

# CHAPTER 1

## The NOvA experiment

The NuMI Off-axis  $\nu_e$  Appearance (NOvA) [1] is a long-baseline neutrino oscillation experiment based at the Fermi National Accelerator Laboratory (Fermilab) [2]. NOvA receives an off-axis  $\nu_\mu$  and  $\bar{\nu}_\mu$  beam from Fermilab’s Neutrinos from the Main Injector (NuMI) neutrino source (Sec. 1.1) and measures the  $\nu_e$  or  $\bar{\nu}_e$  appearance and the  $\nu_\mu$  or  $\bar{\nu}_\mu$  disappearance between its two highly active and finely segmented detectors (Sec. 1.4) [3].

The capability to measure both the  $\nu_e$  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  $\theta_{23}$ , and the possible Charge conjugation - Parity (CP) symmetry violation in the neutrino sector [3–7]. NOvA data also enables measurements of  $\theta_{13}$ ,  $\theta_{23}$  and  $|\Delta m_{32}^2|$  [3], measurements of neutrino differential cross sections in the Near Detector (ND) [8–11], constraints on the possible sterile neutrino models [12, 13], monitoring for supernova neutrino activity [14, 15], searches for magnetic monopoles [16], or 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. 1.8.

NOvA started taking data in February 2014 and is expected to run through 2026 [17], or until Fermilab begins redirecting its efforts towards the startup of the upcoming Deep Underground Neutrino Experiment (DUNE) experiment [18].

### 1.1 The Neutrino Beam

The neutrino beam for NOvA comes from the Fermilab-based NuMI neutrino source [19]. The schematic description of NuMI is shown in Fig. 1.1, starting on the left hand side with 120 GeV protons from the Main Injector (MI), part of the Fermilab accel-

erator complex. The proton beam is divided into  $10\ \mu\text{s}$  long pulses, with  $\sim 5 \times 10^{13}$  Protons On Target (POT) per spill every  $\sim 1.3\ \text{s}$  long cycle time, resulting in a proton beam power of  $\sim 800\ \text{kW}$  (current record  $959\ \text{kW}$  [20]), with upgrades currently underway to surpass  $1\ \text{MW}$  [21].

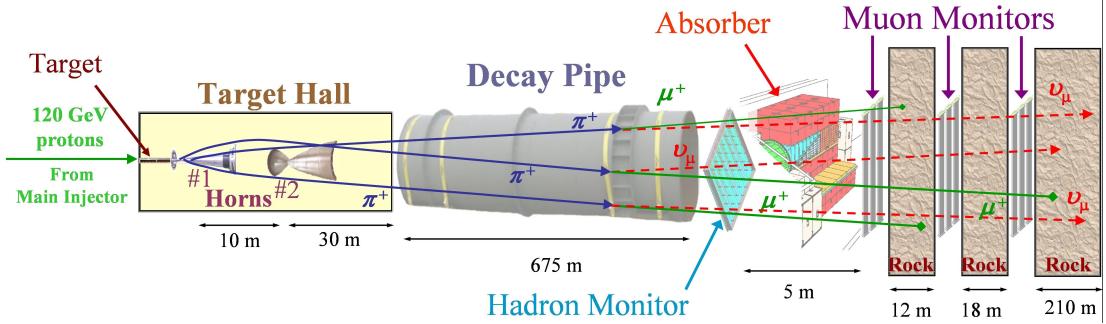


Figure 1.1: The NuMI neutrino beam starts on the left hand side with protons from the MI impinged on a graphite target producing mainly pions and kaons. These are then focused and charge-selected by two focusing horns, after which they decay inside the decay pipe into a high-purity  $\nu_\mu$  or  $\bar{\nu}_\mu$  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 [19].

The proton beam passes through a collimating baffle before hitting a  $\sim 1.2\ \text{m}$ -long (equal to about two interaction lengths) graphite target [22], producing hadrons, predominantly pions and kaons [19]. 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. 1.2, displaying the very high purity of the  $\nu_\mu$  or  $\bar{\nu}_\mu$  component in the **FHC** ro **RHC** beam respectively [19].

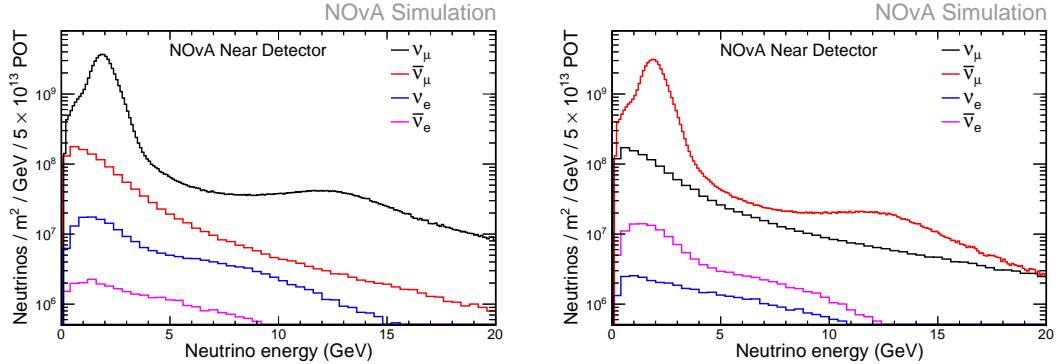


Figure 1.2: The components of the neutrino beam at the **NOvA ND** per one **NuMI** spill in the **FHC** regime shown on the left and the **RHC** regime on the right. The  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) composition in the **FHC** (**RHC**) regime is 93.8% (92.5%), with a wrong sign contribution of 5.3% (6.6%) and only 0.9% (0.9%) contamination by  $\nu_e$  ( $\bar{\nu}_e$ ), showing the high purity of  $\nu_\mu$  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 [23].

The resulting neutrino beam energy distribution is peaked at  $\sim 7$  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 [7, 24], as can be seen in Fig. 1.3. 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  $\nu_e$  appearance analysis [24].

## 1.2 The **NOvA** Detectors

The two main **NOvA** detectors are the **ND**, located in **Fermilab**  $\sim 1$  km from the **NuMI** target and  $\sim 100$  m under ground, and the **FD**, located  $\sim 810$  km from **Fermilab** at Ash River in north Minnesota, partially underground with a rock overburden [24]. **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 [4]. Additionally, **NOvA** operated a Test Beam detector, described in detail in Sec. ???. The scales of the **ND** and **FD** are shown in Fig. 1.4.

All **NOvA** detectors are highly segmented, highly active, functionally identical

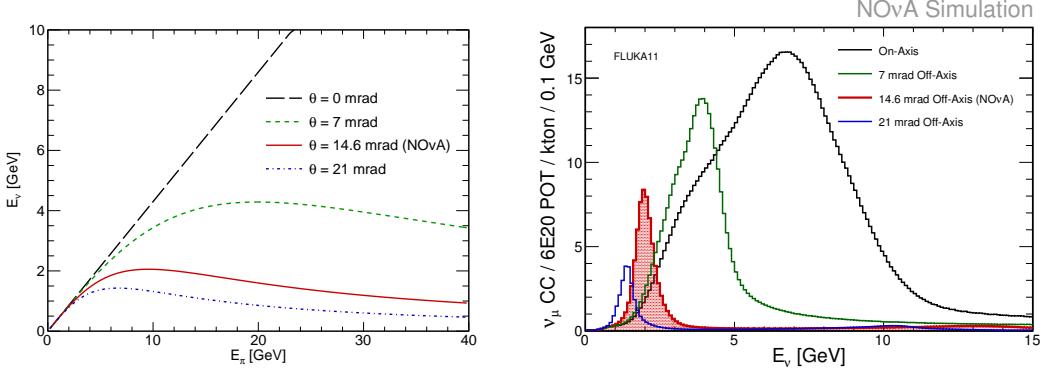


Figure 1.3: (Left) Dependence of the neutrino energy on the parent pion’s energy and (right) neutrino energy distribution for an on-axis beam and three different off-axis beam designs. The case for **NOvA** is shown in red and results in a narrow neutrino energy distribution around 2 GeV, with limited dependence on the parent pion’s energy. Figure from [24]

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  $\sim 4.1$  m for the **ND** and  $\sim 15.6$  m for the **FD** [24]. An example of a **FD** cell is shown on the right of Fig. 1.4.

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  $\sim 3$  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. 1.3). 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  $\nu_\mu$  charged current interactions [4, 24].

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

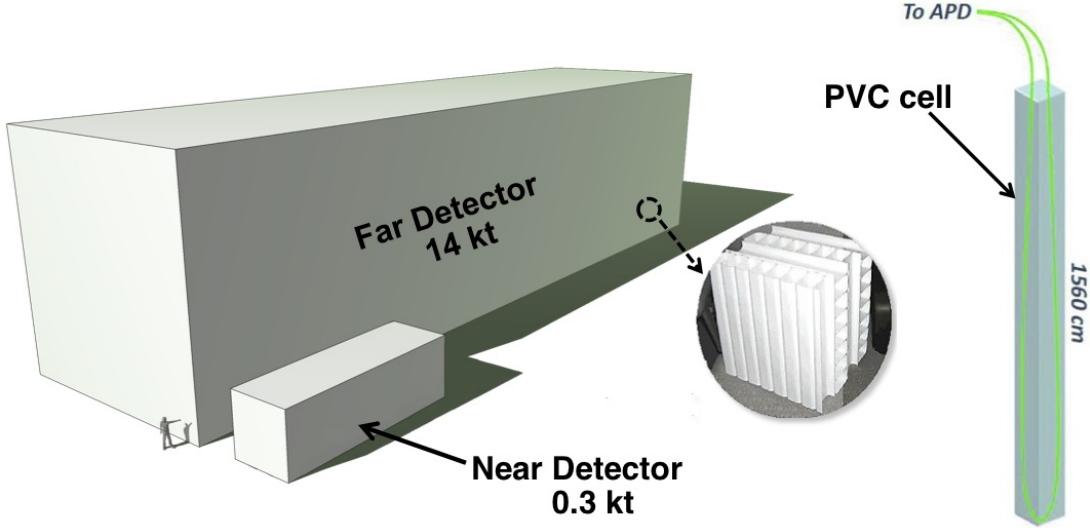


Figure 1.4: Schematic description of the scale and composition of the NOvA ND and FD. The inset shows a photo of the orthogonal planes made out of PVC cells. An example of a FD cell containing liquid scintillator and a looped WLS fibre attached to an APD is shown on the right [25].

along the beam direction.

Each cell is filled with a liquid scintillator consisting of mineral oil with 4.1% pseudocumene as the scintillant [26]. 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  $\sim 8$  times before being captured by the Wavelength Shifting (WLS) fibre [24].

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 [17]. The active volume, consisting only of the liquid scintillator without the PVC structure, makes up about 70% of the total detector volume [24].

The NOvA detectors are specifically designed for electromagnetic shower identification, with a radiation length of 38 cm, which amounts to  $\sim 7$  planes for particles travelling perpendicular to the detector planes [4]. This is particularly useful to distinguish electrons from  $\pi^0$ 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  $0.86 \text{ g/cm}^3$  [27], which gives us the required range of  $\sim 5 \text{ g/cm}^2$ . Comparing this to measured values for the electron range [28] in the continuous slowing down approximation in

a Polyethylene (approximation of the NOvA scintillator [29]), gives us an estimate of the lowest detectable electron energy as  $E_e \gtrsim 10$  MeV.

### 1.3 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 [24]. An example APD is shown in Fig. 1.5. 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  $-15^\circ\text{C}$  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.

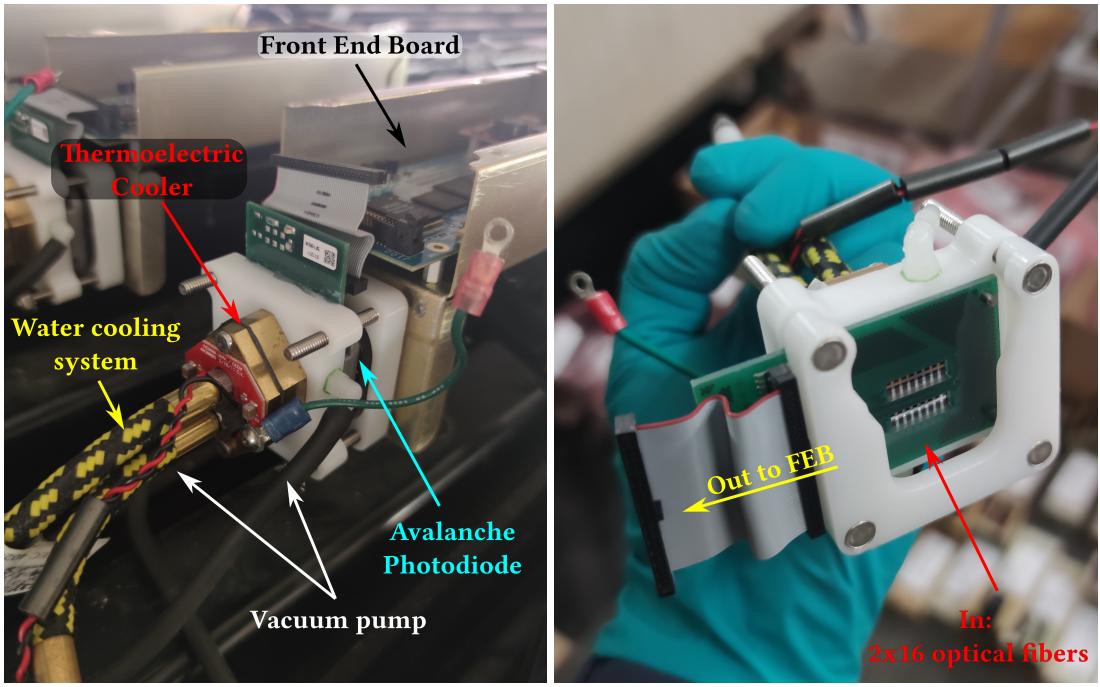


Figure 1.5: The modules with APDs for NOvA mounted on top of the detector on the left picture, and shown from the bottom on the right. The individual components of the module are described. The left picture shows a disconnected ribbon cable and ground cable, which are normally connected to the front end board.

Each APD is connected to a single Front End Board (FEB), shown in Fig. 1.6. 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 [24]. 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 [30].

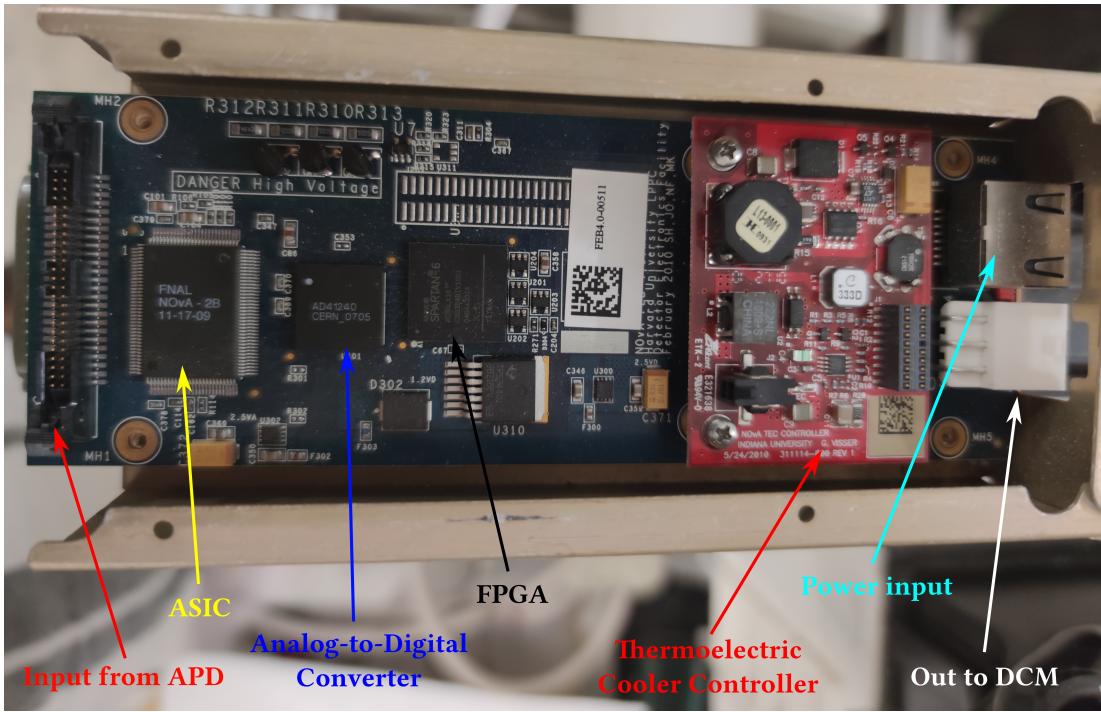


Figure 1.6: An example of a **NOvA** FEB with individual components labelled.

All of the **NOvA** front end electronics (**APDs** and **FEBs**) are operated in a continuous readout mode, without requiring any external triggers [24]. 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 [30].

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 [30].

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 [30]. 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 [31].

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’ [31]. Additionally, individual readout channel are assessed on a per-subrun basis, with those with too high or too low hit rates marked as ‘bad’ [32]. Both the ‘good runs’ list and the ‘bad channel’ maps are used to inform event processing and during simulation to emulate real detector conditions.

## 1.4 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 [33]. 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 [34] Monte Carlo (MC) event generator with a detailed model of the [NuMI](#) beamline [35], as described in Sec. 1.1. The simulation starts with the 120 GeV/c

**MI** protons interacting within the long carbon target and producing hadrons, mainly  $\pi$ ,  $K$  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 [36]. 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. 1.8). For the most common  $\pi$ ,  $K$  and  $p$  production, **PPFX** uses the NA49 measurements [37–39] 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 [40] for the  $\pi$  production and  $K/\pi$  ratios from the Main Injector Particle Production (MIPP) [41] 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 [42, 43] **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 [44–46], of the hadron incident interactions [47], and of the 120 GeV/c protons on a **NuMI** replica target [48]. The Fermilab-based EMPHATIC experiment [49] 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 [50] 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 Quasi-Elastic (QE) Charged Current (CC) scattering, the Resonant baryon pro-

duction (Res), the Deep Inelastic Scattering (DIS), and the Coherent  $\pi$  (COH $\pi$ ). The special case of the two particle - two hole (2p2h) interaction via Meson Exchange Current (MEC) and the Final State Interaction (FSI) inside the 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  $\nu_\mu$ CC data for a better constraint of the CCMEC interactions. NOvA also uses a set of external  $\pi$  interaction measurements to constrain the FSI model. Table 1.1 shows the list of models and tunes for different interaction modes in NOvA [7].

Table 1.1: Models and tunes used in the NOvA simulation of neutrino interactions.

Interaction	Model	Tune
CCQE	València [51]	External $\nu - D$ data [52]
CCMEC	València [53, 54]	NOvA $\nu_\mu$ CC data
Res & COH $\pi$	Berger-Sehgal [55, 56]	External $\nu - A$ data
DIS	Bodek-Yang [57, 58]	External $\nu - A$ data
FSI	Semi-classical cascade [59]	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) [60]. The simulated cosmic muons are also used to calibrate NOvA detectors [36].

Particles that are created from neutrino interactions and cosmic rays are propagated through the NOvA detectors using the GEANT4 v10.4.p02 [34], which outputs the energy deposited in the scintillator. This is then passed to a custom NOvA software of the light model [36], 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 [61], 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 [9]. 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 [36]. 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 [36].

## 1.5 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  $\nu_e$  appearance search in mind, focusing on identifying the  $\nu_e$ **CC** signal against the  $\nu_\mu$ **CC** and Neutral Current (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** [62].

The output from the **DAQ** system for each channel is called a *raw hit*. Hits are grouped into 550  $\mu\text{s}$ -long windows and passed to an offline reconstruction chain [62]. Reconstruction starts by grouping hits into *slices* based on their proximity to other hits in both time and space [63]. 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 [64], representing particle directions. These lines are passed to the Elastic Arms algorithm [65] 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 [66, 67]. 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) [62]. Figure 1.7 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.

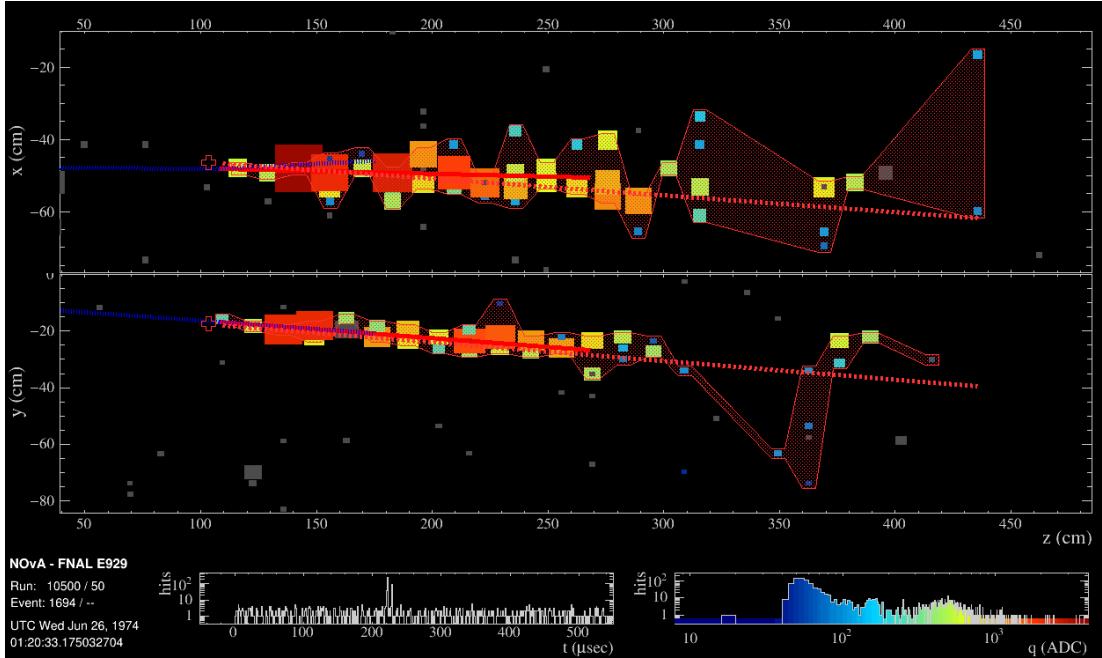


Figure 1.7: Reconstruction of a simulated single electron event in the NOvA ND. The red cross is the reconstructed vertex, the shaded area shows the cluster of hits into a prong and the dotted red line shows the estimated shower direction. The blue dotted line shows the true direct of the scattering neutrino and the solid red line the true momentum of the scattered electron. Figure from internal NOvA database [68].

For particles that are represented by tracks rather than showers (especially muons), the reconstruction takes the slice hits and forms ‘Kalman tracks’ based on a Kalman filter [69]. 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 [70, 71], 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’ [72]. 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 Machine 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. 1.8. Muons are easily identifiable as single long tracks which decay into an electron (or positron) if stopping inside of the detector. Both electrons and  $\pi^0$ '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  $\pi^0$ .

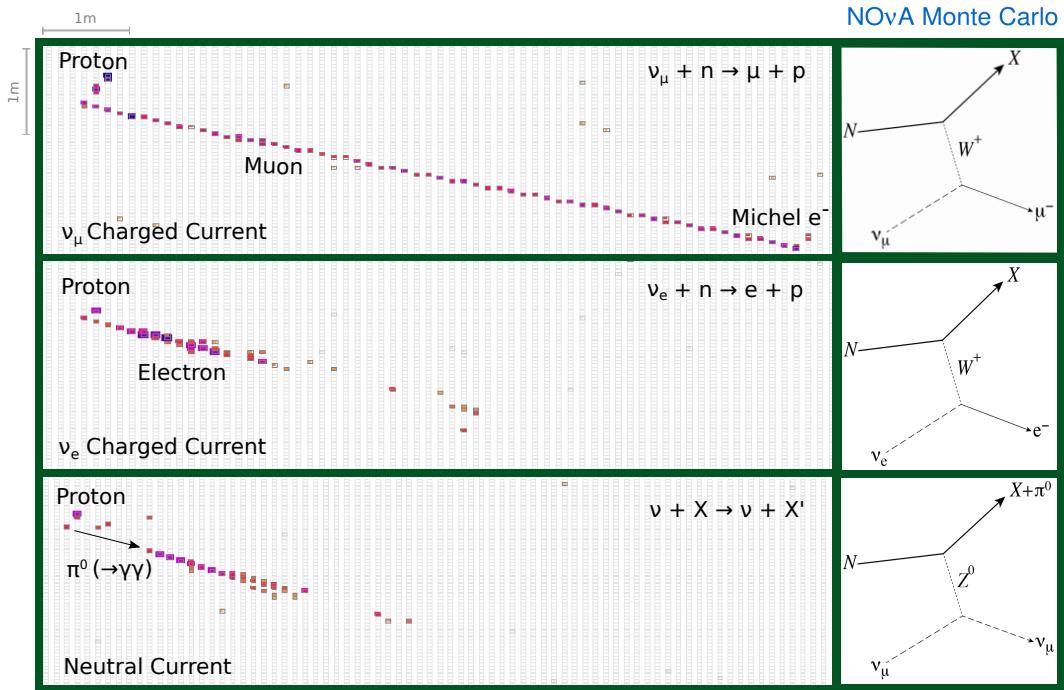


Figure 1.8: Different event topologies as seen in the NOvA detectors with corresponding Feynman diagrams [62]. Each event is a simulated 2.15 GeV neutrino interacting in a NOvA detector producing a 0.78 GeV proton and a second 1.86 GeV particle depending on the interactions type. The figure shows only 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 [73] architecture named Convolutional Visual Network (CVN) [74]. 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:  $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$ ,

**NC**, or cosmic. The same architecture, but applied to the Fuzzy-K prongs, is called *ProngCVN* [75], 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. 1.7. 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) [69] and uses the reconstructed Kalman tracks as inputs.

## 1.6 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. 1.3. The conversion of the peak **ADC** values into physical units of energy requires calibrating the **NOvA** detectors [76], 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** [60] **MC** generator, as outlined in Sec. 1.4.

Cosmic muon tracks are reconstructed using the window cosmic track algorithm described in Sec. 1.5. The selection of well reconstructed cosmic tracks requires that at least 80% of all hits from the reconstructed slice contribute to the track [29]. 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. 1.8.

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. 1.9. 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. 1.9), this channel is ignored and the tricell condition looks one cell further [76]. 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

$$E_{dep} \text{ [MeV]} = \text{Signal [ADC]} \times S_d \times TS_{d,i}^{\text{CALIB}} \times R_{d,i}(t) \times A_d(t). \quad (1.1)$$

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

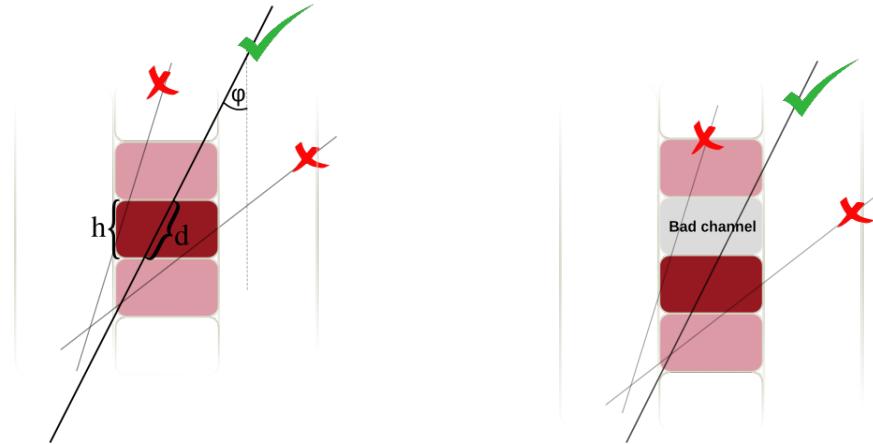


Figure 1.9: Illustration of the tricell condition. Only the hits with two surrounding hits in the same plane are used in the NOvA calibration, as shown on the left plot. This is to ensure a good quality of the path length ( $d$ ) reconstruction, which is calculated from the known cell height ( $h$ ) and the reconstructed track angle ( $\varphi$ ). 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.

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 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. 1.1. 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 [76].

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 between 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. 1.10. These FB bins describe the relative differences in the detector response between individual cells [77].

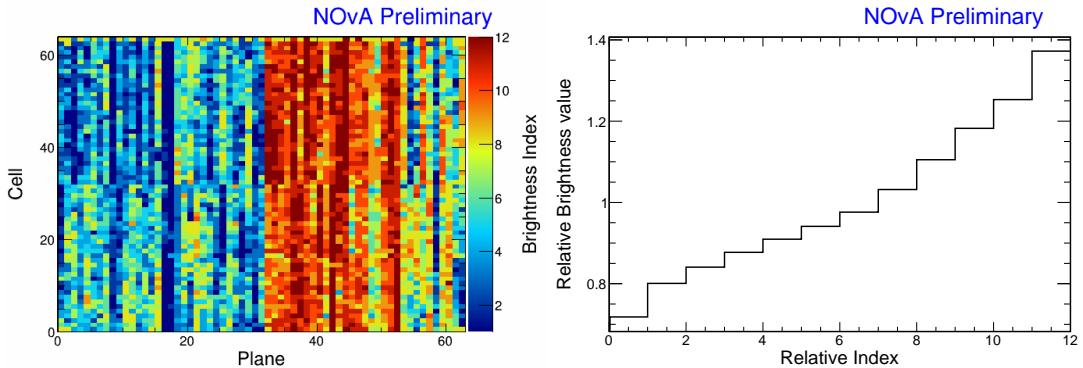


Figure 1.10: Distribution of the NOvA detector cells into 12 brightness bins (left plot), each representing a relative difference in energy response (right plot) due to different brightnesses of the fibres, scintillators, or readout. This is an example from the NOvA Test Beam detector, described in Sec. ??, 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).

### 1.6.1 Scale

The scale calibration factor from Eq. 1.1 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. 1.3).

### 1.6.2 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 [76].

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** ( $\text{PE}_{\text{Poisson}\lambda}$ ) and the number of the ‘reconstructed’ **PE** seen by the **APD** ( $\text{PE}_{\text{Reco}}$ ).

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** ( $E_{\text{MIP}}$ ), which is estimated from simulation for the **NOvA** scintillator as  $E_{\text{MIP}} = 1.78 \text{ MeV/cm}$  and the true deposited energy ( $E_{\text{true}}$ ).

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

$$TS_i = \frac{\text{PE}_{\text{Poisson}\lambda}}{\text{PE}_{\text{Reco}}} \frac{E_{\text{MIP}}}{E_{\text{true}}}. \quad (1.2)$$

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.

### 1.6.3 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. 1.11. The relative calibration scale is then calculated as the ratio between the average response in **PE/cm** across the entire detector (can differ between

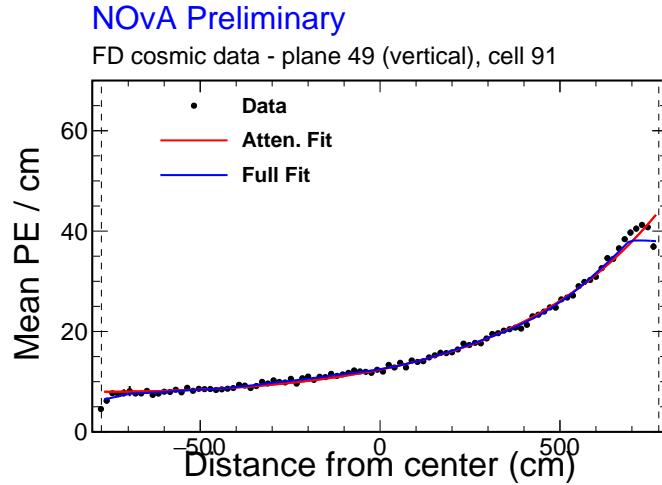


Figure 1.11: Example attenuation fit for a single cell in the NOvA FD across its full length, as shown by dashed vertical lines. The red line shows the initial exponential fit and the blue line shows the full fit after the LOWESS correction, both described in text. Figure from [78].

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 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  $w$  [76].

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. 1.11 as black dots. The threshold and shielding correction described in Sec. 1.6.2 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

$$y = C + A \left( \exp \left( \frac{w}{X} \right) + \exp \left( -\frac{L+w}{X} \right) \right), \quad (1.3)$$

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 atten-

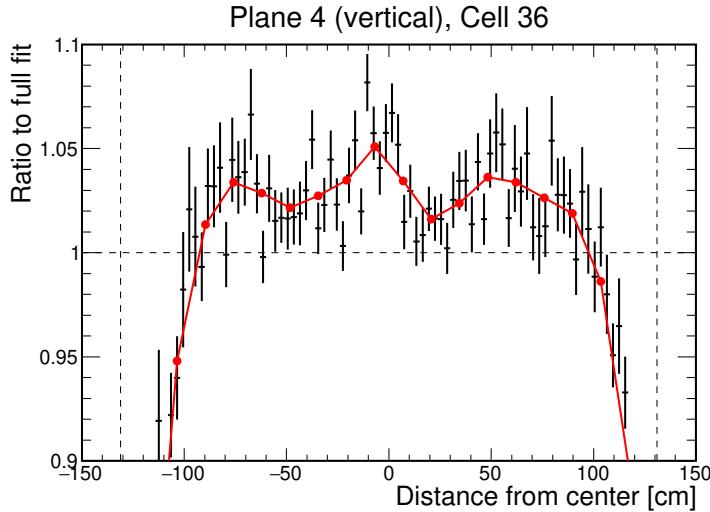


Figure 1.12: Example LOWESS correction for the residual differences after the exponential part of the attenuation fit of the NOvA relative calibration. This is an example for a single cell in the NOvA Test Beam detector with black points showing the residual differences and red line the LOWESS correction, both described in text.

uation length respectively. An example of the exponential fit is shown as a red curve in Fig. 1.11.

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. 1.12. 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. 1.11.

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  $\chi^2$  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*.

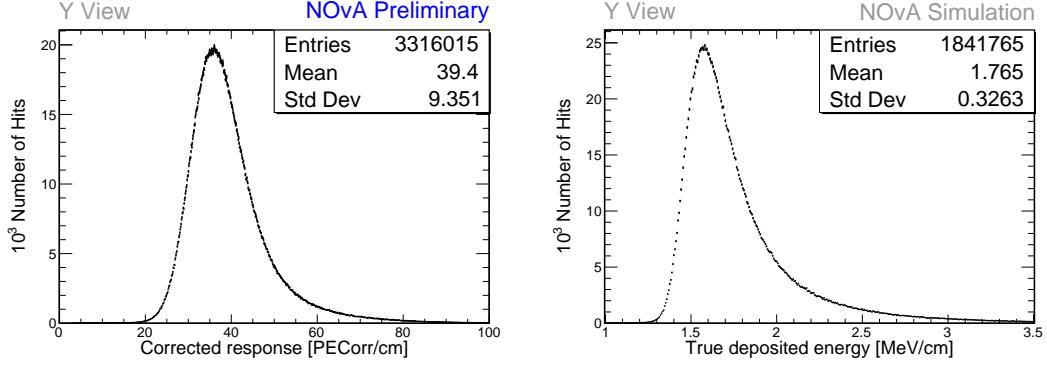


Figure 1.13: The absolute energy scale is calculated as the ratio between the simulated mean true deposited energy (right) and the mean reconstructed energy response (left) for selected stopping muons in each view and each data period or simulation.

#### 1.6.4 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 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 [29].

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. 1.13. 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. 1.13, 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

$$\text{Absolute Energy Scale} = \frac{\text{MEU}_{\text{True}} \text{ [MeV/cm]}}{\text{MEU}_{\text{Reco}} \text{ [PECorr/cm]}}. \quad (1.4)$$

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.

## 1.7 Energy Estimation

The deposited energy from detector calibration (Sec. 1.6) is only the first step in estimating the neutrino energy ( $E_\nu$ ) required for the main **NOvA** analyses.

For the  $\nu_\mu$  disappearance analysis, the  $\nu_\mu$  energy is measured as the sum of the muon energy and the energy of the hadronic shower [7]. 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  $\nu_\mu$  energy minus the reconstructed muon energy, versus the visible (not corrected for the dead material) deposited energy of the hadronic system [75].

For the  $\nu_e$  appearance analysis, the  $\nu_e$  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) [75]. 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  $\pi^0$  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  $\nu_e$  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.

## 1.8 Systematic Uncertainties at **NOvA**

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 [7] and the sterile neutrino [13] 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 anal-

yses, such as the cross section analyses [8–11]. 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 [36]. The uncertainty for hadron production is estimated by the **PPFX** (describe in Sec. 1.4) 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*

*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  $3\sigma$  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,  $\pi^0$  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 2

# 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 ( $\nu$ -on-e) elastic scattering interactions at low electron recoil energies, proportional to the value of the effective neutrino magnetic moment, over the Standard Model (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 would provide a definitive evidence of new Beyond Standard Model (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 implication for astrophysics and cosmology [79].

*COMMENT: Well technically, the best limits come from cosmology, but those are model-dependent. Should I mention it (don't really understand it that well tbh*

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 [80] a low energy excess of solar neutrinos, which could correspond to a signal from an anomalously large effective magnetic moment of solar neutrinos within  $\mu_{\nu_\odot} \in (0.14, 0.29) \times 10^{-10} \mu_B$  at 90 % Confidence Level (C.L.), where  $\nu_\odot$  marks solar neutrinos. However, this result was disfavoured by the follow-up XENONnT experiment in 2022 [81], which saw no excess and set the current best world 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 [82, 83], placing less

stringent limits on its value. Given some basic assumptions [83, 84] 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 [85].

The best results for  $\nu_\mu$  and  $\bar{\nu}_\mu$  come from accelerator-based stopped pion neutrino sources [86, 87], 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.** [86]. Stopped pion neutrino sources provide a well-understood beams made up of  $\nu_\mu$ ,  $\bar{\nu}_\mu$  and  $\nu_e$  with energies up to 52.8 MeV. Slightly looser limits come from pion decay-in-flight accelerator-based measurements (similar to **NOvA**) [88, 89], 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 [90], providing a (statistics-only) limit of  $\mu_{\nu_\mu} < 15.8 \times 10^{-10} \mu_B$  at 90 % **C.L..**

Additionally,  **$\nu$ -on-e** elastic scattering interactions are used in various other analyses in **NOvA**, specifically in efforts to constrain the neutrino beam prediction [91, 92] and in the search for Light Dark Matter (LDM) [93]. 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. 2.1, focusing on the effective neutrino magnetic moment and its implications for  **$\nu$ -on-e** measurements and other theoretical considerations. In Sec. 2.2, 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. 2.3 will explain the selection of events for this analysis, while Sec. 2.4 will cover the electron recoil energy and angle resolution studies and the choice of binning. Sec. 2.5 will address the relevant systematic uncertainties and Sec. 2.6 will introduce

the methods used in the statistical analysis of the measurement. Finally, I will present the results of this analysis in Sec. 2.7 and discuss their implications in Sec. 2.8. Section 2.9 will summarise the findings of this analysis.

## 2.1 Theory of neutrino magnetic moment

**TO DO:** *Also check out NeutrinoMassesPheno2007.pdf, sec 6.4*

As was described in Sec. ??, 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. These interactions are described by the neutrino charge radius, described in section 2.1.2 **TO DO: Re-write this since I'm not going to include the other elmag properties section** [79].

In general **BSM** theories, considering interactions with a single photon as shown on Fig. 2.1, neutrino electromagnetic interactions can be described by an *effective* interaction Hamiltonian [94]

$$\mathcal{H}_{em}^{(\nu)}(x) = \sum_{k,j=1}^N \bar{\nu}_k(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x). \quad (2.1)$$

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

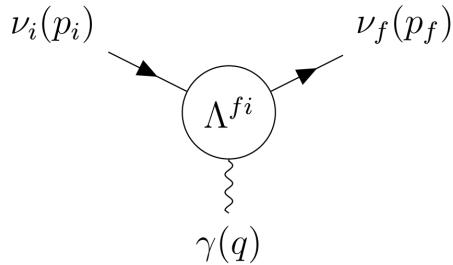


Figure 2.1: Effective coupling of neutrinos with one photon electromagnetic field.

The vertex function  $\Lambda_\mu^{fi}(q)$  is generally a matrix and in the most general case consistent with the **SM** gauge invariance [95, 96] can be written in terms of linearly independent products of Dirac matrices ( $\gamma$ ) and only depends on the four momentum

of the photon ( $q = p_f - p_i$ ):

$$\begin{aligned} \Lambda_\mu^{fi}(q) = & \mathbb{F}_1^{fi}(q^2) q_\mu + \mathbb{F}_2^{fi}(q^2) q_\mu \gamma_5 + \mathbb{F}_3^{fi}(q^2) \gamma_\mu + \mathbb{F}_4^{fi}(q^2) \gamma_\mu \gamma_5 + \\ & \mathbb{F}_5^{fi}(q^2) \sigma_{\mu\nu} q^\nu + \mathbb{F}_6^{fi}(q^2) \epsilon_{\mu\nu\rho\gamma} q^\nu \sigma^{\rho\gamma}, \end{aligned} \quad (2.2)$$

where  $\mathbb{F}_i^{fi}(q^2)$  are six Lorentz invariant form factors and  $\delta$  and  $\epsilon$  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

$$\Lambda_\mu^{fi}(q) = (\gamma_\mu - q_\mu q^2/q^2) \left[ \mathbb{F}_Q^{fi}(q^2) + \mathbb{F}_A^{fi}(q^2) q^2 \gamma_5 \right] - i \sigma_{\mu\nu} q^\nu \left[ \mathbb{F}_M^{fi}(q^2) + i \mathbb{F}_E^{fi}(q^2) \gamma_5 \right], \quad (2.3)$$

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. The neutrino charge radius corresponds to the second term in the expansion of the charge form factor [94].

The above expression can be simplified as [97]

$$\Lambda_\mu^{fi}(q) = \gamma_\mu \left( Q_{\nu_{fi}} + \frac{q^2}{6} \langle r^2 \rangle_{\nu_{fi}} \right) - i \sigma_{\mu\nu} q^\nu \mu_{\nu_{fi}}, \quad (2.4)$$

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 effect of the neutrino charge radius and the anapole moment, or of the neutrino magnetic and electric moment respectively [94]. These are the three neutrino electromagnetic properties (charge, charge radius and magnetic moment) measured in the experiments.

*TO DO: Add a note briefly describing the other elmag properties and mentioning that they could be measured as well, but not describe here. Maybe refer reader to the theoretical overview paper*

[PDG] The coupling of neutrinos to an electromagnetic field is characterized by a  $3 \times 3$  matrix  $\lambda$  of the magnetic ( $\mu$ ) and electric ( $d$ ) dipole moments  $\lambda = [mu - id]$ .

For Majorana neutrinos the matrix  $\lambda$  is antisymmetric and only transition moments are allowed, while for Dirac neutrinos  $\lambda$  is a general  $3 \times 3$  matrix.

### 2.1.1 Neutrino electric and magnetic dipole moments

The size and effect of neutrino electromagnetic properties depend on the specific **BSM** theory. Evaluating the one loop diagrams in the minimally extended **SM** with three right-handed Dirac neutrinos as described in Sec. ?? gives the first approximation of the electric and magnetic moments:

$$\left. \frac{\mu_{kj}^D}{i\epsilon_{kj}^D} \right\} \simeq \frac{3eG_F}{16\sqrt{2}\pi^2} (m_k \pm m_j) \left( \delta_{kj} - \frac{1}{2} \sum_{l=e,\mu,\tau} U_{lk}^* U_{lj} \frac{m_l^2}{m_W^2} \right), \quad (2.5)$$

where  $m_k, m_j$  are the neutrino masses and  $m_l$  are the masses of charged leptons which appear in the loop diagrams [94]. Also,  $D$  superscript denotes Dirac neutrinos,  $e$  is the electron charge,  $G_F$  is the Fermi coupling constant, and  $U$  is the Pontecorvo-Maki-Nakagawa-Sakata (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

$$\mu_{kk}^D \simeq \frac{3eG_F m_k}{8\sqrt{2}\pi^2} \simeq 3.2 \times 10^{-19} \left( \frac{m_k}{\text{eV}} \right) \mu_B, \quad (2.6)$$

where  $\mu_B$  is the Bohr magneton which represents the value of the electron magnetic moment [94]. Neutrino magnetic moments are therefore strongly suppressed by the smallness of neutrino masses, with theoretical predictions in Eq. 2.6 several orders of magnitude below the reach of current experiments [97].

The transition magnetic moments from Eq. 2.5 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. 2.5. Therefore an experimental observation of a magnetic moment larger than in Eq. 2.6 would indicate physics beyond the minimally extended **SM** [94, 98].

**TO DO:** *Actually write why these values are different for Majorana neutrinos than for Dirac neutrinos* Majorana neutrinos in a minimal extension can be obtained by either adding a  $SU(2)_L$  Higgs triplet, or right handed neutrinos together with a  $SU(2)_L$  Higgs singlet [94]. If we neglect the Feynman diagrams which depend on the model of the scalar sector, the magnetic and electric dipole moments are

$$\mu_{kj}^M \simeq -\frac{3ieG_F}{16\sqrt{2}\pi^2} (m_k + m_j) \sum_{l=e,\mu,\tau} \text{Im}[U_{lk}^* U_{lj}] \frac{m_l^2}{m_W^2}, \quad (2.7)$$

$$\epsilon_{kj}^M \simeq \frac{3ieG_F}{16\sqrt{2}\pi^2} (m_k - m_j) \sum_{l=e,\mu,\tau} \text{Re}[U_{lk}^* U_{lj}] \frac{m_l^2}{m_W^2}. \quad (2.8)$$

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 [94].

[PDG] In the standard electroweak theory extended to include neutrino masses (see FUJIKAWA 80)  $\mu_\nu = 3eG_F m_\nu / (8\pi^2 \sqrt{2}) = 3.2 \times 10^{-19} \frac{m_\nu}{\text{eV}} \mu_B$ , i.e. it is unobservably small given the known small neutrino masses. In more general models there is no longer a proportionality between neutrino mass and its magnetic moment, even though only massive neutrinos have nonvanishing magnetic moments without fine tuning.

**TO DO:** *Re-read the natural upper bounds paper* It is possible [98] to obtain a ‘natural’ upper limits on the size of the neutrino magnetic moment by calculating its contribution to the neutrino mass by standard model radiative corrections. **TO DO:** *I don’t think this is clear enough, how is this done* For Dirac neutrinos, the radiative correction induced by neutrino magnetic moment, generated at an energy scale  $\Lambda_{NP}$ , to the neutrino mass is generically

$$m_\nu^D \sim \frac{\mu_\nu^D}{3 \times 10^{-15} \mu_B} [\Lambda(\text{TeV})]^2 \text{eV}. \quad (2.9)$$

So for  $\Lambda_{NP} \simeq 1\text{TeV}$  and  $m_\nu \lesssim 0.3\text{eV}$  the limit becomes  $\mu_\nu^D \lesssim 10^{-15} \mu_B$ . This applies only if New Physics (NP) is well above the electroweak scale ( $\Lambda_{EW} \sim 100\text{GeV}$ )

**TO DO:** *Finish this sentence.* However, there are theories that contain a Dirac neutrino magnetic moment higher than this limit, for example in frameworks of minimal

super-symmetric standard model, by adding more Higgs doublets, or by considering large extra dimensions **TO DO: Add references to the specific theories?** [94].

Similar limit for Majorana neutrino magnetic moment would be less stringent than for Dirac neutrinos due to the antisymmetry of the Majorana neutrino magnetic moment form factors **TO DO: Probably explain here a bit more what does this mean.** Considering  $m_\nu \lesssim 0.3\text{eV}$ , the limit can be expressed as

$$\mu_{\tau\mu}, \mu_{\tau e} \lesssim 10^{-9} [\Lambda (\text{TeV})]^{-2} \quad (2.10)$$

$$\mu_{\mu e} \lesssim 3 \times 10^{-7} [\Lambda (\text{TeV})]^{-2} \quad (2.11)$$

which is shown in the flavour basis **TO DO: Explain here what is the flavour basis,** which relates to the framework used previously via the **PMNS** matrix as

$$\mu_{ij} = \sum_{\alpha\beta} \mu_{\alpha\beta} U_{\alpha i}^* U_{\beta j}, \quad \alpha, \beta \in \{e, \mu, \tau\}. \quad (2.12)$$

**TO DO: Add a discussion about the triangular inequalities**

These considerations imply, that if a magnetic moment  $\mu \gtrsim 10^{-15} \mu_B$  would be measured, it is more plausible that neutrinos are Majorana fermions and that the scale of lepton violation would be well below the conventional see-saw scale [98] **TO DO: double check this claim, also reword this sentence.**

### Effective neutrino magnetic moment

Since experiments detect neutrino flavour states, not the mass states, what we measure is an effective ‘flavour’ magnetic moment  $\mu_{\text{eff}}$ .  $\mu_{\text{eff}}$  is influenced by mixing of the neutrino magnetic moments (and electric moments) expressed in the mass basis (as described above) and neutrino oscillations **TO DO: This basis relation was already partly described above, mention that and combine the descriptions.** In the ultra-relativistic limit, the neutrino effective magnetic moment is

$$\mu_{\nu_l}^2 (L, E_\nu) = \sum_j \left| \sum_k U_{lk}^* e^{\mp i \Delta m_{kj}^2 L / 2E_\nu} (\mu_{jk} - i\epsilon_{jk}) \right|^2, \quad (2.13)$$

where the minus sign in the exponent is for neutrinos and the plus sign for antineutrinos [94]. 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 can be expressed as

$$\mu_{\nu_l}^2 = \mu_{\bar{\nu}_l}^2 \simeq \sum_j \left| \sum_k U_{lk}^* (\mu_{jk} - i\epsilon_{jk}) \right|^2 = [U (\mu^2 + \epsilon^2) U^\dagger + 2 \text{Im} (U \mu \epsilon U^\dagger)]_{ll'}, \quad (2.14)$$

which is independent of the neutrino energy *TO DO: Figure out how does this relate to the mag moment cross section which does depend on the neutrino energy!*.

*TO DO: Consider if this paragraph is actually important* Since the effective magnetic moment depends on the flavour of the studied neutrino, it is different (but related) for neutrino experiments studying neutrinos from different sources. Additionally some experiments, namely 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. Theorists publish papers trying to extrapolate the measured effective magnetic moments to each neutrino flavour, but necessarily apply assumptions that might not hold in all BSM theories.

[PDG] Laboratory bounds on  $\lambda$  are obtained via elastic  $\nu$ -on-e scattering, where the scattered neutrino is not observed. The combinations of matrix elements of  $\lambda$  that are constrained by various experiments depend on the initial neutrino flavor and on its propagation between source and detector (e.g., solar  $\nu_e$  and reactor  $\bar{\nu}_e$  do not constrain the same combinations).

### 2.1.2 Other neutrino electromagnetic properties

*COMMENT: I am not going to report results on these, so should I even mention them here? Maybe it's enough to just mention that they exist in the intro section... TO DO: This section is not finished, most of this text is just copied from some theory papers for now*

*TO DO: See also StatusAndPerspectiveOfNuMM2016.pdf*

Neutrino electric charge is heavily constraint by the measurements on the neutrality of matter (since generally neutrinos having an electric charge would also mean that neutrons have charge which would affect all heavier nuclei). It is also constrained by the SN1987A, since neutrino having an effective charge would lengthen its path through the extragalactic magnetic fields and would arrive on earth later. It can also be obtained from nu-on-e scatter from the relationship between neutrino millicharge and magnetic moment. [nuElmagInt2015.pdf - sec. VIIA] **TO DO: Make this description shorter, just a single sentence and combine with the charge radius**

The neutrino charge radius is determined by the second term in the expansion of the neutrino charge form factor and can be interpreted using the Fourier transform of a spherically symmetric charge distribution. It can also be negative since the charge density is not a positively defined quantity. In the SM the charge radius has the form of (possible other definitions exist)

$$\langle r_{\nu_l}^2 \rangle_{\text{SM}} = \frac{G_F}{4\sqrt{2}\pi^2} \left[ 3 - 2 \log \left( \frac{m_l^2}{m_W^2} \right) \right]. \quad (2.15)$$

This corresponds to  $\langle r_{\nu_\mu}^2 \rangle_{\text{SM}} = 2.4 \times 10^{-33} \text{ cm}^2$  and similar scale for other neutrino flavours. [nuElmagInt2015.pdf - sec. VIIB]

[nuElmagInt2015.pdf - sec. VIIB] The effect of the neutrino charge radius on the neutrino-on-electron scattering cross section is through the following shift of the vector coupling constant (Grau and Grifols, 1986; Degrassi, Sirlin, and VMarciano, 1989; Vogel and Engel, 1989; Hagiwara et al., 1994):

$$g_V^{\nu_l} \rightarrow g_V^{\nu_l} + \frac{2}{3} m_W^2 \langle r_{\nu_l}^2 \rangle \sin^2 \theta_W \quad (2.16)$$

[nuElmagInt2015.pdf - sec. VIIB] The current experimental limits for muon neutrinos are from **TO DO: check the current exp. limits** Hirsch, Nardi, and Restrepo (2003) who obtained the following 90% C.L. bounds on  $\langle r_{\nu_\mu}^2 \rangle$  from a reanalysis of CHARM-II (Vilain et al., 1995) and CCFR (McFarland et al., 1998) data:

$$-0.52 \times 10^{-32} < \langle r_{\nu_\mu}^2 \rangle < 0.68 \times 10^{-32} \text{ cm}^2 \quad (2.17)$$

In the Standard Model, the neutrino anapole moment is somehow coupled with

the neutrino charge radii and is functionally identical. the phenomenology of neutrino anapole moments is similar to that of neutrino charge radii. Hence, the limits on the neutrino charge radii discussed in Sec. VII.B also apply to the neutrino anapole moments multiplied by 6. in the standard model the neutrino charge radius and the anapole moment are not defined separately and one can interpret arbitrarily the charge form factor as a charge radius or as an anapole moment. Therefore, the standard model values for the neutrino charge radii in Eqs. (7.35)–(7.38) can be interpreted also as values of the corresponding neutrino anapole moments. [nuElmagInt2015.pdf - sec. VIIC]

It is possible to consider the toroidal dipole moment as a characteristic of the neutrino which is more convenient and transparent than the anapole moment for the description of T-invariant interactions with nonconservation of the P and C symmetries. the toroidal and anapole moments coincide in the static limit when the masses of the initial and final neutrino states are equal to each other. The toroidal (anapole) interactions of a Majorana as well as a Dirac neutrino are expected to contribute to the total cross section of neutrino elastic scattering off electrons, quarks, and nuclei. Because of the fact that the toroidal (anapole) interactions contribute to the helicity preserving part of the scattering of neutrinos on electrons, quarks, and nuclei, its contributions to cross sections are similar to those of the neutrino charge radius. In principle, these contributions can be probed and information about toroidal moments can be extracted in low-energy scattering experiments in the future. Different effects of the neutrino toroidal moment are discussed by Ginzburg and Tsytovich (1985), Bukina, Dubovik, and Kuznetsov (1998a, 1998b), and Dubovik and Kuznetsov (1998). In particular, it has been shown that the neutrino toroidal electromagnetic interactions can produce Cherenkov radiation of neutrinos propagating in a medium. [nuElmagInt2015.pdf - sec. VIIC]

### 2.1.3 Measuring neutrino magnetic moment

The most sensitive method to measure neutrino magnetic moment is the low energy elastic scattering of (anti)neutrinos on electrons [94]. The diagram for this interaction is shown in Fig. 2.2 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 ( $\theta$ ).

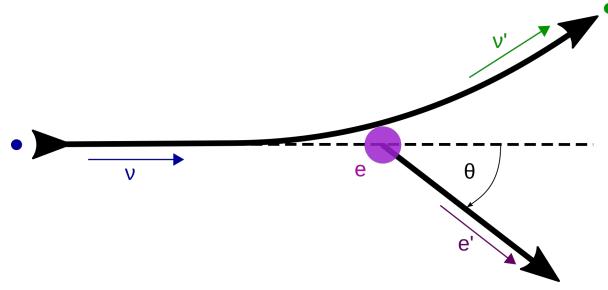


Figure 2.2: Neutrino-on-electron elastic scattering diagram

**COMMENT:** *Is this derivation too trivial to mention in a thesis? Should I just mention the results? I wanted to have this in the technote, but probably too detailed for a thesis... TO DO: Also change all we to passive voice - or should I keep we here?* From simple  $2 \rightarrow 2$  kinematics we can calculate

$$(P_\nu - P_{e'})^2 = (P_{\nu'} - P_e)^2, \quad (2.18)$$

$$m_\nu^2 + m_e^2 - 2E_\nu E_{e'} + 2E_\nu p_{e'} \cos \theta = m_\nu^2 + m_e^2 - 2E_{\nu'} m_e. \quad (2.19)$$

Using the energy conservation

$$E_\nu + m_e = E_{\nu'} + E_{e'} = E_{\nu'} + T_e + m_e \Rightarrow E_{\nu'} = E_\nu - T_e \quad (2.20)$$

we get

$$E_\nu p_{e'} \cos \theta = E_\nu E_{e'} - E_{\nu'} m_e = E_\nu (T_e + m_e) - (E_\nu - T_e) m_e = T_e (E_\nu + m_e), \quad (2.21)$$

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{E_{e'}^2 - m_e^2}} = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e^2}{T_e^2 + 2T_e m_e}}. \quad (2.22)$$

And finally we get

$$\cos \theta = \frac{E_\nu + m_e}{E_\nu} \sqrt{\frac{T_e}{T_e + 2m_e}}. \quad (2.23)$$

We can rearrange the Eq. 2.23 to get

$$T_e = \frac{2m_e E_\nu^2 \cos^2 \theta}{(E_\nu + m_e)^2 - E_\nu^2 \cos^2 \theta}. \quad (2.24)$$

Electron's kinetic energy is therefore kinematically constrained by the energy con-

servation as

$$T_e \leq \frac{2E_\nu^2}{2E_\nu + m_e}, \quad (2.25)$$

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

Considering  $E_\nu \sim \text{GeV}$ , we can approximate  $\frac{m_e^2}{E_\nu^2} \rightarrow 0$  and from Fig.2.3 we can see that we can approximate all recoil angles to be very small, therefore  $\theta^2 \cong (1 - \cos^2 \theta)$ . Using Eq.2.23 we get

$$T_e \theta^2 \cong T_e \left( 1 - \left( \frac{E_\nu + m_e}{E_\nu} \right)^2 \frac{T_e}{T_e + 2m_e} \right) = T_e \left( 1 - \left( 1 + \frac{2m_e}{E_\nu} \right) \frac{T_e}{T_e + 2m_e} \right), \quad (2.26)$$

therefore

$$T_e \theta^2 \cong \frac{2m_e T_e}{T_e + 2m_e} \left( 1 - \frac{T_e}{E_\nu} \right) = 2m_e \left( \frac{1}{1 + \frac{2m_e}{T_e}} \right) \left( 1 - \frac{T_e}{E_\nu} \right), \quad (2.27)$$

and finally

$$T_e \theta^2 \cong 2m_e \left( 1 - \frac{T_e}{E_\nu} \right) < 2m_e. \quad (2.28)$$

This is a strong limit that clearly distinguishes the  $\nu\text{-on-e}$  elastic scattering events from other similar interaction involving single electron (mainly the  $\nu_e\text{CC}$  interaction).

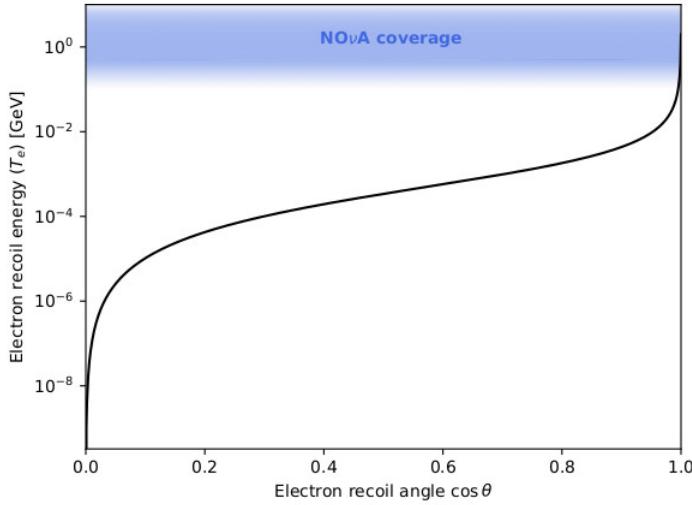


Figure 2.3: Relation between the recoil electron's kinetic energy and angle for  $\nu\text{-on-e}$  elastic scattering. The coverage of the **NOvA** detectors for measuring the electron recoil energy is shown in blue. Only very forwards electron's are recorded in **NOvA**.

### Neutrino magnetic moment cross section

**COMMENT:** *Should this only be a subsubsection?* In the ultra-relativistic limit, the neutrino magnetic moment changes the neutrino helicity, turning active neutrinos into sterile **TO DO: cite this properly**. Since the **SM** weak interaction conserves helicity we can simply add the two contribution to the  **$\nu$ -on-e** cross section incoherently [94]:

$$\frac{d\sigma_{\nu_le^-}}{dT_e} = \left( \frac{d\sigma_{\nu_le^-}}{dT_e} \right)_{\text{SM}} + \left( \frac{d\sigma_{\nu_le^-}}{dT_e} \right)_{\text{MAG}}. \quad (2.29)$$

The **SM** contribution can be expressed as [94]:

$$\begin{aligned} \left( \frac{d\sigma_{\nu_le^-}}{dT_e} \right)_{\text{SM}} = \frac{G_F^2 m_e}{2\pi} & \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left( 1 - \frac{T_e}{E_\nu} \right)^2 \right. \\ & \left. + ((g_A^{\nu_l})^2 - (g_V^{\nu_l})^2) \frac{m_e T_e}{E_\nu^2} \right\}, \end{aligned} \quad (2.30)$$

where the coupling constants  $g_V$  and  $g_A$  are different for different neutrino flavours and for antineutrinos. Their values are:

$$g_V^{\nu_e} = 2 \sin^2 \theta_W + 1/2, \quad g_A^{\nu_e} = 1/2, \quad (2.31)$$

$$g_V^{\nu_{\mu,\tau}} = 2 \sin^2 \theta_W - 1/2, \quad g_A^{\nu_{\mu,\tau}} = -1/2. \quad (2.32)$$

For antineutrinos  $g_A \rightarrow -g_A$ .

**TO DO: Decide if this is actually useful or not** Using Eq. 2.24 it is possible to get the differential cross section for  $\cos \theta$ :

$$dT_e = \frac{4m_e E_\nu^2 (m_e + E_\nu)^2}{[(m_e + E_\nu)^2 - E_\nu^2 \cos^2 \theta]^2} \cos \theta d\cos \theta \quad (2.33)$$

as

$$\begin{aligned} \left( \frac{d\sigma_{\nu_le^-}}{d\cos \theta} \right)_{\text{SM}} = \frac{2G_F^2 E_\nu^2 m_e^2 \cos \theta (E_\nu + m_e)^2}{\pi ((E_\nu + m_e)^2 - E_\nu^2 \cos^2 \theta)^2} \\ \left\{ (g_V^{\nu_l} + g_A^{\nu_l})^2 + (g_V^{\nu_l} - g_A^{\nu_l})^2 \left( 1 - \frac{2m_e E_\nu \cos^2 \theta}{(E_\nu + m_e)^2 - E_\nu^2 \cos^2 \theta} \right)^2 + \right. \\ \left. ((g_A^{\nu_l})^2 - (g_V^{\nu_l})^2) \frac{2m_e^2 \cos^2 \theta}{((E_\nu + m_e)^2 - E_\nu^2 \cos^2 \theta)} \right\}, \end{aligned} \quad (2.34)$$

Table 2.1: Neutrino-on-electron elastic scattering total cross sections. **TO DO: Move units to title and add cross sections with thresholds. Also reference this somewhere in text** from Fundamentals of neutrino Physics and Astrophysics, p.139

Process	Total cross section
$\nu_e + e^-$	$\simeq 93 \times 10^{-43} E_\nu \text{cm}^2 \text{GeV}^{-1}$
$\bar{\nu}_e + e^-$	$\simeq 39 \times 10^{-43} E_\nu \text{cm}^2 \text{GeV}^{-1}$
$\nu_{\mu,\tau} + e^-$	$\simeq 15 \times 10^{-43} E_\nu \text{cm}^2 \text{GeV}^{-1}$
$\bar{\nu}_{\mu,\tau} + e^-$	$\simeq 13 \times 10^{-43} E_\nu \text{cm}^2 \text{GeV}^{-1}$

The neutrino magnetic moment contribution is **TO DO: include derivation from [?]** [94]:

$$\left( \frac{d\sigma_{\nu_le^-}}{dT_e} \right)_{\text{MAG}} = \frac{\pi\alpha^2}{m_e^2} \left( \frac{1}{T_e} - \frac{1}{E_\nu} \right) \left( \frac{\mu_{\nu_l}}{\mu_B} \right)^2, \quad (2.35)$$

where  $\alpha$  is the fine structure constant **TO DO: Calculate the total mag moment cross sections.**

Comparison of the **SM** and the neutrino magnetic moment cross sections is shown on Fig.2.4. Whereas the **SM** cross section is flat with  $T_e \rightarrow 0$ , the neutrino magnetic moment cross section keeps increasing to infinity. However, this reach is limited by the experimental capabilities of detecting such low energetic neutrinos. Possible **NOvA** coverage is shown in a shaded blue and it is uncertain we could actually reach as low as 100 MeV **TO DO: Change this claims a little bit.**

As can be seen in Fig. 2.4 and Fig. 2.5, the magnetic moment contribution exceeds the **SM** contribution for low enough  $T_e$ . This can be approximated as [94]:

$$T_e \lesssim \frac{\pi^2 \alpha^2}{G_F^2 m_e^3} \left( \frac{\mu_\nu}{\mu_B} \right)^2 \simeq 2.9 \times 10^{19} \left( \frac{\mu_\nu}{\mu_B} \right)^2 [\text{MeV}], \quad (2.36)$$

which does not depend on the neutrino energy and makes experiments sensitive to lower energetic electrons more sensitive to the neutrino magnetic moment. This is especially true for the recent dark matter experiments which put stringent limits on the solar neutrino effective magnetic moment, as described in the following section.

## 2.2 Analysis overview

Our analysis strategy is to compare the count of the recorded neutrino events in data with the prediction. The prediction consists of the signal, which is directly related to

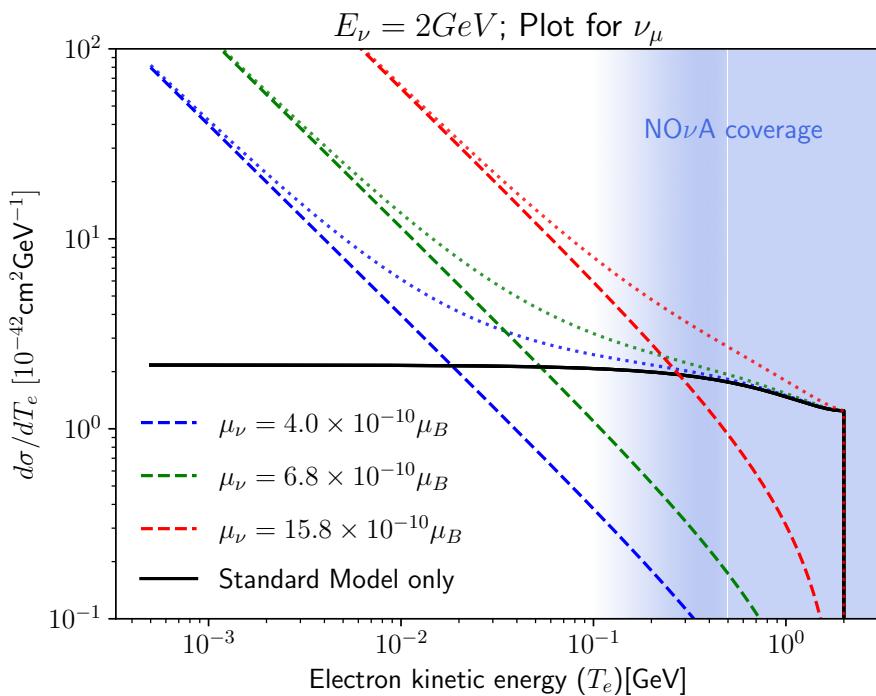


Figure 2.4: Comparison of the neutrino magnetic moment (coloured) and the SM (black) cross sections for the  $\nu$ -on-e elastic scattering. Different colours depict different values of the neutrino magnetic moment. Dashed lines are the individual cross sections and dotted lines are the added total cross section with the standard model contribution. NOvA coverage of electron recoil energies is shown in shaded blue TO DO: Reference the colours on the figures to the origins of the values (LSND and Biao).

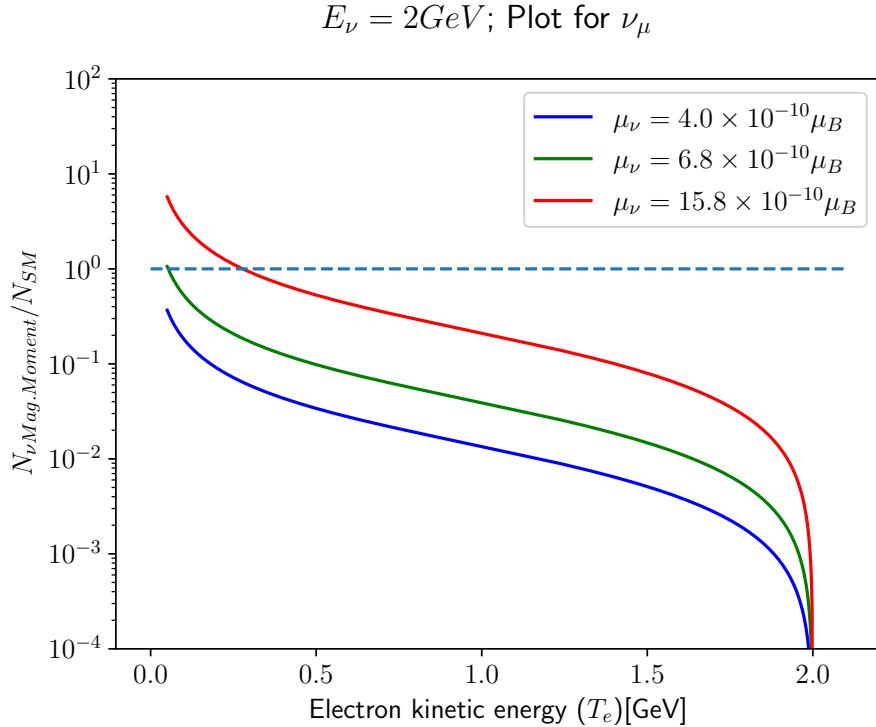


Figure 2.5: Ratio of the neutrino magnetic moment cross section to the **SM** cross section for the  $\nu$ -on-e elastic scattering. Different colours depict different effective muon neutrino magnetic moment values.

the value of the neutrino magnetic moment, and the background, which corresponds to the predicted events under the **SM**. The signal is defined as true  $\nu$ -on-e events with the neutrino magnetic moment cross section instead of the **SM** one. Additionally, we require the true vertex to be contained inside of the **ND** to remove events that originates from outside of the detector. Background is everything else.

The data used in this analysis was collected from the start of the **NOvA ND** data taking on the 22<sup>nd</sup> of August 2014, until the 3<sup>rd</sup> of February 2021. This is the **ND** data that was used in the latest **NOvA** neutrino oscillations result [7], with an additional one year of data taking. The **ND** collected more data since February 2021 which is however still being processed and it is not available at the time of writing this thesis. The full **ND**-equivalent exposure of the data sample is approximately  $13.8 \times 10^{20}$  **POT**. This exposure is used throughout the rest of this chapter to scale the predicted distributions and number of events. **COMMENT: Should I also talk about the RHC sample here? Future data?**

Maybe also mention something about the data that was excluded - bad runs and bad channels?

This analysis uses the standard **NOvA** simulation and reconstruction tools, as were discussed in Sec. 1.4 and 1.5. The simulation was created with approximately  $4 \times$  larger statistics than is available in data to limit statistical uncertainties from simulation. The total exposure for the simulation is approximately  $55.4 \times 10^{20}$  POT. However, for the studies of the systematic uncertainties, only a smaller portion of this full sample is used, specifically  $19.3 \times 10^{20}$  POT ND-equivalent.

The corrections for the known limitations in the simulation are applied in the form of event-by-event analysis weights, which weight each single event based on how it is affected by that particular variation in simulation. To correct for known deficiencies in simulation of neutrino flux or cross sections we apply weights calculated for each event. This includes the external measurements that correct the neutrino beam prediction inside **PPFX** as described in Sec. 1.4, and for the non- $\nu$ -on-e background, also the internal and external measurements that constrain the neutrino interaction prediction inside **GENIE**. These are not applied to the  $\nu$ -on-e events, as they are assumed to be known precisely from theory. However, the **GENIE MC** simulation doesn't consider radiative corrections for the  $\nu$ -on-e events, which are however trivial to implement.

Mention here where did I get the original **GENIE** cross section from (reference Yiwen's talk or technote, plus the original paper that was used). nu-on-e technote[91]

**TO DO:** *Write out the actual version of the weight. Including the original and the corrected XSec constants*

MINERvA paper [99]: At tree level, the neutrino-electron scattering cross section is given by... (basically same as I have in the theory) corrected for updated electroweak couplings, CLL and CLR [17] and one-loop electroweak radiative corrections as calculated in Ref. [18]. One deficiency of the calculation of Ref. [18] is that it does not contain the term in the one-loop cross section proportional to CLL CLR. This deficiency is corrected in a recent calculation [38], and that result is given below. However, as illustrated in Eq. (A1) this term also contains an additional power of  $m/Enu$  compared to the terms proportional to C2 LL and C2 LR, and the entire term is therefore negligible at the few-GeV neutrino energies of the MINERvA experiment.

Say that we are not using the third part of the correction because it is tiny and it makes no difference. (tried and tested)

[ND group's technote] In GENIE, the cross section of the nuone elastic scattering signal is calculated at the tree level. To improve the precision of the simulated nuone elastic scattering cross section, we performed radiative corrections to the GENIE nuone elastic scattering as shown in Appendix A. The precision of the simulated nuone elastic scattering cross section is improved by tuning CLL and CLR to one-loop values obtained from global fits to electroweak data 14 and 2. The radiative correction also includes additional low-energy terms in the expression of differential cross section of nuone elastic scattering. In comparison, the neutrino interactions in the NOvA detector are simulated using the GENIE neutrino event generator, where the Weinberg Angle is 0.501716712132. After radiative corrections, the total number of nuone elastic scattering increases 0.83% from the standard GENIE MC.

**TO DO:** *correct the equation* Calculated as

$$weight_{\text{Radiative Corr.}} = \frac{d\sigma_{\nu\text{-on-}e}}{dy} \Big|_{\text{Radiative Corr.}} / \frac{d\sigma_{\nu\text{-on-}e}}{dy} \Big|_{\text{GENIE 3}} ; y = \frac{E_e - m_e}{E_\nu} \quad (2.37)$$

**TO DO:** *What does this do and why does it work? Reference the theory part as to why is the magnetic moment signal simply a rescaling of the GENIE cross section.*

Using the same tree-level cross section from GENIE as in the rad. corr. weight.

**TO DO:** *Write the name of the weight in CAFAna/nuone namespace and where it is located*

**TO DO:** *correct the equation* Calculated as

$$weight_{\nu\text{-Mag. Moment}} = \frac{d\sigma_{\nu\text{-on-}e}}{dy} \Big|_{\nu\text{-Mag. Moment}} / \frac{d\sigma_{\nu\text{-on-}e}}{dy} \Big|_{\text{GENIE 3}} ; y = \frac{E_e - m_e}{E_\nu} \quad (2.38)$$

Due to the relatively low cross section of the  $\nu\text{-on-}e$  interaction, the nominal simulation sample contains too few  $\nu\text{-on-}e$  events, which could result in a significant statistical uncertainty from simulation. To avoid this, we created a  $\nu\text{-on-}e$ -enhanced simulation sample which contains mainly  $\nu\text{-on-}e$  events with a little non- $\nu\text{-on-}e$  background overlaid on top to properly account for the possible reconstruction effects of the pileup of neutrino interactions in one spill [91]. In the real detector, the hits from the true  $\nu\text{-on-}e$  interaction can be clustered to another interaction, or additional hits can be clustered together into the  $\nu\text{-on-}e$  event. The total exposure of the  $\nu\text{-on-}e$ -enhanced sample is  $1.72 \times 10^{24}$  POT. To save up on unnecessary disk space and pro-

cessing usage, the enhanced  $\nu$ -on-e sample does not include any cross section related parameters and variables, as the  $\nu$ -on-e interaction is assumed to be known exactly from theory.

The cross section tuning procedure in NOvA (Sec. 1.4) applies large weights to MEC events in some parts of the parameter space. However, after the full event selection described below in Sec. 2.3 there is only a small amount of MEC events, specifically  $\nu_e$ CC MEC events, left in the detector. Applying large tuning corrections to only a small number of events results in large statistical fluctuations. To avoid this, we created another special sample with enhanced number of  $\nu_e$ CC MEC events. We followed the same procedure as for the  $\nu$ -on-e-enhanced sample, resulting in the final exposure of  $1.99 \times 10^{24}$  POT.

The summary of the simulation samples and analysis weights for the three different types of signal and background component is shown in Tab. 2.2.

Table 2.2: Overview of the simulation samples and analysis weight used for the different signal and background components.

Signal type	Sample	Weight
Signal	Enhanced $\nu$ -on-e	Flux & $\nu$ Mag. Moment
$\nu$ -on-e background	Enhanced $\nu$ -on-e	Flux & Rad. Corr.
$\nu_e$ CC MEC background	Enhanced $\nu_e$ CC MEC	Flux & Cross Sec.
Other background	Nominal ND	Flux & Cross Sec.

## 2.3 Event selection

We are searching for  $\nu$ -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  $\nu_e$ CC interactions, which produce electron with an additional activity, and interactions that produce  $\pi^0$ , which decays into two photons producing electromagnetic showers, where each can look similar to the  $\nu$ -on-e signal. Additionally, there are  $\nu_\mu$ CC interactions, which are generally easy to identify 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. Then, we apply pre-selection cuts that remove obvious background. The exact cut is selected by limiting the reduction of the signal efficiency to about 0.25 %. Following this, we apply the containment cuts 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 consider several variables that could be used for the signal selection and evaluate their combined performance for a signal selection. We choose 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

$$\text{FOM} = \frac{\text{Signal}}{\sqrt{\text{Background}}}. \quad (2.39)$$

The summary of the cut values for the event selection of neutrino magnetic moment signal is presented in Tab. 2.3, showing the label for the event selection variable, its description and the cut value chosen. These event selection in total reduces signal 44.51 %,  $\nu\text{-on-e}$  background 70.40 % and other background 99.97 %. After the full event selection, the predicted number of signal events for  $\mu_\nu = 10^{-9} \mu_B$  is 23.31 and the total number of background events under the SM hypothesis is 678.26. The most likely improvement is in probing the low energetic events and making sure they make sense. Additionally, it is possible to use a specially designed control regions to mitigate the very high non- $\nu\text{-on-e}$  background.

### 2.3.1 Data Collection Quality

To ensure good data quality, we apply the following criteria to data only. These involve the the spill time cut, at least  $2^{12}$  POT per spill, the current in the focusing horn within  $1 < I_{Horn} < -198$ , position of the beam is within  $\pm 2$  cm in both x and y axis and that the width of the beam is within 0.57 and 1.58 cm. Additionally, we remove events that are incomplete, or with problems in one or more DCMs.

### 2.3.2 Reconstruction Quality

Since electron are reconstructed by slicing, then vertexing, then reconstructing prongs. To identify electron we request that there is a valid reconstructed vertex and at least one reconstructed prong. Even though electrons only consist of a single shower, we

Table 2.3: Summary of the cut values for the event selection of neutrino magnetic moment signal showing the label for the event selection variable, its description and the cut value chosen. **COMMENT:** *Should I include the loose cuts here even when they were made stricter during TMVA?*

<b>Label</b>	<b>Description</b>	<b>Cut</b>
<b>Valid Vtx</b>	Valid reconstructed vertex	$> 0$
<b>Nº Prongs</b>	Number of reconstructed prongs	$> 0$
<b>Hits / Plane</b>	Number of hits per plane	$< 5$
<b>Low <math>E_{Shower}</math></b>	Low cut on calorimetric energy of the most energetic shower	$> 0.5 \text{ GeV}$
<b>Nº Hits Loose</b>	Preliminary cut on the total number of hits for all prongs in a slice	$< 200$
<b>Prong Length</b>	Length of the longest prong	$< 540 \text{ cm}$
<b><math>E\theta^2</math> Loose</b>	Preliminary cut on the product of the calorimetric energy and angle squared of the leading shower	$< 0.05 \text{ GeV} \times \text{rad}^2$
<b>High <math>E_{Shower}</math> Loose</b>	Preliminary upper cut on the calorimetric energy of the most energetic shower	$< 5.5 \text{ GeV}$
<b>Fiducial</b>	Vertex x position	$> -177 \text{ cm}$ $< 177 \text{ cm}$
	Vertex y position	$> -177 \text{ cm}$ $< 177 \text{ cm}$
	Vertex z position	$> 50 \text{ cm}$ $< 1050 \text{ cm}$
<b>Containment</b>	Minimum hit position in x	$> -177 \text{ cm}$
	Maximum hit position in x	$< 177 \text{ cm}$
	Minimum hit position in y	$> -185 \text{ cm}$
	Maximum hit position in y	$< 177 \text{ cm}$
	Minimum hit position in z	$> 55 \text{ cm}$
	Maximum hit position in z	$< 1270 \text{ cm}$
$E_{Shower}/E_{Tot}$	Fraction of energy contained in the most energetic shower	$> 0.91$
<b>Nº Hits</b>	Total number of hits for all prongs in a slice	$< 116$
<b>High <math>E_{Shower}</math></b>	Calorimetric energy of the most energetic shower	$< 1.4 \text{ GeV}$
<b><math>\nu</math>-on-e ID</b>	CVN-based $\nu$ -on-e identifier	$> 0.65$
<b><math>E\pi^0</math> ID</b>	CVN-based $\nu$ -on-e and $\pi^0$ identifier	$> 0.63$
<b><math>E\theta^2</math></b>	Product of the calorimetric energy and angle squared of the leading shower	$< 0.0048 \text{ GeV} \times \text{rad}^2$

don't reject events with more than one prongs in a slice, as the reconstruction can wrongly assign noise hits as a separate prong. We do not want to reject these events as we might still recover the true signal event from there.

Figure 2.6 and Tab. 2.4 show that about 67 % signal events do not have a valid reconstructed vertex. This is due to the concentration of the signal events at very low electron recoil energies, which can often consist of a single hit or only a few hits. As can be seen in the bottom plot of Fig. 2.6, events with small true electron recoil energy have much smaller vertex reconstruction efficiency than higher energetic electrons. However, improving NOvA vertex reconstruction at low energies might significantly aid the search for the neutrino magnetic moment. Ongoing work is improving the vertex reconstruction by using ML approach instead of the currently used Hough transform together with Elastic Arms [100].

Additionally, we're placing a cut on the number of hits per plane to  $< 5$ . This is to remove the so-called 'FEB flashers', which are caused by a very high energy deposit in one cell, such that it affects all the other channel on the same APD [101]. The cut value was chosen so that it removes  $\leq 0.25\%$  signal events, which is the same criterion as is used for the basic event 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. 2.7.

**COMMENT:** *Already applying the cut here to help reduce the events for TMVA. This cut is based purely on reco quality (we don't trust events below 0.5GeV, especially not for the CVN nuone ID variables)*

**TO DO:** *discuss the energy cut, should this be removed? What is the effect on the event count? Why was this included in the first place (the identifiers are not as strong for lower energies - is this true though? - also there are further unexplored backgrounds that would need to be further studied and explore. Maybe depends on where would we move the cut...)*

The reconstructed calorimetric energy of the primary shower is required to be  $E_{cal} > 0.5\text{ GeV}$  as shown in Fig. 2.8. This is to remove region in the parameter space with large backgrounds. However, due to the nature of the neutrino magnetic moment signal, this cut also removes a majority of our signal events (exactly how much?).

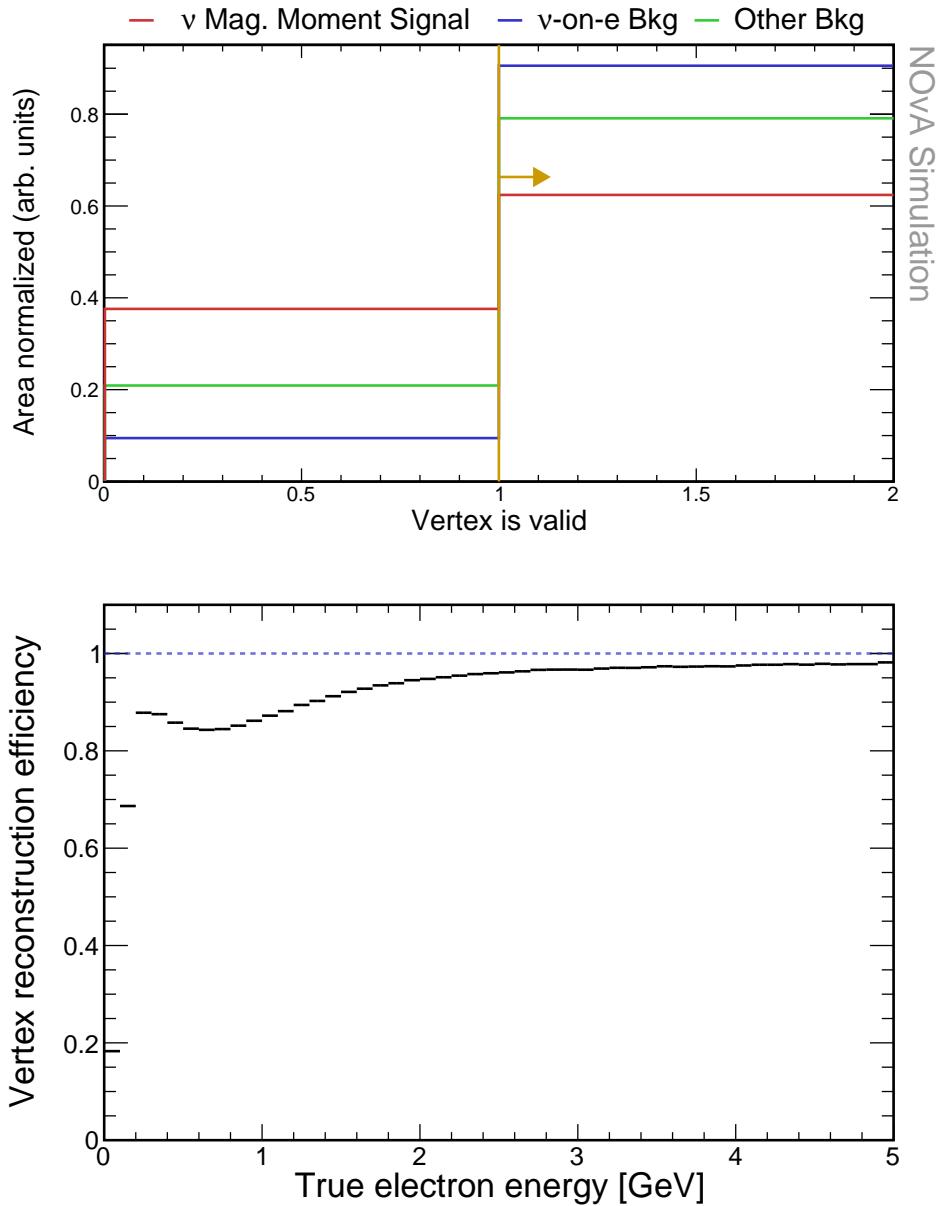


Figure 2.6: Top: Relative comparison of the signal (red),  $\nu$ -on-e background (blue), and other background (green) events for the vertex reconstruction quality selection. Each histogram is area-normalised and the first bin corresponds to events without a valid vertex and second bin to events with correctly reconstructed vertex. The yellow line indicates the chosen cut value: 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.

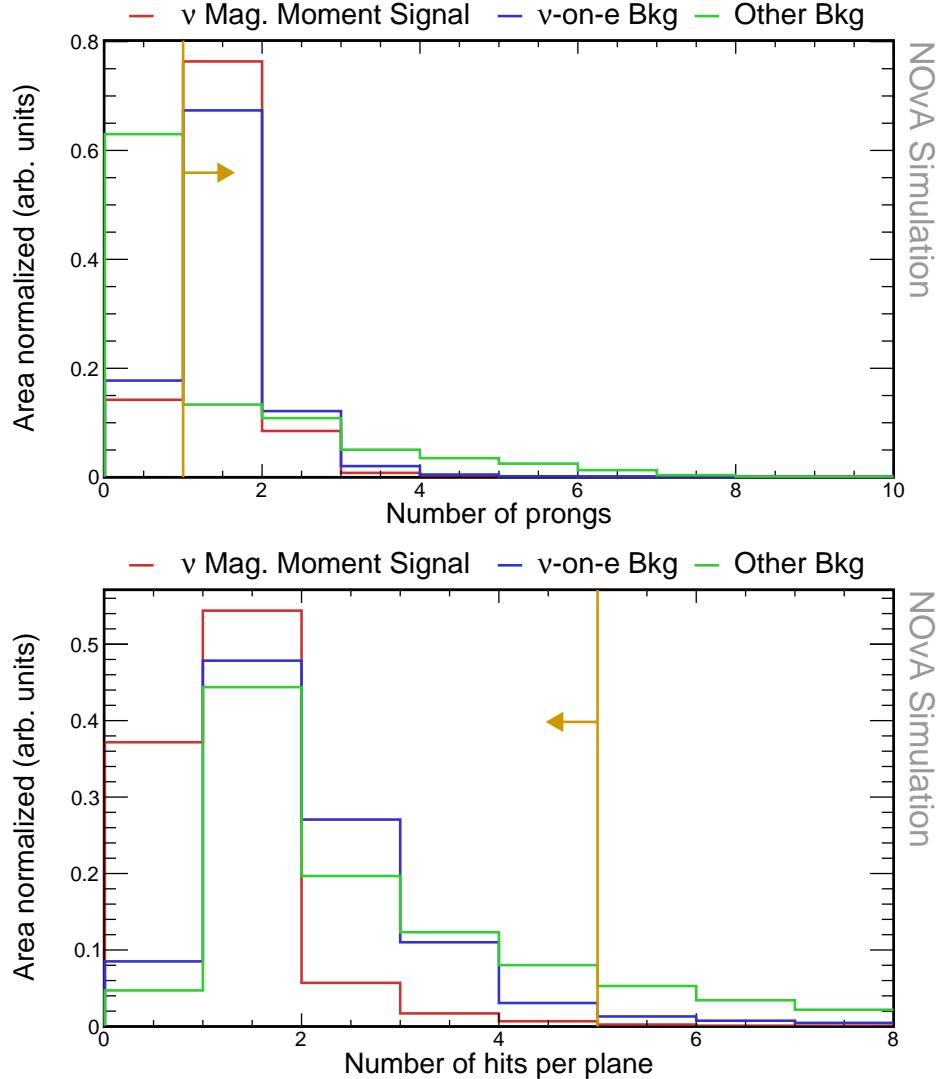


Figure 2.7: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the number of prongs (top) and the number of hits per plane (bottom) distributions. Events in both plots are required to have a valid reconstructed vertex and in the bottom plot also 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.

This is due to a presence of large background that has not been studied very well. No NOvA analysis really uses events with such low energies. However, after further studies and validation, it is likely that these cut can be pushed to lower electron recoil energy, especially by using better event identifiers to remove the large background there.

NOvA is not super well suited for a low energy detection and there are troubles identifying very low energetic event. Majority of the analyses in NOvA only use events with energies above 0.5 GeV. nueCCXSec only uses events above 1 GeV. The numuCCpi0 XSec ana had a low E cutoff at 0.1GeV

*COMMENT: How does the energy resolution and bias come into play here? 0.5GeV for us is not the same as for the 3fl or for some other ND analyses. This needs to be properly investigated in the future*

Maybe also say that Test Beam will be crucial in improving the vertex and energy resolution within NOvA, including electrons.

Table 2.4: 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.

<b>Selection</b>	<b>Signal</b>		<b><math>\nu</math>-on-e bkg</b>		<b>Other bkg</b>	
	$N_{evt}$	$\epsilon_{rel} (\%)$	$N_{evt}$	$\epsilon_{rel} (\%)$	$N_{evt}$	$\epsilon_{rel} (\%)$
<b>No Cut</b>	269.77	100	$3.43 \times 10^3$	100	$2.96 \times 10^8$	100
<b>Valid Vtx</b>	180.58	66.94	$3.33 \times 10^3$	96.94	$2.34 \times 10^8$	79.10
<b>N° Prongs</b>	174.69	96.74	$3.23 \times 10^3$	96.99	$8.66 \times 10^7$	37.00
<b>Hits / Plane</b>	174.36	99.81	$3.22 \times 10^3$	93.83	$7.32 \times 10^7$	84.55
<b>Low <math>E_{Shower}</math></b>	48.75	27.96	$2.71 \times 10^3$	84.10	$4.06 \times 10^7$	55.52

### 2.3.3 Basic Event Selection

Basic event selection cuts aim to remove obvious background events without affecting the signal too much. The criterion for these cuts will be that each of them has to limit the signal efficiency by approximately 0.25 %. This means that in total the pre-selection cuts will lower the signal efficiency by only approximately 1 %. We are using the same variables for these cuts as were used in the event selection for the  $\nu_e$  appearance ND constraint for the three flavour neutrino oscillation measurements

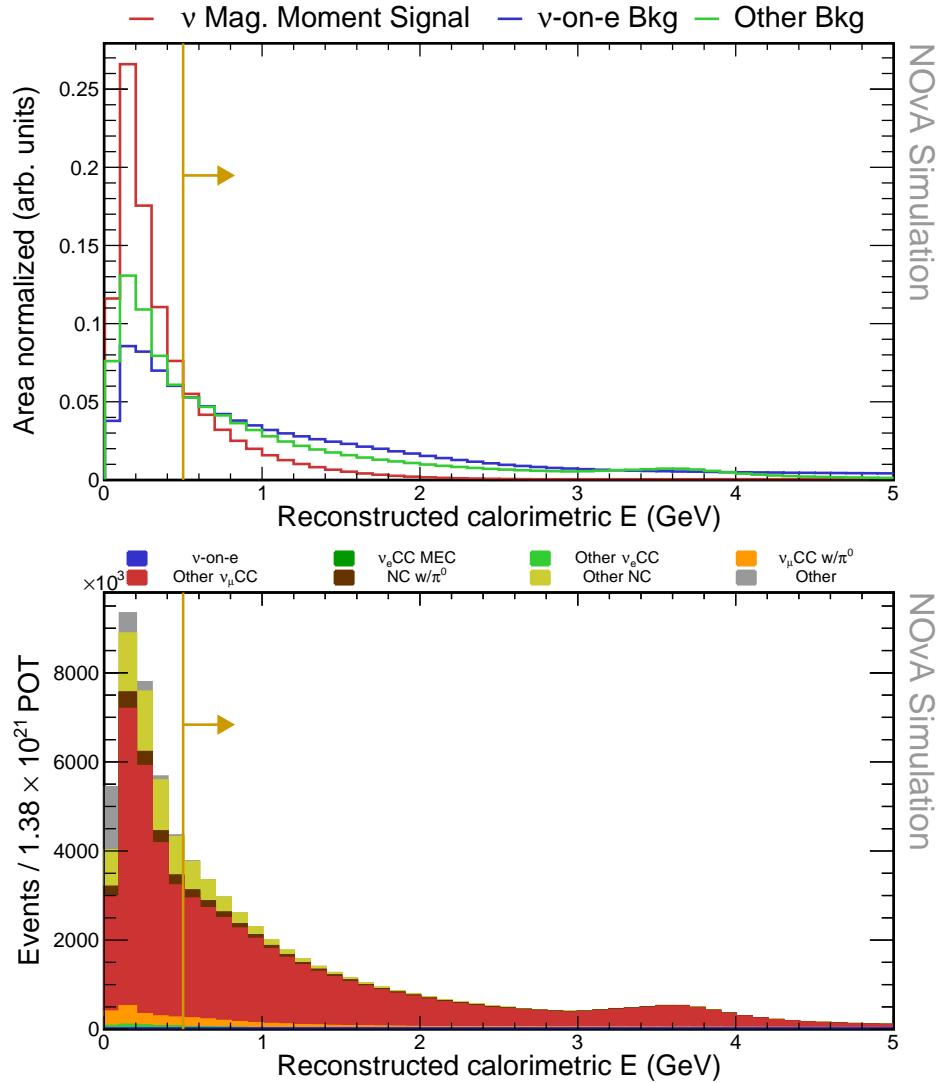


Figure 2.8: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the reconstructed calorimetric energy distribution. All histograms are area-normalised. Bottom: Decomposition of background into various sub-samples, normalised to the data POT exposure. Events in both plots are required to have a valid reconstructed vertex, at least one reconstructed prong and at most 5 hits per plane. Yellow lines indicate the cut value for the reconstructed calorimetric energy, with arrows pointing towards the preserved events.

[7]. Additionally, we are also using a cut on the product of the reconstructed calorimetric energy and the square of the reconstructed angle between the recoil electron and the neutrino beam direction. The electron is assumed to be the most energetic reconstructed showers. The reconstructed showers are ordered based on their deposited energies, therefore the first reconstructed prong is assumed to be the most energetic. In case of the  $\nu$ -on-e events, this should be the electron.

They also remove the obvious  $\nu_\mu$ CC interactions by requiring that the summed number of cells for all prongs in the slice is  $< 200$  and the length of the longest prong is  $< 540$  cm. Relative comparison of signal,  $\nu$ -on-e background, and other background distributions for the pre-selection variables is shown on Fig. ??.

Additionally, as discussed in Sec. 2.1.3, from theory we know what the true recoil electron for the  $\nu$ -on-e interaction is supposed to be limited by  $E\theta^2 < 2m_e$ . Due to reconstruction deficiencies, the reconstructed  $E\theta^2$  will not have such a strict cut-off for  $\nu$ -on-e events, this variable can however be used to distinguish them from the  $\nu_e$ CC events, for which the electron has a much more isotropic distribution.

On top of that, we are also placing a loose cut on the maximum calorimetric energy, as the signal is limited to low energies, as can be seen in Fig. 2.11.

Some of the signal events can be reconstructed with the opposite direction than the beam. These events might still be useful though and we want to keep them. 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.

Table 2.5: Basic event 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.

<b>Selection</b>	<b>Signal</b>		<b><math>\nu</math>-on-e bkg</b>		<b>Other bkg</b>	
	$N_{\text{evt}}$	$\epsilon_{\text{rel}} (\%)$	$N_{\text{evt}}$	$\epsilon_{\text{rel}} (\%)$	$N_{\text{evt}}$	$\epsilon_{\text{rel}} (\%)$
<b>Reco Quality</b>	48.75	100	$2.71 \times 10^3$	100	$4.06 \times 10^7$	100
<b>N° Hits Loose</b>	48.64	99.78	$2.32 \times 10^3$	85.63	$3.08 \times 10^7$	75.67
<b>Prong Length</b>	48.52	99.75	$2.26 \times 10^3$	97.39	$2.17 \times 10^7$	70.66
<b><math>E\theta^2</math> Loose</b>	48.39	99.73	$2.25 \times 10^3$	99.71	$6.00 \times 10^6$	27.62
<b>High <math>E_{\text{Shower}}</math> Loose</b>	48.27	99.76	$2.03 \times 10^3$	90.04	$5.98 \times 10^6$	99.67

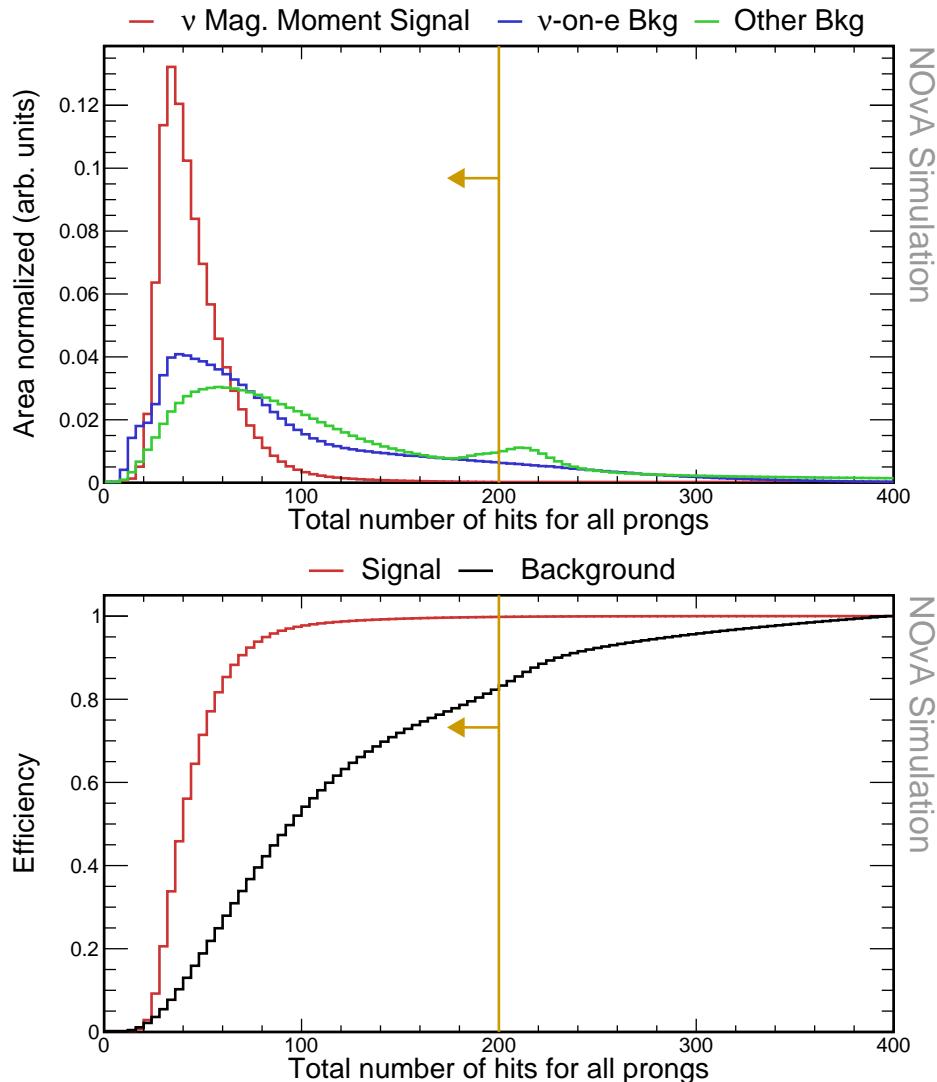


Figure 2.9: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of total number of hits from all reconstructed prongs in the slice. All histograms are area-normalised. Bottom: Cumulative signal (red) and background (black) 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.

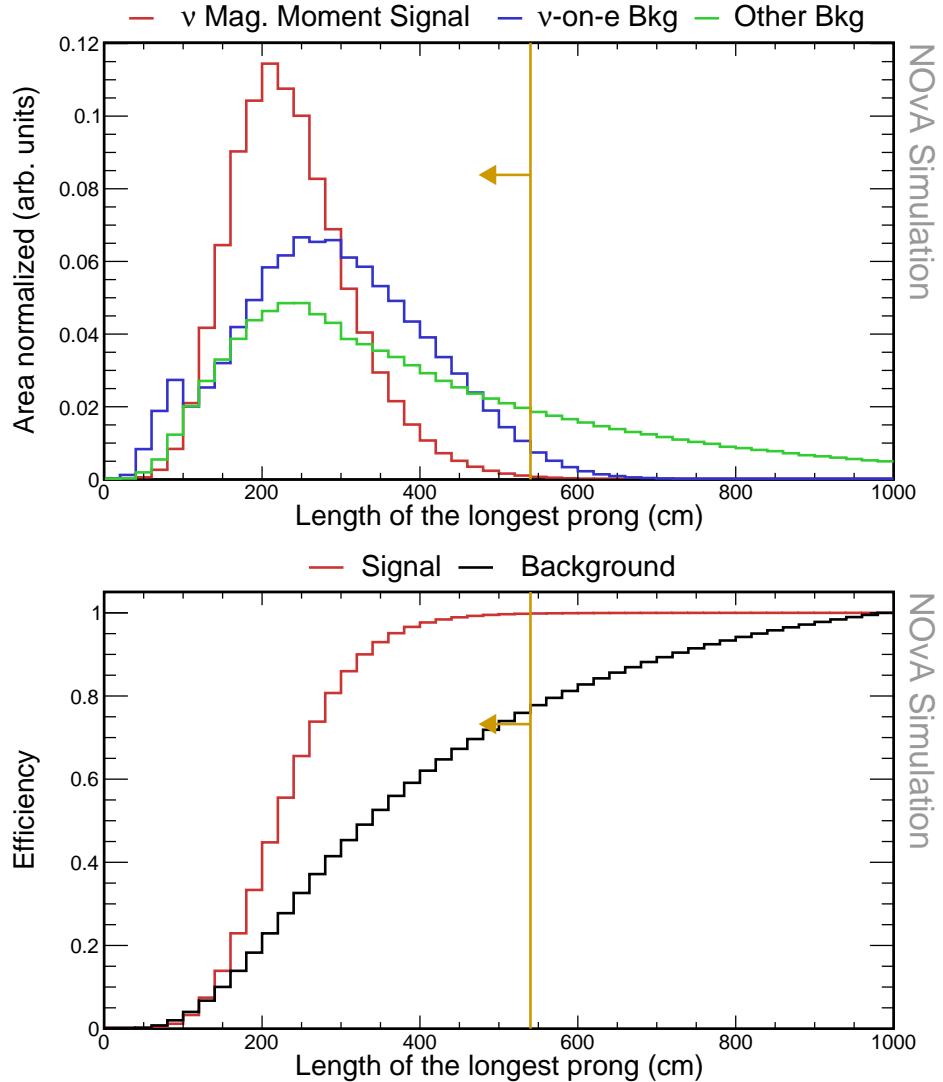


Figure 2.10: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of the length of the longest reconstructed prong in slice. All histograms are area-normalised. Bottom: Cumulative signal (red) and background (black) efficiency 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.

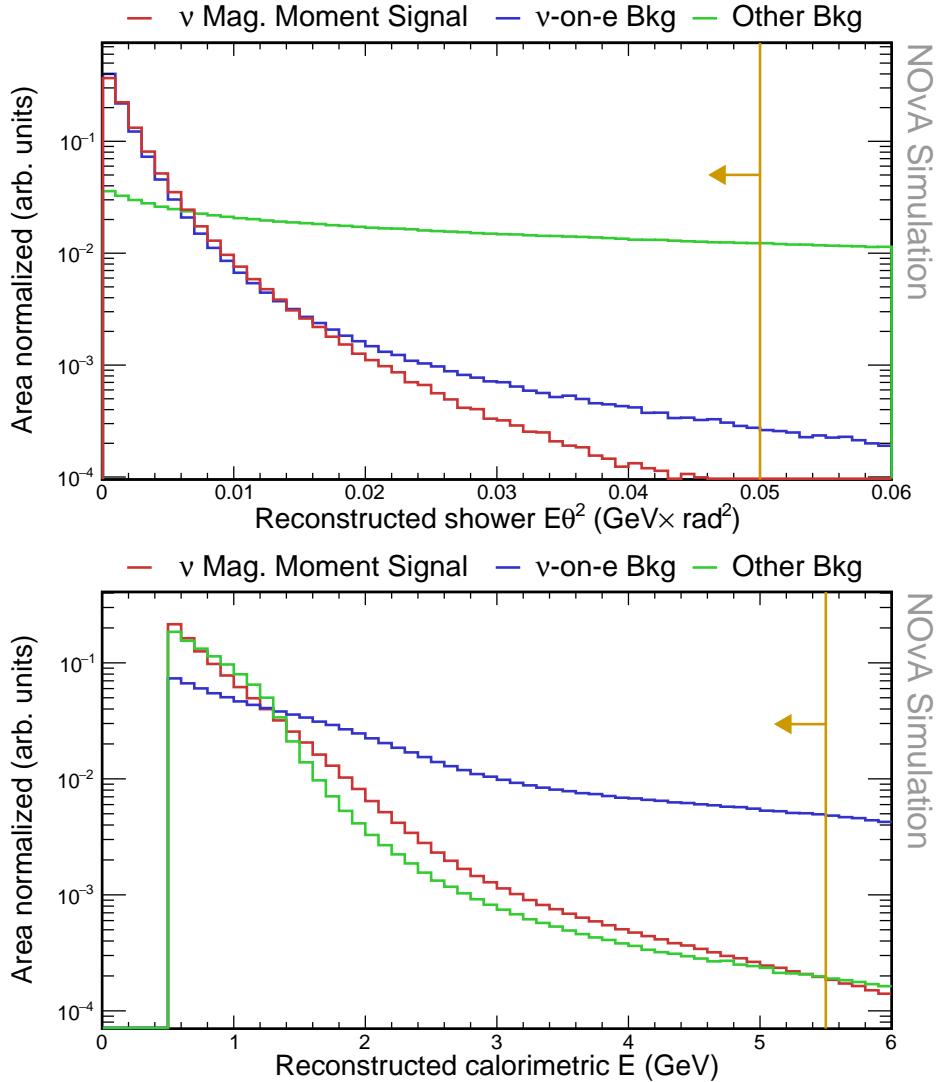


Figure 2.11: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of the reconstructed energy of the leading shower multiplied by its angle from the incoming neutrino beam direction squared (top) and of the reconstructed energy of the leading shower (bottom). All histograms are area-normalised with logarithmic y axis. Yellow lines indicate the cut value for the corresponding variables, 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, while the hits in the bottom plot are also required to pass the  $E\theta^2$  cut.

### 2.3.4 Fiducial and containment cuts

[nueXSec ana, docdb:37668] For both the X and Y vertices the distributions are asymmetric when comparing across the origin, in terms of vertex position. This is primarily due to particles coming from the +y and -x from events in the rock surrounding the detector. This corresponds to the direction of the NuMI target from the near detector. ...We require all activity from neutrino activity be deposited outside of the muon catcher.

**TO DO:** *Describe what does the fiducial cut do* We require that the reconstructed vertex is contained within the following volume:  $-175 < Vtx_X < 175, -175 < Vtx_Y < 175, 95 < Vtx_Z < 1095$  cm.

To ensure all the energy is contained within the detector and to remove events originating outside of the detector (rock muons), we require that the extreme positions of hits for all prongs in the slice are within the following volume:  $-175 < \min_X, \max_X < 175, -175 < \min_Y, \max_Y < 175, 105 < \min_Z, \max_Z < 1270$  cm.

**COMMENT:** *Also made this a bit stricter from the ND group's values as it didn't really make sense*

Table 2.6: 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.

<b>Selection</b>	<b>Signal</b>		<b><math>\nu</math>-on-e bkg</b>		<b>Other bkg</b>	
	$N_{evt}$	$\epsilon_{rel} (\%)$	$N_{evt}$	$\epsilon_{rel} (\%)$	$N_{evt}$	$\epsilon_{rel} (\%)$
<b>Basic selection</b>	48.27	100	$2.03 \times 10^3$	100	$5.98 \times 10^6$	100
<b>Fiducial</b>	45.51	94.27	$1.89 \times 10^3$	93.36	$2.89 \times 10^6$	48.22
<b>Containment</b>	42.01	92.31	$1.62 \times 10^3$	85.42	$7.22 \times 10^5$	25.04

### 2.3.5 Event Selection Optimization

**COMMENT:** *This is where I started the TMVA*

#### Single Shower Requirement

To selection events with a single particle we require that the fraction of energy contained in the most energetic shower is  $> 0.8$ , that the summed energy of all cells

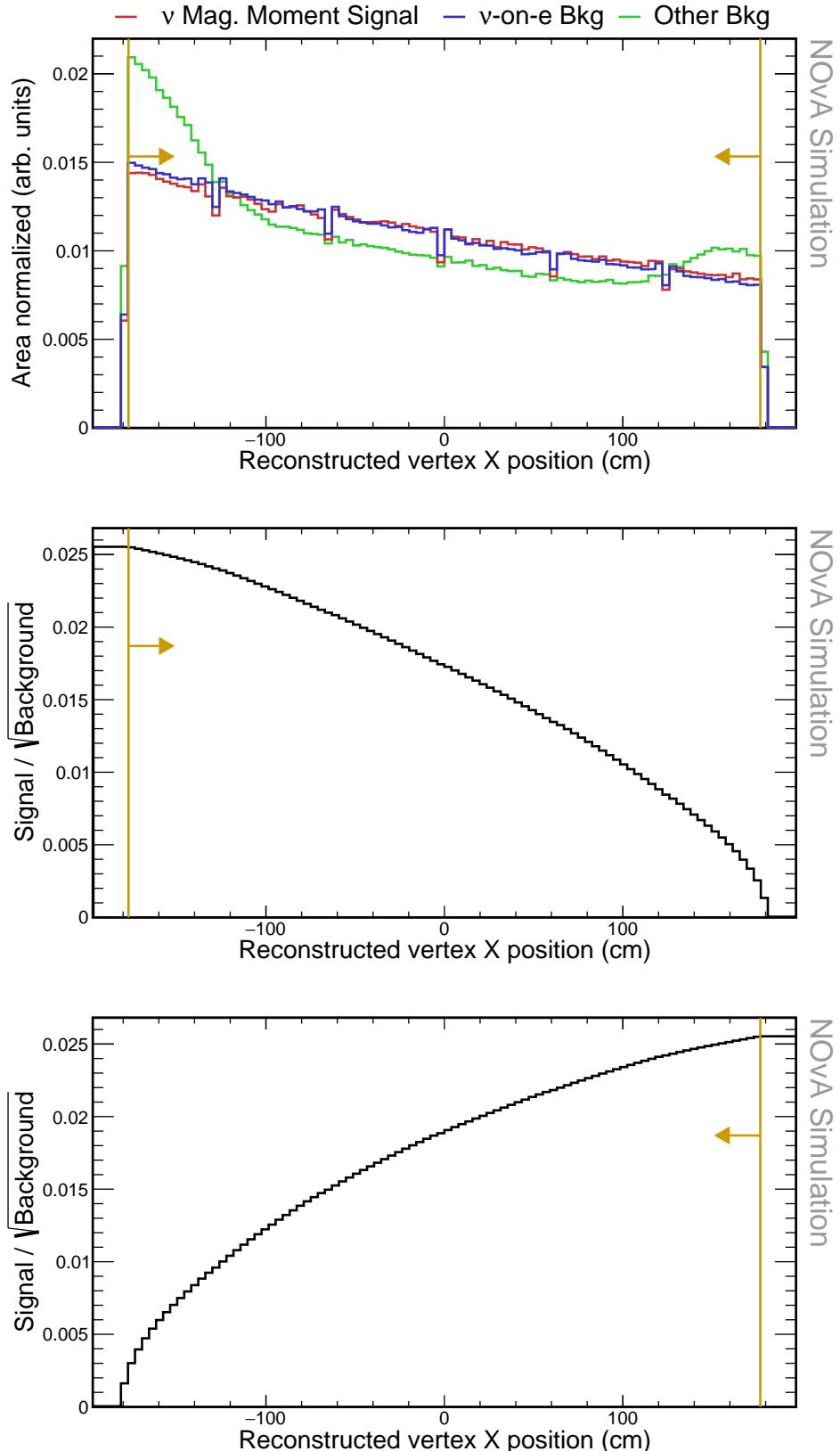


Figure 2.12: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of the x position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, 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 basic 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.

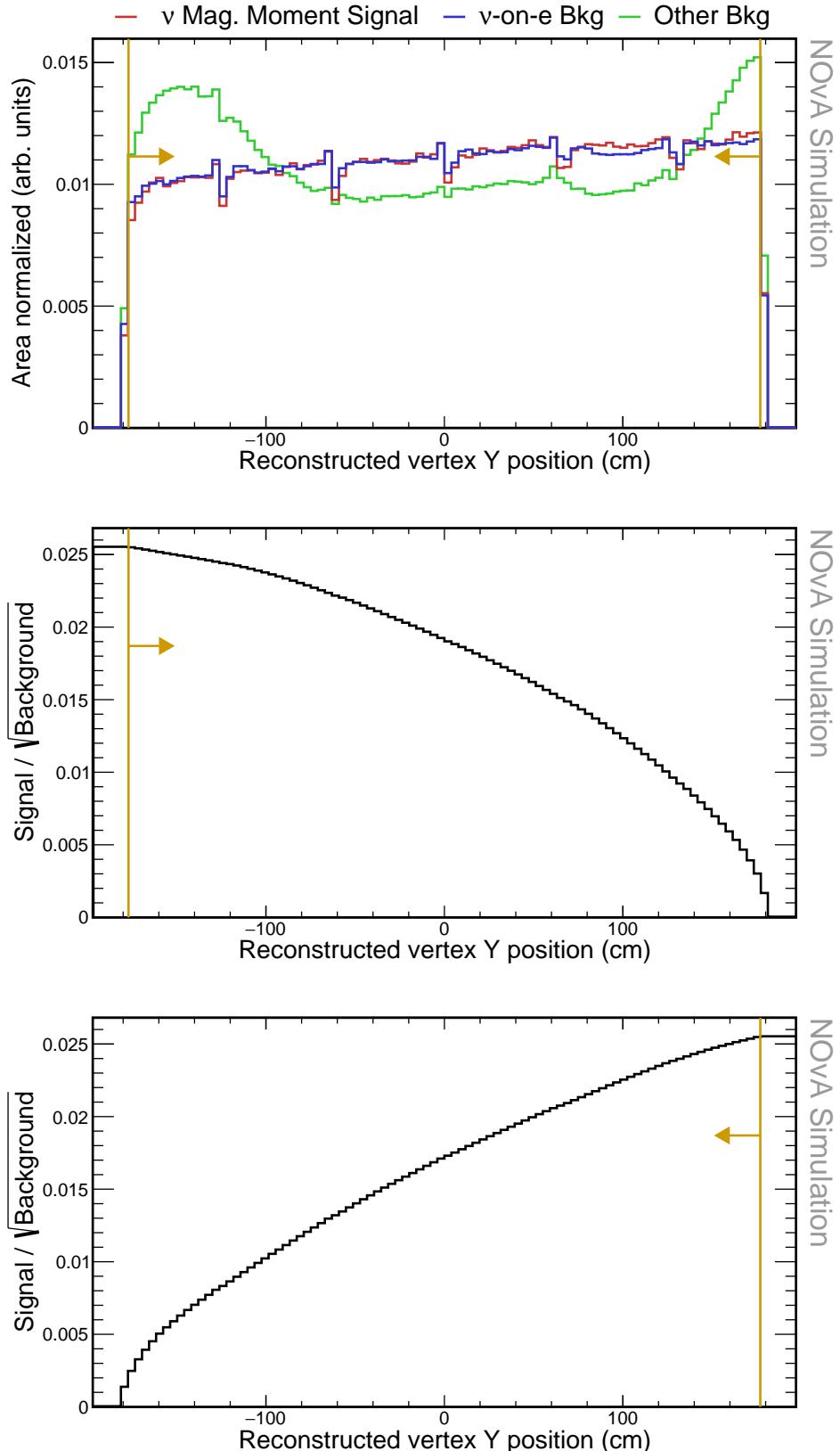


Figure 2.13: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of the y position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, 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 basic 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.

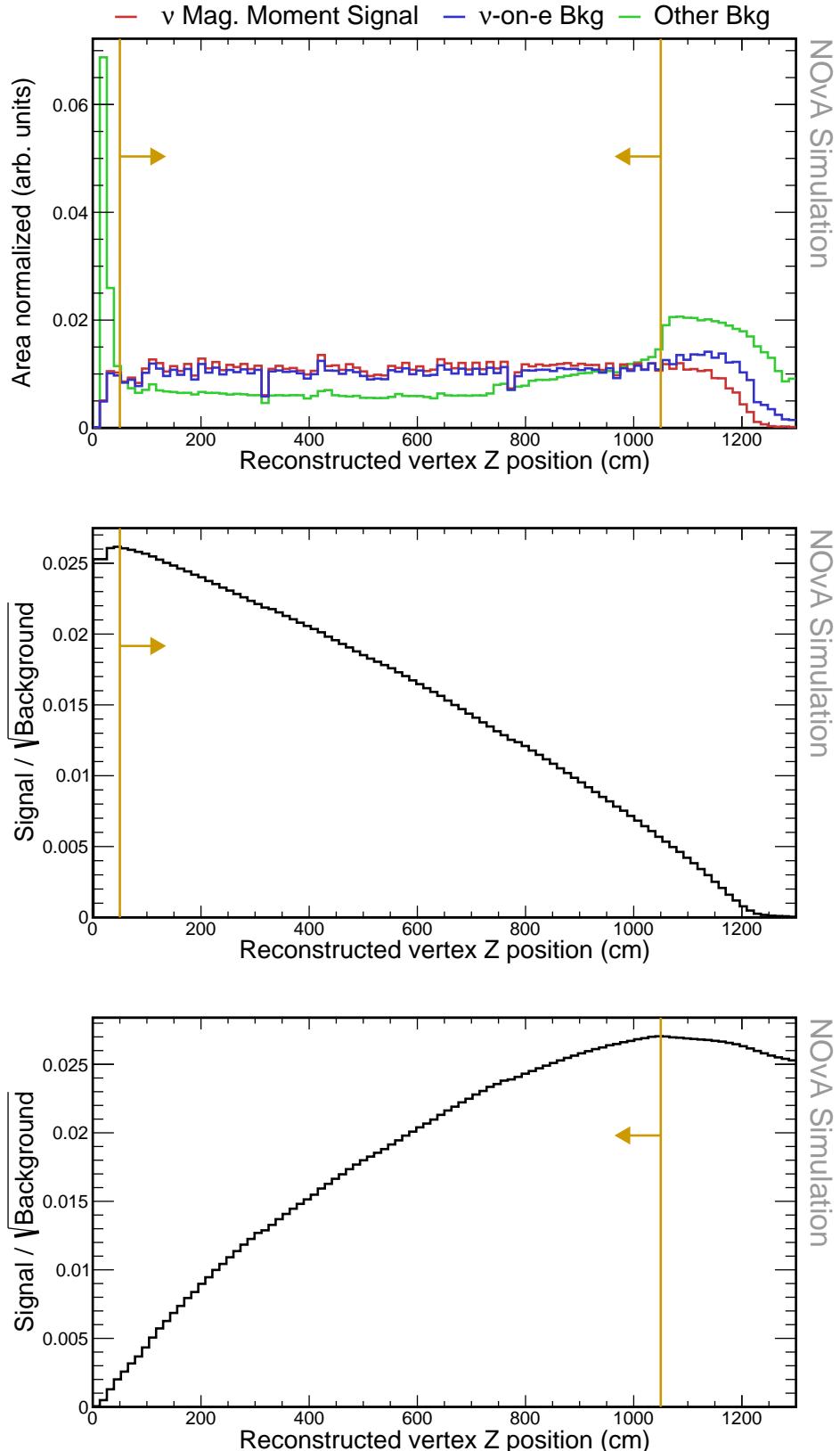


Figure 2.14: Top: Relative comparison of signal (red),  $\nu$ -on-e background (blue), and other background (green) events in the distribution of the z position of the reconstructed vertex. All histograms are area-normalized. Middle and bottom: Cumulative FOM calculated as the number of signal events, 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 basic 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.

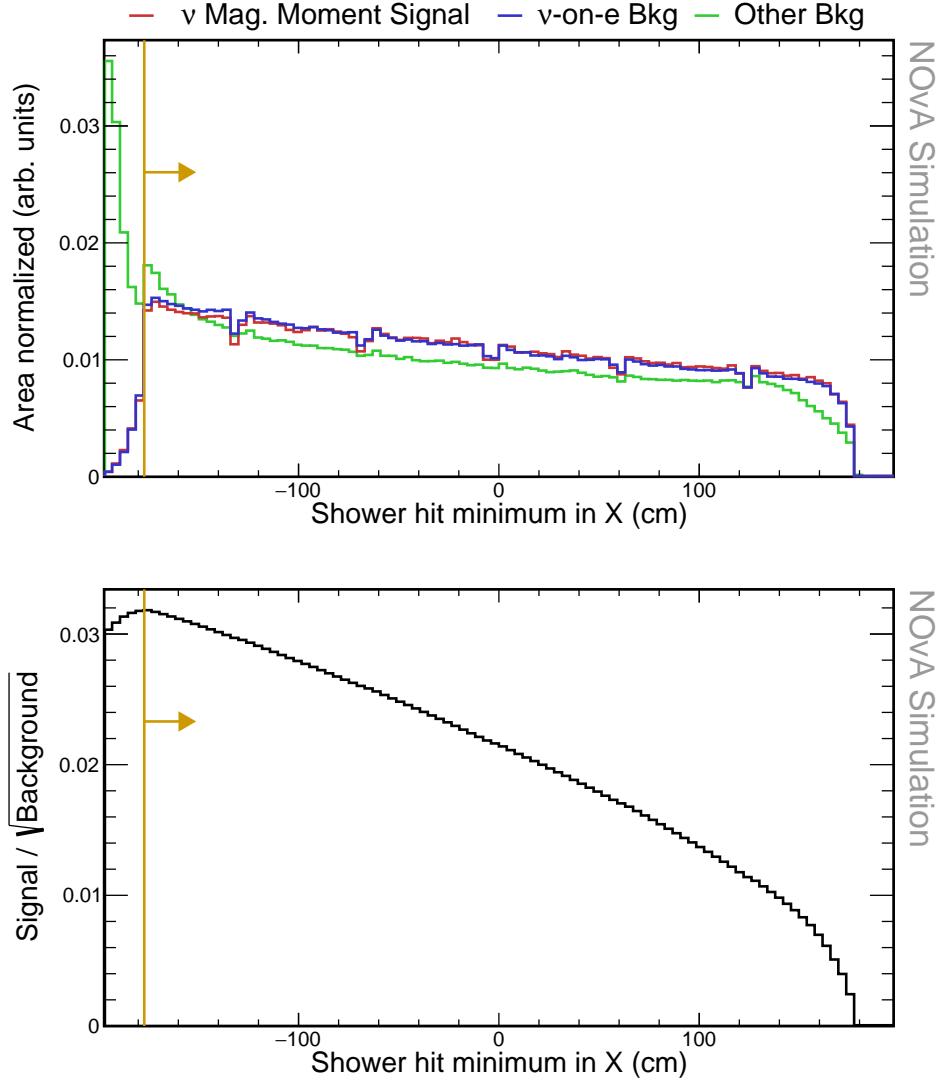


Figure 2.15: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the x axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

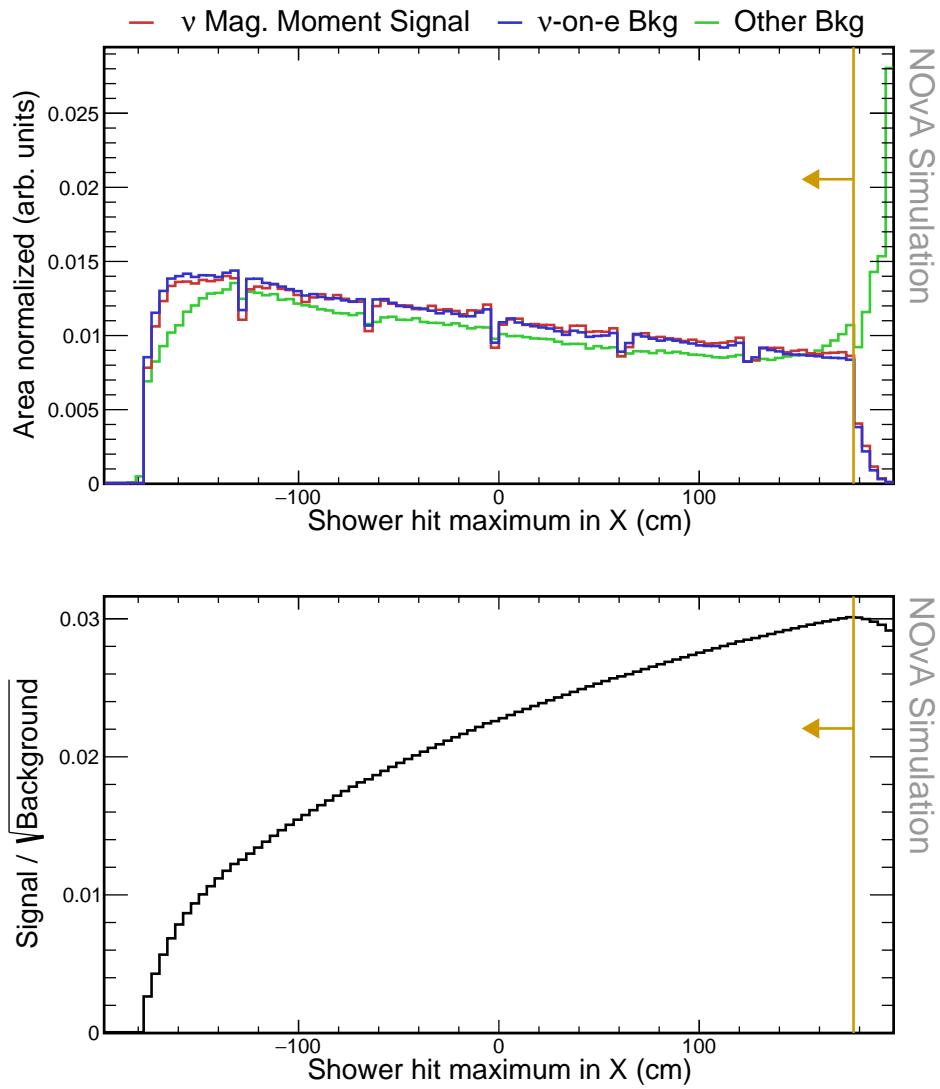


Figure 2.16: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the x axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

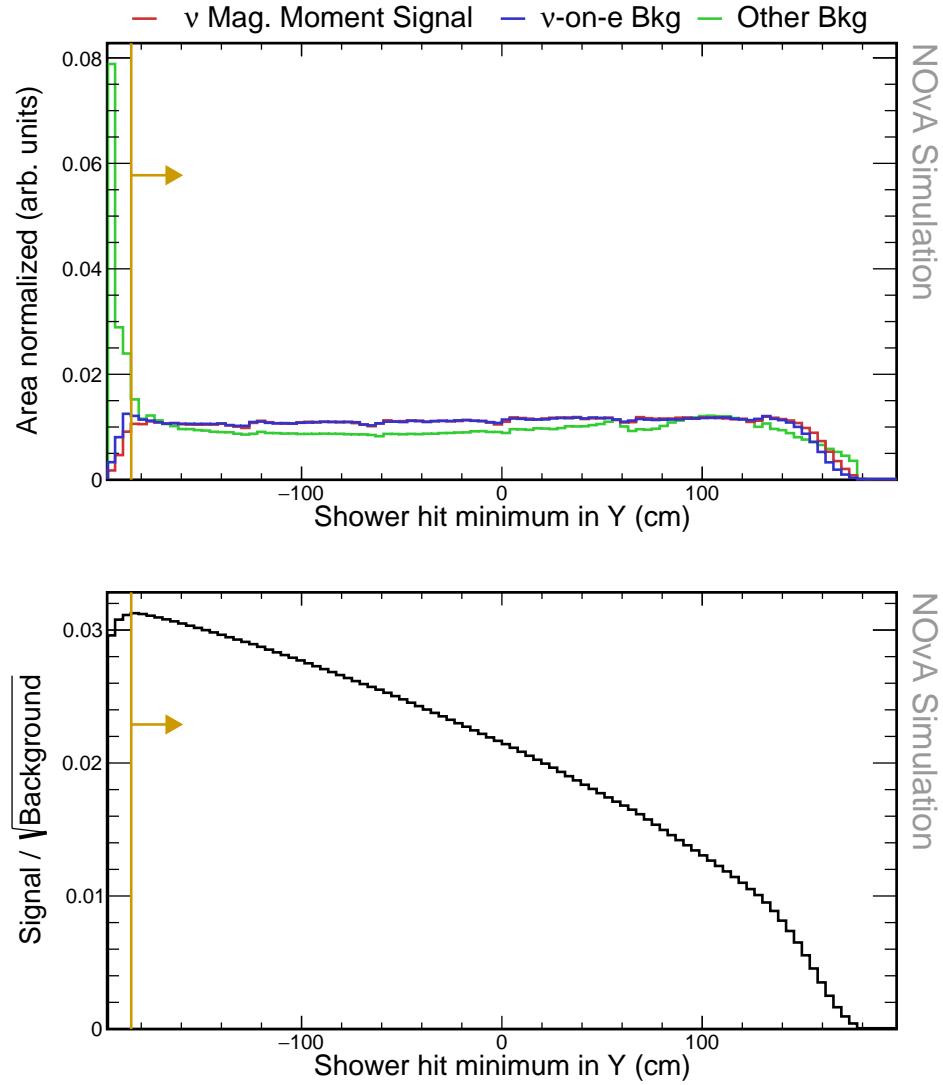


Figure 2.17: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the y axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

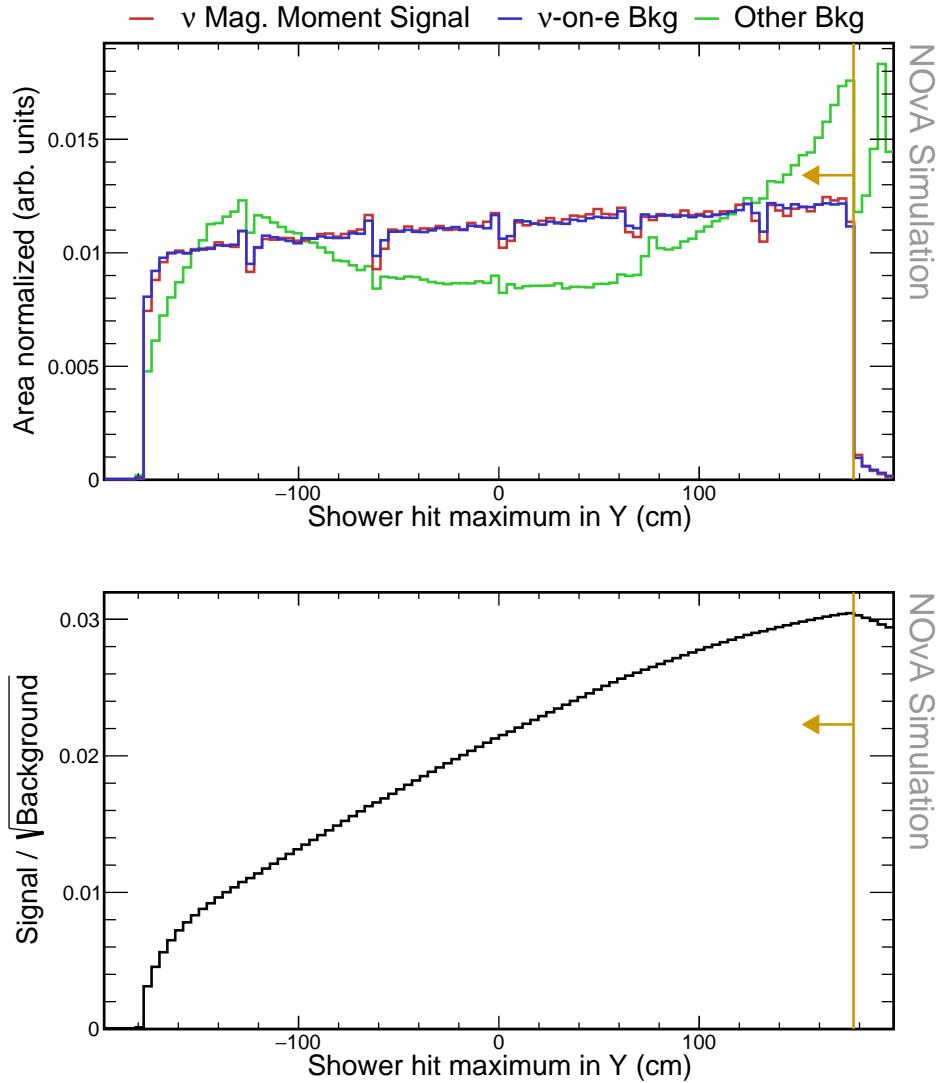


Figure 2.18: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the y axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

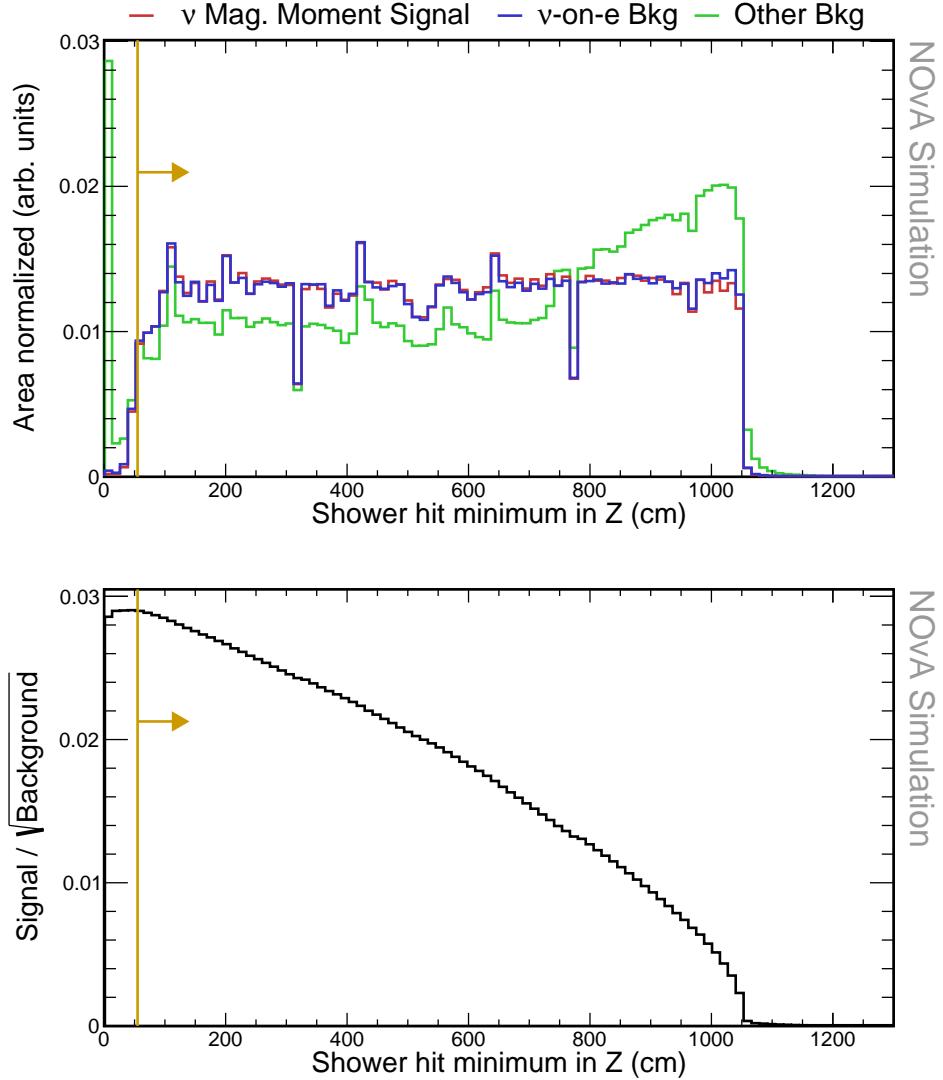


Figure 2.19: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the z axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

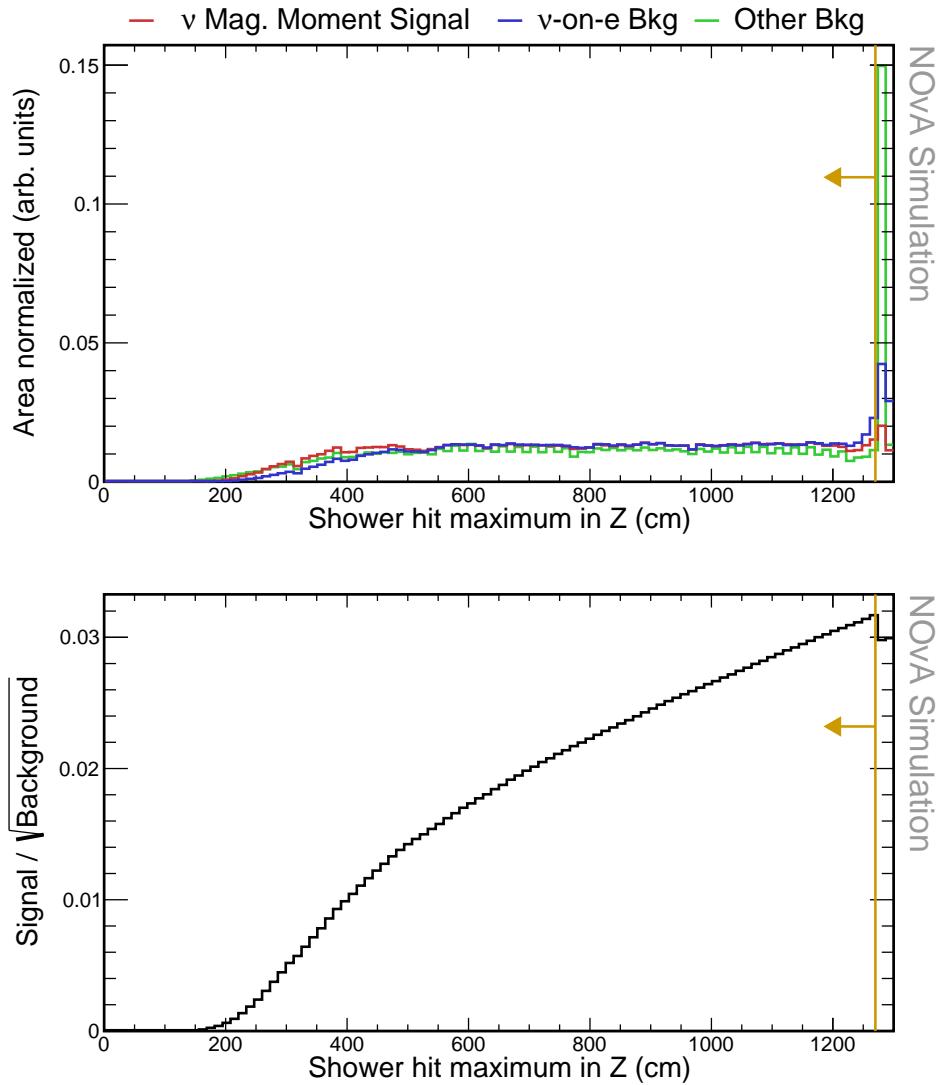


Figure 2.20: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the minimum and maximum position of the reconstructed shower along the z axis. Pre-selection and fiducial cuts were applied to make these plots. Gold lines show the values of the containment cuts.

(above threshold and within  $\pm 8$  planes from the vertex) outside of the most energetic shower is  $< 0.02$  GeV, and that the distance between the vertex and the start of the primary shower is  $< 20$  cm.

## Event Classifiers

We are using two event classifiers based on convolution neural network that were developed specifically to identify  $\nu$ -on-e interactions. The first one (Nuone ID) is trained to select  $\nu$ -on-e events and the second one (Epi0 ID) is trained on the events passing the Nuone ID to reject the  $\pi^0$  background. Our selection requires that Nuone ID  $> 0.73$  and that Epi0 ID  $> 0.92$ .

**TO DO: reference theory for the kinematics of nuone scattering** We require that the product of reconstructed energy of the primary shower and the square of its angle from the Z axis is  $E_{cal}\theta^2 < 0.005$  GeV  $\times$  rad $^2$ .

**TO DO: Add plots of distributions of the event selection variables with two columns.  
LHS shows no cuts applied and RHS shows all previous cuts applied**

Using the many plots below that show the effect of each of the cuts on the signal and all background events. (For signal we are showing NuMM=...)

[ND group's technote] Two event classifiers (NuoneID and Epi0ID) based on convolutional neural network (CNN) are trained to identify nuone elastic scattering events (NuoneID) and to further reject background with pi0 in the final state (Epi0ID). The CNN architecture adopted for this analysis is the one used for NOvA CVN [12]. It takes the pixel map of a slice as the input and has deeper and more complicated neural networks than the ANNs used in the previous round of analysis [11]. The training for both classifiers (NuoneID and Epi0ID) were done with single electron samples as the signal in order to mitigate the model dependence. A nuone elastic scattering has an electron in the final state which could deposit energy in the detector. Single electron events share this feature with nuone elastic scattering, but have more uniform distribution of energy, angle between the shower direction and the beam direction. This additional feature could prevent CNN models from overfitting the feature of the very small scattering angle. To make comparisons, test samples of signal and background are normalized to 1.1E21. The output categories are  $\nu$ -on-e,  $\pi^0$ ,  $\nu_e$ CC and other. The  $\nu$ -on-e and  $\pi^0$  outputs are used for the training of the Epi0ID. The pre-selection ap-

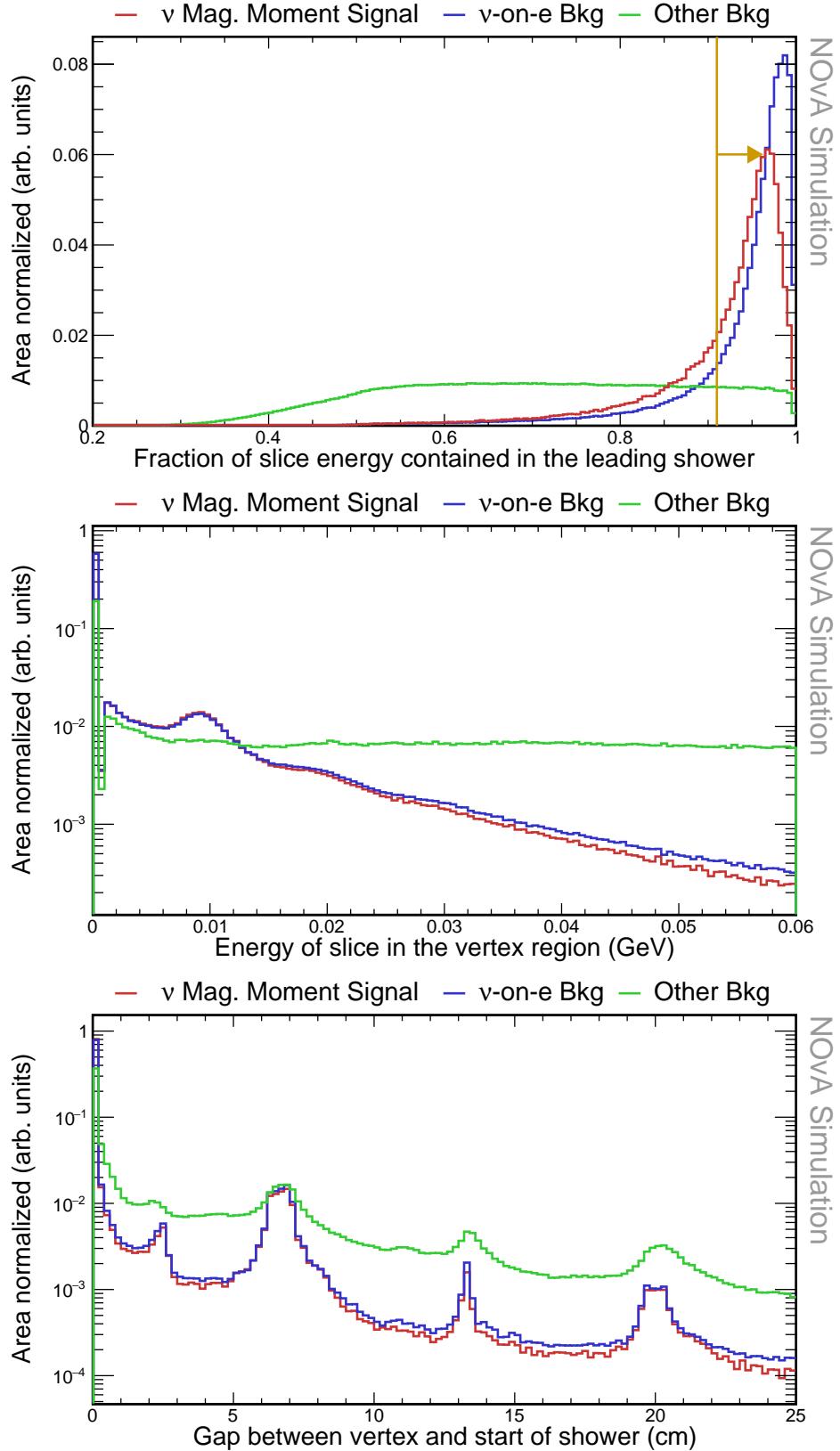


Figure 2.21: TMVA variables before the TMVA results. Relative comparison of signal,  $\nu$ -on-e background, and other background events for the reconstructed vertex. Every previous cut was applied to make these plots, including the ShwECont for the middle and the bottom plot and the VtxE cut for the bottom plot. Gold lines show the cut values that create the fiducial volume.

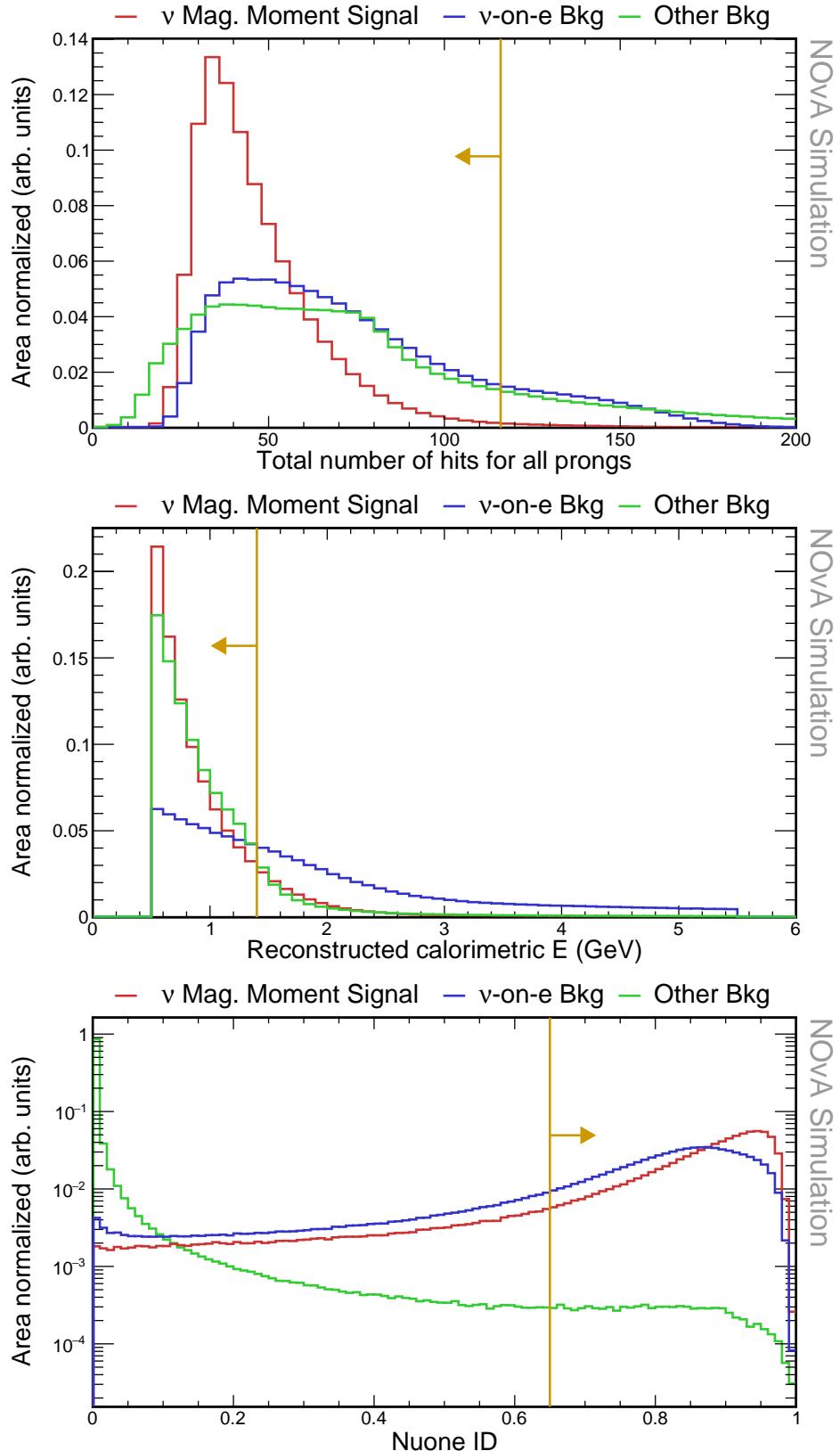


Figure 2.22: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the reconstructed vertex. No cuts were applied to make these plots. All the previous cuts were applied, including the cut on the shower energy. No single particle or event ID cuts were applied yet though. Gold lines show the cut values that create the fiducial volume.

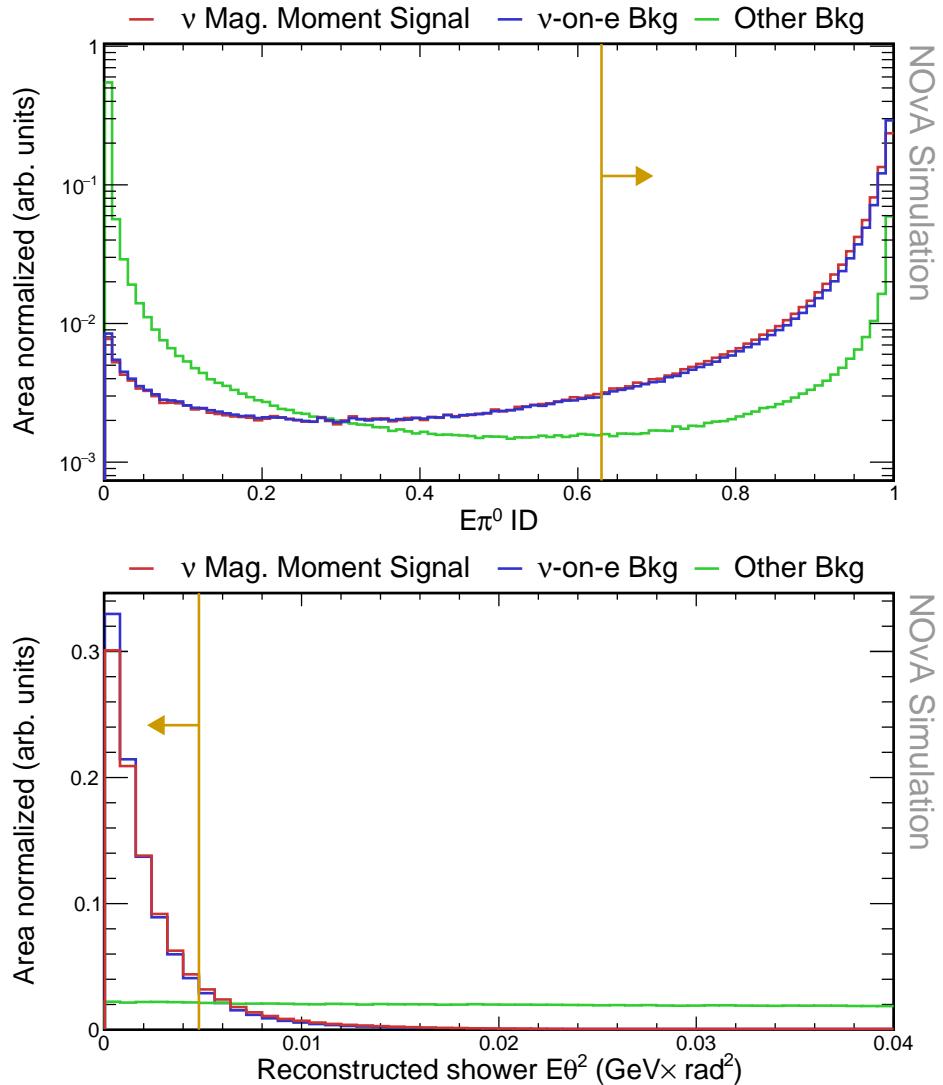


Figure 2.23: Relative comparison of signal,  $\nu$ -on-e background, and other background events for the reconstructed vertex. No cuts were applied to make these plots. All the previous cuts were applied, including the cut on the shower energy. No single particle or event ID cuts were applied yet though. Gold lines show the cut values that create the fiducial volume.

plied is: ND group's preselection ( $L < 800$  cm,  $N_{plane} < 120$ ,  $N_{cell} < 600$ ), loose containment ( $-190 < X < 190$ ,  $-190 < Y < 190$ ,  $50 < Z < 1500$  cm), loose single particle cut ( $E_{vtx} < 0.05$  GeV,  $gap < 20$  cm,  $E_{shower}/E_{tot} > 0.9$  **COMMENT: These are quite strict actually.**). The training accuracy for NuoneID is about 85% and for Epi0ID is about 96%. After each round of training, the trained model is saved to make predictions on the test sample so we know how the actual performance of the classifiers evolves over different epochs.

## Multivariate Analysis

TMVA [102]

These event selection in total reduces signal 44.51 %,  $\nu$ -on-e background 70.40 % and other background 99.97 %. After the full event selection, the predicted number of signal events for  $\mu_\nu = 10^{-9} \mu_B$  is 23.31 and the total number of background events under the SM hypothesis is 678.26. The most likely improvement is in probing the low energetic events and making sure they make sense. Additionally, it is possible to use a specially designed control regions to mitigate the very high non- $\nu$ -on-e background.

Table 2.7: 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.

<b>Selection</b>	<b>Signal</b>		<b><math>\nu</math>-on-e bkg</b>		<b>Other bkg</b>	
	$N_{evt}$	$\epsilon_{rel}$ (%)	$N_{evt}$	$\epsilon_{rel}$ (%)	$N_{evt}$	$\epsilon_{rel}$ (%)
<b>Pre-selection</b>	42.01	100	$1.62 \times 10^3$	100	$7.22 \times 10^5$	100
$E_{Shower}/E_{Tot}$	40.32	95.98	$1.57 \times 10^3$	96.87	$2.79 \times 10^5$	38.60
<b>Nº Hits</b>	39.93	99.03	$1.34 \times 10^3$	85.56	$2.63 \times 10^5$	94.24
<b>High <math>E_{Shower}</math></b>	34.70	86.91	714.28	53.28	$2.22 \times 10^5$	84.58
<b><math>\nu</math>-on-e ID</b>	29.41	84.75	600.38	84.05	$3.36 \times 10^3$	1.51
<b><math>E\pi^0</math> ID</b>	27.46	93.37	560.56	93.37	$2.18 \times 10^3$	64.72
<b><math>E\theta^2</math></b>	23.31	84.88	478.83	85.42	199.42	9.17

**TO DO:** Add a discussion of possible improvements on the event selection on its limitations - mostly for the analysis review committee From here we can see that ... Maybe what can be improved is... This can likely be improved upon by specifically selection low energy events and removing the cut on the reconstructed shower energy.

## 2.4 Energy resolution and binning

**TO DO:** *Add the energy resolution and binning plots* Describe what events were used for the energy resolution study and how it was performed

What are the results

Final plot

The electron energy and angle distributions and resolutions. Are we going to fit in E, Th, or ETh2? Is there something else?

Show plots of Reco V True for both energy and angle. (Should I show it with or without the energy cut?). Also show the resolution plots.

Maybe also mention that Test Beam will help with improving the dead materials correction and generally improving the bias and resolution of the reconstructed energy, which won't have to depend on the comparison to simulation

## 2.5 Systematic uncertainties

## 2.6 Statistical analysis

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.

## 2.7 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

## 2.8 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?

## 2.9 Conclusion

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

**$\nu$ -on-e** neutrino-on-electron. 25, 26, 32, 36, 37, 39–45, 47, 48, 50–54, 56–59, 65, 69

**2p2h** two particle - two hole. 10

**ADC** Analog-to-Digital Converter. 7, 14, 17, 18

**APD** Avalanche Photodiode. 5–7, 10, 17, 18, 46

**ASIC** Application-Specific Integrated Circuit. 7

**BDT** Boosted Decision Tree. 14

**BPF** Break Point Fitter. 12

**BSM** Beyond Standard Model. 25–27, 29, 32

**C.L.** Confidence Level. 25, 26

**CC** Charged Current. 9–11, 36, 43, 51, 65

**CMC** Comprehensive Model Configuration. 10

**CNN** Convolutional Neural Network. 13

**COH $\pi$**  Coherent  $\pi$  (production). 10

**CP** Charge conjugation - Parity (symmetry). 1

**CRY** Cosmic-Ray Shower Generator. 10, 14

**CVN** Convolutional Visual Network. 13, 45

**DAQ** Data Acquisition. 7, 11, 16

**DCM** Data Concentration Module. 7, 8, 44

**DIS** Deep Inelastic Scattering. 10

**DUNE** Deep Underground Neutrino Experiment. 1, 9

**FB** Fibre Brightness. 17, 18

**FD** Far Detector. 3–7, 10, 11, 17–19, 22

**FEB** Front End Board. 6–8, 17, 46

**Fermilab** Fermi National Accelerator Laboratory. 1, 3, 9

**FHC** Forward Horn Current (neutrino mode). 2, 3

**FOM** Figure Of Merit. 44, 56–58

**FPGA** Field Programmable Gate Array. 7

**FSI** Final State Interaction. 10

**LDM** Light Dark Matter. 26

**LOWESS** Locally Weighted Scatter plot Smoothing. 19, 20

**MC** Monte Carlo. 8–10, 14, 41

**MEC** Meson Exchange Current. 10, 43

**MEU** Muon Energy Unit. 21

**MI** Main Injector. 1, 2, 9

**MIP** Minimum Ionising Particle. 14, 18, 21

**MIPP** Main Injector Particle Production (experiment). 9

**ML** Machine Learning. 13, 14, 46

**NC** Neutral Current. 11, 14

**ND** Near Detector. 1, 3–5, 7, 11, 12, 22, 24–26, 32, 40, 41, 43, 49

**NDOS** Near Detector on the Surface. 3

**NOvA** NuMI Off-axis  $\nu_e$  Appearance (experiment). 1, 3–14, 16–22, 24–26, 32, 36, 38–41, 43, 46, 49

**NP** New Physics. 30

**NuMI** Neutrinos from the Main Injector. 1–3, 8, 9, 11

**PE** Photo Electron. 6, 7, 15, 17–19

**PECorr** Corrected Photo Electrons. 19, 21

**PID** Particle Identification. 13

**PMNS** Pontecorvo-Maki-Nakagawa-Sakata. 29–31

**POT** Protons On Target. 2, 40–44, 50

**PPFX** Package to Predict the Flux. 9, 23, 41

**PVC** Polyvinyl chloride. 4–6, 22

**QE** Quasi Elastic (interaction). 9, 10

**ReMid** Reconstructed Muon Identifier. 14

**Res** Resonant baryon production. 9, 10

**RHC** Reverse Horn Current (antineutrino mode). 2, 3

**SM** Standard Model. 25, 27, 29, 37–40, 44, 69

**WLS** Wavelength Shifting (fibre). 5, 6, 10, 14, 16, 18, 21

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