



Measuring the Muon Neutrino Magnetic Moment in the NOvA Near Detector

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

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

Brighton, United Kingdom,

March 18, 2024

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DOCTORAL THESIS

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ABSTRACT

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

Keywords: neutrino NOvA electromagnetic testbeam calibration

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CHAPTER 1

The NOvA experiment

The NuMI Off-axis ν_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 ν_μ and $\bar{\nu}_\mu$ beam from FERMILAB’s Neutrinos from the Main Injector (NuMI) neutrino source, described in Sec. 1.1, and measures $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance between its two highly active and finely segmented detectors, described in Sec. 1.4 [3].

The capability to measure both ν_e and $\bar{\nu}_e$ appearance, coupled with a significant matter effect induced by the long baseline, allows NOvA to address some of the most important questions in neutrino physics to date, such as the neutrino mass ordering, the octant of θ_{23} , and the possible Charge conjugation - Parity (CP) violation in the neutrino sector [3–7]. NOvA data also enables measurements of the values of θ_{13} , θ_{23} and $|\Delta m_{atm}^2|$ [3], measurements of neutrino differential cross sections in the near detector [8–11], constraints on the possible sterile neutrino models [12, 13], monitoring for supernova neutrino activity [14, 15], searches for magnetic monopoles [16], and constraints on the neutrino electromagnetic properties (this thesis). Using two functionally identical detectors mitigates the 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]. *TO DO: Add DUNE into this and find the LOI reference*

1.1 The Neutrino Beam

The neutrino beam for NOvA comes from the FERMILAB-based NuMI neutrino source [18]. 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 accelerator complex. The proton beam is divided into 10 μ s long pulses, with $\sim 5 \times$

10^{13} Protons On Target (POT) per spill every ~ 1.3 s long cycle time, resulting in a proton beam power of ~ 800 kW, with upgrades currently underway to surpass 1 MW [19].

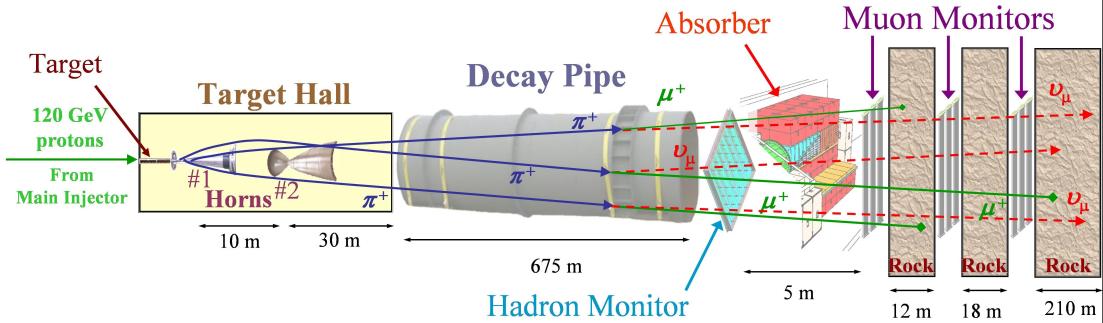


Figure 1.1: The NuMI neutrino beam starts on the left hand side with protons from the MI impinged on a graphite target producing mainly pions and kaons. These are then focused and charge-selected by two focusing horns, after which they decay inside the decay pipe into a high-purity ν_μ , or $\bar{\nu}_\mu$ beam. The residual hadrons are stopped and monitored in the hadron absorber and the remaining muons are recorded with muon monitors and absorbed inside the rock. Figure from [18].

The proton beam passes through a collimating baffle before hitting a ~ 1.2 m-long (equal to about two interaction lengths) graphite target [20], producing hadrons, predominantly pions and kaons [18]. 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 all the 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 Near Detector (ND), shown as a rate of Charged current (CC) events, is pre-

sented in Fig. 1.2, displaying the very high purity ν_μ component in the **FHC** beam, and the high purity $\bar{\nu}_\mu$ component in the **RHC** mode [18].

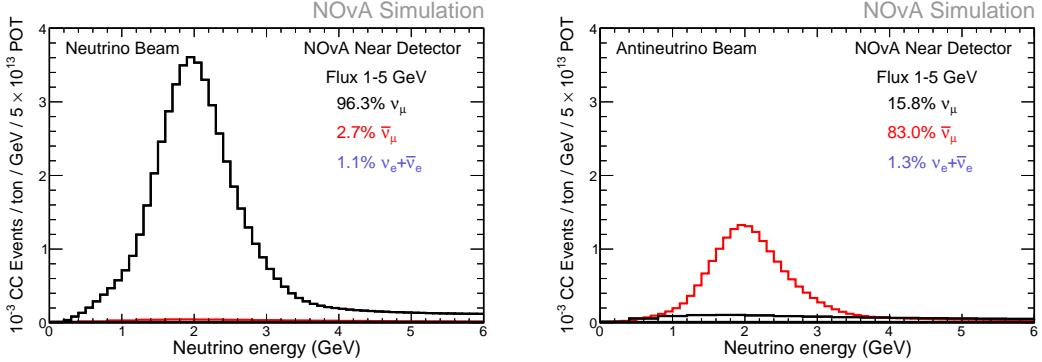


Figure 1.2: The **CC** event rates for different neutrino flavours, as measured at the **NOvA ND** in the **FHC** regime shown on the left, or the **RHC** regime on the right. The contribution of neutrino flavours to the event rates is also displayed, showing the high purity of the neutrino beam for **NOvA**. Figure from internal **NOvA** repository.

The resulting neutrino beam energy distribution is peaked at ~ 7 GeV with a wide energy band. However, thanks to the kinematics of the dominant pion decay, by placing **NOvA** detector 14.6 mrad ($\approx 0.8^\circ$) off the main **NuMI** beam axis, we achieve a narrow band neutrino flux peaked at 1.8 GeV [7, 21], 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 ν_e appearance analysis [21].

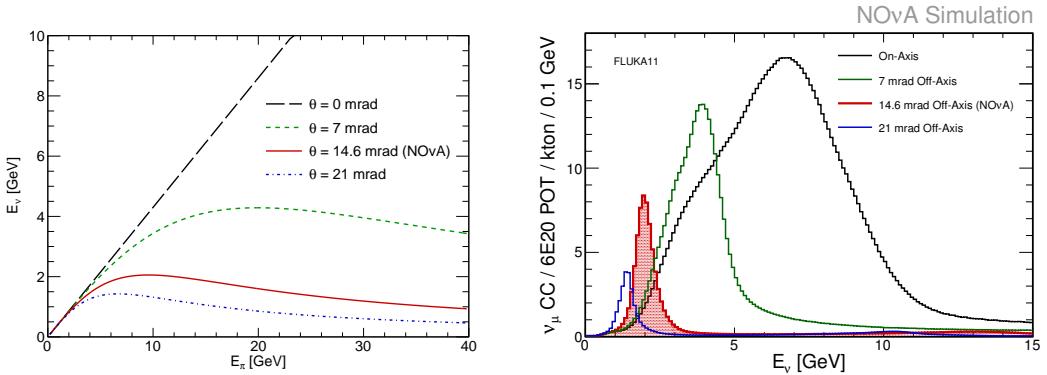


Figure 1.3: (Left) Dependence of the neutrino energy on the parent pion's energy and (right) neutrino energy distribution for an on-axis beam and three different off-axis beam designs. The case for **NOvA** is shown here in red and results in a narrow neutrino energy distribution around 2 GeV, with limited dependence on the parent pion's energy. Figure from [21]

1.2 The NOvA Detectors

The two main NOvA detectors are the ND, located in FERMILAB ~ 1 km from the NuMI target and ~ 100 m under ground, and the Far Detector (FD), located ~ 810 km from FERMILAB at Ash River in north Minnesota, partially underground with a rock overburden [21]. NOvA also operated a detector prototype called Near Detector on the Surface (NDOS) used for early research and development of detector components and analysis [4]. Additionally, NOvA operated a Test Beam (TB) detector, described in detail in Sec. ???. The scale of ND and FD is shown in Fig. 1.4.

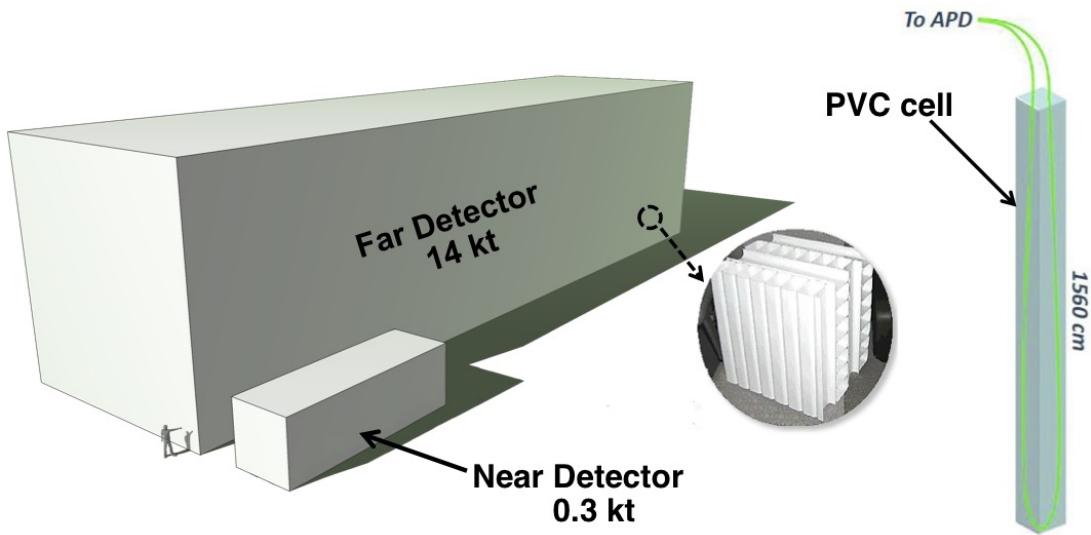


Figure 1.4: Schematic description of scale and composition of the NOvA detectors. The inset shows a photo of the orthogonal planes made out of PVC cells. An example of a FD cell containing liquid scintillator and a looped WLS fibre attached to an APD is shown on the right [22].

All NOvA detectors are highly segmented, highly active, functionally identical tracking calorimeters made up of Polyvinyl chloride (PVC) cells filled with liquid scintillator. Each cell is a long rectangular cuboid with depth of 5.9 cm and width of 3.8 cm (with some variations), with cell length extending to the full width/height of each detector, which is ~ 4.1 m for the ND and ~ 15.6 m for the FD [21]. 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 ~ 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. However, the **ND** also consists of a Muon Catcher region, positioned right after the active region, consisting of 22 planes of the normal **NOvA** detector design, 2 modules high and 3 modules wide, sandwiched with 10 steel plates to help range out muons mainly from the ν_μ charged current interactions [4, 21].

TO DO: *Describe the coordinate system in NOvA*

Each cell is filled with a liquid scintillator consisting of mineral oil with 4.1% pseudocumene as the scintillant [23]. 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. As light travels through the fibre, it is attenuated by about a fraction of ten for the **FD** cells **TO DO:** *Figure out what is the correct statement here.* The **PVC** walls of the detector cells are loaded with highly reflective titanium dioxide, with light typically bouncing off the **PVC** walls about 8 times before being captured by the fibre [21].

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 [21].

The **NOvA** detectors are specifically designed for electromagnetic shower identification, with a radiation length of 38 cm, which amounts to ~ 7 planes for particles travelling perpendicular to the detector planes [4]. This is particularly useful to distinguish electrons and π^0 s.

TO DO: *Talk here or in the next section about minimum electron energy to be recorded by NOvA detector and electronics. Maybe in all sections including reconstruction to tie them together*

1.3 Readout and Data Acquisition

The signal from the Wavelength Shifting (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 [21]. An example APD is shown in Fig. 1.5. Both ends of each fibre are connected to one of the 32 pixels on the APD, with each APD reading out signal from one module. To maximise the signal to noise ratio, the APDs are cooled to $-15\text{ }^{\circ}\text{C}$ 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's and WLS fibre's response, result in a signal requirement of at least 20 photoelectrons in response to minimum ionizing radiation at the far end of the FD cell.

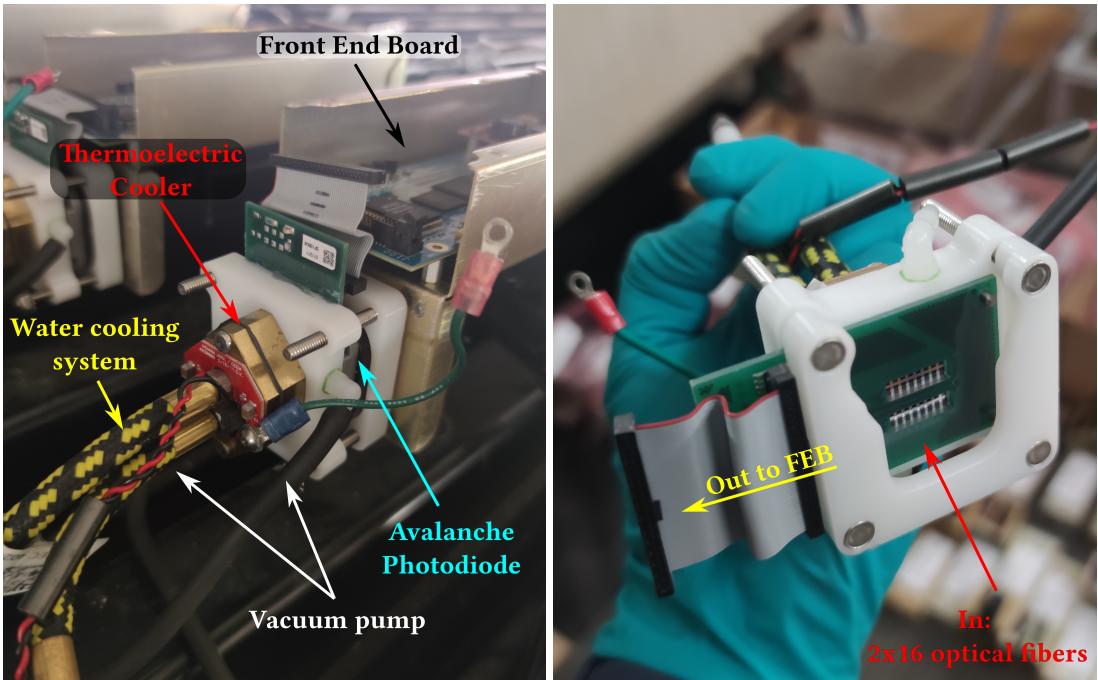


Figure 1.5: The modules with APDs for NOvA mounted on top of the detector on the left picture, and shown from the bottom on the right. The individual components of the module are described. The left picture shows a disconnected ribbon cable and ground cable, which are normally connected to the front 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 design 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 Photo Electron (PE)s, which, compared to an average photoelectron yield from the far end of the **FD** cell of 30, results in a good signal and noise separation [21]. 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 [24].

TO DO: *Find out what is the pedestal/threshold that's being subtracted*

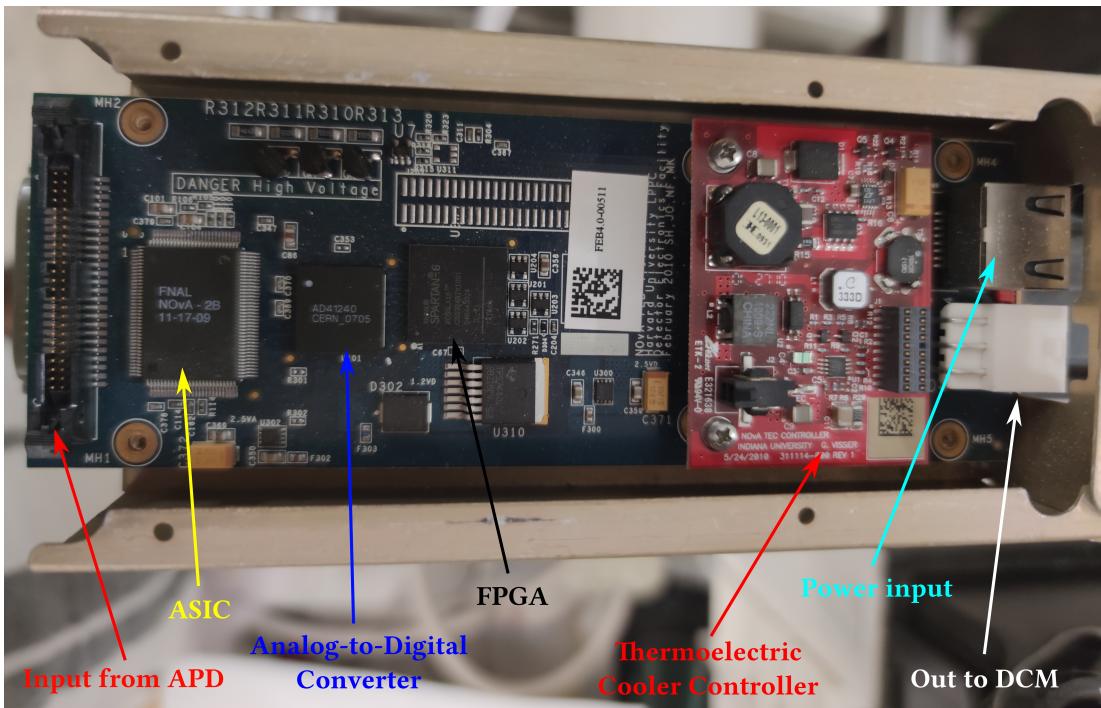


Figure 1.6: An example of a **NOvA FEB** with individual components labelled.

All of the **NOvA** front end electronics (**APDs** and **FEBs**) are operated in a continuous readout mode, without requiring any external triggers [21]. 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 [24].

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 de-

tector [24].

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 readout of comic events for detector calibration and monitoring, or on a time of activity-based data-driven trigger [24]. 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, or sent to an online monitoring system.

COMMENT: Maybe talk about data quality as well? Probably should since I want to talk about good runs and bad channels in the TB calib chapter

1.4 Simulation

COMMENT: Should I divide the simulation into the individual stages? I had it like that originally, but for example the simulation of cosmics is only very short and not sure what section would I put it under

To extract neutrino oscillation parameters, or to test a hypothesis, **NOvA** uses a series of simulations to make predictions according to various physical models [25]. 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 response.

To simulate the neutrino beam, **NOvA** uses the GEANT4 v9.2.p03 [26] based Monte Carlo (MC) simulation with a detailed model of the **NuMI** beamline [27], as it was described in Sec. 1.4. The simulation starts with **MI** protons interacting within the long carbon target and producing hadrons, mainly π , K and p , followed by transport and possible further interaction of these hadrons within the focusing system, until finally ending with hadron decays producing the neutrino beam.

To account for the imprecise theoretical models used in GEANT4, we use the Package to Predict the Flux (PPFX) to incorporate external measurements of yields and cross sections of hadron production inside the target and other **NuMI** materials into the prediction [28]. The current version of **PPFX** is limited by the results available during its creation and only corrects the most frequent interactions while assigning

large systematics uncertainties to the rest (see Sec. 1.8). For the most common π production, **PPFX** uses the NA49 measurements [29] of 158 GeV/c protons interacting on a thin (few percent of interaction length) carbon target, with a few data point from Barton et al [30] to expand the kinematic coverage. These then have to be scaled to the 20 – 120 GeV/c incident proton energies seen in **NOvA** using the FLUKA [31, 32] **MC** generator. For the K production from $p + C$ interaction, important for higher neutrino energies and electron neutrinos, **PPFX** uses the NA49 K data [33] together with the NA49 π data [29] multiplied by the K/π ratios of yields on thin carbon target from the MIPP experiment [34]. Lastly, for the nucleon production, **PPFX** uses the NA49 data on quasi elastic interactions [35]. All the other interactions inside **NuMI**, such as interaction in non-carbon targets, or interactions with hadrons other than protons, are either extrapolated from the previously mentioned measurements, or are not corrected for and a significant systematic uncertainty is assigned to them [28].

There's two new experiments that measured the production and interaction of hadrons on various targets and incident energies, specifically designed to improve the prediction of neutrino beams. I worked on implementing data from the NA61 experiment on hadron production from $p + C$ interaction on a thin carbon target at 31 GeV/c [36], motivated by possible reduction in the K production systematic uncertainty. This work is still ongoing and will be implemented into **PPFX** and **NOvA** together with the rest of the NA61 measurement. The most impactful ones will be the measurement of hadron production from $p + C$ interaction on a thin carbon target at 120 GeV/c [37] (no energy scaling required), measurements of $p + C$ and $p + Be$ at different incident energies [38], $\pi + C$ and $\pi + Be$ measurements at 60 GeV/c [39], resonance production measurements from 120 GeV/C $p + C$ [40], and probably the most impactful one, the yet unpublished measurement of hadron production yield on a **NOvA**-era **NuMI** replica target at 120 GeV/c [41]. NA61 also measured the hadron production yield for the Tokai to Kamioka (T2K) experiment's replica target [42], which significantly reduced the neutrino flux systematic uncertainty for the **T2K** measurements [41]. The second experiment is EMPHATIC [43], which is currently analysing their data on a broad range of hadron production measurements, mainly the secondary and tertiary interactions of various projectiles with a wide range of in-

cident energies and thin target materials, complementary to the NA61 measurements.

COMMENT: The description of neutrino interactions, including QE/Res/DIS scattering and nuclear effects will probably be in the theory chapter. If not I'll add it here.

COMMENT: Might have to describe some of these interaction models a bit more if any of the cross section uncertainty for the magnetic moment analysis turns up to be significant

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 [44] 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) CC scattering, the Resonant baryon production (RES), the Deep Inelastic Scattering (DIS), and the Coherent pion production (COH π). Special case of CC interaction with two nucleons producing two holes via Meson Exchange Current (MEC) is also considered. Particles created in these processes are then propagated inside the nucleus according to the Final State Interaction (FSI). All of these are set by the Comprehensive Model Configuration (CMC) and NOvA currently uses the N1810j0000 CMC. Additionally, NOvA adds a tune to NOvA ν_μ CC data for the CCMEC interactions and a set of external π 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 [45]	External $\nu - D$ data [46]
CCMEC	València [47, 48]	NOvA ν_μ CC data
RES & COH π	Berger-Sehgal [49, 50]	External $\nu - A$ data
DIS	Bodek-Yang [51, 52]	External $\nu - A$ data
FSI	Semi-classical cascade [53]	External $\pi - {}^{12}C$ data

Since the FD is on the surface we also need to include a simulation of cosmic rays generated with the CRY [54] MC generator. The simulated cosmic muons are also used to calibrate NOvA detectors [28].

Particles that are created from neutrino interactions and cosmic rays are propagated through the NOvA detectors using an updated version of GEANT4 v10.4.p02 [26].

The output of this simulation is the energy deposited in the scintillator, which is then passed to a custom **NOvA** simulation software [28]. The scintillation light generated by the deposited energy is parametrized using the Birks-Chou model [55], which corrects for recombination in organic scintillators at high deposited energies. The normalization factors for the produced scintillation light (the light yield), as well as for the Cherenkov light, which can affect the light readout, are tuned to **NOvA** cosmic data [9]. The light collection by the **WLS** fibres and its transport to the **APDs**, as well as the **APD** response use a parametrized simulation, which makes use of the fact that all the **NOvA** cells and their readout are generally the same across the detectors [28]. The simulation of the readout electronics is done by another custom **NOvA** parametrized model, which mainly account for a random electronics noise, with output in the same format as raw data.

Due to the high neutrino rate in the **ND**, there are neutrinos interacting in the surrounding rock creating particles that make it to the detector and act as background. To simulate these rock events we use the same simulation as for neutrino interactions inside the detector. However, since only a few particles make it into the detector, it would be very time consuming to run this simulation for every neutrino. Therefore, we create a separate simulation that includes the surrounding rock and then overlay the results into the normal **NOvA** simulation chain, which doesn't include the rock, so that the rate matches the **NuMI** neutrino rate [28].

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 ν_e appearance search in mind, focusing on identifying the ν_e **CC** signal against the ν_μ **CC** and Neutral Current (NC) backgrounds. Each **NOvA** detector has to deal with a different challenges, with multiple neutrinos interacting in the **ND** during one beam spill, and a large cosmic background in the **FD** [56].

The readout from each cell from the **DAQ** (see Sec. 1.3) is called a *channel* and the **DAQ** output from each channel is called a *raw hit*. **DAQ** groups hits into $550\,\mu\text{s}$ windows and passes them to an offline reconstruction chain [56]. Reconstruction

starts by grouping hits into *slices* based on their proximity to other hits in both time and space [57]. **COMMENT: Maybe include rawhit to cellhit to recohit**

For events that produce hadronic and electromagnetic showers, we first identify lines through major features using a modified Hough transform [58]. These lines representing momentum directions are then passed to the Elastic Arms algorithm [59] to identify *vertex* candidates from their intersection points. Hits are then clustered into *prongs*, group of hits with a start point and a direction, using a k-means algorithm called FuzzyK [60, 61]. 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 (or just prongs) [56]. Figure 1.7 shows an example simulated electron shower with the reconstructed vertex (red cross) and prong (red shaded area) grouping all hits that should be a part of the shower together, while removing background hits in grey.

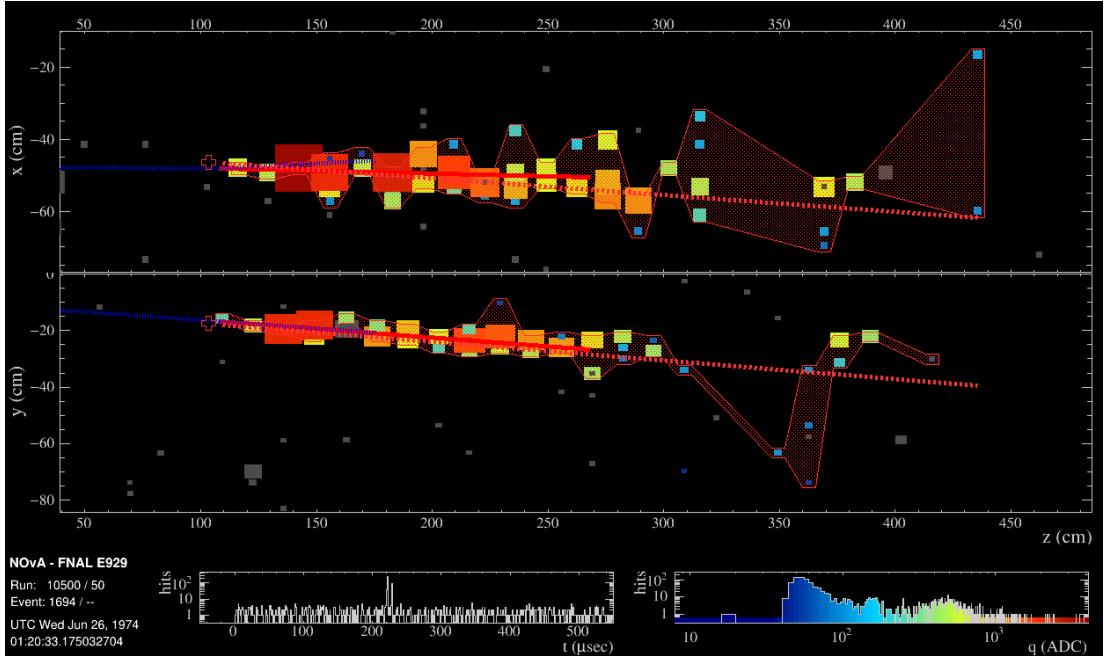


Figure 1.7: Reconstruction of a simulated single electron event in the [NOvA ND](#). The red cross is the reconstructed vertex, the shaded area shows the cluster of hits into a shower and the dotted red line shows the estimated momentum of that shower. The blue dotted line shows the true momentum of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

For particles that are represented by tracks rather than showers (especially muons) we take the slice hits and form the *Kalman tracks* based on a Kalman filter [62]. 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 3D prongs and forms Break Point Fitter (BPF) tracks [63, 64], using a model of Coulomb scattering and energy loss. BPF tracks also contain 4-momentum information based on various particle assumption, most notably muon assumption. For cosmic particles, mostly muons, we use another track reconstruction algorithm, called the window cosmic track algorithm [65]. The window cosmic track algorithm uses a sliding 5 plane-long window, starting from the end of the detector, in which it fits a straight line to the recorded hits, before sliding the window forward and repeating the process. This way it accounts for possible Coulomb scattering of cosmic muons.

To identify individual particles and remove backgrounds, NOvA uses several Machine Learning (ML) algorithms, outputs of which are used in for Particle Identification (PID) in various NOvA analyses. The most common topologies for particles interacting in NOvA detectors are shown on Fig. 1.8. Muons are easily identifiable as a single long track which decays into an electron (or positron) if it stops inside the detector. Both electrons and π^0 's produce electromagnetic showers, but thanks to the low-Z composition and high granularity of the detector, there is a gap between the interaction vertex and the electromagnetic shower.

NOvA employs a Convolutional Neural Network (CNN) based on the GoogLeNet [66] architecture named Convolutional Visual Network (CVN) [67], which uses slice hits to classify interactions into one of the four categories: ν_e , ν_μ , ν_τ , or NC. The same architecture, but applied to the Fuzzy-K prongs and called ProngCVN [68], is used to identify the individual prongs based on what particles they most likely correspond to. A special ML algorithm for identifying muons, based on a Boosted Decision Tree (BDT) with inputs from the Kalman track, is called Reconstructed Muon Identifier (REMid) [62].

1.6 Detector Calibration

The energy deposited within the NOvA detectors is represented by the peak ADC values for each cell the particle passed through, which are obtained from the readout

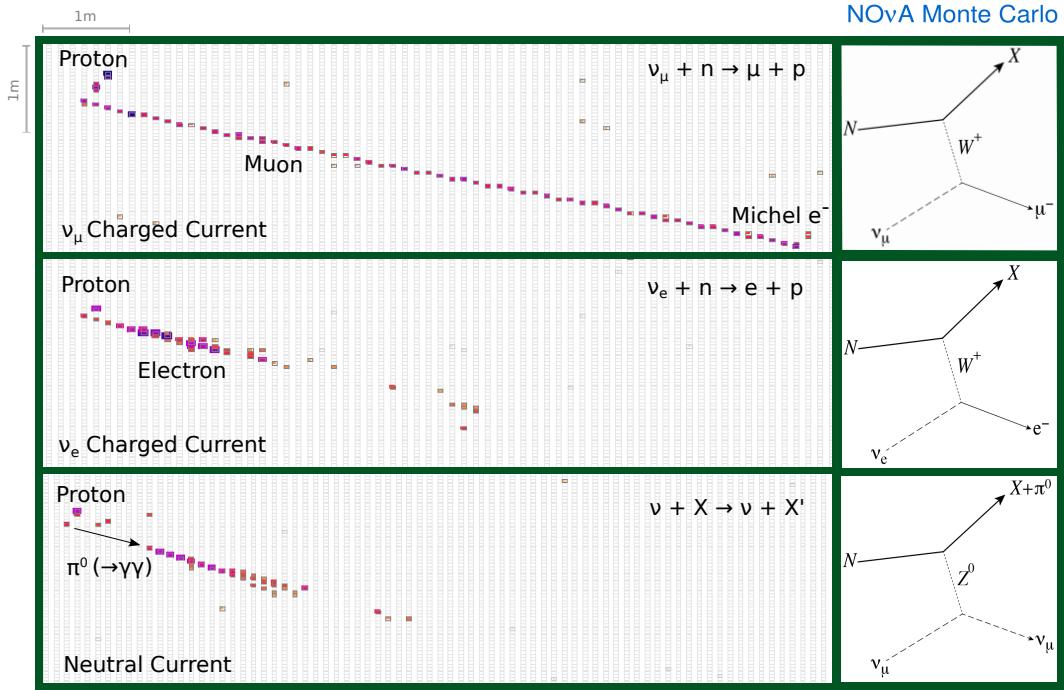


Figure 1.8: Different event topologies as seen in the **NOvA** detectors with corresponding Feynman diagrams [56]. Each event is a simulated 2.15 GeV neutrino interacting in a **NOvA** detector producing a 0.78 GeV proton and a second 1.86 GeV particle depending on the interactions type. The figure show one view and the colouring represents the deposited energy.

electronics, as described in Sec. 1.3. To convert **ADC** into physical units we need to calibrate the **NOvA** detectors [69], while accounting for the attenuation of light along the **WLS** fibres, or for differences between individual cell. The purpose of calibration is to calculate a conversion factor from $\text{ADC} \rightarrow \text{MeV}$ units, so that the same energy deposited at any place within any detector and at any time, is recorded as the same value.

NOvA uses cosmic ray muons for calibration due to their abundance in the **NOvA** detectors and a consistent energy deposition. We use hits from muons stopping inside the detectors, from a window when they are almost exactly minimum ionising particles (MIP), to calculate the absolute energy scale. The cosmic muons are collected using a periodic data-driven trigger, removing events with timestamps overlapping with the beam spill window. For the simulation of cosmic muons we use the **CRY** [54] **MC** generator, as outlined in Sec. 1.4.

COMMENT: I talk about this selection later on in the Test Beam calibration chapter when I talk about the data-based simulation. Should I therefore elaborate more on this

or is this enough? We reconstruct the cosmic muon tracks using the window cosmic track algorithm explained in Sec. 1.5. To select good quality cosmic tracks we require that at least 80% of all hits from the reconstructed slice contribute to the track [70]. Additionally, all tracks must cross at least 70 cm along the z axis and must have at least 20% of their total track direction in the z axis, since very vertical tracks tend to not be reconstructed well. *COMMENT: There are additional selection criteria which are not as important, do I need to mention them?*. To select stopping muons we look for Michel electrons, which get produced by decaying muons at the end of their tracks, as can be seen on the top panel of Fig. 1.8.

The energy deposited in a cell is proportional to the distance the particle travels through the cell. To ensure we use precise estimate of the path length, we only use hits that satisfy the *tri-cell* condition, shown on the left of Fig. 1.9. This means that each hit must have a corresponding hit in both of the surrounding cells in the same plane. This allows us to calculate the path length 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), we ignore this channel and look one cell further. We can then calculate the path length simply as the cell width divided by the cosine of the direction angle [69].

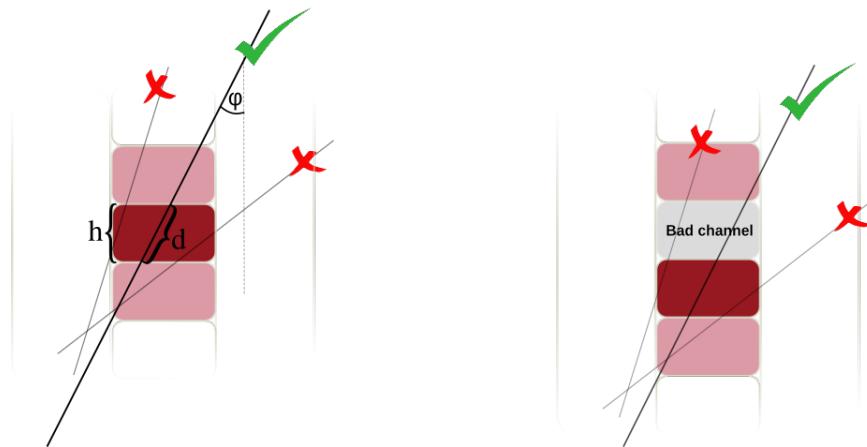


Figure 1.9: Illustration of the tricell condition. We only use hits that have two surrounding hits in the same plane to be used in the NOvA calibration, shown on the left plot. This is to ensure a good quality of the path length (d) reconstruction, which is calculated from the known cell height (h) and the reconstructed track angle (φ). In case the hit is next to a bad channel, as shown on the right plot, we ignore this bad channel and require a hit in the next cell over.

The calibration conversion factor from the signal recorded by the detector readout

and the actual deposited energy can be expressed by Eq. 1.1.

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

Here we can see that calibration consists of four separate and complementary factors: the Scale (S_d), the Threshold/Shielding correction ($TS_{d,i}$), the Relative calibration ($R_{d,i}(t)$) and the Absolute calibration ($A_d(t)$), all described below. Each part is calculated for each detector separately, as indicated by the subscript d . The 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 running conditions and separated by significant changes to the readout or [DAQ](#) systems, including the summer shutdown, or by a fixed time interval.

The Threshold/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 denoted as a subscript i in Eq. 1.1. For data, the position of hit in a detector is described by the plane number, the 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 [69].

For simulation, we do not use the plane number to determine the position within a detector, as by construction all detector planes should have the exact same readout. This significantly reduced 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 detector response between individual planes, caused by different *brightness* qualities of the fibres, zipped or twisted fibres, different qualities of the scintillator, possible air bubble, or potentially others. Since we want to include these differences into simulation without having to simulate every cell individually, we divide all cells into 12 equally populated Fibre Brightness (FB) bins based on the uncorrected average response in the center of that cell, as shown on Fig. 1.10. These brightness bins describe the relative differences in the detector response between individual cells [71].

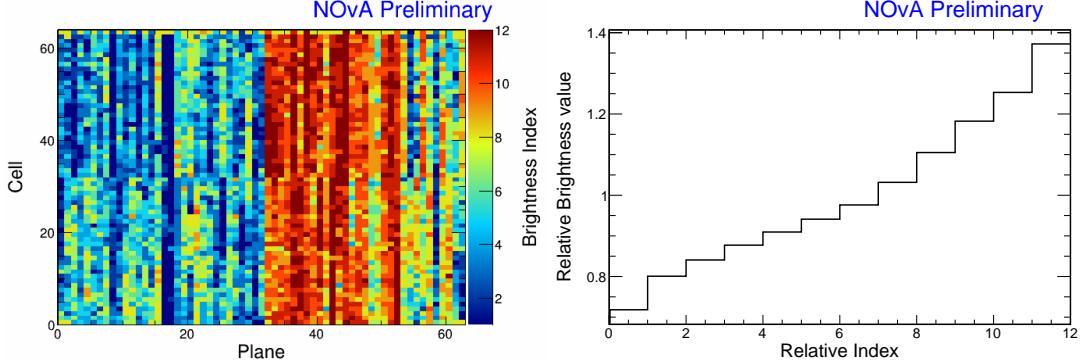


Figure 1.10: Distribution of the NOvA detector cells into 12 brightness bins (left plot), each representing a relative difference in energy response (right plot) due to different brightnesses of the fibres, scintillators, or readout. This is an example from the NOvA Test Beam detector, where the left 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](#) [69]. 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 fluctuation, 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 number of simulated [PE](#) seen by the [APD](#) (PE_{true}) and the Poisson mean number of simulation photons created in the scintillator by the same deposited energy (λ).

The second assumption is that the spectrum of cosmic muons is uniform within each detector. Again, this is generally true, but breaks down at the [FD](#), which is big

enough that the top of the detector shields the bottom part of the detector and affects the energy distribution. The shielding correction is calculated from simulation as a ratio between the true energy deposited by a charged particle (E_{true}) and the expected deposited energy if the particle was MIP (E_{MIP}).

The total Threshold and Shielding correction is calculated for simulated events in each cell, FB bin and w position according to Eq. 1.2. The final correction is a fit to the mean correction value along w in each cell and FB bin.

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

1.6.3 Relative calibration

Relative calibration corrects mainly for the attenuation of the scintillator light as it travels through the WLS fibre to the readout. Since the correction is calculated for each cell independently, it effectively corrects for the relative differences between detector cells as well. The result of the Relative calibration is the detector response to a particle in the units of Corrected Photo Electrons (PECORR), which is calculated as the ratio between an average response in PE across the entire detector (can differ across detectors) and the result of the “attenuation fit” in that particular position within the detector. This way the PECORR should be uniform across the detector along the plane number, cell number and w distributions [69].

To do the attenuation fit, we first create the “attenuation profiles” for each detector cell. Attenuation profiles are profile histograms of mean detector response over the travelled path length, in the units of PE/cm, along the position within the cell. An example attenuation profile is shown on Fig. 1.11 as black dots. We then apply the Threshold and Shielding correction described above before doing the attenuation fit, which consists of two steps.

1. The first step is a three-parameter exponential fit according to Eq. 1.3

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

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-

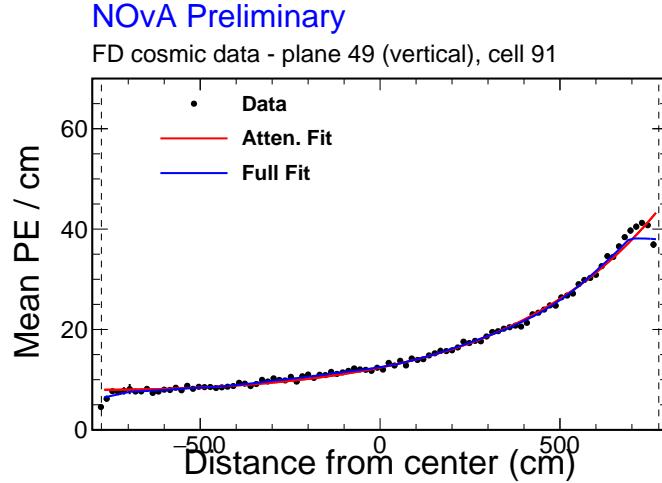


Figure 1.11: Example attenuation fit for a single cell in the NOvA FD across its full length, as shown by dashed vertical lines. The red line shows the initial exponential fit and the blue line shows the full fit after the LOWESS correction, both described in text. Figure from [72].

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

2. The second step is smoothing out of the residual differences between the exponential fit and the original distribution with the Locally Weighted Scatter plot Smoothing (LOWESS) method, shown on Fig. 1.12. We use 20 points across the length of each cell to create a smoothed distribution of the residual values. Result of the LOWESS correction is then combined with the exponential fit into the full attenuation fit, shown as a blue line on Fig. 1.11.

Even after an application of 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 cell at the edge of the detector. To ensure a good quality of the attenuation fit, we calculate the total χ^2 between the attenuation fit and the fitted response and only call a cell *calibrated*, if the final $\chi^2 < 0.2$. If $\chi^2 > 0.2$, we ignore the results for this cell and mark it as *uncalibrated*.

1.6.4 Absolute calibration

For the absolute calibration we only use hits from muons stopping inside the detector, 1 – 2 m from the end of their tracks. This is when they are approximately minimum

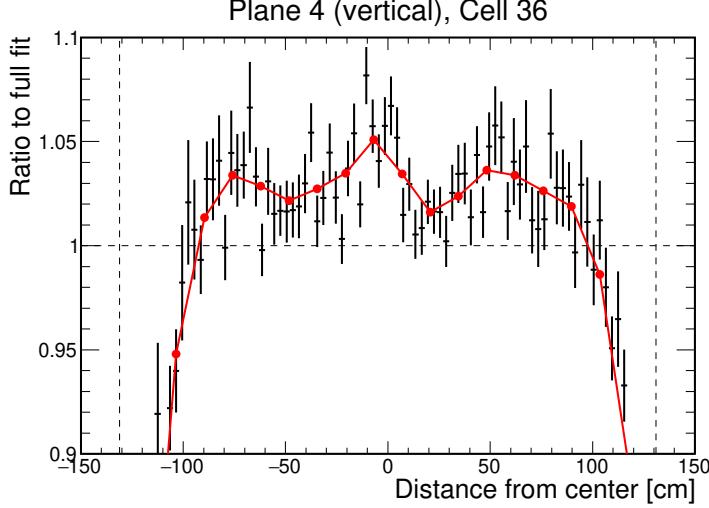


Figure 1.12: Example [LOWESS](#) correction for the residual differences after the exponential part of the attenuation fit of the [NOvA](#) Relative calibration. This is an example for a single cell in the [NOvA](#) TB detector with black point showing the residual differences and red line the [LOWESS](#) correction, both described in text.

ionizing particles and their energy deposition is well understood. We also remove hits at the edges of each cell, to mitigate the effects at the end of the [WLS](#) fibres and the lower number of events at the edge of the detector [70].

We apply the results of the relative calibration to the selected hits to get the distribution of the corrected detector response in the units of [PECORR/cm](#), as shown on the left of Fig. 1.13. We then take the mean of this distribution, separately in each of the two views, and in each time period and simulation version, which we call the *reconstructed* Muon Energy Unit (MEU). Analogously, we take the mean of the true deposited energy in the units of MeV/cm from simulation, shown on the right of Fig. 1.13, and call it the *true* MEU. We then take the average over the two views and calculate the absolute energy scale for each time period and simulation version as the ratio $MEU_{True} \text{ [MeV/cm]} / MEU_{Reco} \text{ [PECORR/cm]}$.

We save these absolute energy scales, as well as the results of the attenuation fit, in a set of lookup tables, which are used any time a hit is recorded in the NOvA detector and processed through the NOvA data processing algorithms.

1.7 Energy estimation

COMMENT: Should I include this section or not?

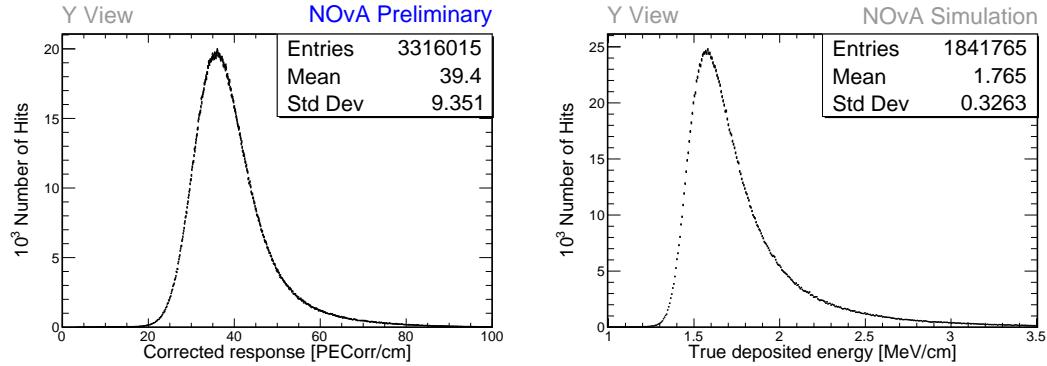


Figure 1.13: To calculate the absolute energy scale we take the mean reconstructed energy response (left) for selected stopping muons for each view and each data period or simulation, and use it to divide the simulated mean true deposited energy (right).

1.8 Systematic Uncertainties at NOvA

TO DO: *Describe the general systematic uncertainties for NOvA* COMMENT: *These subsections below might end up just being paragraphs, depends how much I want to write about them*

1.8.1 Systematic Uncertainties Related to the NOvA Neutrino Beam

TO DO: *Describe the Hadron production and focusing systematic uncertainties*

TO DO: *Principal component analysis*

COMMENT: *Maybe briefly also mention the POT scaling normalization uncertainty.*

Constraining the Hadron Production Systematic Uncertainty in NOvA

1.8.2 Systematic uncertainties for NOvA detectors

Neutrino interaction systematic uncertainties

Energy scale systematic uncertainty

Cell edge calibration systematic uncertainty

Detector ageing systematic uncertainty

COMMENT: *Should I include the neutron systematics, muon energy scale systematic, or tau scale systematics? Are these detector systematics? Should find out...*

Acronyms

ADC Analog-to-Digital Converter. [7](#), [13](#), [14](#), [17](#)

APD Avalanche Photodiode. [4](#), [6](#), [7](#), [11](#), [17](#)

ASIC Application-Specific Integrated Circuit. [6](#), [7](#)

BDT Boosted Decision Tree. [13](#)

BPF Break Point Fitter. [13](#)

CC Charged current. [2](#), [3](#), [10](#), [11](#)

CMC Comprehensive Model Configuration. [10](#)

CNN Convolutional Neural Network. [13](#)

COH π Coherent pion production. [10](#)

CP Charge conjugation - Parity (symmetry). [1](#)

CVN Convolutional Visual Network. [13](#)

DAQ Data Acquisition. [6](#), [11](#), [16](#)

DCM Data Concentration Module. [7](#)

DIS Deep Inelastic Scattering. [10](#)

FB Fibre Brightness. [16](#), [18](#)

FD Far Detector. [4](#)–[7](#), [10](#), [11](#), [16](#), [17](#), [19](#)

FEB Front End Board. [6](#), [7](#)

FERMILAB Fermi National Accelerator Laboratory. [1](#), [4](#)

FHC Forward Horn Current (neutrino mode). [2](#), [3](#)

FPGA Field Programmable Gate Array. [7](#)

FSI Final State Interaction. [10](#)

LOWESS Locally Weighted Scatter plot Smoothing. 19, 20

MC Monte Carlo. 8–10, 14

MEC Meson Exchange Current. 10

MEU Muon Energy Unit. 20

MI Main Injector. 1, 2, 8

MIP minimum ionising particles. 14, 18

ML Machine Learning. 13

NC Neutral Current. 11, 13

ND Near Detector. 2–5, 7, 11, 12

NDOS Near Detector on the Surface. 4

NOvA NuMI Off-axis ν_e Appearance (experiment). 1–15, 17, 19, 20

NuMI Neutrinos from the Main Injector. 1–4, 8, 9, 11

PE Photo Electron. 7, 17, 18

PECorr Corrected Photo Electrons. 18, 20

PID Particle Identification. 13

POT Protons On Target. 2

PPFX Package to Predict the Flux. 8, 9

PVC Polyvinyl chloride. 4–6

QE Quasi Elastic (interaction). 10

REMIN Reconstructed Muon Identifier. 13

RES Resonant baryon production. 10

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

T2K Tokai to Kamioka (experiment). 9

TB Test Beam. 4, 20

WLS Wavelength Shifting (fibre). 4, 6, 11, 14, 16, 18, 20

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