UNIVERSITY OF LIVERPOOL

Cross section measurements at the T2K near detector

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for the T2K Collaboration

Synopsis

- Brief introduction to T2K
- ν_μ selection at the near detector ND280
  - Constraints to oscillation fits from the near detector data
    - See K. Mahn talk this afternoon
  - First Charged Current ν_μ inclusive cross section measurement
- ν_e and NC-π^0 samples in the near detector

T2K Physics Goals

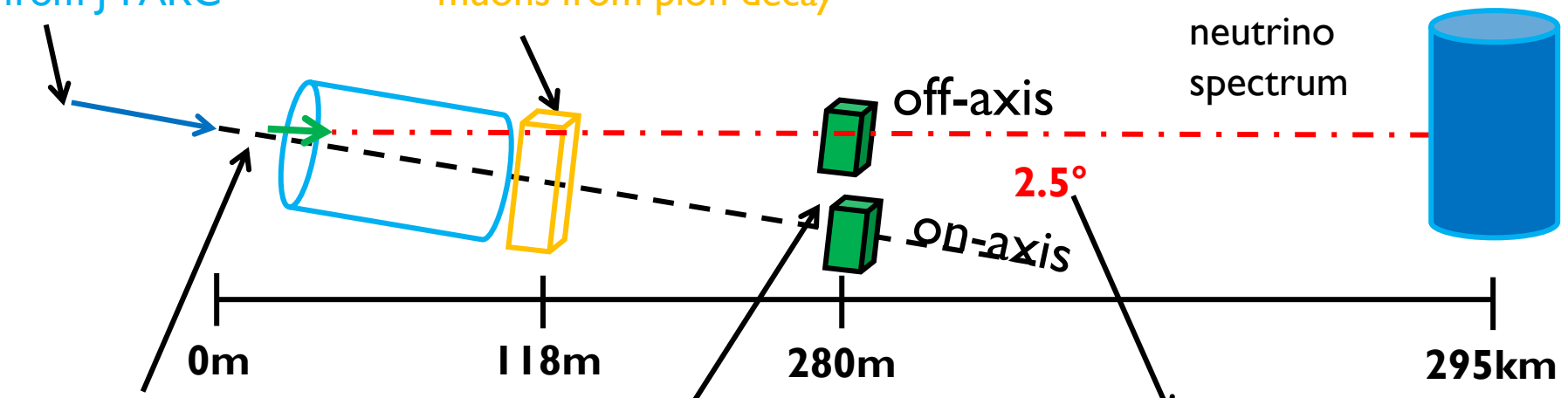
- 2012 Physics runs started on March 8
- Precision measurement of the ν_e appearance signal
- Precision measurements of θ_{23} and Δm^2_{23}
- Measure various neutrino cross sections at the near detector
- Detect possible hints of CP-violation and mass hierarchy

T2K: The First Off-axis Long Baseline Accelerator Neutrino Oscillation Experiment

30 GeV protons from J-PARC

Muon Monitor to tag muons from pion decay

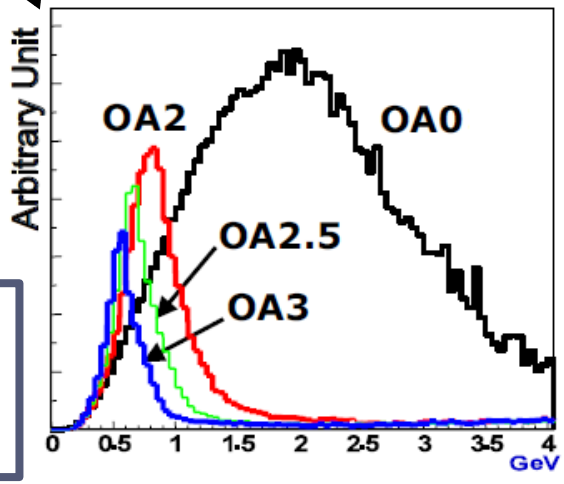
Far Detector (Super-K) to measure oscillated neutrino spectrum



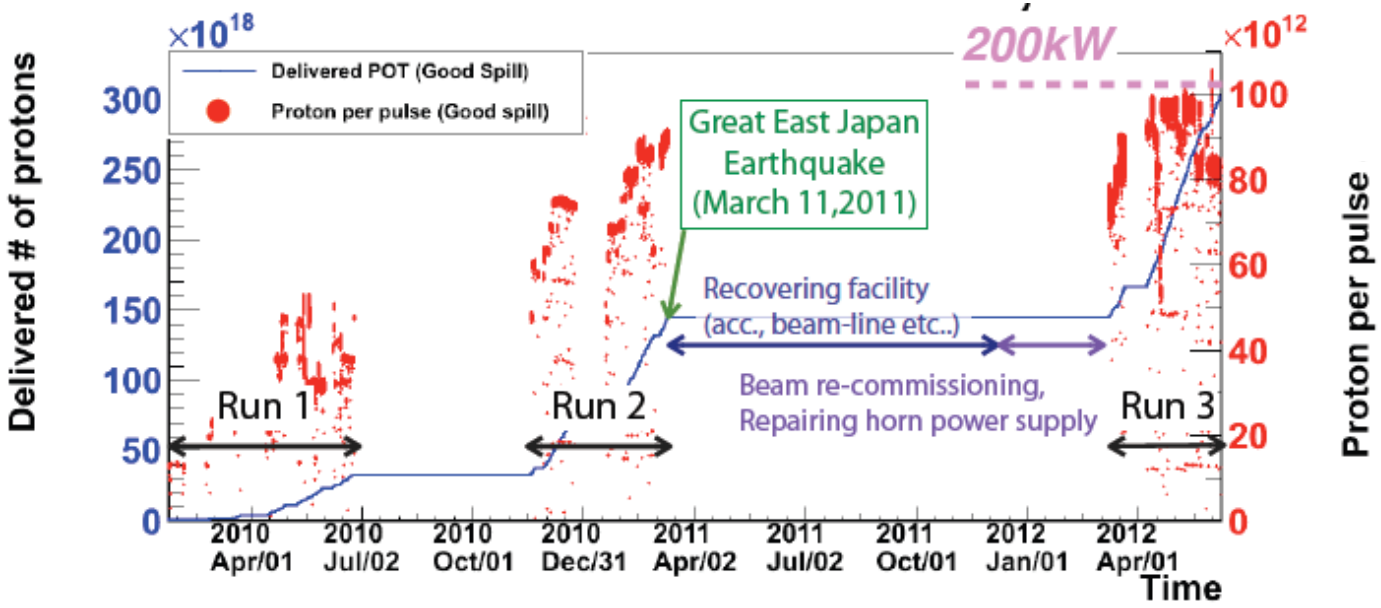
Proton beam on graphite target
3 magnetic horns focus π, K (250kA/200kA)
π,K decay in a 96m decay volume (He~1atm)
Small ν_e fraction ~1%

Near Detectors
INGRID (on-axis): To profile the neutrino beam
ND280 (off-axis): To measure neutrino interactions and backgrounds

Accelerator Design goal: 750 kW
Reached before earthquake: 145 kW
Post-earthquake: 200 kW



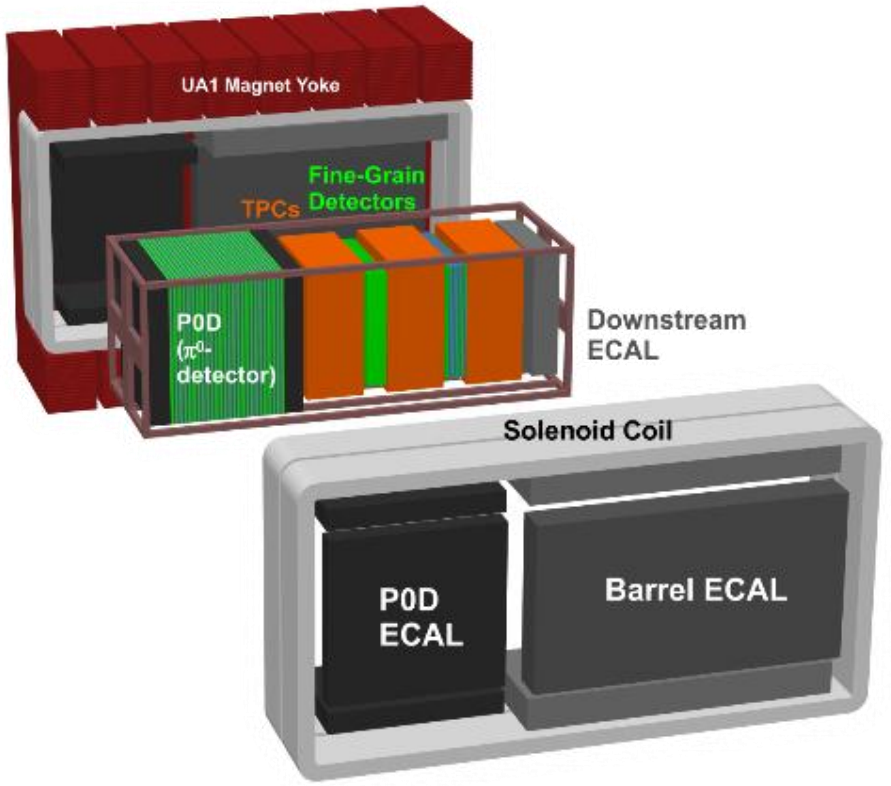
Data Collected And Analysed



	Run Periods			
	Run 1	Run 2	Run 3b	Run 3c
Protons on Target ($x10^{20}$)	0.323	1.108	0.214	0.911
Average Horn Current (kA)	249.7	249.7	204.7	249.8

T2K Near Detector ND280

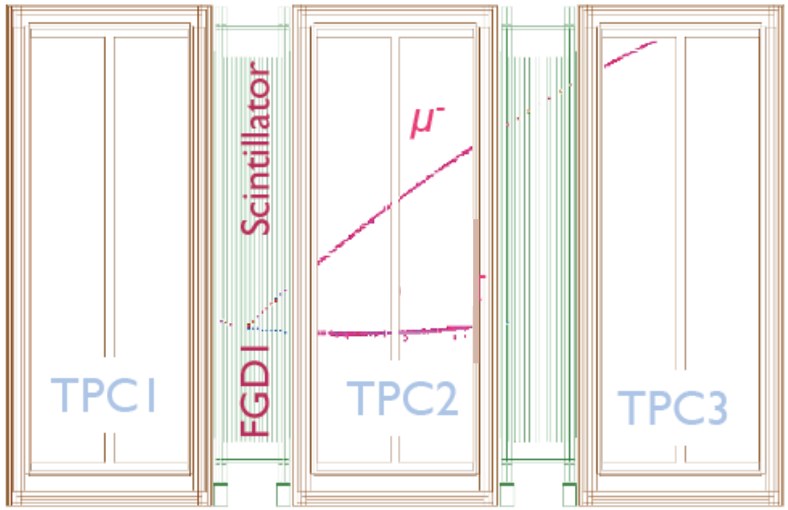
- Measure neutrino interactions and estimate the background contaminations
  - UA1 magnet - 0.2T field
  - Front optimized to measure π^0 interactions (P0D)
  - Rear optimized to measure charged current interactions
    - 2 Fine Grained Detectors (FGD)
      - Carbon and Water targets
    - 3 Time Projection Chambers (TPC)
      - Tracking, dE/dx
  - Surrounded by the electromagnetic calorimeter (ECal) and muon detector

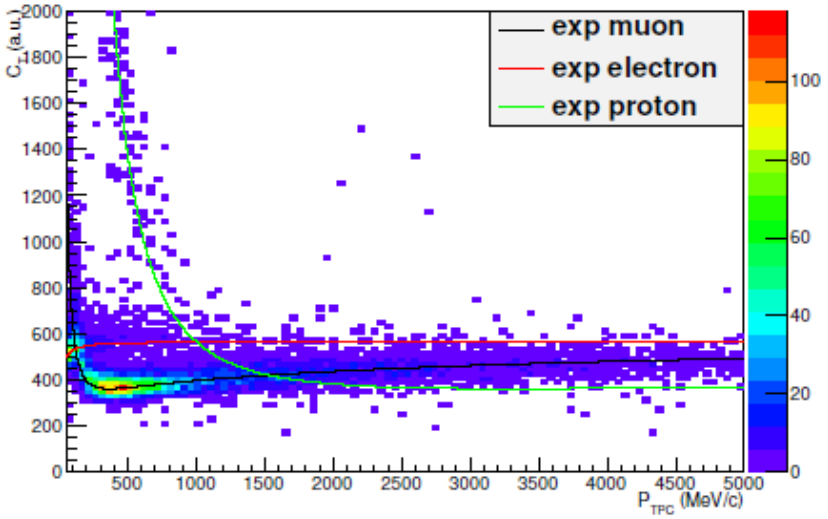


Muon neutrino selection at the near detector

ND280 ν_μ Measurement – Run1+2

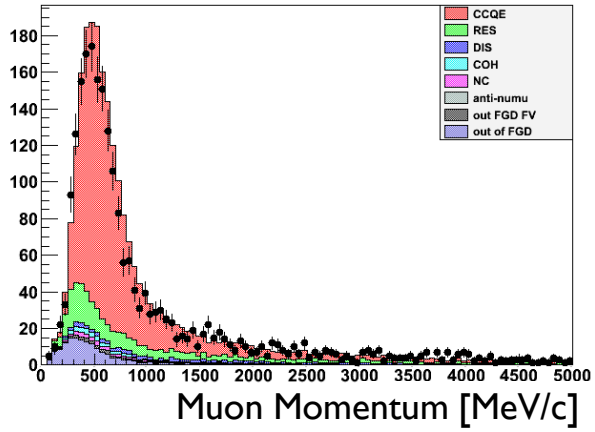
- ν_μ interactions in FGD1
  - 1.08×10^{20} POT
  - Negative track in TPC with 18 TPC hits minimum
  - Vertex in the FGD1 fiducial volume
  - Upstream TPC veto
  - TPC dE/dx compatible with the muon hypothesis
  - 4485 candidates selected
  - Charge Current Quasi-Elastic (CCQE) selection
    - Only one FGD-TPC track which has to be negative
    - No Michel electrons
    - 2354 events selected
  - All other events selected are classified as CC non-quasi elastic (CCnQE)

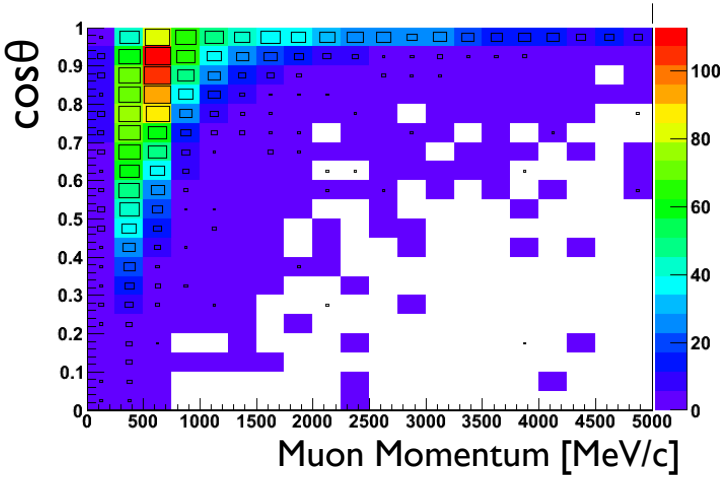




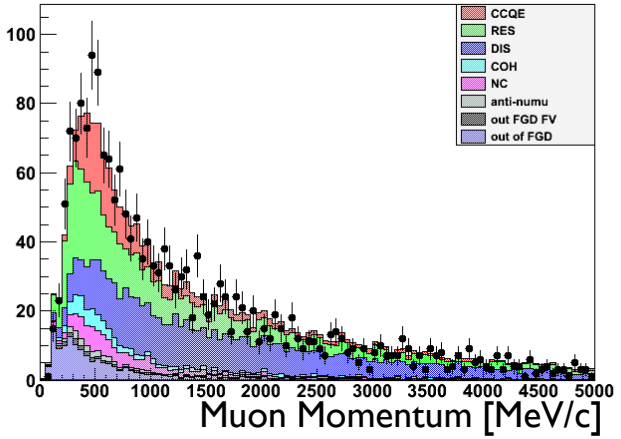
ND280 muon p-θ Distributions

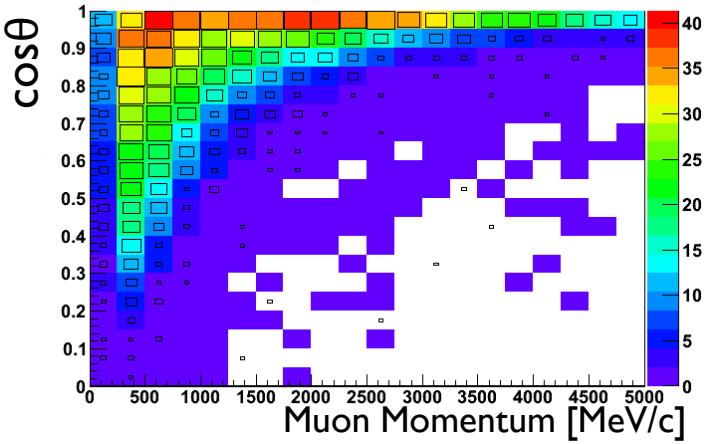
- CCQE





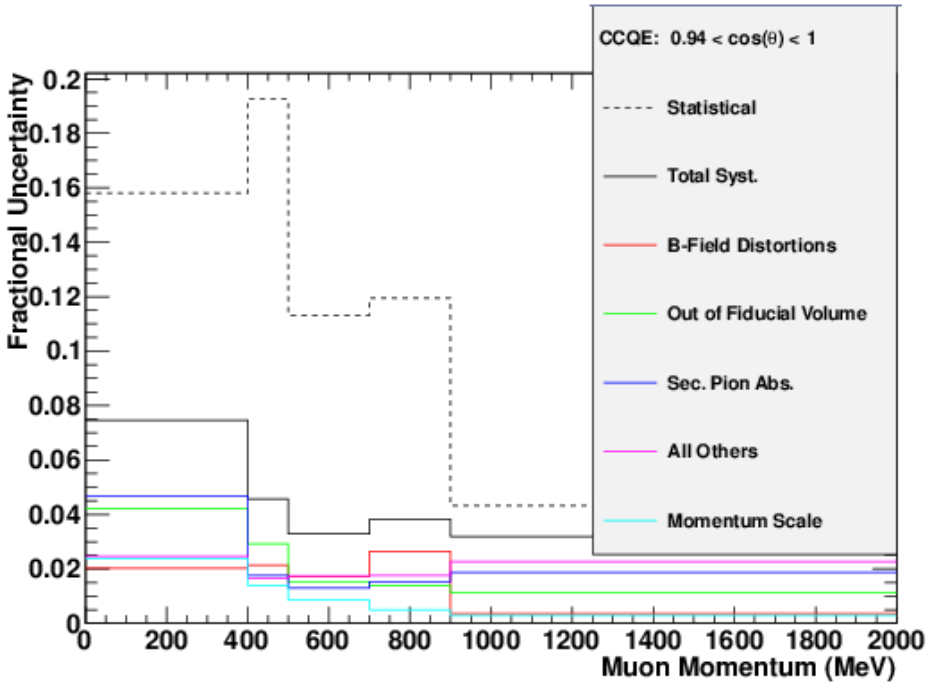
- CCnQE





ND280 Systematic Uncertainties

- Main CCQE fractional uncertainties

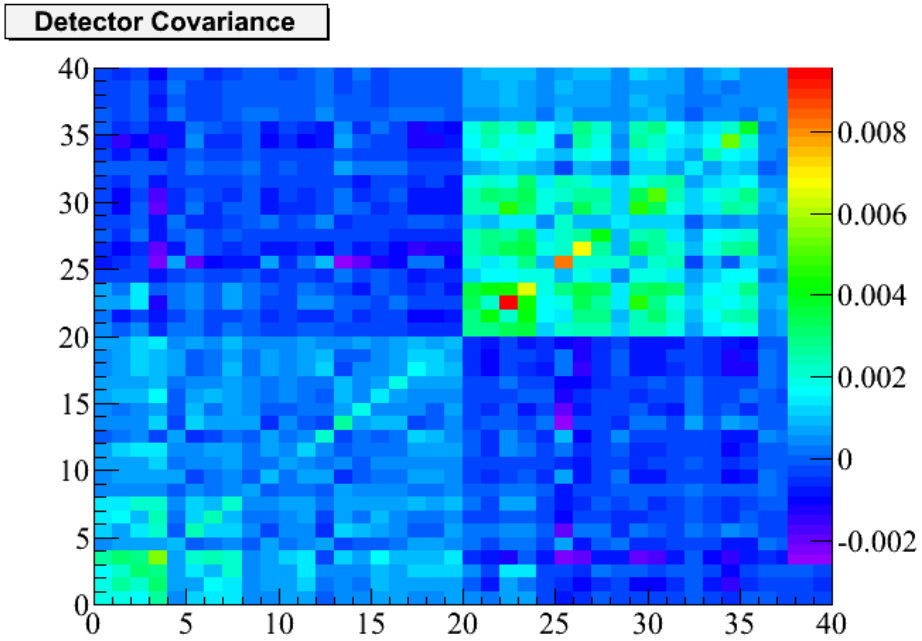


- Statistical error dominates
- B-Field distortions
  - Resolution, mis-alignment and non-linearities of the magnetic field
  - Drift electron path can be distorted due to imperfections in the magnetic field
    - Bias on the reconstructed momentum if the track shape is distorted
- Out of FGD fiducial volume events
  - Neutral particles from outside the tracker
  - Hit and track mis-reconstruction
- Physics related
  - Secondary pion interactions
    - Absorption and charge exchange after the pion has left the nucleus

ND280 Detector Systematic Covariance

- Full 40×40 fractional covariance matrix for the all the CCQE and CCnQE systematics
  - 4 θ-bins × 5 p-bins for both CCQE and CCnQE

p_μ (GeV/c)	CCQE p_μ Bin	CCnQE p_μ Bin
[0, 0.4]	0-4	20-24
[0.4, 0.5]	4-8	24-28
[0.5, 0.7]	8-12	28-32
[0.7, 0.9]	12-16	32-36
[> 0.9]	16-20	36-40

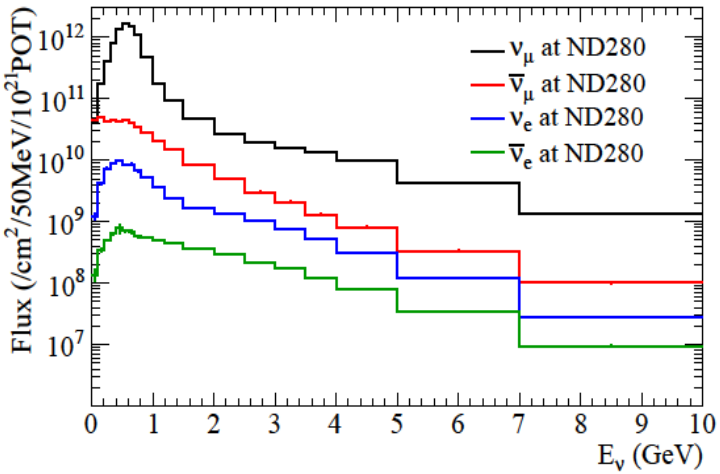


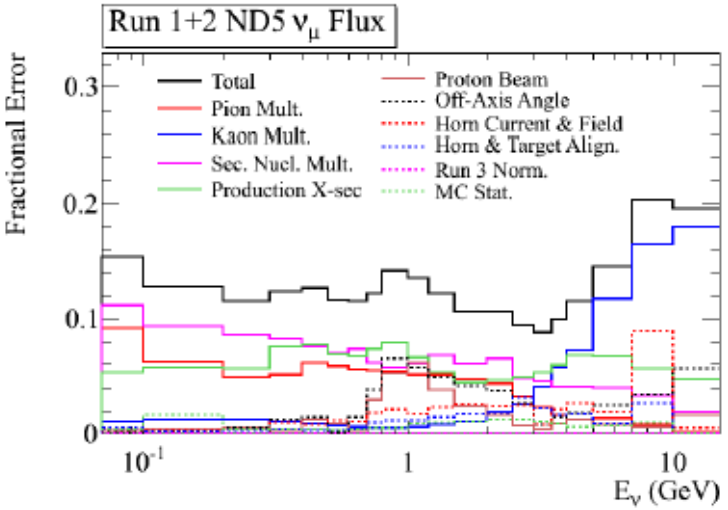
$\cos\theta_\mu$
[-1.0, 0.84]
[0.84, 0.90]
[0.90, 0.94]
[0.94, 1.0]

For each p_μ the bins iterate through $\cos\theta_\mu$ bins from [-1.0,1.0]

Inputs To Beam And Cross Section

- **Beam inputs**
  - Binned energy spectra for all neutrino flavors
  - Flux covariances between the near and far detector fluxes
    - Full MC (FLUKA)
    - External data: NA61 (π, K)
    - Measurements from beam and muon monitors
- **Neutrino interaction model**
  - NEUT for neutrino interactions
  - Prior uncertainties constrained by fits to external data





Neutrino Cross Section Parameterization And Uncertainties

	Value and Uncertainty
$M_A^{QE}\ (GeV/c^2)$	1.21±0.45
$M_A^{RES}\ (GeV/c^2)$	1.162±0.110
Fermi Momentum (MeV/c)	217±30
Spectral Function	0(off)±1(on)
CC Other Shape (GeV)	0.00±0.40
W shape (MeV/c^2)	87.7±45.3
Pion-less Δ decay	0.2±0.04

	Value and uncertainty
CCQE Norm. 0-1.5 GeV	1.000±0.110
CCQE Norm. 1.5-3.5 GeV	1.00±0.30
CCQE Norm. >3.5 GeV	1.00±0.30
CC1π Norm. 0-2.5 GeV	1.63±0.43
CC1π Norm. >2.5 GeV	1.00±0.40
NC1π^0 Norm	1.19±0.43
CC Coherent	1.0±1.0
NC Other	1.0±0.3

Charged Current ν_μ inclusive cross section measurement

Differential Cross Section Measurement

- Flux averaged inclusive ν_μ Charged Current differential cross section

$$\left\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial cos\theta_\mu} \right\rangle kl = \frac{\widehat{N_{kl}}}{T \Phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}}$$

- T → Number of target nucleons
- ϕ → Integrated flux
- Δp, Δcosθ → Bin width
- N_{kl} → The unfolded number of events in true p_μ and cosθ bins
  - Unfolding algorithm based on Bayes' theorem to provide the un-smearing matrix

The Unfolding Algorithm

- $\widehat{\mathrm{N}}_{t_k} = \frac{1}{\varepsilon_k} \sum_{j=1}^{n_r} P_m\left(t_k|r_j\right)\left(N_{r_j} - s_{POT} B_{r_j}\right)$

Efficiency

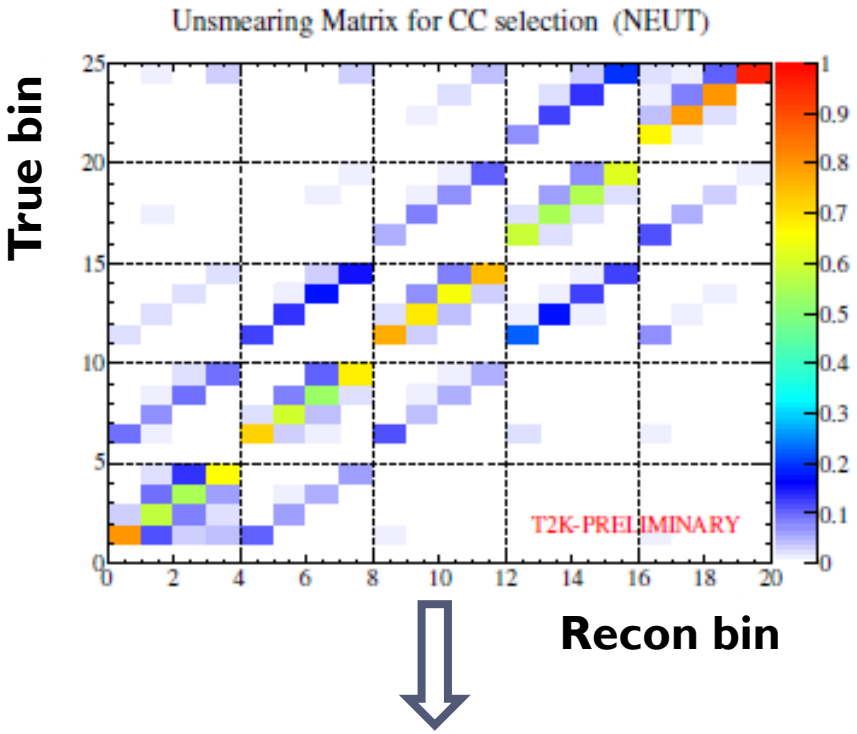
Probability to observe an event in the true bin k, knowing that it was reconstructed in the bin j

Number of reconstructed events in the bin j

Number of predicted background events in bin j, normalized to the data POT

- $P_m\left(t_k|r_j\right) = \frac{P\left(r_j|t_k\right)P_m(t_k)}{\sum_{a=1}^{n_t} P\left(r_j|t_a\right)P_m(t_a)}$

The Un-smearing Matrix



Width of a box represents a momentum bin. Momentum bins are labelled by increasing momentum. For each momentum, the bins iterate through the angular bins.

True binning $\cos\theta_\mu$	Recon binning $\cos\theta_\mu$
[-1.0, 0.0]	[-1.0, 0.84]
[0.0, 0.84]	
[0.84, 0.90]	[0.84, 0.90]
[0.90, 0.94]	[0.90, 0.94]
[0.94, 1.0]	[0.94, 1.0]

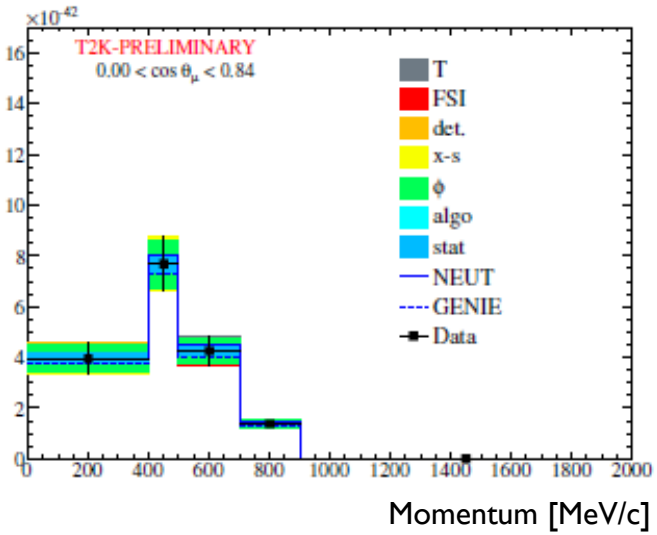
p_μ (GeV/c)
[0, 0.4]
[0.4, 0.5]
[0.5, 0.7]
[0.7, 0.9]
[> 0.9]

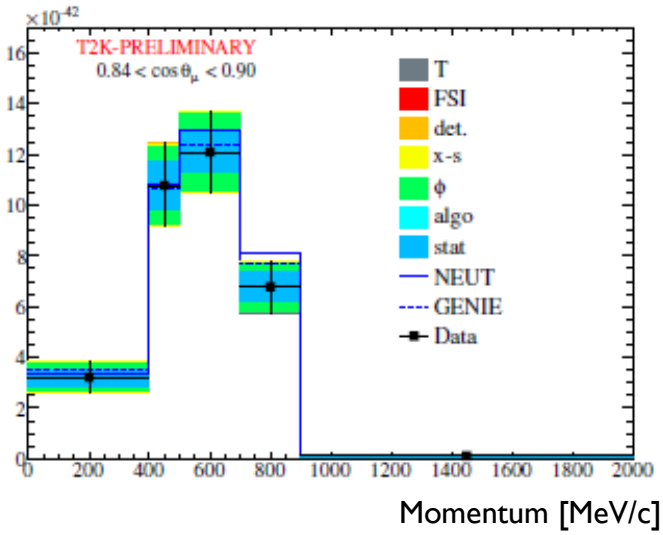
Systematics For Differential Cross Section Measurement

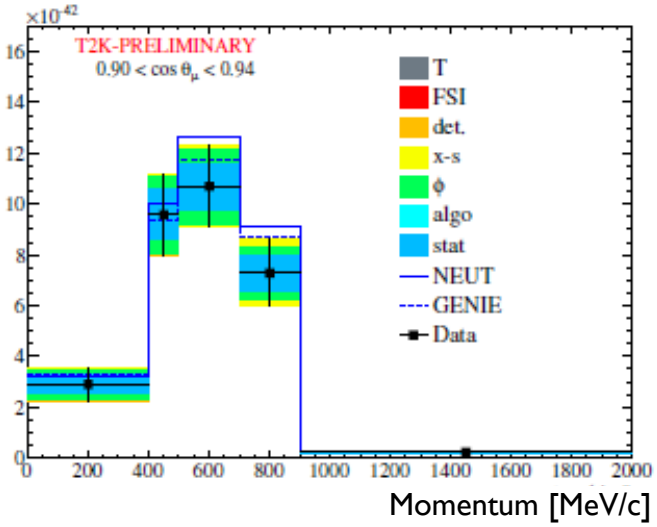
- Cross section model
- Detector response
- Flux
- Systematics are handled with MC reweighting by decomposing the covariance matrices
  - The RMS between the nominal and reweighted number of events are taken as the systematic
  - For spectral function and 1π E_ν shape parameters the uncertainty is the influence of each in a bin when they are turned on
- Target mass
  - Taking into account the full correlations between the nuclei $\delta T/T = 0.67\%$

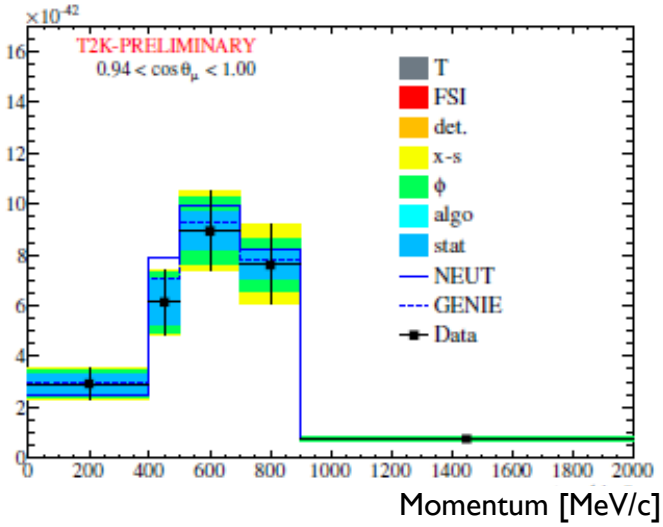
Differential Cross Section Result

$$\frac{d\sigma}{dpdcos\theta}\left(\frac{cm^2}{nucleon\ MeV/c}\right) \times 10^{-42}$$



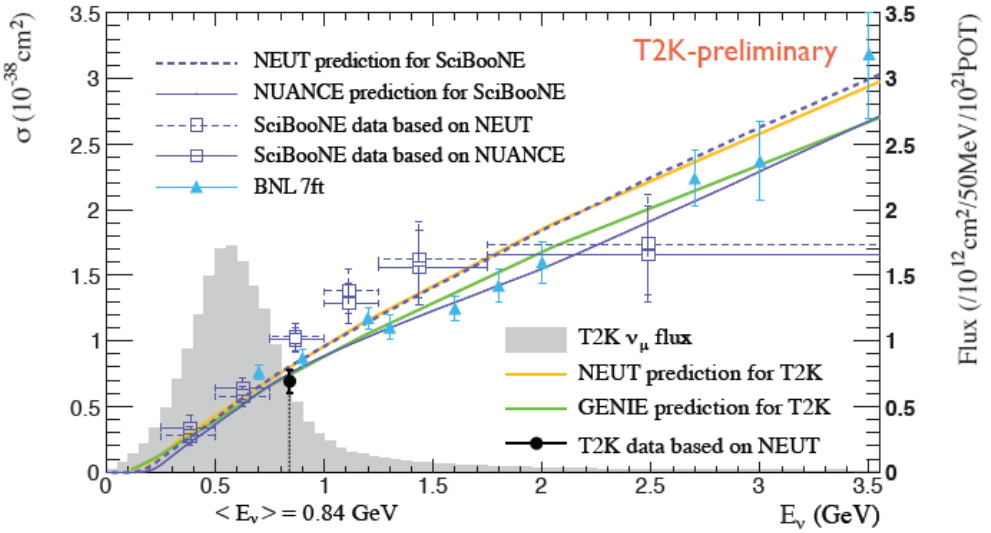






Flux averaged CC Inclusive Cross Section

- $\langle\sigma_{CC}\rangle_{\Phi} = \left(6.93 \pm 0.13(stat) \pm 0.85(syst)\right) \times 10^{-39} \frac{cm^2}{nucleons}$



$$\langle\sigma_{CC}\rangle_{\Phi} = \frac{\hat{N}}{T\Phi}$$

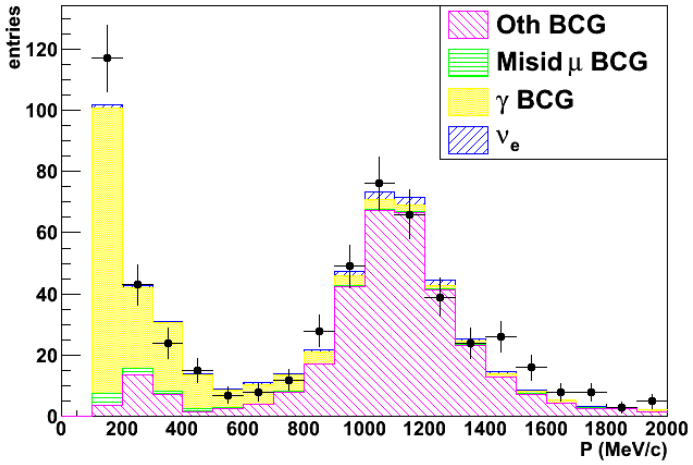
- NEUT prediction $\langle\sigma_{CC}\rangle_{\Phi} = 7.26 \times 10^{-39} \frac{cm^2}{neutrons}$

- GENIE prediction $\langle\sigma_{CC}\rangle_{\Phi} = 6.68 \times 10^{-39} \frac{cm^2}{neutrons}$

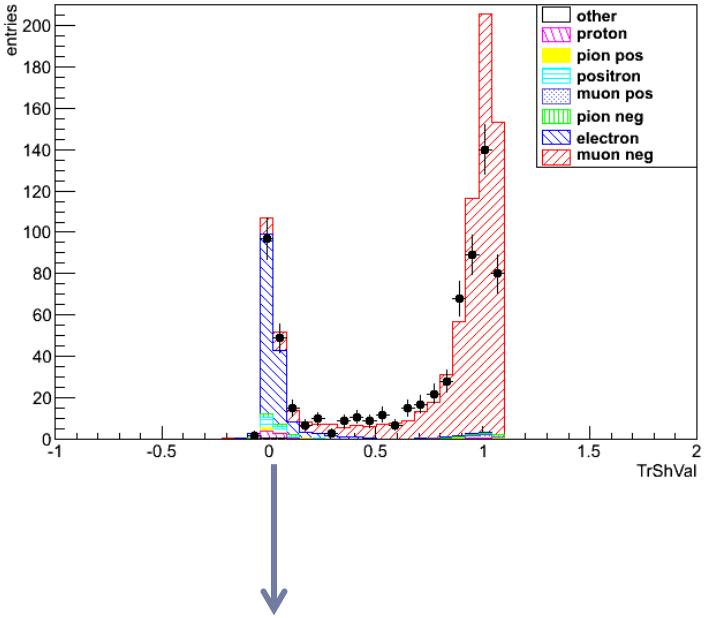
Other event samples for future cross section measurements

ν_e Tracker Selection

- Interactions in both FGDs
- TPC dE/dx compatible with the electron hypothesis
- ECal shower particle identification
- Positive analysis to constraint the γ background



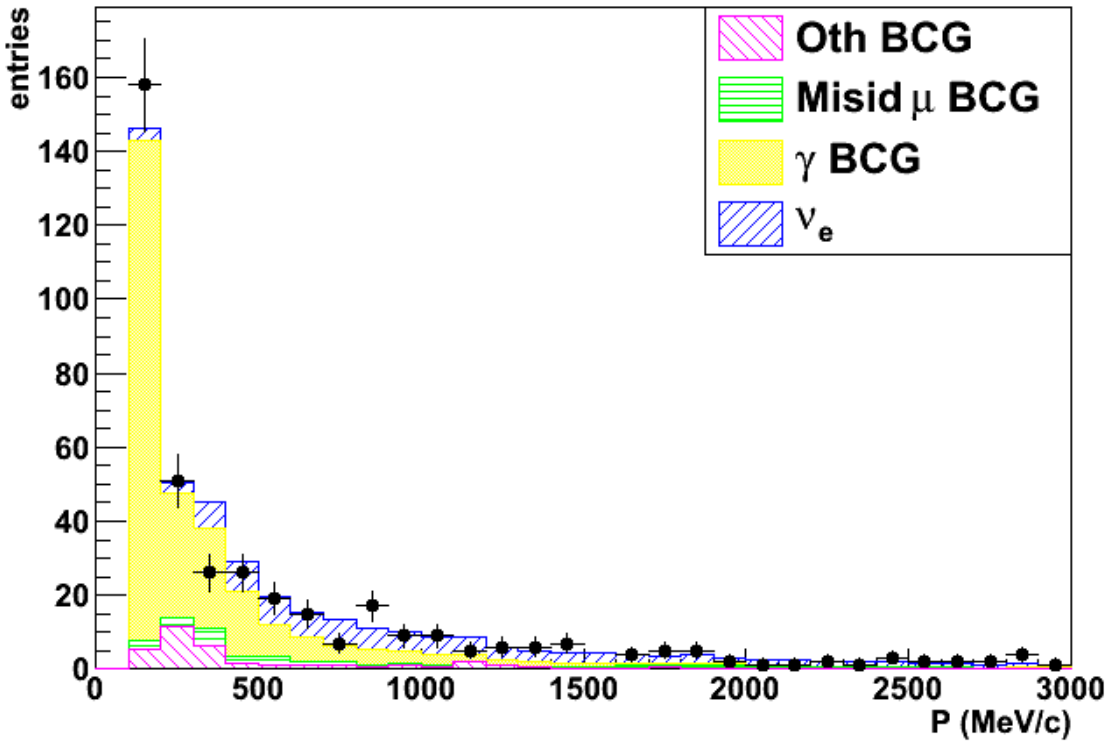
- ECal particle identification



Artificial Neural Network output compatible with the shower hypothesis

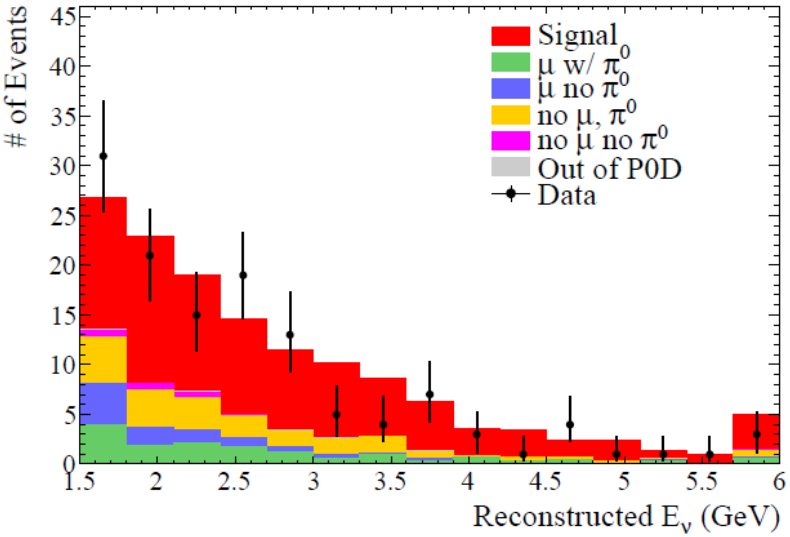
ν_e Tracker Selection

- Data/MC scaling factor
  - $f(\nu_e)= 0.845 \pm 0.146(stat.) \pm 0.107(syst.)$

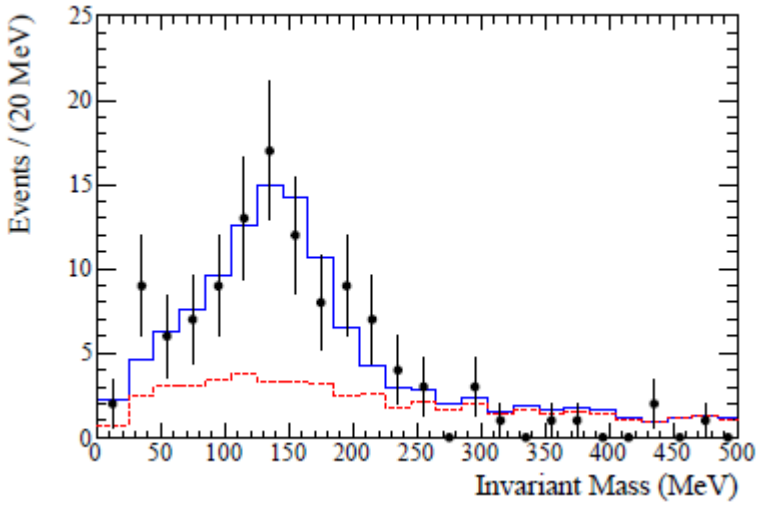


P0D ν_e And NC-π^0 Selection

- P0D ν_e high energy tail selection
  - $R = (D - B)/S$
    - 0.91±0.13(stat.)±0.18(det.)±0.13(flux × xsec.)



- P0D NC-π^0 selection
  - $Data/MC$
    - 0.84±0.16(stat.)±0.18(syst.)
  - $\frac{(Data/MC)_{NC-P0D}}{(Data/MC)_{CC-Tracker}}$
    - 0.81±0.15(stat.)±0.14(syst.)

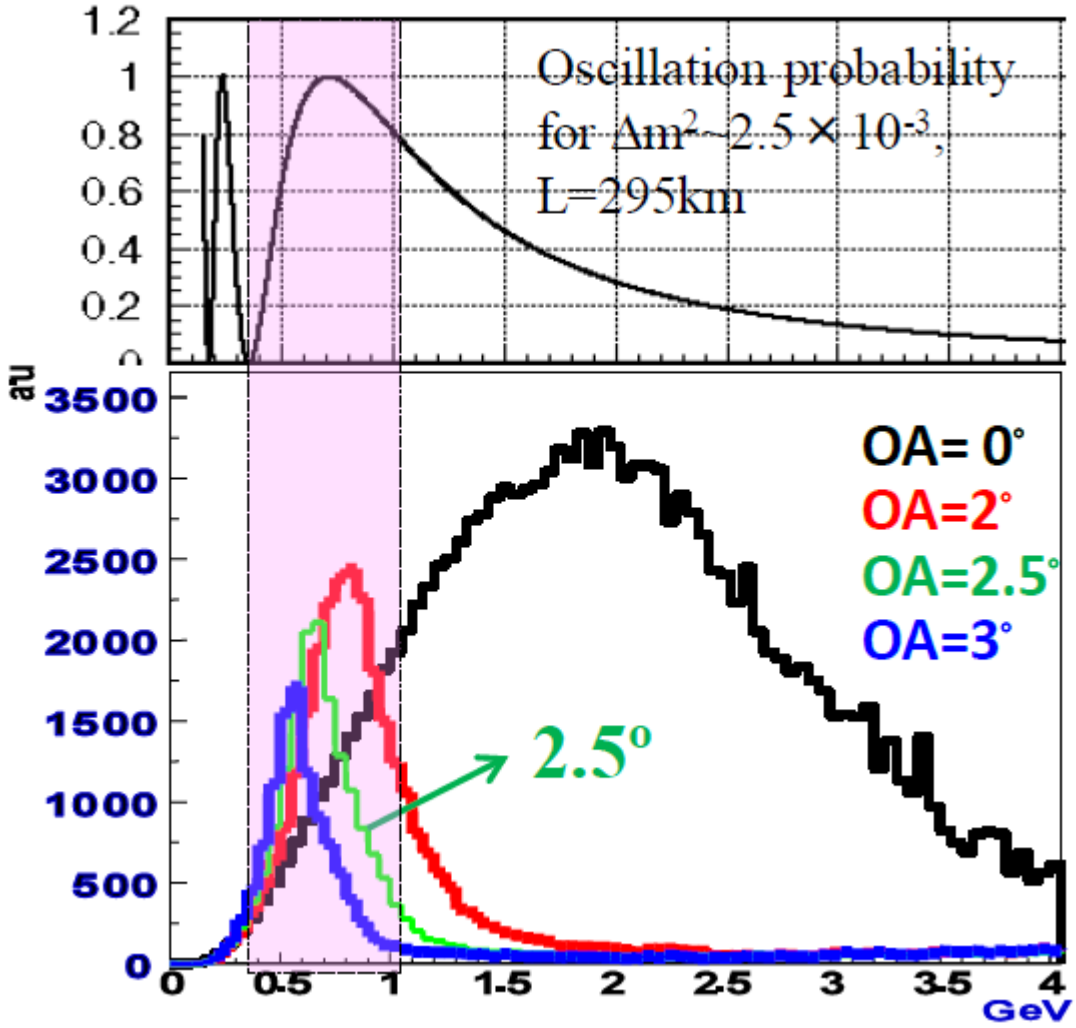


Final Words

- First CC ν_μ inclusive cross section measurement at near detector with Run1+2 data was presented
- ν_e and NC-π^0 selection established
  - Low statistics at the moment
- More cross sections to be measured in the future

Back Up

Off-axis configuration



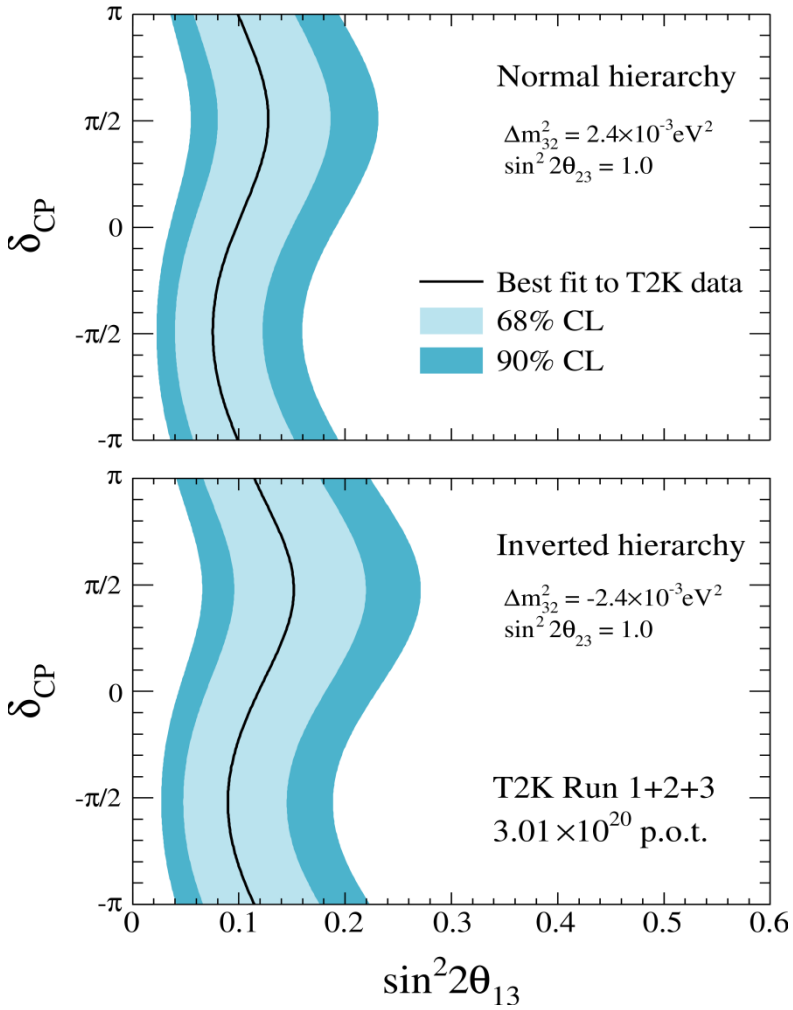
T2K ν_e Appearance Result

- 11 ν_e candidates observed
  - 3.22±0.43 expected if $\theta_{13} = 0$
  - p-value to observe 11 or more events is 0.08% (3.2σ)
- Normal hierarchy bf

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

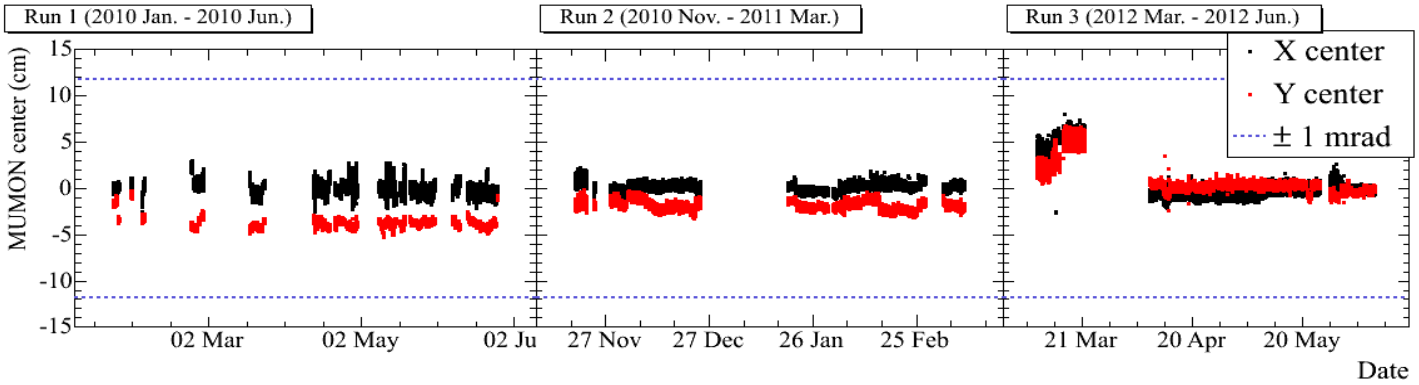
- Inverted hierarchy bf

$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

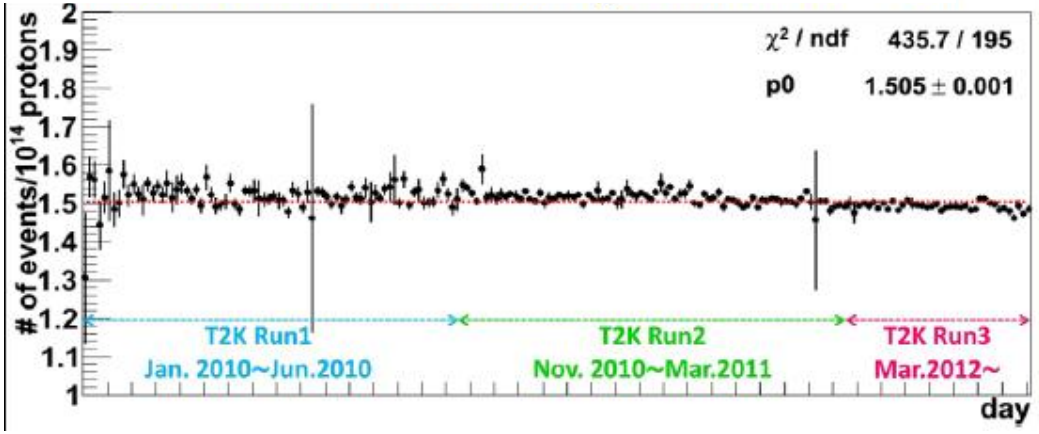


Muon monitor beam direction

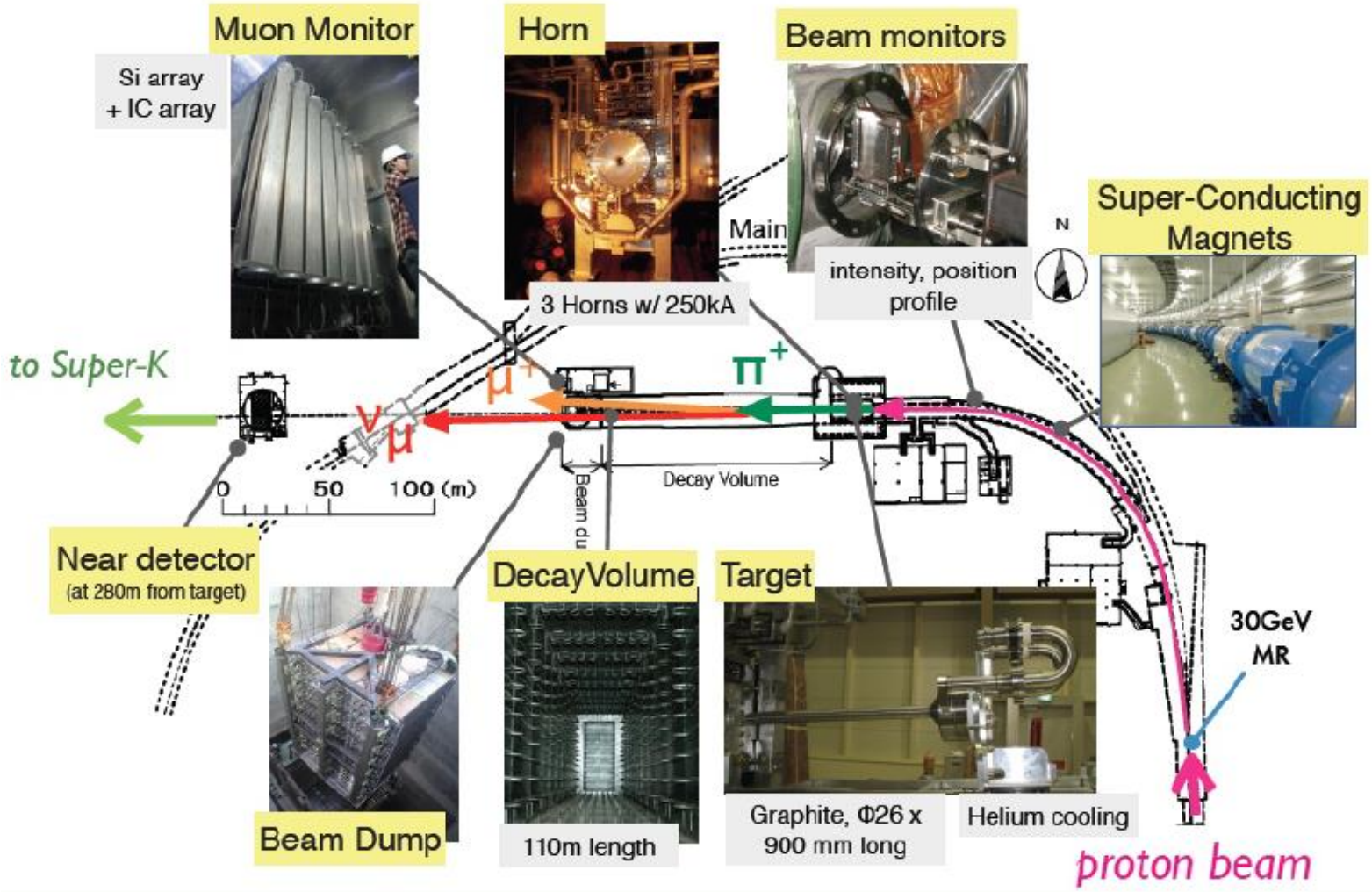
- Muon monitor beam direction
  - Stability << 1mrad



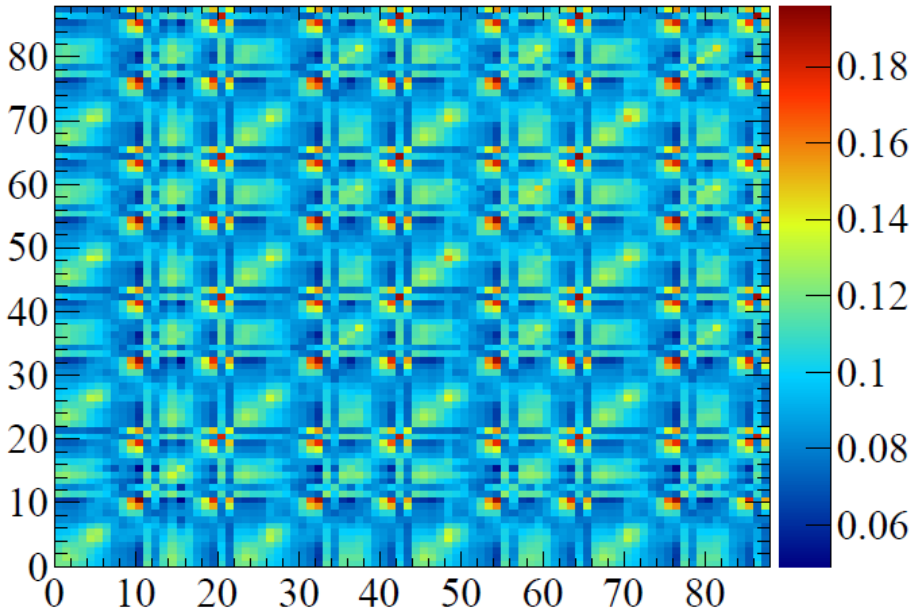
- INGRID interaction rate stability



T2K: Beam Line



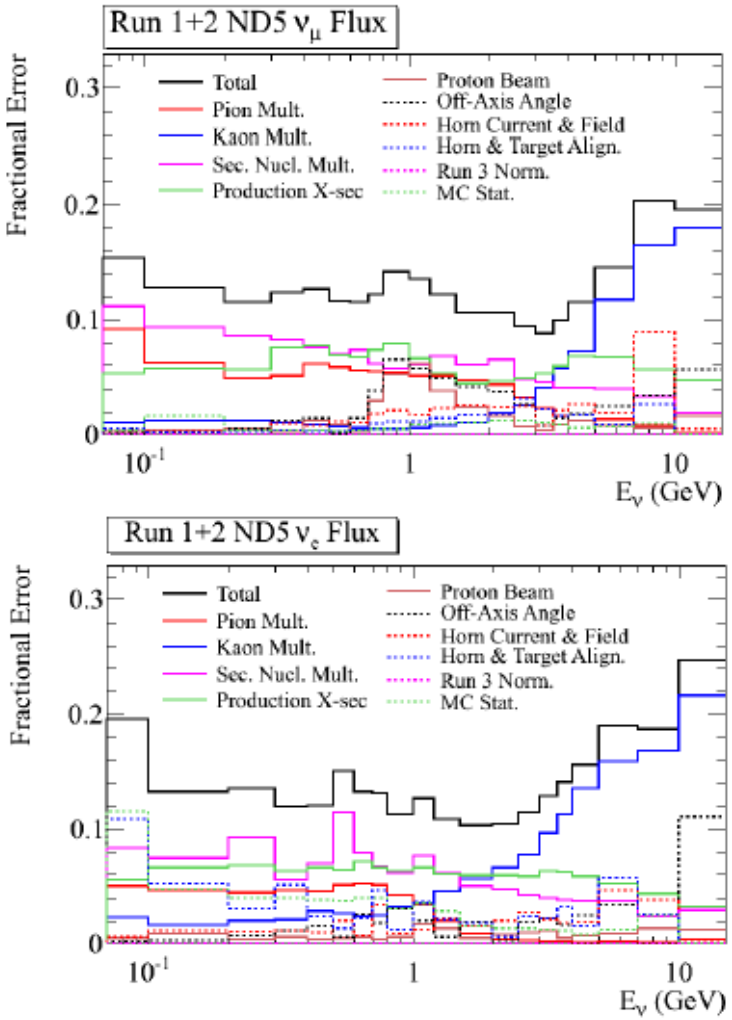
Flux systematics



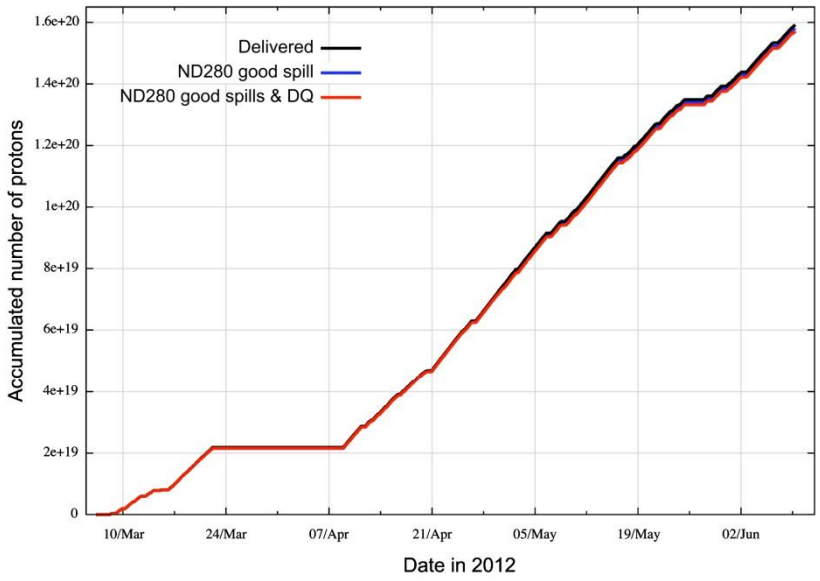
Bin	
0-10	ND280 ν_μ
11-12	ND280 anti-ν_μ
13-19	ND280 ν_e
20-21	ND280 anti-ν_e
22-32	Far Detector ν_μ
33-34	Far Detector anti-ν_μ
35-41	Far Detector ν_e
42-43	Far Detector anti-ν_e
44-87	Far Detector Run3b/3c ν

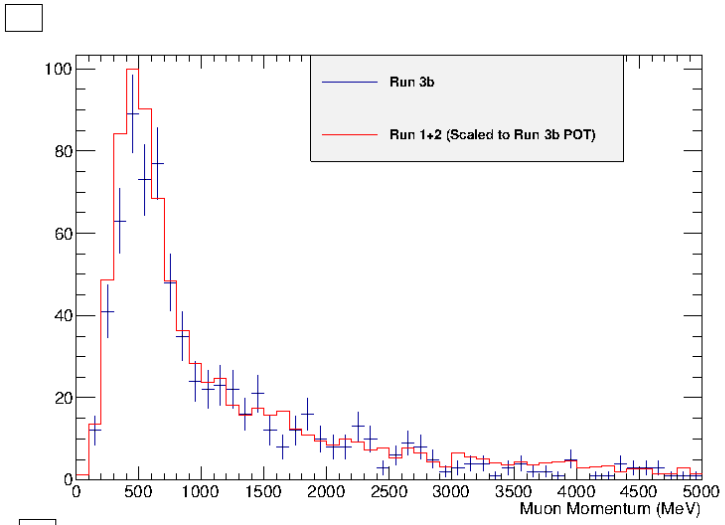
Beam Flux Uncertainties

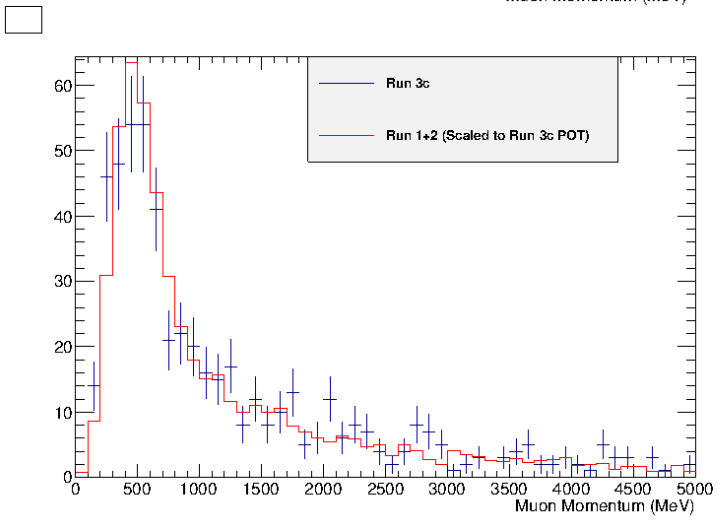
- Kaon production multiplicity
- Pion production multiplicity
- Proton beam
  - Alignment and intensity
- Off-axis angle
- Horn
  - Angular alignment
  - Field asymmetry
  - Absolute current
- Production cross sections
- Target alignment
- Secondary nucleon production
- ND280 phase space



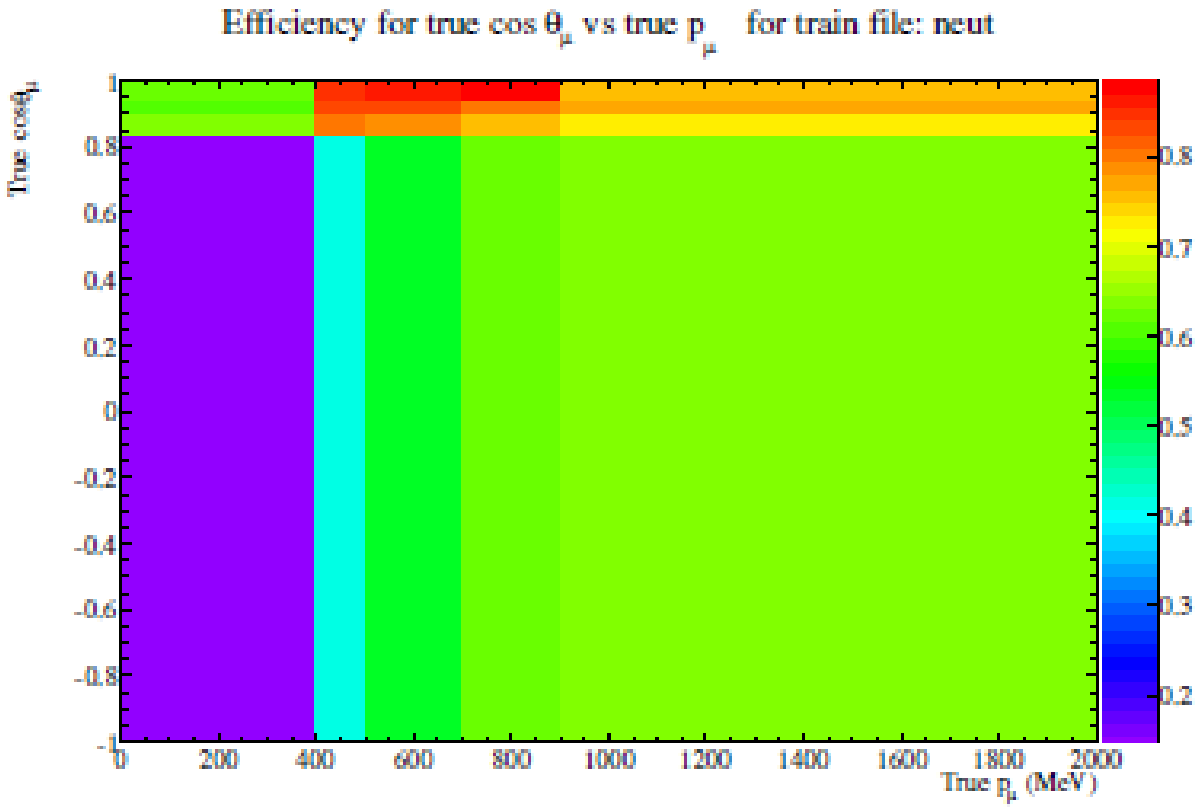
ND280 Run3 Data Cross Check With Run1+2



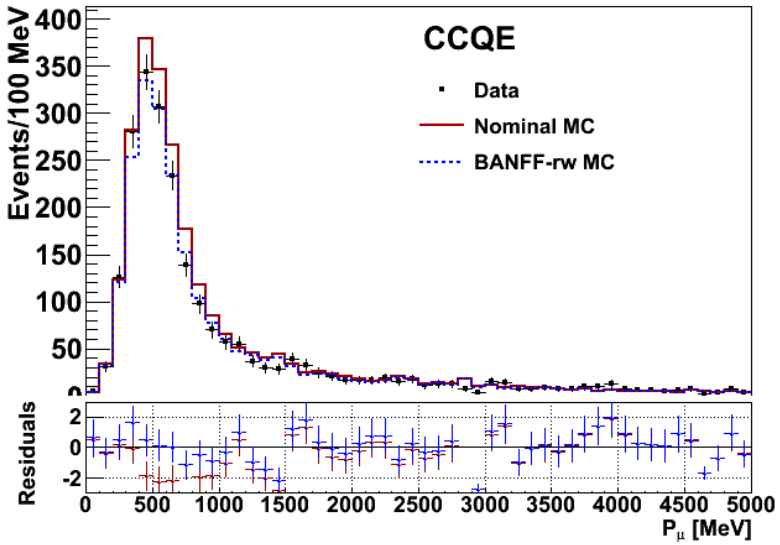


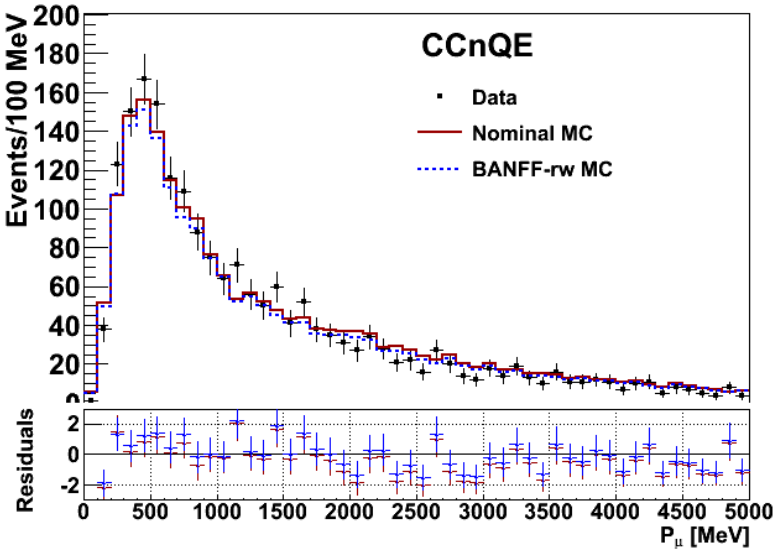


CC Efficiency (MC)



Fit Result From The ND280 Data

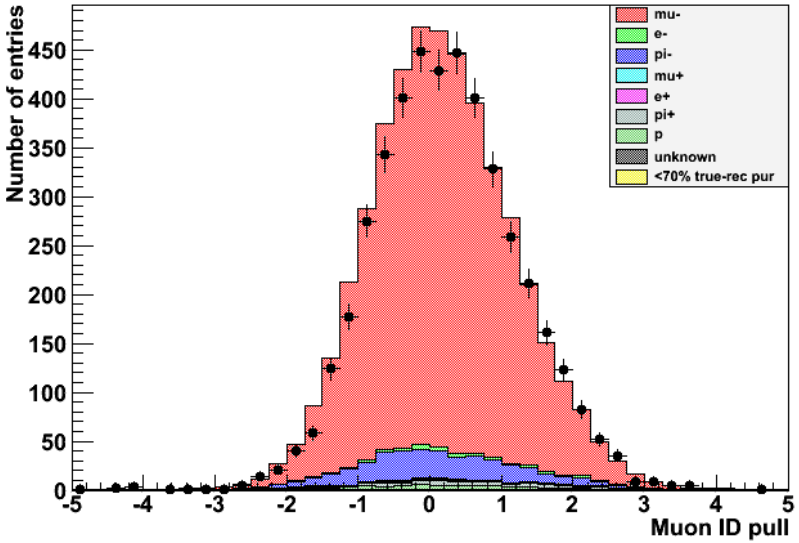


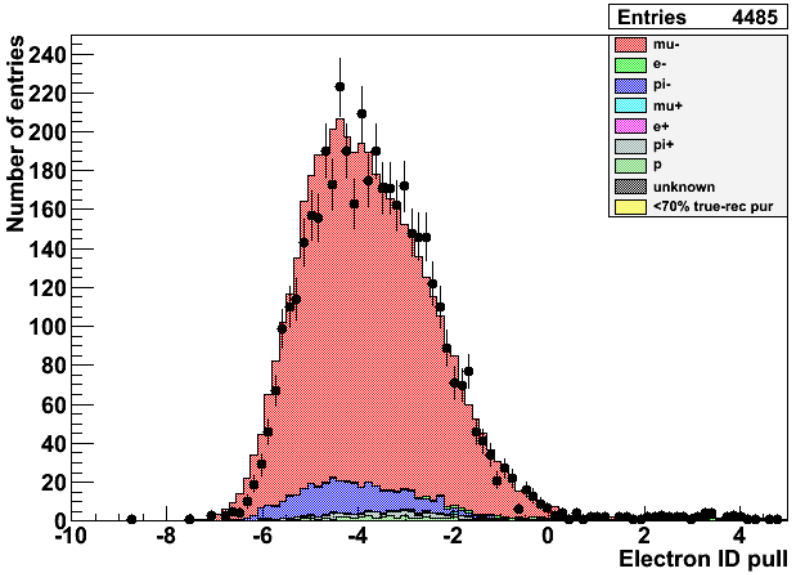


CC ν_μ Inclusive Selection

Cut	Data Run1	MC Run1	Data Run2	MC Run2
CC Inclusive Selection				
Good negative track in FV	2479	2347.9	6358	6148.8
Upstream TPC veto	1741	1800.7	4502	4749.6
PID cut	1202	1266.2	3283	3440.6
CCQE Sub-Sample Selection				
TPC-FGD track = 1	664	727.4	1853	1989.9
No Michel electron	619	676.0	1735	1858.8

TPC Muon-Electron Pulls

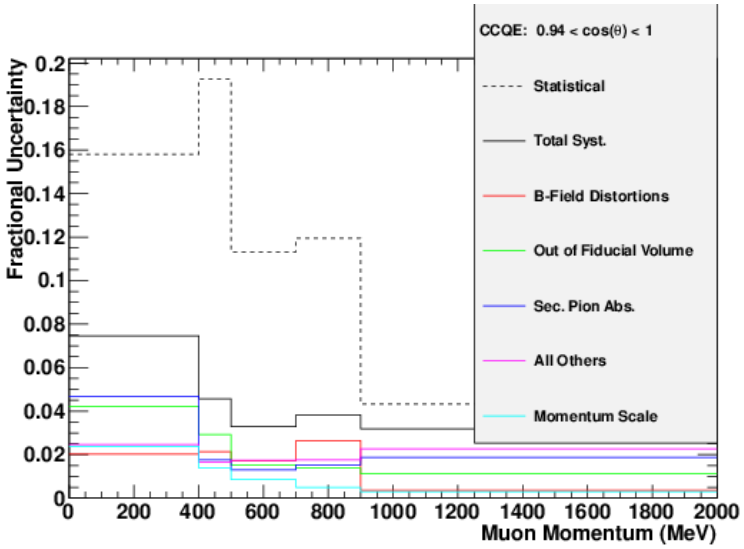


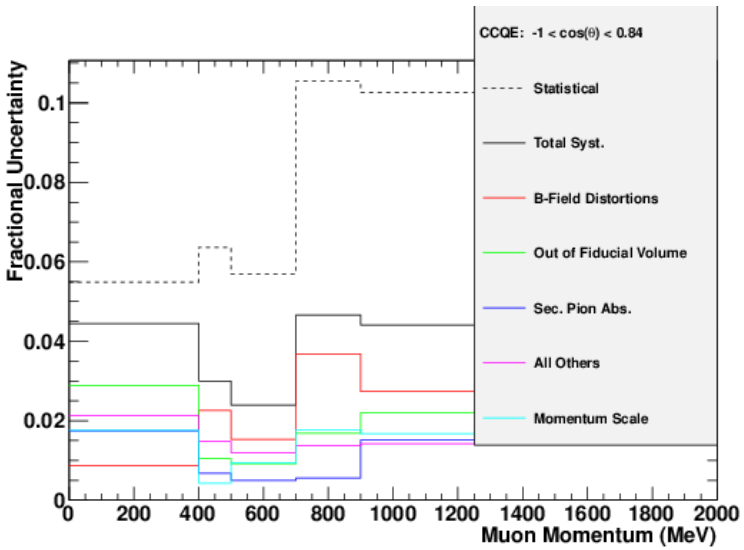


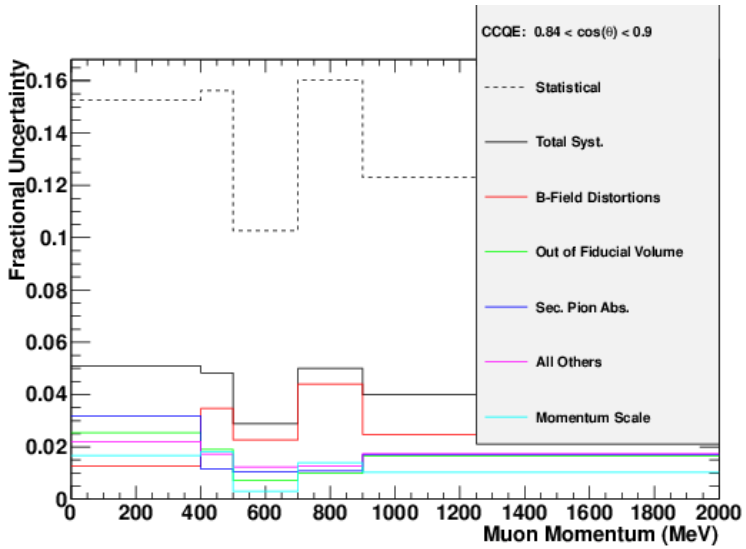
ND280 Detector Systematics Table

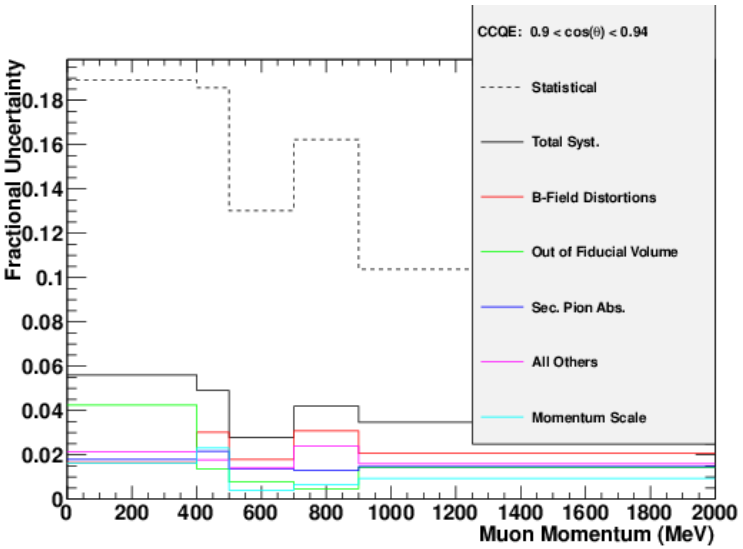
Systematics	Sample	Error (%)
Pion re-interaction	Special MC	3.0
Track quality	Beam data/MC	0.1
TPC single track eff.	Beam data/MC	0.5
TPC double track eff.	Beam data/MC	0.6
TPC particle ID (PID)	Beam data/MC	0.1
TPC momentum scale	External measurements	0.5
TPC mom. distortion	Special MC	~1-7
TPC mom. resolution	Beam data/MC	2.0
TPC-FGD match. eff.	Sand interact. + cosmics	<1
Fiducial mass	External measurements	0.7
Charge mis-ID	Beam data/MC	<0.3
Michel electron eff.	Cosmics	0.5
Cosmic rays	Special MC	0.1
Sand interactions	Special MC	1.5
Out-of-fiducial volume	Several samples	~1-9
Pileup	Beam data/MC	0.2
Track Multiplicity external bkgd	Beam data/MC	1.5

CCQE Fractional Errors









CCnQE Fractional Errors