



Measuring the Muon Neutrino Magnetic Moment in the NOvA Near Detector

Róbert Králik

Supervisor: Dr. Lily Asquith

*A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy to the*

School of Mathematical and Physical Sciences
University of Sussex

In Brighton, United Kingdom

June 21, 2024

I hereby declare that I carried out this thesis independently, and only with the cited sources, literature and other professional sources.

I also declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Brighton, United Kingdom,

June 21, 2024

Róbert Králik

Acknowledgements

School of Mathematical and Physical Sciences, University of Sussex

DOCTORAL THESIS

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ABSTRACT

Measuring an enhanced neutrino magnetic moment would be a clear indication of physics beyond the Standard Model (BSM), shedding light on the correct BSM theory or the potential Majorana nature of neutrinos. It would manifest in the NOvA near detector as an excess of neutrino-on-electron elastic scattering interactions at low electron recoil energies. Leveraging an intense and highly pure muon neutrino beam, along with the finely segmented liquid scintillator detector technology specifically designed for electromagnetic shower separation, enables NOvA to achieve a potentially world-leading sensitivity in probing the effective muon neutrino magnetic moment. Despite facing statistical limitations stemming from the low cross section of the signal process, systematic uncertainties have a significant impact on this result. To address these challenges, the NOvA Test Beam experiment focuses on mitigating some of the largest systematic uncertainties within NOvA by investigating particle interactions and energy deposition in a small-scale replica NOvA detector. This thesis describes the calibration of the NOvA Test Beam detector, which is a crucial step in analysing the Test Beam data before they can be utilised to reduce NOvA systematic uncertainties.
COMMENT: Add final numbers for the analyses, also the POT and such

Keywords: neutrino NOvA electromagnetic testbeam calibration

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CHAPTER 1

Theory of neutrino physics

Neutrinos were first theoretically proposed by Wolfgang Pauli [1, 2] as very light electrically neutral particles with a half-integer spin and a possible magnetic moment [3]. They formed a crucial part of Enrico Fermi's successful theory of β decays [4, 5], which solidified their importance in particle physics even before their first experimental detection. Fermi's theory developed into the Standard Model (SM) of particle physics [6–8], which in its current form contains three generations of fermions. Each generation involves two leptons: one charged lepton and one neutrino, which has no mass, nor magnetic moment.

The SM is mathematically described by a Lagrangian, in which neutrinos are represented by a two-component left-handed chiral fields $\nu_{\alpha L}$, where $\alpha = e, \mu, \tau$ denotes the three neutrino generations, also called flavours [9–11]. Neutrino fields form weak isospin doublets $L_\alpha = \begin{pmatrix} \nu_{\alpha L} \\ \alpha_L \end{pmatrix}$ with their associated left-handed charged lepton fields α_L . Unlike for the charged leptons, there is no right-handed chiral neutrino singlet field in the SM. This means that neutrinos cannot obtain a mass term, since the fermion mass terms arise from the Higgs mechanism [12–14] via the Yukawa coupling of the fermion and the Higgs fields¹ [15], which requires a combination of left-handed and right-handed chiral fields [16]. Additionally, since neutrinos are massless in the SM, all the neutrinos are left-handed helicity particles, and all the antineutrinos ($\bar{\nu}$) are right-handed helicity antiparticles. Therefore, neutrinos and antineutrinos are mutually related not only by a charge conjugation, but by a combined Charge conjugation - Parity (CP) symmetry: $\nu \xleftrightarrow{CP} \bar{\nu}$.

The interaction terms for neutrinos can be separated into two parts, describing the Charged Current (CC) interactions with the W_μ gauge field and the Neutral Current (NC) interaction with the Z_μ gauge field, which are coupled to the W^\pm and Z^0 gauge

¹Further discussion about possible neutrino mass terms in Sec. 1.4

bosons respectively. Neglecting the non-neutrino components, the two neutrino interaction terms are [16]

$$\mathcal{L}_{\text{CC}}^{\text{SM}} = -\frac{g_w}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L} \gamma^\mu \alpha_L W_\mu^+ + \text{h.c.} \quad (1.1)$$

$$\mathcal{L}_{\text{NC}}^{\text{SM}} = -\frac{g_w}{2 \cos(\theta_W)} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z_\mu^0. \quad (1.2)$$

Here g_w is the weak coupling constant, θ_W is the Weinberg angle and γ^μ ($\mu = 0, 1, 2, 3$) are the four Dirac gamma matrices. The $\bar{\nu}_{\alpha L}$ denotes the Dirac adjoint of $\nu_{\alpha L}$ and **h.c.** the hermitian conjugate. These two terms describe all the possible **SM** neutrino interaction vertices. Figure 1.1 shows the **CC** and the **NC** interaction of neutrinos and antineutrinos and, in case of the **CC** diagram, can also be flipped around the vertical axis to show the production of neutrinos from the weak interaction (or decays) of leptons. They can also be rotated 90° to either show the annihilation, or the production of the neutrino-lepton (for **CC**), or neutrino-antineutrino (for **NC**) pairs.

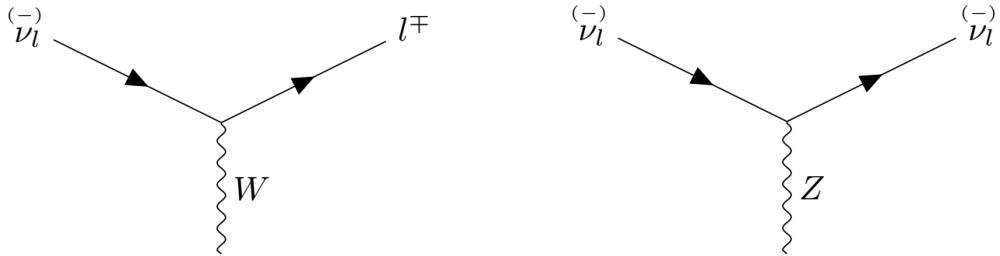


Figure 1.1: Neutrino interaction vertices in the **SM** via the weak charged currents (left) and the neutral currents (right).

1.1 Neutrino Production

Some of the most common neutrino and antineutrino production channels include nucleon transitions via **CC** weak interactions. Specifically, the transition of a neutron into a proton, either as the decay of a free neutron, or as the β^- decay for neutrons bound in nucleus, produces an electron and an electron antineutrino:

$$n \rightarrow p + e^- + \bar{\nu}_e. \quad (1.3)$$

The study of the electron spectrum from β^- decay was the reason Pauli proposed the existence of the neutrino [1]. Additionally, this channel is an abundant source of $\bar{\nu}_e$ from nuclear reactors, which were the first artificial sources of neutrinos, significantly increasing the flux of high energy neutrinos compared to the naturally occurring sources, thus enabling the first ever detection of a neutrino [17–19].

Similarly, the production of an electron neutrino together with a positron via the transition of a proton into a neutron can occur inside the nucleus either as the β^+ decay:

$$p \rightarrow n + e^+ + \nu_e, \quad (1.4)$$

or via the electron capture:

$$p + e^- \rightarrow n + \nu_e. \quad (1.5)$$

This channel occurs in stars and in the first phase of supernovae [16]. However, most supernovae neutrinos are created via a thermal pair production via **NC** interaction

$$e^- + e^+ \rightarrow \nu_\alpha + \bar{\nu}_\alpha \quad (1.6)$$

producing neutrinos and antineutrinos of all flavours. Neutrino pair production via the decay of Z^0 was studied in great detail [20], since the magnitude of the Z^0 decay width depends on the number of neutrino flavours (N_ν) that can couple to Z^0 , with the current best fit $N_\nu = 2.9840 \pm 0082$ [21]. Therefore, there should be exactly three light active neutrino flavours.

An abundant source of ν_μ and $\bar{\nu}_\mu$ is the decay of pions and muons

$$p + X \rightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \quad (1.7)$$

$$\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e), \quad (1.8)$$

which naturally occurs in Earth's atmosphere from the interaction of cosmic ray protons. It is notable, that if all the muons decay by the time they reach Earth's surface, the ratio of $(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e)$ should be exactly 2:1. The same process is also used in the modern accelerator-based neutrino sources, which use protons from accelerators with desired energies, impinge them onto a fixed target, and focus the resulting hadrons (mostly π) to achieve a highly pure and precise source of ν_μ or $\bar{\nu}_\mu$ [22, 23].

Heavier hadrons, such as kaons and charmed particles, can be produced from accelerated protons and other particles, either from natural or artificial origins. These hadrons then also produce neutrinos, including ν_τ and $\bar{\nu}_\tau$ if their energies are high enough [24, 25].

1.2 Neutrino Interactions

The interaction of neutrinos with matter can either be categorized based on the target, which is generally either an atomic electron or a nucleus, or the neutrino energy.

Neutrino-electron interactions occur either via elastic scattering, which result in a neutrino and an electron, or via the inverse muon (or tau) decay, which contains a muon (or tau) in the final state. Both of these interactions at the lowest order involve only free leptons and are very well understood theoretically. The elastic scattering has no energy threshold and can occur for any neutrino. On the other hand, due to the large difference between m_e and m_μ/m_τ , the inverse muon decay has an energy threshold of $E_{\nu_\mu} > 10.92 \text{ GeV}$, and the inverse tau decay $E_{\nu_\tau} > 3 \text{ TeV}$ [16, 26].

Neutrino-nucleus interactions can be, to an extent, approximated by the interaction of a neutrino with quasi-free nucleons inside the nucleus [27]. These interactions can be separated into different interaction channels based on what happens to the nucleon and therefore on the resulting particles. The interaction channels depend on the neutrino incident energy, as illustrated on the case of ν_μ CC interactions in Fig. 1.2.

At lower energies, neutrino-nucleon interactions result in the production of either a nucleon together with a neutrino in the case of NC elastic scattering, or a nucleon with a charged lepton in the case of CC Quasi-Elastic (QE) interactions. The CCQE interaction of an antineutrino on a proton

$$\bar{\nu}_\alpha + p \rightarrow n + \alpha^+ \quad (1.9)$$

is called the inverse β decay and was used for the first ever detection of neutrinos (specifically $\bar{\nu}_e$ from a nuclear reactor) [17, 18]. Together with the interaction of a neutrino on a neutron

$$\nu_\alpha + n \rightarrow p + \alpha^- \quad (1.10)$$

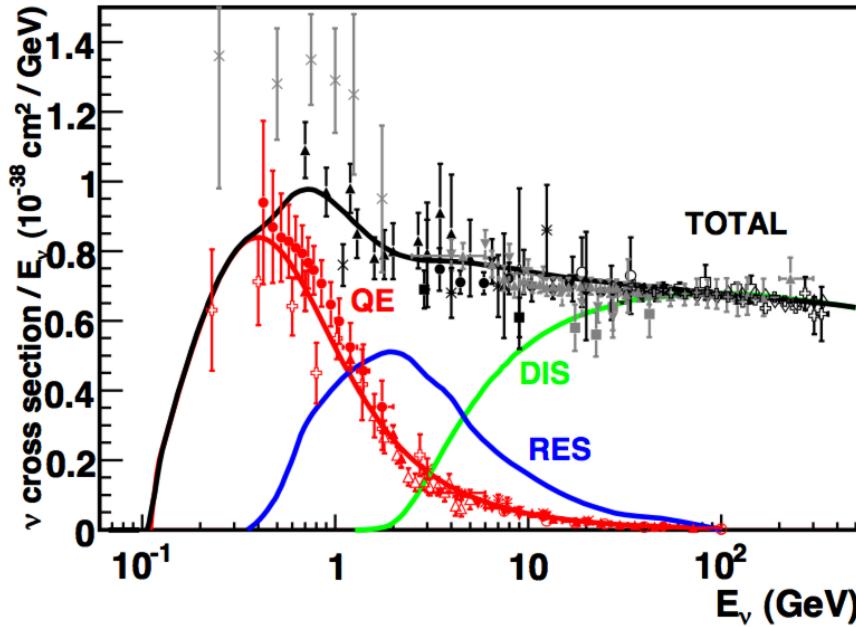


Figure 1.2: Neutrino CC cross sections on an isolated nucleon divided by the neutrino energy based on the interaction types: Quasi-Elastic (QE), Resonant baryon production (Res) and Deep Inelastic Scattering (DIS). Figure is from [28] and compares the measured data [27] and the prediction provided by the NUANCE generator [29].

they serve as fundamental processes for neutrino detection [24, 30, 31]. There is no low energy threshold for the ν_e CCQE interaction, however, there is a threshold for $\bar{\nu}_e$: $E_{\bar{\nu}_e} \gtrsim 1.8$ MeV and for the other neutrino and antineutrino flavours: $E_{\nu_\mu} \gtrsim 110$ MeV and $E_{\nu_\tau} \gtrsim 3.5$ GeV.

At higher energies, neutrinos can transfer enough energy to the outgoing nucleon to excite it into a resonant baryon, which then decays back into the original nucleon and into one or more additional particles. This Resonant baryon production (Res) has a threshold of about 270 MeV for ν_μ and can be distinguished by the presence of an additional π on top of the CCQE products, or, at higher energies, even of multiple additional π 's or other hadrons. Increasing the neutrino incident energy even higher means that neutrinos can start probing the quark contents of the individual nucleons in the Deep Inelastic Scattering (DIS), as can be seen in Fig. 1.2.

Even though the approximation of nuclei as collections of quasi-free nucleons is useful, it has been shown [32] there are important nuclear effects that have to be considered. For example the Fermi motion of nucleons and their binding inside the nucleus, or Pauli's exclusion principle resulting in nucleon energy levels [33]. Another important example is the two particle - two hole (2p2h) interaction [34–36],

which occurs when neutrinos interact with a correlated pair of nucleons and can significantly increase the [QE](#) cross section [33]. The [2p2h](#) interaction often occurs via the Meson Exchange Current (MEC), where the meson effectively propagates the interaction between the two correlated nucleons. Furthermore, the products of all of the aforementioned interactions can re-interact inside of the nucleus in Final State Interactions (FSIs), which can alter the particle content observed in the detector.

Additionally, if the total energy transferred to the nucleus is small neutrinos can interact with the entire nucleus coherently, where the contributions from each individual nucleon are added together. At low energies, neutrinos can interact via the Coherent Elastic ν -Nucleus Scattering (CEvNS) [37], which results in the excitation of the nucleus. At higher energies, neutrinos can interact via the Coherent π (COH π) production, which produces a single π without transferring much momentum to the nucleus. In case of the [NCCOH \$\pi\$](#) production the produced π is neutral and for the [CCCOH \$\pi\$](#) there is an additional charged lepton and the produced π is positive (negative) for (anti)neutrinos. As the produced π receives most of the transferred momentum from the neutrinos, it generally travels in the same direction as the initial neutrino and can be difficult to distinguish, especially from e and γ signals in a detector [33].

1.3 Neutrino Oscillation

The idea that neutrinos can oscillate originates as a possibility of transitions between neutrinos and antineutrinos [38, 39], analogically to the already known oscillations of $K^0 \leftrightarrow \overline{K^0}$. This was adapted to the oscillations between different neutrino flavours [40, 41], by considering that the flavour neutrino states ν_α , which are the eigenstates of weak interactions described in Eq. 1.1 and 1.2, are not identical to the mass neutrino states ν_k , which are the eigenstates of the vacuum Hamiltonian \mathcal{H}_0 :

$$\mathcal{H}_0 |\nu_k\rangle = E_k |\nu_k\rangle, k = 1, 2, 3, \dots, \quad (1.11)$$

with energy E_k . Instead, the neutrino flavour and mass eigenstates are related as

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle, \quad (1.12)$$

where U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, named after the authors [16, 42]. U is defined as unitary, which makes the inverse relation simply

$$|\nu_k\rangle = \sum_{\alpha} U_{\alpha k} |\nu_{\alpha}\rangle. \quad (1.13)$$

Using the Schrödinger equation

$$i \frac{d}{dt} |\nu_k(t)\rangle = \mathcal{H} |\nu_k(t)\rangle, \quad (1.14)$$

the evolution of massive neutrino states in vacuum ($\mathcal{H} = \mathcal{H}_0$) can be described by plane waves

$$|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle. \quad (1.15)$$

The energy of a neutrino state with mass m_k and momentum \vec{p}

$$E_k = \sqrt{\vec{p}^2 + m_k^2} \quad (1.16)$$

can be approximated as

$$E_k \xrightarrow{m^2 \ll p^2 \approx E^2} E + \frac{m_k^2}{2E}, \quad (1.17)$$

assuming small neutrinos masses and for ultra-relativistic neutrinos [16]. Additionally, as it is generally easier to measure the distance neutrinos travel (L), rather than the time (t), and given the notation $c \equiv 1$, where c is the speed of light in vacuum, it is common to interchange $L \leftrightarrow t$.

Given the orthogonality of neutrino states, $\langle \nu_k | \nu_j \rangle = \delta_{kj}$ and $\langle \nu_{\alpha} | \nu_{\beta} \rangle = \delta_{\alpha\beta}$, and using Eq. 1.15, 1.12 and 1.13, the amplitude of the oscillation (transition) from $\nu_{\alpha} \rightarrow \nu_{\beta}$ over the ‘baseline’ L can be written as

$$A_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L) \equiv \langle \nu_{\beta} | \nu_{\alpha}(L) \rangle = \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k L} \quad (1.18)$$

and the probability as

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L) = |A_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L)|^2 = \sum_{k,j} U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* e^{-i(E_k - E_j)L}. \quad (1.19)$$

Using Eq. 1.17 and by defining the neutrino mass splitting (also called the mass

squared difference) as

$$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2, \quad (1.20)$$

the oscillation probability can be expressed as

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L) = \sum_{k,j} U_{\alpha k}^* U_{\beta j} U_{\alpha j} U_{\beta k}^* e^{-i \frac{\Delta m_{kj}^2 L}{2E}}. \quad (1.21)$$

So far no assumption has been made as to the specific number of neutrino mass or flavour states. However, as was described above in Sec. 1.1, from the decay of Z^0 we know there are probably exactly three active neutrino flavour states, ν_e , ν_μ and ν_τ . Consequently, it is common to also consider exactly three neutrino mass states. This is often called the three neutrino paradigm. Therefore, the **PMNS** matrix can be written as [16]:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \\ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1.22)$$

where $c_{ij} \equiv \cos \theta_{ij}$ and $s_{ij} \equiv \sin \theta_{ij}$. The matrix is parametrized using three mixing angles θ_{12} , θ_{13} , and θ_{23} and one phase², often denoted δ_{CP} . This phase describes a possible **CP** symmetry violation in neutrino oscillations, which would result in a difference between the neutrino and antineutrino oscillation probabilities.

When neutrinos pass through matter, their evolution changes due to coherent elastic **CC** and **NC** scattering. However, since the **NC** scattering affects all neutrino flavours equivalently, it does not have any effect on neutrino oscillations. Additionally, as electrons are the only charged leptons present in matter, only the relative difference between the **CC** interactions of ν_e and of the other flavours needs to be considered. The effective interaction potential of neutrinos passing through matter

²If neutrinos are Majorana particles, they can have two additional phases, which however do not enter into neutrino oscillation probabilities

with an electron density N_e can be written as

$$V_{CC} = \pm \sqrt{2} G_F N_e. \quad (1.23)$$

Here G_F is the Fermi coupling constant and the plus or minus sign is for neutrinos or antineutrinos respectively. The electron density (and therefore the interaction potential) can change along the neutrino path, as it does in the Sun, which can resonantly increase the probability of oscillations, as described by the Mikheyev-Smirnov-Wolfenstein (MSW) effect [43, 44]. However, in accelerator based experiments, where neutrinos only pass through the surface of the Earth, the N_e can be approximated as a constant.

The effect of neutrinos passing through matter on oscillation probabilities can be expressed as shifts to mixing angles and to mass squared differences, proportional to the V_{CC} . Since the matter effect differs for neutrinos and antineutrinos, it needs to be carefully considered especially for the δ_{CP} measurement, which relies on the comparison of neutrino to antineutrino oscillations [16].

The first experimental signs of neutrino oscillations appeared as an apparent deficit of solar neutrinos compared to their predicted flux [30]. However, due to low confidence in the prediction of the solar neutrino flux, no conclusion could have been drawn. Similarly, experiments measuring atmospheric neutrinos [45–48] saw a disagreement between the measurement and the prediction for the $\nu_\mu : \nu_e$ fraction of the atmospheric neutrino flux. This *atmospheric neutrino anomaly* was finally resolved by the Super-Kamiokande (SK) experiment [49], reporting the first experimental evidence for neutrino oscillations. The *solar neutrino anomaly* was resolved shortly after by the Sudbury Neutrino Observatory (SNO) experiment [50], which compared the NC rate, unaffected by neutrino oscillations, to the rate of CC neutrino interactions. This was proof that solar neutrinos oscillate without reliance on the model of the Sun. This result also confirmed the importance of accounting for the matter effect in neutrino oscillations, especially for the oscillation of solar neutrinos, due to the large matter density in the Sun.

The difference between the frequency of solar neutrino oscillations and that observed in atmospheric neutrinos proves that there are at least two mass splittings governing neutrino oscillations. As a result, there must be at least three separate

neutrino mass states, with at least two of them possessing non-zero masses. This is in direct contradiction to the SM and is to-date the only laboratory-based observation of physics Beyond Standard Model (BSM) [51].

Currently, the three neutrino paradigm of oscillations between three neutrino flavour states via three neutrino mass states is well established [52, 53]. The magnitudes of both the neutrino mass splittings and of two mixing angles, θ_{12} and θ_{13} , are measured within 3%. The third mixing angle θ_{23} is measured to be close to the maximum mixing value of 45°. However, there are three main questions yet to be determined for neutrino oscillations [51]:

1. What is the sign of the larger neutrino mass splitting? Is the electron neutrino made up of the lightest neutrino mass states (normal ordering), or the heaviest (inverted ordering)?
2. Is $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ$? These two options determine the $\nu_\mu : \nu_\tau$ relative contributions to the neutrino mass states and are also referred to as the upper and the lower octant respectively.
3. Is there CP violation in neutrino oscillations? What is the value of δ_{CP} ? If neutrinos oscillate differently than antineutrinos, this could be an important part of the matter-antimatter asymmetry in the Universe.

All three of these questions are jointly investigated in the current Long Baseline (LBL) accelerator neutrino oscillation experiments, namely the NuMI Off-axis ν_e Appearance (NOvA) [54] and the Tokai to Kamioka (T2K) [55] experiments. Both use precise ν_μ and $\bar{\nu}_\mu$ beams, affected by the matter effect, and compare the rates of ν_μ and $\bar{\nu}_\mu$ disappearance and ν_e and $\bar{\nu}_e$ appearance to constrain neutrino oscillation parameters [51]. The same methods will be used in the next generation LBL neutrino oscillation experiments, namely the Deep Underground Neutrino Experiment (DUNE) [56] and the Hyper-Kamiokande (HK) [57] experiment, which should give the final answers to all three neutrino oscillation questions [51].

1.4 Neutrino Mass

The absolute values of neutrino masses are currently not known and cannot be directly measured in neutrino oscillation experiments. However, results from experiments measuring the kinematic distribution of β decays [58], or from cosmology [59], currently set a limit for each neutrino mass to $< 1 \text{ eV}$. This is several orders of magnitude smaller than the charged fermion masses, suggesting that **BSM** theories which introduce neutrino masses should have a different mechanism for their generation than the one used for the other fermions [52]. Furthermore, in order to introduce neutrino masses into the **SM**, it is necessary to either add new fields, break the renormalizability of the **SM** Lagrangian, or do both [42]. Also, massive neutrinos can no longer be described by Weyl spinors

The most straight-forward solution, often called the *minimally extended SM*, is to add the missing right-handed chiral neutrino fields, which would enable neutrino mass generation through Yukawa couplings with the Higgs field. These right-handed fields would however be singlets under all the **SM** gauge symmetries and would therefore not participate in any of the **SM** interactions. Neutrinos created by these fields are called *sterile* and could potentially mix with the *active* neutrinos via neutrino oscillations. There are however a few issues with the minimally extended **SM**. Since the mass generation mechanism is the same as for the charged fermions, there is no theoretical explanation for the relative smallness of neutrino masses. There is also currently no experimental confirmation of oscillations between active and sterile neutrinos [52], although there are some possible indications [60, 61]. Additionally, having to add new fields by hand makes the **SM** an incorrect description of reality even at low energies. This is an issue, as it is generally believed that **SM** is at least a good low energy effective theory of a more complex general theory and only breaks down at some New Physics (NP) threshold value Λ_{NP} [62].

Adding new non-renormalizable terms to the **SM** Lagrangian, which are suppressed by this **NP** scale as $1/\Lambda_{NP}$, would maintain the renormalizability (and validity) of the **SM** at energies well below Λ_{NP} [62]. It is possible to create such a term using only the existing **SM** fields and preserving the **SM** gauge symmetries, which after spontaneous symmetry breaking generates neutrino mass terms. Additionally, three of the newly generated masses are also suppressed as $1/\Lambda_{NP}$ and belong to

mostly left-handed (active) fields, while the rest are very large ($\sim \Lambda_{NP}$) and belong to mostly sterile neutrinos, which are therefore also called Heavy Neutral Leptons (HNLs). This is called the see-saw mechanism [63] and provides a natural explanation for the smallness of neutrino masses. Furthermore, the large masses of HNL make them more likely to avoid experimental detection. However, neutrinos with masses produced by this mechanism all have to be Majorana particles [64].

If neutrinos are Majorana particles, they are equivalent to their own antiparticles (via charge conjugation). The particles described as antineutrinos in the previous sections are however still different to neutrinos, although for Majorana neutrinos they only differ by parity transformation. Therefore, Majorana neutrinos and antineutrinos can be seen as two different spin states of a two-state ‘Majorana particle’. This is in contrast to neutrinos being Dirac particles, which have four independent states (neutrino/antineutrino, each with two independent spin states), same as the other fermions and as in the minimally extended SM [16]. It is possible for neutrinos to be Majorana particles as they have no electric charge. However, all the other additive quantum numbers, including the total lepton number, must vanish for Majorana neutrinos as well. This means that Majorana neutrinos can effectively annihilate with each other, violating the total lepton number by two units.

A sure way of finding out whether neutrinos are Majorana particles or not is an observation of a neutrino-less double β decay [62]. This is currently a subject of an extensive experimental investigation without a concrete conclusion [52]. Neutrinos being Majorana particles does not affect neutrino oscillations, however, other measurements could probe the nature of neutrinos, or possible theories BSM, such as the measurements of the possible neutrino magnetic moment [51].

CHAPTER 2

The NOvA experiment

The NOvA [65] experiment is a long-baseline neutrino oscillation experiment based at the Fermi National Accelerator Laboratory (Fermilab) [66]. NOvA receives an off-axis ν_μ and $\bar{\nu}_\mu$ beam from Fermilab’s Neutrinos from the Main Injector (NuMI) neutrino source (Sec. 2.1) and measures ν_e or $\bar{\nu}_e$ appearance and ν_μ or $\bar{\nu}_\mu$ disappearance between its two highly active and finely segmented detectors (Sec. 2.4) [67].

The capability to measure both ν_e and the $\bar{\nu}_e$ appearance, coupled with a significant matter effect induced by its long baseline, allows NOvA to address some of the most important questions in neutrino physics to date, such as the neutrino mass ordering, the octant of θ_{23} , and the possible CP symmetry violation in the neutrino sector [54, 67–70]. NOvA data also enables measurements of θ_{13} , θ_{23} and $|\Delta m_{32}^2|$ [67], measurements of neutrino differential cross sections in the Near Detector (ND) [71–74], constraints on possible sterile neutrino models [75, 76], monitoring for supernova neutrino activity [77, 78], searches for magnetic monopoles [79], and constraints on the neutrino electromagnetic properties (this thesis). Using two functionally identical detectors mitigates the dominant systematic uncertainties of neutrino oscillation measurements, described in Sec. 2.8.

NOvA started taking data in February 2014 and is expected to run through 2026 [80], or until Fermilab begins redirecting its efforts towards the startup of the upcoming DUNE experiment [81].

2.1 The Neutrino Beam

The neutrino beam for NOvA comes from the Fermilab-based NuMI neutrino source [82]. The schematic description of NuMI is shown in Fig. 2.1, starting on the left hand side with 120 GeV protons from the Main Injector (MI), part of the Fermilab accelerator complex. The proton beam is divided into 10 μs long pulses, with $\sim 5 \times 10^{13}$

Protons On Target (POT) per spill every ~ 1.3 s long cycle time, resulting in a proton beam power of ~ 800 kW (current record 959 kW [83]), with upgrades currently underway to surpass 1 MW [84].

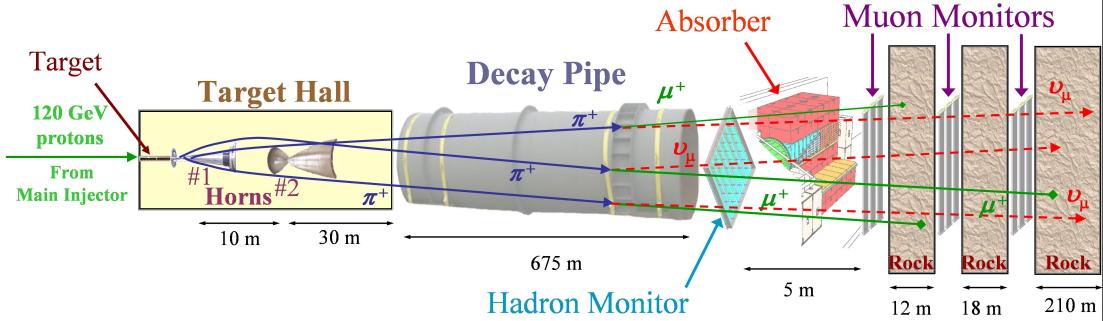


Figure 2.1: The NuMI neutrino beam starts on the left hand side with protons from the MI impinged on a graphite target producing mainly pions and kaons. These are then focused and charge-selected by two focusing horns, after which they decay inside the decay pipe into a high-purity ν_μ or $\bar{\nu}_\mu$ beam. The residual hadrons are stopped and monitored in the hadron absorber and the remaining muons are recorded with muon monitors and absorbed inside the rock. Figure from [82].

The proton beam passes through a collimating baffle before hitting a ~ 1.2 m-long (equal to about two interaction lengths) graphite target [85], producing hadrons, predominantly pions and kaons [82]. These are then focused and selected by two parabolic magnetic ‘horns’. The focused hadrons pass through a 675 m-long decay pipe filled with helium to create a low density environment for hadrons to propagate and decay in flight into either neutrinos or antineutrinos. High energy hadrons that do not decay in the decay pipe are absorbed within a massive aluminium, steel, and concrete hadron absorber and monitored with a hadron monitor. The leftover muons are ranged out in dolomite rock after the absorber and monitored using three muon monitors. The hadron and muon monitors are ionization chambers, used to monitor the quality, location and relative intensity of the beam.

Using a positive current inside the horns focuses positively charged particles, which then decay into neutrinos, and removes negatively charged particles. Reversing the horn current focuses negatively charged particles, which decay into antineutrinos, and defocuses positively charged particles. The neutrino mode is therefore called Forward Horn Current (FHC) and the antineutrino mode is called Reverse Horn Current (RHC). The composition of the neutrino beam for both these modes at the NOvA ND is shown in Fig. 2.2, displaying the very high purity of the ν_μ or $\bar{\nu}_\mu$

component in the **FHC** ro **RHC** beam respectively [82].

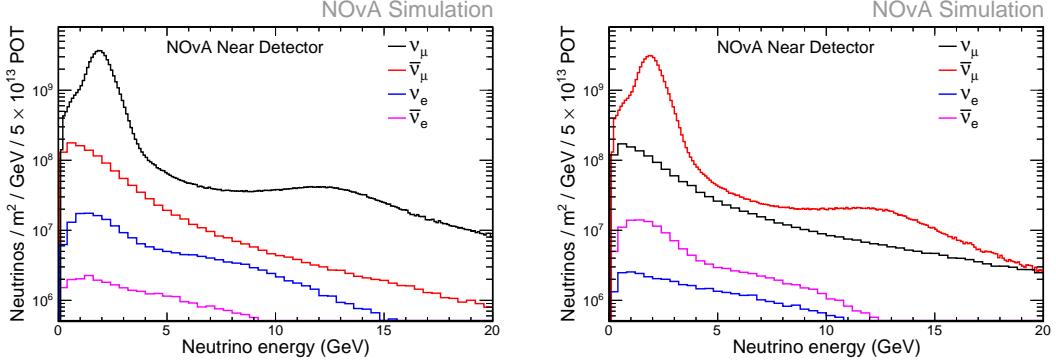


Figure 2.2: The components of the neutrino beam at the **NOvA ND** per one **NuMI** spill in the **FHC** regime shown on the left and the **RHC** regime on the right. The ν_μ ($\bar{\nu}_\mu$) composition in the **FHC** (**RHC**) regime is 93.8% (92.5%), with a wrong sign contribution of 5.3% (6.6%) and only 0.9% (0.9%) contamination by ν_e ($\bar{\nu}_e$), showing the high purity of ν_μ and $\bar{\nu}_\mu$ in the neutrino beam for **NOvA**. Beam composition values calculated for neutrinos with energies between 1 – 5 GeV. Figures are from internal **NOvA** repository [86].

The resulting neutrino beam energy distribution is peaked at ~ 7 GeV with a wide energy band. However, thanks to the kinematics of the dominant pion decay, by placing the **NOvA ND** and Far Detector (FD) 14.6 mrad ($\approx 0.8^\circ$) off the main **NuMI** beam axis, **NOvA** achieves a narrow band neutrino flux peaked at 1.8 GeV [54, 87], as can be seen in Fig. 2.3. Using an off-axis neutrino flux increases the neutrino beam around 2 GeV about 5-fold compared to the on-axis flux and narrow-band peak enhances background rejection for the ν_e appearance analysis [87].

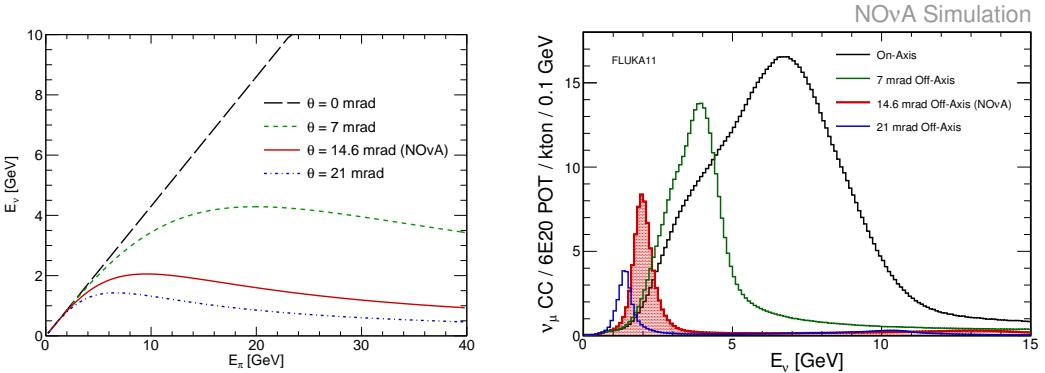


Figure 2.3: (Left) Dependence of the neutrino energy on the parent pion's energy and (right) neutrino energy distribution for an on-axis beam and three different off-axis beam designs. The case for **NOvA** is shown in red and results in a narrow neutrino energy distribution around 2 GeV, with limited dependence on the parent pion's energy. Figure from [87]

2.2 The NOvA Detectors

The two main NOvA detectors are the ND, located in Fermilab ~ 1 km from the NuMI target and ~ 100 m under ground, and the FD, located ~ 810 km from Fermilab at Ash River in north Minnesota, partially underground with a rock overburden [87]. NOvA also operated a detector prototype called Near Detector on the Surface (NDOS), which was used for early research and development of detector components and analysis [68]. Additionally, NOvA operated a Test Beam detector, described in detail in Sec. ??.

The scales of the ND and FD are shown in Fig. 2.4.

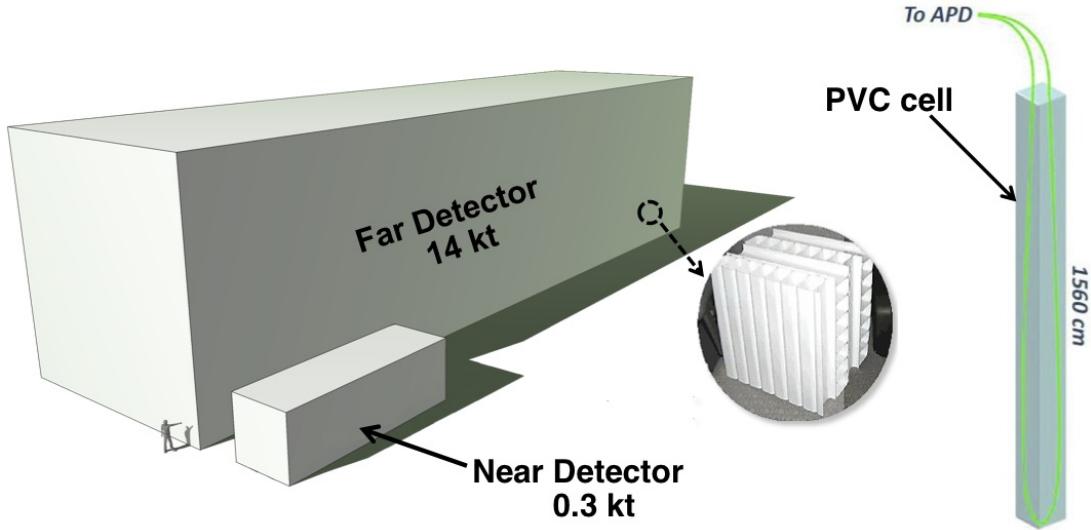


Figure 2.4: Schematic description of the scale and composition of the NOvA ND and FD. The inset shows a photo of the orthogonal planes made out of PVC cells. An example of a FD cell containing liquid scintillator and a looped WLS fibre attached to an APD is shown on the right [88].

All NOvA detectors are highly segmented, highly active, functionally identical tracking calorimeters made up of Polyvinyl chloride (PVC) cells filled with liquid scintillator. Each cell is a long rectangular cuboid with depth of 5.9 cm and width of 3.8 cm (with some variations), with cell length extending to the full width/height of each detector, which is ~ 4.1 m for the ND and ~ 15.6 m for the FD [87]. An example of a FD cell is shown on the right of Fig. 2.4.

Cells are connected side-by-side into a 16 cell-wide extrusions with 3.3 mm-wide walls between cells and 4.9 mm-wide walls on the outsides of the extrusions. The first and last cell of each extrusion are ~ 3 mm narrower than the rest of the cells. Two extrusions are connected side-by-side to form a 32 cell-wide module, with each

module having a separate readout (see Sec. 2.3). In the **FD**, 12 modules are connected side-by-side to form one plane of the detector. In the **ND** only 3 modules make up a plane. Planes are positioned one after another, alternating between vertical and horizontal orientation, and grouped into diblocks, each containing 64 planes. The **FD** contains 14 diblocks, totalling 896 planes, whereas the **ND** contains 3 diblocks totalling 192 planes. The **ND** also contains a Muon Catcher region, positioned right after the active region, consisting of 22 planes of the normal **NOvA** detector design, 2 modules high and 3 modules wide, sandwiched with 10 steel plates to help range out muons mainly from the ν_μ charged current interactions [68, 87].

The **NOvA** coordinate system is centred with $(0, 0, 0)$ in the centre of the first plane, relative to the beam direction. The x axis runs from left to right when facing the detector, y axis from bottom to top and z axis runs perpendicular to the planes along the beam direction.

Each cell is filled with a liquid scintillator consisting of mineral oil with 4.1% pseudocumene as the scintillant [89]. Each cell contains a single wavelength shifting fibre with double the length of the cell, looping at one end and connecting to the readout at the other. The **PVC** walls of the cells are loaded with highly reflective titanium dioxide, with light typically bouncing off the **PVC** walls ~ 8 times before being captured by the Wavelength Shifting (WLS) fibre [87].

The final dimensions of the **FD** are $15.6\text{ m} \times 15.6\text{ m} \times 60\text{ m}$ with a total mass of 14 kT and for the **ND** the dimensions are $3.8\text{ m} \times 3.8\text{ m} \times 12.8\text{ m}$ with a mass of about 0.3 kT [80]. The active volume, consisting only of the liquid scintillator without the **PVC** structure, makes up about 70% of the total detector volume [87].

The **NOvA** detectors are specifically designed for electromagnetic shower identification, with a radiation length of 38 cm, which amounts to ~ 7 planes for particles travelling perpendicular to the detector planes [68]. This is particularly useful to distinguish electrons from π^0 s.

We can calculate the minimum energy an electron needs to have to cross one cell (5.9 cm) of the **NOvA** detector by using the measured scintillator density 0.86 g/cm^3 [90], which gives us the required range of $\sim 5\text{ g/cm}^2$. Comparing this to measured values for the electron range [91] in the continuous slowing down approximation in a Polyethylene (approximation of the **NOvA** scintillator [92]), gives us an estimate of

the lowest detectable electron energy as $E_e \gtrsim 10$ MeV.

2.3 Readout and Data Acquisition

The signal from the [WLS](#) fibres is read out by an Avalanche Photodiode (APD), converting the scintillation light into electrical signal, with a high quantum efficiency of $\sim 85\%$ and a gain of 100 [87]. An example [APD](#) is shown in Fig. 2.5. Both ends of each fibre correspond to a single readout channel and are connected to one of the 32 pixels on the [APD](#), organized in four rows of 8 pixels, with each [APD](#) reading out signal from one module. To maximise the signal to noise ratio, the [APDs](#) are cooled to -15°C by a thermoelectric cooler, with heat carried away by a water cooling system.

The combination of the [APD](#) quantum efficiency and the light yield, determined by the [PVC](#) reflectivity and the scintillator and [WLS](#) fibre responses, result in a signal requirement of at least 20 Photo Electron (PE) in response to minimum ionizing radiation at the far end of the [FD](#) cell.

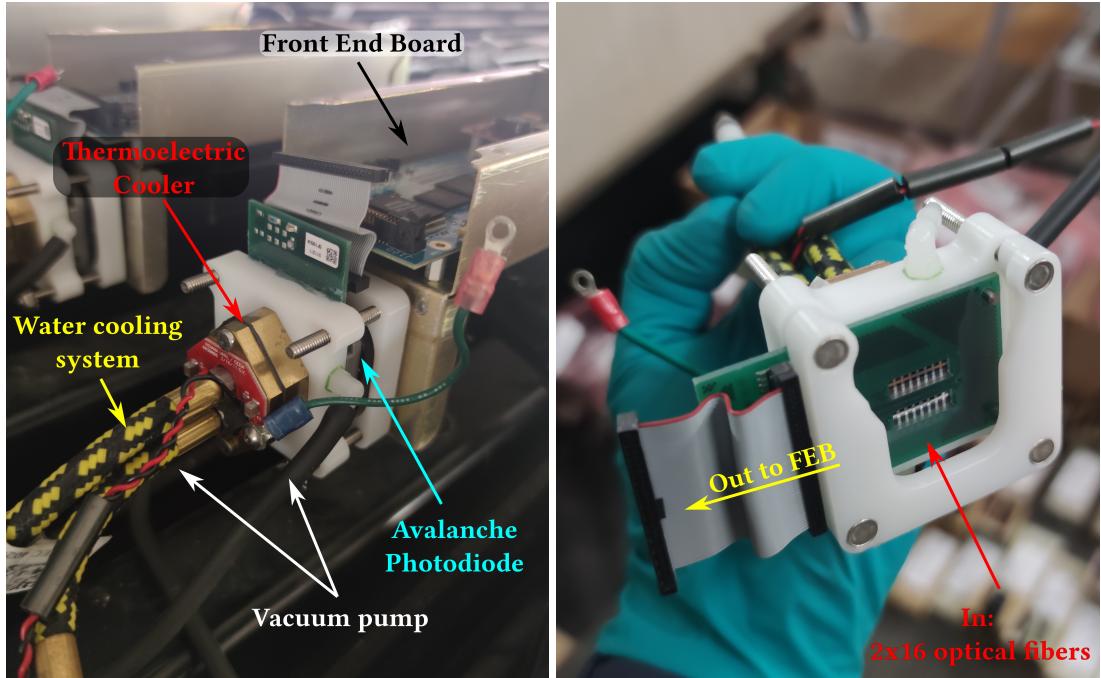


Figure 2.5: The modules with [APDs](#) for [NOvA](#) mounted on top of the detector on the left picture, and shown from the bottom on the right. The individual components of the module are described. The left picture shows a disconnected ribbon cable and ground cable, which are normally connected to the front end board.

Each [APD](#) is connected to a single Front End Board (FEB), shown in Fig. 2.6. The FEB amplifies and integrates the [APD](#) signal, determines its amplitude and arrival

time, before passing it to the Data Acquisition (DAQ) system. On the FEB the APD signal is first passed to a custom NOvA Application-Specific Integrated Circuit (ASIC), which is designed to maximize the detector sensitivity to small signals. ASICs amplify, shape and combine the signal, before sending it to an Analog-to-Digital Converter (ADC). The combined noise from the APD and the amplifier is equivalent to about 4 PEs, which, compared to an average PE yield from the far end of the FD cell of 30, results in a good signal and noise separation [87]. The digitized data from an ADC is sent to a Field Programmable Gate Array (FPGA), which extracts the time and amplitude of the ADC signals, while subtracting noise based on a settable threshold. The FPGAs employ multiple correlated sampling methods to reduce noise and improve time resolution of the signal [93].

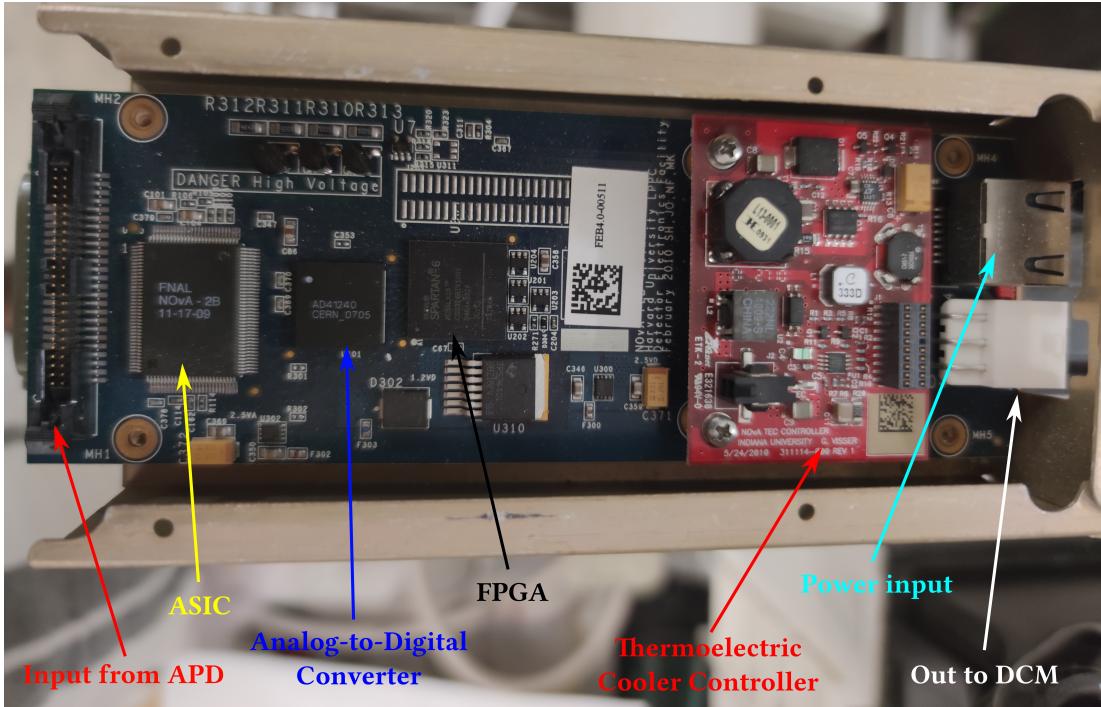


Figure 2.6: An example of a NOvA FEB with individual components labelled.

All of the NOvA front end electronics (APDs and FEBs) are operated in a continuous readout mode, without requiring any external triggers [87]. Due to higher detector activity during beam spills, the ND FEBs work at a higher frequency of 8 MHz, whereas the FD FEBs suffice with 2 MHz sampling frequency [93].

Data from up to 64 FEBs are concentrated in a Data Concentration Module (DCM), which concatenates and packages the data into 5 ms time slices, before sending it to the buffer nodes. DCMs are also connected to the timing system and pass a single

unified timing measurement to the [FEBs](#) to maintain synchronization across the detector [93].

The buffer nodes cache the data for at least 20 seconds while receiving information from the trigger system. Each trigger uses a time window based either on the time of the [NuMI](#) beam spill, on a periodic interval for monitoring and for the readout of cosmic events, or on one of the activity-based data-driven triggers [93]. Data that fall within any of the trigger windows are sent to a data logger system, where they are merged to form events, before being written to files for offline processing and sent to an online monitoring system. Files are organized based on a unique combination of run and subrun numbers, with runs corresponding to data taking periods with constant detector conditions and limited to either 64 subruns or 24 hours. Subruns are delineated either by a 2 GB file size constraint or a 1-hour timeout limit [94].

The detectors are continuously monitored to ensure data stability and quality. Subruns with suboptimal detector conditions or with events failing basic quality criteria are flagged as ‘bad’ and recorded in a ‘bad runs list’ [94]. Additionally, individual readout channel are assessed on a per-subrun basis, with those with too high or too low hit rates marked as ‘bad’ [95]. Both the ‘good runs’ list and the ‘bad channel’ maps are used to inform event processing and during simulation to emulate real detector conditions.

2.4 Simulation

To extract neutrino oscillation parameters, or to test a hypothesis, [NOvA](#) uses a series of simulations to make predictions according to various physical models [96]. The simulation chain can be divided into four parts: simulation of the neutrino beam, simulation of neutrino interactions within the [NOvA](#) detectors, simulation of cosmic particles interacting in the [NOvA](#) detector and simulation of the detector and readout response.

To simulate the neutrino beam, [NOvA](#) uses a simulation based on the GEANT4 v9.2.p03 [97] Monte Carlo (MC) event generator with a detailed model of the [NuMI](#) beamline [98], as described in Sec. 2.1. The simulation starts with the 120 GeV/c [MI](#) protons interacting within the long carbon target and producing hadrons, mainly

π , K and secondary protons. This is followed by transport and possible further interaction of hadrons within the focusing system, until finally ending with hadron decays producing the neutrino beam.

To account for the inherently imprecise theoretical models used in GEANT4, [NOvA](#) uses the Package to Predict the Flux ([PPFX](#)) to incorporate external measurements of yields and cross sections of hadron interactions inside the target and the other [NuMI](#) materials into the neutrino beam prediction [99]. The current version of [PPFX](#) is limited by the results available during its creation and only corrects the most frequent interactions while assigning conservative systematic uncertainties to the rest (see Sec. 2.8). For the most common π , K and p production, [PPFX](#) uses the NA49 measurements [100–102] of 158 GeV/c protons interacting on a thin (few percent of interaction length) carbon target. To expand the kinematic coverage, [PPFX](#) uses a few data points from Barton et al [103] for the π production and K/π ratios from the Main Injector Particle Production (MIPP) [104] experiment for the production of K . These results have to be scaled to the 20 – 120 GeV/c incident proton moment seen throughout [NuMI](#) using the FLUKA [105, 106] [MC](#) generator.

There are two new experiments that measure the production and interaction of hadrons on various targets and incident energies, specifically designed to improve the prediction of neutrino beams. The most impactful measurements from the NA61 experiment are of the 120 GeV/c protons on a thin carbon target [107–109], of the hadron incident interactions on various materials [110], and of the 120 GeV/c protons on a [NuMI](#) replica target [111]. The Fermilab-based EMPHATIC experiment [112] is currently analysing a broad range of hadron production and secondary and tertiary interaction measurements for neutrino beam prediction with a significant involvement of [NOvA](#) and [DUNE](#) collaborators.

The output of the neutrino beam simulation is passed to the simulation of neutrino interactions inside the detectors, which is done with the GENIE v3.0.6 [113] neutrino [MC](#) generator. GENIE allows users to choose the particular models for different types of neutrino interactions and particle propagation within the nucleus, as well as possible tunes to external measurements. The four main interaction modes in GENIE are the [QE CC](#) scattering, the [Res](#), the [DIS](#), and the [COH \$\pi\$](#) production. The special case of the [2p2h](#) interaction via [MEC](#) and the [FSI](#) inside a nucleus are also considered. The

initial state of the nucleus is represented by a local Fermi gas in the [QE](#) and [2p2h](#) models, while a global relativistic Fermi gas is used for all other processes. All of these are set by the Comprehensive Model Configuration (CMC), which is currently N1810j0000 for [NOvA](#). Additionally, [NOvA](#) adds a costume tune to the [NOvA](#) ν_μ [CC](#) data for a better constraint of the [CCMEC](#) interactions. [NOvA](#) also uses a set of external π interaction measurements to constrain the [FSI](#) model. Table 2.1 shows the list of models and tunes for different interaction modes in [NOvA](#) [54].

Table 2.1: Models and tunes used in the [NOvA](#) simulation of neutrino interactions.

| Interaction | Model | Tune |
|-----------------|------------------------------|--|
| CCQE | València [114] | External $\nu - D$ data [115] |
| CCMEC | València [116, 117] | NOvA ν_μ CC data |
| Res & COH π | Berger-Sehgal [118, 119] | External $\nu - A$ data |
| DIS | Bodek-Yang [120, 121] | External $\nu - A$ data |
| FSI | Semi-classical cascade [122] | External $\pi - {}^{12}C$ data |

Since the [FD](#) is on the surface [NOvA](#) also uses a simulation of cosmic rays generated with the [MC](#) Cosmic-Ray Shower Generator (CRY) [123]. The simulated cosmic muons are also used to calibrate [NOvA](#) detectors [99].

Particles that are created from neutrino interactions and cosmic rays are propagated through the [NOvA](#) detectors using the GEANT4 v10.4.p02 [97], which outputs the energy deposited in the scintillator. This is then passed to a custom [NOvA](#) software of the light model [99], which calculates the amount of scintillation light produced for the deposited energy based on a Poisson distribution. The scintillation light production is parametrized using the Birks-Chou model [124], which corrects for the recombination in organic scintillators at high deposited energies. The scintillator light yield and the inherent production of the Cherenkov light, which can affect the light readout, are tuned to [NOvA](#) data [72]. The light collection by the [WLS](#) fibres, its transport to the [APDs](#), and the [APD](#) response use a parametrized simulation, as the [NOvA](#) cells and their readout are generally the same across the detectors [99]. The simulation of the readout electronics is done by another custom [NOvA](#) parametrized model, which accounts for random noise in the readout electronics and outputs true events in the same format as the real data.

Due to the high neutrino rate in the [ND](#), there are neutrinos interacting in the surrounding rock creating particles, mainly muons, that make it to the detector and

act as background. However, since only a few ‘rock muons’ make it into the detector, it would be very time consuming to run a simulation which includes the rock around the **ND** for every neutrino. Instead, **NOvA** creates a separate simulation that includes the surrounding rock and then overlays these results into the nominal **NOvA** simulation chain to match the **NuMI** neutrino rate [99].

2.5 Data Processing and Event Reconstruction

Both data and simulation events for all **NOvA** detectors are passed through the same event reconstruction and particle identification algorithms. The reconstruction was specifically developed with the ν_e appearance search in mind, focusing on identifying the ν_e **CC** signal against the ν_μ **CC** and **NC** backgrounds. Each **NOvA** detector has to deal with different challenges, with multiple neutrinos interacting during one beam spill in the **ND**, and a large cosmic background in the **FD** [125].

The output from the **DAQ** system for each channel is called a *raw hit*. Hits are grouped into 550 μs -long windows and passed to an offline reconstruction chain [125]. Reconstruction starts by grouping hits into *slices* based on their proximity to other hits in both time and space [126]. Slices are designed to ideally contain only a single neutrino interaction event.

For events that produce hadronic and electromagnetic showers, reconstruction first identifies straight lines through major features using a modified Hough transform [127], representing particle directions. These lines are passed to the Elastic Arms algorithm [128] to identify *vertex* candidates from their intersection points. Hits are then clustered into *prongs*, which are collections of hits with a start point, based on the vertex, and a direction, using a k-means algorithm called FuzzyK [129, 130]. Here ‘fuzzy’ means that each hit can belong to multiple prongs. Prongs are first created separately for each view (also called 2D prongs) and then, if possible, view-matched into 3D prongs (from here on referred to as prongs) [125]. Figure 2.7 shows an example of a simulated electron shower, where the reconstructed vertex is shown as a red cross and the prong as a red shaded area. The prong groups together all the hits that are part of the shower, while removing the background hits, shown in grey.

For particles that are represented by tracks rather than showers (especially muons),

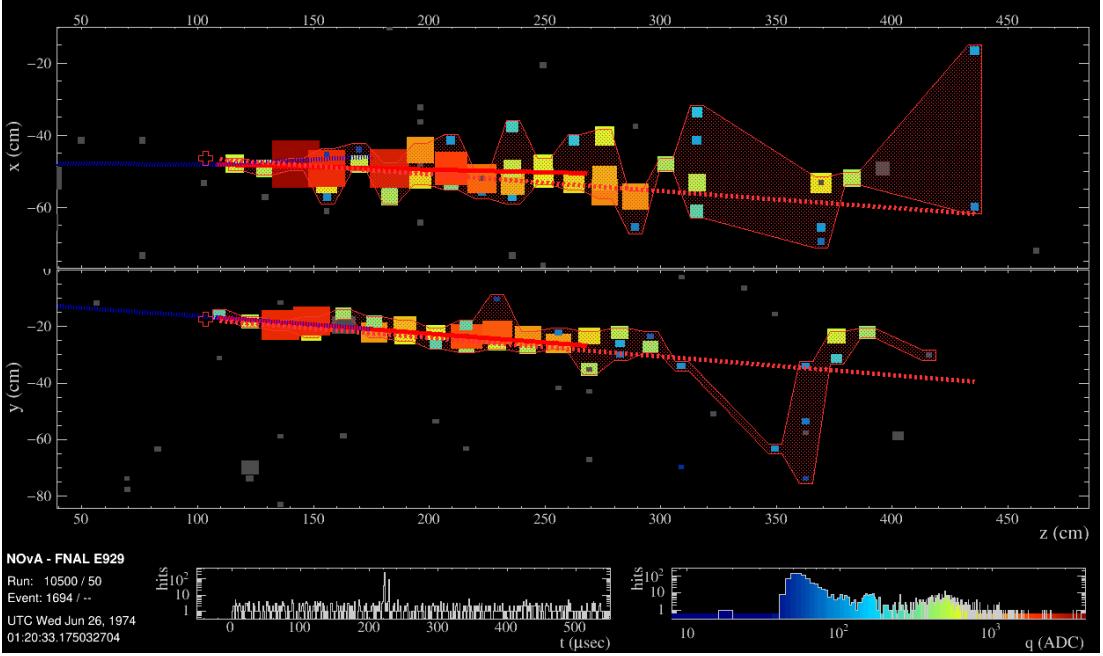


Figure 2.7: Reconstruction of a simulated single electron event in the NOvA ND. The red cross is the reconstructed vertex, the shaded area shows the cluster of hits into a prong and the dotted red line shows the estimated shower direction. The blue dotted line shows the true direct of the scattering neutrino and the solid red line the true momentum of the scattered electron. Figure from internal NOvA database [131].

the reconstruction takes the slice hits and forms ‘Kalman tracks’ based on a Kalman filter [132]. In addition to the start point and the direction, which exist also for prongs, tracks also contain information on the vector of trajectory points that make up the track and on the end point - and therefore on the track length. A parallel tracking algorithm takes in the Elastic Arms vertex and the Fuzzy-K prongs and forms Break Point Fitter (BPF) tracks [133, 134], using a model of Coulomb scattering and energy loss. BPF tracks also contain an information on the particle 4-momenta based on various particle assumptions, most notably the muon assumption. For cosmic particles, mostly muons, NOvA uses another track reconstruction algorithm, called ‘window cosmic track’ [135]. It uses a sliding 5 plane-long window, in which it fits a straight line to the recorded hits. The window starts from the end of the detector and then slides forward and repeats the fitting process until all hits are processed. This way it accounts for possible Coulomb scattering of cosmic muons. The intersection of each cosmic track with the edge of the detector (or extrapolation of the track to the edge of the detector) is reconstructed as the ‘cosmic ray vertex’.

To identify individual particles and remove backgrounds, NOvA uses several Ma-

chine Learning (ML) algorithms, outputs of which are used in combination with the information from classical reconstruction algorithms for Particle Identification (PID). The most common topologies for particles interacting in NOvA detectors are shown in Fig. 2.8. Muons are easily identifiable as single long tracks which decay into an electron (or positron) if stopping inside of the detector. Both electrons and π^0 's produce electromagnetic showers, but thanks to the low-Z composition and high granularity of the detector, there is a gap between the interaction vertex and the electromagnetic shower for the π^0 .

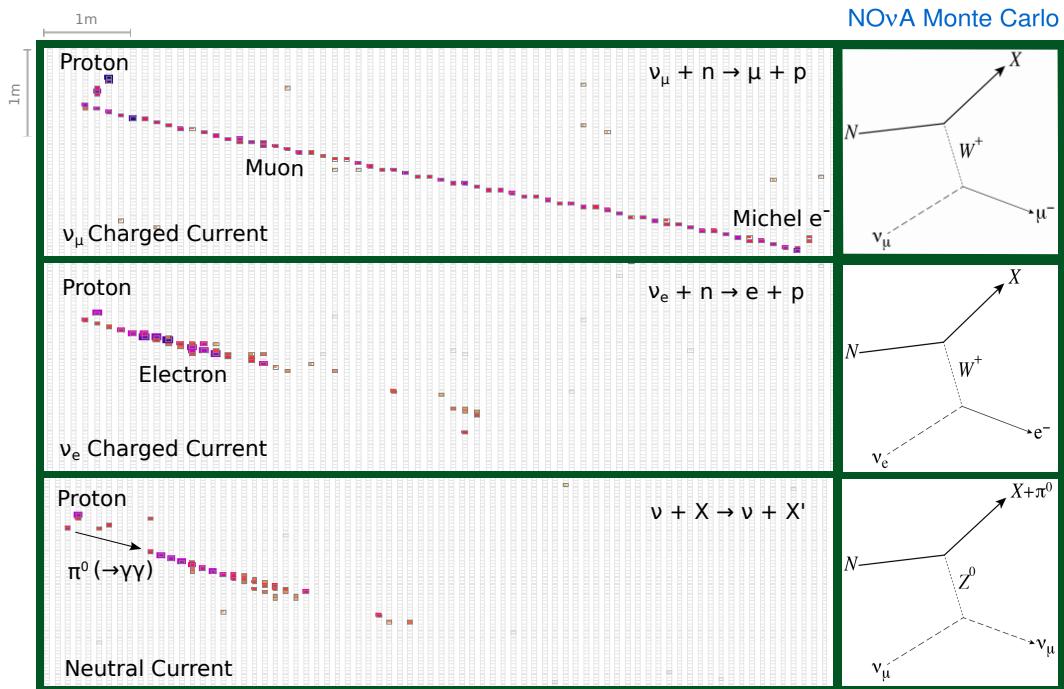


Figure 2.8: Different event topologies as seen in the NOvA detectors with corresponding Feynman diagrams [125]. Each event is a simulated 2.15 GeV neutrino interacting in a NOvA detector producing a 0.78 GeV proton and a second 1.86 GeV particle depending on the interactions type. The figure shows only one view and the colouring represents the deposited energy.

One of the ML algorithms that NOvA employs is a Convolutional Neural Network (CNN) based on the GoogLeNet [136] architecture named Convolutional Visual Network (CVN) [137]. When it is applied to identify entire events it is called *EventCVN* and uses slice hits to classify interactions into one of the five categories: ν_e , ν_μ , ν_τ , NC, or cosmic. The same architecture, but applied to the Fuzzy-K prongs, is called *ProngCVN* [138], and is used to identify what particles the prongs most likely correspond to. This assignment is useful in calculation of prong energy, as described in

Sec. 2.7. Another [ML](#) algorithm is specifically designed for identifying muons and is based on a Boosted Decision Tree (BDT). It is called Reconstructed Muon Identifier (ReMId) [132] and uses the reconstructed Kalman tracks as inputs.

2.6 Detector Calibration

The energy deposited within [NOvA](#) detectors is represented by the peak [ADC](#) values for each cell the particle passed through, obtained from the readout electronics, as described in Sec. 2.3. The conversion of the peak [ADC](#) values into physical units of energy requires calibrating the [NOvA](#) detectors [139], while accounting for the attenuation of light along the [WLS](#) fibres, or for differences between individual cells. The purpose of calibration is to calculate a conversion factor from $\text{ADC} \rightarrow \text{MeV}$ for every part of the detector, so that the same energy deposited anywhere and at any time, is recorded as the same value of the reconstructed energy.

[NOvA](#) uses cosmic ray muons for calibration due to their abundance in the [NOvA](#) detectors and their consistent energy deposition. To calculate the absolute energy scale, [NOvA](#) selects a subsample of muons stopping inside of the detectors when they are almost exactly Minimum Ionising Particle (MIP) and therefore have a well understood energy deposition. The cosmic muons are collected using a periodic trigger with the same length as the beam trigger, whilst removing events with timestamps overlapping with the beam spill window. The simulation of cosmic muons is created using the [CRY](#) [123] [MC](#) generator, as outlined in Sec. 2.4.

Cosmic muon tracks are reconstructed using the window cosmic track algorithm described in Sec. 2.5. The selection of well reconstructed cosmic tracks requires that at least 80% of all hits from the reconstructed slice contribute to the track [92]. Each track must have at least 2 hits in both the x and y views and the difference in the number of planes the track crossed between the views must be at most 10% of the total number of planes. Also, the plane where each track starts or stops in one view must be within 3 planes of the start or stop plane in the other view. Additionally, since tracks that do not cross many planes tend to not be reconstructed very well, the extent of each track in the z direction must be at least 70 cm and tracks must have at least 20% of their total track direction in the z axis. Tracks with on average more

than 6 cells per plane and with path lengths through the cell larger than 10 cm are removed for the same reason. Furthermore, all the reconstructed tracks must start at most 10 cm from the edge inside of the detector and stop at most 10 cm outside of the detector. Lastly, tracks with trajectory points far away from each other are also removed. The selection of stopping muons for the absolute energy scale relies on identifying Michel electrons, which are produced by decaying muons at the end of their tracks, as can be seen on the top panel of Fig. 2.8.

Since the energy deposited in a cell is proportional to the distance the particle travels through the cell, the input variable for calibration is the deposited energy divided by the path length through the cell PE/cm . To ensure the path length is well calculated, all hits used in calibration must satisfy the so-called ‘tricell’ condition, shown in Fig. 2.9. This means that for each calibration hit, there must be a corresponding hit in both of the surrounding cells in the same plane for the same track. The path length can then be calculated simply from the height of the cell and the angle of the reconstructed track. In case there is a bad channel in a neighbouring cell (right side of Fig. 2.9), this channel is ignored and the tricell condition looks one cell further [139]. If the tricell condition fails, the hit can still pass the ‘z tricell’ condition, which is a longitudinal equivalent of the tricell condition and requires a hit in both the neighbouring planes in the same view and with the same cell number. The ‘z tricell’ hits are saved separately and may be used if there are no hits satisfying the original tricell condition. This is especially useful for the cells on the edge of the detector, which fail the tricell condition due to only having one neighbouring cell.

The calibration conversion factor from the signal recorded by the detector readout to the deposited energy can be expressed by as

$$E_{dep} \text{ [MeV]} = \text{Signal [ADC]} \times S_d \times TS_{d,i}^{\text{CALIB}} \times R_{d,i}(t) \times A_d(t). \quad (2.1)$$

The calibration scale therefore consists of four separate and complementary factors: the Scale (S_d), the Threshold and Shielding correction ($TS_{d,i}$), the Relative calibration ($R_{d,i}(t)$) and the Absolute calibration ($A_d(t)$), all described below. Each part is calculated for each detector separately, as indicated by the subscript d . The threshold and shielding correction is only used during calibration and is omitted when applying the calibration results. The relative and absolute calibrations are calculated for

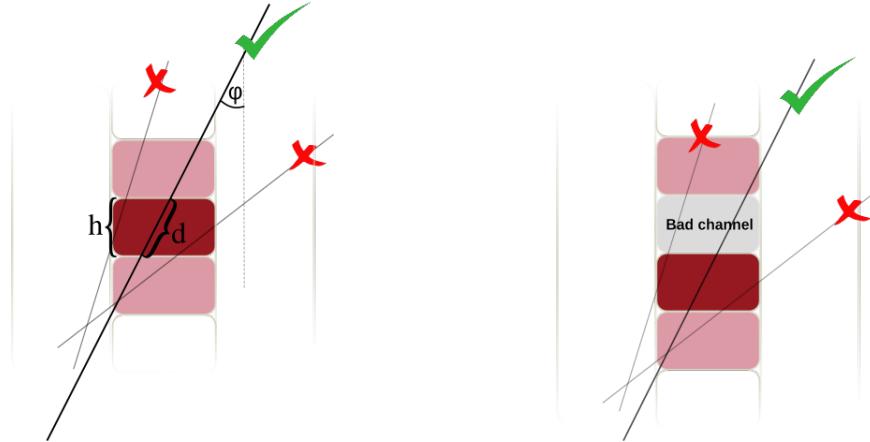


Figure 2.9: Illustration of the tricell condition. Only the hits with two surrounding hits in the same plane are used in the [NOvA](#) calibration, as shown on the left plot. This is to ensure a good quality of the path length (d) reconstruction, which is calculated from the known cell height (h) and the reconstructed track angle (φ). In case the hit is next to a bad channel, as shown on the right plot, the bad channel is ignored and the tricell condition requires a hit in the next cell over.

each time period separately to account for possible changes in the energy deposition throughout the time, possibly caused by the ageing of the scintillator oil, or of the readout electronics. The time periods are either determined by a fixed time interval, or by running conditions separated by significant changes to the readout or the [DAQ](#) systems, including the summer shutdown.

The threshold and shielding correction and the relative calibration calculate a calibration factor for each position within the detector to account for variations caused by the attenuation of light as it travels through the [WLS](#) fibres, or by differences between individual cells. This is expressed with a subscript i in Eq. 2.1. For data, the position of a hit in the detector is described by the plane number, cell number and the position within the cell (w). w is calculated as the projection of the cosmic track to the central cell axis and its value is equivalent to the x axis (y axis) coordinate of the projection for the horizontal (vertical) cells, with the 0 value at the centre of the cell [139].

For simulation, the calibration does not use the plane number to determine the position within a detector, as by construction all detector planes should have the same readout. This significantly reduces the requirements for the number of events that need to be simulated, reconstructed, and calibrated, especially for the [FD](#) with 896 planes. However, in reality there are some variations in the detector response be-

tween individual planes, caused by different *brightness* qualities of the fibres, zipped or twisted fibres, different qualities of the scintillator, possible air bubbles, and potentially other factors. To include these differences in simulation without having to simulate every cell individually, all the cells are divided into 12 equally populated Fibre Brightness (FB) bins based on the uncorrected average response in the center of that cell, as shown in Fig. 2.10. These FB bins describe the relative differences in the detector response between individual cells [140].

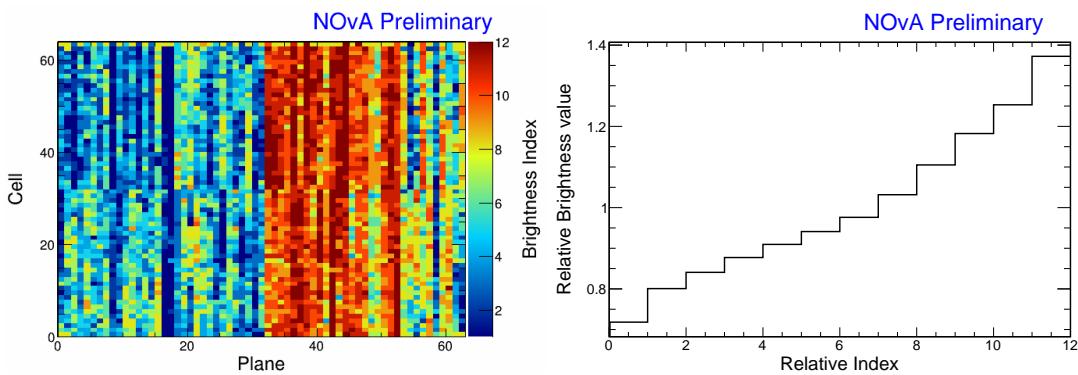


Figure 2.10: Distribution of the NOvA detector cells into 12 brightness bins (left plot), each representing a relative difference in energy response (right plot) due to different brightnesses of the fibres, scintillators, or readout. This is an example from the NOvA Test Beam detector, described in Sec. ??, where the left side of the detector (planes 1-32) has clearly lower response relative to the right side of the detector (planes 33-64).

2.6.1 Scale

The scale calibration factor from Eq. 2.1 is a simple conversion from the peak ADC value into the number of PEs. This factor only depends on the APD gain (which was different in the beginning of NOvA data taking) and on the FEB type (different between detectors, as described in Sec. 2.3).

2.6.2 Threshold and Shielding Correction

The threshold and shielding correction accounts for two assumptions, which hold true in most cases in NOvA, but fall short for some hits at the bottom of the detector, or far away from the readout, especially for the FD [139].

The first assumption is that the ADC response to the photon signal is linear, which is mostly true except close to the APD threshold. Energy deposited far away from the

readout may produce photons that get attenuated enough to be shifted below the threshold. However, due to natural fluctuations of the number of photons created by the energy deposition, the same deposited energy may also produce photons that would make it over the threshold, therefore making it appear that the actual deposited energy was higher than in reality, introducing a bias to the calibration. The threshold correction is calculated using simulation, as the ratio between the mean of the Poisson distribution of the true number of the created PE ($\text{PE}_{Poisson\lambda}$) and the number of the ‘reconstructed’ PE seen by the APD (PE_{Reco}).

The second assumption is that the spectrum of cosmic muons is uniform within each detector. Again, this is generally true, but breaks down in the FD, which is big enough for the top of the detector to shield the bottom of the detector and therefore affect the energy distribution. The shielding correction is calculated from simulation as a ratio between the expected deposited energy if the particle was a MIP (E_{MIP}), which is estimated from simulation for the NOvA scintillator as $E_{MIP} = 1.78 \text{ MeV/cm}$ and the true deposited energy (E_{true}).

The total threshold and shielding correction is calculated for simulated events in each cell, FB bin and w as

$$TS_i = \frac{\text{PE}_{Poisson\lambda}}{\text{PE}_{Reco}} \frac{E_{MIP}}{E_{True}}. \quad (2.2)$$

To ensure that the correction changes smoothly across each cell position, the final correction is calculated as a fit to the mean correction value along w in each cell and FB bin.

2.6.3 Relative Calibration

The main goal of the relative calibration is to correct for the attenuation of the scintillator light as it travels through the WLS fibre to the readout. The attenuation in each cell is estimated by performing an ‘attenuation fit’ to the mean response in PE/cm, as shown in Fig. 2.11. The relative calibration scale is then calculated as the ratio between the average response in PE/cm across the entire detector (can differ between detectors) and the result of the attenuation fit in each particular position within the detector. The response after applying the relative calibration scale is expressed as

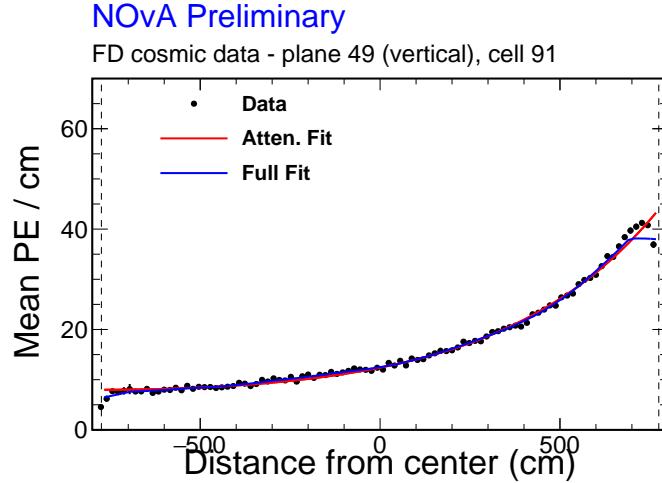


Figure 2.11: Example attenuation fit for a single cell in the NOvA FD across its full length, as shown by dashed vertical lines. The red line shows the initial exponential fit and the blue line shows the full fit after the LOWESS correction, both described in text. Figure from [141].

Corrected Photo Electronss (PECorrs). Since the relative calibration scale is calculated for each cell independently, it effectively corrects for the relative differences between detector cells as well as for the attenuation. Therefore, the resulting distribution of PECorr/cm should be uniform across the detector, especially along the plane, cell and w [139].

The first step to do the attenuation fit is to create ‘attenuation profiles’ for each cell. Attenuation profiles are profile histograms of mean detector response over the path length through the cell, in the units of PE/cm , along the position within the cell. An example attenuation profile is shown in Fig. 2.11 as black dots. The threshold and shielding correction described in Sec. 2.6.2 is applied to the attenuation profiles before doing the attenuation fit, which consists of two steps.

1. The first step is a three-parameter exponential fit according to

$$y = C + A \left(\exp \left(\frac{w}{X} \right) + \exp \left(-\frac{L+w}{X} \right) \right), \quad (2.3)$$

where y is the fitted response, L is the length of the cell and C , A and X are the fitted parameters representing the background, attenuation scale and attenuation length respectively. An example of the exponential fit is shown as a red curve in Fig. 2.11.

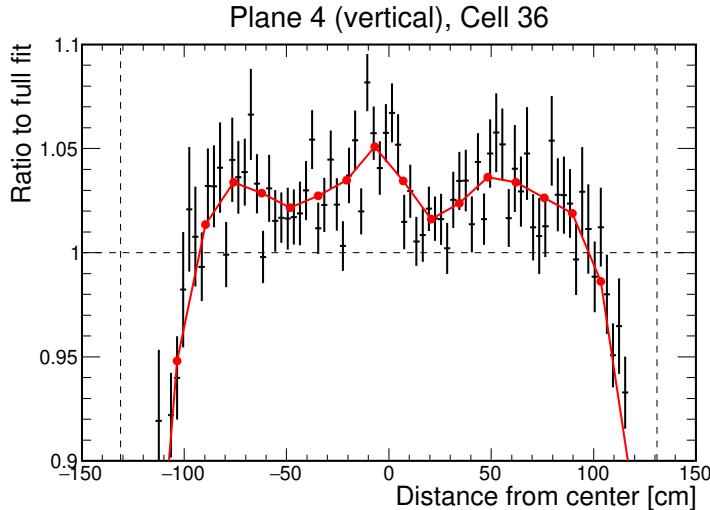


Figure 2.12: Example [LOWESS](#) correction for the residual differences after the exponential part of the attenuation fit of the [NOvA](#) relative calibration. This is an example for a single cell in the [NOvA](#) Test Beam detector with black points showing the residual differences and red line the [LOWESS](#) correction, both described in text.

2. The second step is the smoothing out of residual differences between the exponential fit and the original distribution with the Locally Weighted Scatter plot Smoothing (LOWESS) method, shown in Fig. 2.12. The residual differences get evened out by creating a smooth distribution of 20 locally weighted points across the length of each cell. The result of the [LOWESS](#) correction is then combined with the exponential fit into the full attenuation fit, shown as a blue line in Fig. 2.11.

Even after applying the [LOWESS](#) correction, there are sometimes large differences between the attenuation fit and the fitted response. This is usually caused by a small number of events in that cell, common for cells at the edge of the detector. To ensure a good quality of the attenuation fit, the total χ^2 between the attenuation fit and the fitted response is calculated and only cells with the final $\chi^2 \leq 0.2$ are counted as *calibrated*. Cells with $\chi^2 > 0.2$ are ignored in further processing and marked as *uncalibrated*.

2.6.4 Absolute Calibration

The absolute calibration only uses hits from muons stopping inside of the detector, in a track window 1 – 2 m from the end of their tracks. This is when they are approximately [MIP](#) and their energy deposition is well understood. Additionally, hits at the

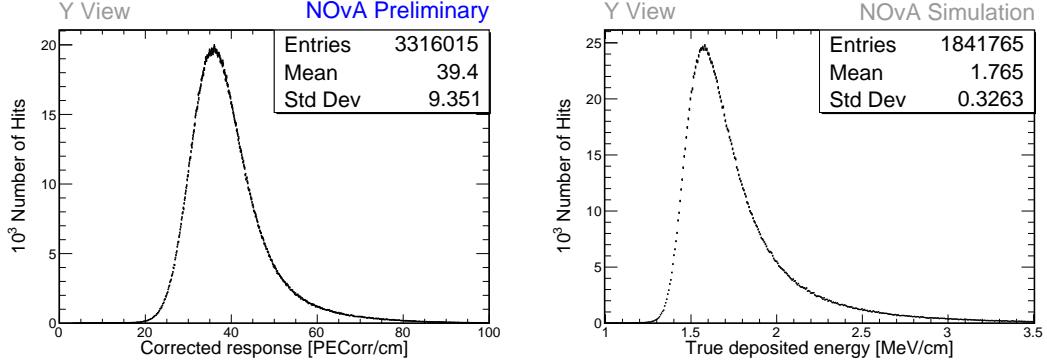


Figure 2.13: The absolute energy scale is calculated as the ratio between the simulated mean true deposited energy (right) and the mean reconstructed energy response (left) for selected stopping muons in each view and each data period or simulation.

edges of each cell are removed to mitigate the effects at the end of the [WLS](#) fibres and the lower number of events at the edge of the detector [92].

First, the relative calibration results are applied to the selected stopping muon hits to get a distribution of the corrected detector response in [PECorr](#)/cm, as shown on the left of Fig. 2.13. The mean of this distribution is called the *reconstructed Muon Energy Unit* ([MEU](#)) and is calculated separately in each of the two views, and in each time period or version of simulation. Analogously, the mean of the true deposited energy in MeV/cm from simulation, shown on the right of Fig. 2.13, is called the *true MEU*. The absolute energy scale (the absolute calibration scale) is then the ratio between the true and the reconstructed [MEU](#) value, where both the [MEU](#) values are taken as a simple average over the two views

$$\text{Absolute Energy Scale} = \frac{\text{MEU}_{\text{True}} \text{ [MeV/cm]}}{\text{MEU}_{\text{Reco}} \text{ [PECorr/cm]}}. \quad (2.4)$$

The values of the absolute energy scales for each data period and simulation, as well as the results of the attenuation fit, are saved in a set of lookup tables, which are then used any time a hit is recorded in the [NOvA](#) detector and processed and reconstructed with the [NOvA](#) algorithms described above.

2.7 Energy Estimation

The deposited energy from detector calibration (Sec. 2.6) is only the first step in estimating the neutrino energy (E_ν) required for the main [NOvA](#) analyses.

For the ν_μ disappearance analysis, the ν_μ energy is measured as the sum of the muon energy and the energy of the hadronic shower [54]. The muon energy is identified from the length of its track, without the need of the calibration results. The energy of the hadronic shower is estimated from simulation as a fit to the 2D distribution of the true ν_μ energy minus the reconstructed muon energy, versus the visible (not corrected for the dead material) deposited energy of the hadronic system [138].

For the ν_e appearance analysis, the ν_e energy is calculated using a quartic fit to the 2D distribution of the electromagnetic versus the hadronic calorimetric energies, both corrected for the energy deposition in the dead material (PVC cells) [138]. The dead material correction is currently just a simple scaling of the deposited energy from calibration for all particles and is calculated from the measurement of the π^0 mass peak in the NOvA ND. This correction is correct only for electromagnetic showers and is not directly applicable to hadronic showers. The fit to determine the ν_e energy keeps the normalization of both the electromagnetic and the hadronic energies free, so the exact value of the dead material correction is not important. It is however used in other, non-neutrino oscillation analyses.

2.8 Systematic Uncertainties

Systematic uncertainties in NOvA analyses arise from the imperfect knowledge on the individual components of the NOvA experiment, or from the known shortcomings of the prediction used to extract the measured parameters. Even though different analyses in NOvA need to consider different systematic uncertainties and their effect on the results varies, there are a few commonalities across all NOvA analyses that are explained below.

Both the 3-flavour [54] and the sterile neutrino [76] oscillation analyses in NOvA use the ND to constrain the FD prediction, which significantly reduces the effect of the neutrino beam and interaction prediction systematic uncertainties. On the other hand, these are the leading sources of systematic uncertainties for the ND-only analyses, such as the cross section analyses [71–74]. The leading systematic uncertainty for the neutrino oscillation measurements comes from the detector calibration uncertainty. Significant uncertainties for all NOvA measurements also come from the

neutron modelling, the detector simulation and the muon energy estimation. There are other sources of systematic uncertainties that are not mentioned here as they are sub-dominant, or specific to a certain analysis.

TO DO: Mention here how are the systematics used - shifting the spectra and doing the full analysis ‘separately’ for each shifted prediction. Then we compare these shifted predictions with the nominal one

The systematic uncertainty on the prediction of the neutrino beam consists of two parts: the hadron production and the beam focusing uncertainties [99]. The uncertainty for hadron production is estimated by the **PPFX** (describe in Sec. 2.4) using the multi-universe technique. Here we create 100 **PPFX** universes in which the inputs from the external measurements used to constrain the hadron production are randomly floated around their central values within their respective systematic uncertainties. Parts of the hadron production that are not constrained by external measurements are given a conservatively large systematic uncertainty. The beam focusing systematic uncertainties account for the uncertainties on the horn and target positions, the horn current, the beam position on the target, the beam spot size, and the effect of Earth’s magnetic field in the beam pipe. *TO DO: Describe the beam PCA and how can we limit the beam uncertainty*

TO DO: Describe the neutrino interaction modelling systematic uncertainties [3fl technote] There’s in total 77 neutrino interaction related systematic uncertainty knobs that are randomly varied during fitting. Only the ones that contribute are actually accepted during a fit.

TO DO: Describe the detector modelling systematic uncertainties

The systematic uncertainty arising from the simulation of the detector response can be divided into the scaling of the overall light level inside the simulation and of the Cherenkov light component.

The systematic uncertainty on the Cherenkov light scaling factor is calculated by profiling over the factor during the light model tune and taking the 3σ confidence interval around the best fit value as the systematic uncertainty, resulting in a $\pm 6.2\%$ relative uncertainty on the Cherenkov scaling factor. Similarly, the light level uncertainty was calculated by profiling over the light level scaling factor, resulting in a $\pm 5\%$ relative uncertainty on the light level scaling factor.

TO DO: *Describe the neutron uncertainty - only if I decide I need it*

There are three systematic uncertainty arising from the calibration procedure: the absolute energy scale, the shape (relative residual variations along the cell, especially on its edges) and detector ageing.

Other standard candles are used to set the systematic uncertainty on the absolute energy scale. This is calculated as the difference between the data and simulation reconstructed energy for beam muons and protons in the ND, rock muons in the ND, π^0 measurement in the ND and Michel electrons in the ND. These discrepancies drove the decision to set the systematic uncertainty on the absolute energy scale to 5 %. Measurements from the NOvA Test Beam experiment will help reduce this systematic uncertainty.

[3fl technote] The calibration shape systematic uncertainty was defined based on data/MC differences. The uncertainty was parameterized with a linear shape, with different slopes in the middle of the detector vs the edges, determined by linear fits to data/MC ratios.

[3fl technote] The detector ageing uncertainty is implemented as a simple linear drift downward in light level as a function of time, and a corresponding drift upward in the overall calibration scale to compensate. This is intended to mimic the impact of the number of hits above thresholds falling over time, while the overall calorimetric energy remains the same. For a more detailed summary, see Section 4.3 in the Prod5 detector simulation technote [2].

TO DO: *Describe the calibration uncertainties*

CHAPTER 3

Measuring the Muon Neutrino Magnetic Moment

In this analysis, I aim to detect a potential signal of the effective muon neutrino magnetic moment in the **NOvA ND**. This signal would manifest as an excess of neutrino-on-electron (ν -on-e) elastic scattering interactions at low electron recoil energies, proportional to the value of the effective neutrino magnetic moment, over the **SM** background. If no significant excess is observed, I will establish an upper limit on the effective muon neutrino magnetic moment.

Detecting the neutrino magnetic moment (μ_ν) would provide a definitive evidence of new **BSM** physics, and measuring its value would help identify the appropriate **BSM** theory. As current and planned experiments can only detect an anomalously large neutrino magnetic moment, observing such a signature would strongly suggest that neutrinos are Majorana particles and would have significant implications for astrophysics and cosmology [51].

The best model-independent experimental results on the neutrino magnetic moment come from experiments searching for dark matter using xenon-based detectors. These highly sensitive detectors detect solar neutrinos, which are part of the background in dark matter searches but can be reanalyzed for other purposes. In 2020, the XENON1T experiment observed [142] a low energy excess of solar neutrinos, which could correspond to a signal from an anomalously large effective magnetic moment within $\mu_{\nu_\odot} \in (0.14, 0.29) \times 10^{-10} \mu_B$ at 90 % Confidence Level (C.L.), where ν_\odot marks solar neutrinos. However, this result was disfavoured by the follow-up XENONnT experiment in 2022 [143], which saw no excess and set the current world-leading limit on neutrino magnetic moment at $\mu_{\nu_\odot} < 0.063 \times 10^{-10} \mu_B$ at 90 % C.L.. Other solar neutrino experiments also reported null results regarding neutrino magnetic moment [144, 145], placing less stringent limits on its value. Given some basic assumptions [145, 146] this limit for solar neutrinos would correspond to a limit on muon neutrino

effective magnetic moment of $\mu_{\nu_\mu} < 0.137 \times 10^{-10} \mu_B$. However, the relationship between effective magnetic moments of different neutrino flavours may be non-trivial, especially in the context of possible new **BSM** physics, and studying muon neutrinos remains an important endeavour [147].

The best results for ν_μ and $\bar{\nu}_\mu$ come from accelerator-based stopped pion neutrino sources [148, 149], which also do not observe any low energy excess and provide an upper limit on the effective muon neutrino magnetic moment of $\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B$ at 90 % C.L. [148]. Stopped pion neutrino sources provide a well-understood beams made up of ν_μ , $\bar{\nu}_\mu$ and ν_e with energies up to 52.8 MeV. Slightly looser limits come from pion decay-in-flight accelerator-based measurements (similar to NOvA)[150, 151], which provide a limit of $\mu_{\nu_\mu} < 8.5 \times 10^{-10} \mu_B$ at 90 % C.L..

Thanks to the very intense and highly pure beam of muon neutrinos and antineutrinos, and a detector designed for the reconstruction and identification of events with electrons in the final state, NOvA is well-positioned to provide a highly competitive, and possibly even world-leading, measurement (or limit) of the effective muon neutrino magnetic moment. A previous analysis of NOvA ND data for a measurement of the effective muon neutrino magnetic moment was presented in a thesis [152], providing a (statistics-only) limit of $\mu_{\nu_\mu} < 15.8 \times 10^{-10} \mu_B$ at 90 % C.L..

Additionally, ν -on-e elastic scattering interactions are used in various other analyses in NOvA, specifically in efforts to constrain the neutrino beam prediction [153, 154] and in the search for Light Dark Matter (LDM) [155]. These analyses developed various tools and methods that can be utilized in the search for neutrino magnetic moment.

In this chapter, I will provide an overview of the theory of neutrino electromagnetic interactions in Sec. 3.1, focusing on the effective neutrino magnetic moment and its implications for ν -on-e measurements and other theoretical considerations. In Sec. 3.2, I will discuss the analysis strategy, the signal and background definition, as well as the data and simulation samples and the analysis weights. Following this, Sec. 3.3 will explain the selection of events for this analysis, while Sec. 3.4 will address the relevant systematic uncertainties. I will present the results of this analysis in Sec. 3.5 and discuss their implications in Sec. 3.6. Finally, section 3.7 will summarise the findings of this analysis.

3.1 Theory of neutrino magnetic moment

As was described in Sec. 1, neutrinos in the SM are massless and electrically neutral particles. However, even SM neutrinos can have electromagnetic interaction through loop diagrams involving charged leptons and the W boson, covered by the neutrino charge radius [51].

In general BSM theories, considering interactions with a single photon as shown on Fig. 3.1, neutrino electromagnetic interactions can be described by an effective interaction Hamiltonian [156]

$$\mathcal{H}_{em}^{(\nu)}(x) = \sum_{k,j=1}^N \bar{\nu}_k(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x). \quad (3.1)$$

Here $\nu_k(x)$, $k = 1, \dots, N$, are neutrino fields in the mass basis with N neutrino mass states, Λ_μ^{kj} is a general vertex function and $A^\mu(x)$ is the electromagnetic field.

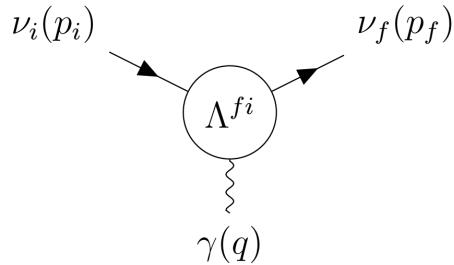


Figure 3.1: Effective coupling of neutrinos with one photon electromagnetic field.

The vertex function $\Lambda_\mu^{fi}(q)$ is generally a matrix and, in the most general case consistent with the SM gauge invariance [157, 158], can be written in terms of linearly independent products of Dirac matrices (γ) and only depends on the four momentum of the photon ($q = p_f - p_i$):

$$\begin{aligned} \Lambda_\mu^{fi}(q) = & \mathbb{F}_1^{fi}(q^2) q_\mu + \mathbb{F}_2^{fi}(q^2) q_\mu \gamma_5 + \mathbb{F}_3^{fi}(q^2) \gamma_\mu + \mathbb{F}_4^{fi}(q^2) \gamma_\mu \gamma_5 + \\ & \mathbb{F}_5^{fi}(q^2) \sigma_{\mu\nu} q^\nu + \mathbb{F}_6^{fi}(q^2) \epsilon_{\mu\nu\rho\gamma} q^\nu \sigma^{\rho\gamma}, \end{aligned} \quad (3.2)$$

where $\mathbb{F}_i^{fi}(q^2)$ are six Lorentz invariant form factors and δ and ϵ are the Dirac delta and the Levi-Civita symbols respectively.

Applying conditions of hermiticity $(\mathcal{H}_{em}^{(\nu)\dagger} = \mathcal{H}_{em}^{(\nu)})$ and of the gauge invariance

of the electromagnetic field, the vertex function can be rewritten as

$$\Lambda_\mu^{fi}(q) = (\gamma_\mu - q_\mu q^2/q^2) \left[\mathbb{F}_Q^{fi}(q^2) + \mathbb{F}_A^{fi}(q^2) q^2 \gamma_5 \right] - i\sigma_{\mu\nu} q^\nu \left[\mathbb{F}_M^{fi}(q^2) + i\mathbb{F}_E^{fi}(q^2) \gamma_5 \right], \quad (3.3)$$

where \mathbb{F}_Q^{fi} , \mathbb{F}_M^{fi} , \mathbb{F}_E^{fi} and \mathbb{F}_A^{fi} are hermitian matrices representing the charge, dipole magnetic, dipole electric and anapole neutrino form factors respectively. It is clear that the vertex function only depends on the square of the four momentum of the photon q^2 . In coupling with a real photon ($q^2 = 0$) these form factors become the neutrino charge and magnetic, electric and anapole moments respectively. Additionally, the neutrino charge radius corresponds to the second term in the expansion of the charge form factor [156].

The above expression can be simplified [159] as

$$\Lambda_\mu^{fi}(q) = \gamma_\mu \left(Q_{\nu_{fi}} + \frac{q^2}{6} \langle r^2 \rangle_{\nu_{fi}} \right) - i\sigma_{\mu\nu} q^\nu \mu_{\nu_{fi}}, \quad (3.4)$$

where $Q_{\nu_{fi}}$, $\langle r^2 \rangle_{\nu_{fi}}$, and $\mu_{\nu_{fi}}$ are the neutrino charge, effective charge radius (also containing anapole moment), and an effective magnetic moment (also containing electric moment) respectively. This is possible thanks to the similar effects of the neutrino charge radius and the anapole moment, and of the neutrino magnetic and electric moments, on neutrino interactions. Therefore, these are the three neutrino electromagnetic properties (charge, effective charge radius and effective magnetic moment) measured in experiments.

The neutrino electric charge is primarily constrained through measurements of the neutrality of matter and cosmological observations, which provide much better constraints than neutrino oscillation experiments [156]. On the other hand, the neutrino charge radius would manifest as an increase in the size of the ν -on-e elastic scattering coupling constants, allowing it to be studied in neutrino oscillation experiments such as NOvA. Additionally, the value of the neutrino charge radius in the SM is only an order of magnitude smaller than the current world-leading limits [52] and measuring it could either confirm the validity neutrino interactions in the SM, or open possibilities to non-standard contributions to neutrino scattering [156]. However, measurement of the neutrino charge radius is not part of this analysis, but may be included in the future re-analysis of the ν -on-e interactions in the NOvA ND.

3.1.1 Neutrino electric and magnetic dipole moments

The size and effect of neutrino electromagnetic properties depend on the specific [BSM](#) theory applied. Evaluating one loop diagrams in the minimally extended [SM](#) with three right-handed Dirac neutrinos, as described in Sec. 1.4, gives the first approximation of the electric and magnetic moments, which are now 3×3 matrices with elements:

$$\left. \begin{aligned} \mu_{kj}^D \\ i\epsilon_{kj}^D \end{aligned} \right\} \simeq \frac{3eG_F}{16\sqrt{2}\pi^2} (m_k \pm m_j) \left(\delta_{kj} - \frac{1}{2} \sum_{l=e,\mu,\tau} U_{lk}^\star U_{lj} \frac{m_l^2}{m_W^2} \right), \quad (3.5)$$

where m_k, m_j are the neutrino masses and m_l are the masses of charged leptons which appear in the loop diagrams [156]. The D superscript denotes Dirac neutrinos and M denotes Majorana neutrinos throughout this section. Also, e is the electron charge, G_F is the Fermi coupling constant, and U is the [PMNS](#) neutrino oscillation matrix. Higher order electromagnetic corrections were neglected, but can also have a significant contribution, depending on the theory.

It can be seen that Dirac neutrinos have no diagonal electric moments ($\epsilon_{kk}^D = 0$) and their diagonal magnetic moments are approximately

$$\mu_{kk}^D \simeq \frac{3eG_F m_k}{8\sqrt{2}\pi^2} \simeq 3.2 \times 10^{-19} \left(\frac{m_k}{\text{eV}} \right) \mu_B, \quad (3.6)$$

where μ_B is the Bohr magneton which represents the value of the electron magnetic moment [156]. Neutrino magnetic moments are therefore strongly suppressed by the smallness of neutrino masses, with theoretical predictions in Eq. 3.6 several orders of magnitude below the reach of current experiments [159].

The transition magnetic moments in the minimally extended [SM](#) from Eq. 3.5 are suppressed with respect to the largest of the diagonal magnetic moments by at least a factor of 10^{-4} due to the m_W^2 in the denominator. The transition electric moments are even smaller due to the mass difference in Eq. 3.5. Therefore an experimental observation of a magnetic moment larger than in Eq. 3.6 would indicate physics beyond the minimally extended [SM](#) [156, 160].

The suppression of the neutrino magnetic moment by the smallness of its mass can be also expressed in a general case [160]. The ‘natural’ upper limits on the size of

the neutrino magnetic moment for any **BSM** theory that has **NP** generated at a scale Λ_{NP} can be expressed as [161]

$$\mu_\nu^D(\mu_B) \lesssim 3 \times 10^{-15} \frac{m_\nu^D \text{ (eV)}}{[\Lambda_{NP} \text{ (TeV)}]^2}. \quad (3.7)$$

Therefore for $\Lambda_{NP} \simeq 1 \text{ TeV}$ and $m_\nu^D \lesssim 1 \text{ eV}$ the limit becomes $\mu_\nu^D \lesssim 3 \times 10^{-15} \mu_B$, well below the current experimental capabilities. However, these upper bounds only apply if **NP** is generated well above the electroweak scale $\Lambda_{EW} \sim 100 \text{ GeV}$ [156].

For Majorana neutrinos, the magnetic and electric form factors (and therefore the magnetic and electric moment matrices) are antisymmetric, thus Majorana neutrinos only have transition moments. The simplest extension of the **SM** that includes Majorana neutrinos requires either the addition of a Higgs triplet, or right-handed neutrinos together with a Higgs singlet [156]. Neglecting the Feynman diagrams which depend on the model of the scalar sector, the magnetic and electric dipole moments are

$$\left. \begin{aligned} \mu_{kj}^M \\ \epsilon_{kj}^D \end{aligned} \right\} \simeq \mp \frac{3ieG_F}{16\sqrt{2}\pi^2} (m_k \pm m_j) \sum_{l=e,\mu,\tau} \text{Im/Re} [U_{lk}^\star U_{lj}] \frac{m_l^2}{m_W^2}, \quad (3.8)$$

where **Im** is for μ_{kj}^M and **Re** is for ϵ_{kj}^D . These are difficult to compare to the Dirac case, due to possible presence of Majorana phases in the **PMNS** matrices, but it is clear that they have the same order of magnitude as Dirac transition dipole moments. However, the neglected model dependent contributions can enhance the transition dipole moments for Majorana neutrinos [156].

The natural upper bound on the Majorana magnetic moment is less strict compared to the Dirac neutrinos, due to the antisymmetric nature of Majorana magnetic moment, which requires an addition of additional Yukawa couplings into the **BSM** theory compared to Dirac neutrinos, which can enhance the maximal possible magnetic moment [160]. The limit for Majorana neutrinos can be expressed as

$$\mu_{\alpha\beta}^M(\mu_B) \leq 4 \times 10^{-9} \frac{[m_\nu^M]_{\alpha\beta} \text{ (eV)}}{[\Lambda_{NP} \text{ (TeV)}]^2} \frac{m_\tau^2}{|m_\alpha^2 - m_\beta^2|}, \quad \alpha, \beta \in \{e, \mu, \tau\}. \quad (3.9)$$

Here, the neutrino magnetic moment is expressed in the flavour basis instead of the mass basis, since the charged lepton masses are diagonal here. The two basis are

related by

$$\mu_{ij} = \sum_{\alpha\beta} \mu_{\alpha\beta} U_{\alpha i}^* U_{\beta j}. \quad (3.10)$$

and the effect of the neutrino magnetic moment on neutrino interactions does not depend on the choice of the basis[62].

These considerations imply, that if a magnetic moment $\mu \gtrsim 10^{-15} \mu_B$ would be measured, neutrinos are almost certainly Majorana particles [160].

Effective neutrino magnetic moment

As mentioned above, the neutrino magnetic moment that is measured in experiments is the so-called effective neutrino magnetic moment, which is a combination of electric and magnetic dipole moments and depends on neutrino source and oscillations. In the ultra-relativistic limit, the neutrino effective magnetic moment is

$$\mu_{\nu_l}^2 (L, E_\nu) = \sum_j \left| \sum_k U_{lk}^* e^{\mp i \Delta m_{kj}^2 L / 2E_\nu} (\mu_{jk} - i\epsilon_{jk}) \right|^2, \quad (3.11)$$

where the minus sign in the exponent is for neutrinos and the plus sign for antineutrinos [156]. Therefore, the only difference between the effective neutrino and antineutrinos magnetic moment is in the phase induced by neutrino oscillations. For experiments with baselines short enough that neutrino oscillations would not have time to develop ($\Delta m^2 L / 2E_\nu \ll \sim 1$), such as the NOvA ND, the effective magnetic moment is the same for neutrinos and antineutrinos and is independent of the neutrino energy.

Since the effective magnetic moment depends on the initial neutrino flavour, it is different for experiments studying neutrinos from different sources. Additionally, experiments such as solar neutrino experiments, need to include matter effects on the neutrino oscillations. Therefore the reports on the value (or upper limit) of the effective neutrino magnetic moment are not directly comparable between different types of neutrino experiments.

3.1.2 Measuring neutrino magnetic moment

The most sensitive method to measure neutrino magnetic moment is the low energy elastic scattering of (anti)neutrinos on electrons [156]. The diagram for this interaction is shown in Fig. 3.2 displaying the two observables, the recoil electron's kinetic energy ($T_e = E_{e'} - m_e$) and the recoil angle with respect to the incoming neutrino beam (θ).

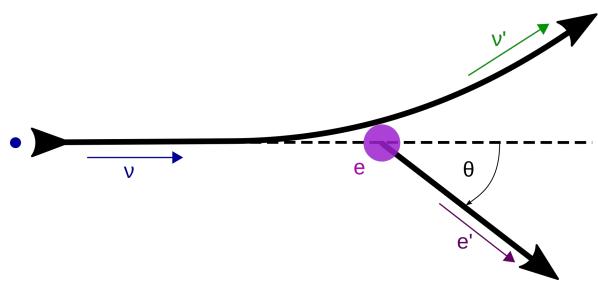


Figure 3.2: Neutrino-on-electron elastic scattering diagram

Since the ν -on-e interaction is governed by simple $2 \rightarrow 2$ kinematics, it is possible to get

$$(P_\nu - P_{e'})^2 = (P_{\nu'} - P_e)^2, \quad (3.12)$$

$$m_\nu^2 + m_e^2 - 2E_\nu E_{e'} + 2E_\nu p_{e'} \cos \theta = m_\nu^2 + m_e^2 - 2E_{\nu'} m_e. \quad (3.13)$$

From the energy conservation

$$E_\nu + m_e = E_{\nu'} + E_{e'} = E_{\nu'} + T_e + m_e \Rightarrow E_{\nu'} = E_\nu - T_e \quad (3.14)$$

follows

$$E_\nu p_{e'} \cos \theta = E_\nu E_{e'} - E_{\nu'} m_e = E_\nu (T_e + m_e) - (E_\nu - T_e) m_e = T_e (E_\nu + m_e), \quad (3.15)$$

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{E_{e'}^2 - m_e^2}} = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{T_e^2 + 2T_e m_e}}. \quad (3.16)$$

And finally

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e}{T_e + 2m_e}}. \quad (3.17)$$

Which can be rearranged to get

$$T_e = \frac{2m_e E_\nu^2 \cos^2 \theta}{(E_\nu + m_e)^2 - E_\nu^2 \cos^2 \theta}. \quad (3.18)$$

Electron's kinetic energy is therefore kinematically constrained by the energy conservation as

$$T_e \leq \frac{2E_\nu^2}{2E_\nu + m_e}, \quad (3.19)$$

which corresponds to the $\cos \theta \rightarrow 1$ when the recoil electron goes exactly forward in the incident neutrino direction, as depicted in Fig. 3.3.

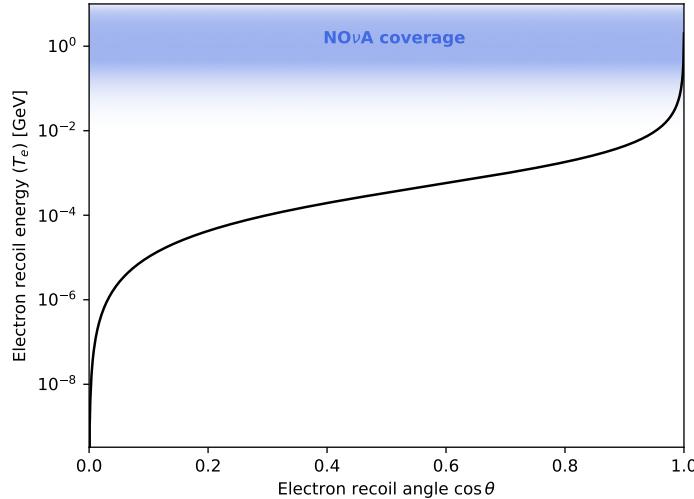


Figure 3.3: Relation between the recoil electron's kinetic energy and angle for the ν -on-e elastic scattering. The coverage of the NOvA detectors for measuring the electron recoil energy is shown in blue. Only very forwards electron's are therefore recorded in NOvA.

Considering $E_\nu \sim \text{GeV}$, it is useful to approximate $\frac{m_e^2}{E_\nu^2} \rightarrow 0$. Additionally, considering only very small electron recoil angles, meaning $\theta^2 \cong (1 - \cos^2 \theta)$, applied to Eq. 3.17 results in

$$T_e \theta^2 \cong T_e \left(1 - \left(\frac{E_\nu + m_e}{E_\nu} \right)^2 \frac{T_e}{T_e + 2m_e} \right) = T_e \left(1 - \left(1 + \frac{2m_e}{E_\nu} \right) \frac{T_e}{T_e + 2m_e} \right), \quad (3.20)$$

therefore

$$T_e \theta^2 \cong \frac{2m_e T_e}{T_e + 2m_e} \left(1 - \frac{T_e}{E_\nu} \right) = 2m_e \left(\frac{1}{1 + \frac{2m_e}{T_e}} \right) \left(1 - \frac{T_e}{E_\nu} \right), \quad (3.21)$$

and finally

$$T_e \theta^2 \cong 2m_e \left(1 - \frac{T_e}{E_\nu} \right) < 2m_e. \quad (3.22)$$

This is a strong limit that very clearly distinguishes the ν -on-e elastic scattering events from other similar interactions involving single electron (mainly the ν_e CC interactions).

Neutrino magnetic moment cross section

In the ultra-relativistic limit, the neutrino magnetic moment interaction flips the neutrino helicity, while the SM weak interaction conserves it, which means it is possible to add the two contribution to the total ν -on-e cross section incoherently (without interference terms) [156]:

$$\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} = \left(\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} \right)_{\text{SM}} + \left(\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} \right)_{\text{MAG}}. \quad (3.23)$$

The SM contribution can be expressed as [16, 156]:

$$\left(\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} \right)_{\text{SM}} = \frac{2G_F^2 m_e}{\pi} \left\{ g_1^2 + g_2^2 \left(1 - \frac{T_e}{E_\nu} \right)^2 - g_1 g_2 \frac{m_e T_e}{E_\nu^2} \right\}, \quad (3.24)$$

where the coupling constants g_1 and g_2 differ for between neutrino flavours and between neutrinos and antineutrinos. Their values are:

$$g_1^{\nu_e} = g_2^{\bar{\nu}_e} = \sin^2 \theta_W + 1/2, \quad g_2^{\nu_e} = g_1^{\bar{\nu}_e} = \sin^2 \theta_W, \quad (3.25)$$

$$g_1^{\nu_{\mu,\tau}} = g_2^{\bar{\nu}_{\mu,\tau}} = \sin^2 \theta_W - 1/2, \quad g_2^{\nu_{\mu,\tau}} = g_1^{\bar{\nu}_{\mu,\tau}} = \sin^2 \theta_W, \quad (3.26)$$

where $\sin^2 \theta_W \cong 0.23$.

The total SM cross section, and therefore the number of SM ν -on-e interactions, depends on the neutrino energy and the minimum measured electron recoil energy. However, in general the cross section for for ν_e is about 2.5 times larger than for the $\bar{\nu}_e$, about 6 times larger than for $\nu_{\mu/\tau}$ and about 7 times larger than for $\bar{\nu}_{\mu/\tau}$.

The neutrino magnetic moment contribution is [156, 162]:

$$\left(\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} \right)_{\text{MAG}} = \frac{\pi \alpha^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \left(\frac{\mu_{\nu_l}}{\mu_B} \right)^2, \quad (3.27)$$

where α is the fine structure constant and μ_{ν_l} is the effective magnetic moment of ν_l . The total cross section now only depends on the neutrino energy and on the effective magnetic moment, but is the same for neutrinos and antineutrinos.

The comparison of the SM and the neutrino magnetic moment differential cross sections is shown in Fig.3.4. Whereas the SM cross section is approximately uniform for $T_e \rightarrow 0$, the neutrino magnetic moment cross section rises to infinity. However, this reach is limited by the experimental capabilities of detecting electrons with very low energies. The (possible) NOvA coverage is shown with a shaded blue region, with current capability reaching $T_e = 0.5$ GeV. Future analyses might extend this reach to lower T_e , with the lowest possible detectable electron recoil energy $T_{e,min} \approx 0.01$ GeV, as discussed in Sec. 2.2.

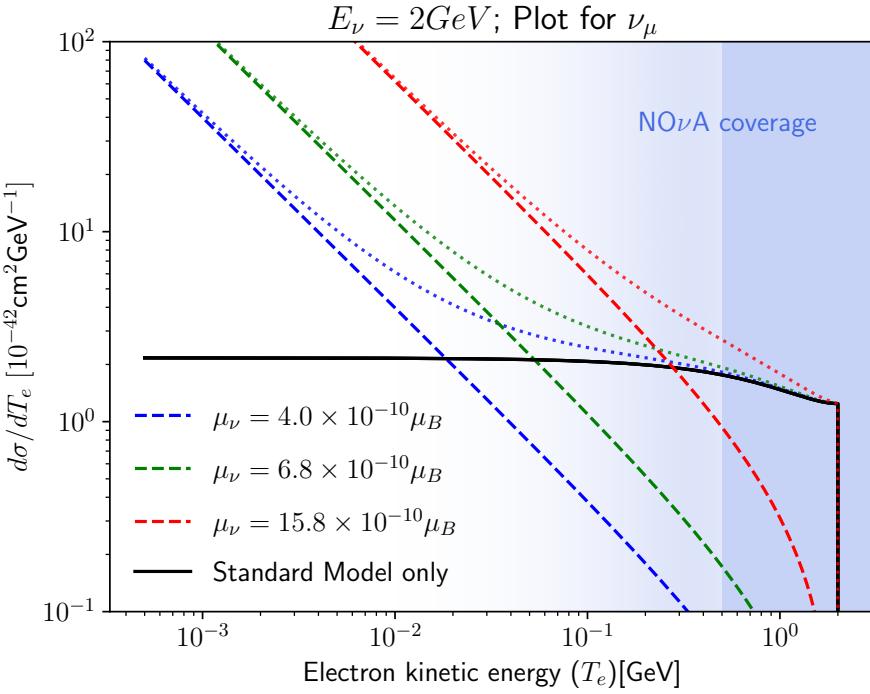


Figure 3.4: Comparison of the neutrino magnetic moment (coloured) and the SM (black) cross sections for the ν -on-e elastic scattering. Different colours depict different values of the neutrino magnetic moment, with red corresponding to the previous NOvA measurement, green the LSND result, and blue a possible ultimate NOvA sensitivity, as discussed in the introduction to this chapter. Dashed lines are the individual cross sections and dotted lines are the added total cross section with the standard model contribution. NOvA coverage of electron recoil energies is shown in shaded blue.

Calculating the ratio of the neutrino magnetic moment and the SM cross sections, as shown in Fig. 3.5, can serve as a proxy to estimate the number of neutrino magnetic

moment events in relation to the predicted number of **SM** events, if the E_ν and T_e are known. Additionally, comparing the ratio of the total cross sections can reveal the expected total number of neutrino magnetic moment events as a function of the predicted number of **SM** events. Considering $E_\nu = 2 \text{ GeV}$, $\mu_\nu = 6.8 \times 10^{-10} \mu_B$ (current best limit for ν_μ from LSND), and integrating differential cross sections for ν_μ in Eq. 3.24 and 3.27 from $T_{e,min}$ to $T_{e,max} \rightarrow 2 \text{ GeV}$ results in

$$\frac{\sigma_{\text{MAG}}}{\sigma_{\text{SM}}} \approx \begin{cases} 0.035 & T_{e,min} = 0.5 \text{ GeV}, \\ 0.14 & T_{e,min} = 0.01 \text{ GeV}. \end{cases} \quad (3.28)$$

Therefore, at the current **NOvA** detection capabilities, there are about 0.035 times as many neutrino magnetic moment ν -on-e events than **SM** ones. This can be compared with the expected statistical uncertainty on the **SM** background, which in case of Poisson distributed events is the square root of the number of predicted events. Consequently, it is possible to assess the minimal number of **SM** ν -on-e events necessary for the magnetic moment signal to be detected above the **SM** background (without considering systematic uncertainties) as

$$N_{\text{SM}} > 1/0.035^2 \approx 816. \quad (3.29)$$

However, this approximation is calculated only for one value of E_ν , but can be used to assess the sensitivity of the experiment.

As can be seen in Fig. 3.4 and Fig. 3.5, the magnetic moment contribution exceeds the **SM** contribution for low enough T_e . This can be approximated as [156]:

$$T_e \lesssim \frac{\pi^2 \alpha^2}{G_F^2 m_e^3} \left(\frac{\mu_\nu}{\mu_B} \right)^2 \simeq 2.9 \times 10^{19} \left(\frac{\mu_\nu}{\mu_B} \right)^2 [\text{MeV}], \quad (3.30)$$

which does not depend on the neutrino energy. Therefore, experiments sensitive to lower energetic electrons are significantly more sensitive to the neutrino magnetic moment.

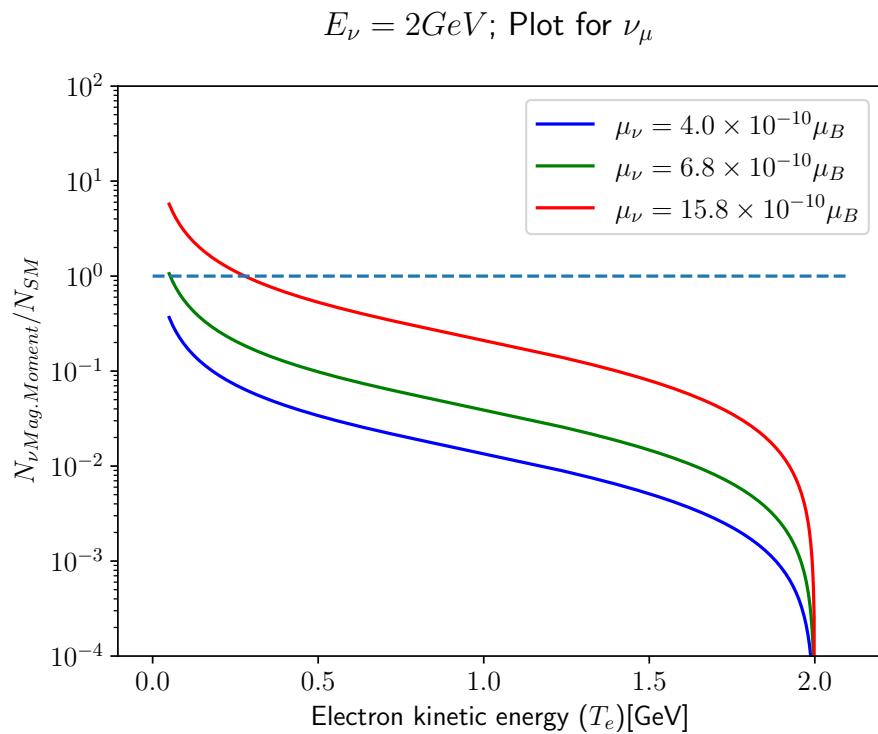


Figure 3.5: Ratio of the neutrino magnetic moment cross section to the SM cross section for the ν -on-e elastic scattering of 2 GeV ν_μ . Different colours depict different effective muon neutrino magnetic moment values, with red corresponding to the previous NOvA measurement, green the LSND result, and blue a possible ultimate NOvA sensitivity, as discussed in the introduction to this chapter.

3.2 Analysis overview

Our analysis strategy for measuring the effective muon neutrino magnetic moment in the NOvA ND is based on comparing the total number of reconstructed and selected events in data with the prediction. The predicted events consist of the signal, which depends on the size of the effective muon neutrino magnetic moment, and of the background, which corresponds to the SM-only (null) hypothesis without any neutrino magnetic moment. We define the signal as true ν -on-e elastic scattering interactions, created with the use of the neutrino magnetic moment cross section instead of the SM cross section, as described in Sec. 3.1.2. Additionally, the signal events are required to have their true interaction vertex contained within the ND to exclude events originating from outside of the detector.

The data used in this analysis were collected from the start of NOvA ND data taking on the August 22nd, 2014, until February 3rd, 2021. This is the ND data that were used in the latest NOvA neutrino oscillations result [54], with an additional year. Although more data have been collected since February 2021, they are still being processed and are not available at the time of writing this thesis. The total exposure of the data sample is approximately 13.8×10^{20} POT. This exposure is used throughout this chapter to scale the predicted distributions and number of events.

This analysis uses the standard NOvA simulation and reconstruction tools, as were discussed in Sec. 2.4 and 2.5. The simulation was created with approximately four times larger statistics than the data to limit statistical uncertainties from simulation. The total exposure for the simulation is approximately 55.4×10^{20} POT. For the systematic uncertainty studies only a portion of this full sample is used, specifically 19.3×10^{20} POT.

Corrections for known limitations in the simulation are applied in the form of analysis weights, which weight each event based on how it is affected by specific variations in the simulation. This includes the corrections for the neutrino beam prediction based on the external measurements used by the PPFX (Sec. 2.4), and, for the non- ν -on-e background only, also the internal and external measurements that constrain the neutrino interaction prediction inside GENIE.

The cross section corrections are not applied to the ν -on-e events, as they are assumed to be known precisely from theory. However, the GENIE MC simulation

only considers tree-level SM ν -on-e interactions [153], as described in Sec. 3.1.2, and doesn't account for any higher order terms, which are described by radiative corrections. Radiative correction can be expressed by two adjustments to the tree-level SM ν -on-e cross section [163]. First, the values of the weak coupling constants are changed as [164]

$$g_1^{\nu_e} \rightarrow 0.7276, \quad g_1^{\nu_\mu} \rightarrow -0.2730, \quad g_2 \rightarrow 0.2334. \quad (3.31)$$

Second, there are additional terms added to the cross section equation. Considering only one-loop corrections, the full ν -on-e cross section can be expressed as¹ [165]

$$\left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\text{Rad. Corr.}} = \frac{G_F^2 s}{\pi} \left\{ g_1^2 \left(1 + \frac{\alpha}{\pi} X_1 \right) + g_2^2 (1-y)^2 \left(1 + \frac{\alpha}{\pi} X_2 \right) - g_1 g_2 \frac{m_e y}{E_\nu} \right\}, \quad (3.32)$$

where

$$y = \frac{T_e + E_\gamma}{E_\nu}, \quad (3.33)$$

$s = 2E_\nu m_e + m_e^2$ is the Mandelstam variable,

$$X_1 = -\frac{2}{3} \log \left(\frac{2yE_\nu}{m_e} \right) + \frac{y^2}{24} - \frac{5y}{12} - \frac{\pi^2}{6} + \frac{23}{72} \quad (3.34)$$

and

$$X_2 = -\frac{2}{3} (1-y)^2 \log \left(\frac{2yE_\nu}{m_e} \right) - \frac{y^2}{18} - \frac{\pi^2}{6} (1-y)^2 - \frac{2y}{9} + \frac{23}{72}. \quad (3.35)$$

In practice, radiative corrections can be implemented as a weight, where each true ν -on-e event is weighted by a ratio

$$\text{weight}_{\text{Rad. Corr.}}(E_\nu, T_e) = \left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\text{Rad. Corr.}} / \left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\text{GENIE 3}} ; \quad (3.36)$$

Analogically to the radiative correction weight, it is possible to create a neutrino magnetic moment weight as a ratio between the neutrino magnetic moment and the SM differential cross sections for the ν -on-e interactions. This can then serve to predict the number of ν -on-e events created by the neutrino magnetic moment interac-

¹There is technically a third correction term X_3 by the $g_1 g_2$ term, which is however negligible for $E_\nu \sim \text{GeV}$.

tion (which make up the signal), without the need for an additional simulation. This is possible thanks to the theoretically very well understood properties of the ν -on-e interaction, as described in Sec. 3.1.2. Therefore, the signal sample is created from the true ν -on-e sample, with the magnetic moment weight applied. The weight has a form:

$$\text{weight}_{\nu\text{-Mag. Mom.}}(E_\nu, T_e) = \left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\nu\text{-Mag. Mom.}} \Bigg/ \left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\text{GENIE 3}}, \quad (3.37)$$

where

$$\left(\frac{d\sigma_{\nu\text{-on-e}}}{dy} \right)_{\nu\text{-Mag. Mom.}} = E_\nu \left(\frac{d\sigma_{\nu\text{-on-e}}}{dT_e} \right)_{\nu\text{-Mag. Mom.}}. \quad (3.38)$$

Due to the relatively low cross section of the ν -on-e interaction, the nominal simulation sample contains very few ν -on-e events, which could result in a significant statistical uncertainty from simulation. To avoid this, we created a ν -on-e-enhanced simulation sample, which is mainly made up of ν -on-e events with a total exposure of 1.72×10^{24} POT. There is a few non- ν -on-e background events overlaid on top of the ν -on-e events to properly account for the possible reconstruction effects of the pileup of neutrino interactions in a single spill [153], since in the real detector, the hits from the true ν -on-e interaction can be clustered together into another interaction, or additional hits can be clustered together into the ν -on-e event. To save up on unnecessary disk space and processing usage, the enhanced ν -on-e sample does not include any cross section related parameters and variables, as the ν -on-e interaction is assumed to be known exactly from theory. Therefore, we do not apply cross section weights or account for cross section systematic uncertainties for ν -on-e events.

The cross section tuning procedure in NOvA (Sec. 2.4) applies large weights to MEC events in some parts of the parameter space. However, after the full event selection (Sec. 3.3) only a small number of MEC events remain in the detector. This was shown to be an issue especially for the ν_e CC MEC events [153]. Applying large tuning corrections to a small number of events results in large statistical fluctuations. To avoid this, we created another special sample with enhanced number of ν_e CC MEC events, following the same procedure as for the ν -on-e-enhanced sample, with an exposure of 1.99×10^{24} POT.

A summary of the simulation samples and analysis weights for the four different

types of signal and background components is shown in Tab. 3.1. In the following chapter, the ν_e CC MEC background is added into the ‘Other background’ sample, even though it is created from a separate simulation.

Table 3.1: Overview of the simulation samples and analysis weight used for the different signal and background components.

| Signal type | Sample | Weight |
|---------------------------|-------------------------|--------------------------|
| Signal | Enhanced ν -on-e | Flux & ν Mag. Moment |
| ν -on-e background | Enhanced ν -on-e | Flux & Rad. Corr. |
| ν_e CC MEC background | Enhanced ν_e CC MEC | Flux & Cross Sec. |
| Other background | Nominal ND | Flux & Cross Sec. |

3.3 Event selection

We are searching for ν -on-e elastic scattering events, characterised by a single very forward going electron shower, specifically focusing on low electron recoil energies. The main background for our analysis come from ν_e CC interactions, which produce an electron with an additional activity, and interactions that produce π^0 , which decays into two photons producing electromagnetic showers, where each can look similar to the ν -on-e signal. Additionally, there are ν_μ CC interactions, which are generally easy to distinguish from our signal, however, their very high abundance in the NOvA ND makes them a dominant background nevertheless.

We explain the motivation behind each cut of the event selection and discuss their effect on the neutrino magnetic moment events below. We also consider possible improvements to the event selection for a future (re-)analysis.

The strategy for event selection is as follows. First, we remove events that failed reconstruction or data collection, described in Sec. 3.3.1 and 3.3.2. Then, we apply pre-selection cuts that remove obvious background (Sec. 3.3.3), while limiting the reduction of the signal efficiency to about 0.25 %. Following this, we apply the containment cuts (Sec. 3.3.4) that remove events that are either not fully contained within the detector, or events that originate from outside of the detector, such as rock muons. Afterwards, we perform a cut-based Multi Variate Analysis (MVA) on a selection of variables useful for distinguishing the signal from the background, discussed in Sec. 3.3.5,

and evaluate their combined performance on the signal selection. We choose the cut values that result in the best statistical significance, based on a chosen Figure Of Merit (FOM). Given that we are searching for a very limited number of signal events on top of a large background, we chose a simple statistics-only FOM

$$\text{FOM} = \frac{\text{Signal}}{\sqrt{\text{Background}}}. \quad (3.39)$$

The summary of the cut values for the event selection of neutrino magnetic moment signal is presented in Tab. 3.2, showing the label for the event selection variable, its description and the cut value chosen. After the full event selection, the predicted number of signal events for $\mu_\nu = 10^{-9}\mu_B$ is 56.80 and the total number of background events under the SM hypothesis is 700.33.

3.3.1 Data Collection Quality

To ensure good data quality, we apply the following criteria to data (not applied to simulation) [166]. A cut on the time of each spill relative to other spills and on the exposure of each spill, where every spill is required to have at least 2^{12} POT. Additionally, the current in the focusing horn is required to be within $-202\text{ kA} < I_{Horn} < -196.4\text{ kA}$, the position of the beam to be within $\pm 2\text{ cm}$ in both x and y axis, and that the width of the beam to be within 0.57 and 1.58 cm. Furthermore, incomplete events, or events with issues in one or more DCMs are removed as well.

3.3.2 Reconstruction Quality

As described in Sec. 2.5, electrons are reconstructed by slicing, then vertexing, then clustering into prongs. To identify electrons we require a valid reconstructed vertex and at least one reconstructed prong. Even though electrons only consist of a single shower, we don't reject events with more than one prong in a slice, as the reconstruction can wrongly assign noise hits as a separate prong. These false secondary prongs can be removed later in the event selection.

Figure 3.6 and Tab. 3.3 show that about 68 % of signal events do not have a valid reconstructed vertex. This is due to the concentration of signal events at very low electron recoil energies, which results in events that can consist of a small number

of hits, or even a single hit. As can be seen in the bottom plot in Fig. 3.6, events with small true electron recoil energies have much smaller vertex reconstruction efficiency than the higher energetic electrons. However, ongoing work is improving the vertex reconstruction in the NOvA detectors with a use of ML instead of the currently used Hough transform combined with Elastic Arms [167]. Improving NOvA vertex reconstruction at low energies can enhance our event selection in the future.

Table 3.2: Summary of the variables and their cut values for the event selection of neutrino magnetic moment signal. Showing the category of the event selection variable, its label, description and the cut value chosen.

| | Label | Description | Cut |
|----------------------|--|--|--|
| Reco Qual. | Valid Vtx | Valid reconstructed vertex | > 0 |
| | Nº Prongs | Number of reconstructed prongs | > 0 |
| | Hits / Plane | Number of hits per plane | < 6 |
| | Low E_{Shower} | Low cut on calorimetric energy of the most energetic shower | $> 0.5 \text{ GeV}$ |
| Pre-selection | Nº Hits Loose | Preliminary cut on the total number of hits for all prongs in a slice | < 280 |
| | Prong Length | Length of the longest prong | $< 640 \text{ cm}$ |
| | $E\theta^2$ Loose | Preliminary cut on the product of the calorimetric energy and angle squared of the leading shower | $< 0.064 \text{ GeV} \times \text{rad}^2$ |
| Fiducial | Vertex | x position | $> -177 \text{ cm}$ |
| | | y position | $< 177 \text{ cm}$ |
| | | z position | $> -177 \text{ cm}$ $< 177 \text{ cm}$ $> 50 \text{ cm}$ $< 1170 \text{ cm}$ |
| | Containment | Minimum hit position in x Maximum hit position in x Minimum hit position in y Maximum hit position in y Minimum hit position in z Maximum hit position in z | $> -177 \text{ cm}$ $< 177 \text{ cm}$ $> -185 \text{ cm}$ $< 177 \text{ cm}$ $> 55 \text{ cm}$ $< 1270 \text{ cm}$ |
| Selection | E_{Shower}/E_{Tot} | Fraction of energy contained in the most energetic shower | > 0.91 |
| | Nº Hits | Total number of hits for all prongs in a slice | < 116 |
| | High E_{Shower} | Calorimetric energy of the most energetic shower | $< 1.4 \text{ GeV}$ |
| | $\nu\text{-on-e ID}$ | CVN-based $\nu\text{-on-e}$ identifier | > 0.65 |
| | $E\pi^0$ ID | CVN-based $\nu\text{-on-e}$ and π^0 identifier | > 0.63 |
| | $E\theta^2$ | Product of the calorimetric energy and angle squared of the leading shower | $< 0.0048 \text{ GeV} \times \text{rad}^2$ |

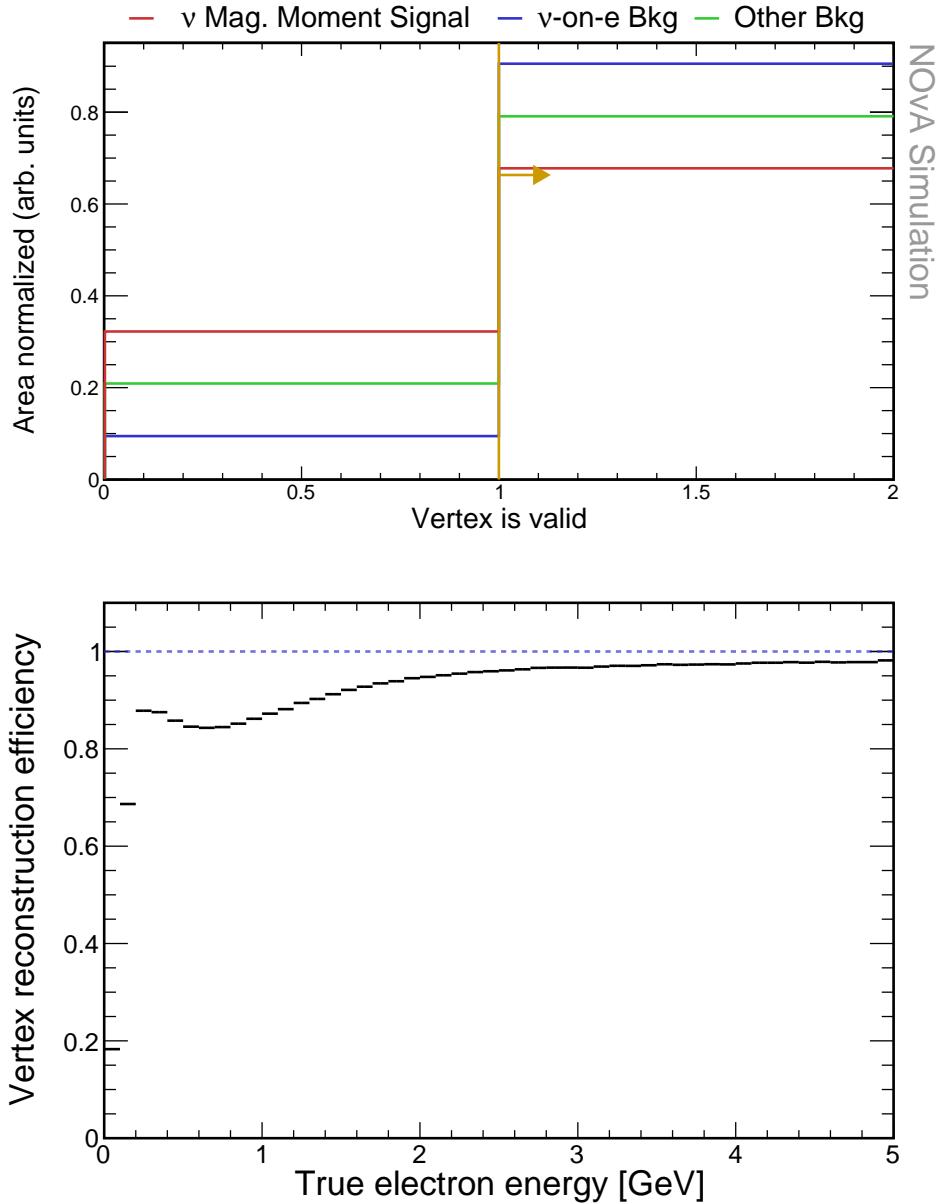


Figure 3.6: Top: Relative comparison of the signal (red), ν -on-e background (blue), and other background (green) events for the vertex reconstruction quality selection. Each histogram is area-normalised and the first bin corresponds to events without a valid vertex and second bin to events with correctly reconstructed vertex. The yellow line indicates the chosen cut value, where all events have to have a valid reconstructed vertex. Bottom: profile histogram of the ‘vertex is valid’ variable as a function of the true electron energy for the true signal events, showing the significant drop in vertex reconstruction efficiency at low electron recoil energies. No selection was applied prior to making these plots.

Additionally, we limit the number of hits per plane to < 6 . This is to remove the so-called ‘FEB flashers’, which are caused by such a high energy deposit in one cell, that it affects all the other channels on the same APD [168]. The cut value was chosen so that it removes approximately 0.25 % signal events, which is the same criterion as is used for the pre-selection cuts described below. Relative comparisons between signal and background for the number of prongs and the number of hits per plane are shown in Fig. 3.7.

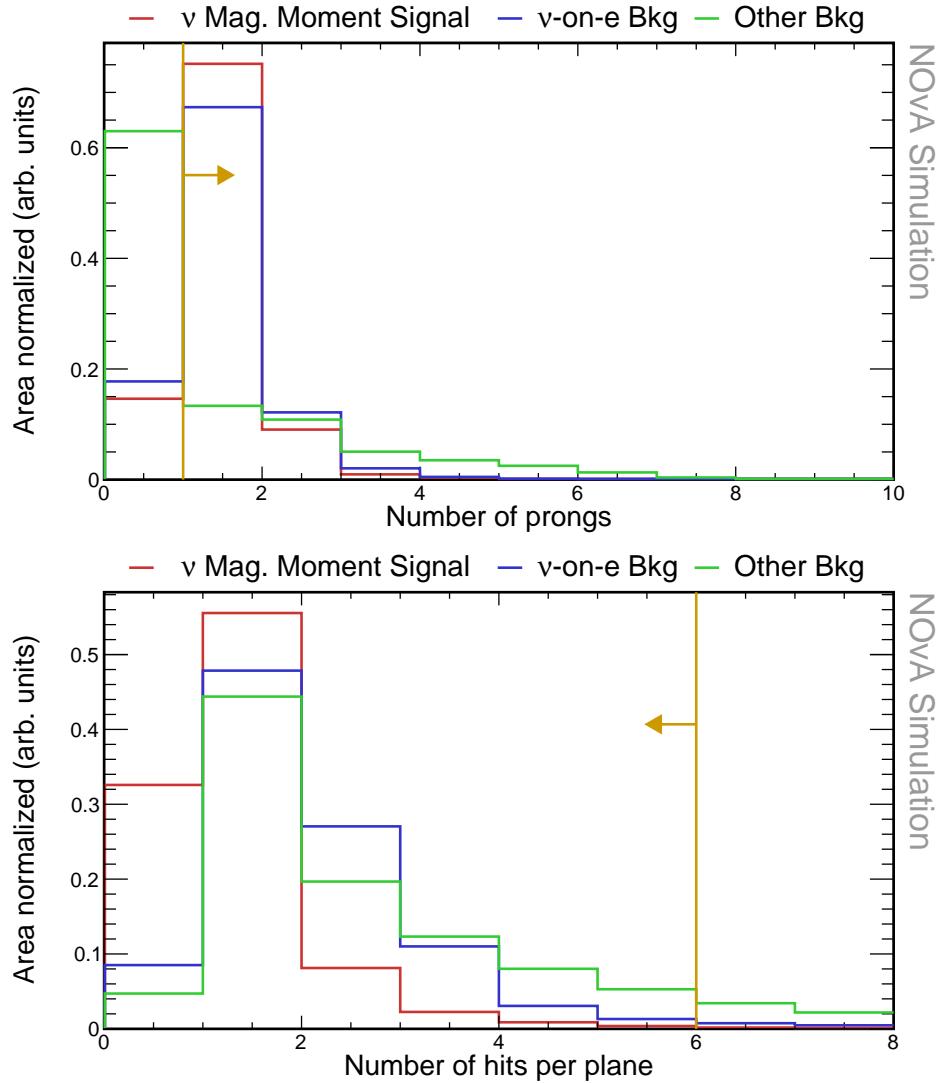


Figure 3.7: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the number of prongs (top) and the number of hits per plane (bottom) distributions. Events in both plots are required to have a valid reconstructed vertex and in the bottom plot also at least one reconstructed prong. Yellow lines indicate the cut values for the shown variables, with arrows pointing towards the preserved events. All histograms are area-normalised.

Furthermore, the reconstructed calorimetric energy of the primary shower is re-

quired to be $E_{cal} > 0.5 \text{ GeV}$ as shown in Fig. 3.8. This is due to the limitations of the currently used **CVN**-based ν -on-e identifiers described in Sec. 3.3.5, which were developed and validated for ν -on-e events with energies above this limit, to avoid the large background at low energies. However, due to the nature of the neutrino magnetic moment signal, which is concentrated at low electron recoil energies, this cut also removes a majority of our signal events, specifically 66.8 %. This large reduction severely impacts the significance of our measurement. On the other hand, it also marks potentially the most impactful improvement available in a future re-analysis. There are other event identifying algorithms available in **NOvA** that could be explored for ν -on-e events to leverage the low energy sample. Additionally, it is possible to develop a purpose-built ν -on-e identifier focusing on low electron recoil energies.
COMMENT: Can you please read this paragraph and tell me what you think about it?

Table 3.3: Event selection cutflow table for the reconstruction quality cuts showing the number of events and the relative efficiency of each cut for each signal sample. The relative efficiency is calculated as number of events remaining after applying the corresponding cut divided by number of event for all the previous cuts. All the cuts are listed in sequence as they are applied.

| Selection | Signal | | ν-on-e bkg | | Other bkg | |
|------------------------------------|---------------|-----------------------|----------------------------------|-----------------------|--------------------|-----------------------|
| | N_{evt} | $\epsilon_{rel} (\%)$ | N_{evt} | $\epsilon_{rel} (\%)$ | N_{evt} | $\epsilon_{rel} (\%)$ |
| No Cut | 817.34 | 100 | 6.82×10^3 | 100 | 2.96×10^8 | 100 |
| Valid Vtx | 553.86 | 67.76 | 6.17×10^3 | 90.55 | 2.34×10^8 | 79.10 |
| Nº Prongs | 472.90 | 85.38 | 5.08×10^3 | 82.25 | 8.66×10^7 | 37.00 |
| Hits / Plane | 471.14 | 99.63 | 4.97×10^3 | 97.85 | 7.32×10^7 | 89.56 |
| Low E_{Shower} | 156.37 | 33.19 | 3.53×10^3 | 71.09 | 4.06×10^7 | 55.12 |

3.3.3 Pre-Selection

Pre-selection aims to remove obvious background events without significantly affecting the signal. The criterion we chose for the selection of these cuts is determined by the reduction of the signal efficiency by approximately 0.25 % with each cut. This results in the total pre-selection reduction of the signal efficiency by approximately 1 %.

The first two variables used for our pre-selection are the same as were used in the event selection for the ν_e appearance **ND** constraint for the three flavour neutrino

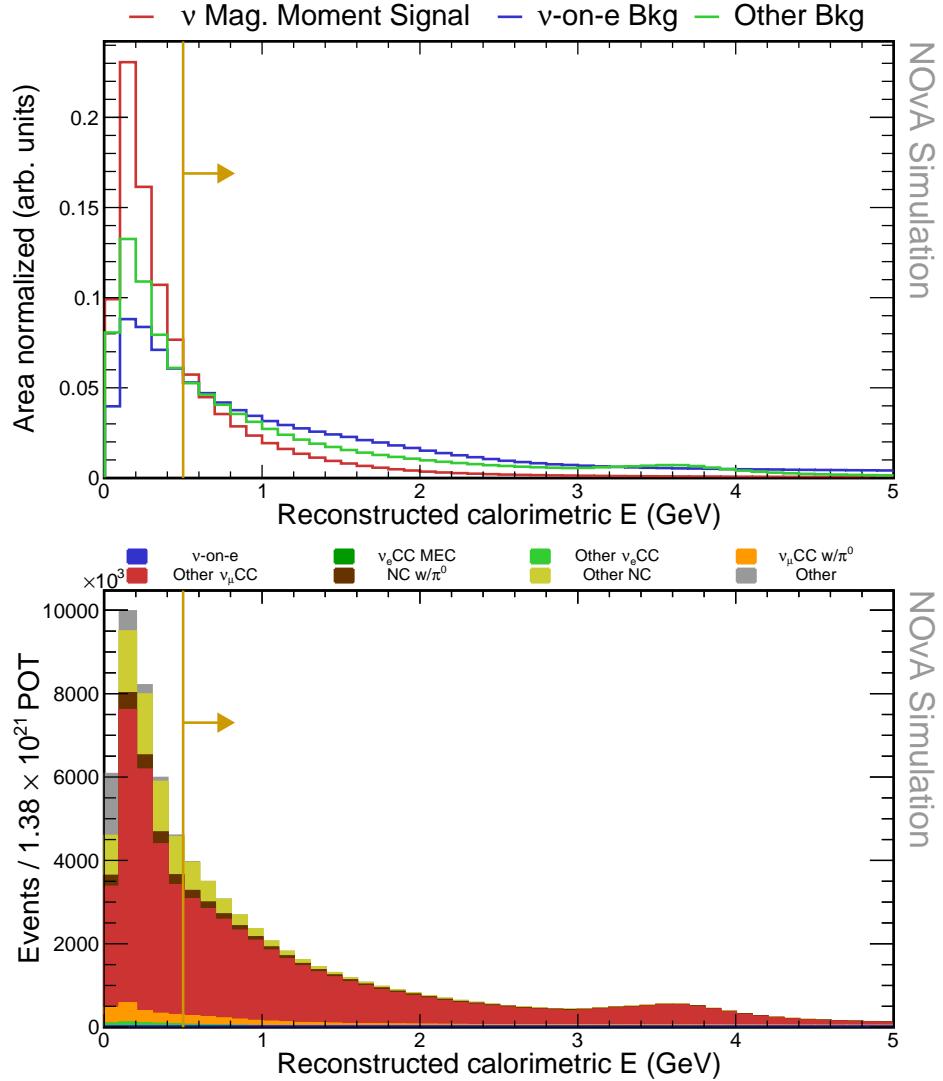


Figure 3.8: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the reconstructed calorimetric energy distribution. All histograms are area-normalised. Bottom: Decomposition of background into various sub-samples, normalised to the data POT exposure. Events in both plots are required to have a valid reconstructed vertex, at least one reconstructed prong and less than 6 hits per plane. Yellow lines indicate the cut value for the reconstructed calorimetric energy, with arrows pointing towards the preserved events.

oscillation measurements [54]. As we are searching for single electron showers, we can reduce backgrounds with multiple final state particles by limiting the total activity in the detector. Specifically, we require that the total number of hits assigned to all the reconstructed prongs is < 280 . This is shown in Fig. 3.9. In general, the main background in NOvA consists of the ν_μ CC interactions, which are characterised by long muon tracks. We therefore limit the length of the longest reconstructed prong to be < 640 cm, as shown in Fig. 3.10.

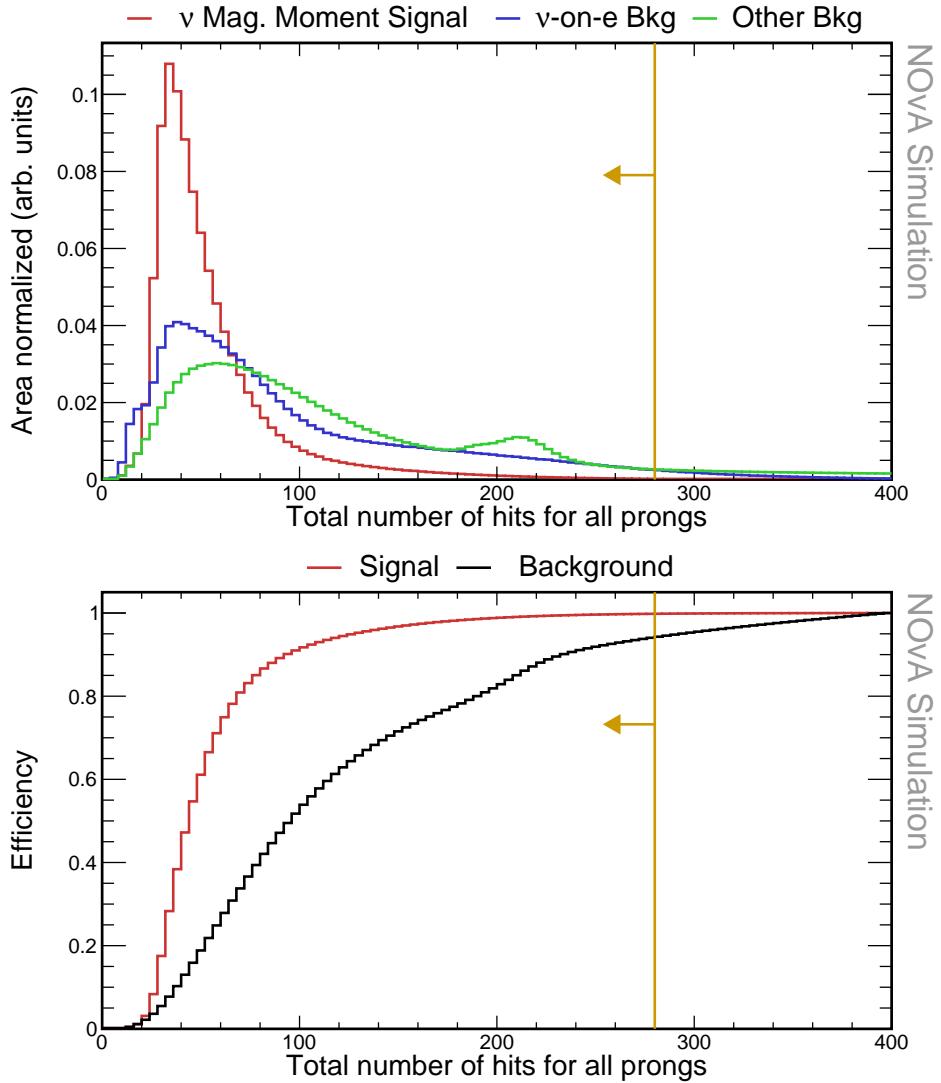


Figure 3.9: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of total number of hits from all reconstructed prongs in the slice. All histograms are area-normalised. Bottom: Cumulative signal (red) and background (black) efficiency calculated as number of signal/background events left of the bin divided by the total number of signal/background events. Yellow lines indicate the cut value for the maximum number of hits, with arrows pointing towards the preserved events. The reconstruction quality cuts were applied before making these plots.

Additionally, as discussed in Sec. 3.1.2, simple $2 \rightarrow 2$ kinematics dictate that the true electron recoil energy and angle for the $\nu\text{-on-e}$ interaction are limited by $E\theta^2 < 2m_e$. This can be used to distinguish the $\nu\text{-on-e}$ elastic scattering from $\nu_e\text{CC}$ interactions, which also have an electron in the final state. However, due to unavoidable reconstruction deficiencies, the reconstructed $E\theta^2$ does not have such a strict cut-off value, and we are placing the pre-selection cut at $E\theta^2 < 0.064$, as can be seen in Fig. 3.11. Furthermore, some of the signal events can be reconstructed with the opposite direction with respect to the beam, which would result in $\theta \approx \pi$ rad. However, this reconstruction failure likely does not impact other reconstructed qualities and these events should be preserved for the final sample. For that reason, we are calculating the angle between the outgoing electron and the neutrino beam direction as $\text{acos}(\text{abs}(\cos \theta))$, which gives the same value whether the shower is reconstructed forward or backwards.

The effect of the pre-selection cuts on the signal and background samples are summarised in Tab. 3.4, where the first row lists the number of events after applying all the reconstruction quality cuts from Sec. 3.3.2. All three of the variables used for the pre-selection are employed again in the MVA, as described in Sec. 3.3.5.

Table 3.4: Pre-selection cutflow table showing the number of events and the relative efficiency of each cut for each signal sample. The relative efficiency is calculated as number of events remaining after applying the corresponding cut divided by number of event for all the previous cuts. All the cuts are listed in sequence as they are applied. The top row corresponds to the sample after applying the reconstruction quality cuts.

| Selection | Signal | | $\nu\text{-on-e}$ bkg | | Other bkg | |
|-------------------------------------|------------------|------------------------------|---|------------------------------|--------------------|------------------------------|
| | N_{evt} | $\epsilon_{\text{rel}} (\%)$ | N_{evt} | $\epsilon_{\text{rel}} (\%)$ | N_{evt} | $\epsilon_{\text{rel}} (\%)$ |
| Reco Quality | 156.37 | 100 | 3.53×10^3 | 100 | 4.28×10^7 | 100 |
| No Hits Loose | 156.05 | 99.79 | 3.41×10^3 | 96.46 | 3.61×10^7 | 84.35 |
| Prong Length | 155.7 | 99.78 | 3.37×10^3 | 98.85 | 2.61×10^7 | 72.36 |
| $E\theta^2$ Loose | 155.14 | 99.64 | 3.33×10^3 | 98.83 | 8.83×10^6 | 33.82 |

3.3.4 Fiducial and containment cuts

To ensure all the deposited energy of the recoil electron is contained within the detector and to remove events originating outside of the detector (such as rock muons for the ND), we constrain the position of the reconstructed vertex and all the prongs in the slice. Decision on where to place the exact cut values is made based on the

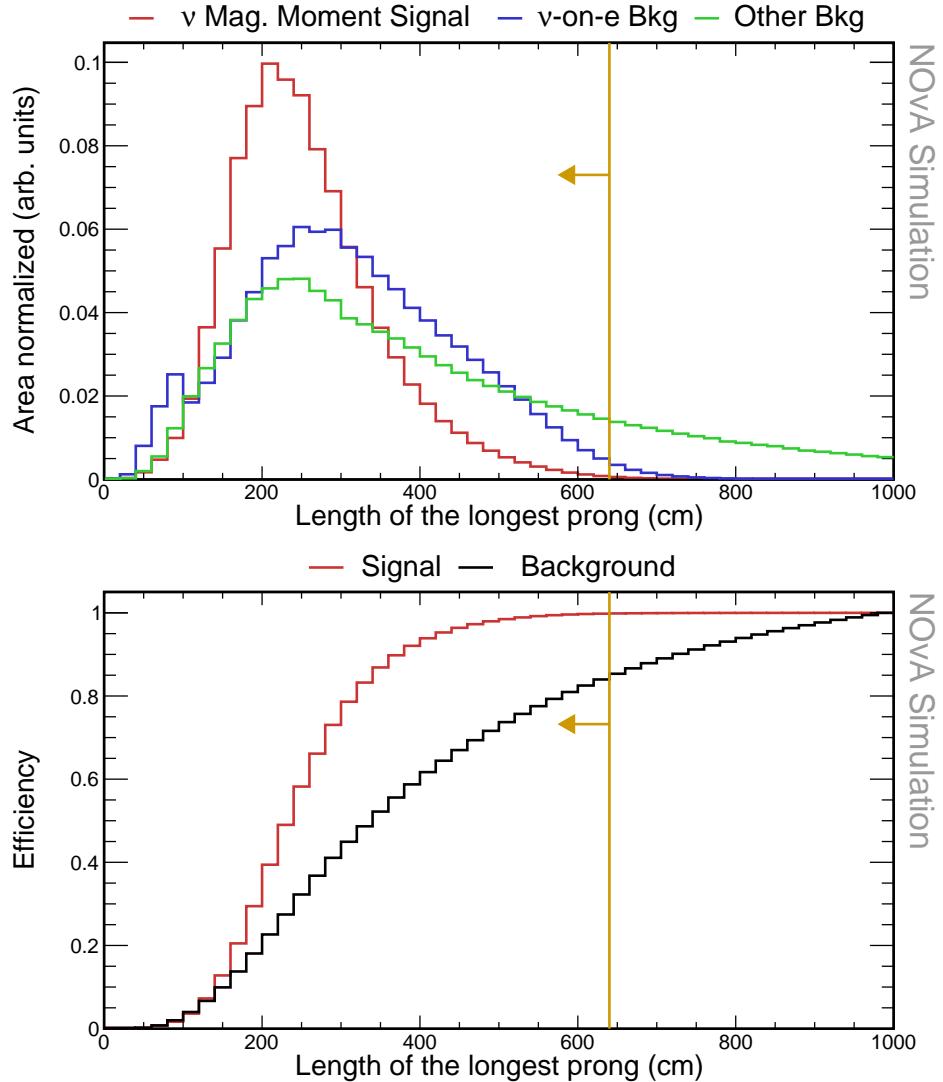


Figure 3.10: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the length of the longest reconstructed prong in slice. All histograms are area-normalised. Bottom: Cumulative signal (red) and background (black) efficiency calculated as number of signal/background events left of the bin divided by the total number of signal/background events. Yellow lines indicate the cut value for the maximum length of the longest prong, with arrows pointing towards the preserved events. The reconstruction quality cuts and the number of hits cut were applied before making these plots.

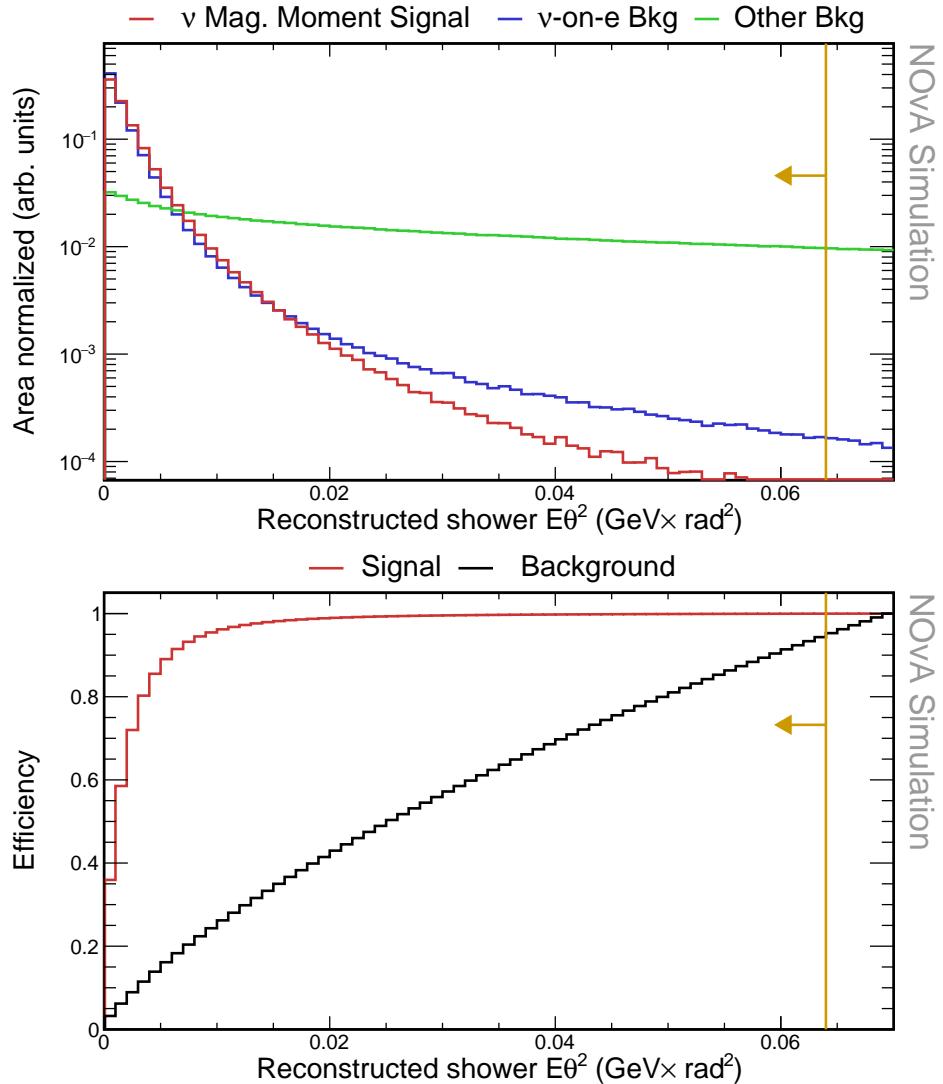


Figure 3.11: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the reconstructed energy of the leading shower multiplied by its angle from the incoming neutrino beam direction squared. All histograms are area-normalised with logarithmic y axis. Bottom: Cumulative signal (red) and background (black) efficiency calculated as number of signal/background events left of the bin divided by the total number of signal/background events. Yellow lines indicate the cut value for the depicted variable, with arrows pointing towards the preserved events. The reconstruction quality cuts, the number of hits cut, and the length of the longest prong cuts were applied before making both of these plots.

maximum FOM value.

The reconstructed vertex is required to be within the fiducial volume, which represents a well-understood and trusted volume of the detector. To select the fiducial volume, we investigate distributions of the reconstructed vertex in the x, y and z direction, shown in Fig. 3.12, 3.13 and 3.14 respectively. Basic reconstruction quality and pre-selection cuts are applied to make these distributions. Additionally, for the x and y position distributions, we require that the vertex is not placed inside of the Muon Catcher by requiring $Vtx_Z < 1270$ cm, as it can significantly affect these distributions. The slanted distributions in x and y are caused by the off-axis nature of the NuMI beam and the periodic peaks are due to a combination of the detector structure and the choice of binning.

The reconstructed vertex is required to be contained within the following volume:

$$-175 \text{ cm} < Vtx_X < 175 \text{ cm}, \quad (3.40)$$

$$-175 \text{ cm} < Vtx_Y < 175 \text{ cm}, \quad (3.41)$$

$$95 \text{ cm} < Vtx_Z < 1170 \text{ cm}. \quad (3.42)$$

Furthermore, we constrain the extreme positions (minimum and maximum) of all the hits within the most energetic prong, which is assumed to represent the electron shower for the signal events. We apply the reconstruction quality, pre-selection and fiducial (vertex position) cuts to their distributions, shown in Fig. 3.15-3.20 **COMMENT: Is it enough to reference these figures like this?**. The extreme hit positions are required to be within the following volume:

$$-175 \text{ cm} < \min_X, \max_X < 175 \text{ cm}, \quad (3.43)$$

$$-175 \text{ cm} < \min_Y, \max_Y < 175 \text{ cm}, \quad (3.44)$$

$$105 \text{ cm} < \min_Z, \max_Z < 1270 \text{ cm}. \quad (3.45)$$

3.3.5 Multivariate Analysis

Following the removal of obvious backgrounds and events not contained within the detector, we aim to optimise the event selection to achieve the highest significance

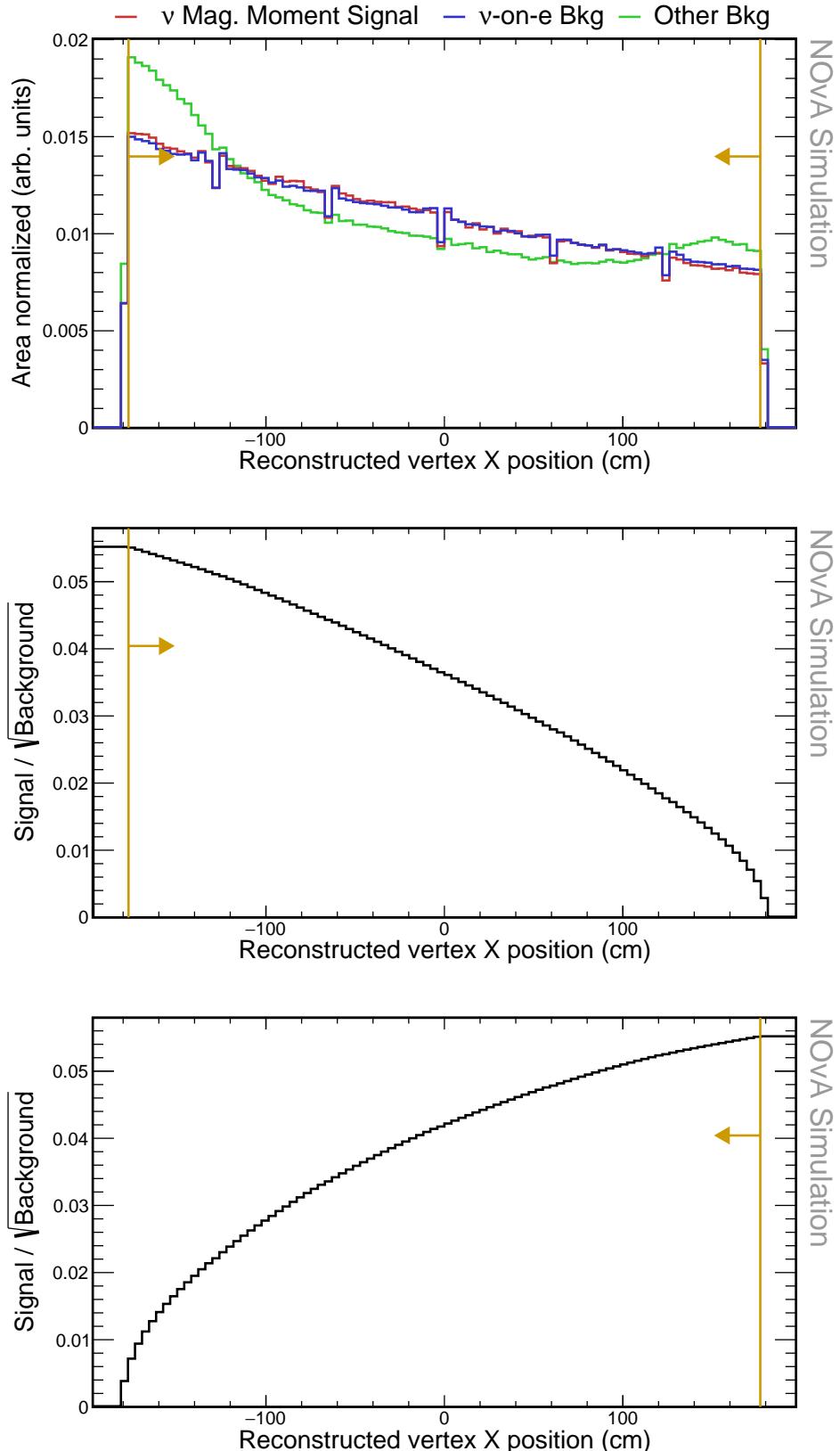


Figure 3.12: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the x position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality and pre-selection cuts were applied prior to making these plots. Additionally, vertex is required to be within the active region of the detector ($Vtx_Z < 1270$ cm). Yellow lines show the cut values that create the fiducial volume, with arrows pointing towards the preserved events.

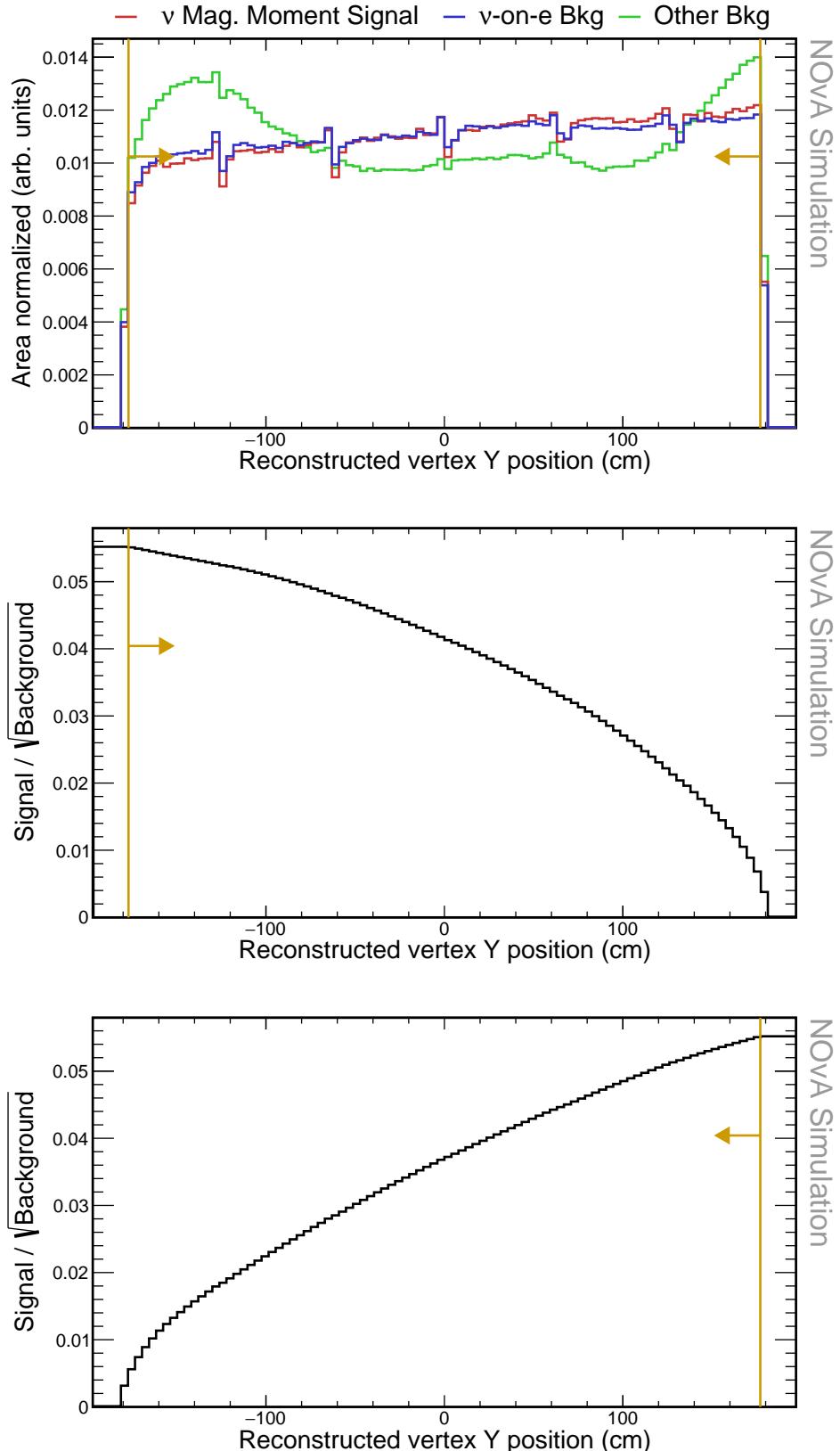


Figure 3.13: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the y position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality and pre-selection cuts were applied prior to making these plots. Additionally, vertex is required to be within the active region of the detector ($Vtx_Z < 1270$ cm). Yellow lines show the cut values that create the fiducial volume, with arrows pointing towards the preserved events.

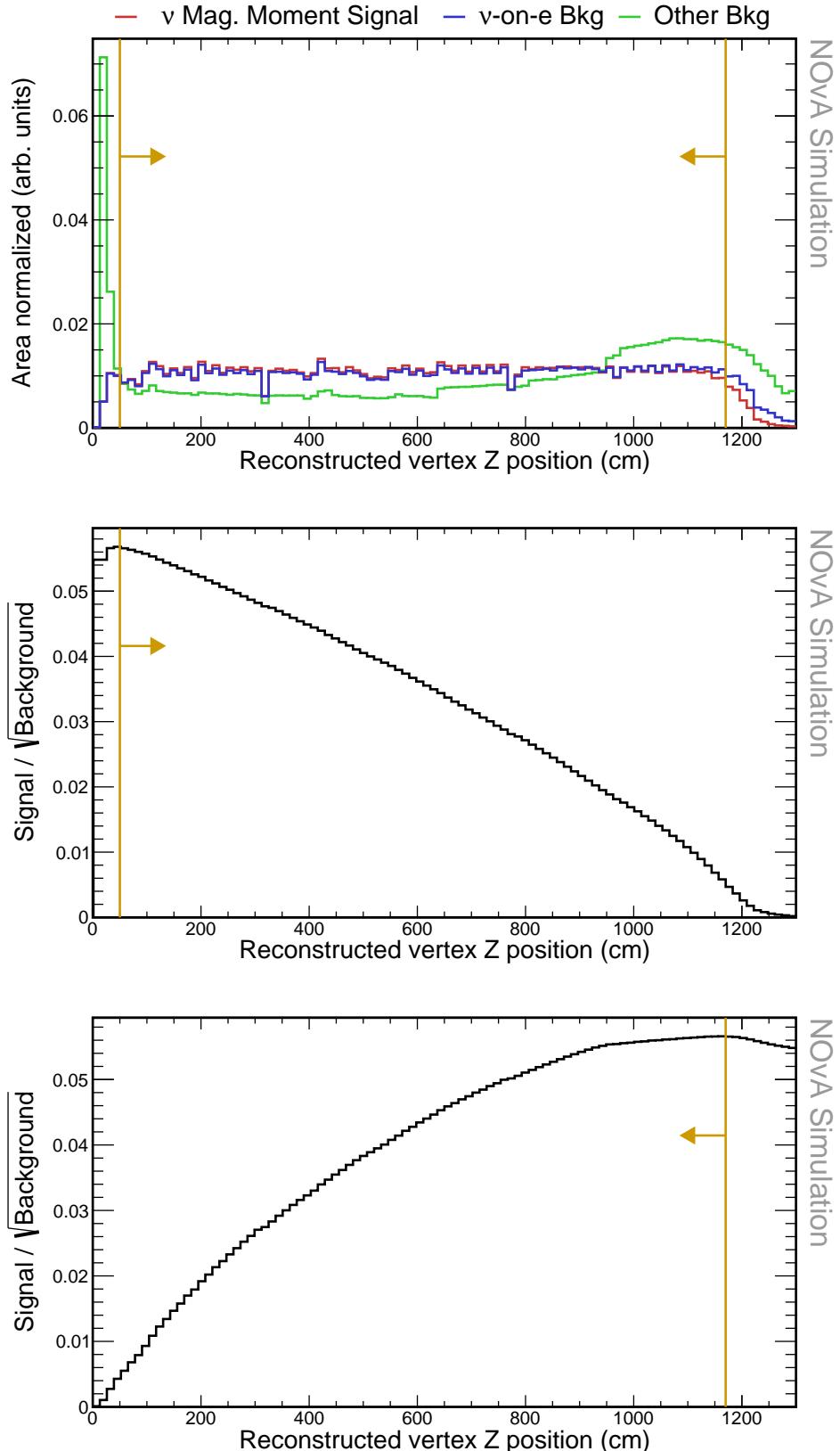


Figure 3.14: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the z position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality and pre-selection cuts were applied prior to making these plots. Yellow lines show the cut values that create the fiducial volume, with arrows pointing towards the preserved events.

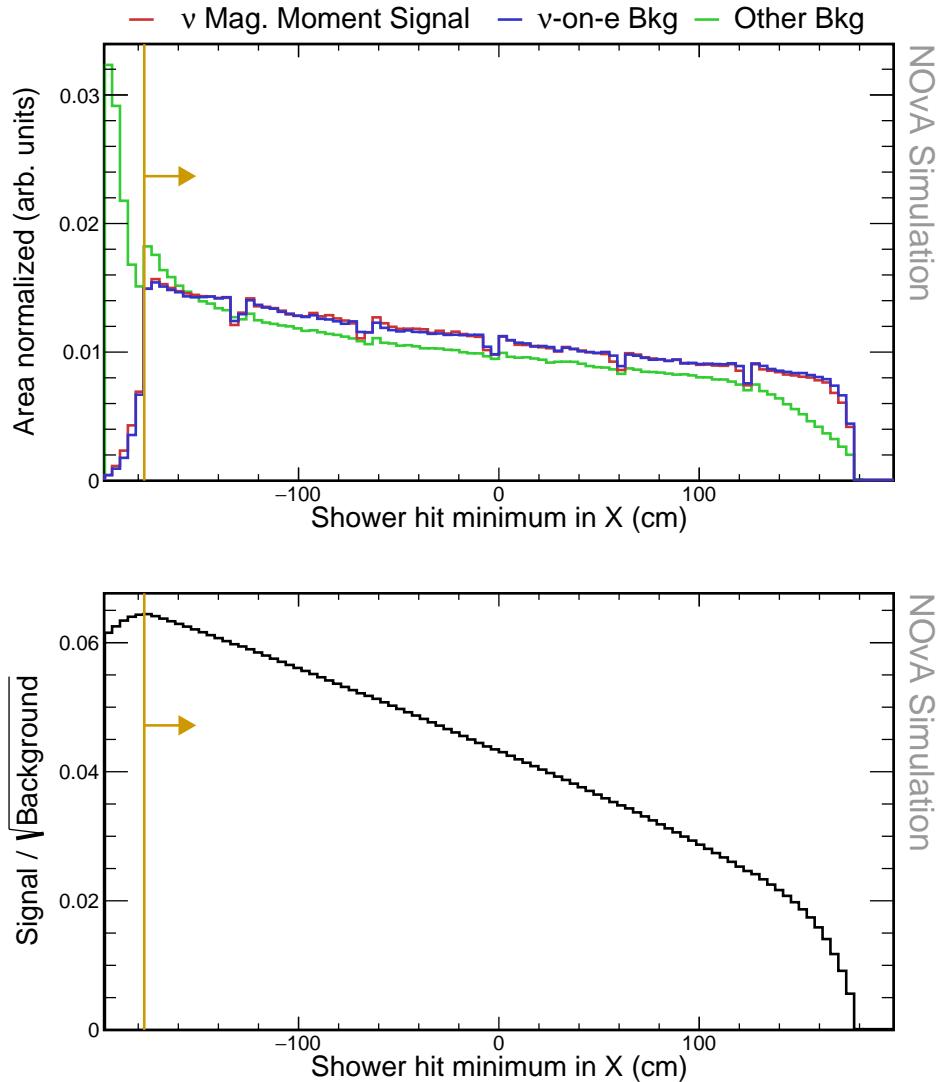


Figure 3.15: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the minimum hit position of the most energetic prong along the x axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

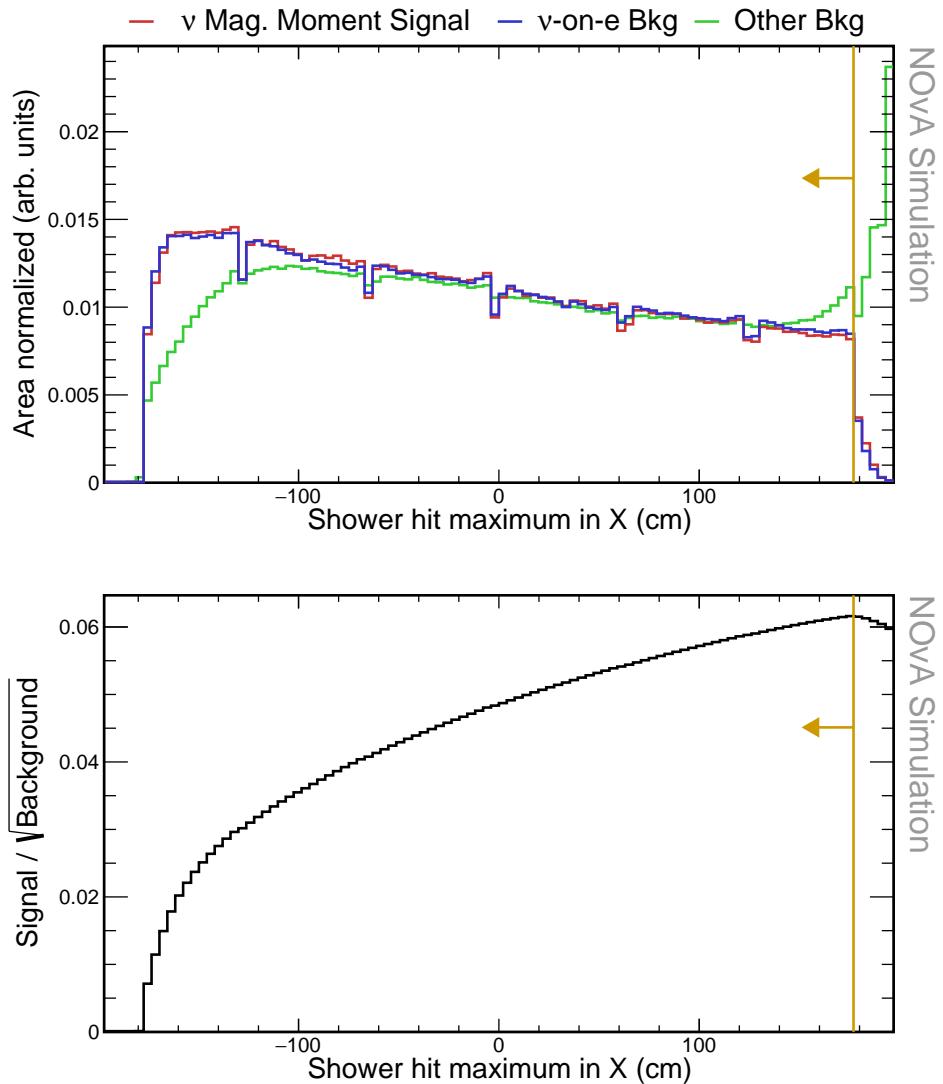


Figure 3.16: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the maximum hit position of the most energetic prong along the x axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

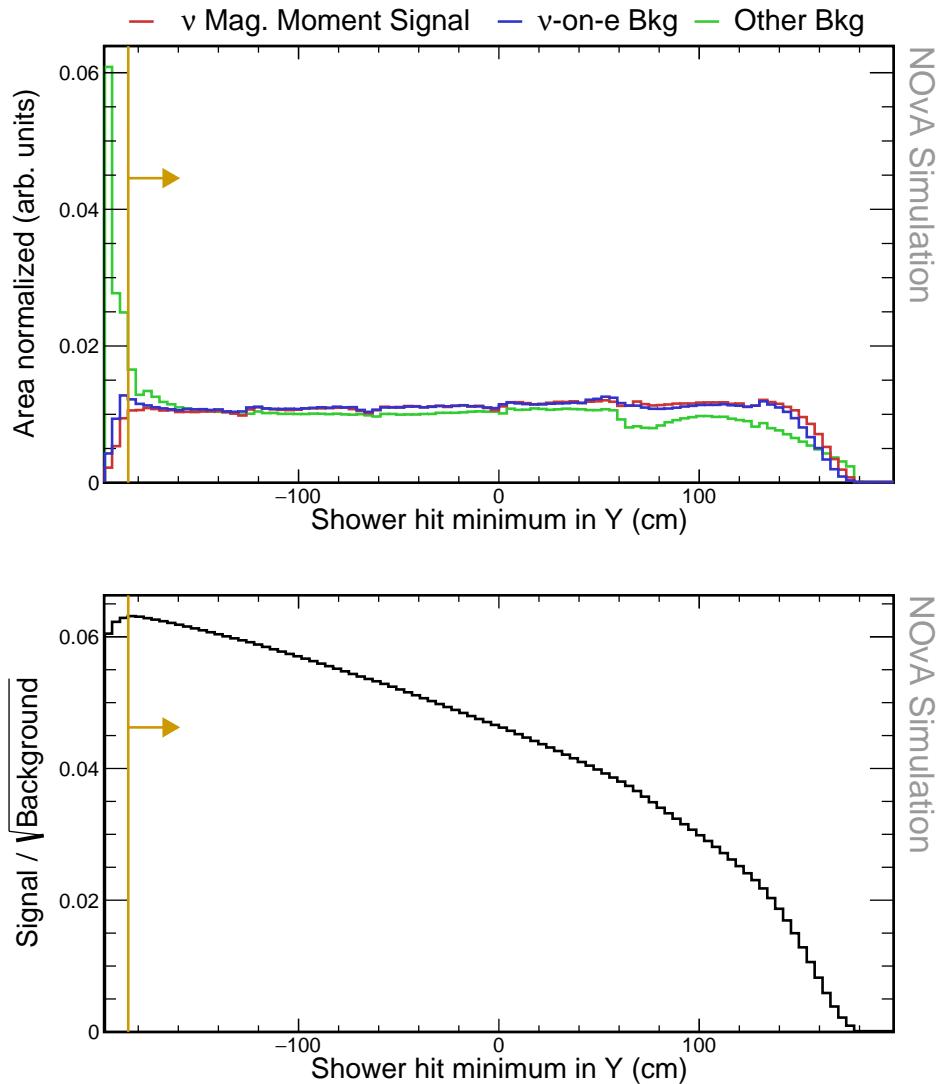


Figure 3.17: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the minimum hit position of the most energetic prong along the y axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

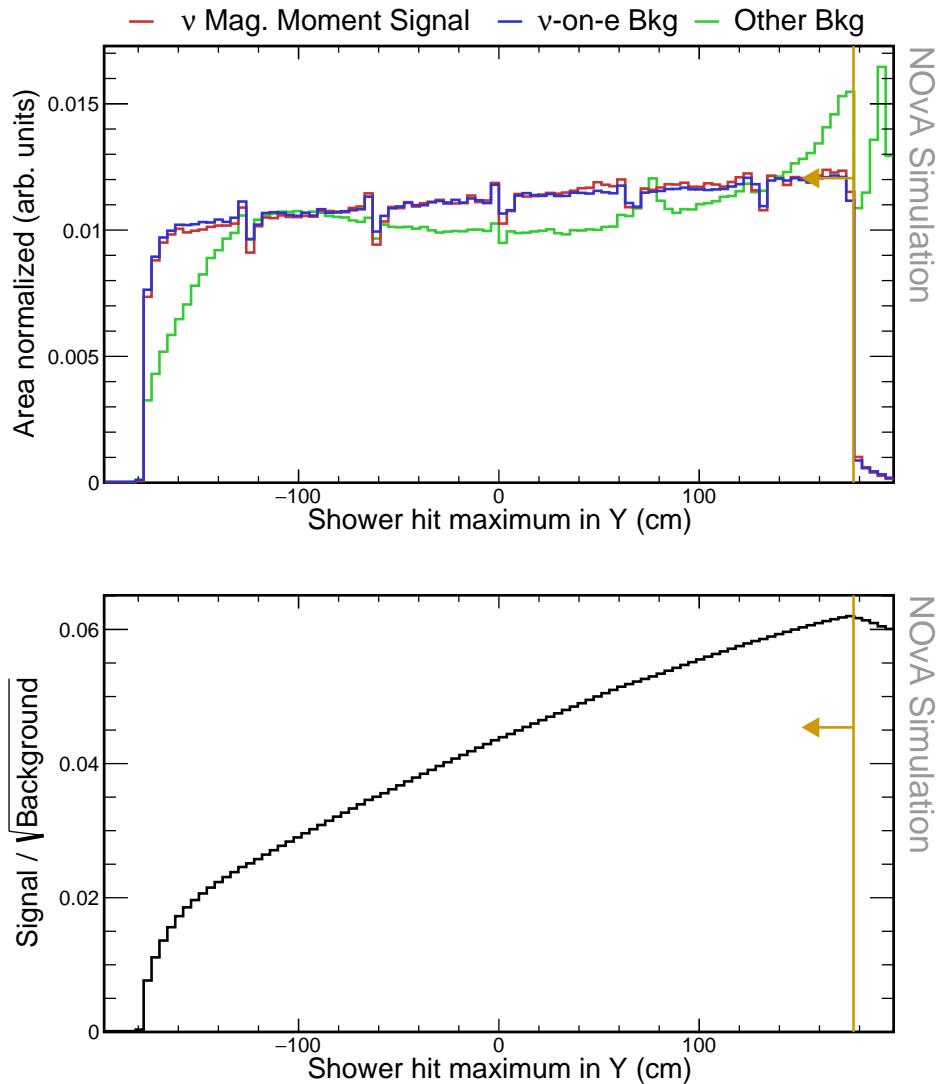


Figure 3.18: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the maximum hit position of the most energetic prong along the y axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

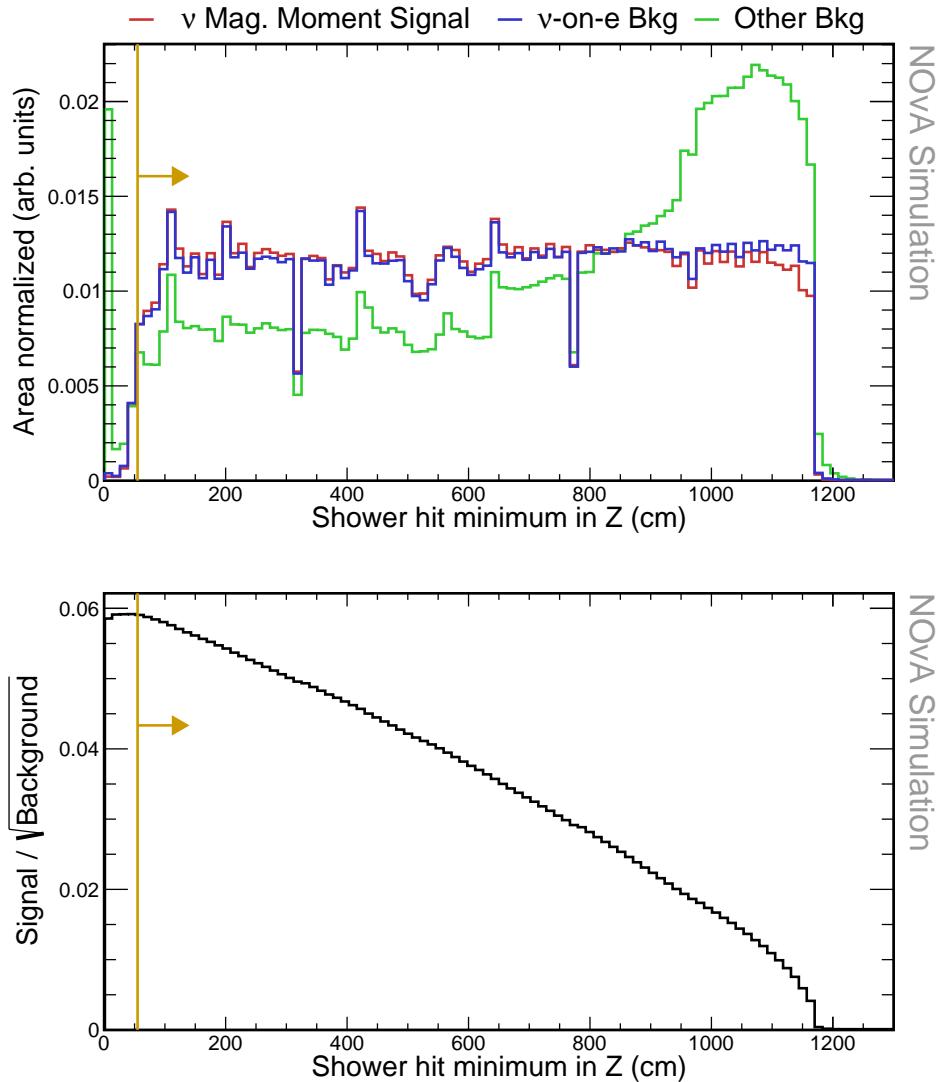


Figure 3.19: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the minimum hit position of the most energetic prong along the z axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

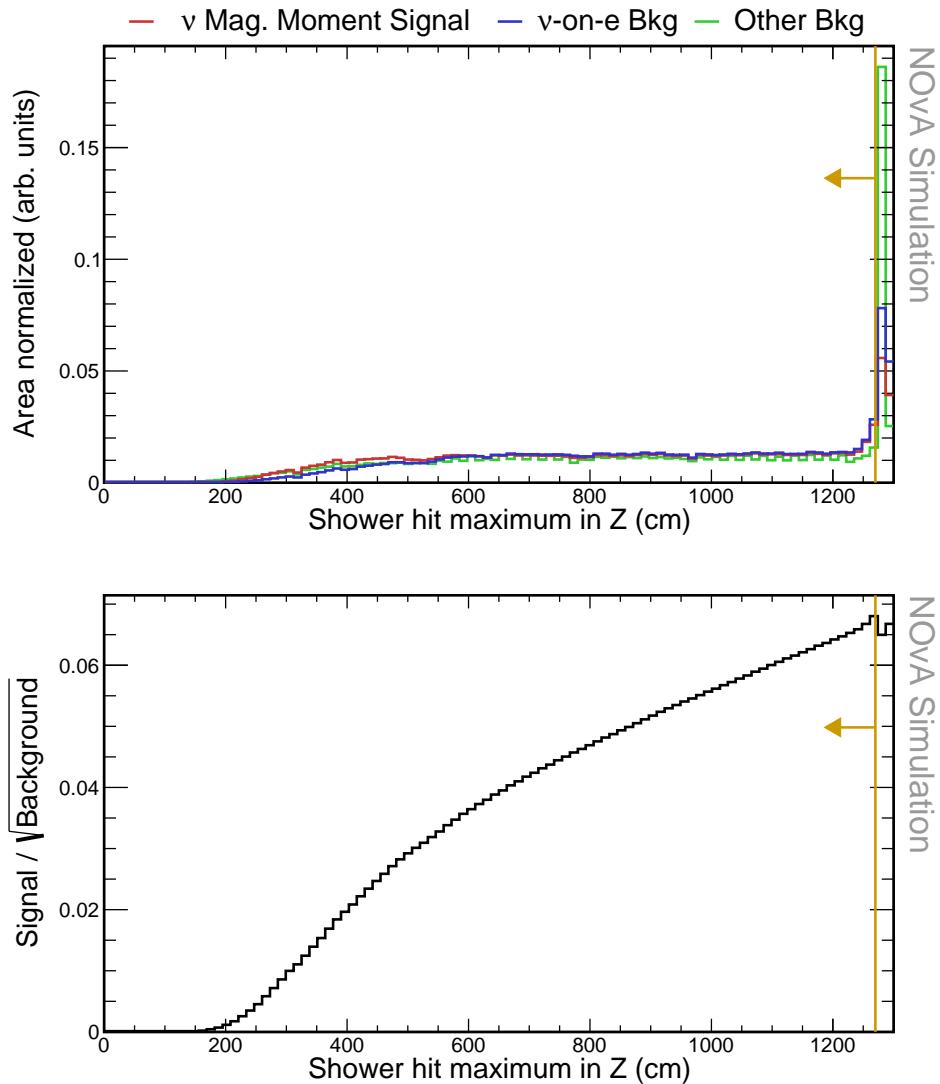


Figure 3.20: Top: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the maximum hit position of the most energetic prong along the z axis. All histograms are area-normalized. Bottom: Cumulative FOM calculated as the number of signal events, divided by the number of background events from that bin until the end of the plot in the direction of the yellow arrow. The reconstruction quality, pre-selection and fiducial cuts were applied prior to making these plots. Yellow lines show the cut values that create the containment volume, with arrows pointing towards the preserved events.

for measuring the effective muon neutrino magnetic moment. This goal is equivalent to maximising our FOM from Eq. 3.39.

For this purpose, we utilise ROOT’s [169] Tool for MVA (TMVA) [170]. Specifically, we employ the rectangular cut optimisation method, which uses multivariate parameter fitters to maximise background rejection across the full range of signal efficiencies. We use the MC sampling fitting method, assuming that for each input variable, there is a single cut value (maximum or minimum) that optimally discriminates between signal and background.

TMVA generally performs better with a limited number of input variables that have strong discriminating power. Therefore, we investigated several input variables and selected only those that achieved significant background rejection. There are additional variables not mentioned here that might achieve better final results, providing opportunities for future re-analyses. Additionally, we do not apply any transformations to the input variables prior to optimisation, which might also improve the final result after dedicated study.

The variables considered include those already used in the pre-selection: the total number of hits for all prongs in slice, the length of the longest prong, and $E\theta^2$, as discussed in Sec. 3.3.3. During the TMVA optimisation, we found that the length of the longest prong did not significantly enhance discriminating power and thus removed it from the set of input variables. Additionally, we included the reconstructed energy of the most energetic shower, as used for reconstruction quality selection in Sec. 3.3.2, intending to restrict events with higher energies, since our signal is concentrated at low electron recoil energies.

Table 3.5: Event selection cutflow table for the containment cuts showing the number of events and the relative efficiency of each cut for each signal sample. The relative efficiency is calculated as number of events remaining after applying the corresponding cut divided by number of event for all the previous cuts. All the cuts are listed in sequence as they are applied. The top row corresponds to the sample after applying the reconstruction quality and pre-selection cuts.

| Selection | Signal | | ν-on-e bkg | | Other bkg | |
|----------------------|---------------|----------------------|----------------------------------|----------------------|--------------------|----------------------|
| | N_{evt} | ϵ_{rel} (%) | N_{evt} | ϵ_{rel} (%) | N_{evt} | ϵ_{rel} (%) |
| Pre-selection | 155.14 | 100 | 3.33×10^3 | 100 | 8.83×10^6 | 100 |
| Fiducial | 143.02 | 92.19 | 2.88×10^3 | 85.60 | 5.96×10^6 | 67.57 |
| Containment | 117.41 | 82.09 | 2.08×10^3 | 72.12 | 1.10×10^6 | 18.38 |

Additionally, we considered all the variables used for the NOvA ν -on-e analysis for the neutrino flux constraint [153]. The first is the fraction of the reconstructed energy of the most energetic shower (E_{Shower}) to the total energy of all the reconstructed prongs in the entire slice (E_{Tot}). This variable distinguished our signal events, which only have a single shower, from events with multiple showers or additional activity. The second is the gap between the vertex and the most energetic shower, which can distinguish between electron and π^0 events, as the latter should have a characteristic gap several cells long. Additionally, we examined the amount of energy contained within ± 8 planes away from the vertex, besides the energy associated with the most energetic prong, which should distinguish the purely leptonic signal from backgrounds with significant hadronic activity. However, the gap and the vertex energy variables underperformed compared to others and were ultimately not used within the TMVA.

We also utilise two CNN-based event classifiers developed for the NOvA ν -on-e analysis for the neutrino flux constraint [153, 154]. These classifiers are specifically designed to identify ν -on-e interactions. The first, named ν -on-e ID, is trained to select ν -on-e events from the primary ν_μ CC background, while the second, named $E\pi^0$ ID, is trained on events passing the ν -on-e ID selection to reject the remaining background with a π^0 . These classifiers use a pixel map of the entire slice as input and are designed with the same CNN architecture as ProngCVN and EventCVN described in Sec. 2.5. *COMMENT: Do I need to describe these more? - pre-selection cuts and so on? Should I mention here that they were evaluated for events above 0.5GeV, or is it enough that I mentioned it in the beginning?*

The result of the TMVA is a set of cuts on each of the input variables that maximises the FOM. The input variables the cuts that were selected for them are shown in Fig. 3.21, 3.22, and 3.23. The effect of these cuts is summarised in Tab. 3.6. Applying the TMVA cuts reduces the signal by 51.62 %, the ν -on-e background by 75.03 % and other background by 99.98 %. The specific values of the cuts resulting from the

TMVA are

$$E_{Shower}/E_{Tot} > 0.91, \quad (3.46)$$

$$\text{Total } N^o \text{ hits for all prongs} < 116, \quad (3.47)$$

$$E_{Shower} < 1.4 \text{ GeV}, \quad (3.48)$$

$$E\theta^2 < 0.0048 \text{ GeV} \times \text{rad}^2, \quad (3.49)$$

$$\nu - on - eID > 0.65, \quad (3.50)$$

$$E\pi^0 ID > 0.63. \quad (3.51)$$

Table 3.6: Event selection cutflow table for the results of the cut-based Multivariate analysis, showing the number of events and the relative efficiency of each cut for each signal sample. The relative efficiency is calculated as number of events remaining after applying the corresponding cut divided by number of event for all the previous cuts. All the cuts are listed in sequence as they are applied. The top row corresponds to the sample after applying the reconstruction quality, pre-selection, fiducial and containment cuts.

| Selection | Signal | | ν-on-e bkg | | Other bkg | |
|-------------------------------------|---------------|-----------------------|----------------------------------|-----------------------|--------------------|-----------------------|
| | N_{evt} | $\epsilon_{rel} (\%)$ | N_{evt} | $\epsilon_{rel} (\%)$ | N_{evt} | $\epsilon_{rel} (\%)$ |
| Contained | 117.41 | 100 | 2.08×10^3 | 100 | 1.10×10^6 | 100 |
| E_{Shower}/E_{Tot} | 113.03 | 96.28 | 2.02×10^3 | 97.32 | 4.53×10^5 | 41.30 |
| N^o Hits | 106.48 | 94.20 | 1.45×10^3 | 71.53 | 4.02×10^5 | 88.78 |
| High E_{Shower} | 85.51 | 80.31 | 777.91 | 53.76 | 3.01×10^5 | 74.84 |
| ν-on-e ID | 72.23 | 84.47 | 652.32 | 83.86 | 4.40×10^3 | 1.46 |
| $E\pi^0$ ID | 67.35 | 93.24 | 608.19 | 93.23 | 2.83×10^3 | 64.34 |
| $E\theta^2$ | 56.80 | 84.33 | 519.09 | 85.35 | 181.24 | 6.40 |

After the full event selection, the predicted number of signal events for $\mu_\nu = 10^{-9}\mu_B$ is 56.80, and the total number of background events under the SM hypothesis is 700.33. This results in

$$\text{Signal Purity} = \frac{\text{Signal}}{\text{Signal+Background}} = 7.50 \%, \quad (3.52)$$

$$\text{Signal Efficiency} = \frac{\text{Signal}}{\text{Signal}_{\text{No Cut}}} = 6.95 \%. \quad (3.53)$$

Also,

$$\frac{\text{Signal}}{\sqrt{\text{Background}}} = 2.15 \quad (3.54)$$

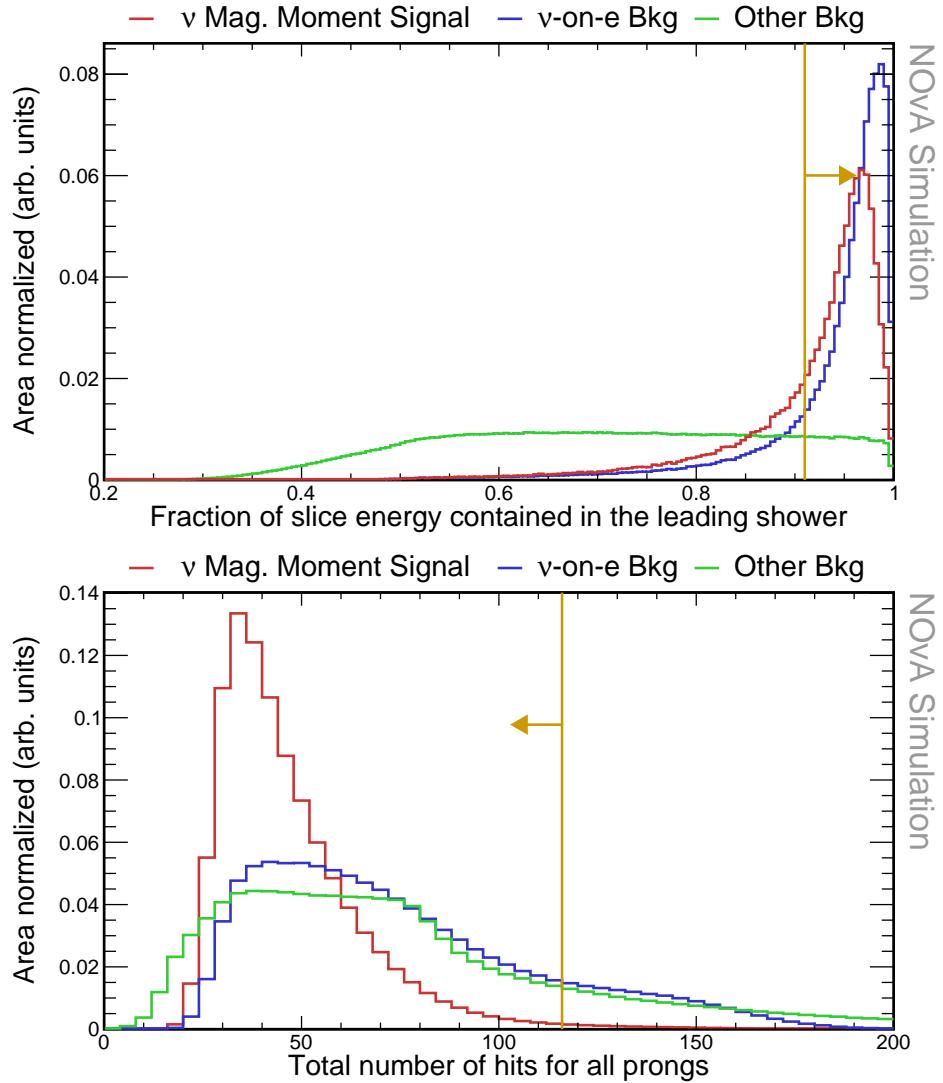


Figure 3.21: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the fraction of the total energy contained in the primary shower (top) and of the total number of hits in the slice (bottom). All histograms are area-normalized. The reconstruction quality, pre-selection, fiducial and containment cuts were applied prior to making these plots. Yellow lines show the cut values on the depicted variables, with arrows pointing towards the preserved events.

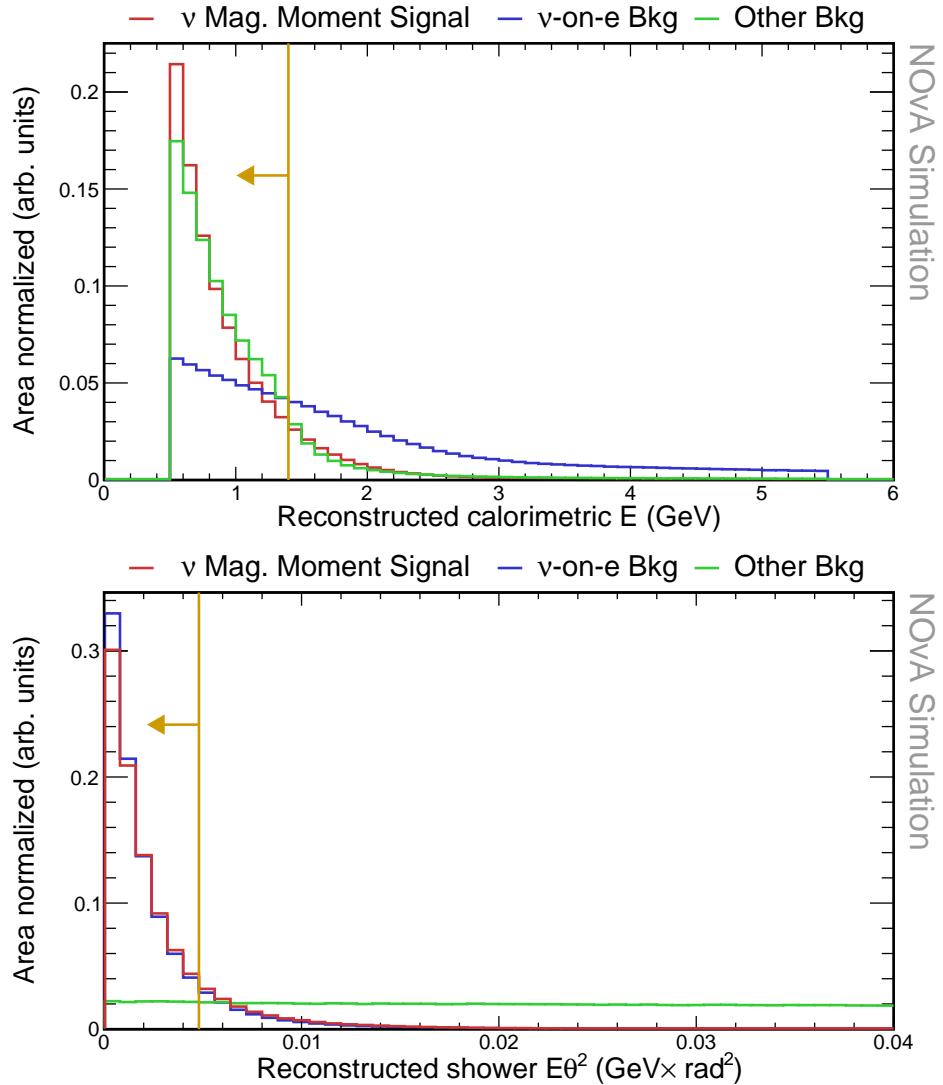


Figure 3.22: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the reconstructed energy of the primary shower (top) and of the reconstructed energy multiplied by the angle from the incoming neutrino beam direction squared.(bottom). All histograms are area-normalized. The reconstruction quality, pre-selection, fiducial and containment cuts were applied prior to making these plots. Yellow lines show the cut values on the depicted variables, with arrows pointing towards the preserved events.

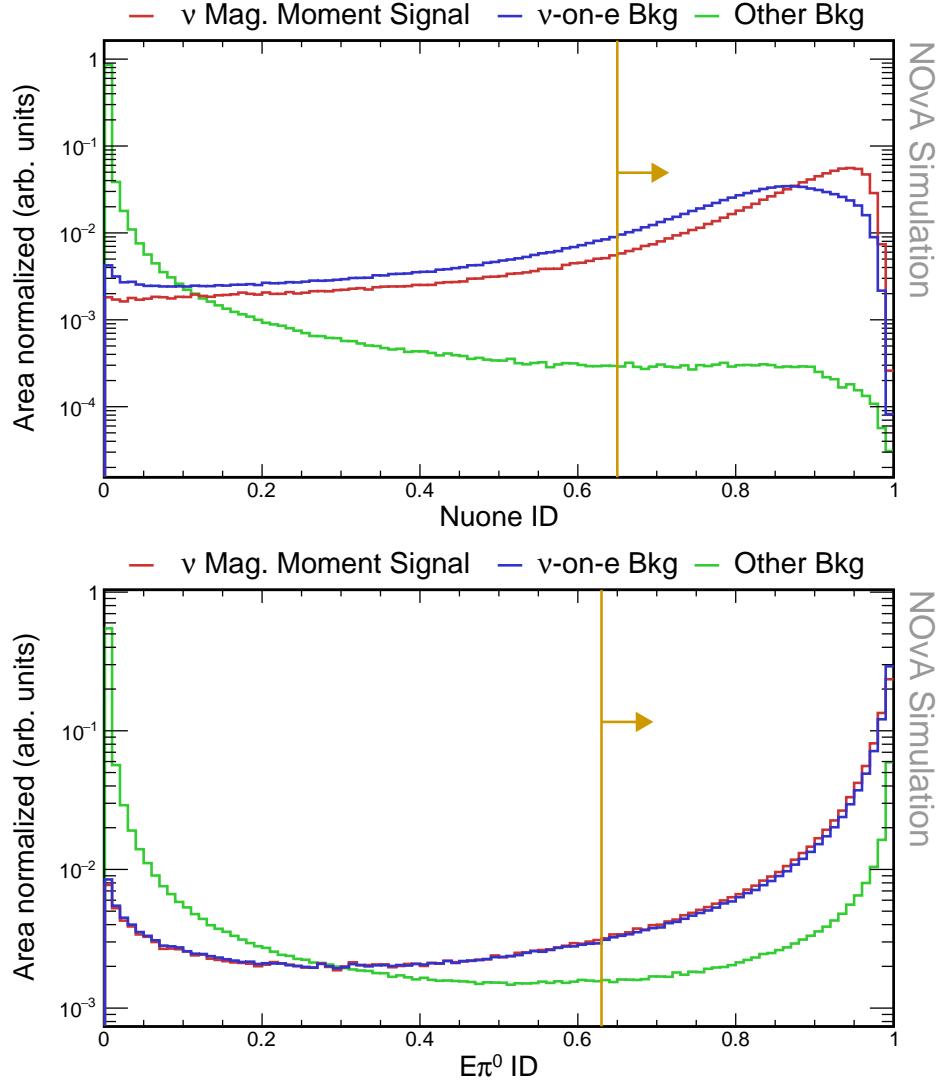


Figure 3.23: Relative comparison of signal (red), ν -on-e background (blue), and other background (green) events in the distribution of the NuoneID (top) and EPi0ID (bottom) event identifiers. All histograms are area-normalized. The reconstruction quality, pre-selection, fiducial and containment cuts were applied prior to making these plots. Yellow lines show the cut values on the depicted variables, with arrows pointing towards the preserved events.

and

$$\text{FOM} = \frac{\text{Signal}}{\sqrt{\text{Signal+Background}}} = 2.06. \quad (3.55)$$

3.4 Systematic uncertainties

3.5 Results

Show the money plot - full prediction in the binned energy distribution, including the full statistical and systematic uncertainties

Write out the total number of measured events and their corresponding uncertainties

Explain what are the results of the fit and the limits, discuss the statistical significance of the result

We are basically doing two separate things:

1. Testing a hypothesis that there is no magnetic moment present in the signal.
Can we reject the null hypothesis given our data?
2. If we can reject the null hypothesis we want to estimate the best fit of the parameter. Additionally, we want to put a limit (set a confidence interval) on the magnetic moment parameter.

What should be included here:

- Fit methodology: Detail the fitting techniques used to extract the muon neutrino magnetic moment from the data.
- Fit validation: Describe how the fit is validated, including any statistical tests used.
- Fake data studies: Explain the use of fake data or Monte Carlo simulations to test the robustness of the analysis.

3.6 Discussion

What should be included here:

- Interpretation: Interpret the results in the context of the current understanding of neutrino physics.
- Implications: Explain the broader implications of your findings for the field of particle physics.
- Future work: Suggest directions for future research based on your results.
 - Improvements in NOvA, more FHC data, including RHC data, better reconstruction, better simulation and calibration, better event selection, including sideband samples, more systematics studies, better fitting techniques...
 - Future beyond NOvA - DUNE
 - * What are the possibilities for DUNE?

3.7 Summary

Summarize the results and compare them to the introduction, including comparisons to other experiments and theory. Restate the significant of the measurement

Closing remarks

Acronyms

ν -on-e neutrino-on-electron. 37, 38, 40, 44–53, 55–63, 65–79

2p2h two particle - two hole. 5, 6, 21

ADC Analog-to-Digital Converter. 19, 26, 29

APD Avalanche Photodiode. 16, 18, 19, 22, 29, 30, 57

ASIC Application-Specific Integrated Circuit. 19

BDT Boosted Decision Tree. 26

BPF Break Point Fitter. 24

BSM Beyond Standard Model. 10–12, 37–39, 41, 42

C.L. Confidence Level. 37, 38

CC Charged Current. 1, 2, 4–6, 8, 9, 21–23, 46, 52, 53, 60, 62, 75

CEvNS Coherent Elastic ν -Nucleus Scattering. 6

CMC Comprehensive Model Configuration. 22

CNN Convolutional Neural Network. 25, 75

COH π Coherent π (production). 6, 21, 22

CP Charge conjugation - Parity (symmetry). 1, 8, 10, 13

CRY Cosmic-Ray Shower Generator. 22, 26

CVN Convolutional Visual Network. 25, 55, 58

DAQ Data Acquisition. 19, 23, 28

DCM Data Concentration Module. 19, 54

DIS Deep Inelastic Scattering. 5, 21, 22

DUNE Deep Underground Neutrino Experiment. 10, 13, 21

FB Fibre Brightness. 29, 30

FD Far Detector. 15–19, 22, 23, 28–31, 34

FEB Front End Board. 18–20, 29, 57

Fermilab Fermi National Accelerator Laboratory. 13, 16, 21

FHC Forward Horn Current (neutrino mode). 14, 15

FOM Figure Of Merit. 54, 62, 65–75, 80

FPGA Field Programmable Gate Array. 19

FSI Final State Interaction. 6, 21, 22

HK Hyper-Kamiokande. 10

HNL Heavy Neutral Lepton. 12

LBL Long Baseline. 10

LDM Light Dark Matter. 38

LOWESS Locally Weighted Scatter plot Smoothing. 31, 32

MC Monte Carlo. 20–22, 26, 50, 74

MEC Meson Exchange Current. 6, 21, 22, 52, 53

MEU Muon Energy Unit. 33

MI Main Injector. 13, 14, 20

MIP Minimum Ionising Particle. 26, 30, 32

MIPP Main Injector Particle Production (experiment). 21

ML Machine Learning. 24–26, 55

MSW Mikheyev-Smirnov-Wolfenstein. 9

MVA Multi Variate Analysis. 53, 62, 74, 84

NC Neutral Current. 1–4, 6, 8, 9, 23, 25

ND Near Detector. 13–17, 19, 22–24, 34, 36–38, 40, 43, 50, 53, 58, 62

NDOS Near Detector on the Surface. 16

NOvA NuMI Off-axis ν_e Appearance (experiment). 10, 13–26, 28–34, 36–38, 40, 43, 45, 47–50, 52, 53, 55, 58, 60, 74, 75

NP New Physics. 11, 42

NuMI Neutrinos from the Main Injector. 13–16, 20, 21, 23, 64

PE Photo Electron. 18, 19, 27, 29–31

PECorr Corrected Photo Electrons. 31, 33

PID Particle Identification. 25

PMNS Pontecorvo-Maki-Nakagawa-Sakata. 7, 8, 41, 42

POT Protons On Target. 13, 50, 52, 54, 59

PPFX Package to Predict the Flux. 21, 35, 50

PVC Polyvinyl chloride. 16–18, 34

QE Quasi Elastic (interaction). 4–6, 21, 22

ReMId Reconstructed Muon Identifier. 26

Res Resonant baryon production. 5, 21, 22

RHC Reverse Horn Current (antineutrino mode). 14, 15

SK Super-Kamiokande. 9

SM Standard Model. 1, 2, 10–12, 37, 39–42, 46–51, 54, 76

SNO Sudbury Neutrino Observatory. 9

T2K Tokai to Kamioka (experiment). 10

TMVA Tool for MVA. 74–76

WLS Wavelength Shifting (fibre). 16–18, 22, 26, 28, 30, 33

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