Recent accelerator long baseline neutrino oscillation results

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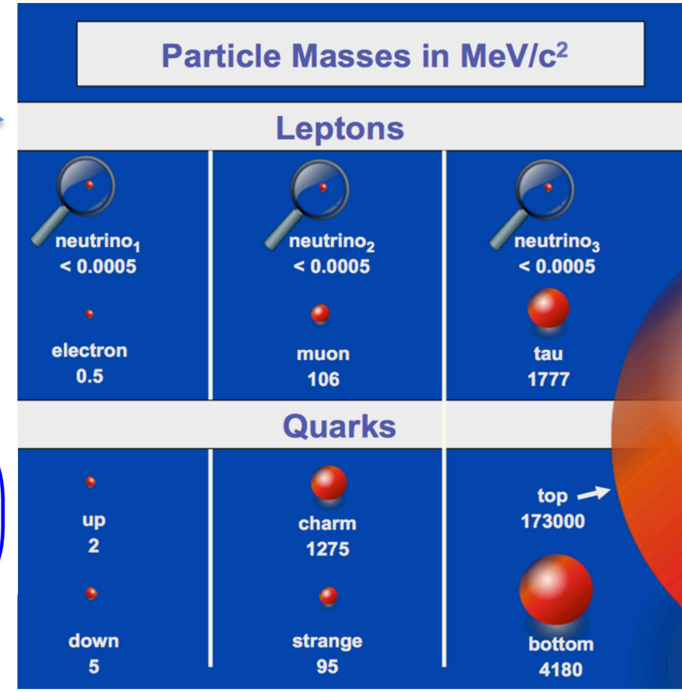
& the T2K Collaboration

1. Introduction
2. Recent T2K & MINOS results
3. Prospects for the next few years
4. Longer term future (10^{+} years)

Neutrino physics – a constant source of surprise & mystery!

Compared with the quarks and charged leptons, why are neutrino masses so small?



Neutrino mixing angles are generally much larger than quark mixing angles; large CP violation effects are **allowed** in the neutrino sector

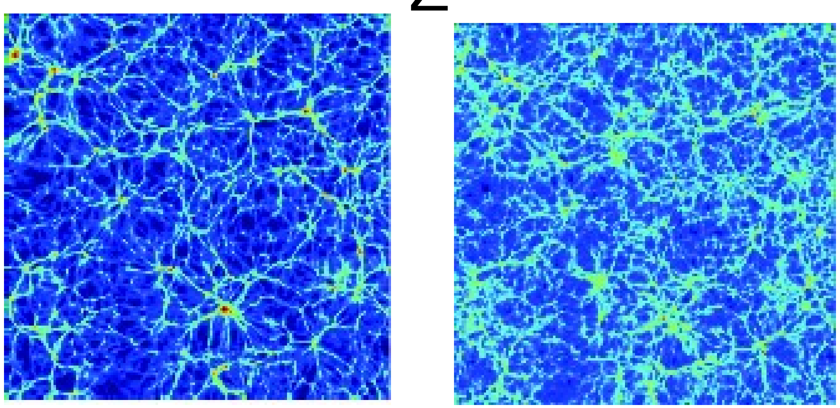
Quarks/CKM

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Neutrinos/PMNS

$$U_\ell = \begin{pmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$

massless ν $\sum$Mass=1.9eV/c^2



Baryon density

Agarwal, Feldman 2010

Neutrinos play a fundamental role in the evolution of the Universe

Can neutrinos explain the matter-antimatter asymmetry of the Universe? e.g. via CP violation and Leptogenesis

The 3 Neutrino Flavour Paradigm§

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

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

Flavour states

Mass states

$s_{ij}=\sin\theta_{ij}$

δ = CP violating phase

"Atmospheric" "Reactor" "Solar"

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Oscillation phenomena have been convincingly observed using solar, atmospheric, reactor and accelerator neutrinos, establishing the 3 neutrino flavour SM paradigm

(§ ignoring Majorana phases)

Neutrino Properties

Known:

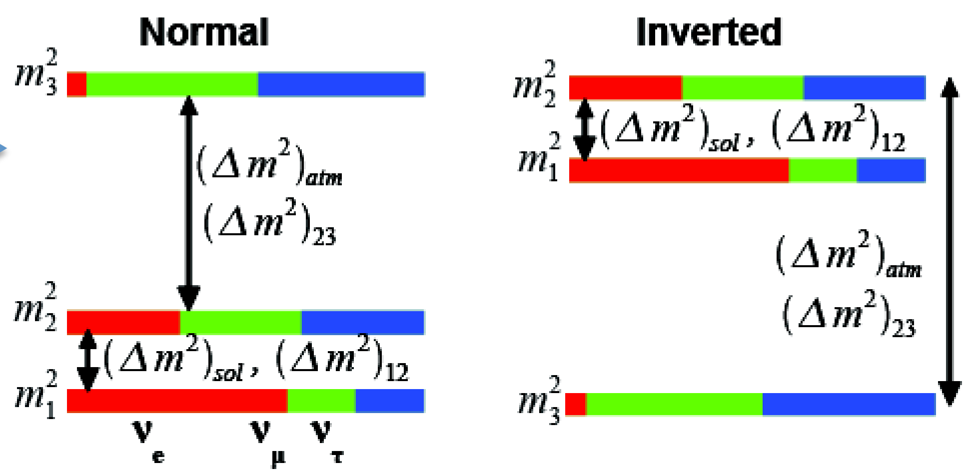
- have mass
- oscillate between flavours
- measured values for
  - $\theta_{12}, \theta_{23}, \theta_{13}$
  - $\Delta m_{21}{}^2, |\Delta m_{32}{}^2|$

Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}\ eV^2$	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}\ eV^2$	2.6
θ_{23}	42°	~10
θ_{13}	9°	8.5

Capozzi et al.
ArXiv:1312.2878
Talk by M. Tortola

Unknown:

- order of the mass states (hierarchy)
- absolute mass of the neutrino
- Is θ_{23} maximal (=45^0)? Or which octant?
- are there more than 3 neutrino types?
- Majorana or Dirac?
- the value of δ_{CP}



Neutrino Mass Hierarchy

Neutrino Oscillation Measurements at Accelerators

(in the absence of matter effects)

Muon neutrino disappearance

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2\frac{\Delta m^2_{31}L}{4E}$$

Survival probability

Electron neutrino appearance

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\underline{\sin^2 2\theta_{13}}\sin^2\frac{\Delta m^2_{31}L}{4E} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\underline{\sin\delta_{CP}} + (\text{CP even term, solar term, matter effect term})$$

Disappearance channel : sensitivity to θ_{23} and (subleading) to the octant

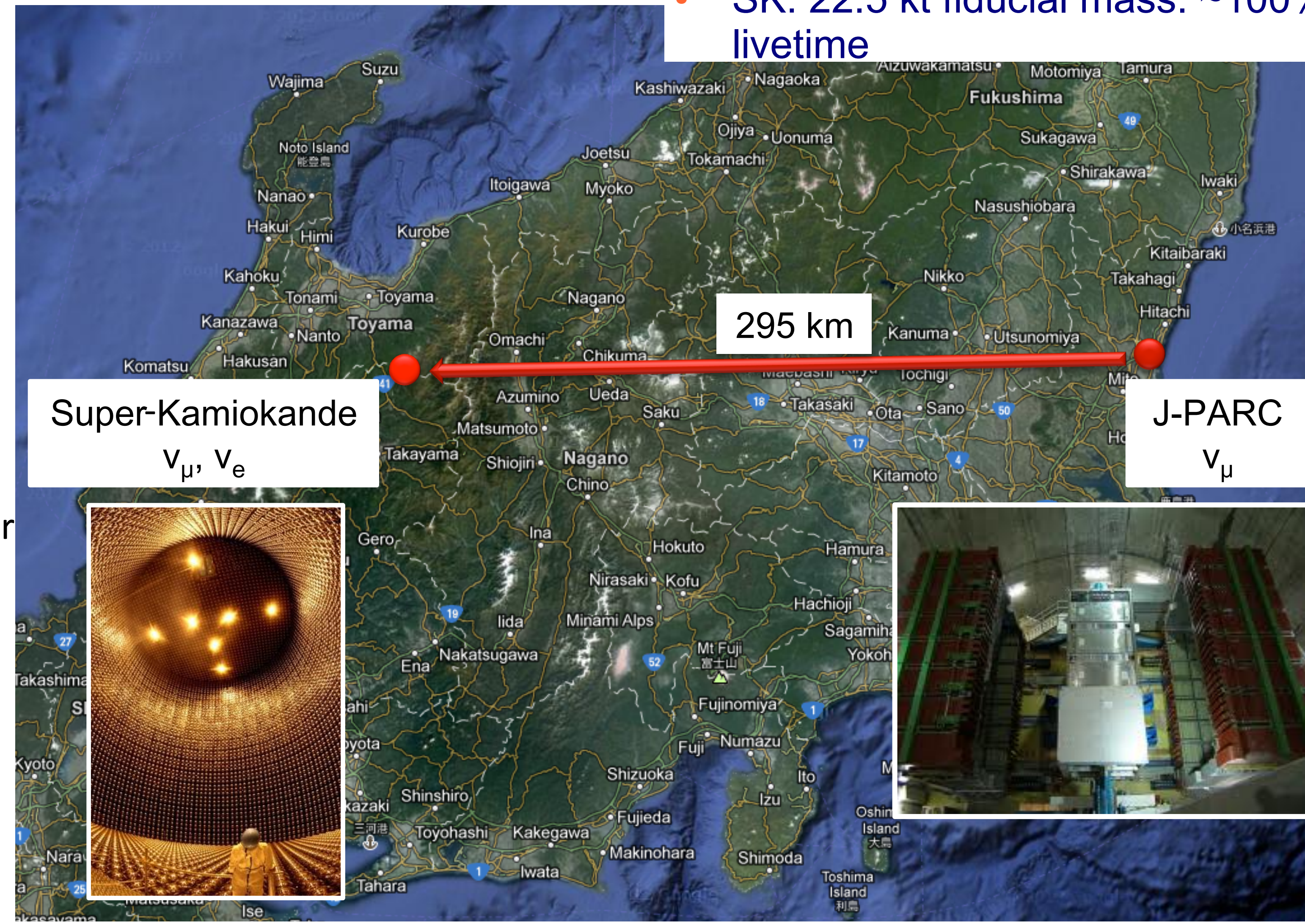
Appearance channel : sensitivity to θ_{13} and (subleading) to the CP phase

T2K experiment

T2K= **T**okai **to** **K**amioka

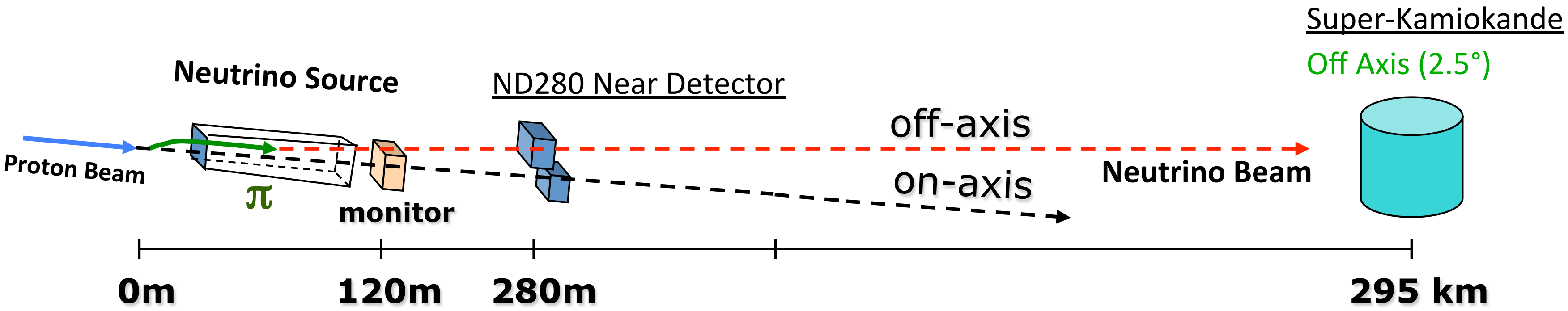
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 6.57 10^{20} Proton On Target (8% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

Far Detector

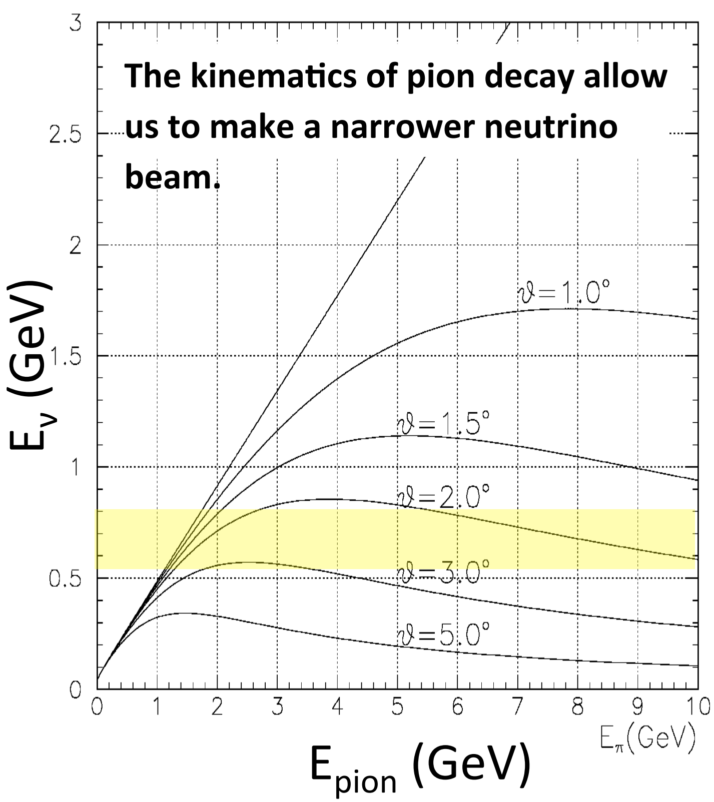


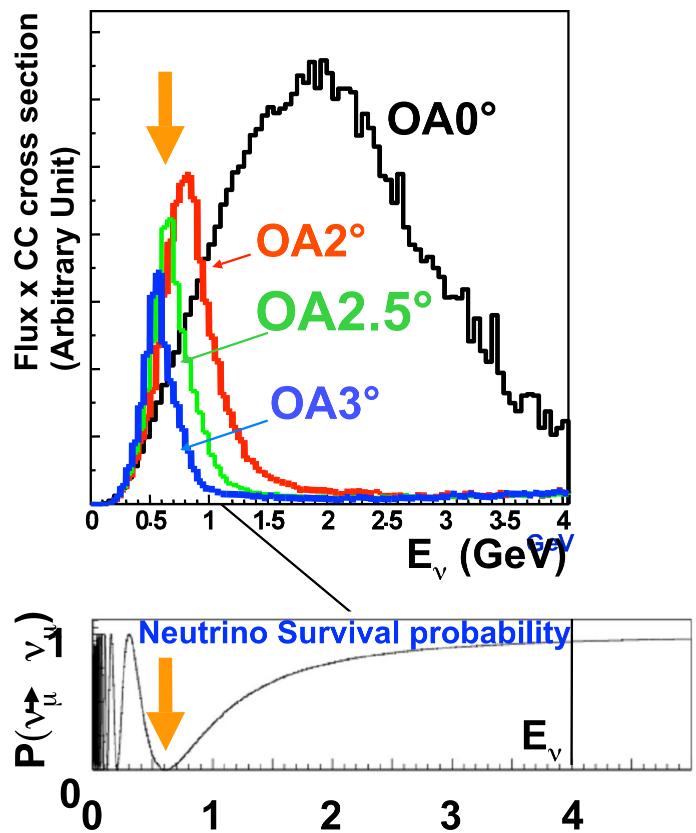
Near Detector

The T2K Off-Axis Beam



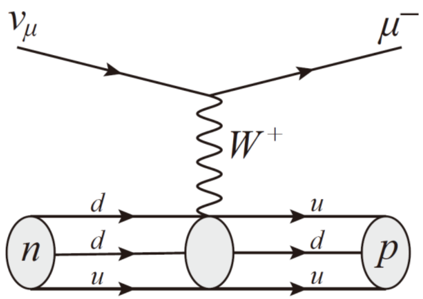
The kinematics of pion decay allow us to make a narrower neutrino beam.





T2K Muon Neutrino (ν_μ) Disappearance Measurement

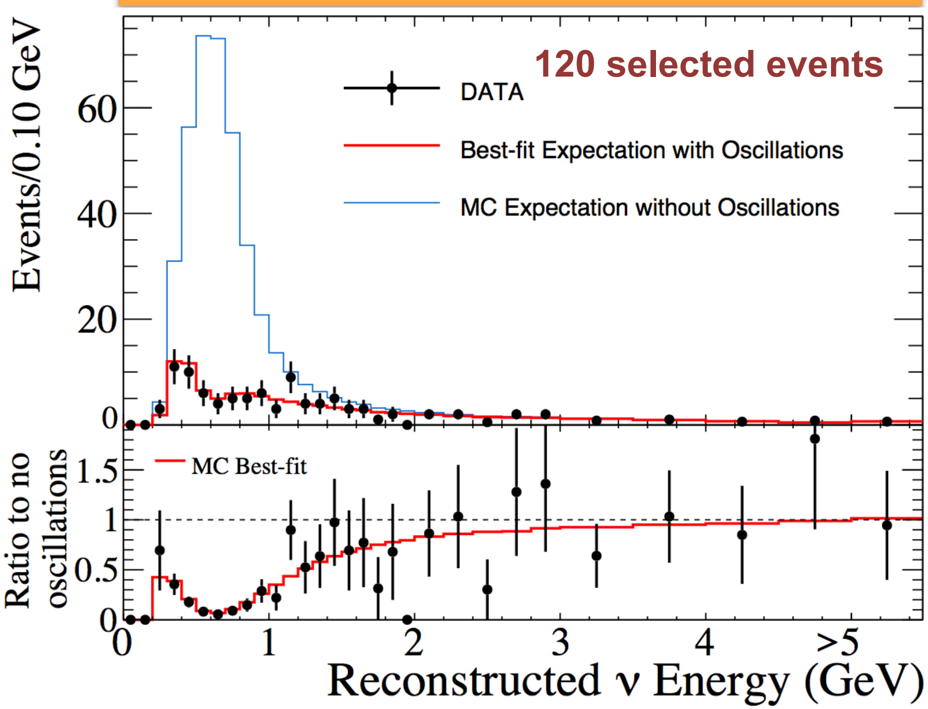
Phys. Rev. Lett. 112, 181801 (2014)



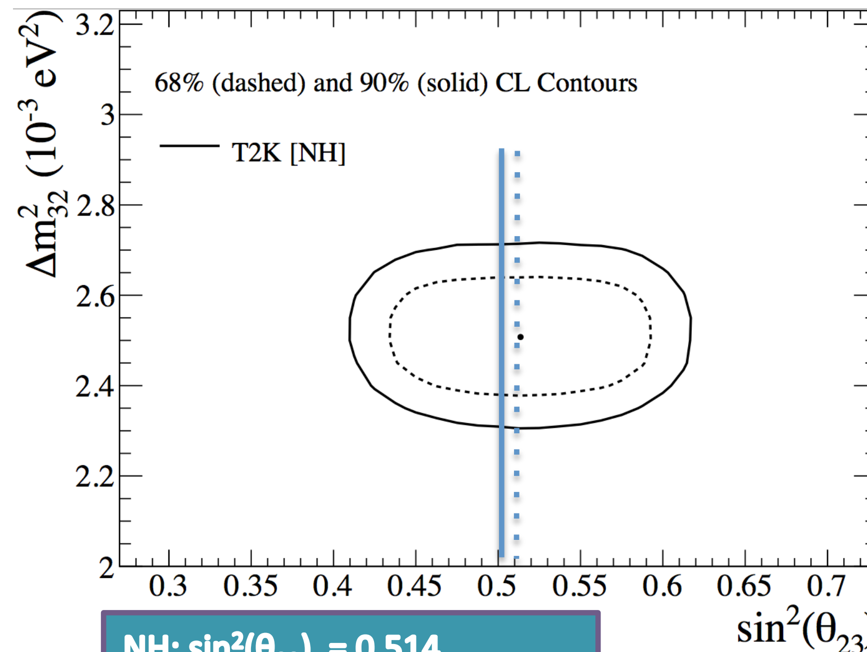
CCQE

Deficit of ν_μ CCQE events at Super-Kamiokande

Shows the power of the off-axis technique!



<u>Maximal mixing is not the same as maximum disappearance if θ_{13} is not zero!</u>

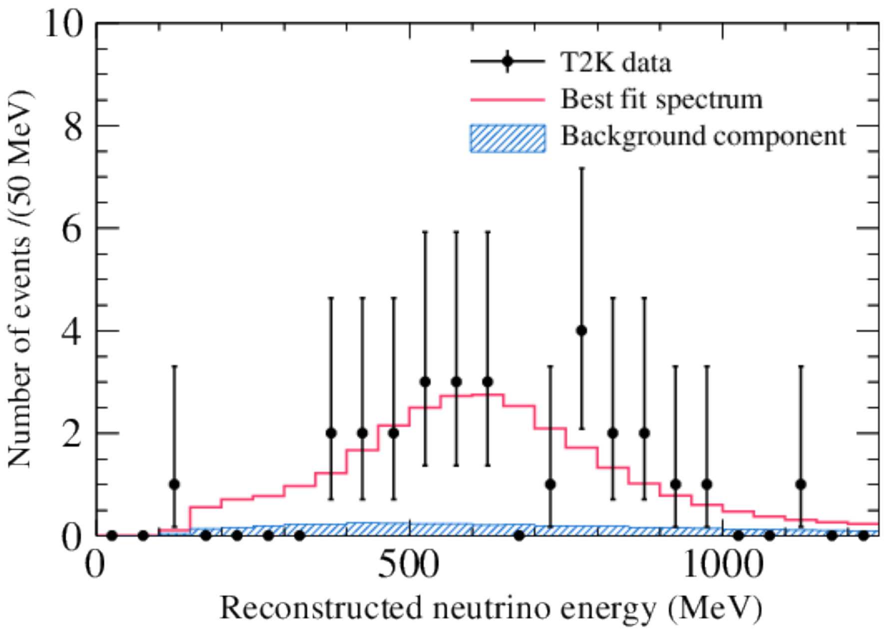


NH: $\sin^2(\theta_{23})$ = 0.514
NH: Δm^2_{32} = 2.51×10^{-3} eV^2

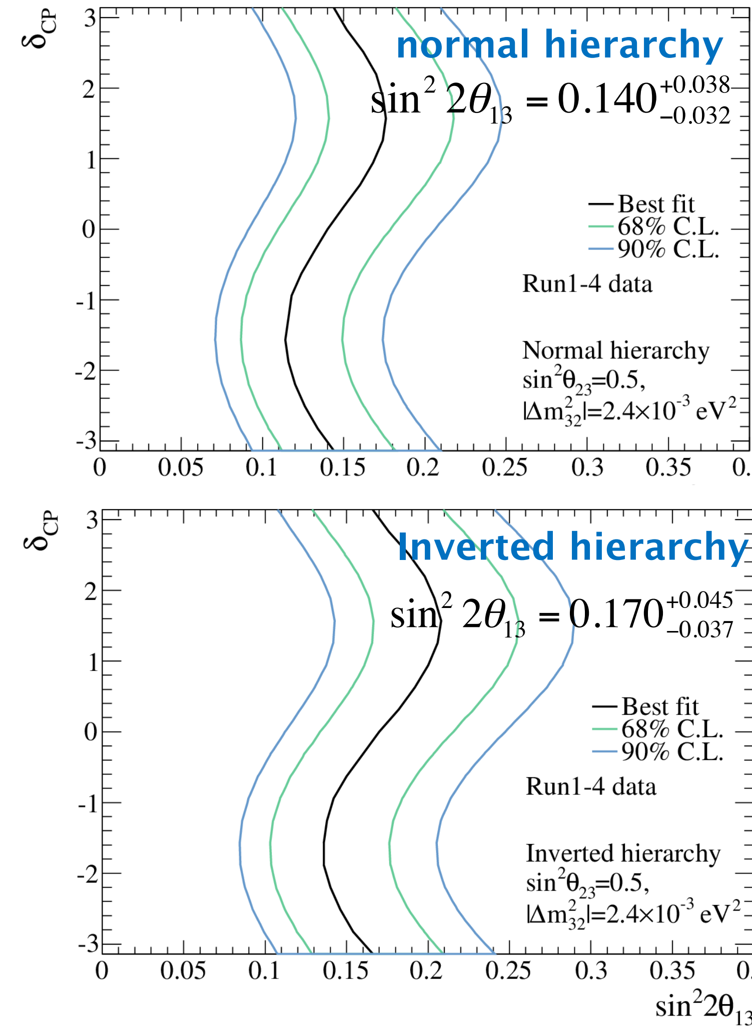
For θ_{13} given by reactor experiments

T2K Electron Neutrino (ν_e) Appearance Observation

ν_eCCQE @ Super-K



Phys. Rev. Lett. 112, 061802 (2014)



4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13}$= 0.1

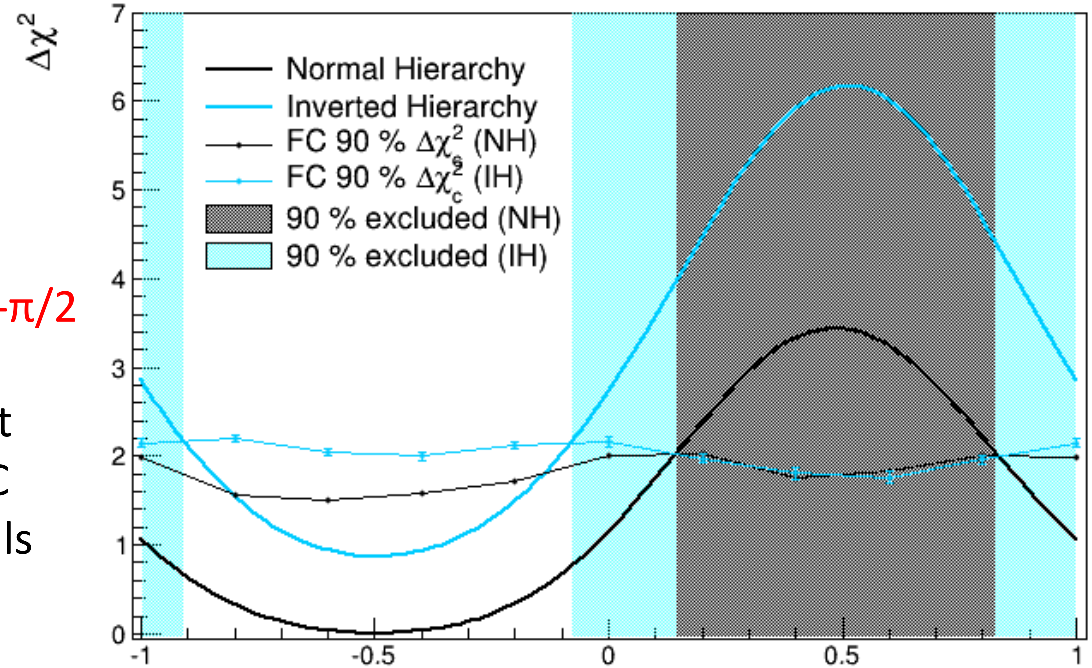
δ_{CP}= 0, $\sin^2\theta_{23}$= 0.5

7.3 σ significance for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel

T2K Joint ν_e + ν_μ Analysis : Constraints on δ_{CP}

PRELIMINARY



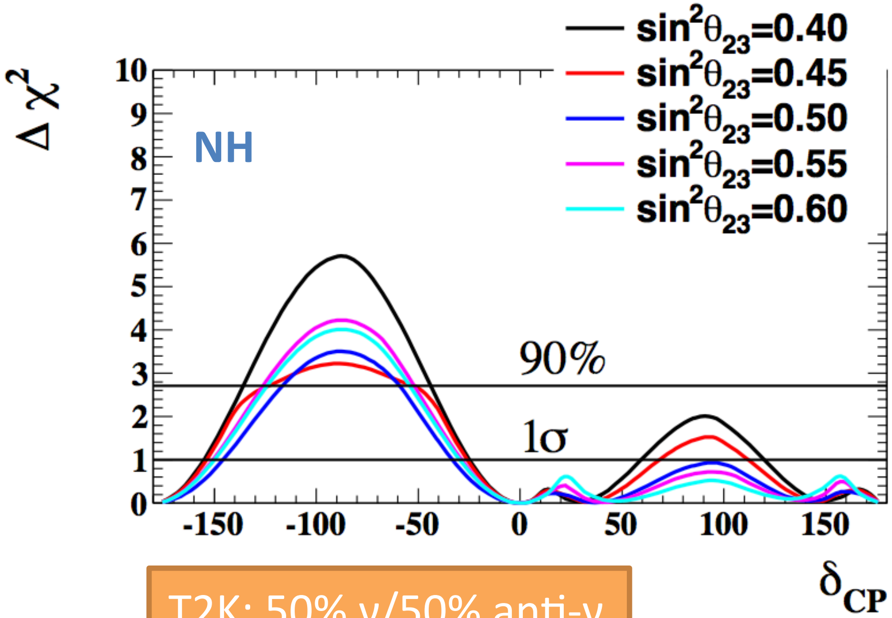
- Combined likelihood ratio fit to the ν_e and ν_μ CCQE samples
- Using PDG 2013 θ_{13} value,T2K finds a (slight) preference for $\delta_{CP} = -\pi/2$ and the Normal mass hierarchy
- Similar results from an independent T2K analysis using Markov chain MC producing Bayesian credible intervals

If Nature has chosen $\delta_{CP} \approx -\pi/2$, this will be very helpful experimentally AND this solution satisfies the leptogenesis bound with no additional CP violation

$$|\sin\theta_{13} \sin\delta_{CP}| \geq 0.11$$

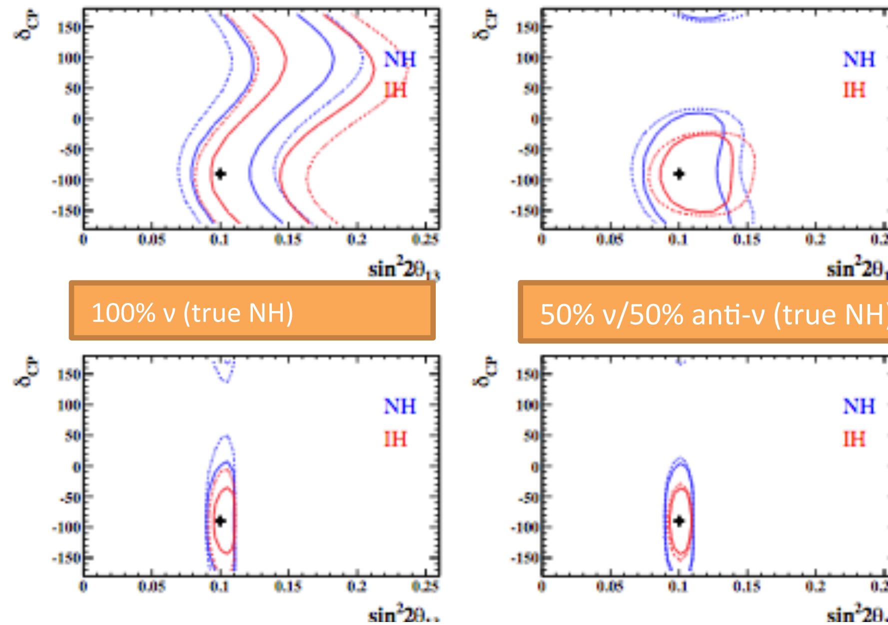
Pascoli, Petcov, Riotta 2007

Future Sensitivity to CPV using T2K



T2K: 50% ν/50% anti-ν

$Sin^2 2\theta_{13}=0.1$, $\delta_{CP}= -\pi/2$



100% ν (true NH)

50% ν/50% anti-ν (true NH)

100% ν (true NH)
w/ Reactor constraint

50% ν/50% anti-ν (true NH)
w/ Reactor constraint

No systematics

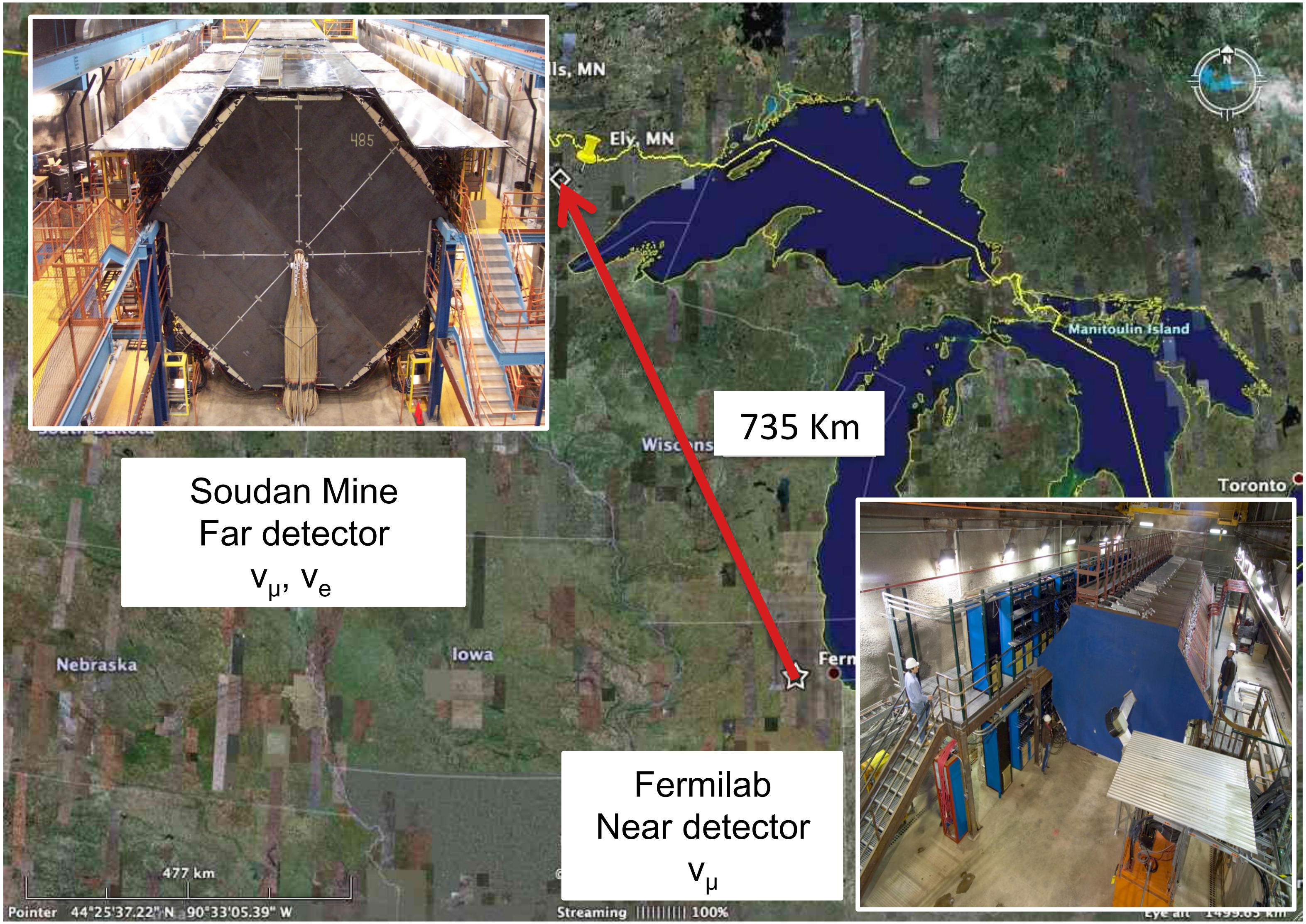
5% error on signal, 10% on background

T2K studies indicate our best sensitivity will be for 50% ν/50% anti-ν running. Anti-nu running also opens a large new physics program.

MINOS

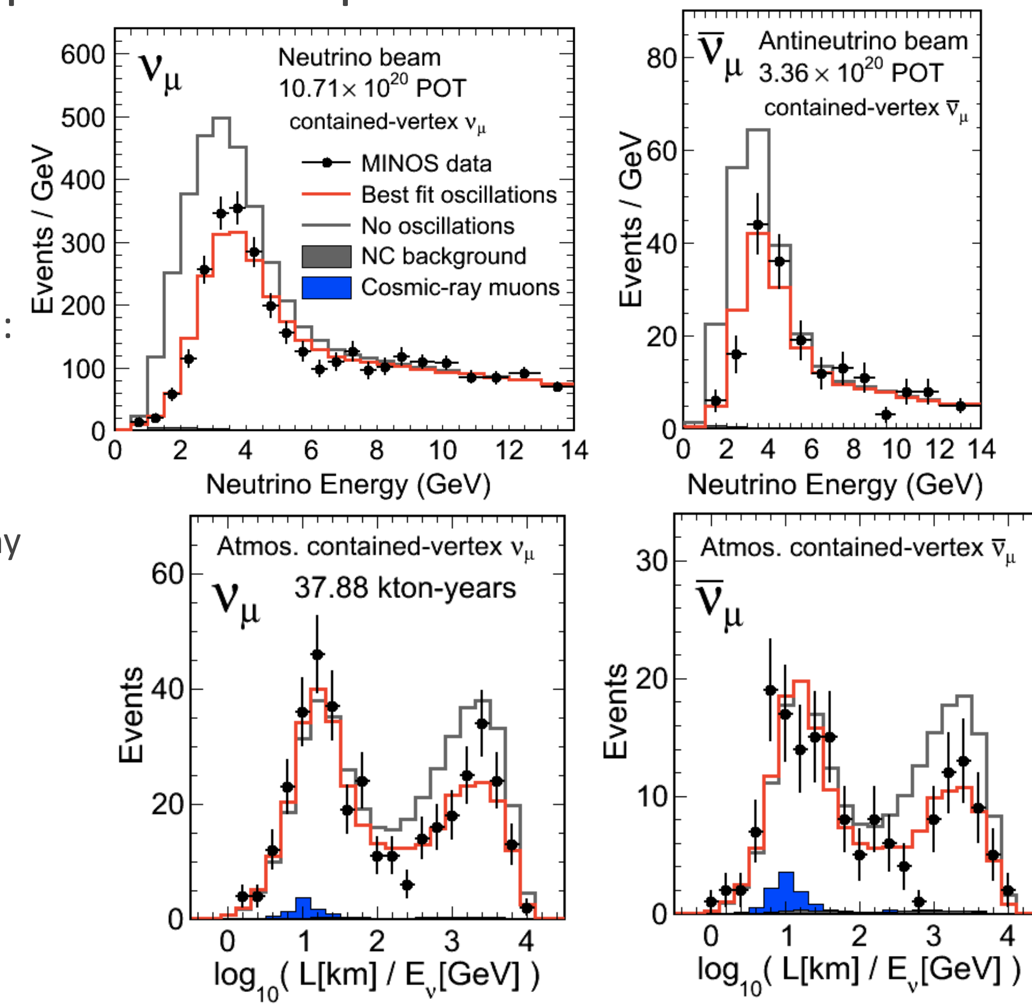
High energy on-axis beam

MINOS= **M**ain **I**njector **N**eutrino **O**scillation **S**earch



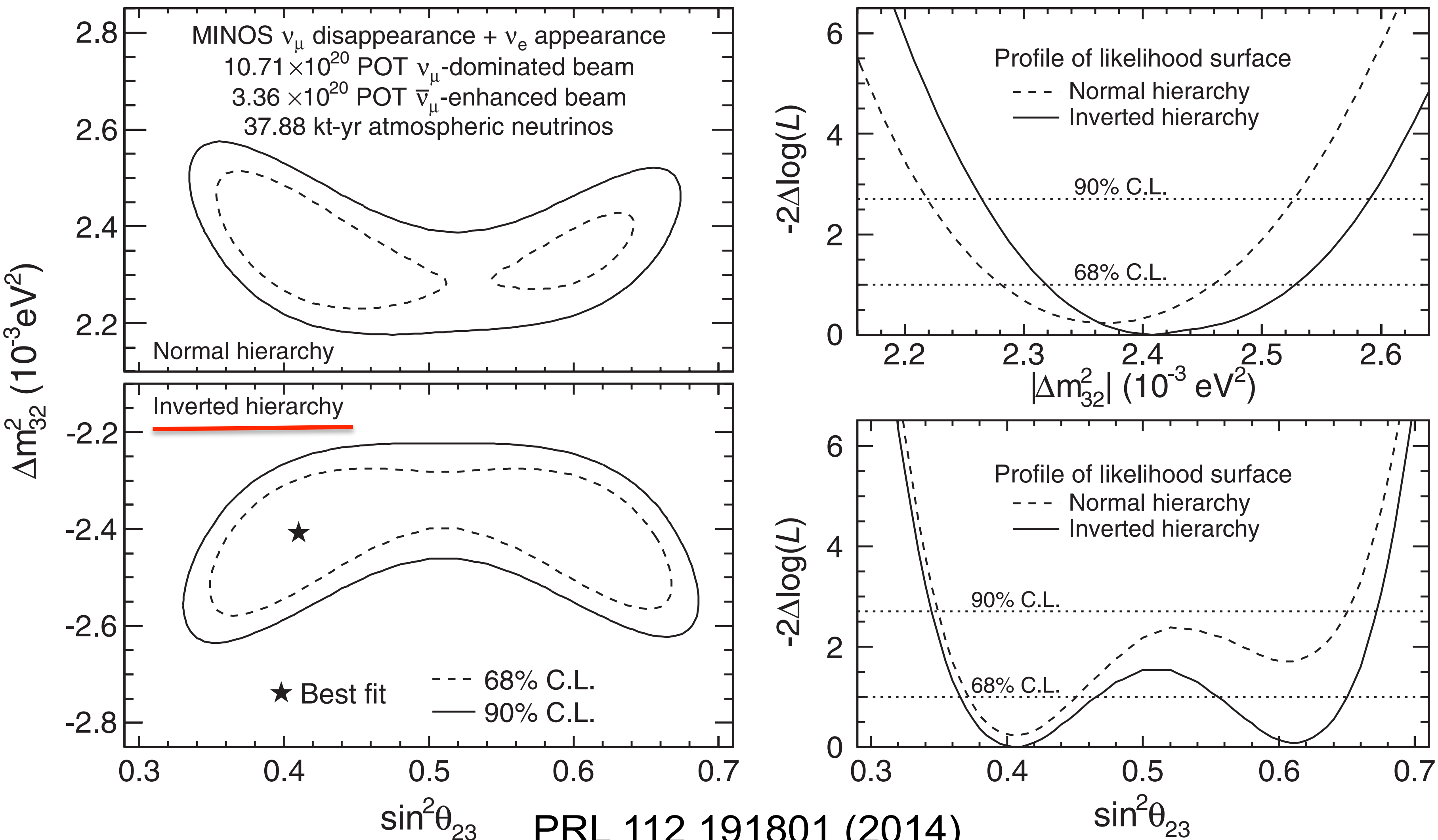
MINOS 3 Flavor Oscillation Analysis

- Analysis combines:
  - Full MINOS ν_μ-CC and $\bar{\nu}_\mu$-CC disappearance sample - *PRL **112**, 191801 (2014)*
  - Full ν_e-CC, $\bar{\nu}_e$-CC appearance sample, described in *PRL **110** 171801 (2013)*
  - Full MINOS and **new MINOS+ atmospheric neutrino samples**
- Sensitive to θ_{13}, θ_{23} octant, mass hierarchy, and δ_{CP} from ν_e sample
- Sensitivity enhanced by atmospherics:
  - Matter effects in multi-GeV, upward-going events
  - Effect seen in neutrinos or antineutrinos, depending on hierarchy
- MINOS first to probe effect with event-by-event charge separation



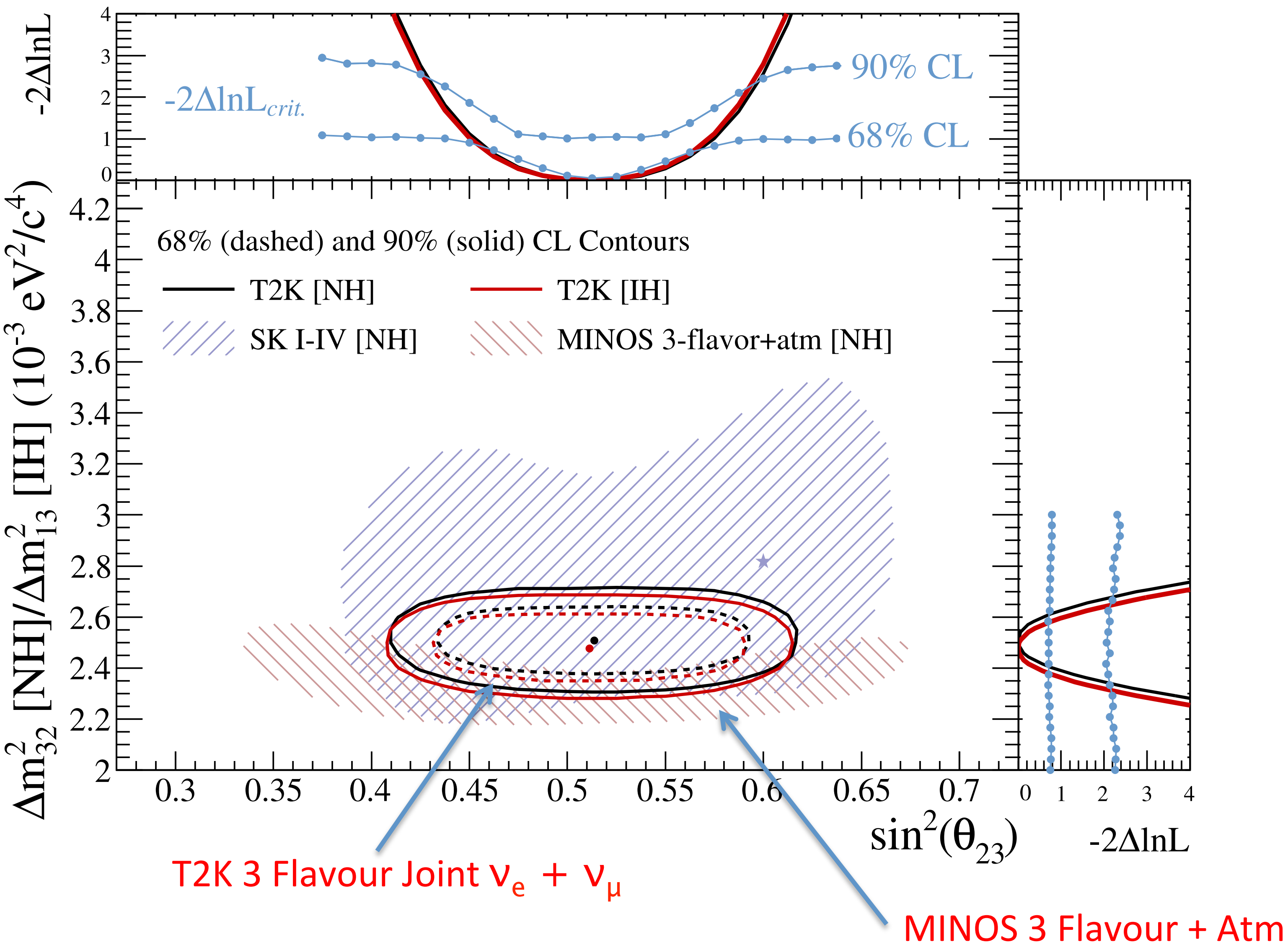
MINOS 3 Flavor Oscillation Analysis

Most precise measurement of $|\Delta m_{32}^2|$ - consistent with Maximal Mixing



PRL 112 191801 (2014)

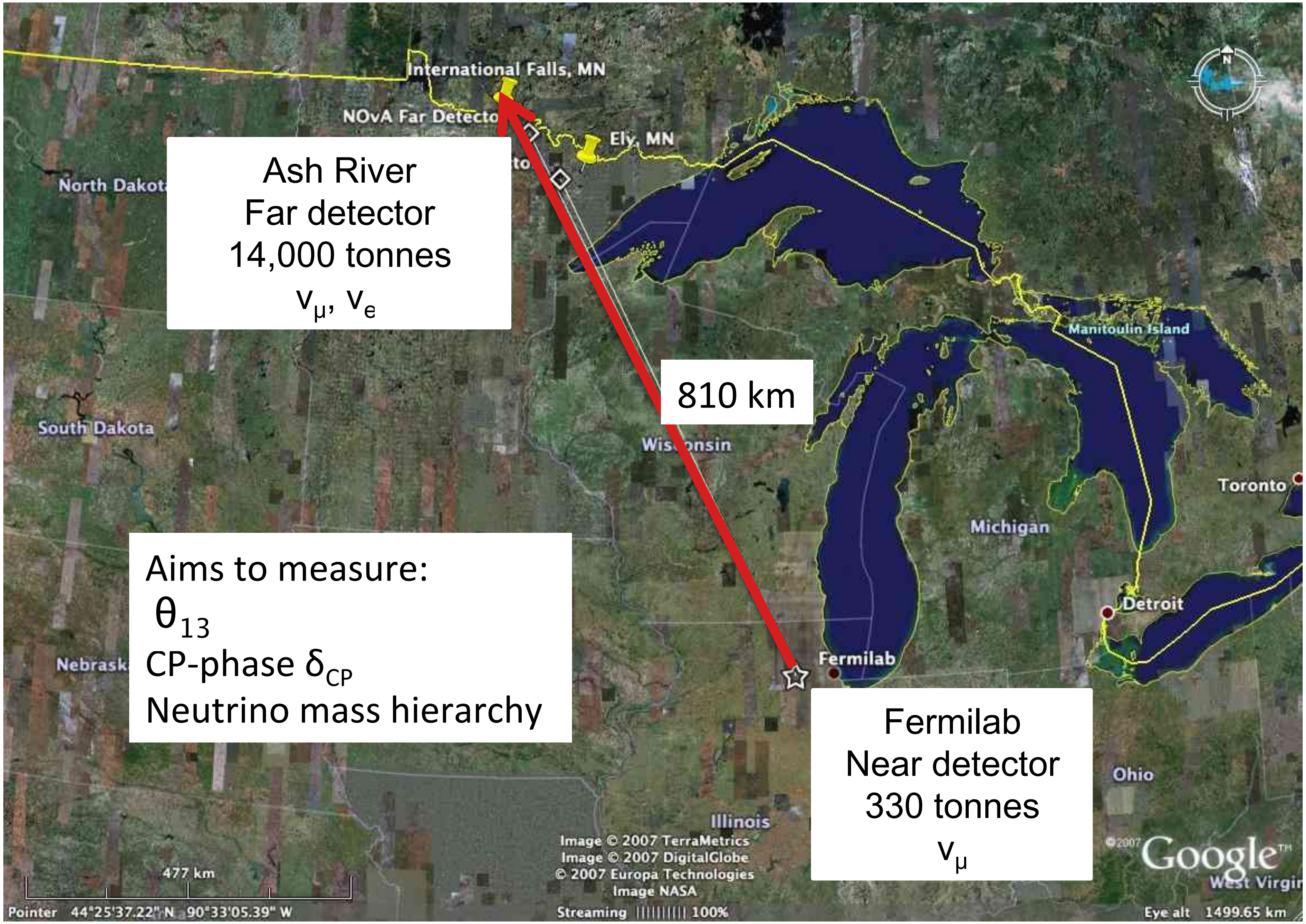
Comparison of T2K with MINOS Disappearance/Atmospheric Results



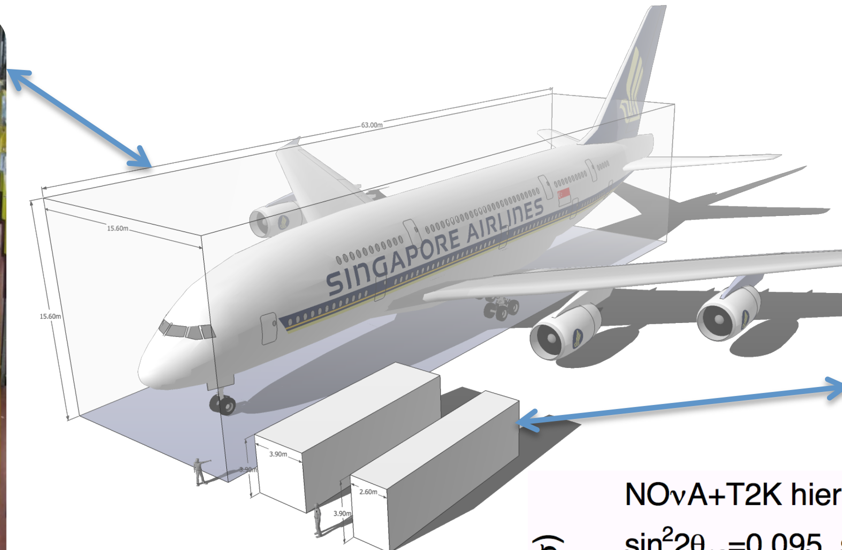
NOvA

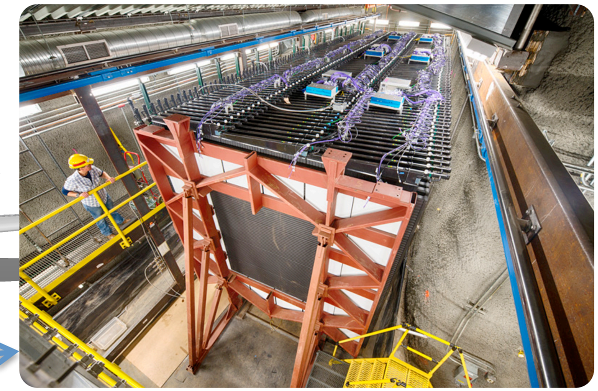
High energy off-axis beam

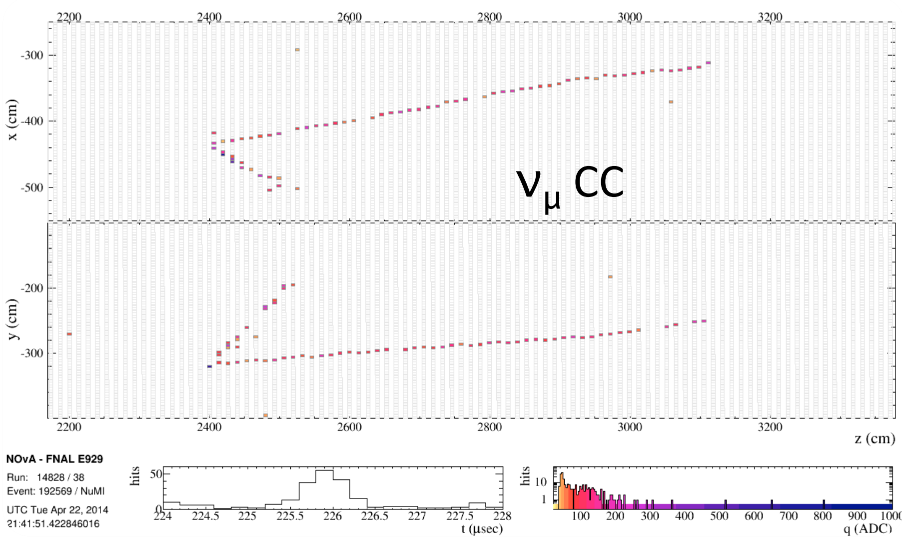
NOvA = NuMI Off-Axis ν_e Appearance

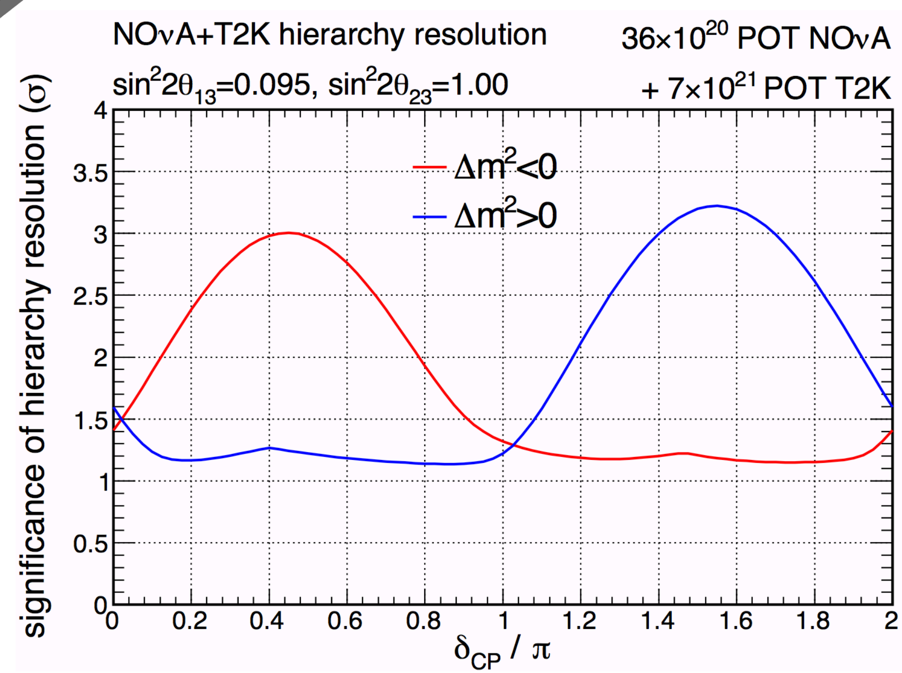


First Neutrino Interactions Observed in NOvA!



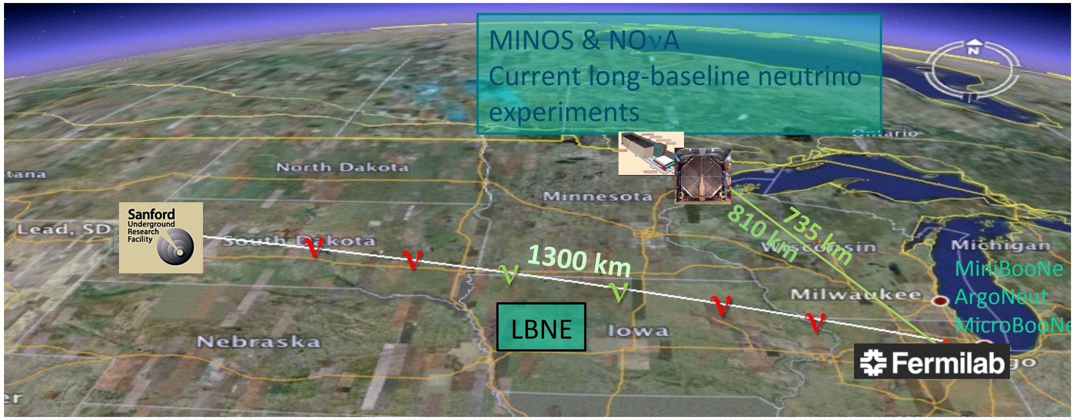






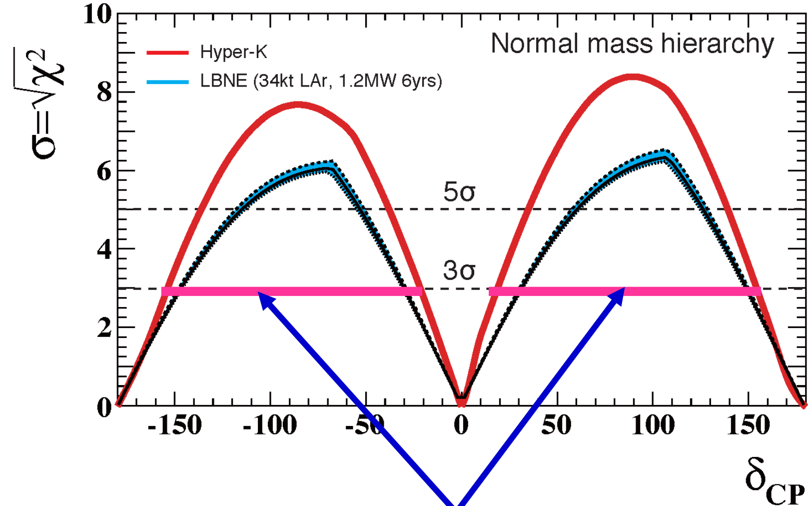
What next (mid-2020's)?

LBN(E/F)

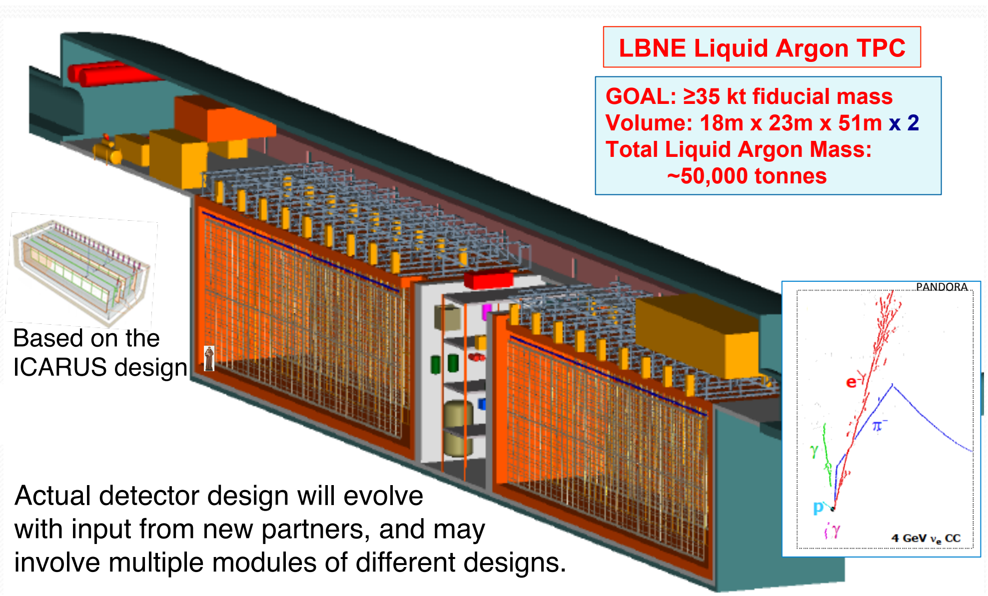


Comprehensive CP Violation, Mass Hierarchy, Non-Standard Interactions and Matter Effects — Need Longer Baseline and High Intensity Broadband Neutrino/Anti-Neutrino Beam

Sensitivity of δ



76% (3σ) of the δ is covered by J-PARC + Hyper-Kamiokande



Hyper-Kamiokande

T2HK

Summary & Conclusions

- During the last 1.5 decades the study of neutrino interactions has revealed many unexpected discoveries, establishing the 3 neutrino flavour mixing paradigm (PMNS) which implies new physics beyond the Standard Model.

- The field is entering the few % precision era due to dedicated experimental efforts on 4 continents.

- The experiments are becoming sensitive to CPV effects via the interplay of reactor and accelerator observables.

- Major efforts are ongoing towards answering the remaining open questions and providing precise tests of the current model.

Back-up Slides

Neutrino Oscillations

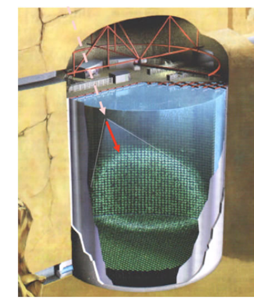
In a simplified 2 flavour model…

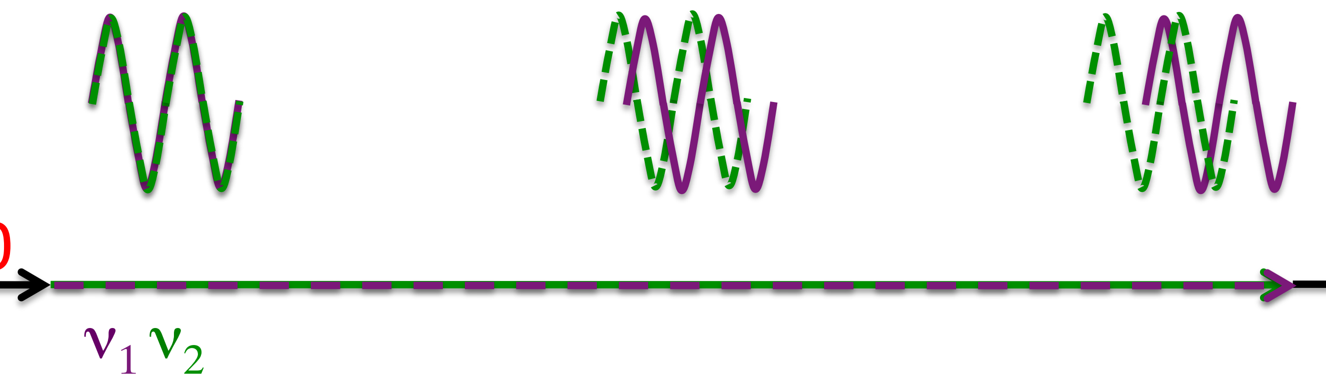
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino **flavour eigenstates** are different to neutrino **mass eigenstates**, propagation over a baseline L of a neutrino of given flavour induces a phase shift, with the possibility of the appearance of the other neutrino flavour

$$\nu_\mu = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$$

$$\nu_1 \rightarrow \exp(-ip_1 x)\ \nu_1$$
$$\nu_2 \rightarrow \exp(-ip_2 x)\ \nu_2$$
$$\Delta\Phi = \Delta m^2 L/(4E)$$

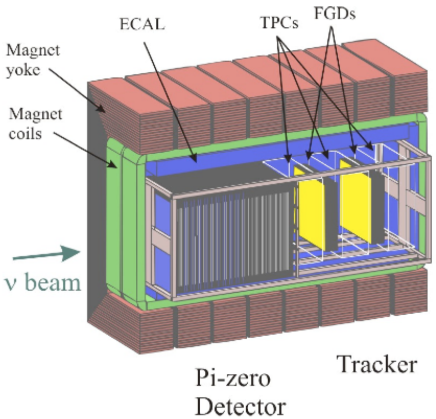


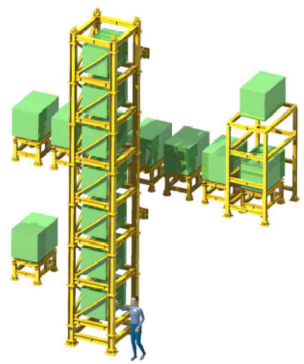


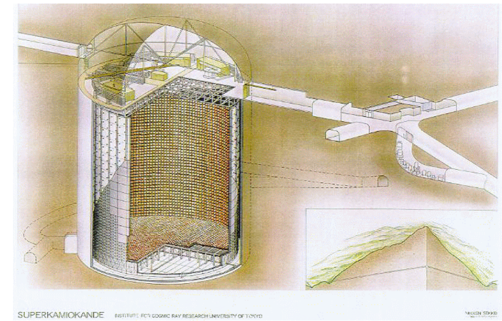
$$\mathrm{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\ \sin^2(\Delta m^2 L/4E)$$

The T2K Experiment Overview

Uses the **J-PARC accelerator** complex for the beam.

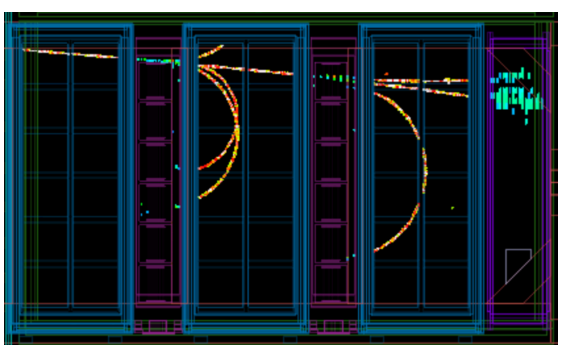






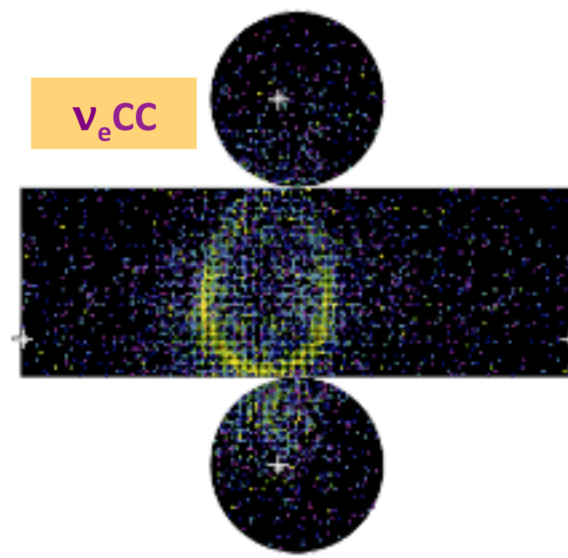
Far detector: Super-K at 295 km.

On and off-axis hybrid **near detectors** at 280m

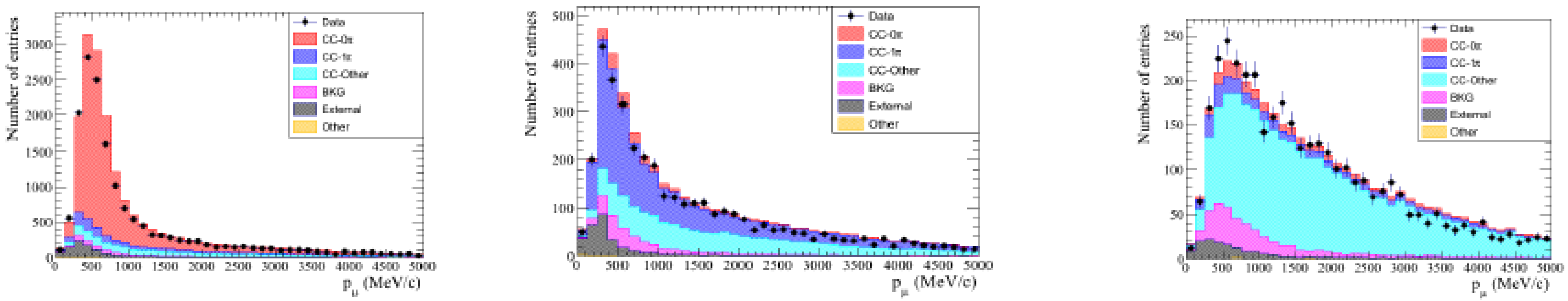


Use information from hadron production experiment NA61

ν_eCC



T2K Near Detector Constraint

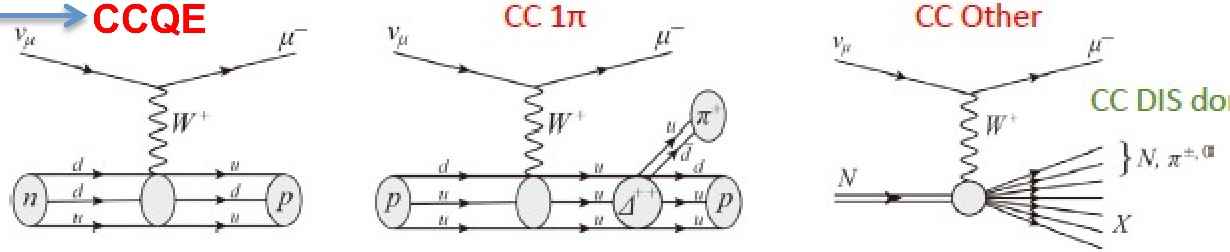


Signal channel for oscillation analysis → **CCQE**

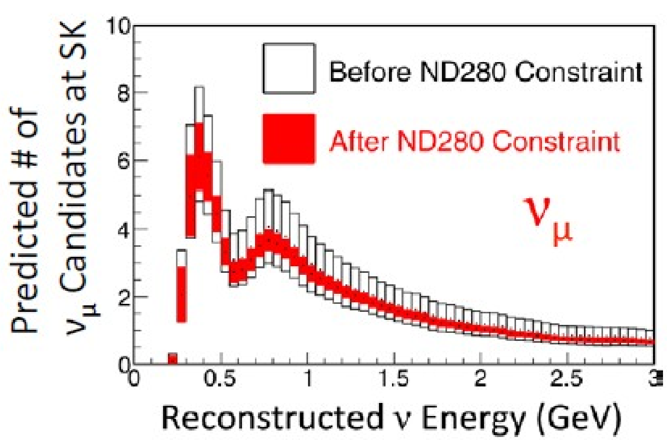
CC 1π

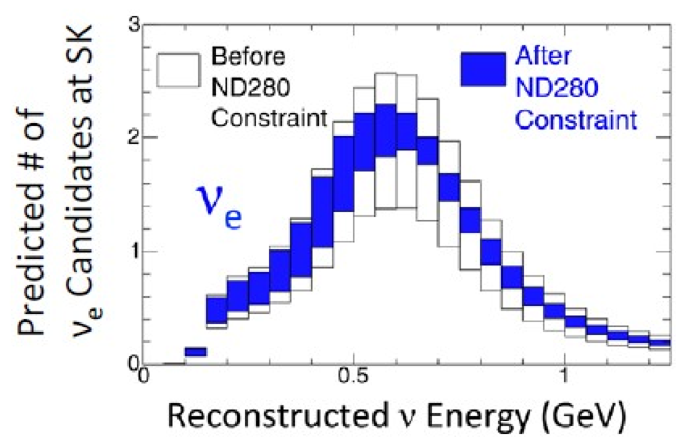
CC Other

CC DIS dominated



Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%



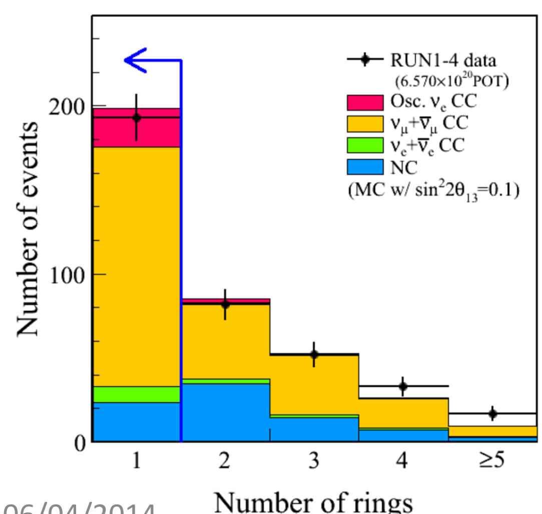


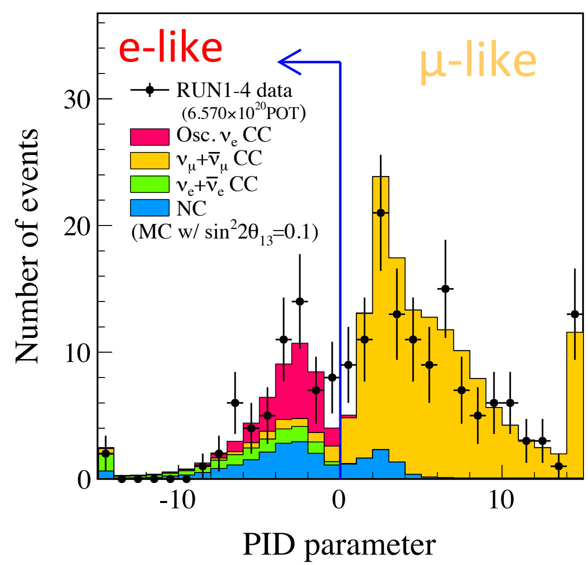
ν_e event selection

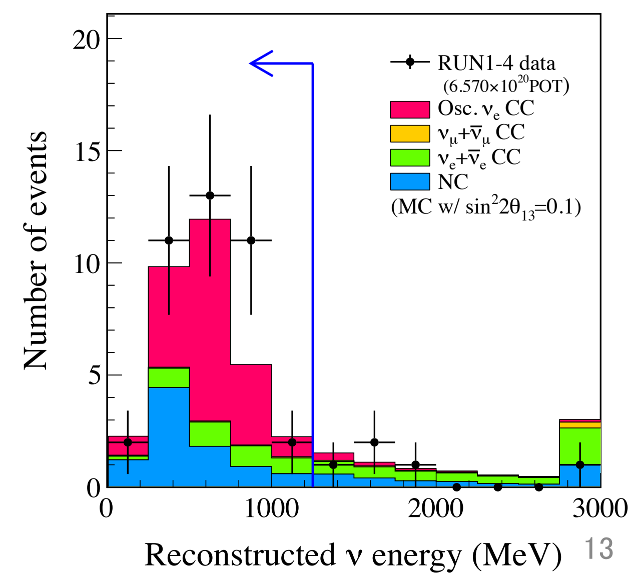
T2K has made improvements in background and error reduction.

- Fully-contained fiducial volume (FCFV) event
- Single-ring e-like event
- $E_{visible}$ > 100 MeV
- # of decay electron = 0
- $0 < E_{\nu}^{rec} < 1250$ MeV
- π^0 cut

28 events in 6.57×10^{20} POT

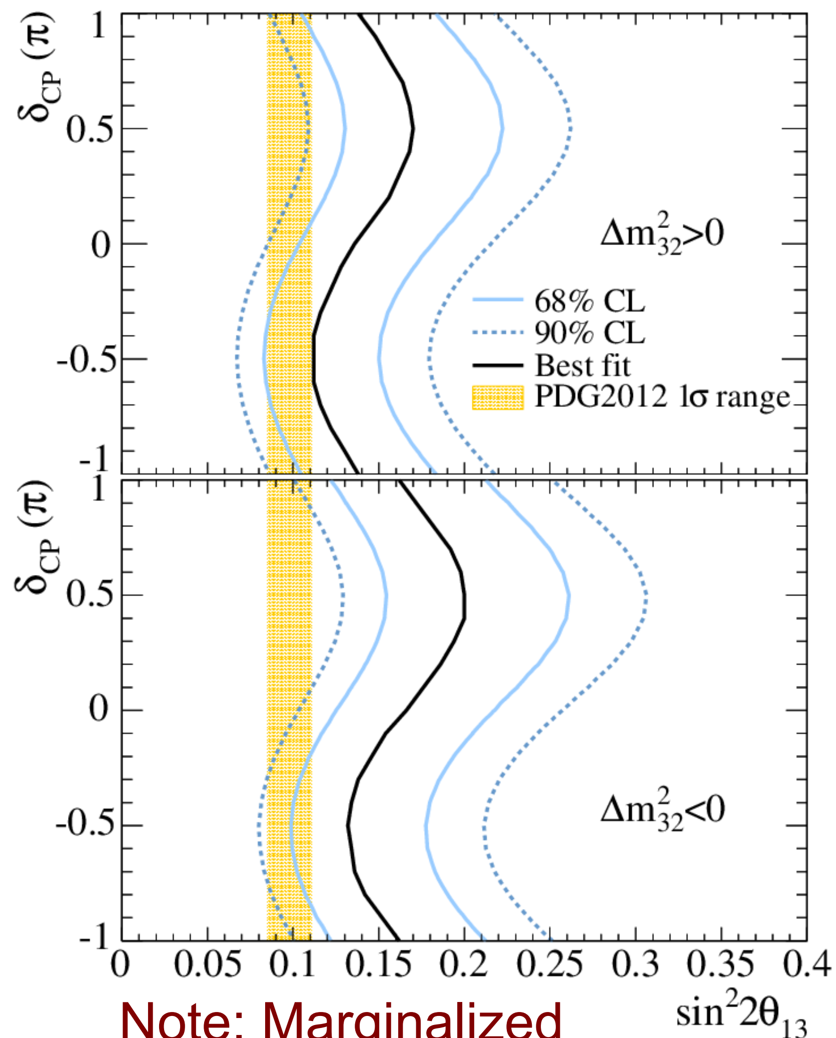






T2K Let's think about these regions!

- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



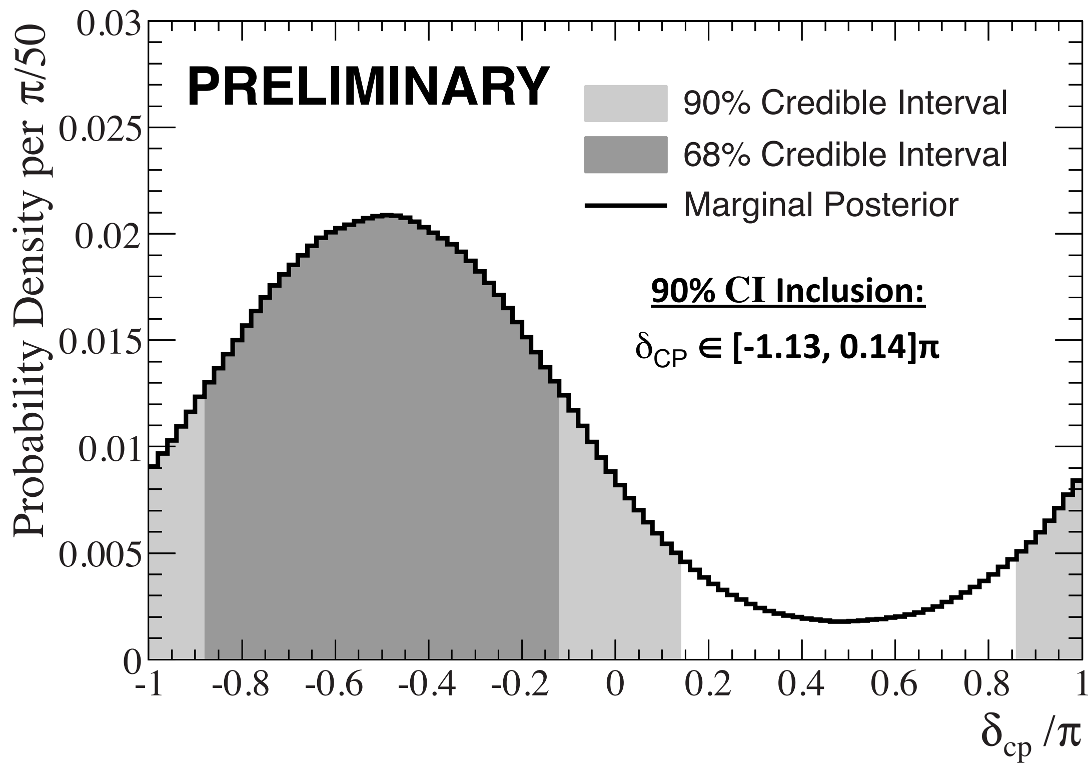
Note: Marginalized over θ_{23} and Δm^2_{32}

T2K Joint $\nu_\mu + \nu_e$ Bayesian Analysis

<u>New Result</u>*:*
Use a Markov Chain Monte Carlo (MCMC) with both T2K-SK $\nu_\mu + \nu_e$ and ND280 samples.

Note: Marginalized over hierarchy.

Assuming flat priors for $\sin^2\theta_{23}$, $|\Delta m^2_{32}|$; P(NH) = P(IH) 0.5



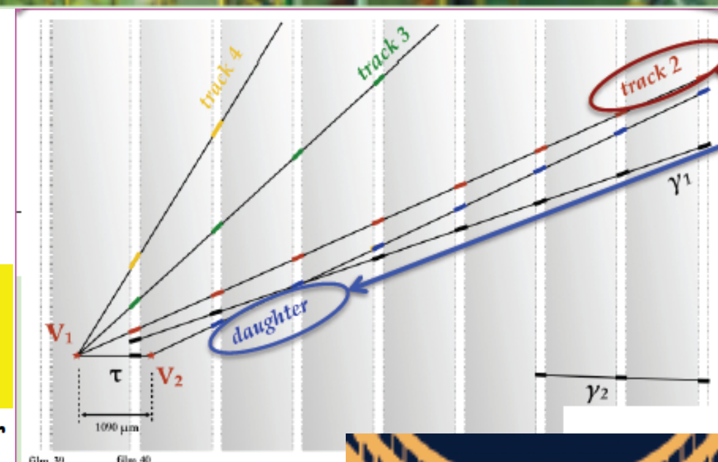
Can compare the probabilities for each MH and θ_{23} octant combination in the posterior probabilities.

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

PRELIMINARY

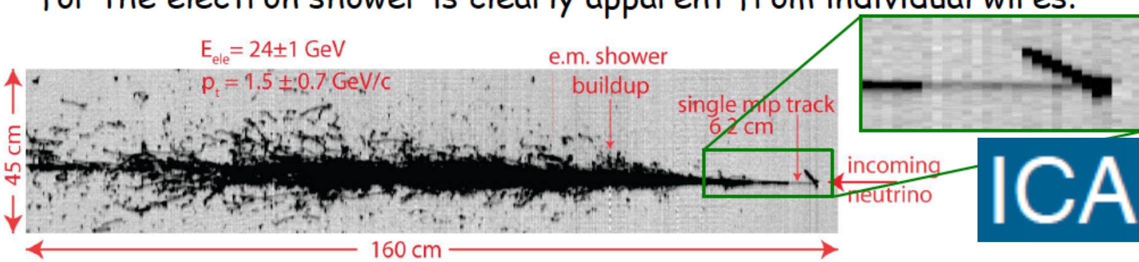
Long Baseline ν Oscillations

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ meV^2$	Total background	Observed
$\tau \to h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \to \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \to e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4



no oscillation excluded at 4.2 σ CL

- The evolution of the actual dE/dx from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.



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Leptogenesis and low energy CP-violation in neutrino physics

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$$|Y_B| \cong 2.8 \times 10^{-13} |\sin\delta| \left(\frac{s_{13}}{0.2}\right)\left(\frac{M_1}{10^9\,\mathrm{GeV}}\right). \tag{91}$$

The asymmetry of interest is predominantly in the lepton number $L_e + L_\mu$. Thus, in order to reproduce the observed baryon asymmetry, taken to lie in the interval $8.0 \times 10^{-11} \lesssim |Y_B| \lesssim 9.2 \times 10^{-11}$, $s_{13}|\sin\delta|$ and M_1, in the case analyzed, should satisfy

$$2.9 \lesssim |\sin\delta| \left(\frac{s_{13}}{0.2}\right)\left(\frac{M_1}{10^{11}\ \mathrm{GeV}}\right) \lesssim 3.3. \tag{92}$$

Given that $s_{13}|\sin\delta| \lesssim 0.2$, the lower bound in this inequality can be satisfied only for $M_1 \gtrsim 2.9 \times 10^{11}$ GeV. Recalling that the flavor effects in leptogenesis of interest are fully developed for $M_1 \lesssim 5 \times 10^{11}$ GeV, we obtain a *lower bound on the values of* $|s_{13}\sin\delta|$ *and* s_{13} *for which we can have successful leptogenesis in the case considered*:

$$|\sin\theta_{13}\sin\delta| \gtrsim 0.11, \quad \sin\theta_{13} \gtrsim 0.11. \tag{93}$$