Neutrino interaction cross sections in the T2K near detectors

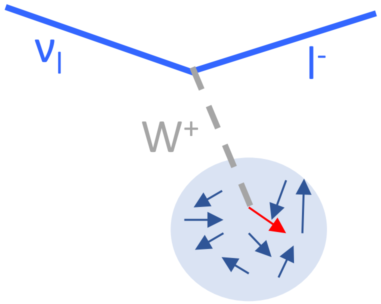
Tianlu Yuan for the T2K collaboration

IPA Symposium

May 8 2017

Why cross sections?

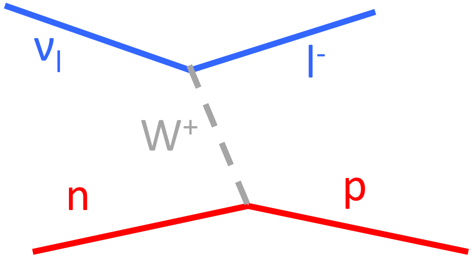
1. Reduce uncertainties for neutrino oscillation measurements
    - Better cross-section knowledge gives more accurate event rate predictions (c.f. talk by T. Kutter)
2. Probe weak interaction
    - Constrain axial vector parameters
3. Probe nuclear effects
    - Very important at ~GeV energies



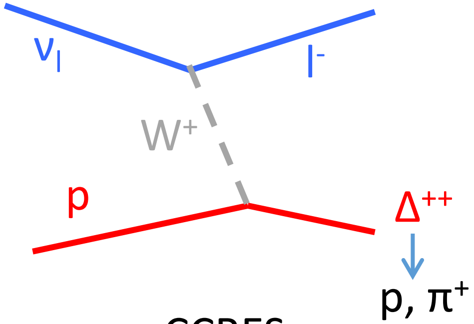
Charged-Current interactions

Free nucleon

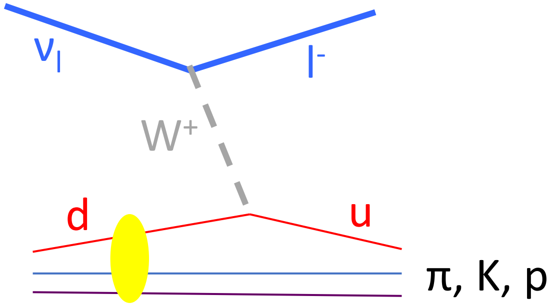
Time →



CCQE

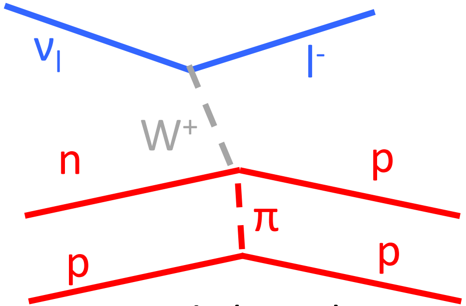


CCRES

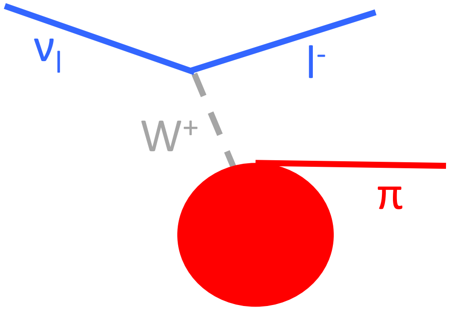


CCDIS

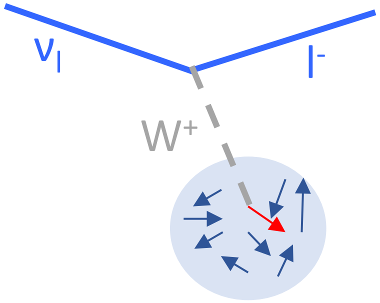
Atomic nucleus



2p2h (MEC)



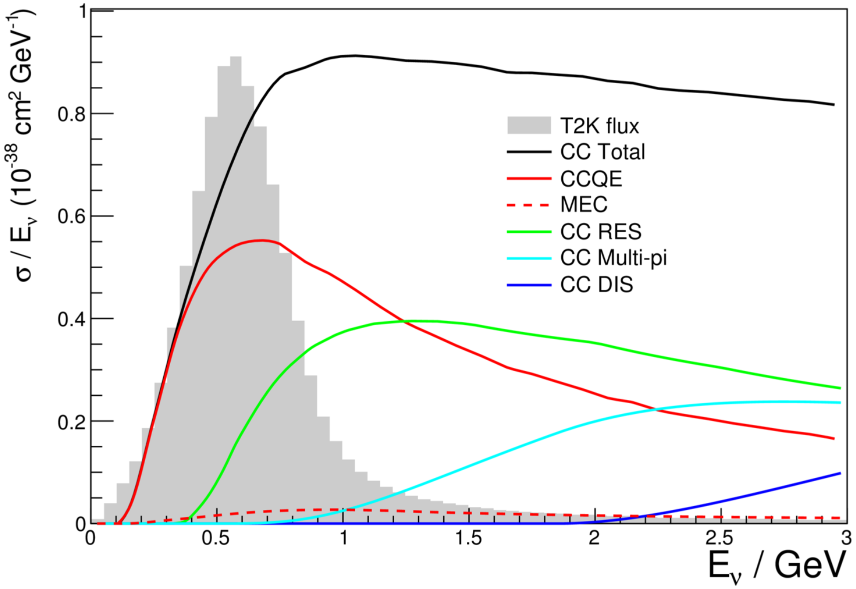
Coherent π-Production



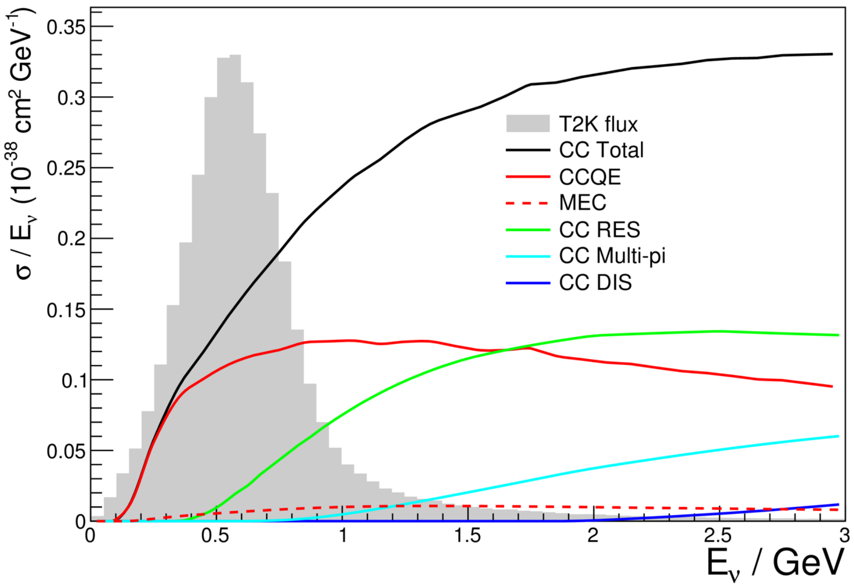
Intranuclear Effects

Per-nucleon cross sections

Neutrino



Antineutrino

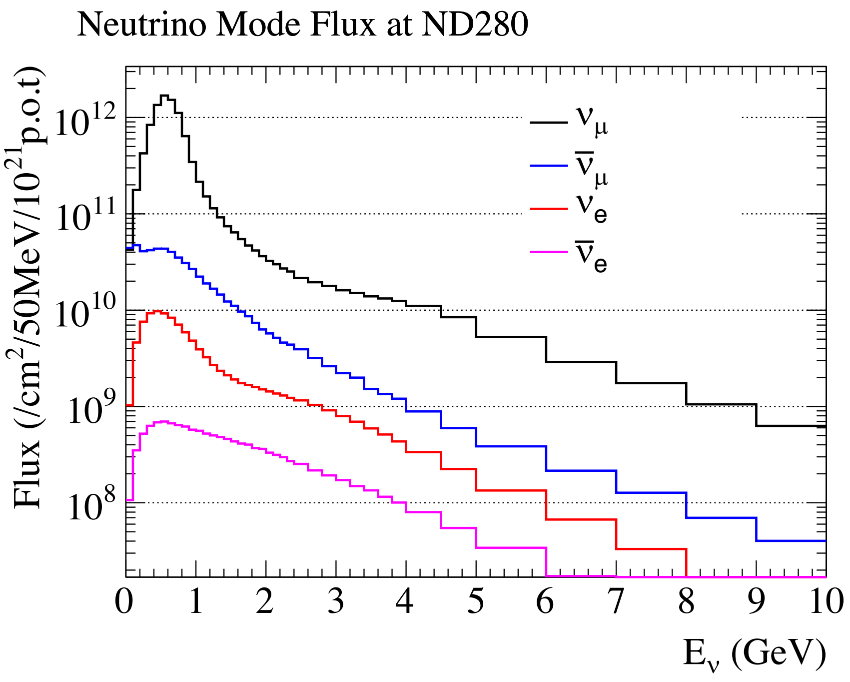


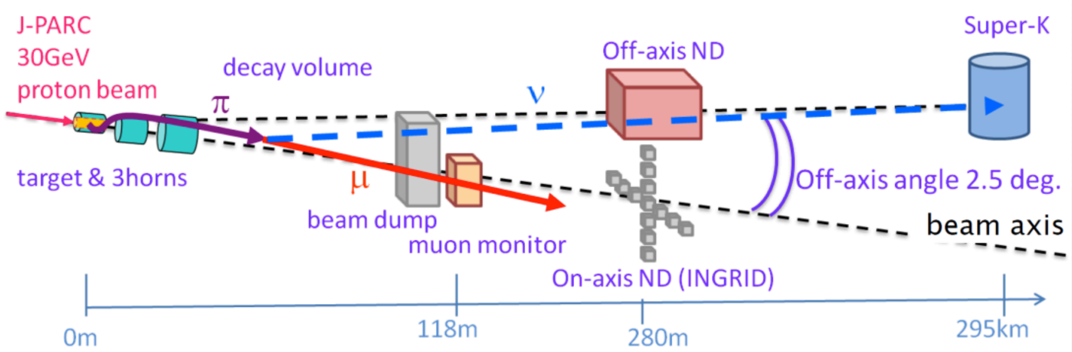
At T2K's peak flux energy, CCQE dominates

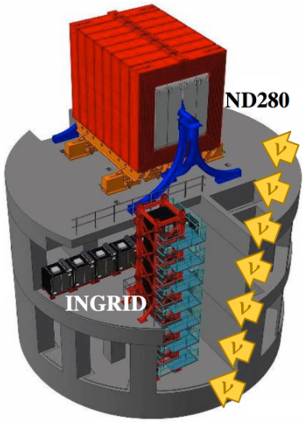
Exclusive measurements are more difficult than inclusive, but also more useful

T2K neutrino flux

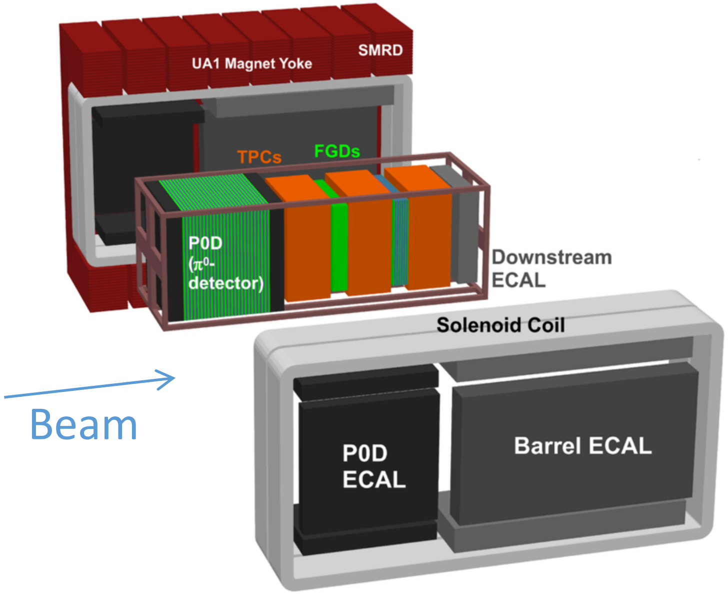
- Primarily ν_μ in neutrino mode
- Other flavors mainly from decays of muons, kaons, and wrong-sign pions
    - 3% wrong-sign contribution
- Constrained by hadron-production data (NA61/SHINE)



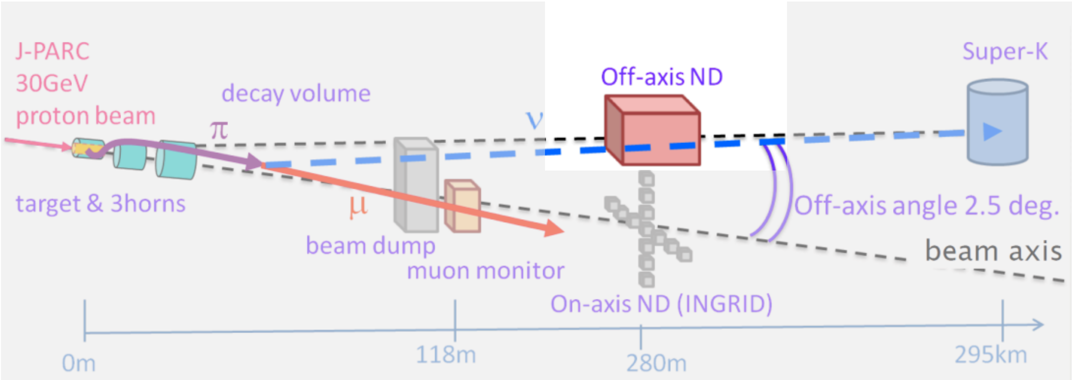


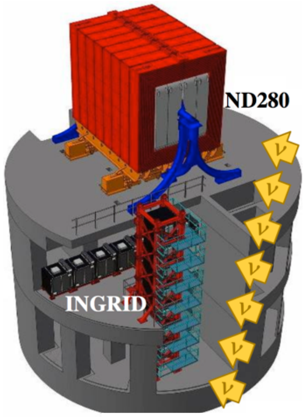


Off-axis Near Detector (ND280)

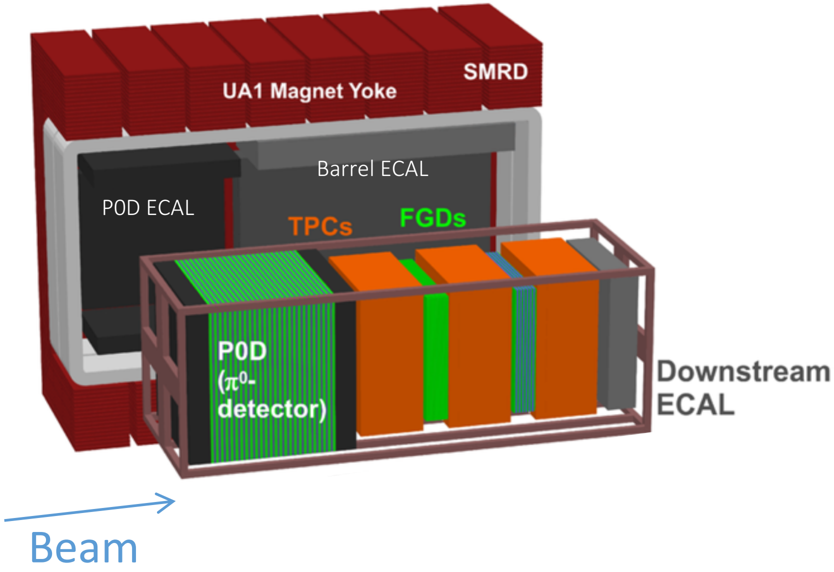


- 2.5° off-axis
- Constrains off-axis flux and background rates
- Carbon (CH), oxygen (H_2O), lead, brass, and gaseous argon targets

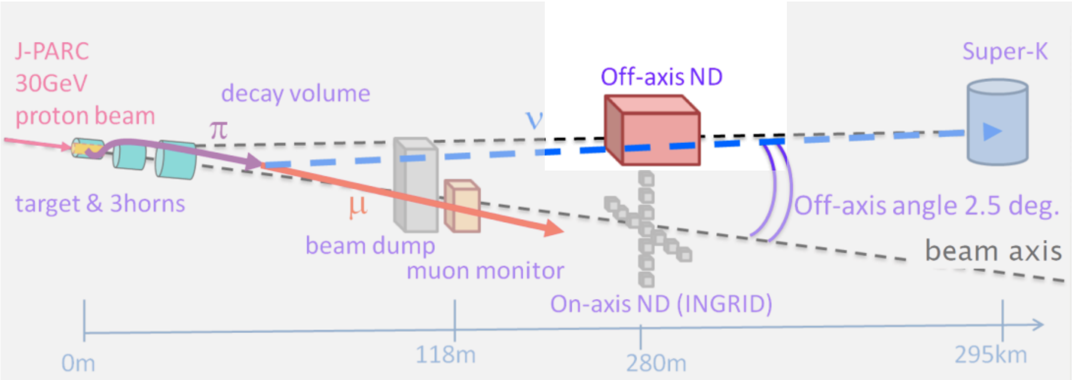




Off-axis Near Detector (ND280)



- Scintillator-based Pi-zero detector (P0D) sits upstream of tracker
  - Water bags can be filled and drained
- Tracker with time projection chambers (TPCs) interspersed with scintillator-based detectors (FGDs) for momentum reconstruction
  - FGD2 has permanent water layers
- Surrounded by calorimeter, side muon detectors, and 0.2 T magnet

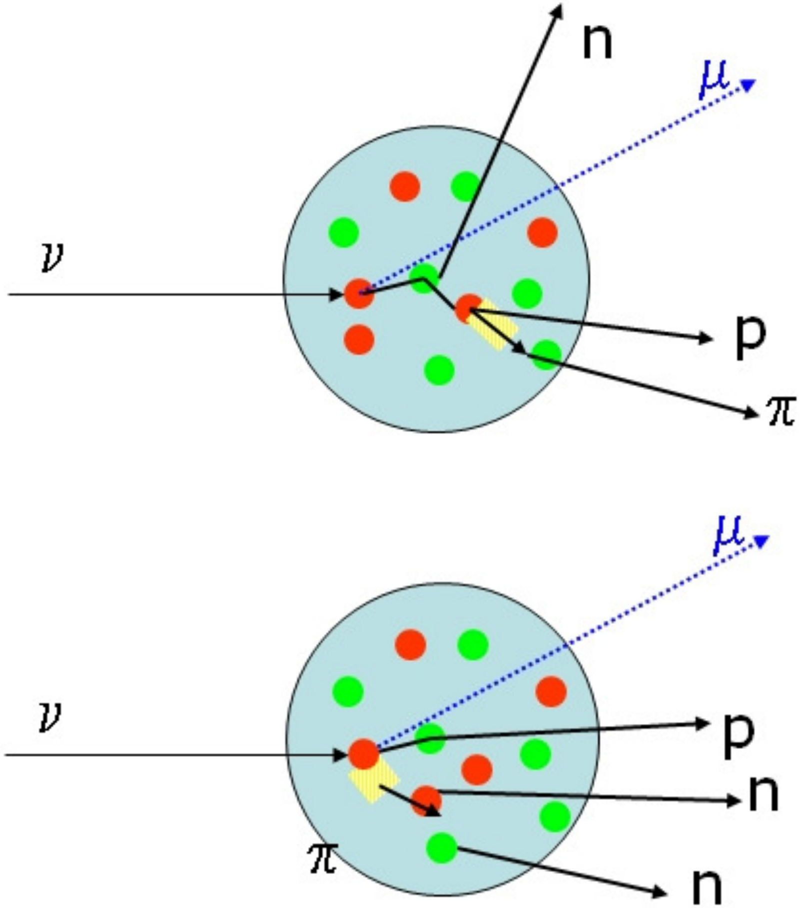


Approaches to cross-section measurements

- Simplest form: $\sigma = \frac{Event\ rate}{Flux * N_{targets} * \epsilon}$
  - Normalize by integrated flux
  - Background and efficiency corrections
  - Uncertainties propagated based on Poisson throws (statistics) or Gaussian variations of physics parameters (systematics)
- Differential measurements need unfolding or forward-folding based on response matrix from MC
  - Forward folding smears MC predictions to fit to reconstructed data
  - Unfolding corrects reconstructed data based on “inverted” response matrix
- Alternatively can fit directly for cross-section parameters but this assumes a model

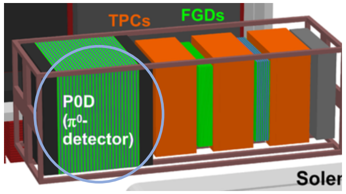
Final state interactions

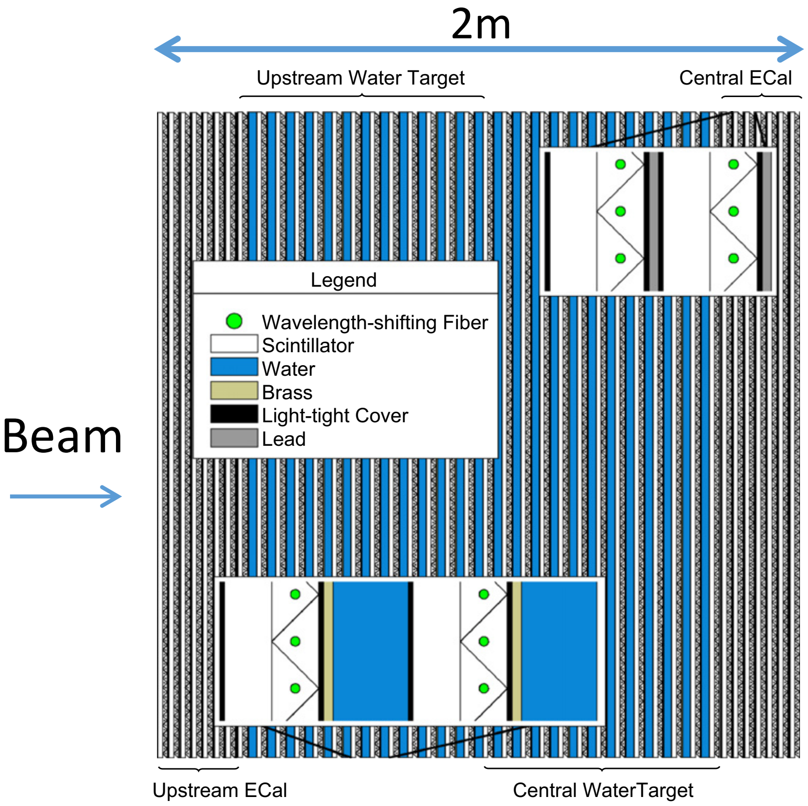
- Particles experience final state interactions (FSI) *within* nucleus
  - E.g. pion absorption/production, charge exchange, rescattering
  - Alters kinematics and final-state topology
- Reduce model dependence by quoting results in detector-observable space
  - CCQE→CCQE-like (CC0π)
  - CCRES→CC1π^+
  - Outgoing particle kinematics



arXiv:1510.05494

ν_μ CC0π on water

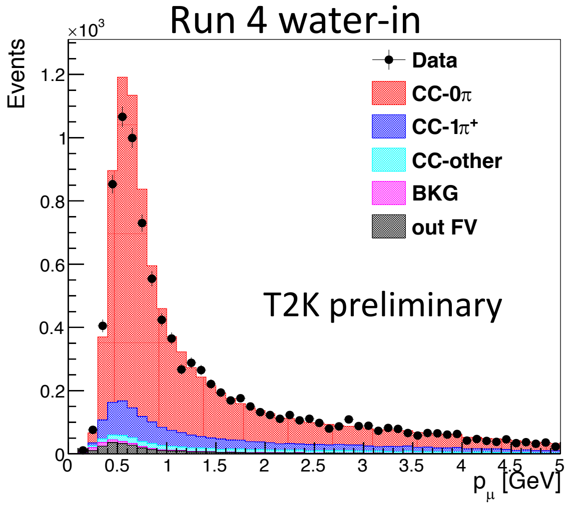


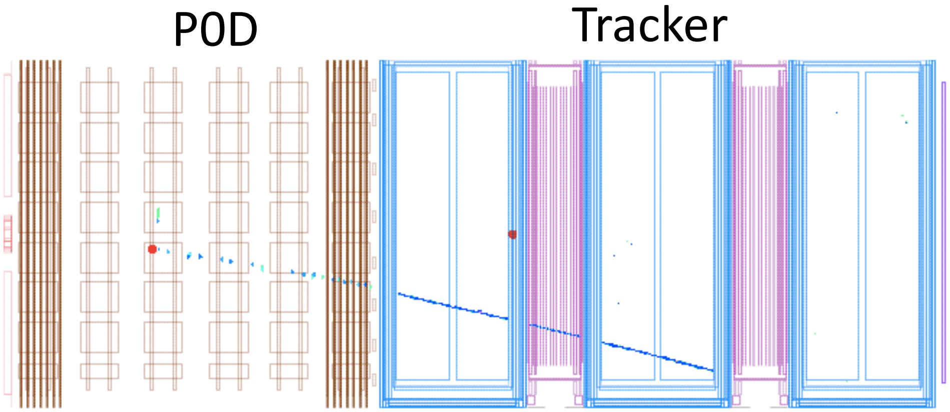


P0D water layers can be filled or drained → "water-in" and "water-out" detector configurations.

Select events in P0D water-target with single outgoing muon candidate that enters the Tracker.

Tracker reconstructs momentum and particle ID



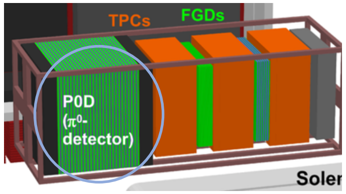


CC interaction in P0D

Runs 2-4	POT	Events
P0D Filled	2.1×10^{20}	12777
P0D Drained	3.5×10^{20}	13370

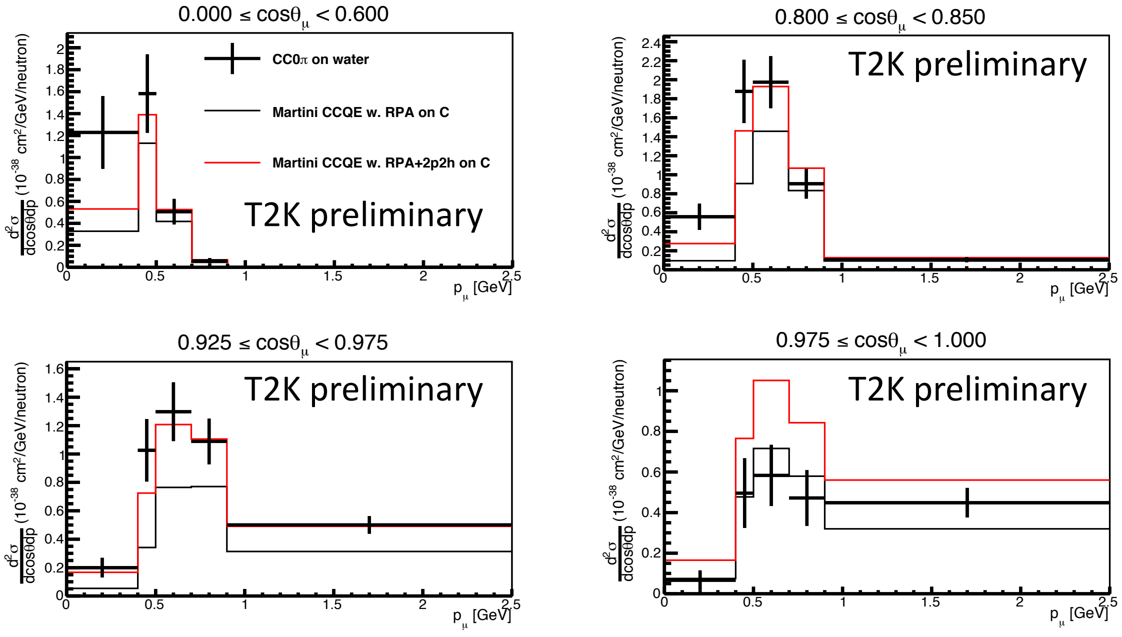
1900 kg water mass

arXiv:1611.03536



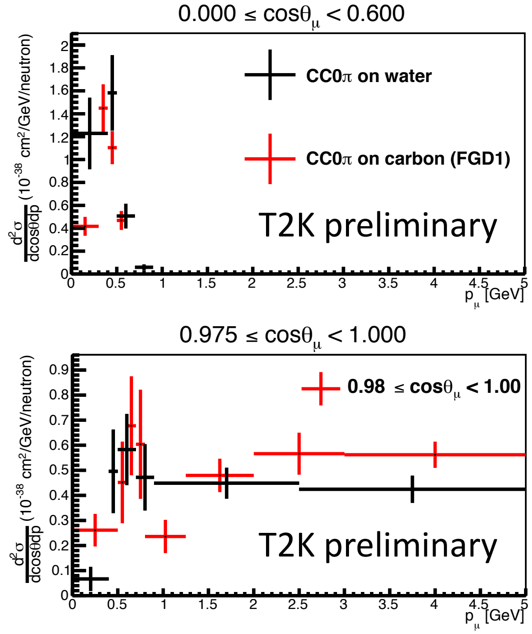
ν_μ CC0π on water

- Unfold water-in and water-out separately
- Subtraction to get cross section on water
- Measurement in p_μ-$\cos\theta_\mu$

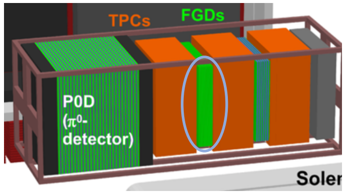


2p2h model gives better agreement

Comparison with PRD 93, 112012

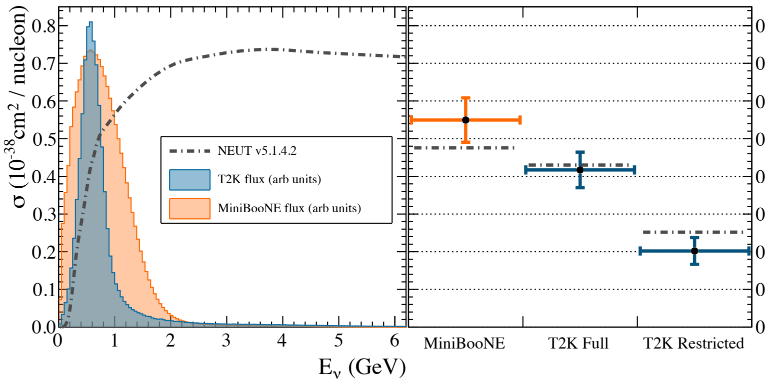


PRD 93, 112012 (2016)

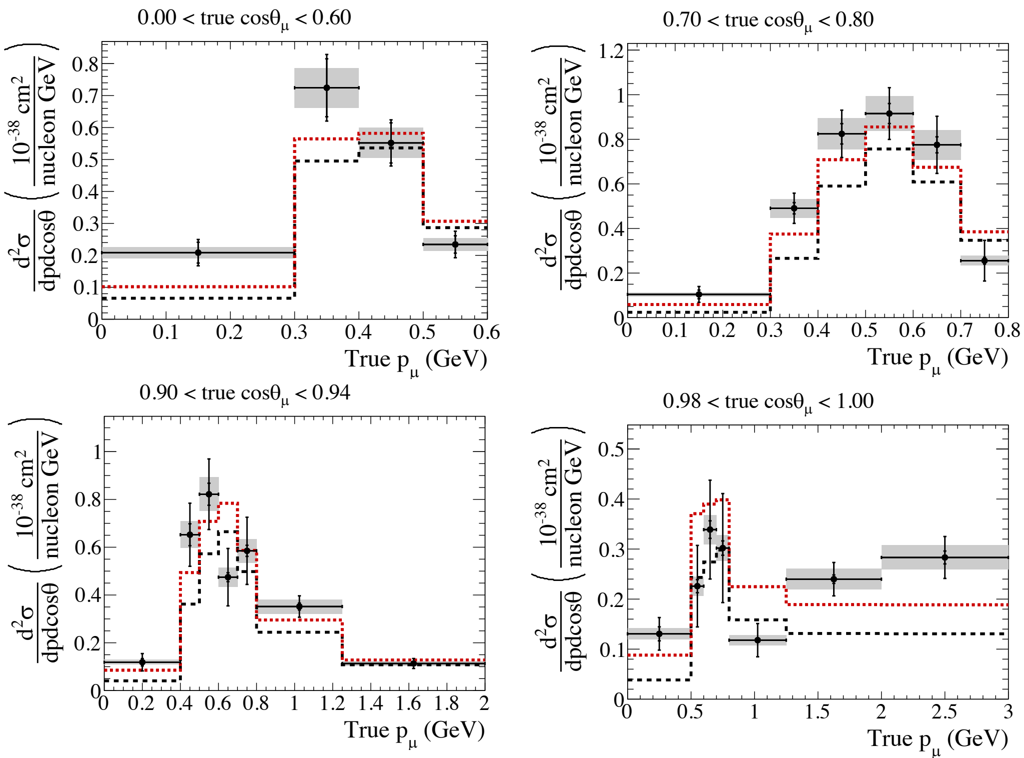


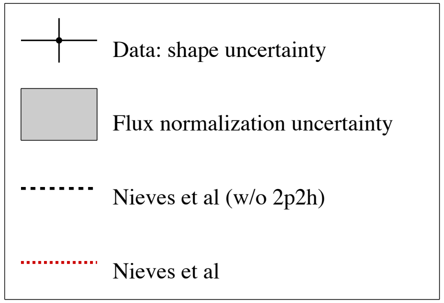
ν_μ CC0π on hydrocarbon

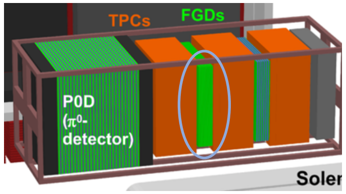
- Require single outgoing muon
- Two independent analyses agree within errors
  1. Binned likelihood fit
  2. Bayesian unfolding
- First double-differential measurement in p_μ-$\cos\theta_\mu$



Comparison of MiniBooNE, T2K full (analysis 1), and T2K restricted (analysis 2) phase space cross sections.

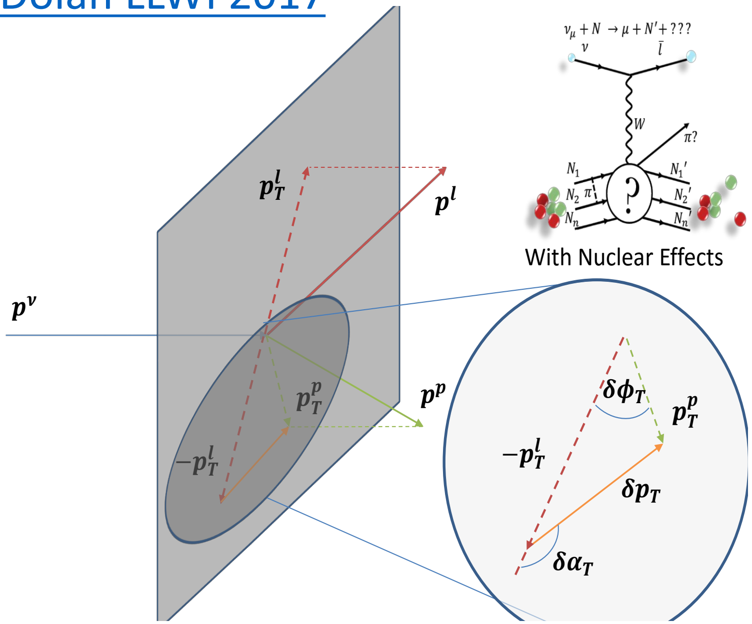




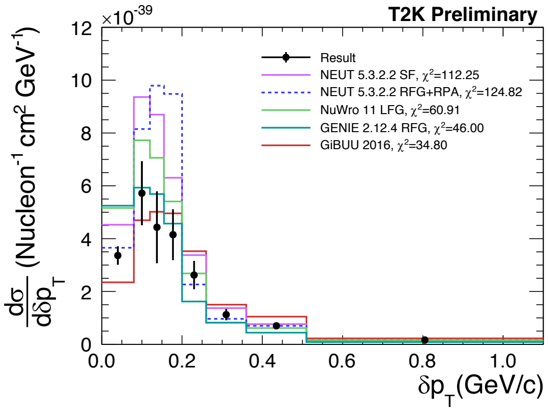


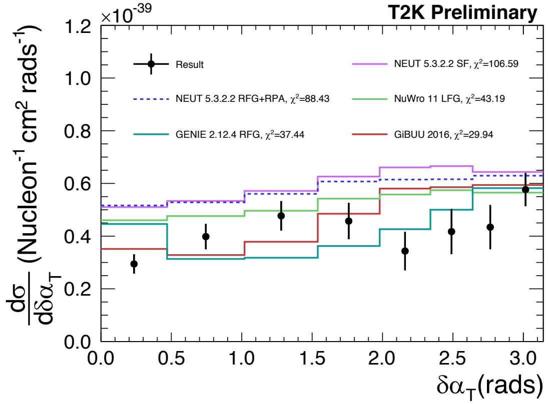
CC0π using transverse kinematic imbalance

S. Dolan LLWI 2017



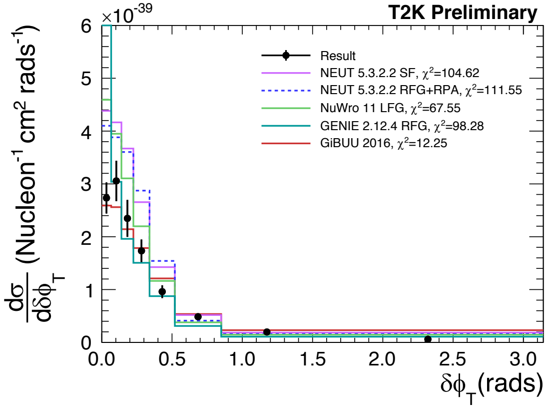
Forward folded, maximum likelihood fit





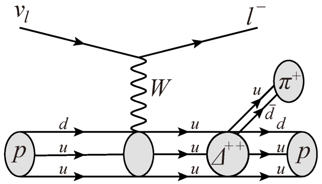
No nuclear effects → $\boldsymbol{p_T^l = -p_T^p}$

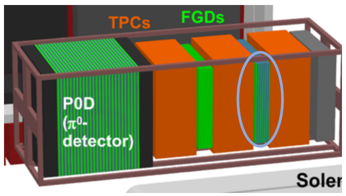
With nuclear effects → Use asymmetries to probe FSIs [PRC 94, 015503 (2016)]



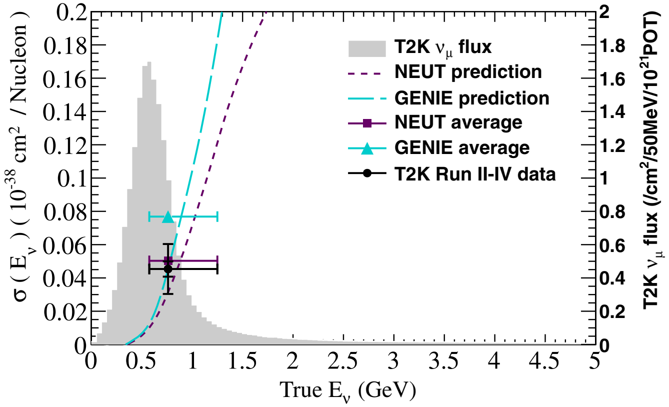
PRD 95, 012010 (2017)

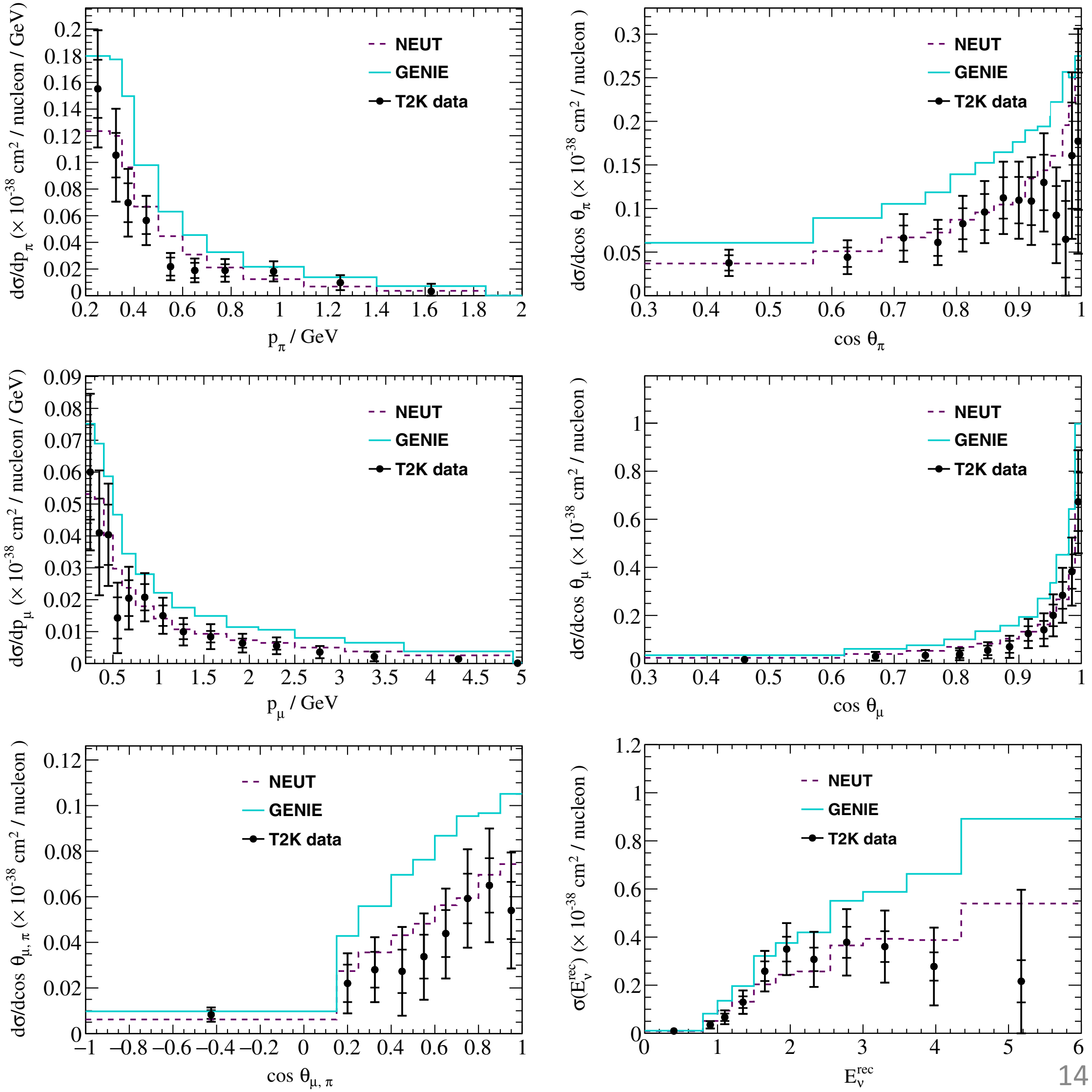
ν_μ CC1π^+ on water





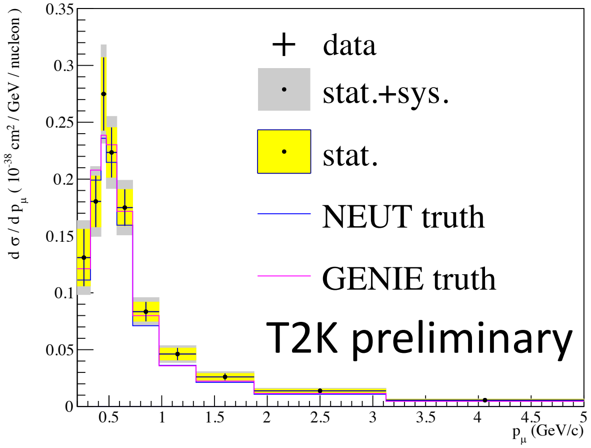
- Events with outgoing muon and π^+
- Water-enhanced sample in x-layers
- Bayesian unfolding
- GENIE differences due to inclusion of DIS to single-pion production

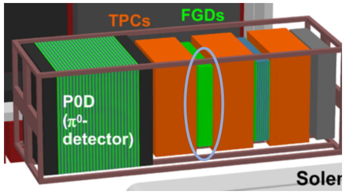




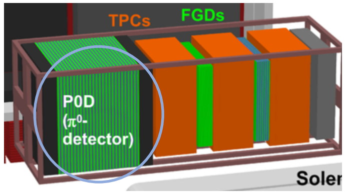
Antineutrino cross sections and cross-section ratios

- CC-Inclusive
- 4.3×10^{19} POT, FGD1
- Bayesian unfolding
- Differential in muon kinematics
- $\sigma = \left(0.176 \pm 0.009\ (stat) \pm 0.018\ (syst)\right)\times10^{-38}$ cm²/nucl





- Total inclusive cross section averaged over materials in P0D
  - Water, scintillator, and brass
- Ratio: $\frac{\sigma(\bar{\nu})}{\sigma(\nu)}$
  - $0.3731 \pm 0.0124(\mathrm{stat}) \pm 0.0152(\mathrm{syst})$
  - NEUT prediction: 0.39
- Asymmetry: $\frac{\sigma(\nu)-\sigma(\bar{\nu})}{\sigma(\nu)+\sigma(\bar{\nu})}$
  - $0.4566 \pm 0.0120\ (\mathrm{stat}) \pm 0.0171\ (\mathrm{syst})$



T2K preliminary

Of note

- On-axis (INGRID)
  - CC-Inclusive on iron and hydrocarbon PRD 90, 052010 (2014)
  - CCQE on hydrocarbon PRD 91, 112002 (2015)
- Off-axis (ND280)
  - CC-Inclusive on carbon PRD 87, 092003 (2013)
  - ν_e CC-Inclusive on carbon PRL 113, 241803 (2014)
  - CCQE on carbon as function of E_ν PRD 92, 112003 (2015)
  - Coherent π^+ on carbon PRL 117, 192501 (2016)

Summary

- T2K continues to produce new and important cross-section measurements
  - Recently published results include differential and double-differential cross sections on water and hydrocarbon
  - Recent preliminary results under preparation for publication
- Ongoing analyses
  - Full phase-space ν_μ CC-Inclusive on hydrocarbon
  - CC-Inclusive on gaseous argon
  - CC0π muon antineutrino on water

Thank you

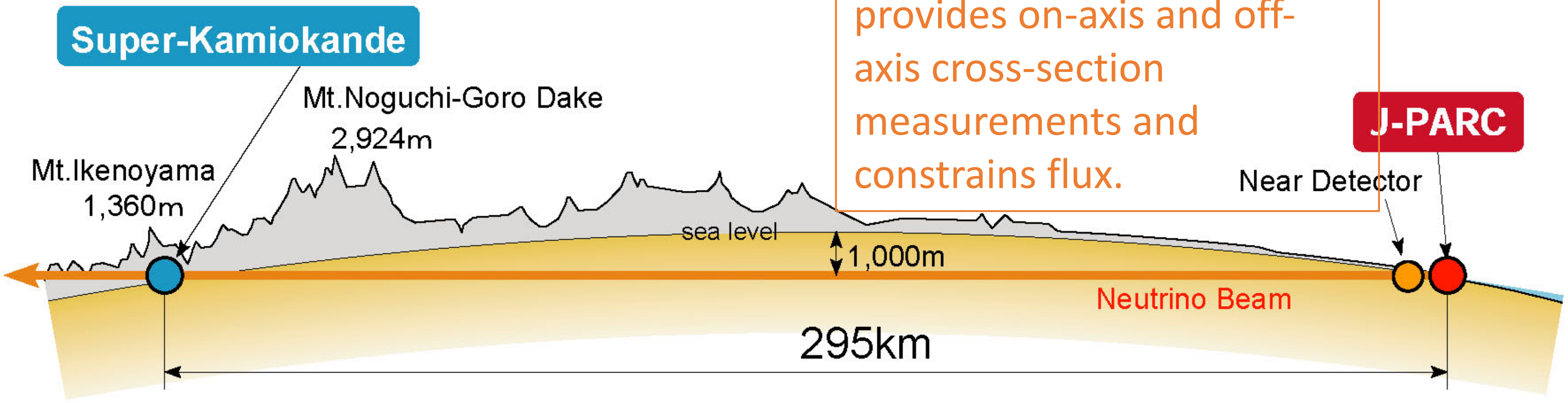
Backups

The Tokai to Kamioka (T2K) Experiment

1. Neutrinos produced here. Primarily ν_μs.

3. Off-axis (2.5°) beam travels 295km through earth to SK.

2. Near detector at 280 m provides on-axis and off-axis cross-section measurements and constrains flux.



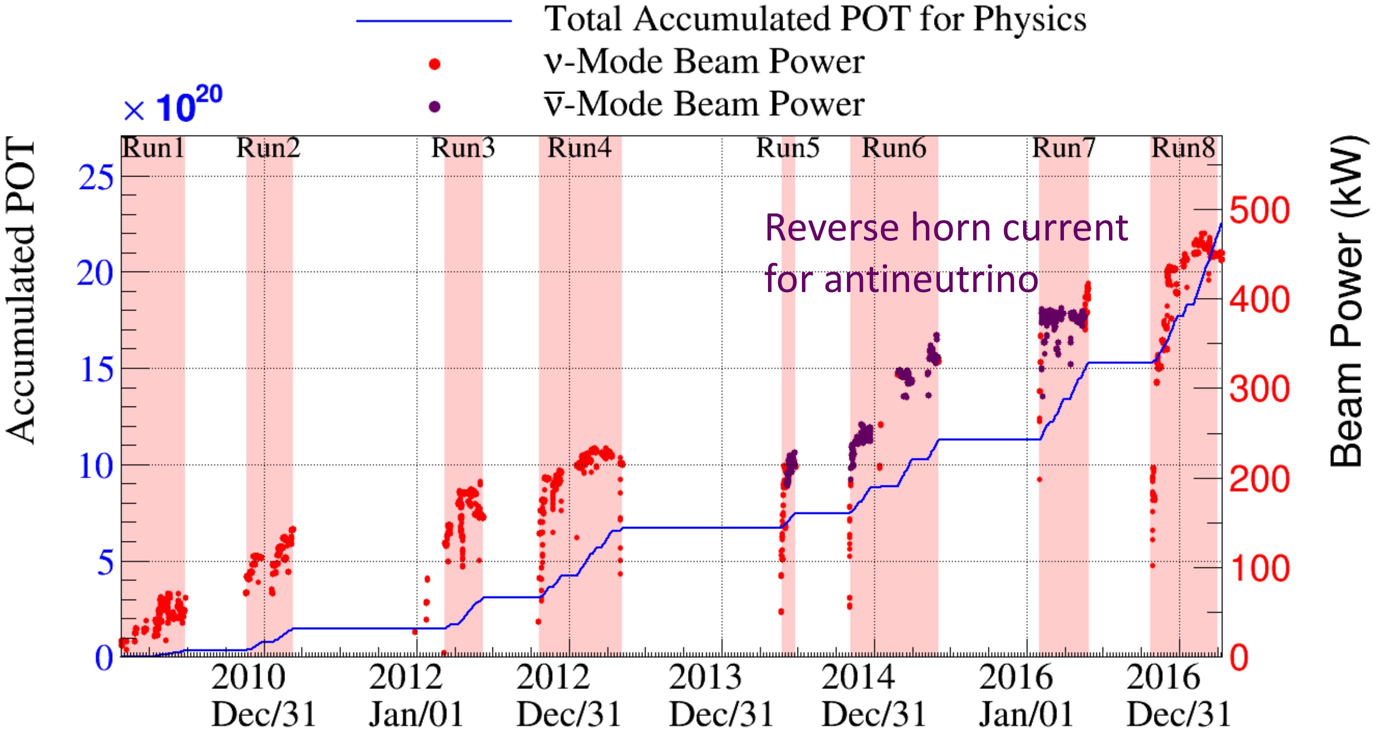
T2K Beamline

Protons on target (POT) totals up to Run 7

POT total: 1.51×10^{21}

ν-mode: 7.57×10^{20}

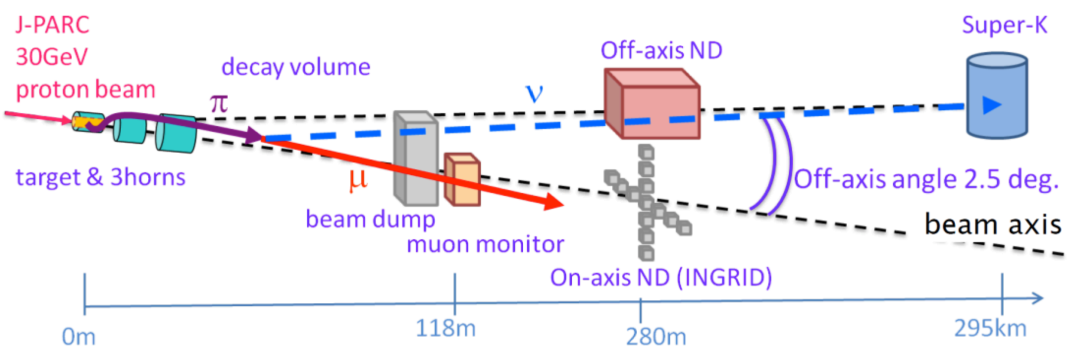
$\bar{\nu}$-mode: 7.53×10^{20}



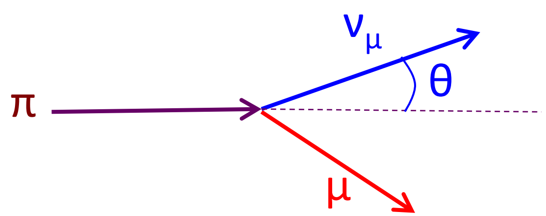
8 bunches per spill

Graphite target

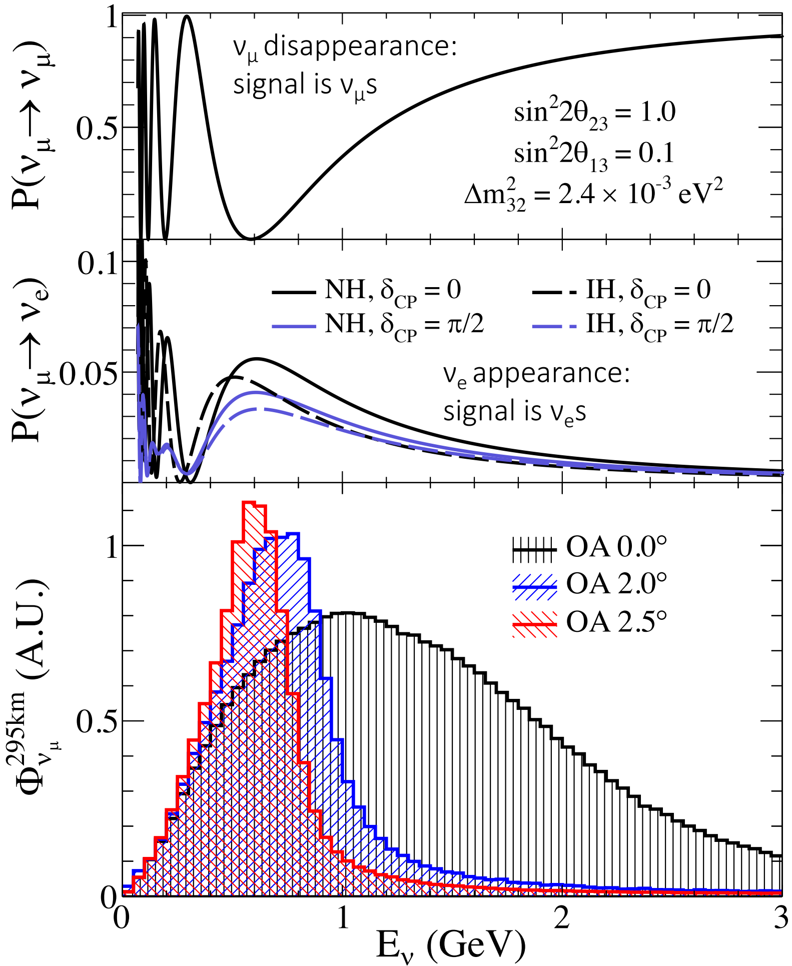
96m decay volume

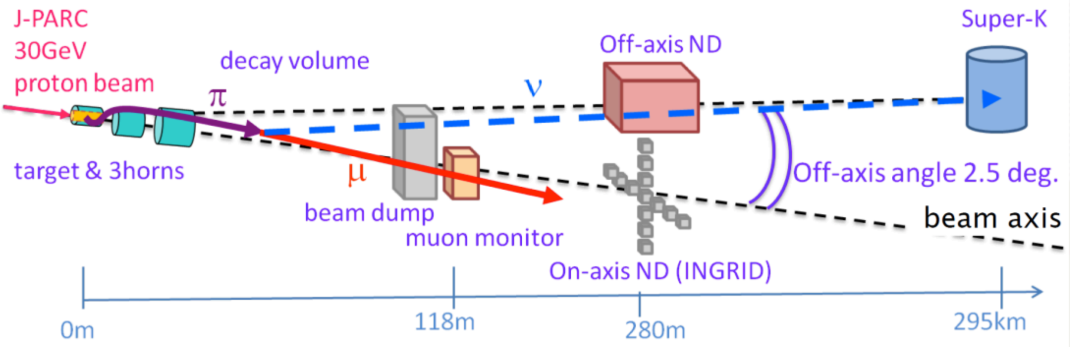


Off-axis Effect



- First exploited by T2K
- Energy of neutrinos from two-body π-decay, at angles relative to π momentum, is capped due to Lorentz boost
  - T2K has narrowband spectrum peaking at ~0.6 GeV at 2.5° off-axis
- Maximizes oscillation probability at far detector and reduces high-E backgrounds

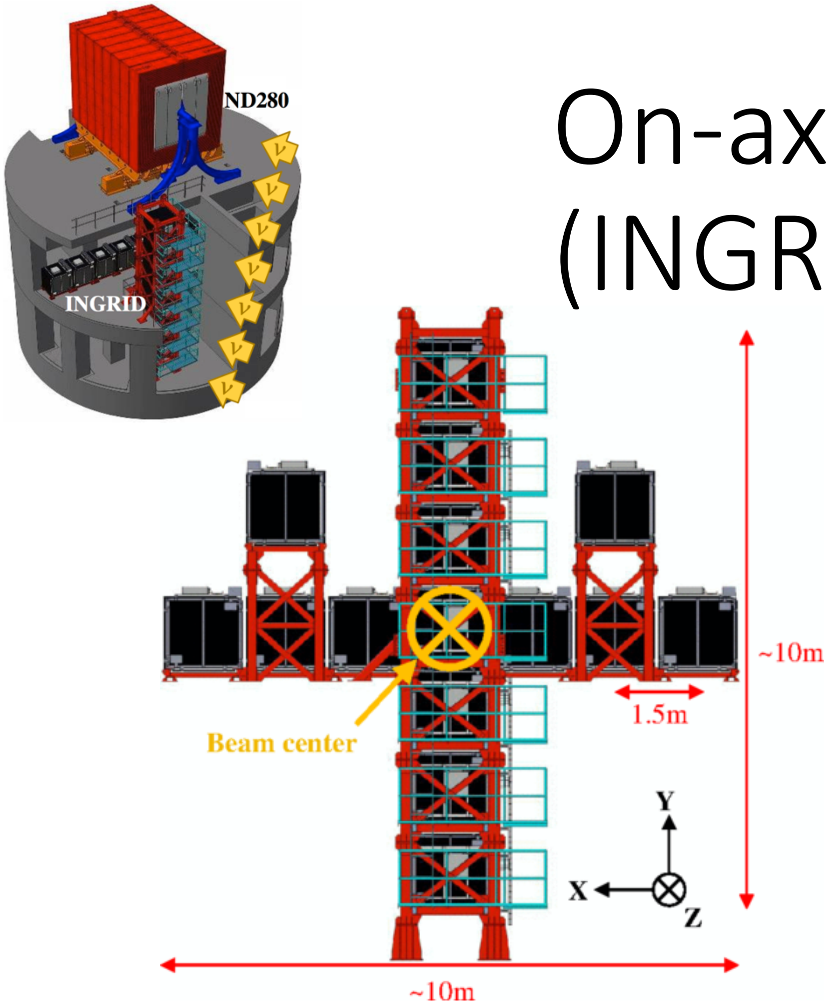


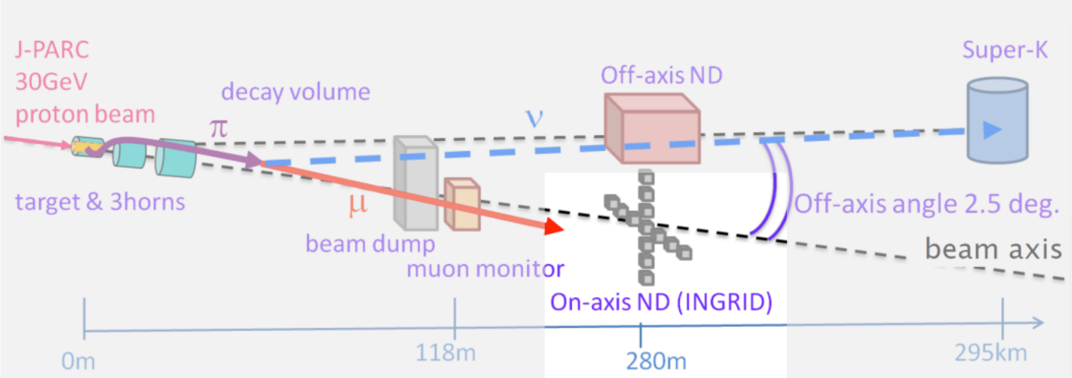


Can tune L/E

On-axis Near Detector (INGRID)

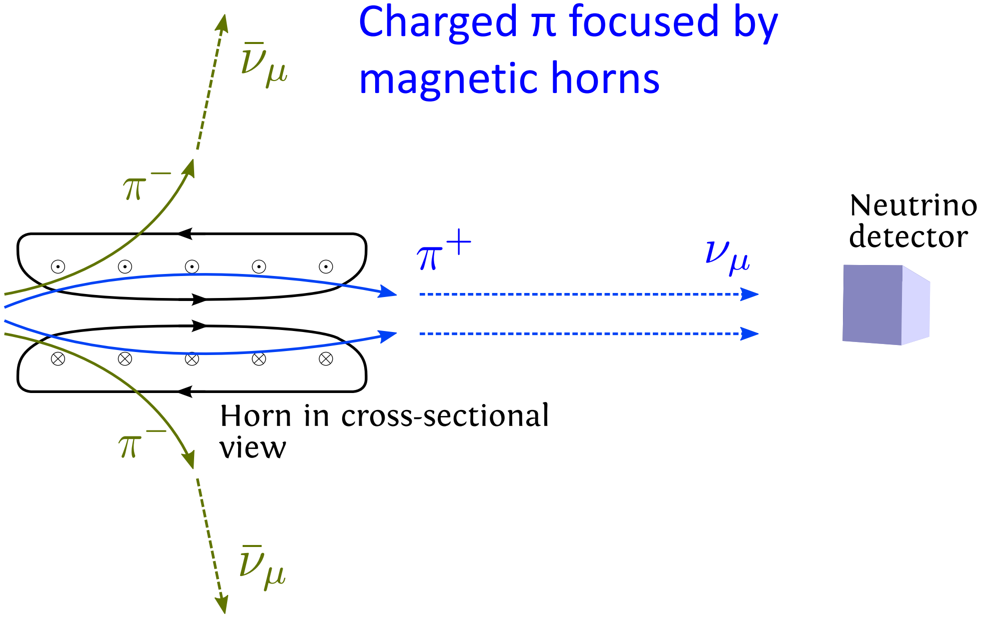
- 16 identical cubic modules arranged vertically and horizontally
  - Each standard module a sandwich of 10 iron and 11 scintillator planes
- 1 Proton Module at center of cross
  - Finer scintillator planes and no iron
- Centered on beam
  - Primary purpose beam monitoring
- Carbon (CH) and iron targets

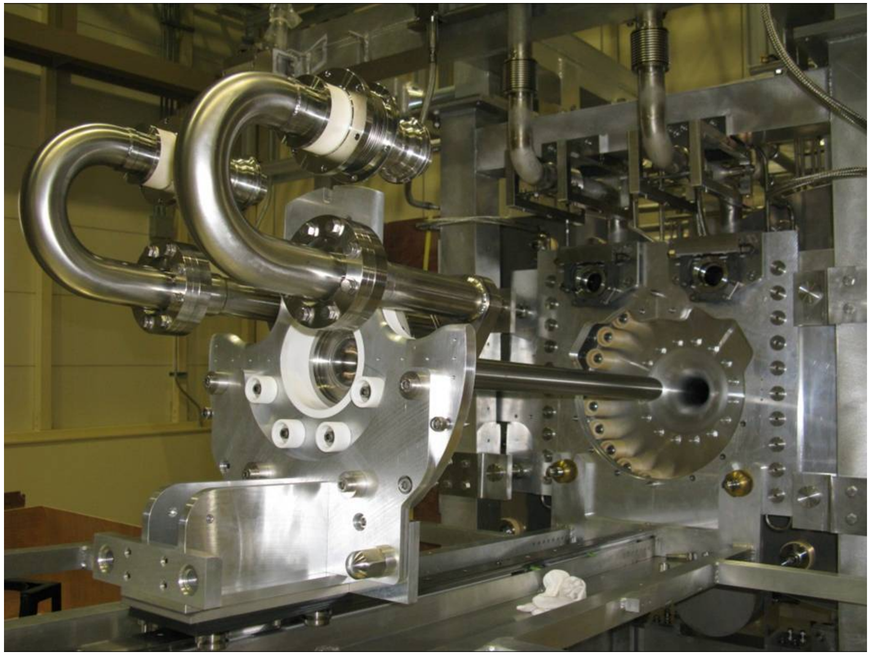




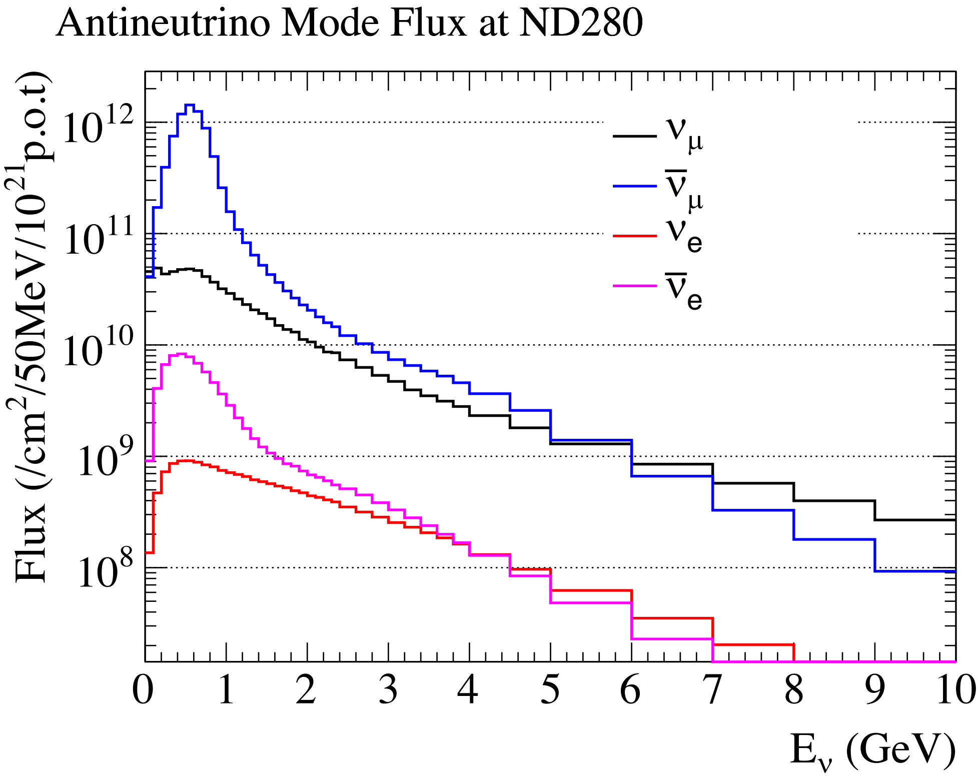
Horn focusing

- Three magnetic horns
- Good data-taking periods +/- 250 kA
  - Identical current on all three

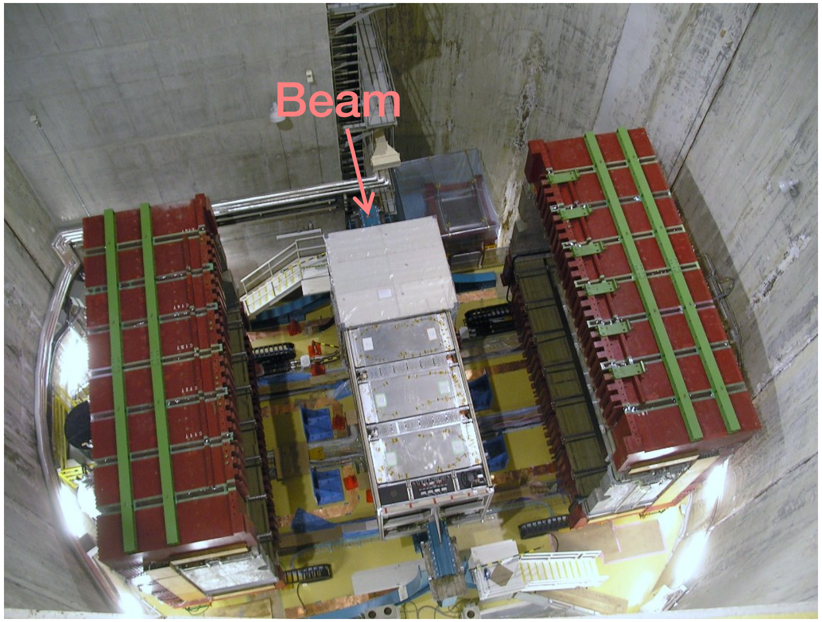


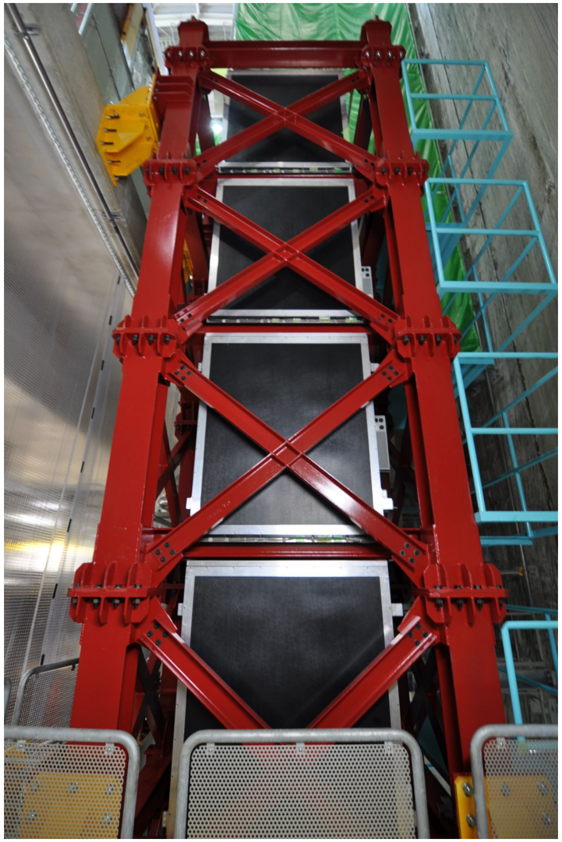


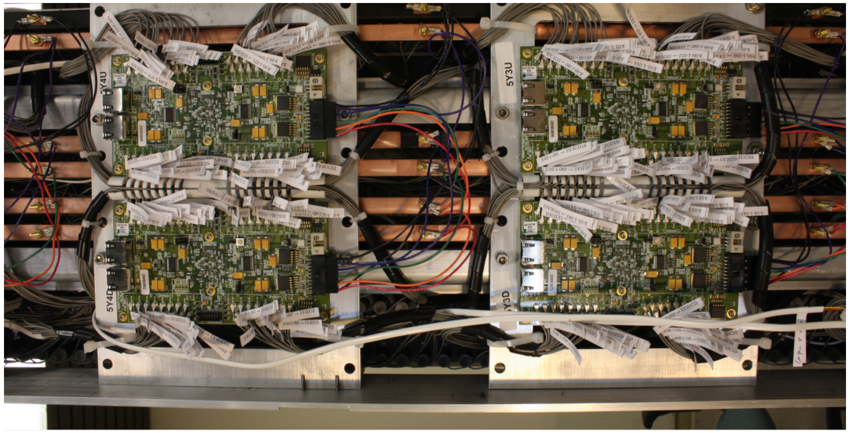
Antineutrino mode flux



ND pictures

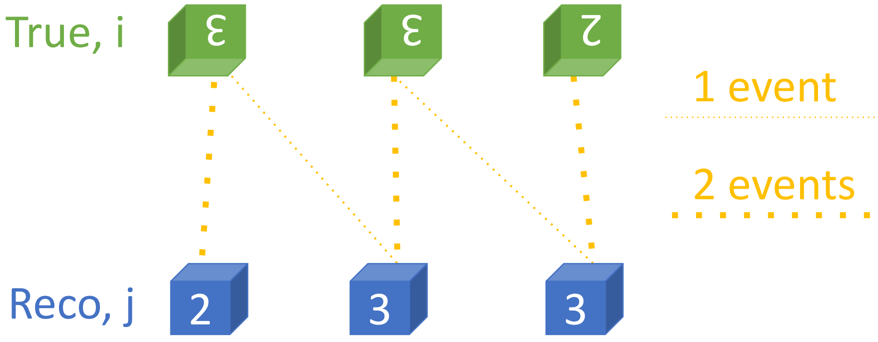






Bayesian Unfolding

- Data observables measured imperfectly
- Would like a way to extract the *true* value of observable from the *reconstructed*
- One way is to construct a *response matrix* $P(j|i)$
- Bayes Theorem then gives the *unfolding matrix*
  - $P(i|j) = P(j|i)P(i)/P(j)$
  - Prior pdf is a choice; we use MC truth
- $N_i^{unf} = P(i|j)N_j^{meas}$

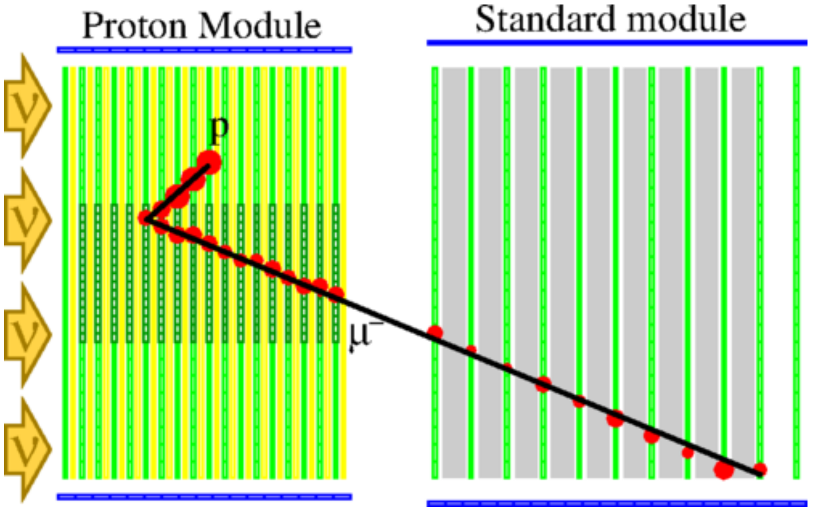


Response Matrix

$$\begin{array}{cc} \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ 0 & \frac{2}{3} & \frac{1}{3} \\ 0 & 0 & 1 \end{pmatrix} & \begin{array}{c} 1 \\ 2 \\ i=3 \end{array} \\ \begin{array}{ccc} j=1 & 2 & 3 \end{array} & \end{array}$$

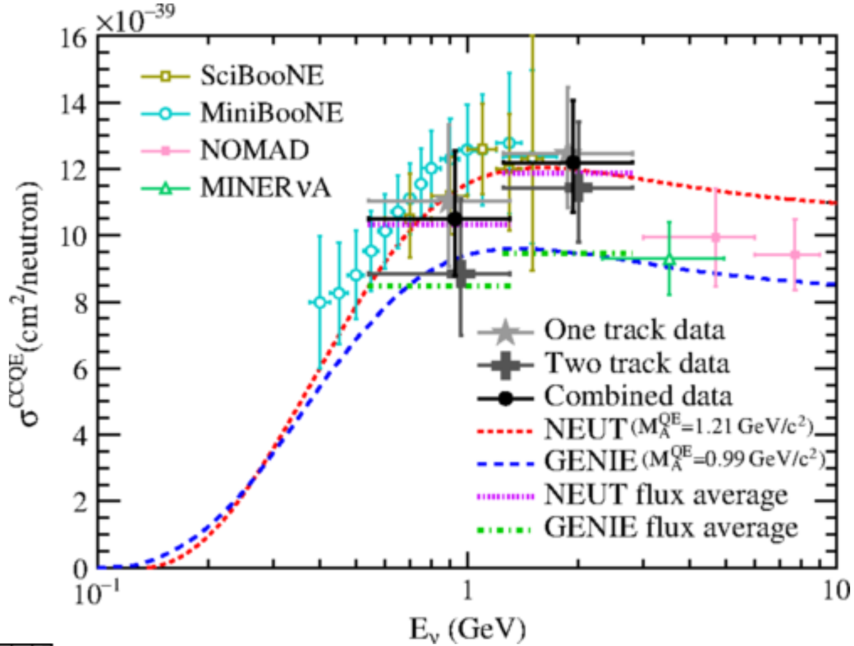
PRD 91, 112002 (2015)

Measurement of ν_μ CCQE at INGRID

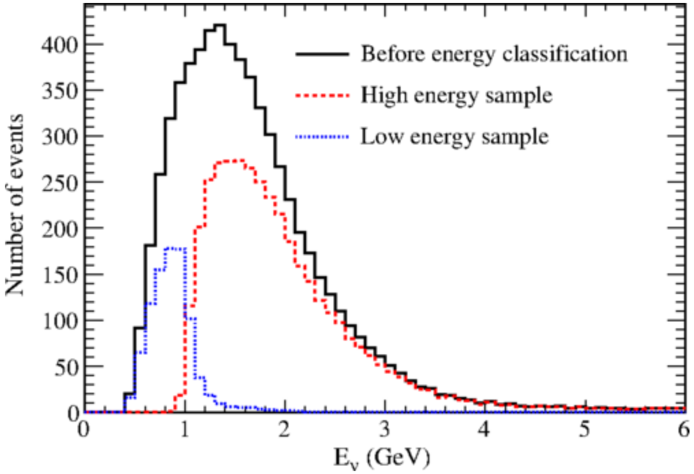


Pure scintillator

Iron and scintillator sandwiched



Energy classification based on track topology in standard module



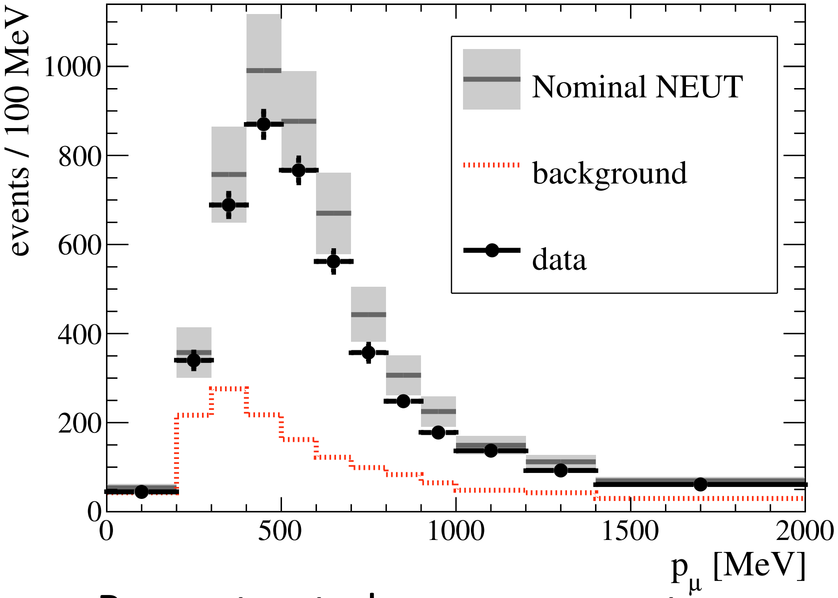
Low and high energy cross sections extracted for one track and two track samples.

Good agreement with predictions from models

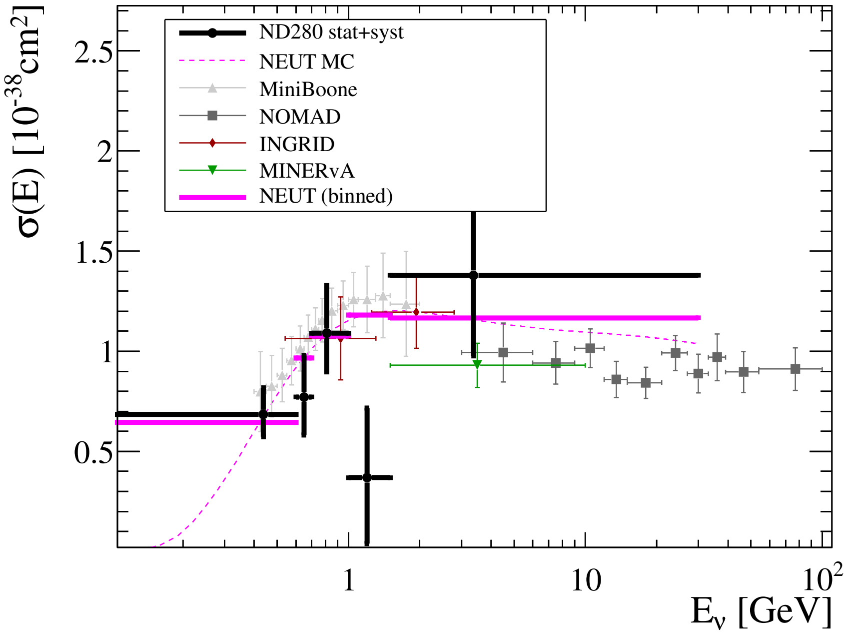
PRD 92, 112003 (2015)

Measurement of ν_μ CCQE at ND280

- Binned likelihood fit to observed p_μ-cos θ_μ
  - Parameterized in E_ν
- Energy dependent cross section extracted



Reconstructed muon momentum



Flux integrated CCQE cross section:
$\sigma = (0.83 \pm 0.12)E\text{-}38\ cm^2/neutron$