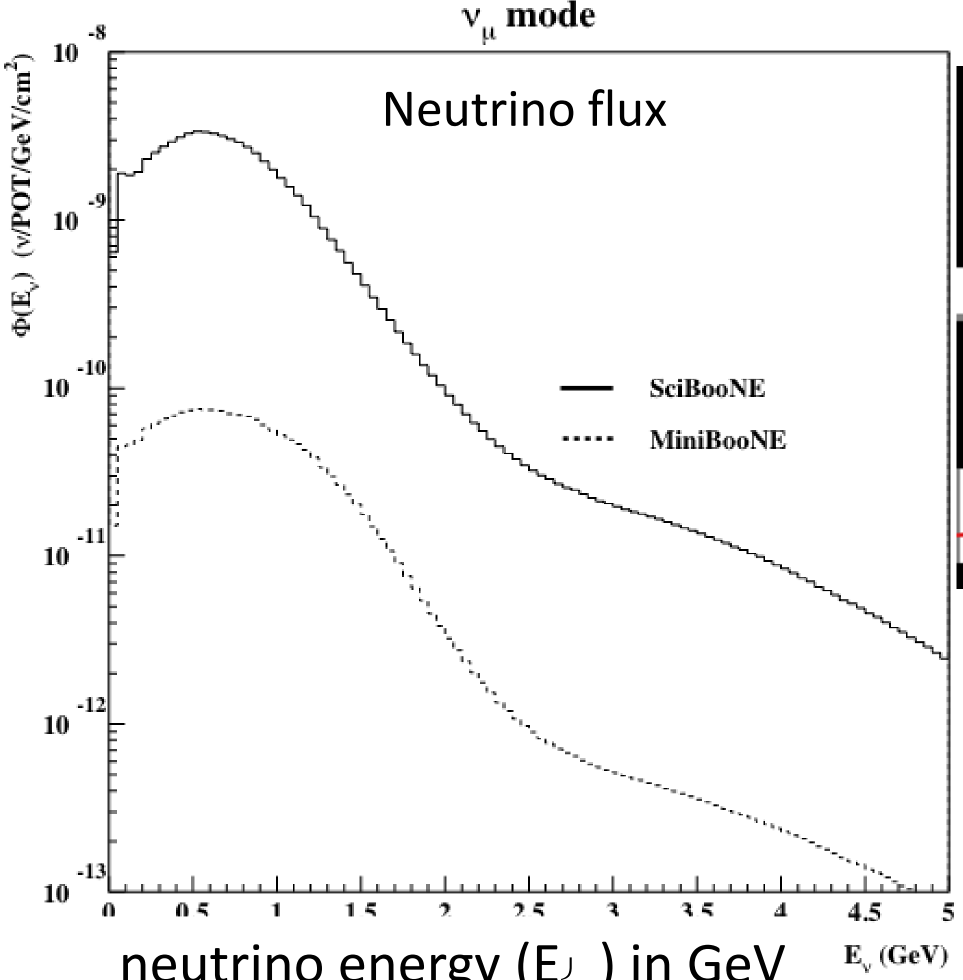
CCQE and SciBooNE, T2K

Neutrino flux



neutrino energy (E{) in GeV

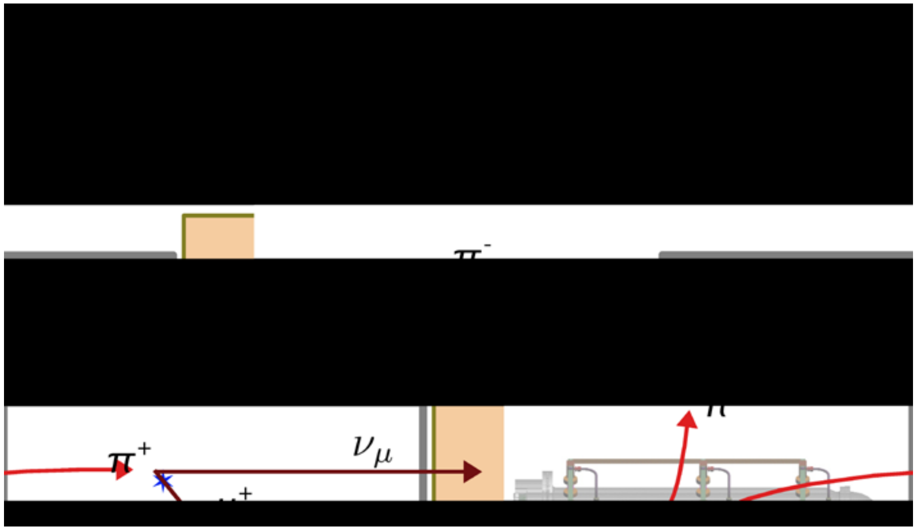
Predominantly { ⌠

- ~6% { ⌠, ~0.5% { ε{ ε

In MiniBooNE: ~1 { per 1e15 POT

In SciBooNE: ~0.5 { per 1e15 POT

~5x closer, ~50x smaller



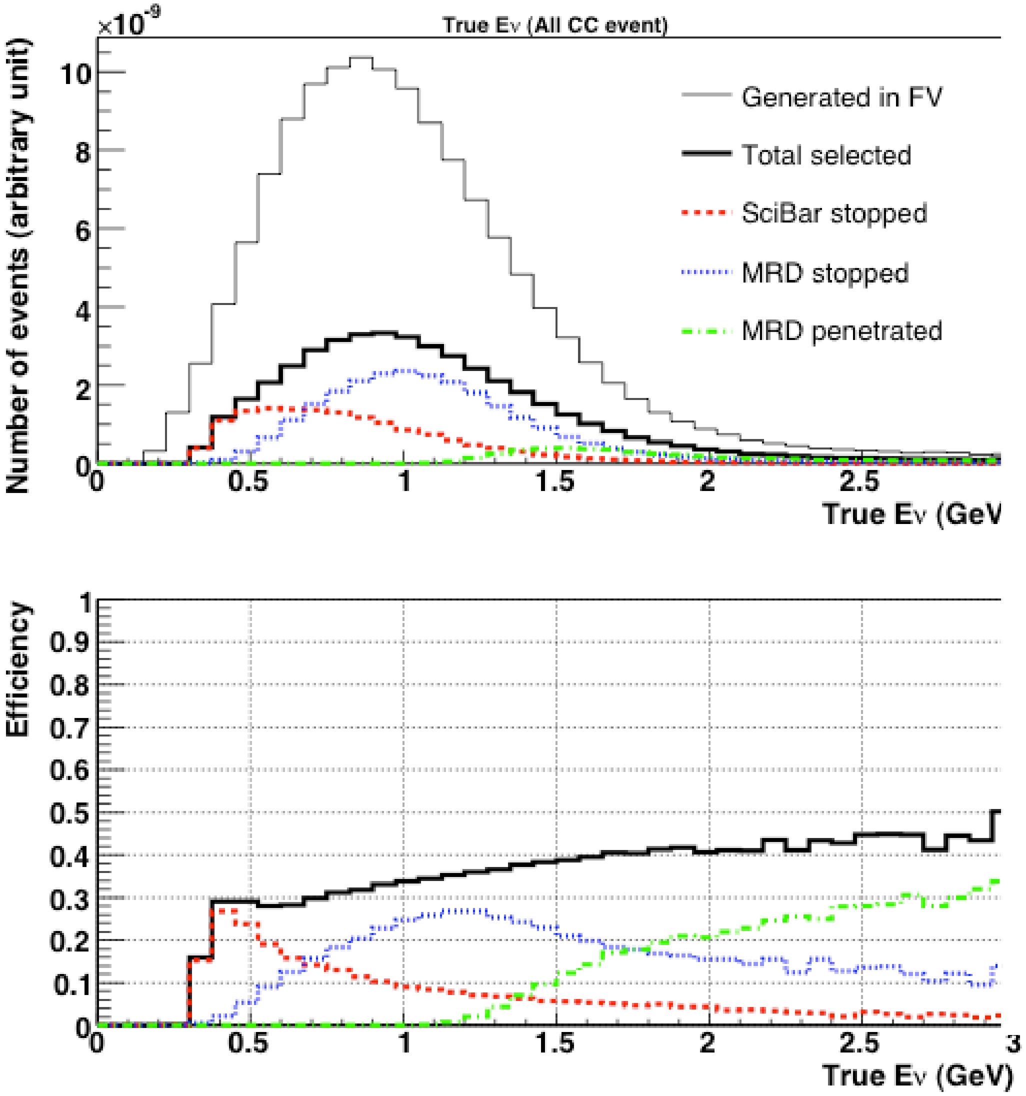
All details of the beamline geometry are modeled in Geant4

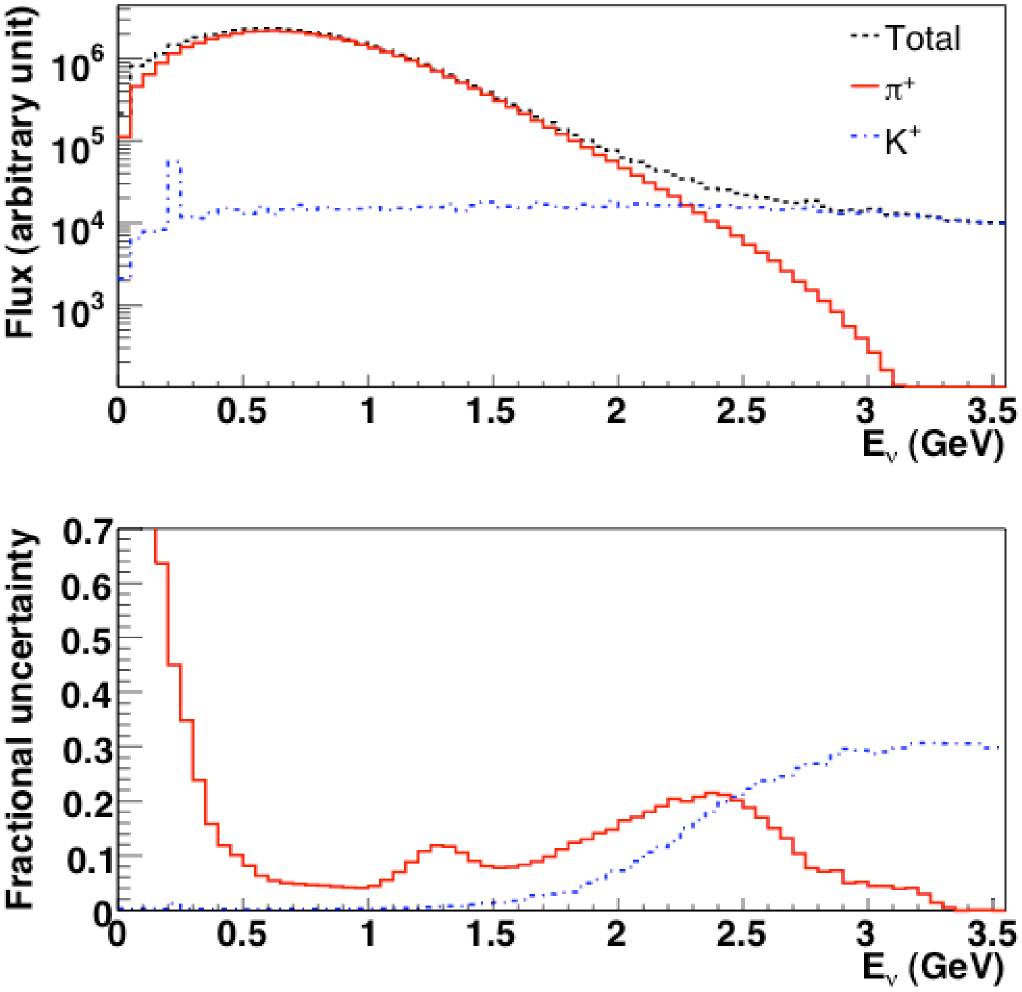
Phys. Rev. D. 79, 072002 (2009)

- 8 GeV/c p + Be target
- meson production (HARP data**ref)
- Single horn focusing
- 50m decay region, SciBooNE @100m from target
- 0.99 x 10^{20} POT neutrino mode dataset

Neutrino flux

CC inclusive selection efficiency vs. E_ν





Flux and fractional uncertainty vs. E_ν

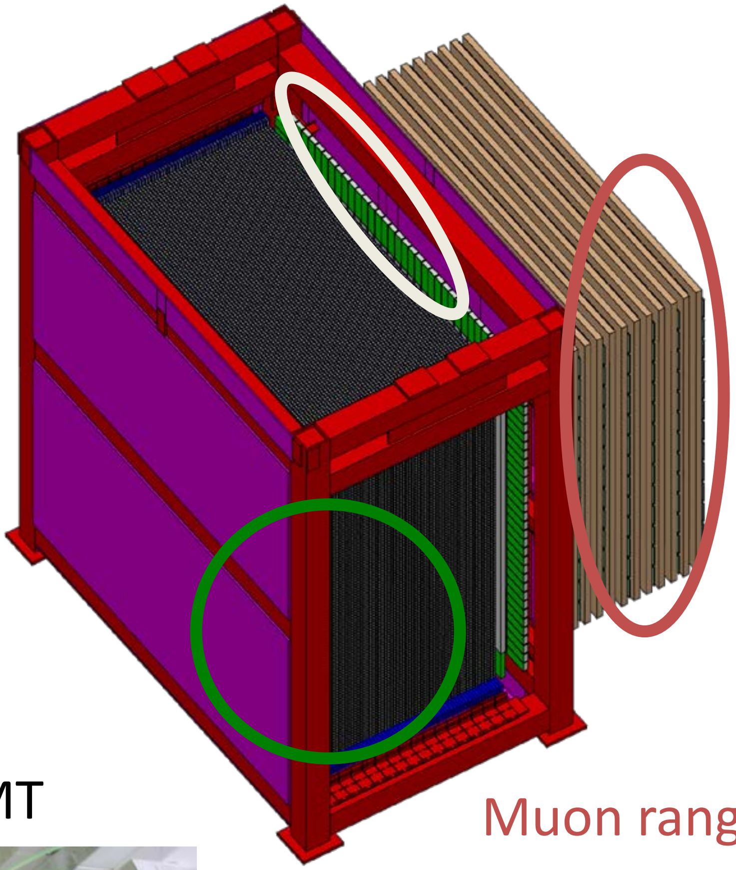
CC inclusive cross section paper

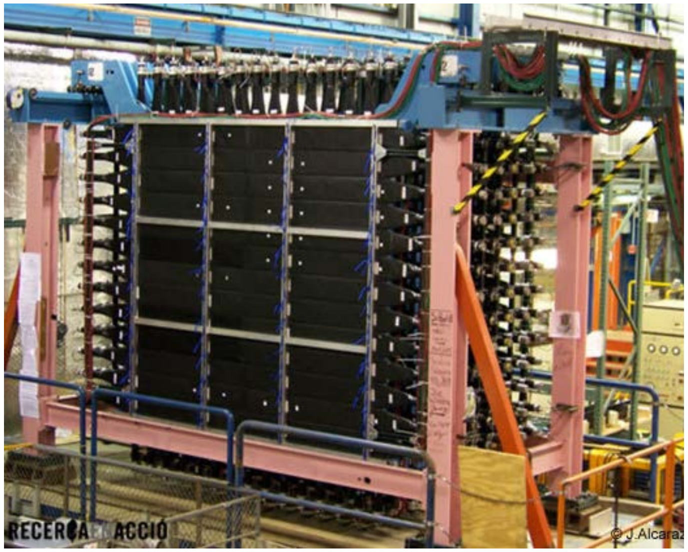
Phys. Rev. D 83, 012005 (2011)

The SciBooNE experiment

Electron Calorimeter (EC)

2 plane "spaghetti" calorimeter (scintillating fiber & lead foil)





SciBar vertex detector

32 x-y planes of 14,336 extruded scintillator

(1.3 cm x 2.5 cm x 300 cm)

15ton (10.6ton FV)

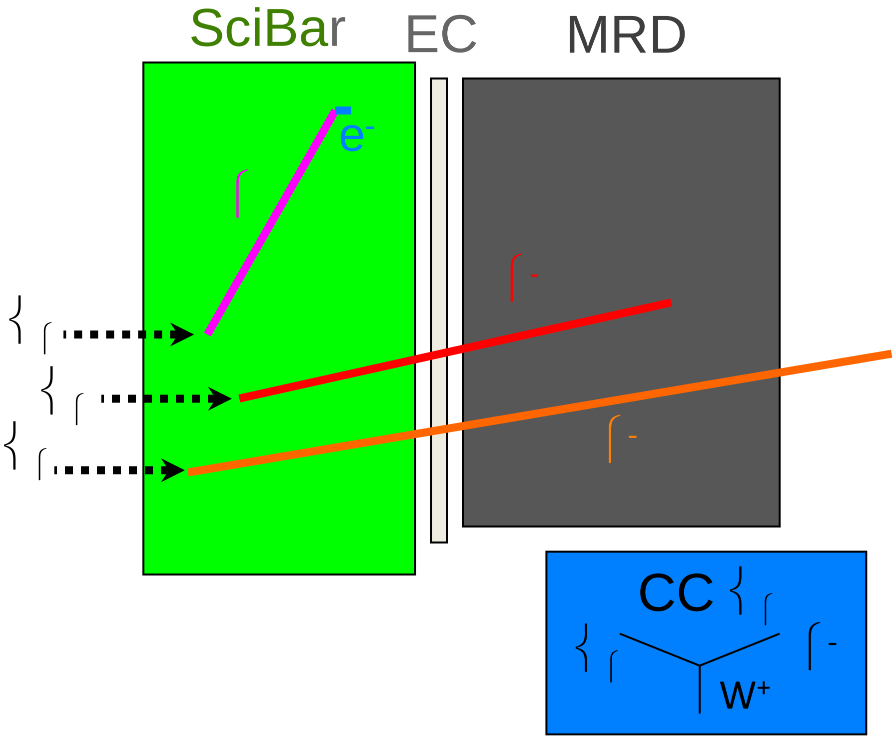
WLS fiber and 64ch. MAPMT

Muon range detector (MRD)

362 scintillator counters strapped vertically and horizontally to 12 iron plates

All detectors are recycled from previous experiments

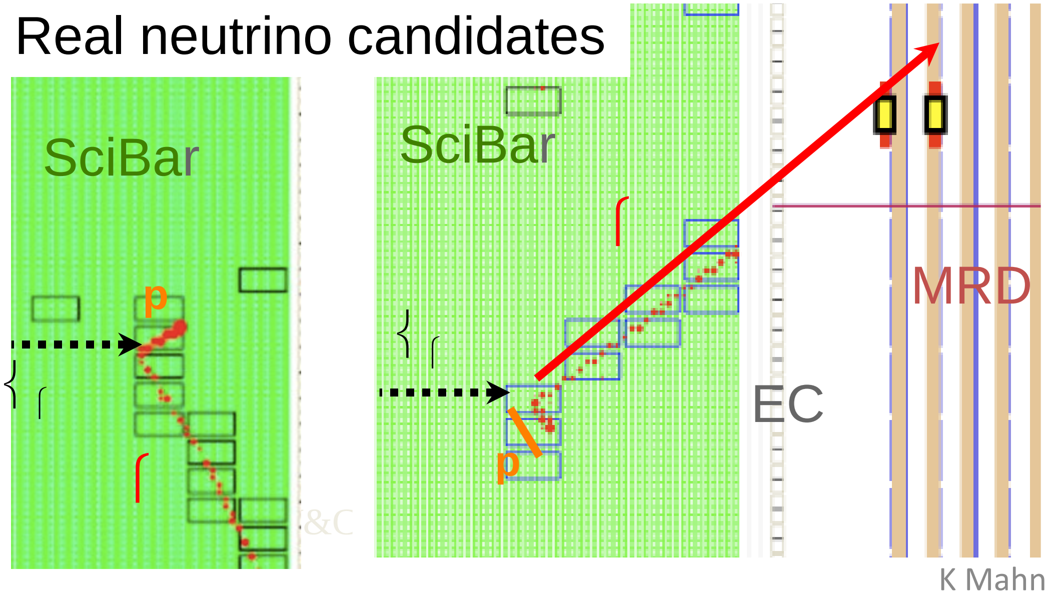
Selecting CC { ⌠ interactions in SciBooNE



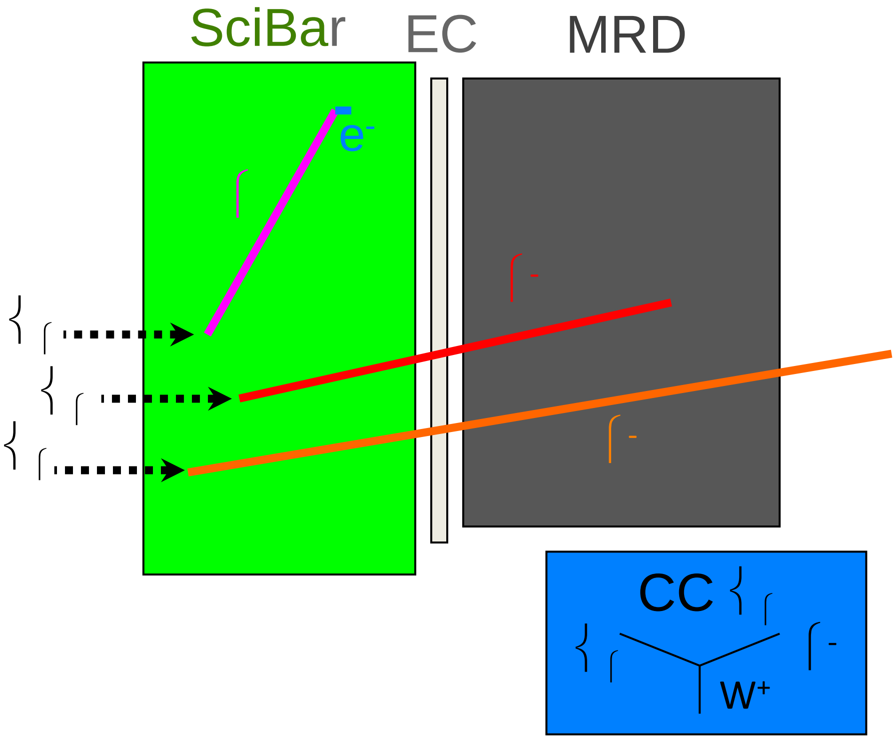
- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts

- "SciBar contained"
- No MRD matched track
- Muon-like determined from dE/dx with or without decay electron tag
- 1 track mu, 2 track mu+e samples use vertex activity (5x5 charge deposit around vertex)
- 2 track mu+p/pi uses dE/dx for proton, pion separation
- 2 track mu+p uses CCQE kinematic cut
- Total cross section provided in J. Walding thesis, backward going track data/MC discrepancies

Real neutrino candidates



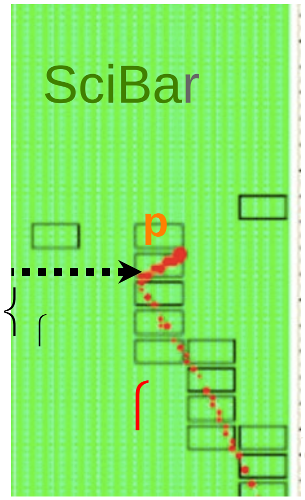
Selecting CC { ⌠ interactions in SciBooNE

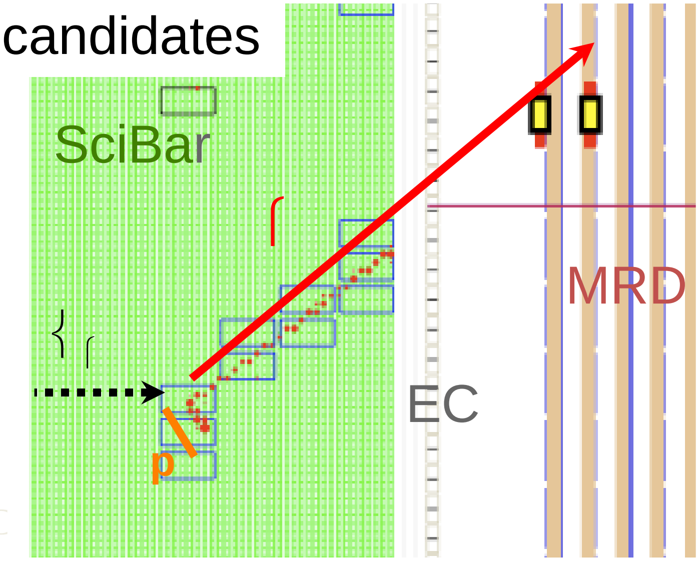


- Select events with the highest momentum track with a vertex in SciBar fiducial volume which pass data quality, beam timing cuts

- “MRD Stopped”
- 1 track “CCQE-like” (~13k, 66% pure)
- if 2 tracks associated to the same vertex, use dE/dx to separate into
- “mu+p” -> “CCQE like” (~3k, 69% pure)
- “mu+pi” -> “CCnon-QE like” used to constrain backgrounds (~1.5k)

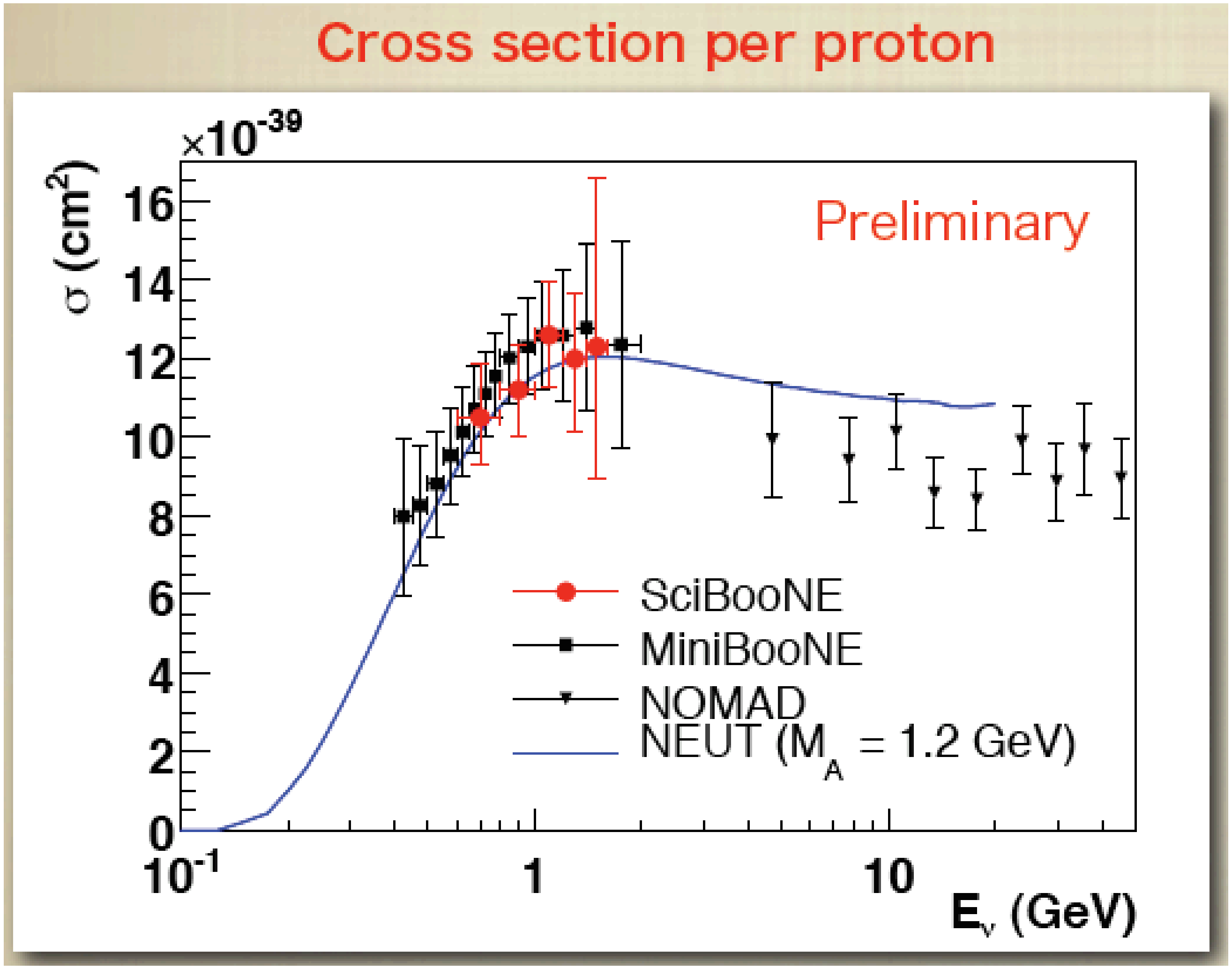
Real neutrino candidates





SciBooNE CCQE measurement

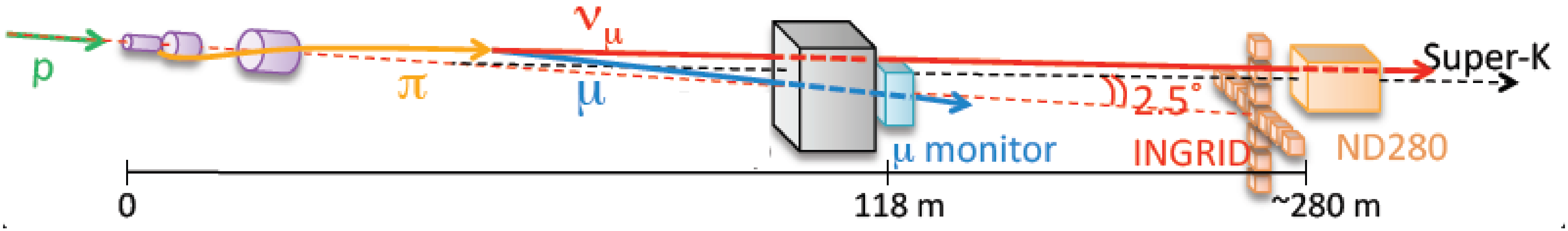
Y. Nakajima, NuInt11



- Fit pmu-thetamu distributions for normalizations in true Enu bins
- 2 track mu+pi sample included in fit for background
  - Nuisance parameter allows for 1->2track migration (from pion FSI)

characteristics of selected ν_μ QE events	SciBooNE values
QE event selection	1 muon or 1 muon + proton *(this selects CC events with no pions and any # of nucleons in the final state)*
Nuclear target	C_8H_8 *(polystyrene PPO(1%), POPOP(0.03%) coated with* TiO_2*)*
Neutrino flux range	$0.6 < E_\nu < 2$ GeV
Sign-selection?	no
Muon angular range	$0 < \theta_\mu < \sim 60^0$
Muon energy range	$0.2 < p_\mu < 1.2$ GeV/c
Proton detection threshold	The minimum reconstructed track length is 8 cm (3 layers), 450 MeV/c proton and 100 MeV/c muon energy thresholds.
How is E_ν determined?	Template fit *(reported* E_ν *is corrected back to true* E_ν *from RFG)*
How is Q^2 determined?	Not used in fit
Monte Carlo generator	NEUT (cross check with NUANCE) *Used 2 track mu+pi selection to tune nonQE fraction*
QE measurements & associated publications	$\sigma(E_\nu^{RFG})$: J. Luis Alcaraz Aunion thesis, NuInt2011 proceedings

T2K Neutrino flux prediction



FLUKA/Geant3 beam simulation

Phys. Rev. D 87, 012001 (2013)

- 3 horn focusing system
- 280m from target:
  - INGRID on-axis ND280 off-axis
- { ⌠ from π^+, K decay

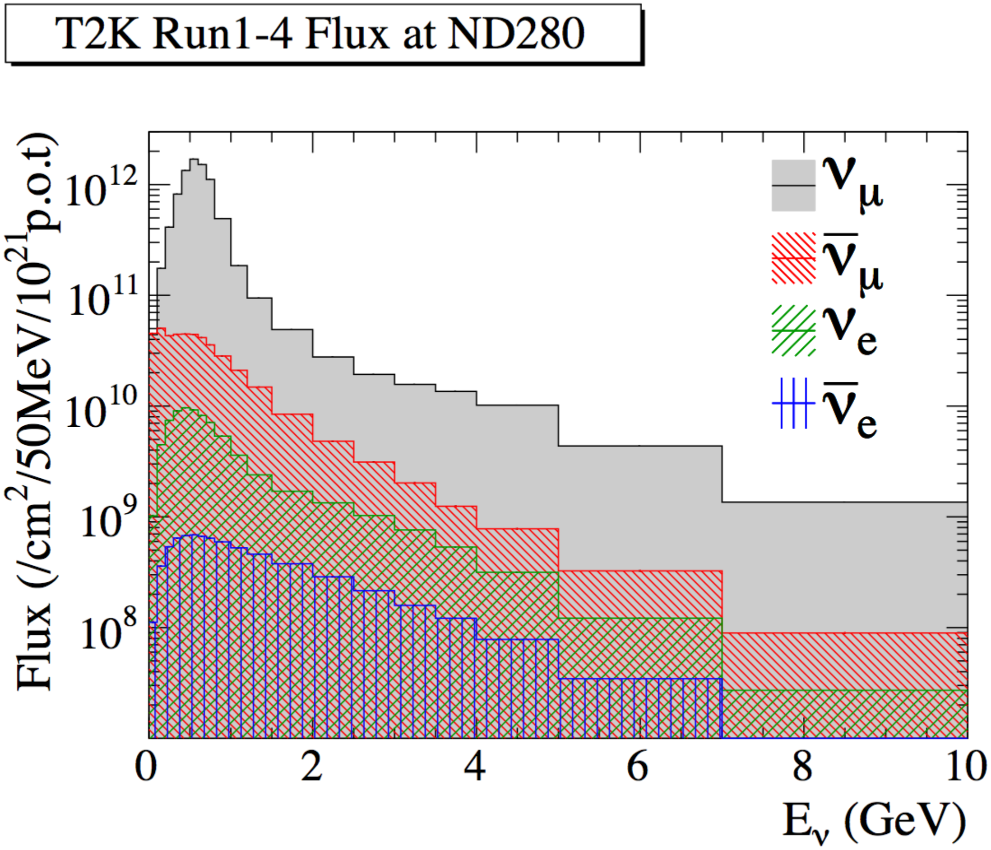
Prediction and uncertainties determined by external or in-situ measurements of:

- proton beam (30 GeV)
- π, K production from NA61 experiment

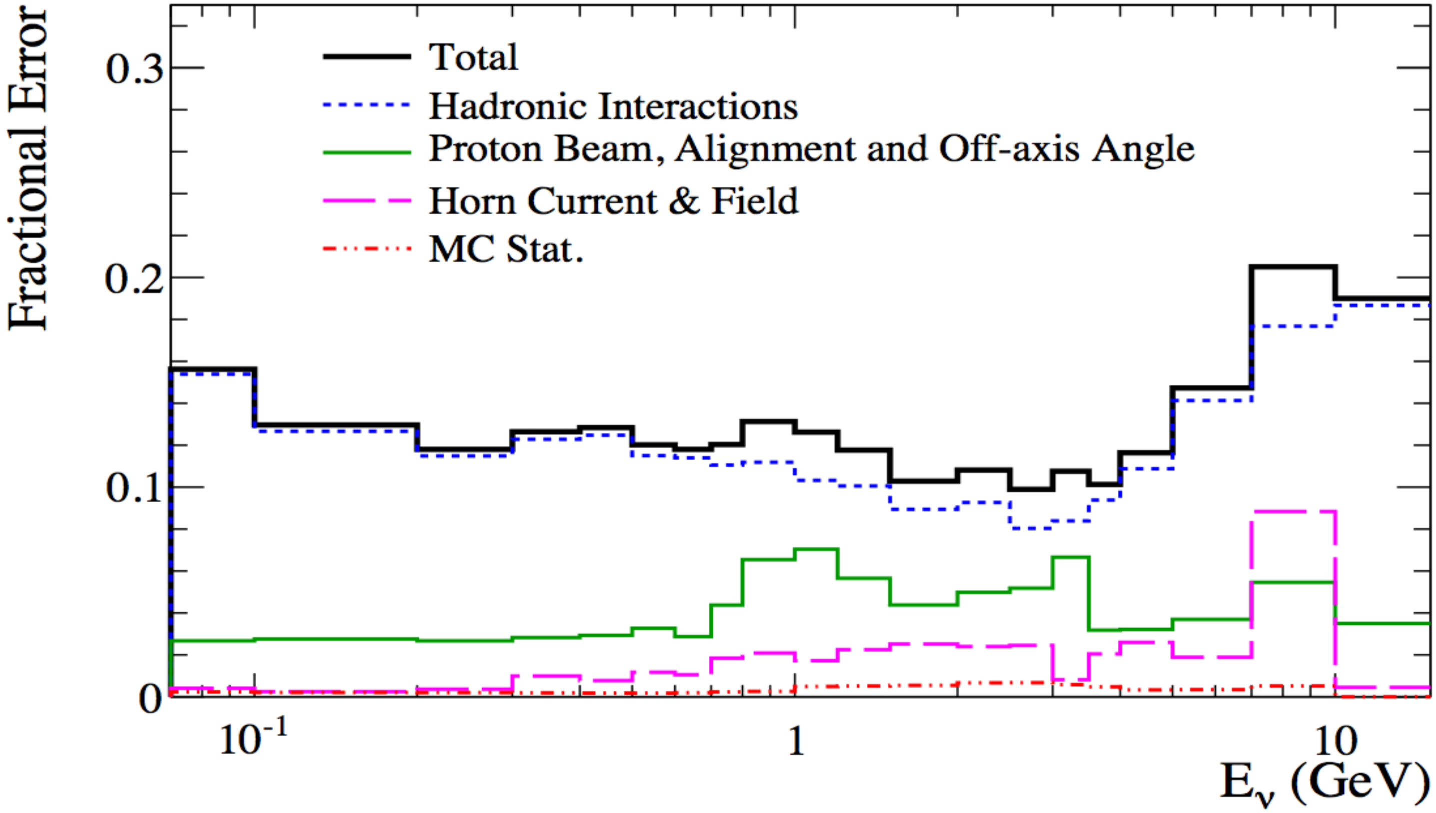
Phys.Rev.C 84, 034604 (2011)

Phys.Rev.C 85, 035210 (2012)

- alignment and off-axis angle



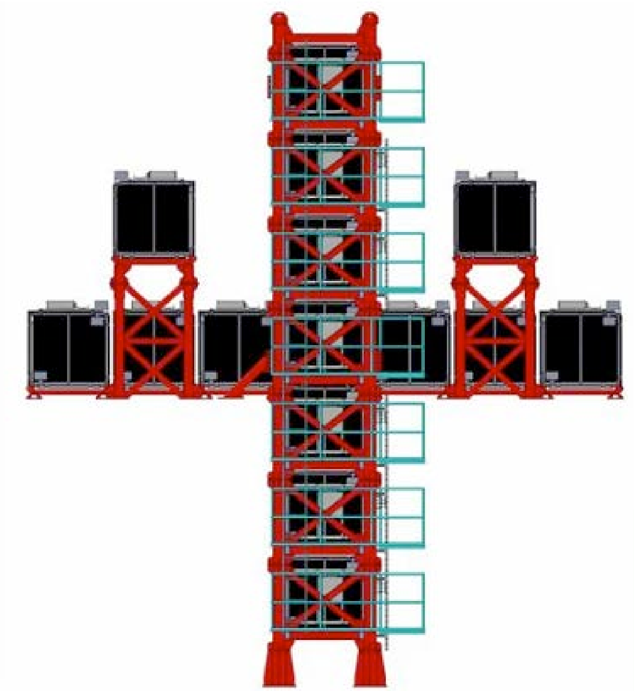
Summary of T2K flux uncertainties



These plots show the effect of the different systematic errors vs. neutrino energy

- Pion production and kaon production were substantially reduced thanks to NA61 data
- Proton beam, alignment and off-axis angle uncertainties are constrained from beam monitors, survey data and INGRID
- Secondary nucleon production (reinteractions of protons, pions within the target which compose ~30% of the flux) will be constrained with new thick target NA61 data

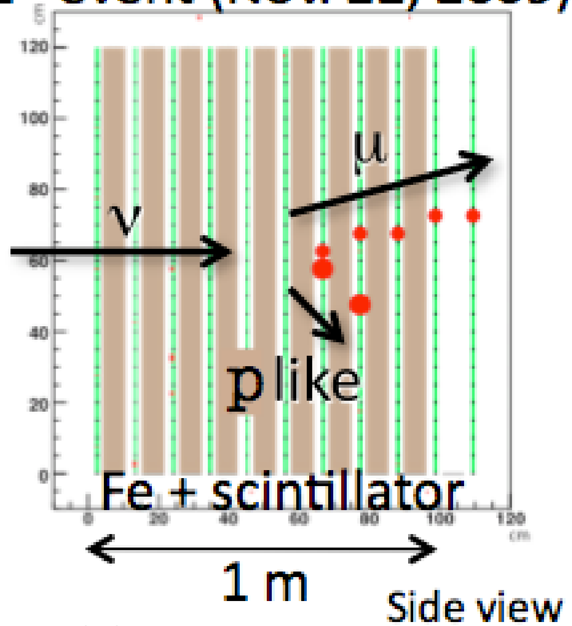
On-axis Interactive Neutrino GRID (INGRID)

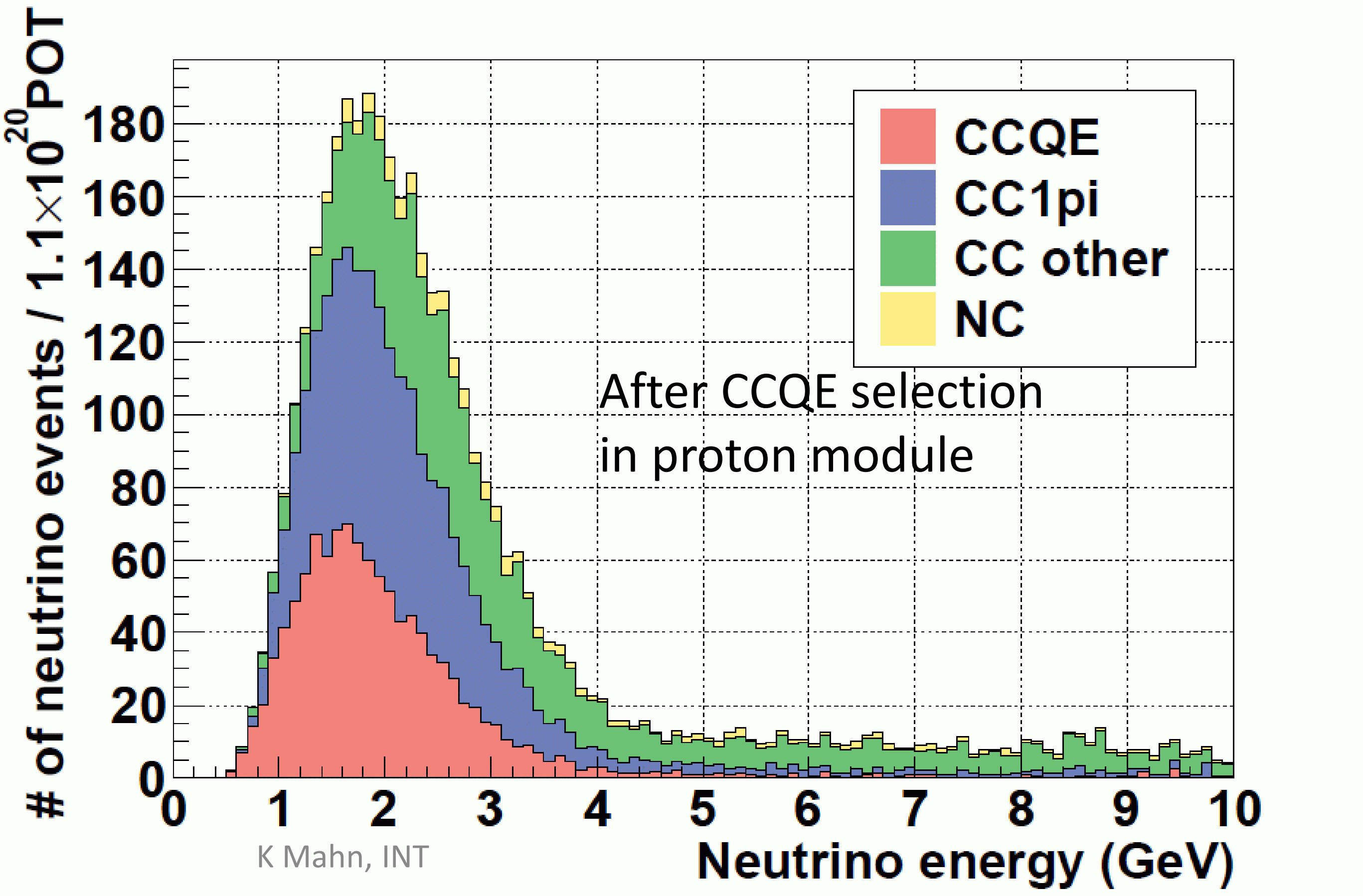


16+1 X-Y iron-scintillator modules arranged in a cross

- 7.1 tons iron / module
- Like SciBar: PPO 1%, POPOP 0.03% polystyrene
- 1cm x 5cm x ~120cm read out with WLS+MPPCs
- 1 "proton" module is all scintillator, located in the center
- Nucl.Instrum.Meth. A623 (2010) 368-370

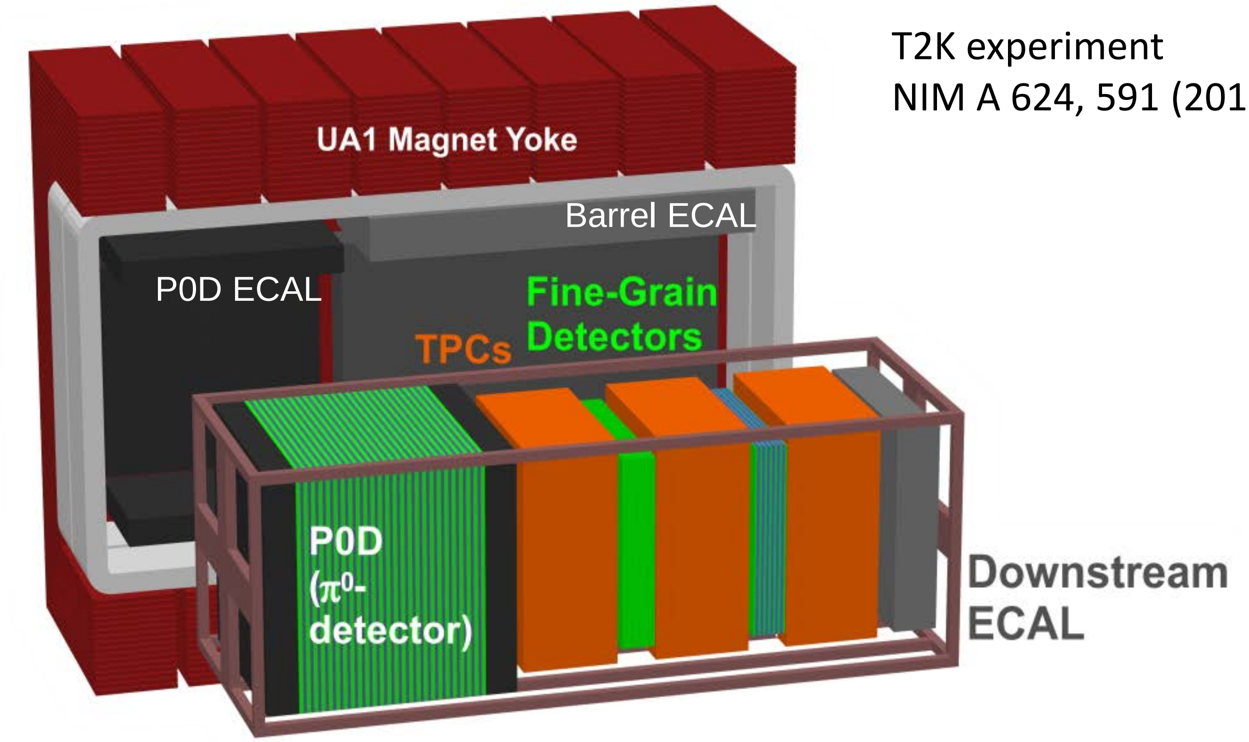
1st event (Nov. 22, 2009)





After CCQE selection in proton module

Off-axis near detectors (ND280)



T2K experiment
NIM A 624, 591 (2010)

All detectors located within 0.2T UA1 magnet

- 2 scintillator based tracking detectors (FGD) Nucl. Instrum. Meth. A 696, 1 (2012)
- 3 Ar - time projection chambers (TPC) NIM A 637, 25 (2011)
- P0D (triangular scintillator bars) Nucl. Instrum. Meth. A 686, 48 (2012))
- Electromagnetic calorimeters (ECALs JINST 8 P10019 (2013))
- Muon range detectors (scintillator in magnet, sMRD Nucl. Instrum. Meth. A 698, 135 (2013))

Selecting CC ½$_{\mu}$ interactions

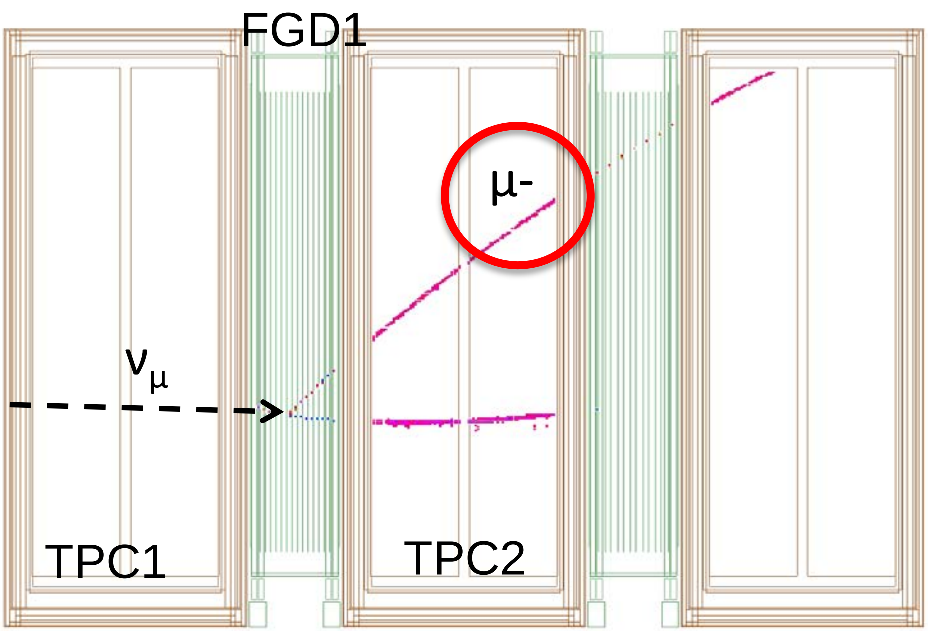
Measure unoscillated ⌠$_{⌠}$(CC) rate

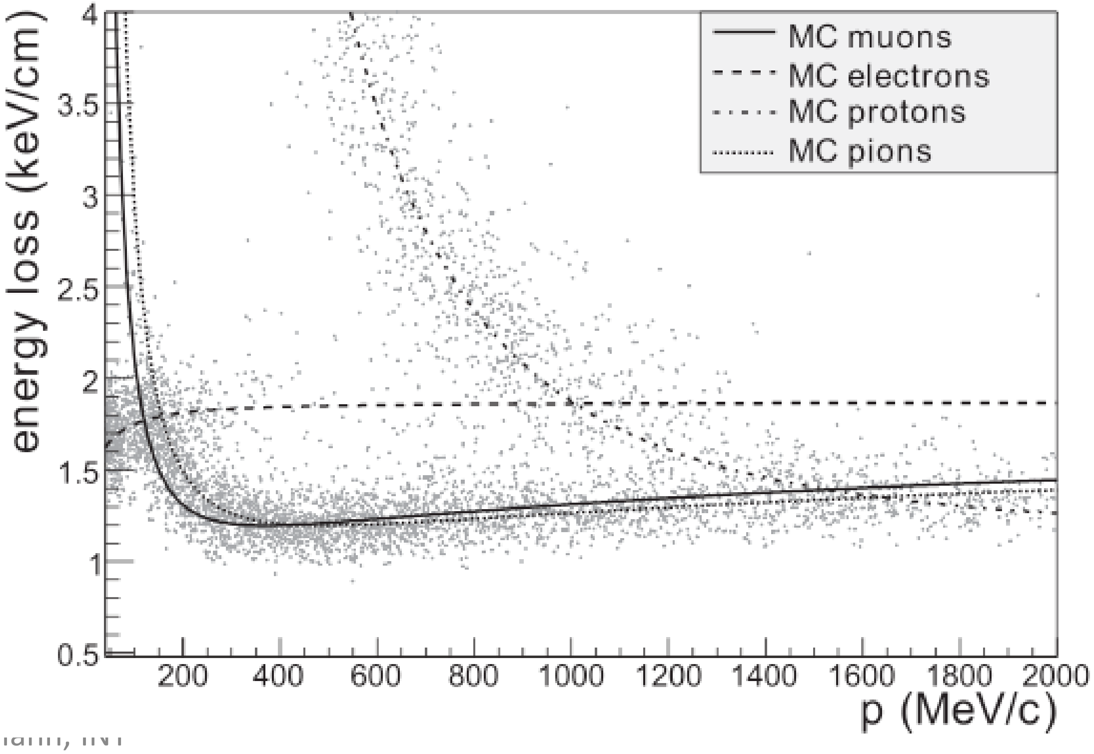
1. Neutrino interaction in FGD1

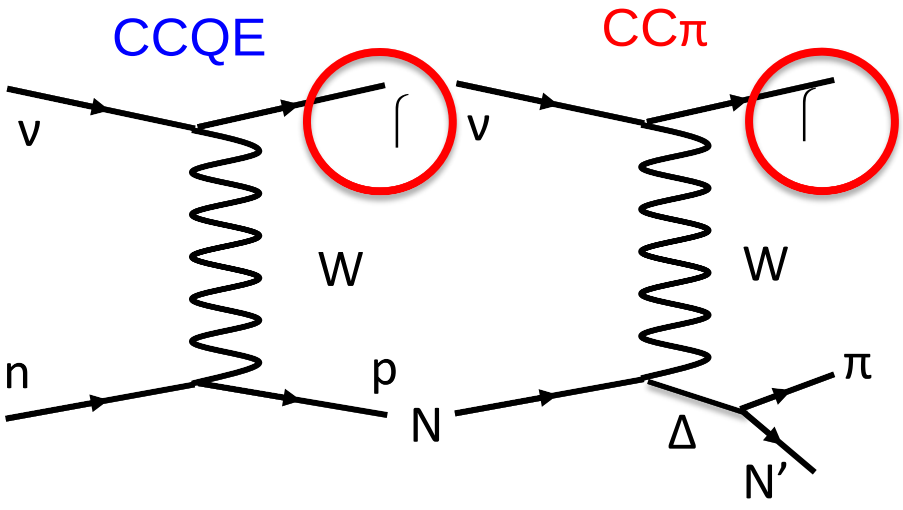
- Veto events with TPC1 tracks
- Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as μ$^-$ candidate

- Energy loss of the track in TPC also consistent with muon hypothesis







Selecting CCQE-enhanced ½$_{\mu}$ interactions

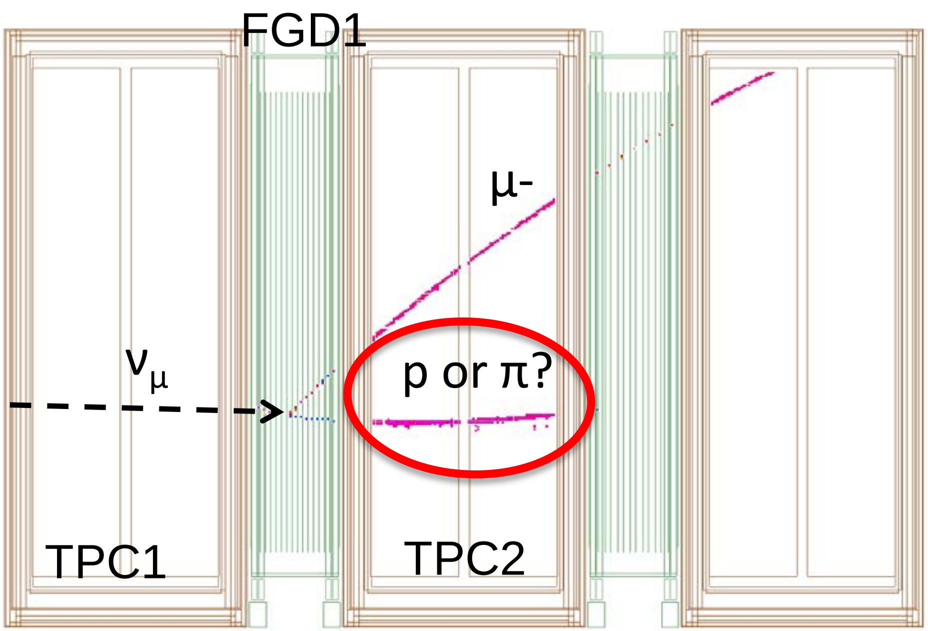
Measure unoscillated ⌠ ⌠(CC) rate

1. Neutrino interaction in FGD1

- Veto events with TPC1 tracks
- Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as μ^- candidate

- Energy loss of the track in TPC also consistent with muon hypothesis



Select CCQE enhanced based on final state:

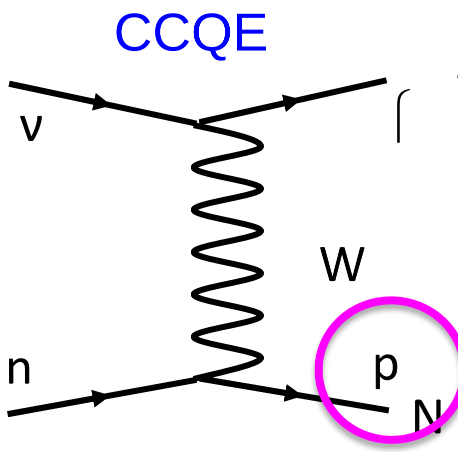
- 1 TPC-FGD matched track
- no decay electron in FGD1

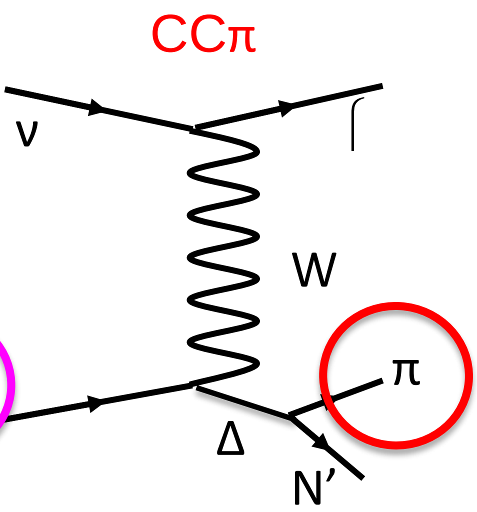
~6k events, efficiency: 40%, purity 72%

2.6 x 10^{20} POT (~5% of T2K goal POT)

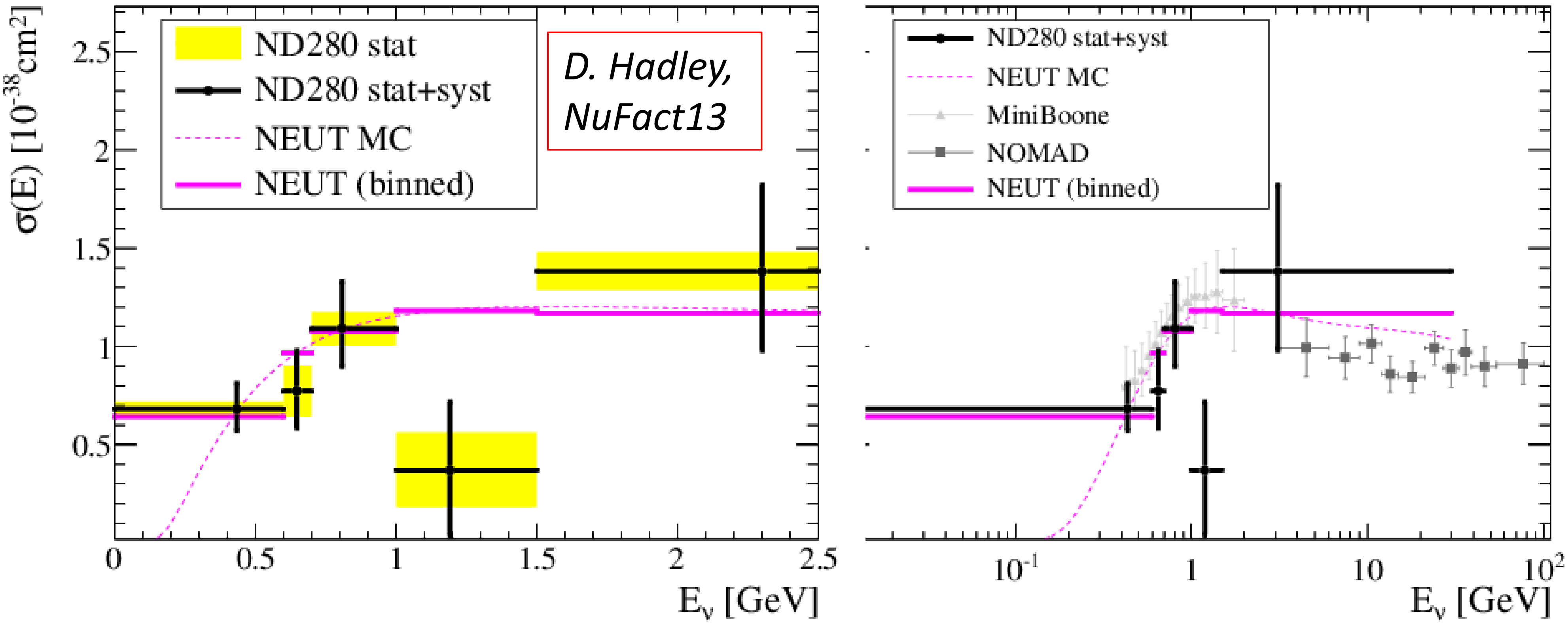
Selection details in:

Phys. Rev. D 88, 032002 (2013)





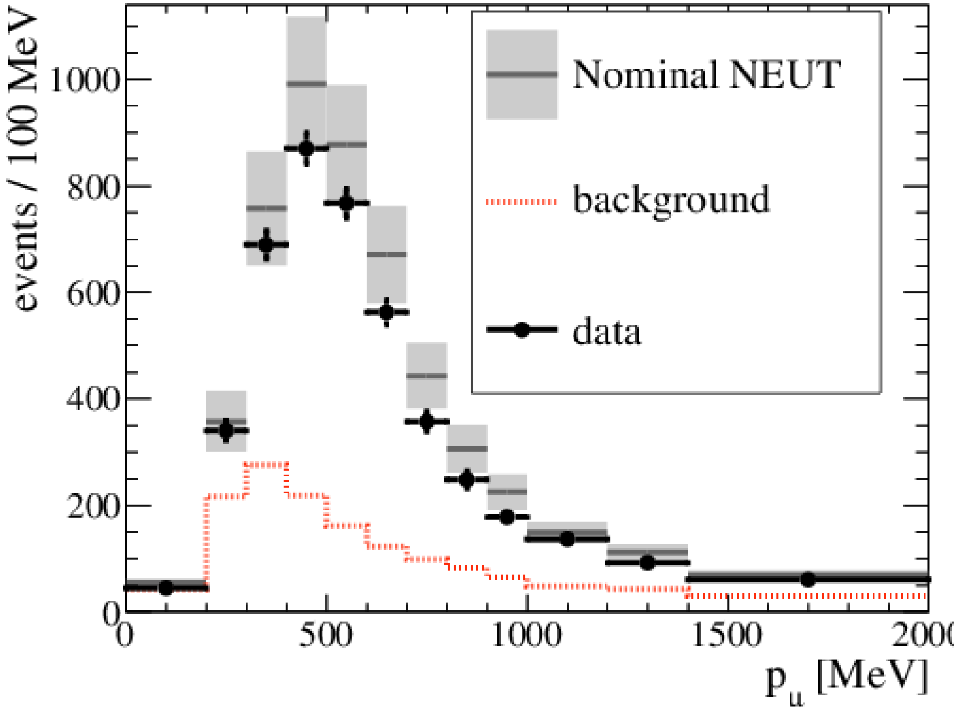
T2K CCQE result

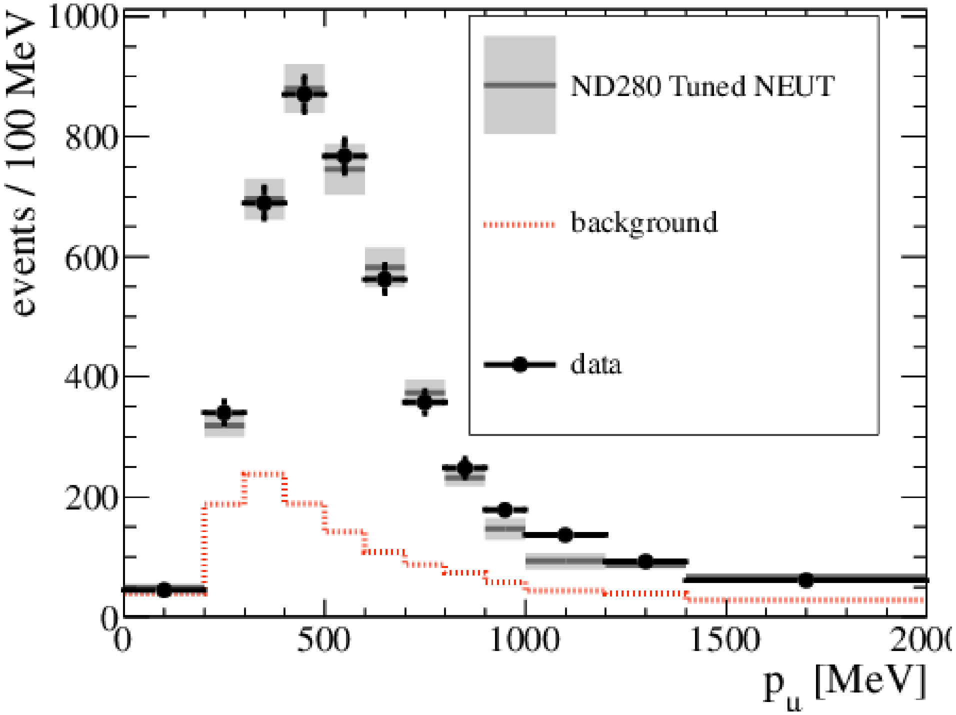


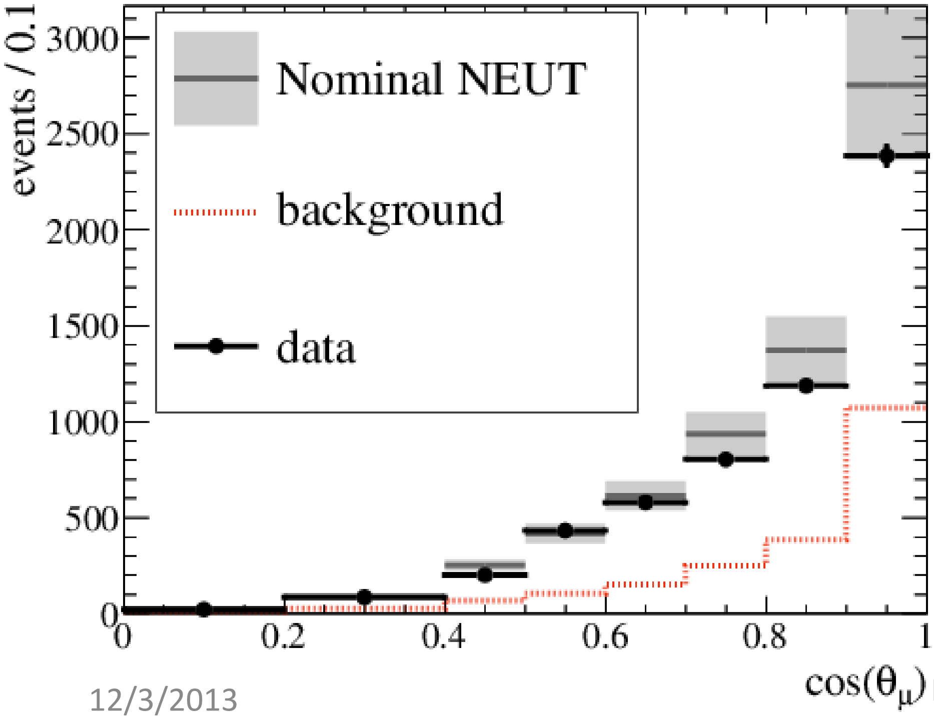
Template fit to p_μ-cos(θ_μ) distributions to determine CCQE cross section

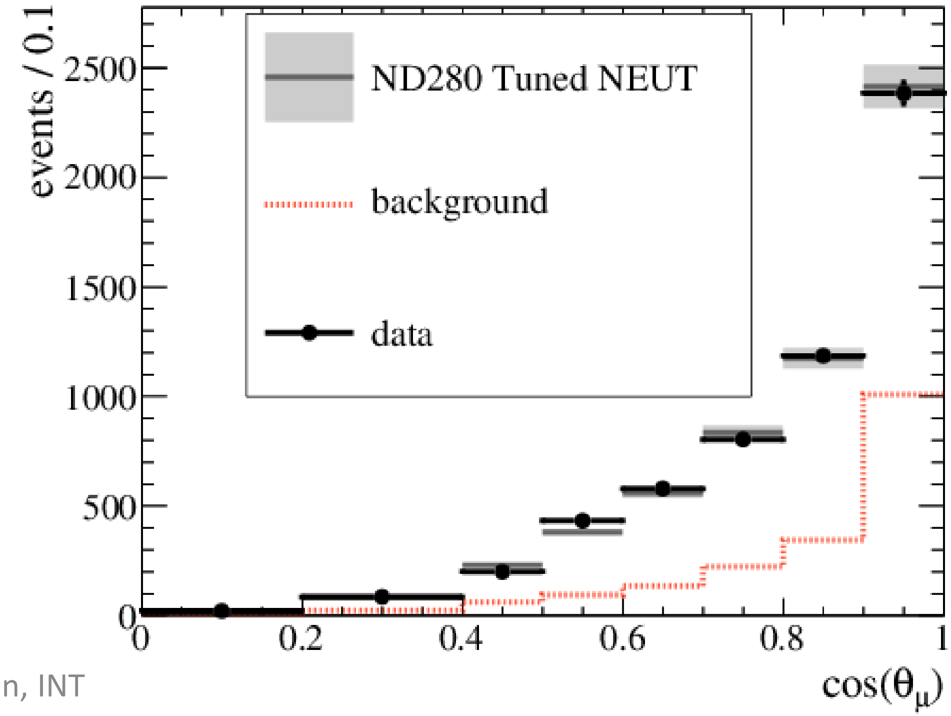
- Relationship from true muon kinematics to Ev set from RFG (nominal NEUT)
- Agreement with nominal NEUT MC
- 4th bin in the range 1.0-1.5GeV is 2.1 sigma low, X^2 test with pseudo experiments gives a p-value of 17%
- Result is similar when other CC inclusive events are used in the fit
- Result is similar when a multinucleon model is considered (Nieves et al)

T2K CCQE enhanced sample: p_μ/cos(¸)$_\mu$

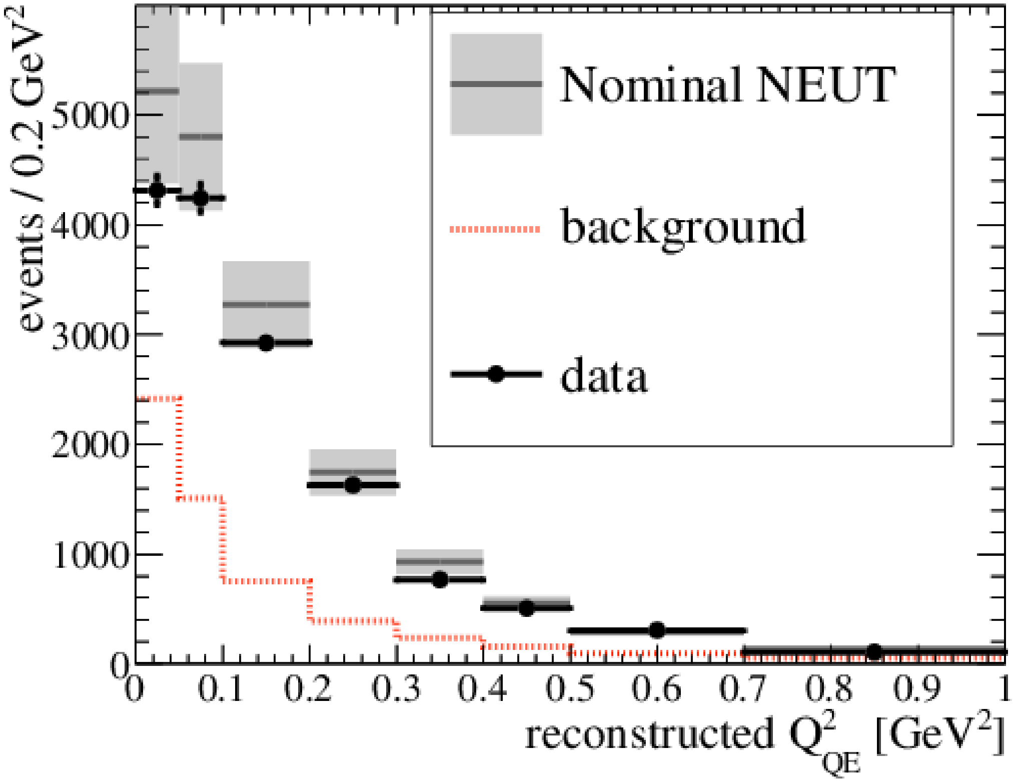


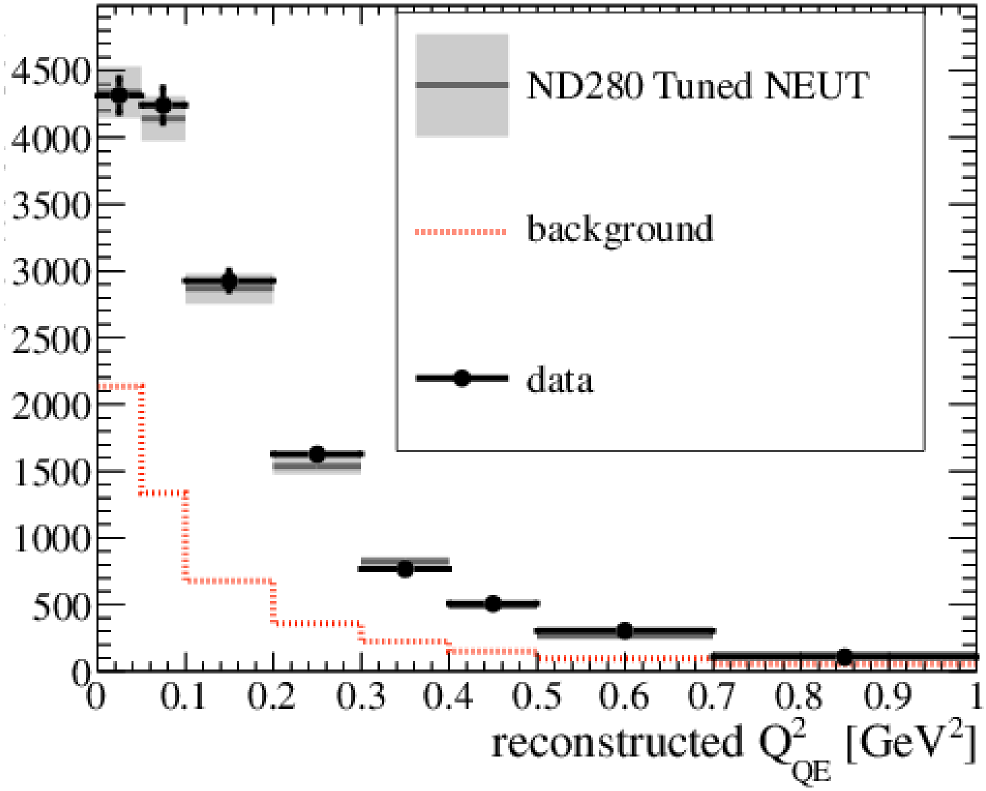






T2K CCQE enhanced sample: Q^2(QE)





Not used for fit

- Q^2(QE) according to MiniBooNE paper
  - see backup slides for definition
- Note not same scale on right and left (sorry!)

characteristics of selected ν_μ QE events	T2K values (2012 analysis)
QE event selection	1 mu-, no charged pi *using TPC track multiplicity, FGD1 decay electron tag*
Nuclear target (FGD)	C_8H_8 *(polystyrene PPO(1%), POPOP(0.03%) coated with* TiO_2*)*
Neutrino flux range	$0.2 < E_\nu < 30$ GeV
Sign-selection?	yes
Muon angular range	$0 < \theta_\mu < \sim 80^0$ *efficiency <5% above* 80^0
Muon energy range	$0 < p_\mu < 30$ GeV/c *At large momentum (>10 GeV?) difficult to determine momentum*
Proton detection threshold	N/A
How is E_ν determined?	Template fit to muon kinematics *(true m kinematics associated to true* E_ν *assuming RFG)*
How is Q^2 determined?	Not used in fit Projections provided vs. Q2(QE) according to MiniBooNE convention
Monte Carlo generator	NEUT *No tuning applied; cross check with inclusion of other CC inclusive events to constrain background*
QE measurements & associated publications	$\sigma(E_\nu^{RFG})$: NuFact2013 proceedings, publication in progress

Future T2K measurements

ND280: expanded selection capabilities with improvements to interdetector timing, reconstruction

- 2013: “CC0π” selection explicit tests on additional tracks for pions
  - using decay electron tag, π-p dE/dx in FGD and TPC
  - Electron-like TPC tracks identify π^0 (often from DIS events)
  - see backup slides
- 2014+: Backward going tracks, high angle tracks, ECAL photon information

Measurements (currently have ~10% of total POT for experiment taken)

- CCQE double differential measurement
- water and carbon targets (FGD2/P0D/INGRID proton module)
- Searches for multinucleon events using: high momentum protons, proton multiplicity, backward vs. forward going events, vertex activity
  - Need to consider multiple multinucleon models
- Comparisons to GENIE, NEUT (updated with a multinucleon model, spectral function)
- INGRID CC inclusive vs. E_ν using varying flux across detector

Backup slides

SciBooNE Reference material

The K2K SciBar detector : **Nucl.Instrum.Meth. A535 (2004) 147-151**

A Study of Charged Current Single Charged Pion Productions on Carbon in a Few-GeV Neutrino Beam - Hiraide, Katsuki FERMILAB-THESIS-2009-02
http://inspirehep.net/record/812790/files/

- "The Birk's constant for the SciBar scintillator is measured to be 0.0208+/-0.0023 cm/MeV [90], using a prototype of SciBar in a proton beam (Figure 5.6)." Ref 90 is: M. Hasegawa, Ph.D. thesis, Kyoto University (2006)

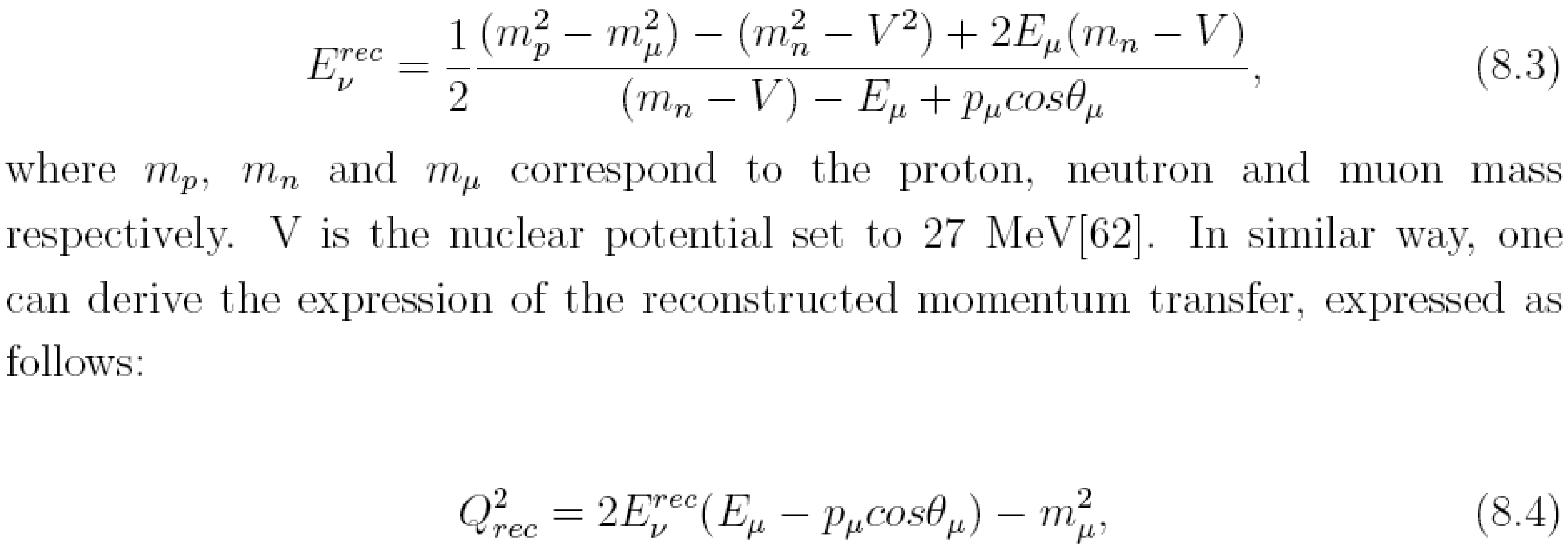
Measurement of the absolute ν_{μ}-CCQE cross section at the SciBooNE experiment - Aunion, Jose Luis Alcaraz FERMILAB-THESIS-2010-45
http://inspirehep.net/record/876786/files/

A sub-GeV charged-current quasi-elastic ν_{μ} cross-section on carbon at SciBooNE - Walding, Joseph James FERMILAB-THESIS-2009-57
http://inspirehep.net/record/855292/files/

Y. Nakajima NuINT2011 talk:
http://nuint11.in/final_nuint/cc%20quasi%20and%20nc%20elastic%20scattering/nakajima_nuint11.pdf

CC inclusive publication: Phys. Rev. D 83, 012005 (2011)

SciBooNE definitions for plots

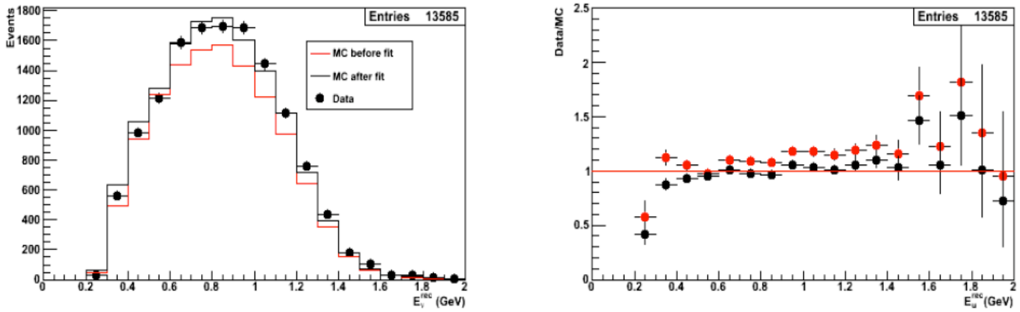


$$E_\nu^{rec} = \frac{1}{2}\frac{(m_p^2 - m_\mu^2) - (m_n^2 - V^2) + 2E_\mu(m_n - V)}{(m_n - V) - E_\mu + p_\mu cos\theta_\mu}, \tag{8.3}$$

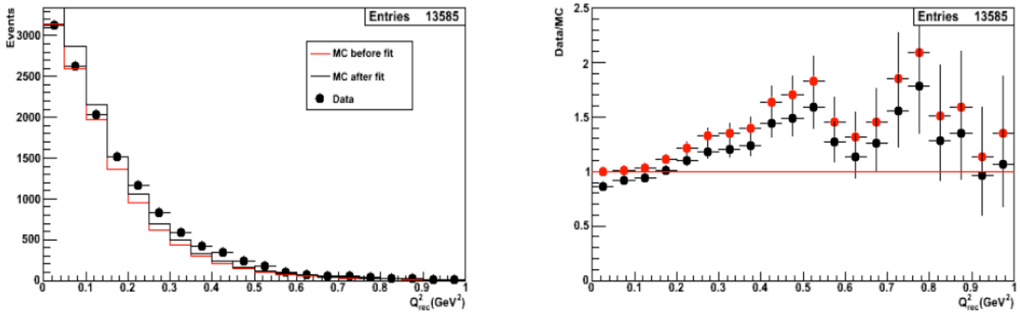
where m_p, m_n and m_μ correspond to the proton, neutron and muon mass respectively. V is the nuclear potential set to 27 MeV[62]. In similar way, one can derive the expression of the reconstructed momentum transfer, expressed as follows:

$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu cos\theta_\mu) - m_\mu^2, \tag{8.4}$$

SciBooNE 1 track selection

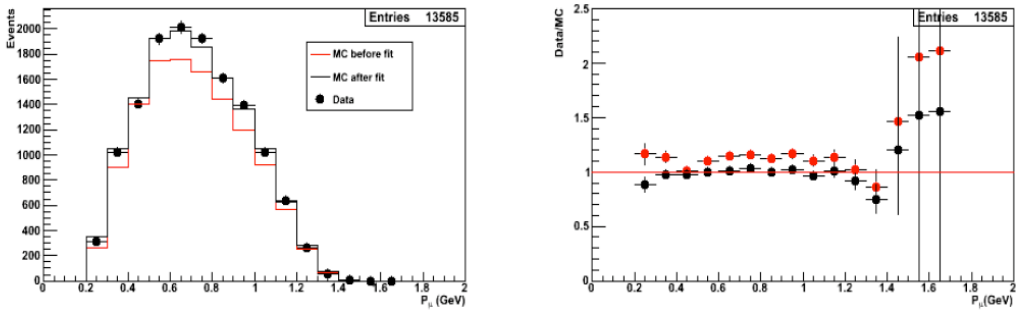


Enu(QE)

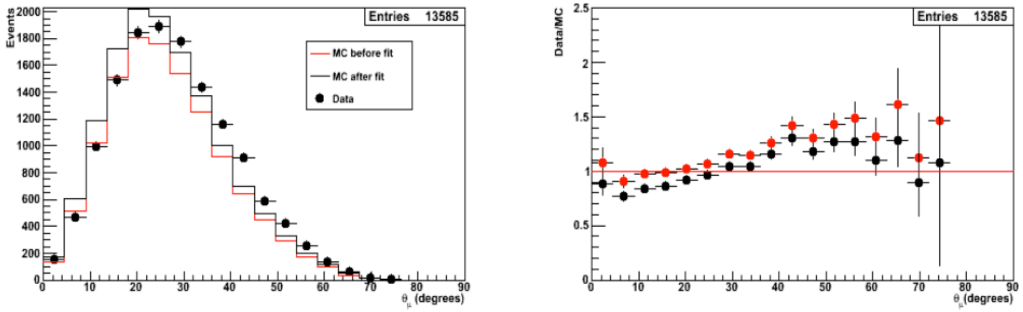


Q2(QE)

Postfit (black)
Prefit (red)

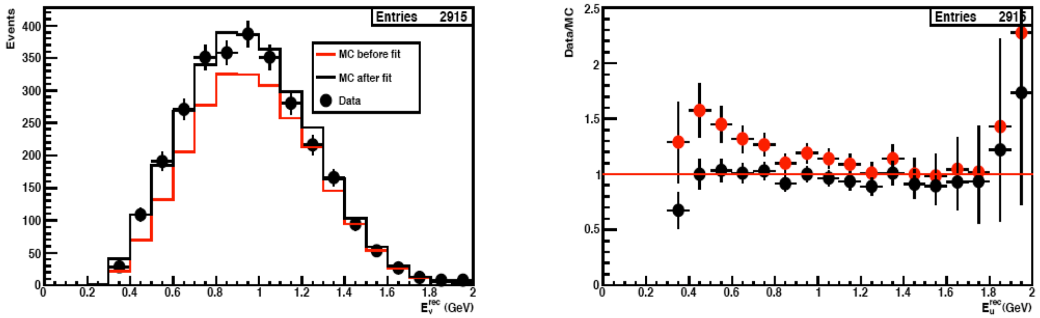


pmu

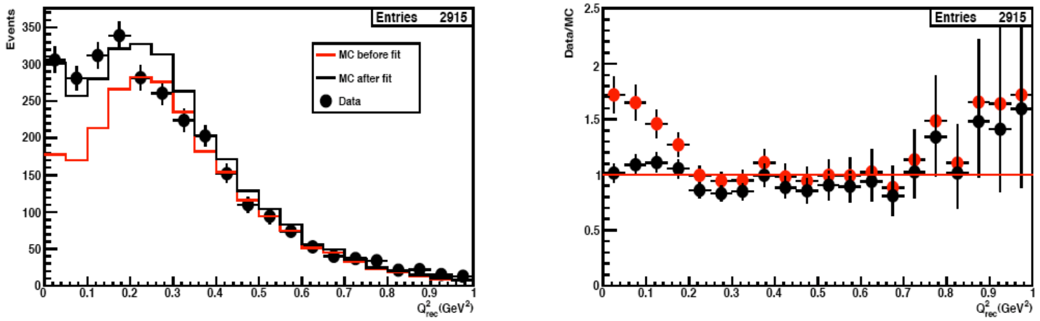


thetamu

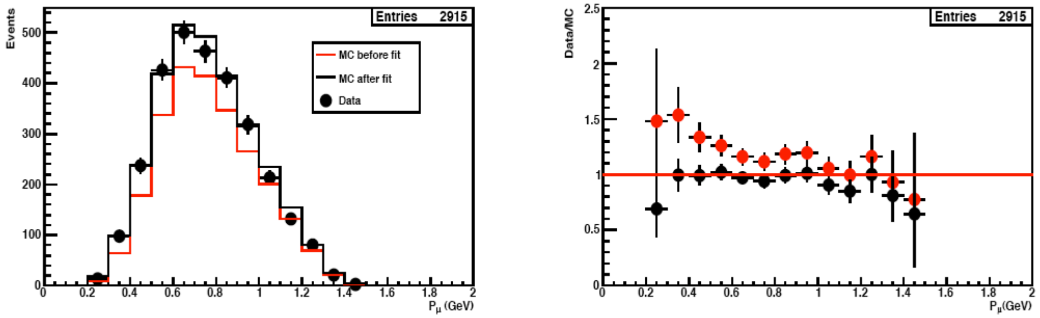
SciBooNE 2 track (mu+p, QE) selection



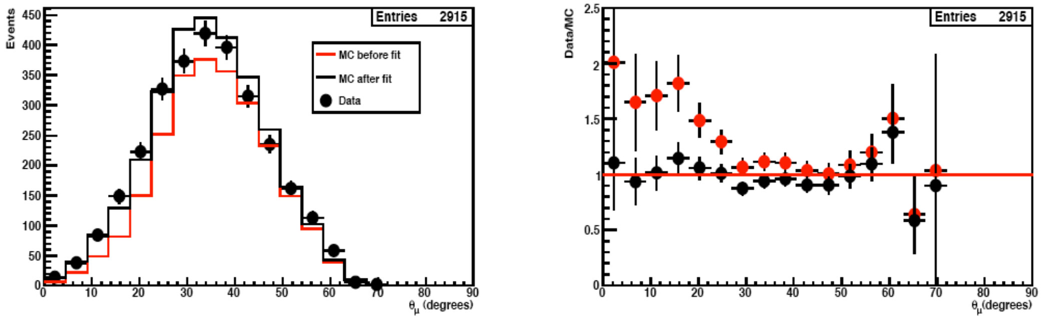
Enu(QE)



Q2(QE)



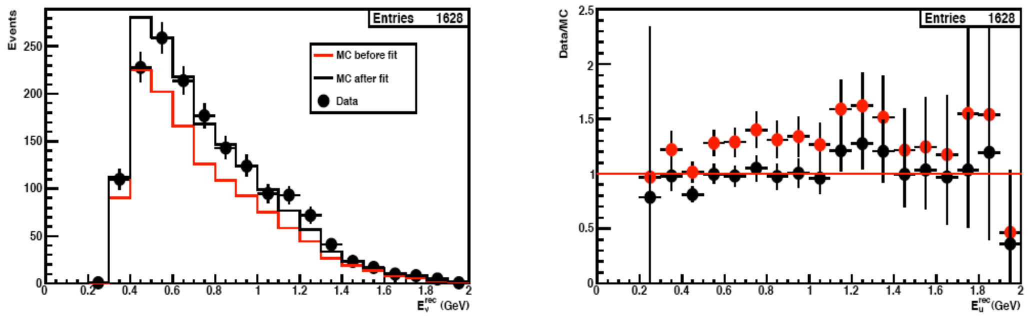
pmu



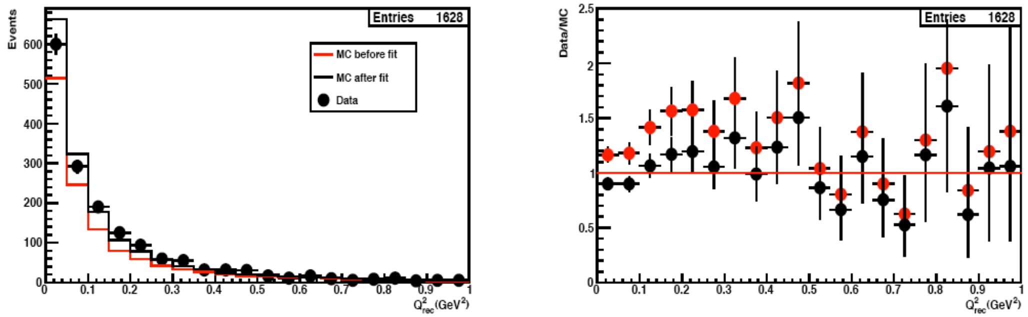
thetamu

Postfit (black)
Prefit (red)

SciBooNE 2 track (mu+pi, nonQE) selection



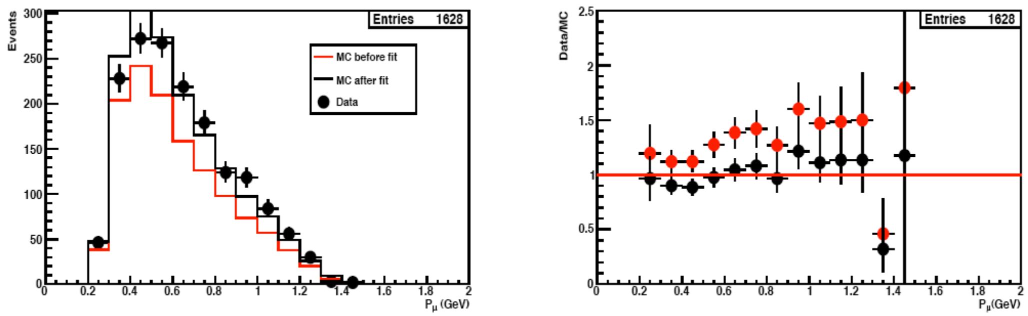
Enu(QE)



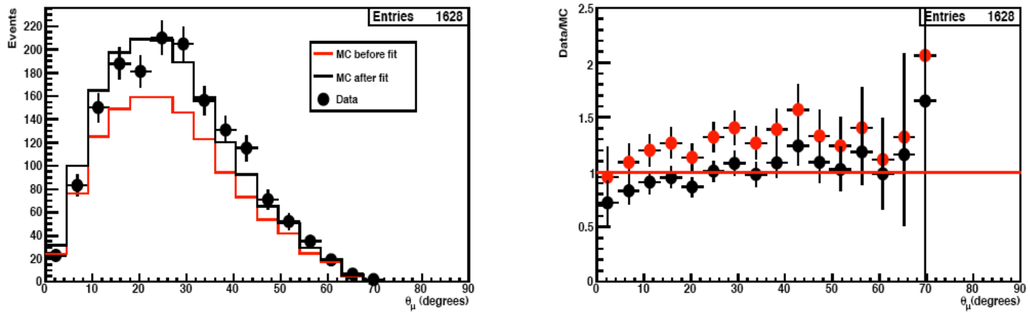
Q2(QE)

Postfit (black)

Prefit (red)

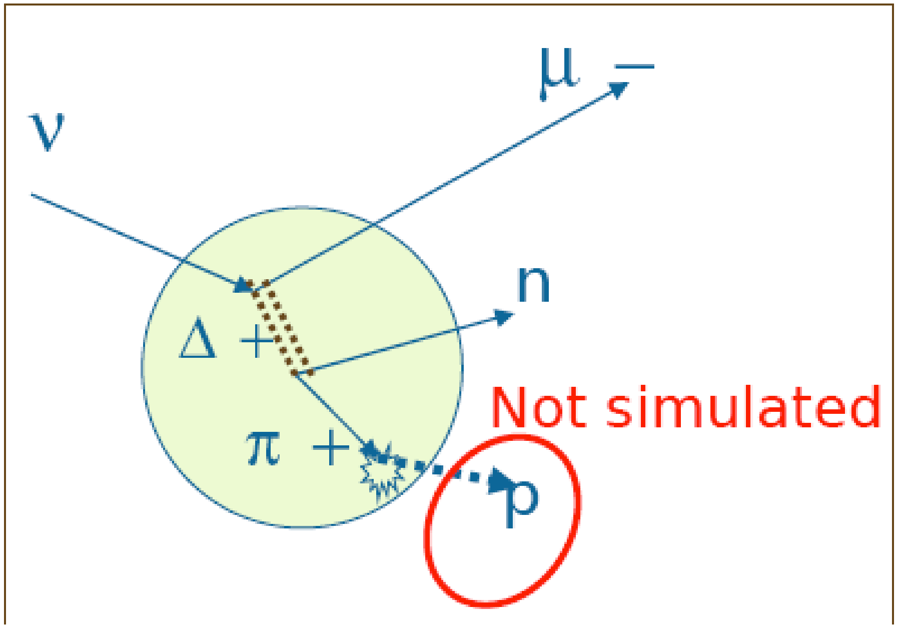


pmu



thetamu

SciBooNE 2 track (mu+pi, nonQE) selection

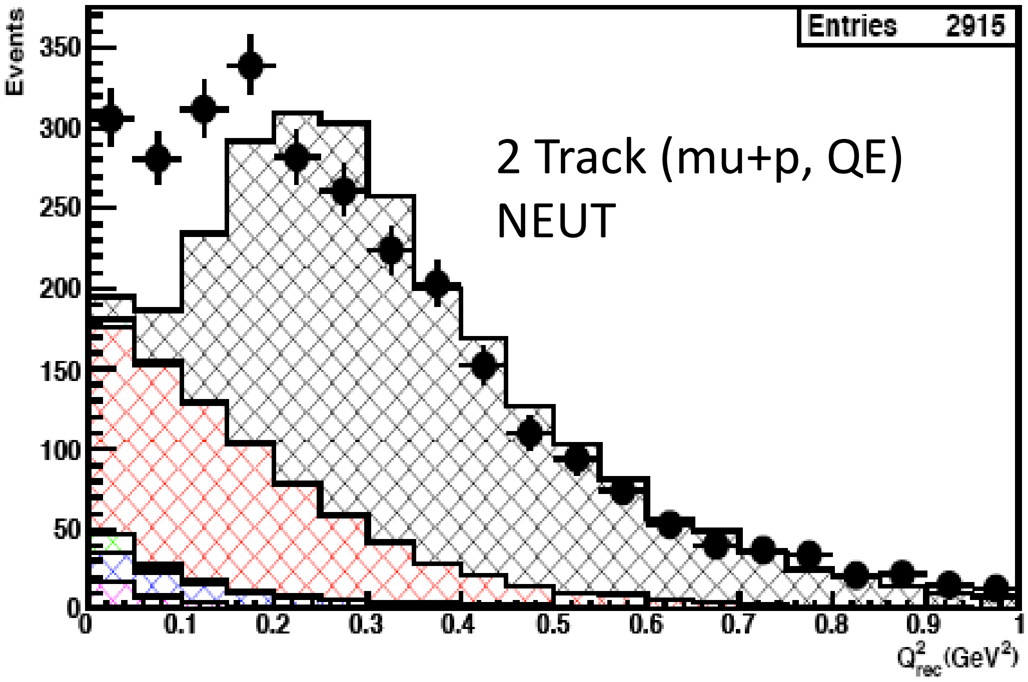


Not simulated

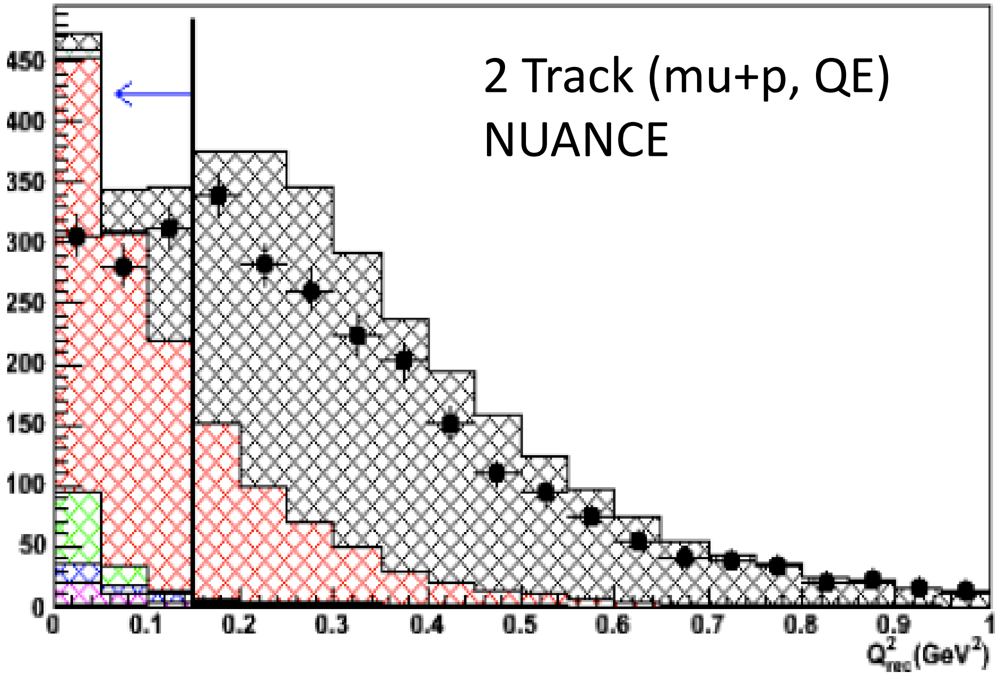
Protons out of CC1pi absorption not simulated in NEUT (and simulated in NUANCE)

These events contributed to low vertex activity

Should revisit with DUET/Piano data?



2 Track (mu+p, QE)
NEUT



2 Track (mu+p, QE)
NUANCE

T2K Reference material

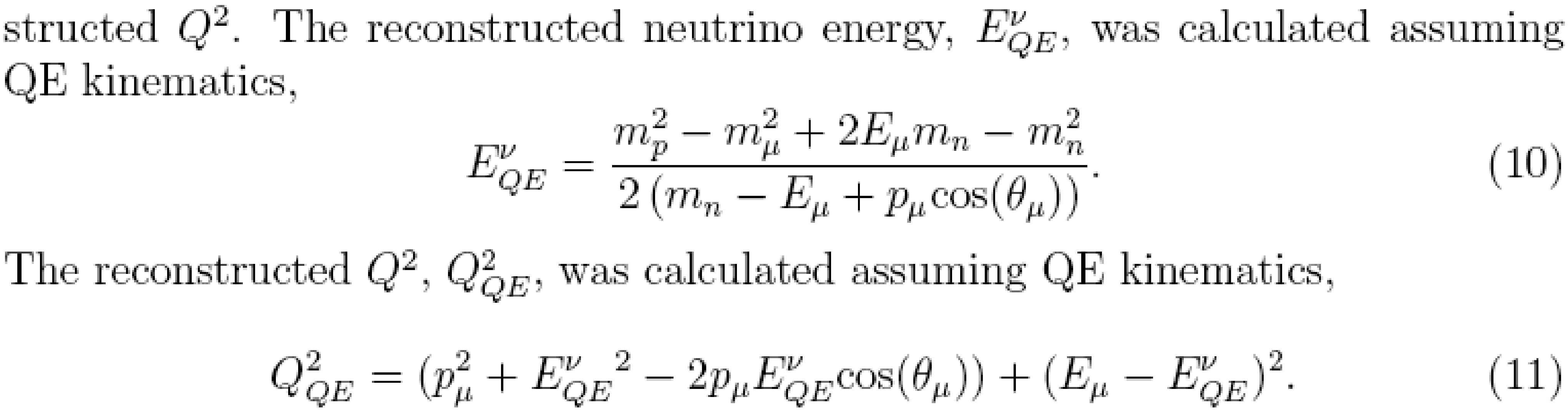
CCQE results (Dave Hadley @ NuFact2013)

- Talk: http://indico.ihep.ac.cn/getFile.py/access?contribId=138&sessionId=6&resId=0&materialId=slides&confId=2996
- Proceedings
- Selection information in 2012 nue oscillation analysis: Phys. Rev. D 88, 032002 (2013)

New selection in 2013 nue oscillation analysis: http://arxiv.org/abs/1311.4750

T2K flux information: http://t2k-experiment.org/publication_category/flux-predictions/

T2K definitions for plots



structed Q^2. The reconstructed neutrino energy, E^{ν}_{QE}, was calculated assuming QE kinematics,

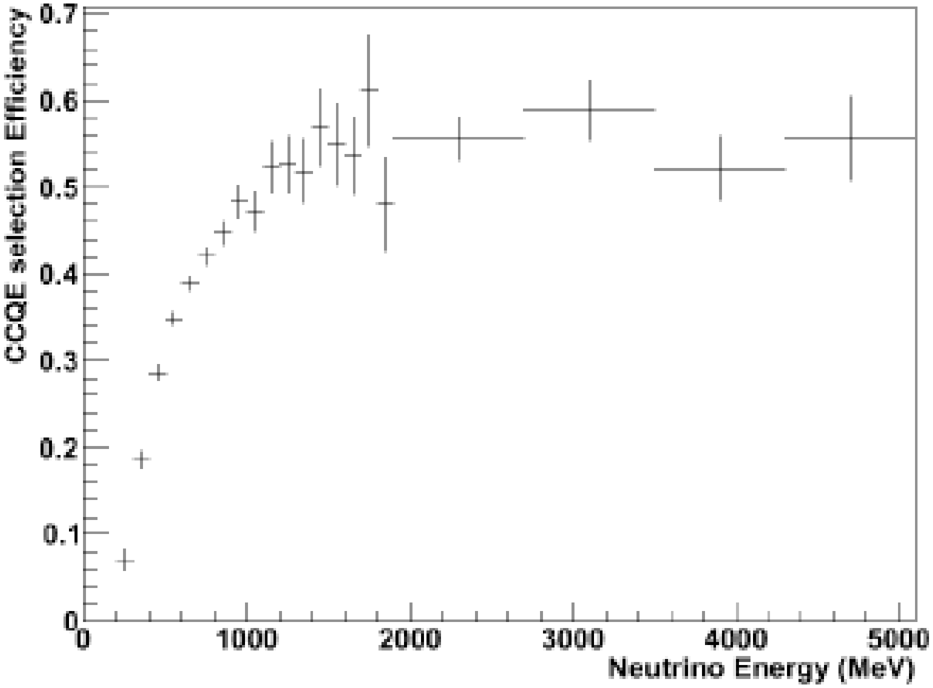
$$E^{\nu}_{QE} = \frac{m_p^2 - m_\mu^2 + 2E_\mu m_n - m_n^2}{2\left(m_n - E_\mu + p_\mu \cos(\theta_\mu)\right)}. \tag{10}$$

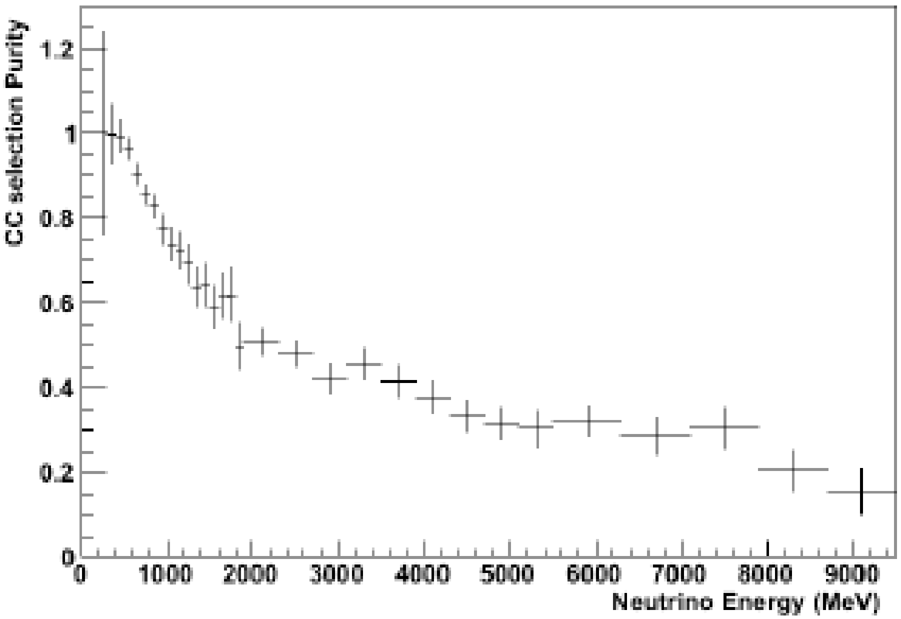
The reconstructed Q^2, Q^2_{QE}, was calculated assuming QE kinematics,

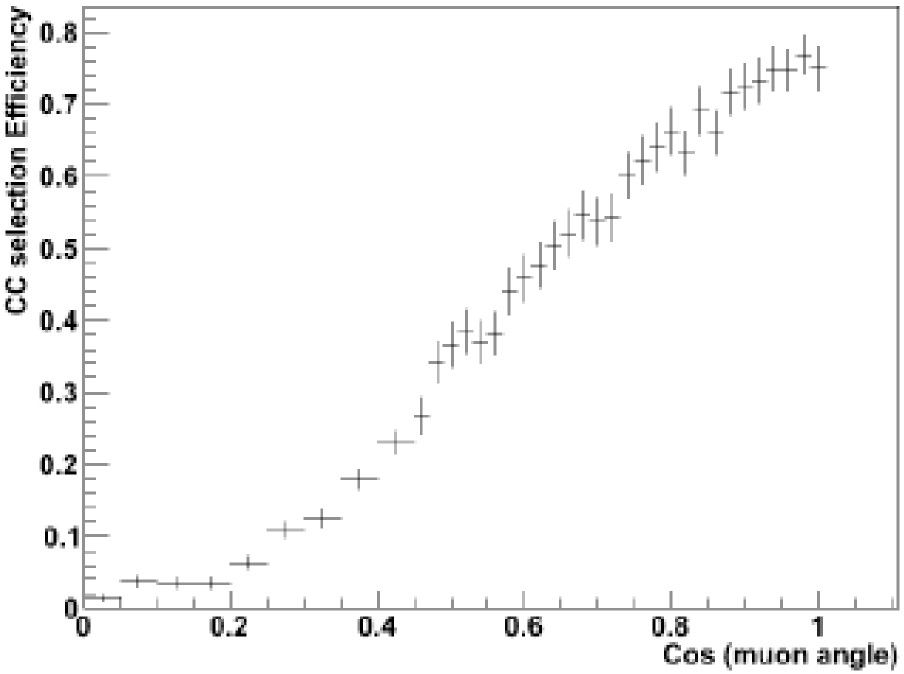
$$Q^2_{QE} = (p_\mu^2 + {E^{\nu}_{QE}}^2 - 2p_\mu E^{\nu}_{QE}\cos(\theta_\mu)) + (E_\mu - E^{\nu}_{QE})^2. \tag{11}$$

T2K CCQE analysis backups

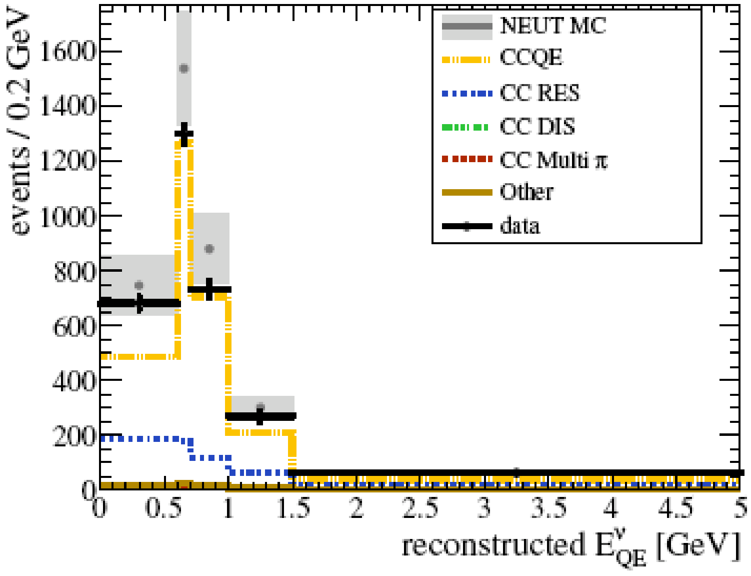
CCQE-enhanced efficiency, purity



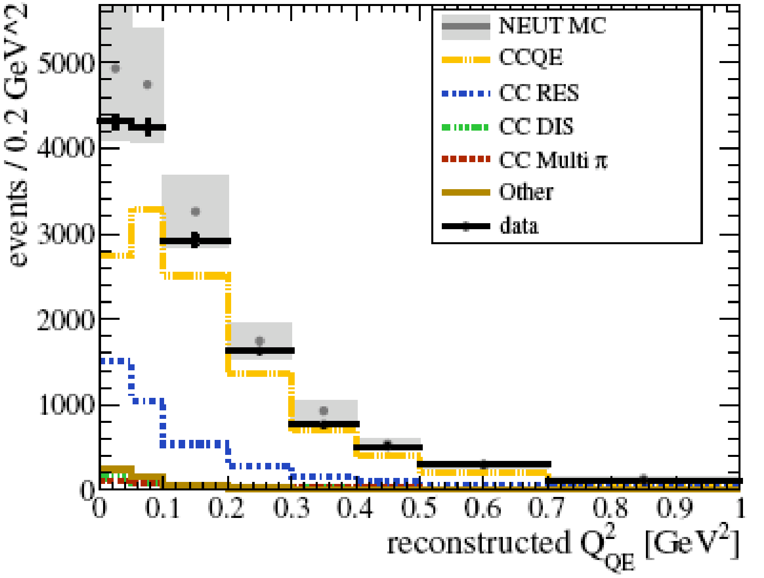




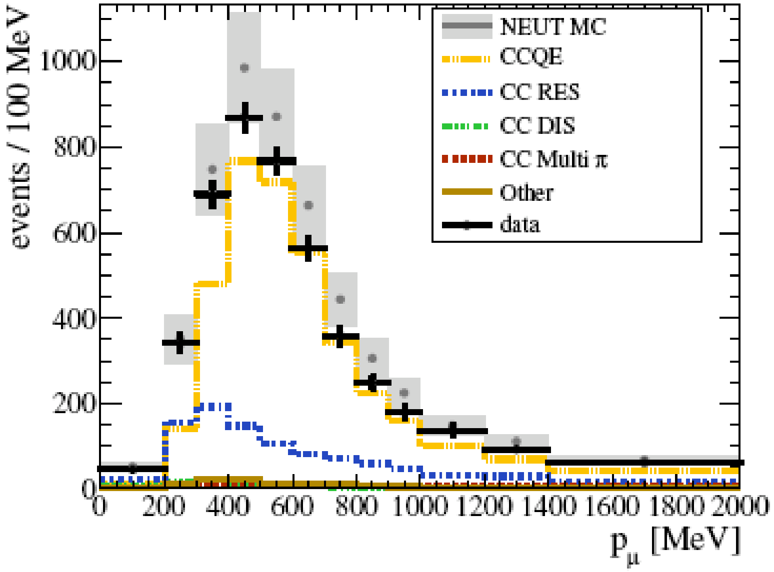
CCQE-enhanced distributions, prior to fit



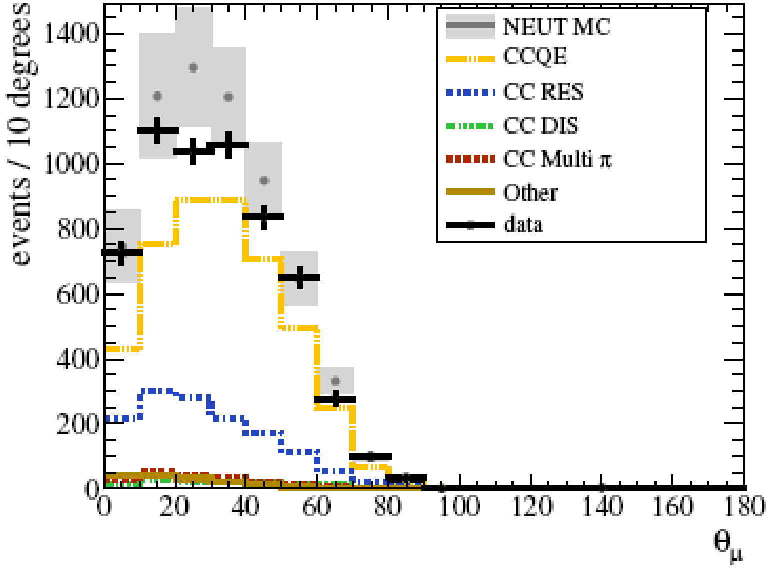
(a) Reconstructed E_ν



(b) Reconstructed Q^2_{QE}

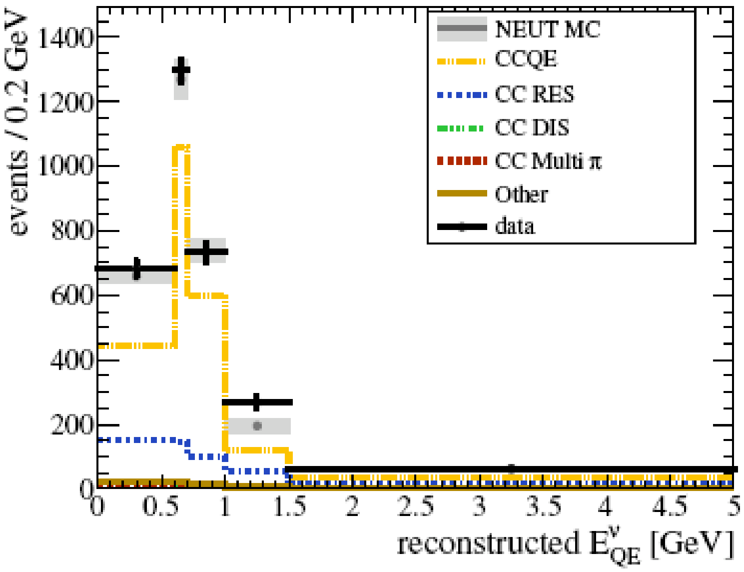


(c) Reconstructed p_μ

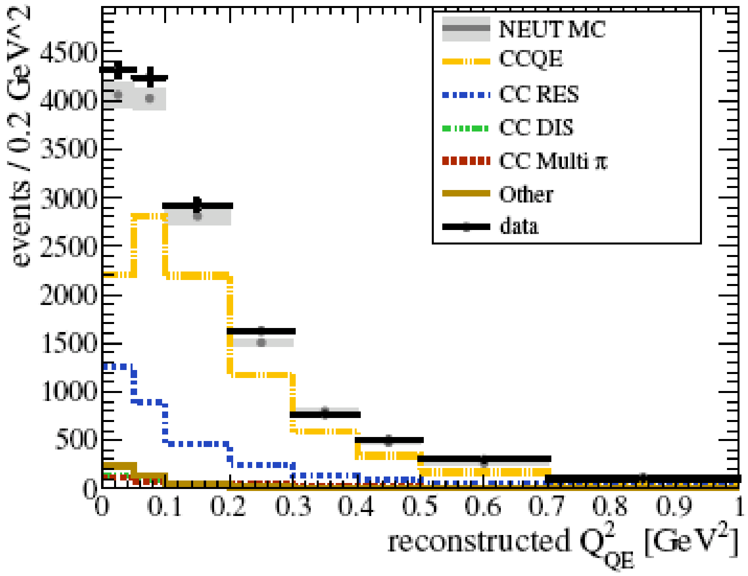


(d) Reconstructed θ_μ

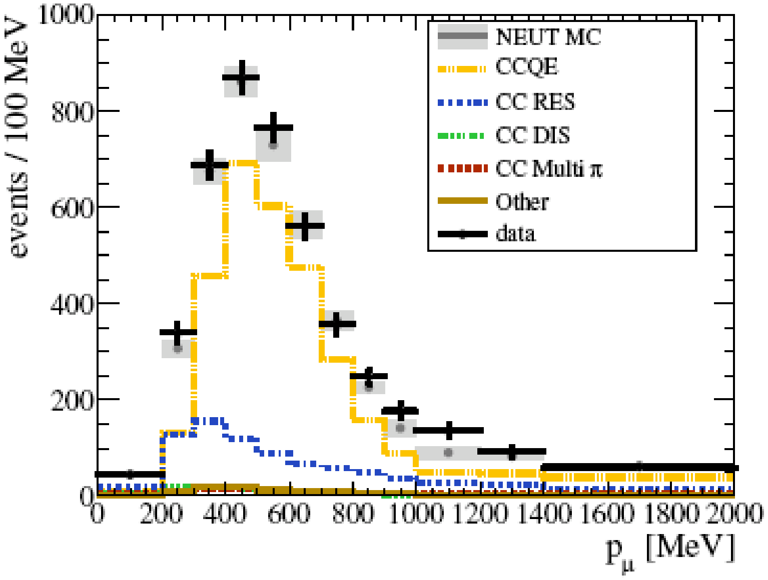
CCQE-enhanced distributions, after fit



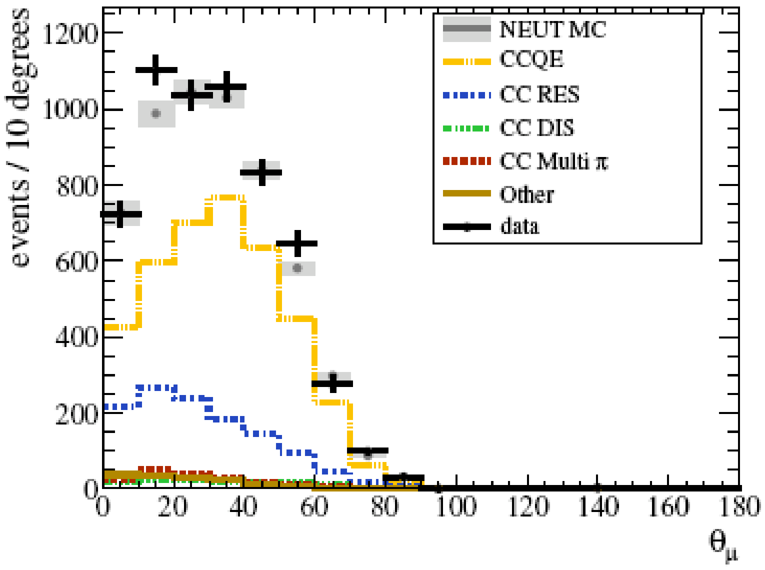
(a) Reconstructed E_ν



(b) Reconstructed Q^2_{QE}

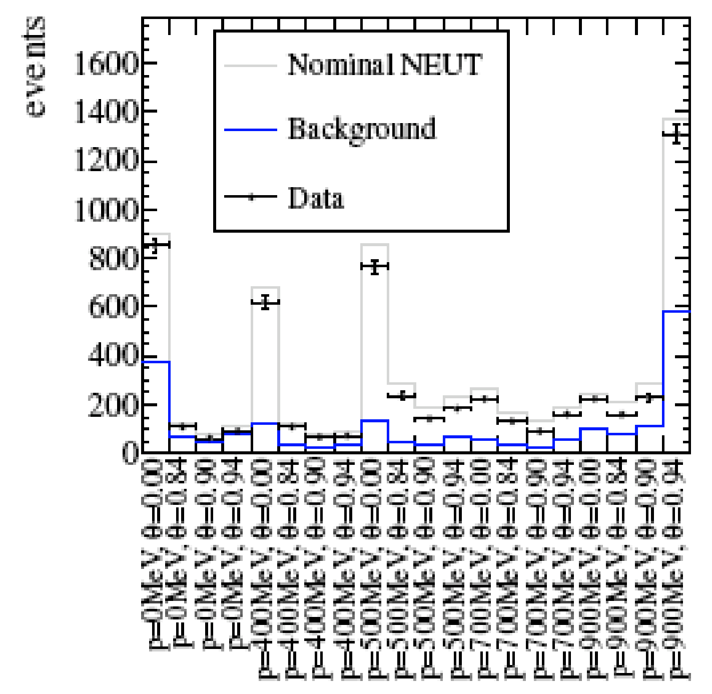


(c) Reconstructed p_μ



(d) Reconstructed θ_μ

Measurement of the CCQE Cross Section



The Log Likelihood Ratio is minimised,

$$
\begin{aligned}
-2\ln\lambda(\theta) = \quad & 2 \sum_{i=1}^{p_\mu - \cos(\theta_\mu)\mathrm{bins}} \Bigg[N_i^{\mathrm{predicted}}(\theta) - N_i^{\mathrm{observed}} \\
& + N_i^{\mathrm{observed}} \ln \frac{N_i^{\mathrm{observed}}}{N_i^{\mathrm{predicted}}(\theta)} \Bigg] \\
& + \ln \frac{\pi_d(\mathbf{d})}{\pi_d(\mathbf{d}_{\mathrm{nominal}})} \\
& + \ln \frac{\pi_f(\mathbf{f})}{\pi_f(\mathbf{f}_{\mathrm{nominal}})} \\
& + \ln \frac{\pi_x(\mathbf{x})}{\pi_x(\mathbf{x}_{\mathrm{nominal}})}
\end{aligned}
\tag{1}
$$

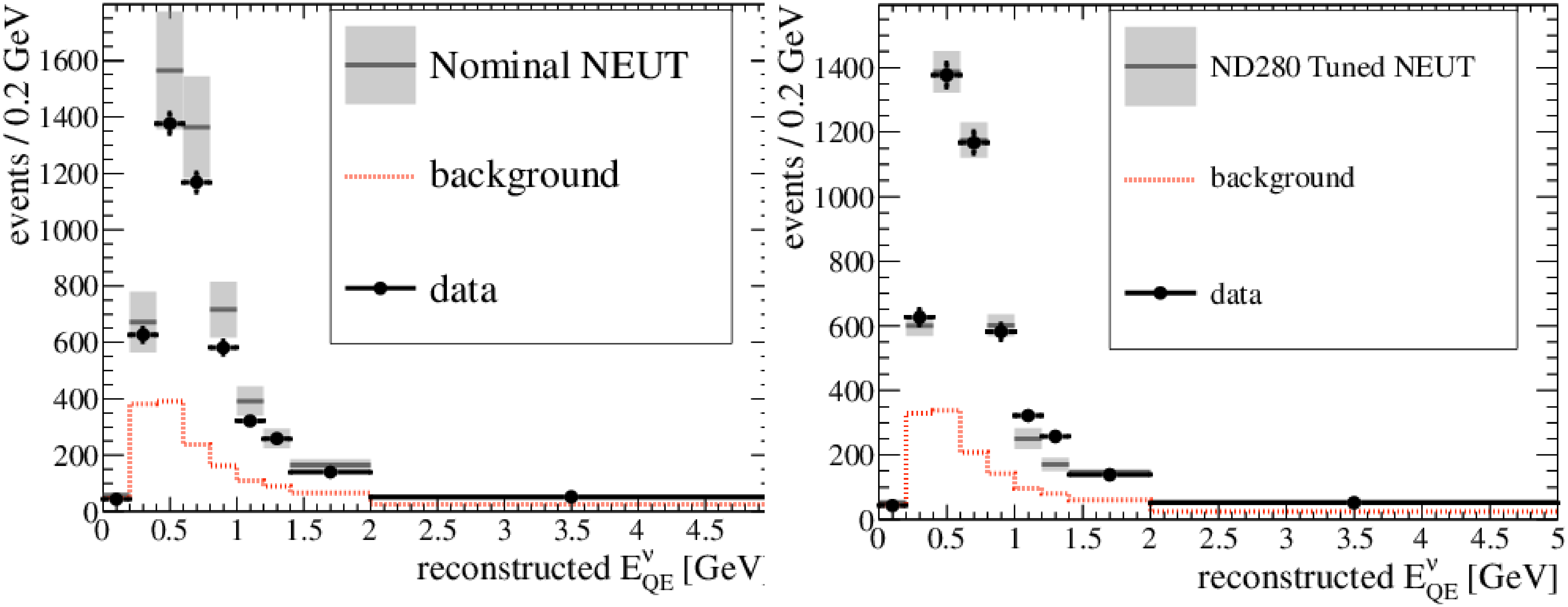
which includes,

- standard Poisson statistical terms
- penalty terms for the systematics

Analysis Method

- Simulated template histograms were fit to the observed $p_\mu - \cos(\theta_\mu)$ distribution.
- The CCQE cross section was extracted by weighting 5 template histograms in bins of E_ν.
- Systematic uncertainties were accounted for by varying bin contents with nuisance parameters.
- A maximum likelihood fit was used to find the best fit parameters.

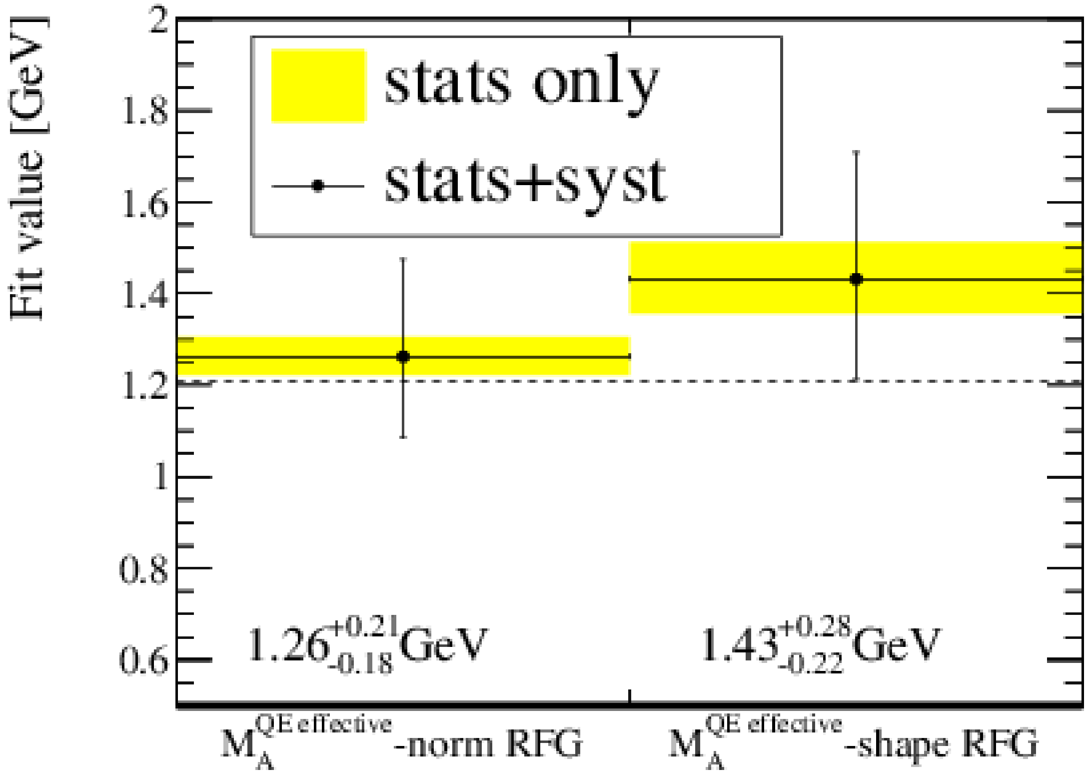
T2K CCQE enhanced sample: Enu(QE)



Not used for fit

- Enu(QE) according to MiniBooNE paper
- Note not same scale on right and left (sorry!)

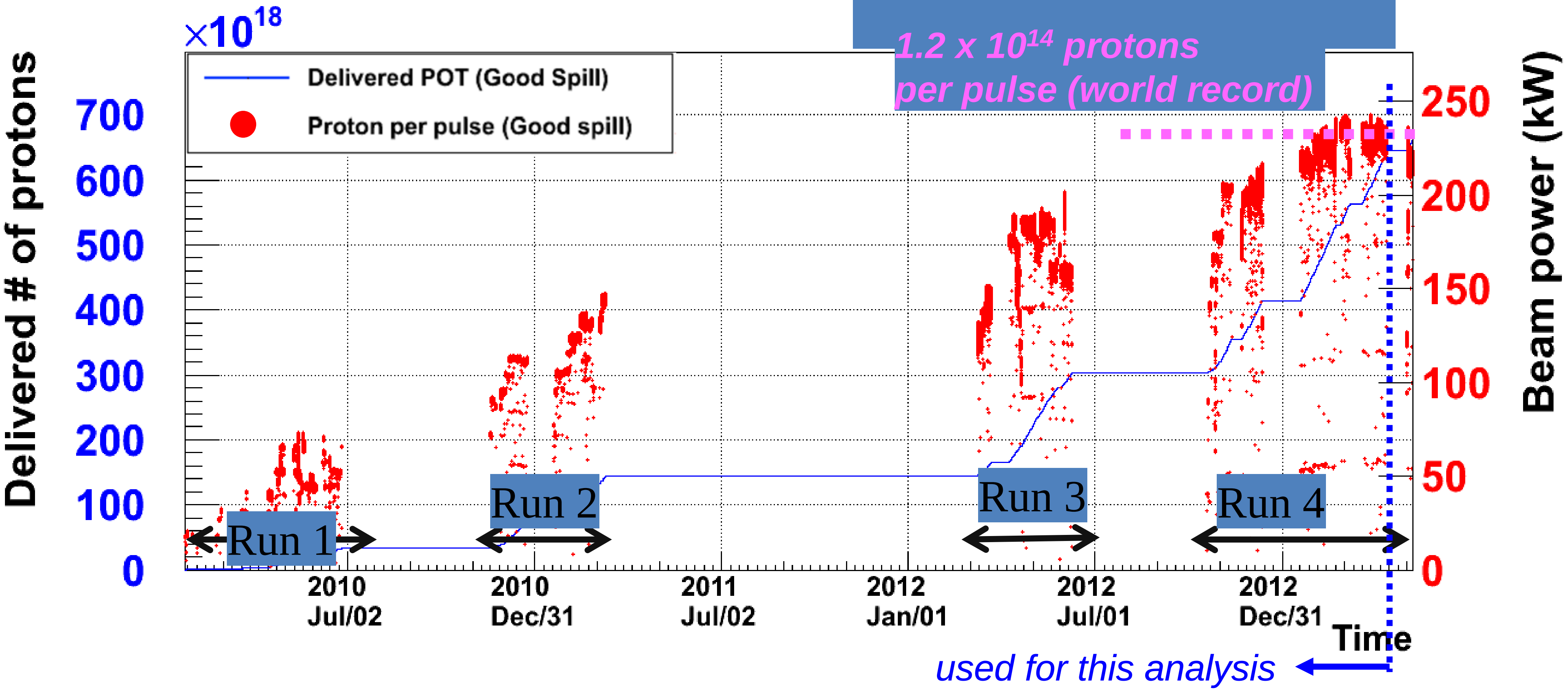
MAQE fit



The best-fit MAQE when fitting with normalisation (left) and shape only (right). Both fit results are consistent with the nominal value used in NEUT. It is possible to fit different values of depending on which effects are included in the model and which effects the input data samples are sensitive to. One should avoid interpreting this result as a measurement of a fundamental parameter. As the meaning of this effective parameter depends on the details of the QE model, comparison with results from other experiments should be done with care.

T2K supplemental plots

Data collected and analyzed



1.2×10^{14} protons per pulse (world record)

used for this analysis

We collected 6.63×10^{20} protons on target (p.o.t.) so far

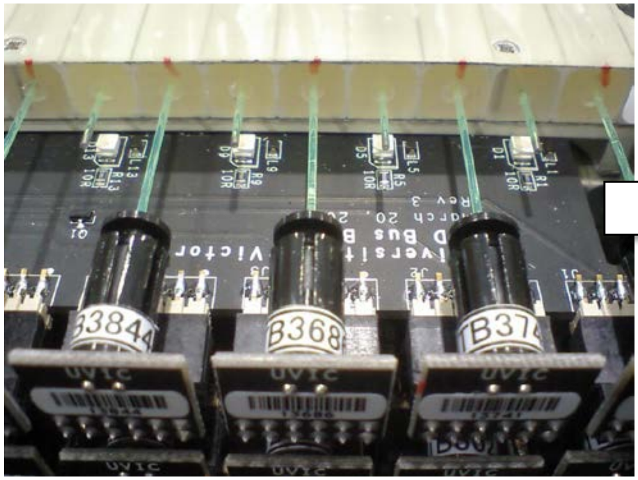
Data for the CCQE analysis = 2.6×10^{20} p.o.t. (till Jul 2012)

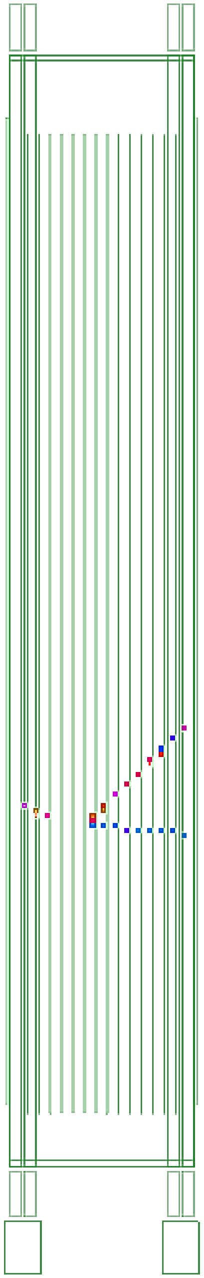
* Including 0.21×10^{20} p.o.t. with 205kA horn operation (13% flux reduction at peak) in Run3 (250kA horn current for nominal operation)

Fine Grained Detectors (FGDs)

Scintillation light (from charged particles) is sent down a wavelength shifting fibre connected to a multi-pixel-photon-counter (MPPC)

- MPPCs function in a magnetic field





X and Y scintillator layers can be used for 3D tracking

1cm^2 bar size provides detailed vertex information

“FGD1” is only scintillator, “FGD2” has alternating water layers

Time projection chambers (TPCs)

Charged particle ionizes 95% Ar, 3% CF4, 2% isobutane (iC4H10) gas

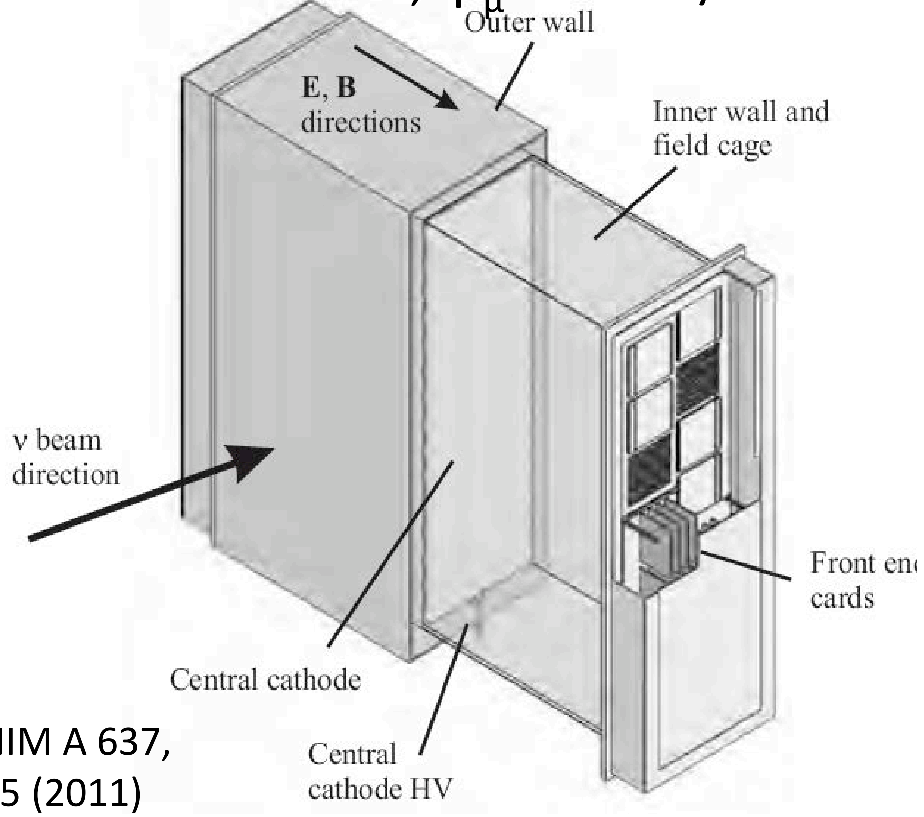
Electrons drift to readout plane (E~25kV, max distance 897mm)

``Wireless” TPC: Use of bulk micromegas detectors in readout

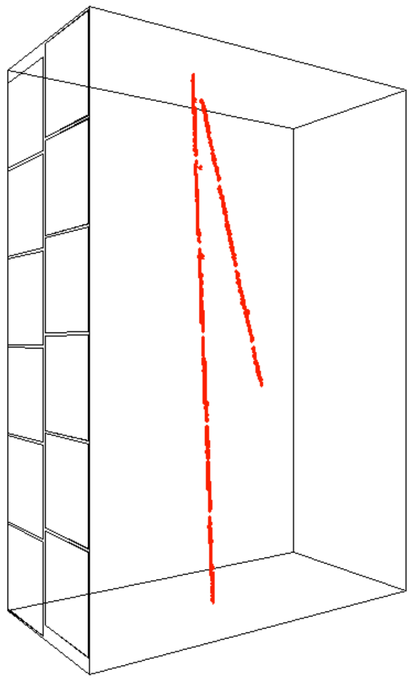
3D tracks are reconstructed provided drift velocity in the gas and timing of entry from other subdetectors

Momentum of the particle can be determined from curvature

- 0.2T B field; p_μ ~ 1 GeV/c has <10% momentum resolution

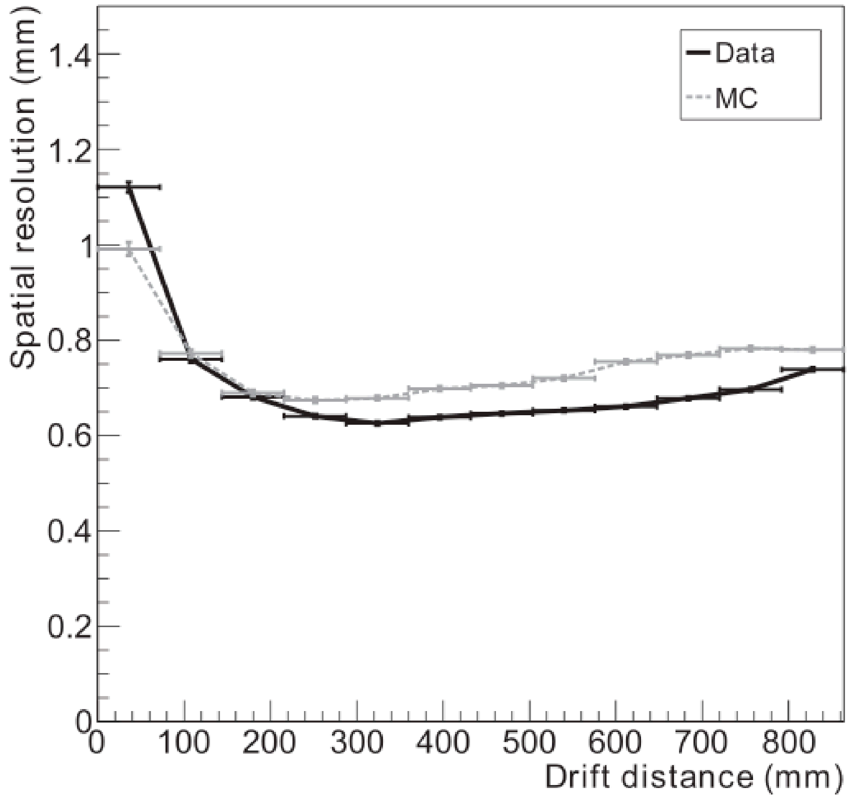


NIM A 637, 25 (2011)



Performance: spatial, momentum resolution

Spatial resolution:



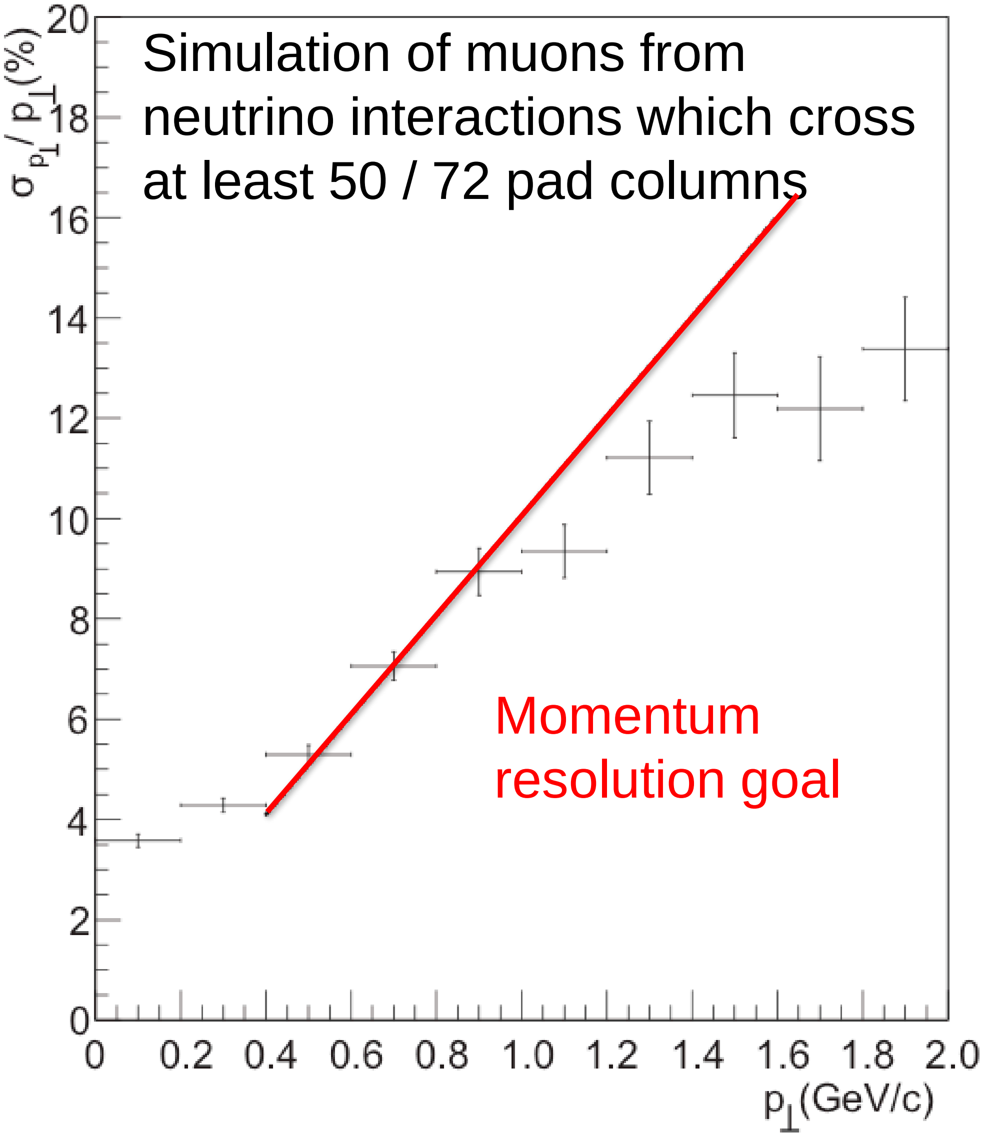
Associate charge deposited in time slices into clusters. Group pads into:

columns (horizontal tracks)

or rows (vertical tracks)

Compare position of a fitted track to location of single cluster

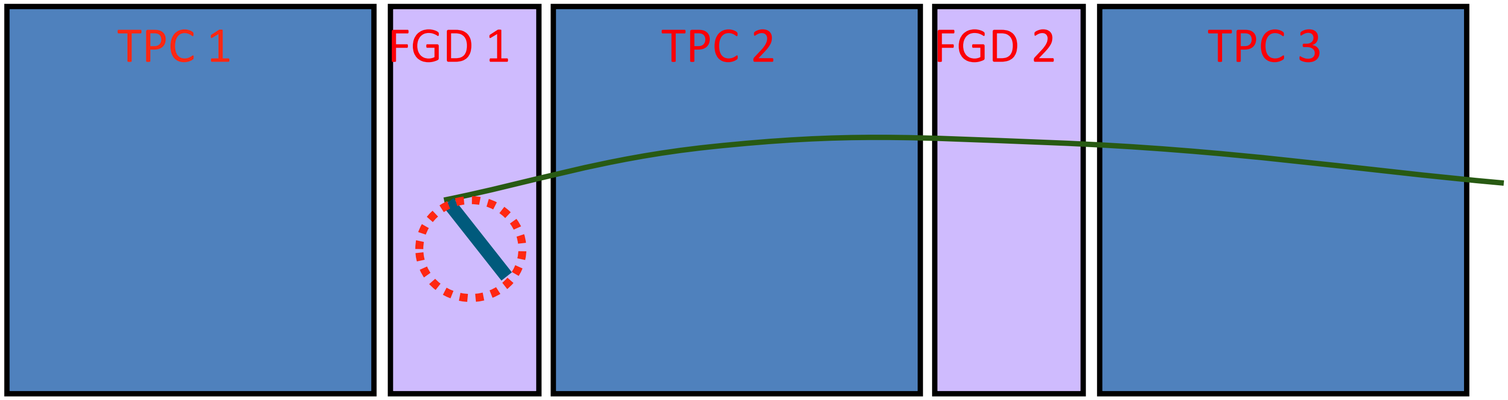
Momentum resolution (B=0.2T)



Simulation of muons from neutrino interactions which cross at least 50 / 72 pad columns

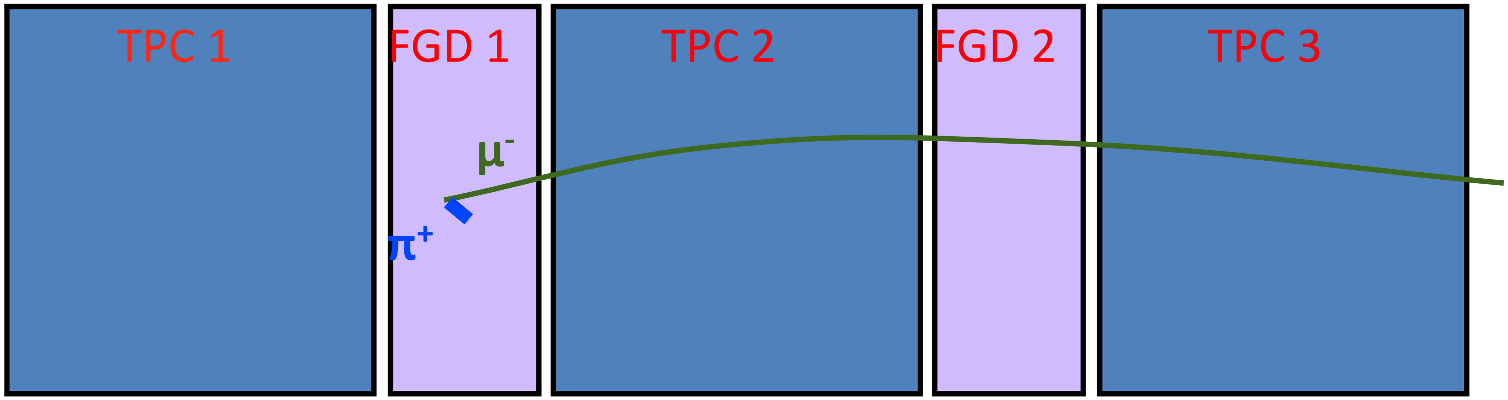
Momentum resolution goal

2013 Selection: FGD-Only Tracks



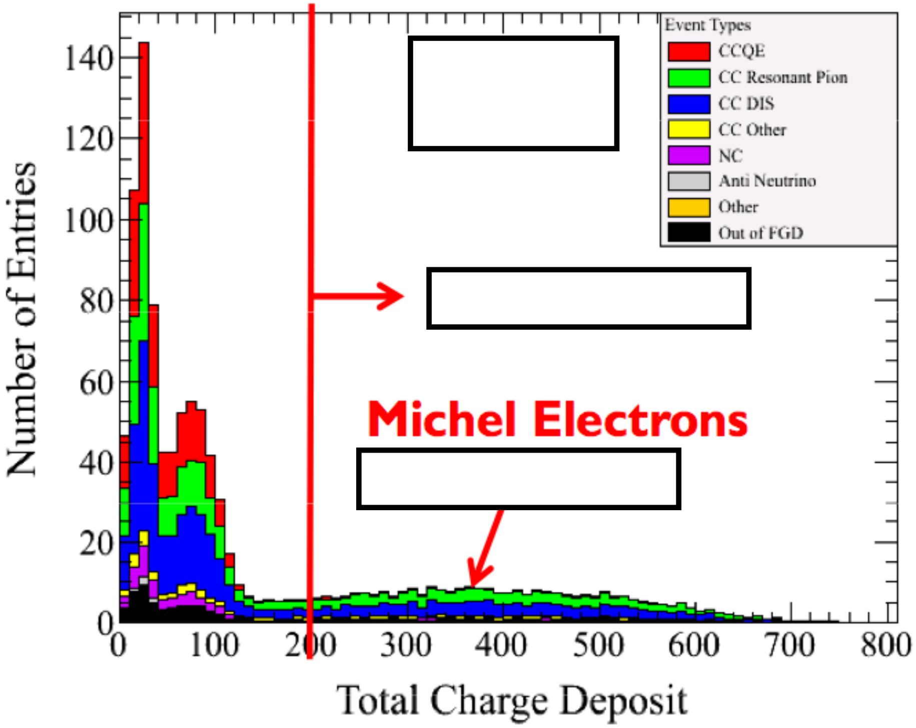
- **FGD-only tracks** = short tracks that do not reach a TPC
- Particle identification based on dE/dx
- **Pion tag** = at least 1 FGD-only track with a charge deposit consistent with a pion
  - Allow at most 1 pion to be tagged in this way
    - FGD-only tracks can break into more than 1 piece due to hadronic interactions and high-angle reconstruction failures

2013 Selection: Michel Tagging



- A Michel electron indicates a short stopped pion near the event vertex
- **Pion tag**:
  - >200 p.e. of “delayed” charge
  - “delayed” means >100 ns after the μ^- track time

Total Charge in a Delayed Time Bin



Michel Electrons

TPC Secondary Tracks

Tag particle based on the most probable particle type

Same TPC quality track as muon

Positive particle in TPC

Particle types = electron, proton, pion

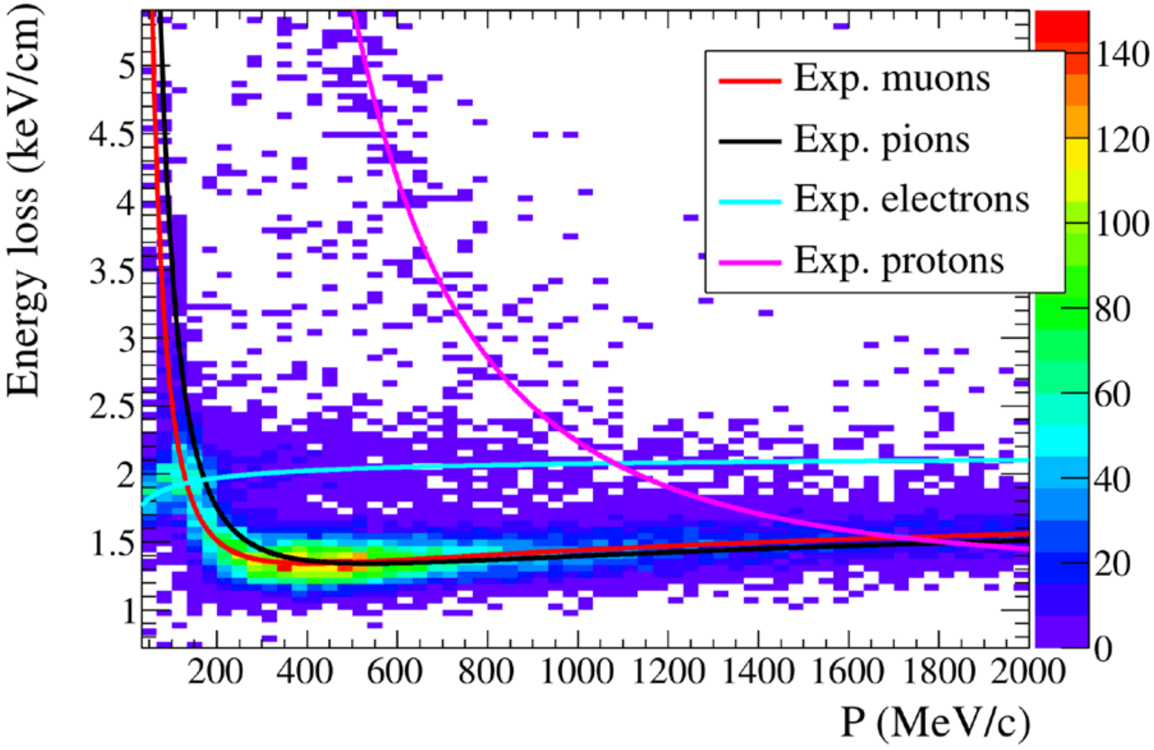
Track compatible with the most probable de/dx positive type.
If identified as electron and p > 900 MeV/c then change to proton.

Negative particle in TPC

Particle types = electron, pion

Track compatible with the most probable de/dx negative type

Negative tracks in the TPC.

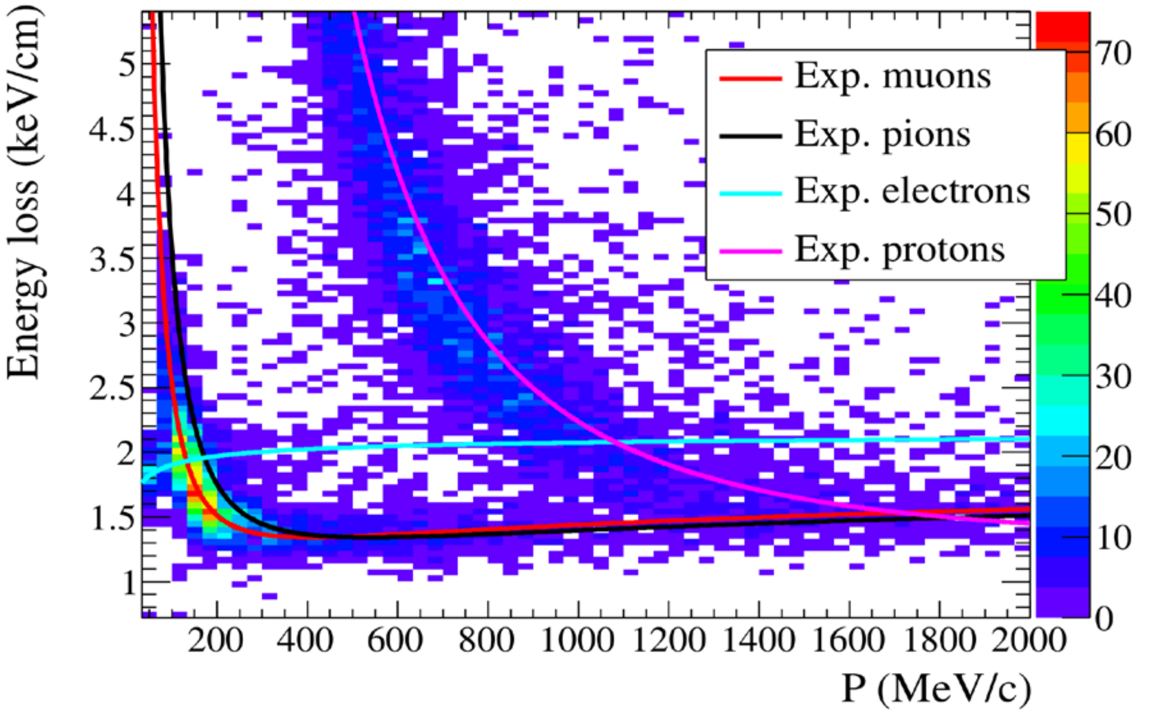


Energy loss of the particle (dE/dx) can be used to separate particle type

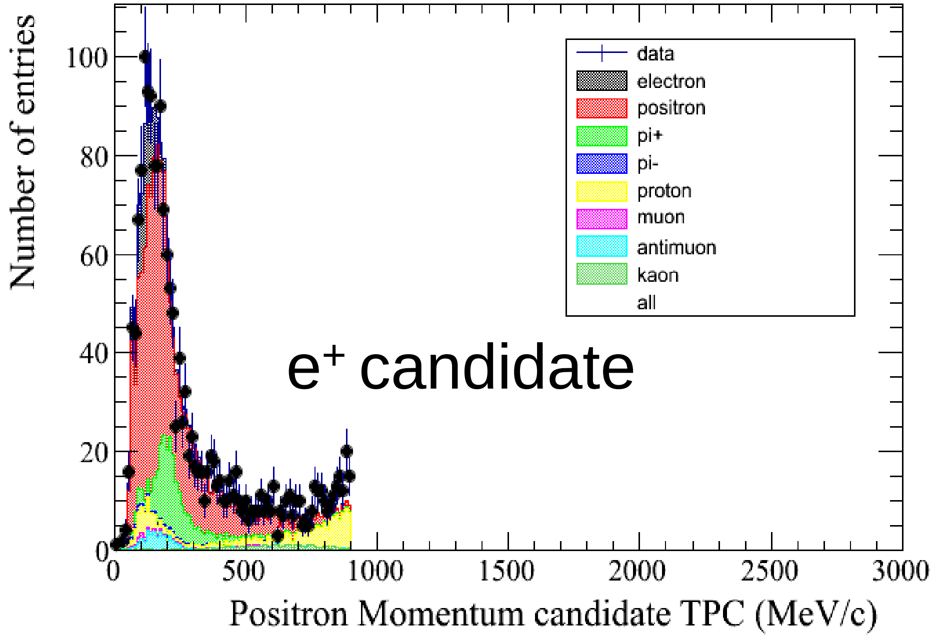
dE/dx resolution for MIPs is 8%

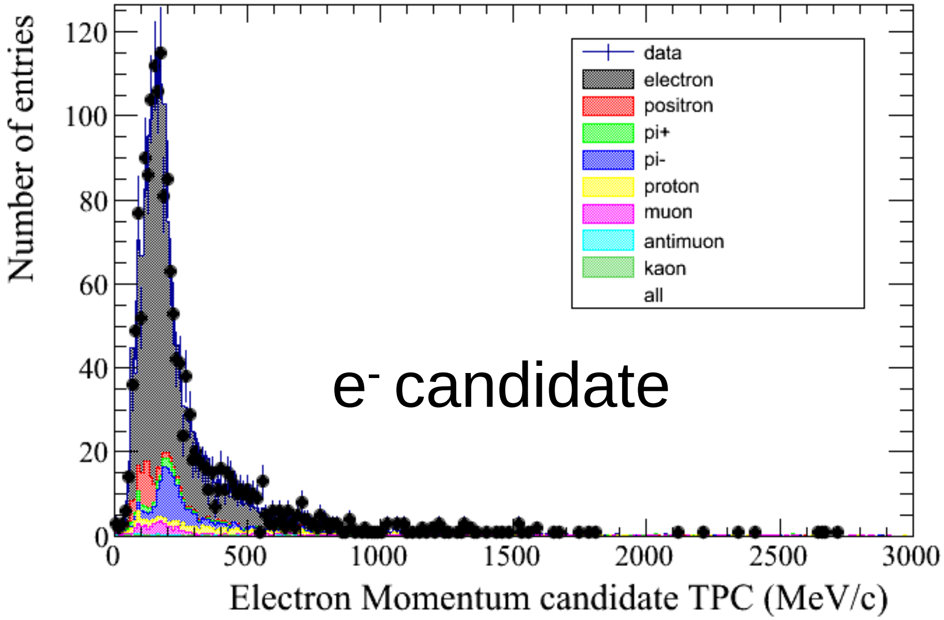
Probability for a muon between 0.2 and 1.0 GeV to be identified using dE/dx as an electron is less than 0.2%

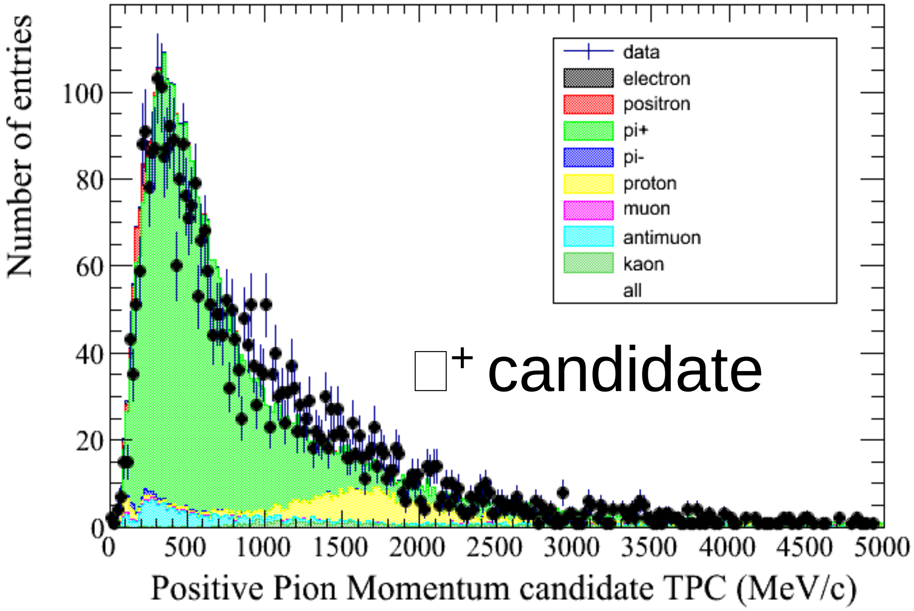
Positive tracks in the TPC.

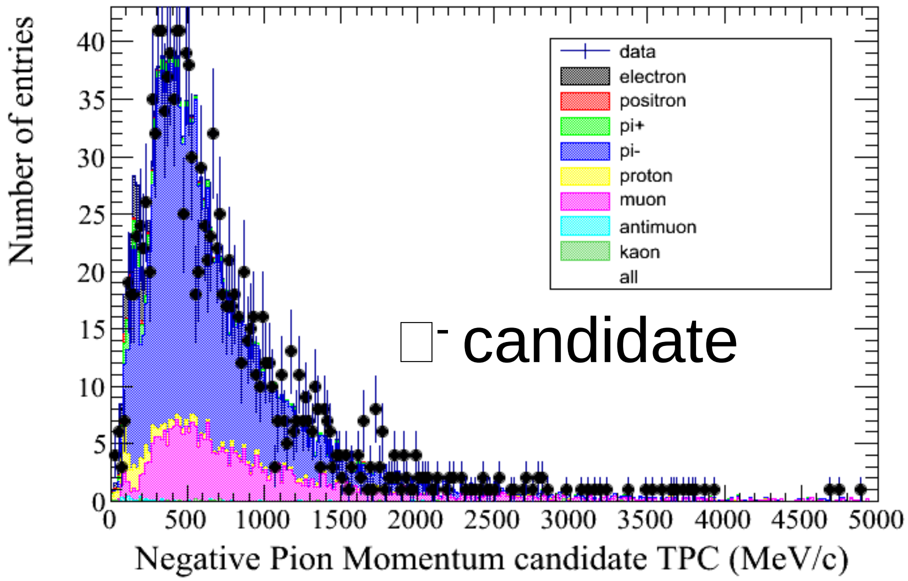


TPC Secondary Tracks



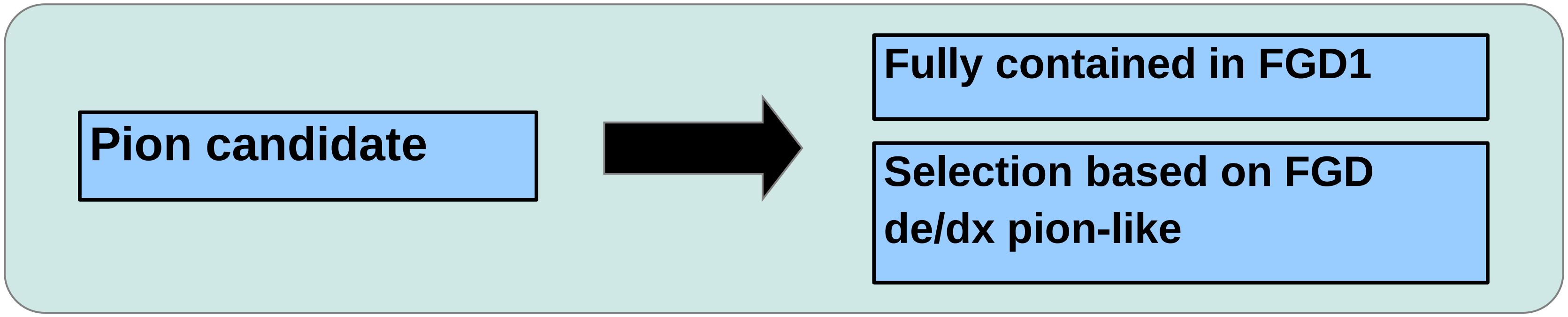






FGD only tracks

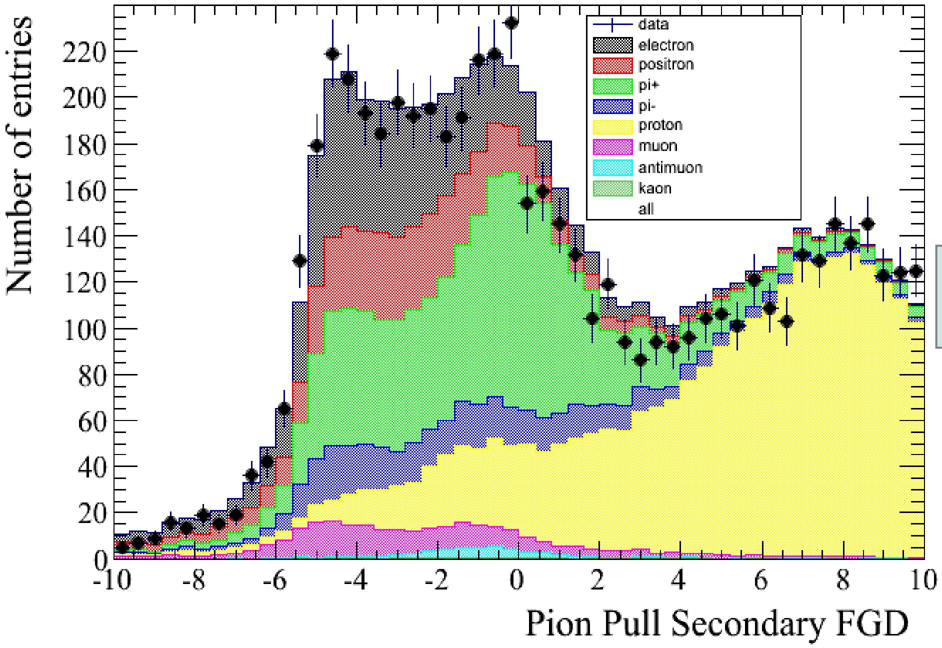
Tracks with segment in the FGD1 and no segments in any TPC



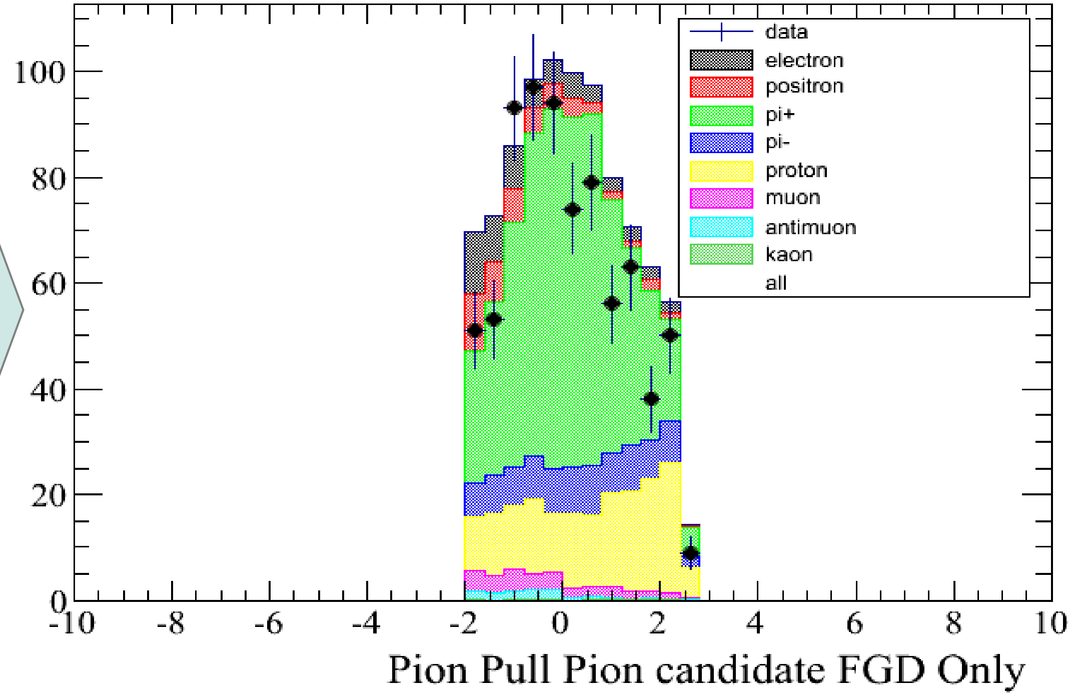
Pion candidate

Fully contained in FGD1

Selection based on FGD de/dx pion-like

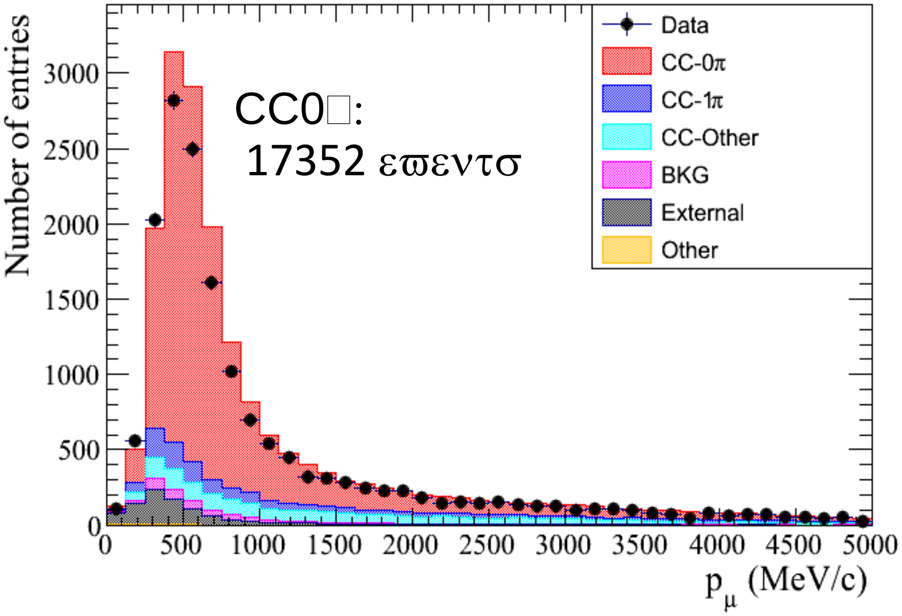


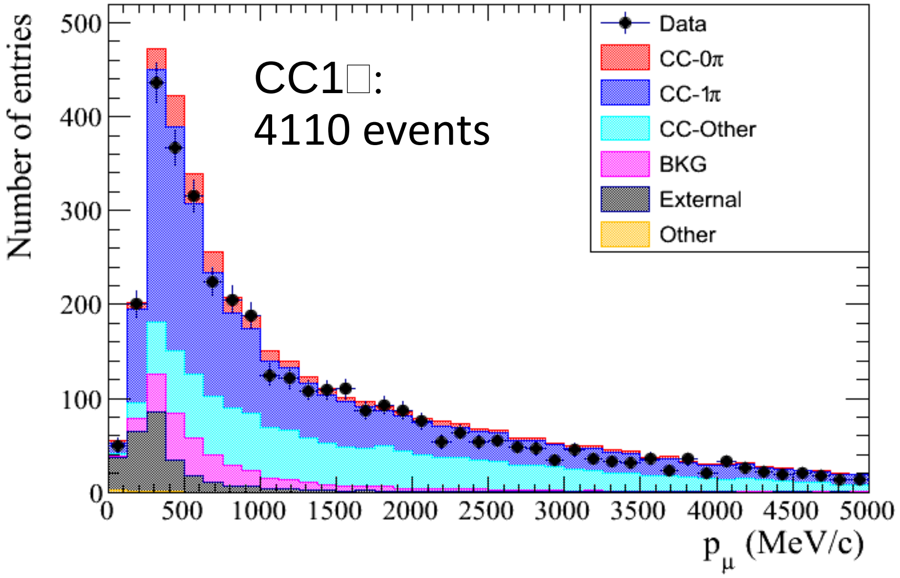
Pion pull before cut selection in FGD

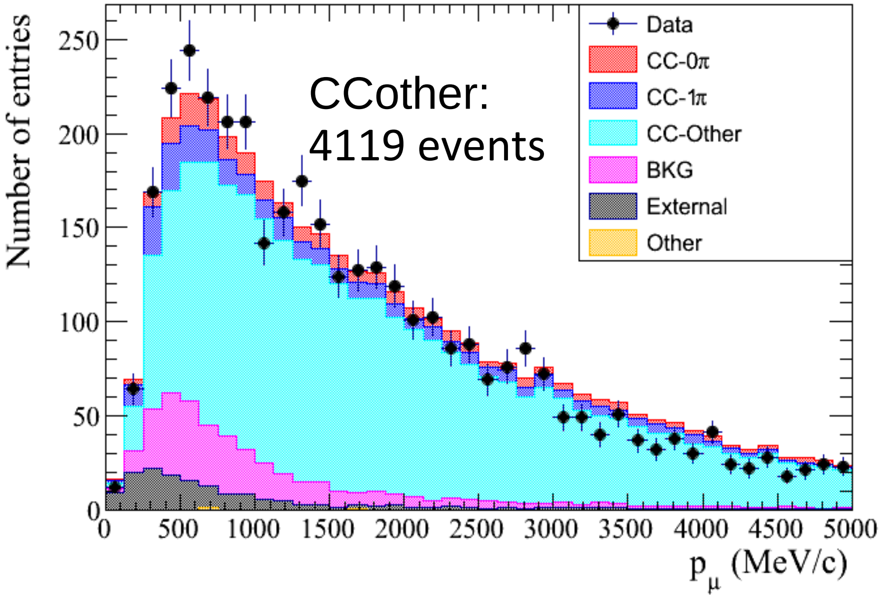


Pion pull after positive pion selection in FGD

2013 selection: muon momentum

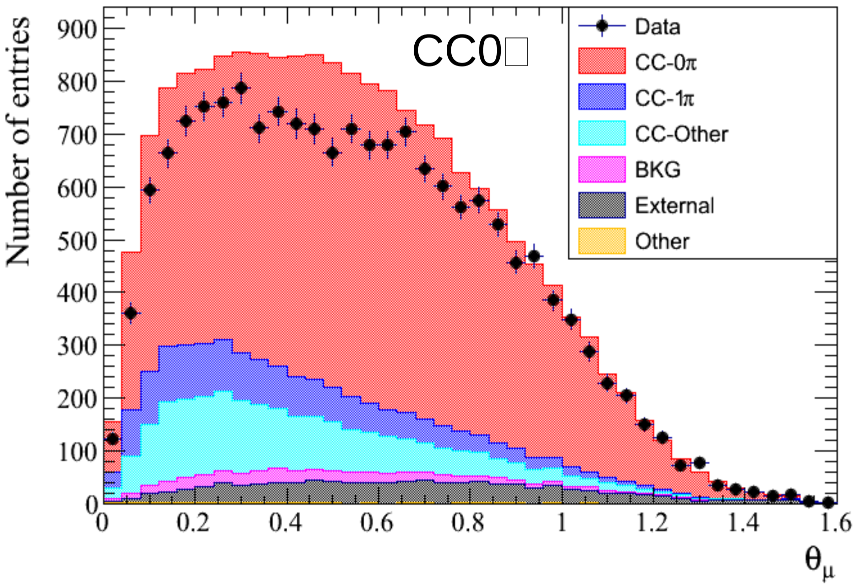


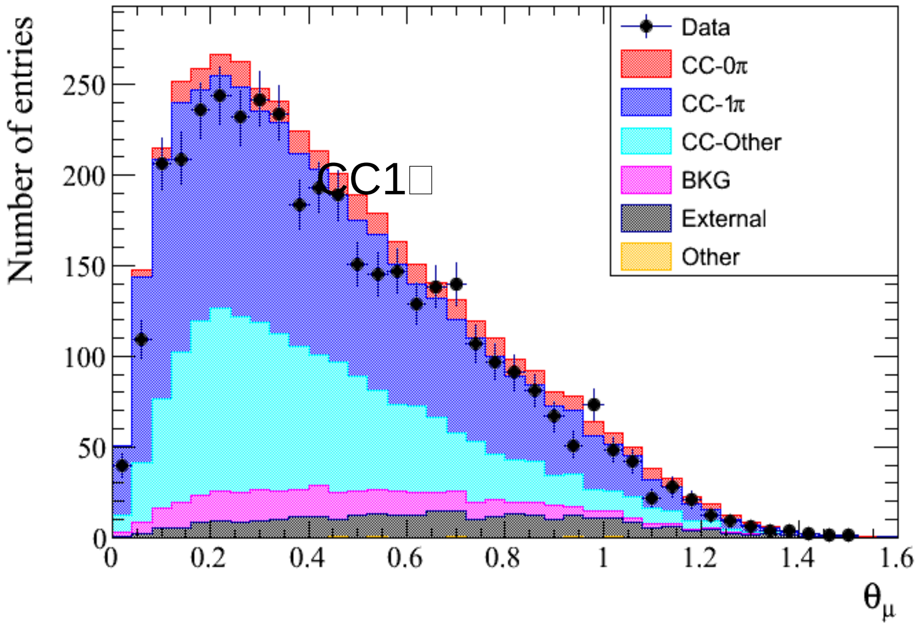


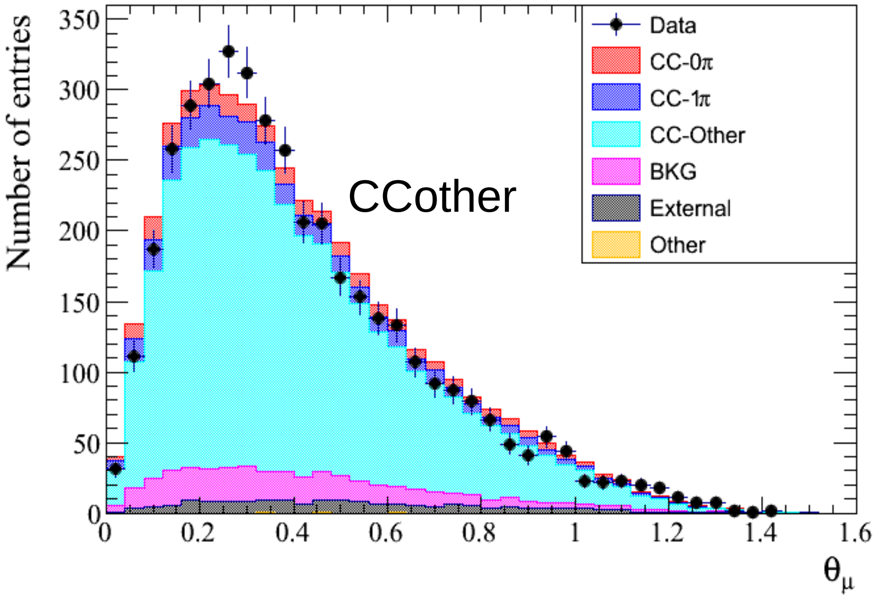


	CC0□ purities	CC1□ purities	CCother purities
CC0□	72.6%	6.4%	5.8%
CC1□	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

2013 selection: muon angle

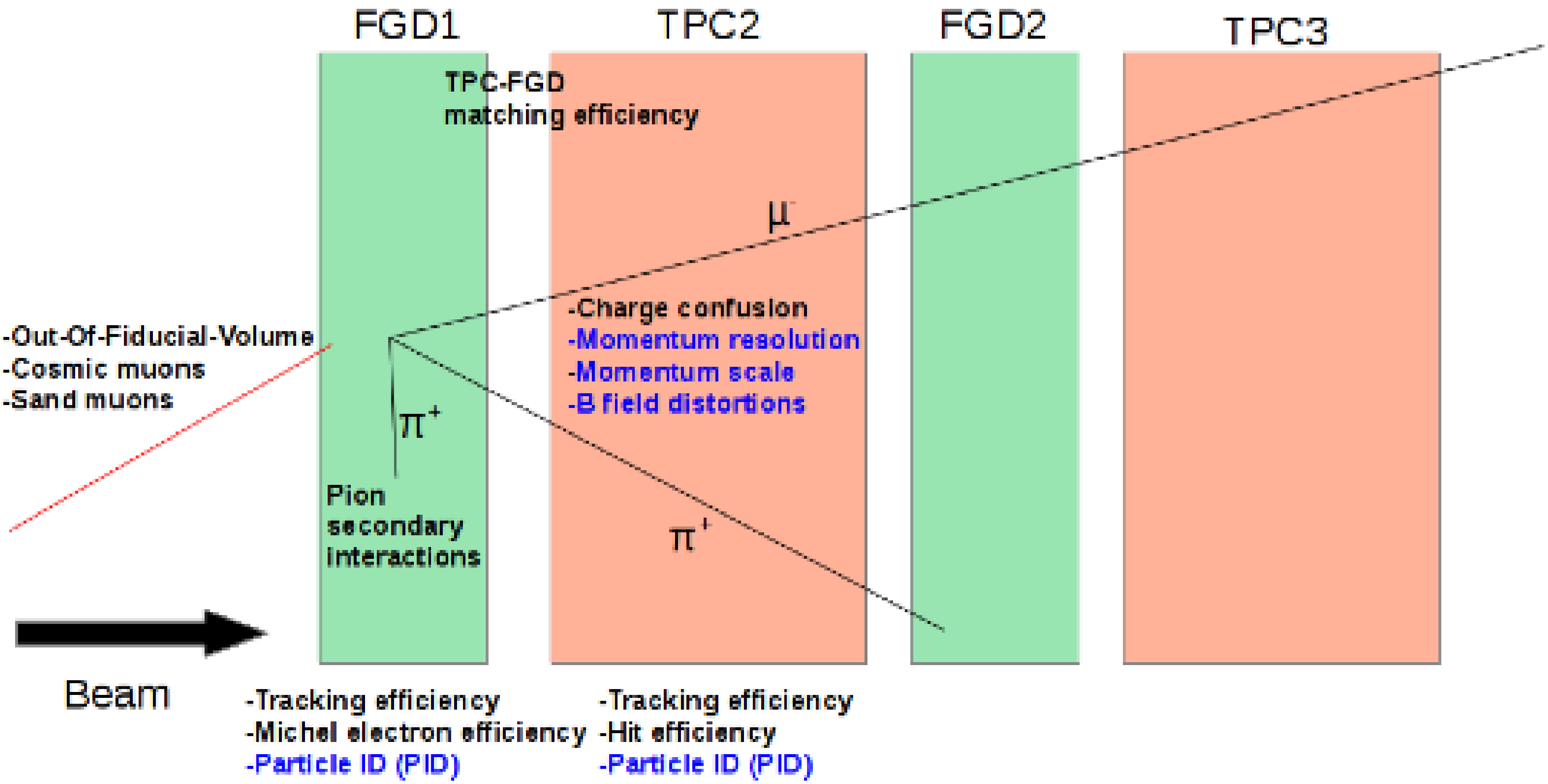






	CC0□ purities	CC1□ purities	CCother purities
CC0□	72.6%	6.4%	5.8%
CC1□	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

Systematic Errors



TPC-FGD
matching efficiency

-Out-Of-Fiducial-Volume
-Cosmic muons
-Sand muons

Pion
secondary
interactions

-Charge confusion
-Momentum resolution
-Momentum scale
-B field distortions

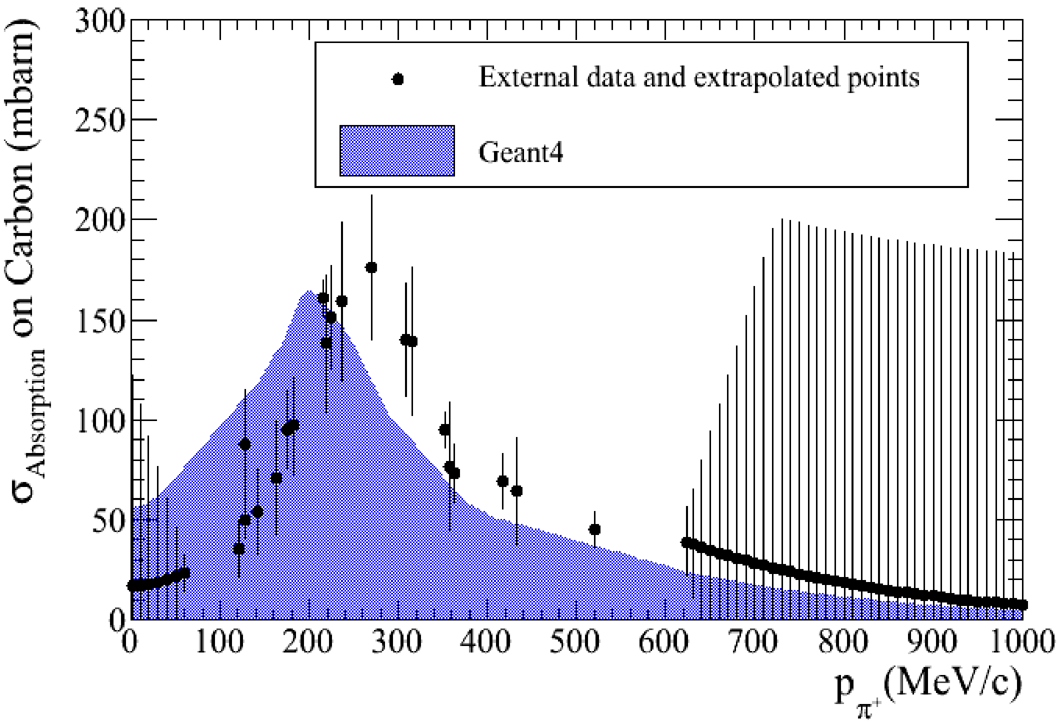
-Tracking efficiency
-Michel electron efficiency
-Particle ID (PID)

-Tracking efficiency
-Hit efficiency
-Particle ID (PID)

- Many sources of systematic error have been evaluated for the ND280 constraint
  - All errors are assigned using data control samples

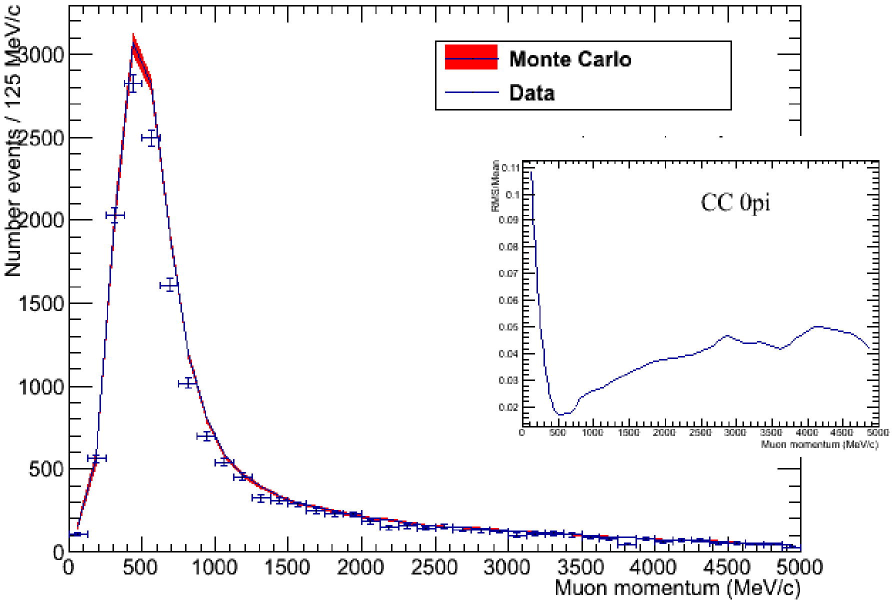
Pion Secondary Interactions

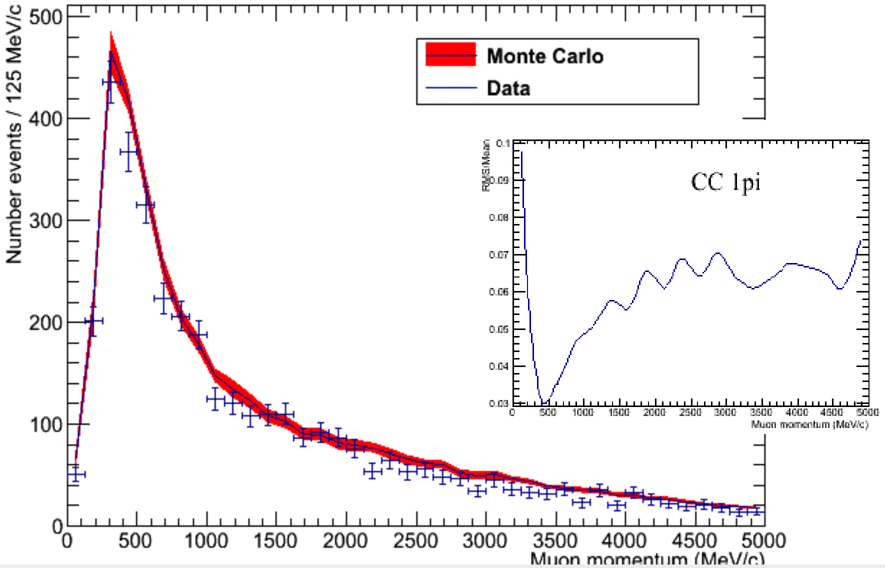
- Several datasets have been compiled for π^+ interactions on Carbon
  - Absorption
  - Charge exchange
  - Quasi-elastic scattering
- The default GEANT4 prediction is adjusted to the measured values
- The systematic uncertainty is set to the error on the data
  - In regions without data, the assumed error is inflated
    - This has a small effect since these regions contain very few pions

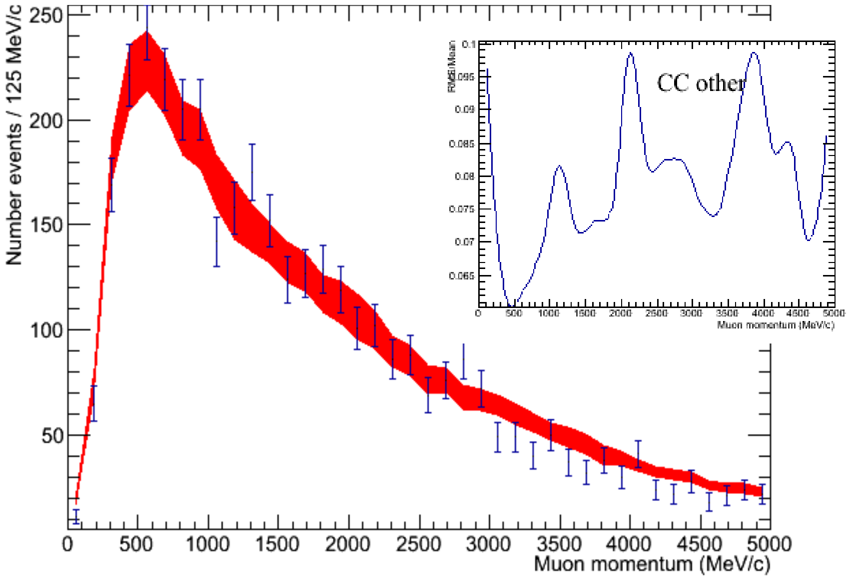


Rowntree et al., Phys. Rev. C60 054610 (1999)
Jones et al., Phys. Rev. C48 2800 (1993)
Levenson et al., Phys. Rev. C28 326 (1983)
Navon et al., Phys. Rev. Lett. 42, 1465 (1979)
Navon et al., Phys. Rev. C22, 717 (1980)
Navon et al., Phys. Rev. C28, 2548 (1983)
Allardyce et al., Nucl. Phys. A209, 1-51 (1973)
Bellotti et al., Nuovo Cimento 14A, 567 (1973)
Bellotti et al., Nuovo Cimento 18A, 75 (1973)
Hilscher et al., Nucl. Phys. A158, 602-606 (1970)
Miller et al., Nuovo Cimento 6, 2742 (1957)
Gelderloos et al., Phys. Rev. C62, 024612 (2000)
Cronin et al., Phys. Rev. 107, 1121 (1957)
Takahashi et al., Phys. Rev. C51, 2542 (1995)

Detector systematics



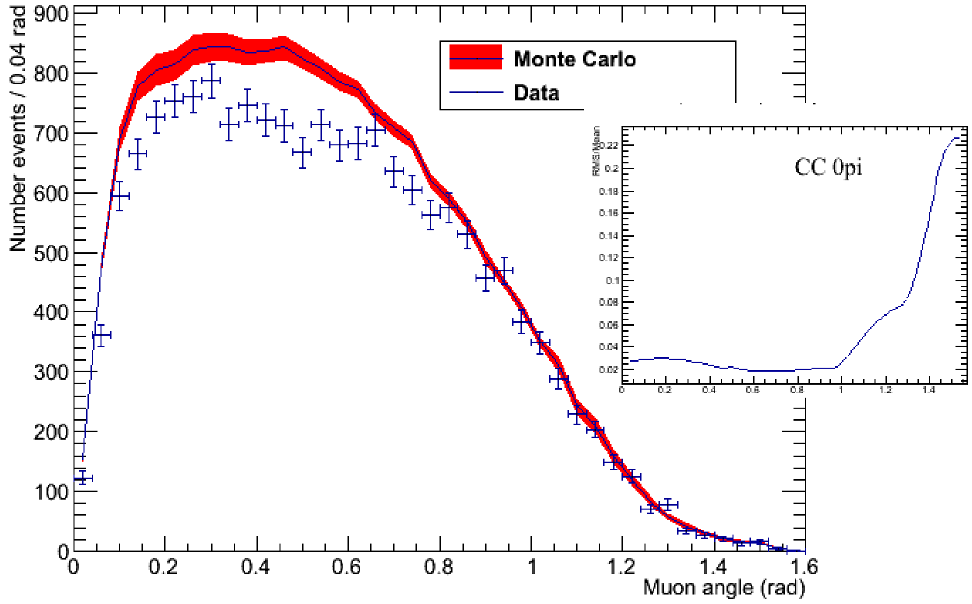


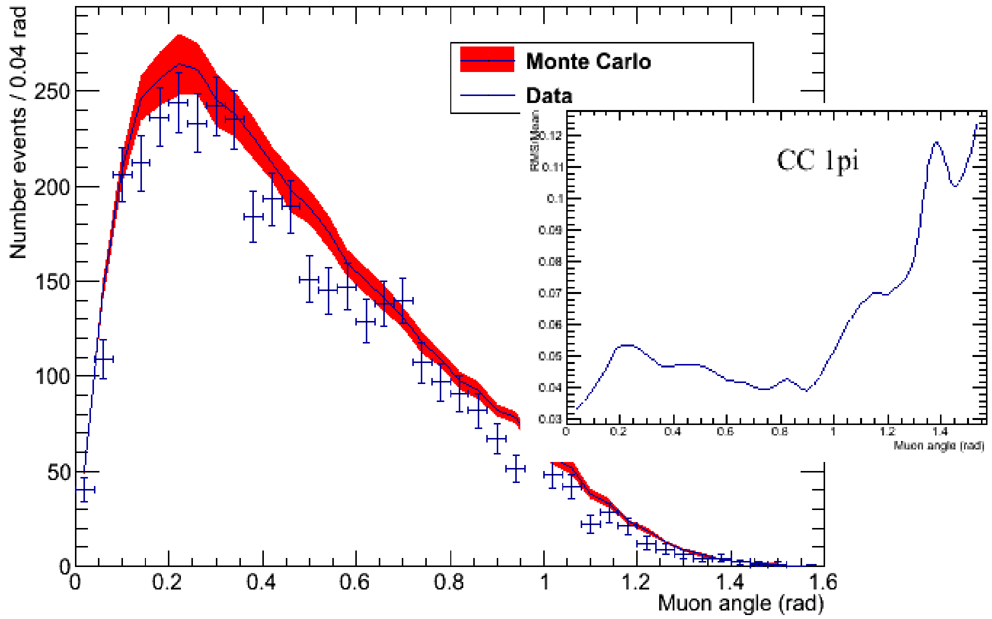


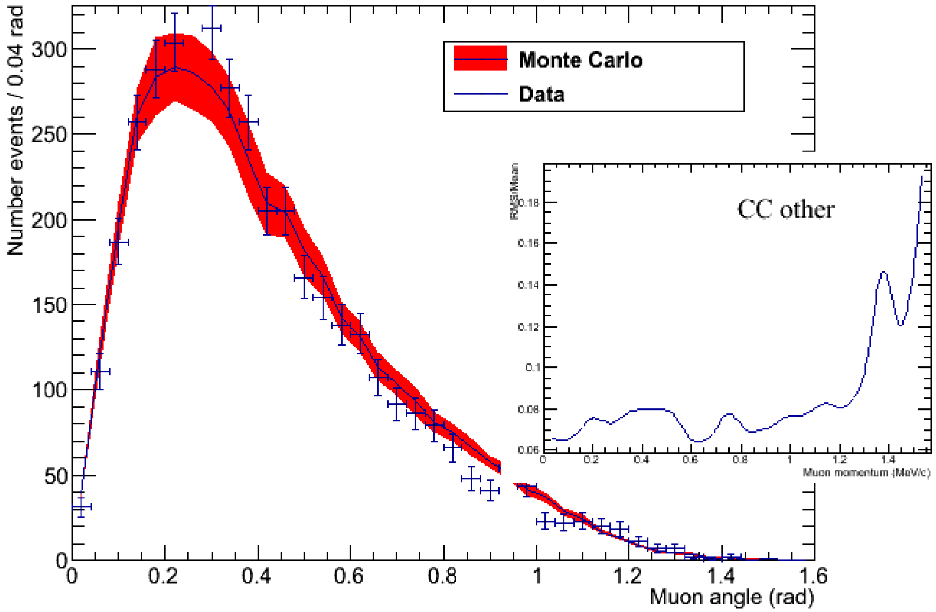
B Field distortion (0.3%)	TPC Tracking efficiency (0.6%)
TPC-FGD matching efficiency (1%)	***TPC Charge confusion (2.2%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (10%)***
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (3.5%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	***Pion secondary interaction (8%)***

Largest relative error in all momentum bins in all categories

Detector systematics







B Field distortion (0.3%)	TPC Tracking efficiency (0.2%)
TPC-FGD matching efficiency (1.8%)	***TPC Charge confusion (5.0%)***
TPC Momentum scale (2%)	***TPC Momentum resolution (5%)***
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	***Out of Fiducial Volume (22%)***
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (9.0%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	***Pion secondary interaction (8%)***

Largest relative error in all angle bins in all categories