



Measuring the 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,

February 20, 2024

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DOCTORAL THESIS

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Detector

by Róbert Králik

ABSTRACT

Abstract

Keywords:

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CHAPTER 1

The NOvA experiment

The NuMI Off-axis ν_e Appearance (NOvA) experiment [1] is a long-baseline neutrino oscillation experiment based at the Fermi National Accelerator Laboratory (Fermilab) [2]. NOvA receives a muon neutrino and antineutrino beam from the Fermilab's NuMI neutrino source measures kinematically-dependent event counts in a Fermilab-based Near Detector (ND), and an ~ 810 km away Far Detector (FD).

The NuMI Off-axis ν_e Appearance (NOvA) experiment is a two detector, long-baseline neutrino oscillation experiment designed for a precision measurement of $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ oscillations [3].

NOvA's primary scientific goals are to determine the neutrino mass hierarchy (normal or inverse ordering of the neutrino masses), determine whether $\theta_{23} > 45^\circ$ or $\theta_{23} < 45^\circ$ (whether the ν_3 state has more ν_μ or ν_τ respectively) and get information on the amount of the CP violation in the neutrino sector (if there is any) [4]. NOvA's physics capability however includes also searching for light sterile neutrinos by studying disappearance of the neutral current (NC) events, measuring different neutrino cross-sections, observing supernova events, slow magnetic monopoles or light dark matter particles, investigating non-standard interactions and seasonal variations of cosmic-originated muons and more [5, 3].

The experiment is managed by Fermi National Accelerator Laboratory (commonly known as Fermilab) with most of NOvA's components located on Fermilab's premises in Batavia, Illinois, near Chicago, including the near detector (ND) located 1 km from the NuMI target hall and 105 m below ground. Only the Far Detector (FD) is located in Ash River, Minnesota, 810.5 km from Fermilab, partially below ground, covered with granite rock (see sec.??) [6, 1].

NOvA started collecting data in 2013, periodically switching between neutrino and antineutrino modes, with first results published in 2016 [7].

NOvA experiment has currently more than 240 scientists and engineers from 51 institutions in six countries [1].

What is NOvA and what is it trying to measure/detect? General overview and description of the following chapter.

Where is it located and general dispositions. It has three detectors and uses a neutrino beam from the NuMI at Fermilab.

Maybe timeline of NOvA or just a general overview

1.1 The Neutrino Beam

Where do neutrinos come from? Fermilab accelerator complex and specifically the NuMI.

When should I talk about the NOvA POT and power? Right in the beginning?

How do protons get accelerated all the way to NuMI.

How does NuMI work? Describe the collimator, the hadron production in the target, the focusing horns, the decay pipe, the hadron monitors (and stopping blocks), and the muon monitors.

The off axis concept

1.2 The NOvA Detectors

General overview of the NOvA detector design and composition. List the percent-wise contribution of elements in the NOvA soup.

Segmentations and general proportions of the detectors, fibers.

The MIP energy loss for electrons (similarly to muons) can be found with a similar method as used in the AbsCal_technote_1stAna in TestBeam (page 2).

Description of the Near Detector, including the Muon Catcher. Maybe a nice graphic showing all three detectors? **TO DO: SOMETHING TO DO**

Also include a brief description of the Test Beam detector here, but probably talk more about it in the NOvA Test Beam detector calibration chapter

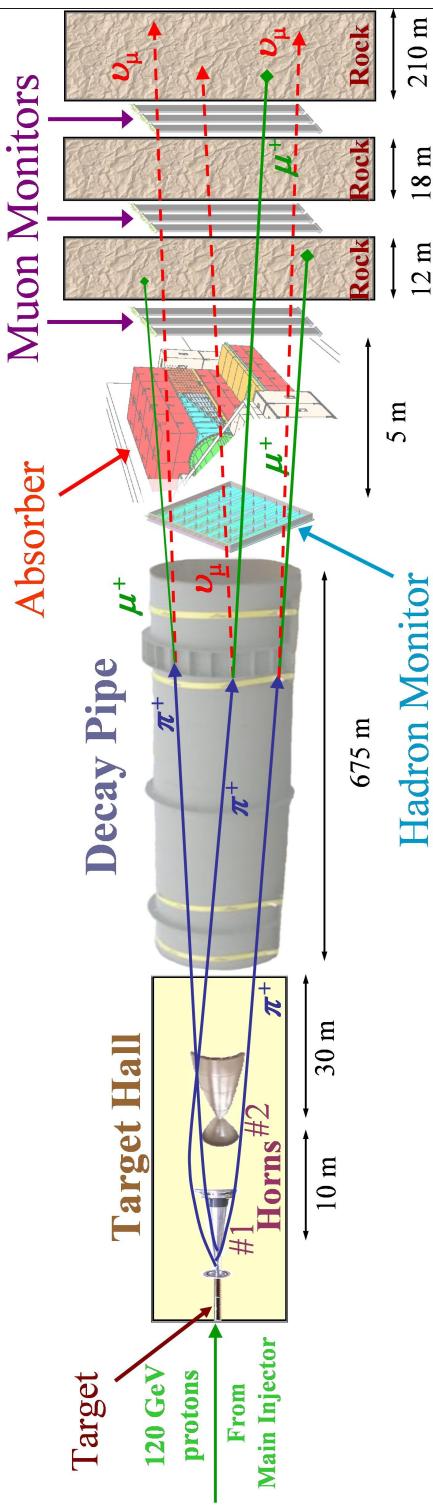


Figure 1.1: The schematic description of the Neutrinos at the Main Injector (NuMI) facility's beam line with a description of individual stages. The beam travels from left to right. Only the option where ν originated from $p \rightarrow \pi \rightarrow \mu + \nu_\mu$ interaction chain is shown, but there are other options, notably $p \rightarrow K \rightarrow \mu + \nu_\mu$ or $p \rightarrow \pi \rightarrow \mu + \nu_e + \nu_\mu$. Figure is from NOvA's internal database.

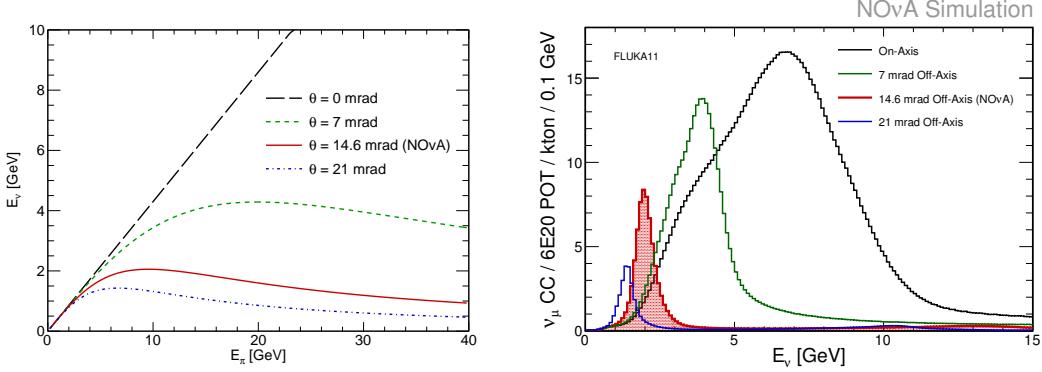


Figure 1.2: Left: Dependence of the neutrino intensity on its energy for four different angles off the main axis. The case for NOvA (shown here in red) shows a narrow peak around 2 GeV, ideal for studying "atmospheric" oscillations driven by Δ_{31}^2 at the NOvA far detector, with still enough intensity. Figure is from NOvA's internal database. Right: Energy dependencies of neutrino on its parent pion for 4 different angles from the main axis. The angle coloured red is the one used in the NOvA experiment where the energy of neutrinos coming from pions flattens to almost a constant close to 2 GeV giving NOvA the desired narrow energy peak.

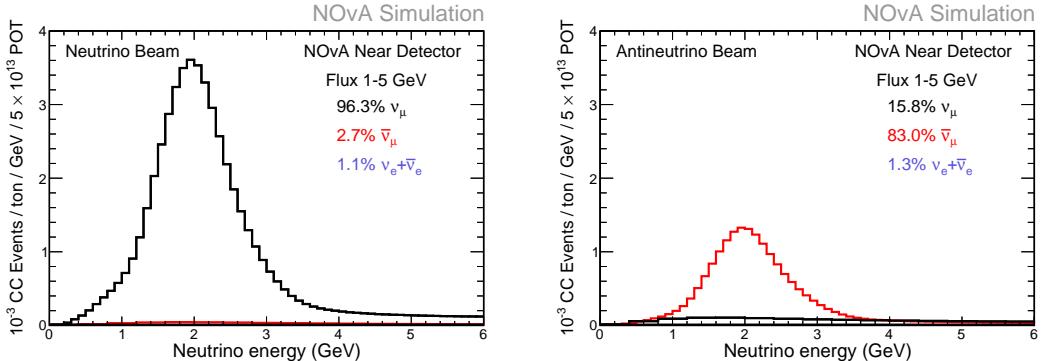


Figure 1.3: CC event rates at the ND in FHC (left) and RHC (right). The events are corrected by kPPFXFluxCVWgtST and kXSecCVWgt2018_NT..

1.3 Data Acquisition

APDs and how they work are pretty well described in the NOvA technical design report. For some reason the TDR I have downloaded doesn't have the full chapter 14. Full TDR can be found in docdb:2678 chapter by chapter.

APD signal first needs to be converted to a digital format with ADC (is there anything before that?). Maybe take a look at docdb:353.

This digital signal is then passed to the FPGA, which does the correlated sampling and time stamping [docdb:353]. **COMMENT: FROM DOCDB:353**

TDR: Major components are the carrier board connector location at the left, which brings the APD signals to the NOvA ASIC, which performs integration, shaping, and

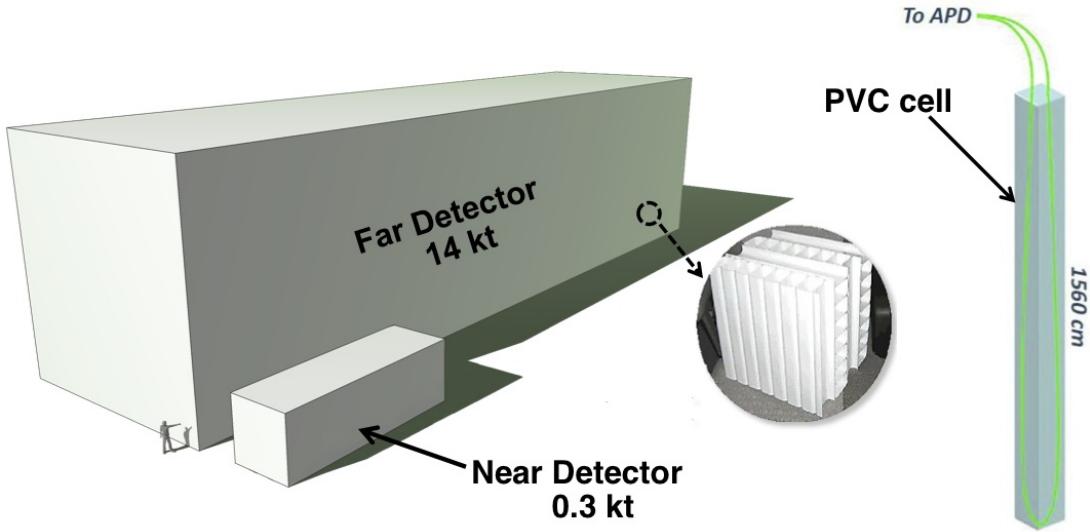


Figure 1.4: Schematic description of scale and composition of the NOvA detectors. Inset showing the orthogonal planes of PVC cells. One cell containing liquid scintillator and a loop of wavelength sifting fibre attached to an avalanche photodiode is also shown [8].

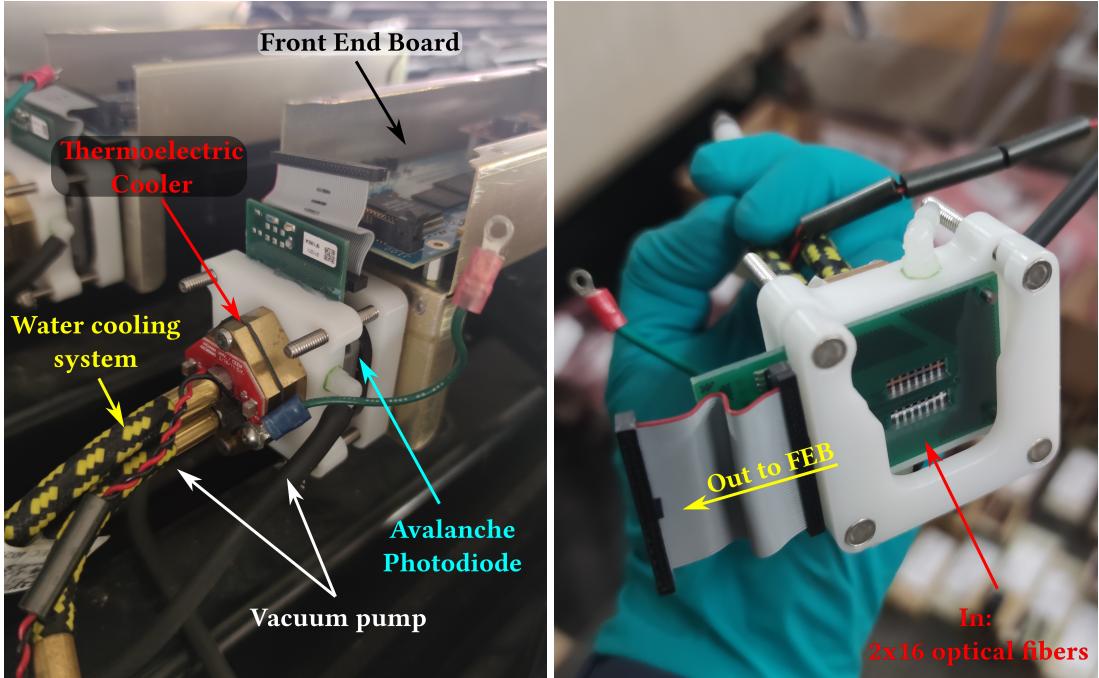


Figure 1.5: The Avalanche Photo Diodes for NOvA

multiplexing. The chip immediately to the right is the ADC to digitize the signals, and FPGA for control, signal processing, and communication. The front end electronics has the responsibility of amplifying and integrating the signals from the APD arrays, determining the amplitude of the signals and their arrival time and presenting that information to the data acquisition system (DAQ). Data from the ADC is sent to an

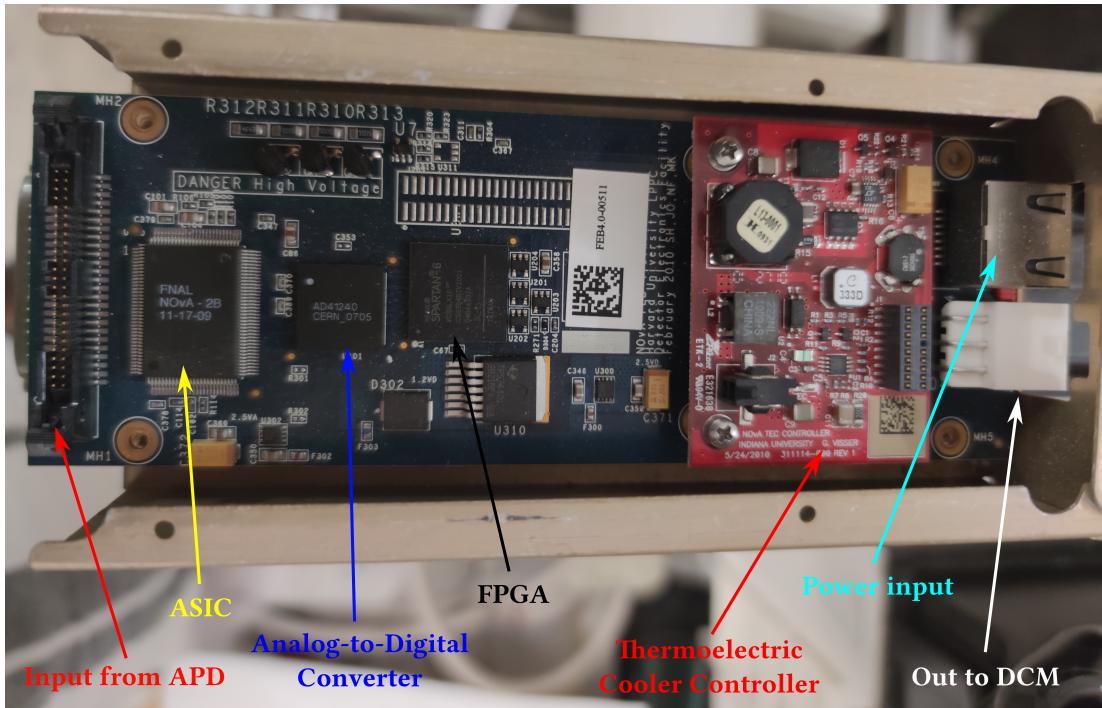


Figure 1.6: The Front End Board for NOvA

FPGA where multiple correlated sampling is used to remove low frequency noise. This type of Digital Signal Processing (DSP) also reduces the noise level and increases the time resolution.

We are saving all the ADC and TDC (Time Digital Converter I believe) values to the RawDigit. Then they are fitting in the Calibrator to a functional form and converted to PE by fitting for the peak ADC.

"The chip will be used in its "Analog" mode in NOvA. In this mode, eight channels of integrator/shaper outputs are fed onto a multiplexer and driven by a differential amplifier onto the output pads. The multiplexer runs at 16 MHz, sending its signal output to the quad ADC. The ADC outputs, in turn, are sent in a continuous stream to an FPGA which processes the data and outputs it onto a data link. In these tests, the data link is standard USB 2.0" [docdb:1904]

DAQ Software (what happens to the signal after the FEBs) is described in docdb:1233. Not sure if this is the final design though.

Triggers

1.4 Data Processing and Event Reconstruction

Basic description of the process from raw data to final predictions (or just cafs?)

Maybe talk about data quality as well? Good runs and so on...

Reconstruction - describe the reconstruction tools used to get the final products, focusing on the electron reconstruction.

Clustering into slices - how is that done?

Reconstruction of prongs and tracks. Electron showers

1.5 Simulation

1.5.1 Neutrino Beam Simulation

Should I mention that in the past we used Fluka, but now we're using Geant4

Package to Predict the FluX

Should I talk about this now or should I talk about the simulations (and their corrections) together?

I did this in the beginning of my thesis so maybe I should mention this. Especially the possible improvements and what I've done for them (enough to say I looked at it?)

Constraining the Hadron Production Systematic Uncertainty in NOvA

Again, should I discuss it here or somewhere else? Maybe not necessary as a full section. Not sure if I should include a discussion on nu-on-e, or low nu studies here, or just PPFX improvements.

1.5.2 Simulation of the Neutrino Interactions

NOvA Reweighting of the Neutrino Interaction Predictions

1.5.3 Simulation of the Detector Response

Should I join this with the other simulation subsection?

1.6 Detector Calibration

The purpose of calibration is to make sure that we get the same amount of energy wherever or whenever it's deposited in whichever of NOvA's detectors and to express this amount of energy in physical units. The NOvA calibration uses cosmic ray muons, which provide a consistent, abundant, and well-understood source of energy deposition.

Creating calibration samples

We want to select good quality cosmic ray muons. First, we remove beam related events based on their time stamps relative to the time of the beam spill. Next we apply reconstruction to get the CellHit, slicer, and track information, followed by a track-based selection to remove misreconstructed and poor quality events.

Since energy deposition depends on the path length particle travels through a cell, we only use hits for which we can reliably calculate their path length. We call these hits **tricell** hits, as we require that all accepted hits are accompanied by a recorded hit in both neighbouring cells of the same plane, as shown on Fig. 1.7. In case there is a bad channel in a neighbouring cell, 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 [? ?].

For the absolute calibration we select muons that stop inside the detector, by identifying muons with a Michel electron at the end of their track [?].

For each data period or epoch and for each version of the simulation we create two calibration samples that are used as the input for the relative and absolute calibration. The samples are called [?]

- `pclist` = **list** of **pre-calibrated hist**; Contains all selected cosmic muon events and is used in the relative calibration;
- `pcliststop` = `pclist` files only containing stopping muons used for the absolute calibration

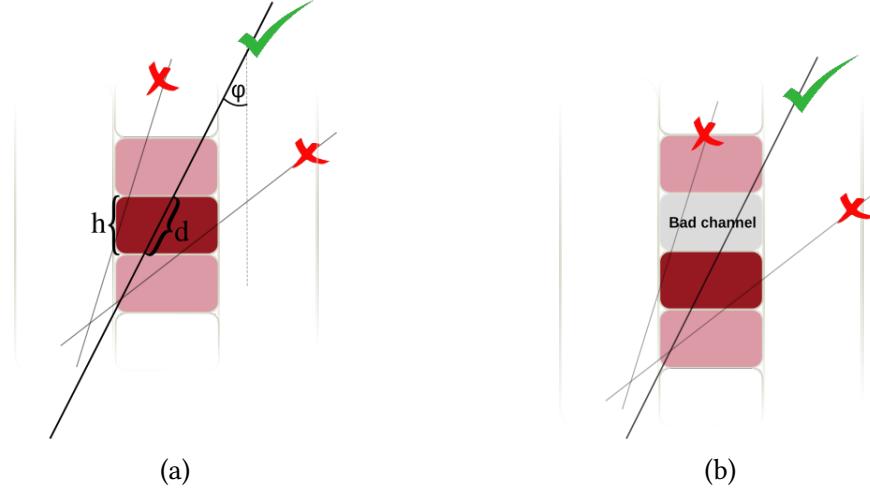


Figure 1.7: Illustration of the tricell condition (a). We only use hits that have two surrounding hits in the same plane to be used in the NOvA calibration. This is to ensure a good quality of the path length (d) reconstruction, which is calculated from the known cell height (h) and the reconstructed track angle (φ). In case the hit is next to a bad channel (b), we ignore this bad channel and require a hit in the next cell over.

Fibre brightness

For data, the relative calibration is done for each individual cell in each plane to properly account for any potential variations, repeating the attenuation fit $N_{cell} \times N_{plane}$ times. However, generating enough simulated events turned out to be computationally expensive. Therefore, assuming the simulated detector is approximately uniform plane to plane, for simulation we can "consolidate" the detector planes and only consider variations in the two views. Therefore for simulation we would repeat the fit $N_{cell} \times N_{view}$ times [? ?].

However, there are some variations in the detector response cell by cell that can be caused by different fibre brightnesses, but also by different qualities of the scintillator, air bubbles, APD gains, looped or zipped fibres and potentially others. We want to include these variations in the simulation to better match data. To emulate these differences in the simulation without the need to simulate every cell individually, we divide each detector into 12 brightness bins, as shown on Fig. 1.8. These brightness bins describe the relative differences in the detector response between individual cells [?]. Therefore in the end, for simulation we perform the attenuation fit $N_{cell} \times N_{view} \times N_{BrightnessBin}$ times.

To divide each detector into the 12 brightness bins, we use results from the relative calibration. Specifically we take the result of the attenuation fit (equal to the

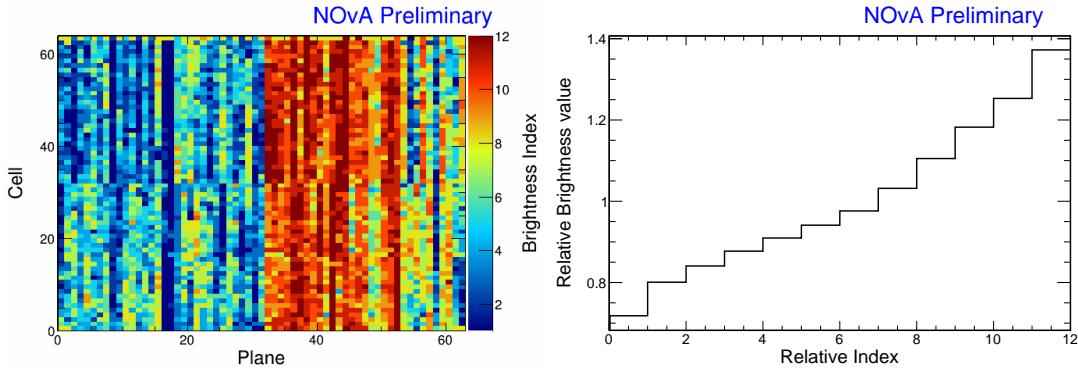


Figure 1.8: The Test Beam detector is (like the standard NOvA detectors) divided into 12 brightness bins (left plot), each representing a relative difference in energy response (right plot) due to different brightnesses of the fibres, scintillators, or readout.

average response) in the centre of each cell to fill a 2D histogram. Then we normalize this histogram by dividing the response in each Cell \times View \times Plane by the average response in the corresponding Cell \times View. All uncalibrated cells get assigned the average response (1 in normalized histogram). Then we make a 1D histogram filled with the normalized responses of each cell and divide this histogram into 12 equally populated bins (so each bin represents approximately the same number of detector cells, shown on the left plot of Fig. 1.8). The mean normalized response in each bin represents the relative brightness value of this bin (right plot of Fig. 1.8).

TO DO: *DESCRIBE THE ABSOLUTE AND RELATIVE CALIBRATION JUST IN TEXT* The NOvA calibration consists of two parts [?]:

1. The **relative calibration** corrects for attenuation of scintillator light as it travels through the cell to the readout, as well as for differences between detector cells. This correction is calculated for each cell separately.
2. Followed by the **absolute calibration**, which only uses stopping muons when they are minimum ionising particles. In the absolute calibration we calculate a scale between the measured energy deposition, corrected by the relative calibration, and the simulated energy deposition in physical units of MeV. This scale is calculated for each time period and each detector separately, which ensures the energy deposition is directly comparable wherever or whenever it occurred.

TO DO: *JUST DESCRIBE THESE UNITS IN TEXT INSTEAD OF HERE* The basic units and variables used to define energy deposited in the NOvA detectors are listed in table

1.1.

ADC	The digitized charge collected by the APDs from the Analog to Digital Converter [?].
PE	Number of Photo Electrons. Calculated by a simple rescaling of the best estimate of the peak ADC. The PE per ADC scale only depends on the FEB type and the APD gain settings. This conversion is done before the calibration and PE serves as the base unit for calibration.
PECorr	Corrected PE after applying the relative calibration results. The correction is a ratio between an average energy response (a pre-determined semi-arbitrary number) and the result of the the relative calibration fit (also called attenuation fit), which depends on w, cell, plane, epoch and detector. This makes the energy response equivalent across each detector.
MEU	Muon Energy Unit is the mean detector response to a stopping cosmic minimum ionising muon. For true variables it's equivalent to the mean MeV/cm and for reconstructed variables to the mean PECorr/cm.
MeV	Estimated energy deposited in the scintillator calculated from PECorr using the results of the absolute calibration. Additional correction for dead material needs to be made in order to get an estimate of the calorimetric energy.

Table 1.1: Definitions of variables commonly used in calibration [? ?].

TO DO: CHANGE THIS EQUATION TO BE SIMPLER AND ALSO INCLUDE T/S CORRECTIONS

The final result of the NOvA calibration is the deposited energy in terms of physical units, which is in effect calculated as:

$$E_{dep}[\text{MeV}] = \underbrace{\frac{\text{MEU}_{truth}[\text{MeV}/\text{cm}]}{\text{MEU}_{reco}[\text{PECorr}/\text{cm}]}}_{\text{Absolute calibration}} \times \underbrace{\frac{\text{Average response}[\text{PECorr}]}{\text{Fitted response}[\text{PE}]}}_{\text{Relative calibration}} \times \underbrace{\left[\frac{\text{PE}}{\text{ADC}} \right]}_{\text{Scale}} \times \text{Signal}[\text{ADC}],$$

(Detector, epoch)

(Detector, epoch, plane, cell, w)

(APD Gain, FEB)

(1.1)

where both the relative calibration results (blue fraction) and the absolute calibration results (red fraction) are stored in a database and applied together with the ADC-to-PE scale during processing of every hit in the NOvA detectors.

1.6.1 Threshold and shielding correction

Energy deposited far away from the readout may get attenuated enough to be shifted below the threshold. These low energy depositions would be missing from the attenuation fit, biasing it towards larger light levels with increasing distance from the readout. Similar effect, specifically for the vertical cells, is caused by using cosmic muons for calibration and applying it to beam muons. The top of the detector effectively shields the bottom, skewing the energy distribution of cosmic muons. To correct for both of these effect, we use the simulation plist sample to calculate the threshold and shielding (also called threshold and shadowing) correction by comparing the true and reconstructed information. We apply this correction before the attenuation fits [?].

1.6.2 Relative calibration

Relative calibration corrects for the attenuation of the scintillator light by fitting the average detector response over the position in each cell (w), separately for every cell inside each detector. Dividing the "average response" of the detector by the result of the attenuation fit for each Plane \times Cell $\times w$ combination effectively removes relative differences within and between all cells across the entire detector. The average response is a single constant number chosen to approximately represent the average response in the middle of the cell. Its value is for the far detector and Test Beam 39.91 PE/cm and for the near detector 37.51 PE/cm. The value of the average response has no impact of the calibration results, as the absolute scale of the detector response is determined during the absolute calibration and relative calibration only serves to remove the relative differences [? ?].

To create the attenuation fit we use the following procedure [?]:

1. Create the *attenuation profiles*. Attenuation profiles are essentially profile histograms of detector response in terms of PE/cm as a function of position in the cell (w) for each cell in all planes. We construct the attenuation profiles over a little wider range than the actual length of the cell and always with 100 bins for each detector. This means that smaller detectors, like the Test Beam detector, have a finer binning ($\sim 3\text{cm/bin}$) compared to the Far Detector ($\sim 18\text{cm/bin}$).

2. Analyse the attenuation profiles. The job to create the attenuation profiles also creates validation histograms, which should be analysed prior to performing the attenuation fit to make sure the attenuation profiles look as expected.
3. Apply the threshold and shielding correction that was created before the relative calibration.
4. Do the attenuation fit over the full length of each cell. The fit consists of
 - (a) an exponential fit, which combines two cases. First, when the scintillating light travels the short distance straight to the readout, and second, when it goes to the far side of the cell and loops around before going to the readout. The fitted function has a form:

$$y = C + A \left(\exp\left(\frac{w}{X}\right) + \exp\left(-\frac{L+w}{X}\right) \right), \quad (1.2)$$

where y is the fitted response, L is the length of the cell and C , A and X are the fitted parameters. X also represents the attenuation length.

- (b) Smoothing of the residuals from the exponential fit, mainly at the end of cells, with the LOcally WEighted Scatter plot Smoothing (LOWESS) method.
5. Check the plots of the attenuation fit for a selection of cells.
6. Save the fit result to the database in the form of two csv tables. The `calib_atten_consts.csv` table holds the results of the exponential fit, together with the final χ^2 of the fit. The `calib_atten_points.csv` table holds the results of the LOWESS smoothing.

To ensure the quality of the attenuation fit, we only apply the results if the final $\chi^2 < 0.2$. If $\chi^2 > 0.2$, we ignore the results for this cell and mark it as *uncalibrated*.

1.6.3 Absolute calibration

To find the absolute energy scale, we apply the relative calibration results on the stopping muon sample and look at the energy they deposited in cells 1-2 meters from the end of their tracks. In this track window they are approximately minimum ionising

particles and their energy deposition is almost constant and well understood. Additionally, we don't use hits from the edges of a cell, as those might be affected by the lower number of events, fibre endings, or loops.

For each calibrated data and simulation sample we take a mean of the corrected deposited energy distribution, separate for each view. We then take a simple average from the two views to get the final MEU_{reco} in units of PECorr/cm for each sample [?]. Additionally, from simulation we can get the mean of the distribution of the true deposited energy in the scintillator, MEU_{truth} in units of MeV/cm for the same sample of stopping muons.

We ignore the energy that is lost in the dead material (PVC extrusions) and deal with it separately. The absolute energy scale for each sample is then the ratio of $\text{MEU}_{truth}/\text{MEU}_{reco}$. We save these absolute energy scales in another csv table called `calib_abs_consts.csv` which stores the MEU values and their errors.

As part of the absolute calibration we also produce validation plots that show the effect of calibration on the distribution of the stopping muons. We analyse these plots and if everything looks all right we load all the csv tables into the database.

1.7 Source of systematic uncertainties at NOvA

1.7.1 Systematic Uncertainties Related to the NOvA Neutrino Beam

Hadron production and focusing systematic uncertainties

Principal component analysis

Maybe briefly also mention the POT scaling normalization uncertainty.

1.7.2 Systematic uncertainties for NOvA detectors

Neutrino interaction systematic uncertainties

Energy scale systematic uncertainty

Cell edge calibration systematic uncertainty

Detector ageing systematic uncertainty

Glossary

PMNS	Pontecorvo-Maki-Nakagawa-Sakata (matrix)
SNU	Solar Neutrino Unit
CC	Charged Current (interaction)
NC	Neutral Current
MSW	Mikheyev-Smirnov-Wolfenstein (effect)
SK	Super-Kamiokande (experiment)
NO	Normal Ordering (of masses)
IO	Inverted Ordering (of masses)
SBL	Short Baseline
LBL	Long Baseline
LSND	Liquid Scintillator Neutrino Detector
MiniBooNE	Mini Booster Neutrino Experiment
SBN	Short Baseline Neutrino (program)
NOvA	NuMI Off-axis ν_e Appearance (experiment)
NuMI	Neutrinos from the Main Injector
ND	Near Detector
FD	Far Detector
FHC	Forward Horn Current (neutrino mode)
RHC	Reverse Horn Current (antineutrino mode)
HC	Horn Current
LE	Low Energy (mode of NuMI)
ME	Medium Energy (mode of NuMI)
APD	Avalanche Photodiode
CVN	Convolutional Neural Network
MC	Monte Carlo
PPFX	Package to Predict the Flux
CMS	Center of Mass (frame)
BENDecomp	Beam Electron Neutrino Decomposition

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