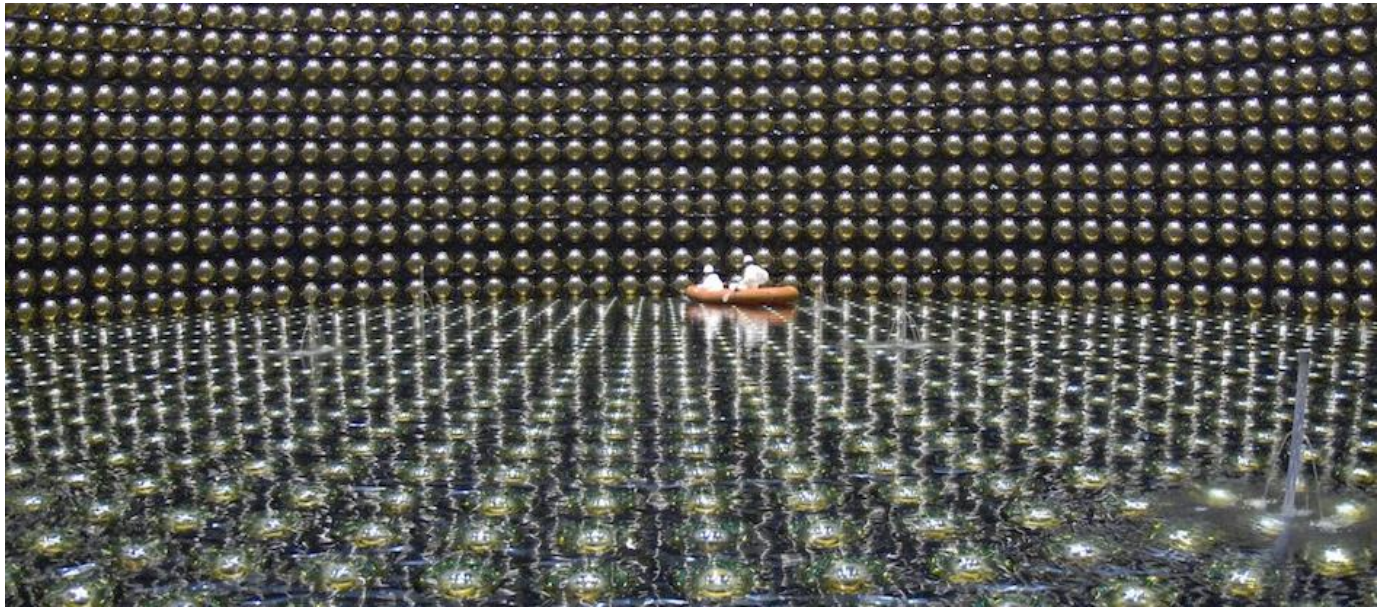
THE UNIVERSITY OF WARWICK

T2K

Results from T2K

IPA 2014, 18th August 2014

Martin Haigh, University of Warwick
for the T2K Collaboration



Neutrino oscillations

Flavour states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Mass states

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillations

Flavour states ≠ Mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillations

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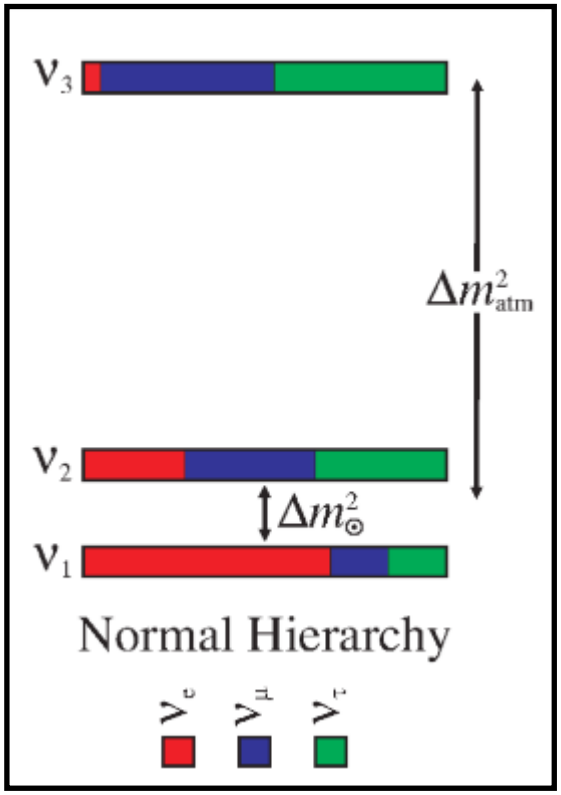
ν_μ disappearance
Accelerator,
Atmospherics

ν_e appearance/disappearance
Accelerator,
SBL reactor

ν_e disappearance
LBL reactor,
Solar



Neutrino oscillations

Flavour states ≠ Mass states

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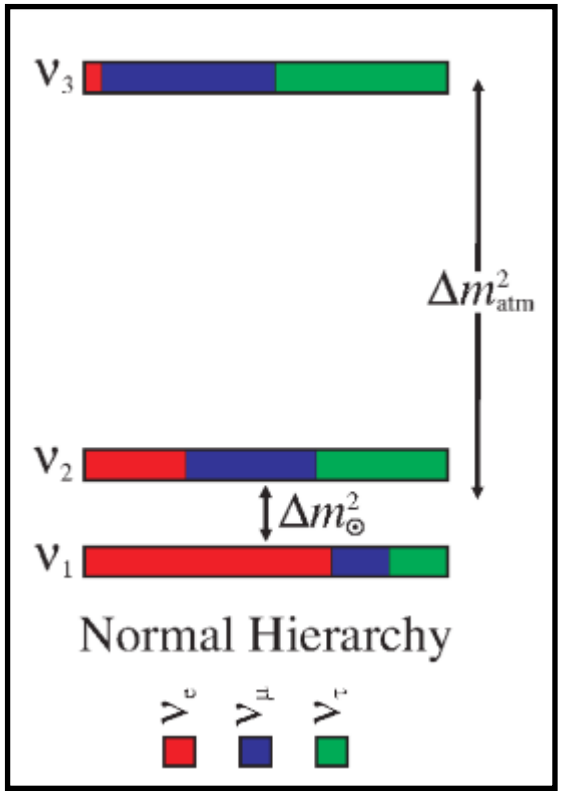


- T2K analyses:
  - **ν_μ disappearance**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

  - **ν_e appearance**

$$P(\nu_\mu \to \nu_e) \approx \sin^2(\theta_{13})\sin^2(2\theta_{23})\sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

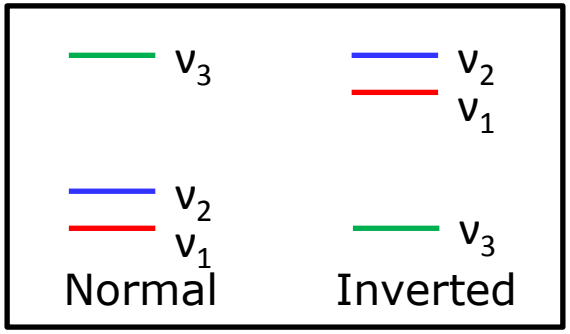
- Approximations good where $L/E \ll (\Delta m^2_{\odot})^{-1}$.
- Terms depending on δ appear at higher order in appearance probability.

State of play and motivation

- Many oscillation parameters already measured!

$\theta_{12} \sim 34°$	Solar+KamLAND
$\theta_{23} \sim 45°$	Super-K, MINOS, T2K
$\theta_{13} \sim 9°$	Daya Bay, RENO, Double CHOOZ (T2K in appearance channel)
$\Delta m^2_{\odot} \sim 7.65 \times 10^{-5}$ eV^2	Solar+KamLAND
$\lvert\Delta m^2_{atm}\rvert \sim 2.4 \times 10^{-3}$ eV^2	MINOS, T2K

- Still unknown:
  - Sign of Δm^2_{atm} (mass hierarchy), two possibilities:
    - Normal hierarchy (NH): $m_3 > m_1, m_2$
    - Inverted hierarchy (IH): $m_3 < m_1, m_2$
  - Octant of θ_{23}, i.e. $\theta_{23} < 45°$, $\theta_{23} > 45°$, maximal!?
  - CP violating phase δ.
    - Non-zero CP violation in the lepton sector means leptogenesis is a potential source of matter-antimatter asymmetry!

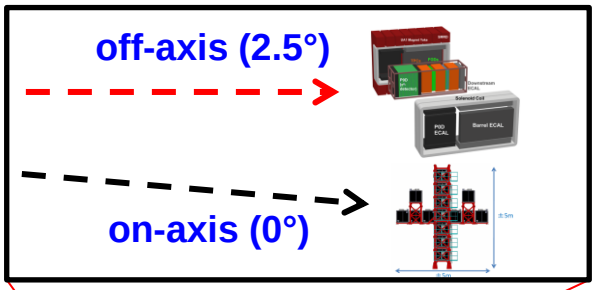


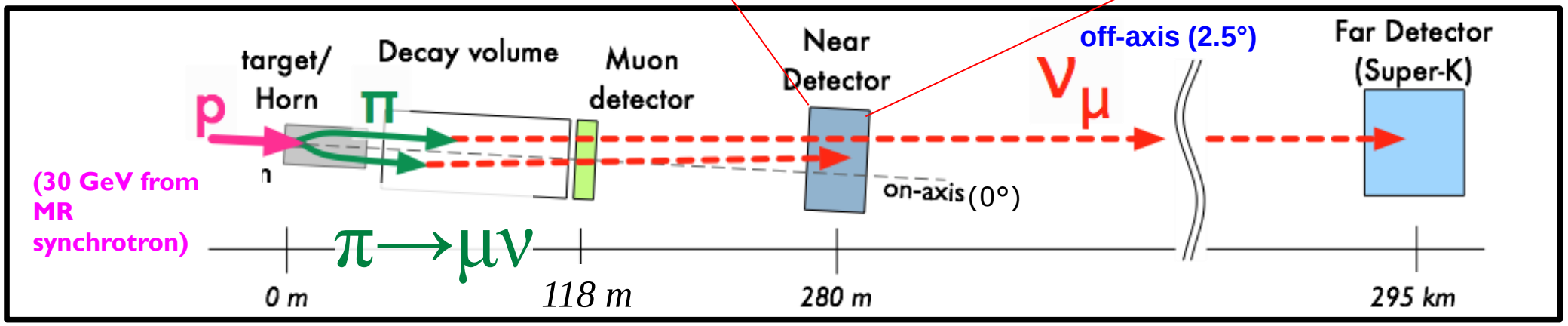
- T2K still refining measurements of known parameters and also has enough sensitivity to give hints on mass hierarchy and δ. Determination of octant depends on true θ_{23}.

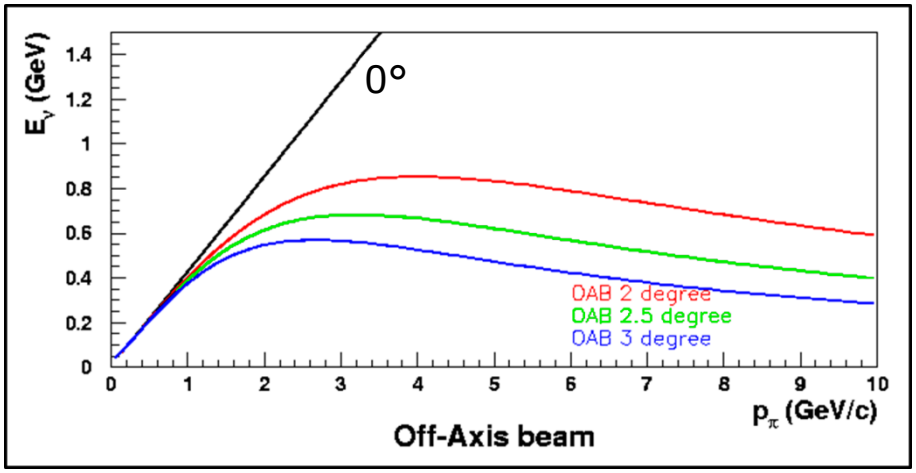
T2K Experiment

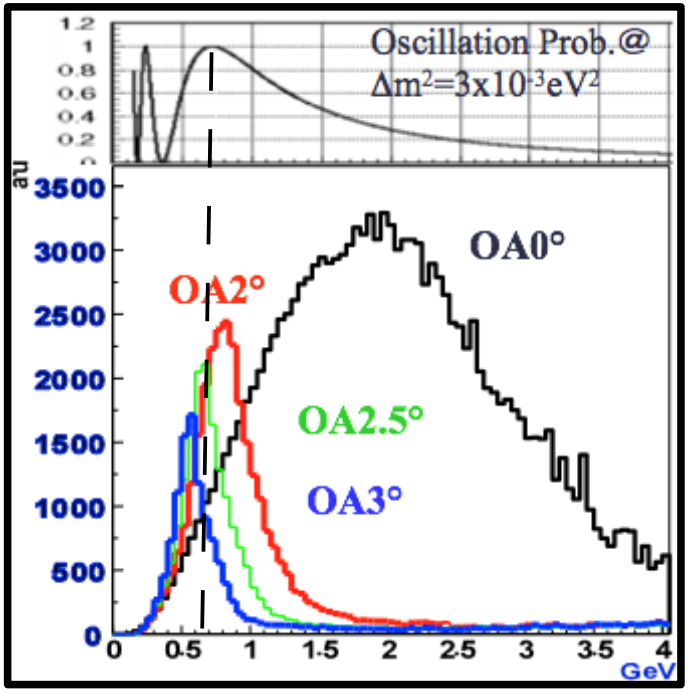
- Long-baseline experiment in Japan.
  - ν_μ beam produced at J-PARC on East coast.
  - Far detector is the Super-Kamiokande Water Cherenkov detector.
  - Also a suite of near detectors.

Design principle





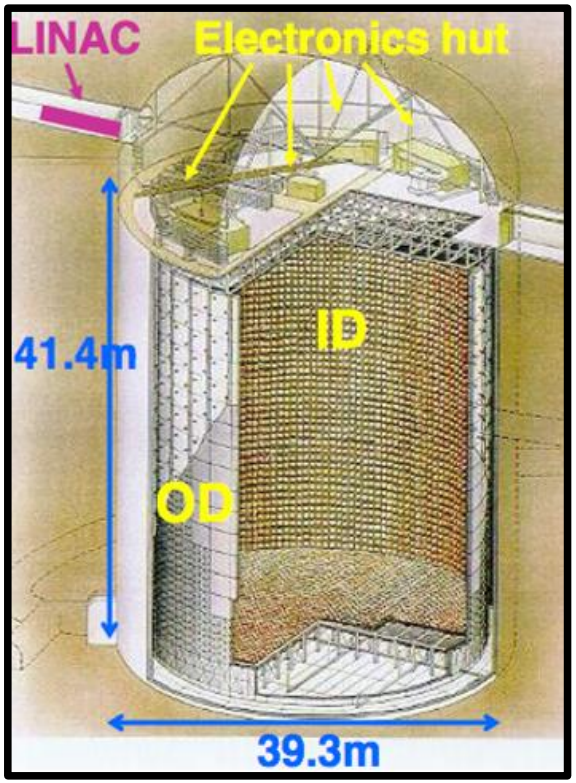


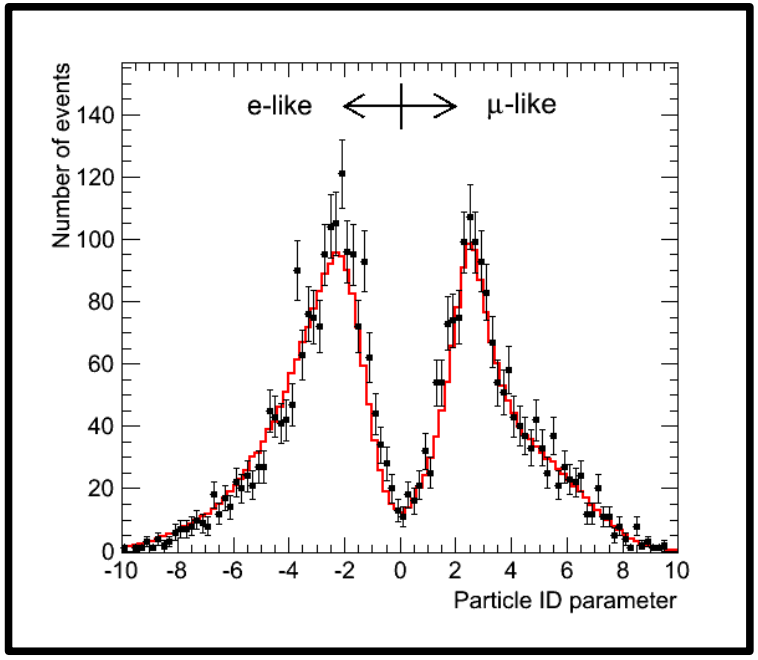


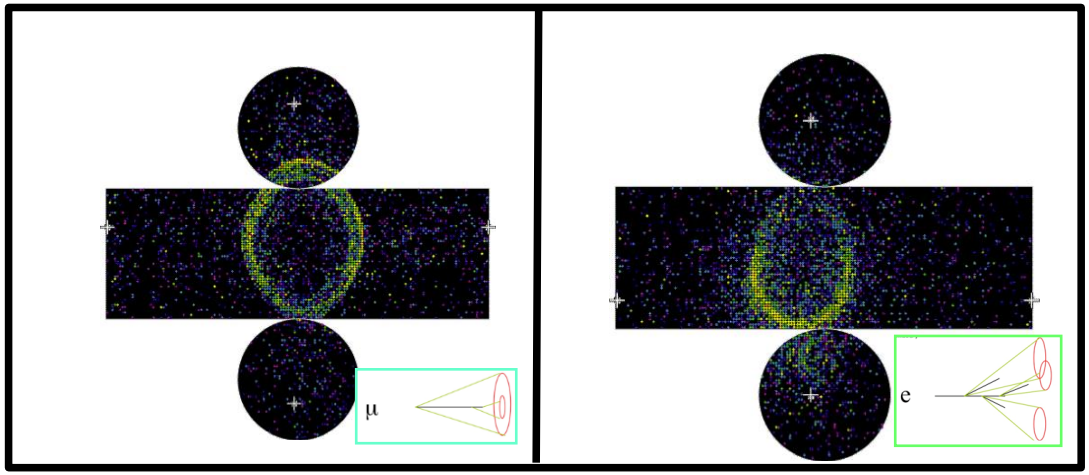
- Novel feature - off-axis beam to reduce high-energy tail
  - Narrow-band beam around oscillation maximum
  - Feed-down from mis-reconstructed DIS/resonance events at SK into analysis region reduced.

Super-K detector

- Located in Mozumi mine with 1km rock overburden (2700 m.w.e.)
- 22.5 kt fiducial mass water Cherenkov detector
  - Inner detector ~ 11000 20-inch PMTs
  - Outer veto ~ 1900 8-inch PMTs
- Excellent μ/e separation from ring shape/opening angle
- New for T2K:
  - 100% livetime DAQ system
  - Improved algorithm for NC-π^0 rejection



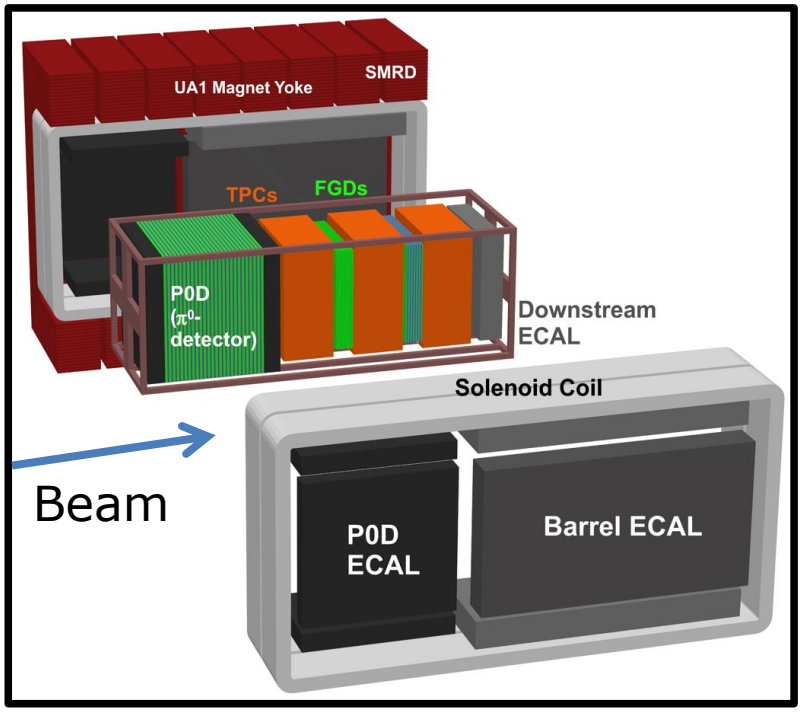




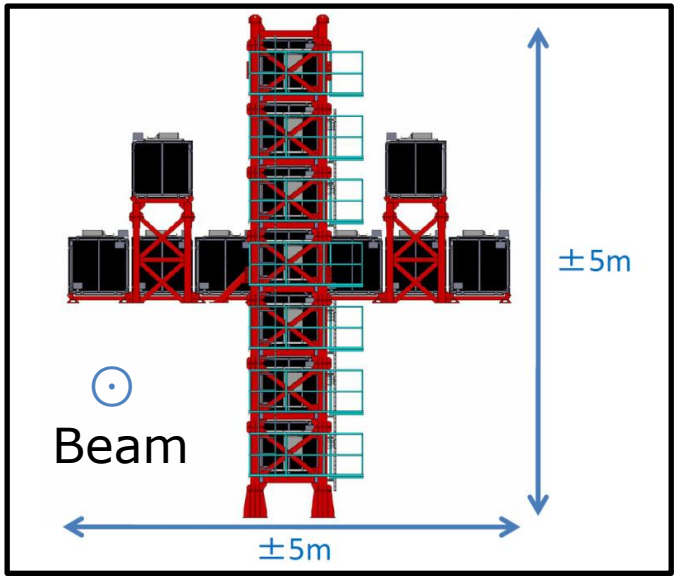
MC, μ-like MC, e-like

Near detectors

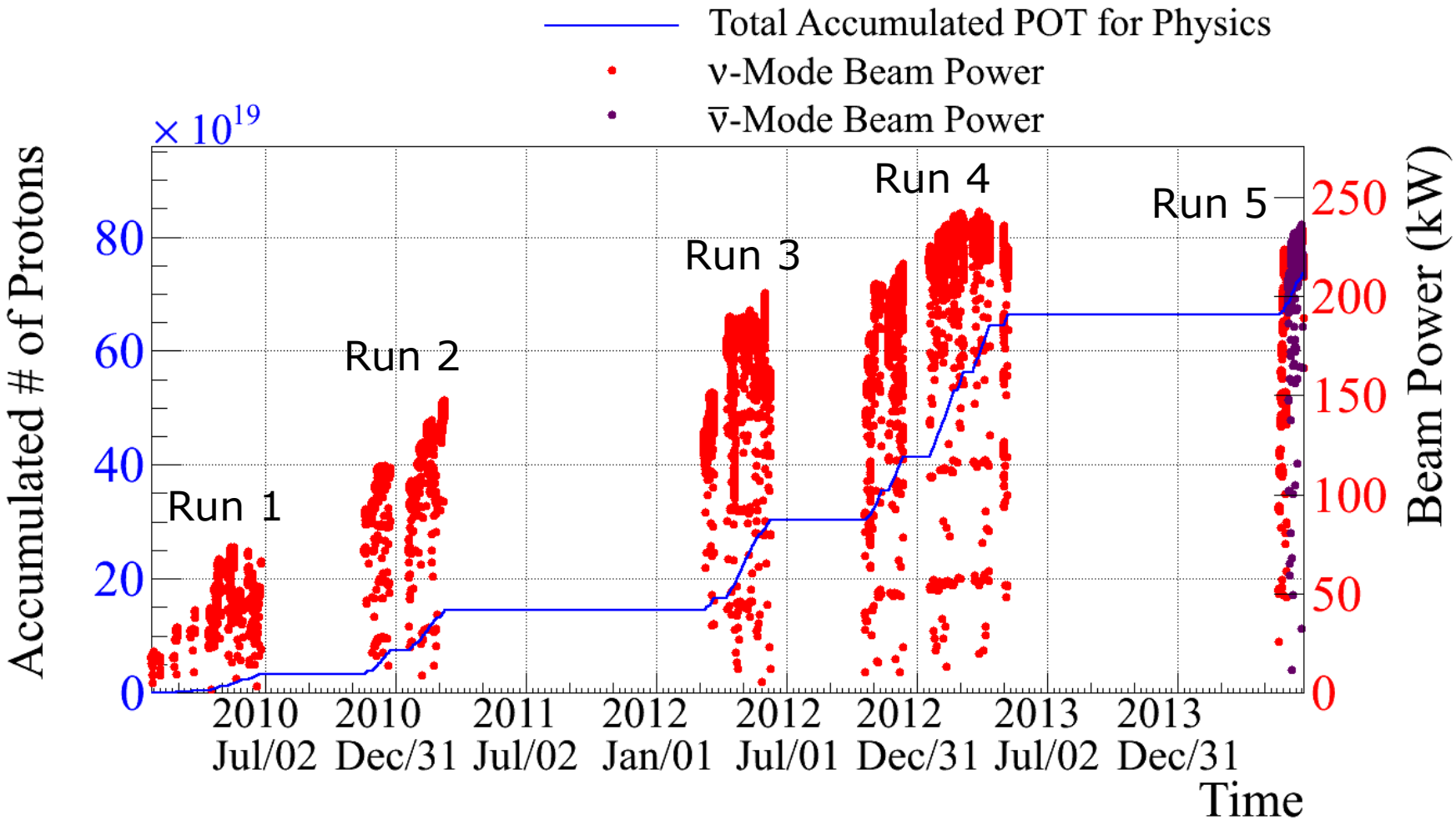
- "ND280" detector
  - Same off-axis angle as Super-K => many shared systematics cancel between near and far detectors
  - FGD – plastic scintillator neutrino targets, one fully active and one with water layers
  - Gas TPCs for momentum measurement and PID
  - Subdetector optimised for π^0 detection at upstream end of detector
  - Surrounded by ECAL and MRDs, with 0.2T magnet



- "INGRID" detector
  - On-axis beam monitor – measure flux and beam profile
  - 13 modules in a "plus" configuration centred on beam axis, with two diagonal modules
  - Each module is a $1m^3$ iron-plastic scintillator sampling calorimeter

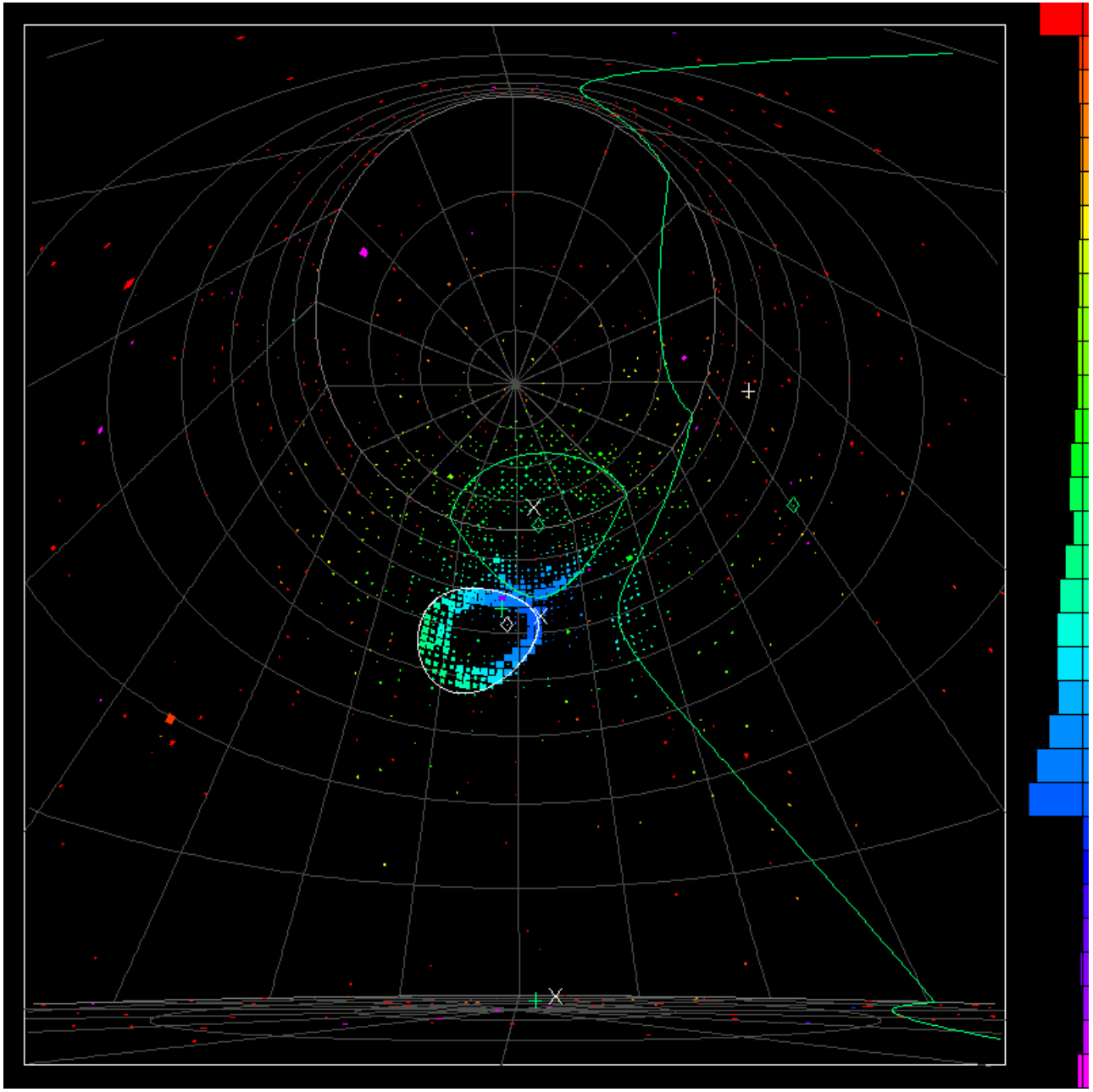


Delivered flux



- Flux from 6.6x10^{20} Protons on Target (POT) used in current analyses (Runs 1-4).
- Total POT to date:
  - 6.88×10^{20} POT for ν beam.
  - 0.51×10^{20} POT for $\bar{\nu}$ beam – first $\bar{\nu}$ beam taken this summer!

1st event of $\bar{\nu}$ beam!

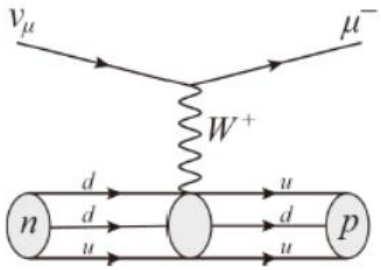


- 1 muon-like ring.
- 2 fuzzy rings with invariant mass 132.6 MeV/c^2.
- Looks like $\mu+\pi^0$.

Neutrino interactions at T2K

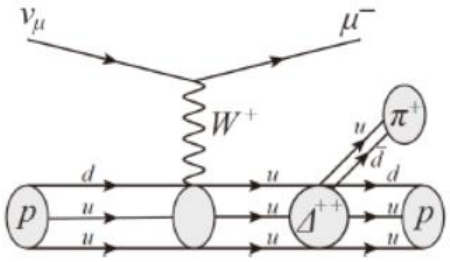
- Charged-current (CC) events – neutrino in, same-flavour charged lepton out.
- Charged-current quasi-elastic (CCQE)

$$\nu_l + n \rightarrow l^- + p$$

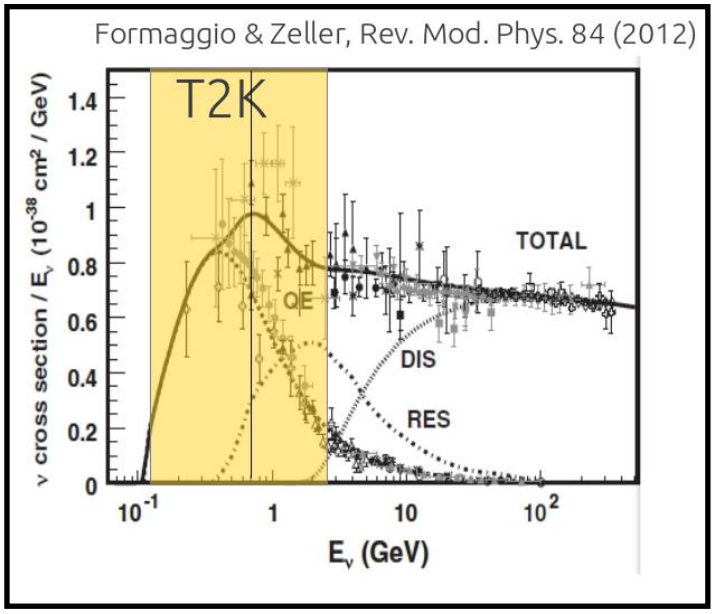


- Charged-current resonant pion production

$$\nu_l + p \rightarrow l^- + N^* \rightarrow l^- + N' + \pi$$

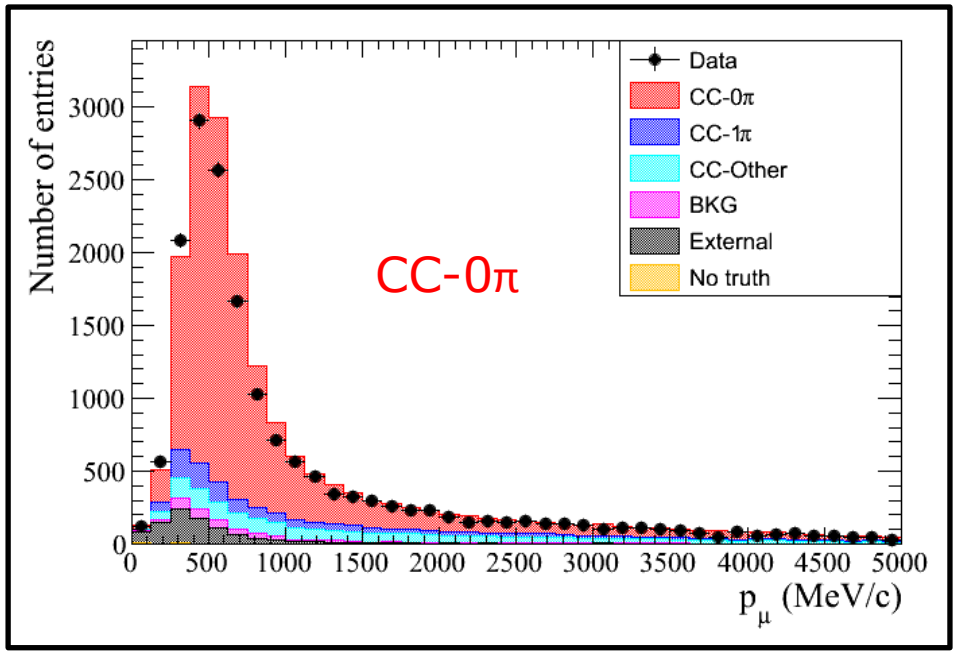


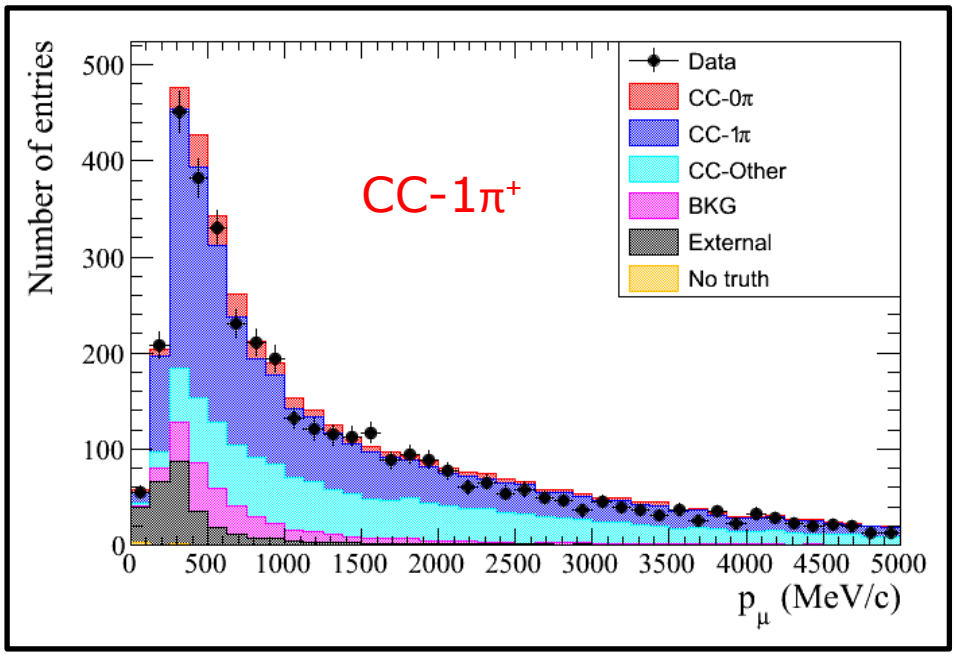
- Some deep inelastic scattering, but not so important at T2K energies
- Also get neutral–current (NC) versions of these interactions

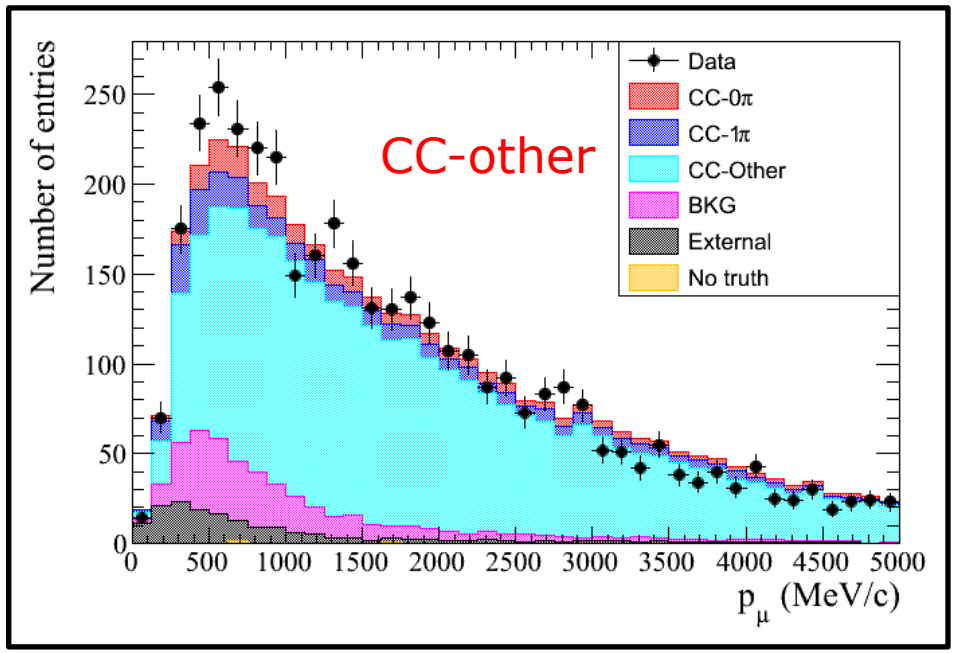


ND280 analysis

- ν_μ CC selection:
  - Vertex in FGD1
  - highest-momentum negative track in TPC2 is muon-like
- Identify pions in events:
  - π^+/π^- from right-charged track in TPC
  - π^+ from Michel electron in FGD1
  - π^0 from electron-compatible track in TPC2
- Split events according to pion content and fit distributions with flux and x-sec systematics floating



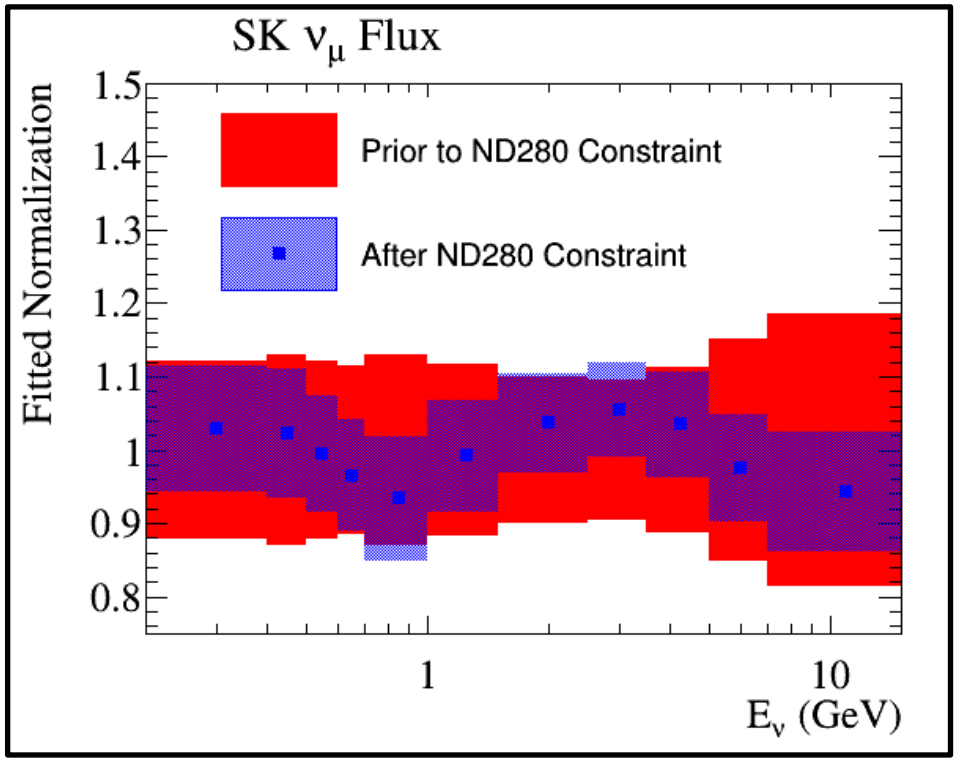


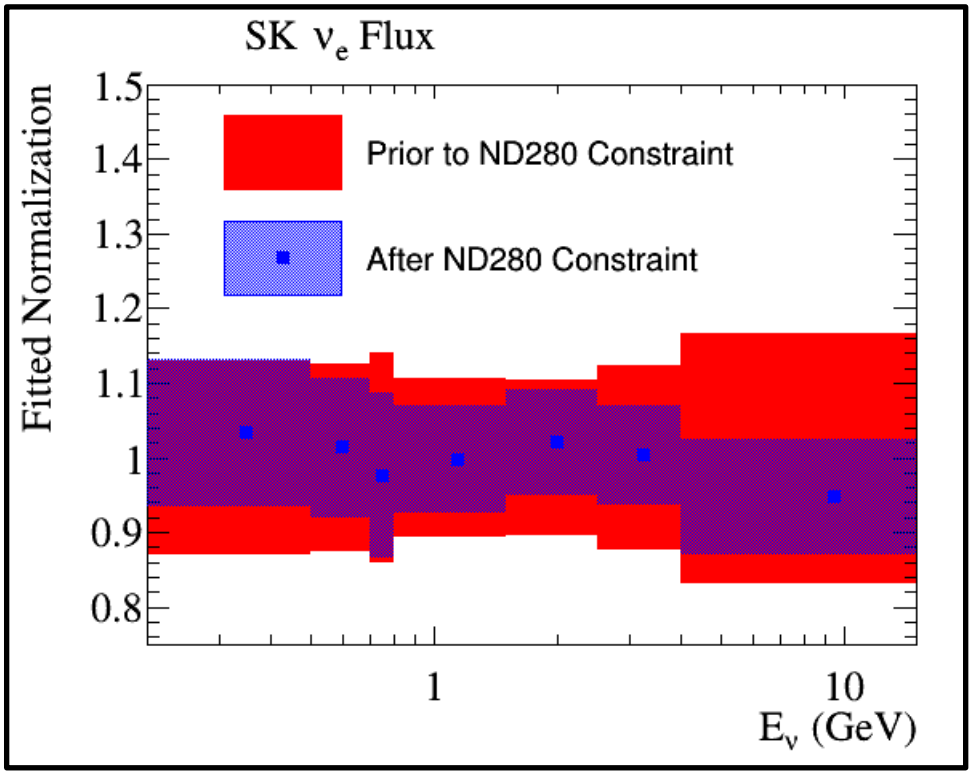


ND280 flux and cross-section constraints

- ND280 data are fitted to flux and cross-section parameters based on external constraints and nominal beam MC.
- Significant reduction in Super-K systematics, particularly x-sec.

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

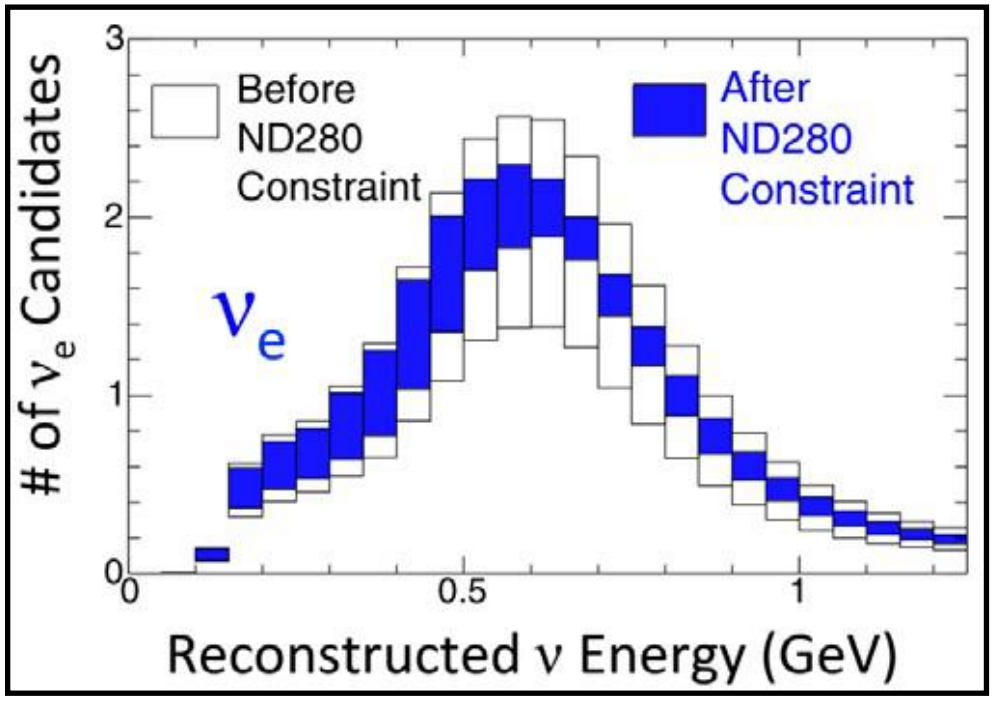


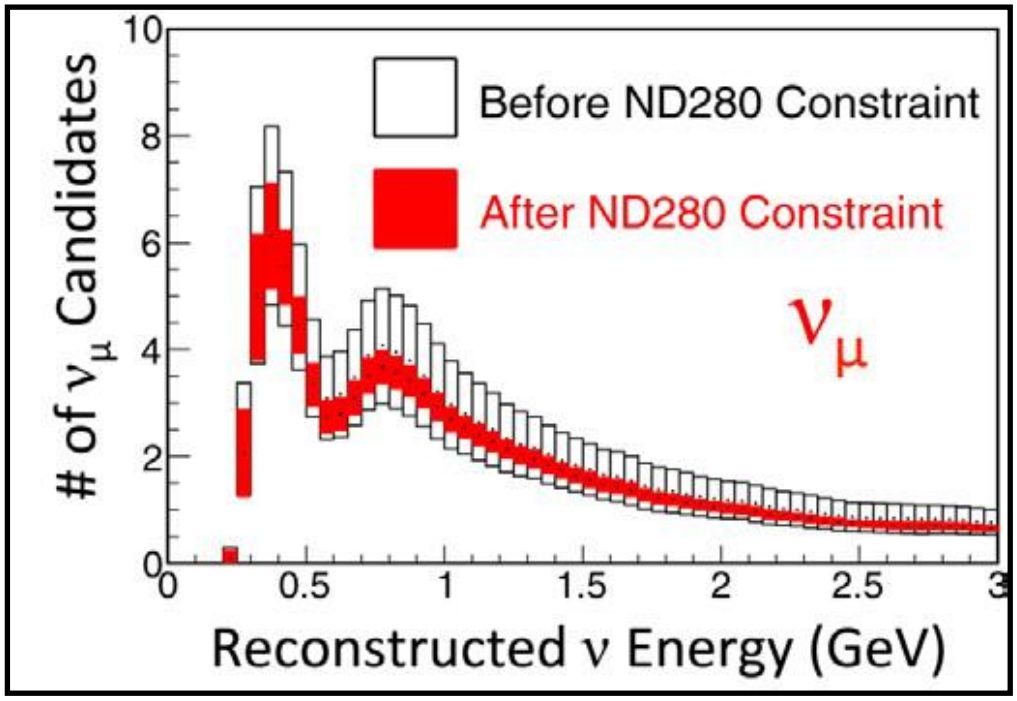


ND280 constraints on SK event rates

- Big improvement in event rate predictions from ND280 fit!

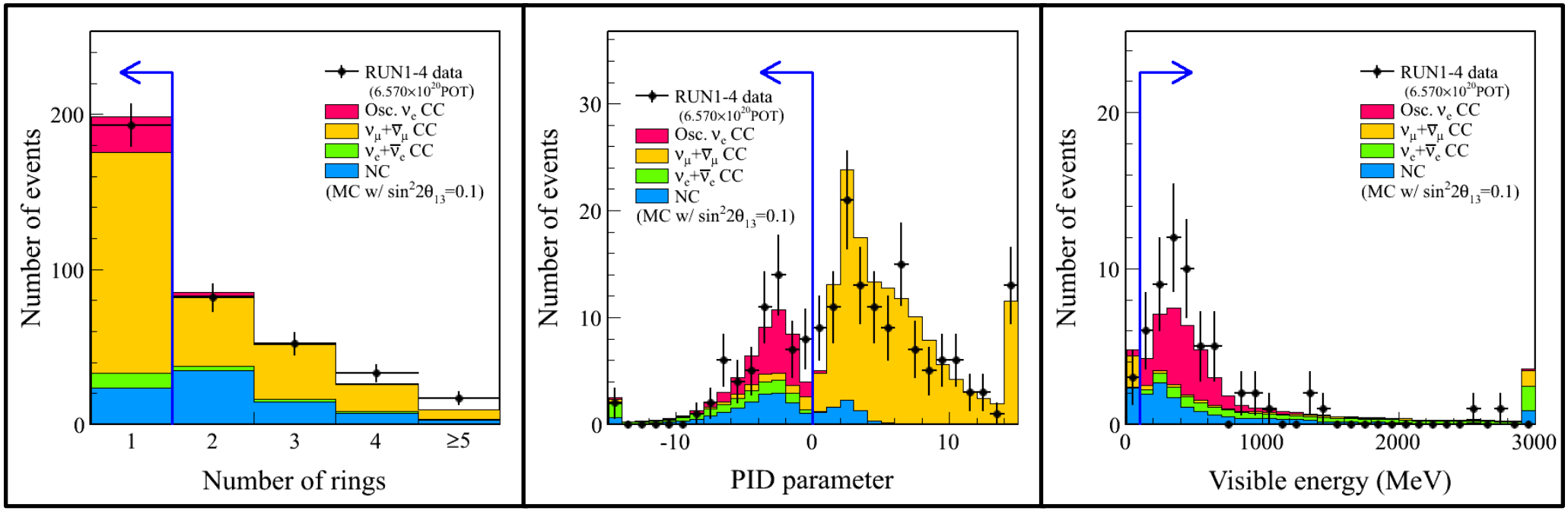
	ν_e Prediction (Events)	Error from Constrained Parameters
No ND280 Constraint	22.6	26.5%
ND280 Constraint	20.4	3.0%



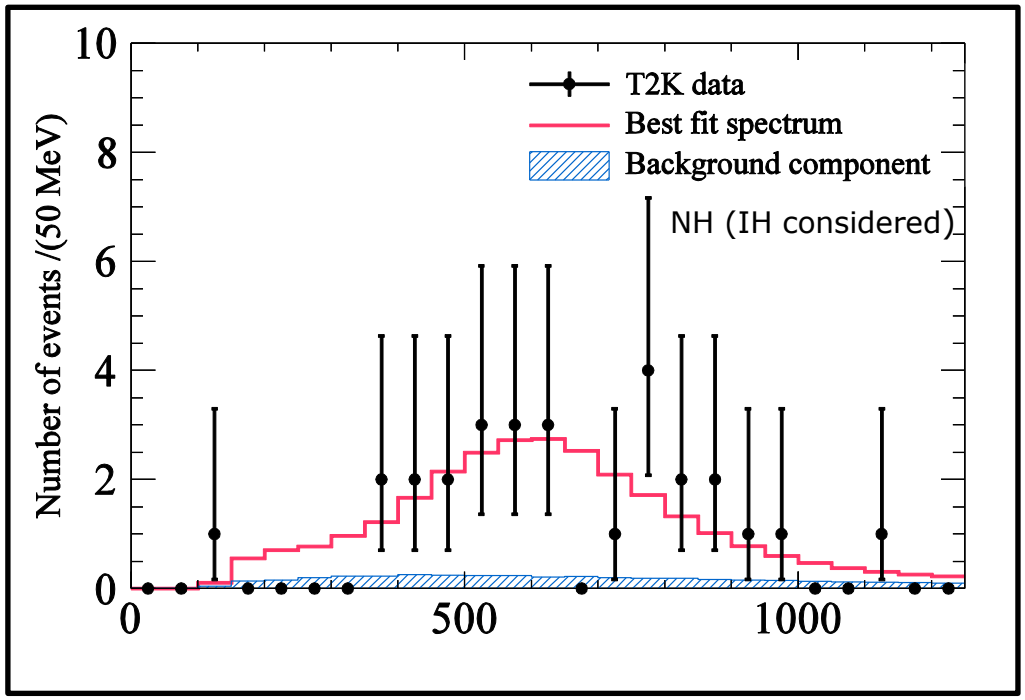


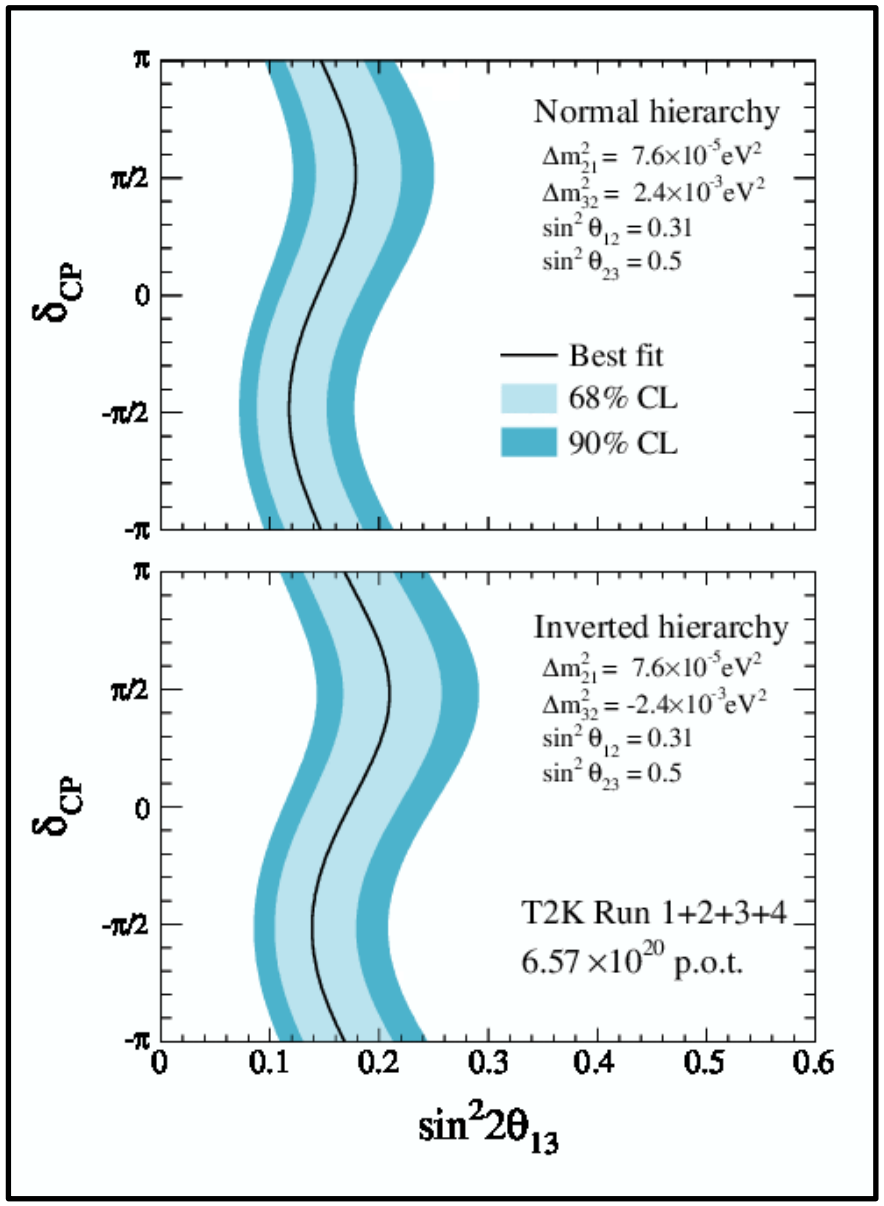
Super-K ν_e selection

- Cuts used for T2K analysis:
  - Fully contained fiducial volume (FCFV) event
  - Single ring e-like event
  - Visible energy > 100 MeV
  - No Michel electrons
  - $0<E_{\nu}^{rec}<1250$ MeV
  - π^0 likelihood cut



ν_e appearance results (Phys Rev. Lett. 112, 061802 (2014))

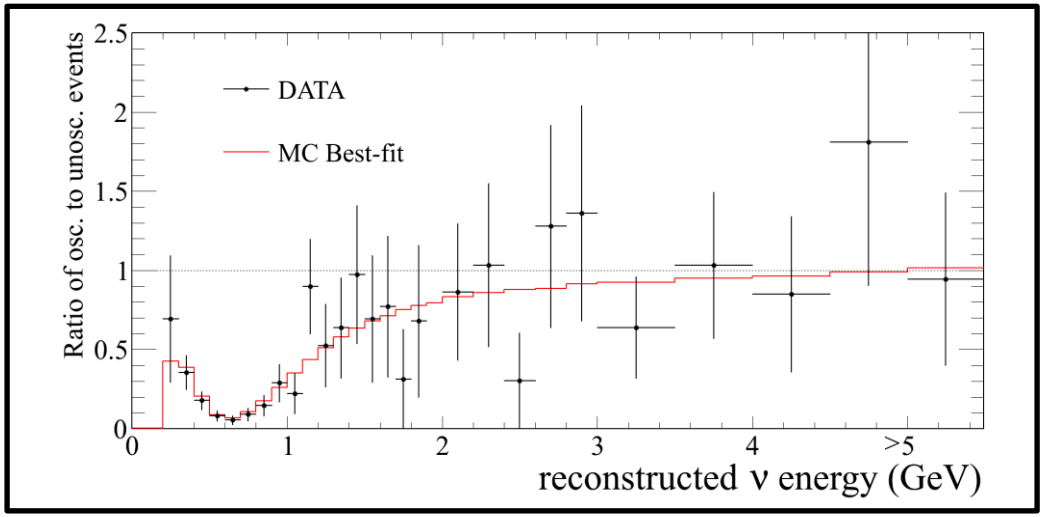


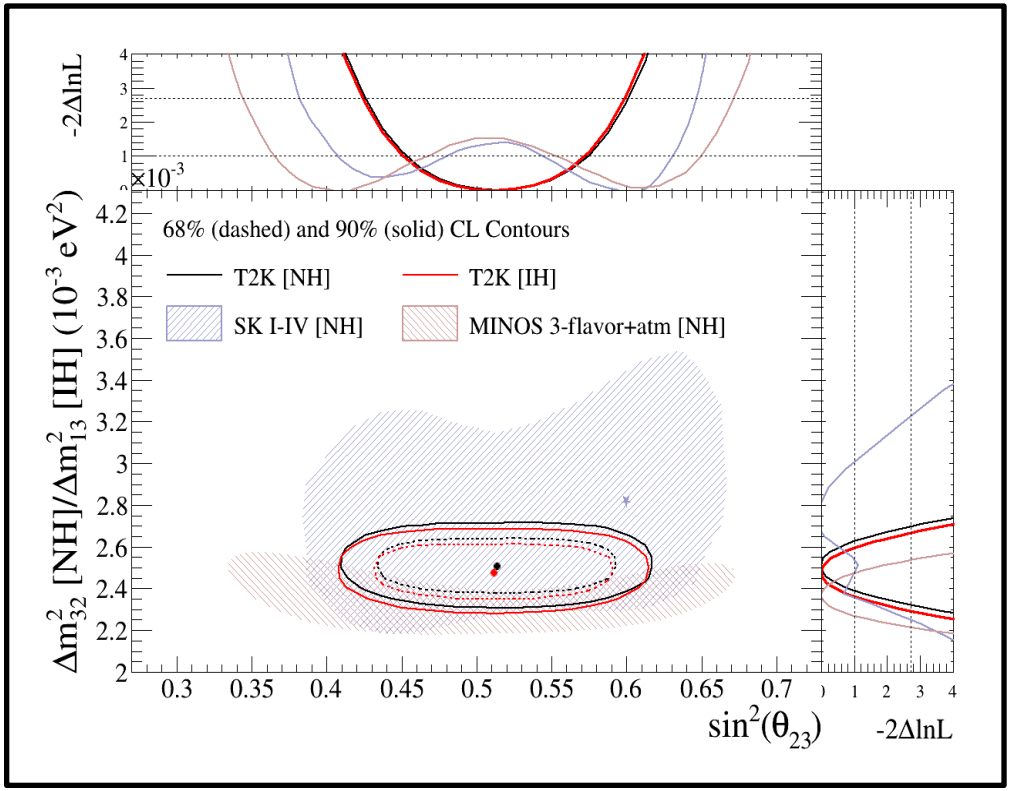


- 28 events observed
- Background for $\theta_{13} = 0$ of (4.92±0.55) events
- $\theta_{13} = 0$ excluded at 7.3σ!

ν_μ disappearance results (Phys. Rev. Lett. 112, 181801 (2014))

- 3-flavour fit using θ_{13} from reactor measurements
- World-leading measurement of atmospheric mixing angle θ_{23}!
- Still no hint of θ_{23} octant

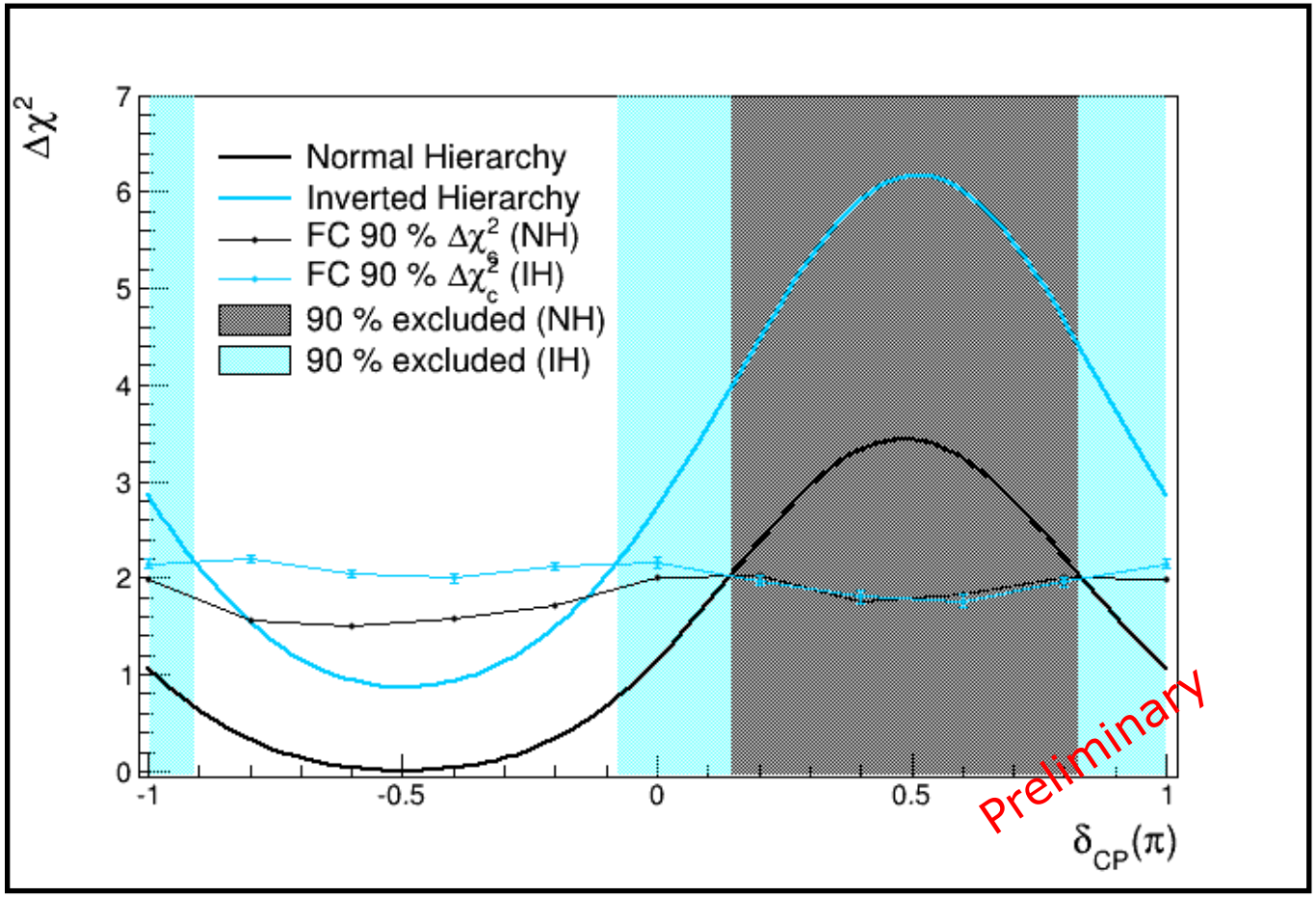




Parameter	Best-fit Value
$\sin^2(\theta_{23})$ [NH]	$0.514^{+0.055}_{-0.056}$
Δm^2_{32} (x10^{-3} eV^2) [NH]	2.51±0.10
$\sin^2(\theta_{23})$ [IH]	0.511±0.055
Δm^2_{13} (x10^{-3} eV^2) [IH]	2.48±0.10

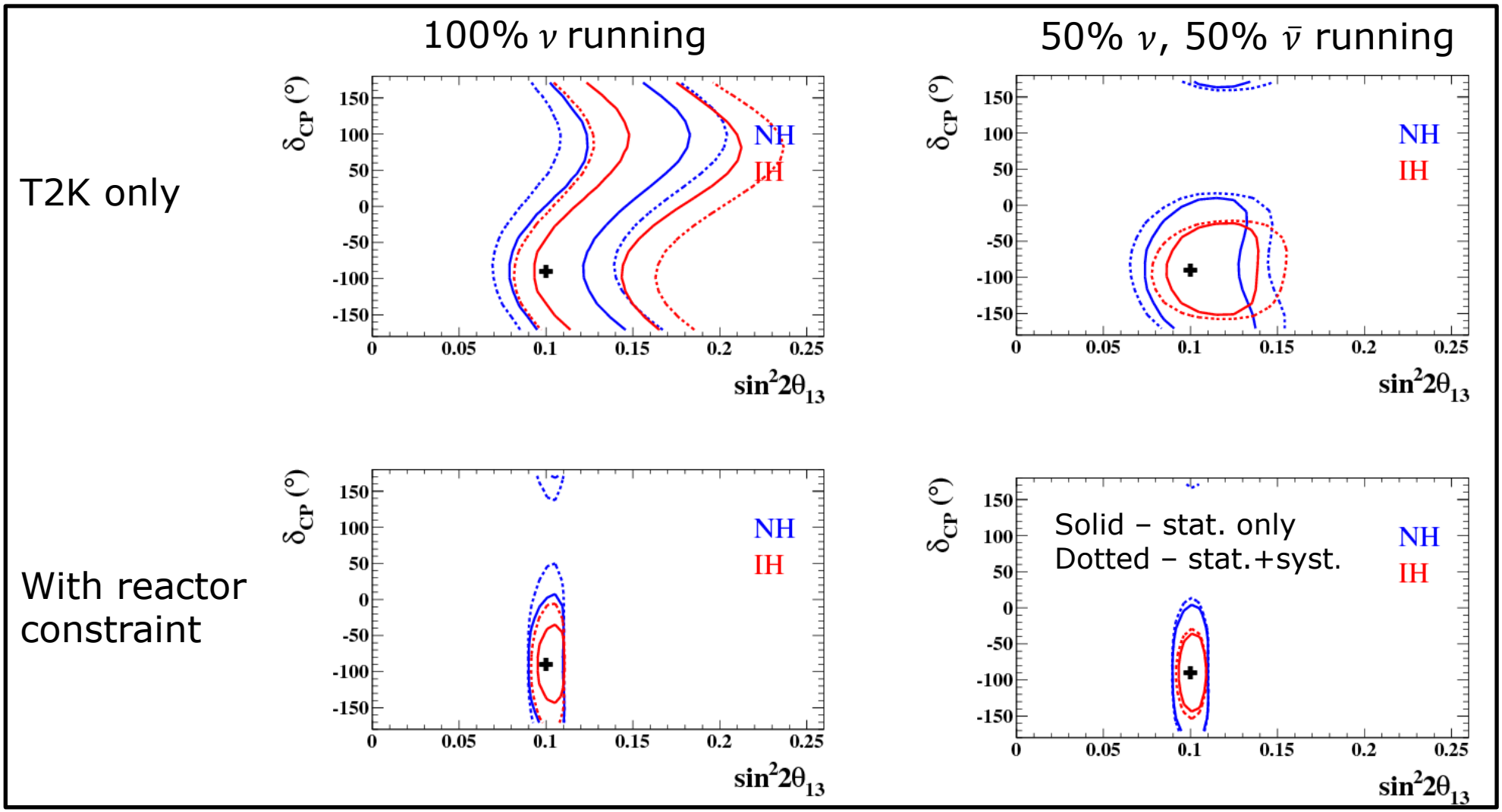
Joint oscillation fit

- Simultaneous likelihood fit to both ν_μ and ν_e spectra.
- Also include reactor constraint as in PDG13 - θ_{13} from these measurements smaller than for T2K.
- Combined results show weak preference for NH, $\delta \sim -0.5\,\pi$.
- Obviously not significant, but gives an intriguing hint that nature may have given us a "lucky" δ.



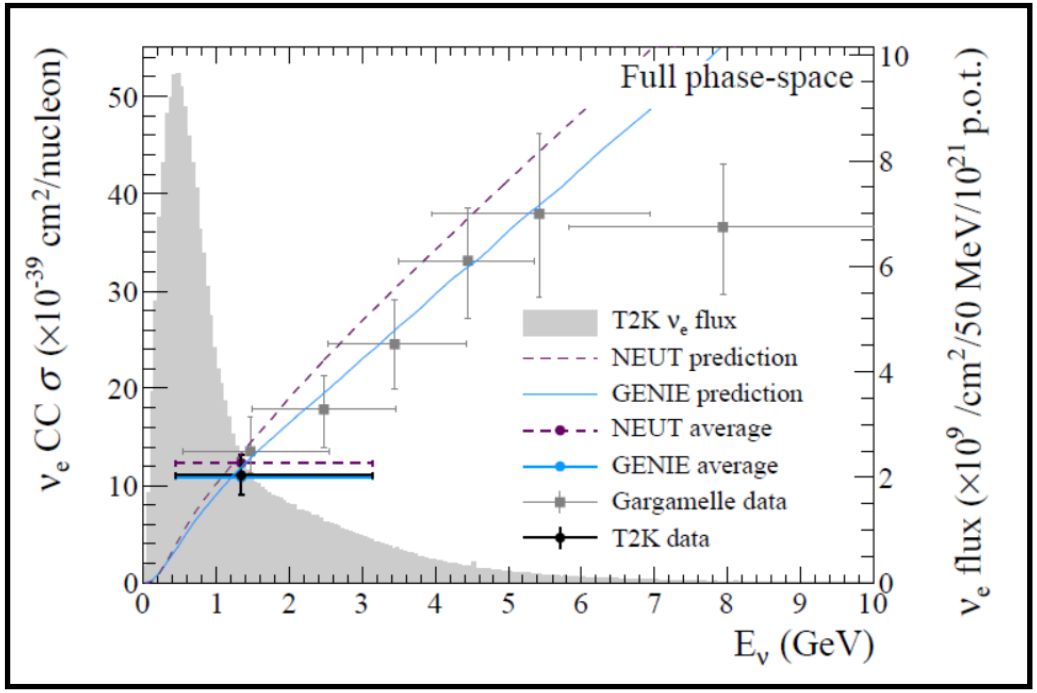
Future sensitivity

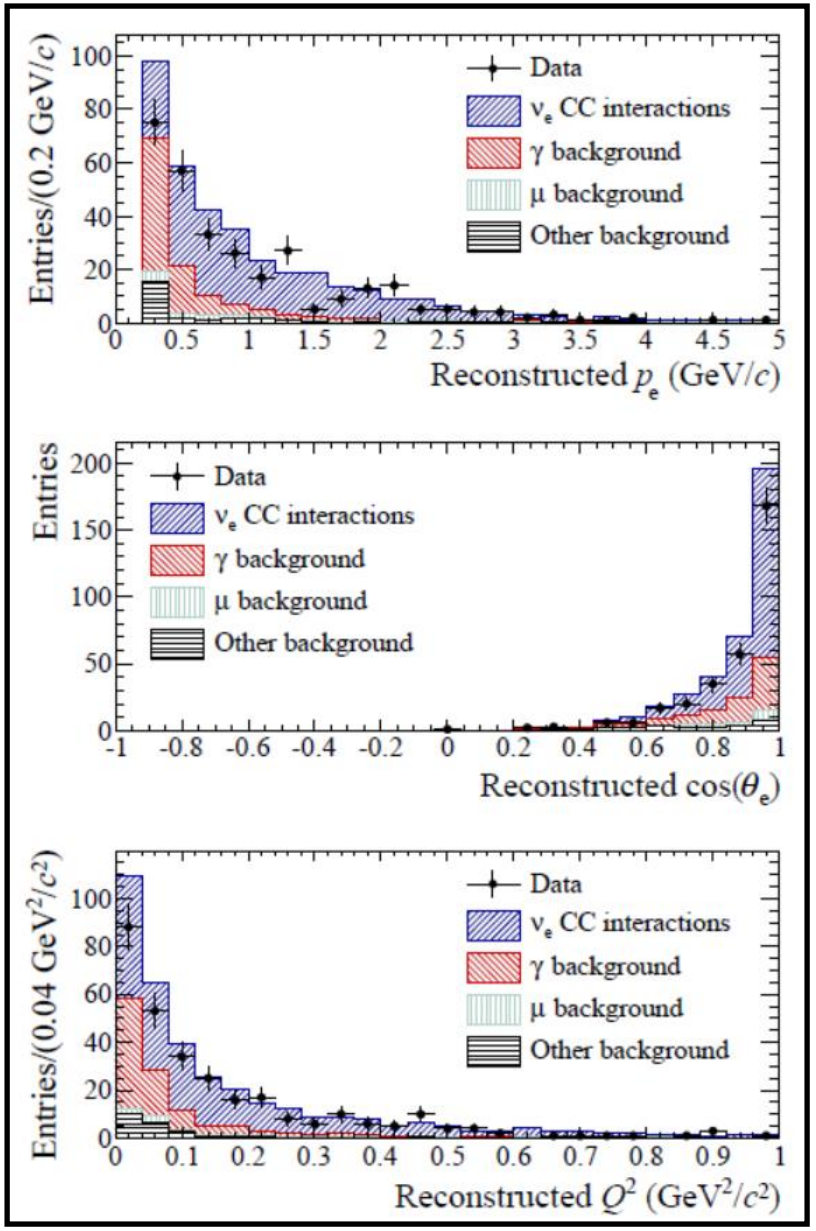
- Assume case that is weakly preferred by existing data ($\sin^2 2\theta_{13}$ = 0.1 from reactors, NH, δ=-0.5π). Obviously this case is also lucky since CP violation is large.
- Plots shown are for 7.8x10^{21} POT T2K running, and anticipated final reactor constraint.
- Sensitivity maximised for 50% ν, 50% $\bar{\nu}$ running.



ν_e CC-inclusive cross-section on Carbon
(arXiv:1407.7389)

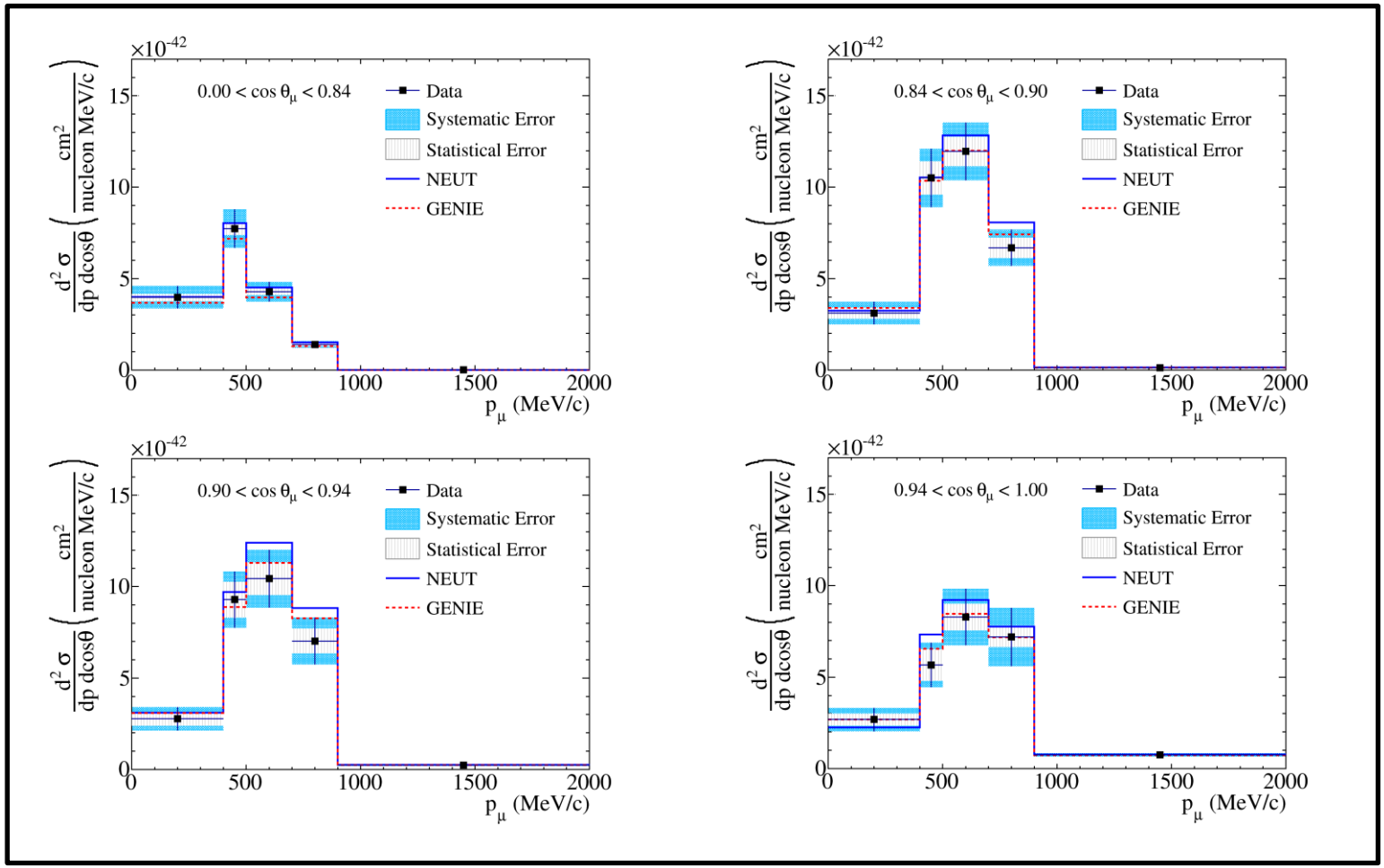
- Select ν_e events in the ND280 FGD1:
  - Negative electron-like track in TPC2, vertex in FGD1
  - Events with positive track are subject to invariant mass cut
  - Veto activity upstream in the detector
- First differential ν_e cross-section measurement at these energies!
- Good agreement with generators and Gargamelle.
- Differential cross-section plots available in the paper.





ν_μ CC-inclusive cross-section on Carbon

(PRD 87, 092003 (2013))

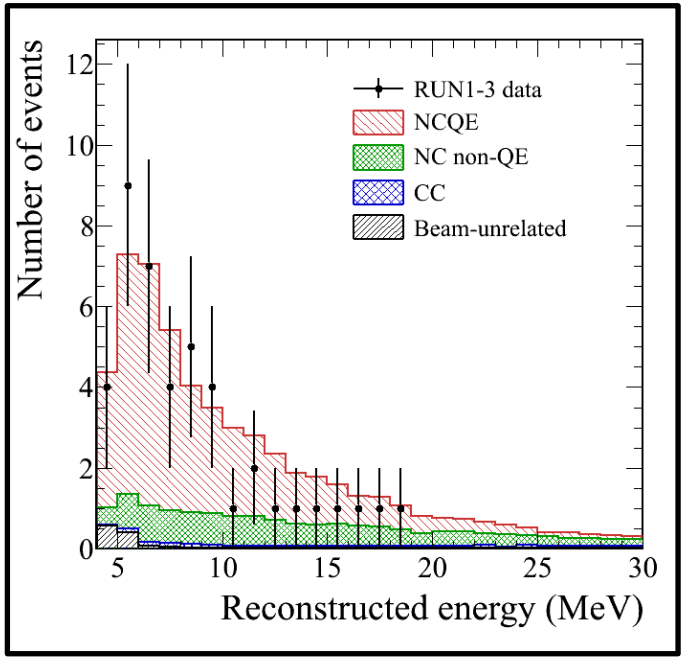


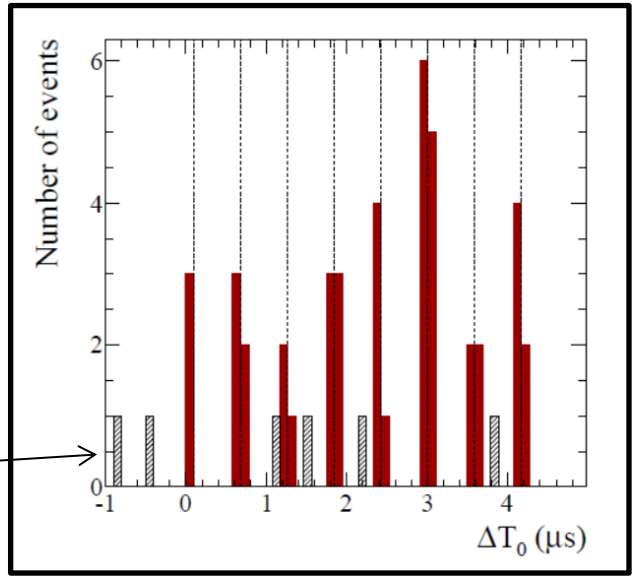
- Muon-like events in ND280 selected.
  - Unfold reconstructed p_μ – $\sin\theta_\mu$ distributions to get estimate of true kinematic distributions.
  - Get double-differential and total cross-sections integrated over beam flux.

NCQE cross-section from de-excitation γs

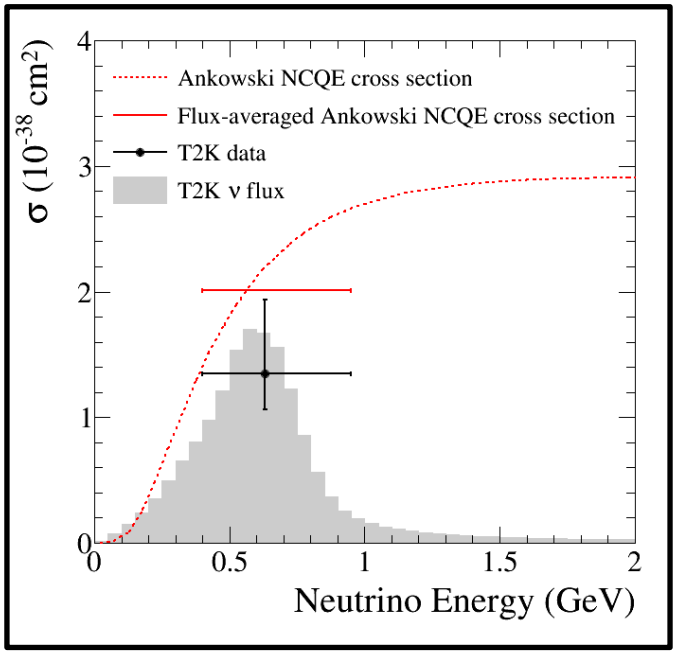
(arXiv:1403.3140)

- First measurement of NCQE neutrino interaction cross-section on Oxygen, using Super-K.
- Cuts:
  - In beam timing window, no high-energy preceding event
  - 4 MeV < E < 30 MeV, observed light has large Cherenkov angle (exclude low-energy muons)
  - Other standard cuts for removing non-beam background.
- Beam data ideal for this measurement since beam window cut limits effect of natural radioactivity.





Grey entries fail timing cut



Summary and outlook

- T2K has now collected over 7×10^{20} POT of data.
  - Antineutrino running demonstrated during recent run period.
- T2K is continuing to produce exciting results:
  - 7.3σ exclusion of $\theta_{13} = 0$ in ν_e appearance channel.
  - World's most precise measurement of θ_{23}.
  - Neutrino cross-section measurements being made in O(1GeV) range.
- Will continue to combine T2K data with constraints from NOvA and reactors to improve constraints on MH and CP violation.
- Only at 8% of design luminosity, and antineutrino running is just starting.
  - Lots more data and exciting results still to come!

Backup

ν_e CC-inclusive differential cross-sections