Recent results from T2K on neutrino interaction

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on behalf of the T2K collaboration

WIN13 @Natal

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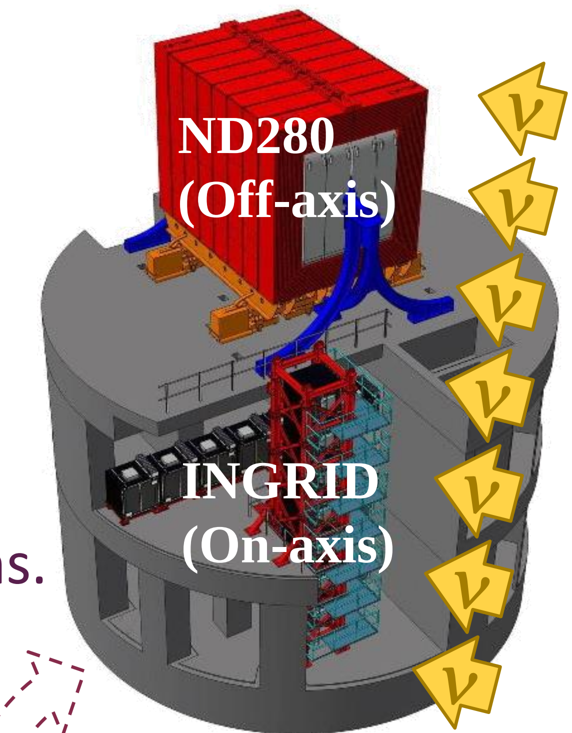
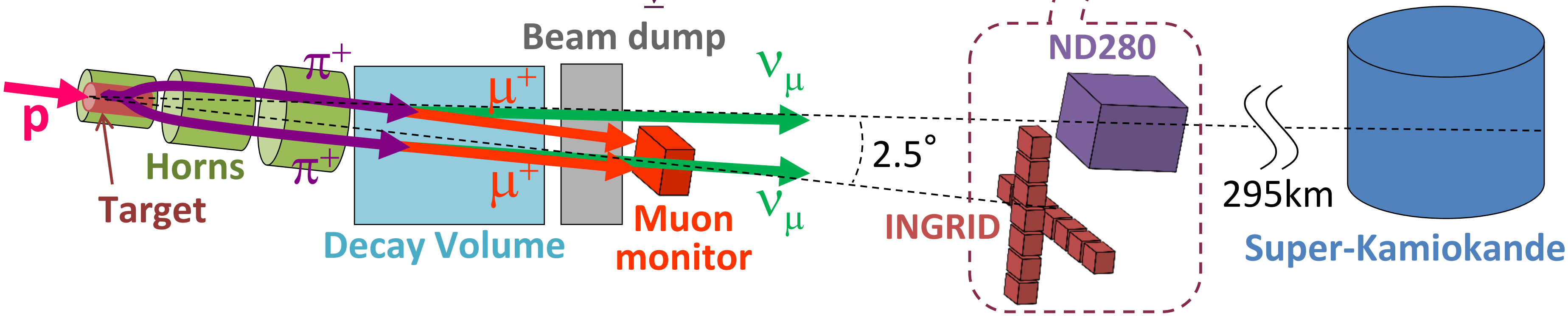
The T2K experiment

- High intensity neutrino beam from J-PARC.
- Super-Kamiokande, located 295km from neutrino generation point.
- ND280 (off-axis) and INGRID (on-axis) located 280m from neutrino generation point.

- Precise measurement of neutrino oscillations.
- Precise measurement of neutrino nucleus interactions at $E_\nu \sim 1$GeV.

T2K Near detectors





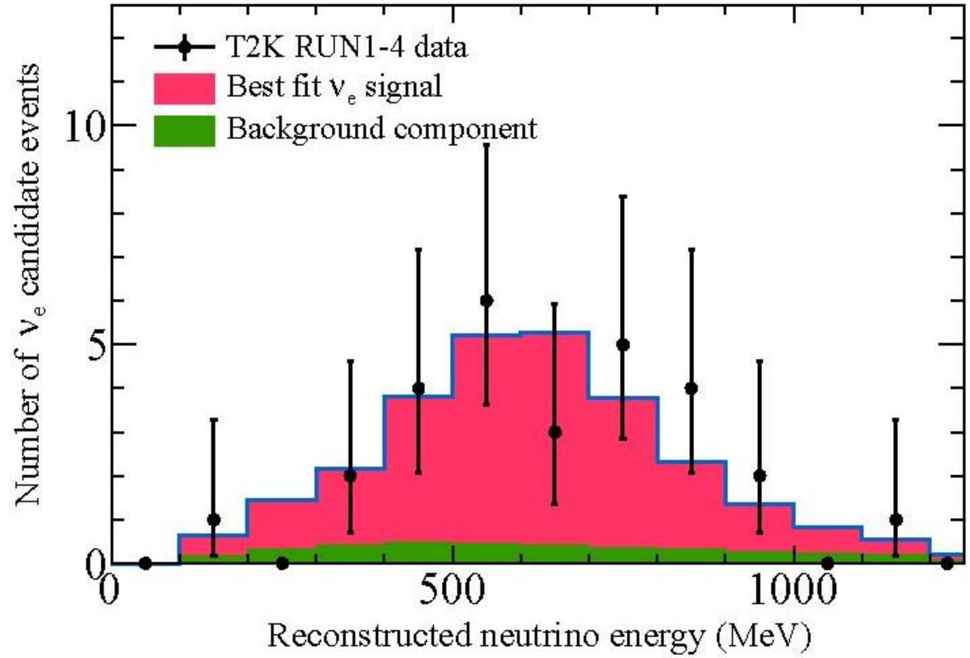
$\nu_\mu \rightarrow \nu_e$ observation

» T2K has made the first observation of $\nu_\mu \rightarrow \nu_e$ oscillation. (7.5σ) https://indico.cern.ch/getFile.py/access?contribId=9&sessionId=1&resId=0&materialId=slides&confId=234536

» Uncertainty of neutrino interactions is the dominant systematic error source.

» Precise measurement of neutrino interactions will have a big impact on oscillation precision in the future.

Reconstructed neutrino energy

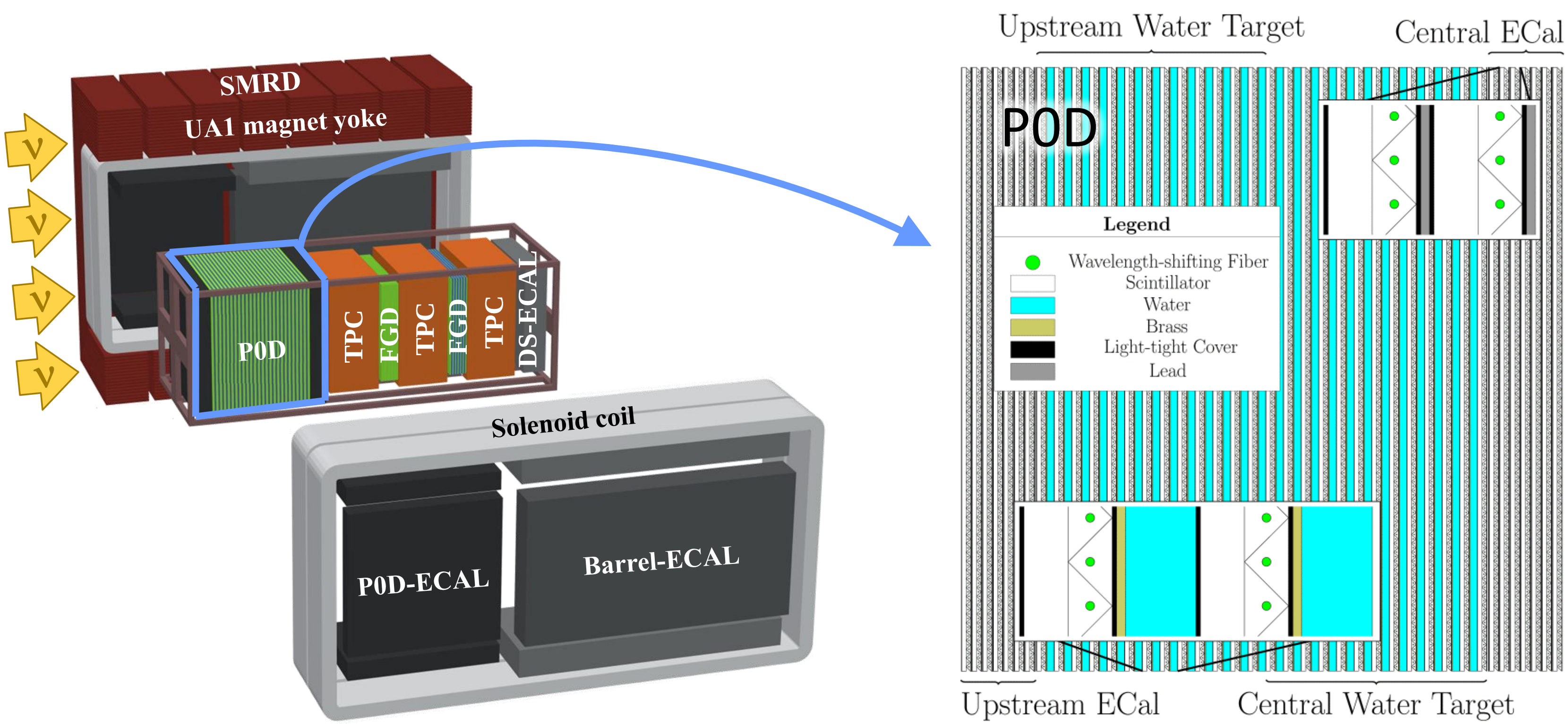


Systematic errors on the number of ν_e candidates

Error source	$\sin^2 2\theta_{13}$=0.0	$\sin^2 2\theta_{13}$=0.1
Beam flux + ν int. in T2K fit	4.9%	3.0%
ν int. (other experiments)	6.7%	7.5%
Far detector	7.3%	3.5%
Total	11.1%	8.8%

ND280 (off-axis near detector)

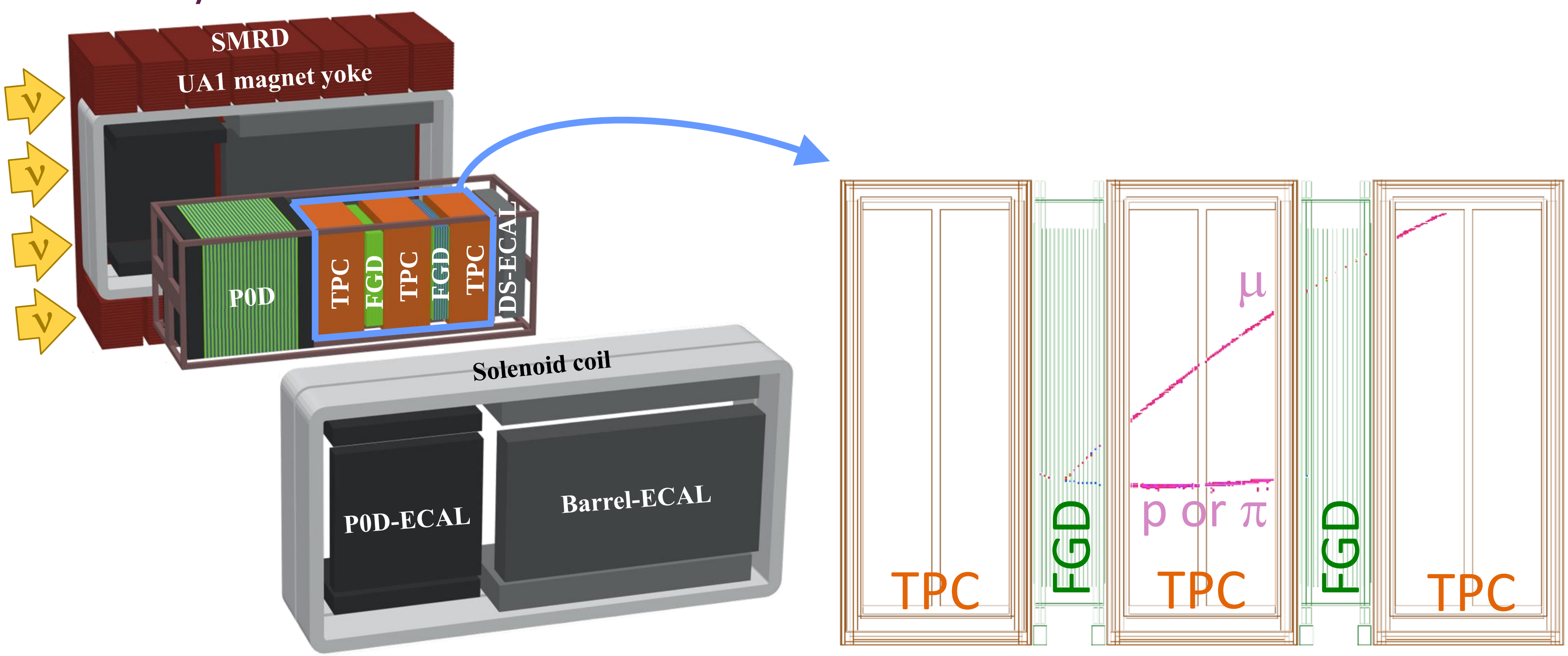
- » UA1 dipole magnet
  - Provide 0.2T magnetic field.
- » π^0 detector (P0D)
  - Water target section(center): water, scintillator and brass.
  - ECal sections (upstream and downstream): scintillator and lead.



ND280 (off-axis near detector)

» Tracker (FGD+TPC)

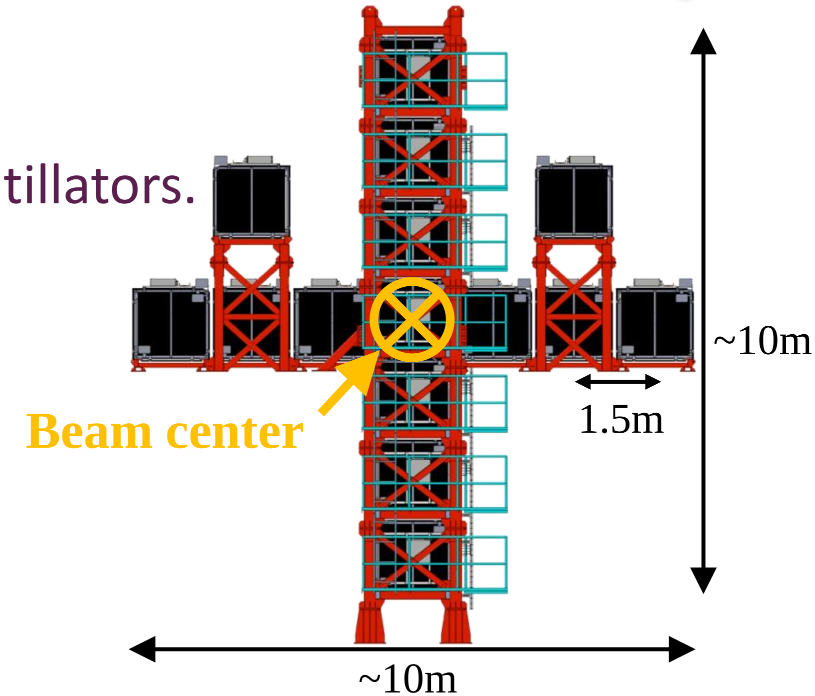
- The Fine Grained Detector (FGD) consists of layers of 10×10mm plastic scintillator bars.
- FGDs provide target mass and vertex reconstruction.
- The Time Projection Chambers (TPCs) provide PID based on dE/dx and momentum based on the track curvature.

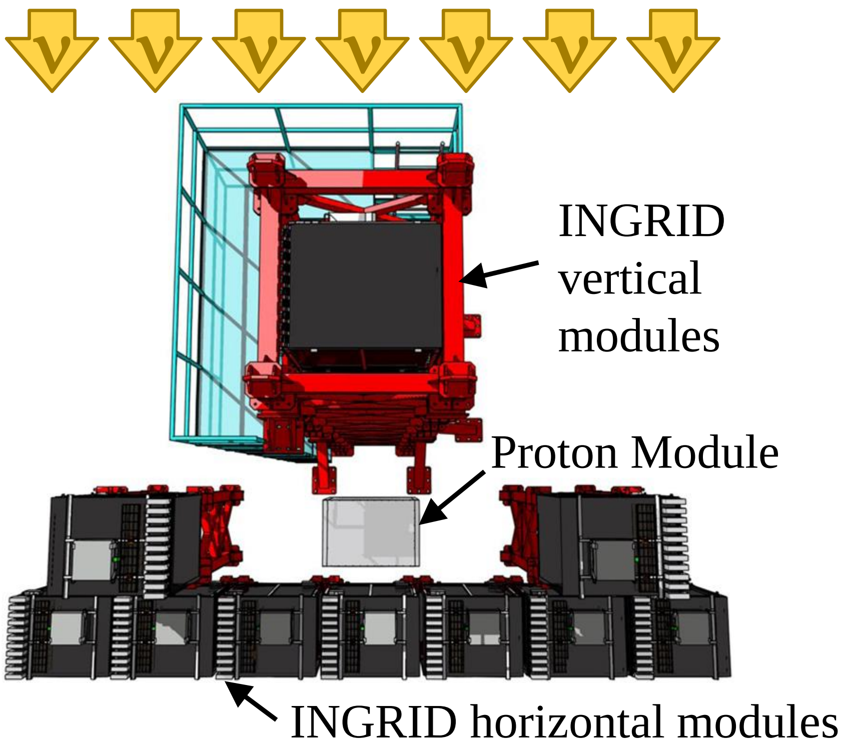


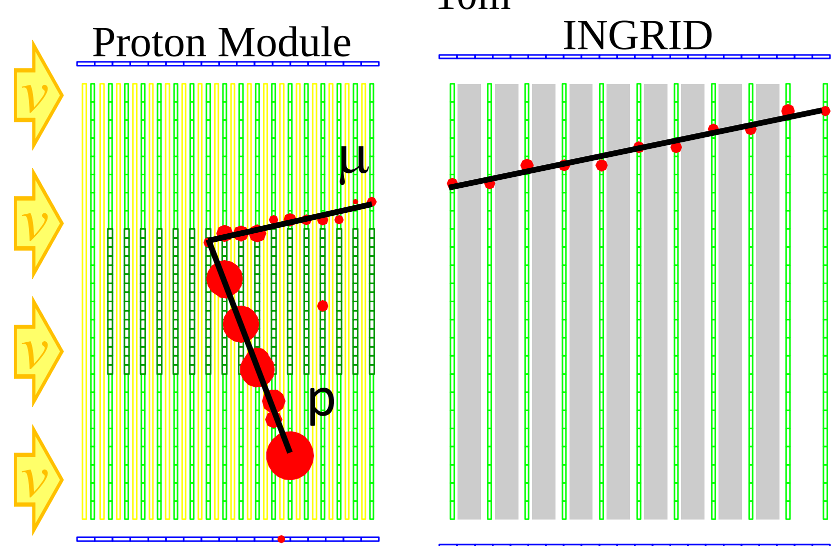
INGRID (on-axis near detector)

» 16 standard INGRID modules.
  - Sandwich structure of iron and scintillators.
  - Mass ratio of iron is 95%.

» 1 extra module, (Proton Module).
  - Full scintillator module.







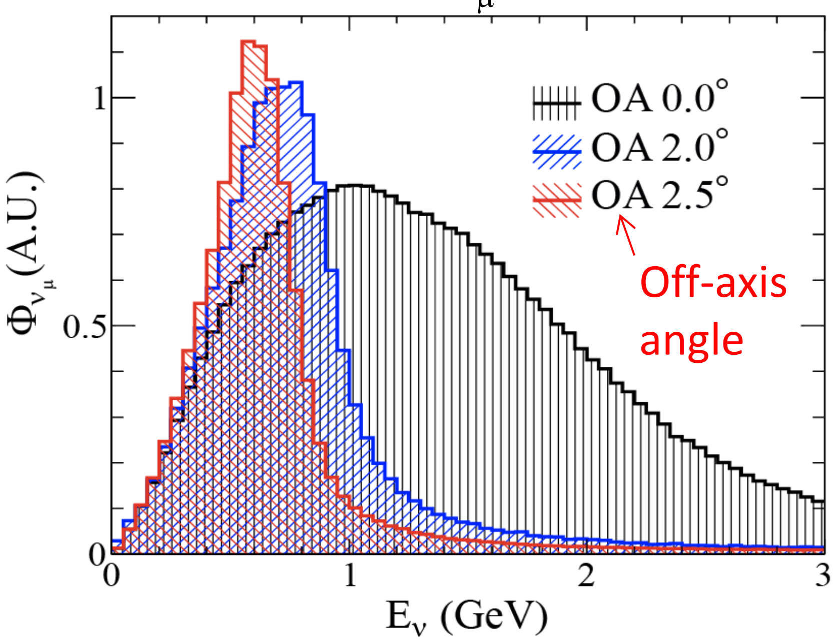
Neutrino interaction around 1GeV

» T2K uses NEUT and GENIE to generate neutrino interaction.

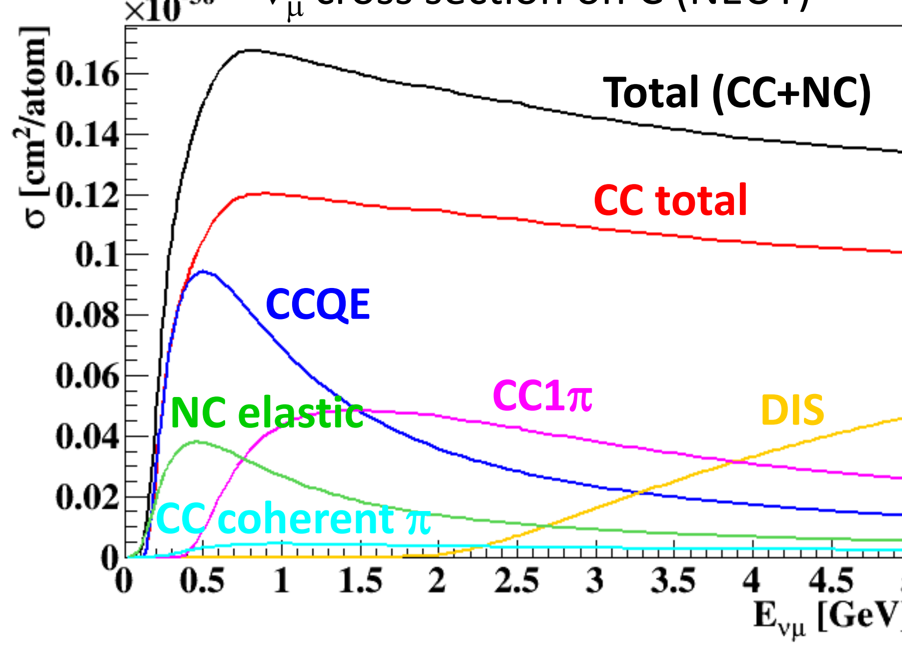
- Charged current quasi-elastic (CCQE) $\nu_\mu + n \rightarrow \mu^- + p$
- Neutral current elastic (NCE) $\nu_\mu + N \rightarrow \nu_\mu + N$
- Single π,η,K resonance production $\nu_\mu + N \rightarrow l + N' + \pi(\eta, K)$
- Coherent π production $\nu_\mu + X \rightarrow l + X' + \pi$
- Deep inelastic scattering (DIS) $\nu_\mu + N \rightarrow l + N' + m\pi(\eta, K)$

T2K signal mode

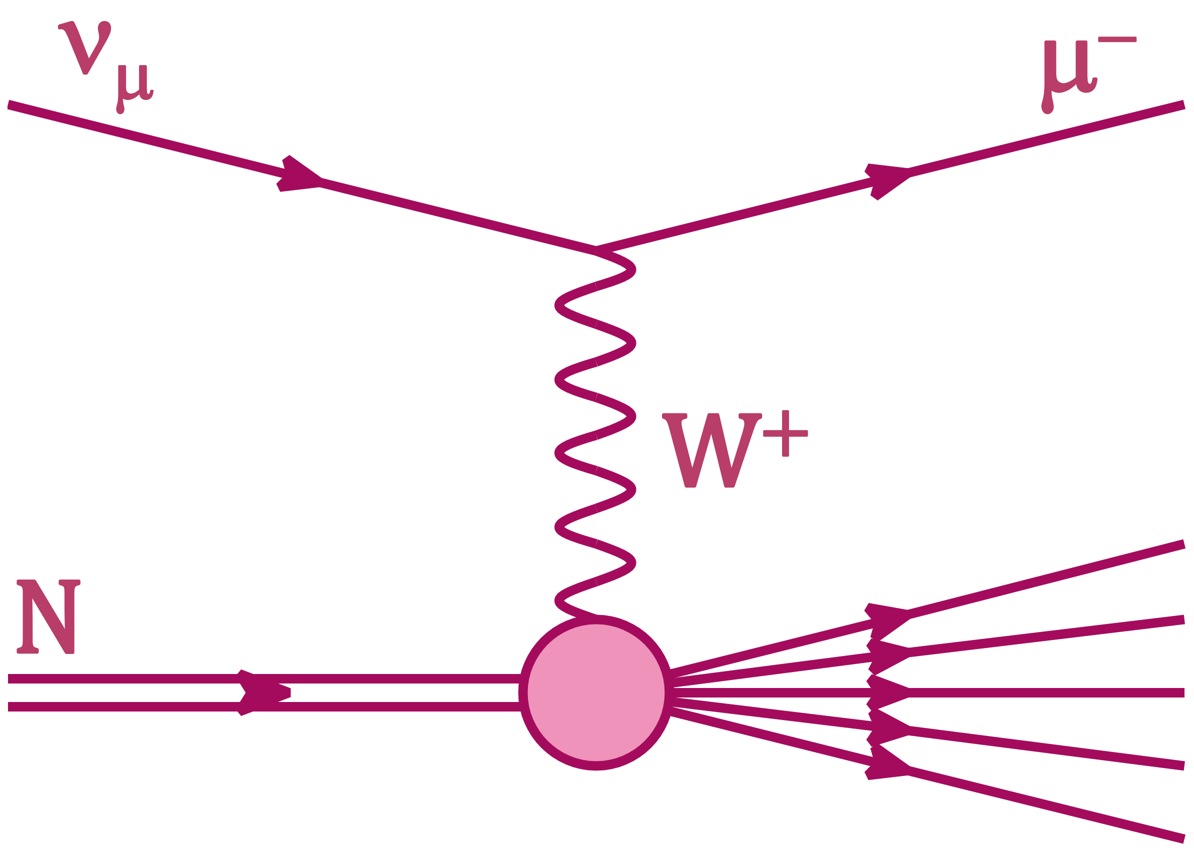
T2K ν_μ flux



ν_μ cross section on C (NEUT)



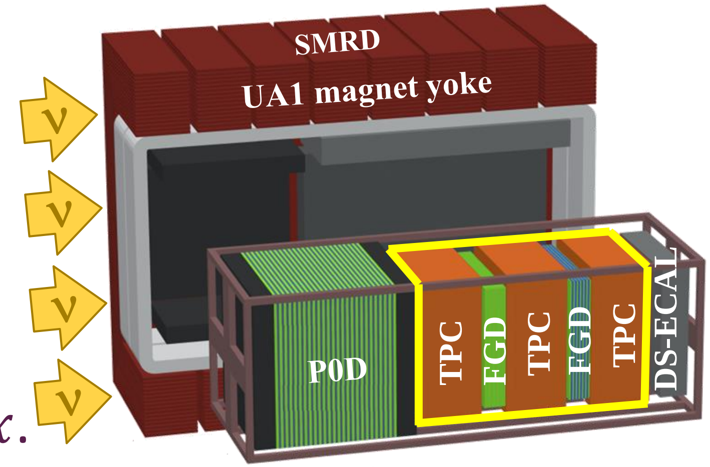
Flux averaged CC-inclusive cross section measurement with ND280 tracker



Measurements with tracker

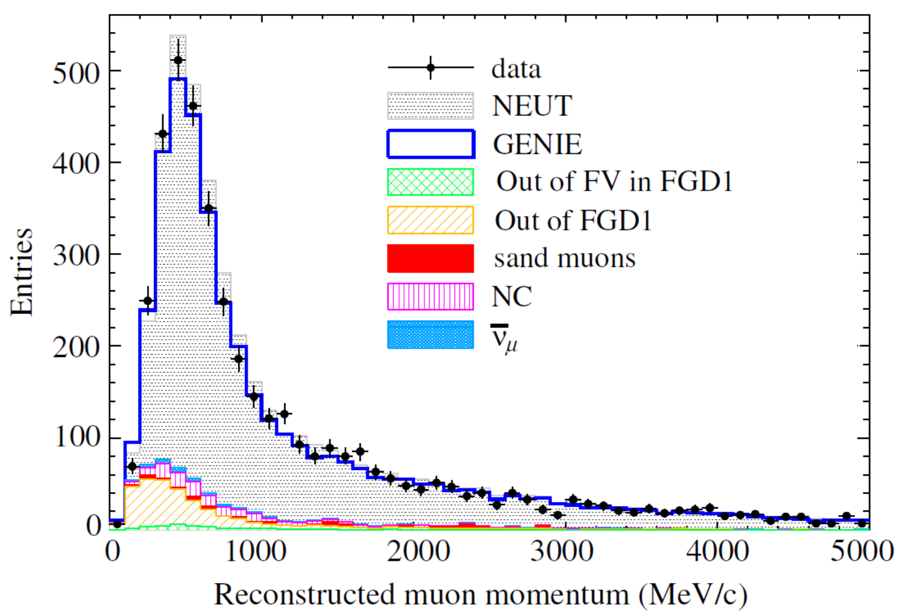
» <u>Select events with μ^-.</u>

- Upstream veto cut.
- Negative charge track starting from the FGD fiducial volume to TPC.
- Particle identification with TPC dE/dx.

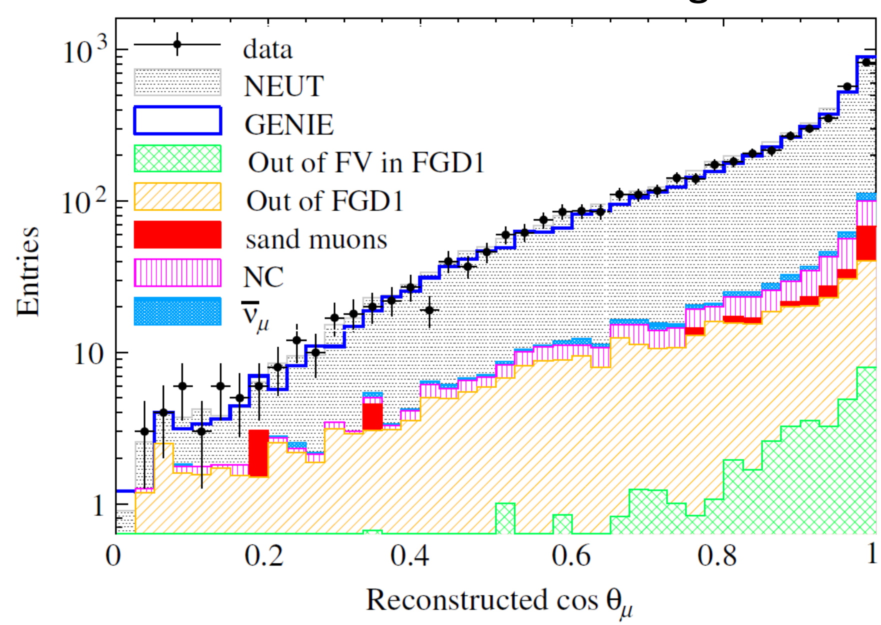


» CC purity = 87%, CC efficiency = 50%.

Reconstructed muon momentum



Reconstructed muon angle



Flux averaged CC-inclusive cross section

» We get

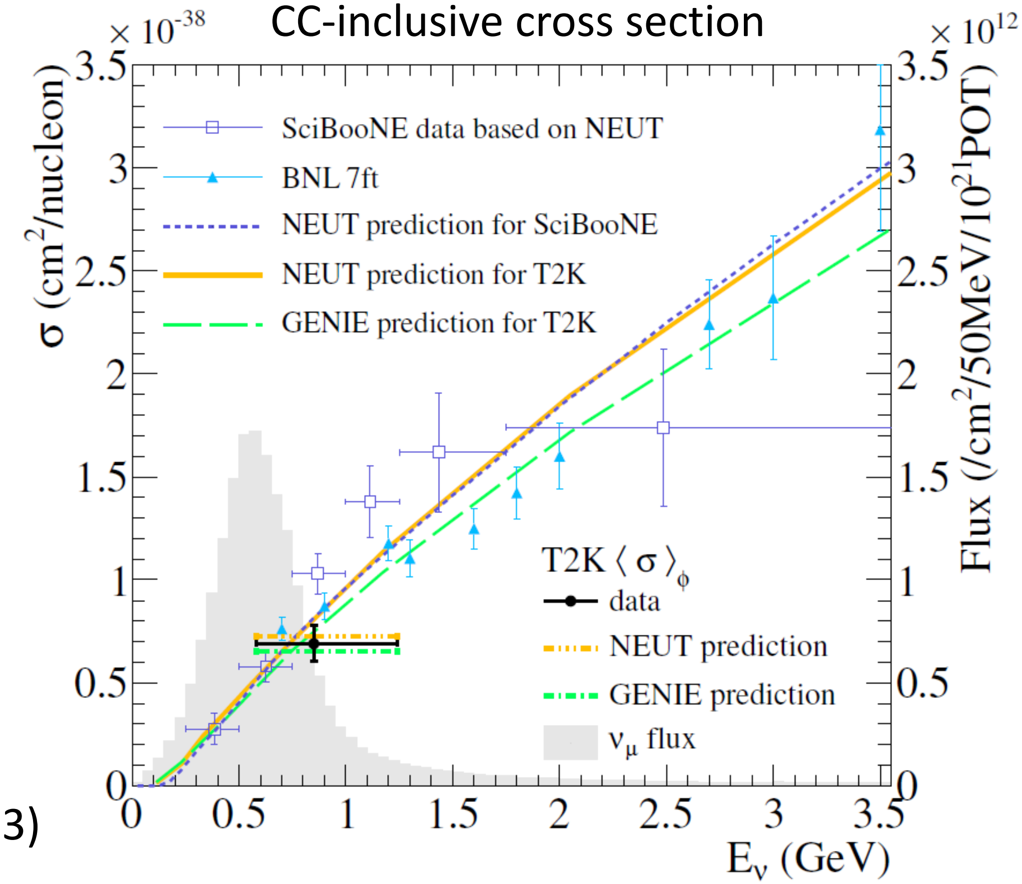
$$\langle\sigma_{CC}\rangle_\Phi = \left(6.91 \pm 0.13(stat.) \pm 0.84(syst.)\right) \times 10^{-39}\,\frac{\mathrm{cm}^2}{\mathrm{nucleon}}$$

- Uncertainty of neutrino flux 10∼15% is the dominant error source for all measurements.

» It agrees with the existing model predictions.

- $\left\langle\sigma_{CC}^{NEUT}\right\rangle_\Phi = 7.27 \times 10^{-39}\,\frac{\mathrm{cm}^2}{\mathrm{nucleon}}$
- $\left\langle\sigma_{CC}^{GENIE}\right\rangle_\Phi = 6.54 \times 10^{-39}\,\frac{\mathrm{cm}^2}{\mathrm{nucleon}}$

CC-inclusive cross section

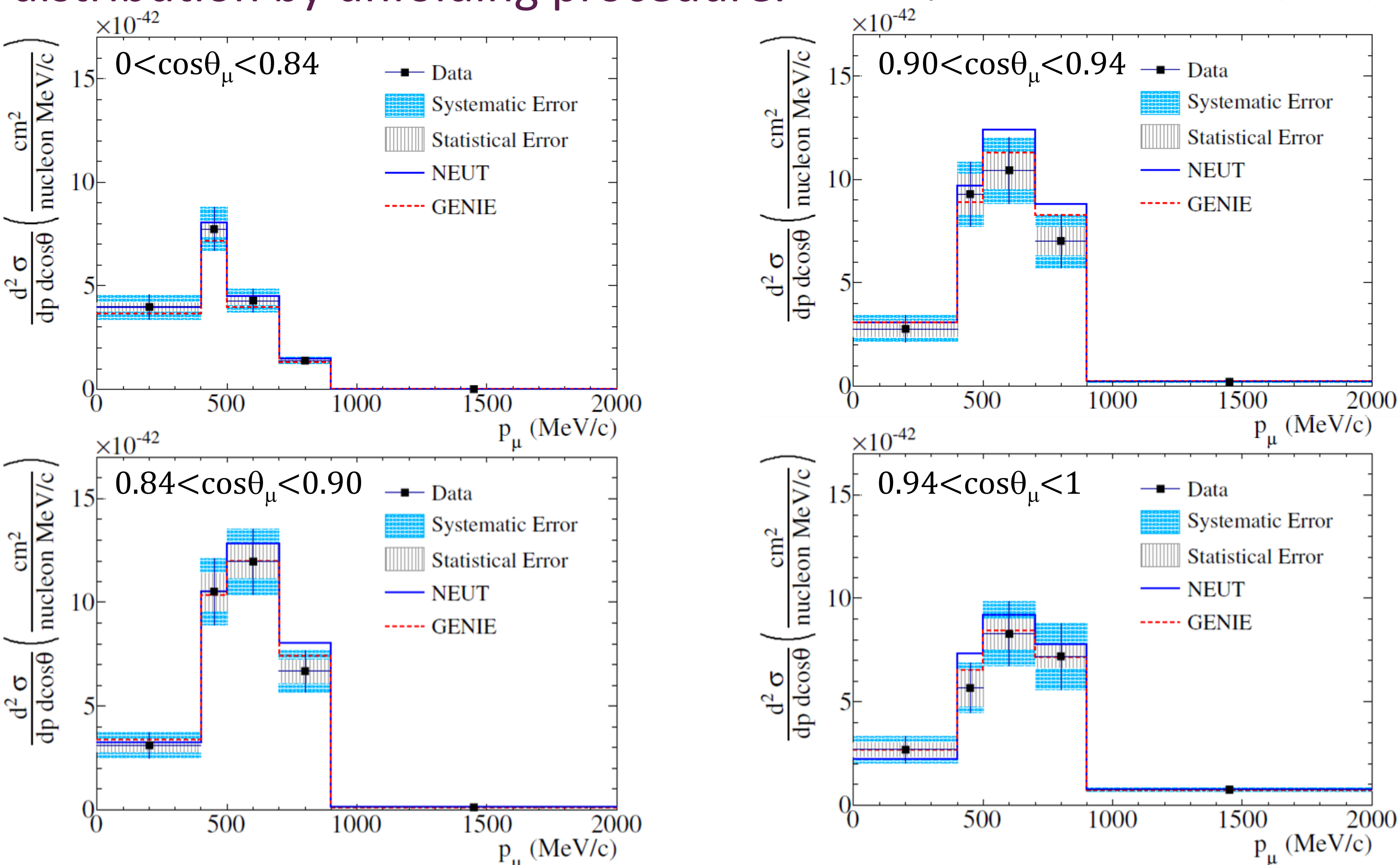


Phys. Rev. D 87, 092003 (2013)

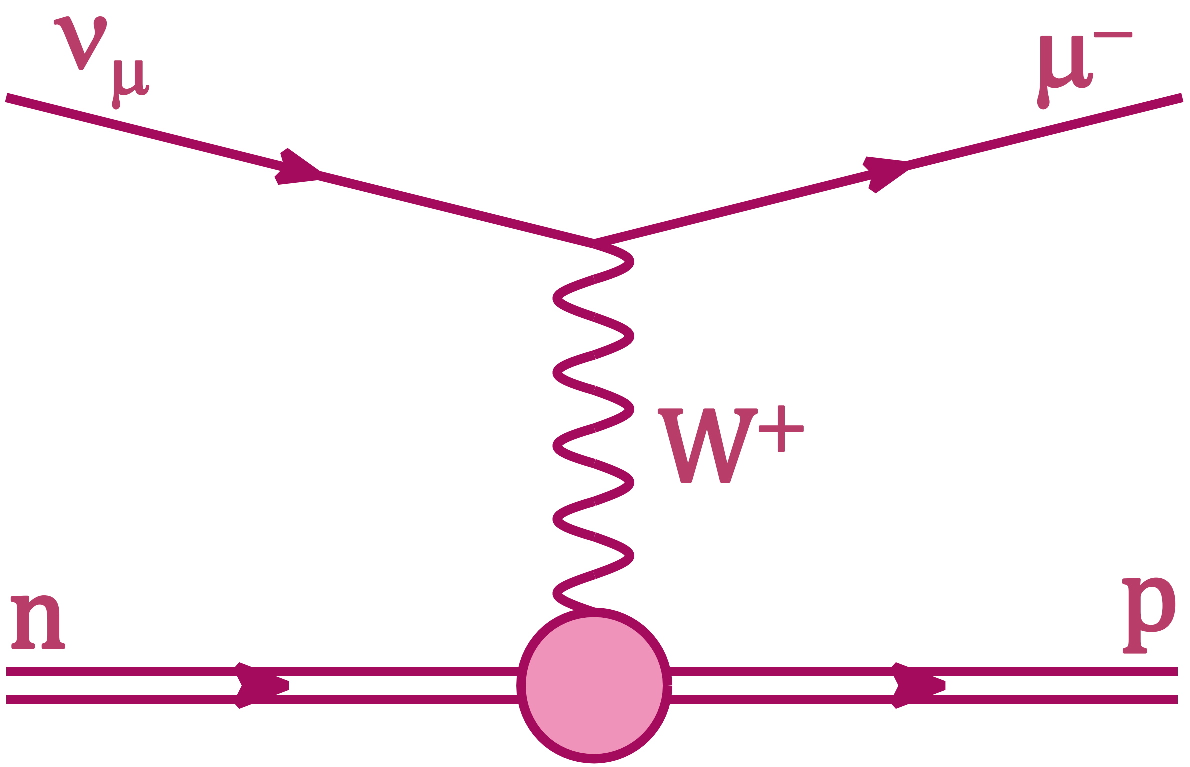
Differential CC-inclusive cross section

» Measured $p_\mu - \theta_\mu$ distribution is converted to true $p_\mu - \theta_\mu$ distribution by unfolding procedure.

Phys. Rev. D 87, 092003 (2013)



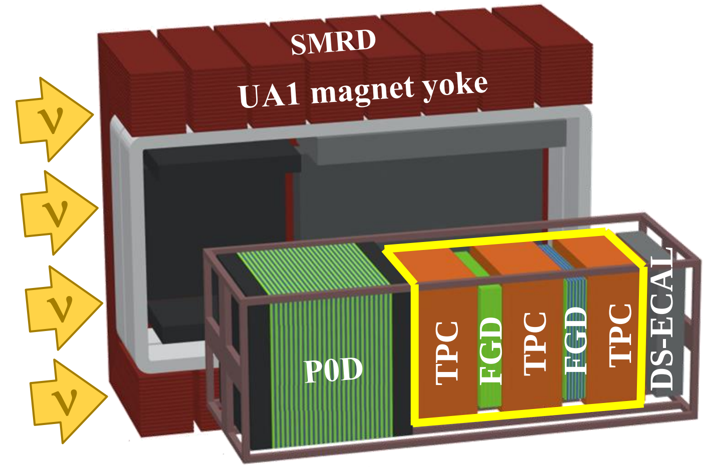
CCQE cross section measurement with ND280 tracker



CCQE selection with tracker

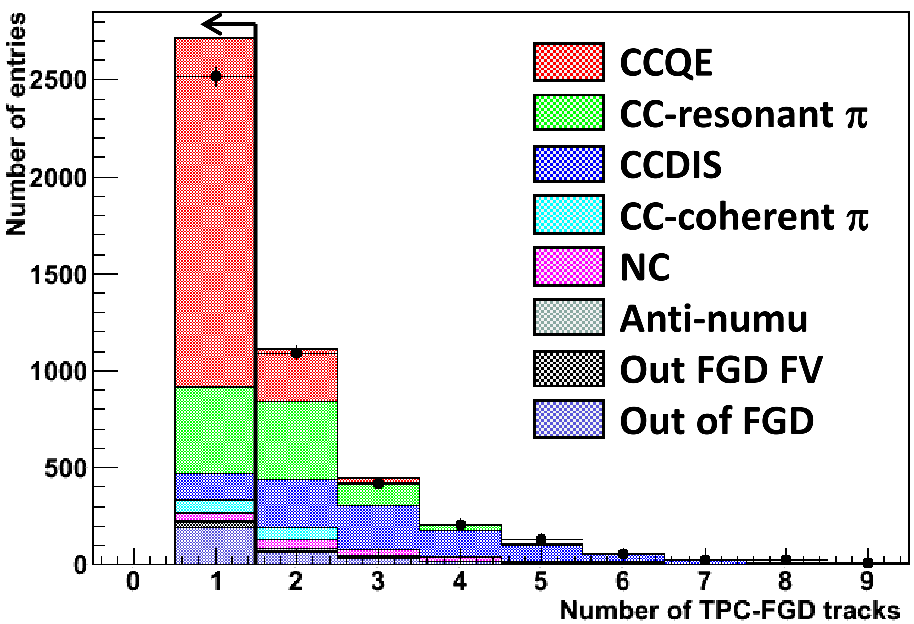
» Select event with 1 μ^- and no π.

- μ^- event selection (described before).
- Only one track from FGD to TPC.
- No delayed energy deposition from Michel electrons.

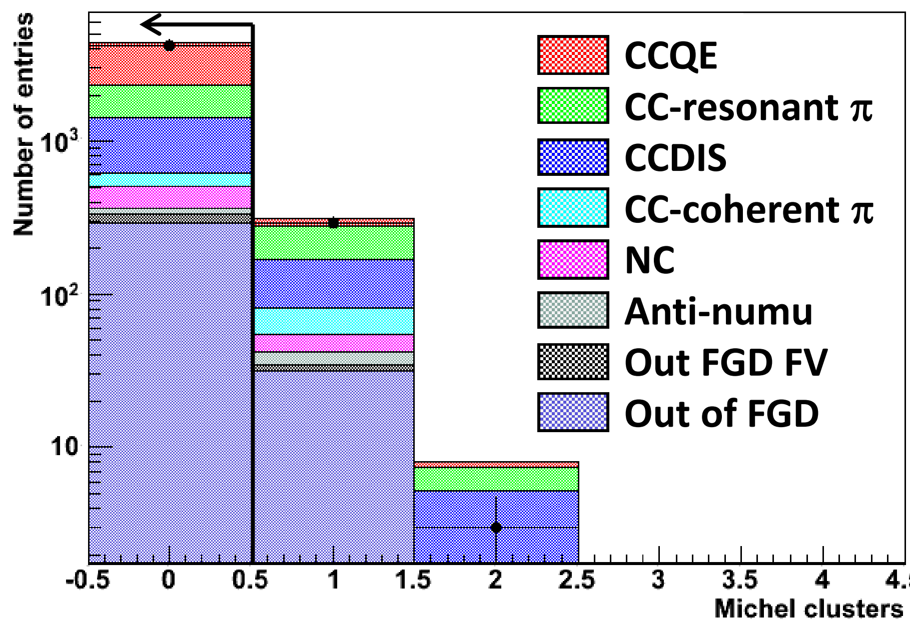


» CCQE purity = 72%, CCQE efficiency = 40%.

Number of TPC-FGD tracks



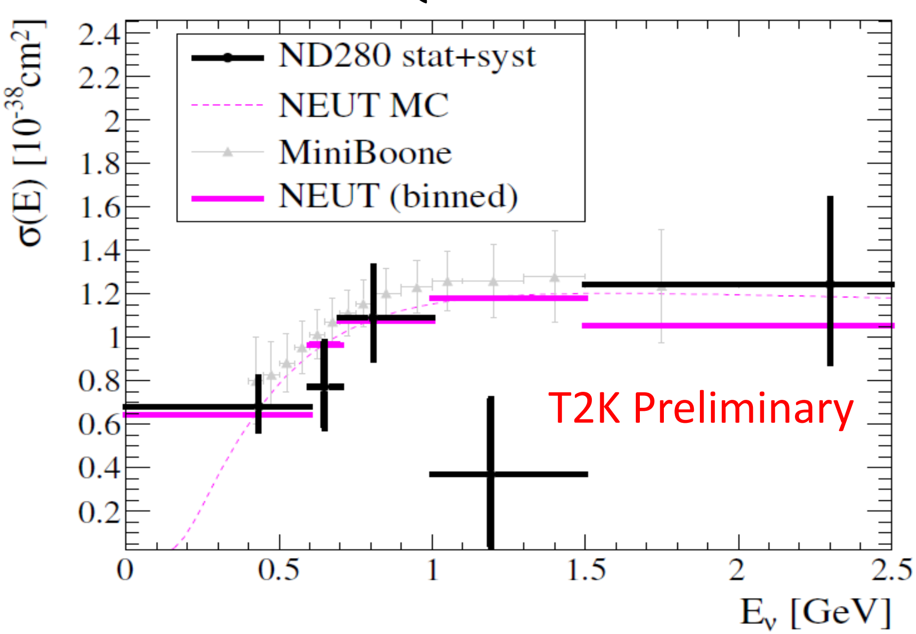
Number of Michel clusters



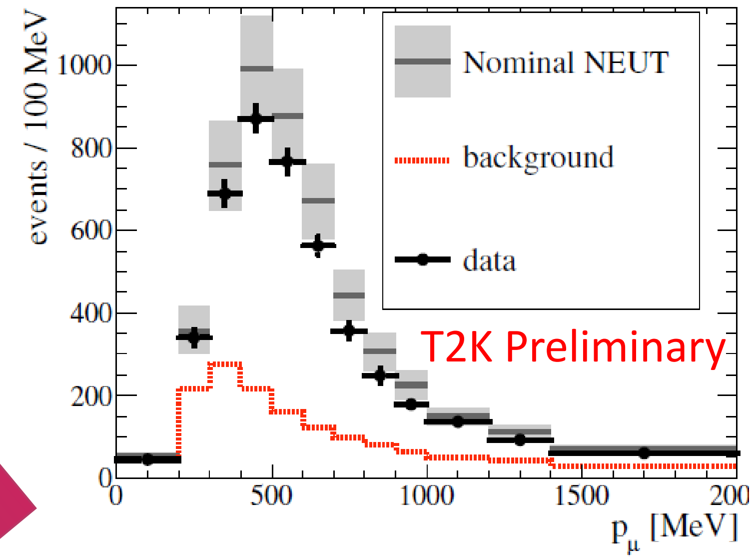
CCQE cross section

- Fit the MC to $p_\mu - \cos\theta_\mu$ distribution to extract cross section in bins of E_ν.
- χ^2 test gives a p-value of 17%.
  → Good agreement with our model.
- Best fit M_A^{QE} value, $1.26^{+0.21}_{-0.18}$GeV, is consistent with our model, 1.21GeV.

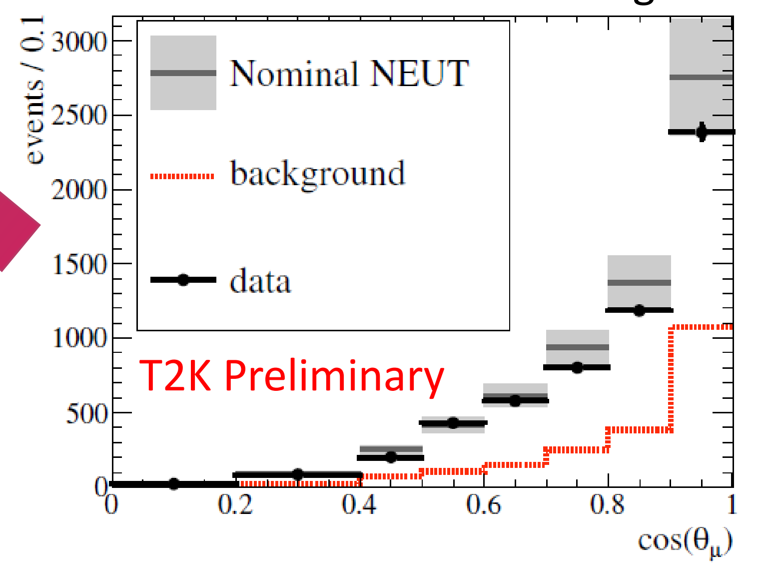
CCQE cross section



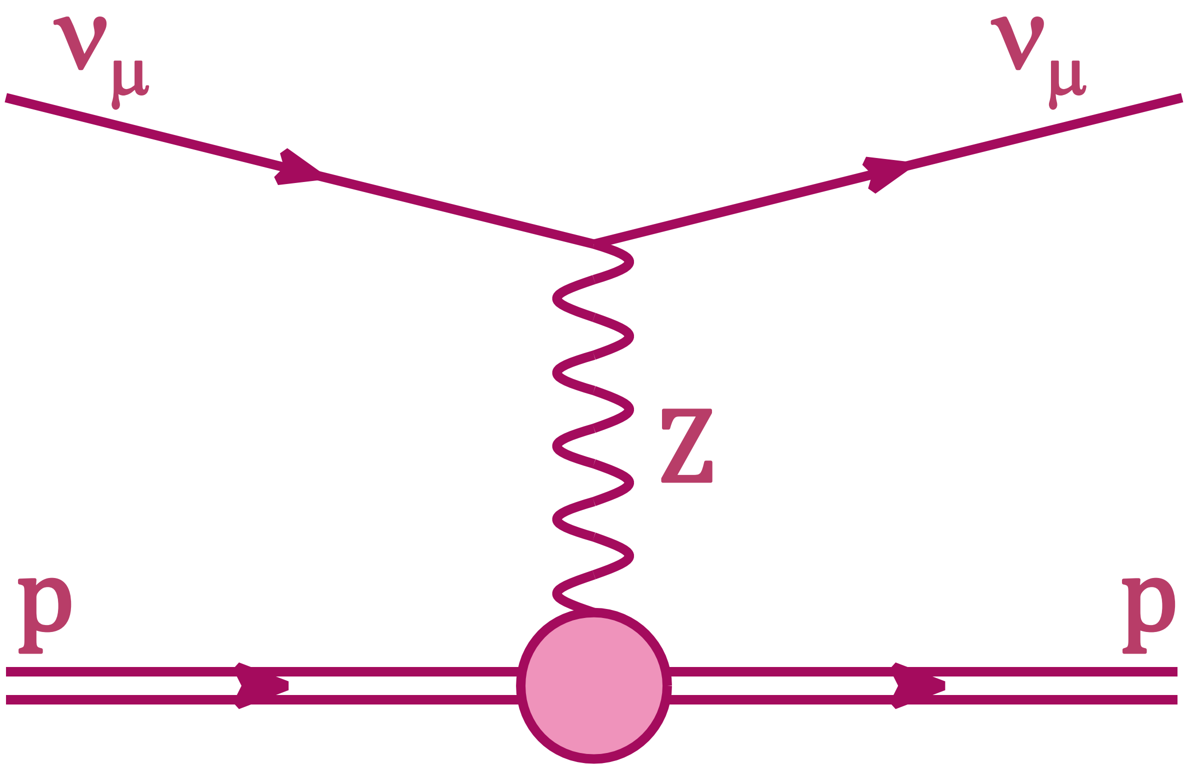
Reconstructed muon momentum



Reconstructed muon angle



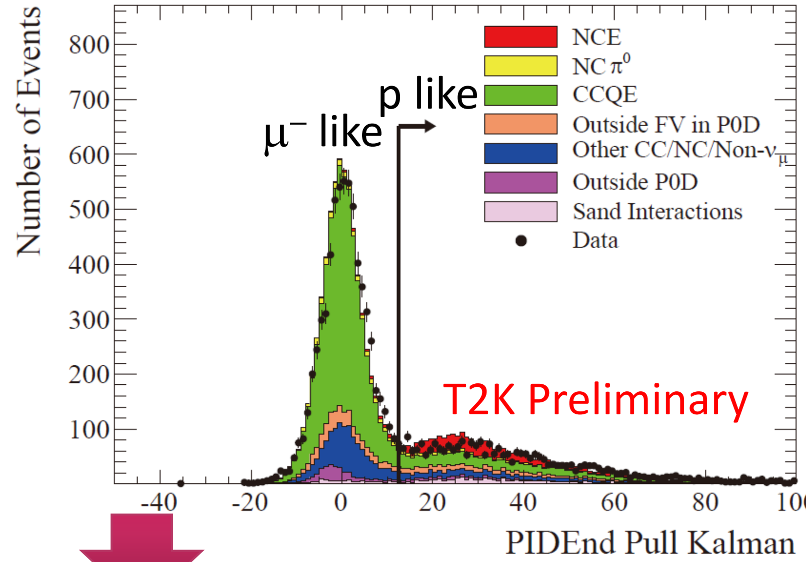
Flux averaged NC elastic cross section measurement with ND280 P0D



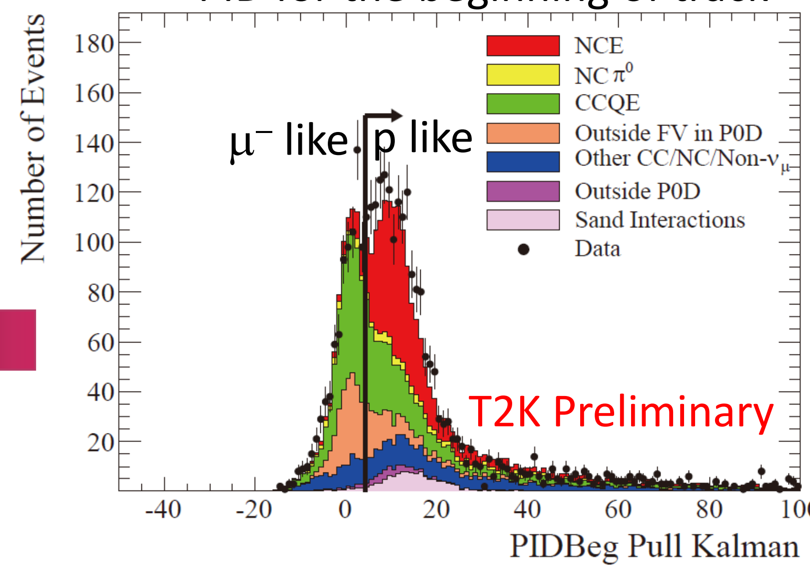
NC elastic selection with P0D

- Event selection
  - Vertex in fiducial volume.
  - PID for the end of the track.
  - PID for the beginning of track.
  - No Michel electrons.
- NC elastic purity = 46%,
  NC elastic efficiency = 14%.

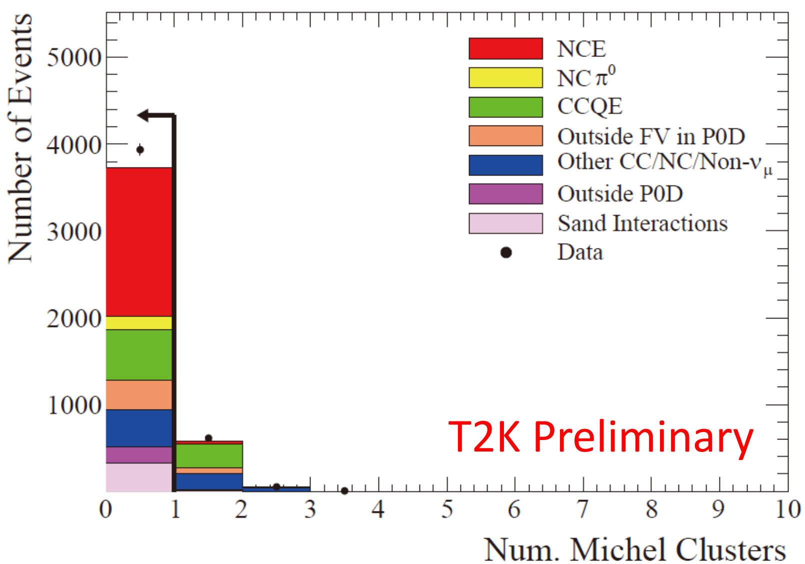
PID for the end of track



PID for the beginning of track



Number of Michel clusters

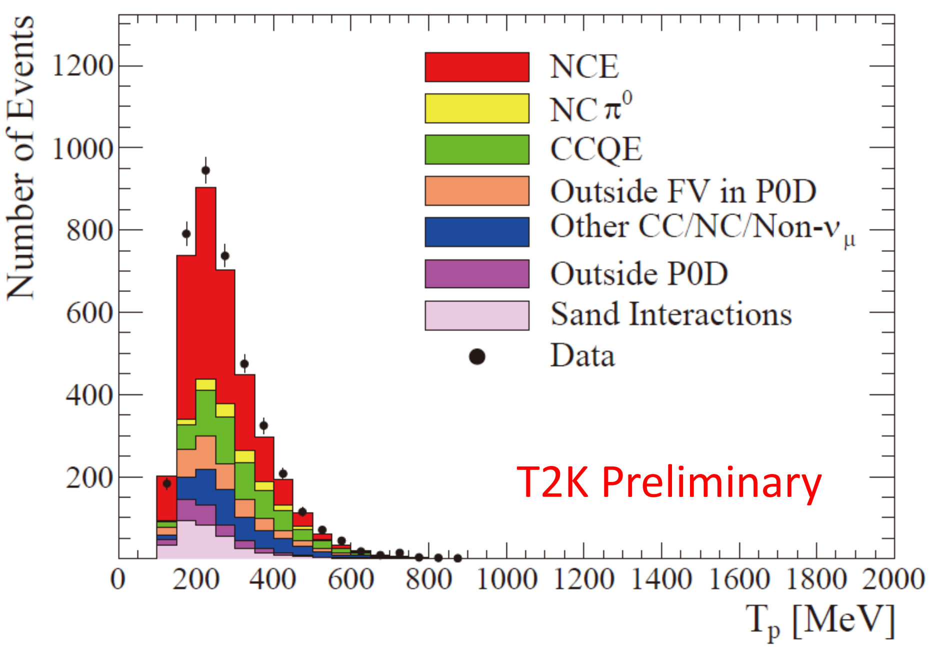


Flux averaged NC elastic cross section

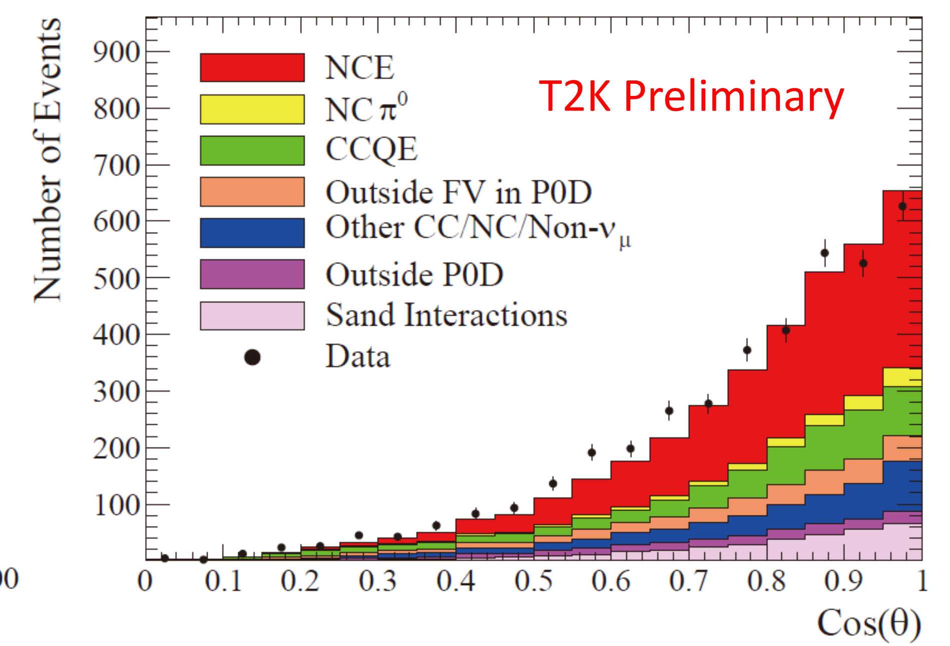
» The cross section result is compatible with the model predictions.

- $\langle \sigma_{NCE} \rangle_\Phi = \left(2.24 \pm 0.07(stat.)^{+0.53}_{-0.63}(syst.)\right) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleon}}$
- $\left\langle \sigma_{NCE}^{NEUT} \right\rangle_\Phi = 2.02 \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleon}}$
- $\left\langle \sigma_{NCE}^{GENIE} \right\rangle_\Phi = 1.78 \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleon}}$

Track kinetic energy



Track angle



Ongoing studies

» Measurements with ND280 tracker.
- $CC1\pi^+$ cross section measurement.
- CC-coherent π cross section measurement.

» Measurements with ND280 P0D.
- $CC1\pi^+$ cross section measurement.
- NC elastic differential measurement (water-in – water-out).

» Measurements with INGRID (+ Proton Module).
- CC-inclusive cross section measurement.
  + Flux averaged.
  + In bins of E_ν.
- CCQE cross section measurement.
- CC-coherent π cross section measurement.

Flux averaged CC-inclusive cross section with INGRID

» Fe target for INGRID module, CH target for Proton Module.

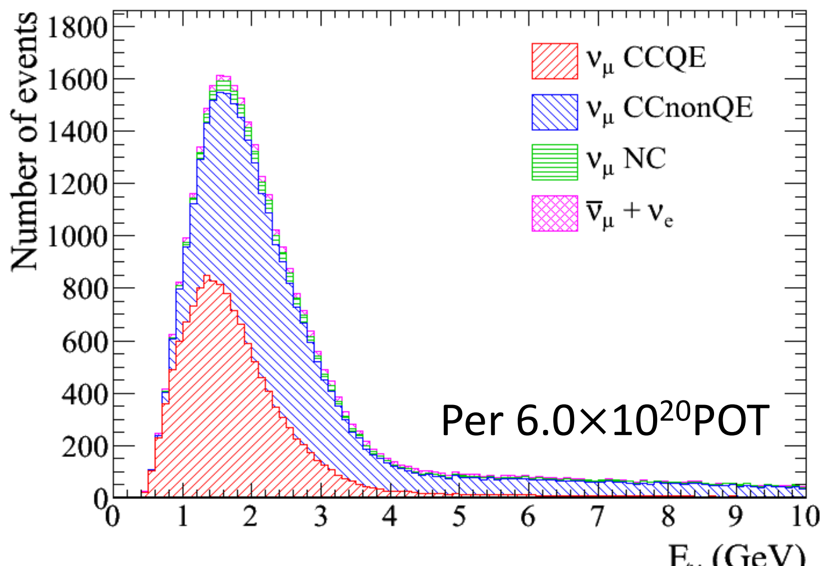
» Measurement of CC-inclusive cross section on Fe and CH.

- CC purity = 88%, CC efficiency = 43% for INGRID module.
- CC purity = 87%, CC efficiency = 41% for Proton Module.

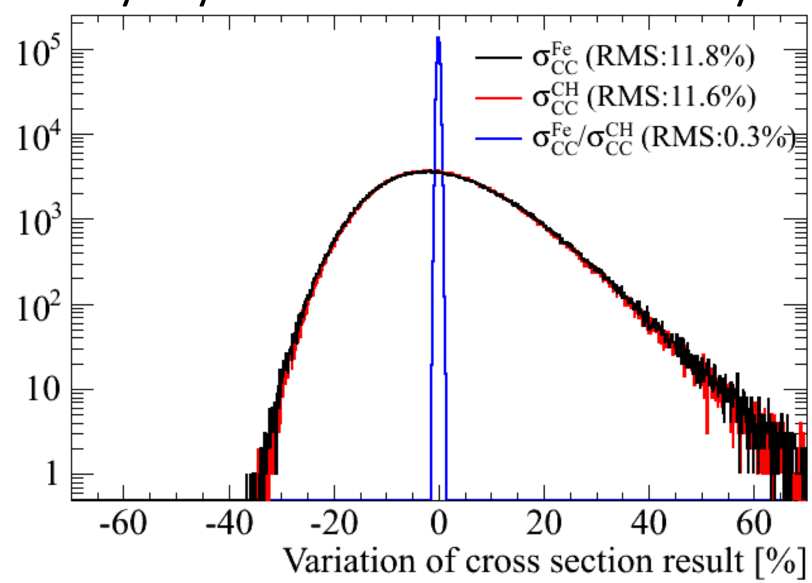
» Measurement of CC-inclusive cross section ratio on Fe/CH.

- Error is suppressed thanks to cancelation between σ_{Fe} and σ_{CH}.

True E_ν spectrum of selected events in Proton Module

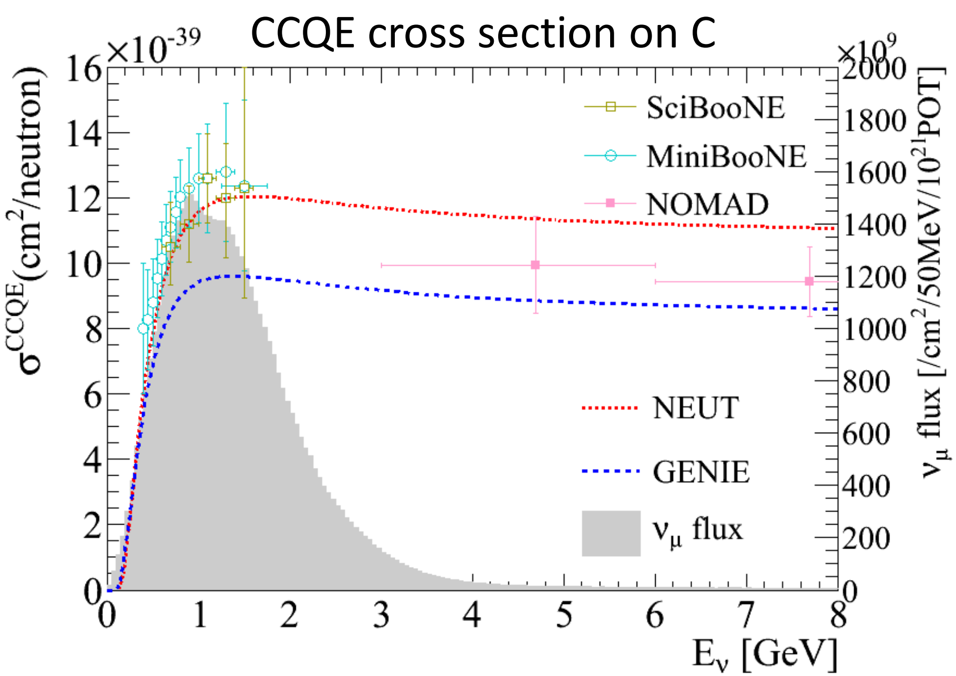


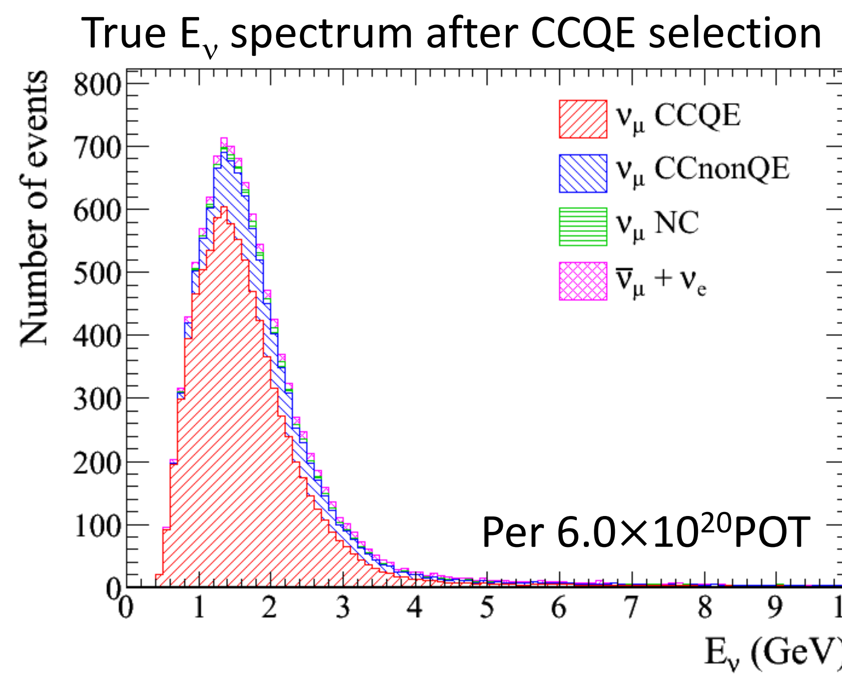
Variation of the cross section results by Toy MC for the flux uncertainty



CCQE cross section with Proton Module

- » T2K on-axis neutrinos are distributed on 0~4GeV. (higher and wider than off-axis neutrinos.)
- » MiniBooNE and SciBooNE CCQE results can be verified.
- » Unmeasured CCQE cross section on 2~3GeV can be measured.
- » CCQE purity = 79%, CCQE efficiency = 31%.





Summary

- In addition to the neutrino oscillation measurement, we are measuring neutrino cross sections and this will have a big impact on oscillation precision in the future.
- CC-inclusive cross section and CCQE cross section are measured with ND280 tracker.

$$\langle\sigma_{CC}\rangle_\Phi = \left(6.91 \pm 0.13(stat.) \pm 0.84(syst.)\right) \times 10^{-39}\ \frac{\mathrm{cm}^2}{\mathrm{nucleon}}$$

$$M_A^{QE} = 1.26^{+0.21}_{-0.18}\ \text{GeV}$$

- NC elastic cross section is measured with ND280 P0D.

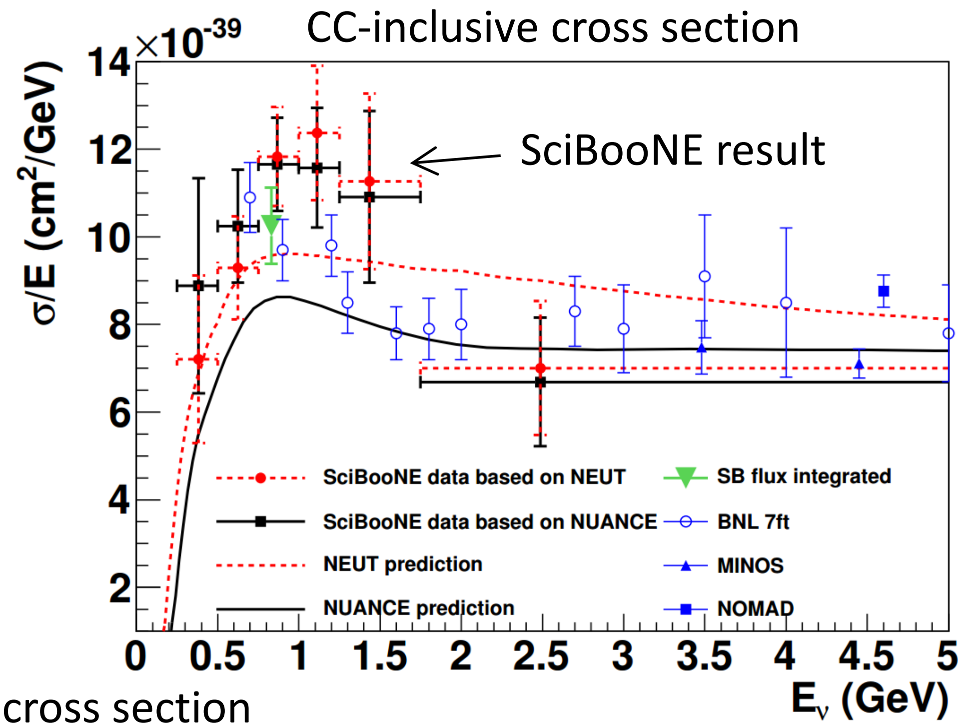
$$\langle\sigma_{NCE}\rangle_\Phi = \left(2.24 \pm 0.07(stat.)^{+0.53}_{-0.63}(syst.)\right) \times 10^{-39}\ \frac{\mathrm{cm}^2}{\mathrm{nucleon}}$$

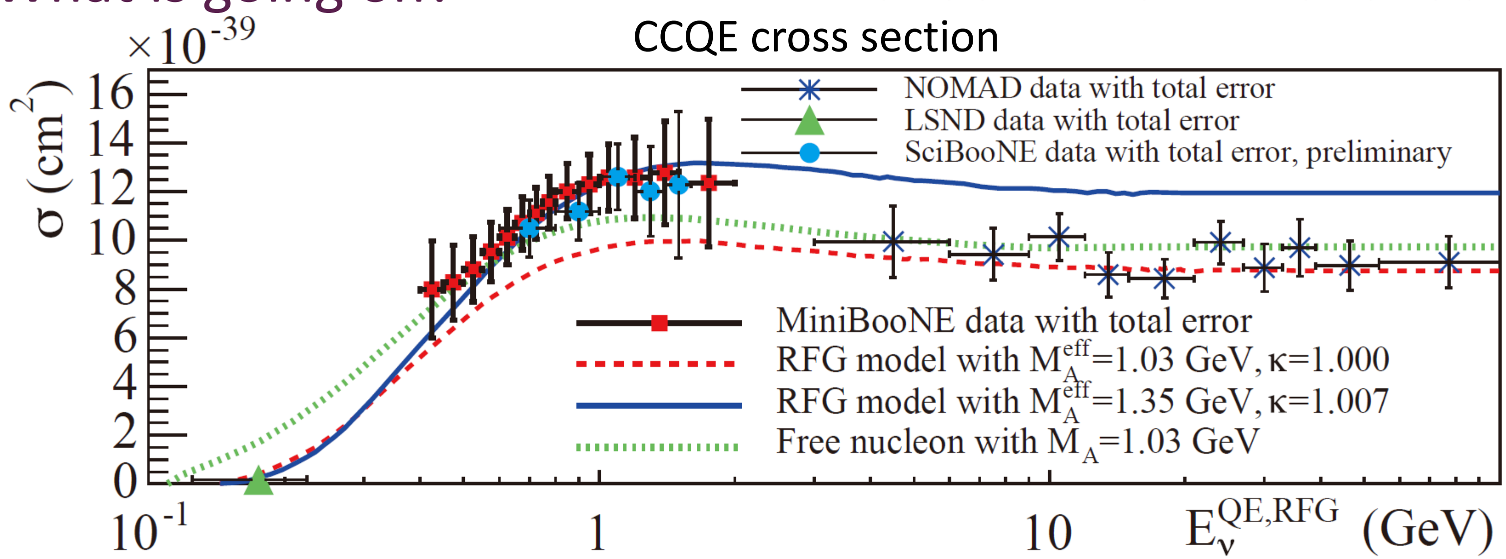
- The cross section results are compatible with the existing model predictions.
- Flux uncertainty, dominant error source of cross section measurement, would be reduced with new CERN-NA61 hadron production measurement.
- Many other exciting results to come.

Back up

Neutrino interaction around 1GeV

- » M_A has been measured to be 1.03GeV/c² in νD_2 and pion electroproduction.
- » A slew of low energy data (MiniBooNE, SciBooNE, K2K) prefers a higher axial mass and therefore higher σ.
- » What is going on?





Flux averaged CC-inclusive cross section measurement method

Differential cross section definition:

# of interactions in true bin

$$\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial \cos\theta_\mu} \rangle_{kl} = \frac{N^{\text{int}}_{kl}}{T \phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}}$$

# of target nucleons — flux

2D binning: (k,l) → 1D binning: k

Method

Unfolding

un-smearing matrix — background in rec. bin

$$N^{\text{int}}_k \approx \widehat{N}_k = \frac{U_{kj}}{\epsilon_k}(N^{sel}_j - B_j)$$

efficiency — # of sel. events

unfolding based on Bayes' theorem

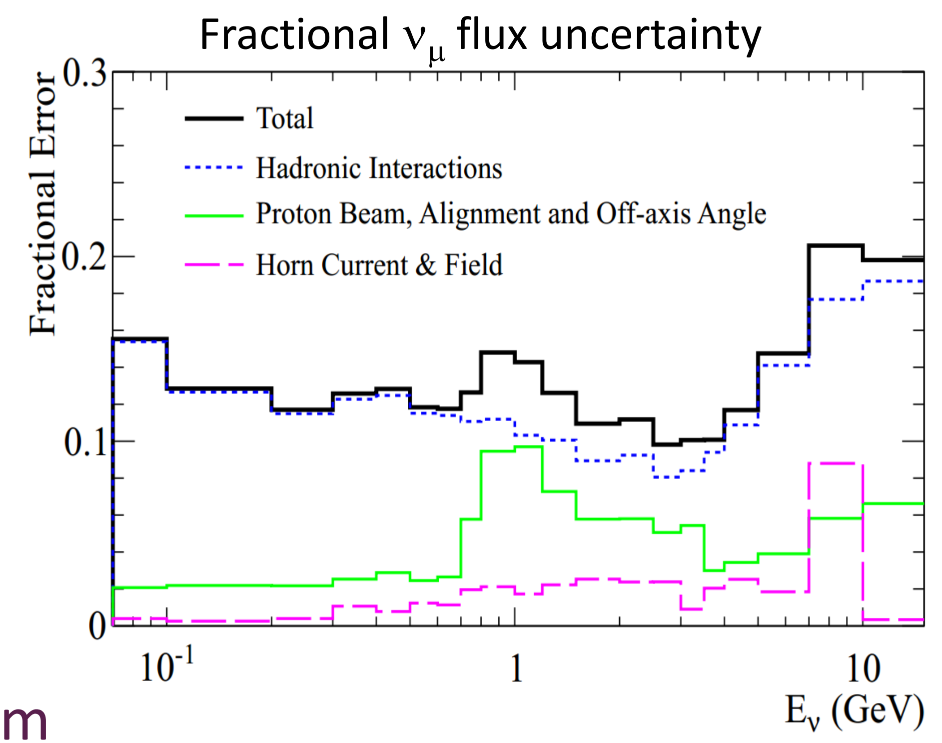
$$U_{kj} = P(k|j) = \frac{P(j|k)P(k)}{\sum_\alpha P(j|\alpha)}$$

U_{kj} = probability to have an interaction in bin k, when having reconstructed the event in bin j

Systematic uncertainty

» Systematic error sources.
- Neutrino flux.
- Neutrino interaction model and final state interaction.
- Detector response.

» ν_μ flux uncertainty is ~15%.
→ Dominant error source.



» Neutrino interaction model and FSI uncertainties come from comparison with external data. (MiniBooNE, SciBooNE etc.)

» Detector uncertainty comes from uncertainties on the backgrounds in the selected sample and the uncertainties on reconstruction.

Systematic uncertainty of neutrino interaction model

- Nominal value and uncertainty of axial vector mass or Fermi momentum come from external data.
- Normalization uncertainties comes from discrepancies between the neutrino interaction model and the external data.

Normalization uncertainties

Parameters	Energy range (GeV)	Error
CCQE	$0.0 < E_\nu < 1.5$	11 %
CCQE	$1.5 < E_\nu < 3.5$	30 %
CCQE	$3.5 < E_\nu$	30 %
CC-1π	$0.0 < E_\nu < 2.5$	43 %
CC-1π	$2.5 < E_\nu$	40 %
CC-COH	$0.0 < E_\nu$	100 %
NC-oth	$0.0 < E_\nu$	30 %
NC-$1\pi^0$	$0.0 < E_\nu$	43 %

Uncertainties of interaction model parameters

Parameters	Nominal value	Error
M_A^{CCQE}	1.21 GeV	37.2 %
M_A^{RES}	1.16 GeV	9.5 %
CC-oth shape	0	40 %
p_F	217 MeV/c	13.8 %
W_{shape}	87.7	51.7 %
pionless Δ decay	0.2	20 %

Parameters	Nominal value	Error
Spectral Function	Off (0)	100 %
1π E_ν shape	Off (0)	50 %

Energy dependent uncertainty for CC-multi.π and CC deep inelastic (40%/E_ν).

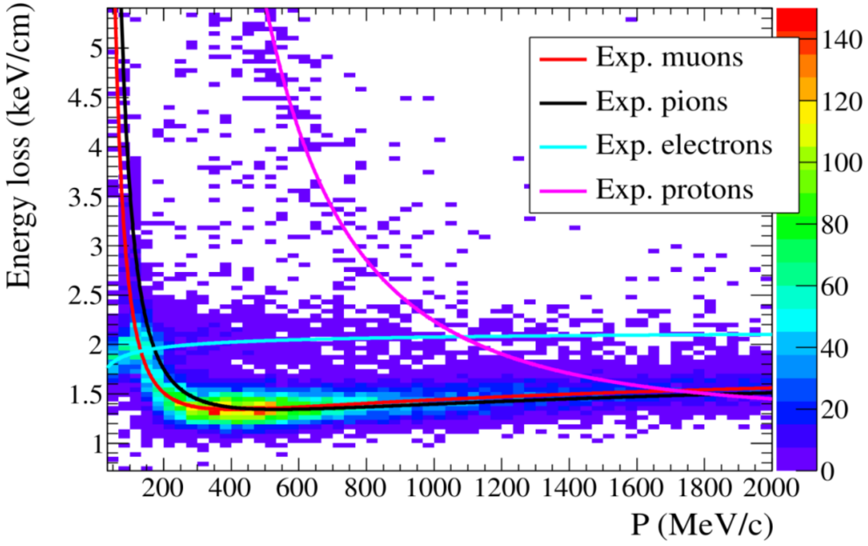
Decay width of the resonance.

20% of all Δ may decay to produce no π.

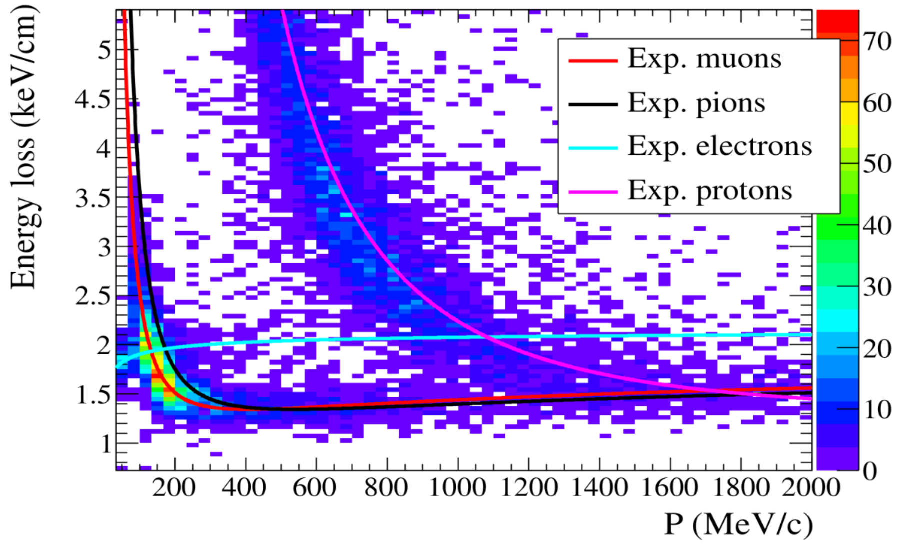
Parameter changing the shape of 1π channel below 1GeV.

TPC particle identification

Negative track in the TPC

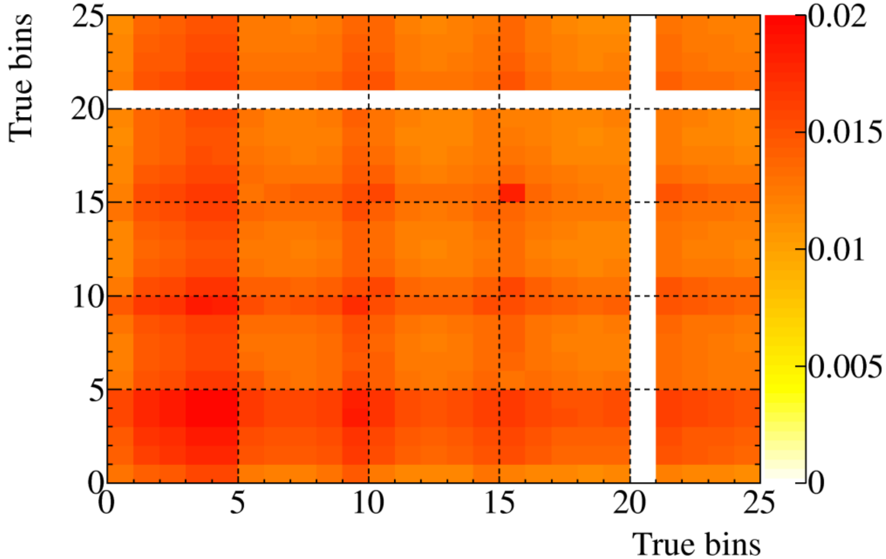


Positive track in the TPC

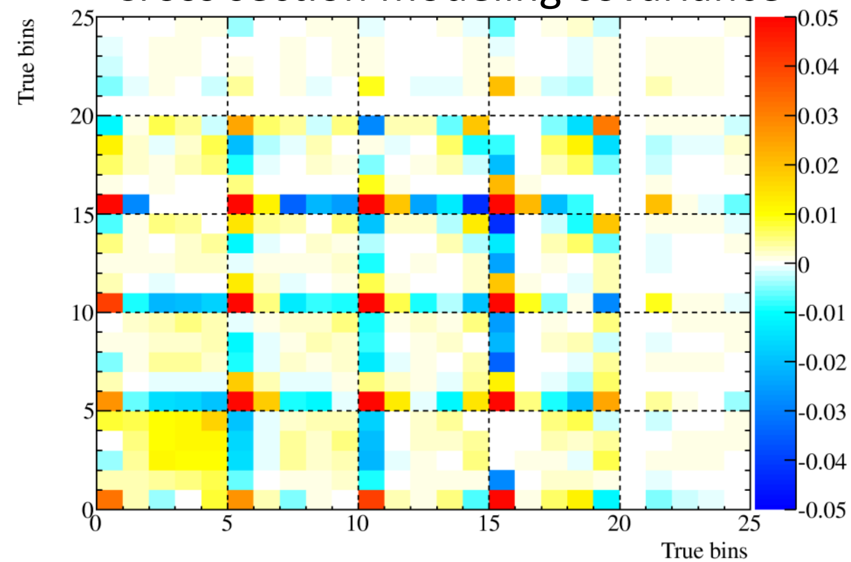


Systematic errors for CC-inclusive analysis

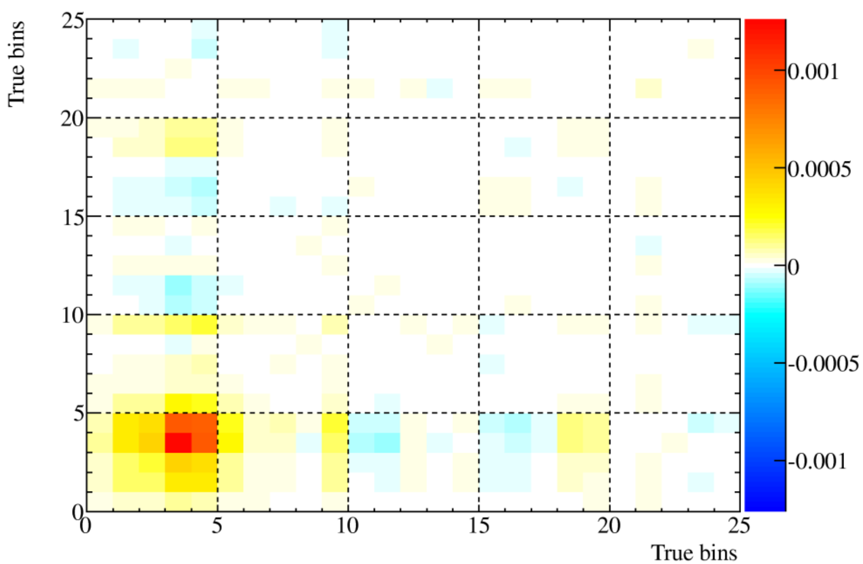
Flux covariance



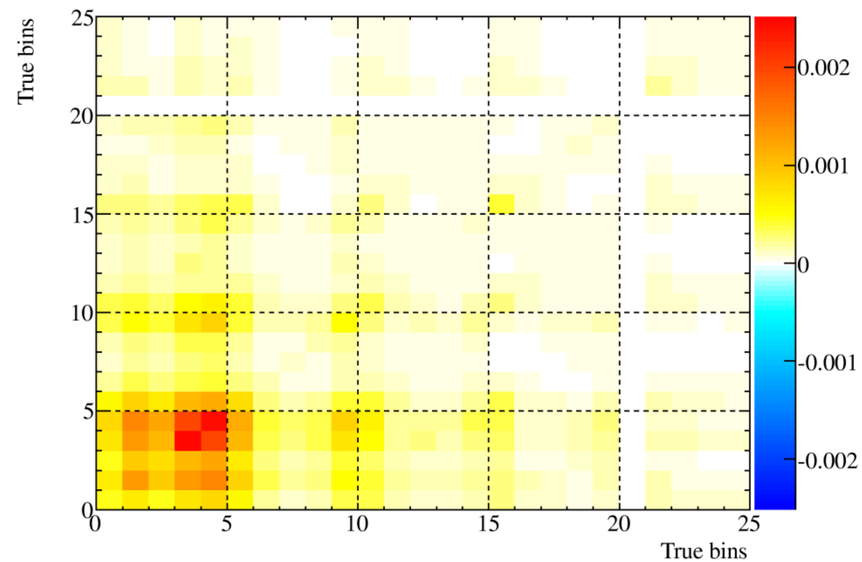
Cross section modeling covariance



FSI covariance

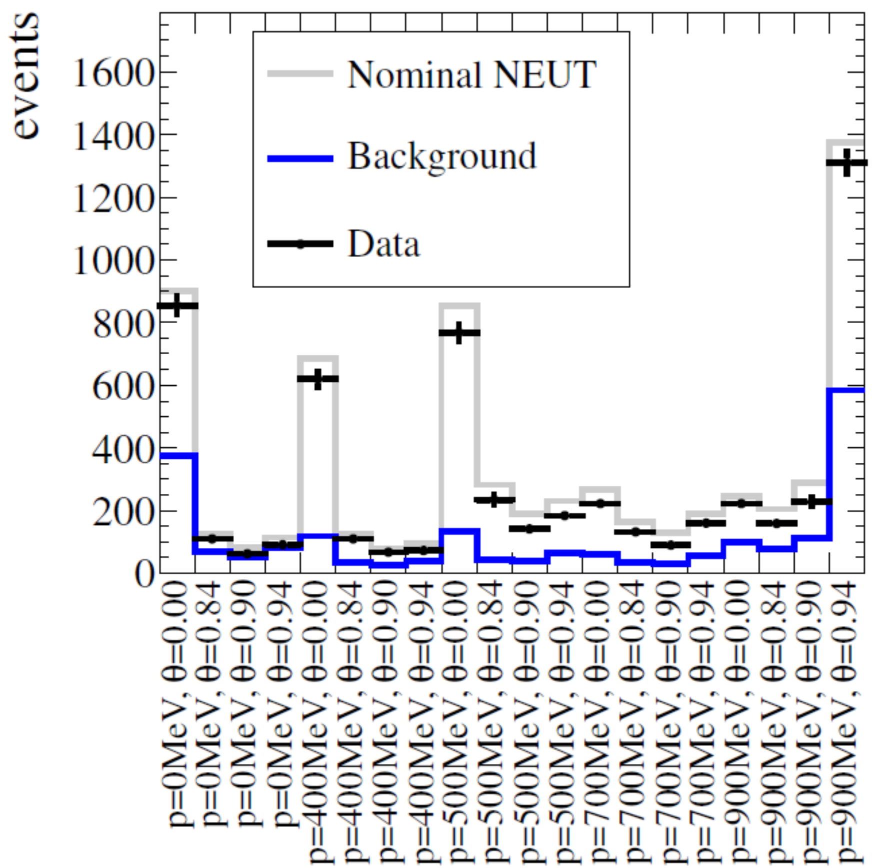


Detector covariance

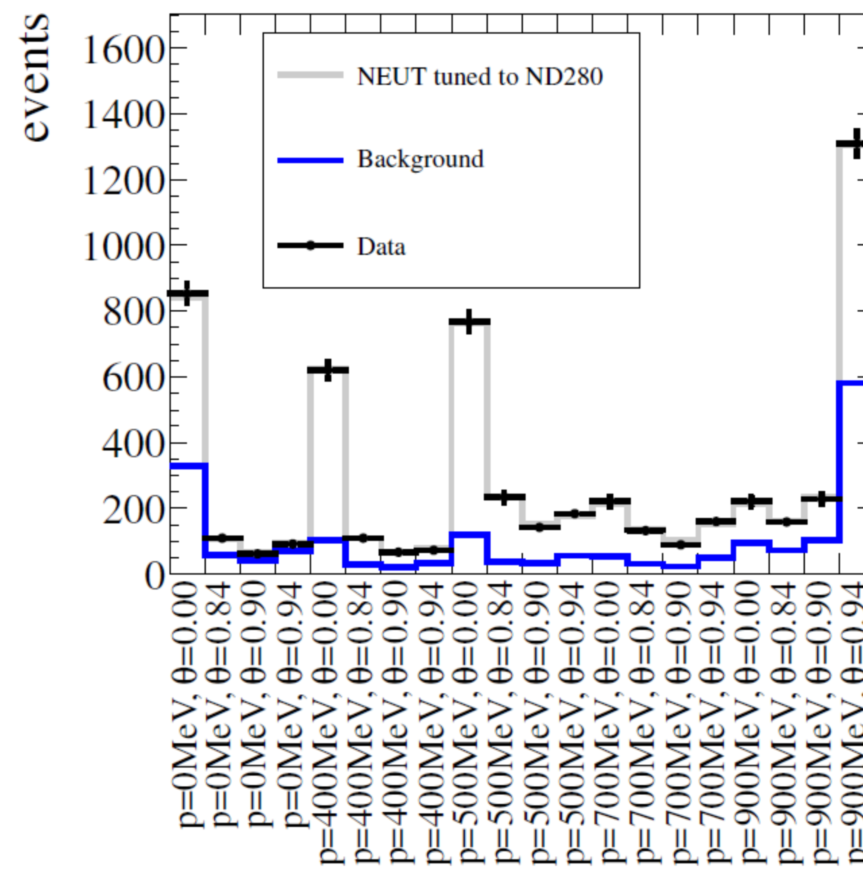


CCQE fitting

Nominal MC

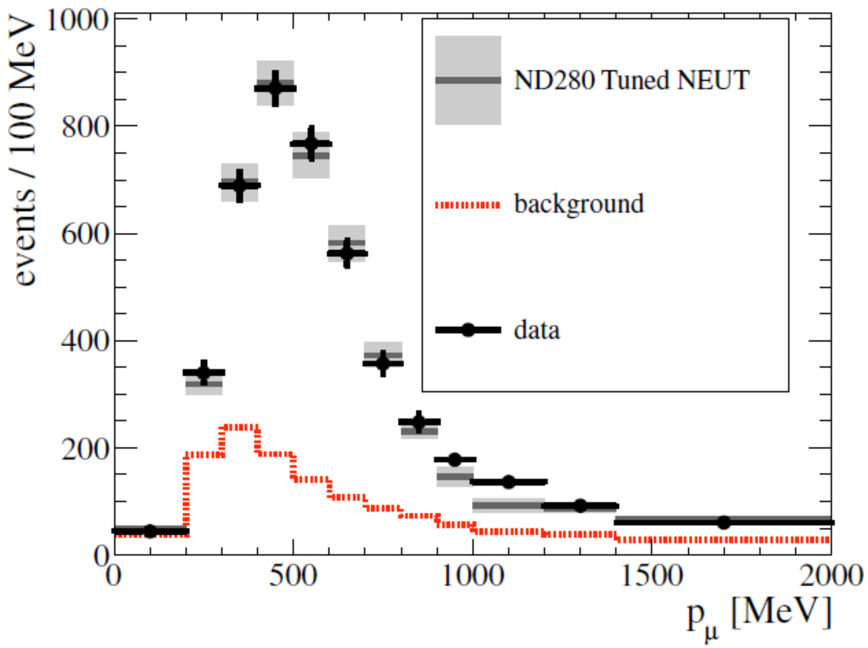


Fitted MC

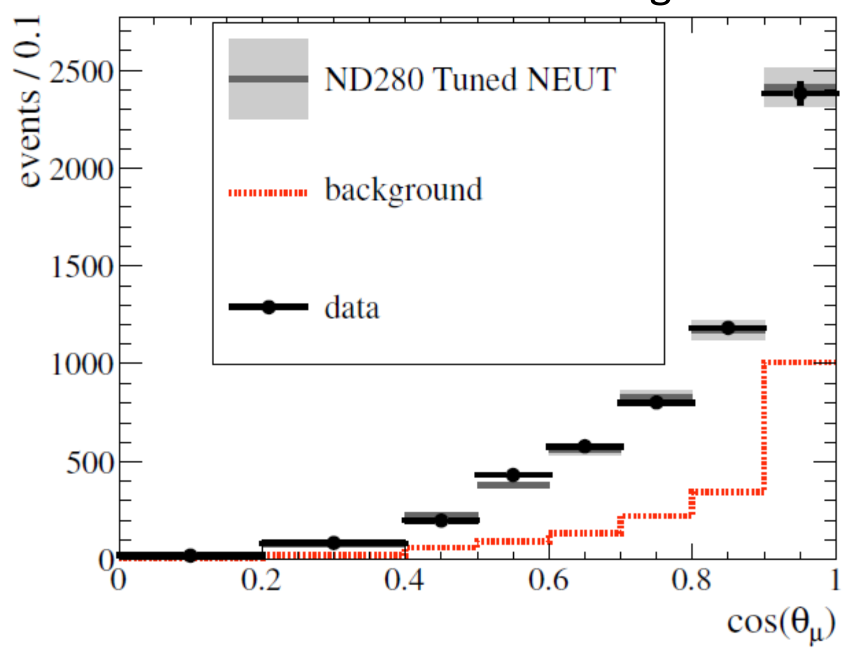


Reconstructed kinematics with fitted MC

Reconstructed muon momentum



Reconstructed muon angle



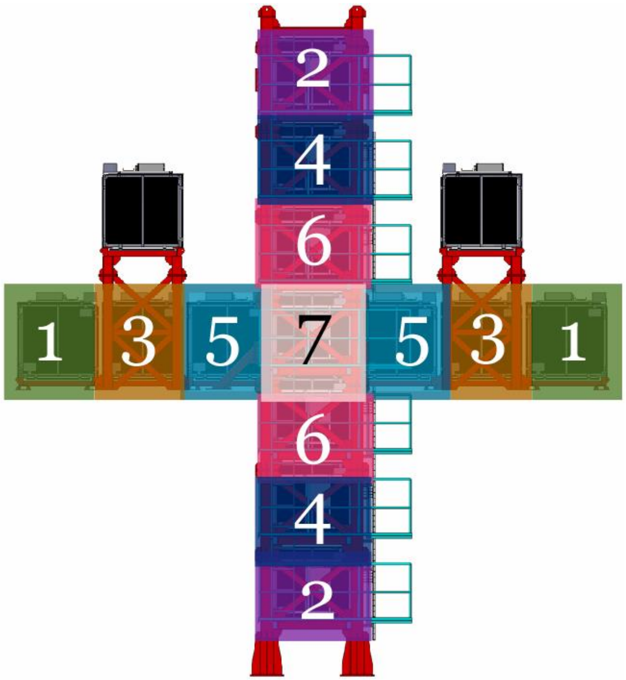
Systematic errors for NC elastic analysis

Systematic Name	Error on cross section
Detector and Reconstruction	
Fiducial Volume	0.72%
PID Algorithm	1.12%
Reconstruction Road Following	1.66%
Michel Efficiency	0.98%
Number of targets	0.7%
Physics	
Cross section model parameters	+14.33%, -16.60%
Pion Absorption	2.29%
Secondary Interactions	2.5%
Outside background scaling factor	6.40%
Beam Flux	
Flux	+17.5%, -21.5%
Total Systematics	+23.88%, -28.22%
Total Statistical	±3.3%

CC-inclusive cross section with INGRID in bins of E_ν

- Neutrino energy spectrum on each INGRID module is different.
- Categorize events by module group.
- In addition, categorize events by topology group.
- Fit the MC model to the numbers of events in the groups to extract CC-inclusive cross section in bins of E_ν.

Module groups



Energy spectrum of neutrino events in each module group