

Long-Baseline Experiments

Ed Kearns

Boston University

ICFA Neutrino Panel Mini-Workshop

Fermilab

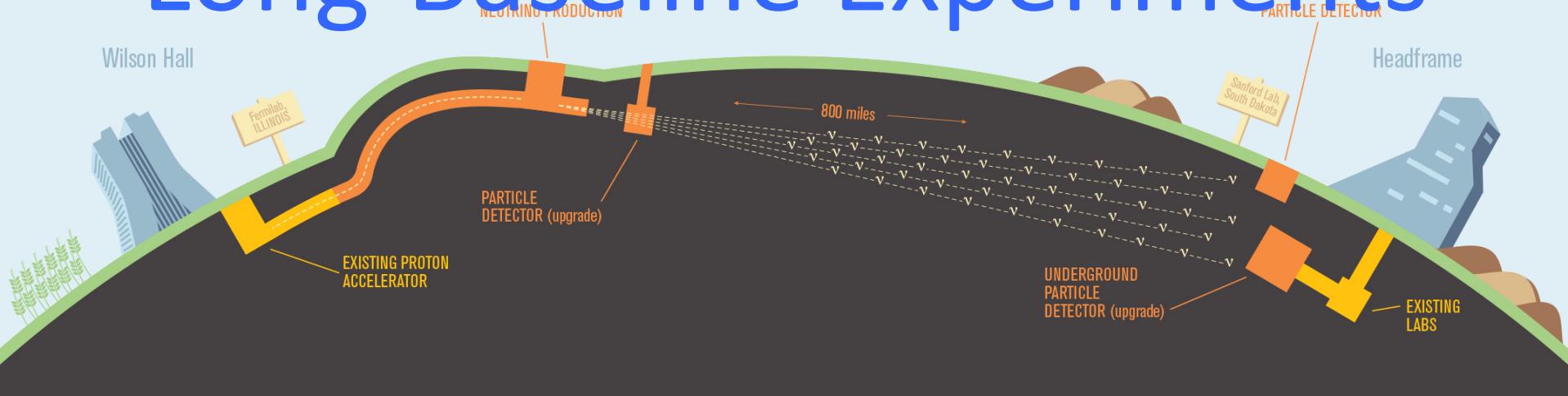
January 30-31, 2014



International Committee for Future Accelerators

Sponsored by the Particles and Fields
Commission of IUPAP

Long-Baseline Experiments



To achieve sufficient statistics:

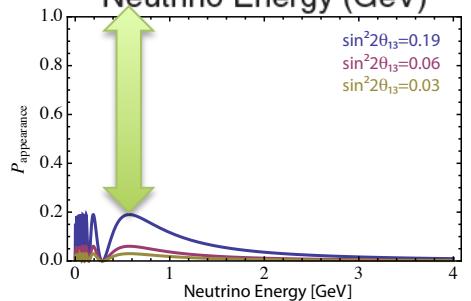
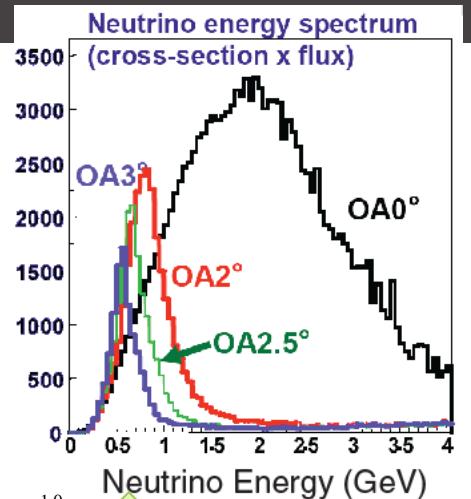
- beam power
- detector mass

To control systematic uncertainty:

- near detector
- hadron production experiments (nu flux)
- neutrino cross section experiments

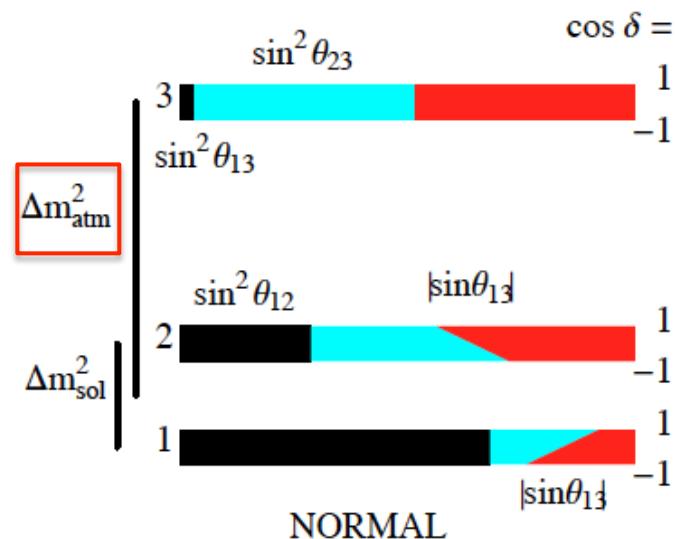
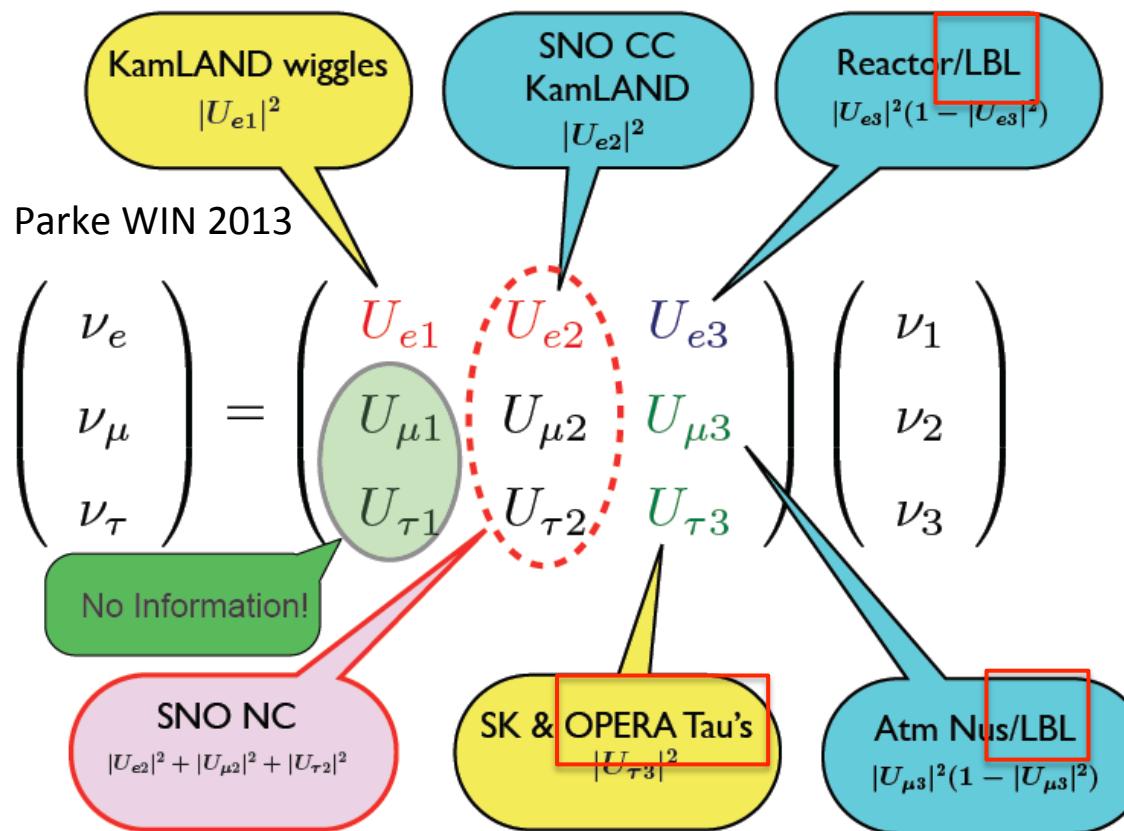
Energy spectrum:

- On-axis = broad band
- Off-axis = narrow band



Long-Baseline Experiments

An essential part in a complete suite of experiments that is responsible for establishing our picture of neutrino oscillations.



Also important: solar neutrinos, atmospheric neutrinos, reactor neutrinos.

Precision Measurements and Missing Measurements

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Mass Hierarchy"
or sign of Δm^2 ?

Parameter	best-fit ($\pm 1\sigma$)
Δm_{21}^2 [10^{-5} eV 2]	$7.54^{+0.26}_{-0.22}$
$ \Delta m^2 $ [10^{-3} eV 2]	$2.43^{+0.06}_{-0.10}$ ($2.42^{+0.07}_{-0.11}$)
$\sin^2 \theta_{12}$	$0.307^{+0.018}_{-0.016}$
$\sin^2 \theta_{23}$	$0.386^{+0.024}_{-0.021}$ ($0.392^{+0.039}_{-0.022}$)
$\sin^2 \theta_{13}$ [173]	0.0241 ± 0.0025 ($0.0244^{+0.0023}_{-0.0025}$)

"Octant": is θ_{23}
different from 45° ?

$$\delta = ?$$

- (A) What is the value of the CP violating δ , and
(B) is it different from 0° ?

Lists of Long-Baseline Experiments

Past

K2K – First confirmation of atmospheric neutrino oscillation

MINOS (just finished) – Precision measurement of parameters,
dedicated antineutrino measurement

Present

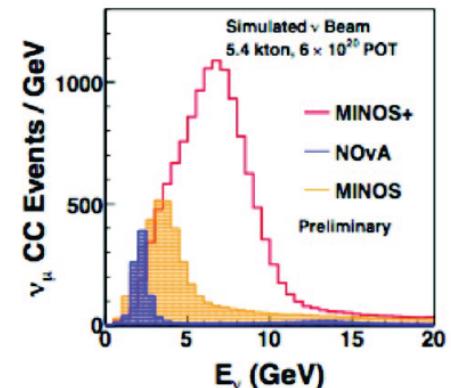
ICARUS – LArTPC technology

OPERA – tau neutrino appearance

MINOS+ - Sterile search using NOvA beam

T2K – Electron neutrino appearance

NOvA – Electron neutrino appearance with sizeable matter effects



Future (the future is uncertain)

LBNE – Wide band beam to LArTPC

T2HK – Narrow band beam, low matter effects, enormous WC

Europe – Many options considered under LAGUNA study + ESS nu source idea

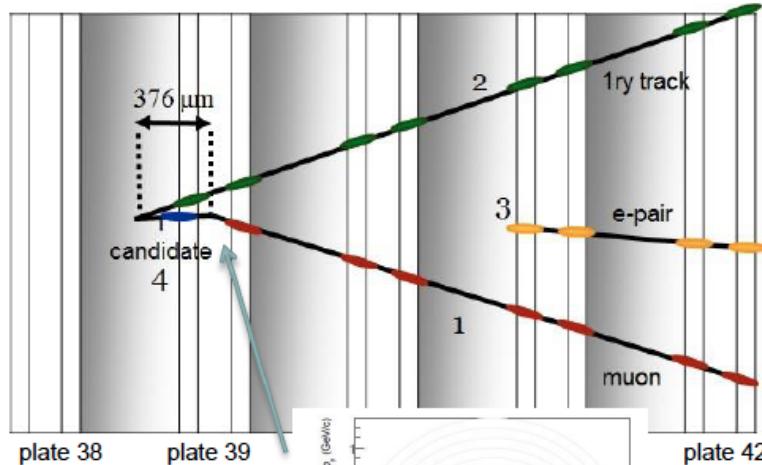
Speculative or far future

CHIPS, nuSTORM, neutrino factory, beta beams

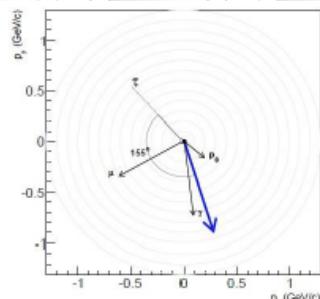
Tau Neutrino Appearance

Third τ candidate: $\tau \rightarrow \mu$

LNGS 2013

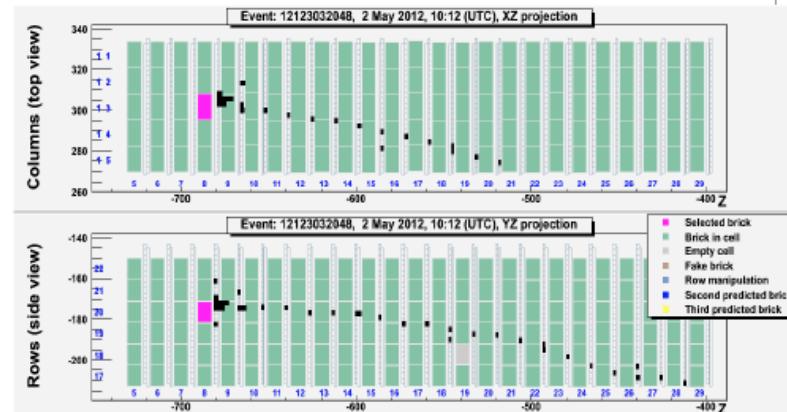


$$\tau^- \rightarrow \mu \nu_\tau$$



γ -attach	ΔZ [mm]	$IP \pm res$ [mm]	ATTACHMENT
1ry VTX	3.1	18.2 ± 13.6	OK
2ry VTX	2.8	68.7 ± 12.2	EXCLUDED

Eduardo Medinaceli – WIN2013



- 3 observed events in the $\tau \rightarrow h$, $\tau \rightarrow 3h$, and $\tau \rightarrow \mu$ channels
- Probability to be explained as a background = 7×10^{-4}
- This correspond to a significance of 3.2σ of non-null observation (3.5 σ significance using a likelihood approach)

Every prediction must be tested, even when we think we know the answer!

Three Neutrino Oscillation

$$P(\nu_\mu \rightarrow \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \underline{\sin 2\theta_{13}} + T_3 \alpha \underline{\sin 2\theta_{13}} + T_4 \alpha^2$$

atmospheric

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2 [(1-x)\Delta]}{(1-x)^2} \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

interference

$$\left\{ \begin{array}{l} T_2 = \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin [(1-x)\Delta]}{(1-x)} \\ T_3 = \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin [(1-x)\Delta]}{(1-x)} \end{array} \right.$$

solar

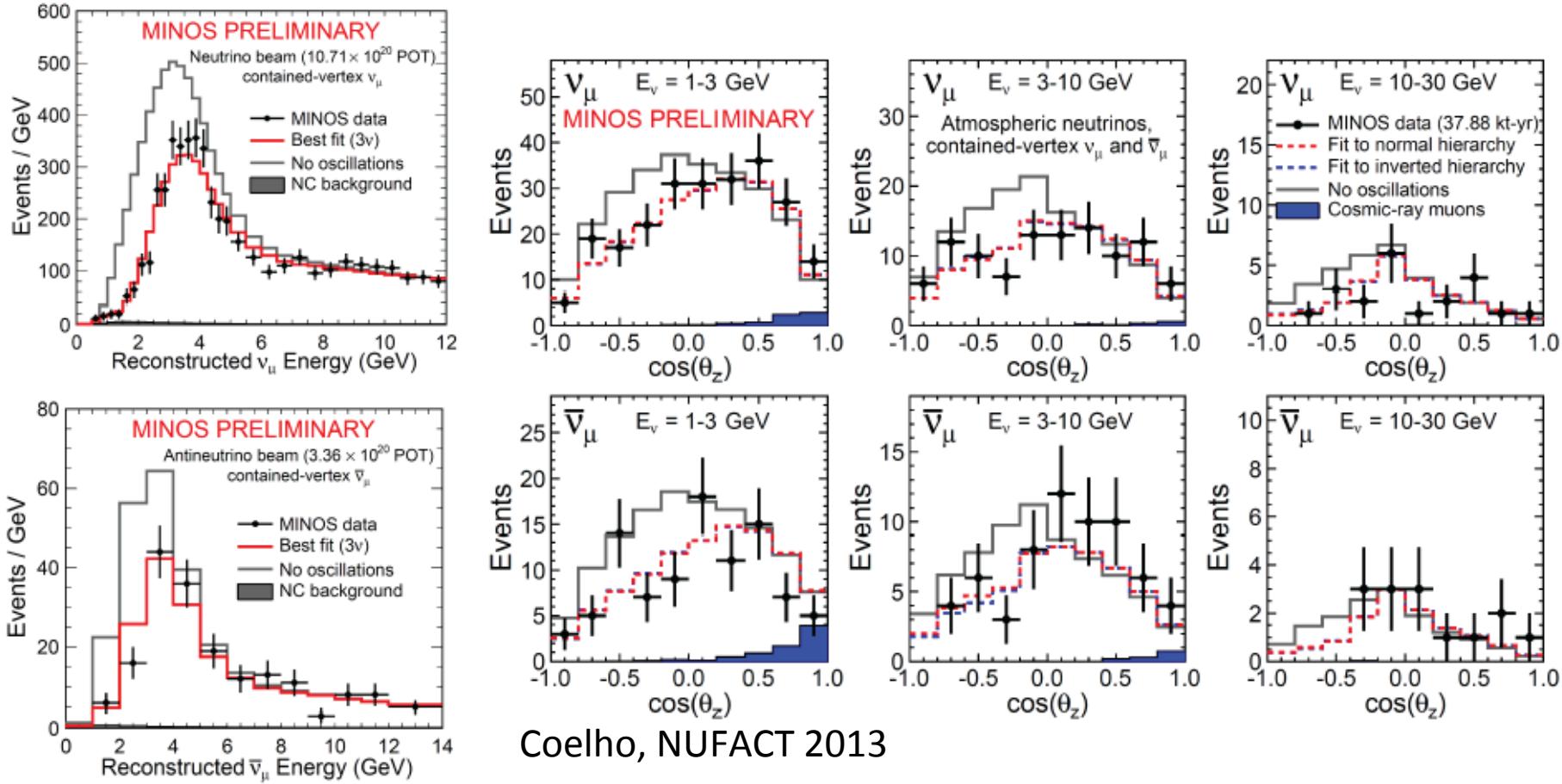
$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \Delta m_{31}^2 L / 4E \quad x = 2\sqrt{2} G_F N_e E / \Delta m_{31}^2 \cong E/12 \text{ GeV}$$

matter effects: for anti-neutrinos, sign of x and $\sin \delta_{CP}$ is changed
 hierarchy inversion also exchanges role of anti-neutrinos and neutrinos

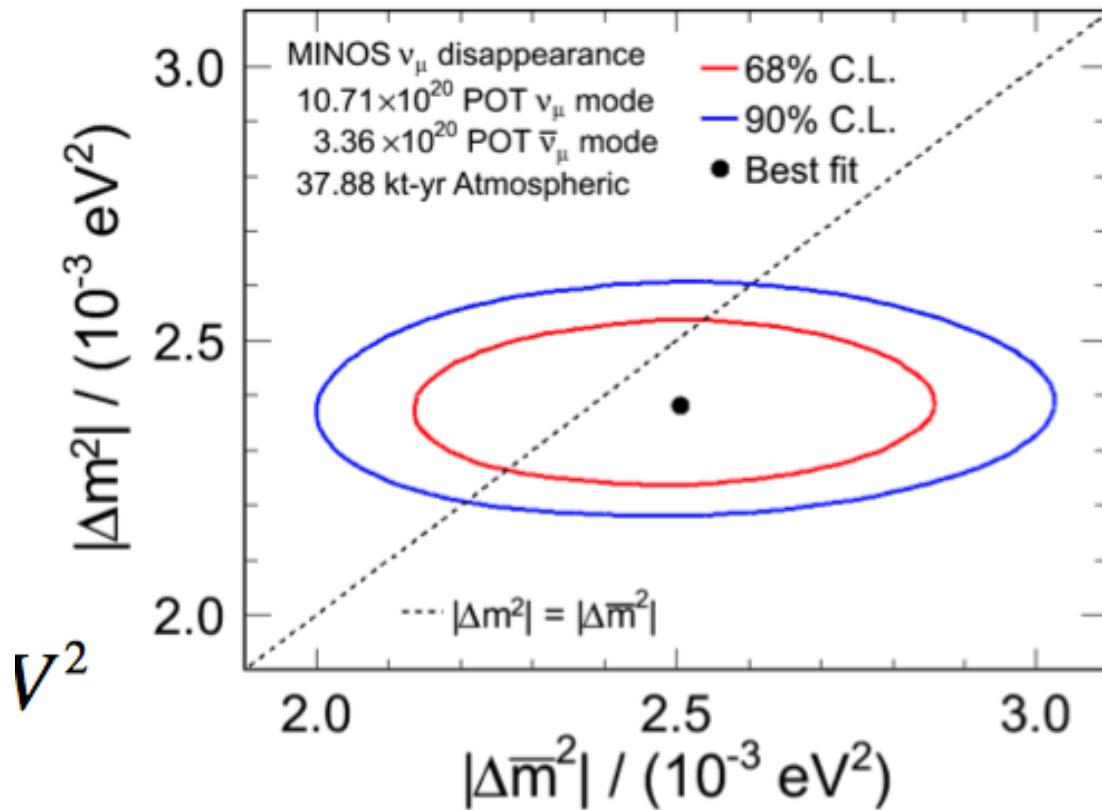
There are similar formula for ν_μ disappearance

Muon Neutrino Disappearance Data from MINOS (3ν analysis)



Coelho, NUFACt 2013

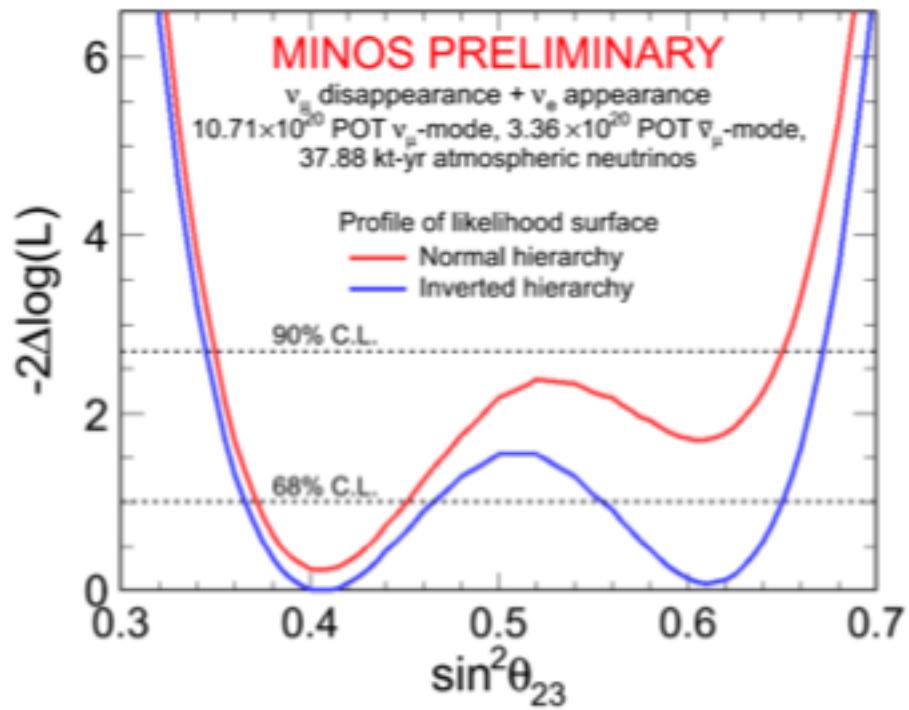
Muon Neutrino Disappearance Results from MINOS



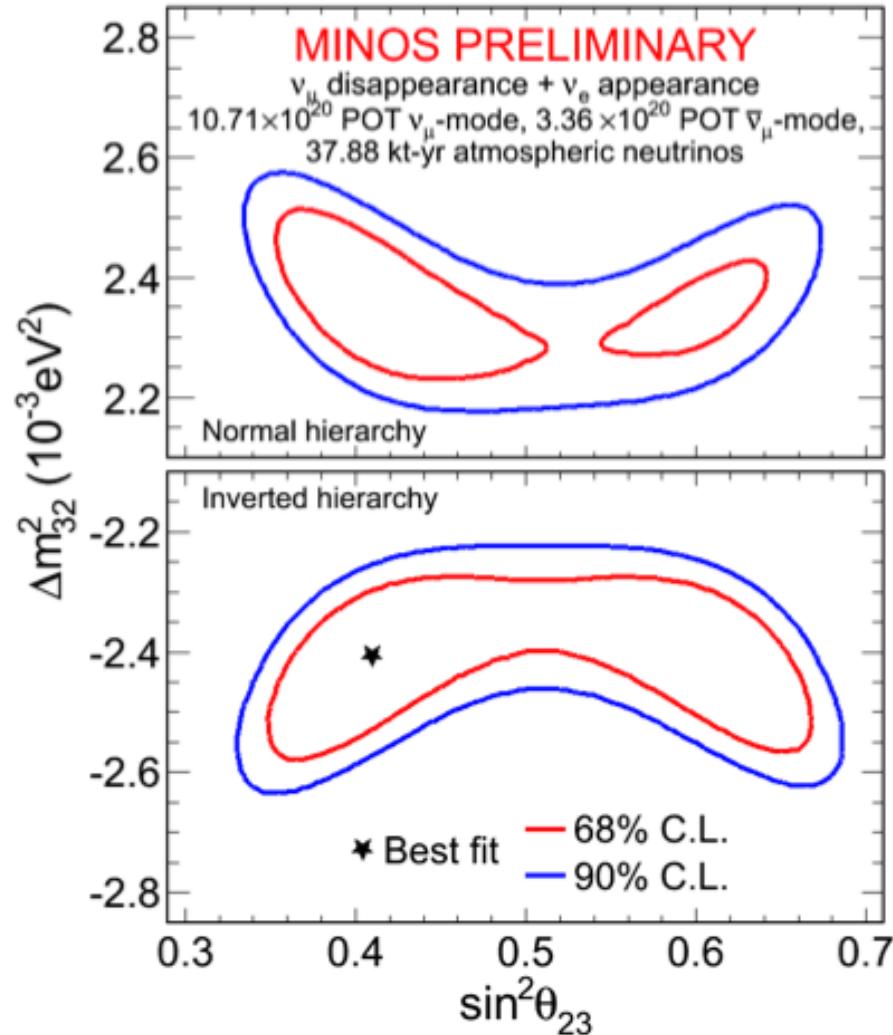
Phys. Rev. Lett. 110, 251801 (2013)

Unique contribution from antinu running
and magnetized detector

Muon Neutrino Disappearance Results from MINOS



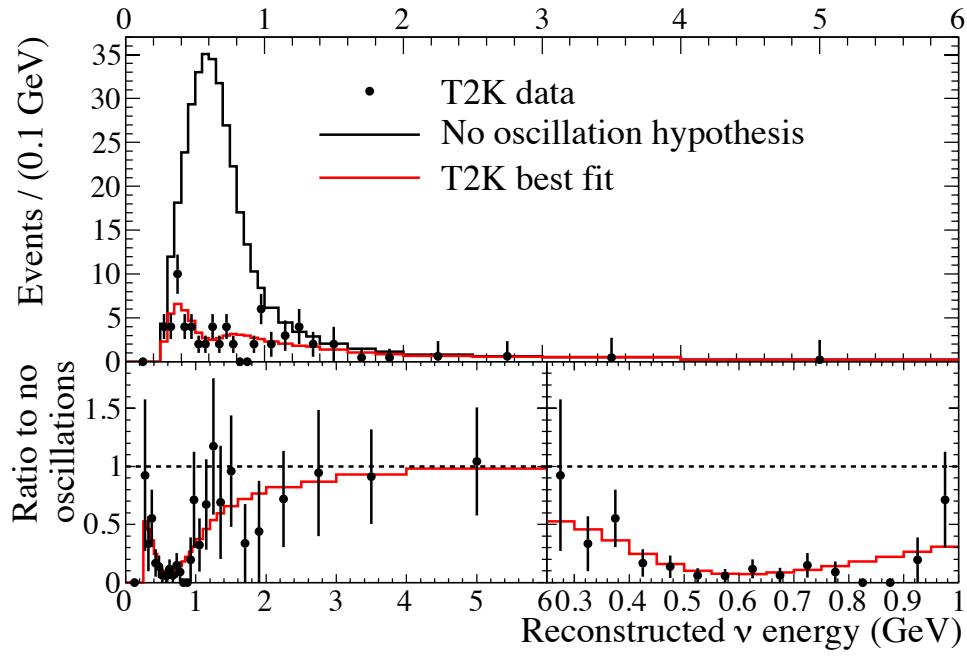
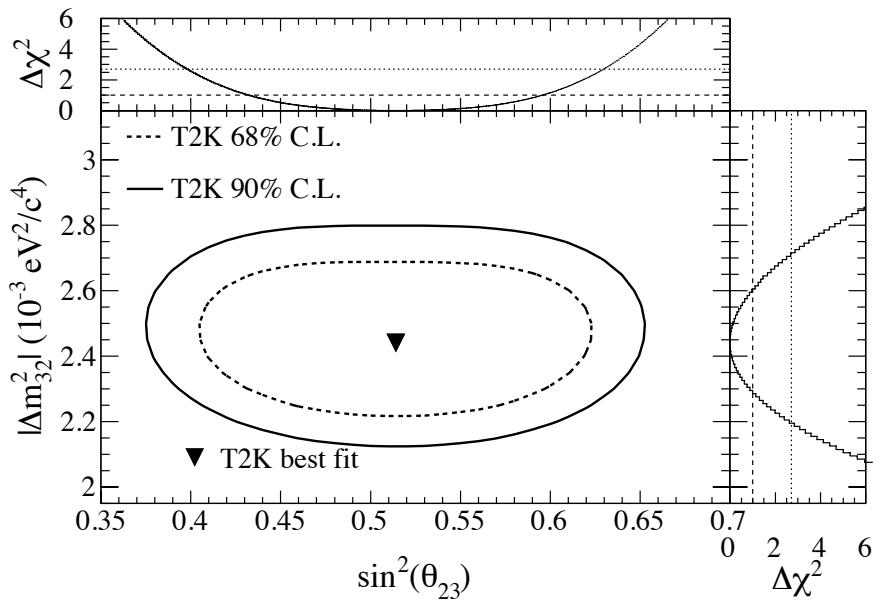
Whitehead NNN 2013



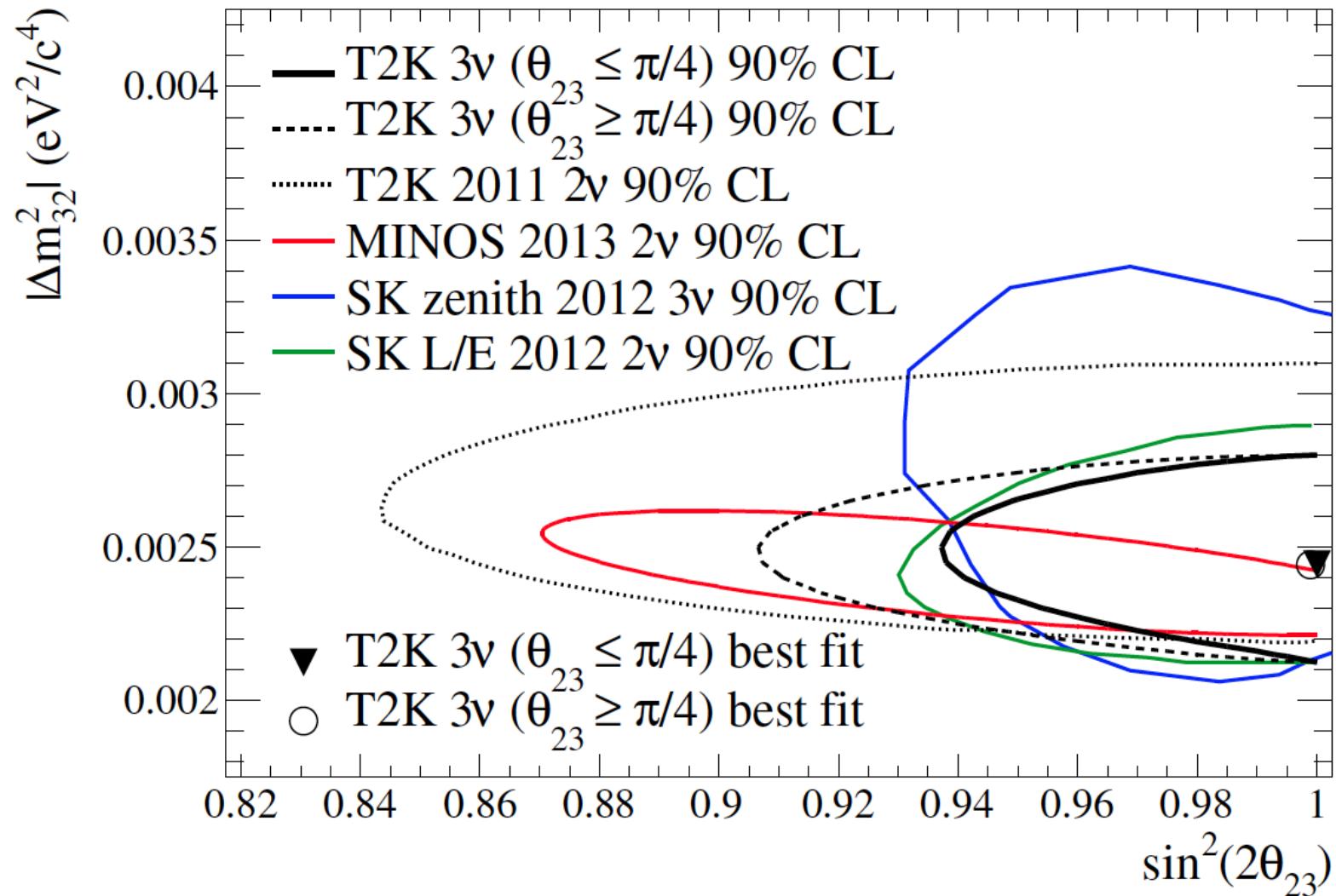
Muon Neutrino Disappearance Data and Results from T2K

Spectacular demonstration
of off-axis obliteration at
1st oscillation maximum

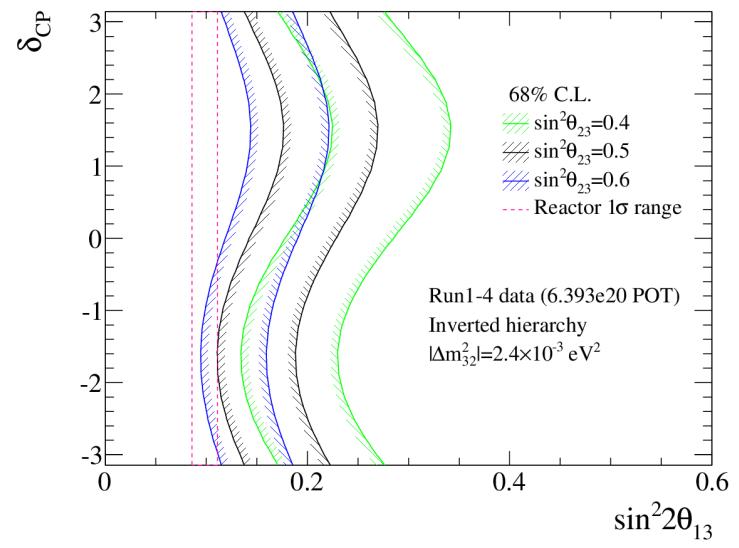
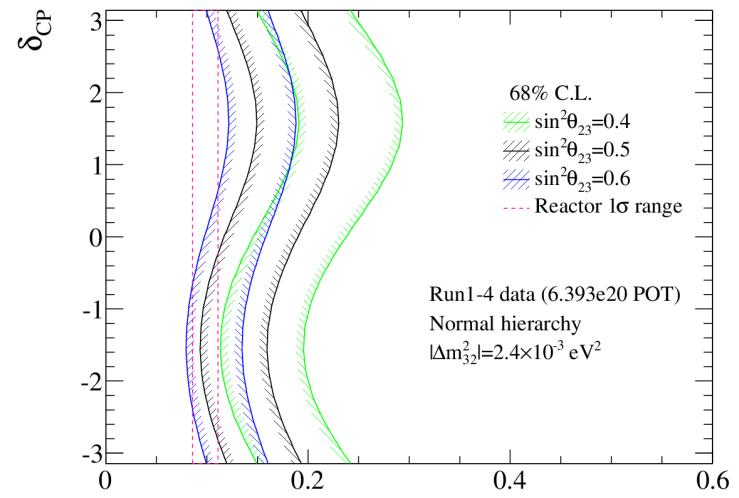
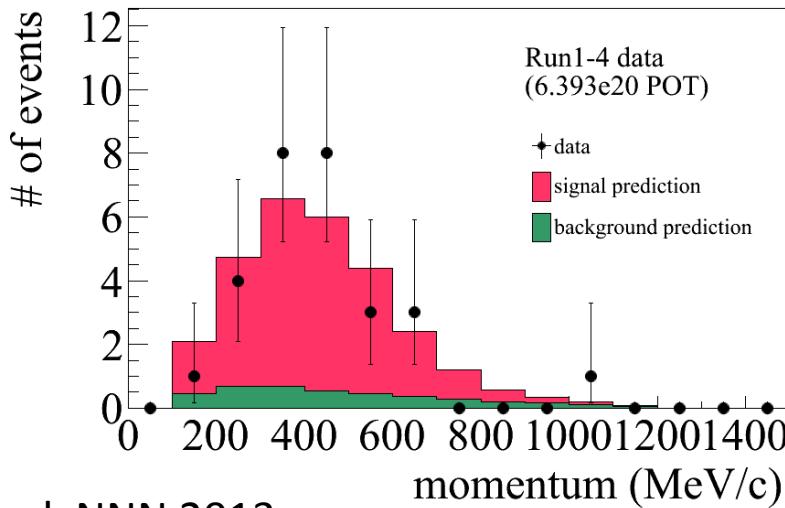
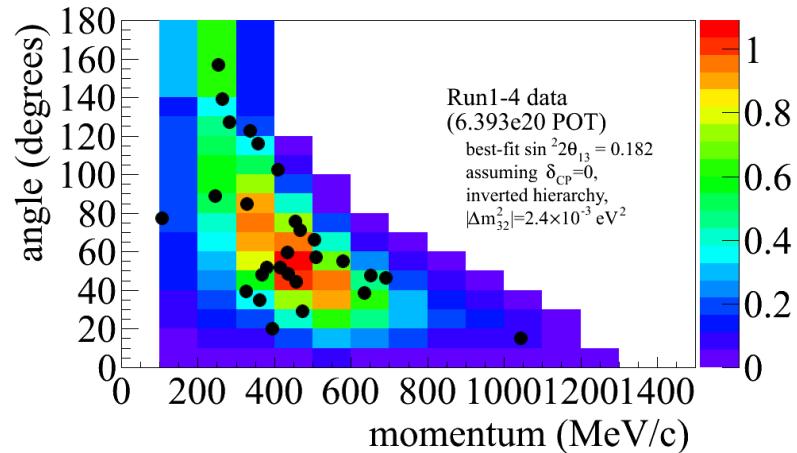
Friend, NuFACT 2013



Muon Neutrino Disappearance Comparison of Results



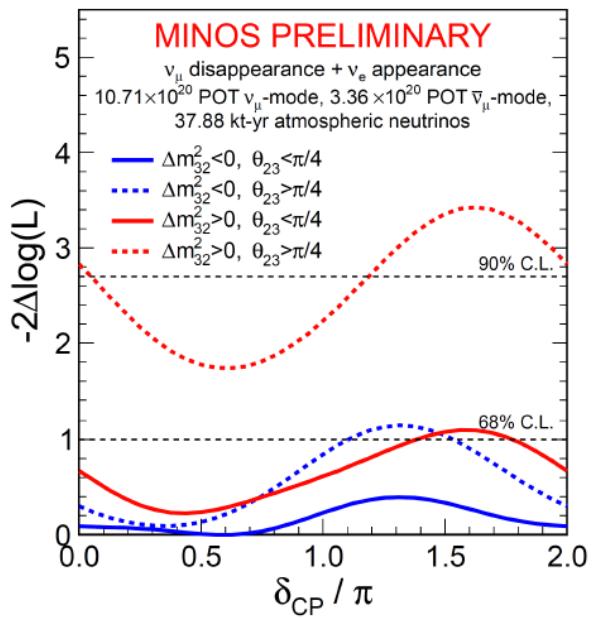
Electron Neutrino Appearance Data and Results from T2K



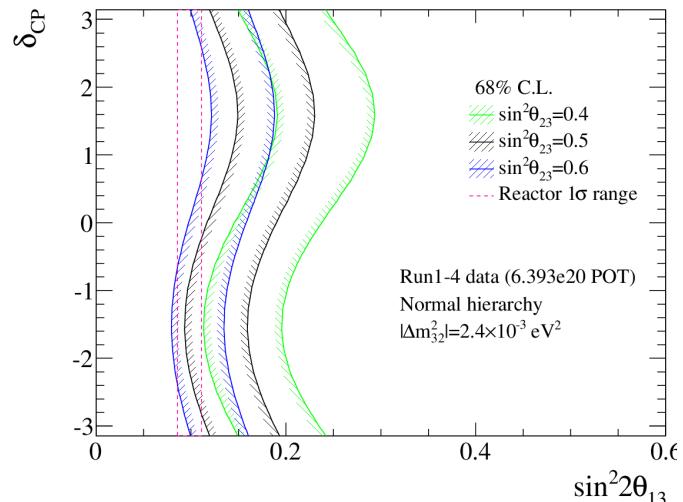
Are hints of CP δ emerging?

Slide inspired by Nakaya, ICFA Japan 2013

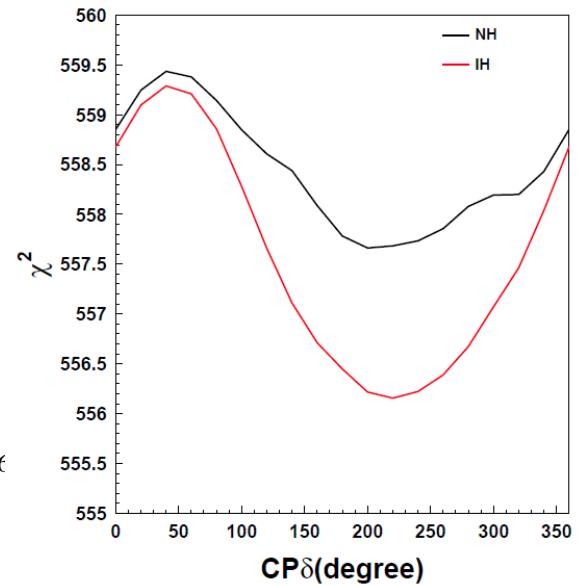
MINOS combined
 $\nu\mu$ disappearance
 νe appearance
Coelho, NUFACt 2013



T2K
 νe appearance
Cherdack NNN 2013



Super-K
atmospheric ν
Raaf NNN 2013



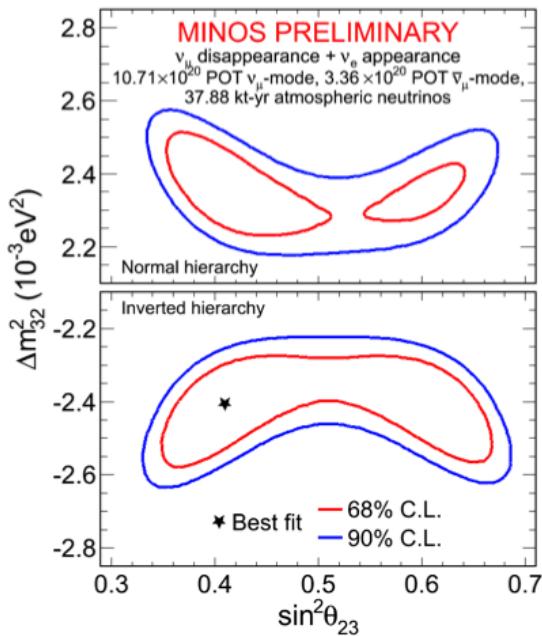
Hmmm. But being forced by maximal oscillation effects.

How about octant of θ_{23} ?

Slide inspired by Nakaya, ICFA Japan 2013

MINOS combined

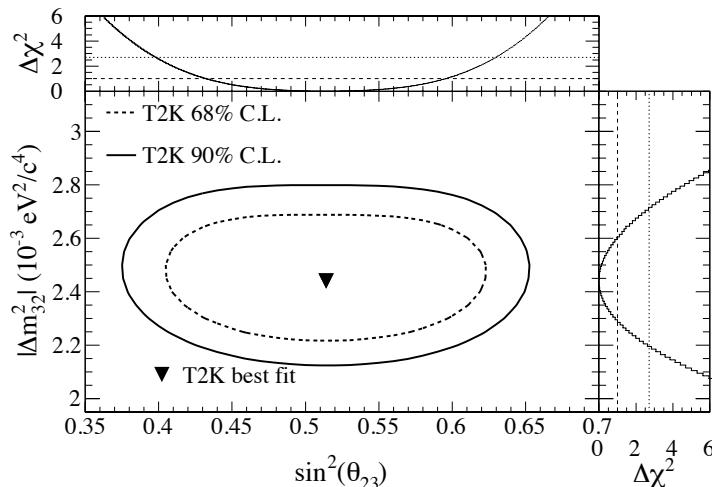
Whitehead, NUFACt 2013



T2K

$\nu\mu$ disappearance

Cherdack NNN 2013

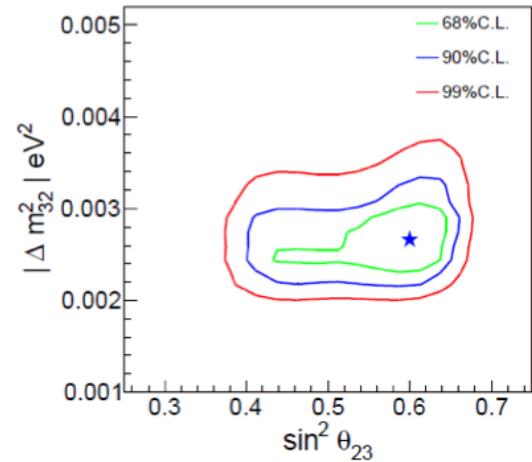


Super-K

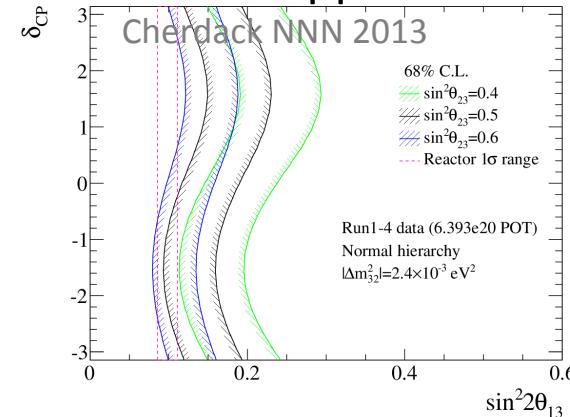
atmospheric ν

Raab NNN 2013

Inverted hierarchy (θ_{13} = reactor)



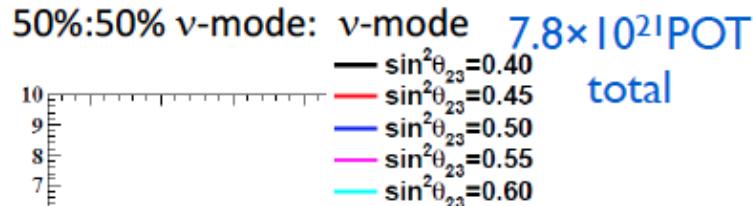
T2K νe appearance



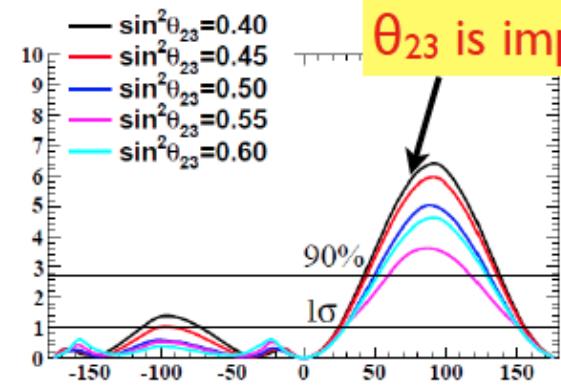
Hints disagree:

1st octant, maximal mixing, and 2nd octant

Combination of T2K plus NOvA

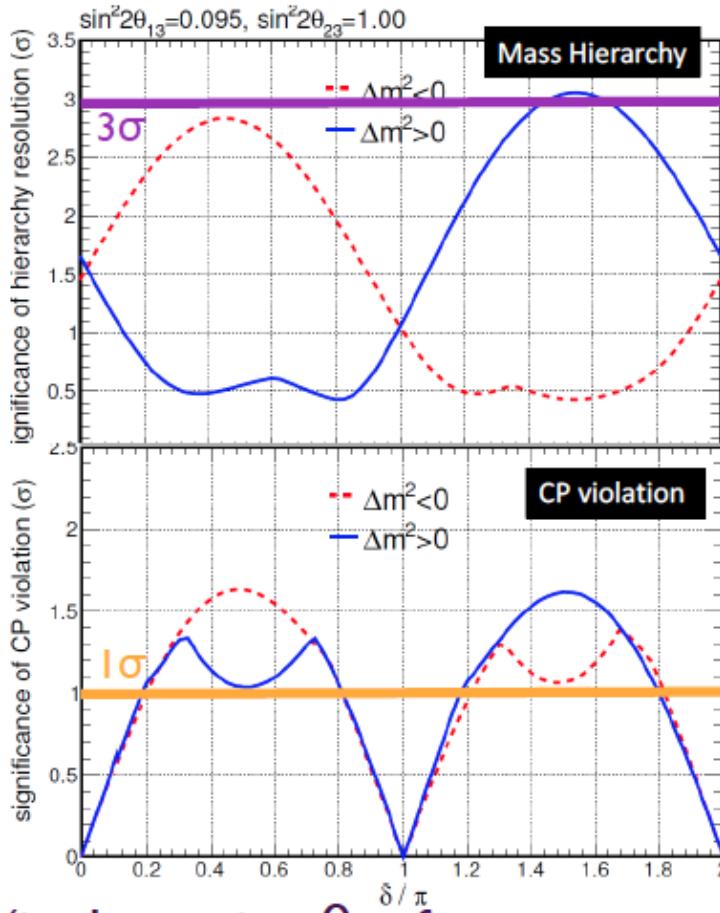


A.Ichikawa, EPS-HEP13



Combination of experiments (incl. precise θ_{13} from reactor)
can enhance sensitivities

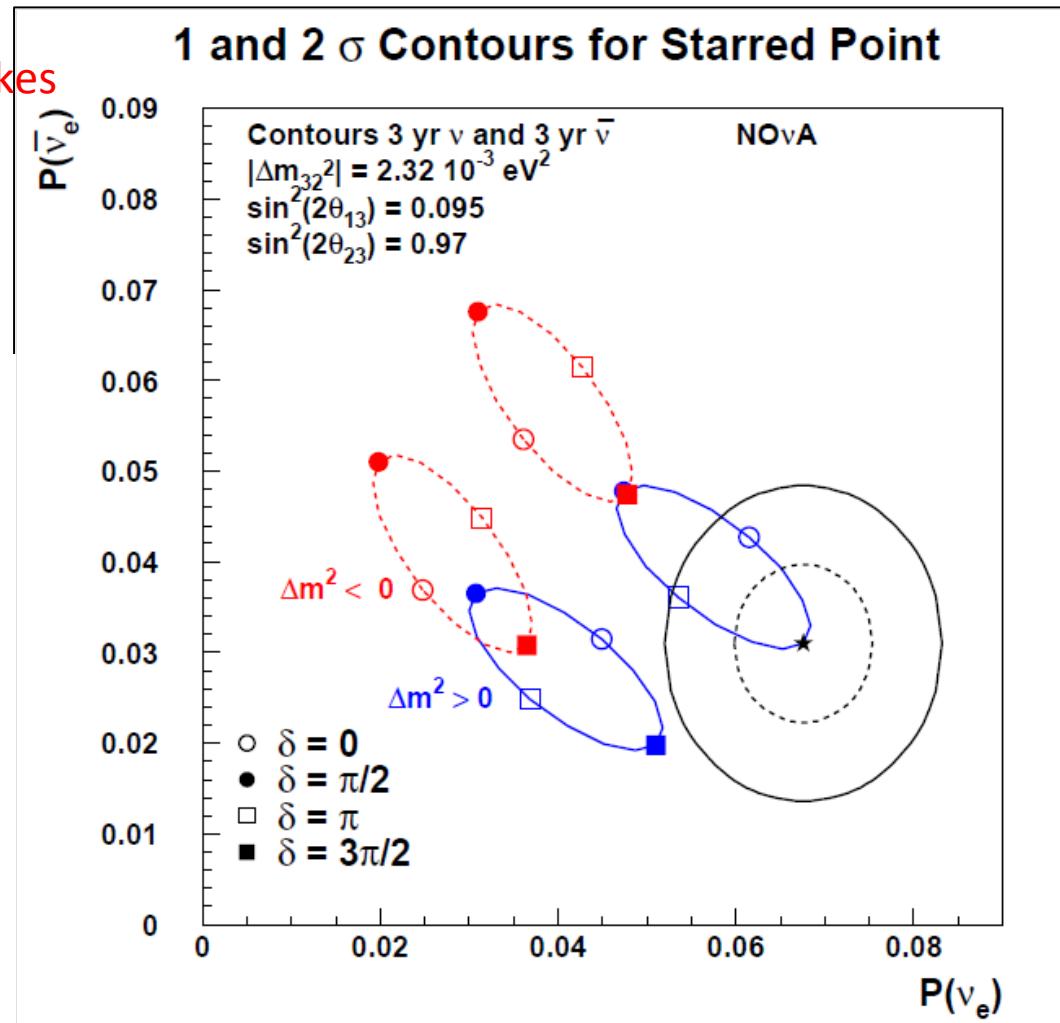
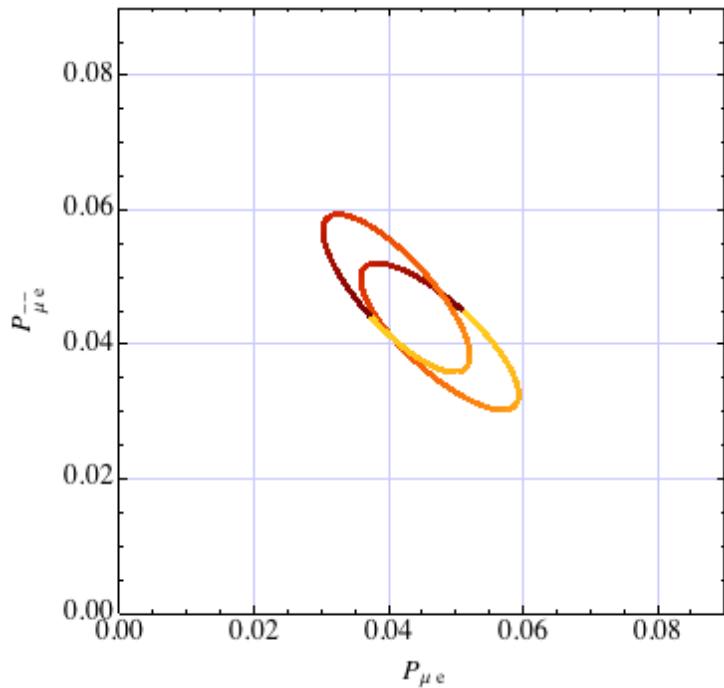
→ Possibility to see hint of CP violation!



This Generation of Experiments

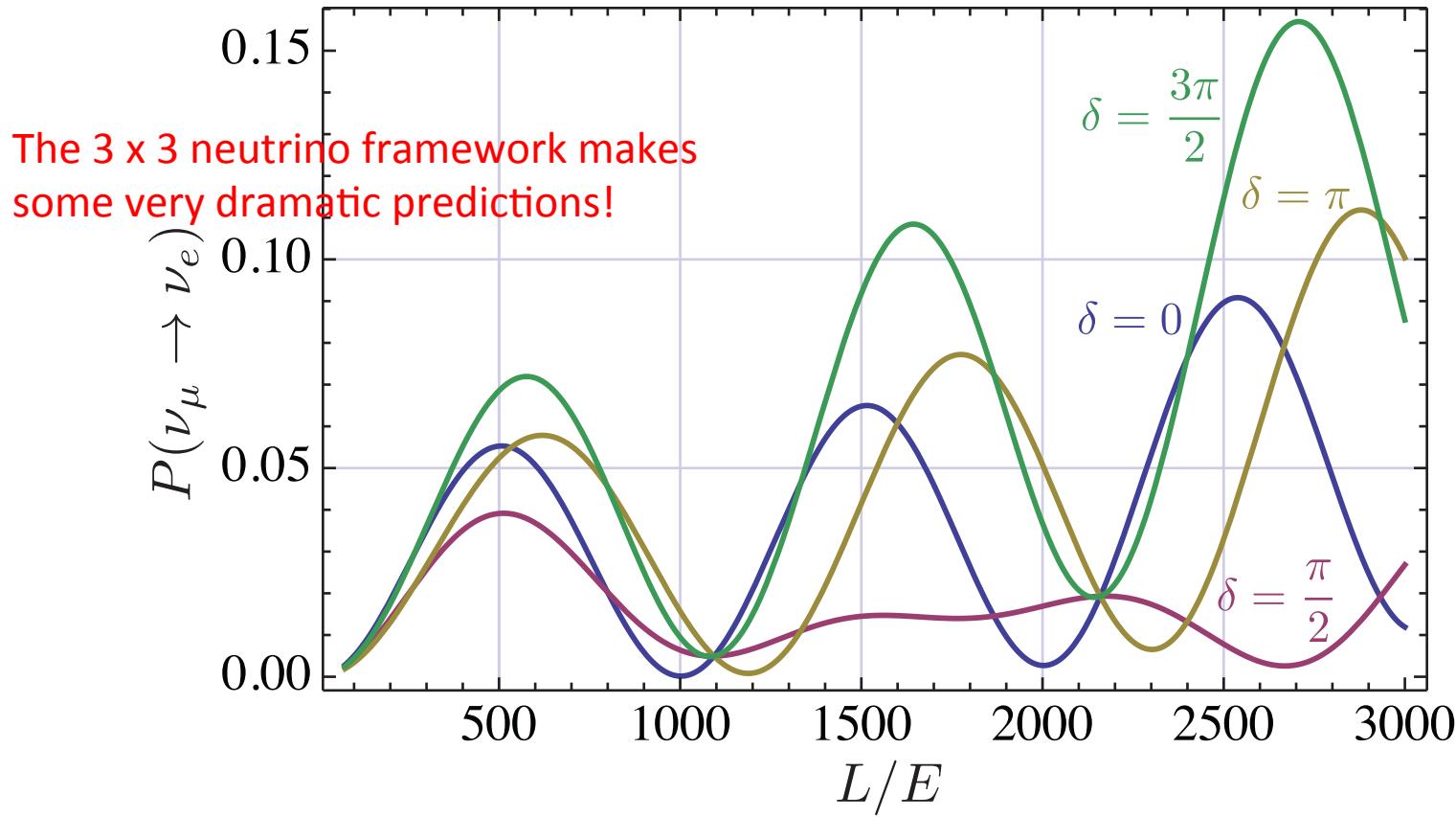
The 3×3 neutrino framework makes some very dramatic predictions!

T2K 0.7 GeV 295 km

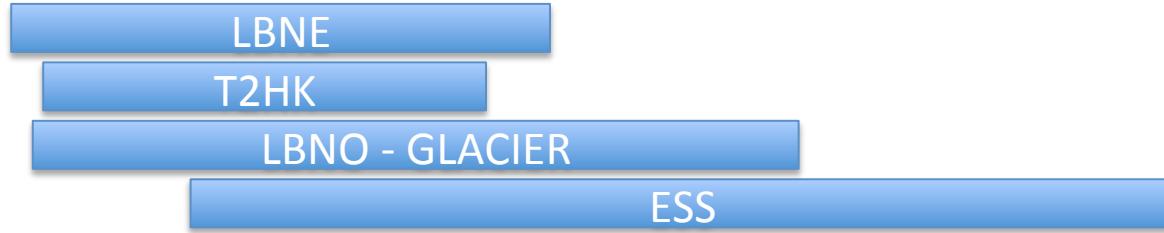


Meuther NNN 2013

Next Generation of Experiments



50% neutrino flux bands
(not event rate)



DAEDALUS

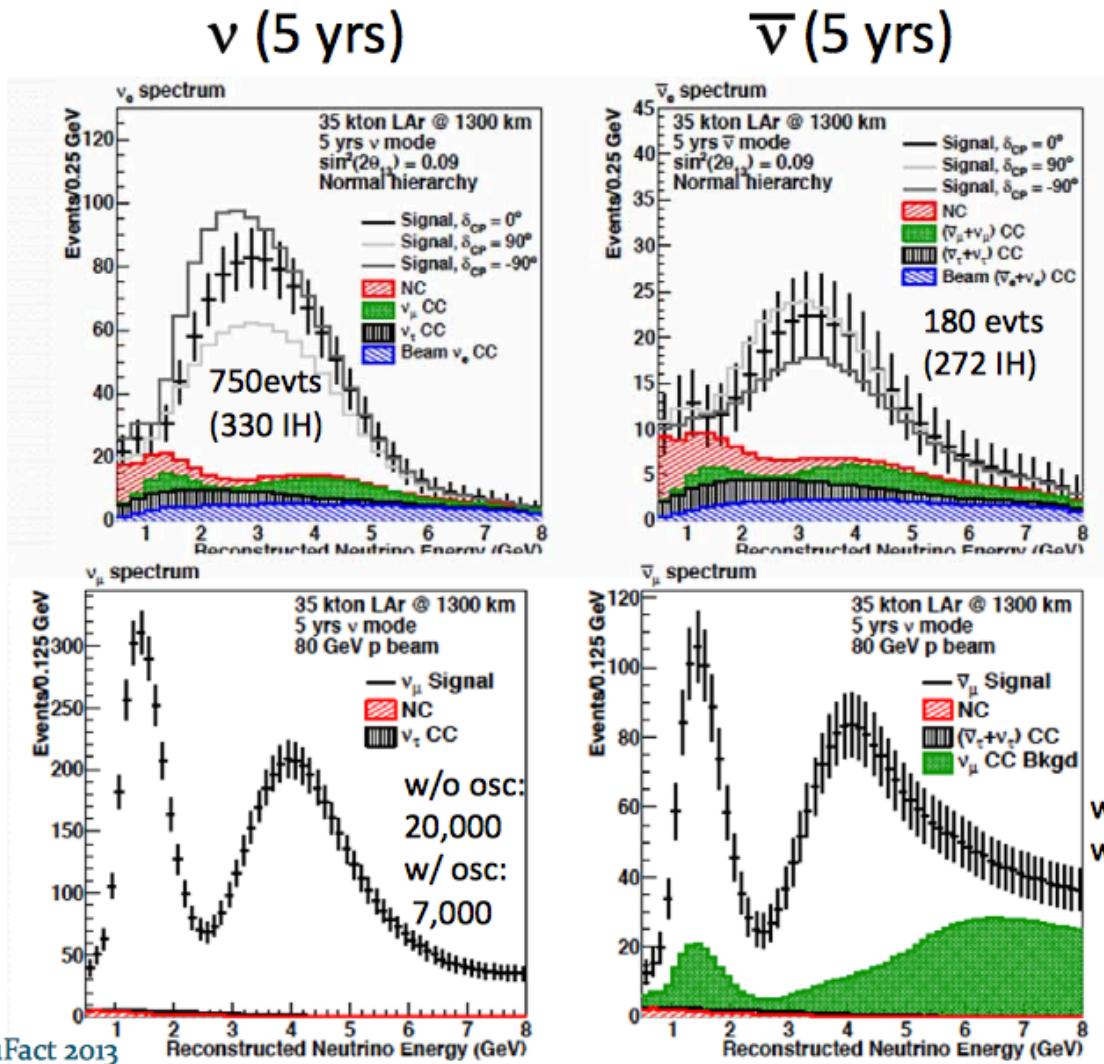
EURONU-MEMPHYS

Idea of measuring oscillation at 2nd maximum is very attractive (Ekelof seminar)

Long Baseline Neutrino Experiment

Appearance

$$\nu_\mu \rightarrow \nu_e$$



Disappearance

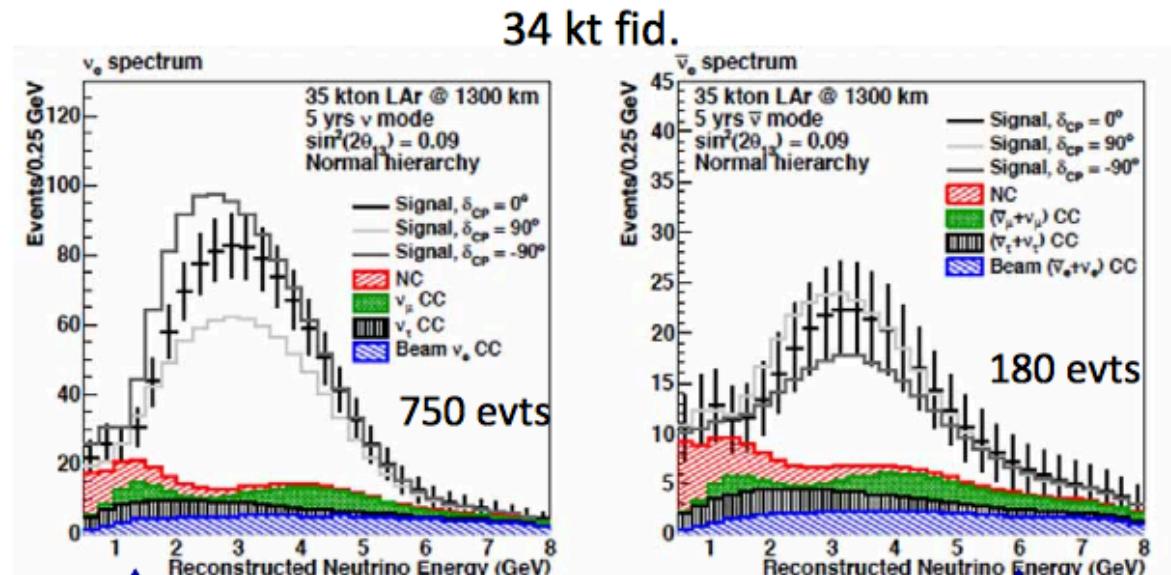
$$\nu_\mu \rightarrow \nu_\mu$$

J.Strait

NuFact 2013

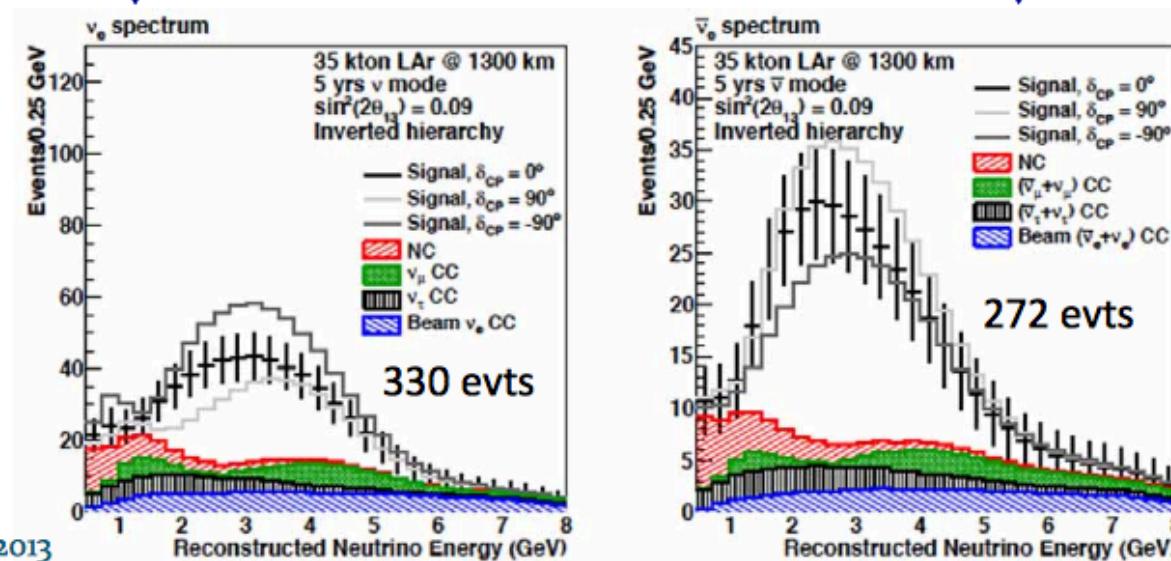
Long Baseline Neutrino Experiment

Normal

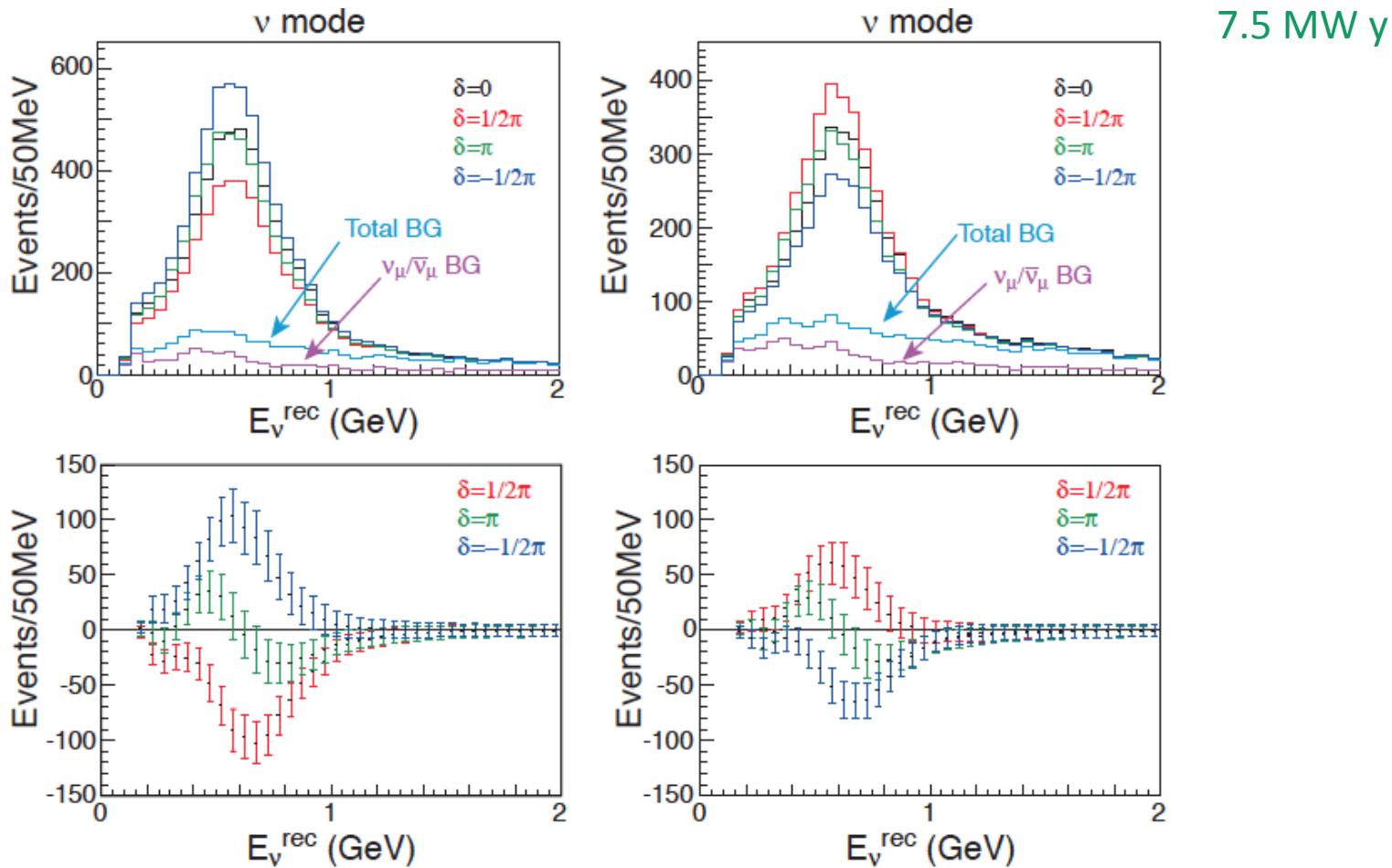


Difference due to mass ordering

Inverted

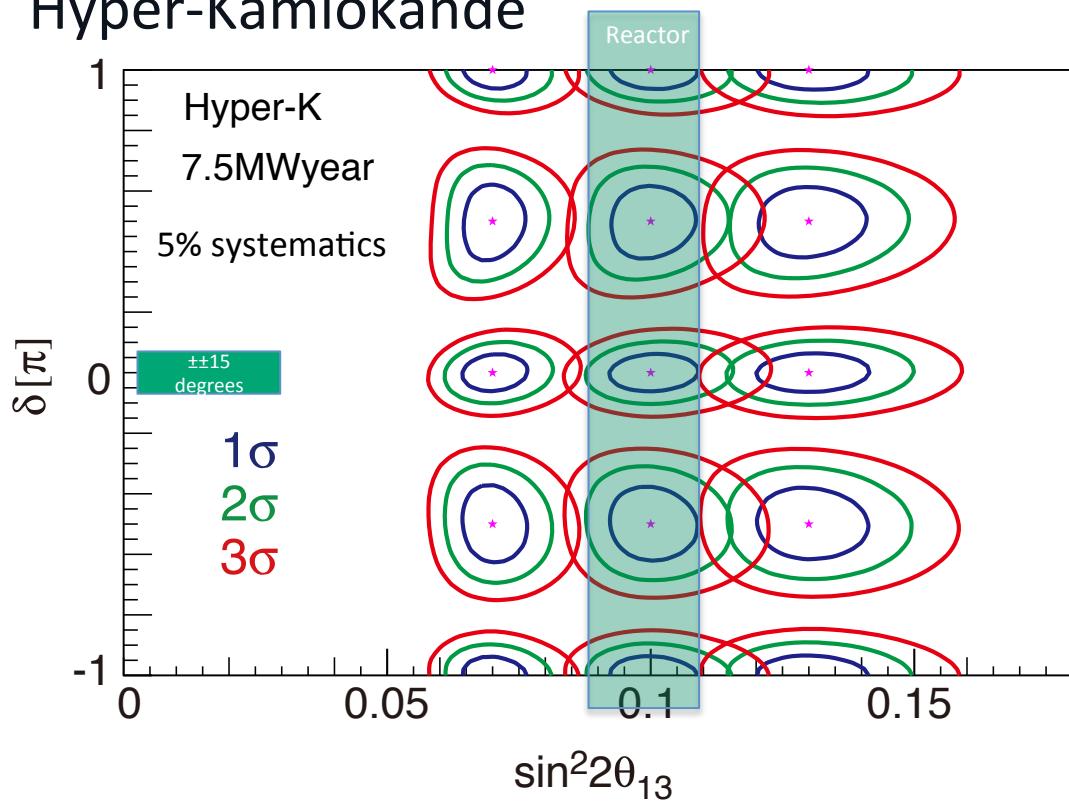


Hyper-Kamiokande (with J-PARC)

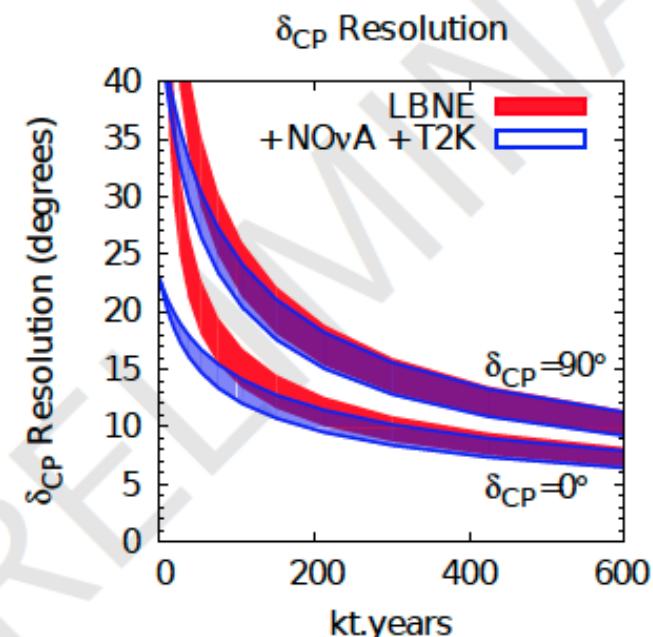


CP Precision

Hyper-Kamiokande



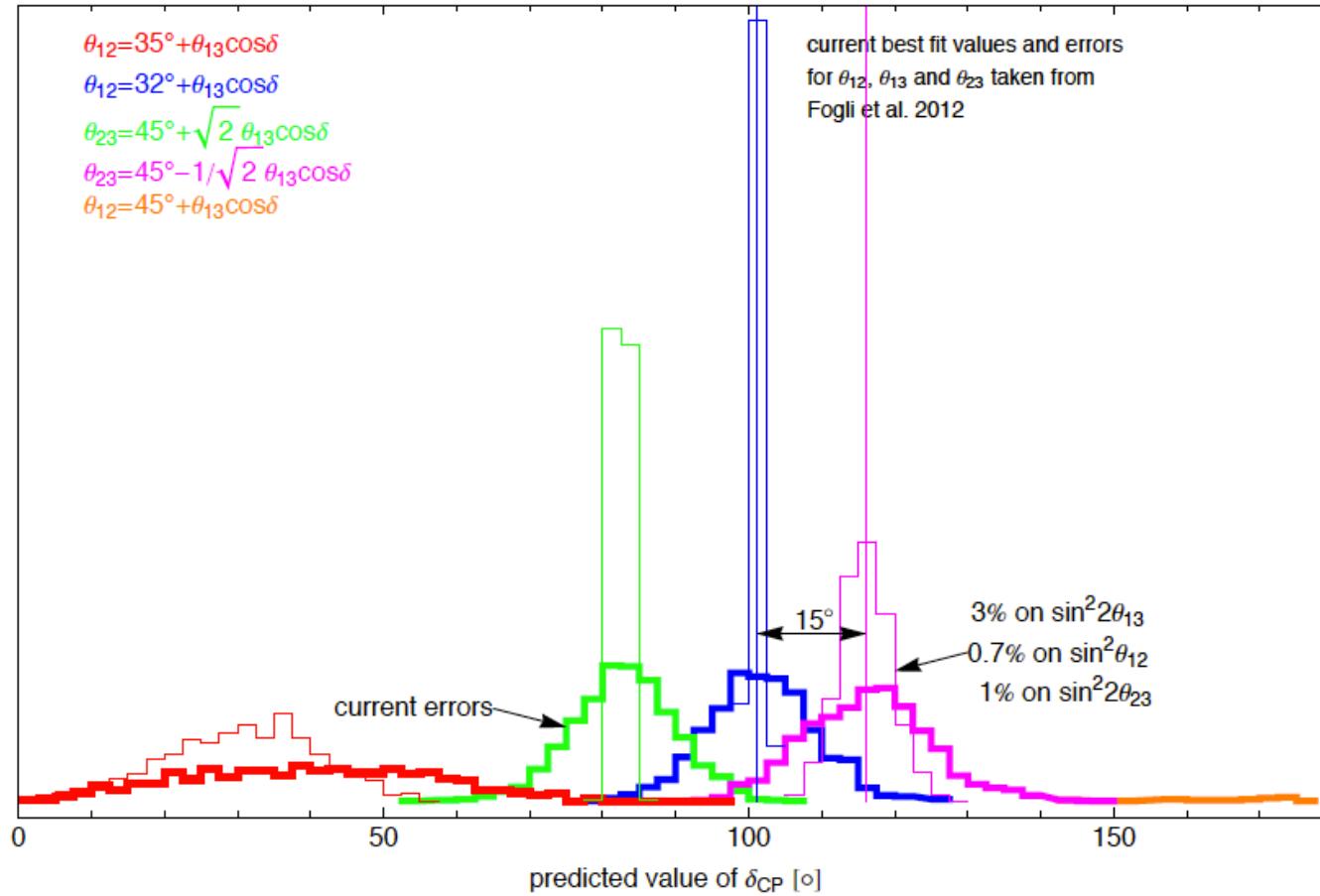
LBNE



Assumes mass hierarchy is determined! –
by other experiments, combinations, atm. neutrinos

Is there a benchmark for CP Precision?

15 degree precision allows for discrimination of some selected sum rules



<http://arxiv.org/abs/arXiv:1310.4340>

Conclusions

A standard picture of 3-flavor neutrino oscillation exists.

The role of long baseline experiments is to clarify that picture
in combination with independent measurements by
Independent experiments (sometimes with the same detector!)

Hints are already starting to emerge for the remainder of
our to-do list: MH, octant, and CP-delta.

We should look for every feature we expect ...
... and keep our eyes out for the unexpected, while we
work on this list!