

Новые результаты эксперимента T2K

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Outline

- neutrino oscillations
- T2K experiment
- ν_e appearance
- ν_μ disappearance
- summary

Neutrino mixing and oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix

$$\begin{array}{c} \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{array} \right) \quad \left(\begin{array}{cccc} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} & 0 \end{array} \right) \quad \left(\begin{array}{cccc} \cos \theta_{12} & \sin \theta_{12} & 0 & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{array} \right) \\ \text{atmospheric} \qquad \text{link between atmospheric and solar} \qquad \text{solar} \end{array}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$\Delta m_{12}^2 + \Delta m_{32}^2 + \Delta m_{31}^2 = 0$$

Only two independent

$$\Delta m_{12}^2 = \Delta m_{sol}^2 = 7 * 10^{-5} \text{ eV}^2$$

$$(\Delta m_{32}^2) = (\Delta m_{atm}^2) = 2.4 * 10^{-3} \text{ eV}^2$$

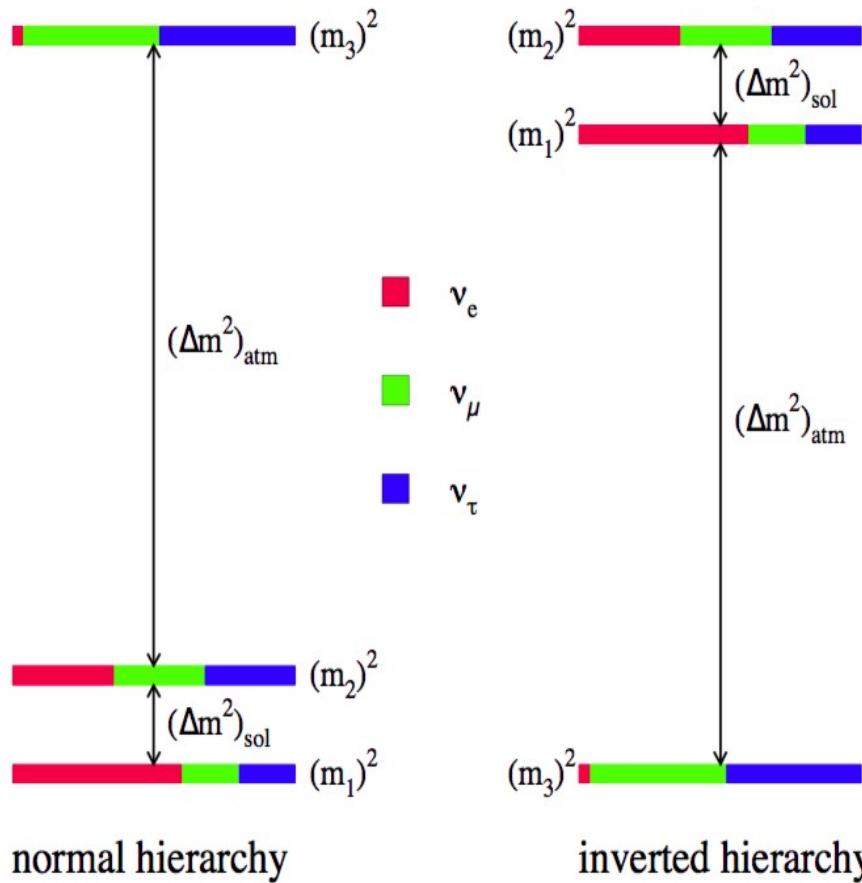
Mass Hierarchy ?

$$\begin{aligned} \theta_{23} &\approx 45^\circ \\ \theta_{13} &= (9 \pm 0.6)^\circ \\ \theta_{12} &= (34 \pm 1)^\circ \\ \delta - ? \end{aligned}$$

Physics motivation



Mass Hierarchy



CP violation

The difference between oscillations of neutrinos and anti-neutrinos ?

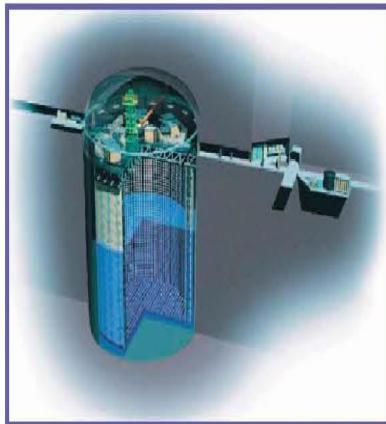
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L \sin 2\theta_{12}}{4E_\nu \sin \theta_{13}} \sin \delta$$

?

Long-Baseline Neutrino Oscillation Experiment

Main Goals:

- measurement θ_{13} (appearance)
- precision measurement of θ_{23} and Δm^2_{32} (disappearance)
- search for CP violation in neutrino oscillations



J-PARC Main Ring
(KEK-JAEA, Tokai)

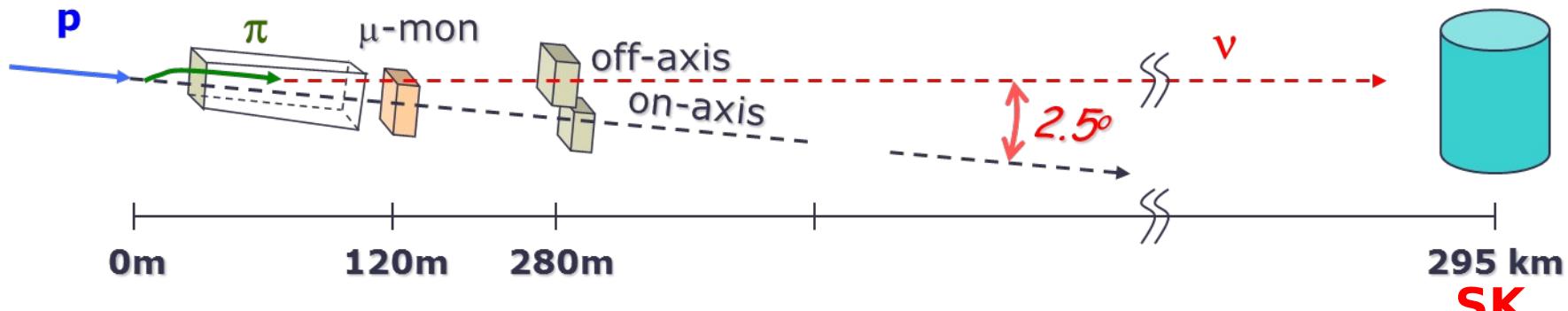
Super-Kamiokande
(ICRR, Univ. Tokyo)

~ 500 members
59 institutions
11 countries

Russia: INR RAS

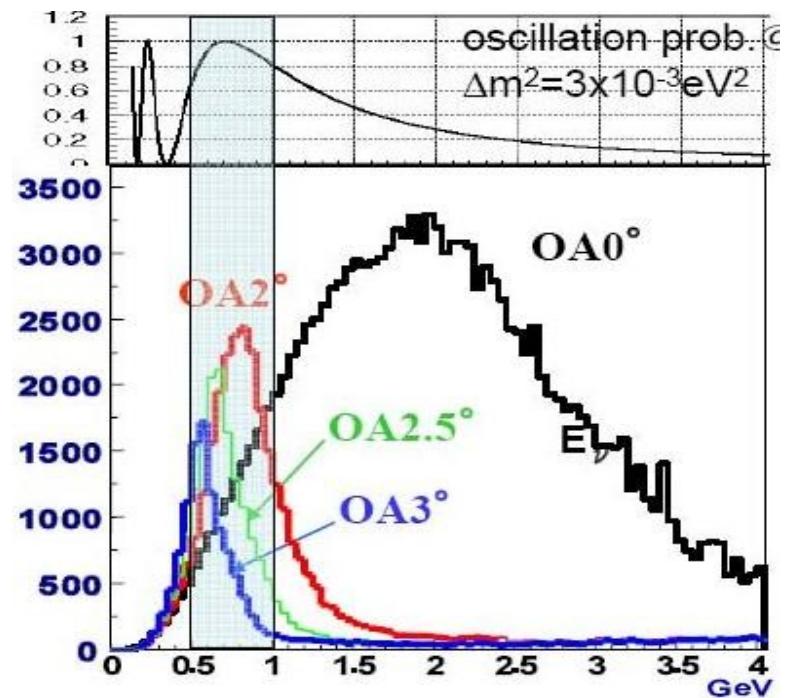


T2K experiment



J-PARC

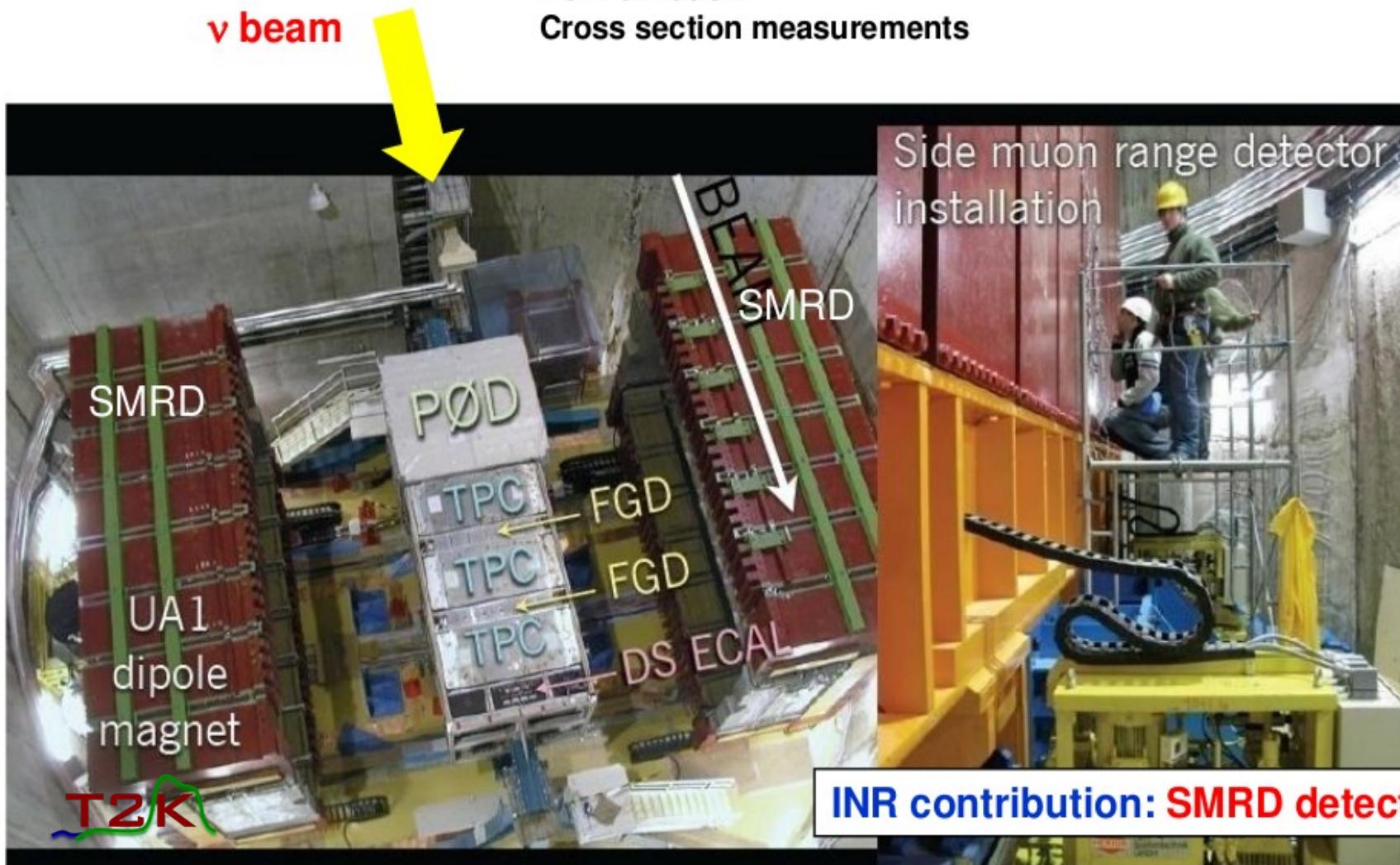
- 750 (now 235) kW 30 GeV proton beam at J-PARC
- Quasi-monochromatic ν_μ (95% purity) beam
- Peak energy \sim 600 MeV tuned to oscillation maximum
- \sim 0.5% ν_e at peak energy
- Reduced high energy tail reduces background



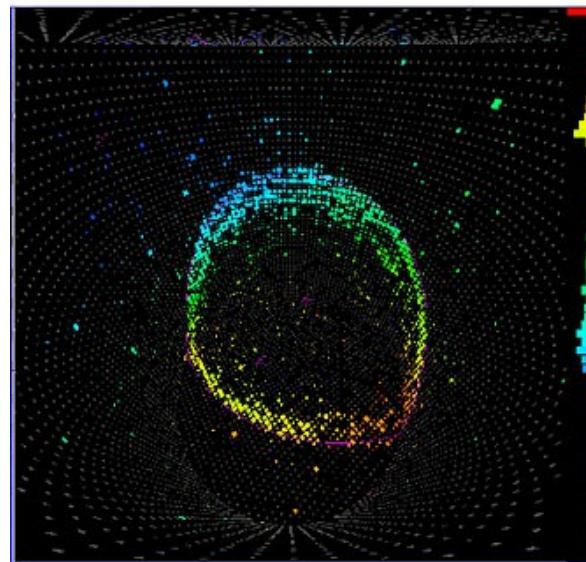
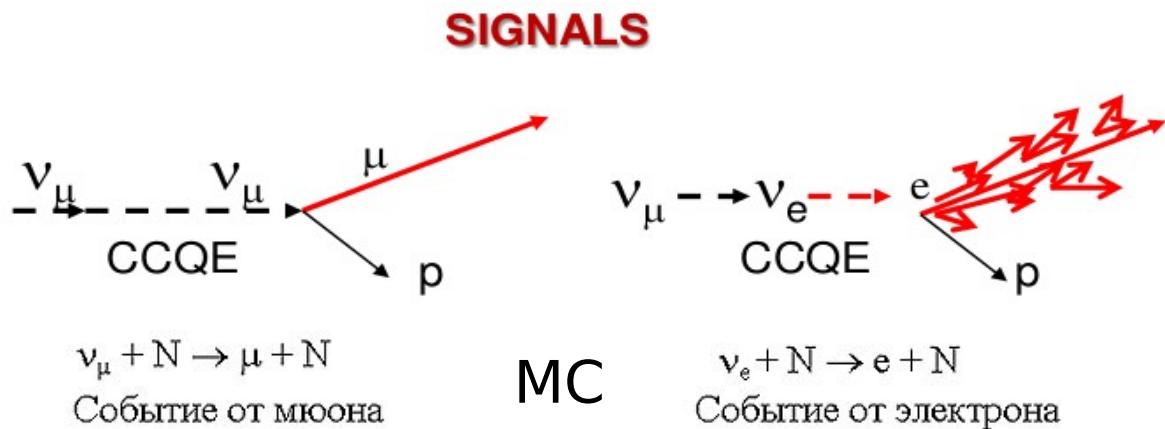
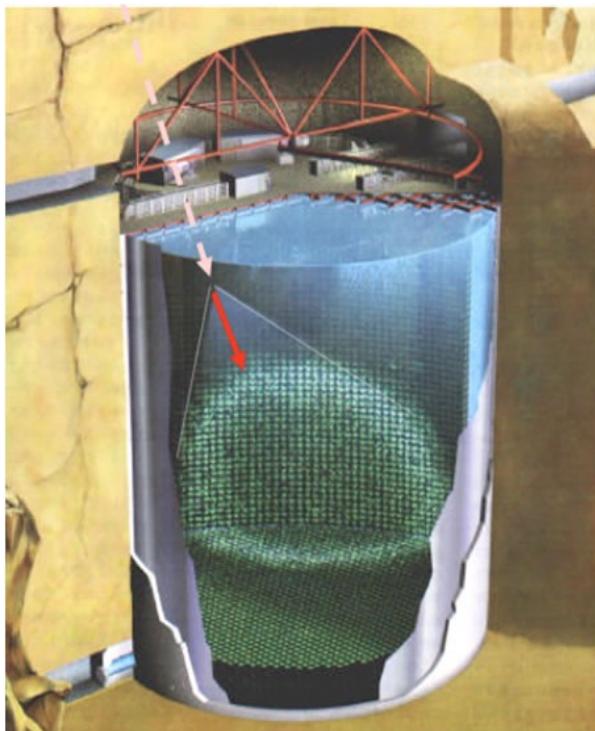
Off-Axis Near Detector



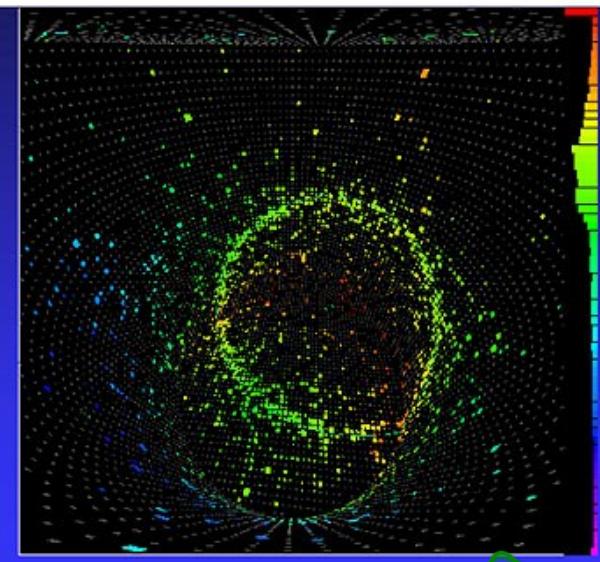
Measurement of unoscillated ν beam
Composition
Normalization
Cross section measurements



Far detector SuperK



μ -like ring



e-like ring T2K

Selection criteria for Nue

T2K

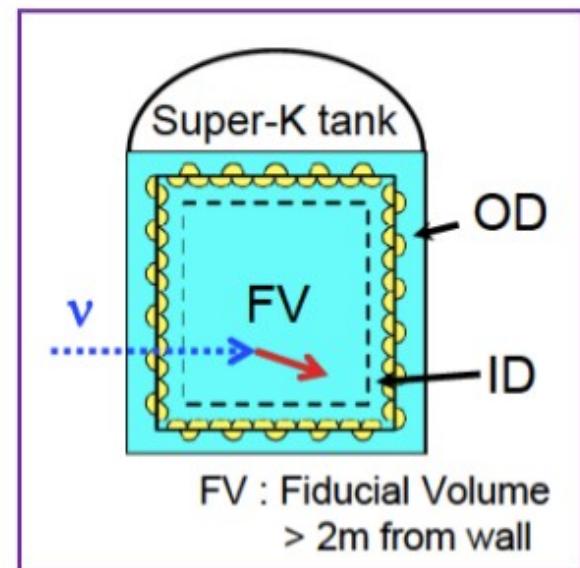
Analysis of the T2K data accumulated for 6.39×10^{20} POT (Run 1-4)

- ▶ Event time compatible with expected arrival time
- ▶ Fully contained in the fiducial volume (>2m from the wall)

ν_e events

Fully-contained events with:

- 1 electron-like ring
- Visible energy > 100 MeV
- No decay electron
- Invariant mass not consistent with π^0
- $100 \text{ MeV} < \text{Energy} < 1250 \text{ MeV}$



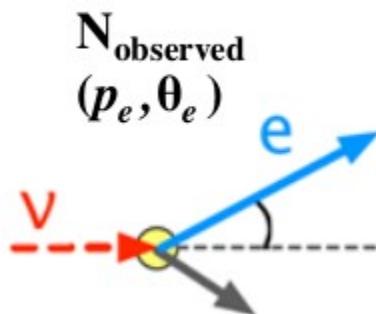
after all cuts
28 Nue candidates

Expect 4.64 ± 0.53
events

Nue appearance

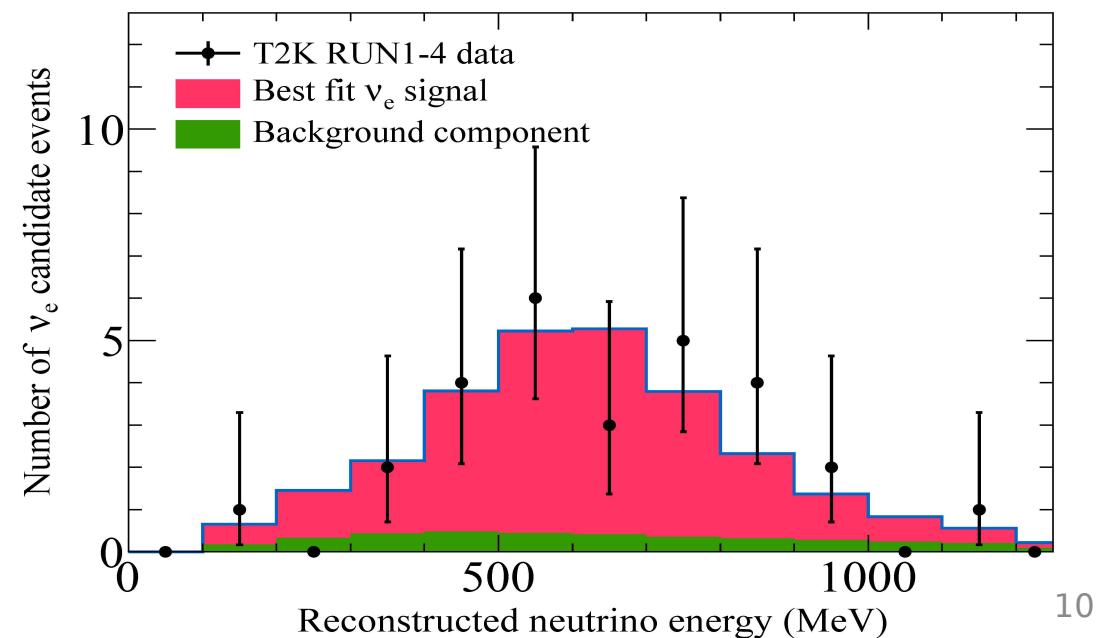
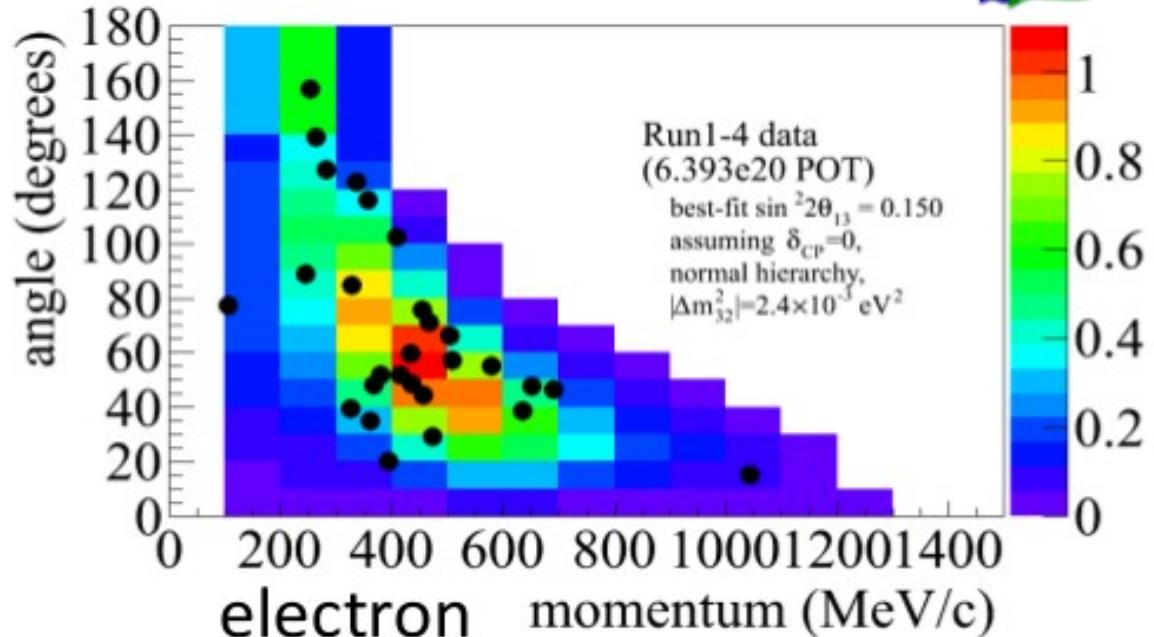
T2K

1st method:

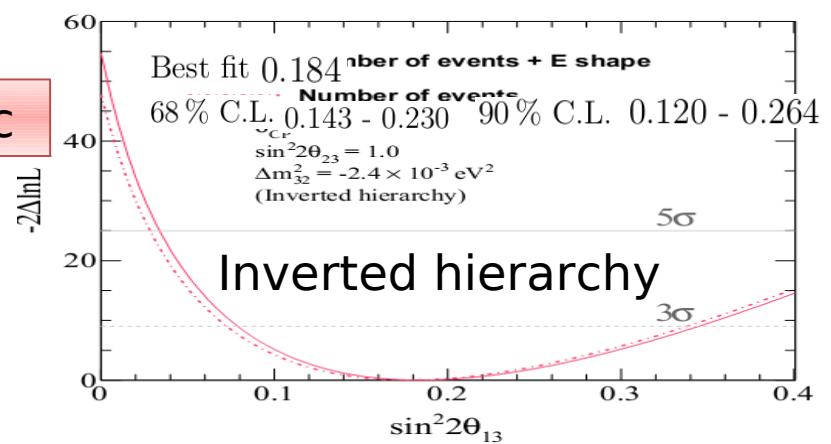
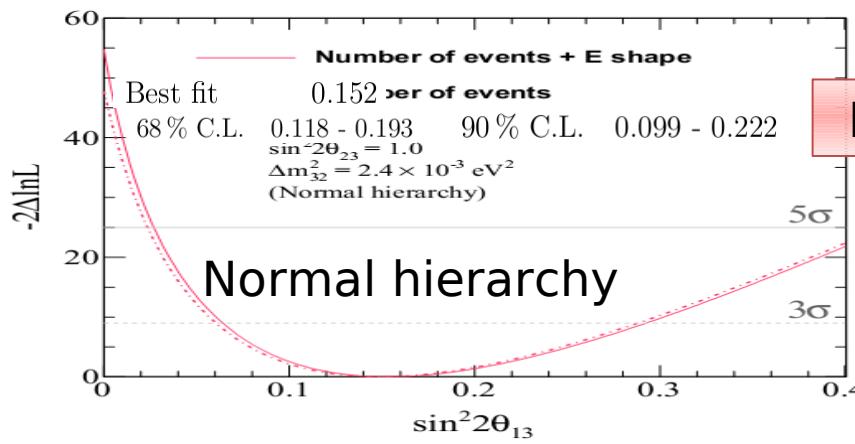
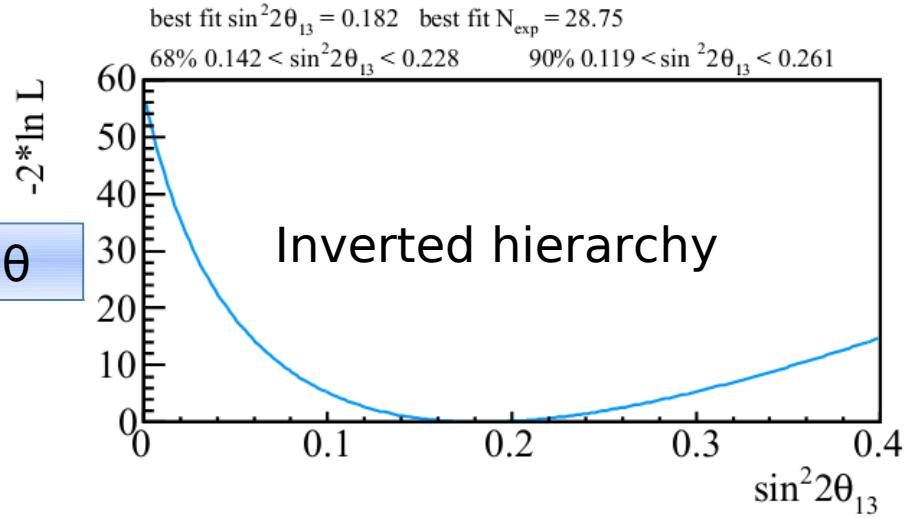
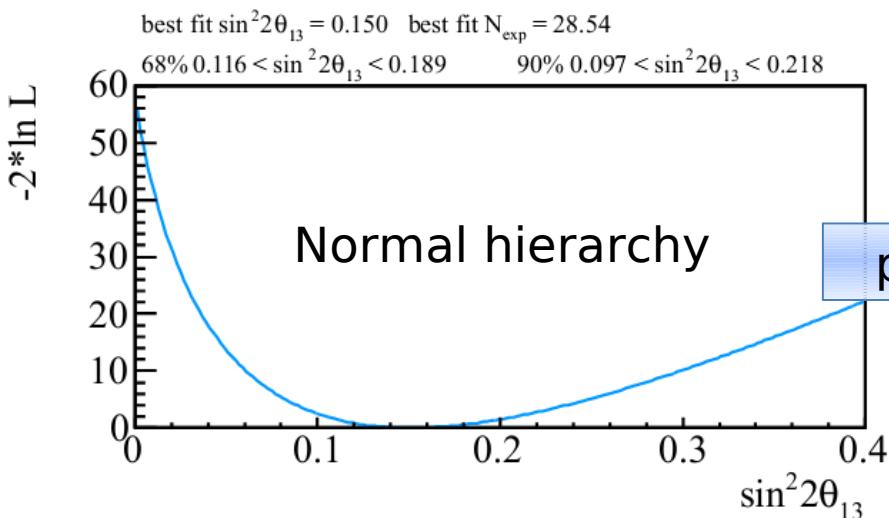


2nd method:

N_{observed}
 E_v reconstructed
shape (1d)



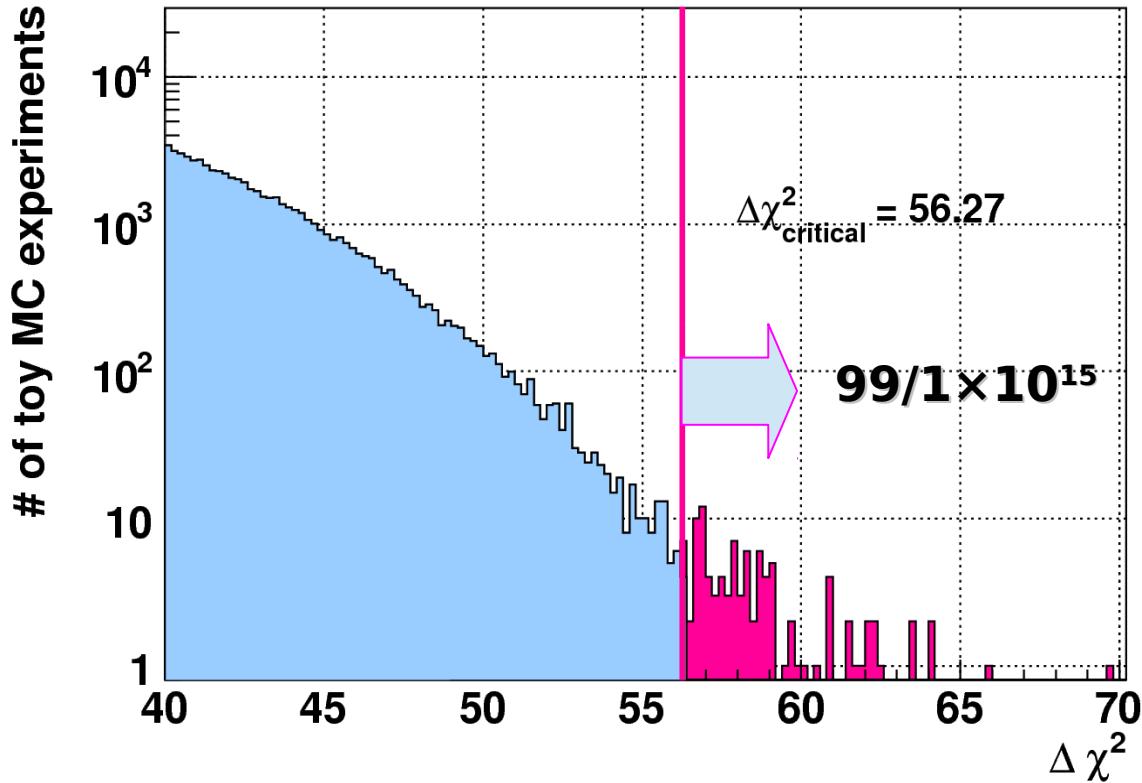
Likelihood curves



significance is calculated as $\sqrt{\Delta\chi^2}$

$$\begin{aligned}\sqrt{-2\Delta\ln L} &= \sqrt{56.27} \\ &= 7.5\sigma\end{aligned}$$

p-value calculation



$$\text{p-value} = 9.9 \times 10^{-14}$$

p-value is calculated as followings:

1. Generate $1e15$ ($5.5e14$ for Erec) toy experiments with $\theta_{13}=0.0$.
2. Fit each toy experiment to extract $-2\Delta\ln L (= \Delta\chi^2)$.
3. p-value is the fraction of toy experiments above $\Delta\chi^2_{\text{data}}$

Result: θ_{13} vs δ



allowed region of $\sin^2 2\theta_{13}$
for each value of δ_{CP}

Best fit for $\delta_{CP}=0$

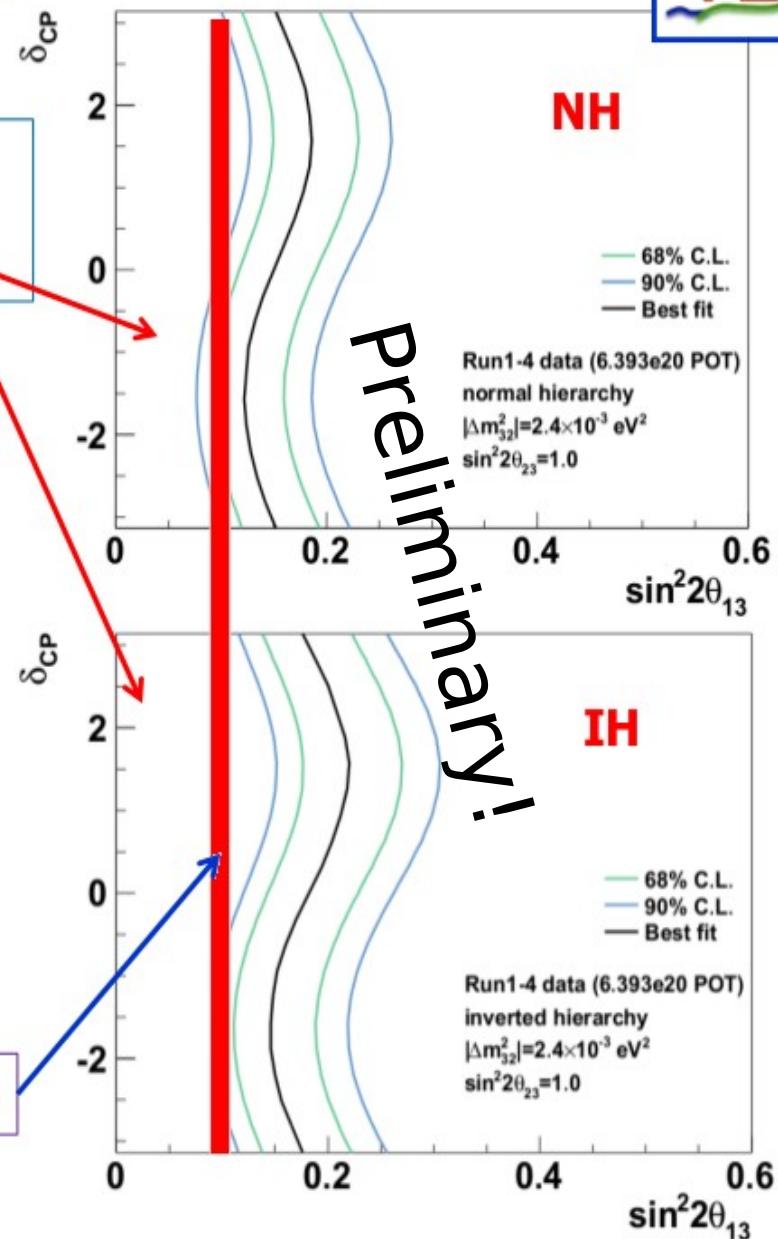
NH

$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

IH

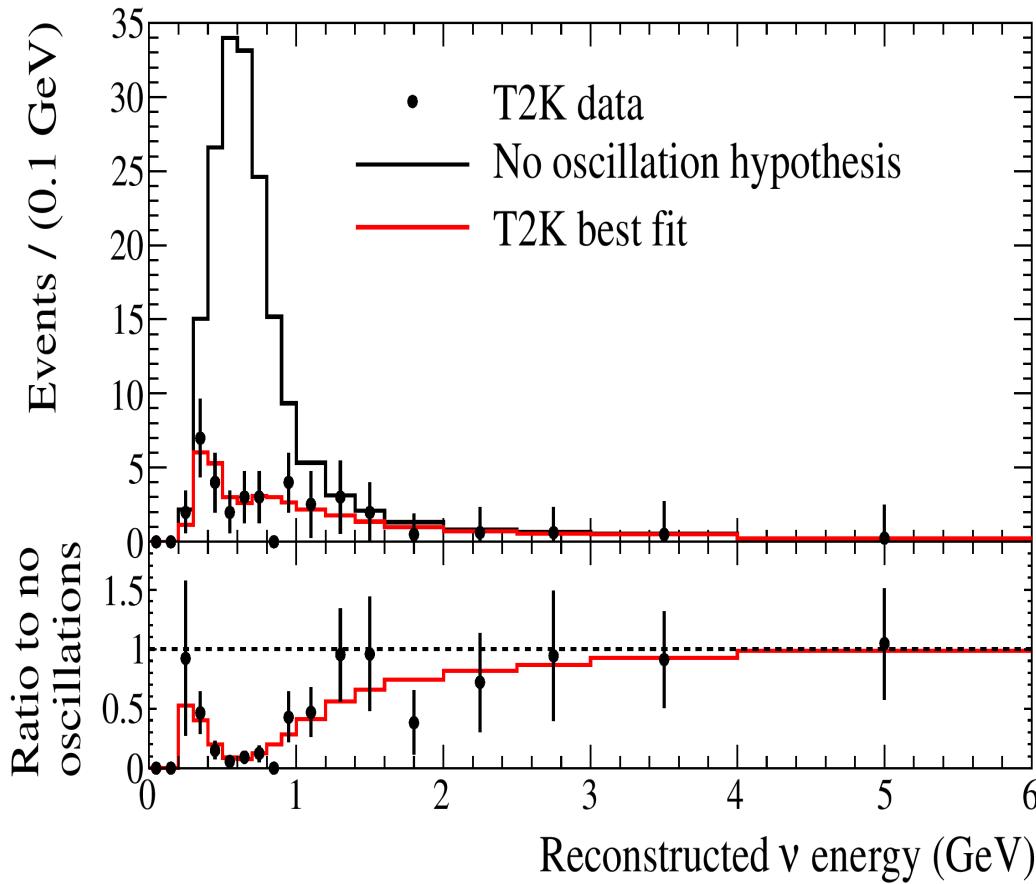
$$\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$$

PDG(2012): $\sin^2 2\theta_{13} : 0.098 \pm 0.013$



$\nu_\mu \rightarrow \nu_\mu$ Disappearance

3×10^{20} POT

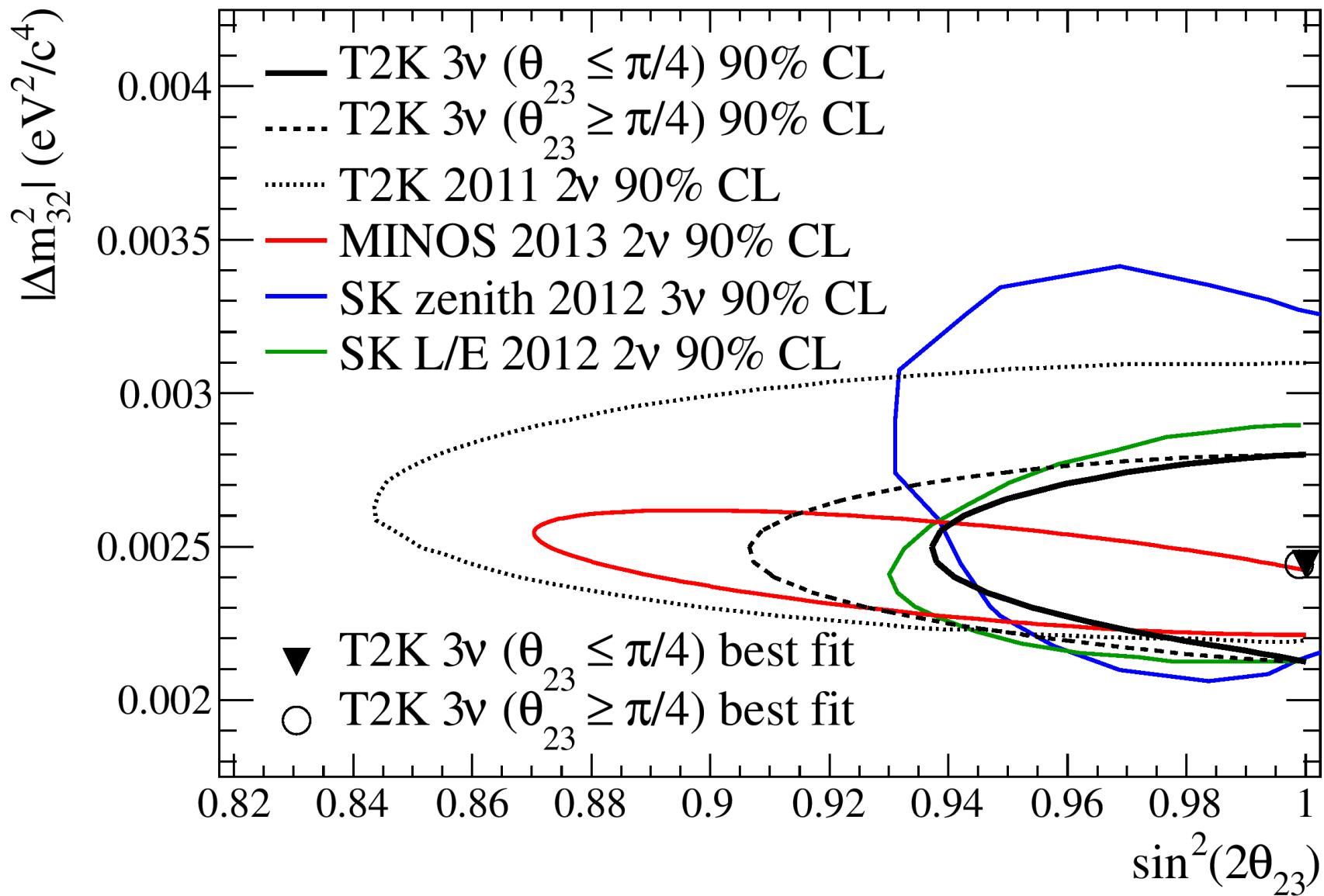


205 ± 17 (syst.) events are expected
 58 muon neutrino event candidates are observed

SK Selection Cuts

- $E_{\text{vis}} > 100$ MeV
- Veto hits < 16
- Fully contained
(Fid. Vol. = 200 cm)
- Single ring
- Muon-like
- $P_{\mu} > 200$ MeV
- 0 or 1 Michel electron

ν_μ disappearance



Conclusion

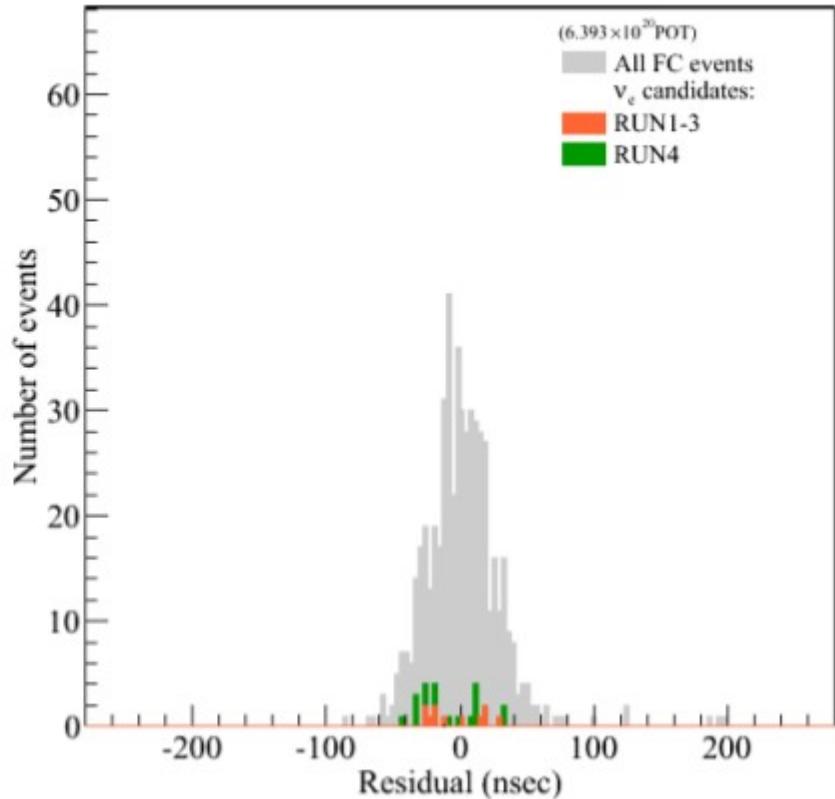
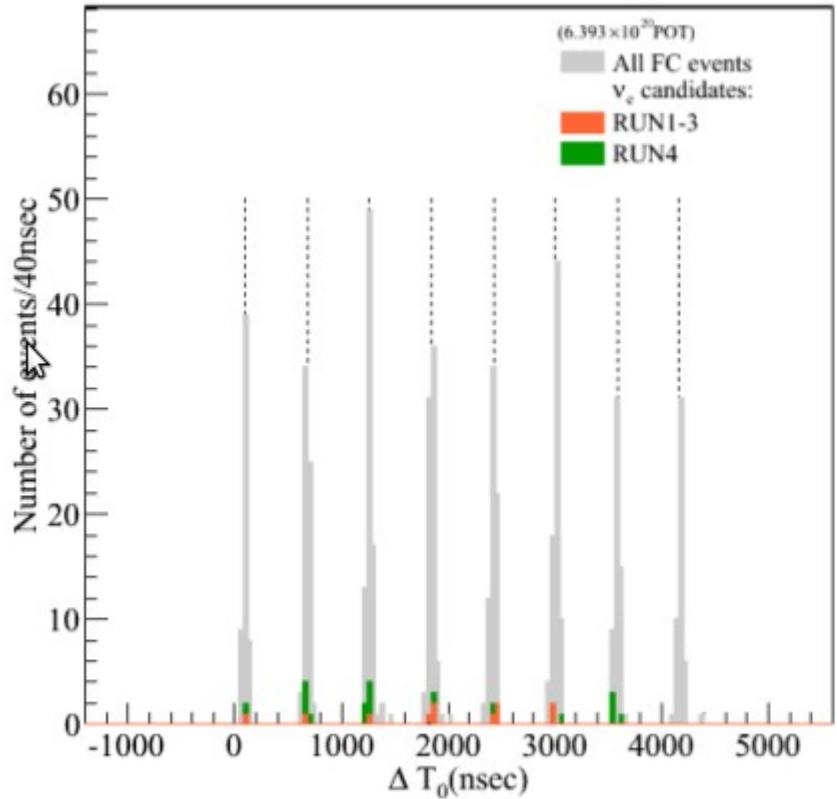


- T2K **discovers** $\nu_\mu \rightarrow \nu_e$ oscillations at 7.5σ significance
- precision measurements of neutrino mixing parameters in $\nu_\mu \rightarrow \nu_\mu$

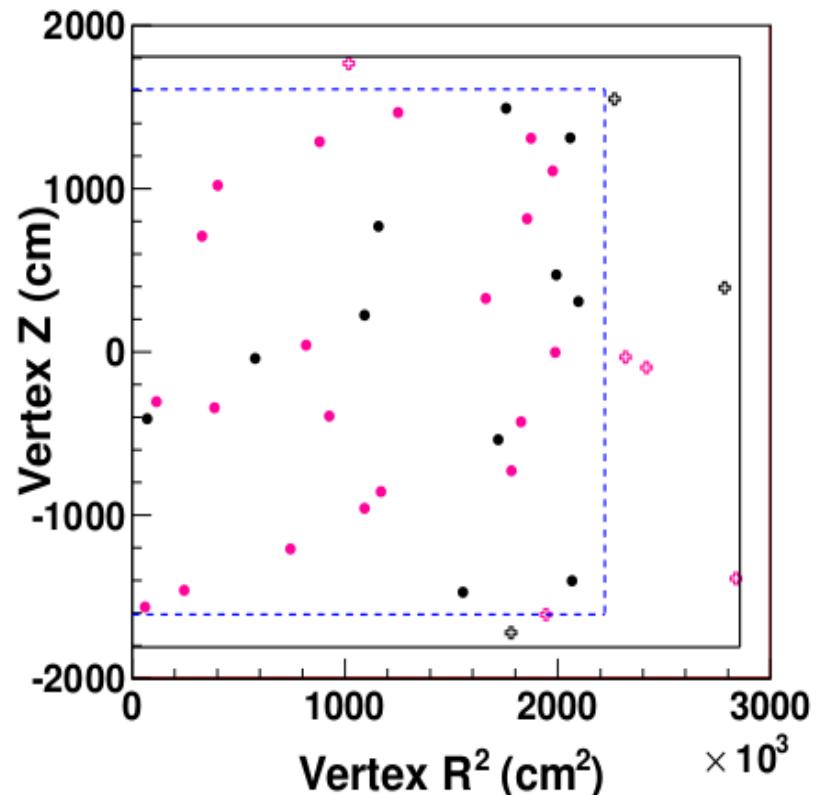
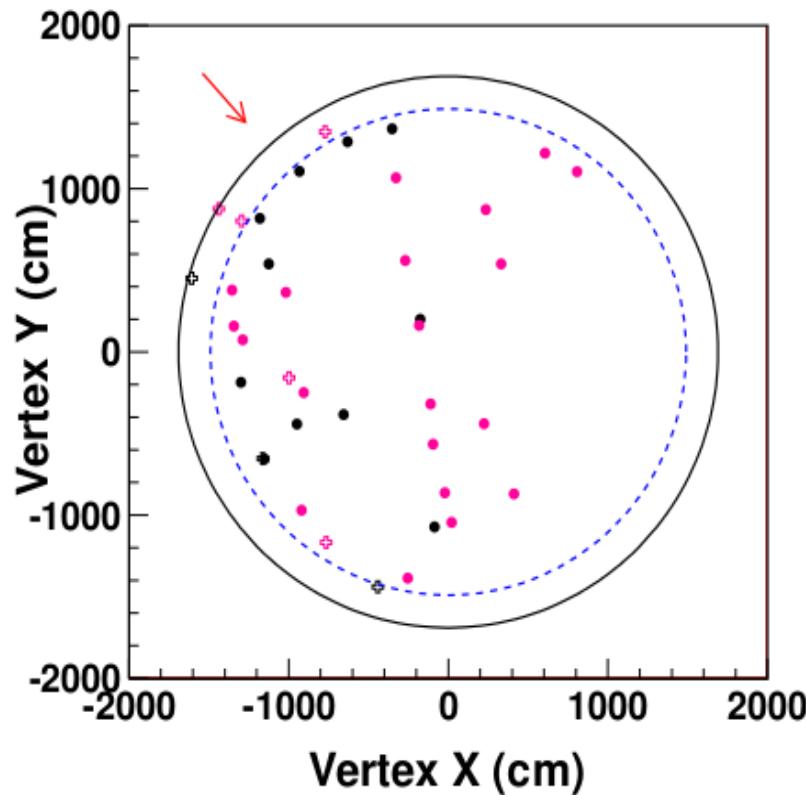
Near future:

- Antineutrino run in 2014
- Combined data with reactor experiments and NOvA for CPV and Mass Hierarchy

Backup Slides



Vertex distributions



Run 1-3 black
Run 4 red