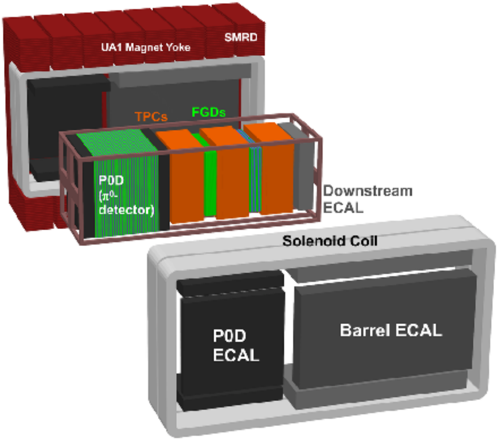
Neutrino Interaction Measurements Using the T2K Near Detectors

Daniel Brook-Roberge
for the T2K Collaboration

University of British Columbia

NuFact11

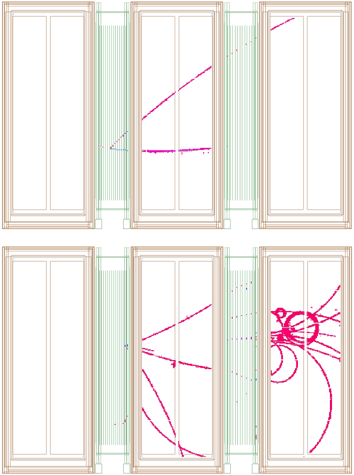
Overview of T2K Near Detector (ND280)



- The main near detector for T2K is a magnetic spectrometer known as ND280.
- The central region of ND280 is surrounded by an electromagnetic calorimeter for electron and photon tagging.
- The yoke of the magnet is instrumented with scintillator planes for use as a cosmic trigger and veto.

For more details of the ND280 complex and its performance, see the talk by N. McCauley from WG2 Weds PM

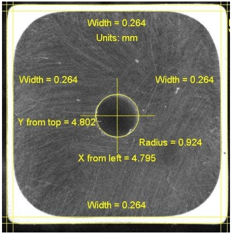
The Tracker

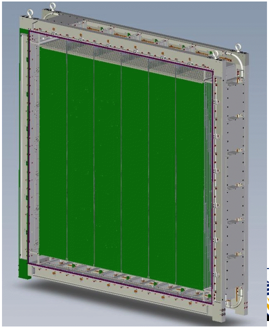


- The Tracker is the part of ND280 optimized for measuring charge-current interactions.
- It consists of three large-volume Time Projection Chambers (TPCs) and two scintillator-based Fine-Grained Detectors (FGDs).
- The TPCs are gas detectors that allow precision 3D tracking and energy loss measurements.
- The TPC measures:
  - Curvature → Momentum and Charge
  - dE/dx → Particle Identification
  - Direction Extrapolated Into FGD → Fiducial Volume Determination

Fine-Grained Detectors

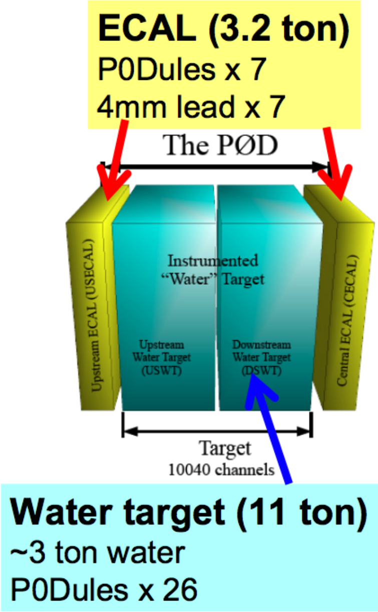
- The FGDs are made of planes of ∼1cm square plastic scintillator bars in alternating orientations.
- Each provides about 1.1 tonnes of target material.
- One FGD consists of 15 planes in each orientation, while the other has 7 pairs of scintillator planes interleaved with 6 water targets.
- The active volume of each FGD is 192cm x 192cm x 30cm in size.



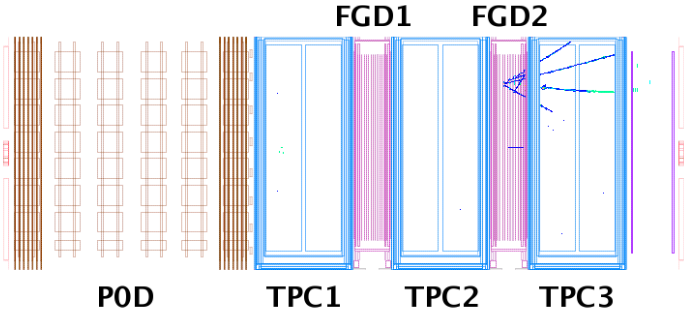


Pi-Zero Detector

- The Pi-Zero Detector, or P0D, is the portion of ND280 designed to measure neutral current interactions.
- It is a hybrid tracking-calorimeter design, with layers of scintillator bars interspersed with lead plates for conversion of electrons and gammas.
- The central region contains water targets that may be filled and drained during running.



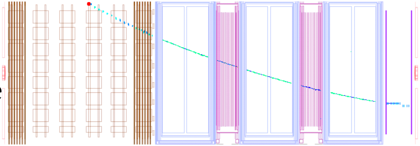
Tracker CC ν_μ Analysis Strategy

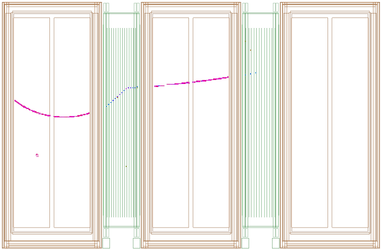


- Current CC analyses in ND280 use the Tracker and aim to study interactions occurring within the FGD.
- The overall analysis has several discrete steps:
  1. Selecting events with neutrino activity
  2. Selecting only tracks originating in the FGD fiducial volume
  3. Choosing the highest-momentum negative track as the muon candidate
  4. Using TPC dE/dx to select actual muons from the candidates

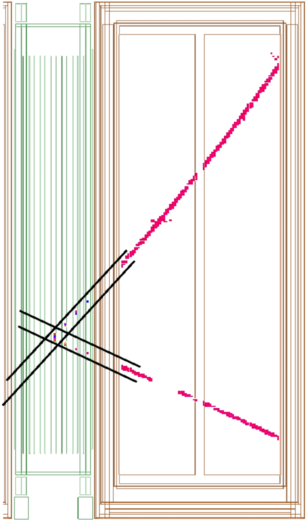
Selection of Neutrino Interactions

- We seek to reject events where charged particles enter the Tracker to isolate neutrino interactions in the FGD.
- Events with tracks in the most upstream TPC are thus rejected.
- While some FGD interactions have backwards-going tracks, the current analysis only looks for forward-going events.
- Events with no TPC track are also rejected.





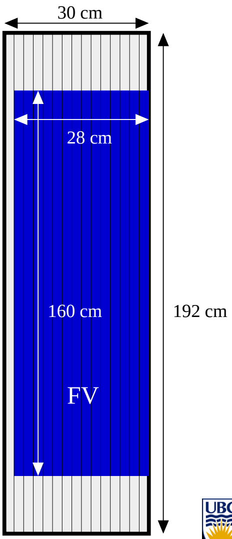
Extrapolation of TPC Tracks



- TPC tracks are fit to a helix around the magnetic field axis.
- These helices are extrapolated into the preceding FGD and hits within 3 cm of the extrapolated track are considered to be associated with the TPC track.
- As the FGD hits only have 2D information, the vertex X and Y positions are taken separately from the deepest matched XZ and YZ hits.

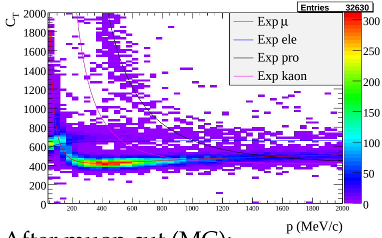
FGD Fiducial Volume Cut

- Once the track origin is determined, the track is rejected if it falls outside the FGD fiducial volume.
- The fiducial volume excludes the outer 20cm transverse to the beam direction, screening particles entering from the side of the FGD.
- It also excludes the first pair of scintillator planes on the upstream side of the FGD, but has no cut on the downstream side.

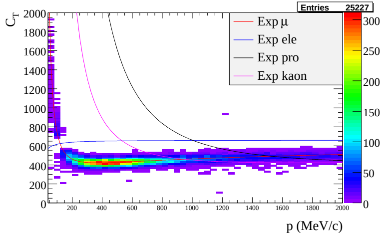


Muon Particle Identification

Before muon cut (MC):

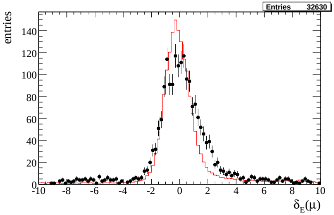


After muon cut (MC):

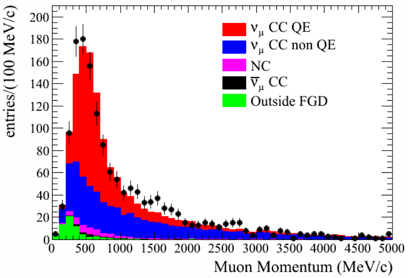


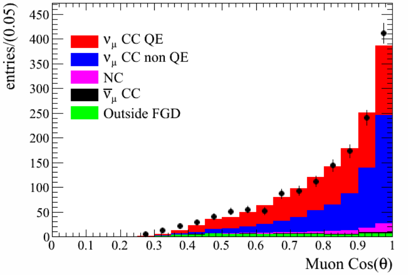
- PID in the TPC is accomplished through comparison of particle dE/dx with the expected value for the measured momentum.
- We calculate a pull δ for each particle hypothesis and then cut on $|\delta(\mu)| < 2.5$ and $|\delta(e)| > 2.5$.

Muon Pull (Data vs MC):



Results of CC Inclusive Measurement





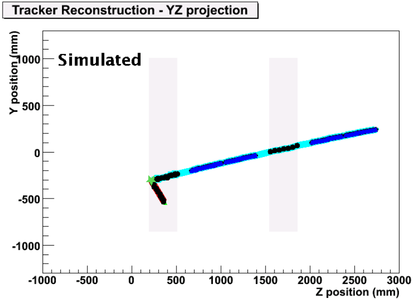
Points are data, histogram is MC

- These results are from data taken in Jan-Jun 2010, with 2.88×10^{19} POT, and have a 91% purity for CC ν_μ interactions.
- Analyzing this data gives a rate normalization Data/MC ratio of
  $$1.036 \pm 0.028(\text{stat}) \; ^{+0.044}_{-0.037}(\text{det syst}) \; \pm 0.038(\text{xsec syst})$$
- This normalization reduces the flux uncertainty for ν_e appearance by half.

Improvements in CC Inclusive Selection

- Many improvements have been made to the selection in preparation for the use of the data taken in Nov 2010-Mar 2011.
- The simple extrapolation approach for associating FGD hits with TPC tracks has been replaced with a more sophisticated 'incremental' approach.
- This approach revises the track parameters following each associated hit, and properly accounts for energy loss in the FGD.
- The blanket TPC1 veto requirement has been removed in favour of a more sophisticated veto which checks whether the TPC1 track appears to be connected with the TPC2/FGD1 track.
- For future oscillation analyses, ND280 spectral information will be used in the fit, rather than a pure normalization.

Extension to CCQE

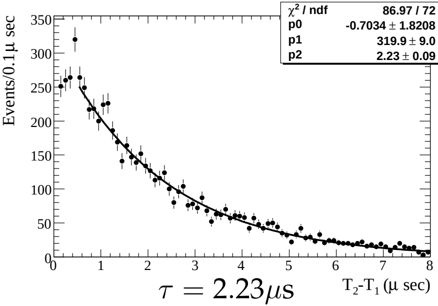


- We would like to extend our CC inclusive selection to CCQE by developing methods to reject events with visible pions.
- We plan three cuts:
  1. Require exactly one TPC/FGD track, which must be negative
  2. Require absence of Michel electron in the FGD
  3. Require no FGD-only reconstructed tracks

Michel Electron Cut

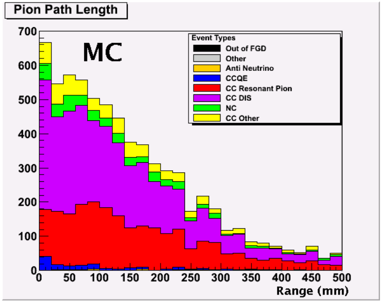
- The FGD takes data over a long enough interval to observe the decay of stopped muons.
- FGD hits are separated into time bins when a gap of 100 ns or longer occurs between hits.
- A delayed time bin with charge over 200 PE is treated as a Michel electron candidate.
- Using a selection of stopping cosmic ray muons, we can correctly reproduce the muon lifetime from the interval between the two time bins (muon and Michel candidate).

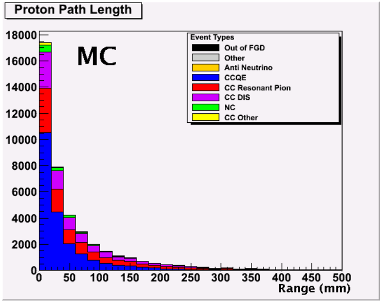
Observed Bin Time Differences:



$\tau = 2.23\mu s$

Proton Identification



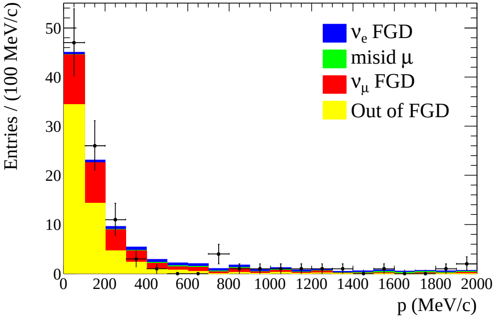


- The natural choice of topology for finding CCQE interactions is one long track and one short.
- At this point, this topology has a poor CCQE efficiency in the Tracker as compared to the single-track topology.
- In particular, the FGD-only reconstruction has low efficiency for tracks under 50 mm in length.
- In future, the FGD PID will be used to separate protons from pions.
- Further work is planned on using the unreconstructed activity near the vertex to identify protons.

Event Selection for Beam ν_e Measurements

- Unlike the ν_μ analysis, the ν_e analysis has high background from neutrino interactions: muons misidentified as electrons, and photons converting in the FGD.
- As such, the selection is more complicated:
  1. Selecting events with neutrino activity
  2. Selecting the highest-momentum track originating in the FGD fiducial volume
  3. Requiring this track to be negative and have momentum over 50 MeV/c
  4. Using TPC dE/dx to select electrons ($-1 < \delta(e) < 2$, $|\delta(\mu)| < 2.5$)
  5. Discarding events with a second TPC track and invariant mass under 100 MeV/c^2 (to eliminate γ conversions)
- After the selection, a likelihood fit is used to determine signal and background fractions.

Signal and Background



- The fit is only done over the 0-2 GeV/c region in electron momentum, and only over the Jan-Jun 2010 data for now (2.88×10^{19} POT).
- The background is split into three components: misidentified muon tracks, ν_μ events in the FGD with no visible muon, and interactions outside the FGD.
- The fit gives the number of ν_e events observed as $7.8 \pm 5.5(\text{stat}) \pm 2.1(\text{syst})$.
- We then find that the ν_e/ν_μ ratio is $(1.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}))\%$
- This analysis sets a 90% CL upper limit on the ν_e fraction of 2.0%.

Connection to Oscillation Measurement

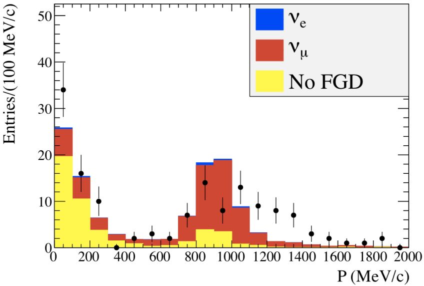
- This value provides a useful check on the validity of our beam simulation.
- We can test this by calculating the double ratio

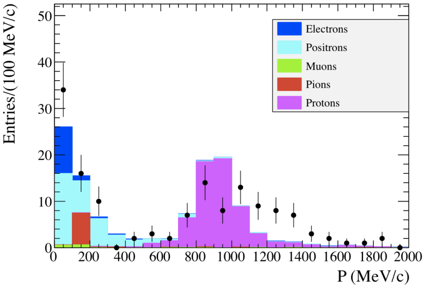
$$\frac{(\nu_e/\nu_\mu)_{data}}{(\nu_e/\nu_\mu)_{MC}} = 0.6 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$$

  showing that there is no anomaly at ND280.
- The beam ν_e fraction is important; we have 6 candidate ν_e events at the far detector, and of the 1.5 expected background events 0.8 are from beam ν_e.
- This measurement is strongly statistics-limited, and will contribute more significantly to the oscillation analysis with more data available.

ν_e Positive Analysis

- As a cross-check on the ν_e analysis, a second version of the analysis was performed requiring a positive track, to produce a sample of positrons.
- Between 100 and 500 MeV/c, there is good agreement between the background and signal fractions for both positive and negative analyses.
- This distribution is also used to constrain the electromagnetic backgrounds in the ν_e likelihood fit.

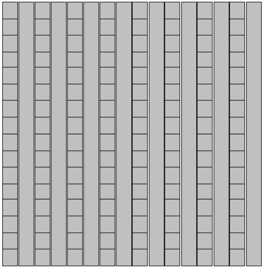




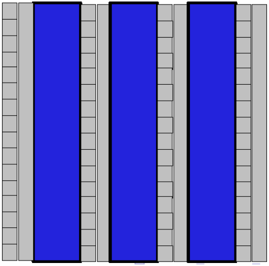
Concept of Water Subtraction

- The two FGDs are different; FGD2 has alternate scintillator layers replaced by passive water layers.
- We would like to measure interaction rates on the water separate from the scintillator.
- If we scale the rate from the all-plastic FGD to the plastic mass in the water FGD and subtract from the water FGD rate, this should accurately estimate the interaction rate on the water.

Plastic FGD:



Water FGD:



FGD Elemental Balance

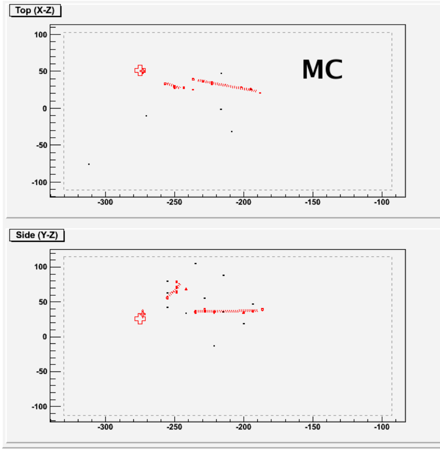
Elemental composition of empty water modules (mg/cm^2):

	C	O	H	Mg	Si	Ti	Total
Polycarbonate panel	259.0 ± 2.3	64.1 ± 0.6	18.9 ± 0.2	0	0	0	342.0 ± 3.0
Polypropylene skins	124.1 ± 3.9	0	20.7 ± 0.7	0	0	0	144.8 ± 4.6
Skin Epoxy	36.8 ± 5.1	25.5 ± 3.6	4.5 ± 0.6	6.8 ± 0.9	9.7 ± 1.4	0	83.2 ± 11.6
Spacers	2.1 ± 0.0	3.1 ± 0.0	0.5 ± 0.0	0	1.5 ± 0.0	0	7.2 ± 0.0
Total (without water)	422.0 ± 6.9	92.7 ± 3.6	44.5 ± 0.9	6.8 ± 0.9	11.2 ± 1.4	0	577.2 ± 12.8
Remnant	0	0	-1.0 ± 1.1	6.8 ± 0.9	6.3 ± 1.7	-8.1 ± 1.3	4.0 ± 13.9

- The water FGD was designed so that it would separate cleanly into mass that resembles scintillator layers and mass that resembles water.
- This is a requirement on the empty water modules; the above table describes a typical example.
- This module contains 490 mg/cm^2 of scintillator-like mass and 84 mg/cm^2 of water-like mass, with only $\sim$4 mg/cm^2 left over.
- The statistical subtraction should thus be valid to the 1% level

π^0 Analysis in the P0D

- π^0s from NCπ^0 events are reconstructed by reconstructing the individual EM showers produced by the decay photons.
- NCπ^0 events are selected by combining a π^0 signature from two clear photon showers with the absence of a muon track.
- Future analyses will include information from the ECAL surrounding the P0D and will contain a subtraction analysis to measure the rate on water.



Thanks to G. Lopez

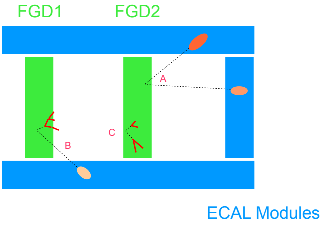
Tracker π^0 Analysis

Goal is to measure π^0 production rates in the FGDs, performing water subtraction to extract cross sections

An order of magnitude less statistics than P0D analyses
However, events are cleaner, and can use TPCs to discriminate CC/NC interactions

At least 3 strategies for Tracker π^0 measurement:

- A ECAL-ECAL conversions
- B FGD-ECal conversions
- C FGD-FGD conversions



Currently have a maturing NC type A analysis involving both photons converting in the Downstream ECAL, with work beginning to extend to the whole ECAL
Development has begun on CC analyses, and an NC type B analysis

Courtesy of P. Guzowski

Outlook and Conclusion

- The ND280 ν_μ analysis is mature and has been used as a flux normalization in the first T2K oscillation papers.
- Enhancements to the ν_μ analysis plan to measure the full neutrino spectrum and split the sample by topology.
- The beam ν_e measurement in ND280 is consistent with the beam MC — with additional statistics it will be able to reduce the ν_e appearance systematic.
- We have a detector capable of a variety of cross-section measurements due to its high resolution and carbon and oxygen targets.

Backup Slides

ν_μ Systematics

Source	Section	err. sys. +	err sys -
TPC1 veto	9.1	0.012	0.012
TPC eff	9.2	/	0.020
TPC ch misid	9.3	0.01	0.01
TPC-FGD match	9.4	0.021	0.021
FV	9.5	/	/
FGD mass	9.5	0.005	0.005
T_0	9.6	0.001	/
highest mom tk	9.7	/	/
PID pull width	9.8.3	0.030	/
Low gain MM	9.8.2	0.004	0.004
pile-up	9.9	0.009	0.009
cosmics	10.1	/	0.004
Out of FGD	10.3	0.009	0.009
Total		**0.042**	**0.036**

Table 19. Summary of the systematical uncertainties.

ν_μ Data Reduction

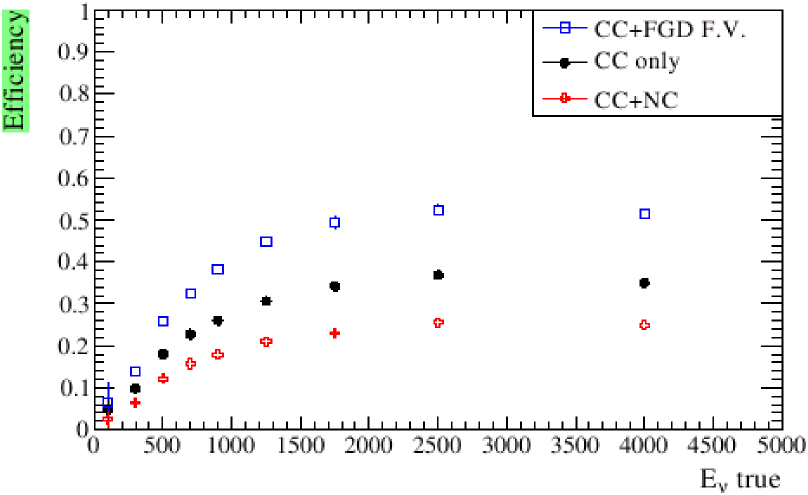
Cut	Selected events	(%)
Total n of spills	870003	100
At least one TPC track	74097	8.52
No track in TPC1	26437	3.04
At least one track in TPC2	16706	1.92
Within the FGD FV	1866	0.21
Negative and p >50 MeV/c	1036	0.12
PID cut	796	0.09
At least one track in TPC3	9731	1.12
Within the FGD FV	1890	0.22
Negative and p >50 MeV/c	1049	0.12
PID cut	733	0.08
Total n	1529	0.18

Table 3. Reduction table for the data.

Component	Fraction (%, before PID)	Fraction (%, after PID)
CCQE	40.6	49.2
CC resonance	19.6	21.7
CC coherent	2.6	3.0
CC DIS	16.4	16.8
NC	5.1	3.8
$\bar{\nu}_\mu$	0.9	0.7
Outside FGD	14.9	4.8

Table 5. True interaction types before and after the PID selection (NEUT)

ν_μ Selection Efficiency



ν_e Systematics

Source	err. sys. +	err sys -
TPC1 veto	0.012	0.012
TPC eff	/	0.020
TPC ch misid	0.01	0.01
TPC-FGD match	0.021	0.021
FV	/	/
FGD mass	0.005	0.005
T_0	0.001	/
highest mom tk	/	/
PID pull width	0.030	/
Low gain MM	0.004	0.004
pile-up	0.009	0.009
cosmics	/	0.004
Out of FGD	0.009	0.009
Total	**0.042**	**0.036**

Table 18. Summary of the detector related uncertainties for the ν_μ analysis.

Charge Misidentification

We checked the charge misidentification by comparing the charge found in each TPC in a track that spans TPCs. The graph shows the fraction of these tracks that have different charges in different TPCs.

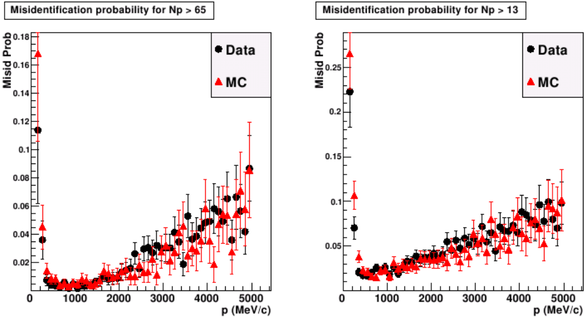


Figure 33. Misidentification probability as a function of the reconstructed momentum in data and Monte Carlo for long tracks (left plot) and short tracks (right plot) [13].

Particle Identification

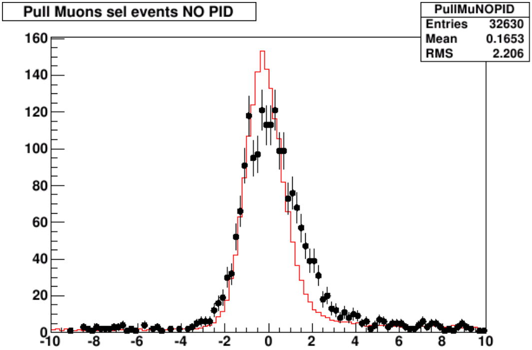


Figure 46. TPC PID muon pull after the run-by-run correction.

Data and MC have differently-shaped pull distributions. The systematic was evaluated by fitting for the Gaussian width of each and calculating the difference in acceptance if they are scaled to have identical widths.

Out-Of-FGD Backgrounds

The ν_μ sample has approximately 5% contamination from interactions outside the FGD in the MC. We can find an enriched sample of out-of-FGD interactions by selecting positive muons and looking at the lowest-energy section, and evaluate the systematic by looking at the data/MC ratio of this selection.