} \times (2.248 \times 10^4) \times \left(\frac{\text{exposure}}{400 \text{ kT yr}} \right). \quad (7.39)$$

2127 Now, using these together with Eqs. (7.26) and (7.27) one can obtain the 90% C.L.
 2128 upper limit on the total annihilation rate at equilibrium for both kind of events. Then,
 2129 applying the computed DM-nucleons capture rates I can translate these into limits on
 2130 the DM-nucleon cross section by means of Eqs. (7.2), (7.5) and (7.6).

2131 Fig. 7.17 shows the obtained limits on the SD DM-nucleon cross section for DUNE,
 2132 using the DIS (up triangles) and QEL (down triangles) events both for the $\tau^+\tau^-$ (blue)
 2133 and the $b\bar{b}$ (red) samples, for an exposure of 400 kT yr. I also include the corresponding

7.7. Example: Leptophilic Dark Matter

2134 current limits from IceCube [9] (solid lines), as well as the projected sensitivities of Pingu
2135 [10] (dashed lines) and Hyper-Kamiokande [11] (dash-dotted lines). For comparison, I
2136 also show the reported direct detection limits from PICASSO [12] (solid green line) and
2137 PICO-60 C₃F₈ [13] (dashed green line).

2138 Notice that, for most of the mass range, the limits one can set by using the DIS
2139 events are stronger than those of the QEL interactions, except for the low mass part
2140 of both the $\tau^+\tau^-$ and the $b\bar{b}$ curves where the QEL events dominate. In general, the
2141 expected sensitivity of DUNE for DM masses $\lesssim 25$ GeV surpasses the stronger current
2142 indirect limits. However, experiments like Hyper-Kamiokande are foreseen to have an
2143 overall better sensitivity in this kind of searches, as they have a bigger active volume
2144 and accept a broader energy range.

2145 A pending question is what happens when we add the RES and MEC charged-current
2146 interaction contributions. In that case it would probably be more convenient to split
2147 the samples by final state interaction topologies. Also, another necessary improvement
2148 would be adding a full detector simulation and reconstructions. This will also require
2149 considering the effect of poorly reconstructed events or final states containing neutral
2150 particles such that they mimic the desired topology at the reconstruction level.

2151 7.7 Example: Leptophilic Dark Matter

2152 In general, the capture rate of DM particles by the Sun via interactions with electrons is
2153 several orders of magnitude smaller than the capture via DM-nucleus scattering. Thus,
2154 it would be sub-leading even when nucleon capture is loop suppressed. As I showed in
2155 Fig. 7.2, the capture rate via scattering off electrons only surpasses the capture rates
2156 via DM-nucleons interactions for DM masses $\lesssim 100 - 500$ MeV.

2157 However, if one considers a model where DM-nucleon interactions are forbidden even
2158 at loop level, then electron interactions will be the sole contributor to DM capture in
2159 the Sun. One can describe such scenario where the DM particles couple to leptons but
2160 not to the quark sector using effective operators.

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2161 In general, assuming that the DM particle is a Dirac fermion, the dimension six
 2162 operators describing the interaction between two DM particles and two leptons can be
 2163 written as:

$$\mathcal{L}_{eff} = G \sum_i (\bar{\chi} \Gamma_\chi^i \chi) (\bar{\ell} \Gamma_\ell^i \ell), \quad (7.40)$$

2164 where $G = 1/\Lambda^2$ is the effective coupling strength, Λ the cut-off of the effective field
 2165 theory and ℓ denotes any lepton. In principle, one should consider all the possible
 2166 Lorentz structures Γ_f^i in order to have a complete set of effective operators.

2167 However, some combinations will induce interactions with nucleons at loop level. As
 2168 we are specifically interested in interactions which forbid any communication with the
 2169 quark sector, I will not consider those [88]. In addition, some of the effective operators
 2170 give rise to velocity-suppressed scattering cross sections between DM particles and
 2171 leptons. I will also neglect those, as the suppression goes with the square of the DM
 2172 halo velocity which in units of the speed of light is $\sim 10^{-6}$.

2173 This way, the only Lorentz tensor structure that do not induce interactions with
 2174 quarks at loop level and gives a contribution to the scattering cross section that is not
 2175 velocity suppress is the axial-axial interaction. The effective Lagrangian is then given
 2176 by:

$$\mathcal{L}_{eff} = \frac{c_A^\chi c_A^\ell}{\Lambda^2} (\bar{\chi} \gamma^\mu \gamma^5 \chi) (\bar{\ell} \gamma_\mu \gamma^5 \ell), \quad (7.41)$$

2177 where c_A^χ and c_A^ℓ are the couplings for the different species. As the DM coupling appears
 2178 as a common factor for any lepton choice, I will redefine the corresponding coupling c_A^ℓ
 2179 to absorb c_A^χ . Also, for simplicity, I will assume that the couplings between the DM
 2180 particles and the leptons are flavour independent, i.e. I have just two couplings, c_A^e for
 2181 charged leptons and c_A^v for neutrinos.

2182 In the case of a scalar DM particle, the lowest order effective interaction with
 2183 leptons happens through a dimension five operator, generating scalar and pseudoscalar
 2184 interactions. However, the former induces interactions with quarks at two loop level
 2185 whereas the latter gives a velocity suppressed scattering cross section.

2186 From the effective Lagrangian in Eq. (7.41) it can be shown that the axial-axial

7.7. Example: Leptophilic Dark Matter

2187 contribution to the scattering cross section for the fermionic DM and a charged lepton
2188 is given by:

$$\sigma_{\text{DM}-e}^{AA} = 3(c_A^e)^2 \frac{m_e^2}{\pi \Lambda^4}. \quad (7.42)$$

2189 If the DM interacts exclusively with fermions, then the only annihilation channels
2190 that will give us a measurable neutrino flux coming out of the Sun are $\tau^+\tau^-$ and $\nu\bar{\nu}$. The
2191 former channel, already explored previously in the more mainstream scenario of the DM
2192 capture via scattering off nucleons, is open only for $m_{\text{DM}} > m_\tau \simeq 1776.86 \pm 0.12$ MeV
2193 [89], a mass region where the solar DM capture by electrons is at least one order of
2194 magnitude smaller than the capture via interactions with nucleons. On the contrary, the
2195 latter allows us to explore a region where the capture rate via scattering off electrons
2196 dominates over the rest.

2197 One downside of focusing in such low mass range is that it falls below the usual
2198 limit of $m_{\text{evap}} \sim 4$ GeV usually explored in the literature. The pretext to explore this
2199 region is the result discussed previously reported in Ref. [4], where DM evaporation in
2200 the Sun for the case of capture via electron scattering could be negligible for masses
2201 as low as $m_{\text{evap}} \sim 200$ MeV. This result is quite sensitive to the high velocity tail of
2202 the DM velocity distribution in equilibrium inside the Sun, and therefore full numerical
2203 simulations would be needed to assess the impact of this effect. However, this falls out of
2204 the scope of our work.

2205 In this case, as I have a specific realisation of the interaction between the DM
2206 and leptons, one can estimate the relic density of our DM for different values of the
2207 couplings and the effective field theory scale Λ . The first step to do so is compute the
2208 self-annihilation cross section. Because I consider cold relics, at the freeze-out time our
2209 DM particles were non-relativistic and so one can expand the annihilation cross section
2210 in terms of the relative velocity v between two annihilating DM particles as [90]:

$$\sigma_{\text{ann}}^{AA}|v| \approx \frac{1}{2\pi\Lambda^4} \sum_\ell \left(c_A^\ell\right)^2 m_\chi^2 \sqrt{1 - \frac{m_\ell^2}{m_\chi^2} \left[\frac{m_\ell^2}{m_\chi^2} + \frac{1}{12} \left(2 - \frac{m_\ell^2}{m_\chi^2}\right) v^2 \right]}, \quad (7.43)$$

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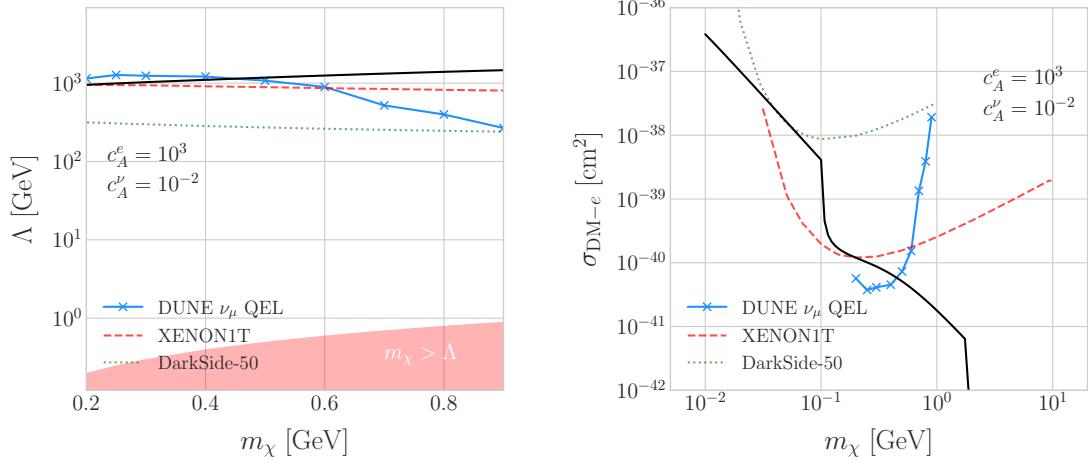


Figure 7.18: Left panel: Projected 90% confidence level sensitivity of DUNE (400 kT yr) to the scale Λ of an EFT containing only leptophilic DM axial-axial interactions (blue line). Right panel: . In both cases the corresponding limits from DarkSide-50 [14] (dotted green line) and XENON1T [15] (dashed 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 $c_A^\nu = 10^{-2}$.

where the sum includes all the possible lepton final states with mass m_ℓ .
 Solving the Boltzmann equation for the evolution of the DM density gives as a solution a relic density of:

$$\Omega_\chi h^2 \approx \frac{(1.04 \times 10^9) x_F}{M_{Pl} \sqrt{g_*} (a + 3b/x_F)}, \quad (7.44)$$

where $x_F = m_\chi/T_F$ being T_F the freeze-out temperature, g_* the number of relativistic degrees of freedom at freeze-out and a and b the terms in the annihilation cross section expansion $\sigma_{ann}|v| \approx a + bv^2 + \mathcal{O}(v^4)$. Using the current best fit for the relic DM density $\Omega_\chi h^2 = 0.1198 \pm 0.0012$ [91] one can use these relations to compute the required effective theory scale Λ at which the correct density is achieved for any combinations of m_χ and c_A^ℓ .

As discussed before, in the low DM mass region QEL interactions dominate. Moreover, if I focus on direct annihilation to neutrinos, the energy of the muon neutrino flux is known as it must be equal to the mass of the DM particle, $E_\nu = m_\chi$. That way, now I do not need to use Eq. (7.33) in order to estimate the momentum transfer to the

7.7. Example: Leptophilic Dark Matter

2224 remnant nucleus, I can simply take:

$$\vec{p}_N = \hat{p}_\nu m_\chi - \vec{p}_\mu - \vec{p}_p. \quad (7.45)$$

2225 To estimate the signal efficiency and background rejection for this case I used again
2226 the MLP classifier from `scikit-learn`, using the same specifications as before. The
2227 only difference now is that I add also the reconstructed neutrino energy as one of the
2228 features to train the classifier with, because the characteristic monoenergetic flux for
2229 each m_χ value will help to distinguish between signal and background events.

2230 In this case, for masses below ~ 500 MeV I obtain a signal efficiency close to unity
2231 while keeping a background rejection of 99.9%. For bigger values of the mass, the signal
2232 efficiency drops significantly if I require to keep the background acceptance under 0.01%.
2233 However, because this kind of search is dominated by the background, sacrificing the
2234 signal acceptance to keep the background rejection to a minimum enhances the reach
2235 of the analysis. This way, for DM masses of the order of $m_\chi \sim 1$ GeV I end up with
2236 efficiencies as low as 1%.

2237 Now, estimating the number of background events using Eq. (7.39) one can go on
2238 and apply Eqs. (7.26) and (7.27) together with Eq. (7.42) to derive the sensitivity of
2239 DUNE to this kind of model. Fig. 7.18 (left panel) shows the potential reach of DUNE
2240 to constrain the EFT scale Λ this model containing only leptophilic DM axial-axial
2241 interactions (blue line), for a choice of couplings $c_A^e = 10^3$ and $c_A^\nu = 10^{-2}$. I also included
2242 the current limits on the DM-electron scattering cross section from DarkSide-50 [14]
2243 (dotted green line) and XENON1T [15] (dashed red line), reworked with Eq. (7.42) to
2244 show their implications for the EFT scale. The values of Λ for which the correct DM relic
2245 density value is achieved for each mass are also shown (black line). This tells us that,
2246 for that specific choice of couplings, DUNE would be sensitive to DM configurations
2247 allowed by the relic density constraint up to a mass of $m_\chi \sim 400$ MeV.

2248 In Fig. 7.18 (right panel) I show the same upper limits but for the DM-electron
2249 scattering cross section. From this view one can see that DUNE would be able to

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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.

2256 Chapter 8

2257 Particle ID in GArSoft

2258 ND-GAr is a magnetised, high-pressure gaseous argon TPC (HPgTPC), surrounded by
2259 an electromagnetic calorimeter (ECal) and a muon detector (commonly refer to as μ ID).
2260 A detailed discussion on the requirements, design, performance and physics of ND-GAr
2261 can be found in the DUNE ND CDR [48] and the ND-GAr whitepaper (cite).

2262 In DUNE Phase II ND-GAr will fulfill the role of TMS, measuring the momentum
2263 and sign of the charged particles exiting ND-LAr. Additionally, it will be able to measure
2264 neutrino interactions inside the HPgTPC, achieving lower energy thresholds than those
2265 of the ND and FD LArTPCs. By doing so ND-GAr will allow to constrain the relevant
2266 systematic uncertainties for the LBL analysis even further.

2267 The goal of the present chapter is to review the requirements that the physics program
2268 of DUNE impose on ND-GAr, present the current status of its design and describe the
2269 GArSoft package, its simulation and reconstruction software.

2270 As decided during the DUNE Phase II workshop in June 2023 [reference], we want
2271 to build ND-GAr physics case by showing:

- 2272 • That ND-GAr can constrain systematic uncertainties that ND-LAr might miss.
- 2273 • The impact on the neutrino oscillation results if such systematic uncertainties are
2274 missed.
- 2275 • That ND-GAr is necessary to reach DUNE's main physics goals.

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2276 This way, the design of ND-GAr will be physics driven.

2277 In order to study the effects of final state interactions (FSI) in CC interactions,
2278 ND-GAr should be able to measure the spectrum of protons and charged pions at low
2279 energies. ND-GAr also needs to be able to measure the pion multiplicity, specially for
2280 energies above 100 MeV as at these energies the pions shower in the LAr, to inform the
2281 pion mass correction in the ND and FD LArTPCs.

2282 In order to correctly identify electrons, muons, pions, kaons and protons ND-GAr
2283 can use a combination of: dE/dx measurements in the HPgTPC, E_{ECAL}/p using the
2284 ECAL total energy and the momentum obtained from magnetic spectroscopy in the
2285 HPgTPC and penetration information through the ECAL and muon tagger.

2286 8.1 dE/dx measurement in the TPC

2287 Among the parameters extracted from the track fitting, ionisation is particularly useful
2288 for particle identification, as it is a function of the particle velocity. Although for the
2289 case of relativistic particles this dependence is not very strong, measuring the track on
2290 a large number of points may allow us to estimate the amount of ionisation accuratel.
2291 This, paired with a measurement of the momentum, may allow us to identify the particle
2292 type.

2293 The first calculation of the energy loss per unit length of relativistic particles using
2294 a quantum-mechanical treatment is due to Bethe [?]. Using this approach, the mean
2295 ionisation rate of a charged particle traveling through a material medium is (using
2296 natural units $G = \hbar = c = 1$):

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi Ne^4}{m_e \beta^2} z^2 \left(\log \frac{2m_e \beta^2 \gamma^2}{I} - \beta^2 \right), \quad (8.1)$$

2297 where N is the number density of electrons in the medium, e the elementary charge, m_e
2298 is the electron mass, z the charge of the particle in units of e , β is the velocity of the
2299 particle, $\gamma = (1 - \beta^2)^{-1}$ and I denotes the effective ionisation potential averaged over
2300 all electrons. This relation is known as the Bethe-Bloch formula.

8.1. dE/dx measurement in the TPC

From Eq. (8.1) one can see that the ionisation loss does not depend explicitly on the mass of the charged particle, that for non-relativistic velocities it falls as β^{-2} , then goes through a minimum and increases as the logarithm of γ . This behaviour at high velocities is commonly known as the relativistic rise. The physical origin of this effect is partly due to the fact that the transverse electromagnetic field of the particle is proportional to γ , therefore as it increases so does the cross section.

It was later understood that the relativistic rise could not grow indefinitely with γ . A way to add this feature in the Bethe-Bloch formula is by introducing the so-called density effect term. It accounts for the polarisation effect of the atoms in the medium, which effectively shield the electromagnetic field of the charged particle halting any further increase of the energy loss [?]. Denoting the correction as $\delta(\beta)$, one can rewrite Eq. (8.1) as:

$$\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi Ne^4}{m_e \beta^2} z^2 \left(\log \frac{2m_e \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\beta)}{2} \right). \quad (8.2)$$

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

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

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

Chapter 8. Particle ID in GArSoft

2328 It happens that neither the Bethe-Bloch theory nor the PAI model from Allison and
2329 Cobb offer a close mathematical form for the ionisation curve. This is the reason why a
2330 full parametrisation of the ionisation curves can be useful. A parametrisation originally
2331 proposed for the ALEPH TPC [?] and later used by the ALICE TPC [?] group that
2332 manages to capture the features of the ionisation energy loss is:

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \log \left[P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right] \right), \quad (8.3)$$

2333 where P_i are five free parameters. Hereafter, we will refer to Eq. (8.3) as the ALEPH
2334 dE/dx parametrisation.

2335 8.1.1 Energy calibration

2336 In order to obtain the amount of energy loss by a charged particle due to ionisation
2337 in our TPC we need to determine the conversion between the charge deposited in our
2338 readout planes and the actual energy depositions. This procedure is known as energy
2339 calibration.

2340 In a general, the first step of the calibration involves a non-uniformity correction,
2341 to make sure that the detector response is uniform throughout the TPC. These are
2342 typically divided into three categories, non-uniformities in the transverse YZ plane,
2343 non-uniformities along the drift direction X and variations of the detector response
2344 over time (would not apply to us as the detector is not built yet). These would correct
2345 for effects such as electron diffusion and attenuation, space charge effects or channel
2346 misconfiguration. However, because at the moment I am only interested in making sure
2347 we recover a sensible result from our simulation, I will not apply uniformity corrections
2348 to our charge deposits.

2349 Other effects, like electron-ion recombination or ADC saturation, lead to a non-linear
2350 relation between the observed charge and the deposited energy in the detector, with the
2351 observed readout charge saturating at high ionisation energies. In this case, because we
2352 are dealing with gaseous argon and therefore recombination is not as important as in

8.1. dE/dx measurement in the TPC

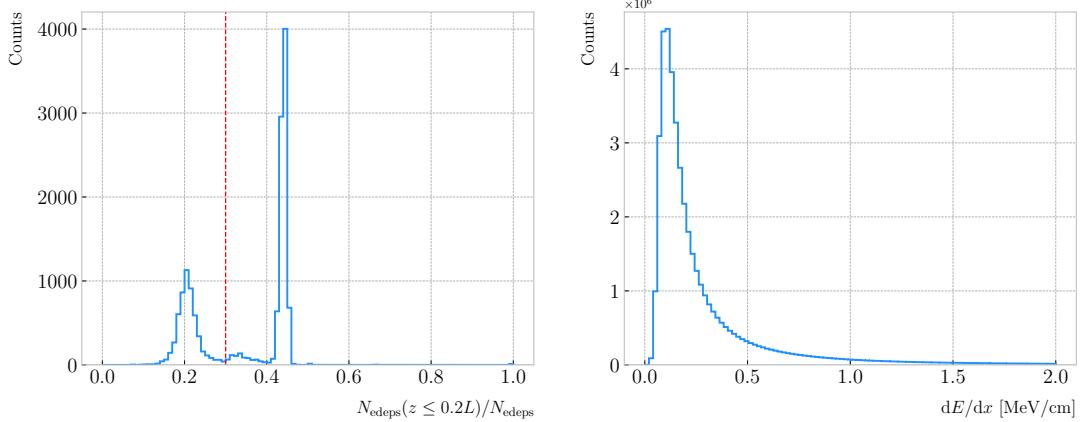


Figure 8.1: Left panel: distribution of the fraction of Geant4-level energy deposits per track with residual range less than 20% of the total track length, for the isotropic proton sample. Right panel: distribution of the ionisation per unit length of the energy deposits in the proton sample after removing the tracks with less than 30% of their energy deposits in the last 20% of the track.

2353 liquid, we do not simulate recombination effects in the TPC. Even so, the simulation of
 2354 the electronic response will still introduce charge saturation, and one needs to correct
 2355 for it in order to obtain the exact amount of energy loss due to ionisation.

2356 By default, the track fitting algorithm in GArSoft provides a `TrackIonization`
 2357 object associated to each reconstructed track. It contains two collections of charge
 2358 deposits, one for each fitting direction, consisting on pairs of charge values (dQ , in ADC)
 2359 and step sizes (dx , in cm).

2360 In order to estimate the ionisation loss in the ND-GAr TPC, I have used an MC
 2361 sample consisting of single, isotropic protons propagating in the TPC. The starting points
 2362 of the protons were sampled inside a $50 \times 50 \times 25$ cm box centered at $(100, -150, 1250)$,
 2363 and their momenta are uniformly distributed in the range $0.25 - 1.75$ GeV. I ran the
 2364 simulated sample through GArSoft's default detector simulation and reconstruction, and
 2365 then a custom analyser module that extracts the ionisation data together with other
 2366 reconstructed track information from the Kalman fit.

2367 For studying the energy loss of the protons I select the reconstructed tracks that
 2368 range out (i.e. slow down to rest) inside the TPC. A characteristic feature of the energy
 2369 loss profile of any stopping ionising particle is the so-called Bragg peak, a pronounced

Chapter 8. Particle ID in GArSoft

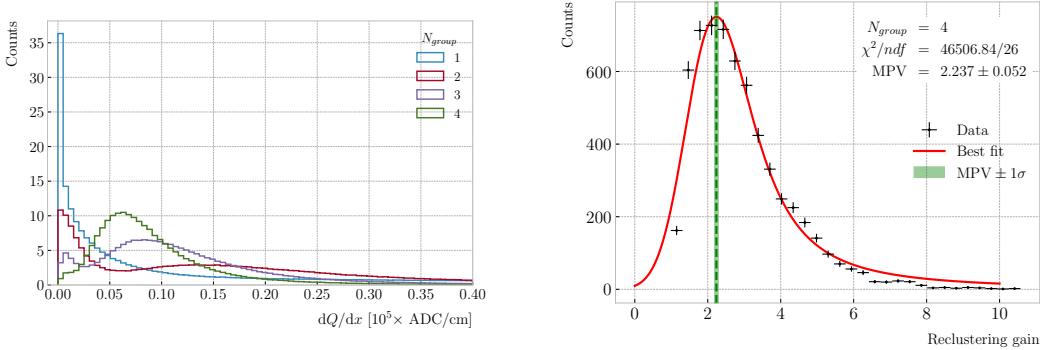


Figure 8.2: Left panel: distribution of the reconstructed ionisation charge per unit length for our MC stopping proton sample. The different colors indicate how many consecutive dQ/dx pairs were grouped together. Right panel: distribution of the median change in dQ/dx per track after $N_{group} = 4$ clusters were reclustered together.

peak that occurs immediately before the particle comes to rest. From Eq. (8.1) we can see that this behaviour is expected, as the energy loss for non-relativistic particles is inversely proportional to β^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 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 length¹. The distribution of this fraction of energy deposits for our proton sample is shown in Fig. 8.1 (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.

Fig. 8.1 (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

¹As 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.

8.1. dE/dx measurement in the TPC

2387 follows the expected shape of a Landau distribution, which describes the fluctuations of
2388 the ionisation energy losses [?]. This distribution has a characteristic asymmetric PDF,
2389 with a long right tail that translates into a high probability for high-energy ionisation
2390 losses. The origin of these fluctuations is mainly the possibility of transferring a high
2391 enough energy to an electron, so it becomes a ionising particle itself.

2392 Now, from the point of view of the reconstruction, the objects that we have available
2393 to extract the ionisation information for the different reconstructed tracks are the
2394 collections of dQ and dx pairs, as stated before. The dQ values come from adding up
2395 the amplitude of all the reconstructed hits in a cluster, which is the input object to the
2396 Kalman fit.

2397 Fig. 8.2 (left panel) shows the distribution of the ionisation charge deposits per
2398 unit length for the track in the stopping proton sample (blue line). As one can notice,
2399 this distribution does not resemble the expected shape of the Landau PDF. This
2400 distribution peaks sharply at 0 and has a heavy tailed behaviour. Notice, however, how
2401 the distribution changes its shape as we group together N_{group} consecutive charge deposit
2402 pairs (red, purple and green lines). The distribution in the $N_{group} = 4$ case already has
2403 a shape which resembles that of the Geant4-level ionisation per unit length, so I will
2404 proceed using this amount of reclustering for the reconstruction-level depositions.

2405 An extra factor I need to account for, when reclustering is applied, is how the overall
2406 dQ/dx per track changes. To do so, we can look at the ratio between the median dQ/dx
2407 after and before the reclustering. Fig. 8.2 (right panel) shows the median enhancement
2408 in dQ/dx per track for the stopping proton sample in the case $N_{group} = 4$. Fitting a
2409 Landau distribution convolved with a Gaussian², I estimate the most probable value of
2410 this ratio to be $G_{group} = 2.24 \pm 0.05$.

2411 At this point, I am left with determining the conversion between the charge deposits
2412 per unit length dQ/dx and the energy deposits per unit length dE/dx . To this end, we
2413 need a way of comparing the two. I can use the residual range z to get a prediction of

²In 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.

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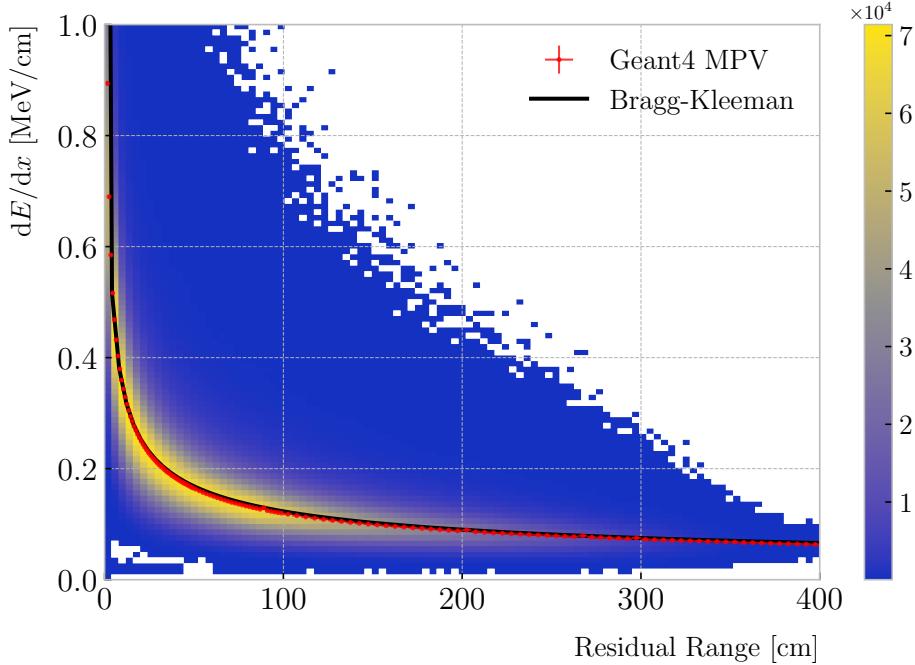


Figure 8.3: Distribution of the Geant4-simulated energy losses per unit length versus residual range for the stopping proton sample. The overlaid points represent the fitted most probable value of the dE/dx distribution in each residual range bin, whereas the curve is their best fit to the Bragg-Kleeman formula from Eq. (8.4).

2414 the most probable dE/dx by using the following empirical parametrisation [?]:

$$\frac{dE}{dx}(z) = \frac{z^{\frac{1}{p}-1}}{p\Lambda^{\frac{1}{p}}}, \quad (8.4)$$

2415 which is quoted in the literature as the Bragg-Kleeman formula. In order to obtain the
 2416 p and Λ parameters I perform a fit using the energy losses and the residual ranges given
 2417 by the Geant4 stage of our proton sample.

2418 Within our simulation, the residual range is sampled with a maximum size of
 2419 5 mm. Therefore, to perform the fit to the Bragg-Kleeman formula, we can use a
 2420 fine-grained residual range binning. For each of the residual range bins I extract the
 2421 dE/dx distribution and fit it to a LanGauss distribution, to obtain the value of the
 2422 most probable dE/dx in the bin together with a statistical uncertainty. I then fit Eq.
 2423 (8.4) to these most probable values and the centres of the residual range bins. This

8.1. dE/dx measurement in the TPC

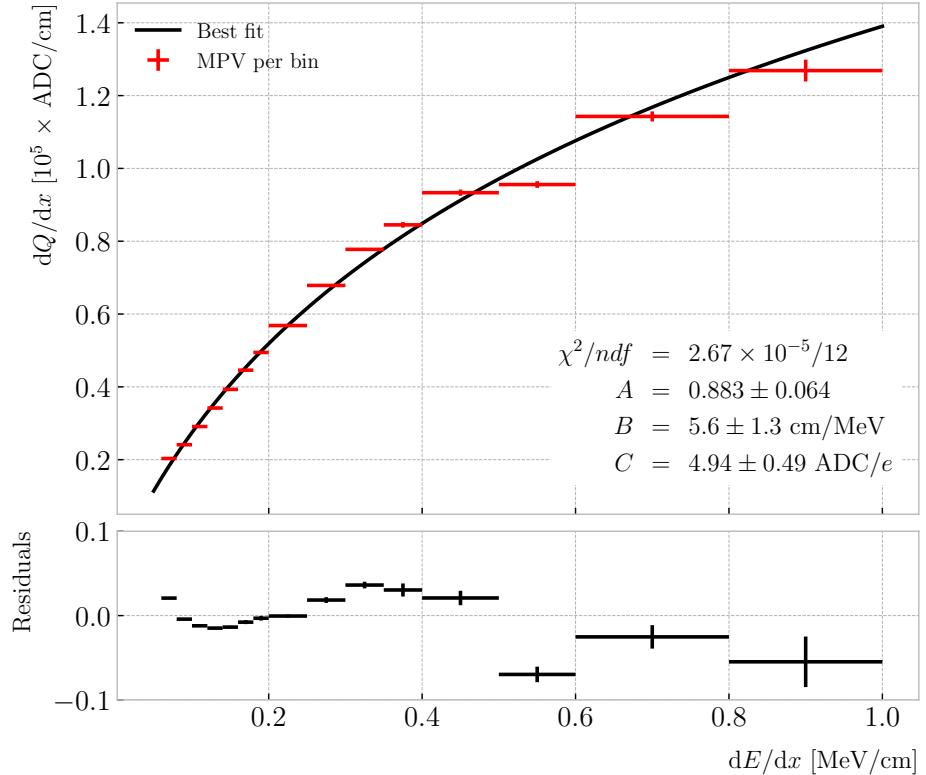


Figure 8.4: Fitted most probable dQ/dx values for each dE/dx bin (red points), obtained from the stopping proton sample. The overlaid curve (black line) represents the best fit to the logarithmic calibration function from Eq. (8.5).

procedure is depicted in Fig. 8.3, where I show the distribution of the energy loss per unit length versus the residual range, together with the most probable dE/dx values and their uncertainty in each bin (red points) and the curve with the best fit of the Bragg-Kleeman relation to those values (black line). The best fit is obtained for the parameter values $p = 1.8192 \pm 0.0005$ and $\Lambda = 0.3497 \pm 0.0008 \text{ cm/MeV}^p$ ³.

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

In order to parametrise the charge saturation, we can use the following logarithmic

³These strange units for Λ come from dimensional analysis, just to keep the Bragg-Kleeman formula (8.4) consistent.

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2433 function inspired by the modified box model for recombination:

$$\frac{dE}{dx} = \frac{e^{\frac{dQ}{dx}B\frac{W_{ion}}{G_{group}C}} - A}{B}, \quad (8.5)$$

2434 where A and B are the calibration parameters we need to determine, W_{ion} is the average
 2435 energy to produce an electron-ion pair, G_{group} is the gain from the reclustering discussed
 2436 above and C is the calibration constant to convert number of electrons to ADC counts,
 2437 commonly refer to as gain (also to be obtained in the fit). In this case, I use a value for the
 2438 electron-ion production energy of $W_{ion} = 26.4$ eV [?]. This value, used in our simulation
 2439 as well, was measured for gaseous argon in normal conditions, and therefore should
 2440 be checked in the future to describe correctly the high-pressure argon-CH₄ mixture of
 2441 ND-GAr.

2442 For the calibration fit I follow a procedure similar to the previous one for Eq. (8.4).
 2443 Binning the dE/dx range, I fit a LanGauss distribution to the corresponding dQ/dx
 2444 distribution to obtain the most probable value. The resulting data points (red bars) are
 2445 shown in Fig. 8.4 (top panel), the horizontal error bars depict the width of the dE/dx
 2446 bin whereas the vertical bars represent the error associated to the most probable value
 2447 estimation. A fit to the logarithmic function in Eq. (8.5) is also shown (black line).
 2448 For this I weighted the data points using the inverse of their relative error, obtaining a
 2449 reduced chi-square value of $\chi^2/ndf = 2.22 \times 10^{-6}$. The best fit parameters I found from
 2450 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. In
 2451 Fig. 8.4 (bottom panel) I show the residuals between the data points and the fit.

2452 The value for the gain I obtained from the fit is in reasonable agreement with our
 2453 expectation. This value is set in GArSoft to 5 ADC/e by default.

2454 One interesting thing to check is what induces this non-linear relation between charge
 2455 and energy. The only effects that modify the amount of electrons reaching the readout
 2456 planes in the simulation are the transverse diffusion and the finite electron lifetime.
 2457 Once the electrons reach the readout chambers, the pad response functions are applied,
 2458 together with an electrons-to-ADC conversion and the ADC saturation limit.

8.1. dE/dx measurement in the TPC

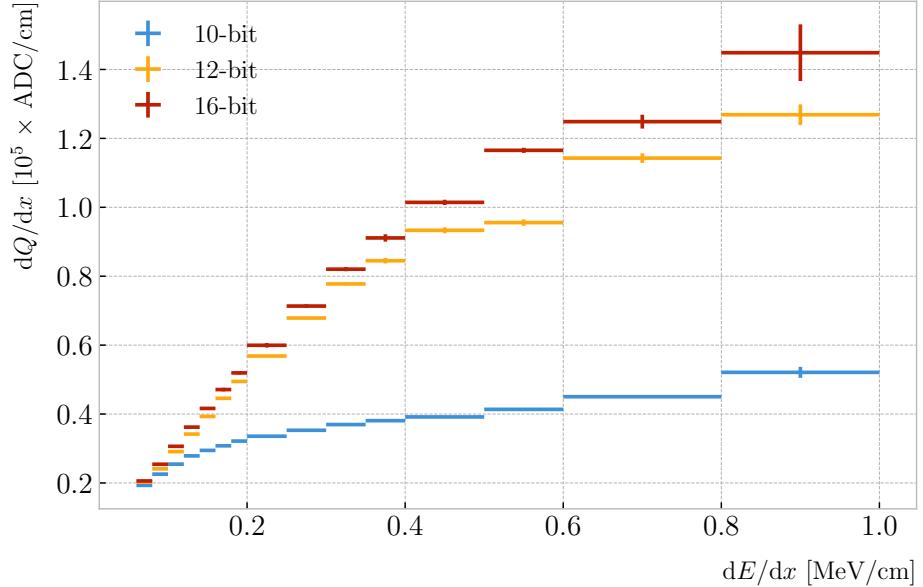


Figure 8.5: Fitted most probable dQ/dx values for each dE/dx bin for three different ADC bit limits, 10 (blue points), 12 (default, yellow points) and 16-bit (red points).

Table 8.1: Calibration parameters obtained from the fit of the ND-GAr simulated stopping proton sample to the calibration function from Eq. (8.5). The fits were performed for the 10, 12, and 16-bit ADC limits.

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

By default, GArSot applies a 12-bit ADC limit, which can be changed in the simulation configuration. However, it can only be increased up to 16-bit, as we represent the ADC collection as a `std::vector<short>`. This way, I tried to change the saturation parameter to see how it affects the relation between reconstructed charge and energy. Fig. 8.5 shows a comparison between the most probable dQ/dx for 10, 12 and 16-bit ADC limits. As expected, the lower the limit is the sooner the charge saturates. For higher ADC limits the relation between energy and charge remains linear up to higher dE/dx values, but even for the 16-bit limit the saturation is noticeable for values $\gtrsim 0.5$ MeV/cm.

In Tab. 8.1 I also show the results of fitting the samples with 10 and 16-bits ADC

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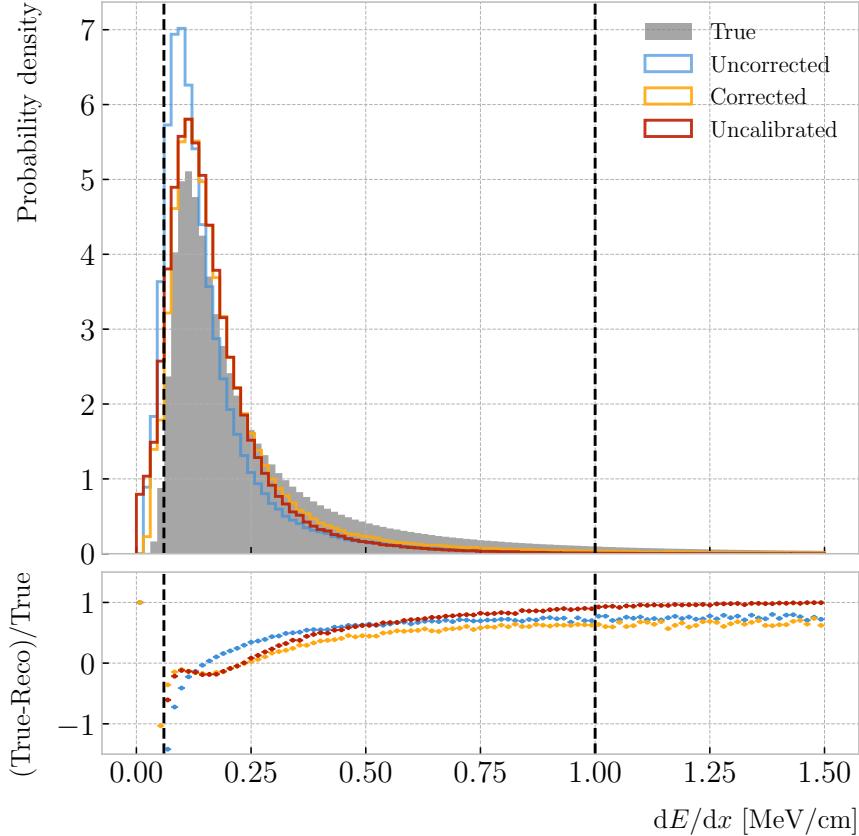


Figure 8.6: Top panel: area normalised dE/dx distributions for the true (solid grey) and the reconstructed energy deposits in the stopping proton sample, both after applying the calibration (blue) and the calibration and the normalisation correction (yellow). Also shown is the distribution obtained by 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.

limits to the calibration function from Eq. (8.5), using the weights based on their relative error as described previously. One interesting feature to notice is how different the best fit points look for the 10-bit ADC saturation when compared to the other two, which are consistent with each other.

At this point we can compare the dE/dx distribution one gets from Geant4, i.e. the true energy loss distribution, and the distribution I found by applying the calibration function to our collection of reconstructed dQ/dx values. Fig. 8.6 (top panel) shows the true (solid grey) and reconstructed (blue, labeled as uncorrected) distributions together. The dashed vertical lines indicate the region of validity of the calibration fit, i.e. the left

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and right edges of the first and last dE/dx bin respectively. Notice that these histograms are area-normalised, as the total number of true energy deposits is much higher than the number of reconstructed charge deposits. This is due to a combination of effects, like the finite spatial resolution of the detector, the hit clustering used in the track fitting and the reclustering we have applied here.

The two distributions are significantly different. That can be seen clearly when looking at the fractional residuals, shown in Fig. 8.6 (bottom panel). In particular, the position of the peak is off, which could bias the mean energy loss predictions. It seems like the difference between these may be due to an overall scaling factor. One possibility is to scale the most probable value of the reconstructed distribution to the most probable value predicted by Geant4. I do this by fitting both distributions using a LanGauss function, obtaining $dE/dx_{MPV, true} = 0.1145 \pm 0.0005$ MeV/cm and $dE/dx_{MPV, reco} = 0.0928 \pm 0.0005$ MeV/cm for the true and reconstructed most probable values respectively. These can be translated into a scaling factor $S = 0.579 \pm 0.006$.

The result of applying the scaling correction can be seen in Fig. 8.6 (top panel). The corrected dE/dx distribution (yellow, labeled as corrected) peaks around the same value the true distribution does, as expected. Moreover, the high energy region is also slightly better described. For low ionisations, below the lower limit of the calibration fit, the differences between true and reconstructed are still significant. This low energy excess may be migration of some events from the peak region. The overall effect of the correction can be seen in the fractional residual plot in Fig. 8.6 (bottom panel).

One can also check what happens if instead of applying the logarithmic calibration we simply scale the dQ/dx distribution (post reclustering) to have the same most probable value as the true dE/dx distribution. In this case, following an analogous procedure to the one described earlier, I found the scaling factor $S_{uncalibrated} = 0.414 \pm 0.002$ MeV/ADC⁴. The resulting distribution (red, labeled as uncalibrated) is also shown in in Fig. 8.6 (top panel). The behaviour of the new distribution is similar to the corrected case at low energy losses, around the peak of the true distribution, but it is worse at describing the

⁴Notice that now the scaling factor is not dimensionless, as it acts more like a conversion factor here.

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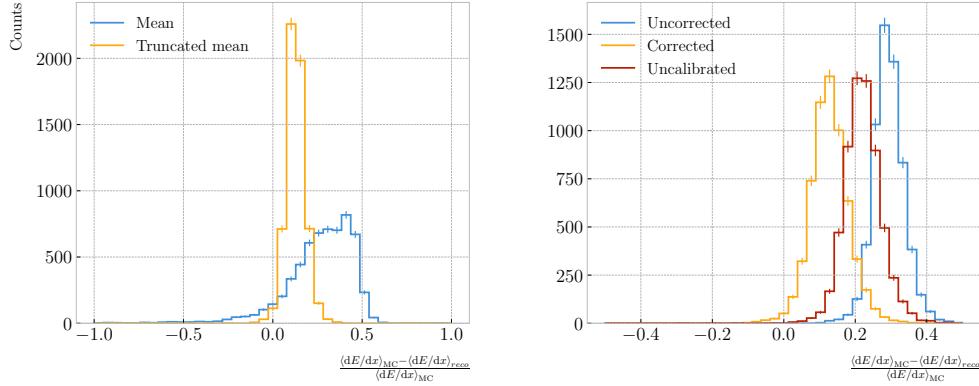


Figure 8.7: Left panel: fractional residuals between the true and the corrected dE/dx means (blue) and the 60% truncated means (yellow), for each event in the stopping proton sample. Right panel: fractional residuals between the true and the uncorrected (blue), corrected (yellow) and uncalibrated (red) dE/dx 60% truncated means, for each event in the stopping proton sample.

2505 high energy tail. This is expected, it is in the high ionisation regime where saturation
2506 effects apply and therefore calibration is needed.

2507 8.1.2 Truncated dE/dx mean

2508 Once we have a collection of dE/dx values for each reconstructed track, we can compute
2509 the corresponding most probable ionisation loss per unit length of the particle. This
2510 is the value predicted by the Bethe-Bloch or the PAI models, and together with a
2511 measurement of the momentum it allows for particle identification.

2512 However, estimating the most probable dE/dx value for each reconstructed track
2513 is not a trivial task. As mentioned before, the dE/dx distributions follow Landau-like
2514 distributions. Therefore, one should perform e.g. a LanGauss fit to correctly estimate
2515 the most probable values. Automating this kind of fits is often problematic, as they
2516 usually incur in convergence problems. Moreover, the reconstructed dE/dx distributions
2517 we obtain tend to have relatively small statistics, which may also produce poor fits. In
2518 practice, doing these unsupervised fits may degrade our performance, and a more robust
2519 method is preferred.

2520 A possibility could be taking the mean of the reconstructed dE/dx distribution for

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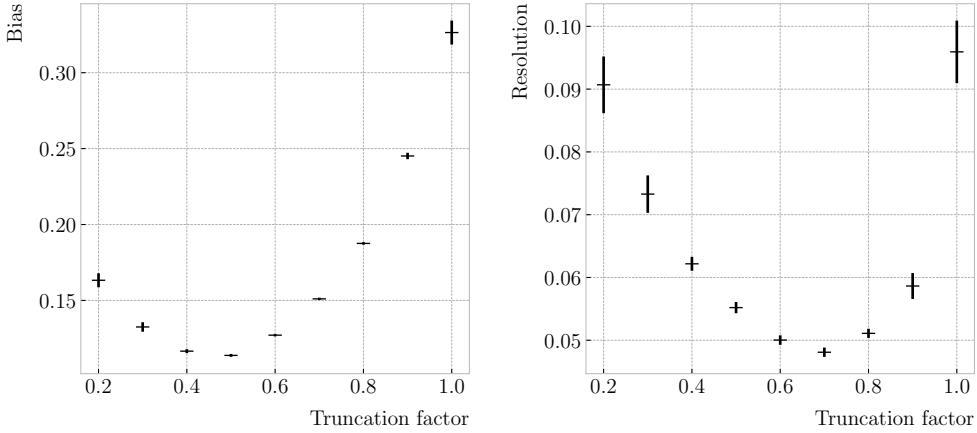


Figure 8.8: Estimated values of the mean dE/dx bias (left panel) and resolution (right panel) obtained using the corrected data from the stopping proton sample, for different values of the truncation factor.

each particle. The problem with this approach is that the high energy Landau tail, combined with our limited statistics, can induce large fluctuations in the computation 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. In Fig. 8.7 (left panel) I show 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

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2539 (blue), corrected (yellow) and uncalibrated (red) distributions. The results are shown
 2540 in Fig. 8.7 (right panel). While the widths of these distributions are similar, the bias
 2541 obtained for the corrected sample, i.e. calibration function and correction factor applied,
 2542 is a factor of ~ 2 lower than in the uncalibrated case and almost three times smaller
 2543 than for the uncorrected sample.

2544 The next step is to optimise the level of truncation we are going to apply to our
 2545 data. To do so, I used different truncation factors, i.e. the percentage of energy-ordered
 2546 reconstructed energy deposits we keep to compute the mean, on the corrected dE/dx
 2547 sample of the stopping protons. Then, following the same procedure of computing the
 2548 fractional residuals as before, I fitted the resulting histograms using a double Gaussian
 2549 function. This is simply the sum of two Gaussian functions of the type:

$$g(x; \mu, \sigma, A) = A e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \quad (8.6)$$

2550 I do not add the classical normalisation factor of the Gaussian, $1/\sqrt{2\pi}\sigma$, therefore
 2551 the amplitude A simply represents the maximum of the function. One of the two
 2552 Gaussian functions describes the core part of the distribution, while the other captures
 2553 the behaviour of the tails.

2554 For each truncation factor, I look at the bias and the resolution I obtain. I define
 2555 these as the weighted means of the corresponding parameters in the fits:

$$\bar{x} = \frac{A_{core} x_{core} + A_{tail} x_{tail}}{A_{core} + A_{tail}}, \quad (8.7)$$

2556 where A_{core} and A_{tail} are the amplitudes of the core and tail distributions respectively
 2557 and x is either the mean μ or the width σ of said distributions.

2558 Fig. 8.8 shows the bias (left panel) and the resolution (right panel) I obtained for
 2559 the stopping proton sample, using different values of the truncation. From these, it
 2560 can be seen that a truncation factor of 50% minimises the bias in the estimation, while
 2561 70% gives the best resolution. That way, I settled on the intermediate value of 60%

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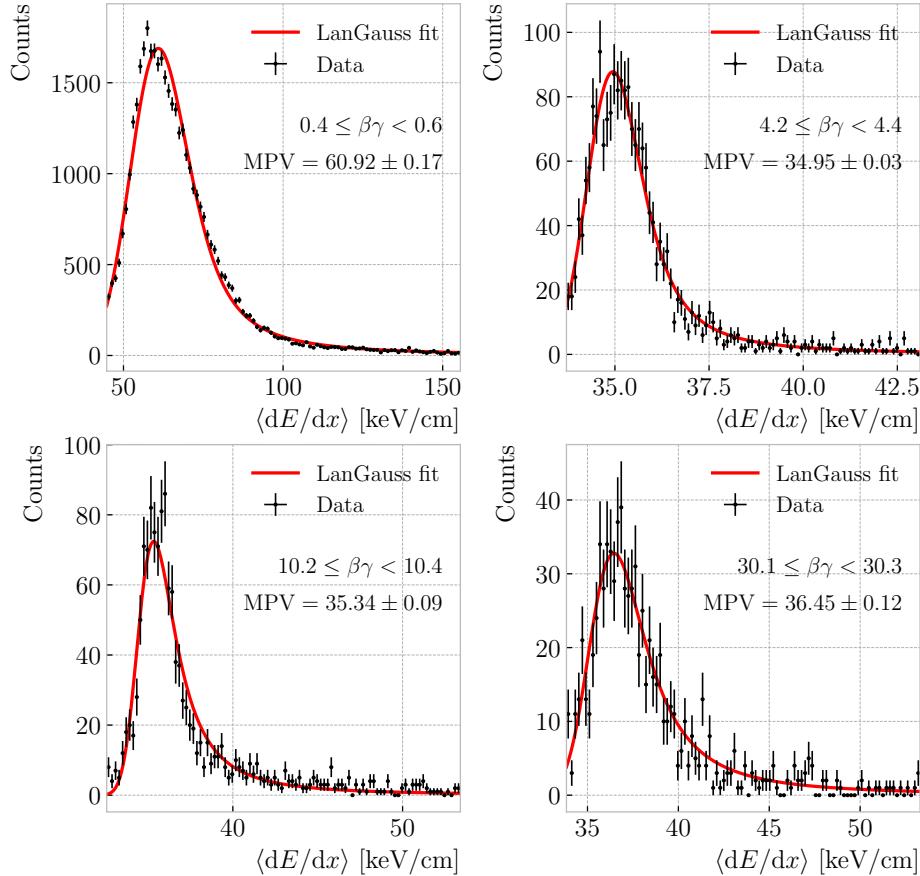


Figure 8.9: Examples of the truncated mean dE/dx LanGauss fits for various $\beta\gamma$ bins, from a simulated FHC neutrino sample.

truncation, which yields a $\langle dE/dx \rangle$ resolution of 5.00 ± 0.08 % for stopping protons.

8.1.3 Mean dE/dx parametrisation

Now that we have a way to estimate the mean energy loss of a particle in the HPgTPC, we can determine the value of the free parameters in the ALEPH formula, Eq. (8.3). For this, I used a sample of 10^5 reconstructed FHC neutrino events inside ND-GAr. In this case I cannot use the stopping proton sample, as we need to cover the full kinematic range of interest for the neutrino interactions in our detector.

The original data does not contain an estimation of the velocity of the tracks, instead the tracks have a value for the reconstructed momentum and the associated PDG code of the Geant4-level particle that created the track. Therefore, one can select some of the

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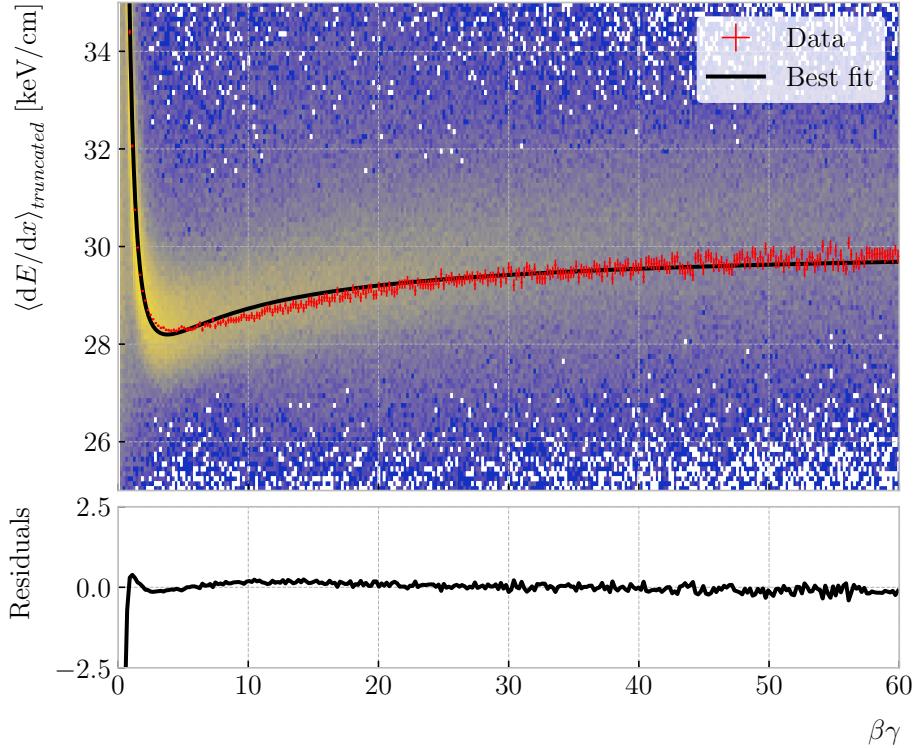


Figure 8.10: Truncated mean dE/dx obtained for the FHC neutrino sample as a function of the $\beta\gamma$ product (upper panel). Also shown are the fitted most probable values for each $\beta\gamma$ bin (red points) and the best fit obtained using the ALEPH parametrisation (black line). The residuals resulting from the fit are shown in the lower panel.

2572 particles in the data, in this case I selected electrons, muons, pions and protons, and
 2573 compute β and γ using the reconstructed momentum and their mass. In terms of $\beta\gamma$
 2574 the mean dE/dx does not depend on the particle species, so one can consider all the
 2575 dataset as a whole. For this fit, I will express β in terms of the $\beta\gamma$ product as:

$$\beta = \frac{\beta\gamma}{\sqrt{1 + (\beta\gamma)^2}}, \quad (8.8)$$

2576 which can be easily proven from the definition of γ .

2577 Next, I bin the data in $\beta\gamma$. I chose a fine binning so as to capture the different
 2578 features of the ionisation curve. Then, for each $\beta\gamma$ slice, I compute the median and the
 2579 interquartile range (IQR) of the $\langle dE/dx \rangle$ distribution. Using these, I make a histogram
 2580 in the range [median - IQR, median + 5 IQR], which I fit to a LanGauss function in

8.2. Muon and pion separation in the ECal and MuID

Table 8.2: Best fit parameters obtained fitting a ND-GAr simulated FHC neutrino sample to the ALEPH mean dE/dx parametrisation from Eq. (8.3).

Parameter	Best fit $\pm 1\sigma$	3σ range
P_1		
P_2		
P_3		
P_4		
P_5		

order to extract the MPV. Using this range accounts for the asymmetric nature of the distributions, while also helps avoiding a second, lower maximum present at low $\beta\gamma$, probably a result of reconstruction failures.

A few examples of these fits are shown in Fig. 8.9. The chosen values of $\beta\gamma$ sit in very distinct points along the $\langle dE/dx \rangle$ curve, going from the high ionisation region at low velocities (top left panel), to the minimum point (top right panel), the beginning of the relativistic rise (bottom left panel), and the plateau produced by the density effect (bottom right panel).

I used the resulting most probable $\langle dE/dx \rangle$ values and the centres of the $\beta\gamma$ bins as the points to fit to the ALEPH formula. The result is shown in Fig. 8.10 (top panel). The best fit parameters

$$\begin{aligned}
 P_1 &= 3.18 \pm 0.70, \\
 P_2 &= 11.70 \pm 2.46, \\
 P_3 &= (1.51 \pm 1.82) \times 10^{-3}, \\
 P_4 &= 1.98 \pm 0.01, \\
 P_5 &= 1.73 \pm 0.32.
 \end{aligned} \tag{8.9}$$

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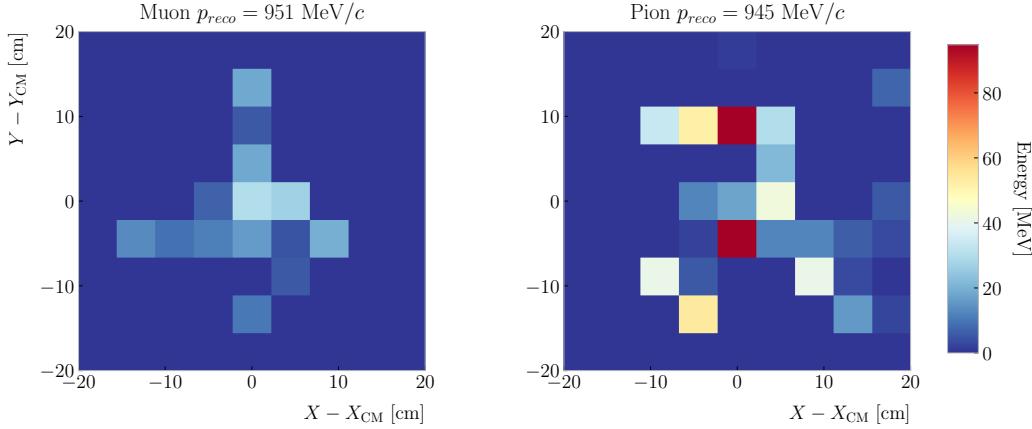


Figure 8.11: Distributions of energy deposits in the ECal for a muon (left) and a charged pion (right) with similar momentum. The energy is projected onto the plane perpendicular to the principal component of the hit clusters, and the positions are relative to the center of the interaction.

2592 8.1.4 Proton identification

2593 8.2 Muon and pion separation in the ECal and MuID

2594 8.2.1 Track-ECal matching

2595 One of the main players in the particle identification, in particular for muon and pion
 2596 separation, is the way we associate clusters in the ECal to reconstructed tracks in the
 2597 TPC. Missing some associations or making wrong ones can bias the ECal quantities
 2598 that we can use for classifying particles. The current algorithm in GArSoft provides
 2599 precise associations, i.e. most of the associations that it produces are correct, but it
 2600 appears to miss an important number of associations (at least when using the default
 2601 configuration).

2602 The current TPC track-ECal cluster association algorithm is divided in four parts.
 2603 It first checks whether the track end point fulfils certain conditions to be extrapolated.
 2604 There are two cut values in this step, one for the drift direction and other radial.

2605 If the point can be extrapolated, the code computes the coordinates of the centre
 2606 of curvature using the Kalman fit estimates at the track end (y , z , $1/R$, ϕ , $\tan\lambda$). It
 2607 then compares the distance between this and the cluster in the (z, y) plane with R . This

8.2. Muon and pion separation in the ECal and MuID

2608 introduces another cut in the perpendicular direction.

2609 The next step is different for clusters in the barrel or in one of the end caps. If it
2610 is a barrel cluster the algorithm extrapolates the track up to the radial distance of the
2611 cluster. There are three possible outcomes, the extrapolated helix can cut the cylinder
2612 of radius r_{clus} two, one or zero times. I get the cut point that is closer to the cluster and
2613 check that it is either in the barrel or the end caps. Computing the difference between
2614 the x coordinates of the cluster and the extrapolated point, the module checks that this
2615 is not greater than a certain cut. If the cluster is in an end cap, I propagate the track
2616 up to the x position of the cluster. Then, the algorithm computes the angle in the (z, y)
2617 plane between the centre of curvature and the cluster, α , and the centre of curvature
2618 and the propagated point, α' . A cut is applied to the quantity $(\alpha - \alpha')R$.

2619 If the cluster contains more than a certain number N of hits, I apply an extra cut to
2620 the dot product of the direction of the track at the propagated x value and the cluster
2621 direction.

2622 The code makes sure to only associate one end of the track (if any) to a cluster.
2623 However, it can associate more than one track to the same cluster. This makes sense,
2624 as different particles can contribute to the same cluster in the ECal, but it makes it
2625 difficult to quantify the relative contributions of the tracks to a certain cluster.

2626 As a way of comparing the performance of this algorithm, a new, simpler association
2627 module was written. The goal was to have a simple and robust algorithm, which depends
2628 on as few parameters as possible and that can produce a one-to-one matching between
2629 tracks and ECal clusters.

2630 For each reconstructed track, the new algorithms applies the same procedure to the
2631 forward and the backward fits irrespective of their end point positions. It first gets the
2632 Kalman fit parameters at the corresponding end point together with the X position, x_0 ,
2633 $(y_0, z_0, 1/R, \phi_0, \tan\lambda)$.

2634 For each ECal cluster, I compute the radial distance to the centre of the TPC and
2635 find the ϕ value in the range $[\phi_0, \phi_0 + \text{sign}(R)\phi_{max}]$ that makes the propagated helix
2636 intersect with the circle defined with such radius. The (x, y, z) position of the helix for

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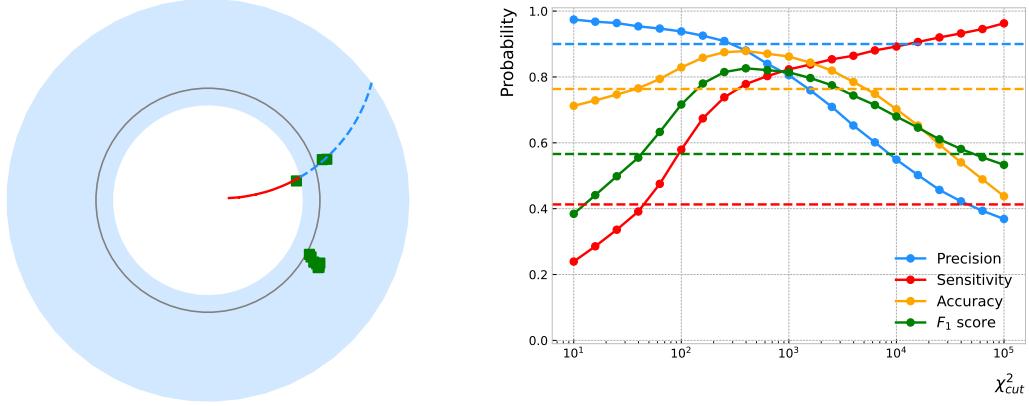


Figure 8.12: Left panel: example reconstructed track (red line) propagated up to an angle $\phi_{max} = \pi/2$ (dashed blue line). Also shown are the ECal clusters in the event (green squares). Right panel: performance metrics.

2637 the ϕ value found (if any) is then computed. In case there are two intersections, I keep
 2638 the one that minimises the distance between (y, z) and (y_c, z_c) .

2639 Fig. 8.12 (left panel) shows an example track (red line) being propagated up to
 2640 $\phi_0 + \text{sign}(R)\pi/2$ (dashed blue line). The image also shows the ECal clusters present
 2641 in the event (green squares). For each of them, the algorithm will try to find the
 2642 intersections of the propagated helix and the circles defined with their corresponding
 2643 radii.

2644 I then calculate χ^2 value based on the Euclidean distance between the propagated
 2645 point and the cluster:

$$\chi^2/n_{df} = \frac{\sum_{n=0}^2 \left(x^{(n)} - x_c^{(n)} \right)^2}{3}. \quad (8.10)$$

2646 If there was no intersection I store a -1 instead. In the end, for each reconstructed track
 2647 in the event one ends up with two collections of χ^2 values, one for each ECal cluster
 2648 and fit directions.

2649 The current code only supports having ECal clusters associated to one end of each
 2650 track. We have two options to decide what track end to keep. The first one tries to
 2651 cheat the selection, looking at the distance between the two track ends and the true
 2652 start position of the associated MC particle. The second one keeps the track end with

8.2. Muon and pion separation in the ECal and MuID

2653 more χ^2 entries below the cut.

2654 This feature of only considering one track end limits the algorithm, making it not
 2655 suitable for reconstructing events with particles originating outside the TPC. However,
 2656 as for the moment the main concern of the group is the study of neutrino interactions
 2657 off the gaseous argon, this is an acceptable assumption.

2658 In order to associate a cluster to a track, I take all clusters with a χ^2 value in the
 2659 range $[0, \chi_{cut}^2]$. If a cluster has been assigned to more than one track we leave it with
 2660 the one with the lowest χ^2 .

2661 This default behaviour of the algorithm can be modified to associate more than one
 2662 track to each cluster. Not only that, but the χ^2 values can be used to assign relative
 2663 weights to the different contributions.

2664 To evaluate the performance of the association method, I use a binary classification
 2665 approach. In this case, I check the leading MC Track IDs associated to the reconstructed
 2666 tracks and ECal clusters. I count an association as true positive (TP) if both Track
 2667 IDs coincide. An association is considered false positive (FP) when the Track IDs are
 2668 different. If a cluster has not been associated to any track but it shares the Track ID
 2669 with a reconstructed track it is counted as a false negative (FN).

2670 Fig. 8.12 (right panel) shows the precision (blue line), sensitivity (red line), accuracy
 2671 (orange line) and F_1 -score (green line) for different values of χ_{cut}^2 . For comparison, the
 2672 same metrics computed for the default algorithm with the current configuration are also
 2673 shown (dashed lines). Notice that we can achieve similar values of the precision with
 2674 this new code while having a considerably higher sensitivity.

2675 One of the possible weak points of this approach is that it relies on the position along
 2676 the drift direction to make the decisions. Within the current ND-GAr design implemented
 2677 in GArSoft, the timing information is provided by the ECal. That effectively means that
 2678 prior to make the track-ECal associations the reconstructed X positions of the track
 2679 trajectories differ from the simulated ones by an amount:

$$x_{reco}^{(n)} - x_{sim}^{(n)} = v_{drift} t_0, \quad (8.11)$$

Chapter 8. Particle ID in GArSoft

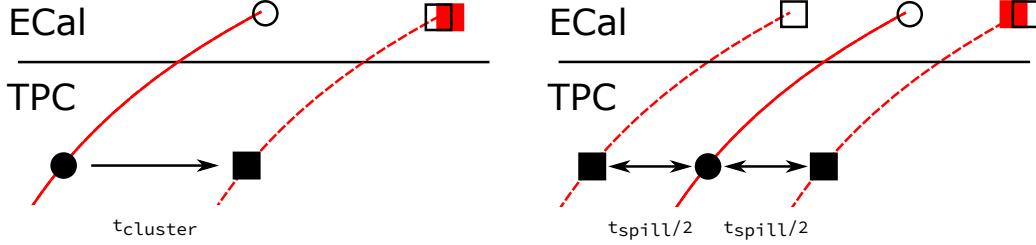


Figure 8.13: Schematics of possible options to deal with track-ECal associations in non-zero t_0 neutrino interaction events. The first option (left panel) tries to correct for the drift direction uncertainty in a cluster-by-cluster basis using the cluster time, $t_{cluster}$. The second option (right panel) is based on a track-by-track approach, propagating two additional helices for each track corrected by factors of $\pm t_{spill}/2$.

2680 where v_{drift} is the mean drift velocity in our medium and the initial time is in the range
 2681 $t_0 \in [0, t_{spill}]$ where t_{spill} is the spill length. For a $10 \mu\text{s}$ spill this translates into a
 2682 maximum 30 cm uncertainty on the drift direction position.

2683 The current default in GArSoft sets $t_0 = 0$, but the functionality to randomly sample
 2684 this within the spill time is in place. Therefore, we need to understand what is the impact
 2685 of a non-zero t_0 on the associations algorithm and foresee possible ways of minimising a
 2686 loss in performance.

2687 Fig. 8.13 represents two different options to tackle the associations problem when
 2688 having events with a non-zero initial time t_0 . The circles represent the original points,
 2689 whereas the squares indicate the corrected positions. The end points of the track and
 2690 the propagated points up to the cluster radius are indicated using filled and unfilled
 2691 markers respectively. The red square represents the position of the cluster.

2692 In the first option (left panel) I try to correct for the drift coordinate position using
 2693 the time associated to the cluster. Assuming that the drift time is much larger than the
 2694 propagation time, $t_{cluster}$ could be used as a good estimation of the t_0 . An alternative
 2695 can be using the earliest time associated to a hit in said cluster. Doing this for each
 2696 cluster before computing the χ^2 value could be used as an alternative to knowing the
 2697 specific value of the t_0 , as when the association is correct this will provide the right
 2698 correction but its impact is small enough to not change the position significantly in the
 2699 case the cluster does not correspond to a given track.

8.3. ECal time-of-flight

2700 The second method depicted in Fig. 8.13 (right panel) tries to propagate three
2701 different helices for each reconstructed track and fit direction. One is the original,
2702 uncorrected helix and the other two are obtained by adding factors of $\pm t_{spill}/2$ when
2703 computing the drift coordinate position. In this case one would compute a set of χ^2
2704 values for each helix, keeping in the end the collection that manages to keep more values
2705 below χ^2_{cut} . An alternative approach could be using a family of helices instead, using
2706 uniformly sampled time correction values in the $\pm t_{spill}/2$ range.

2707 Both options could offer a solution to the t_0 problem, and still need to be explored.

2708 8.2.2 Feature selection and importance

2709 8.2.3 Hyperparameter optimisation

2710 8.2.4 Probability calibration

2711 8.2.5 Performance

2712 8.3 ECal time-of-flight

2713 8.3.1 Arrival time estimations

2714 8.3.2 Proton and pion separation

2715 8.4 Charged pion decay in flight

2716 8.4.1 Track breakpoints

2717 8.5 Neutral particle identification

2718 8.5.1 ECal clustering

2719 Another important reconstruction item is the clustering algorithm of ECal hits in
2720 GArSoft. The default module features a NN algorithm that treats all hits in the same
2721 way, independently of the layer each hit comes from. However, the current ECal design
2722 of ND-GAr has two very different types of scintillator layers. The inner layers are made

Chapter 8. Particle ID in GArSoft

2723 out of tiles, which provide excellent angular and timing resolutions. On the other hand,
2724 the outer layers are cross scintillator strips. That way, an algorithm that treats hits
2725 from both kinds of layers differently may be able to improve the current performance.

2726 Inspired by the reconstruction of T2K’s ND280 downstream ECal [?], the idea was
2727 to put together a clustering module that first builds clusters for the different ECal views
2728 (tiles, strips segmented in the X direction and strips segmented in Y direction), and
2729 then tries to match them together to form the final clusters.

2730 Working on a module-by-module basis, the algorithm first separates the hits depending
2731 on the layer type they come from. Then, it performs a NN clustering for the 3 sets of
2732 hits separately. For the tile hits it clusters together all the hits which are in nearest-
2733 neighbouring tiles and nearest-neighbouring layers, for strip hits it looks at nearest-
2734 neighbouring strips and next-to-nearest-neighbouring layers (as the layers with strips
2735 along the two directions are alternated). For strip clusters an additional cut in the
2736 direction along the strip length is needed.

2737 After this first clustering I then apply a recursive re-clustering for each collection
2738 of strip clusters based on a PCA method. In each case, we loop over the clusters with
2739 $N_{hits} \geq 2$, computing the centre of mass and three principal components. Propagating
2740 these axes up to the layers of the rest of the clusters, we check if the propagated point
2741 and the centre of mass of the second cluster are within next-to-nearest-neighbouring
2742 strips. An additional cut in the direction along the strip length is also needed. Moreover,
2743 I require that the two closest hits across the two clusters are at most in next-to-nearest-
2744 neighbouring strips. I merge the clusters if these three conditions are satisfied. The
2745 re-clustering is repeated until no more cluster pairs pass the cuts.

2746 The clusters in each strip view are combined if their centres of mass are close enough
2747 and they point in the same direction. An alternative approach for the strip cluster
2748 merging could be to compute the overlap between the ellipsoids defined by the principal
2749 axes of the clusters, and then merge the pair if the overlap exceeds some threshold.
2750 Further study is needed to understand if this change would have an impact in the overall
2751 clustering performance.

8.5. Neutral particle identification

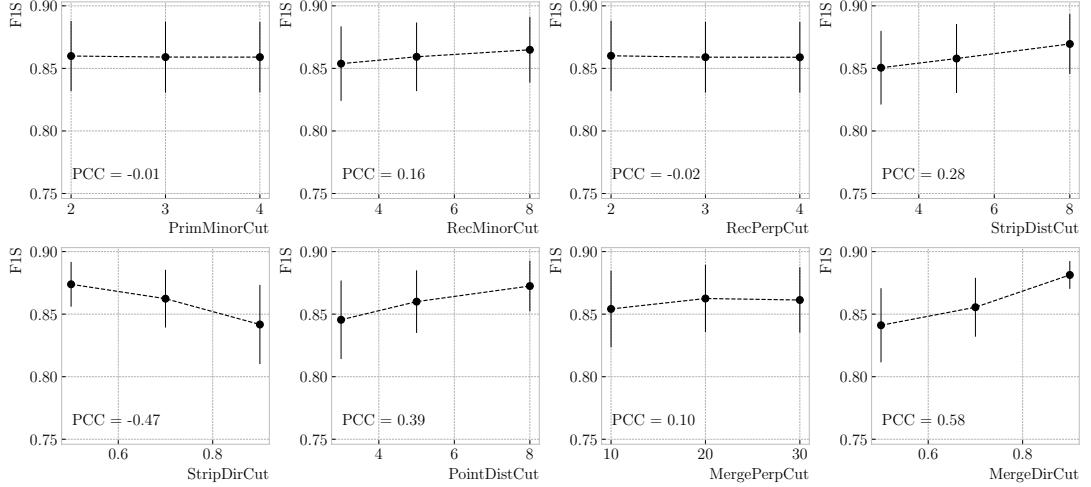


Figure 8.14: Mean values of the F_1 -score marginal distributions for the different free parameters of the new clustering algorithm, with the error bars representing one standard deviation around the mean. The F_1 -score values were computed for the 6561 possible parameter configurations using 1000 ν_μ CC interaction events.

2752 To merge the tile clusters to the combined strip clusters I propagate the principal
 2753 axis of the strip cluster towards the inner layers, up to the centre of mass layer of the
 2754 tile cluster. I merge the clusters if the distance between the propagated point and the
 2755 centre of mass is bellow a certain cut.

2756 The last step is to check if clusters in neighbouring modules should be merged
 2757 together, both across two barrel modules, across end cap modules and between barrel
 2758 end cap modules. I check the distance between the two closest hits in the pair of clusters
 2759 and merge them if it passes this and an additional direction cut.

2760 Fig. ?? presents an example of the clustering steps relevant for strip layer hits, from
 2761 the input hits (top left panel) to the NN clustering (top right panel) and re-clustering
 2762 (bottom left panel) for each strip view and the final merging strip clusters (bottom
 2763 right panel). It shows the hits from a single ECal barrel module in a ν_μ CC interaction
 2764 event with a neutral pion and a proton in the final state. The two clusters on the left
 2765 correspond to the photon pair from the π^0 decay and the one on the upper right corner
 2766 is associated to the proton.

2767 This algorithm has a total number of eight free parameters that need to be optimised.

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Table 8.3: 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

2768 I used a sample of 1000 ν_μ CC interactions in order to obtain the optimal configuration of
 2769 clustering parameters. This sample was generated up to the default ECal hit clustering
 2770 level, so then I could run the new clustering algorithm each time with a different
 2771 configuration of parameters. As the number of parameters is relatively large, I only
 2772 performed a coarse-grained scan of the parameter space. Sampling each of the eight
 2773 parameters at three different points each I obtain 6561 different configurations. These
 2774 parameters, together with the used values, are summarised in Tab. 8.3.

2775 In order to measure the performance of the clustering, I use a binary classification
 2776 approach. For each formed cluster, I identify the Geant4 Track ID of the matching MC
 2777 particle and the energy fraction of each hit. Then, I assign to each cluster the Track ID
 2778 with the highest total energy fraction. For each of the different Track IDs associated to
 2779 the clusters, I select the cluster with the highest energy (only from the hits with the
 2780 same Track ID). I identify such a cluster as the main cluster for that Track ID. I count
 2781 as true positives (TPs) the hits with the correct Track ID in each main cluster. False
 2782 positives (FPs) are the hits with the incorrect Track ID for the cluster they are in, not
 2783 only main clusters. The false negatives (FNs) are the hits with the correct Track ID in
 2784 clusters other than the main.

8.5. Neutral particle identification

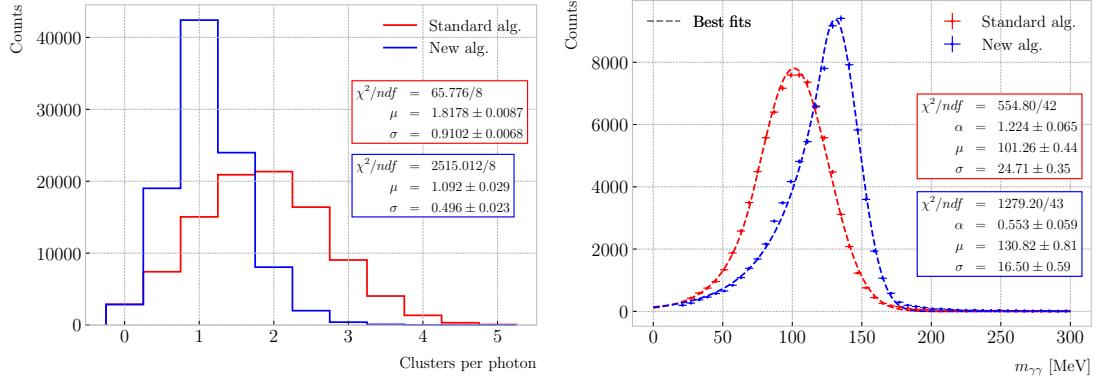


Figure 8.15: Left panel: distributions of the number of ECal clusters per photon from π^0 decays for the standard (red) and new (blue) clustering algorithms. Right panel: reconstructed invariant mass distributions for photon pairs from single π^0 events using the standard (red) and new (blue) ECal clustering algorithms.

Fig. 8.14 shows the computed F_1 -score values for the different cuts. In each case, the central value represents the mean of the F_1 -score distribution for the specified value of the corresponding variable and the vertical error bar represents one standard deviation around the mean. Also shown are the Pearson correlation coefficients of these central values. We can see that five of the variables have a sizeable effect on the F_1 -score, with an absolute difference between the last and first values as big as 4%.

The working configuration is obtained as follows. I first select all configurations with purity $\geq 90\%$. Among those, I choose the combinations that yield the maximum F_1 -score. If more than one configuration remains I select the one with the highest sensitivity. Doing so, I end up with a parameter configuration with an efficiency of 88% and a 90% purity. Compared with the default algorithm, which gives an efficiency of 76% and a purity of 91% for the same sample, I have managed to improve the efficiency by a factor of 1.16.

8.5.2 π^0 reconstruction

One of the potential applications of the new ECal hit clustering is the reconstruction of neutral particles, in particular pions. Neutral pions decay promptly after being produced, through the $\pi^0 \rightarrow \gamma\gamma$ channel ($98.823 \pm 0.034\%$) of the time. The photon pair does

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2802 not leave any traces in the HPgTPC (unless one or both of them converts into an
2803 electron-positron pair), but each of them will produced an electromagnetic shower in
2804 the ECal.

2805 To test the potential impact of the new algorithm in π^0 reconstruction, I generated
2806 a MC sample of single, isotropic neutral pions inside the HPgTPC. All pions were
2807 generated with a momentum $p = 500$ MeV and their initial positions were uniformly
2808 sampled inside a $2 \times 2 \times 2$ m box aligned with the centre of the TPC. I ran both the
2809 default and the new clustering algorithms, using for the latter the optimised configuration
2810 discussed above.

2811 The first thing to notice is that the number of clusters produced per photon has
2812 decreased. Fig. 8.15 (left panel) shows these distributions for the default (red) and new
2813 (blue) algorithms. Using a simple Gaussian fit, we see that the mean number of ECal
2814 clusters per photon went from 1.82 ± 0.01 to 1.09 ± 0.03 . This effectively means that
2815 with the new algorithm the ECal activity of one true particle is typically reconstructed
2816 as a single object. From the reconstruction point of view this can be an advantage. As
2817 now most of the photon energy ends up in a single ECal cluster, I can simply use cluster
2818 pairs to identify the π^0 decay.

2819 In general, one calculates the invariant mass of the photon pair as:

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos \theta)}, \quad (8.12)$$

2820 where E_i are the energies of the photons and θ the opening angle between them. In this
2821 case I can use the energies deposited in the ECal and their incident directions. This
2822 quantity is computed for all possible pairs of clusters, using their position together with
2823 the true decay point. In a more realistic scenario, e.g. ν_μ CC interaction, one could use
2824 the position of the reconstructed primary vertex instead. I also tried to use the principal
2825 direction of the clusters, but that approach gave considerably worse results. For each
2826 event I only keep the pair with an invariant mass closer to the true π^0 mass value.

2827 Fig. 8.15 (right panel) shows the invariant mass distributions for the photon pairs

8.5. Neutral particle identification

we get using the default (red) and the new (blue) ECal clustering algorithms. For the fit I used a modified version of the Crystal Ball function [?], obtained by taking the limit where the parameter controlling the power-law tail goes to infinity:

$$f(x; N, \mu, \sigma, \alpha) = N \cdot \begin{cases} e^{\frac{\alpha(2x-2\mu+\alpha\sigma)}{2\sigma}}; & x \leq \mu - \alpha\sigma, \\ e^{-\frac{(x-\mu)^2}{2\sigma^2}}; & x > \mu - \alpha\sigma. \end{cases} \quad (8.13)$$

Comparing the fitted mean and standard deviation values for the Gaussian cores, we see that the distribution for the new algorithm is a 67% narrower and also peaks much closer to the true m_{π^0} value, going from 101.3 ± 0.4 MeV to 130.8 ± 0.6 MeV.

²⁸³⁴ Chapter 9

²⁸³⁵ Conclusions

²⁸³⁶ Appendix A

²⁸³⁷ An appendix

2838

Bibliography

- 2839 [1] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far*
2840 *Detector Technical Design Report, Volume I Introduction to DUNE*, *JINST* **15**
2841 (2020) T08008 [2002.02967]. 15, 39, 40, 41, 44, 45, 46, 52, 53, 54, 61, 62
- 2842 [2] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far*
2843 *Detector Technical Design Report, Volume IV: Far Detector Single-phase*
2844 *Technology*, *JINST* **15** (2020) T08010 [2002.03010]. 15, 49
- 2845 [3] J.N. Bahcall, A.M. Serenelli and S. Basu, *New solar opacities, abundances,*
2846 *helioseismology, and neutrino fluxes*, *Astrophys. J. Lett.* **621** (2005) L85
2847 [[astro-ph/0412440](#)]. 21, 109, 111
- 2848 [4] R. Garani and S. Palomares-Ruiz, *Dark matter in the Sun: scattering off electrons*
2849 *vs nucleons*, *JCAP* **05** (2017) 007 [[1702.02768](#)]. 21, 107, 108, 110, 111, 112, 135
- 2850 [5] M. Honda, M. Sajjad Athar, T. Kajita, K. Kasahara and S. Midorikawa,
2851 *Atmospheric neutrino flux calculation using the NRLMSISE-00 atmospheric model*,
2852 *Phys. Rev. D* **92** (2015) 023004 [[1502.03916](#)]. 22, 115, 116
- 2853 [6] M. Colom i Bernadich and C. Pérez de los Heros, *Limits on Kaluza-Klein dark*
2854 *matter annihilation in the Sun from recent IceCube results*, *Eur. Phys. J. C*, **80** 2
2855 (2020) 129 **80** (2019) [[1912.04585](#)]. 22, 120
- 2856 [7] ANTARES collaboration, *Search for Dark Matter in the Sun with the ANTARES*
2857 *Neutrino Telescope in the CMSSM and mUED frameworks*, *Nucl. Instrum. Meth. A*
2858 **725** (2013) 76 [[1204.5290](#)]. 22, 120

BIBLIOGRAPHY

- 2859 [8] N. Deutschmann, T. Flacke and J.S. Kim, *Current LHC Constraints on Minimal*
2860 *Universal Extra Dimensions*, *Phys. Lett. B* **771** (2017) 515 [[1702.00410](#)]. 22, 120,
2861 121
- 2862 [9] ICECUBE collaboration, *Search for GeV-scale dark matter annihilation in the Sun*
2863 *with IceCube DeepCore*, *Phys. Rev. D* **105** (2022) 062004 [[2111.09970](#)]. 24, 132,
2864 133
- 2865 [10] C.-S. Chen, F.-F. Lee, G.-L. Lin and Y.-H. Lin, *Probing Dark Matter*
2866 *Self-Interaction in the Sun with IceCube-PINGU*, *JCAP* **10** (2014) 049 [[1408.5471](#)].
2867 24, 132, 133
- 2868 [11] N.F. Bell, M.J. Dolan and S. Robles, *Searching for dark matter in the Sun using*
2869 *Hyper-Kamiokande*, *JCAP* **11** (2021) 004 [[2107.04216](#)]. 24, 132, 133
- 2870 [12] E. Behnke et al., *Final Results of the PICASSO Dark Matter Search Experiment*,
2871 *Astropart. Phys.* **90** (2017) 85 [[1611.01499](#)]. 24, 132, 133
- 2872 [13] PICO collaboration, *Dark Matter Search Results from the Complete Exposure of*
2873 *the PICO-60 C₃F₈ Bubble Chamber*, *Phys. Rev. D* **100** (2019) 022001
2874 [[1902.04031](#)]. 24, 132, 133
- 2875 [14] DARKSIDE collaboration, *Constraints on Sub-GeV Dark-Matter–Electron*
2876 *Scattering from the DarkSide-50 Experiment*, *Phys. Rev. Lett.* **121** (2018) 111303
2877 [[1802.06998](#)]. 24, 136, 137
- 2878 [15] XENON collaboration, *Light Dark Matter Search with Ionization Signals in*
2879 *XENON1T*, *Phys. Rev. Lett.* **123** (2019) 251801 [[1907.11485](#)]. 24, 136, 137
- 2880 [16] P.F. de Salas, D.V. Forero, S. Gariazzo, P. Martínez-Miravé, O. Mena, C.A. Ternes
2881 et al., *2020 global reassessment of the neutrino oscillation picture*, *JHEP* **02** (2021)
2882 071 [[2006.11237](#)]. 27, 36, 41
- 2883 [17] W. Pauli, *Dear radioactive ladies and gentlemen*, *Phys. Today* **31N9** (1978) 27. 31

BIBLIOGRAPHY

- 2884 [18] F. Reines and C.L. Cowan, *Detection of the free neutrino*, *Phys. Rev.* **92** (1953)
2885 830. 31
- 2886 [19] ALEPH, DELPHI, L3, OPAL, SLD, LEP ELECTROWEAK WORKING GROUP,
2887 SLD ELECTROWEAK GROUP, SLD HEAVY FLAVOUR GROUP collaboration,
2888 *Precision electroweak measurements on the Z resonance*, *Phys. Rept.* **427** (2006)
2889 257 [[hep-ex/0509008](#)]. 32
- 2890 [20] SUPER-KAMIOKANDE collaboration, *Evidence for oscillation of atmospheric*
2891 *neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [[hep-ex/9807003](#)]. 32
- 2892 [21] B. Pontecorvo, *Inverse beta processes and nonconservation of lepton charge*, *Zh.*
2893 *Eksp. Teor. Fiz.* **34** (1957) 247. 32
- 2894 [22] Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary*
2895 *particles*, *Prog. Theor. Phys.* **28** (1962) 870. 32
- 2896 [23] L. Wolfenstein, *Neutrino Oscillations in Matter*, *Phys. Rev. D* **17** (1978) 2369. 34
- 2897 [24] B.T. Cleveland, T. Daily, R. Davis, Jr., J.R. Distel, K. Lande, C.K. Lee et al.,
2898 *Measurement of the solar electron neutrino flux with the Homestake chlorine*
2899 *detector*, *Astrophys. J.* **496** (1998) 505. 35
- 2900 [25] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, *Reanalysis of the*
2901 *GALLEX solar neutrino flux and source experiments*, *Phys. Lett. B* **685** (2010) 47
2902 [[1001.2731](#)]. 35
- 2903 [26] SAGE collaboration, *Measurement of the solar neutrino capture rate with gallium*
2904 *metal. III: Results for the 2002–2007 data-taking period*, *Phys. Rev. C* **80** (2009)
2905 015807 [[0901.2200](#)]. 35
- 2906 [27] G. Bellini et al., *Precision measurement of the ^{7}Be solar neutrino interaction rate*
2907 *in Borexino*, *Phys. Rev. Lett.* **107** (2011) 141302 [[1104.1816](#)]. 35

BIBLIOGRAPHY

- 2908 [28] SUPER-KAMIOKANDE collaboration, *Solar neutrino measurements in
super-Kamiokande-I*, *Phys. Rev. D* **73** (2006) 112001 [[hep-ex/0508053](#)]. 35
- 2910 [29] SNO collaboration, *Combined Analysis of all Three Phases of Solar Neutrino Data
from the Sudbury Neutrino Observatory*, *Phys. Rev. C* **88** (2013) 025501
[[1109.0763](#)]. 35
- 2913 [30] SUPER-KAMIOKANDE collaboration, *Atmospheric neutrino oscillation analysis with
external constraints in Super-Kamiokande I-IV*, *Phys. Rev. D* **97** (2018) 072001
[[1710.09126](#)]. 35
- 2916 [31] ICECUBE collaboration, *Measurement of Atmospheric Neutrino Oscillations at
6–56 GeV with IceCube DeepCore*, *Phys. Rev. Lett.* **120** (2018) 071801
[[1707.07081](#)]. 35
- 2919 [32] KAMLAND collaboration, *Reactor On-Off Antineutrino Measurement with
KamLAND*, *Phys. Rev. D* **88** (2013) 033001 [[1303.4667](#)]. 35
- 2921 [33] RENO collaboration, *Measurement of Reactor Antineutrino Oscillation Amplitude
and Frequency at RENO*, *Phys. Rev. Lett.* **121** (2018) 201801 [[1806.00248](#)]. 35
- 2923 [34] DAYA BAY collaboration, *Measurement of the Electron Antineutrino Oscillation
with 1958 Days of Operation at Daya Bay*, *Phys. Rev. Lett.* **121** (2018) 241805
[[1809.02261](#)]. 35
- 2926 [35] K.J. Kelly, P.A.N. Machado, S.J. Parke, Y.F. Perez-Gonzalez and R.Z. Funchal,
Neutrino mass ordering in light of recent data, *Phys. Rev. D* **103** (2021) 013004. 36
- 2928 [36] P. Dunne, “Latest Neutrino Oscillation Results from T2K.” Jul, 2020. 36
- 2929 [37] MINOS collaboration, *Combined analysis of ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$
appearance in MINOS using accelerator and atmospheric neutrinos*, *Phys. Rev. Lett.*
112 (2014) 191801 [[1403.0867](#)]. 36

BIBLIOGRAPHY

- 2932 [38] K2K collaboration, *Measurement of Neutrino Oscillation by the K2K Experiment*,
2933 *Phys. Rev. D* **74** (2006) 072003 [[hep-ex/0606032](#)]. 36
- 2934 [39] DUNE collaboration, *Long-baseline neutrino oscillation physics potential of the*
2935 *DUNE experiment*, *Eur. Phys. J. C* **80** (2020) 978 [[2006.16043](#)]. 36
- 2936 [40] HYPER-KAMIOKANDE collaboration, *Physics potential of Hyper-Kamiokande for*
2937 *neutrino oscillation measurements*, *PoS NuFact2019* (2019) 040. 36
- 2938 [41] DUNE collaboration, *Snowmass Neutrino Frontier: DUNE Physics Summary*,
2939 [2203.06100](#). 41, 42
- 2940 [42] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE), Far*
2941 *Detector Technical Design Report, Volume II: DUNE Physics*, [2002.03005](#). 41, 43,
2942 57, 59, 115, 124, 128
- 2943 [43] SUPER-KAMIOKANDE collaboration, *Search for Proton Decay via $p \rightarrow e^+ \pi_0$ and*
2944 *$p \rightarrow \mu^+ \pi_0$ in a Large Water Cherenkov Detector*, *Phys. Rev. Lett.* **102** (2009)
2945 [141801](#) [[0903.0676](#)]. 42
- 2946 [44] S. Raby, *Grand Unified Theories*, in *2nd World Summit: Physics Beyond the*
2947 *Standard Model*, 8, 2006 [[hep-ph/0608183](#)]. 42
- 2948 [45] KAMIOKANDE-II collaboration, *Observation of a Neutrino Burst from the*
2949 *Supernova SN 1987a*, *Phys. Rev. Lett.* **58** (1987) 1490. 43
- 2950 [46] R.M. Bionta et al., *Observation of a Neutrino Burst in Coincidence with Supernova*
2951 *SN 1987a in the Large Magellanic Cloud*, *Phys. Rev. Lett.* **58** (1987) 1494. 43
- 2952 [47] DUNE collaboration, *The DUNE Far Detector Vertical Drift Technology*,
2953 *Technical Design Report*, [2312.03130](#). 47, 48
- 2954 [48] DUNE collaboration, *Deep Underground Neutrino Experiment (DUNE) Near*
2955 *Detector Conceptual Design Report, Instruments* **5** (2021) 31 [[2103.13910](#)]. 51, 52,
2956 55, 59, 139

BIBLIOGRAPHY

- 2957 [49] J. Strait, E. McCluskey, T. Lundin, J. Willhite, T. Hamernik, V. Papadimitriou
2958 et al., *Long-baseline neutrino facility (lbnf) and deep underground neutrino*
2959 *experiment (dune) conceptual design report volume 3: Long-baseline neutrino*
2960 *facility for dune june 24, 2015*, 1601.05823. 56
- 2961 [50] DUNE DAQ, “dtp-firmware.”
2962 <https://gitlab.cern.ch/dune-daq/readout/dtp-firmware>, 2020. 71
- 2963 [51] DUNE DAQ, “dtp-simulation.”
2964 <https://gitlab.cern.ch/dune-daq/readout/dtp-simulation>, 2020. 74
- 2965 [52] DUNE DAQ, “dtpemulator.”
2966 https://github.com/DUNE-DAQ/dtpemulator/tree/fmlopez/filter_ana, 2022.
2967 74
- 2968 [53] J. McClellan and T. Parks, *A personal history of the Parks-McClellan algorithm*,
2969 *IEEE Signal Processing Magazine* **22** (2005) 82. 75
- 2970 [54] G. Turin, *An introduction to matched filters*, *IEEE Transactions on Information*
2971 *Theory* **6** (1960) 311. 78
- 2972 [55] J.W. Goodman, *Statistical Optics*, Wiley (1985). 80
- 2973 [56] B. Dwork, *Detection of a pulse superimposed on fluctuation noise*, *Proceedings of*
2974 *the IRE* **38** (1950) 771. 81
- 2975 [57] L. Wainstein and V. Zubakov, *Extraction of Signals from Noise*, Prentice-Hall
2976 (1962). 81
- 2977 [58] E.D. Church, *Larsoft: A software package for liquid argon time projection drift*
2978 *chambers*, 1311.6774. 84, 85
- 2979 [59] S.V. Stehman, *Selecting and interpreting measures of thematic classification*
2980 *accuracy*, *Remote Sensing of Environment* **62** (1997) 77. 98

BIBLIOGRAPHY

- 2981 [60] A.A. Taha and A. Hanbury, *Metrics for evaluating 3d medical image segmentation: analysis, selection, and tool*, *BMC Medical Imaging* **15** (2015) . 99
- 2982
- 2983 [61] J. Silk, K.A. Olive and M. Srednicki, *The Photino, the Sun and High-Energy Neutrinos*, *Phys. Rev. Lett.* **55** (1985) 257. 105
- 2984
- 2985 [62] M. Srednicki, K.A. Olive and J. Silk, *High-Energy Neutrinos from the Sun and Cold Dark Matter*, *Nucl. Phys. B* **279** (1987) 804. 105
- 2986
- 2987 [63] J.S. Hagelin, K.W. Ng and K.A. Olive, *A High-energy Neutrino Signature From Supersymmetric Relics*, *Phys. Lett. B* **180** (1986) 375. 105
- 2988
- 2989 [64] T.K. Gaisser, G. Steigman and S. Tilav, *Limits on Cold Dark Matter Candidates from Deep Underground Detectors*, *Phys. Rev. D* **34** (1986) 2206. 105
- 2990
- 2991 [65] N. Bernal, J. Martín-Albo and S. Palomares-Ruiz, *A novel way of constraining WIMPs annihilations in the Sun: MeV neutrinos*, *JCAP* **08** (2013) 011
- 2992
- 2993 [1208.0834]. 105, 106, 107, 113
- 2994 [66] C. Rott, J. Siegal-Gaskins and J.F. Beacom, *New Sensitivity to Solar WIMP Annihilation using Low-Energy Neutrinos*, *Phys. Rev. D* **88** (2013) 055005
- 2995
- 2996 [1208.0827]. 105, 112
- 2997 [67] C. Rott, S. In, J. Kumar and D. Yaylali, *Dark Matter Searches for Monoenergetic Neutrinos Arising from Stopped Meson Decay in the Sun*, *JCAP* **11** (2015) 039
- 2998
- 2999 [1510.00170]. 105
- 3000 [68] DUNE collaboration, *Searching for solar KDAR with DUNE*, *JCAP* **10** (2021) 065
- 3001 [2107.09109]. 105
- 3002 [69] G. Busoni, A. De Simone and W.-C. Huang, *On the Minimum Dark Matter Mass Testable by Neutrinos from the Sun*, *JCAP* **07** (2013) 010 [1305.1817]. 106
- 3003
- 3004 [70] V.A. Bednyakov and F. Simkovic, *Nuclear spin structure in dark matter search: The Zero momentum transfer limit*, *Phys. Part. Nucl.* **36** (2005) 131
- 3005
- 3006 [hep-ph/0406218]. 107

BIBLIOGRAPHY

- 3007 [71] A. Gould, *WIMP Distribution in and Evaporation From the Sun*, *Astrophys. J.* **321**
3008 (1987) 560. 108
- 3009 [72] J.N. Bahcall, M.H. Pinsonneault and S. Basu, *Solar models: Current epoch and*
3010 *time dependences, neutrinos, and helioseismological properties*, *Astrophys. J.* **555**
3011 (2001) 990 [[astro-ph/0010346](#)]. 110
- 3012 [73] T. Golan, J.T. Sobczyk and J. Zmuda, *NuWro: the Wroclaw Monte Carlo*
3013 *Generator of Neutrino Interactions*, *Nucl. Phys. B Proc. Suppl.* **229-232** (2012)
3014 499. 114
- 3015 [74] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for*
3016 *likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [[1007.1727](#)].
3017 115
- 3018 [75] T. Kaluza, *Zum Unitätsproblem der Physik, Sitzungsber. Preuss. Akad. Wiss.*
3019 *Berlin (Math. Phys.)* **1921** (1921) 966 [[1803.08616](#)]. 117
- 3020 [76] O. Klein, *Quantum Theory and Five-Dimensional Theory of Relativity. (In*
3021 *German and English)*, *Z. Phys.* **37** (1926) 895. 117
- 3022 [77] T. Appelquist, H.-C. Cheng and B.A. Dobrescu, *Bounds on universal extra*
3023 *dimensions*, *Phys. Rev. D* **64** (2001) 035002 [[hep-ph/0012100](#)]. 117
- 3024 [78] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The Hierarchy problem and new*
3025 *dimensions at a millimeter*, *Phys. Lett. B* **429** (1998) 263 [[hep-ph/9803315](#)]. 117
- 3026 [79] L. Randall and R. Sundrum, *A Large mass hierarchy from a small extra dimension*,
3027 *Phys. Rev. Lett.* **83** (1999) 3370 [[hep-ph/9905221](#)]. 117
- 3028 [80] G. Servant and T.M.P. Tait, *Is the lightest Kaluza-Klein particle a viable dark*
3029 *matter candidate?*, *Nucl. Phys. B* **650** (2003) 391 [[hep-ph/0206071](#)]. 117
- 3030 [81] H.-C. Cheng, K.T. Matchev and M. Schmaltz, *Radiative corrections to*
3031 *Kaluza-Klein masses*, *Phys. Rev. D* **66** (2002) 036005 [[hep-ph/0204342](#)]. 119

BIBLIOGRAPHY

- 3032 [82] M. Blennow, J. Edsjö and T. Ohlsson, *Neutrinos from WIMP annihilations using a*
3033 *full three-flavor Monte Carlo*, *JCAP* **01** (2008) 021 [[0709.3898](#)]. 119, 122
- 3034 [83] J. Edsjö, J. Elevant and C. Niblaeus, *WimpSim Neutrino Monte Carlo*. 119, 122
- 3035 [84] U. Haisch and A. Weiler, *Bound on minimal universal extra dimensions from*
3036 *anti-B → X(s)gamma*, *Phys. Rev. D* **76** (2007) 034014 [[hep-ph/0703064](#)]. 121
- 3037 [85] A. Freitas and U. Haisch, *Anti-B → X(s) gamma in two universal extra*
3038 *dimensions*, *Phys. Rev. D* **77** (2008) 093008 [[0801.4346](#)]. 121
- 3039 [86] C. Rott, D. Jeong, J. Kumar and D. Yaylali, *Neutrino Topology Reconstruction at*
3040 *DUNE and Applications to Searches for Dark Matter Annihilation in the Sun*,
3041 *JCAP* **07** (2019) 006 [[1903.04175](#)]. 124
- 3042 [87] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel et al.,
3043 *Scikit-learn: Machine learning in Python*, *Journal of Machine Learning Research*
3044 **12** (2011) 2825. 130
- 3045 [88] J. Kopp, V. Niro, T. Schwetz and J. Zupan, *DAMA/LIBRA and leptонically*
3046 *interacting Dark Matter*, *Phys. Rev. D* **80** (2009) 083502 [[0907.3159](#)]. 134
- 3047 [89] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2020**
3048 (2020) 083C01. 135
- 3049 [90] M. Beltran, D. Hooper, E.W. Kolb and Z.C. Krusberg, *Deducing the nature of dark*
3050 *matter from direct and indirect detection experiments in the absence of collider*
3051 *signatures of new physics*, *Phys. Rev. D* **80** (2009) 043509 [[0808.3384](#)]. 135
- 3052 [91] PLANCK collaboration, *Planck 2018 results. VI. Cosmological parameters*, *Astron.*
3053 *Astrophys.* **641** (2020) A6 [[1807.06209](#)]. 136