Long Baseline Accelerator Neutrino Experiments

-Past and Present-

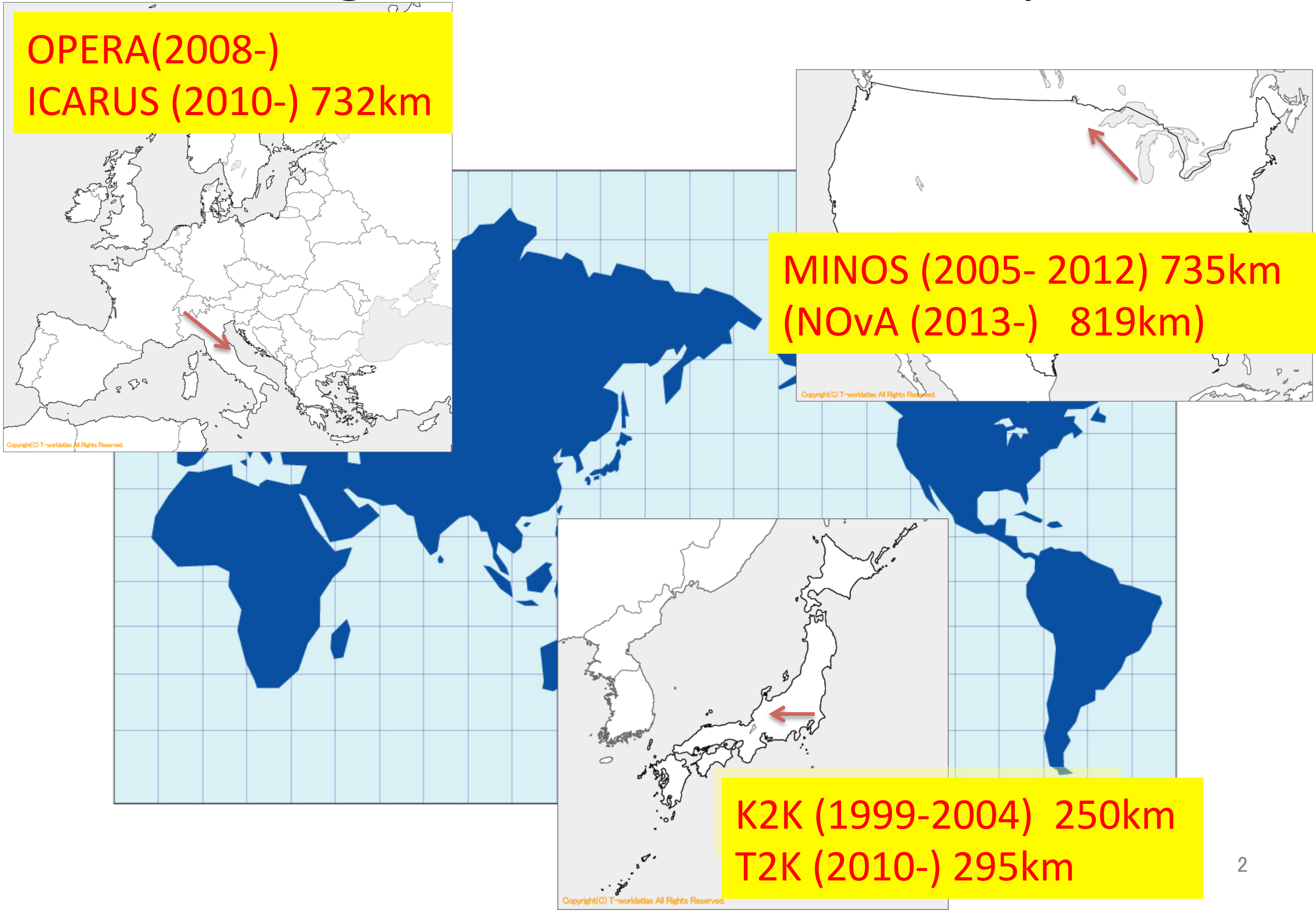
Pontecorvo100

September 18-20, Pisa

Koichiro Nishikawa

KEK

World Long baseline ν oscillation experiments



Recent results

- T2K M. Wilking at EPS conference 13/6/19
- OPERA A. Pastore at EPS conference 13/6/19
- MINOS J.A.B. Coelho at Nu Factory W.S. 13/8/20
  R. Nichol at NEUTRINO 2012
- Daya Bay S. Jetter at Nu Factory W.S. 13/8/20

- Summary talks by
  – A. Ichikawa at EPS conference 13/6/19
  – Sam Zeller at Lepton/Photon 13/6/27

Contents

1. Experimental issues in long baseline experiments with accelerator beam

2. New results

3. A thought on the future

1. Experimental issues

- Only the product F(E) x σ(E) are measurable
  - Flux times cross section as a function of E

$$N_{obs}^{far}(E_\nu) = P_{\nu_\alpha \to \nu_\beta}(E_\nu) \cdot F^{far}(E_\nu) \cdot \sigma(E_\nu)$$

$$N_{obs}^{near}(E_\nu) = F^{near}(E_\nu) \cdot \sigma(E_\nu)$$

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu) = \frac{N_{obs}}{N_{predict}} = \frac{N_{obs}^{far}(E_\nu)}{N_{obs}^{near}(E_\nu)} \cdot \frac{F^{near}(E_\nu)}{F^{far}(E_\nu)} \quad (= \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 \frac{L}{E_\nu}))$$

- To get $P_{\alpha\to\beta}$

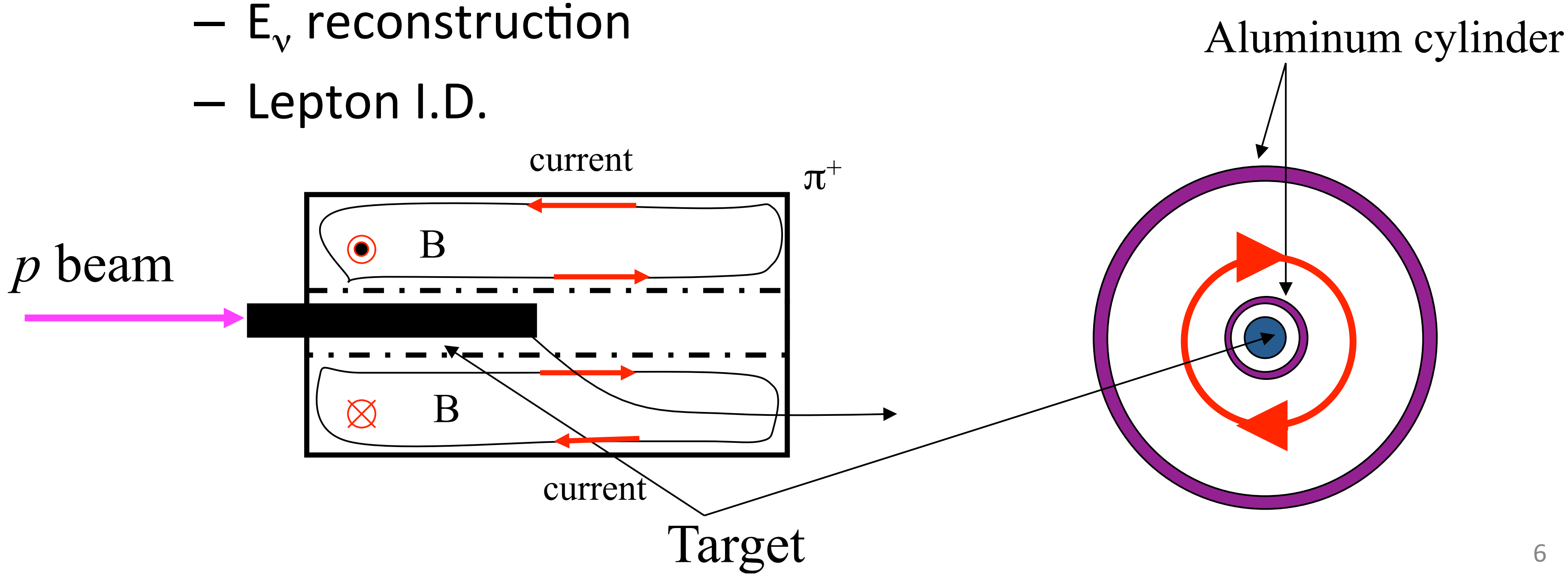
  ① Prediction of neutrino event rate (flux * cross section) without oscillation

  ② Simultaneous measurements at far and near

    - Different spectrum at far and near
    - Neutrino interactions and their cross sections

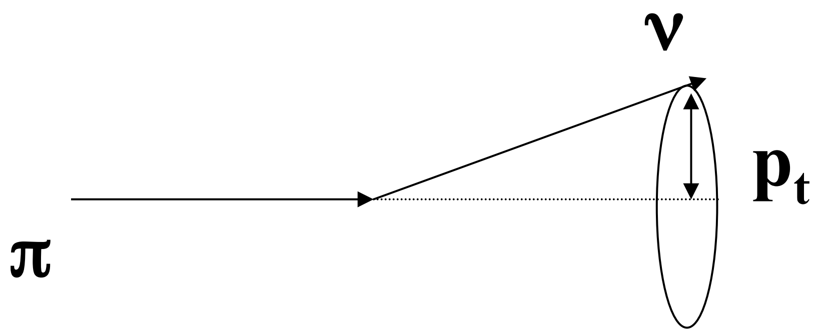
① Highest possible intensity : wide band horn focused beam

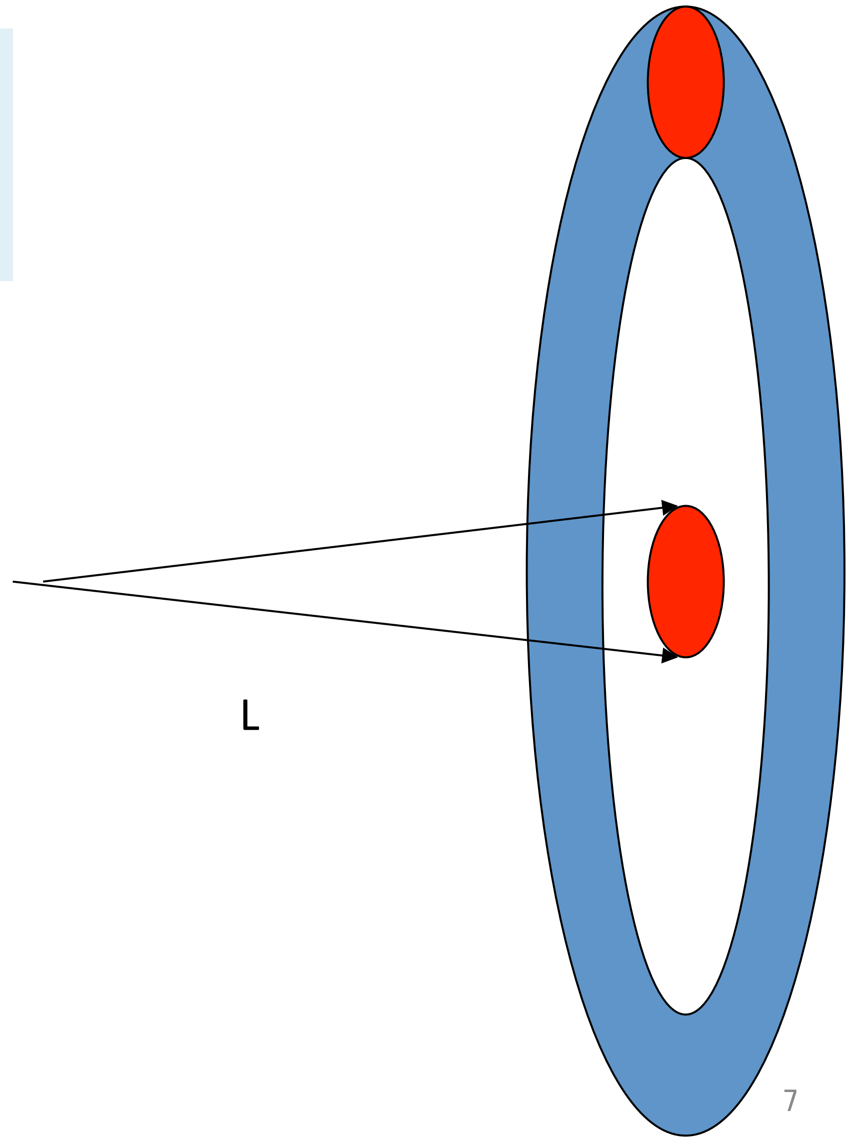
- Focus of π,K as much as possible to forward direction
  - magnetic horn
- Wide range of L/E coverage
- Detector performance in wide range of E
  - E_ν reconstruction
  - Lepton I.D.



Decay Kinematics and Solid angle

To get max neutrino intensity
- Focus pions by horn, quads,..
- 0 degree

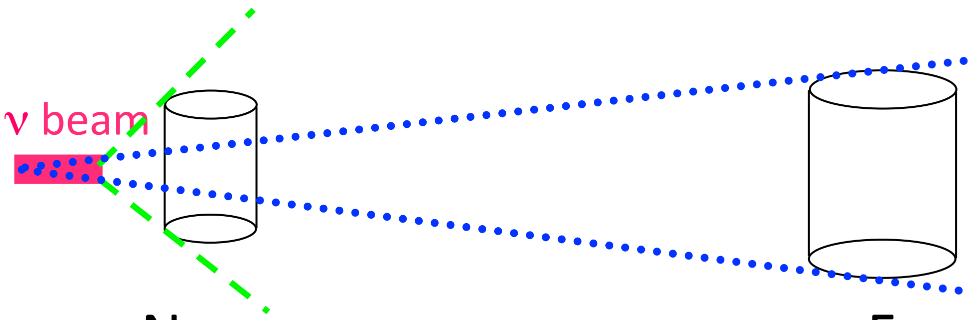




$$\gamma = \frac{E_\pi}{m_\pi}, \; p_{cm} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \sim 35\text{MeV}$$

$$E_\nu(\theta) = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2(1+\gamma^2\theta^2)} E_\pi \approx \frac{0.5E_\pi}{(1+\gamma^2\theta^2)}$$

Different spectrum in wide band beam

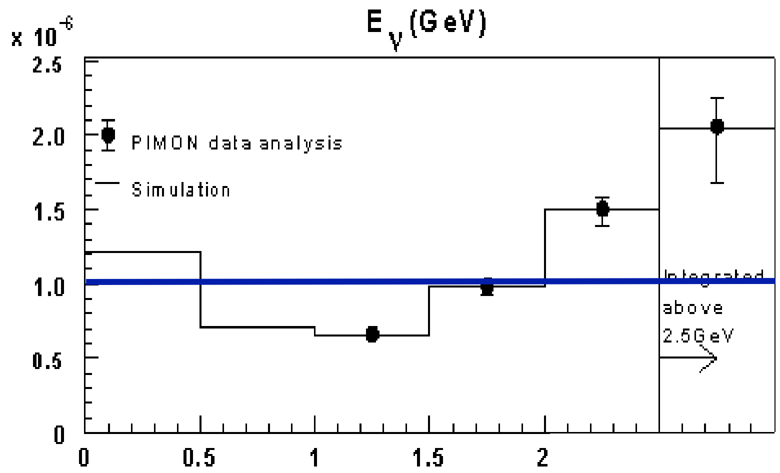


Far/Near E_ν dependence : decay length and angular acceptances

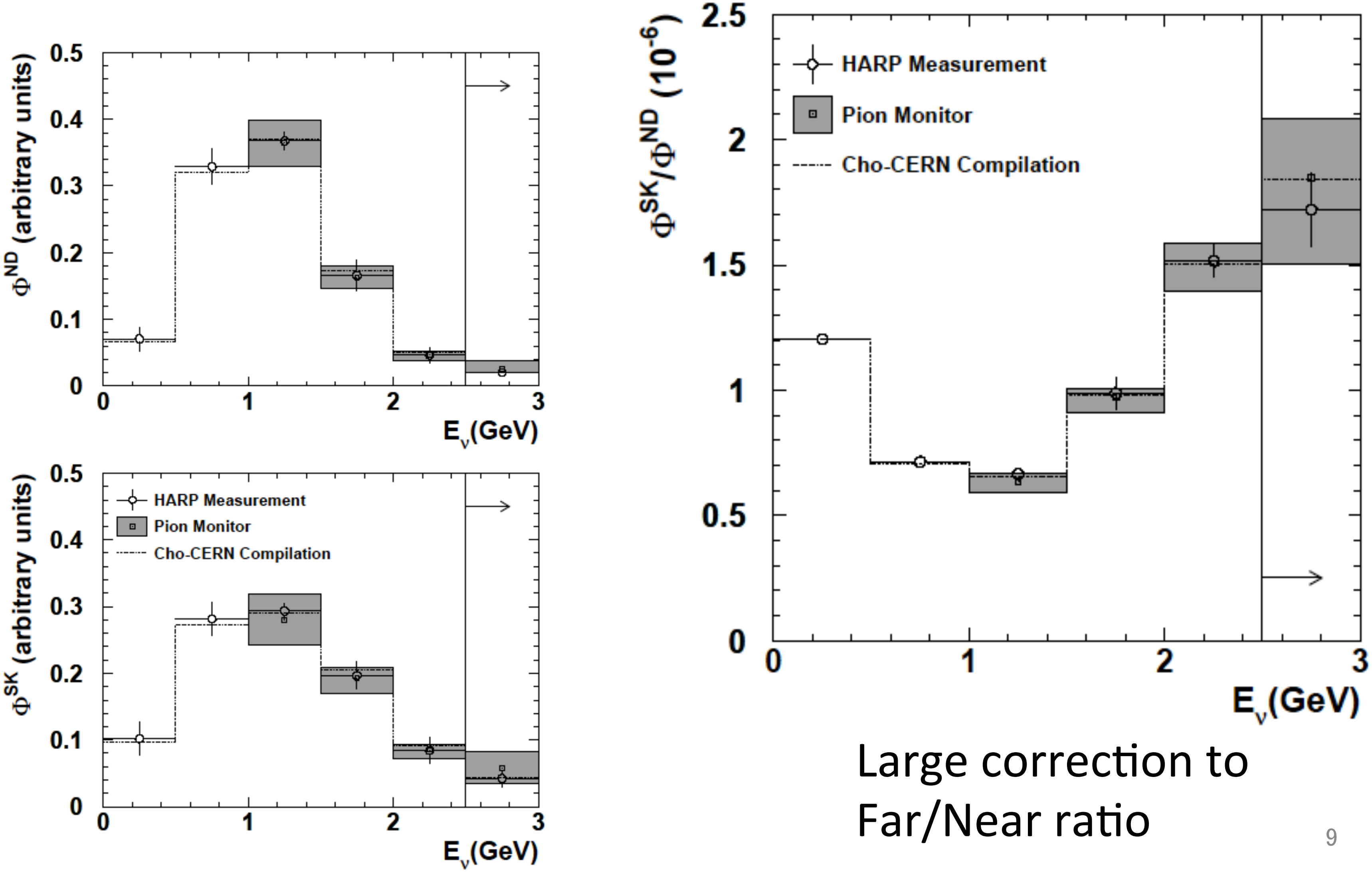
1. Decay angular divergence $1/E\pi$ Far(high E) ↗
2. π decay length $E\pi$ Near(high E) ↗
3. wide angle π decay $E\nu \sim E\pi\ 0.49/(1+\gamma^2\theta^2\pi)$ Near(lowE) ↘

Knowing π, K production (p, θ), focusing, and decay volume geometry

F/N



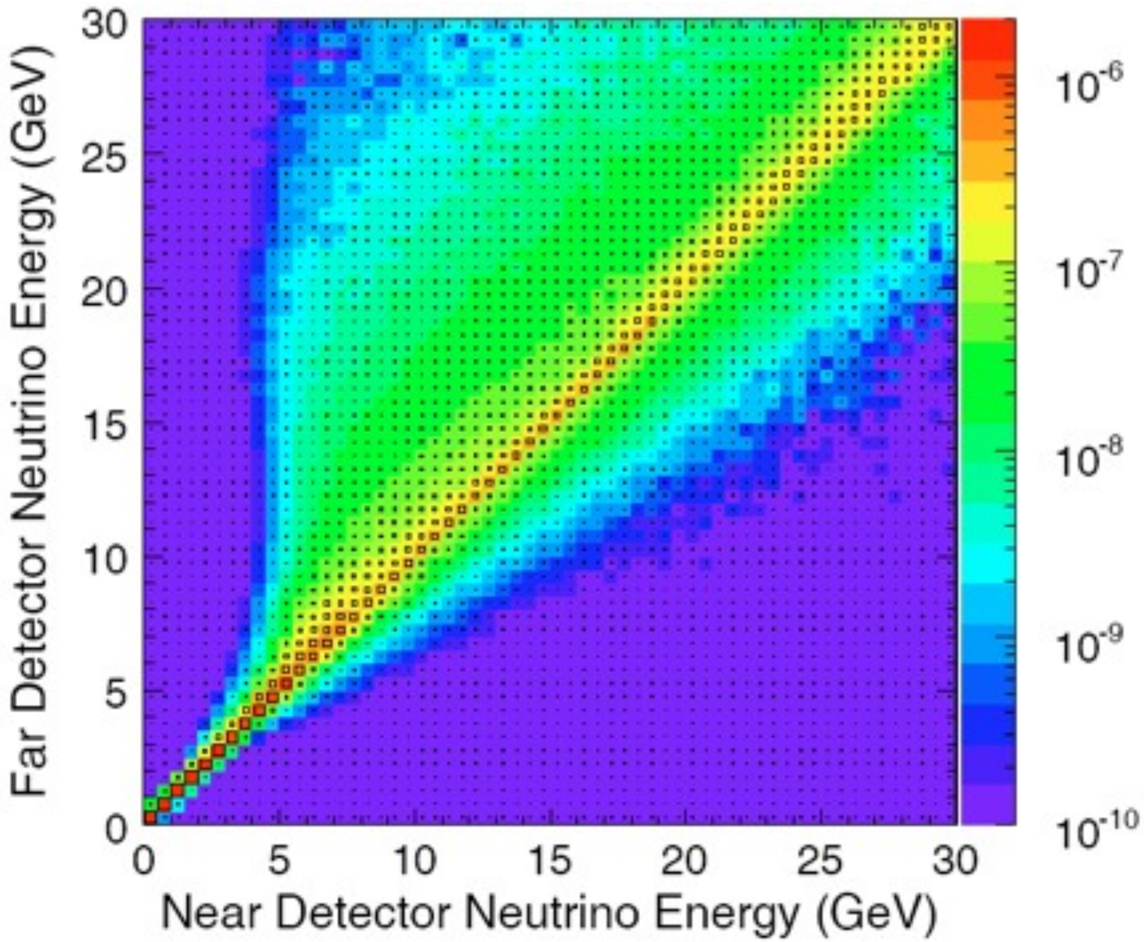
Near Far neutrino spectrum in K2K using HARP hadron production measurements



Large correction to Far/Near ratio

Near Far neutrino spectrum in MINOS

R. Nichol NEUTRINO2012

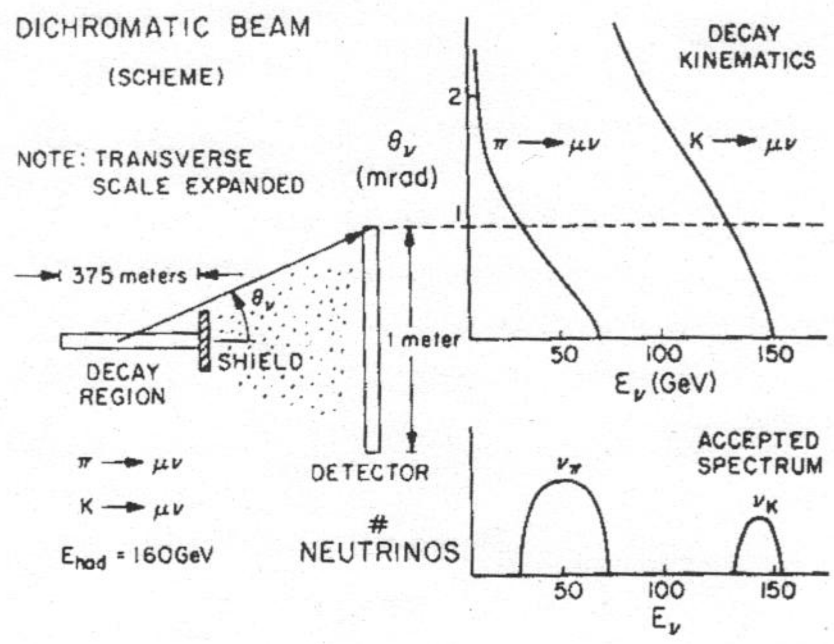


Narrow Band Beam to study high energy neutrino interactions

- Small low energy components
- Acceptance of the beam line limits neutrino intensity
- Incident neutrino energies are two values

$$E_\nu(\pi - \text{decay}) = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2(1+\gamma^2\theta^2)} E_\pi \approx \frac{0.49 E_\pi}{(1+\gamma^2\theta^2)}$$

$$E_\nu(K - \text{decay}) = \frac{m_K^2 - m_\mu^2}{m_K^2(1+\gamma^2\theta^2)} E_\pi \approx \frac{0.96 E_\pi}{(1+\gamma^2\theta^2)}$$



New idea of off-axis beam

1994 TRIUMF KAON factory workshop

Paper presented at the 9th Lake Louise Winter Institute, Lake Louise, Feb. 20–26

TRI-PP-94-34
June 1994

A NEW LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT AT BROOKHAVEN

R. L. HELMER

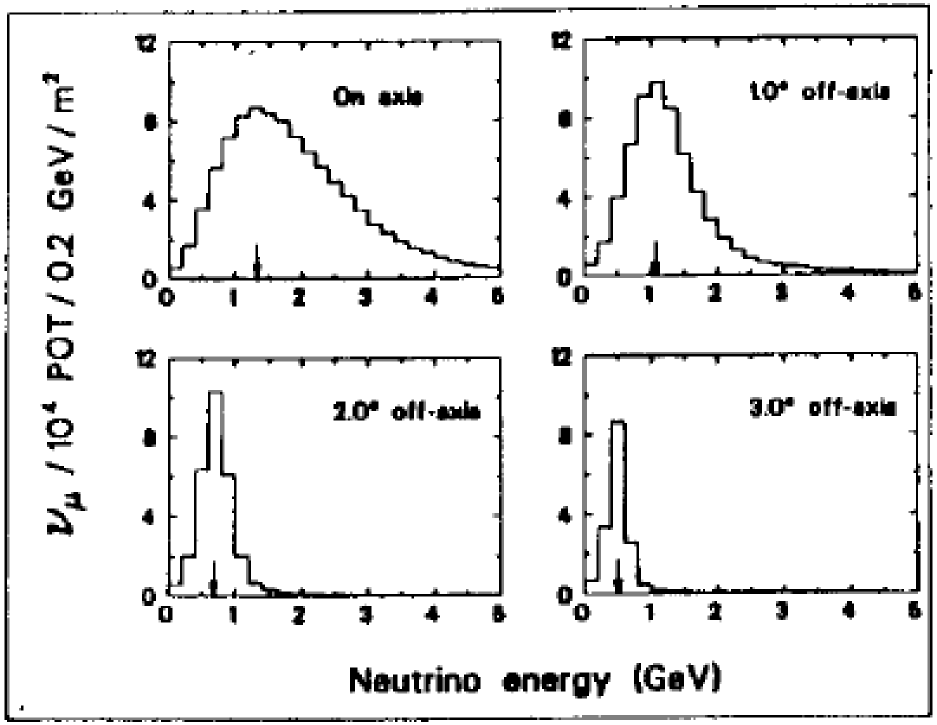
TRIUMF, 4004 Wesbrook Mall
Vancouver, B.C., Canada V6T 2A3

Abstract

J. Anderson	G. Azuelos	M. Barnes
J. Beveridge	G. Chadwick	B. Dall
P. Depommier	F. Farzanpay	D. Frekers
P. Fuchs	P. Gumplinger	S. Hayward
R. Helmer	R. Henderson	G. Jonkmans
H. Laman	B. Larson	R. Meier-Drees
J.-M. Poutissou	M. Sevior	A. Trudel
B. Vander Ende	M. Vetterli	G. Wait
W. Wall	C. Waltham	N. Weiss
D. Wright	S. Yen	

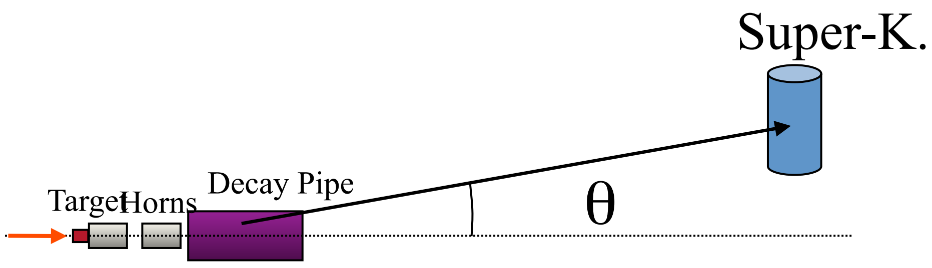
Table 1: Members of the TRIUMF Neutrino Working Group.

seen, there will be no ambiguities in its interpretation.



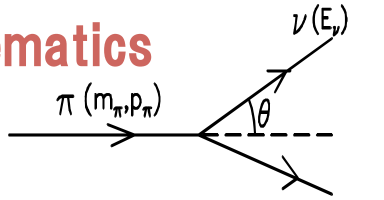
BNL long baseline proposal
(not realized)

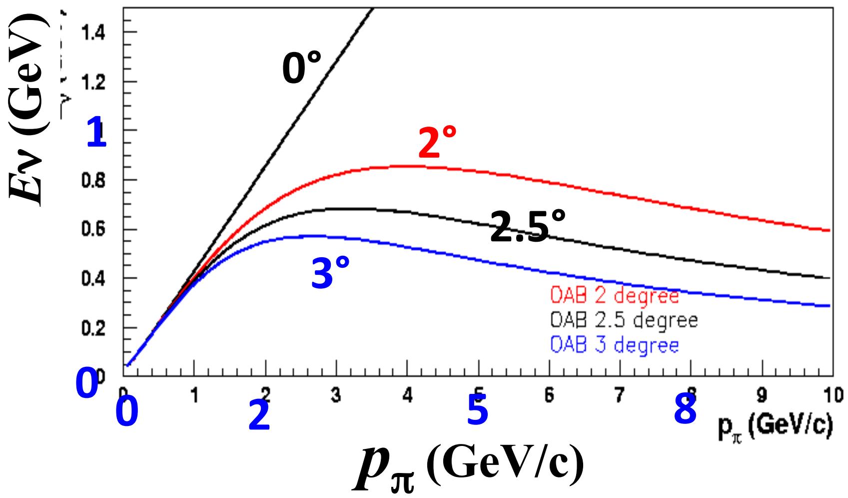
Narrow intense beam: Off-axis beam in T2K

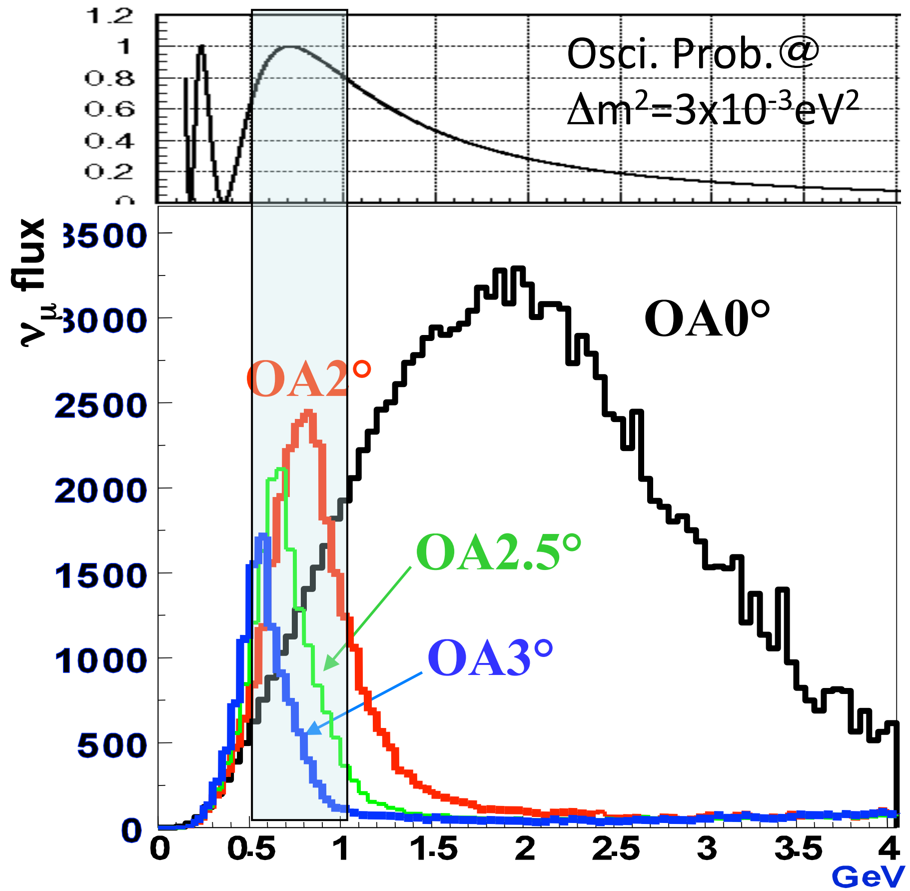


large number of oscillating ν
small H.E. components
Insensitive to pi/K production

π decay Kinematics



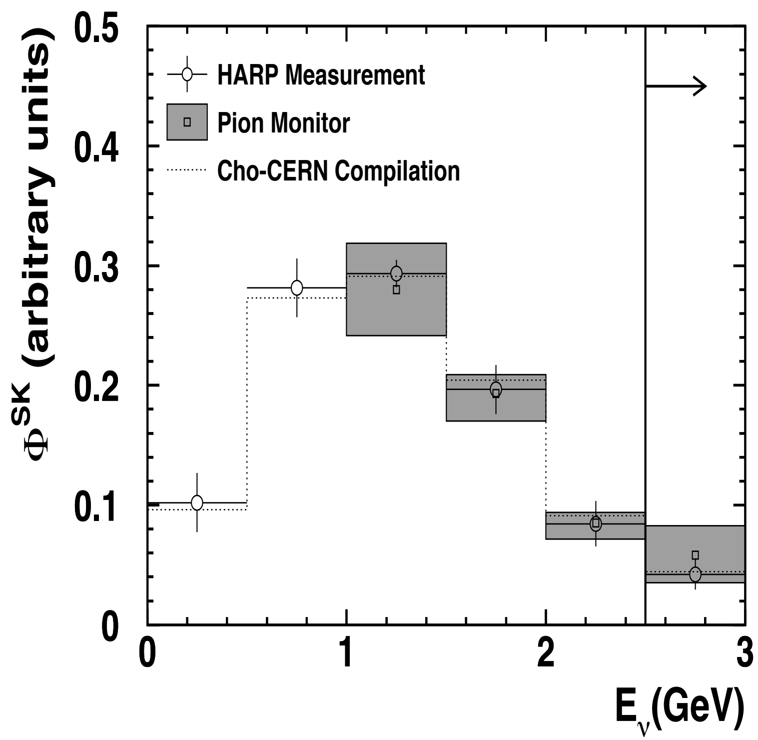




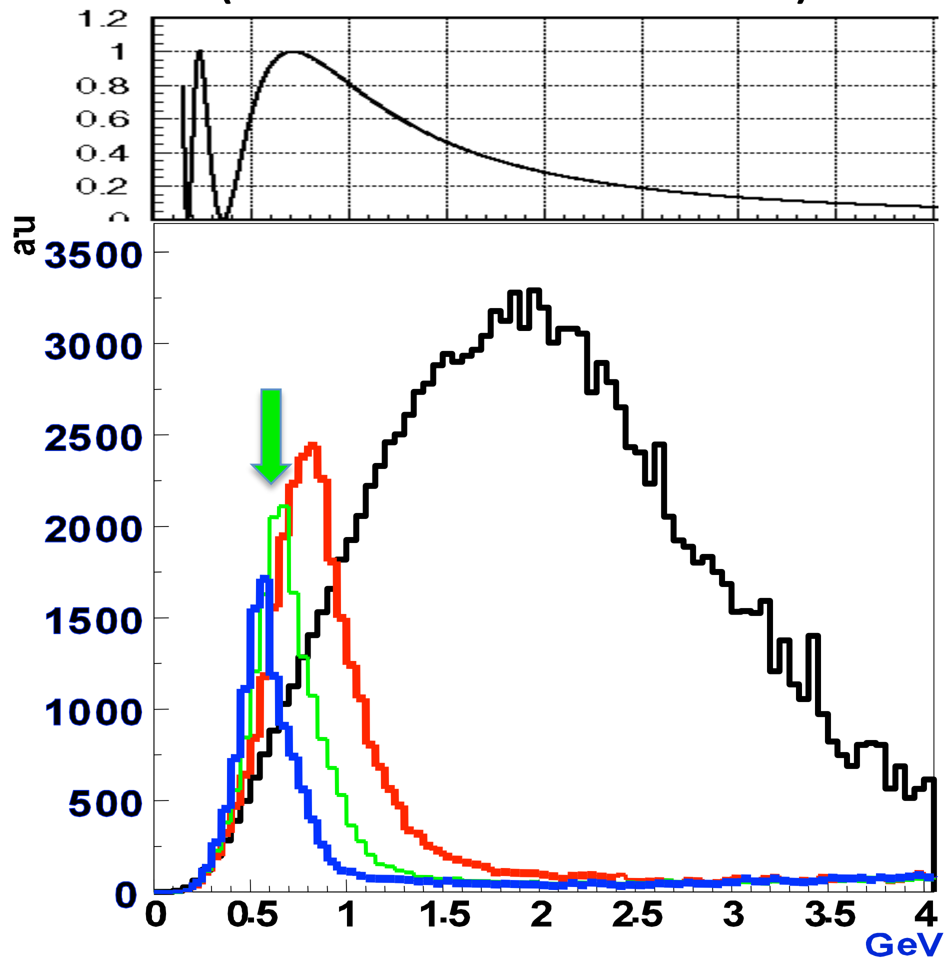
Pions with different energies give neutrinos with similar energy

Comparison of two kinds of beam – example

K2K (wide band beam) and T2K (narrow band beam)



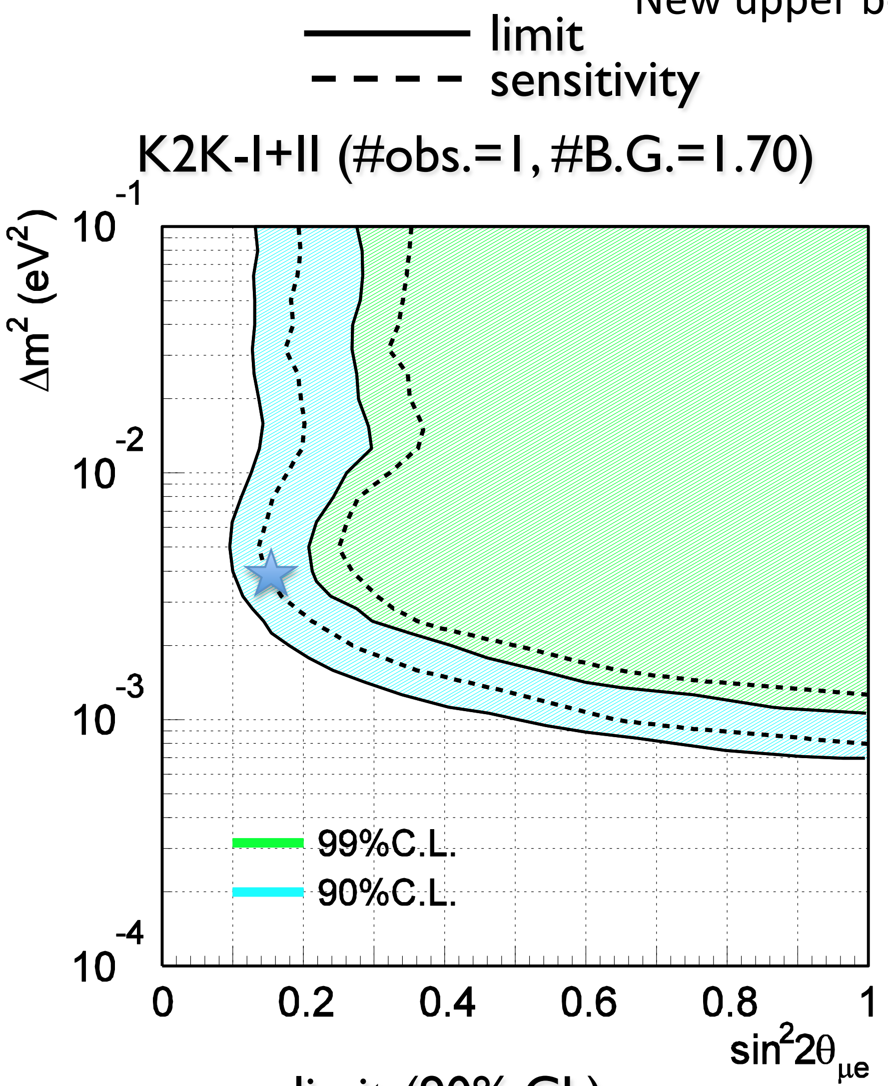
K2K horn focused on-axis beam
12 GeV proton beam



T2K off-axis beam

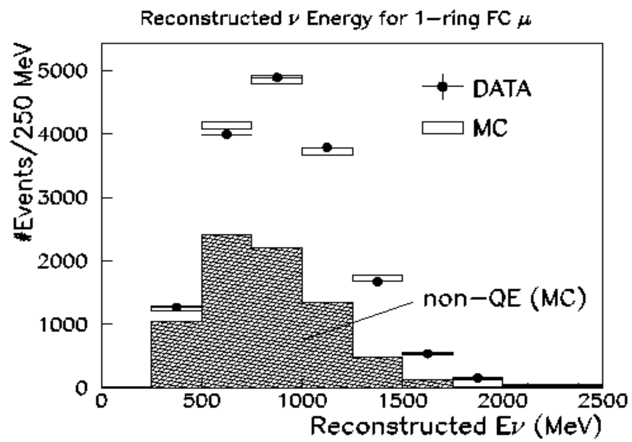
Effect from HE tail
ν_e appearance upper bound in K2K (2005)

New upper bounds w/ HARP F/N:

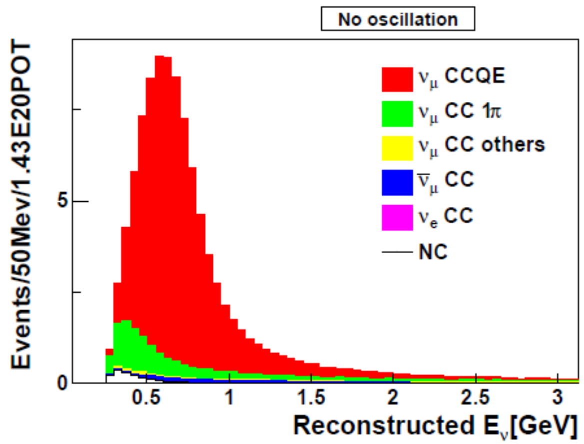


<u>upper limit (90% CL)</u>

$\sin^2 2\theta_{\mu e}$=0.13 @2.8e-3 eV^2



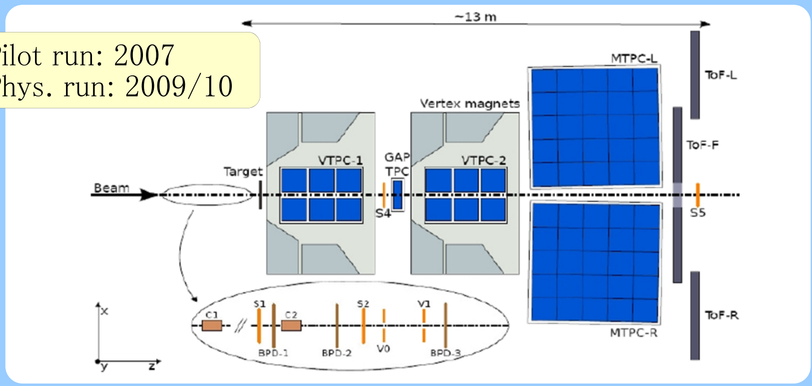
K2K wide band beam



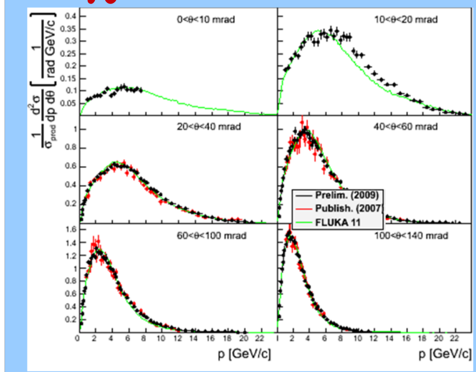
T2K Narrow band beam

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

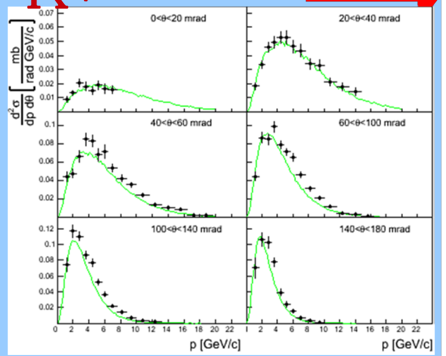
Pilot run: 2007
Phys. run: 2009/10



$\pi+$



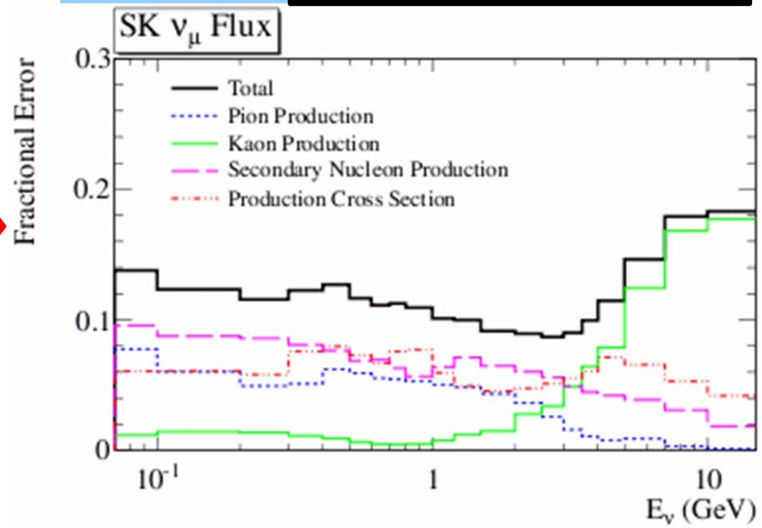
K+



- 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



2.5° Off axis beam

Alexander Korzenev EPS-HEP2013

Relatively insensitive to the pion/kaon spectrum

② Simultaneous measurements at far and near

$$N_{obs}^{far}(E_\nu) = P_{\nu_\alpha \to \nu_\beta}(E_\nu) \cdot F^{far}(E_\nu) \cdot \sigma(E_\nu)$$

$$N_{obs}^{near}(E_\nu) = F^{near}(E_\nu) \cdot \sigma(E_\nu)$$

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu) = \frac{N_{obs}^{far}(E_\nu)}{N_{obs}^{near}(E_\nu)} \cdot \frac{F^{near}(E_\nu)}{F^{far}(E_\nu)} \quad (= \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 \frac{L}{E_\nu}))$$

Step to extract $P_{\alpha\to\beta}$ $\quad E_\nu \to$ E(reconstructed)

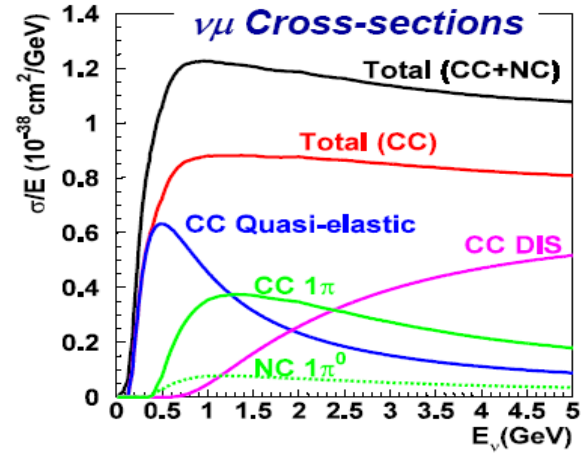
$N_{obs}^{near}(E_r) = F^{near}(E_r) \cdot \sigma(E_r)$ → **Neutrino interaction model** → $F^{near}(E_\nu)$

Flux at far with null oscillation hypothesis → $\frac{F^{far}(E_\nu)}{F^{near}(E_\nu)} \cdot F^{near}(E_\nu) \cdot P_{\alpha\to\beta}(E_\nu)$

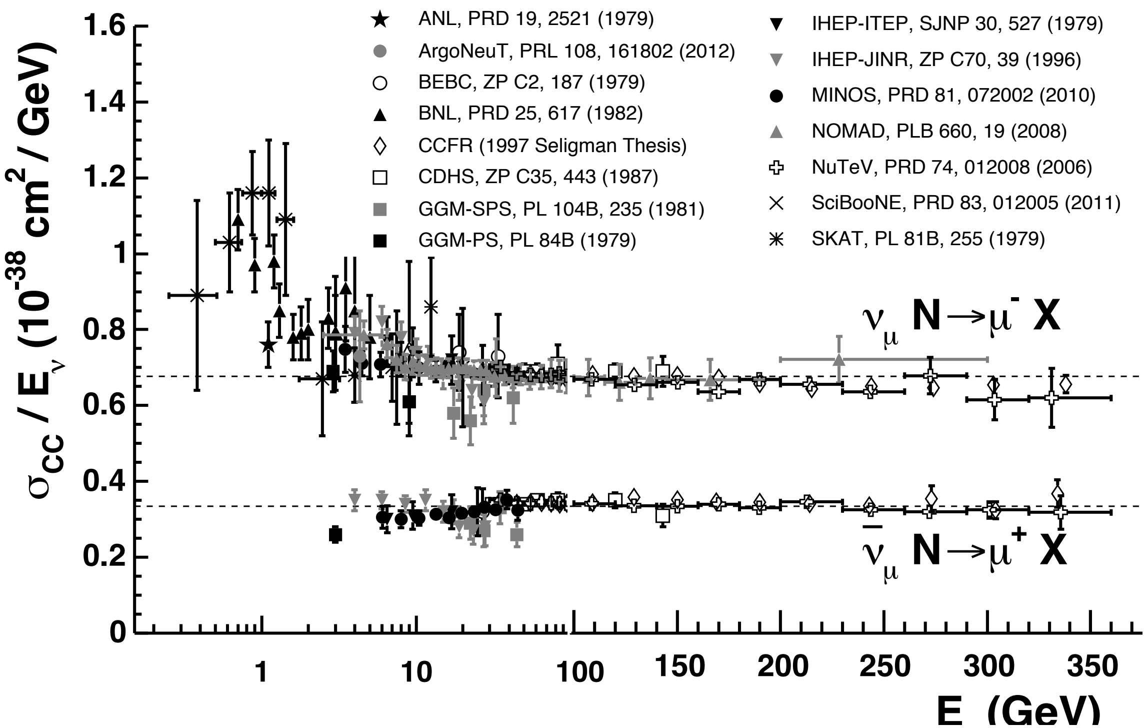
Neutrino interaction model → $N_{obs}^{far}(E_r) \Leftrightarrow P_{\nu_\alpha \to \nu_\beta}(E_\nu) \cdot F^{far}(E_\nu) \cdot \sigma(E_\nu)$

E_r : Various processes contribute

- Nuclear effects at sub-GeV - GeV region
  - Pauli blocking
  - Multi nucleons contribution
  - Final state interactions
- Two detectors



PDG compilation



Neutrino beam and detectors

- Exploratory experiments : wide range of L/E, large correction to F/N
  - K2K, MINOS used wide-band beam
- Knowing what to and where to look for a specific events, like ν_e appearance in ν_μ beam
  - T2K, NOVA off-axis narrow band beam
- Also depends on detector

- Next stage need serious consideration on the matching of

  Physics, Beam, Detector
  - Scintillator
  - Water Cherenkov
  - Liquid Argon
  - Budget
  - …

2. New Results at L(km)/E(GeV)~500

Three generation scheme

3 mixing angles and (3 phases)

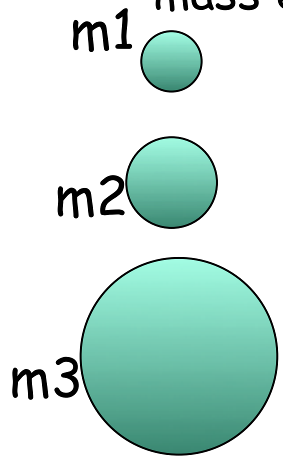
Definition and to be determined by experiments

Three neutrinos

Weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{MNS}} \mathrm{V}_{\mathrm{M}}^{\mathrm{CP}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates



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

cij = cosθij, sij=sinθij

$$V_M^{CP} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

θ_{12}, θ_{23}, θ_{13}
$+ \delta$ (+2 Majorana phase)
Δm_{12}^2, Δm_{23}^2, Δm_{13}^2

Flavor states and mass states

super position $|\nu_e\rangle = a|\nu_1\rangle + b|\nu_2\rangle + c|\nu_3\rangle$

ν_1 is defined as the largest component of ν_e

$$\Rightarrow \quad \theta_{12} < \frac{\pi}{4}, \qquad \theta_{13} < \frac{\pi}{4}$$

Matter effect in solar fix the sign of $m_2 > m_1$

$$\delta m_{12}^2 \approx 8.3 \times 10^{-5} \mathrm{eV}^2 \left(\delta m_{12}^2 > 0\right)$$

To be determined by experiments

$\delta m_{13}^2 > 0$ or <0 ?

$\theta_{23} > \pi/4$ or $\theta_{23} > \pi/4$

What kind of flavor physics behind of this?

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.

Δm^2_{atm}

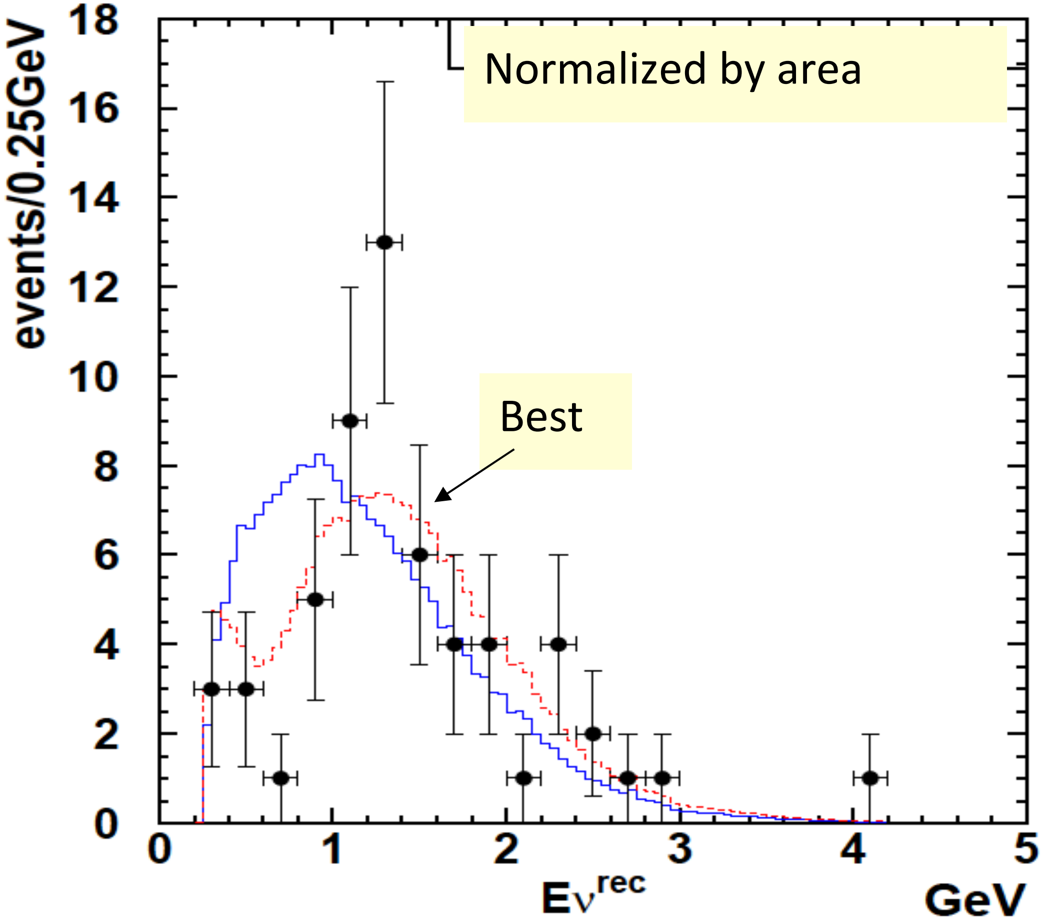
- θ_{13}:ν_e appearance

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

~0.5

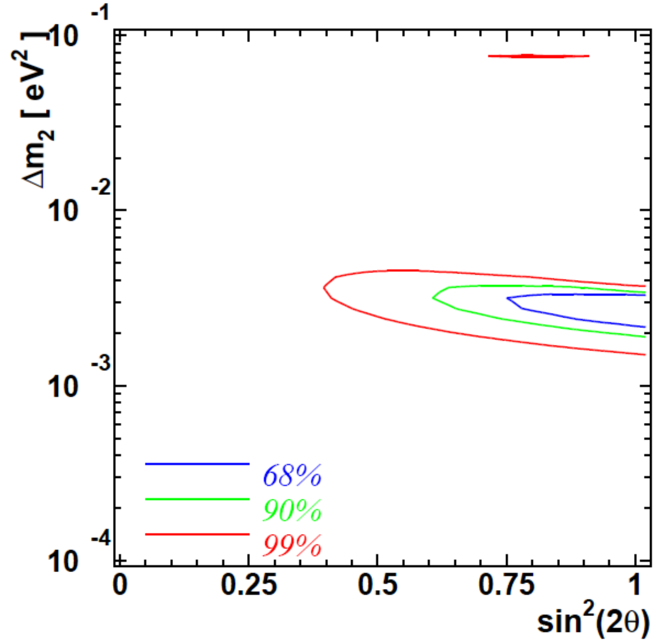
ν_μ disappearance ($\nu_\mu \rightarrow \nu_\tau$?) at L(km)/E(GeV)~500

K2K 1999-2005

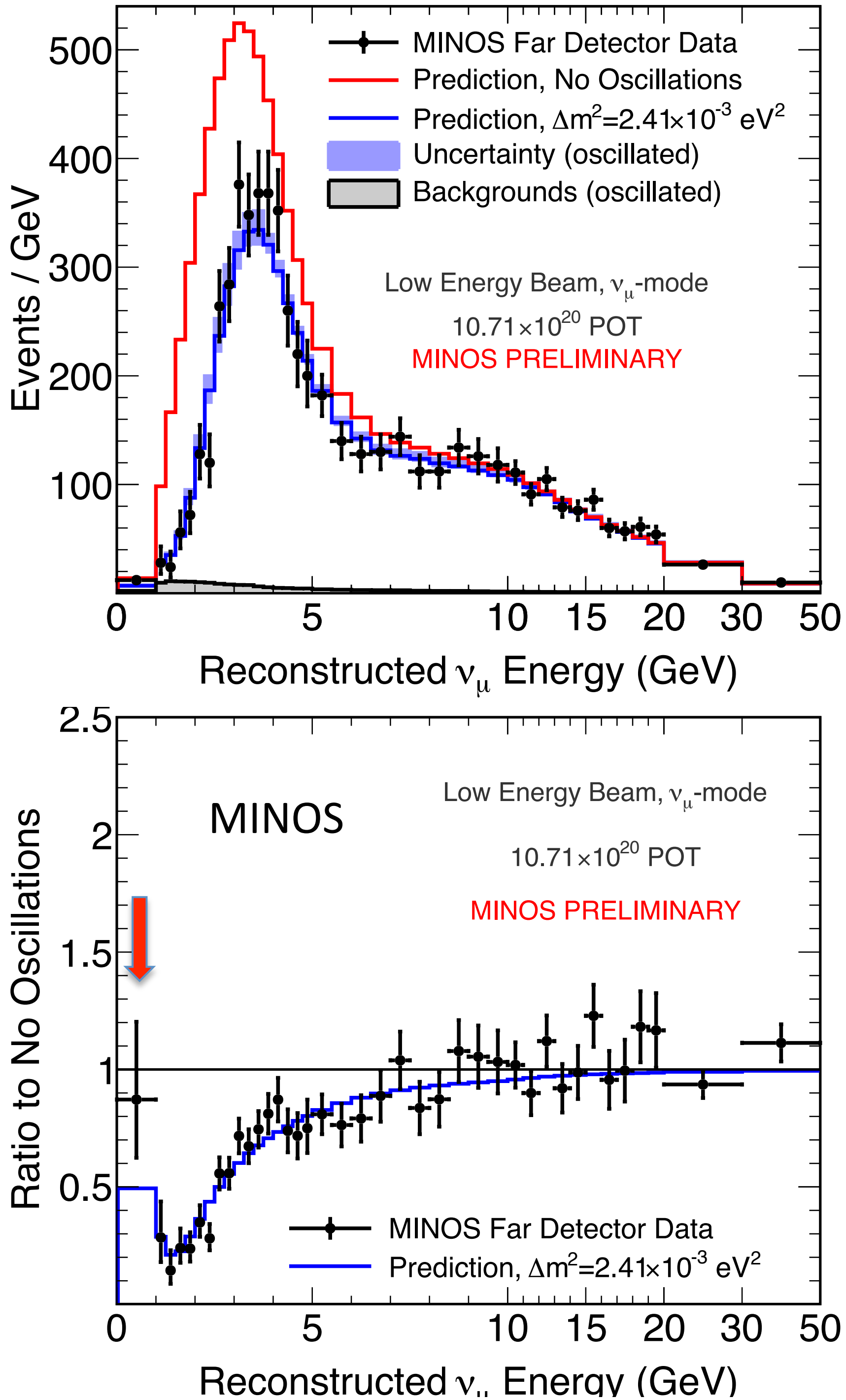


N_{obs}=112

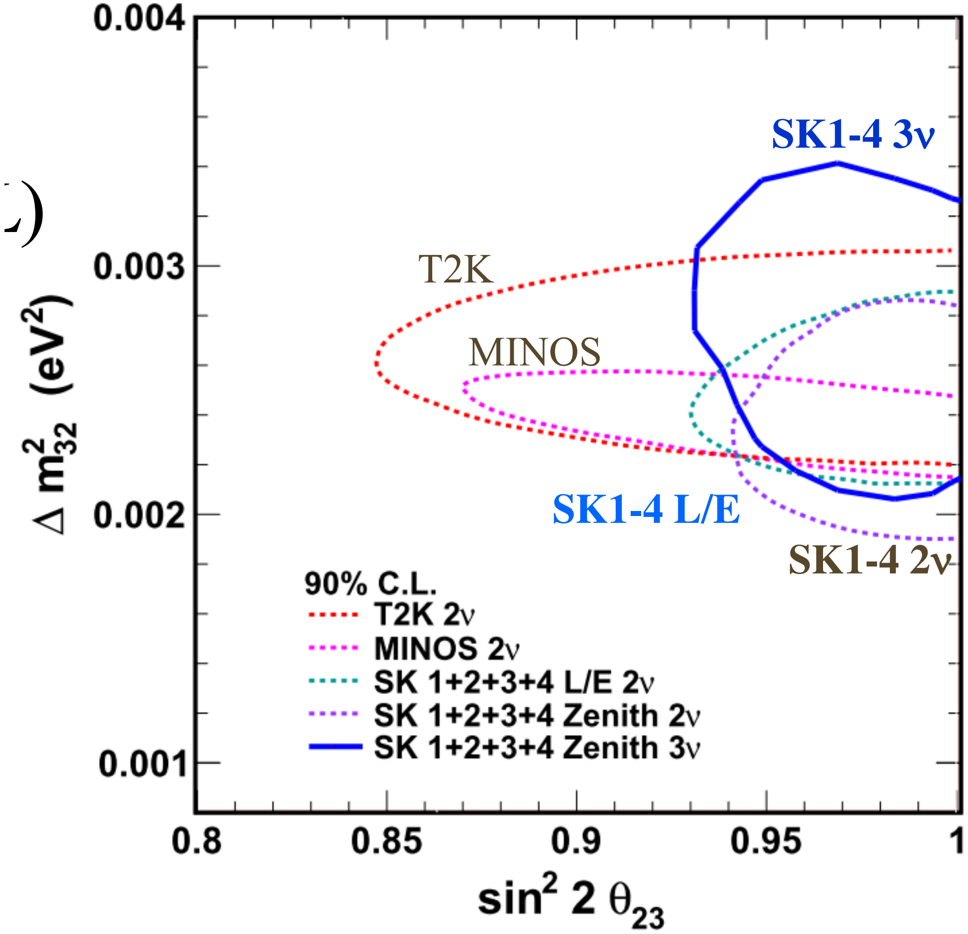
N_{exp}=158.4 $^{+9.4}_{-8.7}$



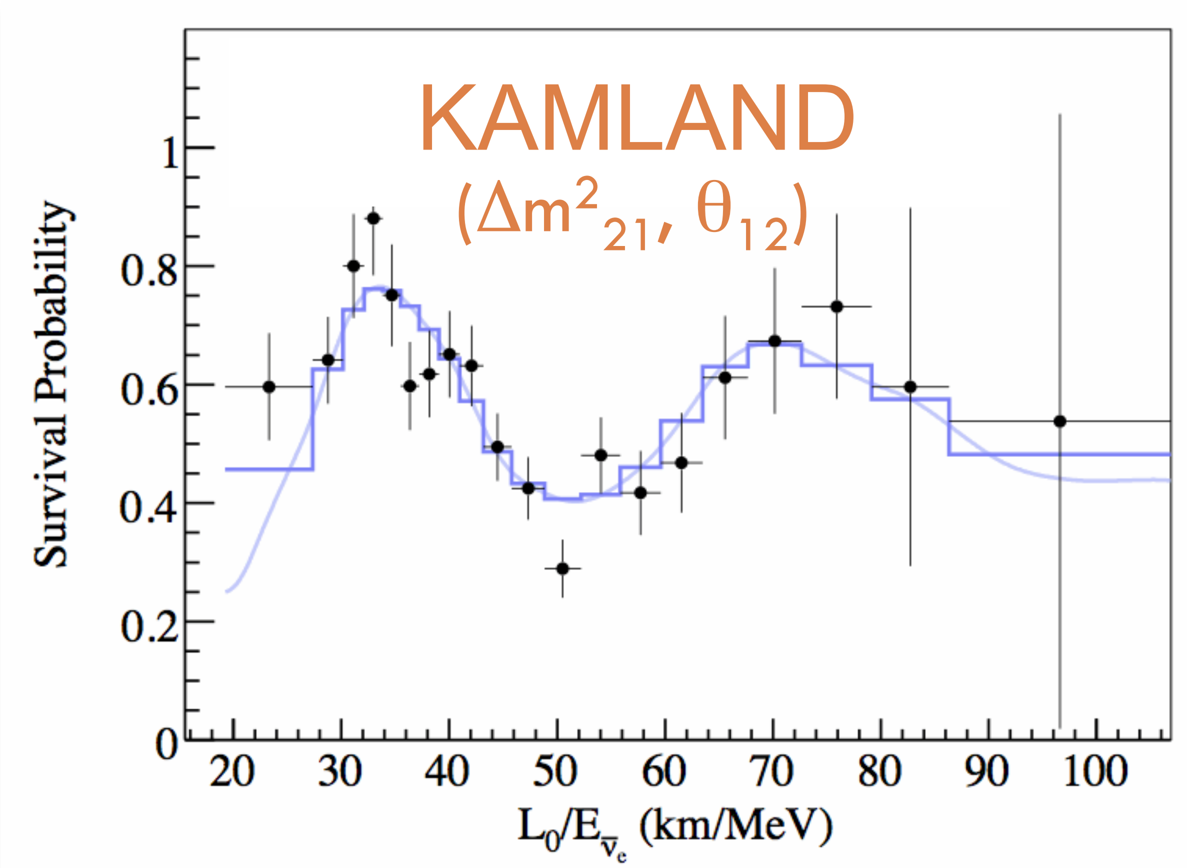
	K2K-I+II	K2K-I only	K2K-II only
Shape + Norm.	**0.0010% (4.41σ)**	0.15% (3.2σ)	0.46% (2.8σ)
Shape only	0.40% (2.9σ)	7.5%	5.0%
Norm. only	0.04% (3.5σ)	0.5%	2.3%



R. Nichol NEUTRINO2012



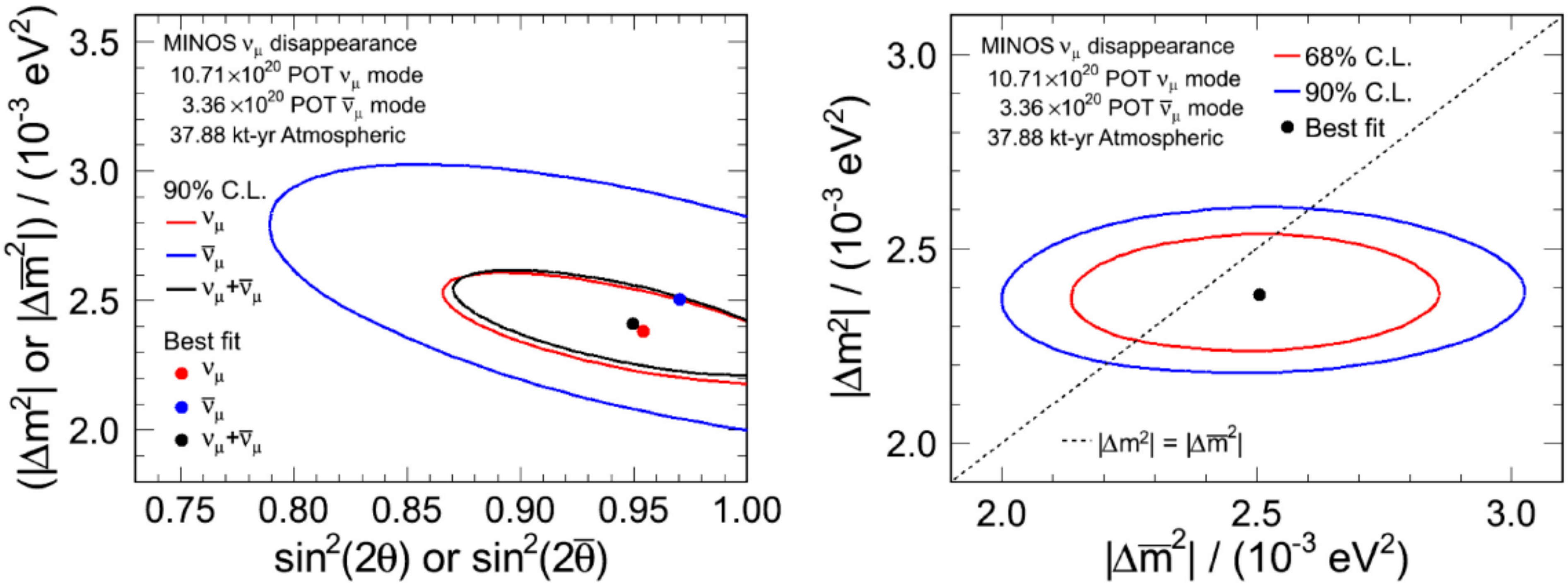
Oscillation behavior of reactor ν at 180km



Both solar and atmospheric Δm^2 region behave
as expected in oscillation by co-existence of flavor and mass states

arXiv:hep-ex/1304.6335

MINOS ν_μ disappearance ν and $\bar{\nu}$



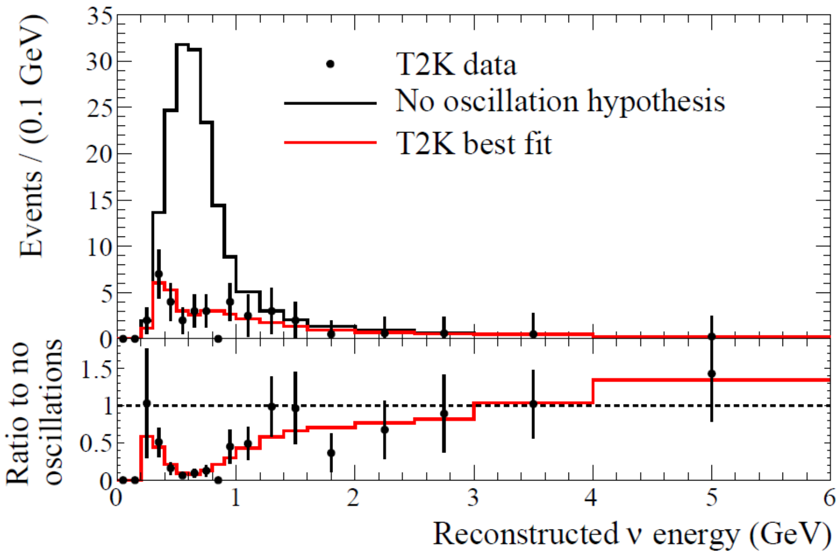
Indication of non-maximal mixing?

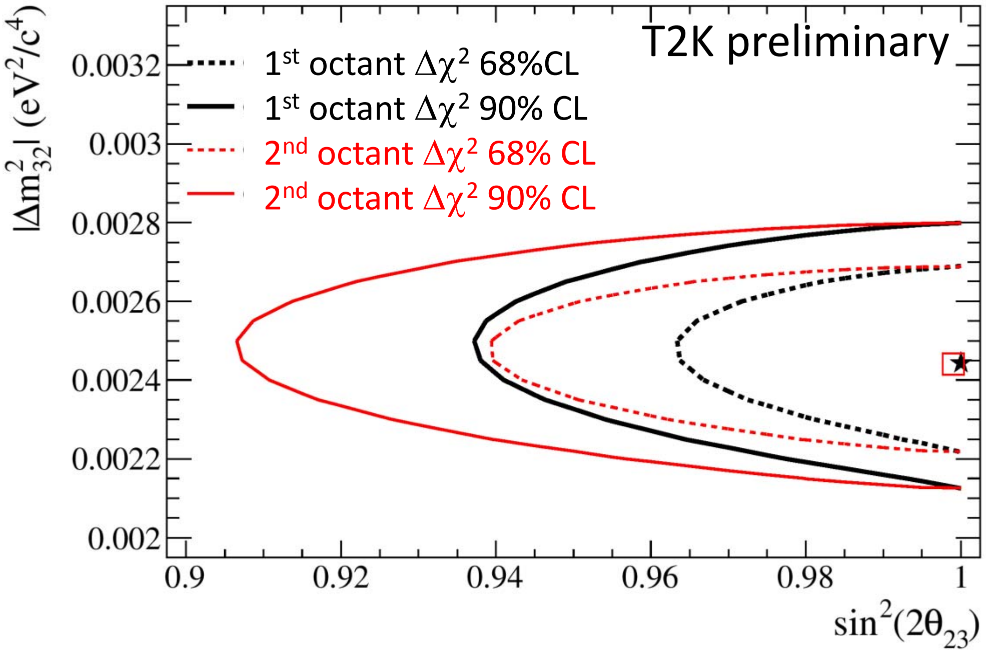
$$|\Delta\bar{m}^2| - |\Delta m^2| = 0.12^{+0.24}_{-0.26} \times 10^{-3}\text{eV}^2$$

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

A.Ichikawa
EPS2013

T2K ν_μ disappearance





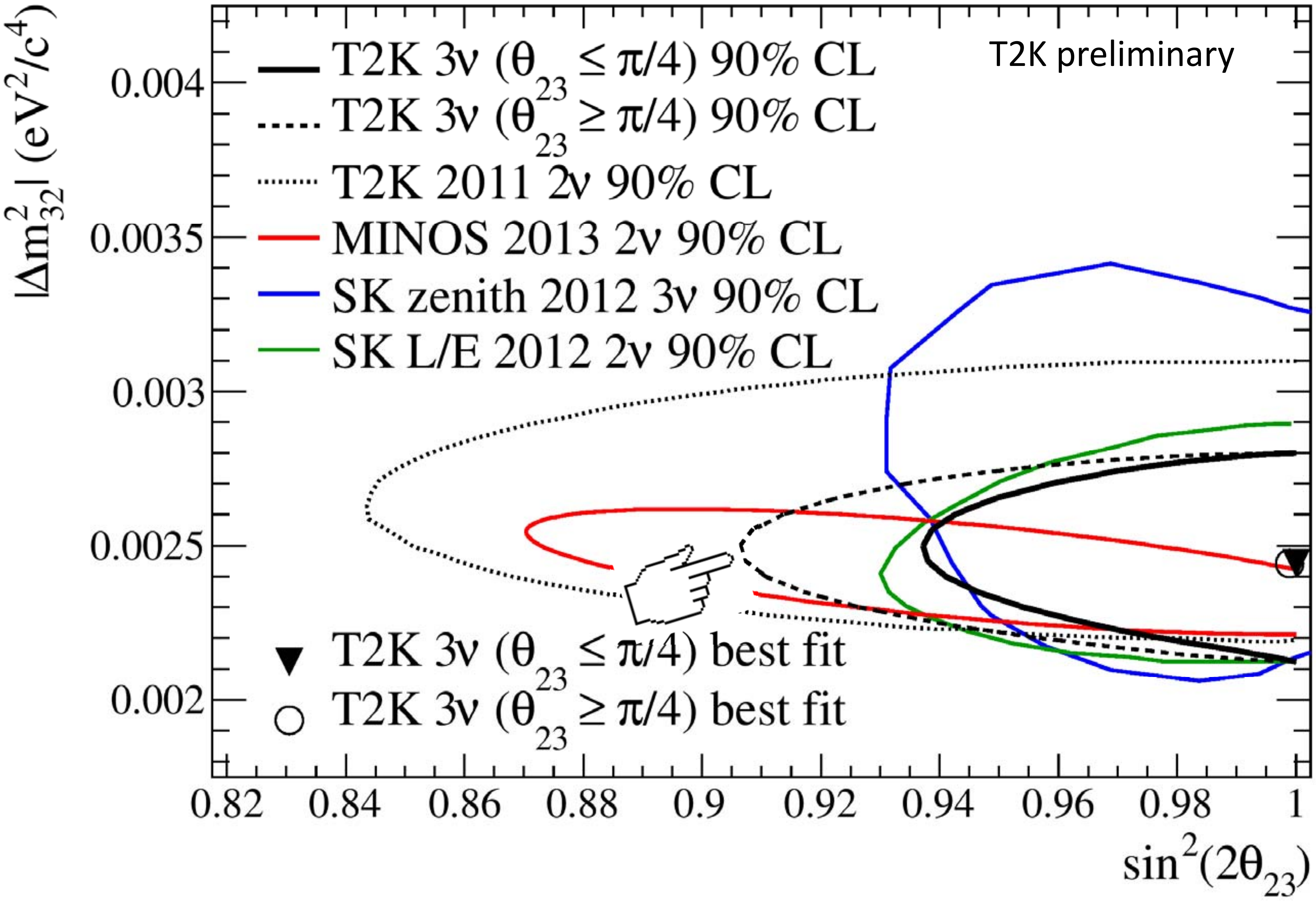
Using data up to Run 3

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.

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

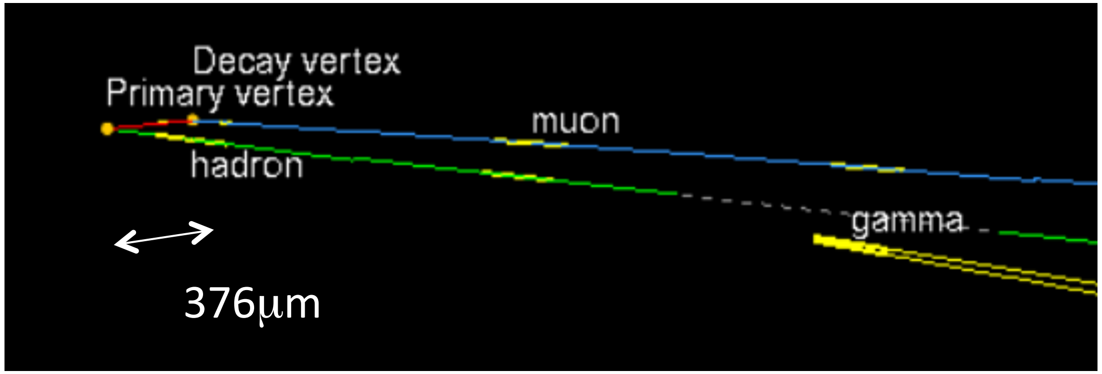
A.Ichikawa EPS2013



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

Summary of ν_μ disappearance ($\nu_\mu \rightarrow \nu_\tau$?) at L(km)/E(GeV)~500

- Oscillation behavior has been observed as predicted in a frame work of co-existence of mass and flavor eigen-states. (not decay nor de-coherence etc.)
- Almost maximum mixing between 2nd and 3rd generation
- $\nu_\mu \rightarrow \nu_\tau$ events observed
- Still plenty of room for $\nu_\mu \rightarrow \nu x$

$\nu_\mu \rightarrow \nu_e$ at L/E~500 (km/GeV)

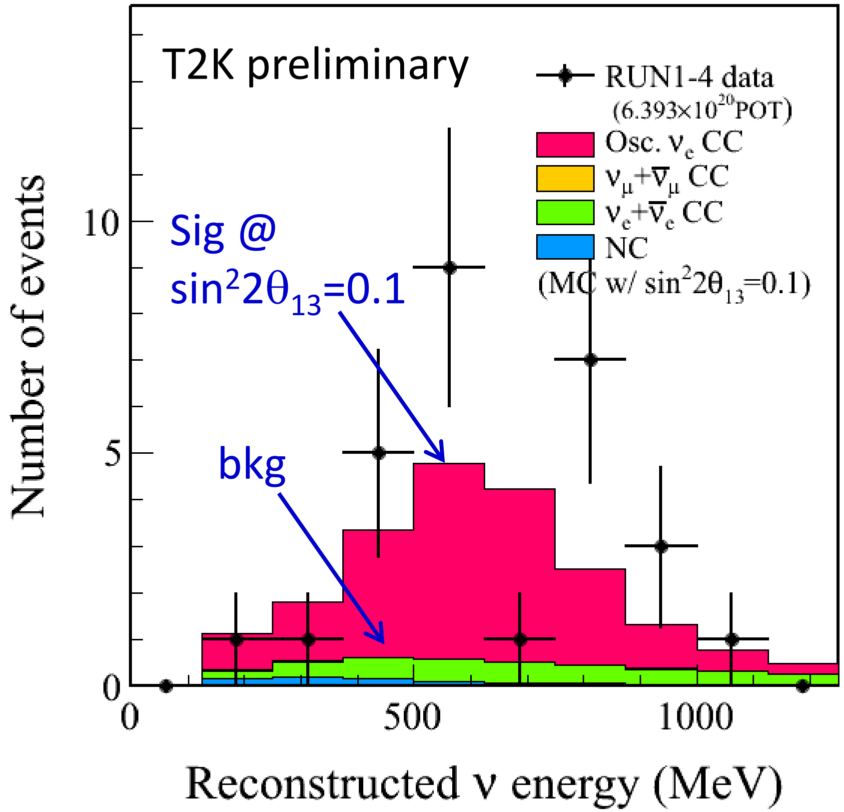
A.Ichikawa EPS2013

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	$3.010\text{x}10^{20}$	$6.393\text{x}10^{20}$ (~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

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

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

- NOTE! $\sin^2\theta_{23}$ is fixed to 0.5 in the fit
- Best fit value w/ 68% C.L. error @ $\delta_{CP}=0$

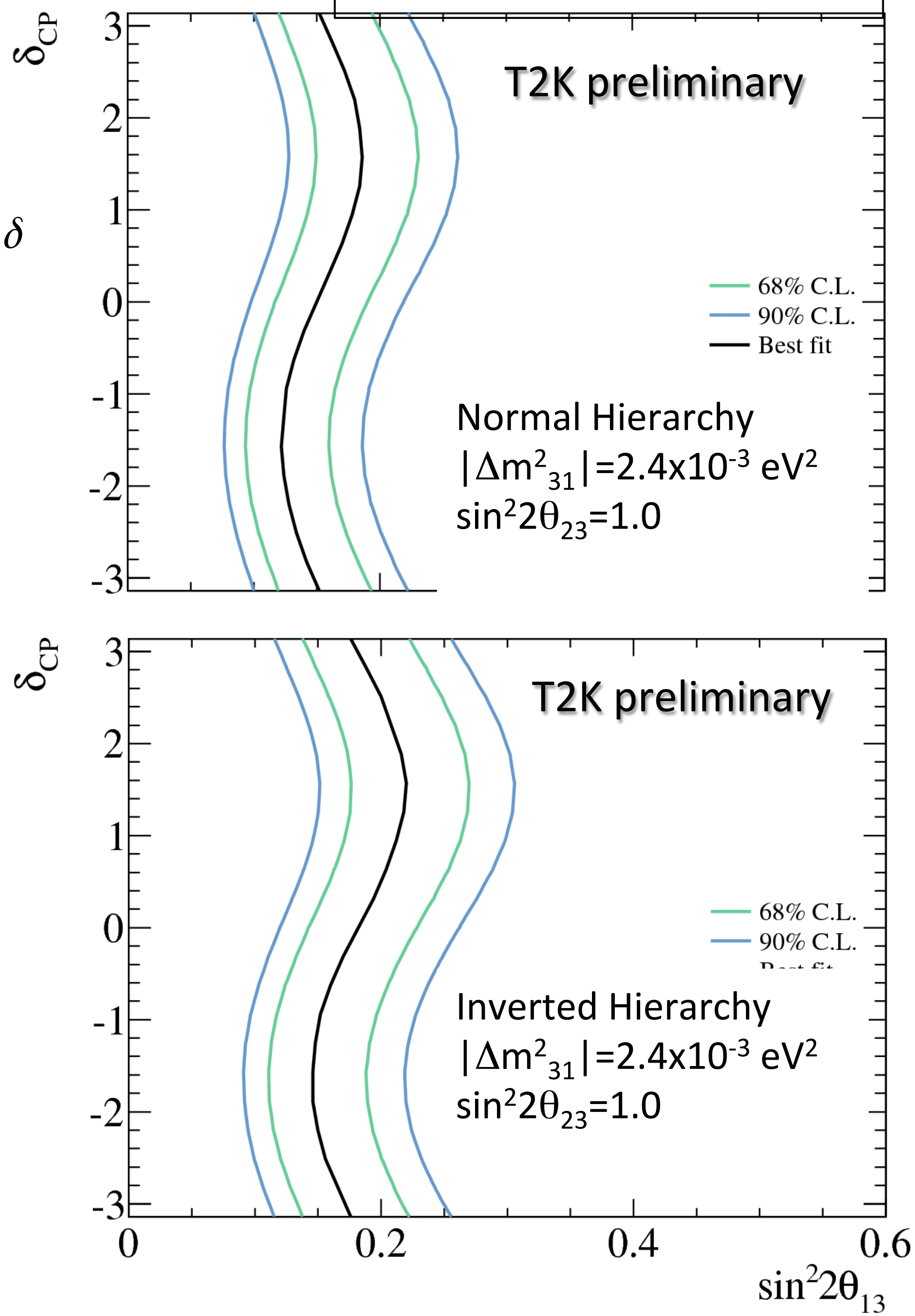
normal hierarchy:

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

inverted hierarchy:

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

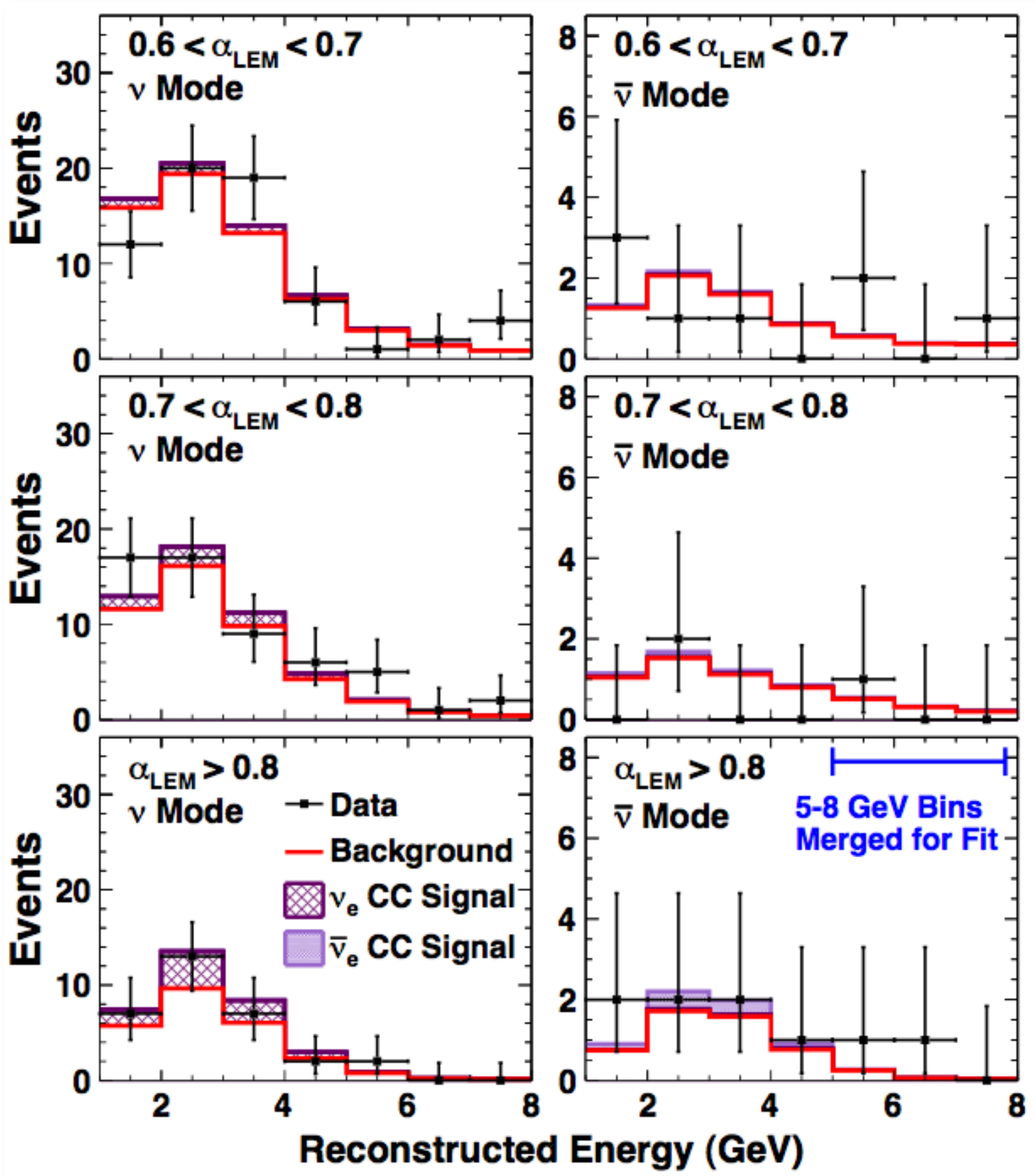
A.Ichikawa EPS2013



• **MINOS**

Zeller LP2013

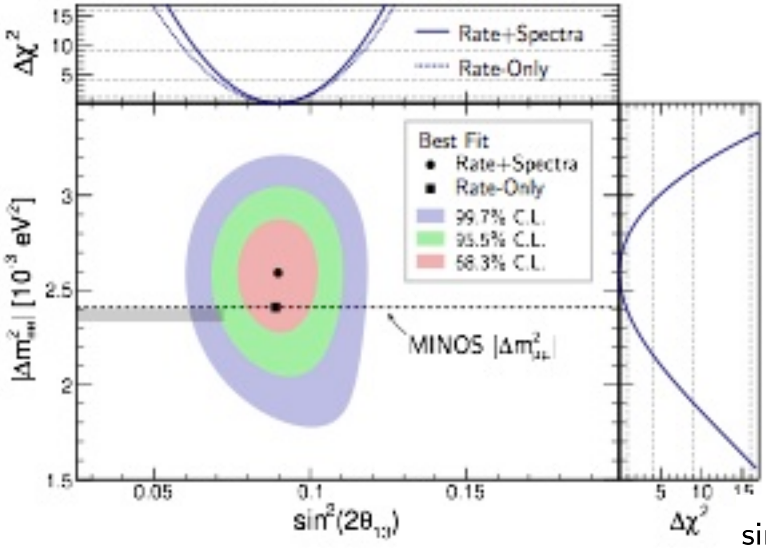
both
ν_e & $\overline{\nu}_e$
data



With reactor results

S. Jetter
NuFact 2013

Daya Bay

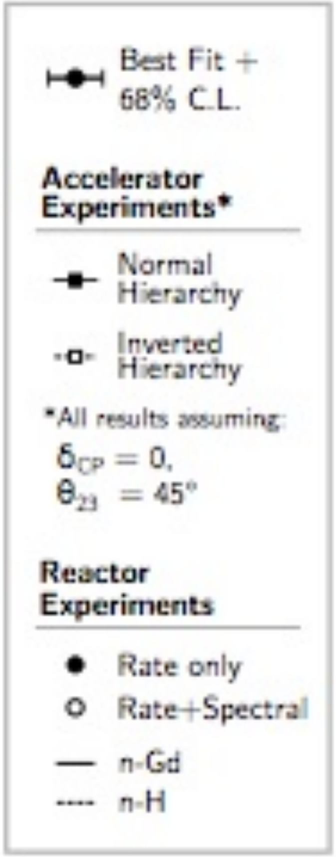


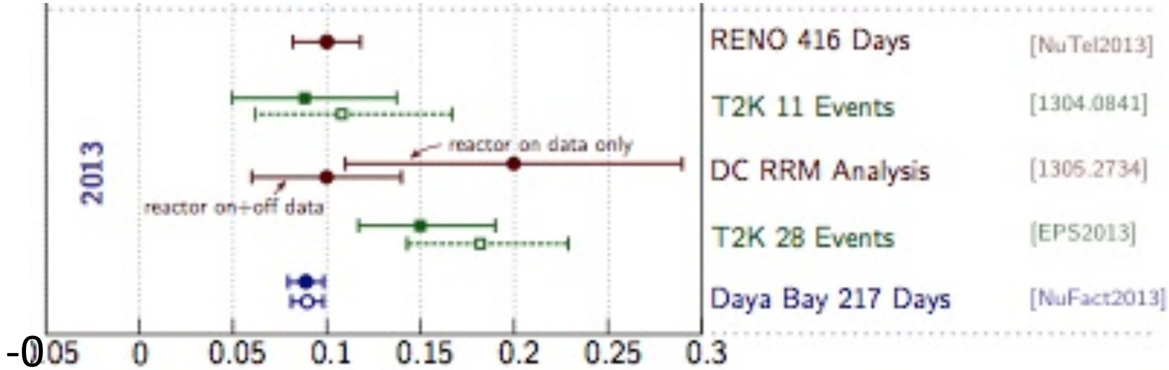
$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \cdot 10^{-3}\text{eV}^2$$

$$\chi^2/N_{\text{DoF}} = 162.7/153$$

$$\sin^2(\Delta m^2_{ee}\tfrac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\tfrac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\tfrac{L}{4E})$$





In three neutrinos frame work

$\nu_\mu \rightarrow \nu_e$

$$\cong s_{23}^2 \sin^2 2\theta_{13}(1+A) - 8c_{13}^2 c_{12}c_{23}s_{12}s_{23}s_{13}\left[\frac{\Delta m_{21}^2 \cdot L}{4E_\nu}\right]s_\delta$$

$$\sim s_{23}^2 \sin^2 2\theta_{13}\ (1 \pm O(0.1))\ \text{-}\ c_{13} \cdot J \cdot 0.03 \cdot s_\delta \quad \approx 0.05(\pm 10\%) - 0.01 \cdot s_\delta$$

$(J \equiv \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sim 0.3)$, $(A = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m_{31}^2} \cong \pm 0.1$ in T2K, $\cong \pm 0.2$ in MINOS,NOVA), $(\frac{\Delta m_{21}^2 \cdot L}{4E_\nu} \cong 0.03)$

s_{23}^2=0.5+O(0-10%) $(\theta_{23} > 4/\pi)$
or 0.5 -O(0-10%) $(\theta_{23} < 4/\pi)$

$\sin^2 2\theta_{13}$=0.09 ± O(10%)

$$P_{\mu\mu} = 1 - (c_{13}^4 \sin^2 2\theta_{23} + \sin^2\theta_{23} \sin^2 2\theta_{13})\sin^2 \frac{\Delta m_{23}^2}{4E_\nu}$$

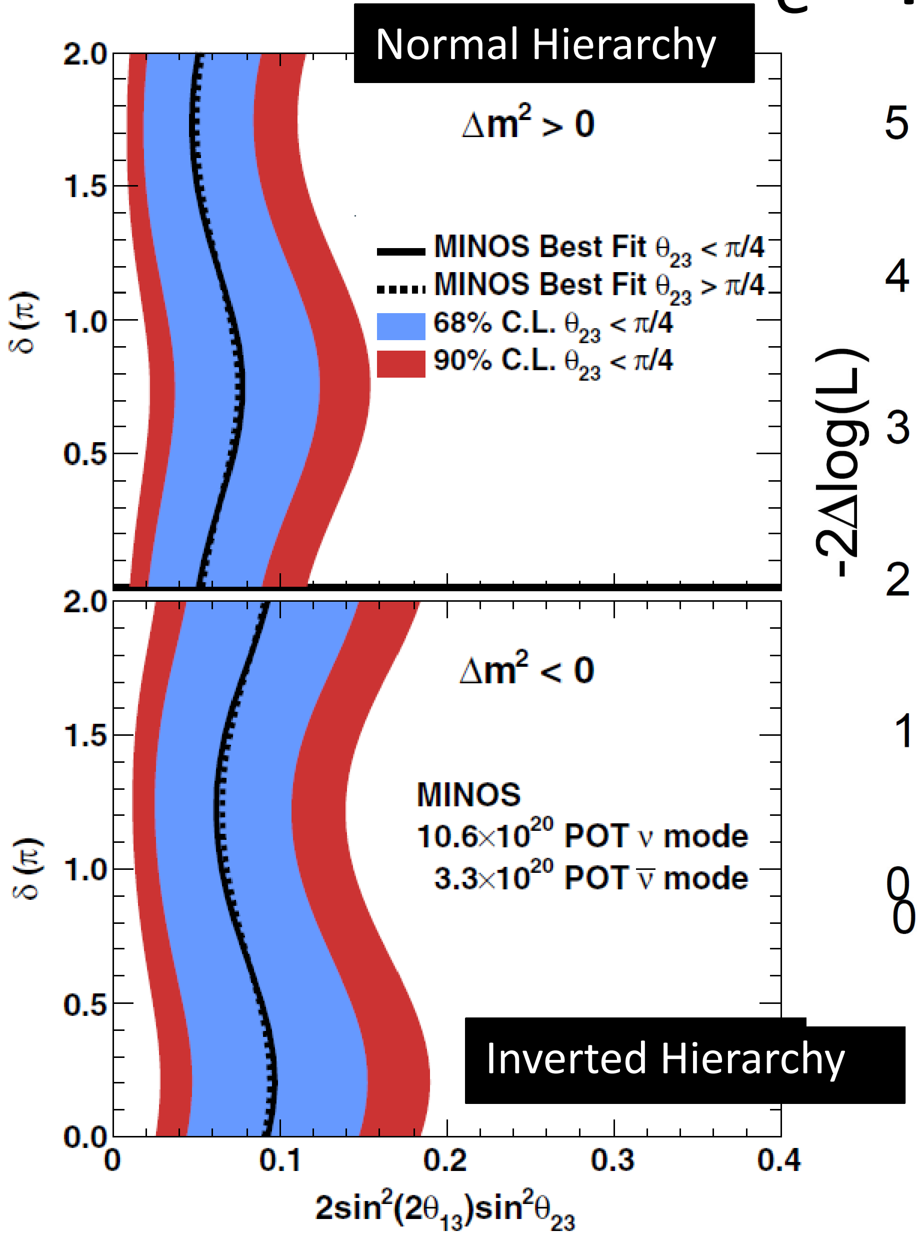
$c_{13} \sim 1$, $\sin^2 2\theta_{23} \sim 1$, $\sin^2\theta_{23} \sim 0.5$, $\sin^2 2\theta_{13} \sim 0.1$

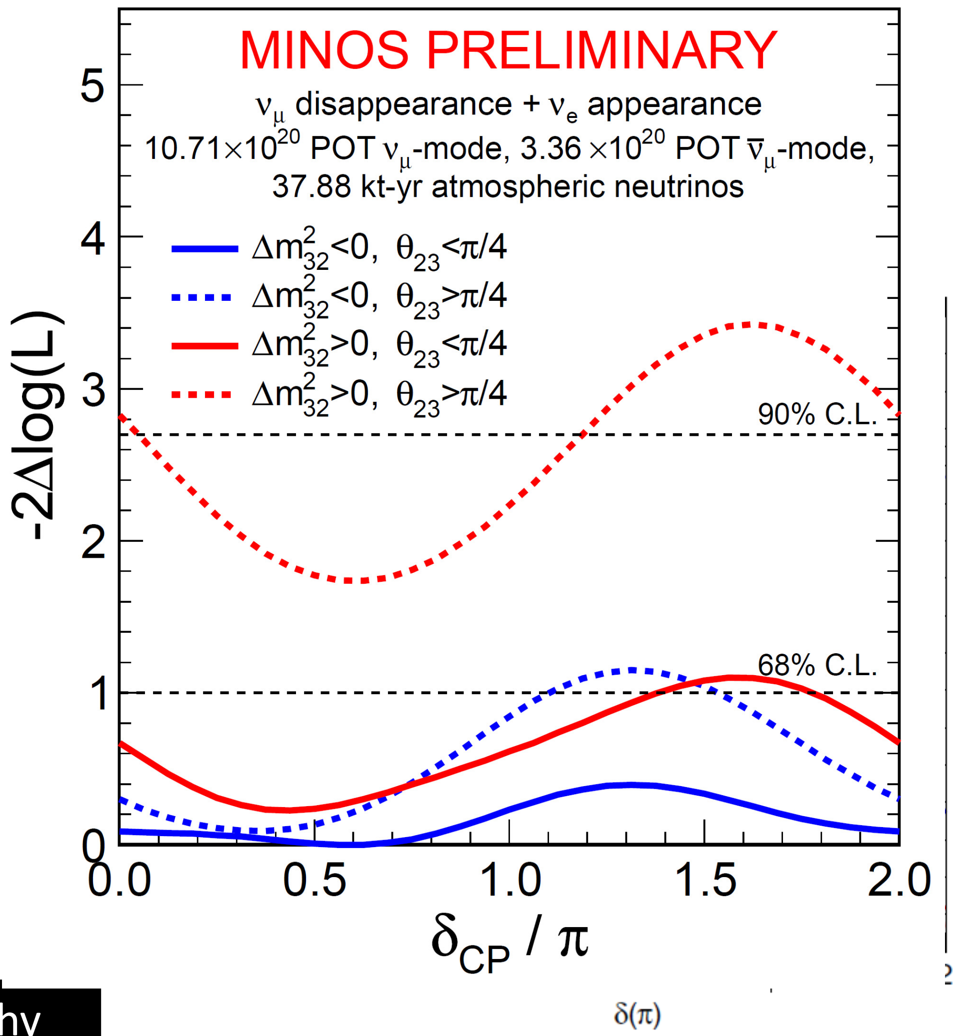
(ν_μ disapp.)

$$P_{ee} = 1 - (\sin^2 2\theta_{13} \sin^2 \Delta_{ee})$$

(Reactor $\overline{\nu_e}$ disapp.)

MINOS ν_e appearance



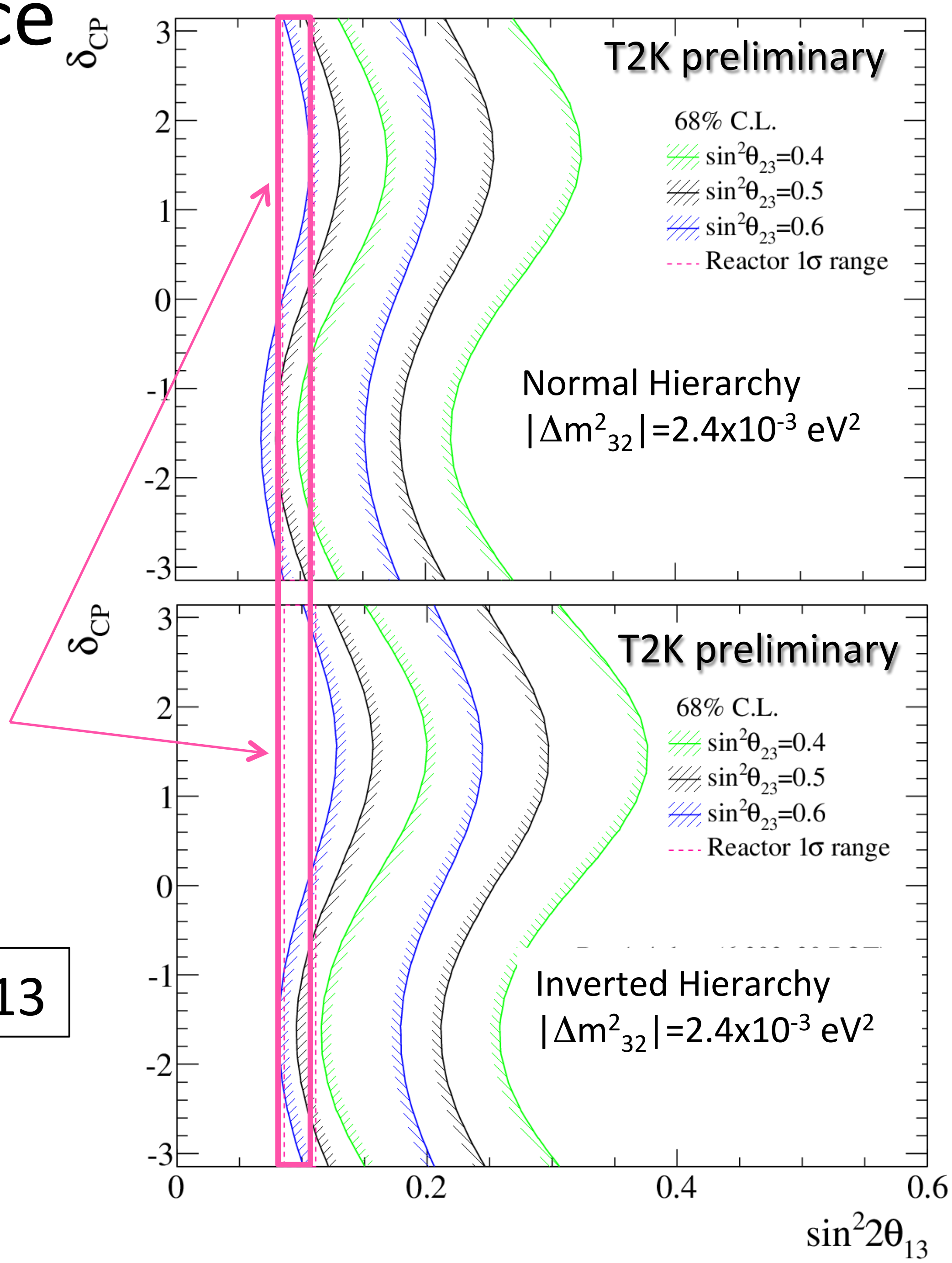


T2K ν_e appearance δ_{CP} vs. $\sin^2 2\theta_{13}$ for different θ_{23}

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

reactor 1σ region (Daya Bay) $\sin^2 2\theta_{13} = 0.090 \pm 0.009$

A.Ichikawa EPS2013



Future T2K CP violation (sinδ≠0) sensitivity

A.Ichikawa EPS2013

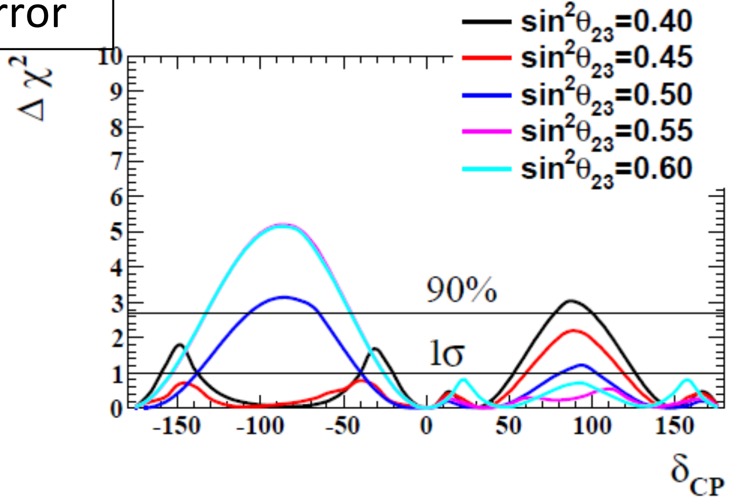
Simultaneously fitting ν_μ disappearance and ν_e appearance data
Use $\sin^2 2\theta_{13}$ constraint by reactor experiment

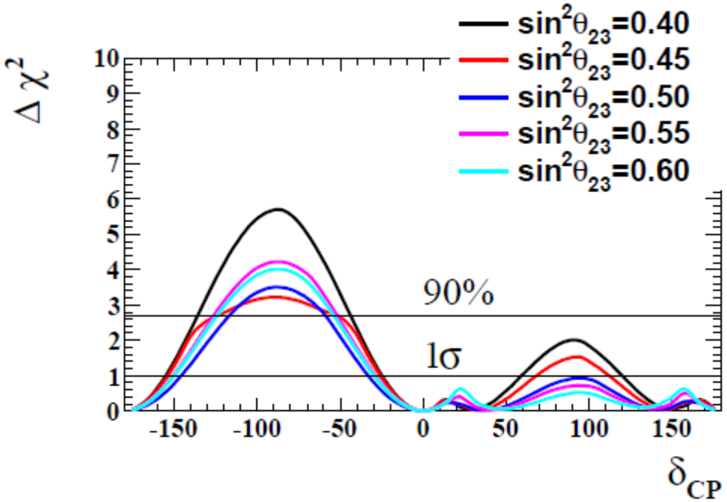
750kW x 5 yrs
No sys. Error

100% ν-mode

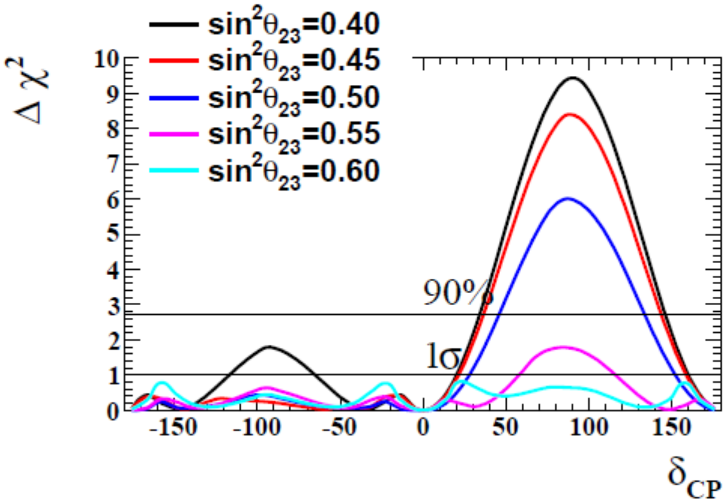
50%:50% ν-mode: anti-ν-mode

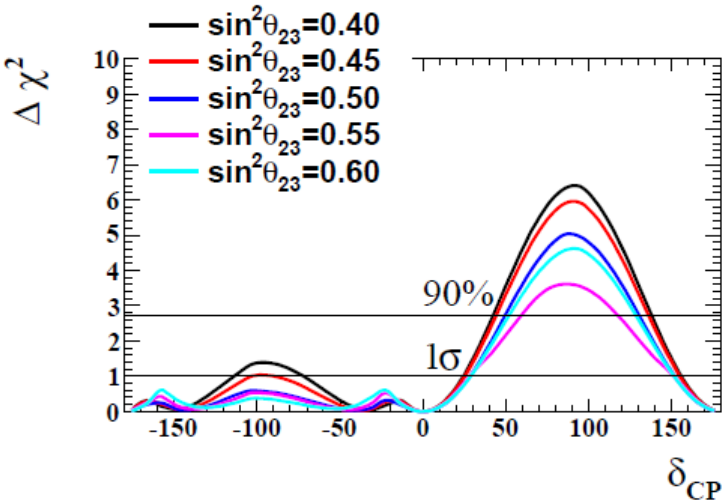
NH





IH





LBN Next generation experiments

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.

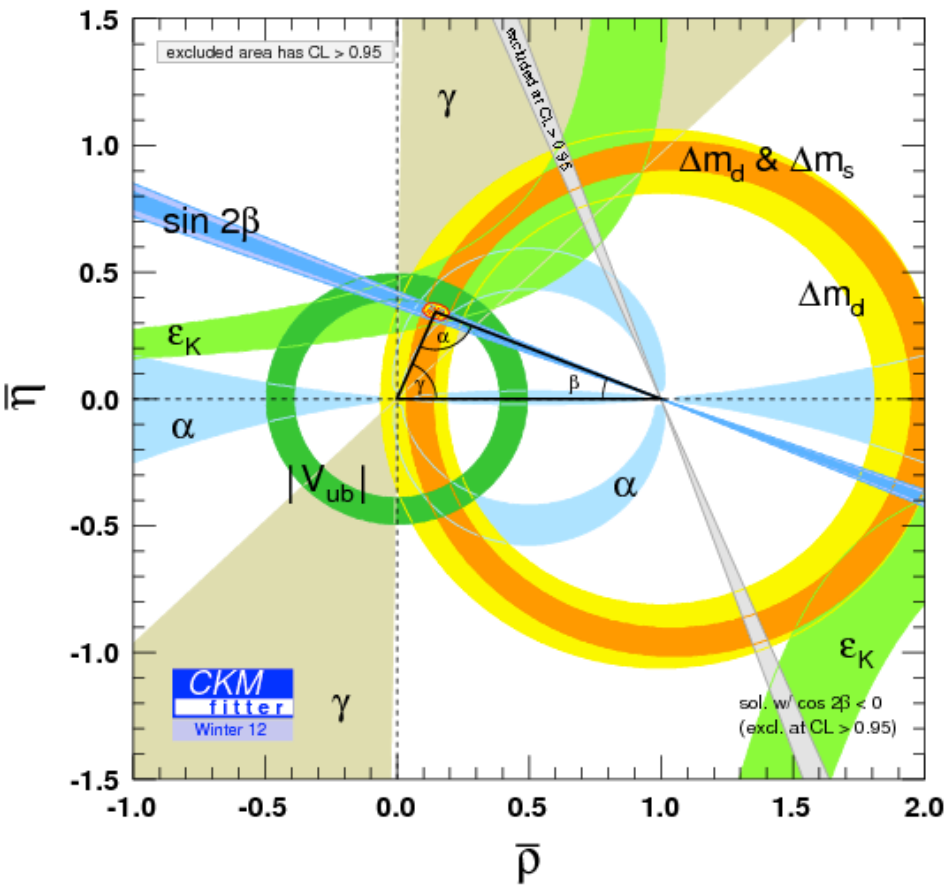
A thought on the future

CP violation studies in quark

- Discovery of KL → $\pi^+\pi^-$
- searches in various K decay modes
- various 'theories', sw, ...

- Cabbibo-Kobayashi-Maskawa theory as the origin of the CPV in K by θ_{KM}
  - $\varepsilon' / \varepsilon$
  - large CPV in B decay

- Search for other CPV sources



CP violation studies

quark

- Discovery of KL → $\pi^+\pi^-$
- searches in various K decay modes
- various 'theories', sw, ….

- Kobayashi-Maskawa theory as the origin of the CPV in K by θ_{KM}
  - $\varepsilon' / \varepsilon$
  - large CPV in B decay

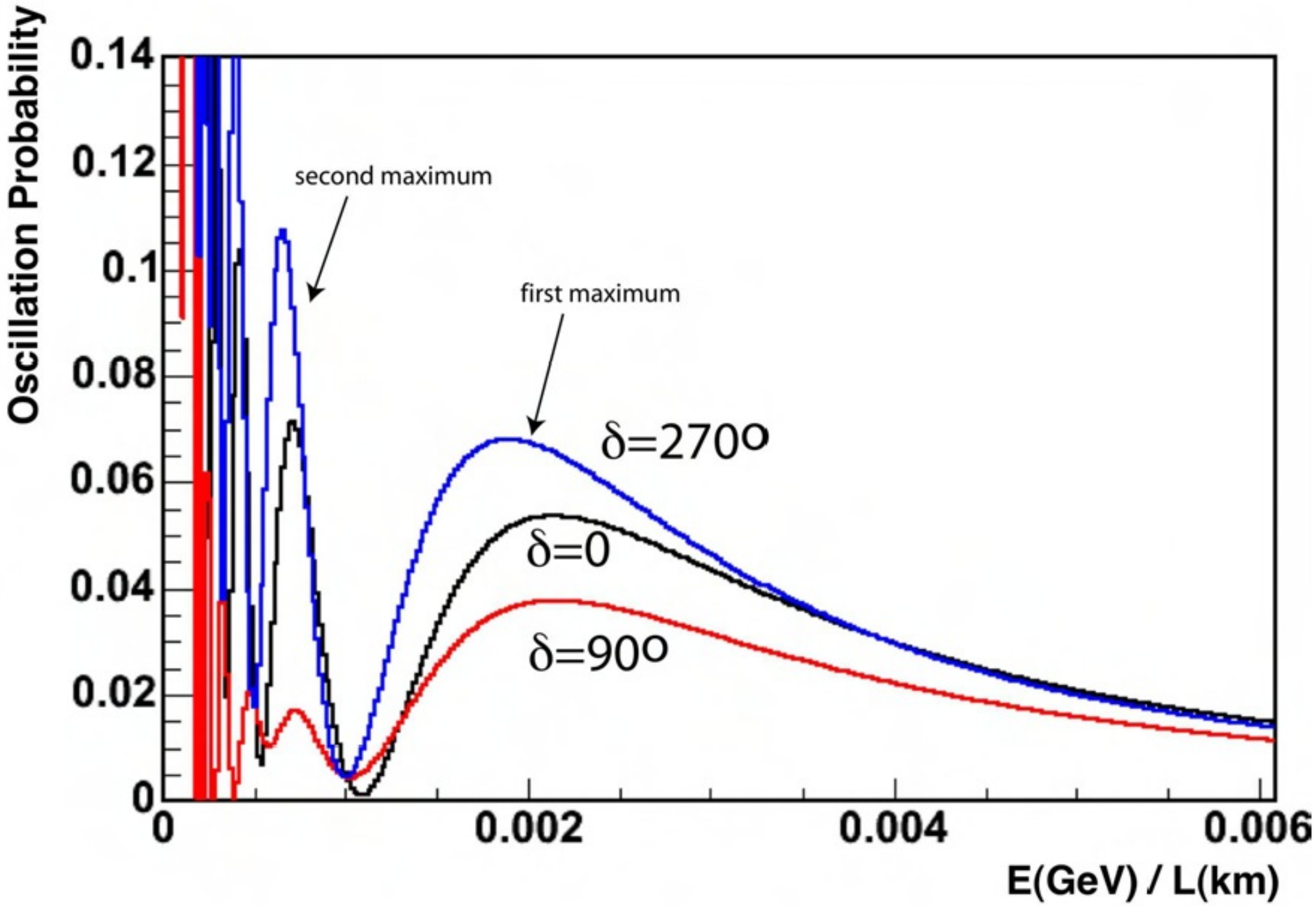
- Dominant source of CPV is δ_{CKM} (phase in 3 generation in quark)

lepton

- Neutrino, anti-neutrino data for remaining parameters in three neutrino frame work
  - Analysis in terms of 3 angles $+\delta_{CP}$

- Is the origin of neutrino anti-neutrino difference due to δ_{CP} ?
- How well one can test the frame work itself ?
  - 1st and 2nd maximum
  - Unitarity triangle
  - Outside of 3 generation F.W.

First / Second Maximum and δ



Interference of Δm^2_{atm} and Δm^2_{sol} oscillation amplitudes

Unitary Triangle in lepton

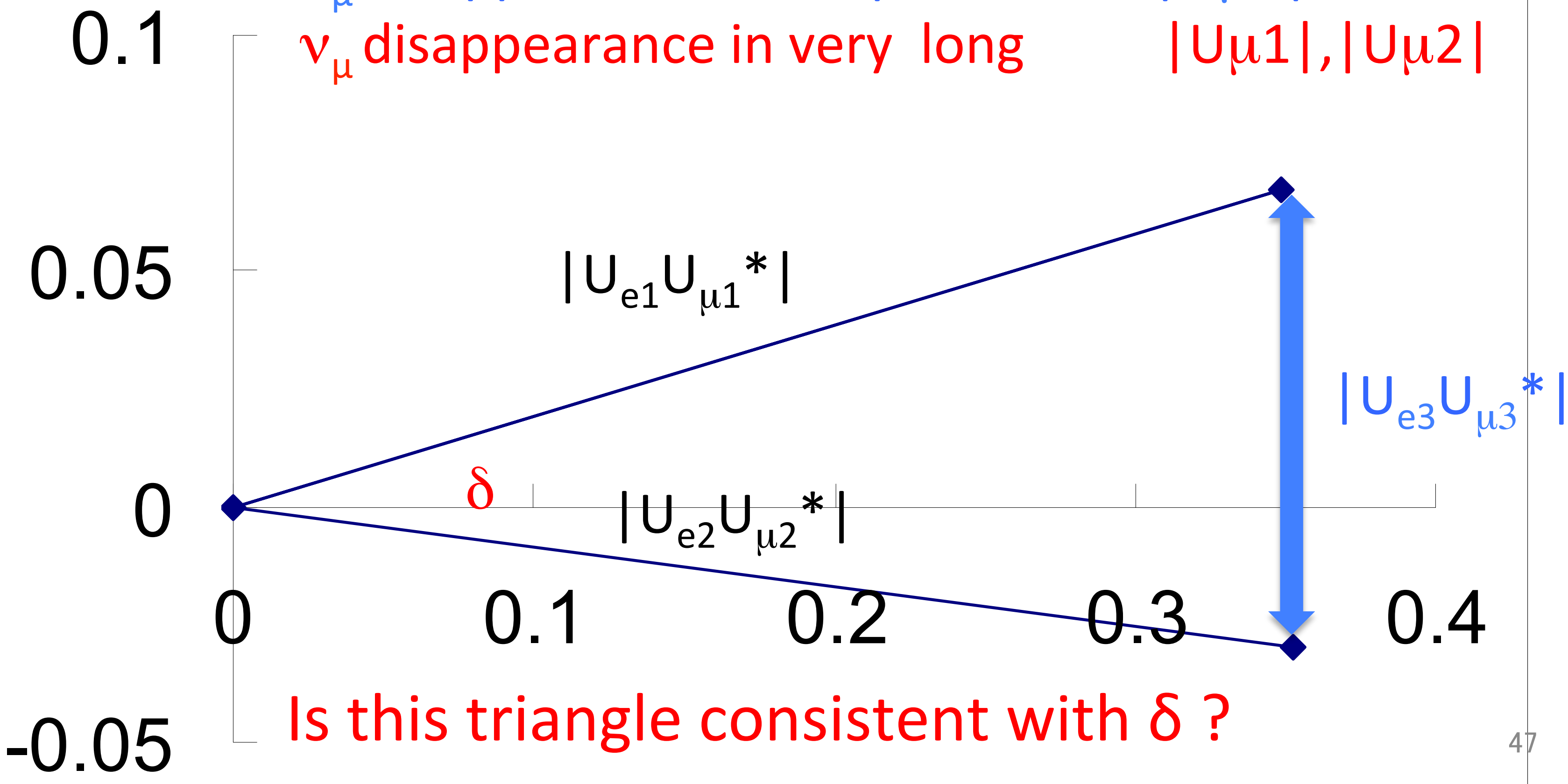
Y.Farzan, A.Yu.Smirnov (hep-ph/0201105)

Solar+very Long baseline reactor |Ue1|, |Ue2|

Reactor ν_e disappearance |Ue3|

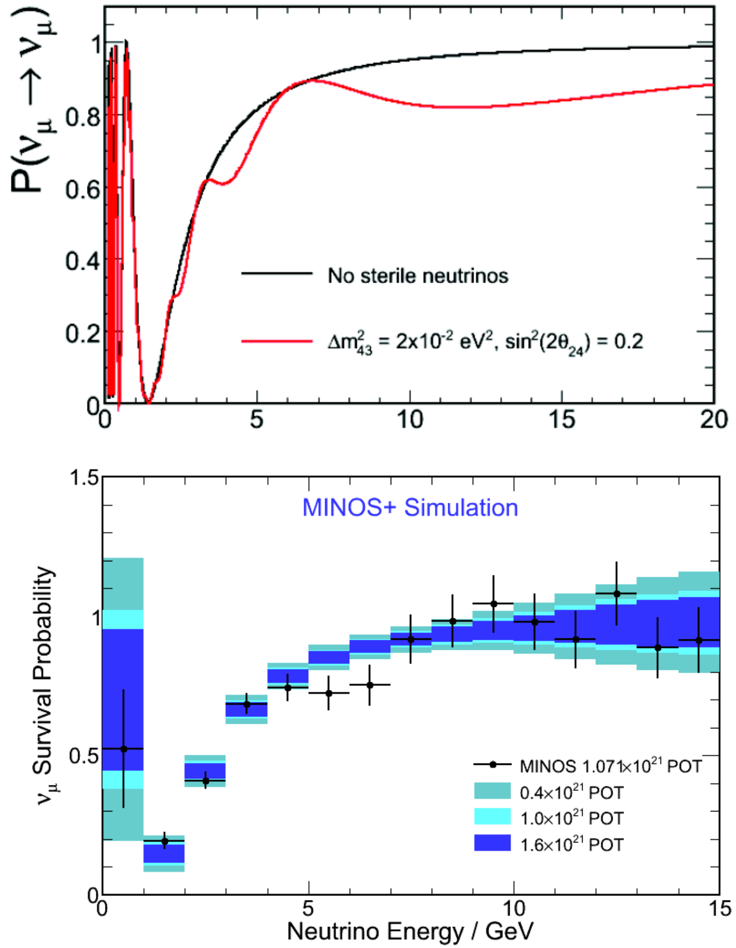
ν_μ disappearnce atmospheric Δm^2 |Uμ3|

ν_μ disappearance in very long |Uμ1|,|Uμ2|



Is this triangle consistent with δ ?

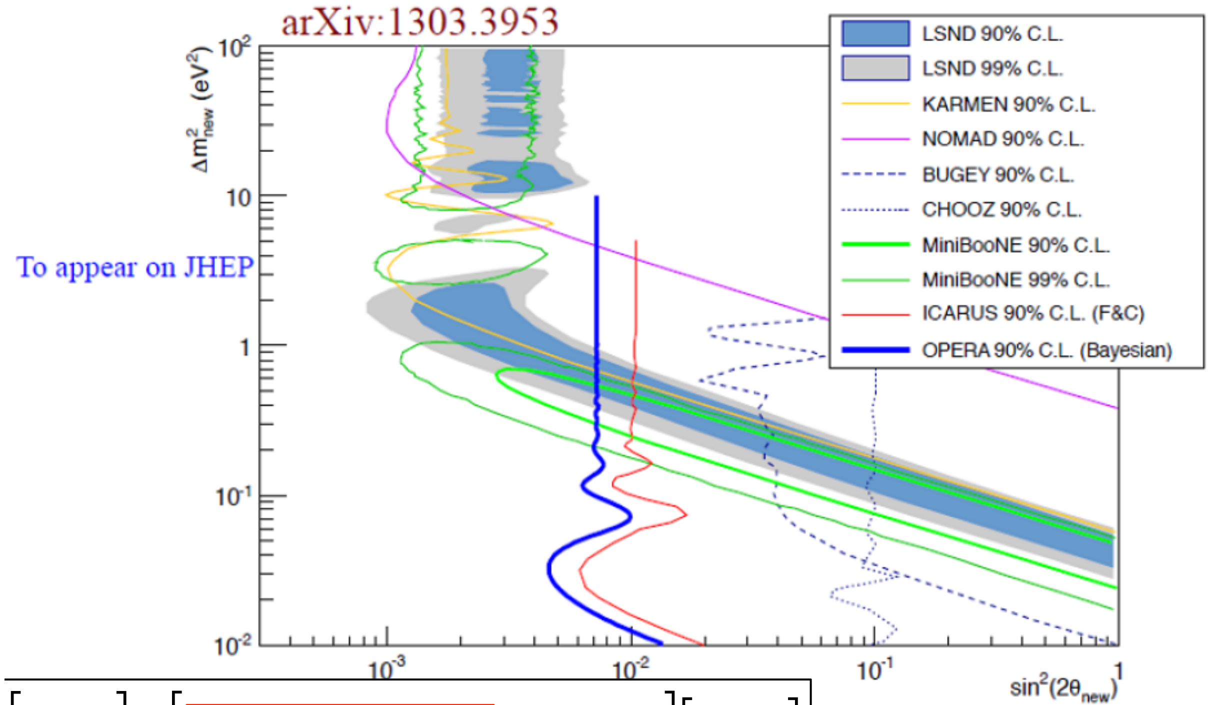
MINOS+



- ◇ Higher energy neutrinos
- ◇ Broad spectrum to test three-flavor paradigm
- ◇ More statistics, different energy, different systematics
- ◇ High statistics with neutrinos and anti-neutrinos
- ◇ Improved sensitivity to:
  - **Sterile neutrinos**
  - Extra-dimensions
  - Non-standard interactions
  - Decoherence
  - Decay

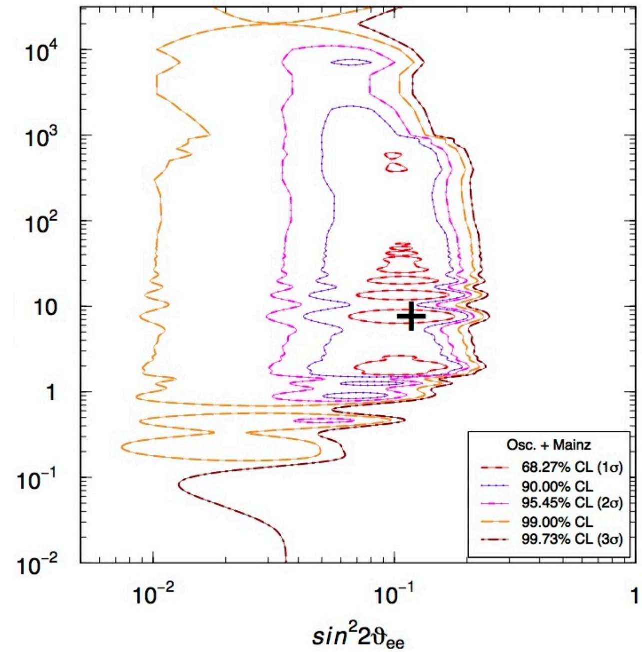
eV sterile neutrino ?

$\nu\mu \rightarrow \nu e$



ν_e and anti-ν_e disappearance

In reactor and β−source



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \bullet \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \bullet \end{bmatrix}$$

Many proposals to confirm/refute at higher confidence level

J-PARC 3GeV RCS stopping π,K

Summary

- Oscillation behavior has been observed as predicted in the frame work of co-existence of three mass and flavor eigen-states.
- All of the mixing angles are large compared to those in quark
- Almost maximum mixing between 2^{nd} and 3^{rd} generation

- Explicit flavor change have been observed in
  - $\nu_\mu \rightarrow \nu_\tau$
  - $\nu_\mu \rightarrow \nu_e$
- Reactor and accelerator data are consistent with three neutrino frame work at ~10% level

- Next generation LBL will clarify the mass hierarchy, 2^{nd} and 3^{rd} mixing and possible CP violation

- Need test of three neutrino frame work
- And identifications of the origin of (to be observed) CP violation