Neutrino mixing: Results from accelerator experiments

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Michael Wilking (T2K)

Elizabeth Worcester (LBNE)

Outline

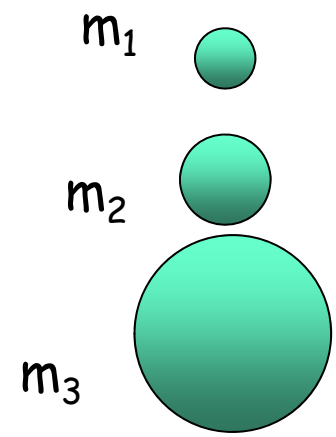
- What are the open questions?
- ν_μ disappearance
- Anomalies (sterile neutrino?)
- Progress towards precision measurement
- **ν_e appearance**
- From now on

Three Flavor Mixing in Lepton Sector

Weak eigenstates

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

mass eigenstates



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

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

θ_{12}, θ_{23}, θ_{13}, δ

Δm^2_{21}, Δm^2_{32}, Δm^2_{31}

* $\Delta m^2_{ji} = m_j^2 - m_i^2$

Two free parameters for the three Δm^2's.

($\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$)

Strange feature of mixing matrix

quark

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.01 & 0.04 \\ 0.008 & 0.04 & 0.89 \end{pmatrix}$$

(writing just magnitude)

lepton

Measured in 2011~2012!

$$U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.55 & \boxed{0.16} \\ -0.49 & 0.52 & 0.55 \\ 0.20 & -0.65 & 0.70 \end{pmatrix}$$

(in case δ=0)

$$\theta_{12} = 34^\circ \pm 1^\circ$$

$$\theta_{23} = 40^\circ + 5^\circ / -2^\circ$$

$$\theta_{13} = \boxed{9.1^\circ \pm 0.6^\circ !}$$

Measured in 2011~2012!

- ✓ 1999: Upper limit (<11°) by Chooz reactor experiment
- ✓ 2011: Indication (2.5σ) of non-zero θ_{13} by T2K ν_e appearance (1.7σ by MINOS)
- ✓ 2012: Evidence of non-zero θ_{13} (>5σ) by reactor ν_e disappearance (Daya Bay, RENO, Double Chooz) 3.1σ by T2K ν_e appearance

Based on PDG 2012

Target of neutrino oscillation experiments

CP phase
KEY to understand the origin of matter dominant universe

Mixing matrix for leptons

Unknown

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

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

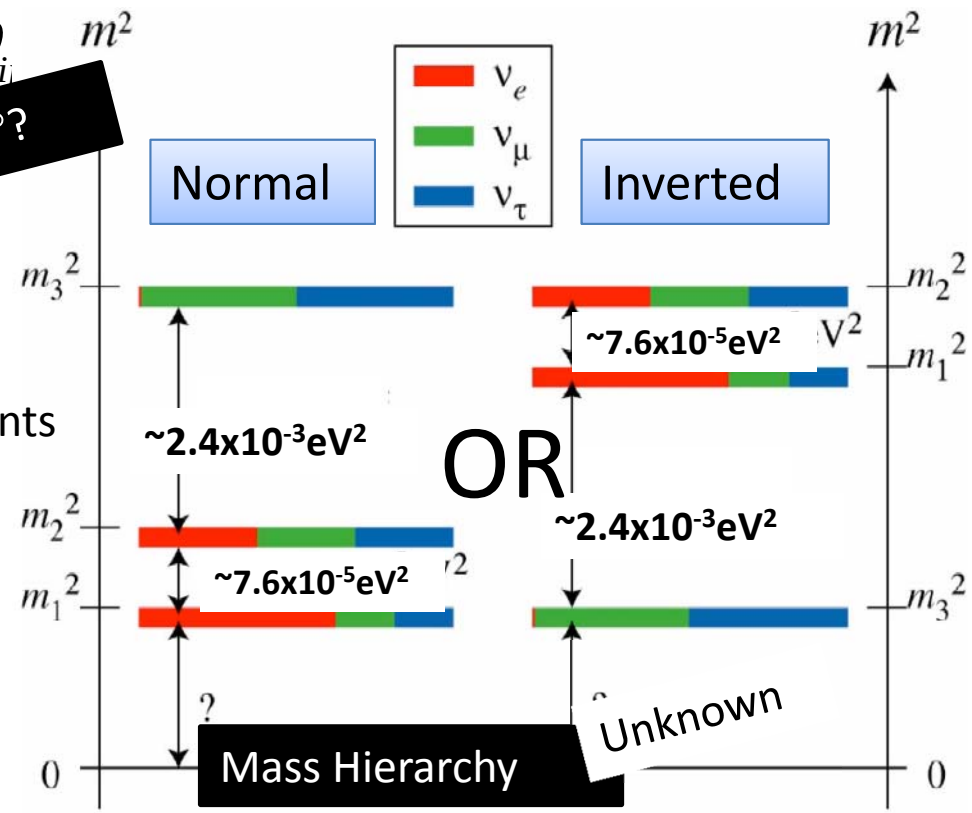
How close to 45°?

$$\theta_{12} = 34° \pm 1°$$

$$\theta_{23} = 40° + 5^{\circ} / -2°$$

$$\theta_{13} = 9.1° \pm 0.6° !$$

Reactor experiments



Big Impact
on 0ν double-β decay search
(hence on Majorana ν confirmation)

Unsolved problems concerning the basic property of neutrino

- Strange features of mixing matrix
- Is CP violated like in the case of quarks?
- Are there only three types of neutrinos?
- Are neutrinos the origin of the matter-dominant universe?
- Why are they so light compared to quarks or charged leptons?
- Are neutrinos Majorana particles?
- Absolute mass
- …..

Experimental approaches

Neutrino oscillation

Double-beta decay

Oscillation at L(km)/E(GeV)~500
Leading term

$$\Delta m_{32}^2 \frac{L}{4E} \sim \Delta m_{31}^2 \frac{L}{4E} \sim \frac{\pi}{2}, \quad \Delta m_{21}^2 \frac{L}{4E} \sim 0$$

- θ_{23} :ν_μ disappearance

Close to 1

$$P_{\mu \to x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left(\Delta m_{32}^2 L / 4E_\nu \right)$$

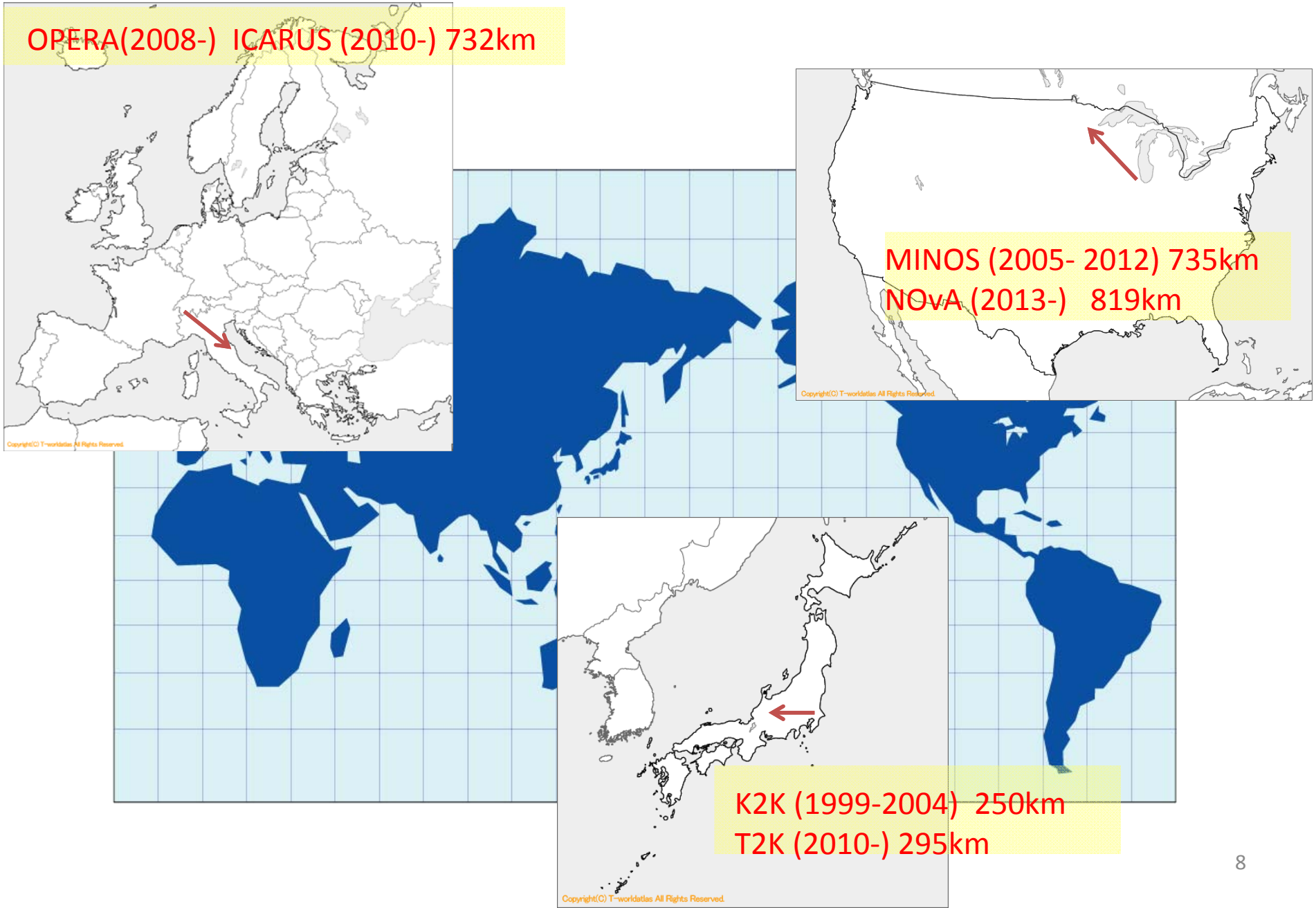
Mainly go to ν_τ.
Since τ production threshold is high (3.5GeV),
it disappears in CC current interaction.

common

- θ_{13}:ν_e appearance

$$P_{\mu \to e} \approx \underset{\sim 0.5}{\sin^2 \theta_{23}} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \left(\Delta m_{31}^2 L / 4E_\nu \right)$$

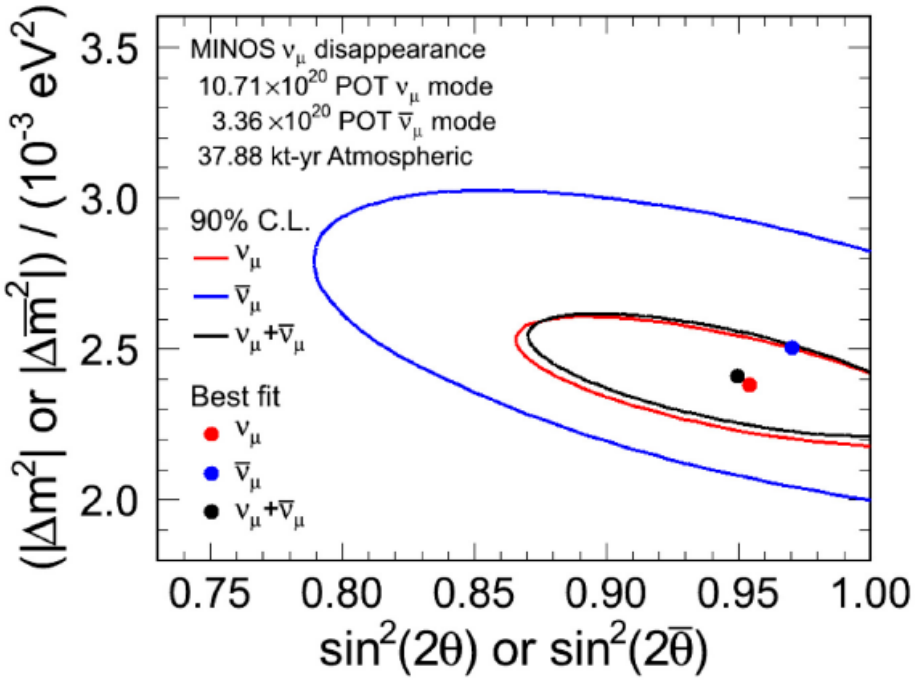
World Long baseline ν oscillation experiments

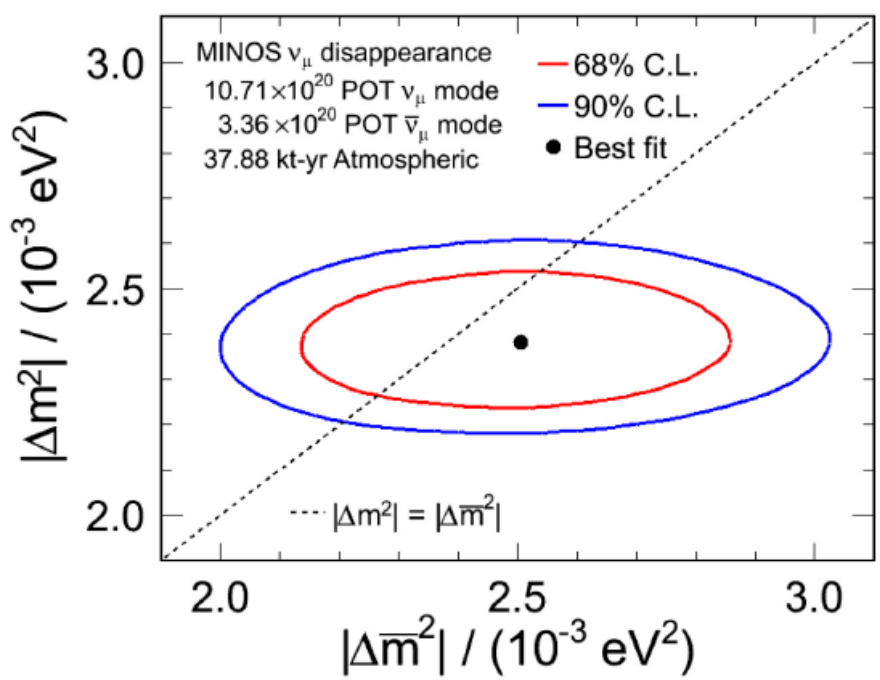


arXiv:hep-ex/1304.6335

MINOS ν_μ disappearance ν vs. $\bar{\nu}$

Leading measurement of $|\Delta m^2_{atm}|$ w/ 4.1% precision using accelerator and atmospheric ν's and $\bar{\nu}$'s.





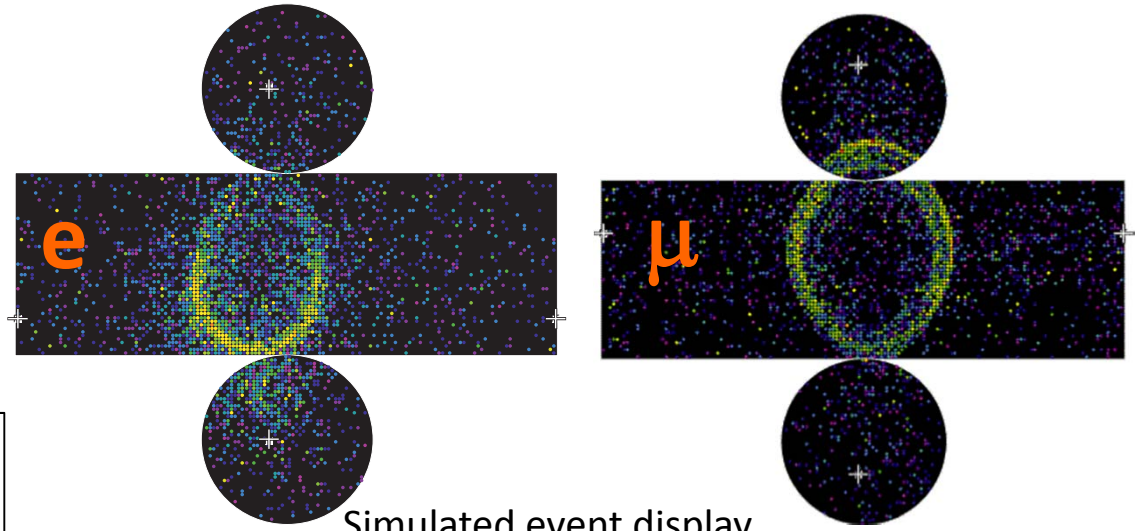
$$\left|\Delta\overline{m}^2\right| - \left|\Delta m^2\right| = 0.12^{+0.24}_{-0.26} \times 10^{-3}\mathrm{eV}^2$$

- MINOS finds consistent values for neutrinos and antineutrino oscillation parameters measured via charged-current disappearance.

Tokai-to-Kamioka (T2K) experiment

~0.6 GeV ν_μ over 295km

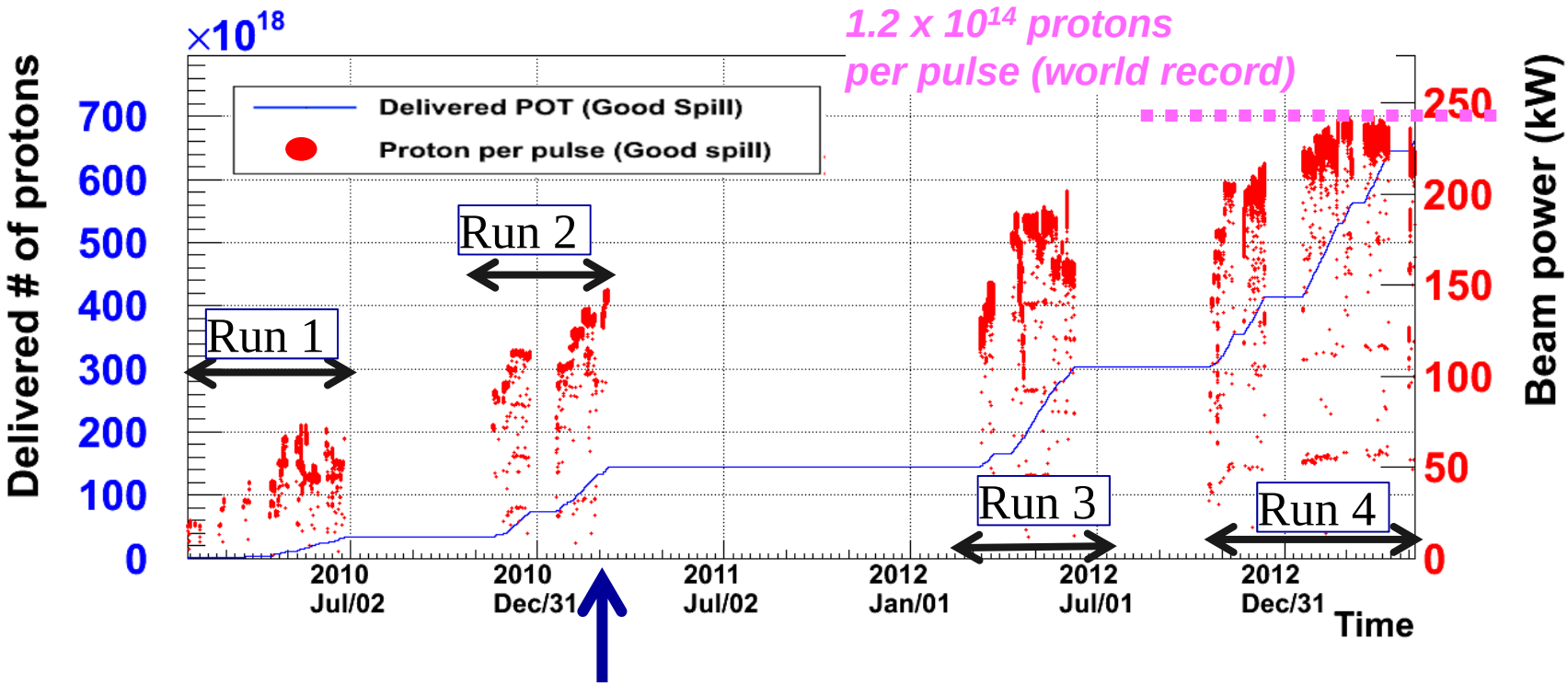
- **ν_e appearance → θ_{13}**
  - e-like ring, π^0 mass cut etc.
- **ν_μ disappearance → θ_{23}**
  - μ-like ring etc.



Simulated event display

Latest results reported
by M. Wilking, EPS HEP2013

T2K data-taking status

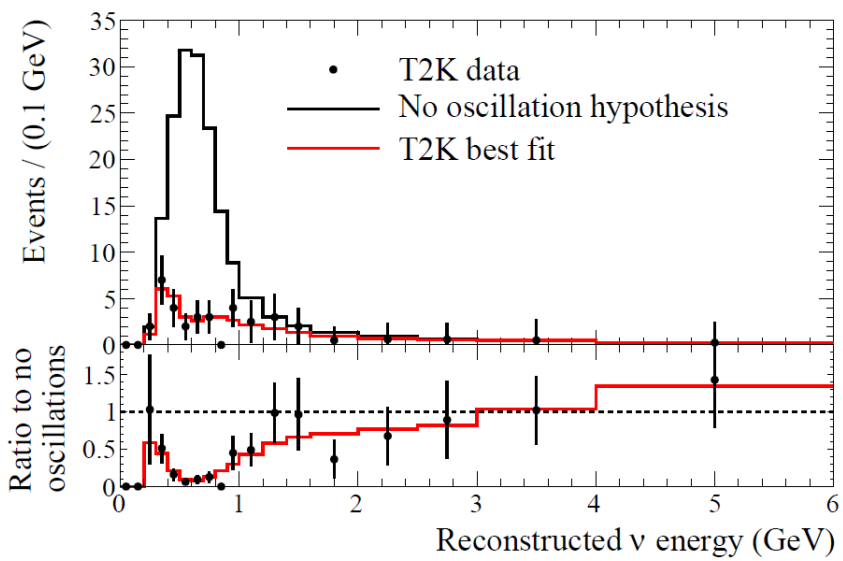


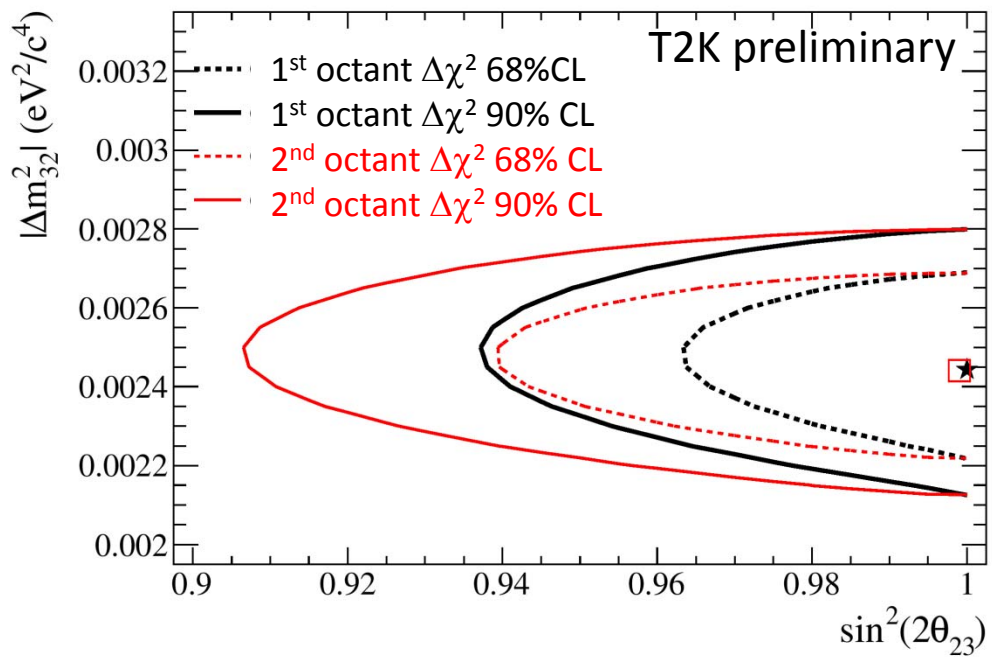
Great East Japan Earthquake

6.63 x 10^{20} protons on target (p.o.t.) so far

8.5% of T2K goal statistics

T2K ν_μ disappearance





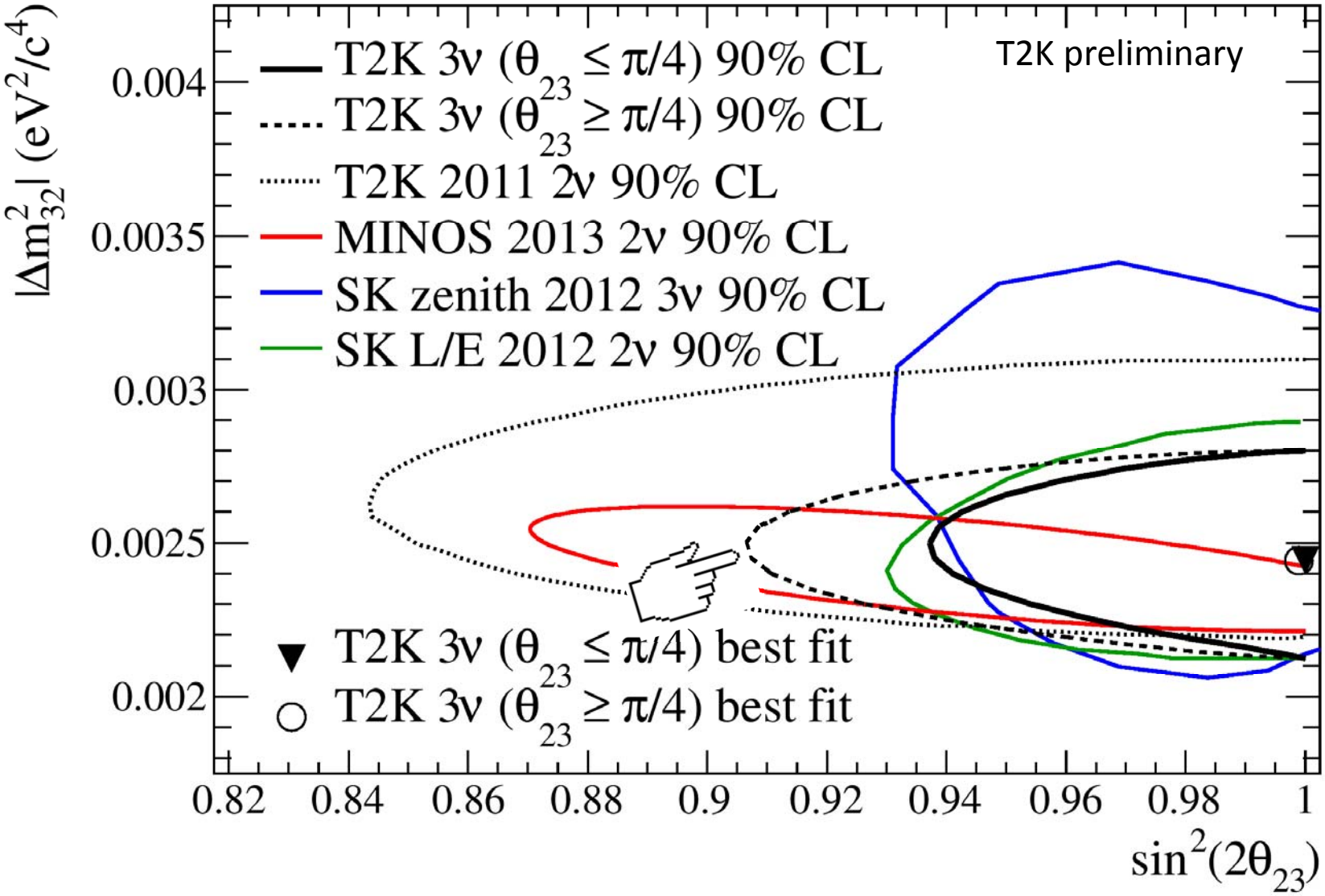
Using data up to Run 3

Only $\theta_{23}<\pi/4$ region was explored in the results released in February 2013.

This time $\theta_{23}>\pi/4$ is also considered. Significant difference appeared.

$$P_{\mu\to\mu} \approx 1 - \left(\underbrace{\cos^4\theta_{13}}_{\sim 1} \cdot \underbrace{\sin^2 2\theta_{23}}_{\sim 1} + \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \cdot \underbrace{\sin^2 2\theta_{13}}_{\sim 0.1}\right)\sin^2\left(\Delta m^2 L / 4E_\nu\right)$$

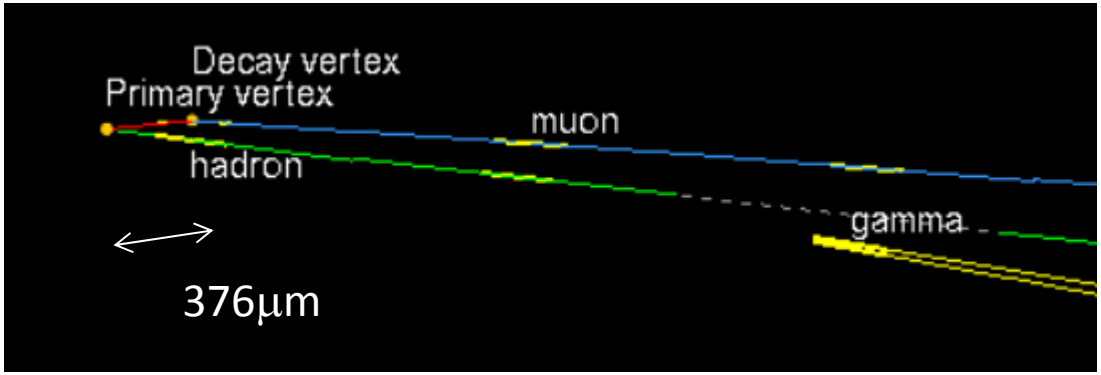
T2K ν_μ disappearance



Confirmation of $\nu_\mu \rightarrow \nu_\tau$ by OPERA

3.8σ ν_τ appearance by Super-K atmospheric data *(Abe et al., PRL 110, 181802 (2013))* from a sample of enhanced τ-like events.

OPERA identifies τ production in event-by-event basis.



Third ν_τ candidate taken in March, 2013

Extended sample

	Signal	Background
$\tau \rightarrow h$	0.66	0.045
$\tau \rightarrow 3h$	0.51	0.090
$\tau \rightarrow \mu$	0.56	0.026
$\tau \rightarrow e$	0.49	0.065
total	2.22	**0.23**

w/ ~60% of data analyzed

3 observed events in the $\tau \rightarrow h$, $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels

Probability to be explained as a background = 7 x 10^{-4}

This corresponds to 3.2 σ significance of non-null observation (3.5 σ significance with a likelihood approach)

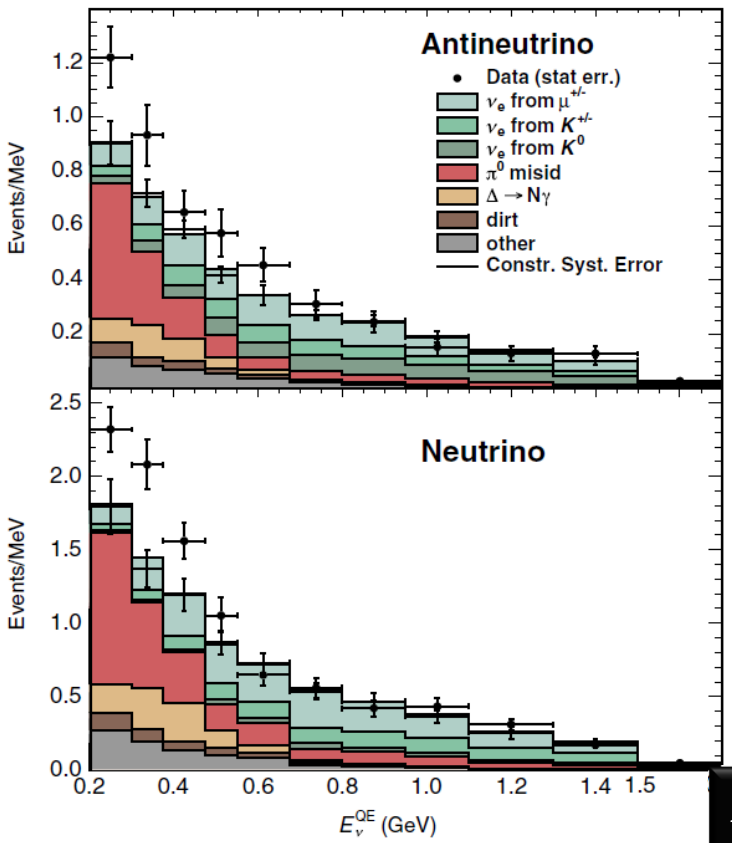
A. Pastore, EPS HEP 2013

Anomalies at small L/E
(Large Δm^2 in case of oscillation w/ sterile ν)

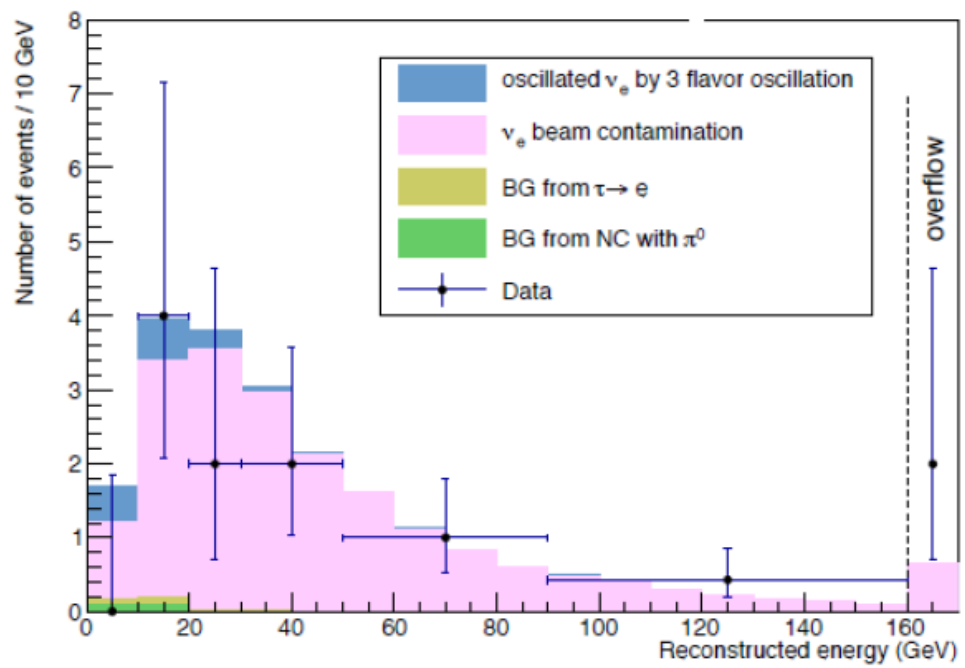
Two anomalies

- ✓ ν_e excess in ν_μ beam by LSND and MiniBooNE
- ✓ ν_e disappearance (reactor and Gallium experiments)

MiniBooNE PRL 110, 161801 (2013)



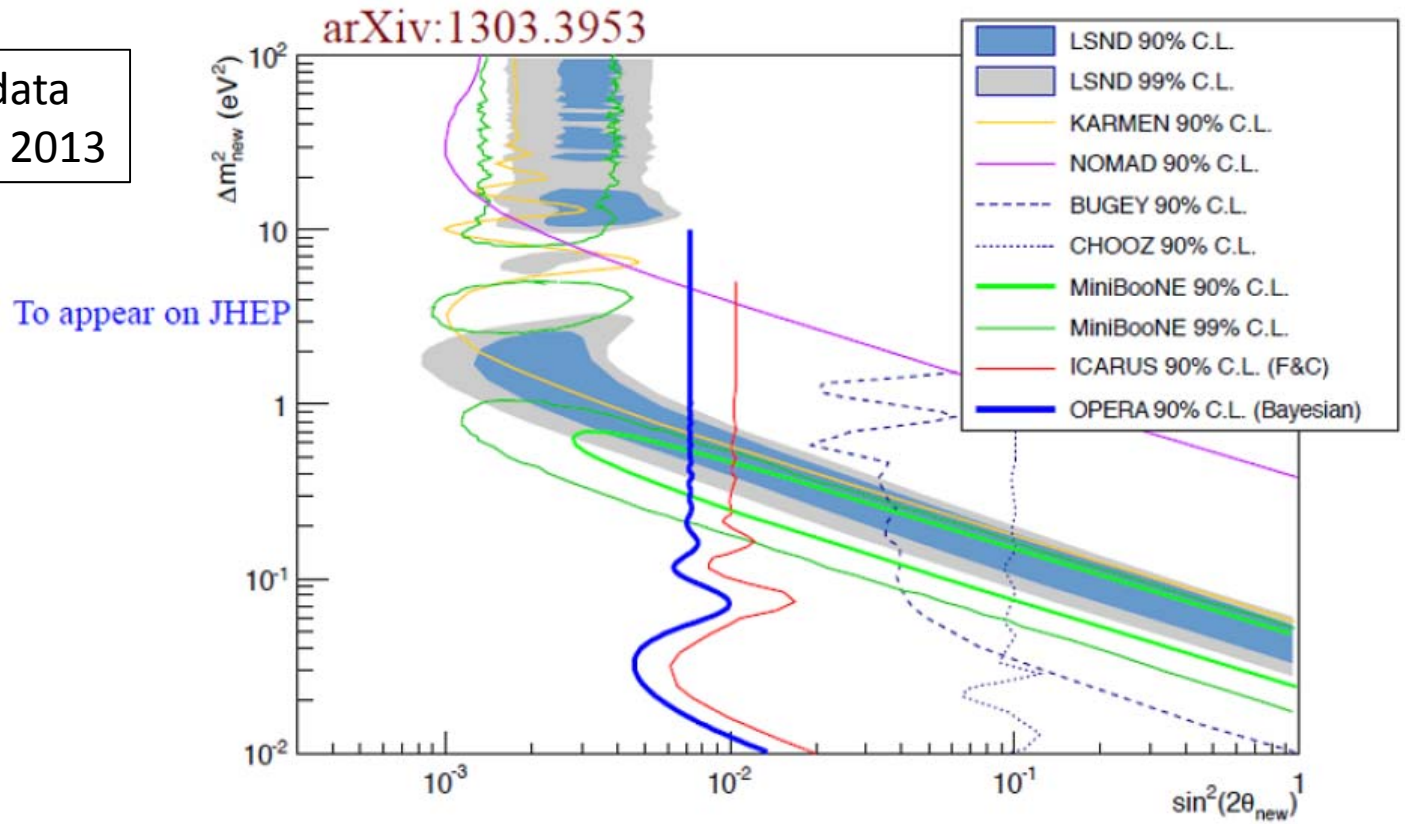
OPERA 2008-2009 data



$\nu_\mu \rightarrow \nu_e$

Anomalies at small L/E
(Large Δm^2 in case of oscillation w/ sterile ν)

OPERA 2008-2009 data
A. Pastore, EPS HEP 2013



Search will be continued in ν_e appearance, ν_μ or ν_e disappearance

Many experimental proposals

- ICARUS/NESSiE at CERN
- MINOS+ using beam from FNAL (running w/ NOvA)
- Possibly T2K, NOvA

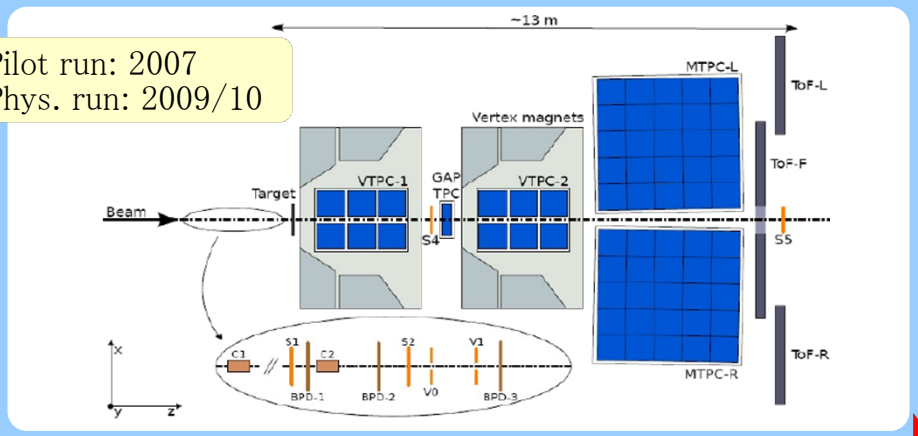
PROGRESSES TOWARDS PRECISION MEASUREMENT

Accelerator Neutrino Physicists have to know about the strong interaction.

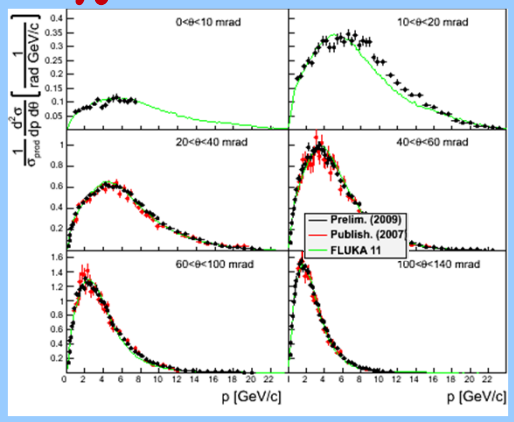
- Flux prediction
  - ν's parent particles are produced by hadron production from p+Nucleus interactions
- Neutrino Interaction
  - ν+Nucleus interaction is affected by nuclear state

NA61/SHINE Hadron production measurements for the ν_μ flux in T2K

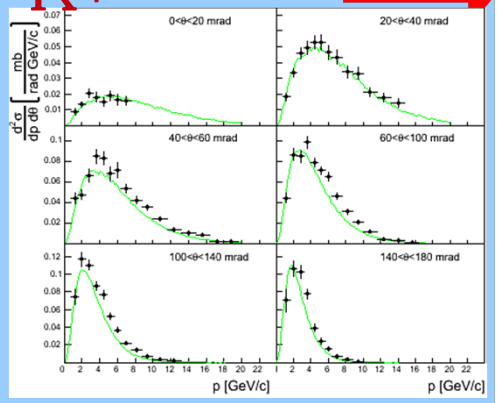
Pilot run: 2007
Phys. run: 2009/10



π^+



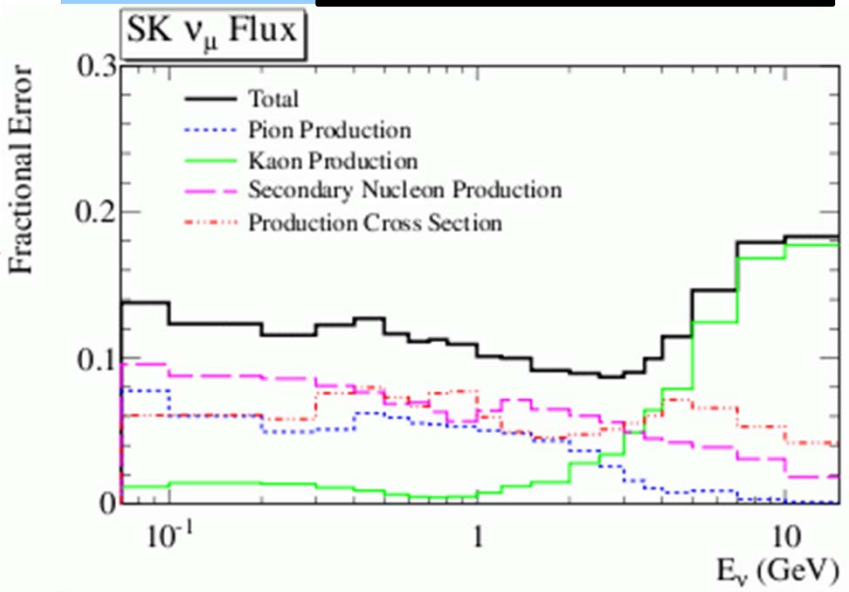
K^+



- Cross sections for $\pi^\pm$, $K^\pm$, p and K^0_S
- Cover ~90% of the p phase space of T2K
- Measurement for NuMI target at 120 GeV/c
- New results are released in EPS-HEP2013

Neutrino Flux Prediction in T2K

Flux uncertainty

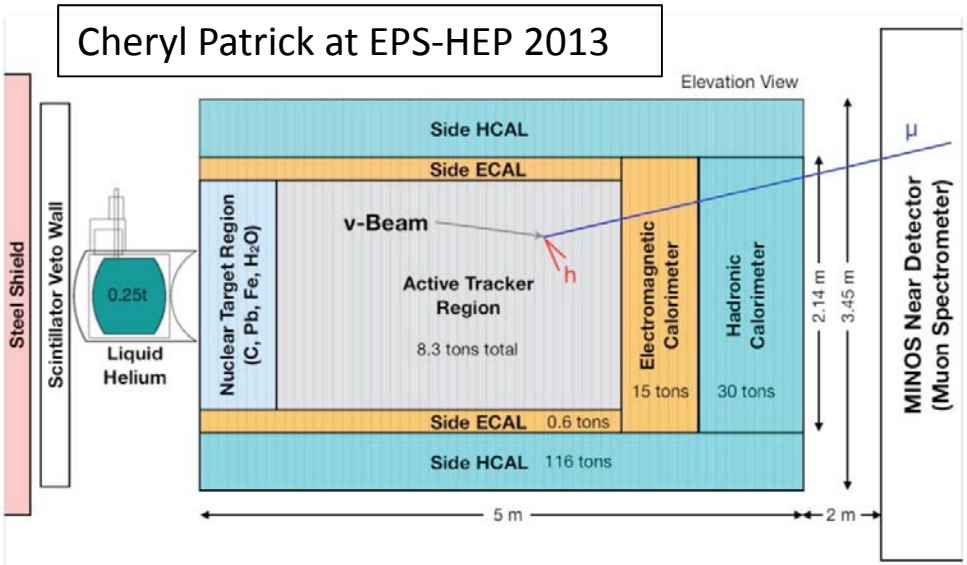


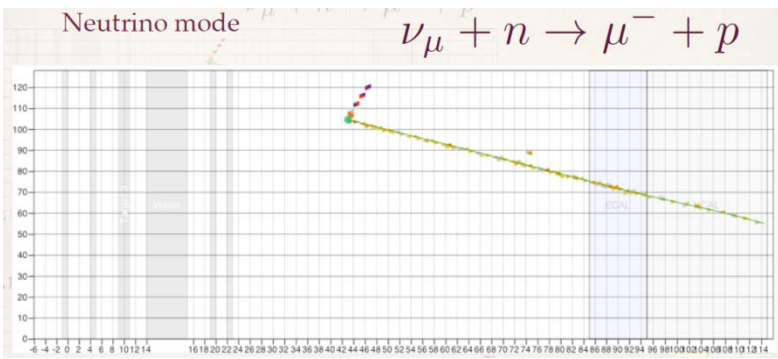
Essential for reliable neutrino measurement

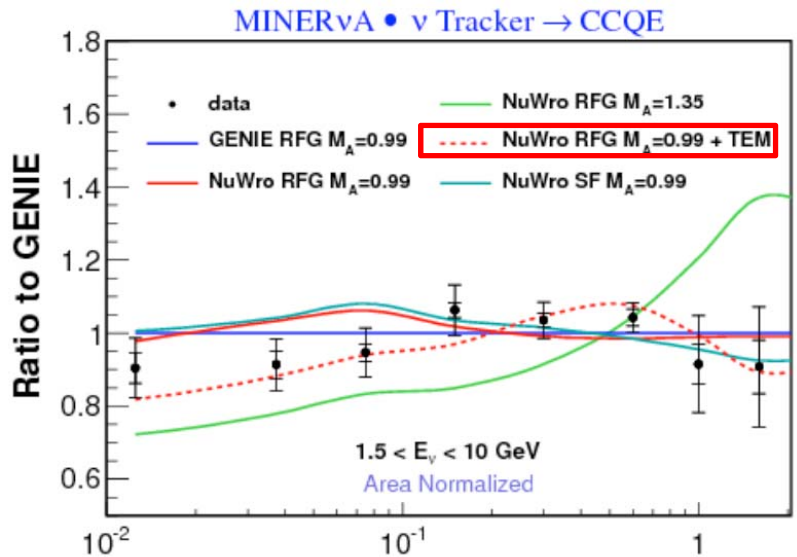
Alexander Korzenev EPS-HEP2013

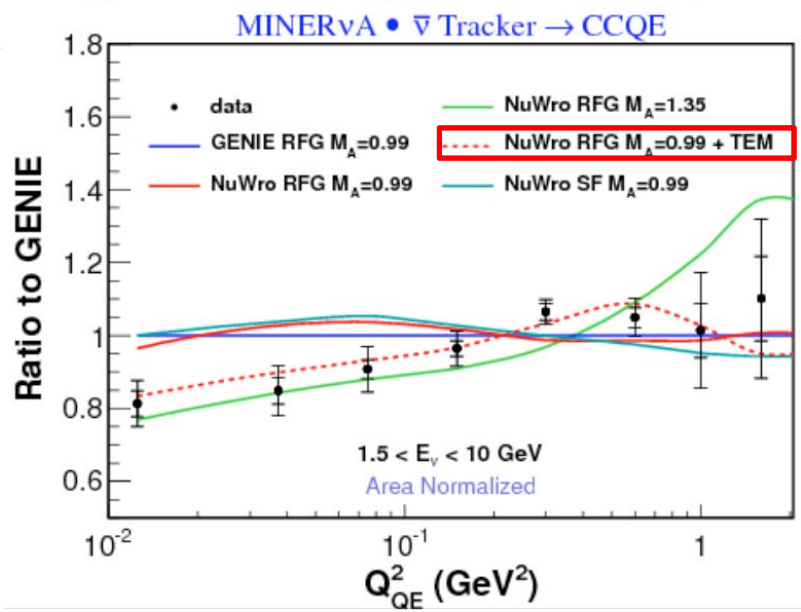
Charged Current Quasi-Elastic scattering by MINERvA (at FNAL MINOS near detector hall)

Cheryl Patrick at EPS-HEP 2013









'n' or 'p' is in the nucleus and interacting w/ other nucleons.

Data favors TEM(Transverse Enhancement), suggesting initial-state correlations

Latest results of ν_e appearance

Key mode for CP δ, Mass Hierarchy
and θ_{23} octant

ν_e appearance (complete version in vacuum)

Leading term

$$P(\nu_\mu \to \nu_e) = 4C_{13}^{\ 2}S_{13}^{\ 2}S_{23}^{\ 2}\sin^2\Phi_{31}$$

$$+8C_{13}^{\ 2}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$-8C_{13}^{\ 2}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$+4S_{12}^{\ 2}C_{13}^{\ 2}(C_{12}^{\ 2}C_{23}^{\ 2} + S_{12}^{\ 2}S_{23}^{\ 2}S_{13}^{\ 2} - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

θ_{13}

CPC

CPV

Solar

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

CP violating term introduced by interference btw. θ_{13} and θ_{12}

$\delta \to -\delta$ for P(anti-$\nu_\mu \to$ anti-ν_e)

ν_e appearance at oscillation maximum

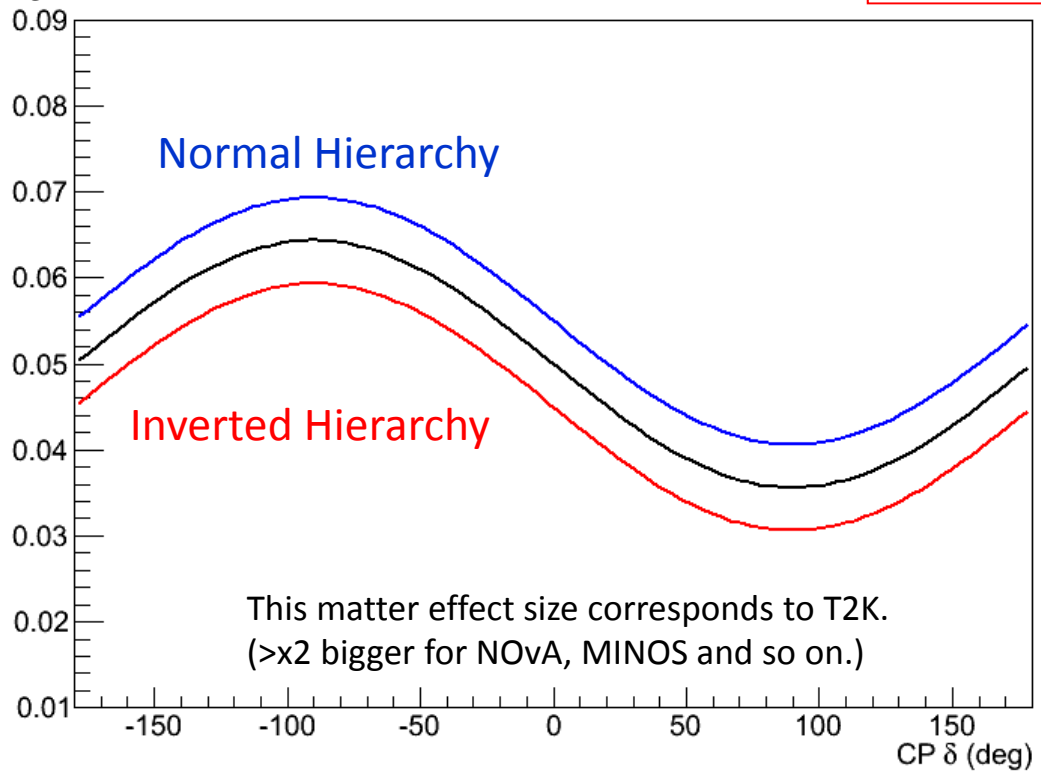
$$P(\nu_\mu \to \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \left(1 + \frac{2a}{\Delta m_{31}^2}\right) - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin\delta$$

Matter effect

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{g\mathrm{cm}^{-3}} \frac{E}{GeV}$$

$P(\nu_\mu \to \nu_e)$

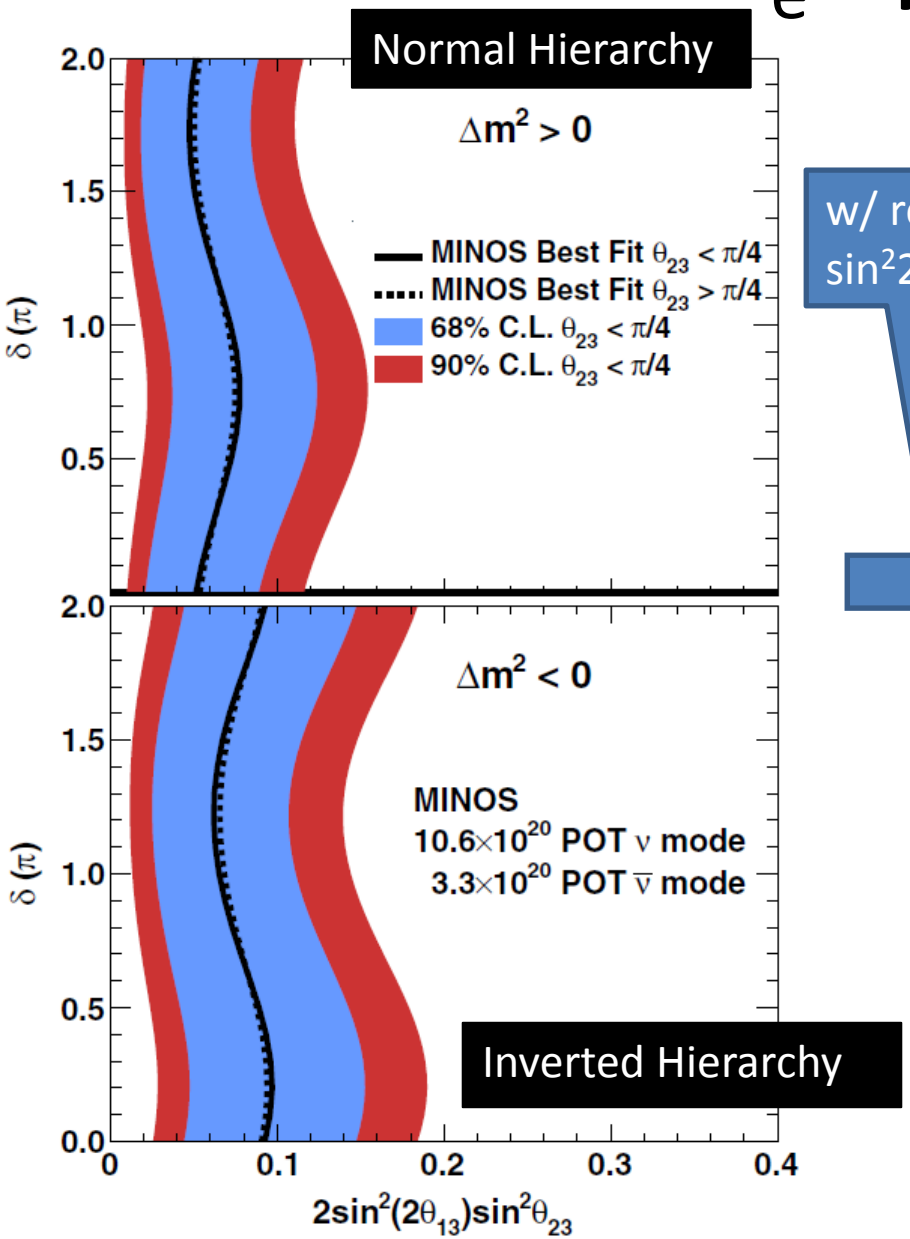


ν_e feels different potential than ν_μ and ν_τ in earth.

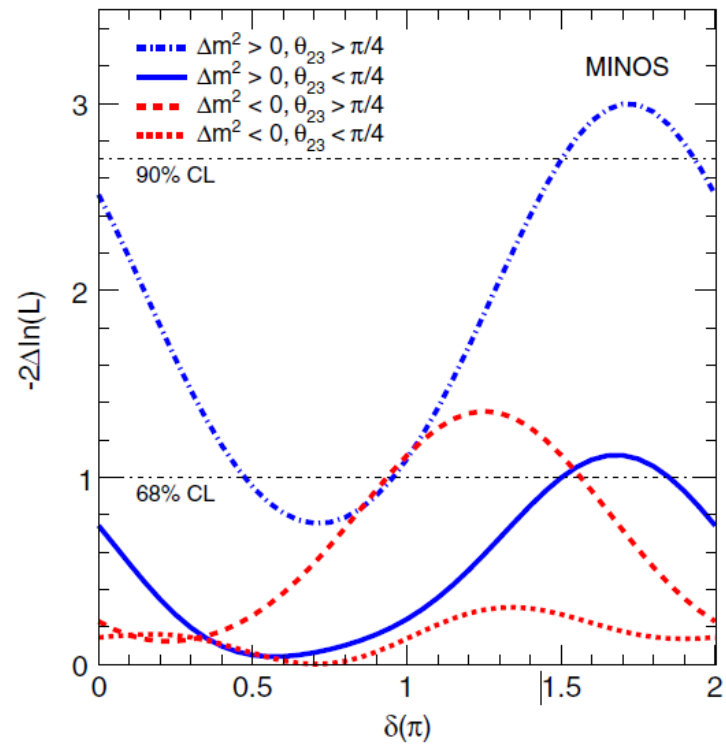
$\delta \to -\delta$, $a \to -a$
for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

MINOS ν_e appearance

PRL 110, 171801(2013)



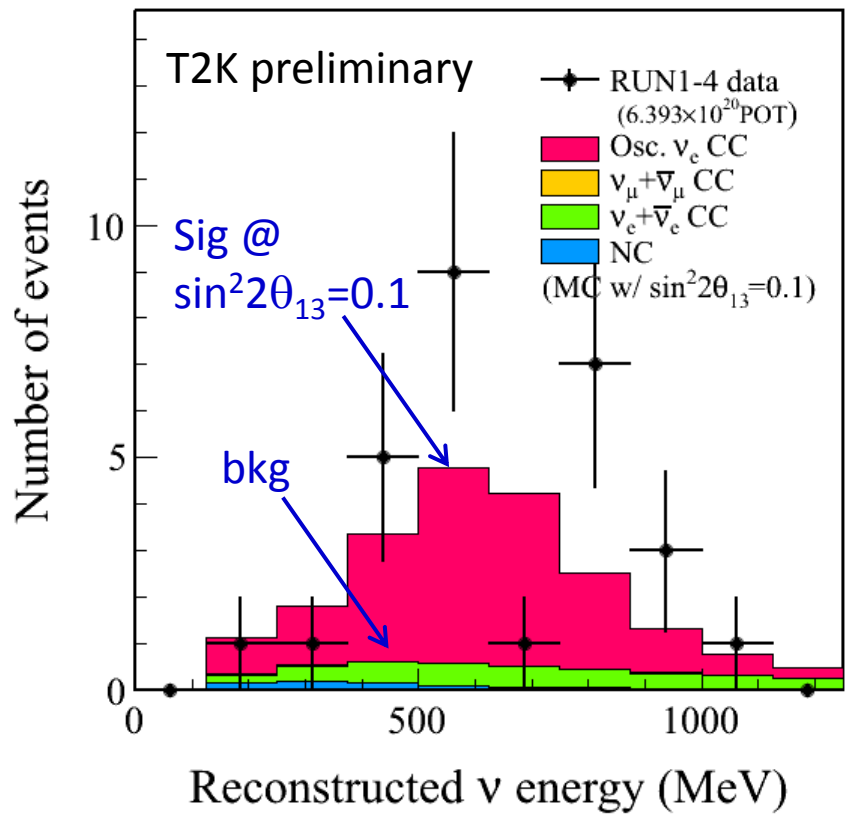
w/ reactor result
$\sin^2 2\theta_{13}=0.098\pm0.013$



T2K ν_e Appearance Updates from 2012

- The background rejection cut is improved using a new SK reconstruction algorithm. Number of BG events reduced from 6.4 to 4.6
- Near detector measurement is improved by using new event categories

	2012(*)	2013(now)
POT	3.010×10^{20}	6.393×10^{20} (~Apr 12)
Bkgs	3.3 ± 0.4	4.64 ± 0.51
Observed ν_e cand. Events	11	**28**
ν_e app. Significance	3.1σ	**7.5σ**



* 2012 result arXiv:1304.0841 (accepted by PRD)

T2K ν_e appearance Results

- Fit using electron (p,θ) distribution
- NOTE! $\sin^2\theta_{23}$ is fixed to 0.5 in the fit

$$P(\nu_\mu \to \nu_e) \cong$$

$$4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \left(1+\frac{2a}{\Delta m_{31}^2}\right) - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin\delta$$

- Best fit value w/ 68% C.L. error @ δ_{CP}=0

normal hierarchy:

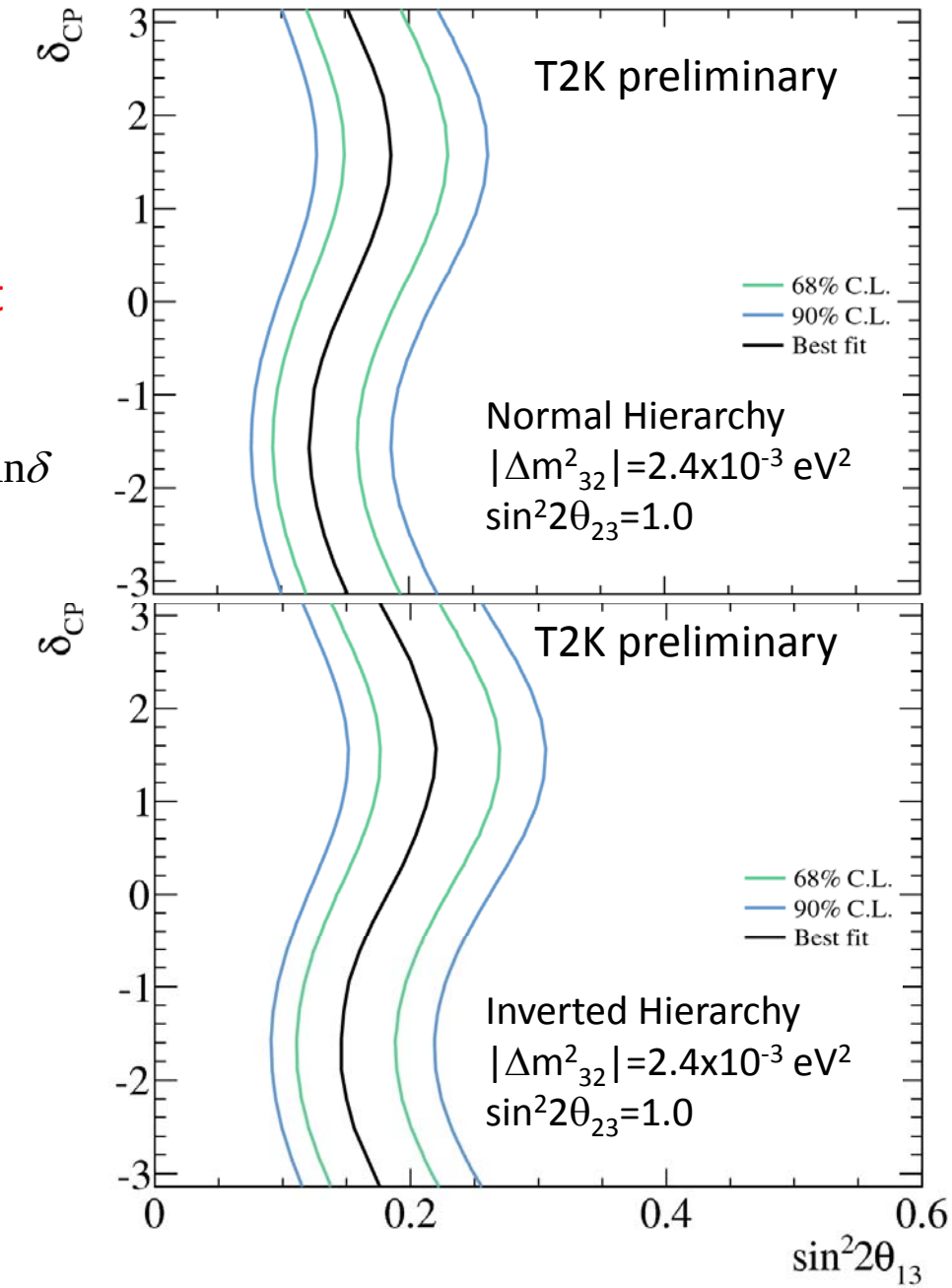
$$\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$$

inverted hierarchy:

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

c.f. reactor results (PDG '12)

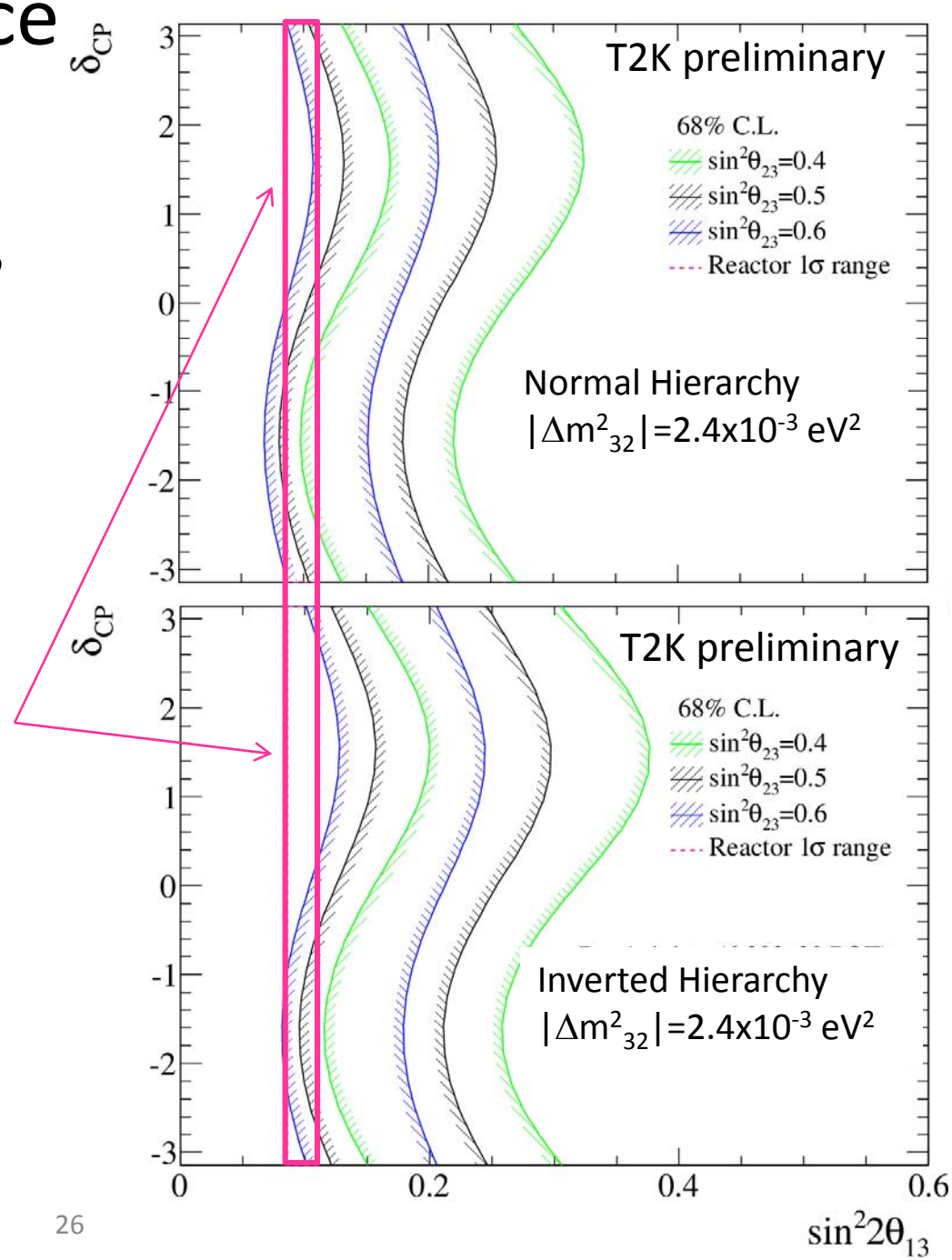
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$



T2K ν_e appearance δ_{CP} vs. $\sin^2 2\theta_{13}$ for different θ_{23}

NOTE: PDG'12 3σ region for $\sin^2\theta_{23}$:0.34-0.64

reactor 1σ region (PDG '12)
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$



FROM NOW ON

T2K CP violation (sinδ≠0) sensitivity

Simultaneously fitting ν_μ disappearance and ν_e appearance data
Use $\sin^2 2\theta_{13}$ constraint by reactor experiment

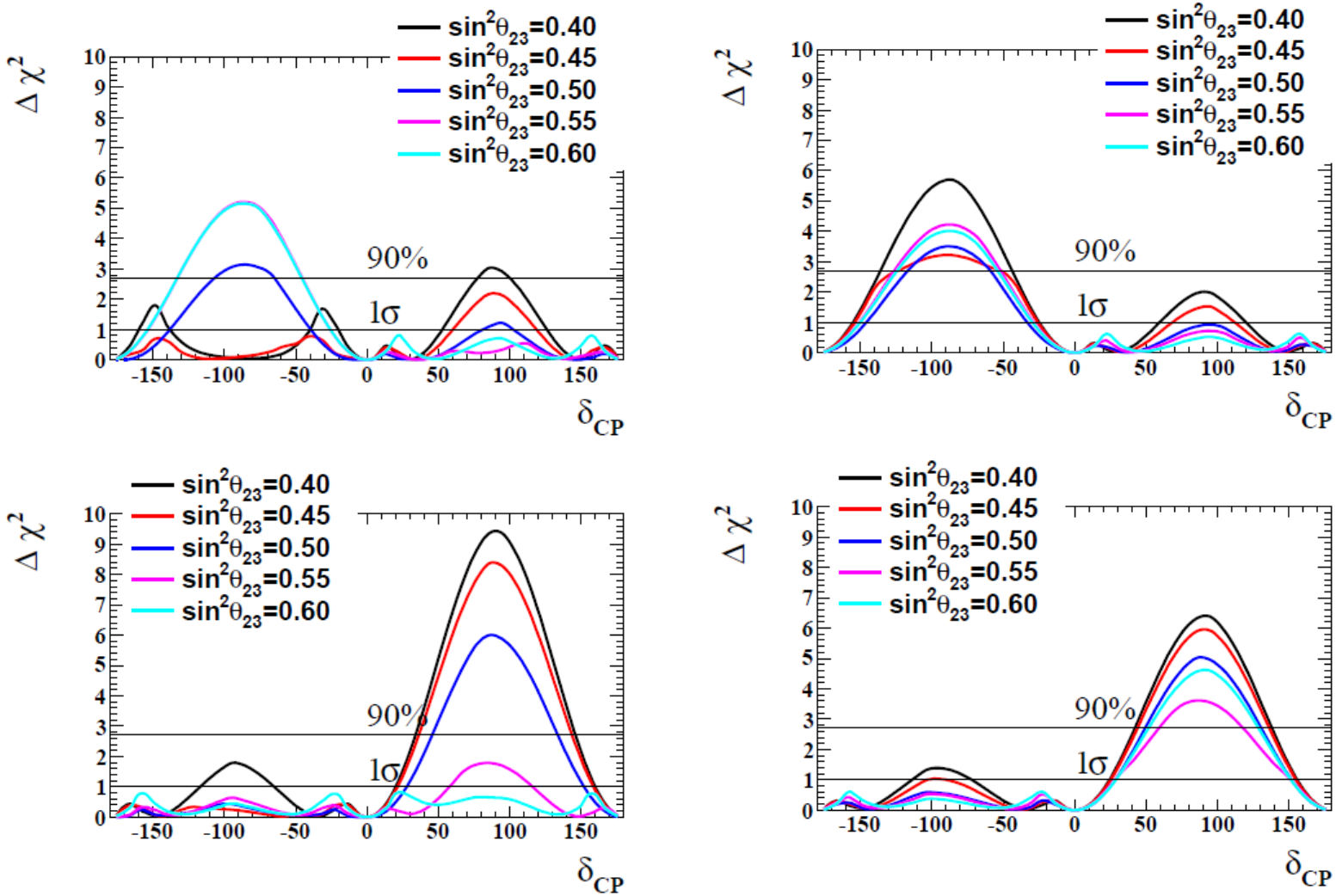
No sys. error

100% ν-mode

50%:50% ν-mode: $\bar{\nu}$-mode

NH

IH

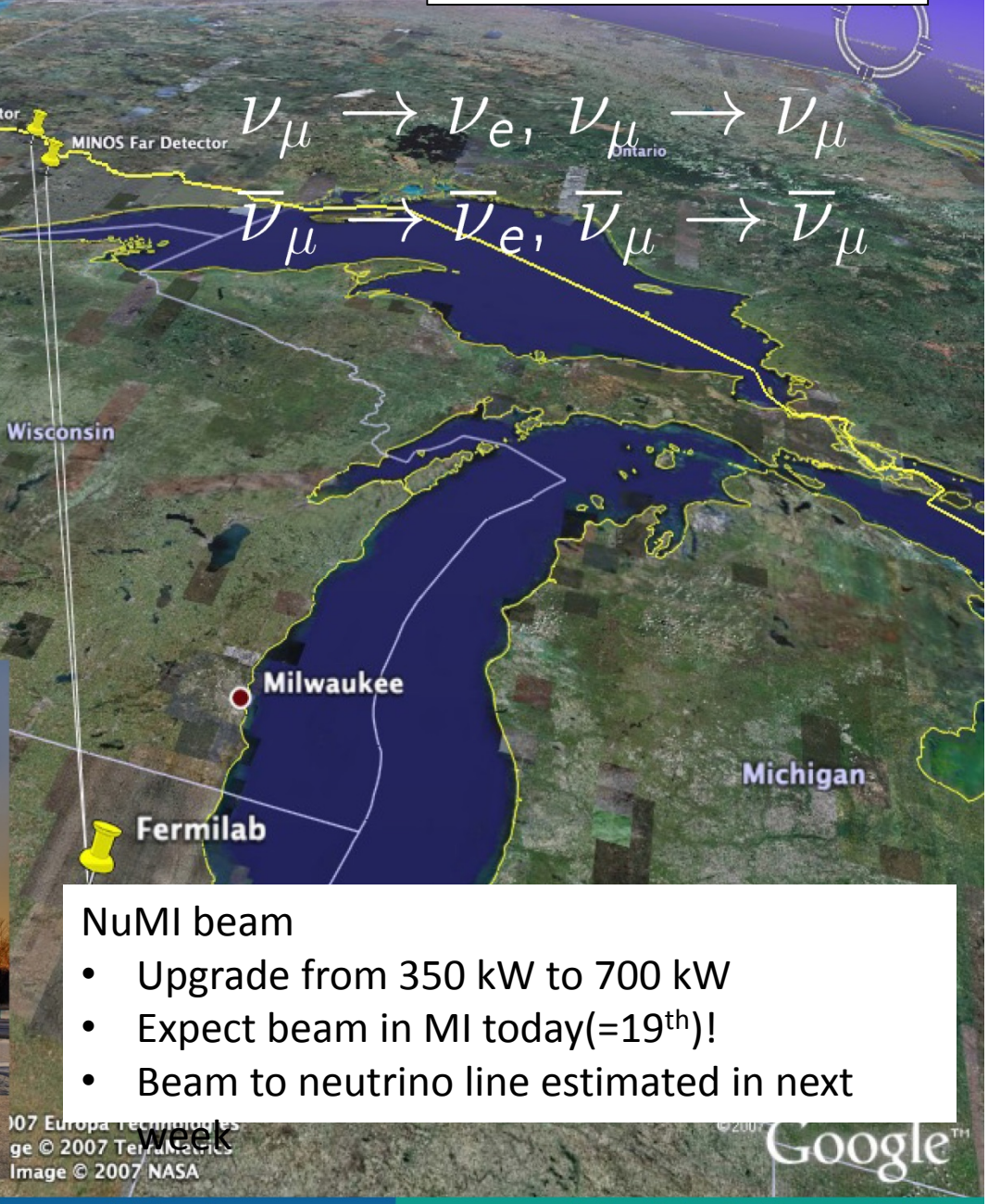


The NOνA Experiment

A. Waldron, EPS HEP2013

$$\nu_\mu \to \nu_e,\ \nu_\mu \to \nu_\mu$$

$$\bar{\nu}_\mu \to \bar{\nu}_e,\ \bar{\nu}_\mu \to \bar{\nu}_\mu$$

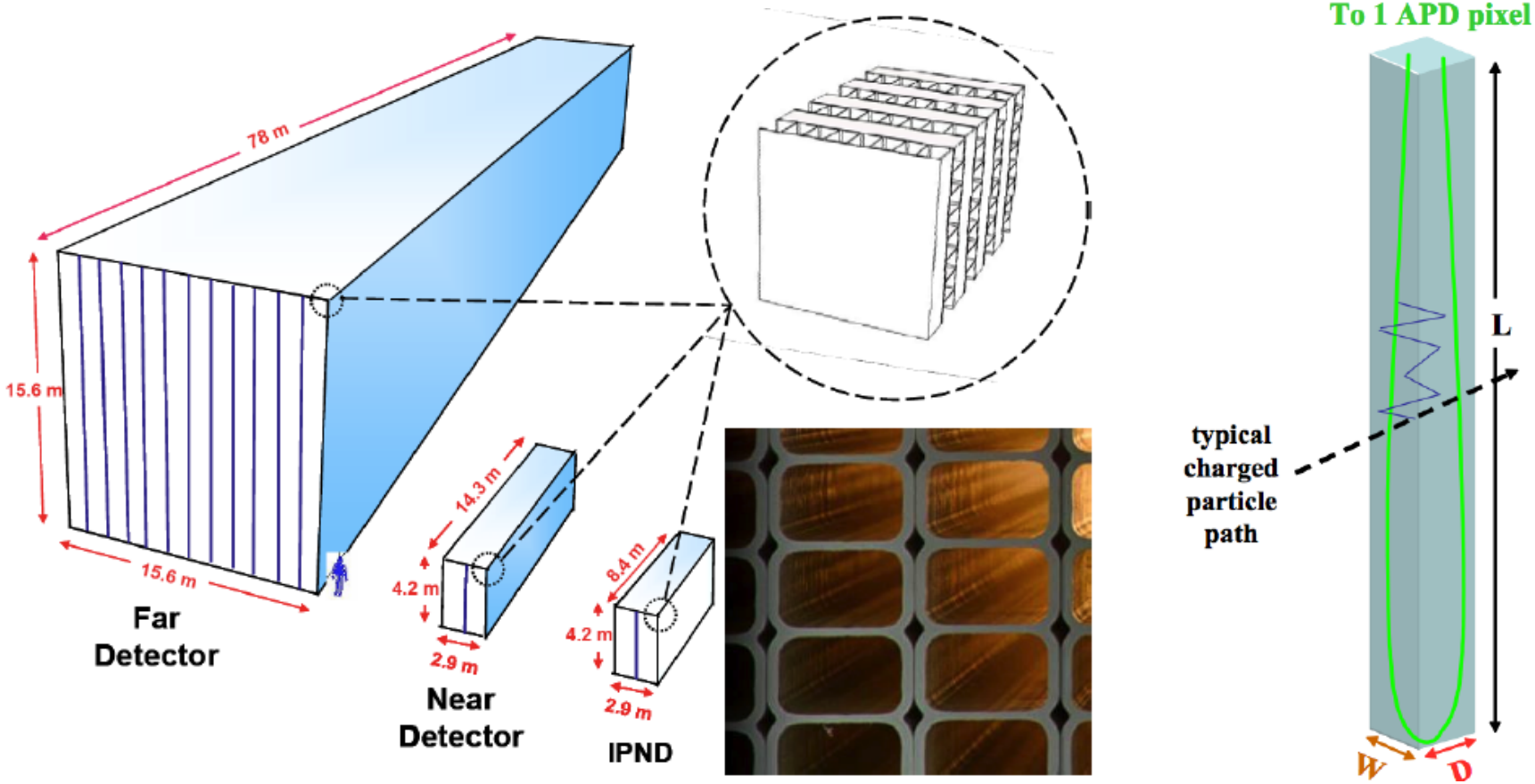


NuMI beam

- Upgrade from 350 kW to 700 kW
- Expect beam in MI today(=19th)!
- Beam to neutrino line estimated in next week

A. Waldron, EPS HEP2013

NOvA Far Detector Construction status



14 kilotons = 28 NOvA Blocks

17 blocks of PVC modules are assembled and installed in place

10.96 blocks are filled with liquid scintillator

4.17 blocks are outfitted with electronics

Expected to complete in April/May 2014

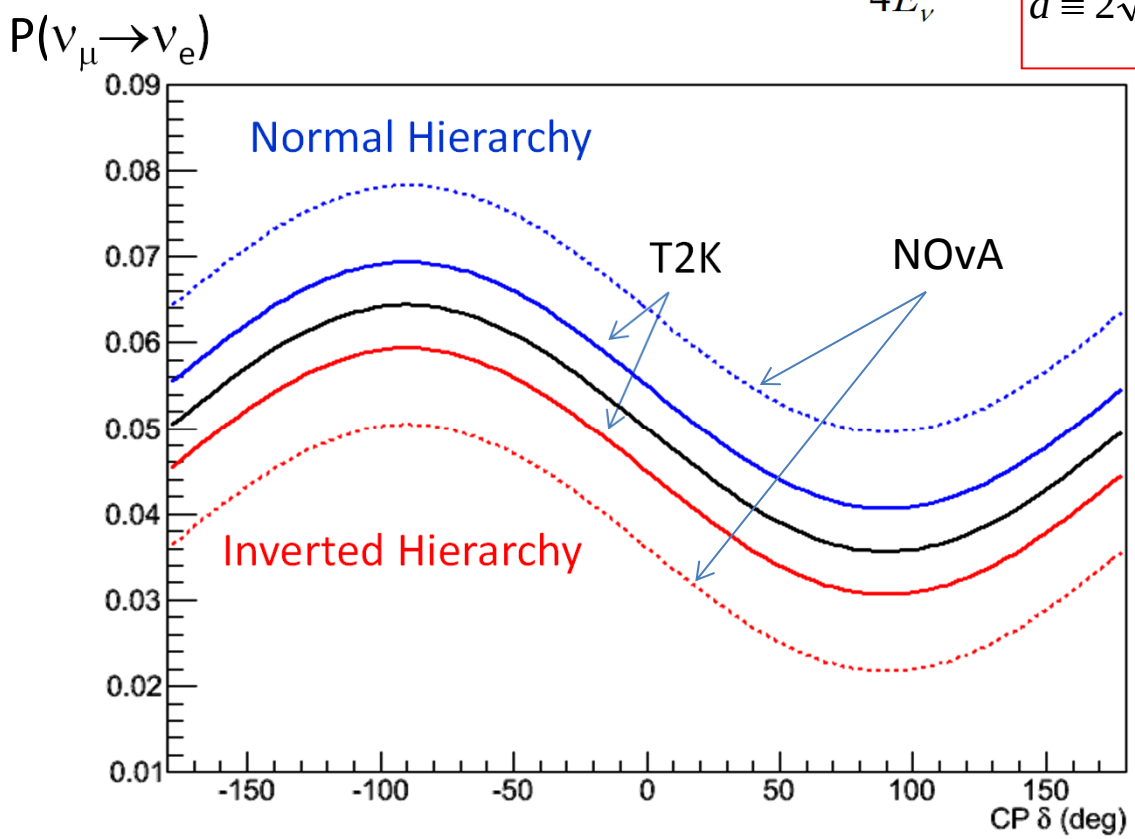
ν_e appearance at oscillation maximum

$$P(\nu_\mu \to \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \left(1 + \frac{2a}{\Delta m_{31}^2}\right) - 8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin\delta$$

Matter effect

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \mathrm{eV}^2 \frac{\rho}{g\mathrm{cm}^{-3}} \frac{E}{GeV}$$



ν_e feels different potential than ν_μ and ν_τ in earth.

$\delta \to -\delta$, $\alpha \to -\alpha$
for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

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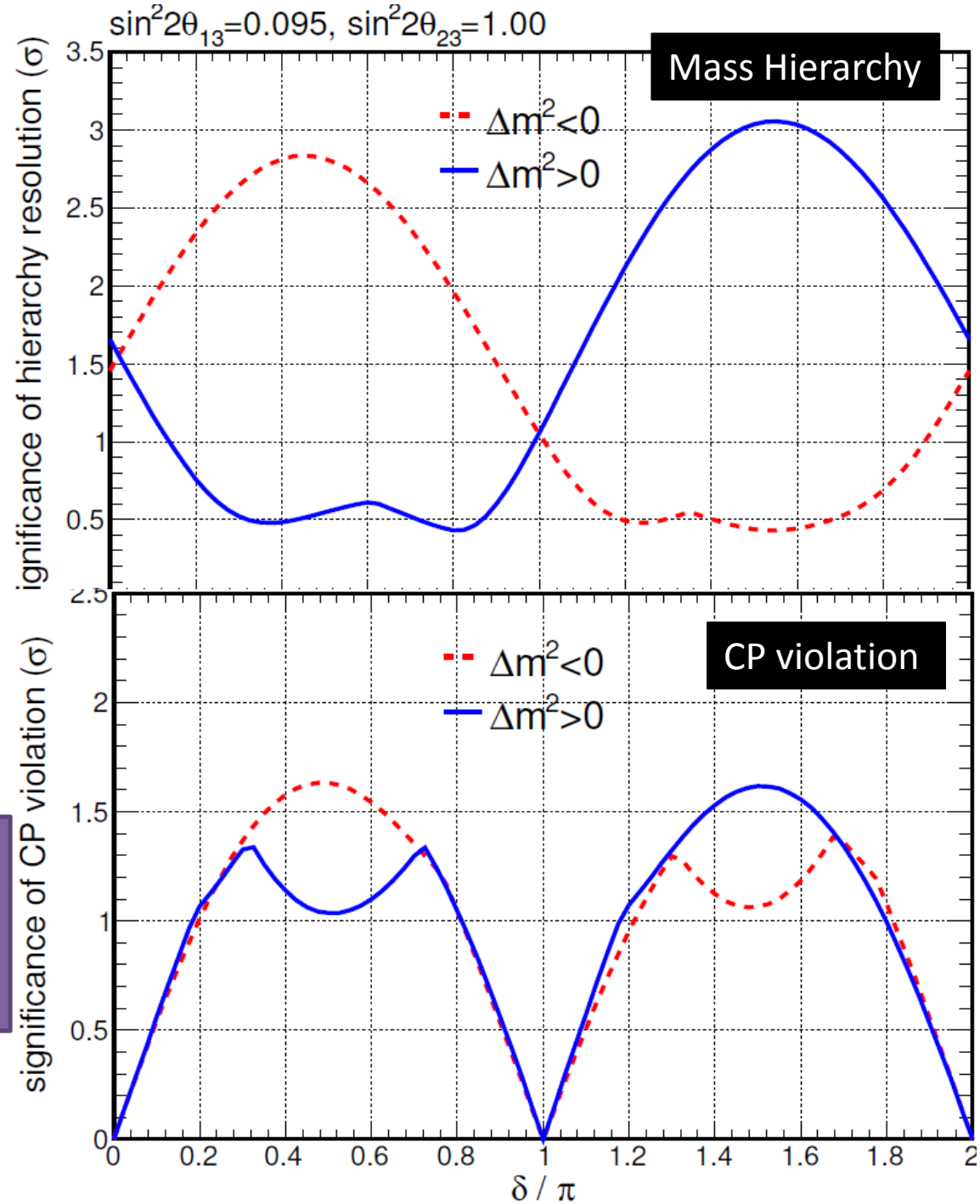
NOvA sensitivity

in case running **3 years in ν-mode** and **3 years in $\bar{\nu}$-mode**.
$\sin^2 2\theta_{13}=0.095$, $\sin^2 2\theta_{23}=1.00$

NOTE! Sensitivities for CP δ and MH are significantly increased by combining T2K(L=295km) and NOvA(L=819km)



LBN Next generation experiments

A short summary of A. Rubbia's talk "Neutrino Program: the future" given on 20th in Joint ECFA-EPS session.

So just two pages summary, here.

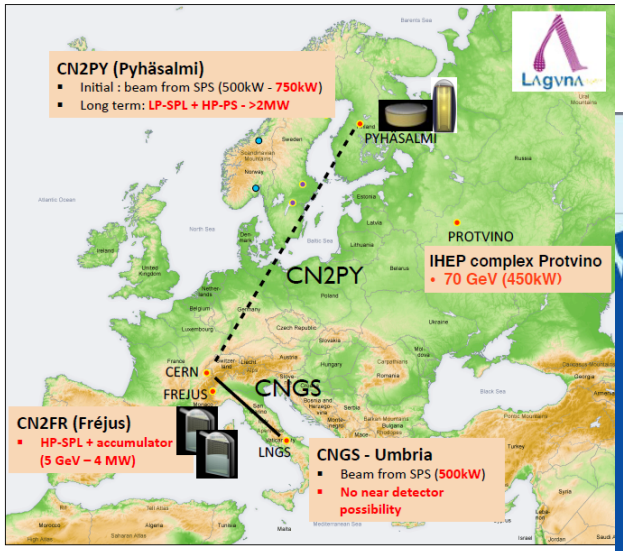
T2K and NOvA would explore the CP phase, θ_{23} and the Mass Hierarchy w/ O(100) ν_e appearance (and ν_μ disappearance) events. ~10% stat. error. (cf. Max. CP asymmetry ~27%)

We may see something in certain lucky cases.

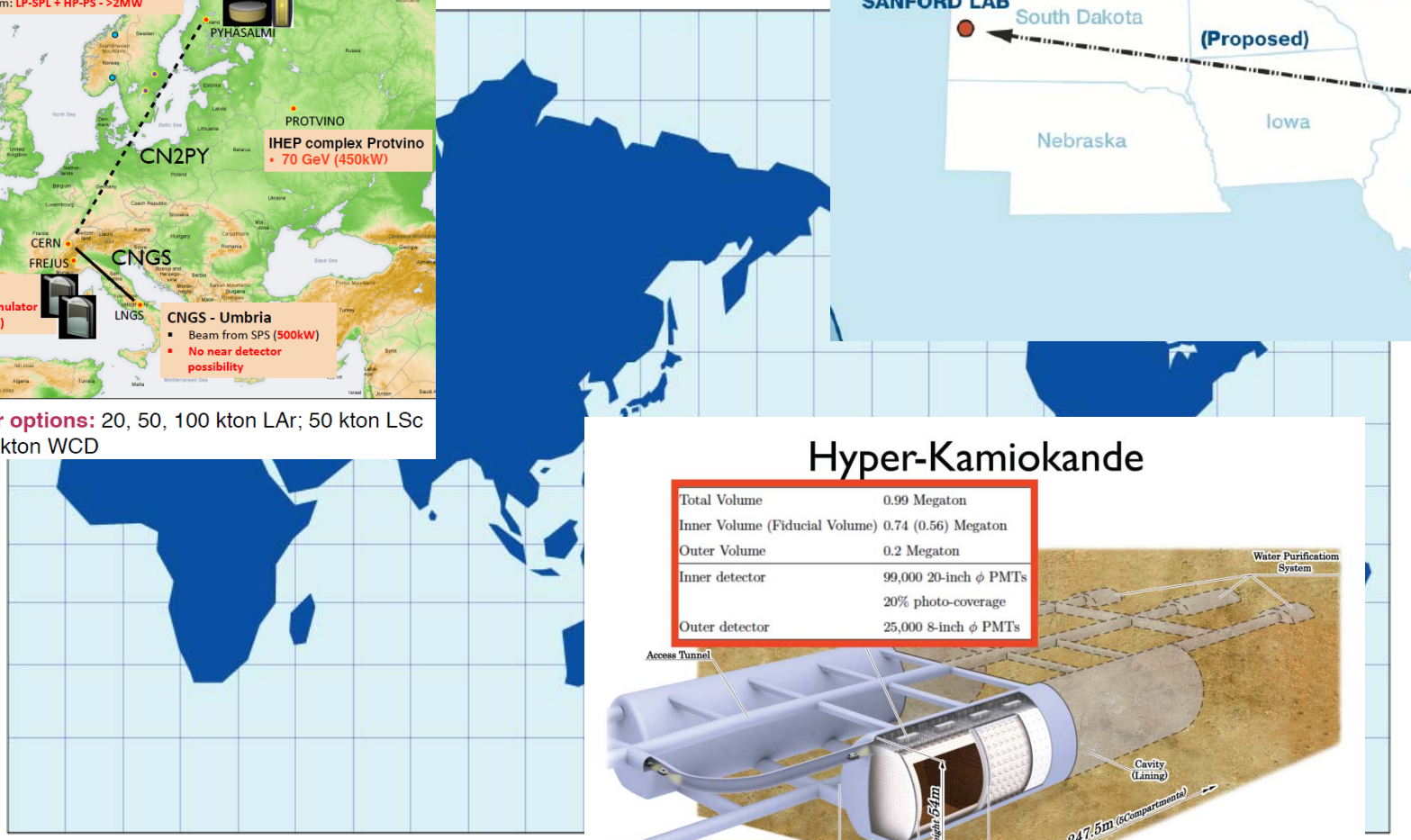
However, in order to fully explore these problems, we need ~10 times more statistics.

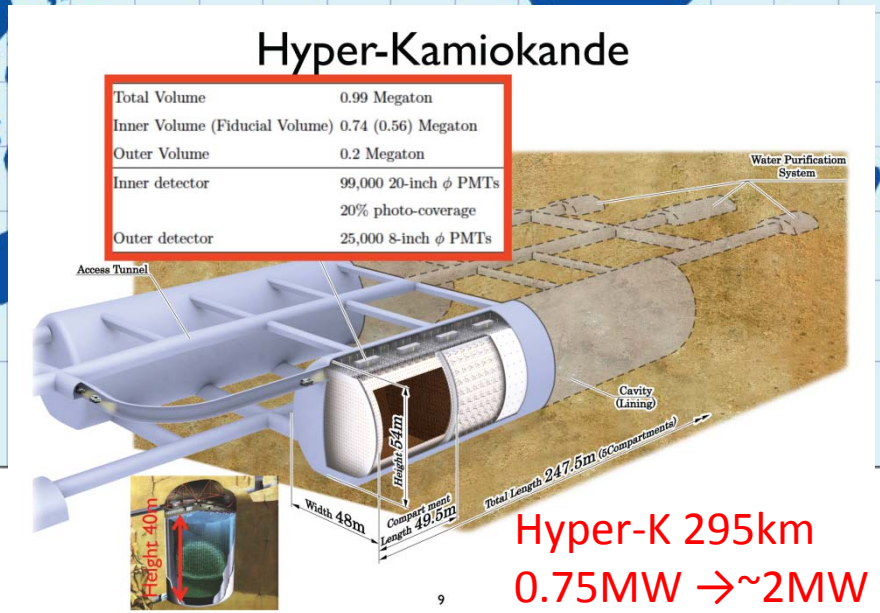
World LBL Future Project

LAGUNA-LBNO 130km?~2,300km?
ESS+WC? 540km?



- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD





Hyper-K 295km
0.75MW →~2MW

Summary

- ν_μ disappearance
  - Confirmed $\nu_\mu \rightarrow \nu_\tau$
  - Precise measurement would answer how close to 45° θ_{23} is. (Current PDG 1σ region is 38° ~45°)
- Anomalies at small L/E need to be solved.
- In the era of Precision measurement
  - Flux and ν interaction
- ν_e appearance
  - Confirmed (T2K 7.5σ)
  - The discovery of non-zero θ_{13} in 2012 is not the end of the story, but is the start of new quest: CP δ, Mass Hierarchy and θ_{23} octant
  - We may start to see something about CP δ.
  - **Stay tuned to T2K and NOvA, and the evolution of future projects**