Recent results from the T2K experiment

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La Thuile, 03.03.2015

Outline

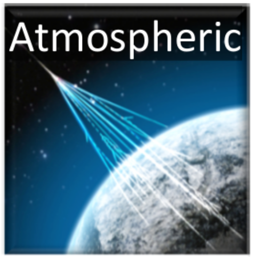
1. T2K experiment overview.
2. Results from oscillation analyses.
3. Other results (selected).
4. Summary.

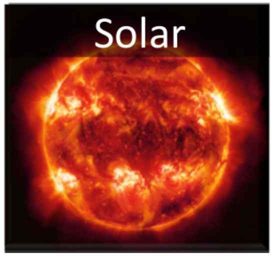
Neutrino oscillations

Flavor eigenstates		Mass eigenstates

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$





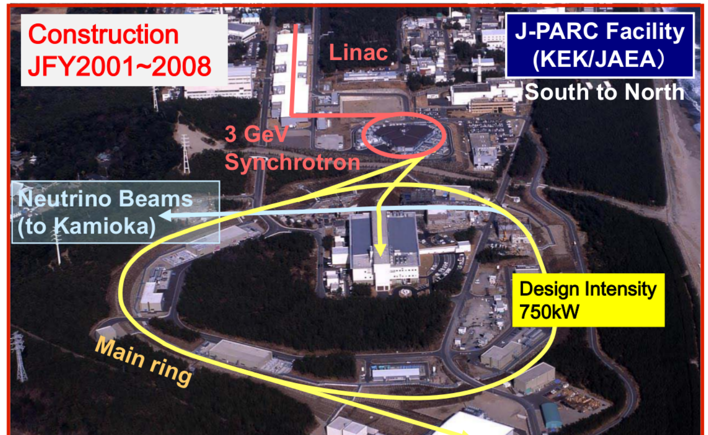
- Oscillation probabilities $P(\nu_\alpha \rightarrow \nu_\beta)$ depend on:
  - 3 mixing angles: θ_{23}, θ_{13}, θ_{12}
  - 1 complex CP phase: δ_{CP}
  - 2 independent mass splittings: Δm^2_{32} , Δm^2_{12}
  - Source-detector distance (L), neutrino energy (E)

- Open questions:
  - Is δ_{CP} non-zero (CP violation in neutrino sector) ?
  - Is θ_{23} 45°(maximal mixing)?
  - Normal: $\mathbf{m_3}$**>**$\mathbf{m_2}$>m_1 (N.H.) or inverted: m_2>$\mathbf{m_1}$**>**$\mathbf{m_3}$ (I.H.) mass hierarchy?

T2K experiment overview

- 11 countries,
- 59 institutions
- ~500 people

- Long-baseline (295 km)
- Almost pure accelerator-produced ν_μ beam

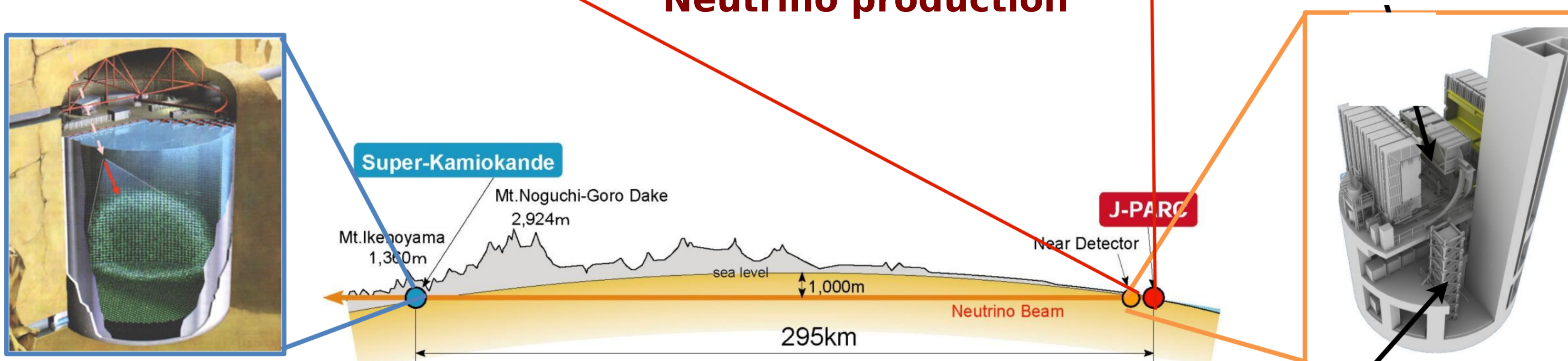


Neutrino production

- Main goals:
  - Measure θ_{13} and estimate δ_{CP} through ν_e appearance - $P(\nu_\mu \to \nu_e)=f(\theta_{13}, \delta_{CP},...)$
  - Measure θ_{23} through ν_μ disappearance - $P(\nu_\mu \to \nu_\mu)=f(\theta_{23},...)$

Far detector

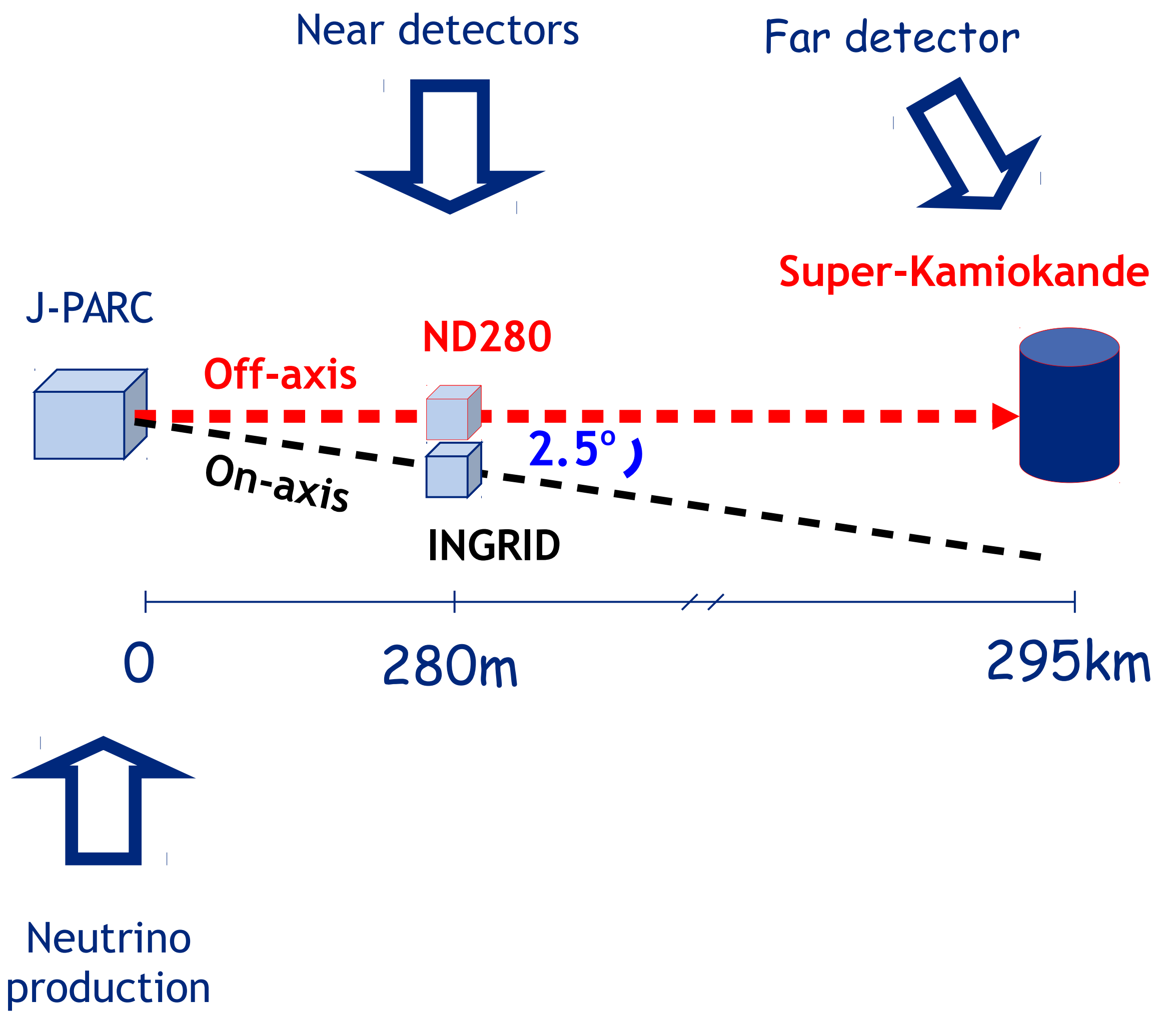
Near detectors

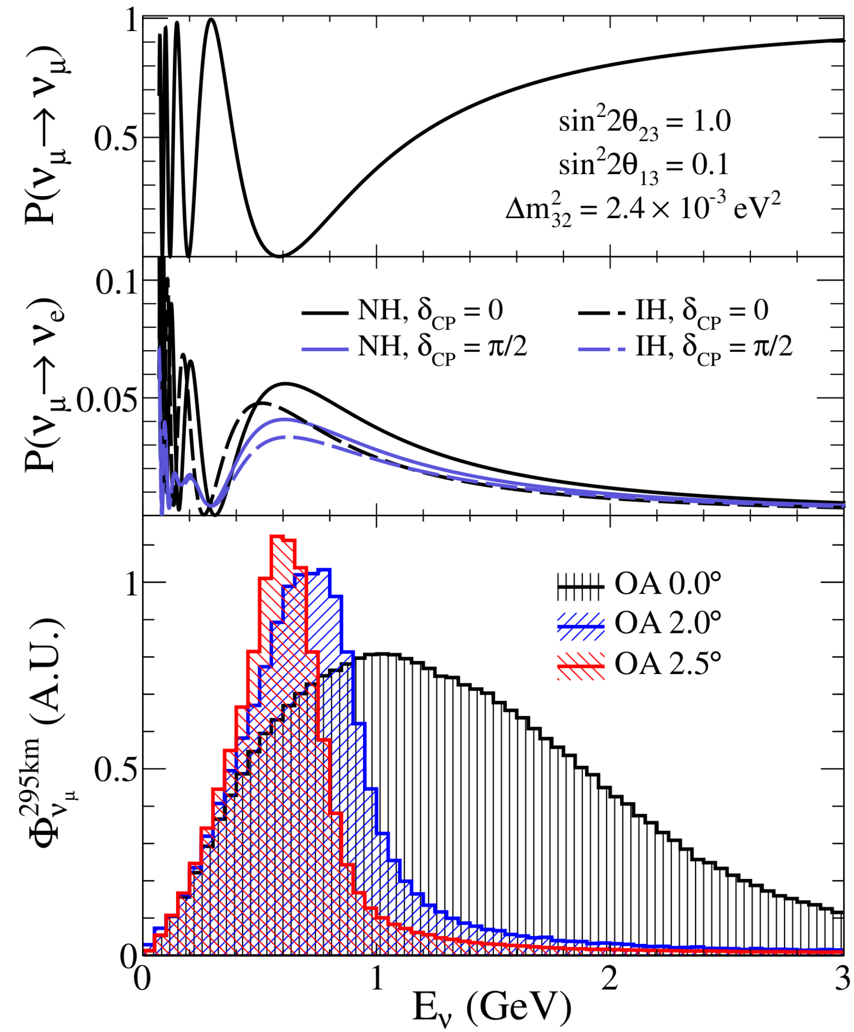


$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin\left(\frac{\Delta m_{21}^2}{4E}\right) \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta_{CP} + \ldots$$

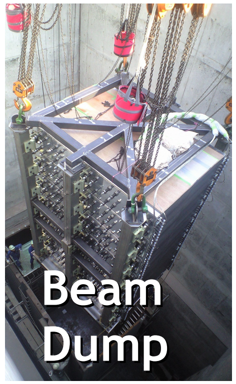
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13} \sin^2\theta_{23} [1 - \cos^2\theta_{13} \sin^2\theta_{23}] \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

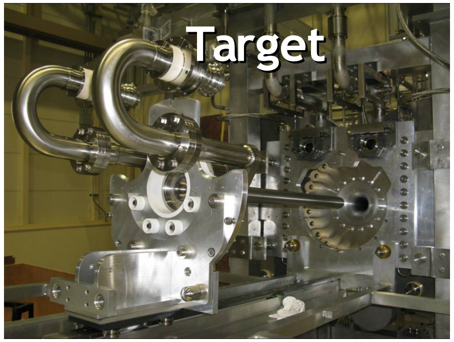
T2K setup & off-axis beam

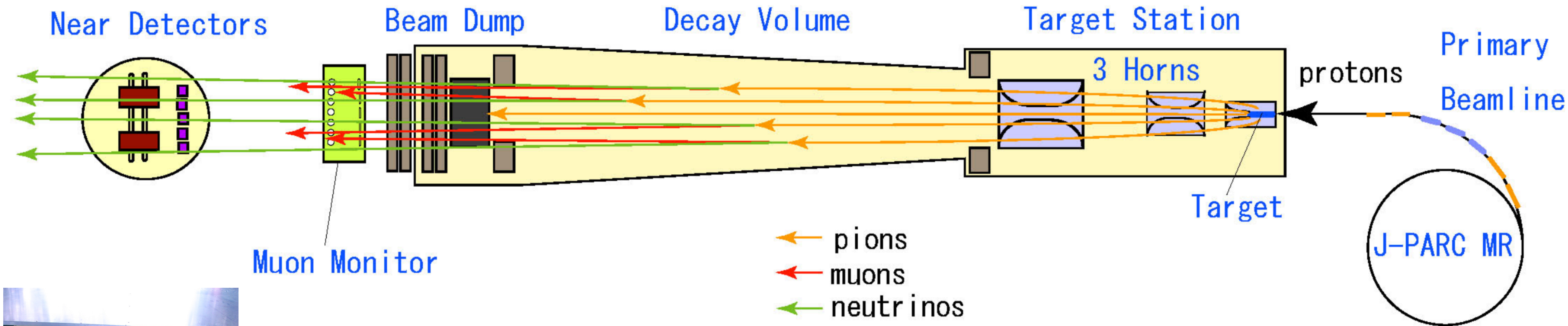


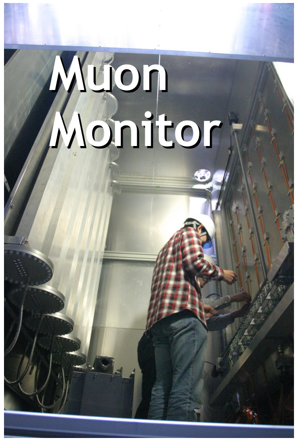


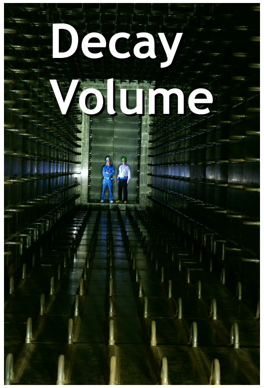
Neutrino production



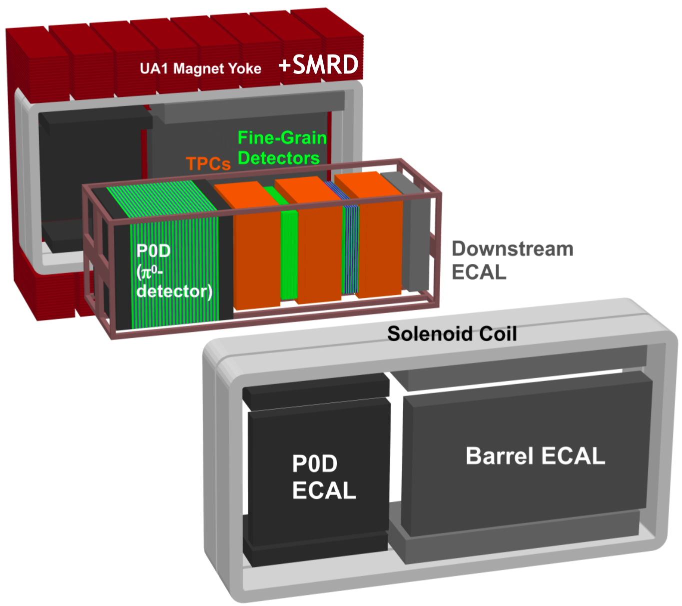




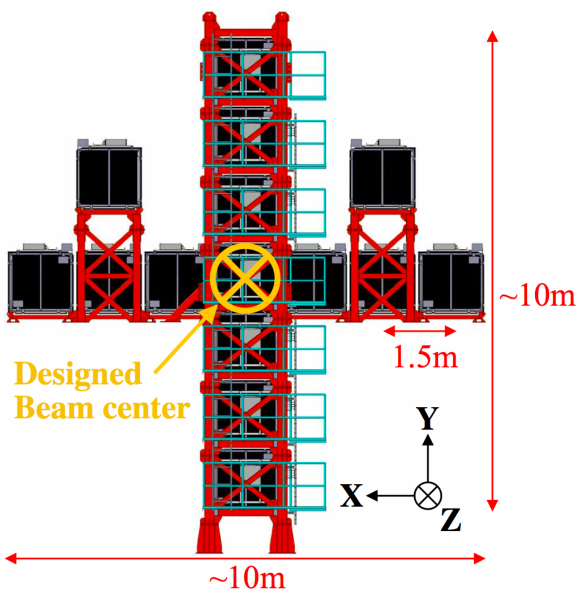




T2K near detectors

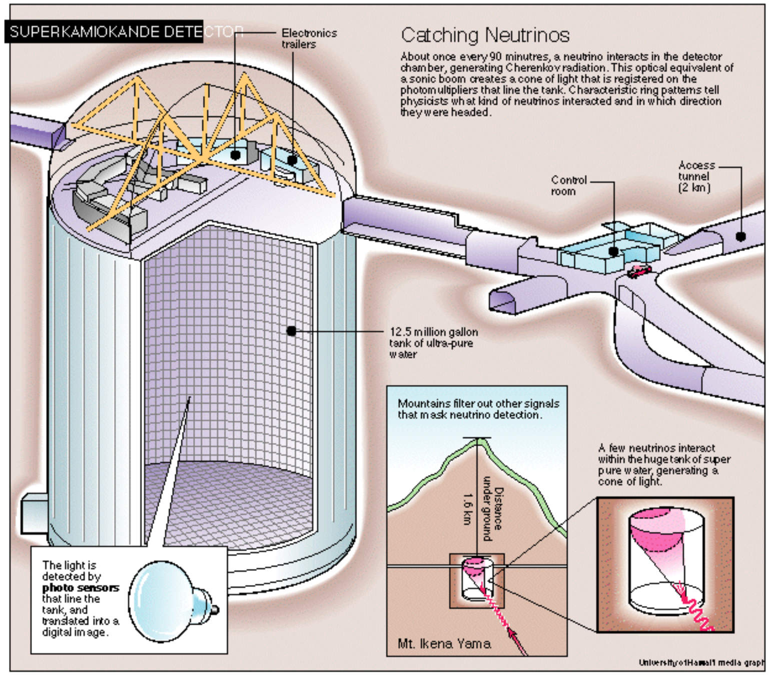


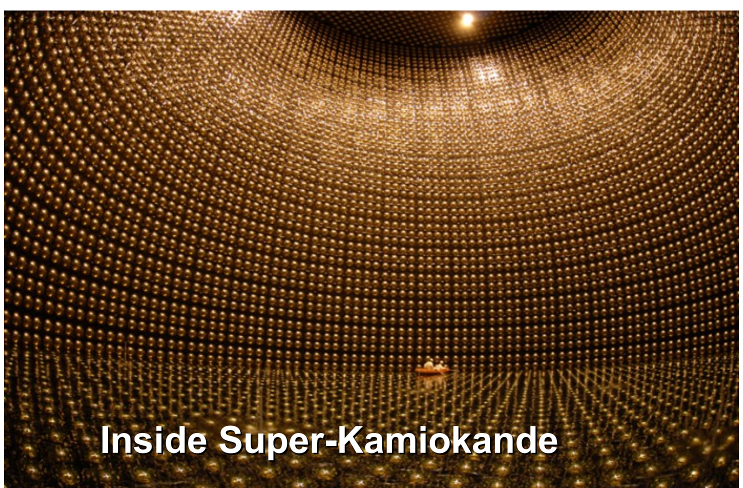
- ND280 off-axis near detector:
  - Several sub-detectors in 0.2T magnetic field:
    - Tracker (TPCs & FGDs), Pizero Detector (P0D), Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD)
  - Measure flux x cross section before the oscillation occurs
  - Measure intrinsic ν_e contamination in the beam
  - Neutrino cross section measurements



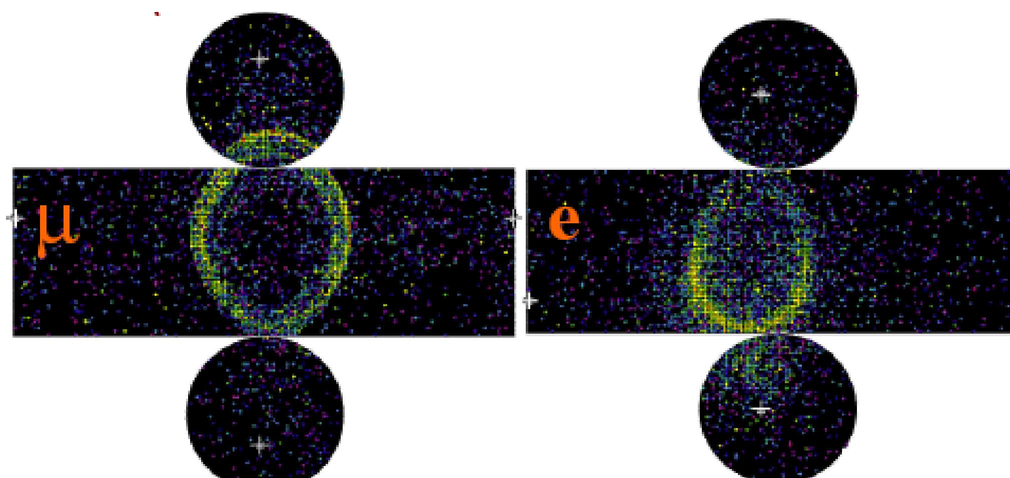
- INGRID on-axis near detector:
  - 16 modules (iron/scintillator sandwich) + additional scintillator-only module (proton module)
  - Count neutrinos by reconstructing muons from ν_μ interactions
  - Monitor beam rate, direction and stability

T2K far detector

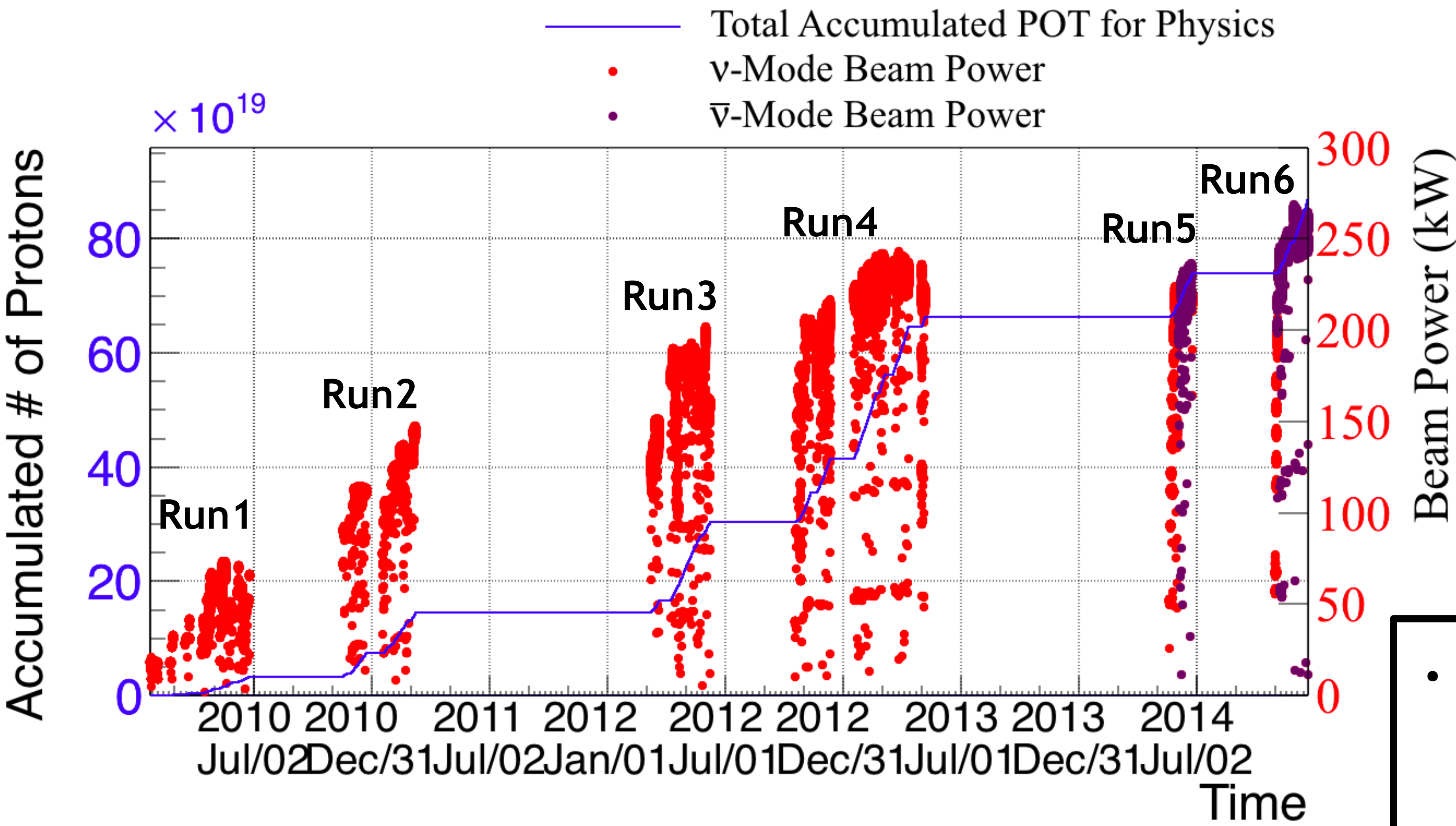




- Super-Kamiokande far detector:
  - Operating since 1996
  - Well understood detector and technology
  - 50 kt water Cherenkov detector
  - 11 000 (inner detector) + 2000 (outer detector) photomultipliers
  - Good electron/muon separation



T2K data

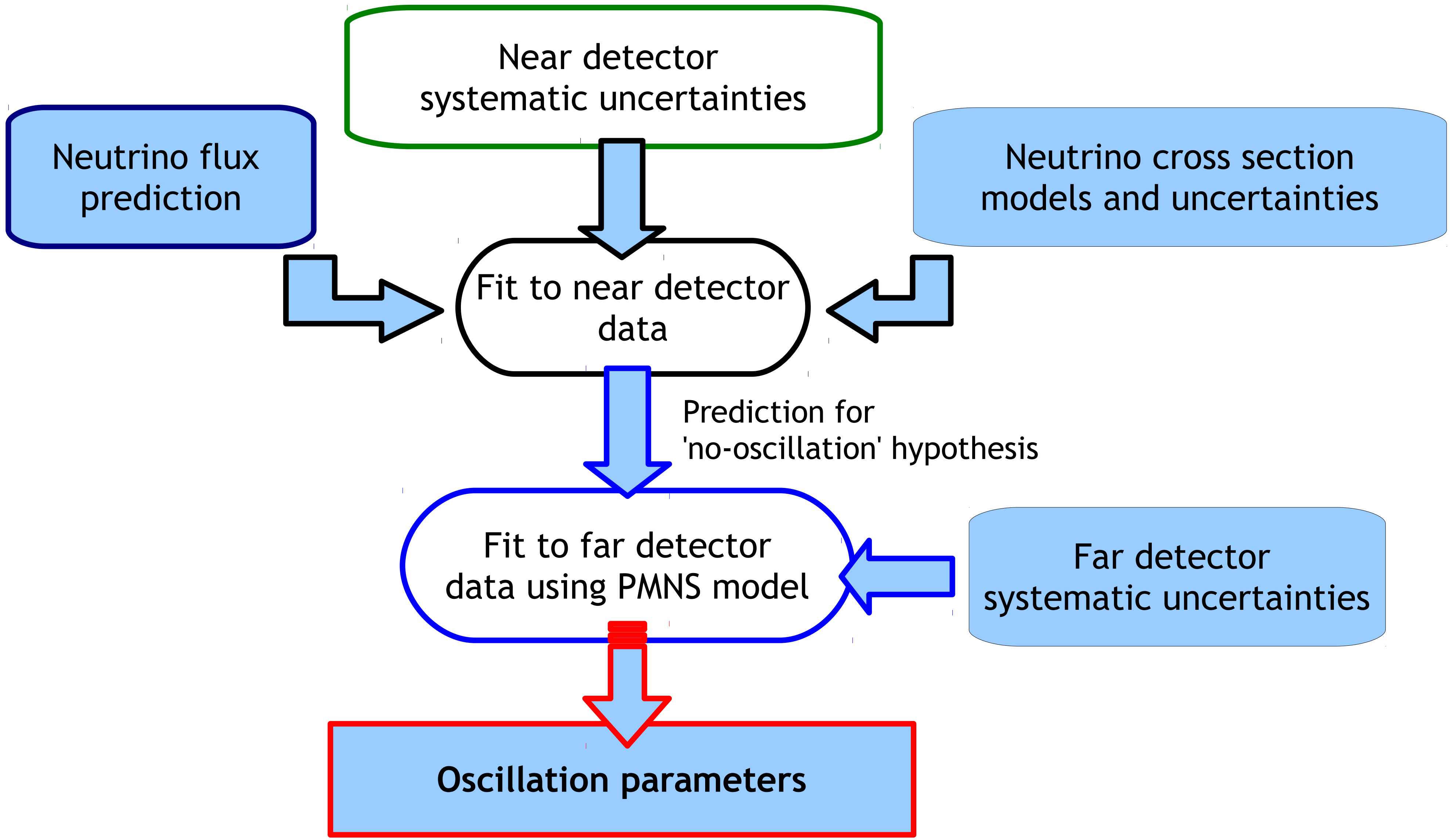


6.57 x 10^{20} POT (Run1 - 4)
used in the analyses presented here

- Integrated for Physics so far:
  - 8.701 x 10^{20} POT
  - Integrated ν-Mode for Physics so far:
    - 6.893 x 10^{20} POT
  - Integrated anti-ν-mode for Physics so far:
    - 1.808 x 10^{20} POT

Long-baseline oscillation analyses

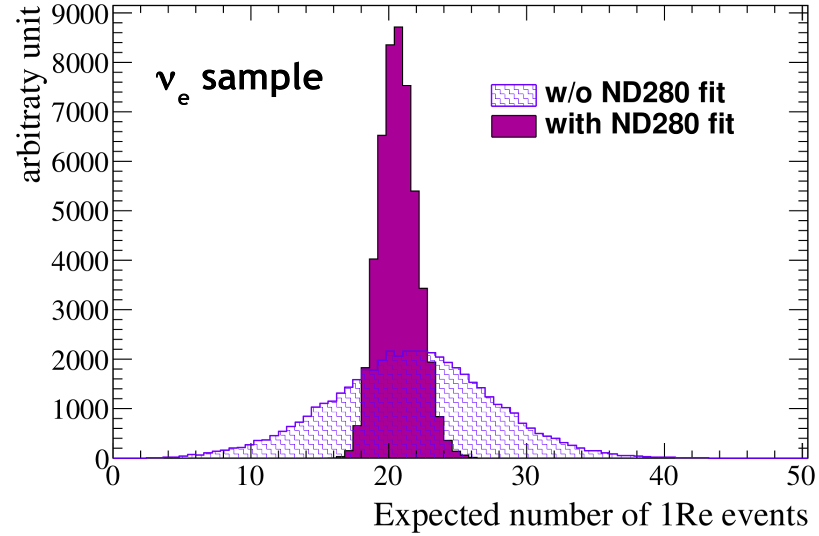
Oscillation analysis strategy

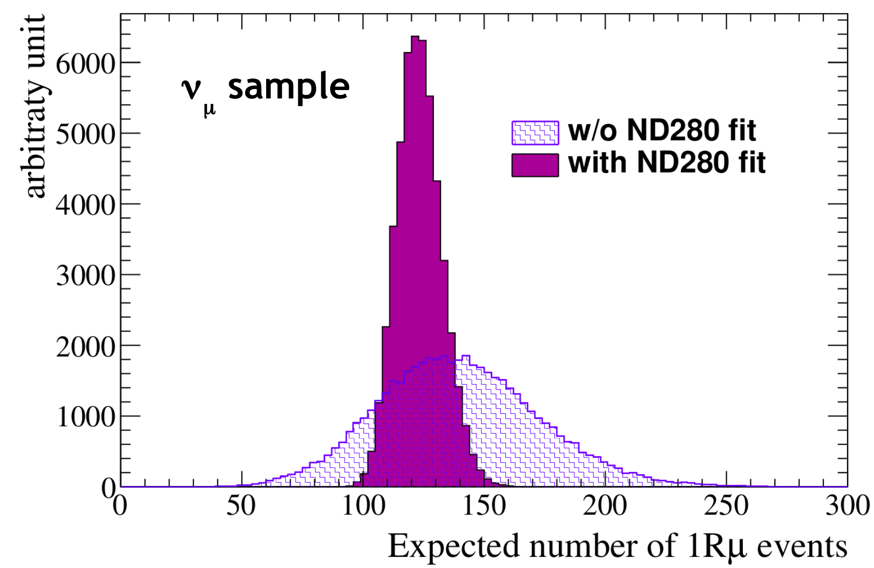


Near detector role

- Significant reduction of systematic uncertainties (flux & cross section) with near detector constraints.

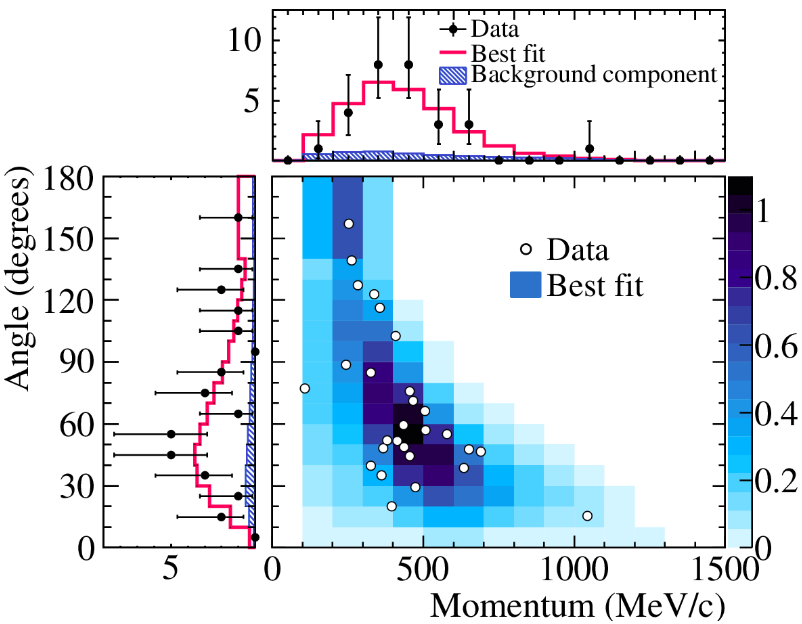
Systematics	ν_μ sample, %	ν_e sample, %
Neutrino flux&cross section (w/o ND280)	2.7 (21.8)	3.1 (26.0)
Neutrino cross sections due to the difference of target between near and far detector	5.0	4.7
Final or secondary hadronic interactions	3.0	2.4
Super-K detector	4.0	2.7
Total (w/o ND280)	**7.7 (23.5)**	**6.8 (26.8)**

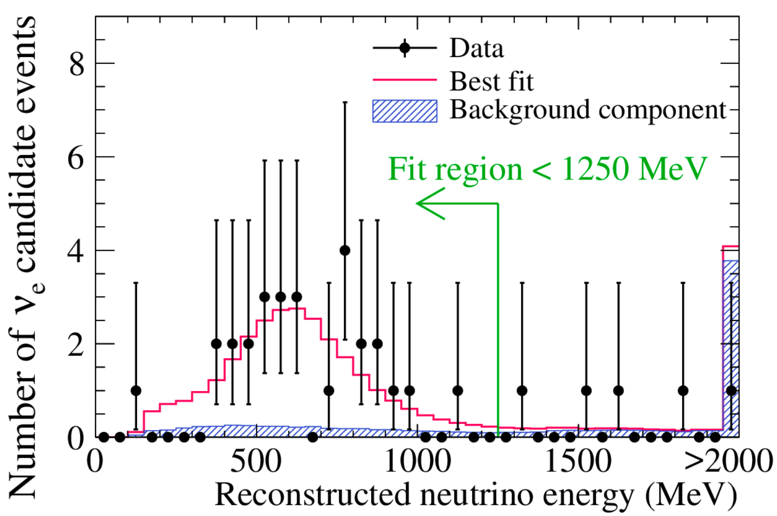




ν_e appearance measurement

Phys.Rev.Lett. 112 (2014) 061802





- Maximum likelihood fit in (p_e,θ_e) to obtain the oscillation parameters
- Result is consistent with the independent analysis using reconstructed neutrino energy E_ν
- Best fit (N.H and δ_{CP}=0):

$$\sin^2 2\theta_{13} = 0.140\,^{+0.038}_{-0.032}$$

- **7.3σ significance for non-zero θ_{13}.**
- **Discovery of ν_e appearance!**

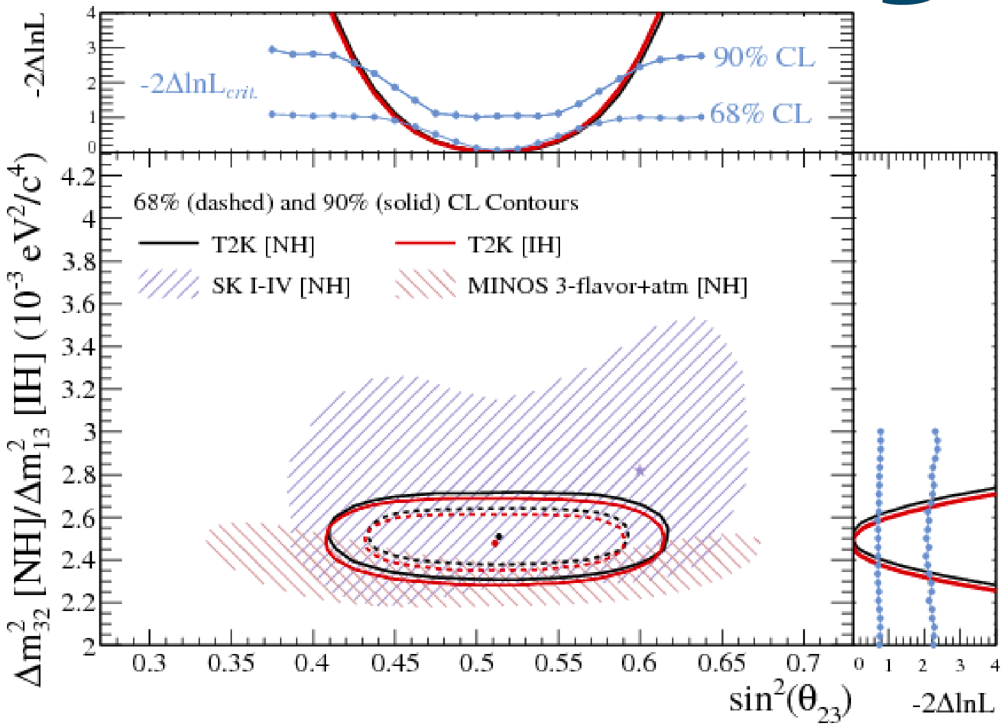
ν_μ disappearance

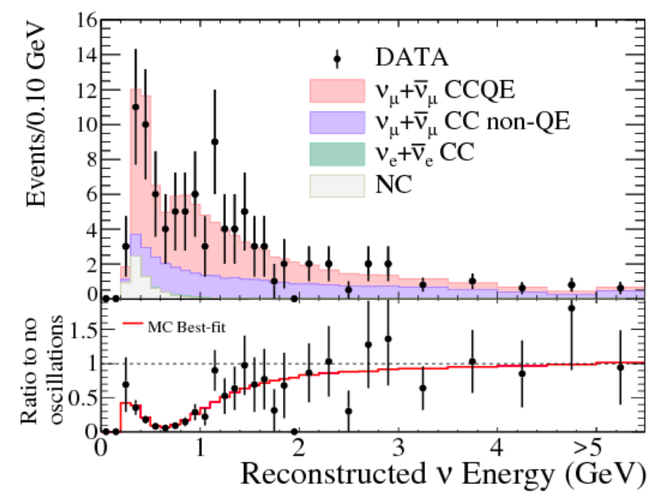
Phys.Rev.Lett. 112 (2014) 181801

- **World leading measurement of θ_{23}!**
- First time the best constraint for θ_{23} comes from an accelerator measurement (not atmospheric)
- Fit using 3 flavor model of oscillations.
- Best fit value (N.H.):

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

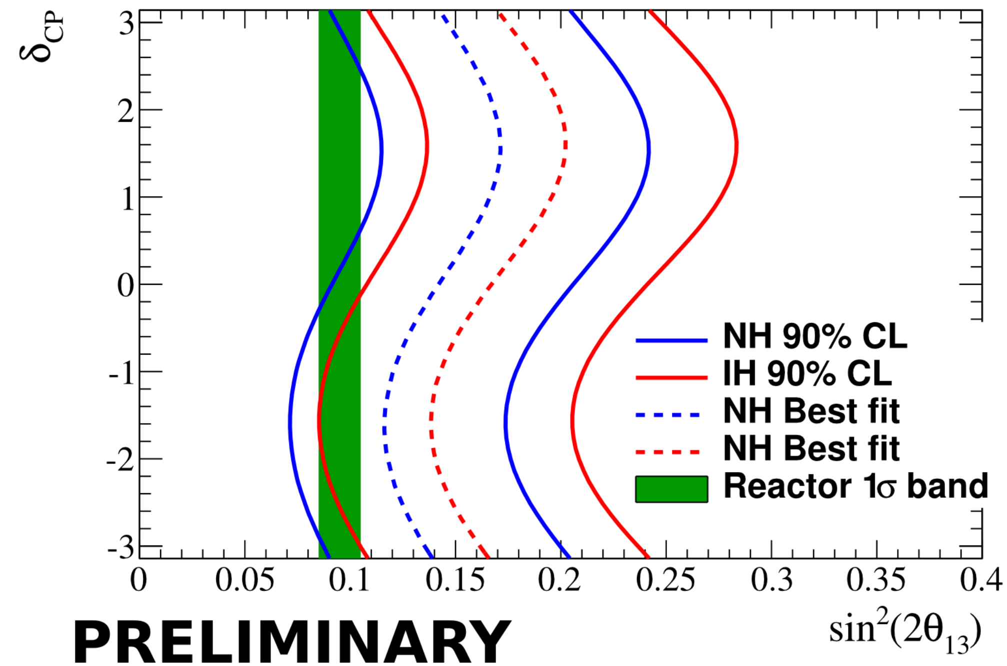
- Maximal mixing is favored.



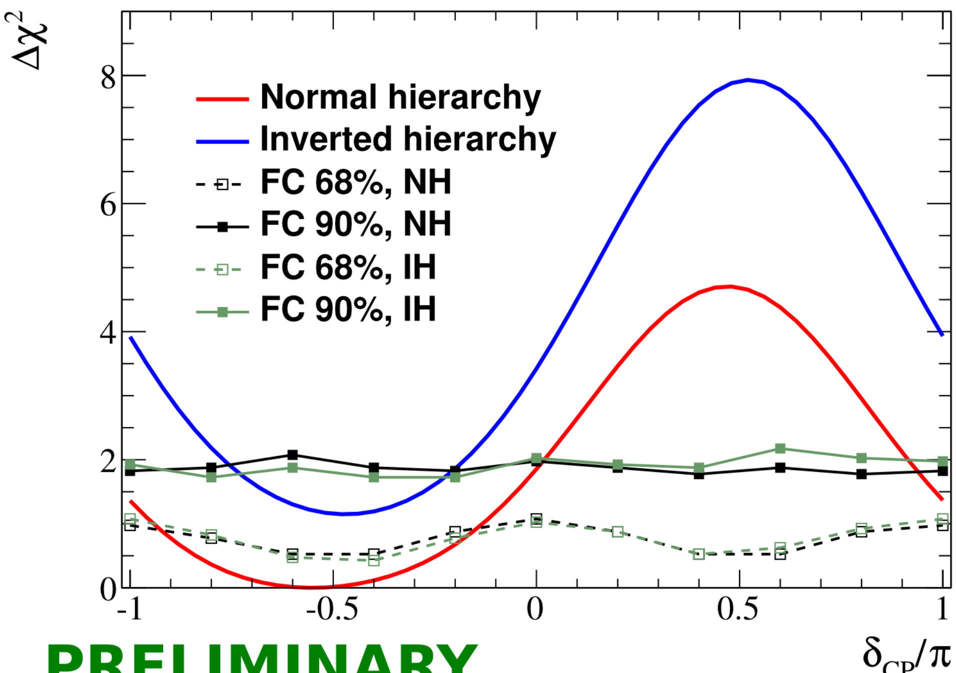


Joint ν_μ/ν_e analyses

- Previously presented:
  - ν_e appearance analysis
  - ν_μ disappearance analysis
- But oscillation probabilities depend on all 4 parameters:
  - Joint analyses (simultaneous fit to ν_μ and ν_e spectra in far detector)



PRELIMINARY



PRELIMINARY

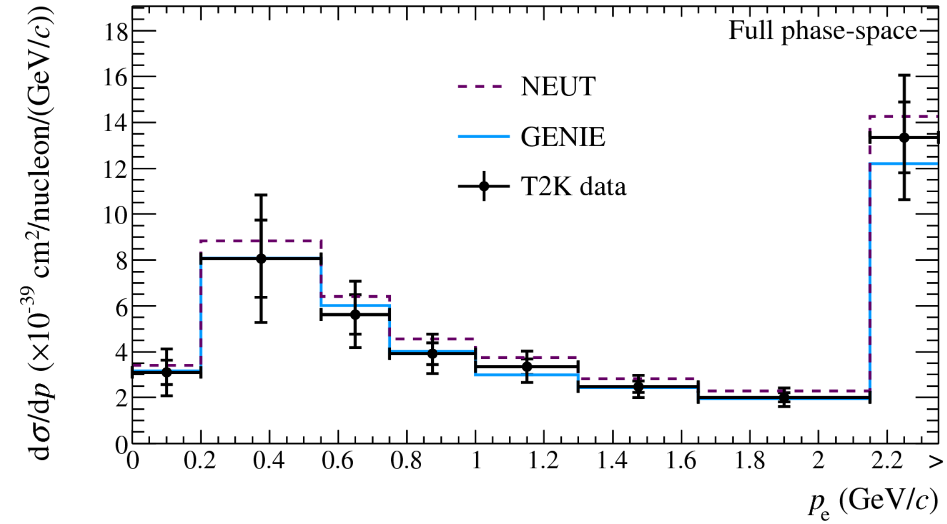
- **Comparing T2K and reactor results → preference for δ_{CP} around $-\pi/2$!**
- Outside 68% C.L.:
  - $[-\pi,-2.92] \cup [-0.46, \pi]$ - N.H.
  - $[-\pi,\pi]$ - I.H.
- Outside 90% C.L:
  - $[0.06,2.95]$ - N.H.
  - $[-\pi,2.95] \cup [-0.71,\pi]$ - I.H.

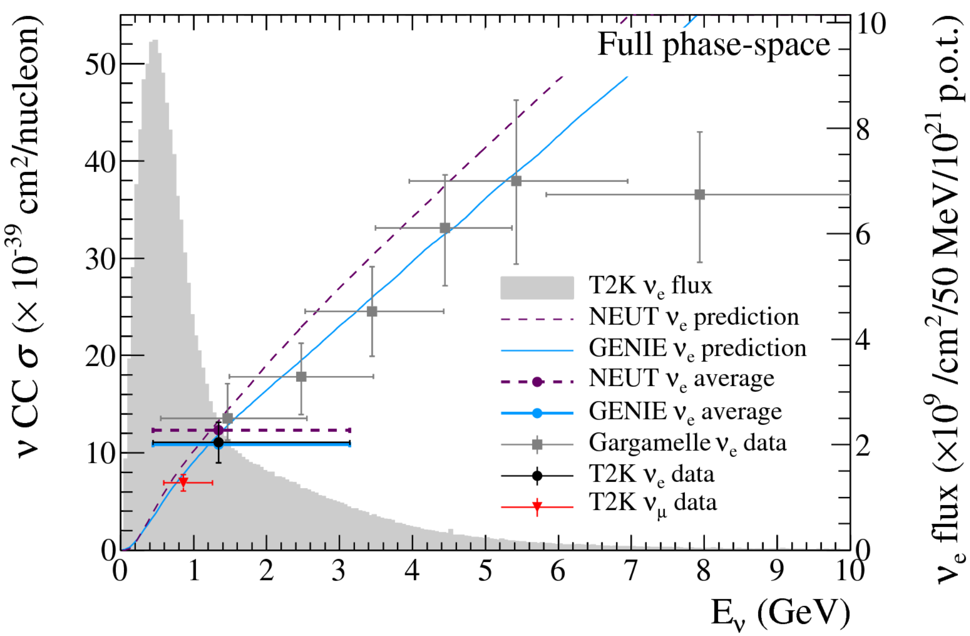
Other analyses

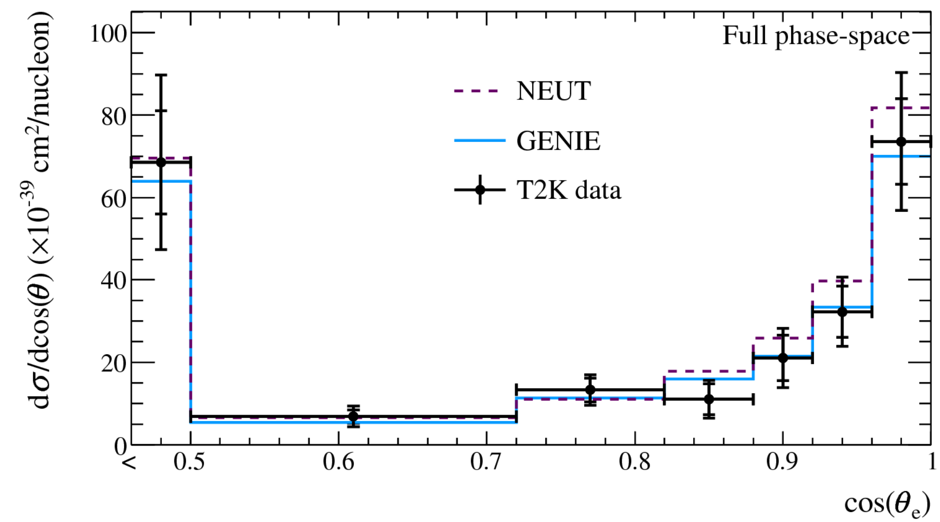
Off-axis cross section results

Phys.Rev.Lett. 113 (2014) 24, 241803

- Used ND280 tracker to select ν_e interactions on hydrocarbon (CH).
- Most significant background comes from $\gamma \rightarrow$ e+e- conversions - constrained by the control sample
- Bayesian unfolding used to produce differential cross section in electron observables and in Q^2_{QE}





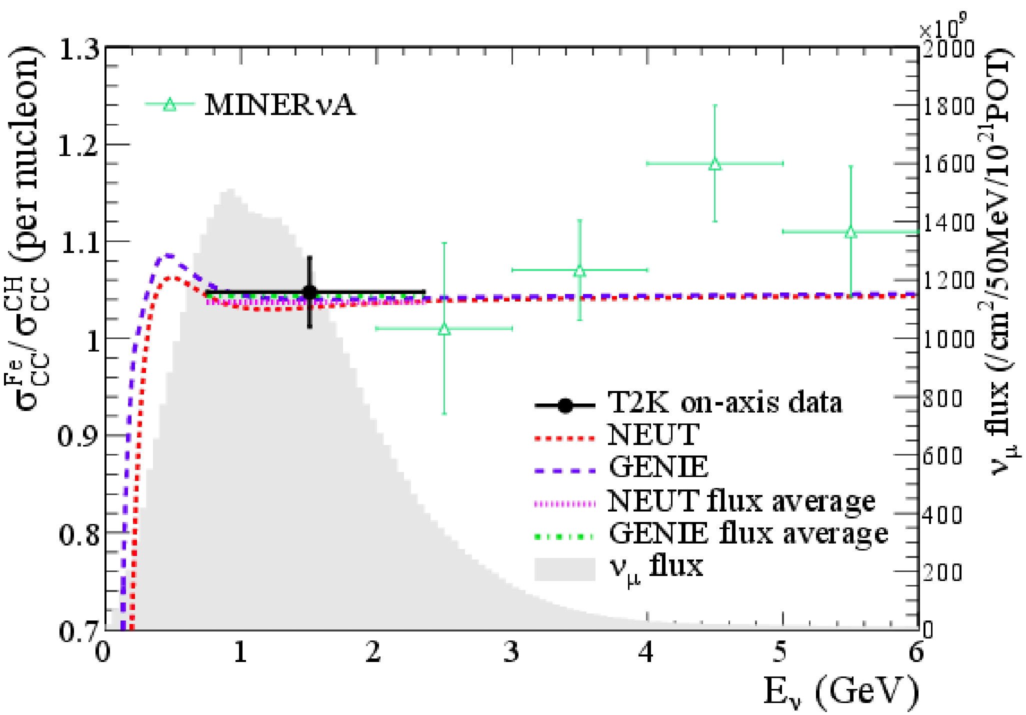


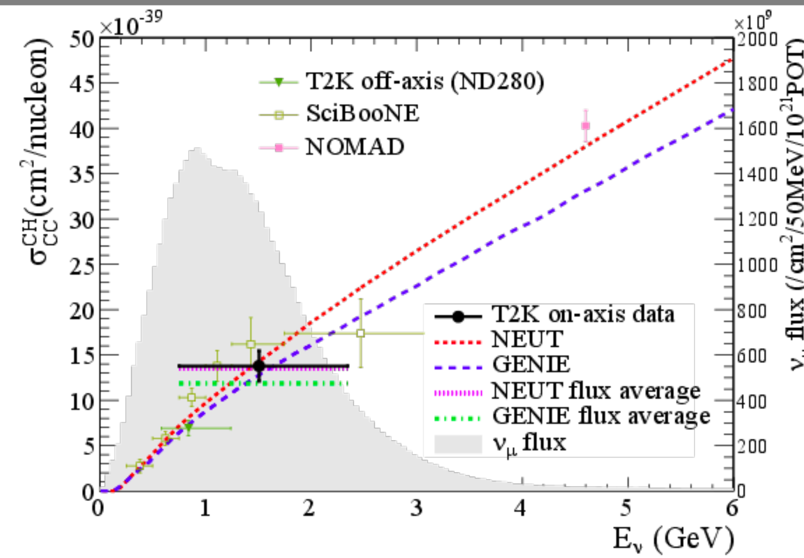
First ν_e CC differential cross section in sub-GeV range!

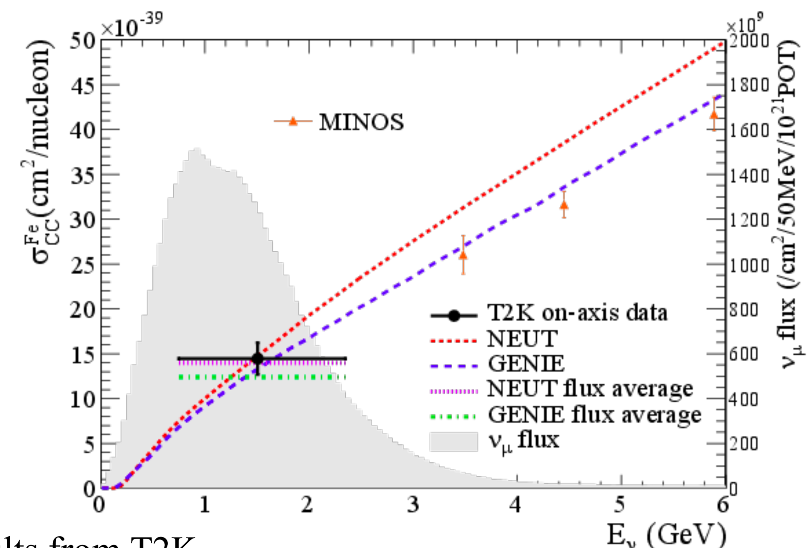
On-axis cross section results

Phys.Rev. D90 (2014) 5, 052010

- The on-axis detector (INGRID) is able to measure neutrino interactions on :
  - Iron (96.23% of Fe in the standard module)
  - Hydrocarbon (98.57% of CH in the proton module)
- Measured ratio of cross sections (Fe/CH)





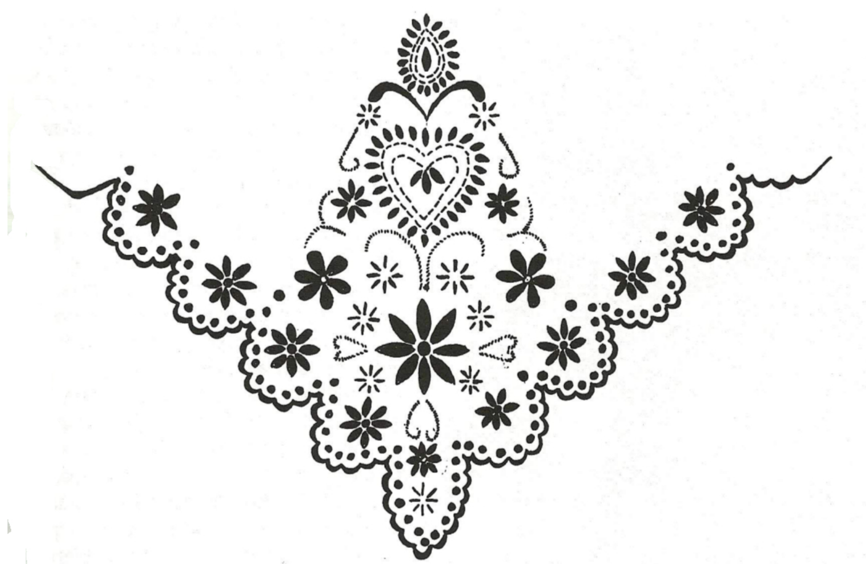


Summary

- Presented results from world-leading accelerator long-baseline neutrino experiment T2K:
  - World best θ_{23} measurement.
  - ν_e appearance discovery.
  - Combining reactor experiments and T2K provides a first (weak) hint on δ_{CP}:
    - Preference for δ_{CP} values around $-\pi/2$.
- T2K is also producing a lot of very useful cross section results:
  - ν_e CC-inclusive cross section on CH (presented here), CC-inclusive cross section on CH and Fe and Fe/CH cross section ratio (presented here),
  - CC-inclusive cross section on CH (Phys.Rev. D87 (2013) 9, 092003), NC-gamma cross section on oxygen (Phys.Rev. D90 (2014) 7, 072012)
- More results are coming!
- Taking data with anti-neutrino mode. Will be able to present first anti-neutrino oscillation results this spring/summer.

Stay tuned!

Thank you for your attention!



Backup slides

Neutrino oscillations

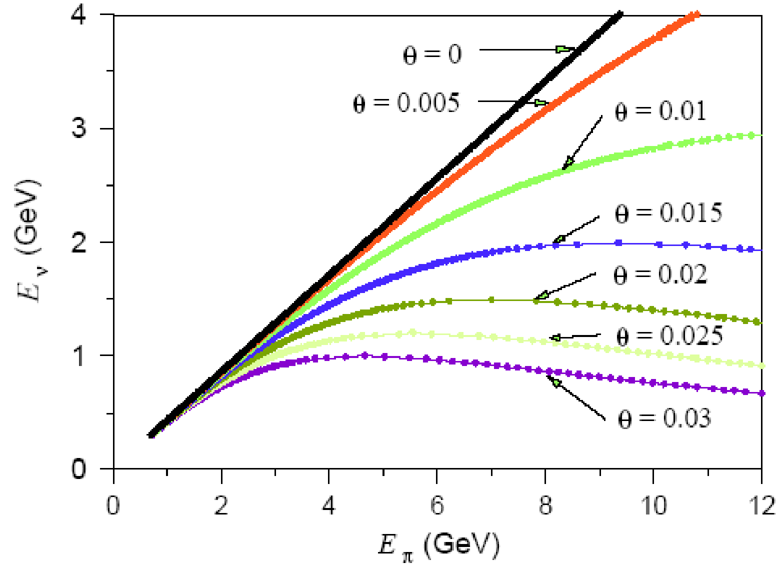
$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \Re(U_{\alpha i}^{*} U_{\beta j} U_{\alpha j} U_{\beta j}^{*}) \cdot \sin^2 \Phi_{ij}$$
$$\pm 2\sum_{i<j} \Im(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}) \cdot \sin^2 \Phi_{ij}$$

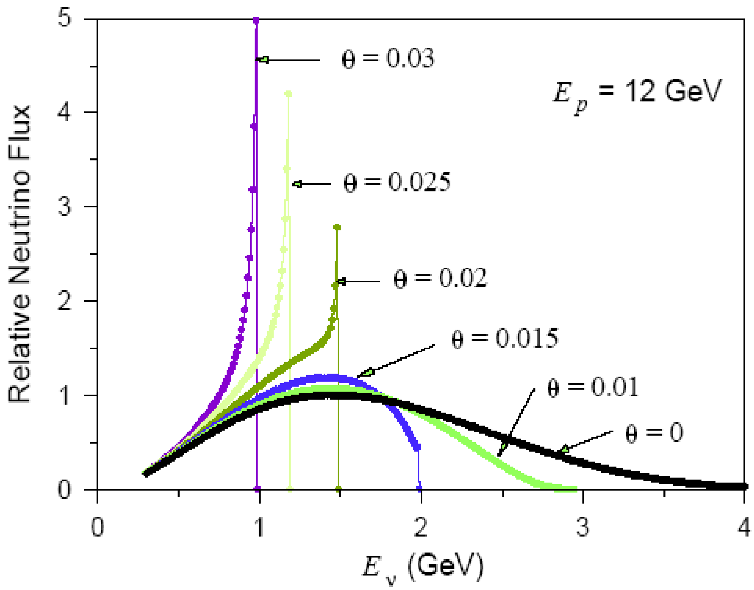
$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu} = 1.27 \cdot \Delta m_{ij}^2 [eV^2] \cdot \frac{L[km]}{E_\nu [GeV]}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) -$$
$$- \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin\left(\frac{\Delta m_{21}^2}{4E}\right) \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta_{CP} + \ldots$$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4\cos^2\theta_{13} \sin^2\theta_{23} [1 - \cos^2\theta_{13} \sin^2\theta_{23}] \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

Off-axis beam



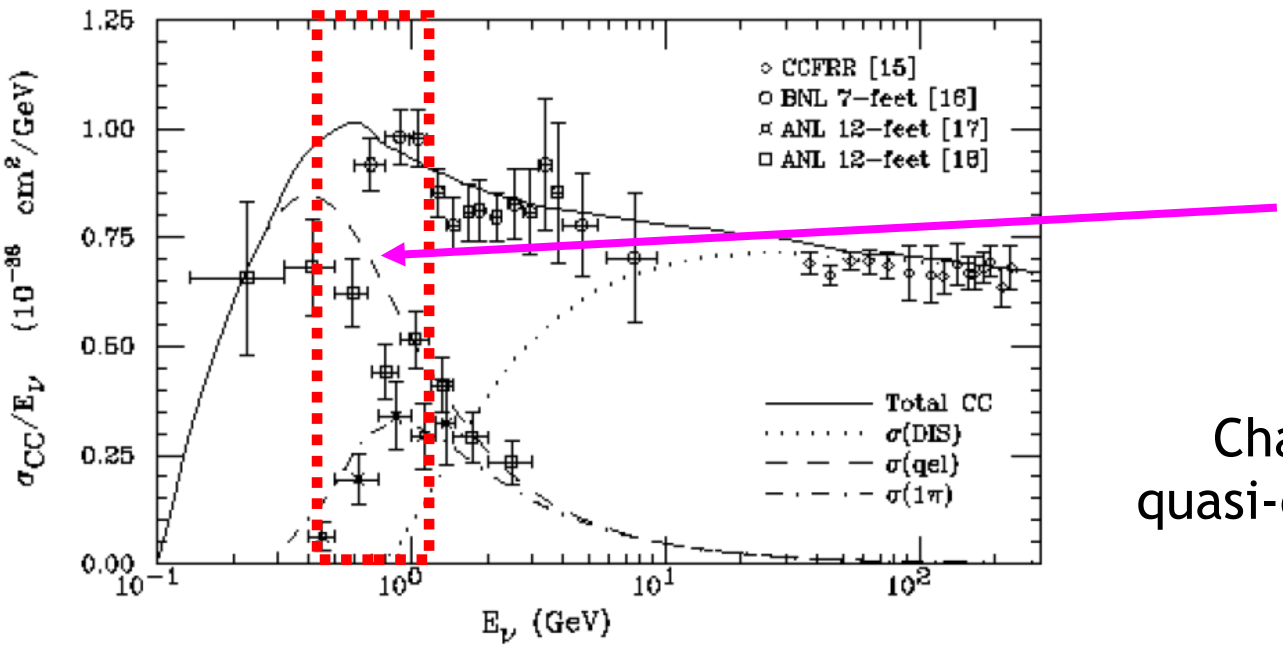


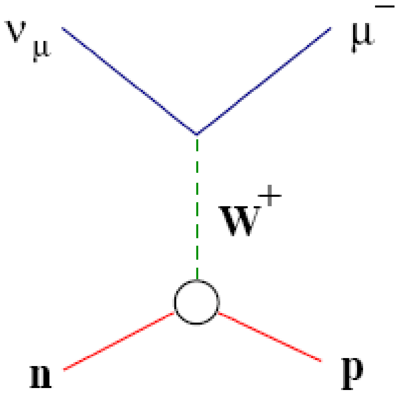
Kirk T. McDonald *An Off-Axis Neutrino Beam*, 2001.

Super-Kamiokande event selection

- Fully-contained, 1 ring events in the fiducial volume:
  - Mu-like selection (120 numu candidates in SK, 446+-22.5 expected):
    - Pmu > 200 MeV
    - Less than 2 Michel electrons
    - Mu-like PID
  - E-like selection (28 nue candidates in SK, 4.92+-0.55 expected):
    - Pe > 100 MeV
    - No Michel electrons
    - Pi0 rejection cut
    - Erec < 1250 MeV
    - E-like PID

CCQE neutrino interactions in T2K

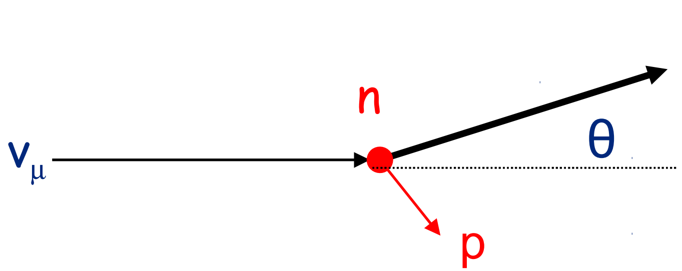




Charged current quasi-elastic scattering (CCQE)

Neutrino energy reconstruction:

$$E_{\nu_\mu} = \frac{m_n E_\mu - m_\mu^2/2}{m_n - E_\mu + p_\mu \cos\theta_\mu}$$



Inverted hierarchy results

- Nu_e appearance:

$$\sin^2 2\theta_{13} = 0.170^{+0.045}_{-0.037}$$

- Nu_mu disappearance:

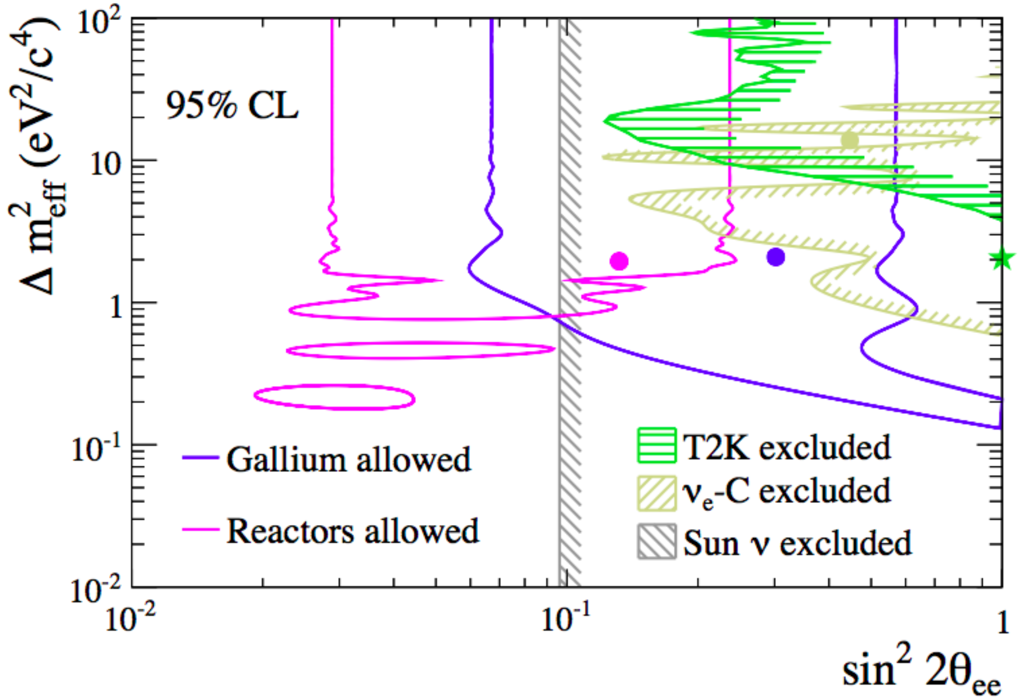
$$\sin^2 \theta_{23} = 0.511^{+0.055}_{-0.055}$$

Short-baseline oscillations

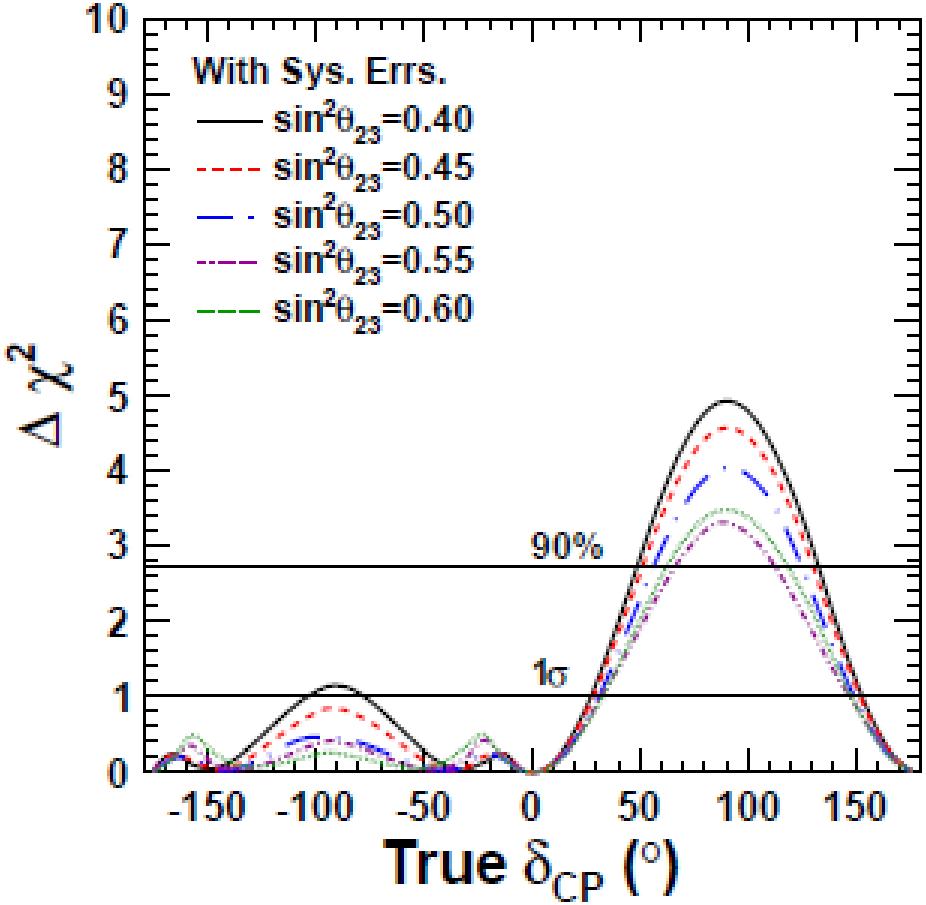
- Look for nue disappearance (oscillations into sterile neutrino in 3+1 model):

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2 (1.27 \frac{\Delta m_{ee}^2 L}{E})$$

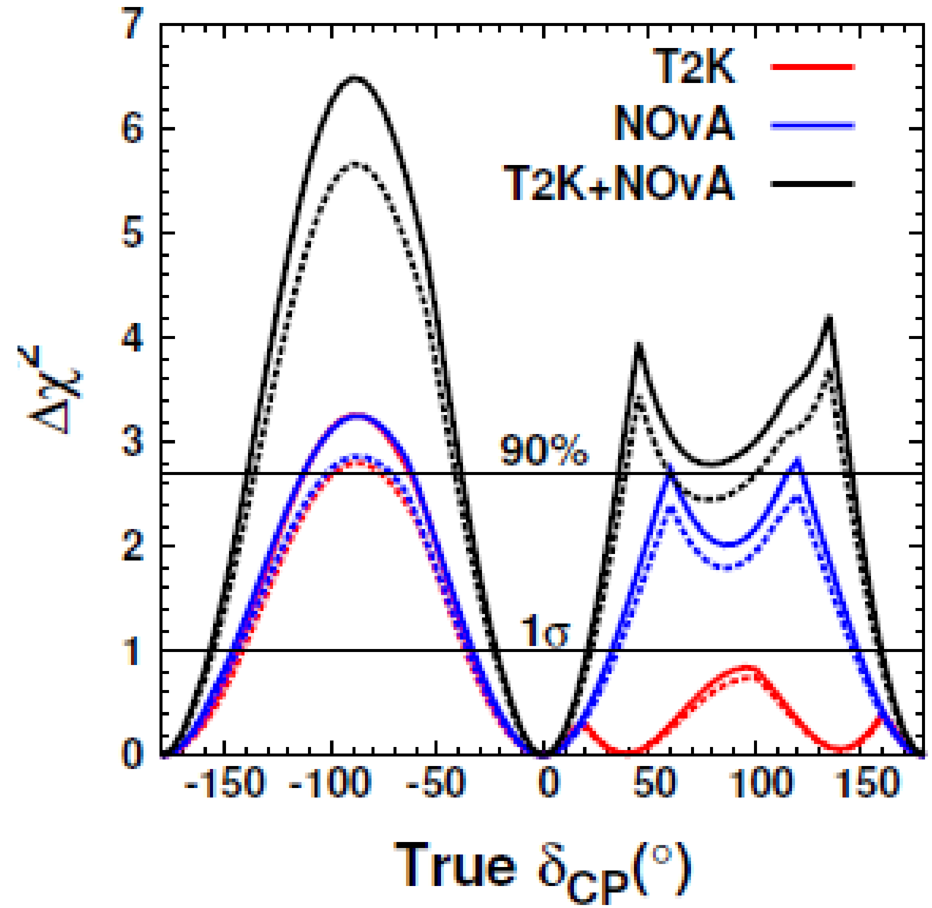
- Short baseline (280 m)
- Selected nue interactions in ND280 tracker
- Assumed no numu disappearance at short baseline



Future sensitivity ($\sin\delta_{CP}=0$ hypothesis)



(d) 50% ν-, 50% $\bar{\nu}$-mode, with the 2012 systematic errors.



(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH