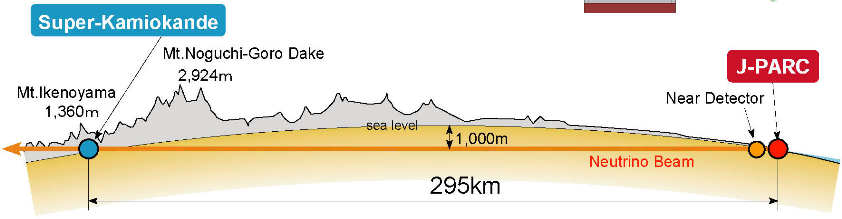
Charged Current Cross Section Measurements at T2K

David Hadley on behalf of the T2K collaboration
NuFact 2013

The T2K Experiment

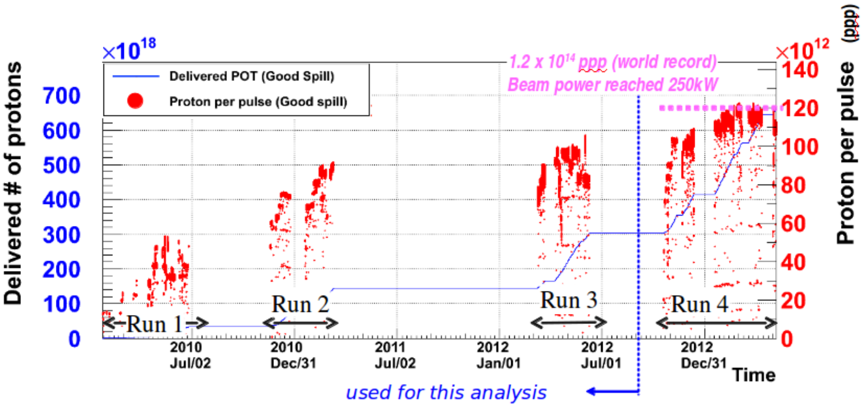


Goals

- discover ν_e appearance in a ν_μ beam
- make precise measurements of ν_μ disappearance
- study neutrino-nucleus interactions at $E_\nu \sim 1\text{GeV}$

- A high intensity proton beam at J-PARC produces a narrow-band ν_μ beam with a peak energy of 0.6GeVat the far detector,
- The Far detector is Super-Kamiokande, a 50kton water Cherenkov detector, located 2.5° off-axis and 295km from the production point.
- Detectors in the ND280 complex at 280m are used to directly measure the neutrino beam properties and neutrino-nucleus interaction cross sections.

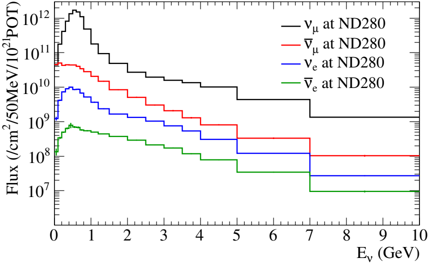
The T2K Beam



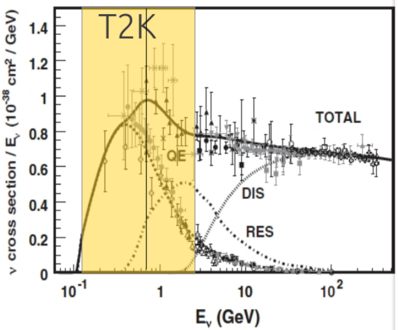
- T2K has collected 6.6×10^{20} POT to date (Run 1-4).
- The analyses presented here are based on 2.7×10^{20} POT (Run 1-3 @ ND280).
- Improved analyses under development will include Run 4.

The T2K Beam

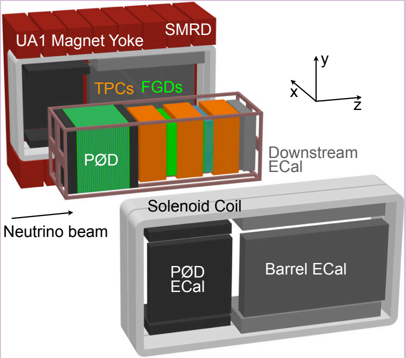
- Narrow-band beam at off axis angle.
- Mostly ν_μ from pion decay.
- Beam has a peak energy $\sim 0.6\mathrm{GeV}$.
- Close to the quasi-elastic peak.
- On-axis near detector INGRID monitors the neutrino beam.
  - INGRID will also make measurements of neutrino cross sections.

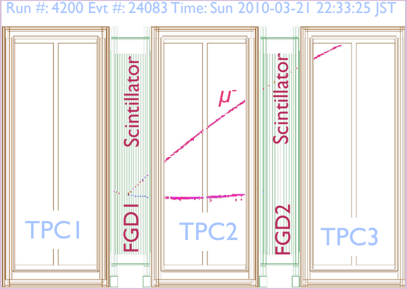


Formaggio & Zeller, Rev. Mod. Phys. 84 (2012)



Off-axis Near Detector (ND280)





ND280 Tracking Detector

- The Fine Grained Detector (FGD1) consists of layers of $10 \times 10\mathrm{mm}$ plastic scintillator bars readout with Multi-Pixel Photon Counters (MPPCs).
- FGDs provide target mass and vertex reconstruction.
- The Time Projection Chambers (TPCs) provided PID based on $\mathrm{d}E/\mathrm{d}x$ in the Argon based gas and momentum measurement from track curvature in the magnetic field.

π^0 *Detector*

- see NCE talk by D. Ruterbories.

T2K, Nucl. Instrum. Meth. A 659, 106 (2011)
FGD, Nucl. Instrum. Meth. A 696, 1 (2012)
TPC Nucl. Instrum. Meth. A 637, 25 (2011)

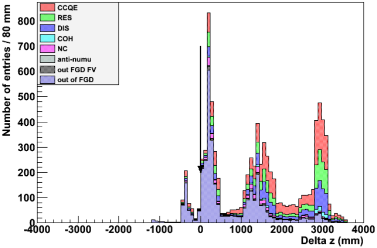
ND280 Event Selection

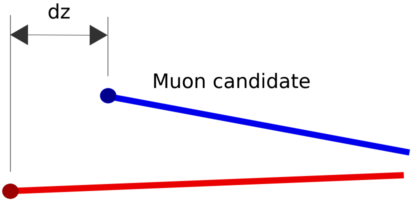
2 samples selected: a QE enhanced, and an non-QE sample.

CC Inclusive Selection $(\mu + X)$

- 1 good-quality negative track starting within the FGD fiducial volume.

ND280 Event Selection





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CC Inclusive Selection ($\mu + X$)

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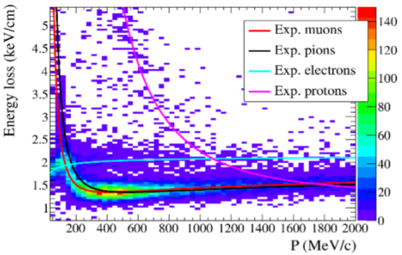
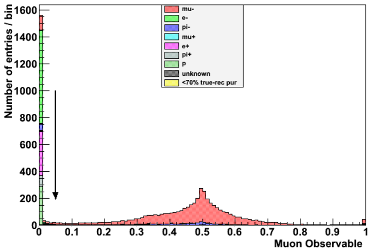
- Upstream veto

ND280 Event Selection





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CC Inclusive Selection $(\mu + X)$

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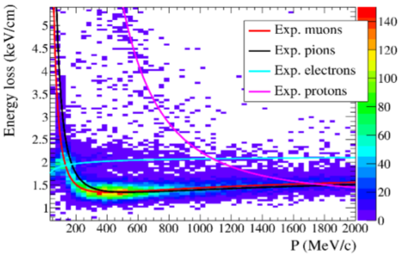
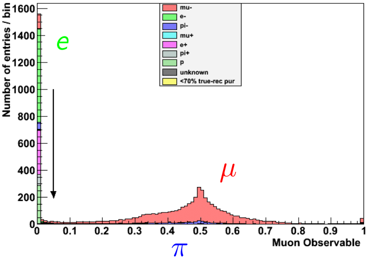
ND280 Event Selection





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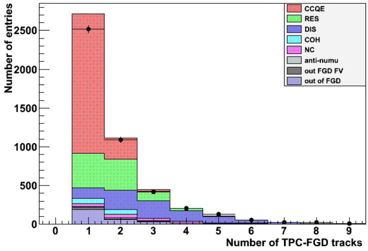

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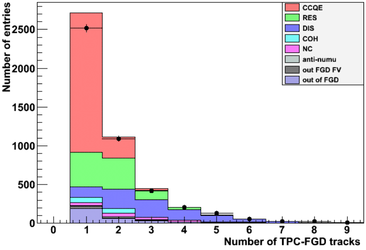
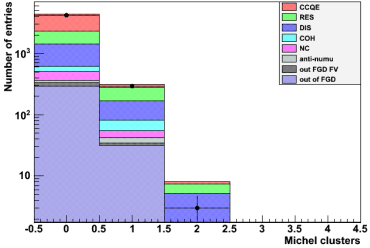
CC QE Selection $(\mu + 0\pi)$

- TPC track veto

ND280 Event Selection





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CC Inclusive Selection ($\mu + X$)

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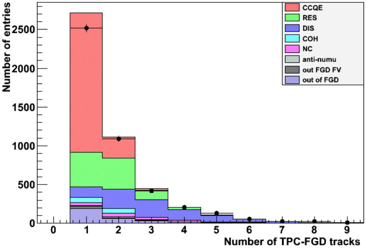
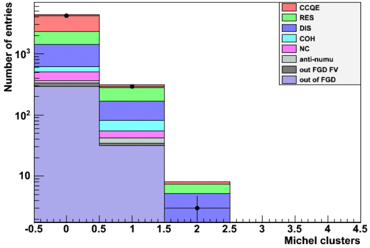
CC QE Selection ($\mu + 0\pi$)

- TPC track veto
- Michel electron veto

ND280 Event Selection





2 samples selected: a QE enhanced, and an non-QE sample.

CC Inclusive Selection $(\mu + X)$

- 1 good-quality negative track starting within the FGD fiducial volume.
- Upstream veto
- Muon PID

CC QE Selection $(\mu + 0\pi)$

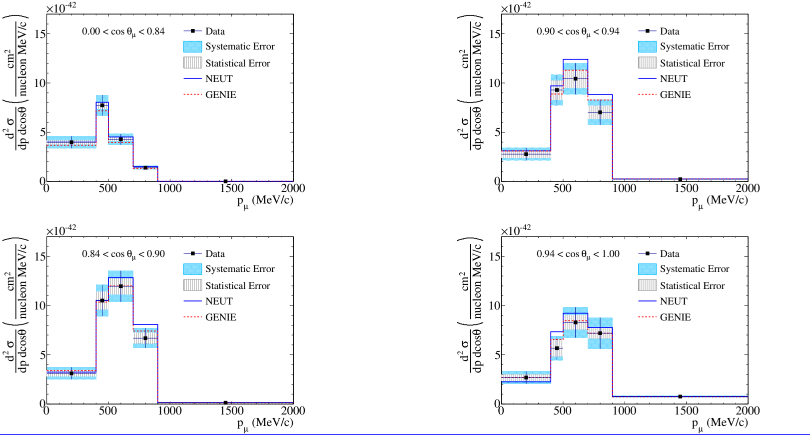
- TPC track veto
- Michel electron veto

Non-QE selection

- any event that fails either of the final 2 cuts

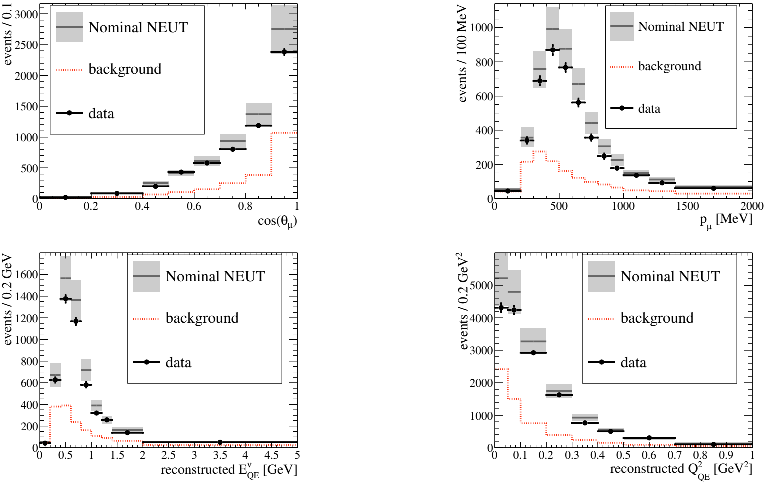
Flux Integrated CC Inclusive Cross Section Measurement

Phys. Rev. D 87, 092003 (2013)



- Combine the QE and non-QE samples.
- Unfold the reconstructed $p_\mu - \cos(\theta_\mu)$ distributions to estimate the true muon kinematics.
- Measure double differential $p_\mu - \cos(\theta_\mu)$ distribution and total flux integrated cross section.

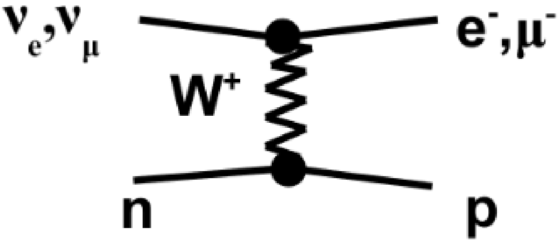
Reconstructed Kinematics



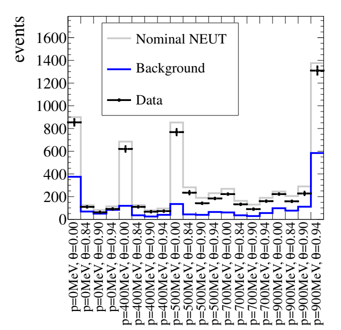
- CCQE efficiency=40%, purity=72%.
- Dominant background from CC resonant pion production.
- E_ν and Q^2 calculated from muon momentum assuming QE kinematics.

NEUT CCQE Model

- Smith-Moniz implementation CCQE
  - Dipole form factor ($M_A^{QE} = 1.2\mathrm{GeV}$)
  - Initial Nucleon state given by relativistic Fermi gas model
- FSI with semi-classical cascade model
- No additional contribution from multi-nucleon effects



Measurement of the CCQE Cross Section



The Log Likelihood Ratio is minimised,

$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{p_\mu-\cos(\theta_\mu)\text{bins}} \left[N_i^{\text{predicted}}(\boldsymbol{\theta}) - N_i^{\text{observed}} + N_i^{\text{observed}} \ln \frac{N_i^{\text{observed}}}{N_i^{\text{predicted}}(\boldsymbol{\theta})} \right] + \ln\frac{\pi_d(\mathbf{d})}{\pi_d(\mathbf{d}_{\text{nominal}})} + \ln\frac{\pi_f(\mathbf{f})}{\pi_f(\mathbf{f}_{\text{nominal}})} + \ln\frac{\pi_x(\mathbf{x})}{\pi_x(\mathbf{x}_{\text{nominal}})} \quad (1)$$

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.

Systematic Uncertainties and Implementation

Flux

- Flux prediction based on measurements at NA61/SHINE and T2K proton beam measurements.
- $\sim 10-15\%$ uncertainty on ν_μ flux.

Implementation

- MC prediction binned in p_μ, $\cos(\theta_\mu)$, E_ν and interaction type.
- Reweight bin contents based on value of nuisance parameters.
- Multi-variate Gaussian priors on nuisance parameters.

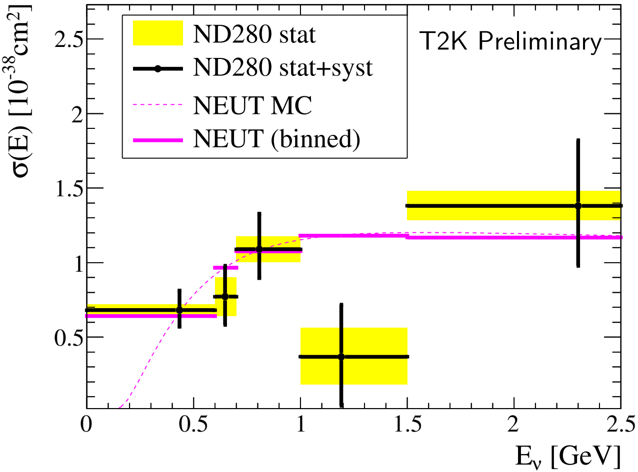
Interaction Model Uncertainties

- Vary model parameters eg M_A^{RES}, p_F etc
- Empirical parameters eg pion background normalisation uncertainties.
- Uncertainties from comparison of NEUT generator with external data

Detector Uncertainties

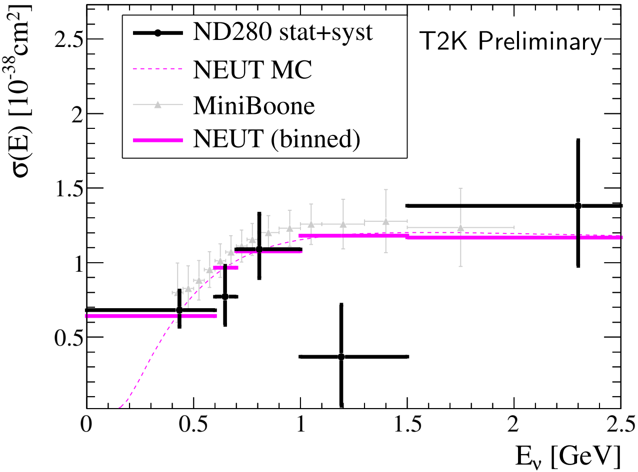
- Estimate uncertainty on rate of selection in $p_\mu - \cos(\theta_\mu)$ bins.
- Dominant uncertainties are from uncertainties on the TPC momentum measurement and out of FV backgrounds.
- $\sim 5-10\%$ overall detector uncertainty.

Measurement of the CCQE Cross Section



A χ^2 test comparing the fitted result with the nominal NEUT model, with $M_A^{QE} = 1.2\mathrm{GeV}$, gives a p-value of 17% indicating agreement between the data and the cross section model.

Measurement of the CCQE Cross Section



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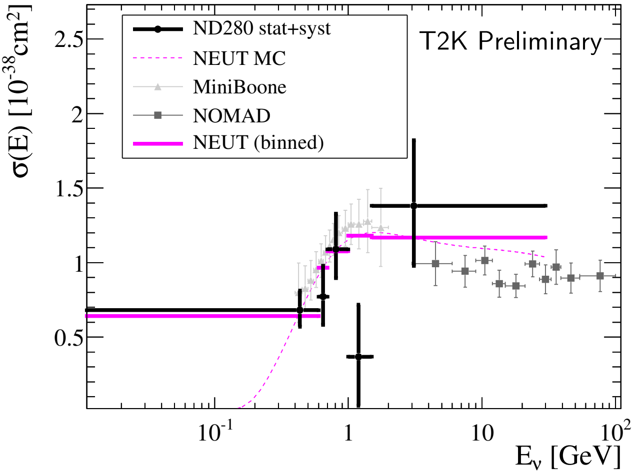
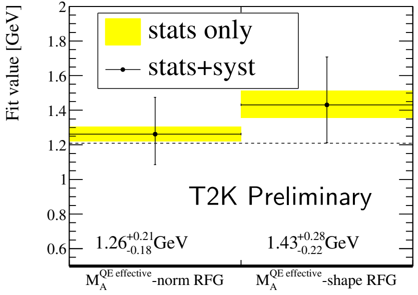


A χ^2 test comparing the fitted result with the nominal NEUT model, with $M_A^{QE} = 1.2\text{GeV}$, gives a *p*-value of 17% indicating agreement between the data and the cross section model.

M_A^{QE}-effective extraction

Fit p_μ-$\cos(\theta_\mu)$ distribution with M_A^{QE} as a free parameter. Fit with 2 settings,

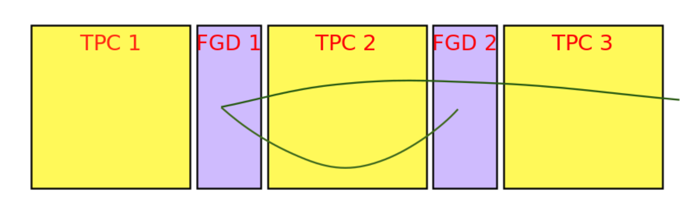
- M_A^{QE} shape-only
- M_A^{QE} normalisation+shape



- Previous experiments have observed a discrepancy in the fitted values of M_A^{QE} between Deuterium and heavier nuclei.
- A large effective M_A^{QE} is believed to account for nuclear effects not included in the model.
- Both fit results are consistent with the value used in NEUT, $M_A^{QE} = 1.2\text{GeV}$.

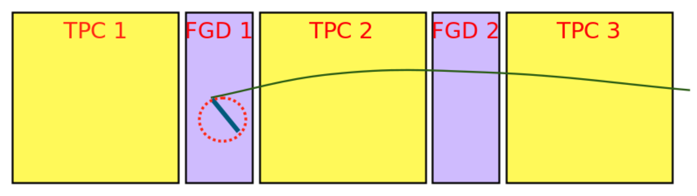
New CC Analysis

Additional TPC+FGD Tracks



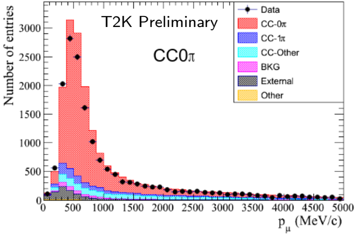
- Highest momentum negative track is selected as the muon candidate.
- Tag pion/electrons/protons by applying PID to additional tracks.

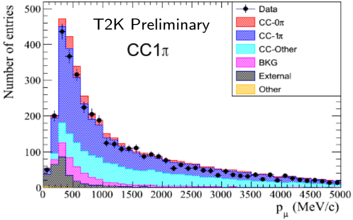
FGD only tracks

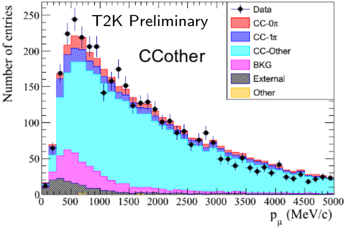


- Use FGD only tracks to tag stopping particles.
- Tag pion from Michel tag or dE/dx in FGD.

New CC Analysis







	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	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%

- Cleaner sample of CC1π to better constrain the π background in CCQE cross section analysis.

New CC Analysis

Parameter	Prior to ND280 Constraint	After ND280 Constraint (Runs 1-4)	After ND280 Constraint (2012 analysis, Runs 1-3)
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072	1.269 ± 0.194
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063	1.223 ± 0.127

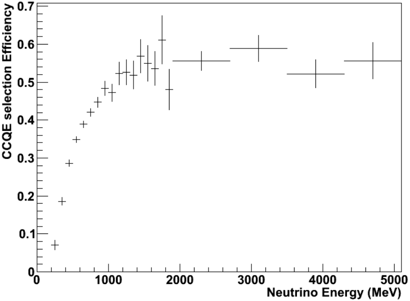
- Some example results from the fit to these samples for the oscillation analysis.
- Significant improvement on the uncertainty on these model parameters.
  - Primarily from analysis improvements, not from increased statistics.
- We should expect similar improvements when these samples are used for cross section measurements.
- See Oscillation Systematics talk by A. Kaboth

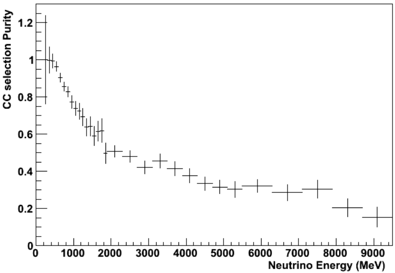
Summary

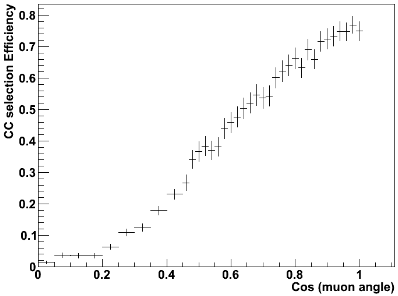
- T2K's first CC inclusive cross section publication was published earlier this year (Phys. Rev. D 87, 092003 (2013)).
- First Preliminary T2K CCQE Cross Section measurement presented in this talk.
- Extraction of CCQE energy dependent cross section and model parameters from fit to ND280 $p_\mu - \cos(\theta_\mu)$.
- Expect better performance in future cross section analyses
  - at least double statistics (current analysis only uses data up to summer 2012)
  - new improved reconstruction
  - selection and analysis

Backup

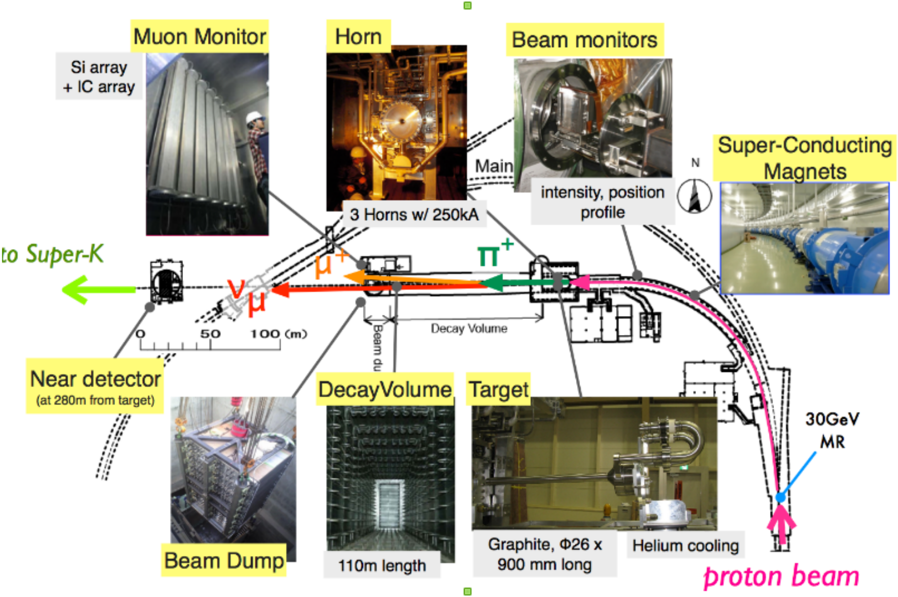
ND280 CC Selection Efficiency and Purity





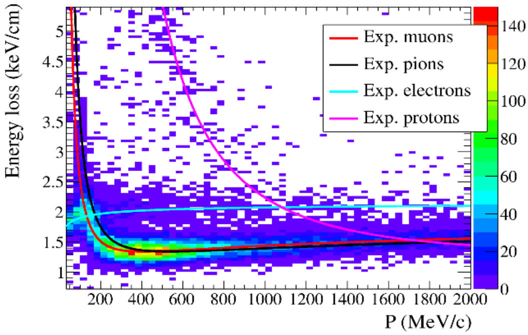


The T2K Beam

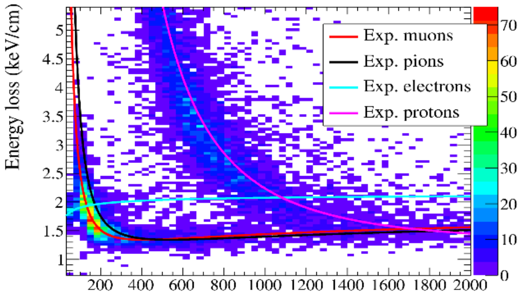

Muon Monitor
Si array
+ IC array
Horn
3 Horns w/ 250kA
Main
Beam monitors
intensity, position
profile
N
Super-Conducting
Magnets
to Super-K
π^+
μ^+
ν
μ
0 50 100 (m)
Decay Volume
Beam du
Near detector
(at 280m from target)
DecayVolume
110m length
Target
Graphite, Φ26 x
900 mm long
Helium cooling
Beam Dump
30GeV
MR
proton beam

ND280 TPC PID

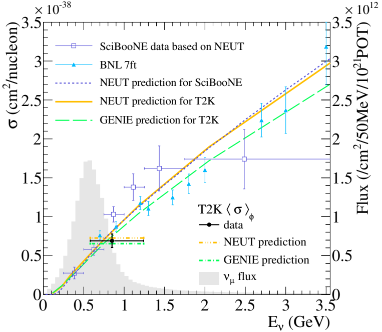
Negative tracks in the TPC.



Positive tracks in the TPC.



Flux Integrated CC Inclusive Cross Section Measurement



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