Neutrino Oscillation Results from T2K

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T2K

Neutrino oscillation physics

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathrm{U}_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4\theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \cdot \sin^2\theta_{23}\right) \cdot \sin^2 \frac{\Delta m_{31}^2 \cdot L}{4E_\nu}$$

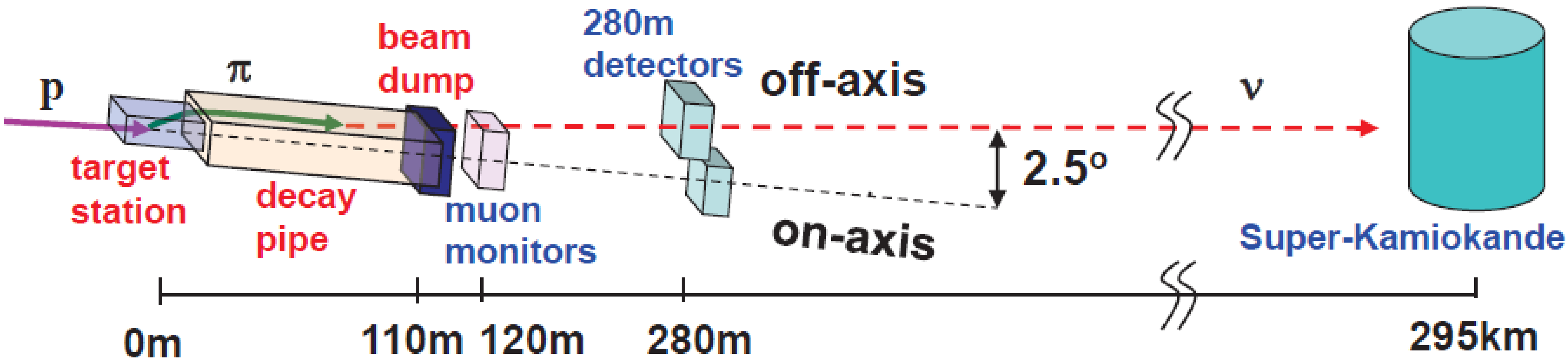
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

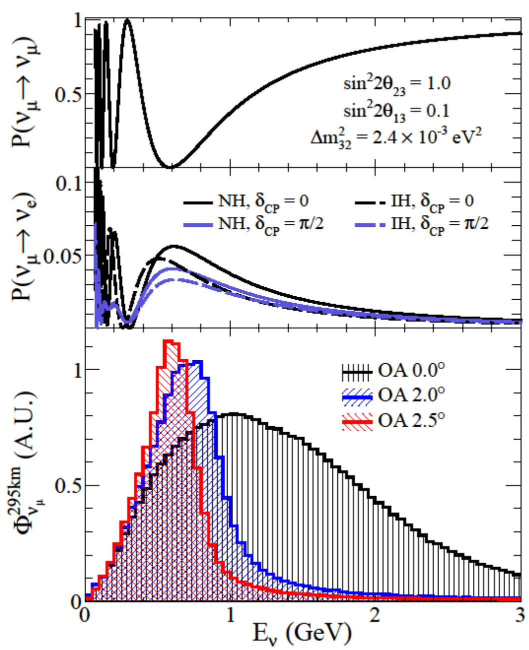
$$+ CPV(\propto \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta_{CP})$$

$$+ MatterTerm$$

- **Open questions**
  - **Mass Hierarchy**
  - **CP Violating Phase δ**
  - **Mixing Angles θ_{13}, θ_{23}**
  - **Absolute Mass Scale**
  - **Dirac or Majorana**

T2K long-baseline neutrino oscillation experiment in Japan

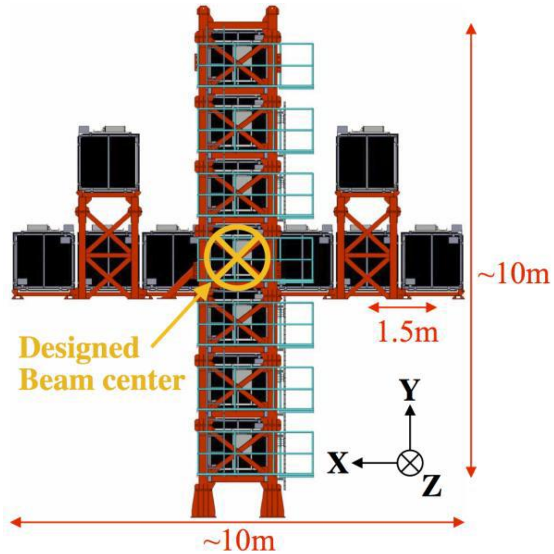


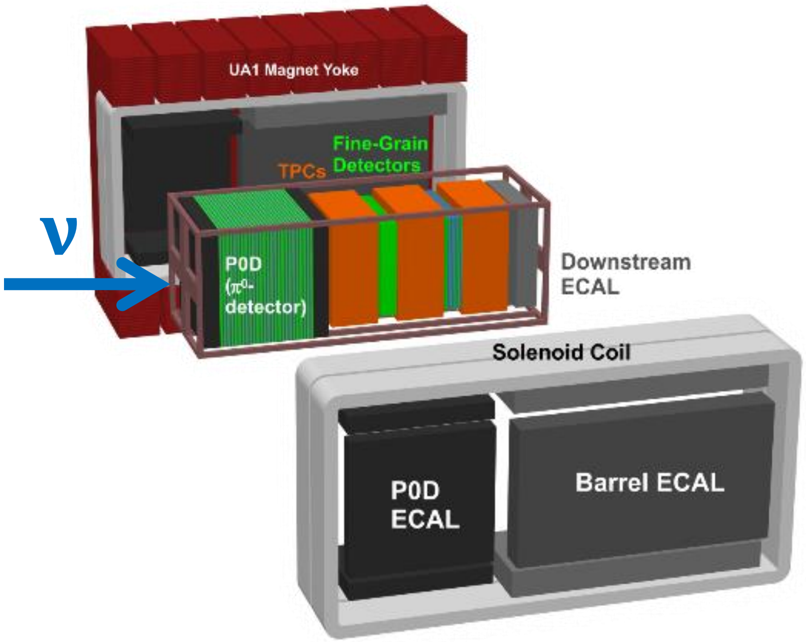


- Off-axis narrow band ν_μ beam to far detector and near detector
  - Enhanced signal at oscillation maximum
  - Reduce high-energy tail background
  - Measure ν_e appearance and ν_μ disappearance

Near detectors

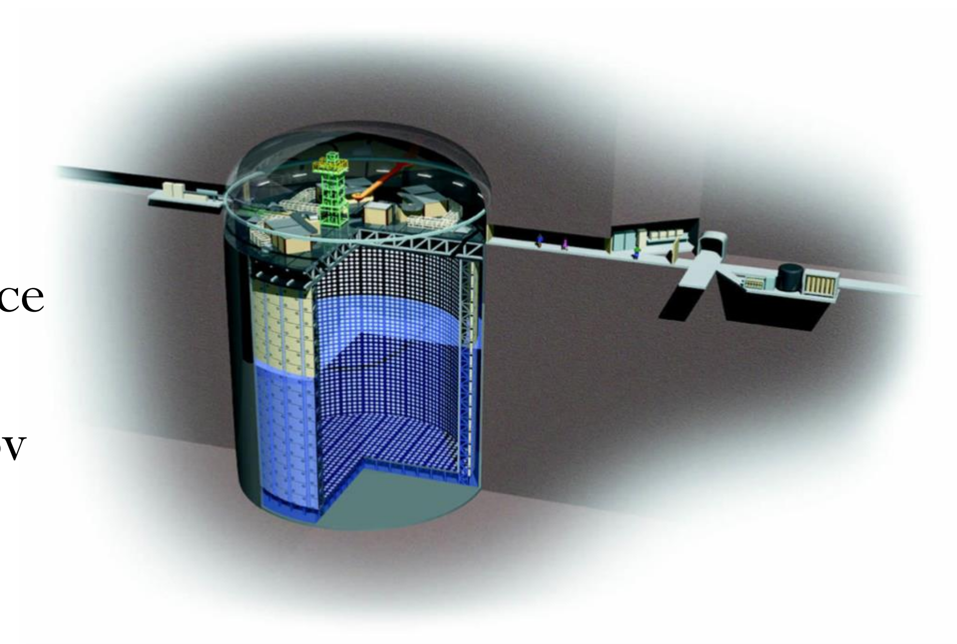
- **INGRID**
  - **On-axis** to measure beam profile, position and stability
  - Carbon and iron targets
- **ND280**
  - **2.5° off-axis** to measure neutrino interactions and estimate the background contaminations
  - Refurbished UA1 magnet - 0.2T field
  - Front optimized to measure π^0 interactions (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 and muon detector

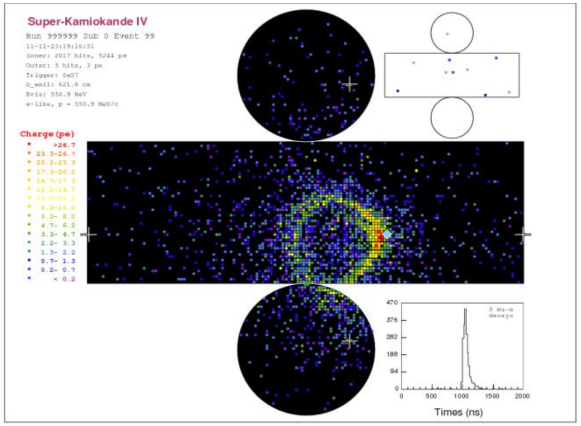




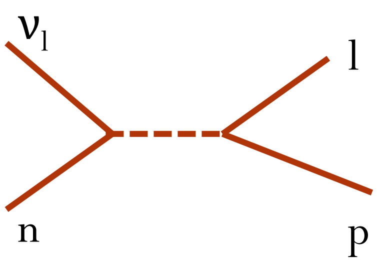
Far detector

- Super-Kamiokande
  - 295 km from beam source and **2.5° off-axis**
  - 50 kton water Cherenkov detector
    - 22.5 kton fiducial mass
  - Excellent e/μ separation

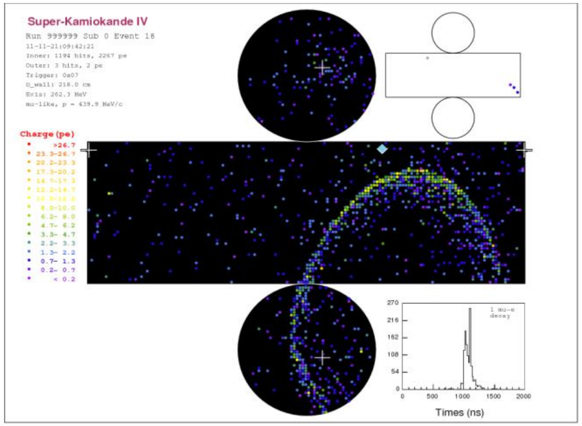




MC e-



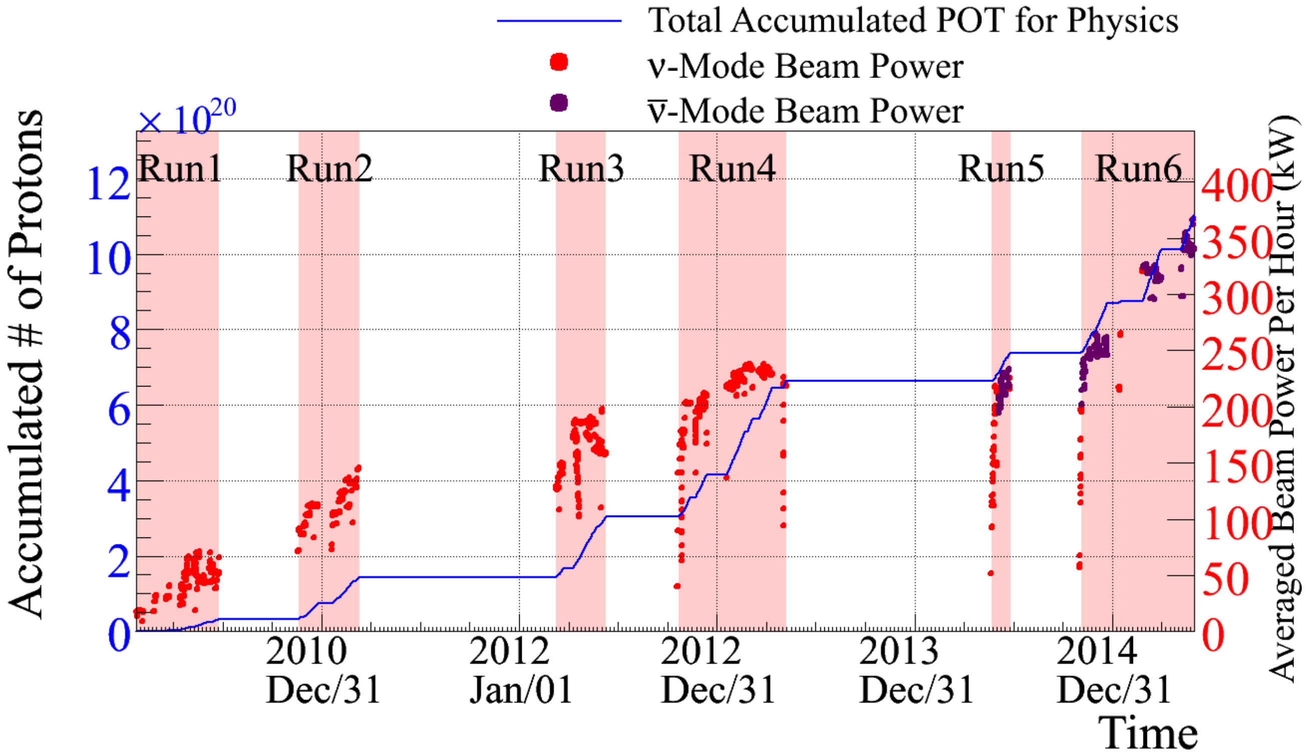
Charge Current quasi elastic (CC-QEL)



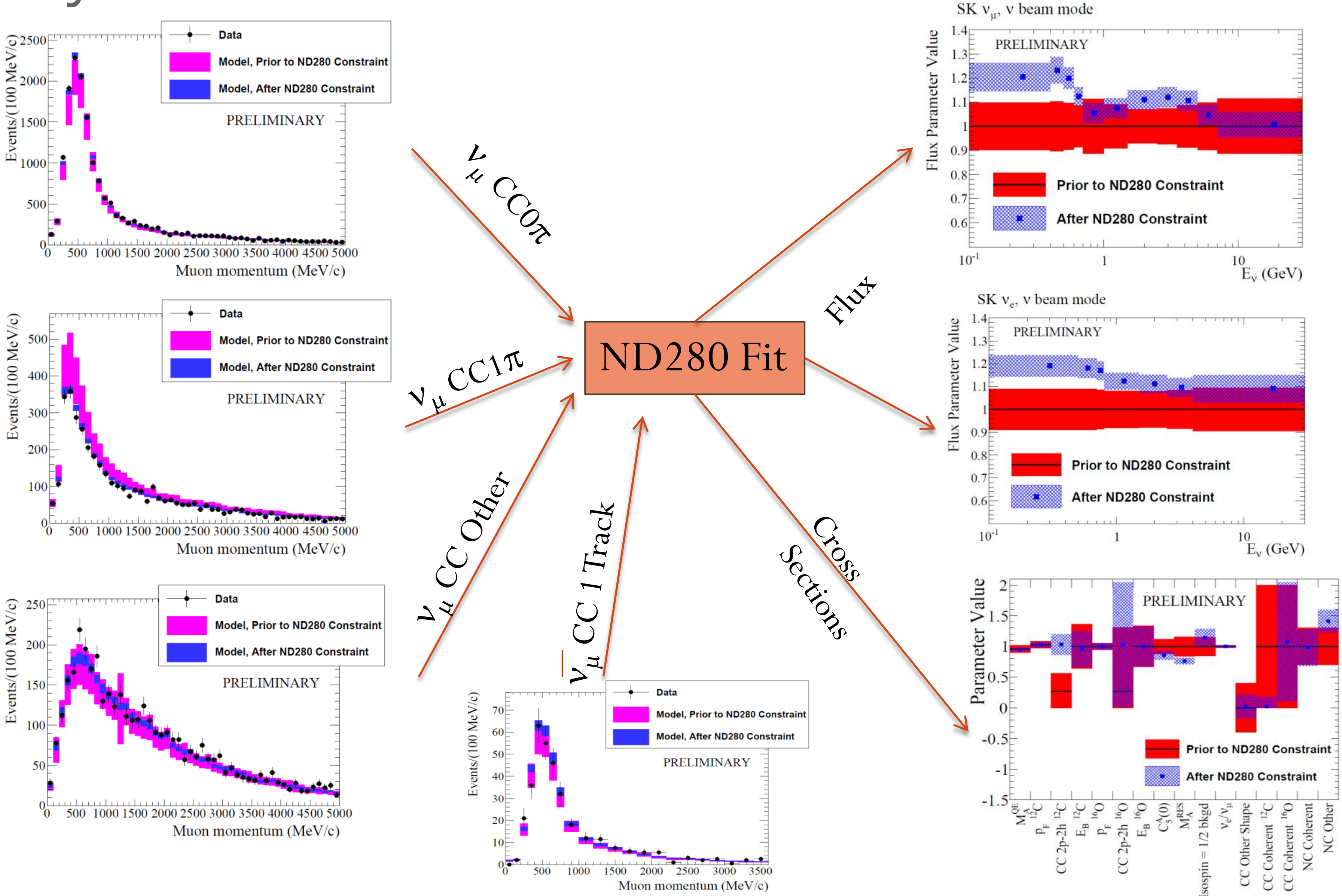
MC μ-

Protons on target (POT) accumulated

- Maximum beam power achieved is 371 kW
  - As of the end of Run6
- Accumulated 7.09×10^{20} POT for ν-mode and 4.04×10^{20} POT for $\bar{\nu}$-mode

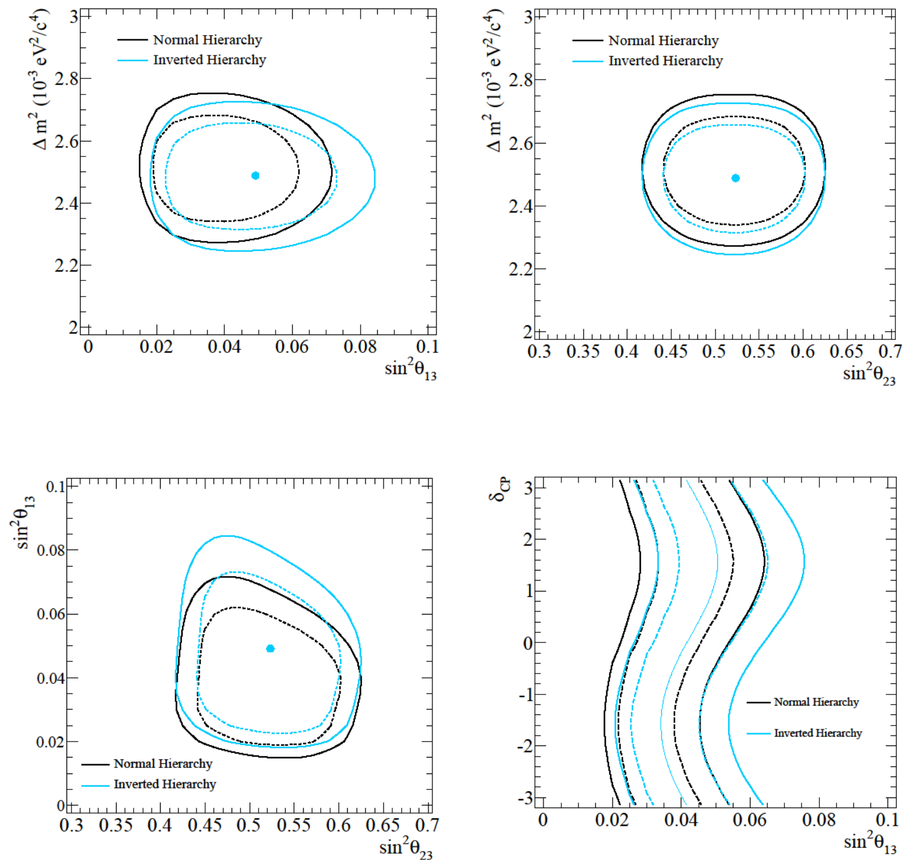


Constraining flux and cross-section systematics with ND280



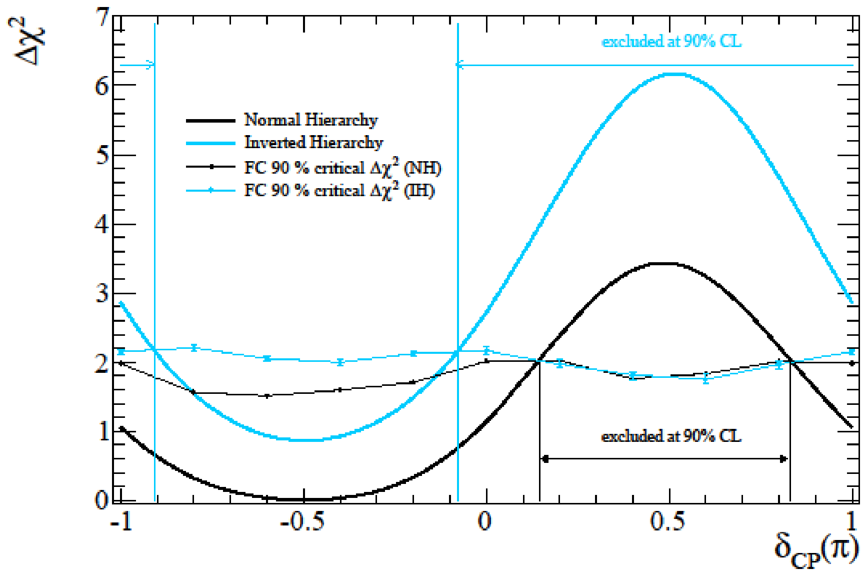
T2K three flavour fit

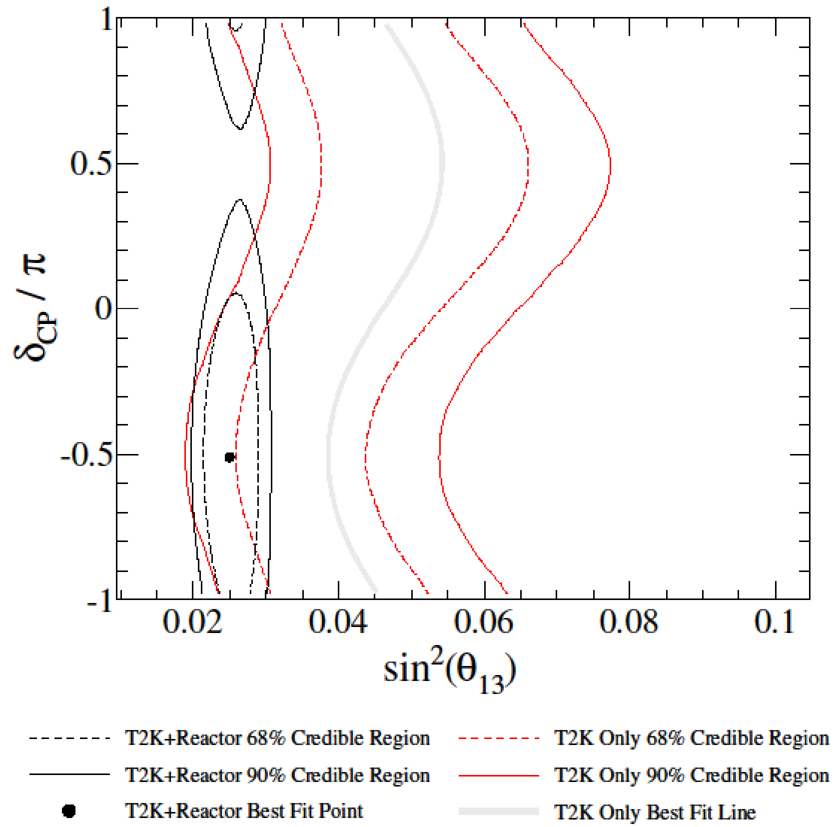
- **Phys. Rev. D 91, 072010, 2015**
- Joint fit to $|\Delta m^2|$, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ_{CP}
- NH best fit results
  - $\mathrm{Sin}^2\theta_{23} = 0.524^{+0.057}_{-0.059}$
  - $\mathrm{Sin}^2\theta_{13} = 0.042^{+0.013}_{-0.021}$
  - $\Delta m^2_{32} = 2.51^{+0.11}_{-0.12} \times 10^{-3}\ \mathrm{eV}^2/c^4$



T2K three flavour fit with reactor constraint

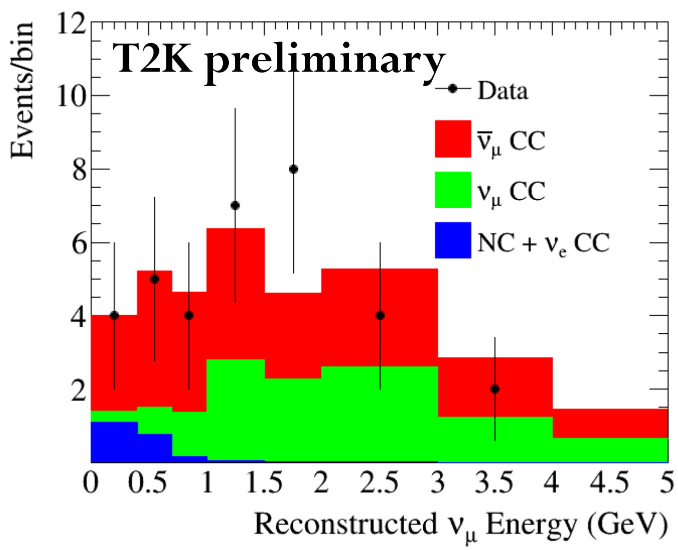
- External constraints from reactor neutrino experiments
  - $\sin^2\theta_{13reactor} = 0.0243 \pm 0.026$
- Start constraining δ_{cp} in the lepton sector

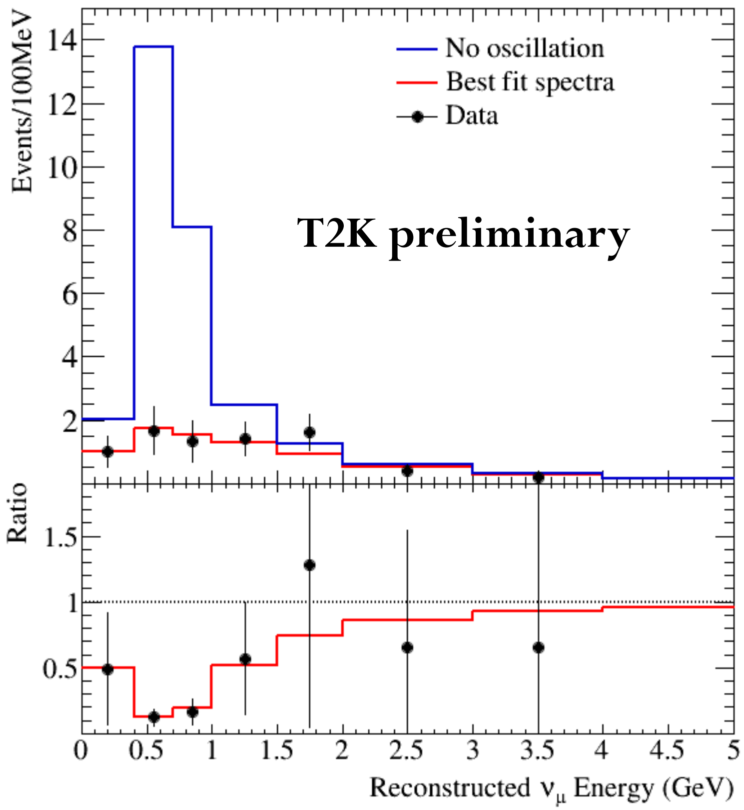




$\bar{\nu}_\mu$ disappearance

- 34 candidates selected
- Clear oscillation dip observed
- Use different parameters for ν and $\bar{\nu}$ for θ_{23} and Δm^2_{23}
- Maximum likelihood fit including shape, normalization and systematic effects



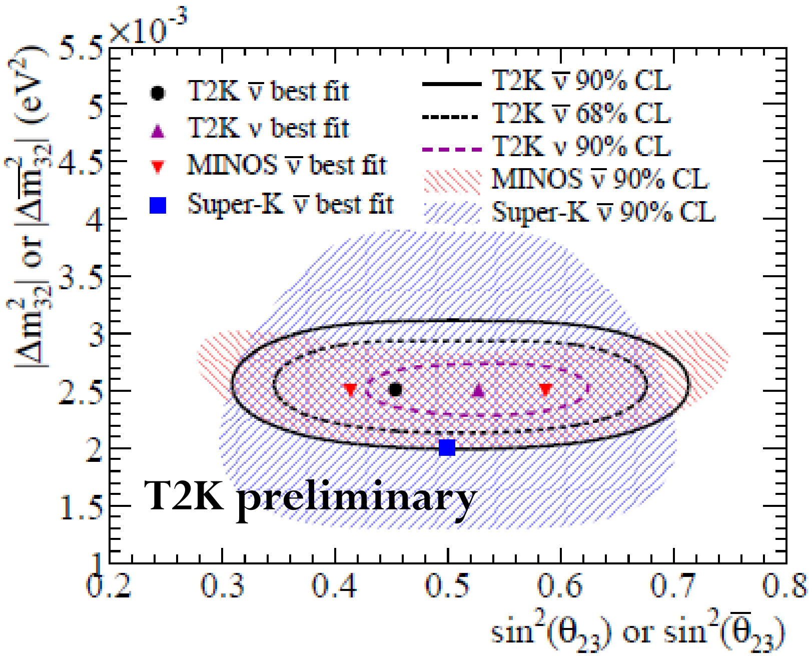


$\bar{\nu}_\mu$ disappearance results

- **arXiv:1512.02495**
- Best fit results
  - $\sin^2\bar{\theta}_{23} = 0.45^{+0.19}_{-0.07}$
  - $\Delta m^2_{\overline{32}} = 2.51^{+0.29}_{-0.25} \times 10^{-3}$ eV^2/c^4

Systematic uncertainty	Error (%)
ND280 unconstrained cross section	10
Flux and ND280 constrained cross section	3.4
Super-Kamiokande detector	3.8
Pion FSI and re-interactions	2.1
Total	**11.6**

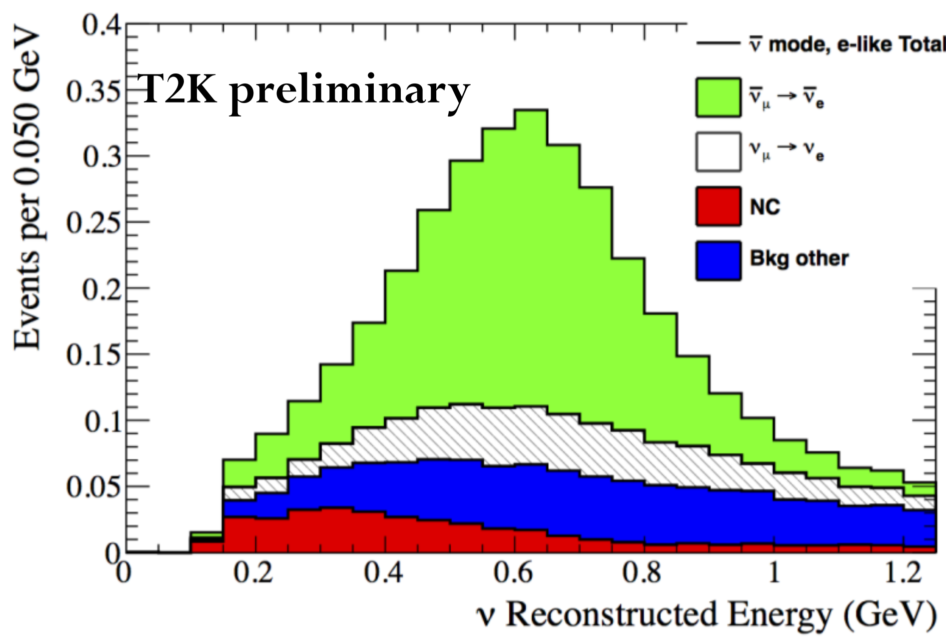
- T2K results compared to Super-K and MINOS results



$\bar{\nu}_e$ appearance

- 3 $\bar{\nu}_e$ candidates
  - ~3.7 expected w/ oscillation
    - 1.96 signal
    - 1.77 background
  - ~1.3 expected w/o oscillation
  - Weak hint for $\bar{\nu}_e$ appearance

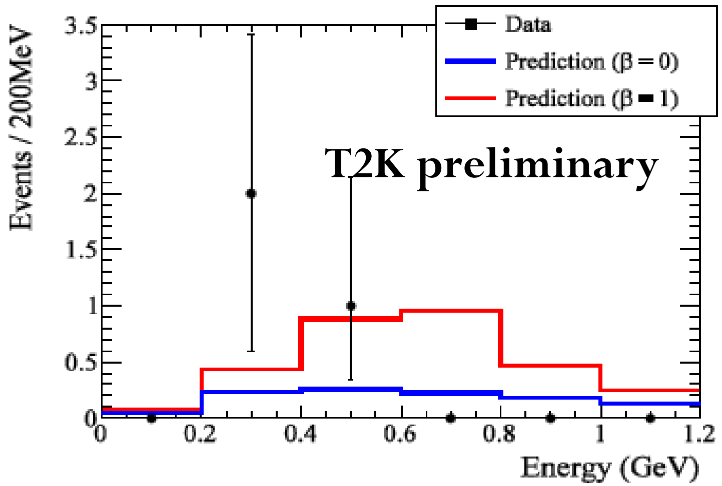
- Introduce discrete parameter β
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - β = 0 no neutrino oscillation
  - β = 1 nominal oscillation

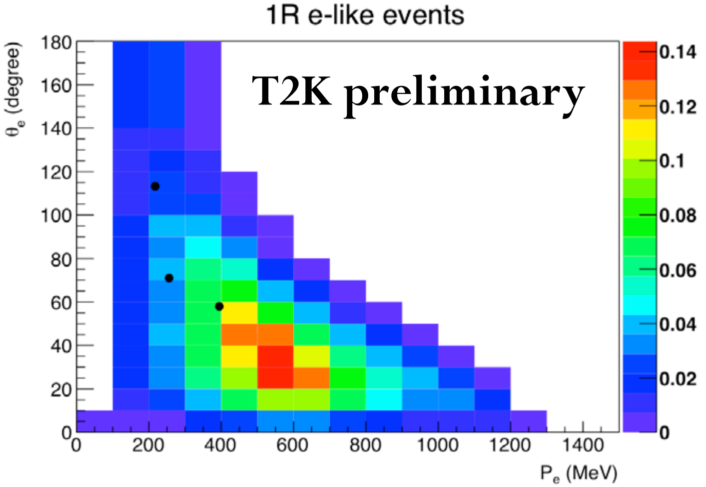


$\bar{\nu}_e$ appearance results

- Two independent methods developed to fit the data
  - Reconstructed neutrino energy (E_{rec})
  - Electron p-θ
- Test statistics $-2[ln L(\beta=1) - ln L(\beta=0)]$
  - p-value(p-θ) = 0.34
  - P-value(E_{rec}) = 0.16
- No clear discrimination between the two β hypotheses

	δ_{CP}=-90°	δ_{CP} = 0°	δ_{CP}=90°
NH	3.73	4.32	4.85
IH	4.18	4.85	5.45





Conclusions and future prospects

- Collect more anti-neutrino data in 2016
  - Improved measurements of the anti-neutrino oscillations
- Joint ν - $\bar{\nu}$ fit
  - Better constraint on δ_{CP}
- Further constraints from ND280
  - FGD2 (contains water) measurements
  - More cross section channels
  - See talk from E. Scantamburlo for more

BACK UP

The T2K Collaboration

~500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
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Japan
ICRR Kamioka
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Kavli IPMU
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Kobe U.
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U. Sheffield
U. Warwick

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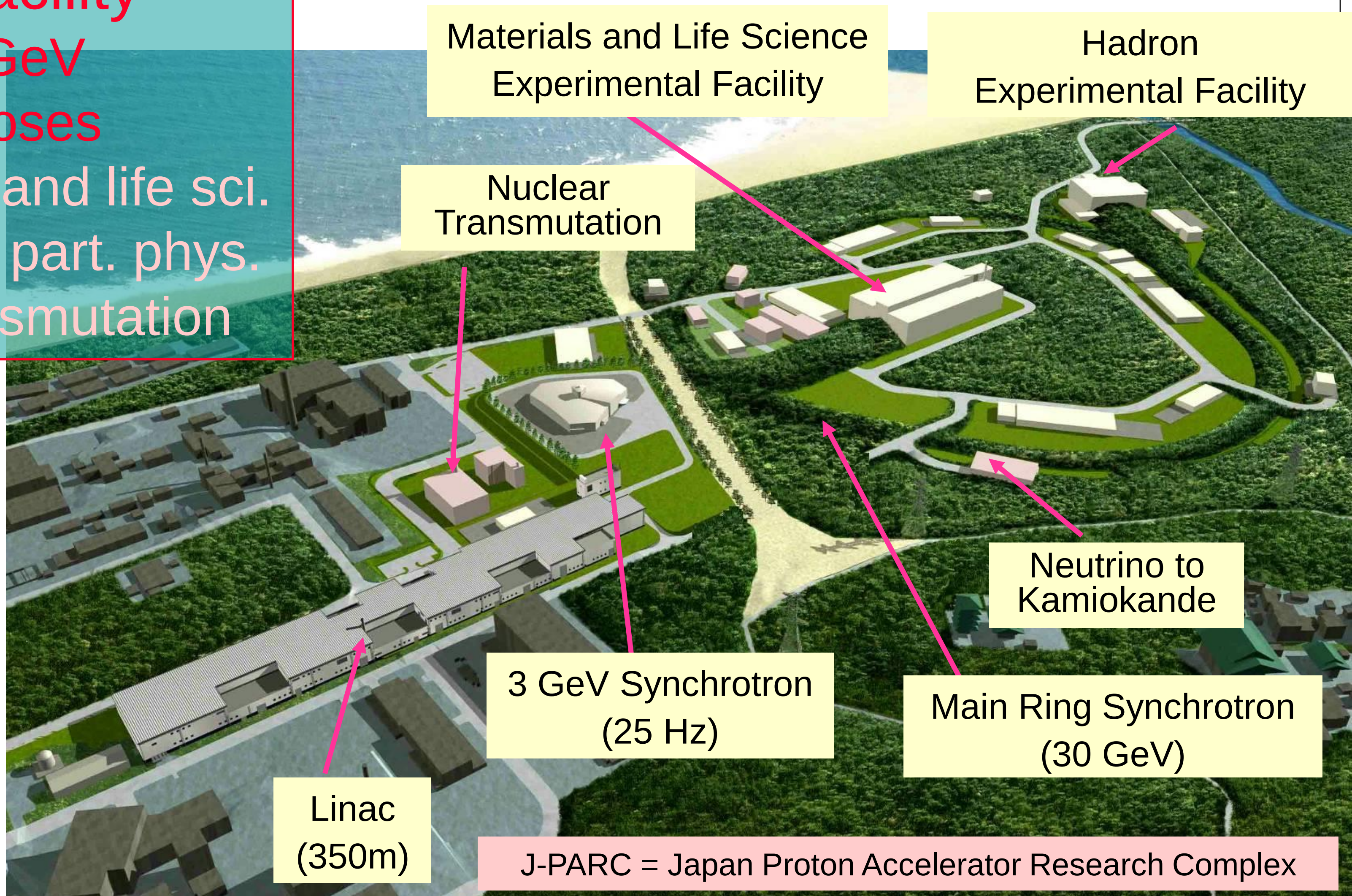
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

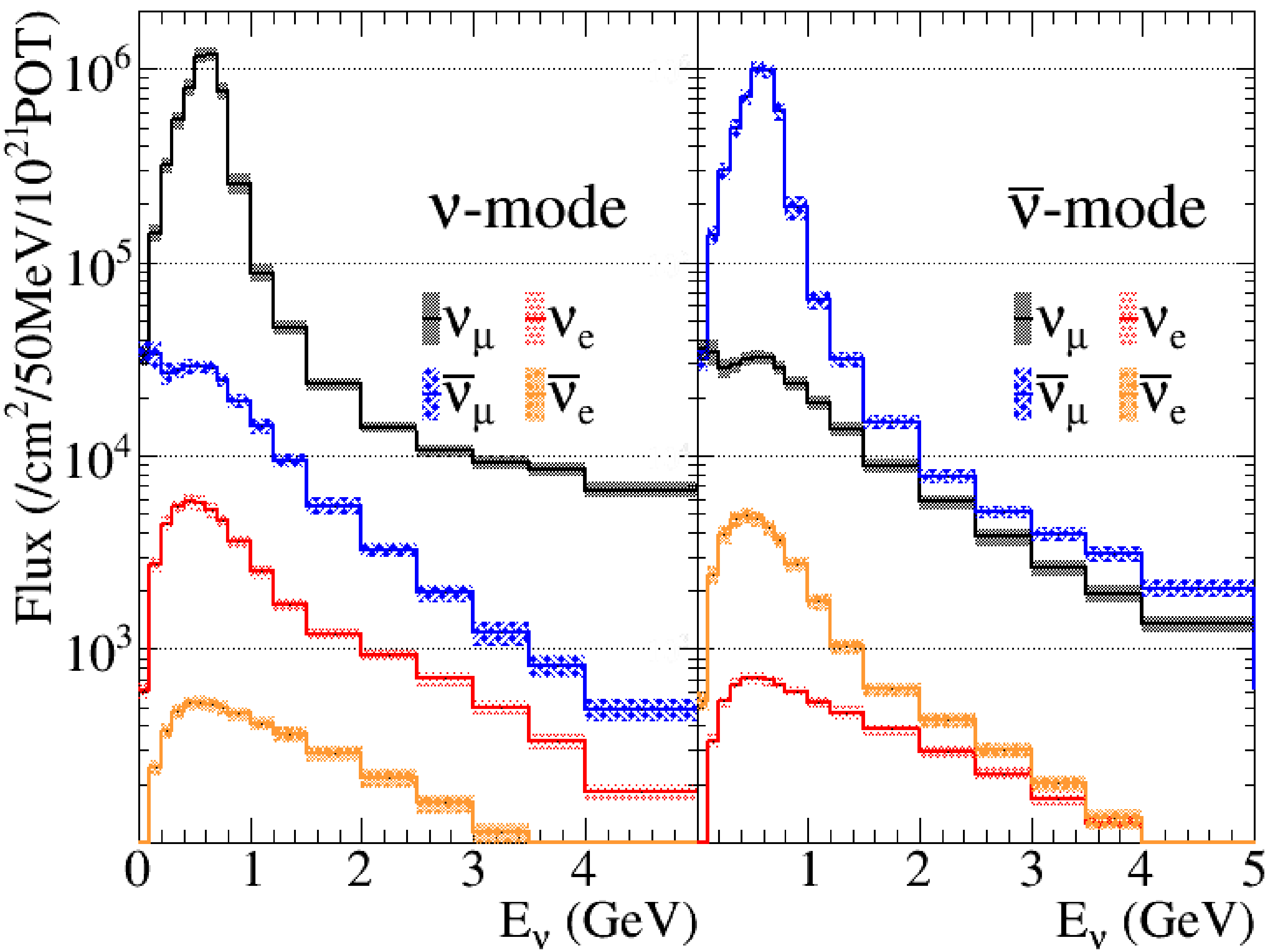
MW Proton Facility : J-PARC

Unique facility
3GeV+30GeV
Multi-purposes

- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation



Neutrino flux



Neutrino phenomenology: from flavor eigenstates to oscillations

- Flavor eigenstates are superpositions of mass eigenstates

$$\left|\nu_i\right\rangle = \sum_{j=1}^{n} U_{ij} \left|\nu_j\right\rangle$$

  - If the unitary mixing matrix U is non-diagonal, then get flavor eigenstates as neutrinos propagate

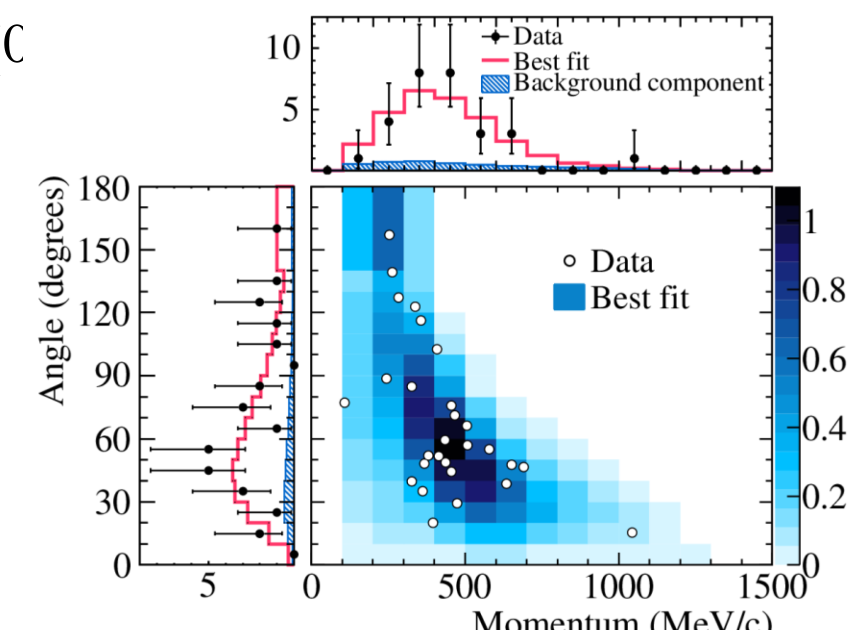
$$\left|\nu(t)\right\rangle = \sum_{j=1}^{n} U_{ij} e^{-iE_j t} \left|\nu_j\right\rangle \sim e^{im_j^2 L/2p} \left|\nu_j\right\rangle$$

- Probability of selecting flavor b, at a distance L

$$P(\nu_a \rightarrow \nu_b) = \delta_{ab} - 4\sum_{i>k} \mathrm{Re}\left(U_{ak}^{*} U_{bi} U_{ai} U_{bk}^{*}\right) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$
$$\pm 2\sum_{i>j} \mathrm{Im}\left(U_{ak}^{*} U_{bi} U_{ai} U_{bk}^{*}\right) \sin\left(\frac{\Delta m^2 L}{2E}\right)$$

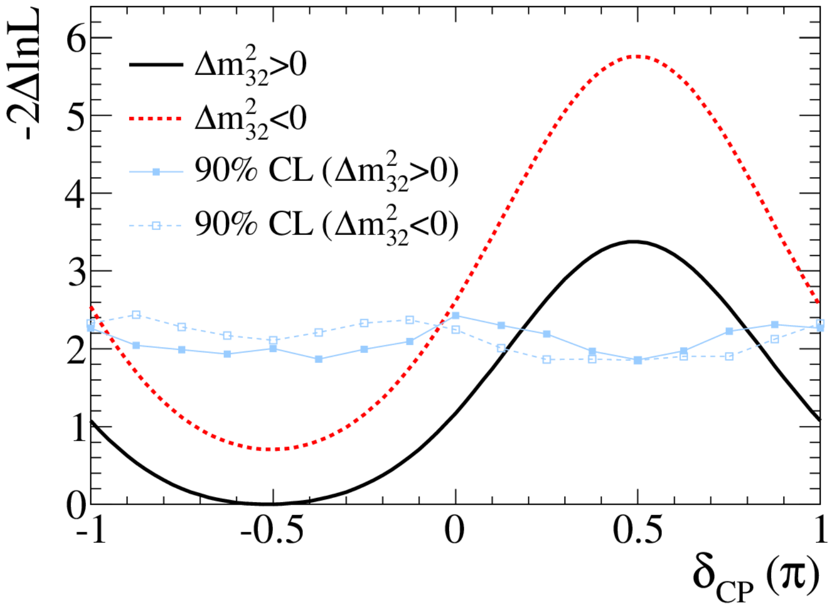
ν_e appearance results

- 28 ν_e candidates selected **(Phys. Rev. Lett. 112, 061802, 2014)**
  - 4.92 ± 0.55 expected background
  - 7.3σ significance
- Best fit result
  - $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ (0
    assuming
    - $|\Delta m^2_{32}| = 2.4 \times 10^{-3}\, eV^2/c^4$
    - $\sin^2\theta_{23} = 0.5$
    - $\delta_{CP} = 0$



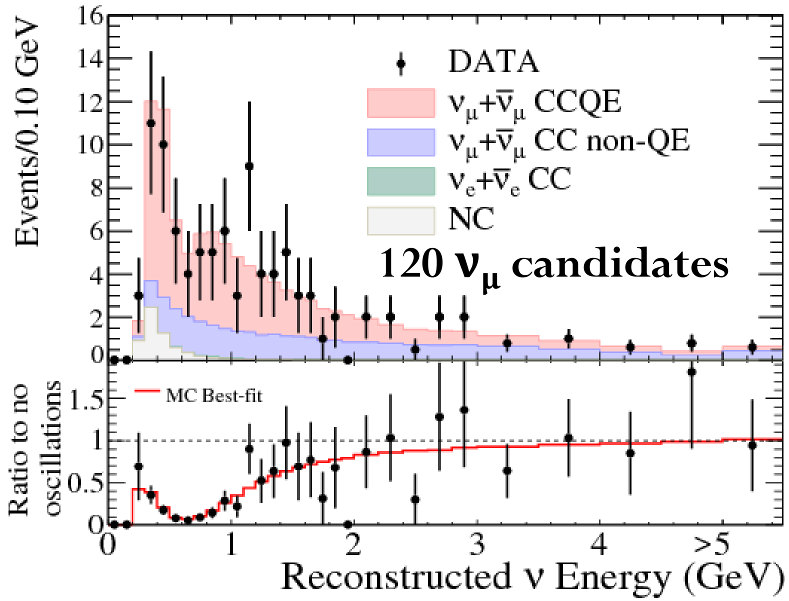
Constraints on δ_{CP}

- Combine T2K and reactor neutrino data to constrain δ_{CP}
  - **Phys. Rev. Lett. 112, 061802, 2014**
  - For NH (IH), excludes δ_{CP} $[0.19, 0.80]\pi$ ($[-0.08, 1.09]\pi$) at 90% CL

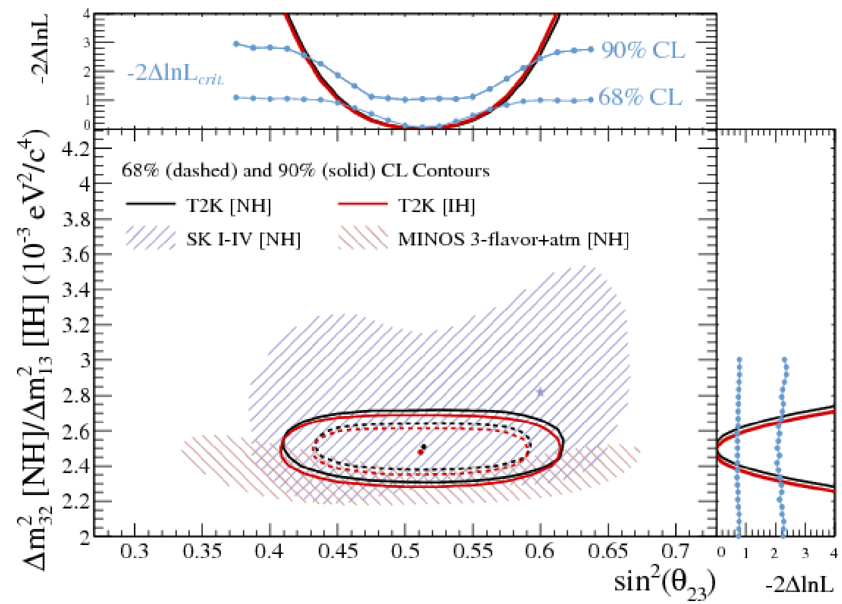


ν_μ disappearance results

Phys. Rev. Lett. 112, 181801, 2014



World leading θ_{23} measurement



Best fit $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$ (0.511±0.055)

$\Delta m^2_{23} = (2.51\pm0.1)\times10^{-3}$ eV^2/c^4 ($\Delta m^2_{13} = (2.48\pm0.1)\times10^{-3}$ eV^2/c^4) for NH (IH)

Future sensitivity for $\bar{\nu}_e$ appearance

- Currently T2K has selected 3 $\bar{\nu}_e$ candidates for 4.01×10^{20} POT
- p-value < 0.02 for 9.0×10^{20} POT
  - No statistical uncertainty and PMNS prediction exactly correct