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Review of Long-baseline Neutrino Oscillation Expts

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European Research Council

Established by the European Commission

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Established by the European Commission

PASCOS, Vietnam

14th July 2016

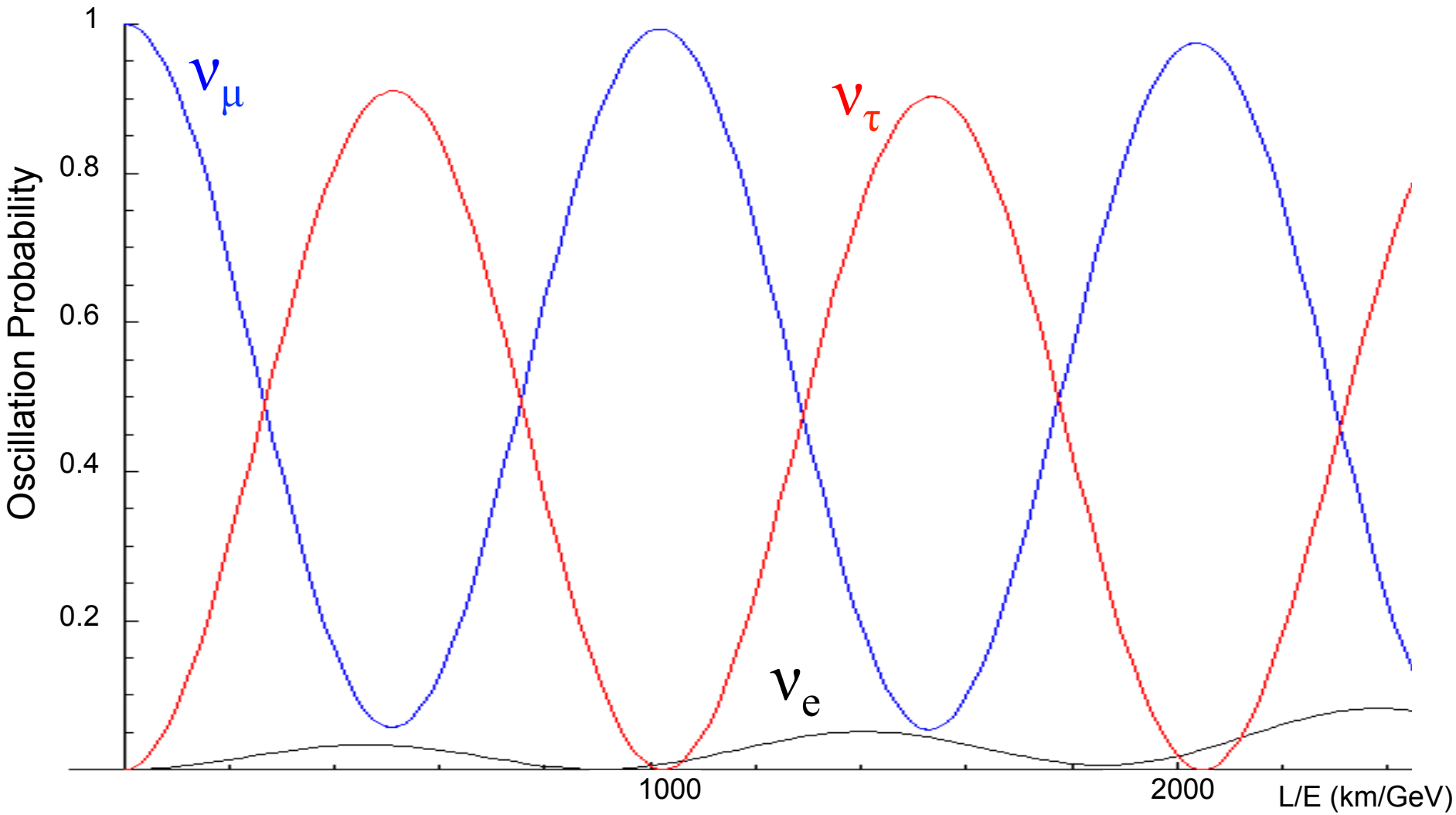
Introduction

- Oscillation probabilities
- Long-baseline approach

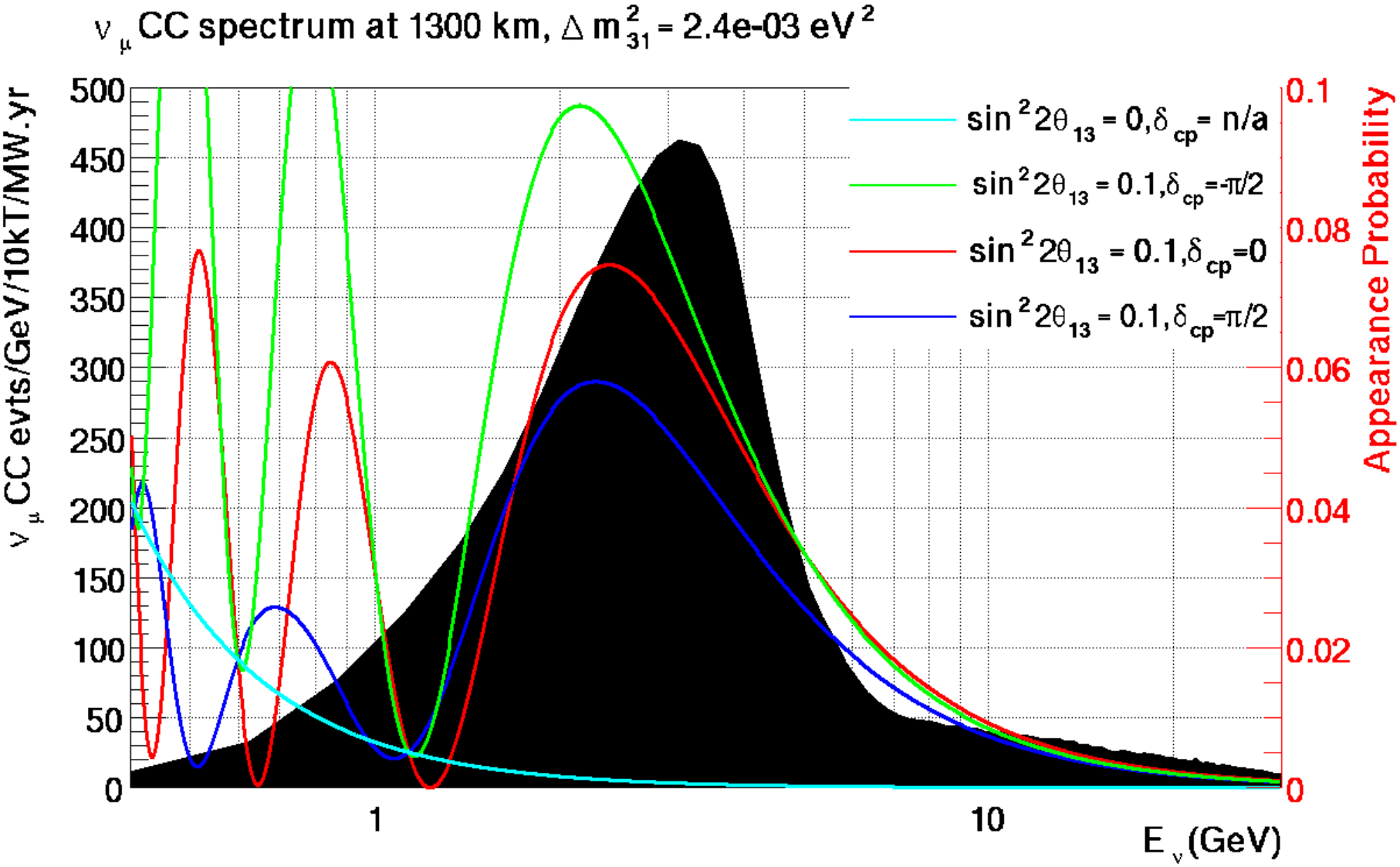
- New NOvA Results
- New T2K Results

- Future experiments: DUNE and HyperK
- Sensitivities

Bigger Picture: starting with ν_μ



Zoom in on ν_e appearance

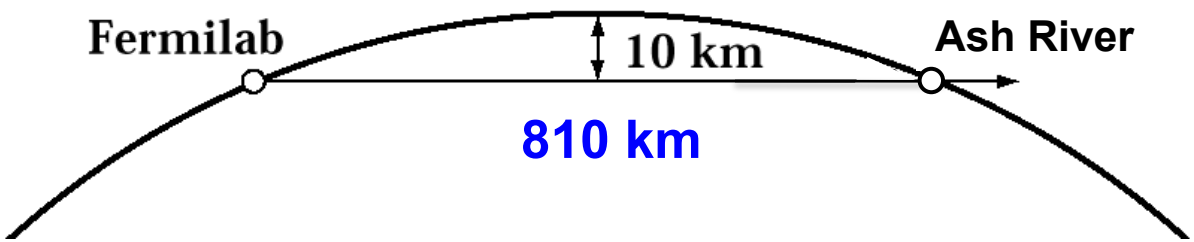


Long-baseline Concept

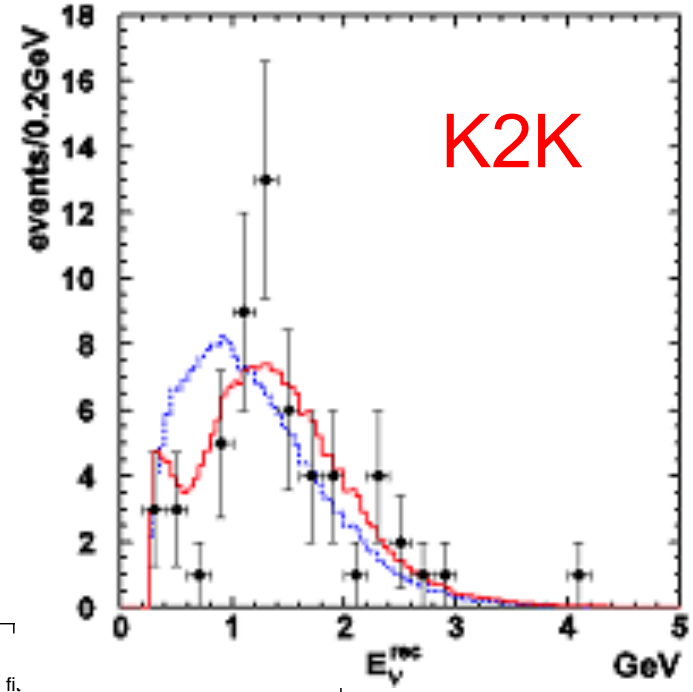
- "Conventional" beam
- Two-detector experiment:

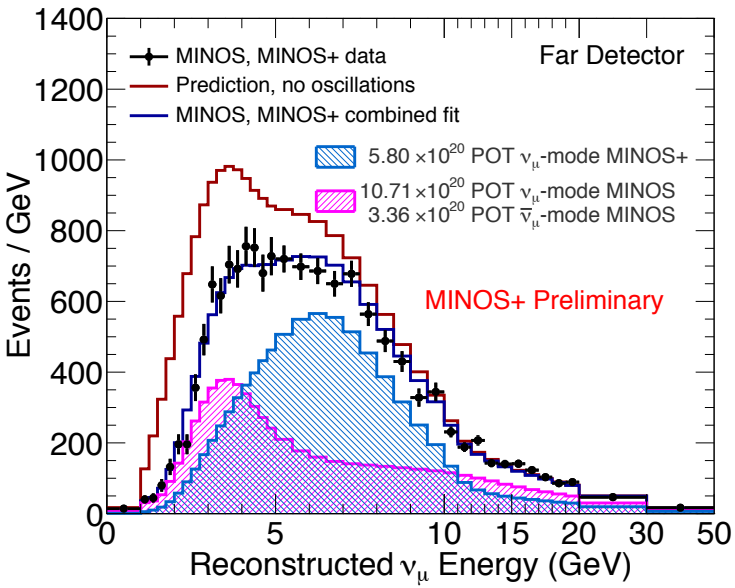
- Near detector
  - measure beam composition
  - energy spectrum

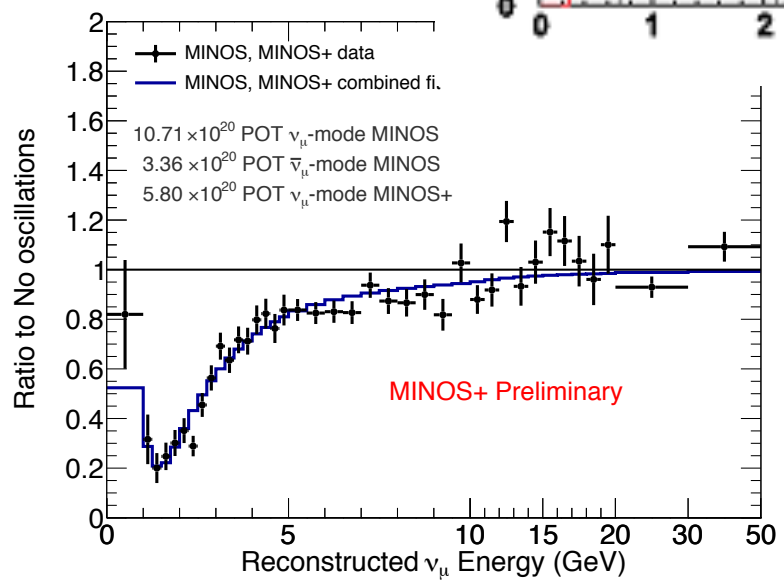
- Far detector
  - measure oscillations and search for new physics



1st Generation Expts







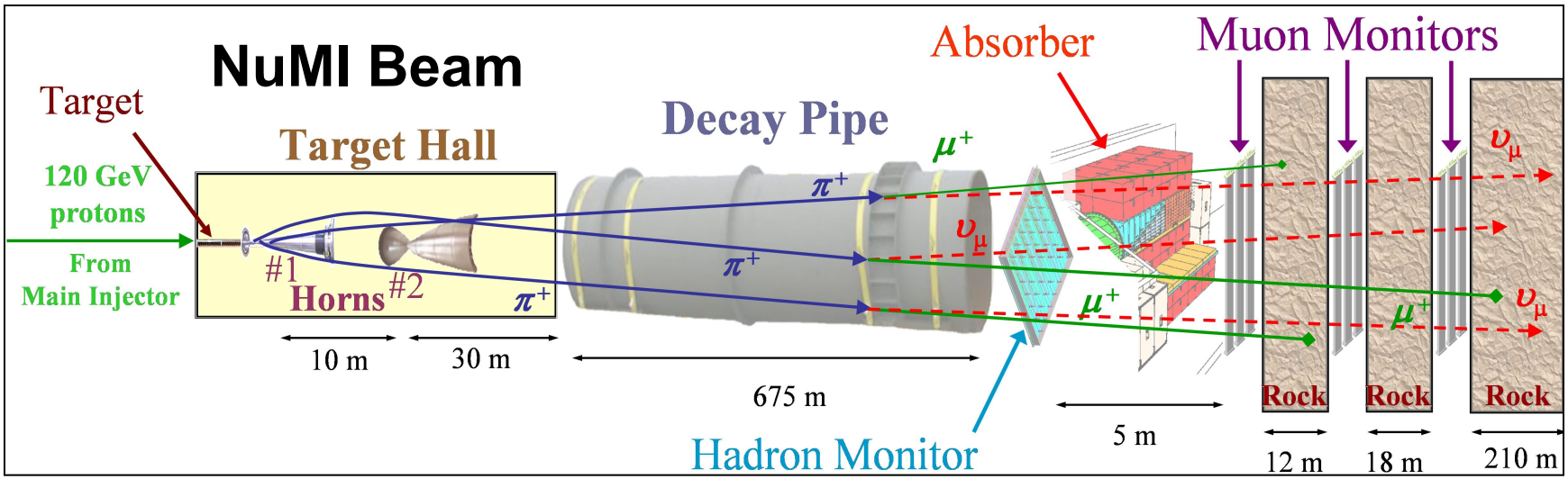
Data is very well-described by three-flavour neutrino oscillations

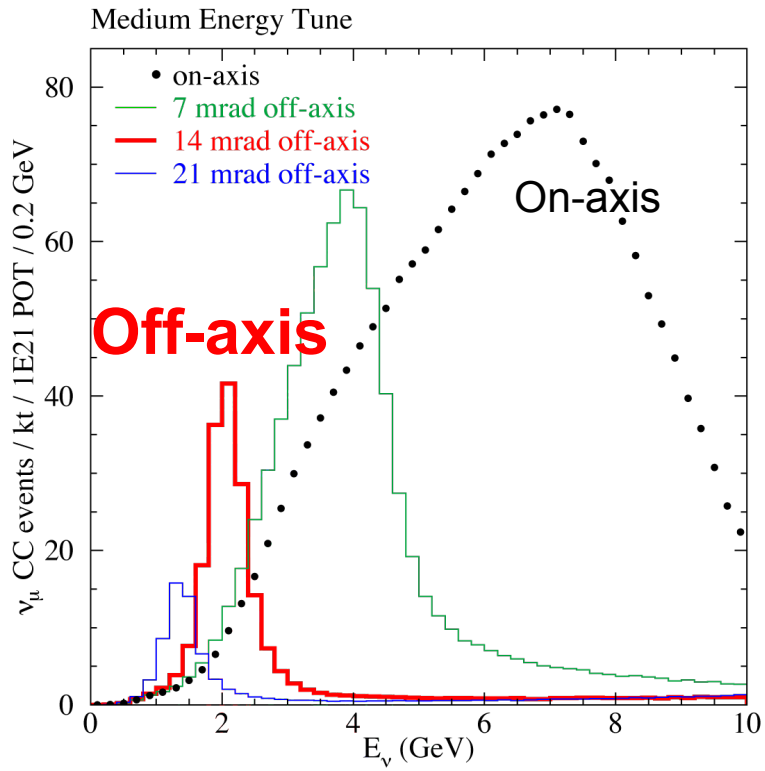
- Twice as much MINOS+ data still to come

[J. Evans, Neutrino]

Key Features of 2nd Generation Expt

- Narrow band (off-axis) beam
- Detectors optimised for
  - ν_e flavour identification
  - ν_e appearance maximum (L/E)
- Higher power beam
- Longer (or shorter) baseline to amplify (or minimize) the matter effect: 10% in T2K and 30% in NOvA


NuMI Beam
Target
Target Hall
120 GeV protons
From Main Injector
#1
Horns
#2
10 m
30 m
Decay Pipe
675 m
Absorber
Muon Monitors
Hadron Monitor
5 m
Rock
Rock
Rock
12 m
18 m
210 m


Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
On-axis
Off-axis
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
E_ν (GeV)
0
20
40
60
80
0
2
4
6
8
10

Focus on ν_e appearance measurements

It's hard to overstate…

- 2012 saw a major breakthrough in neutrino physics
  - Our measurement of θ_{13} has gone from just an upper limit to one of the best
- A new door has been opened to probing
  - CP violation,
  - mass hierarchy
  - octant of θ_{23}

Long-baseline $\nu_\mu \rightarrow \nu_e$

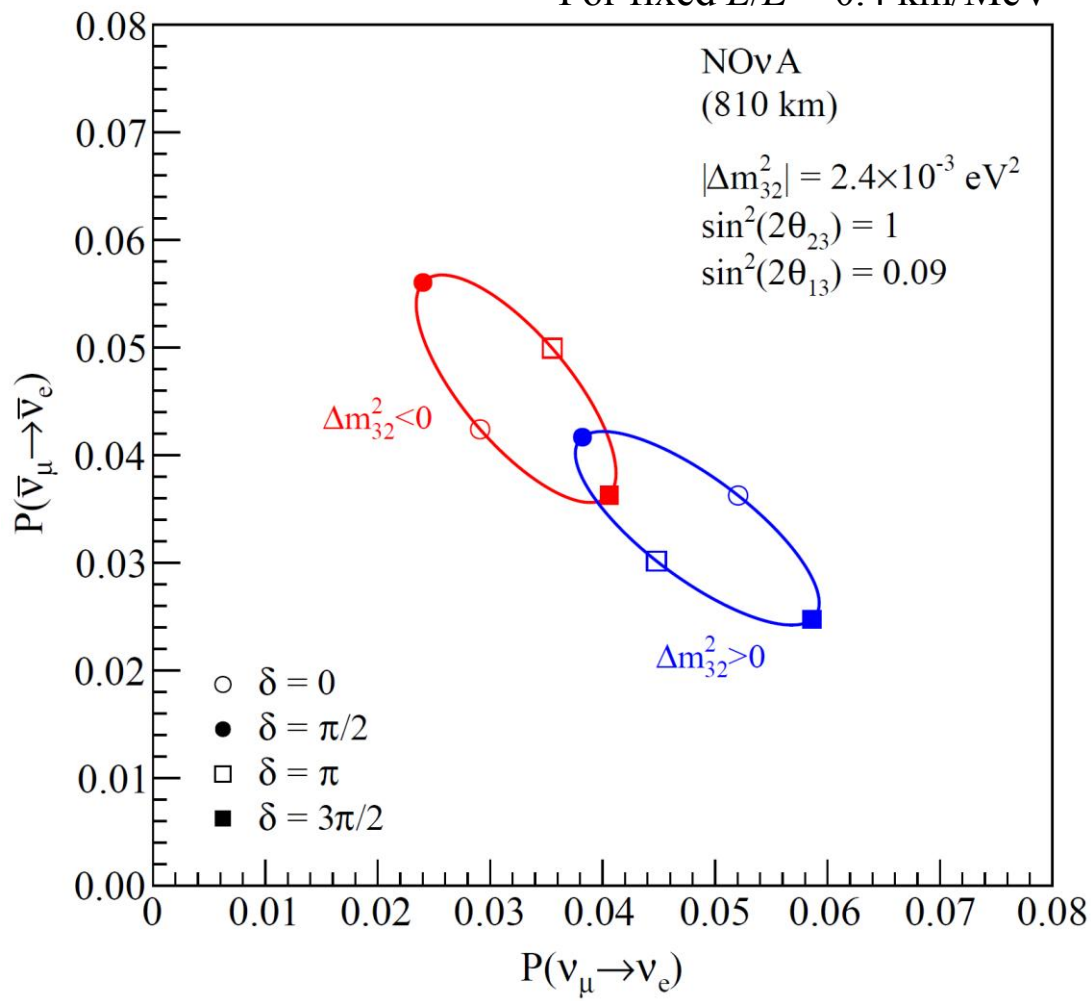
A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

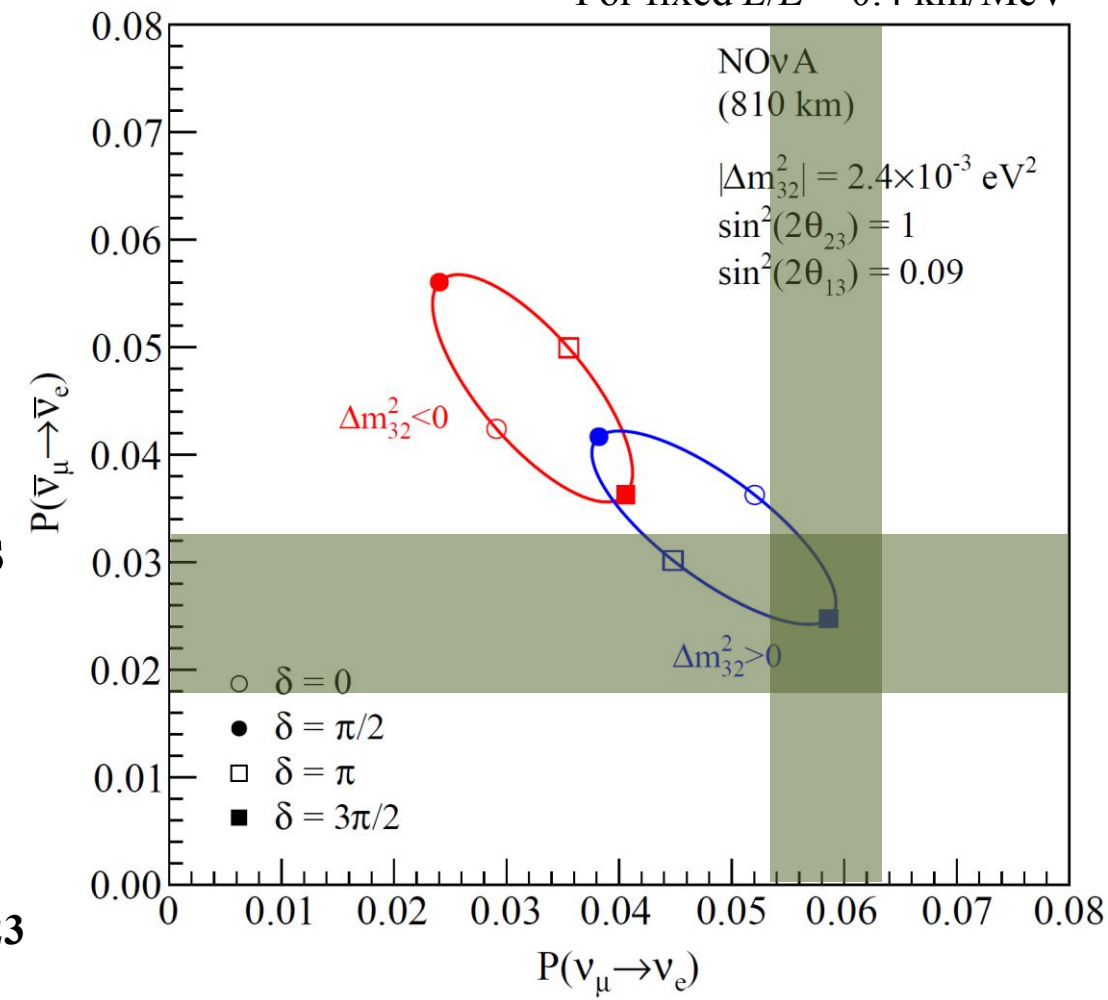
Measure these probabilities

(an example measurement of each shown)

Also:

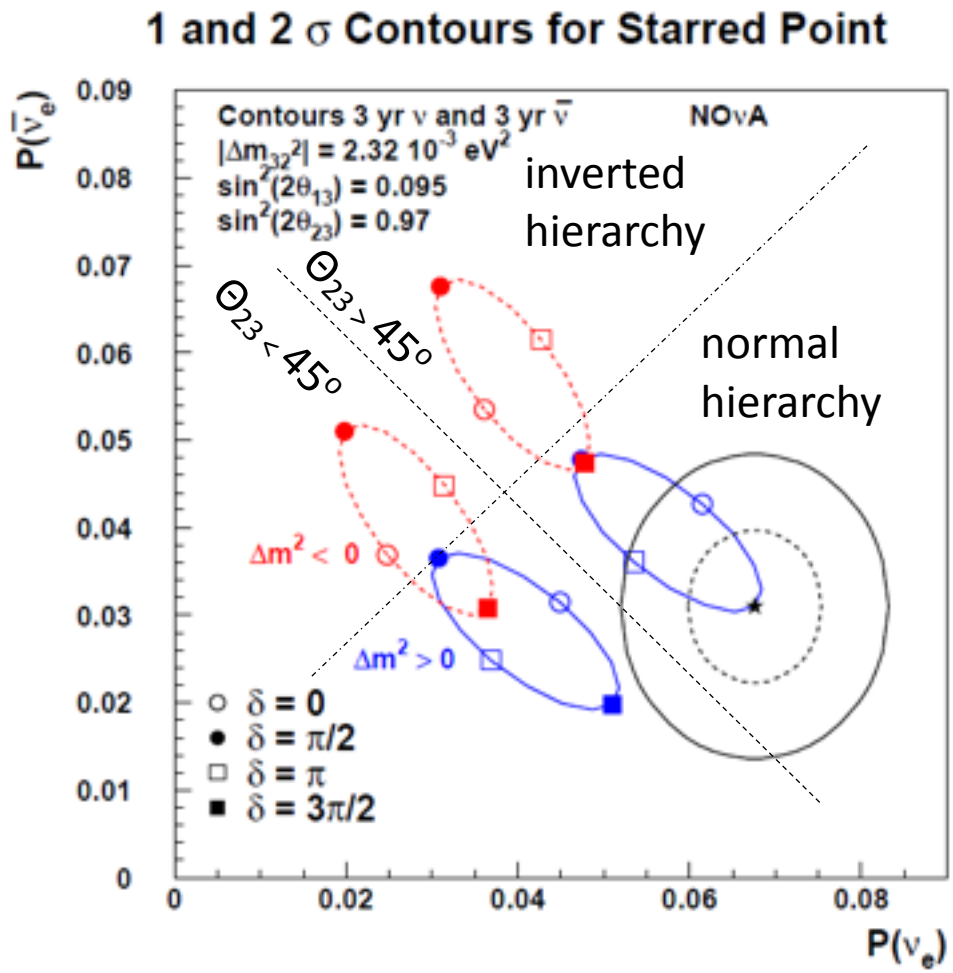
Both probabilities $\propto$ $\sin^2\theta_{23}$

For fixed L/E = 0.4 km/MeV



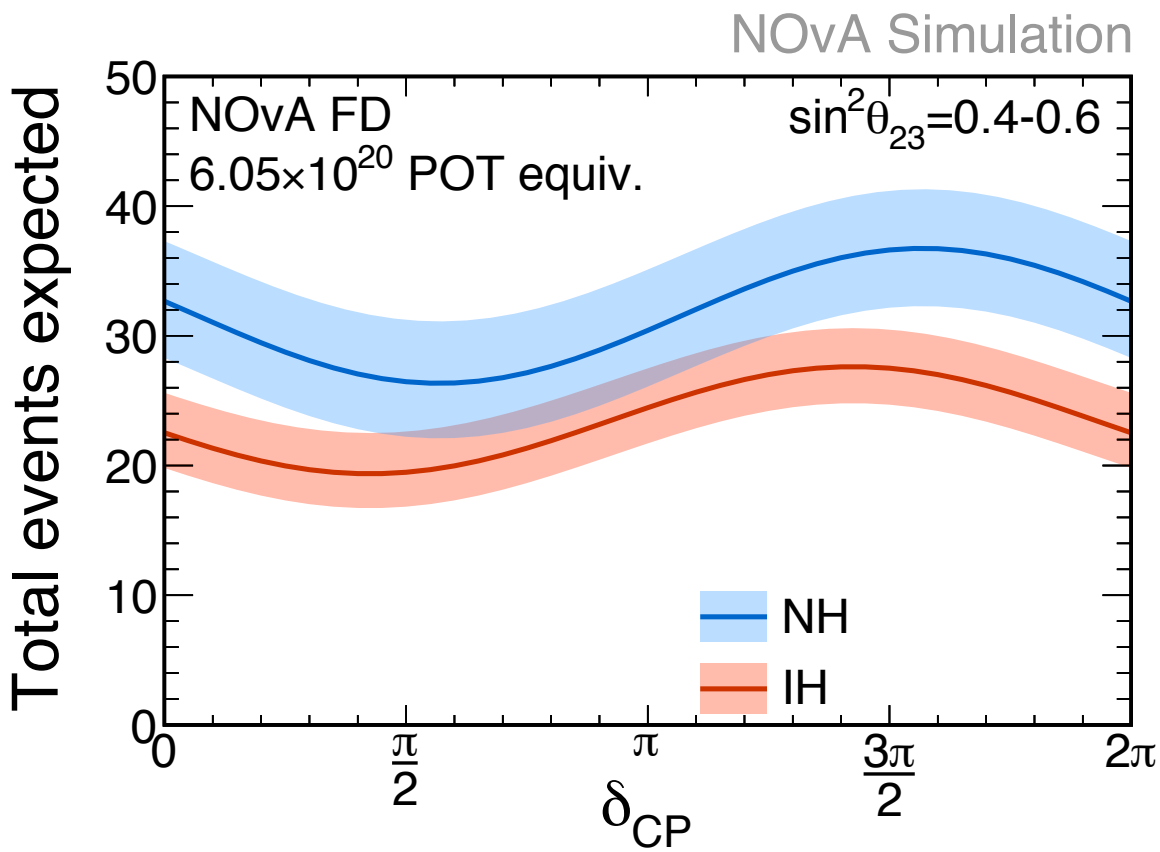
Non-maximal mixing scenario

- If non-maximal then effect of octant becomes apparent
- Big effect, +/- 20%



Recent Experimental Results

NOvA Specific Event Count Predictions



Signal events
(±5% systematic uncertainty):

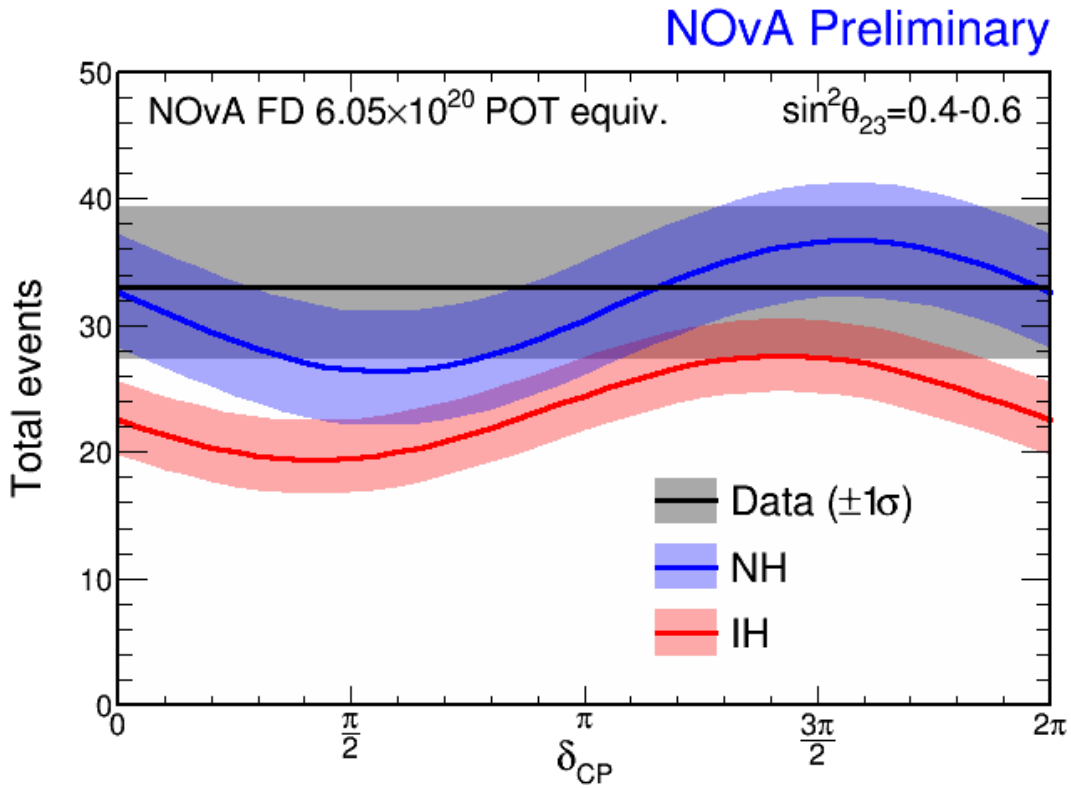
NH, 3π/2,	IH, π/2,
28.2	11.2

Background by component
(±10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

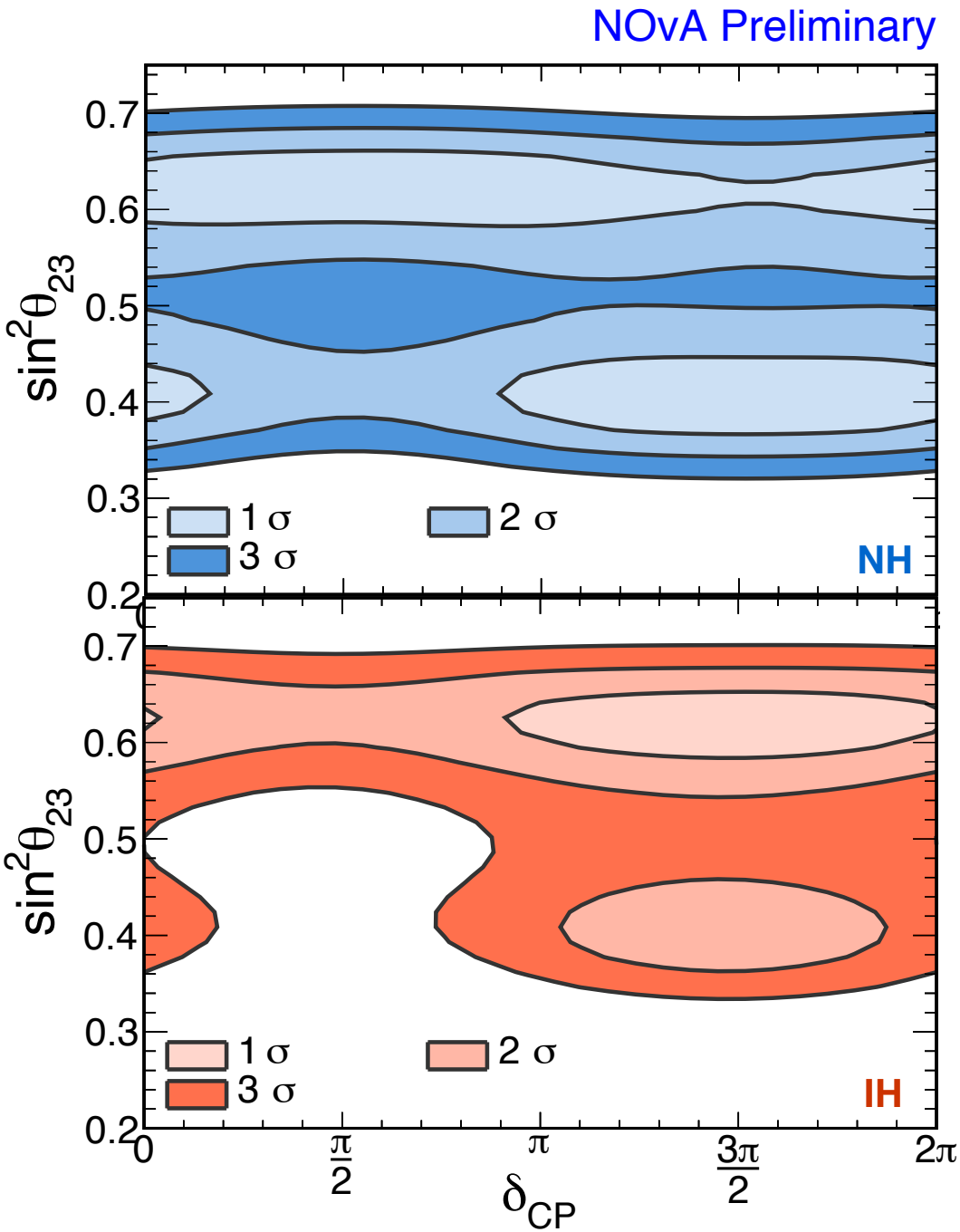
New NOvA Results

Observe 33 events



New NOvA Results

- No strong preference for hierarchy
- Both octants allowed
- Rules out IH, pi/2, lower octant region at 3 sigma



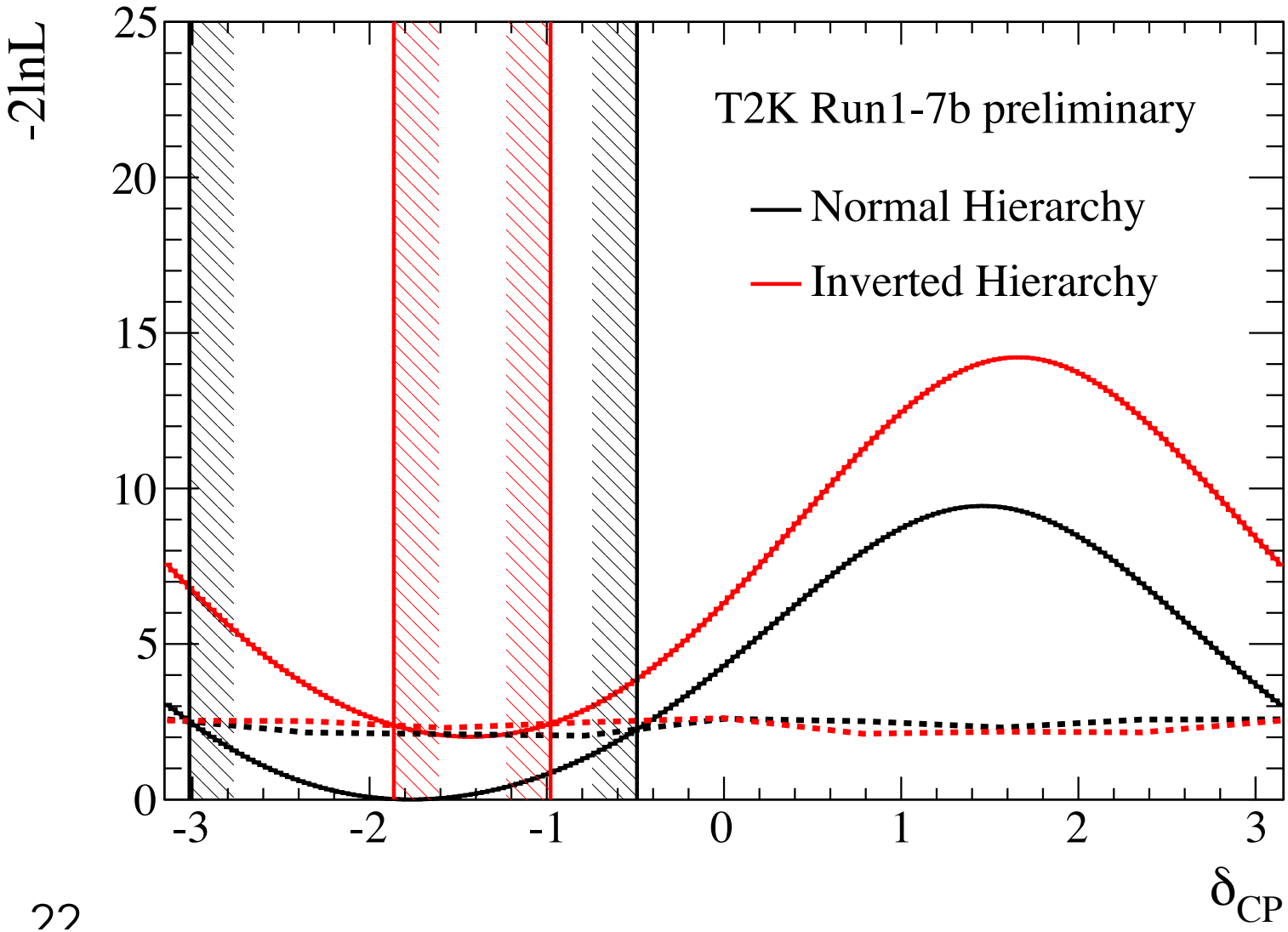
T2K Results

		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π
ν_e	**32**	27.0	22.7	18.5	22.7
$\bar{\nu}_e$	**4**	6.0	6.9	7.7	6.8

Favoured scenario, -pi/2

Some small tension:
Neutrinos too high (upper octant?)
Antineutrinos too low (lower octant?)

T2K Results on deltaCP



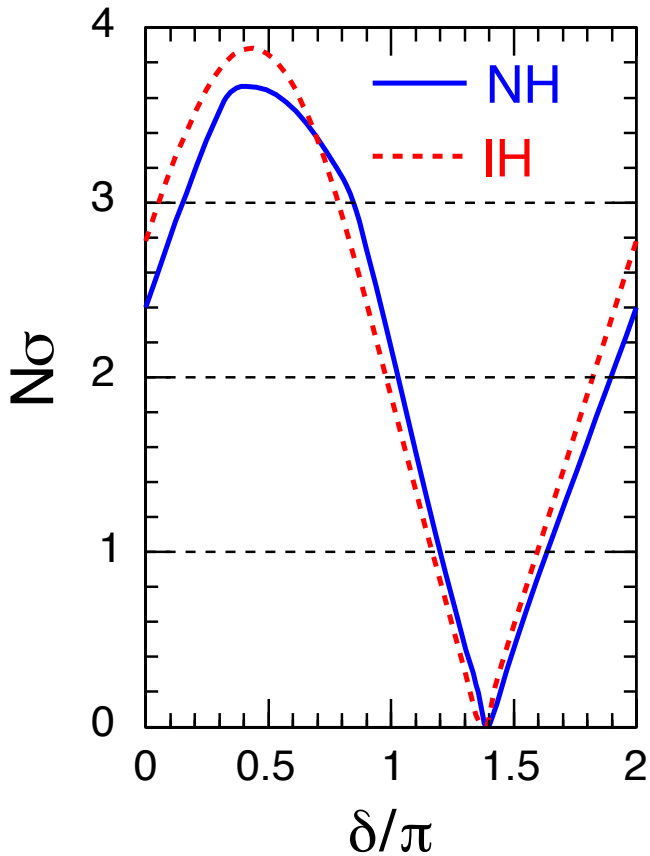
Global Fit

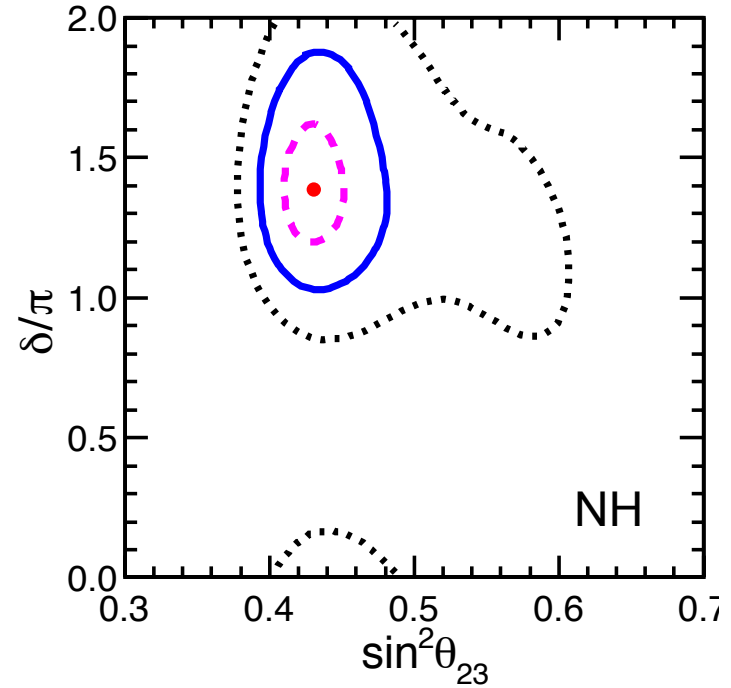
[A. Marrone, Bari]

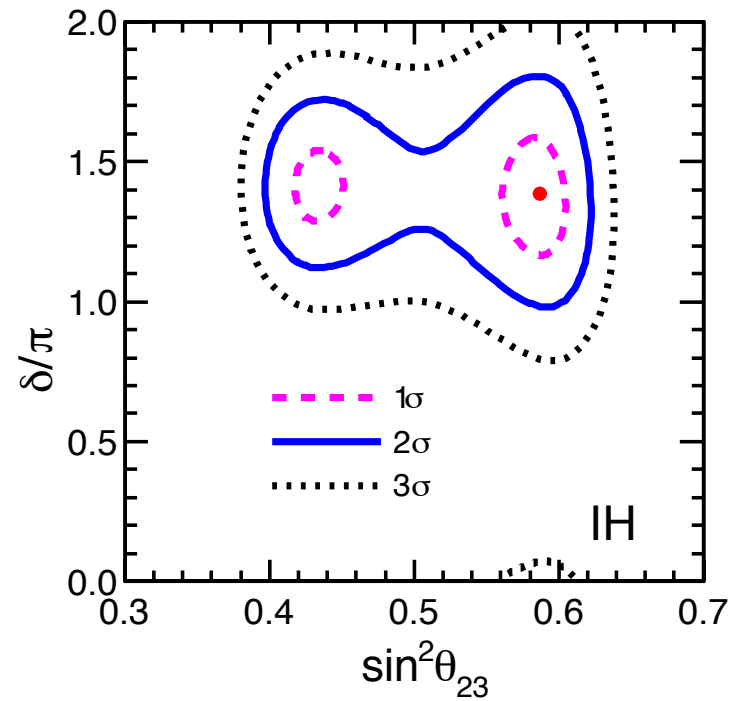
Preliminary: done **during** Neutrino conference last week(!)

No-CPv disfavoured at 2 sigma

pi/2 disfavoured at 3 sigma in BOTH octants





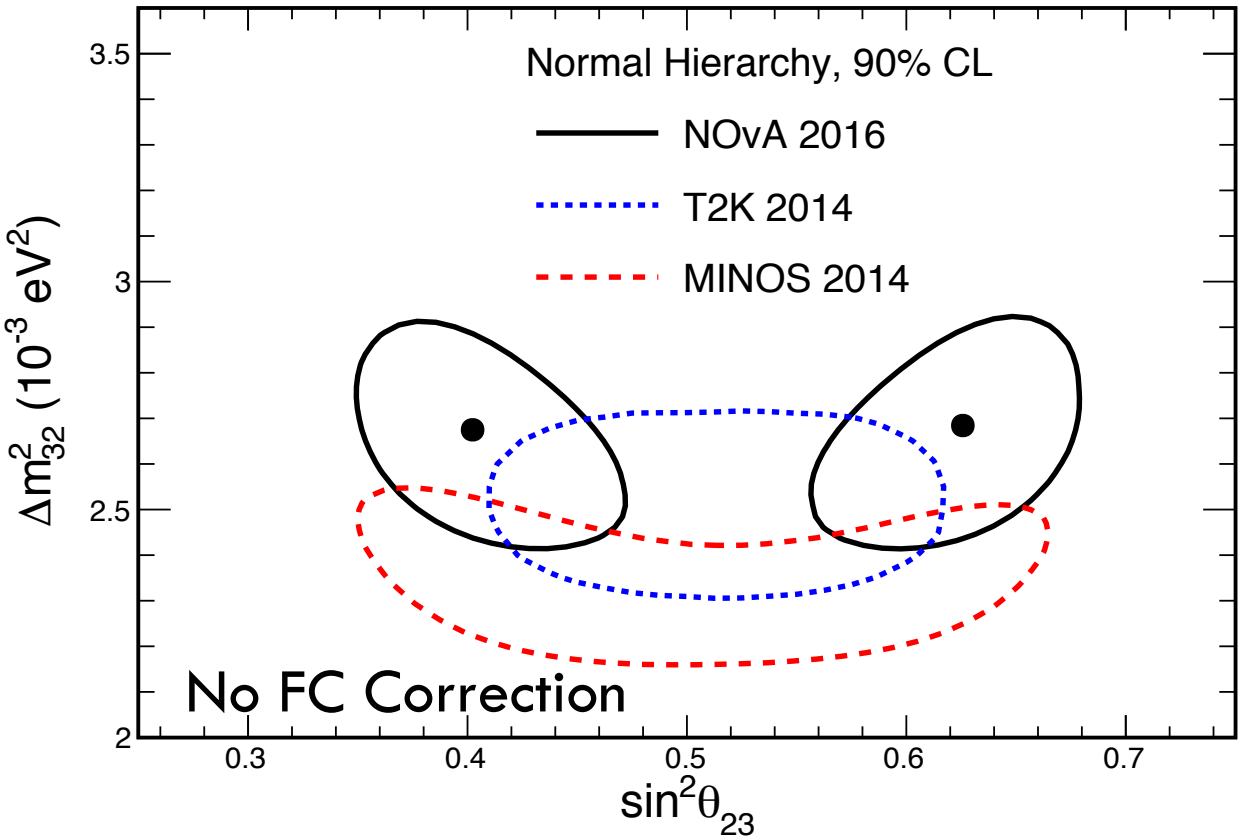


Slight (1.3 sigma) preference for NH

Octant preference dependent on hierarchy

NOvA Muon Neutrino Disappearance

NOvA Preliminary



Best Fit (in NH):

$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5 sigma

The 3rd Generation

Future Long-baseline Neutrino Oscillation Experiments

DUNE Collaboration

[J. Urheim, Neutrino]

Establishment of DUNE as a
fully international scientific collaboration
meant starting from scratch on every organizational aspect

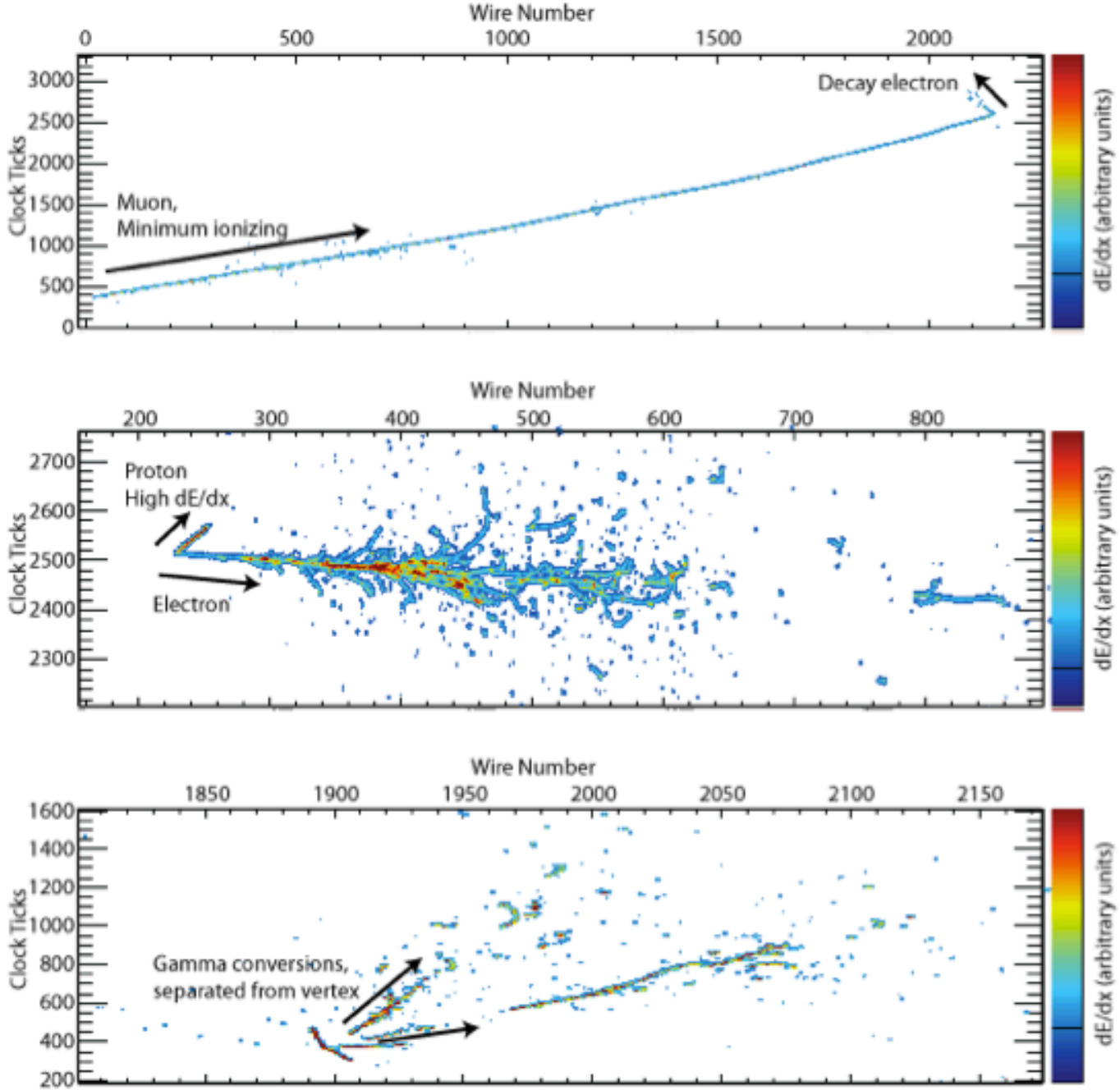
- Now have 856 collaborators…
  …from 149 institutions…in 29 countries
- Strong, inclusive, collaborative spirit driven by ambitious science
- Welcoming to the theory community

DUNE and Liquid Argon

Exquisite LAr detectors (40 kt fiducial)

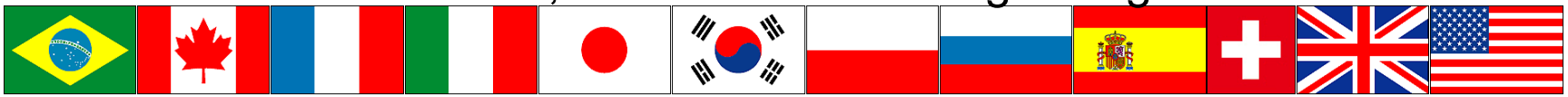
High efficiency and purity

Measure hadronic recoil system



Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

12 countries, ~250 members and growing



- Proto-collaboration formed.
- International steering group
- International conveners
- International chair for international board of representative (IBR)
- International Advisory Committee (HKAC)

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.

MEMORANDUM OF UNDERSTANDING

of the cooperation in the Hyper-Kamiokande project

January 31, 2015

THE INSTITUTE FOR COSMIC RAY RESEARCH OF THE UNIVERSITY OF TOKYO and THE INSTITUTE OF PARTICLE AND NUCLEAR STUDIES OF THE HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION have reached agreement regarding cooperation in promoting the advanced nucleon decay and neutrino experiment program, Hyper-Kamiokande, by understanding that the program would make significant progress in a wide range of fields in physics and astronomy. It is also agreed to review and develop the program in its comprehensive aspects including promoting organization and budget measures.

This agreement is effective for two years from January 31, 2015 and is able to be updated upon the discussion between the two organizations.

Prof. Takaaki KAJITA
Director
Institute for Cosmic Ray Research, The University of Tokyo

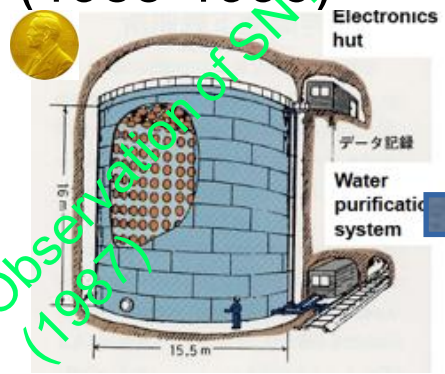
Prof. Masafori YAMAUCHI
Director
Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization

[F. Di Lodovico, Neutrino]

Kamiokande Evolution

- Three generations of large Water Cherenkov in Kamioka.
- **Tank design for Hyper-Kamiokande optimized** .

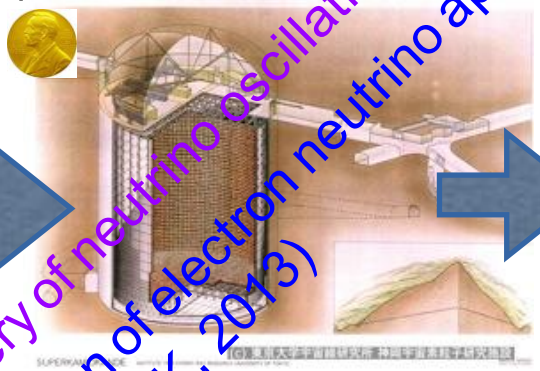
Kamiokande (1983-1996)



3kton

Observation of SN 1987A (1987)

Super-Kamiokande (1996-)



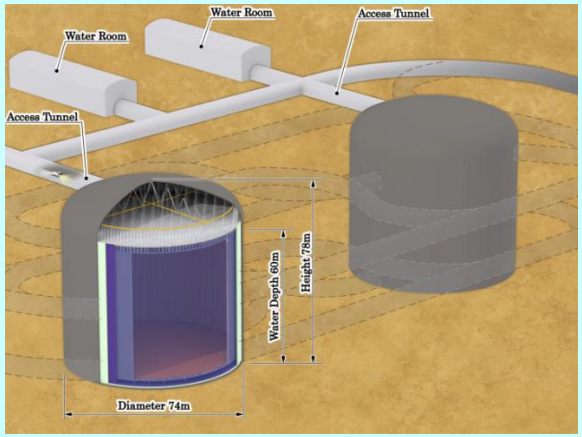
50kton

Discovery of neutrino oscillation (1998)

Observation of electron neutrino appearance (w/ beam, T2K, 2013)

x17

Hyper-Kamiokande (2026-)



0.52Mton=520kton

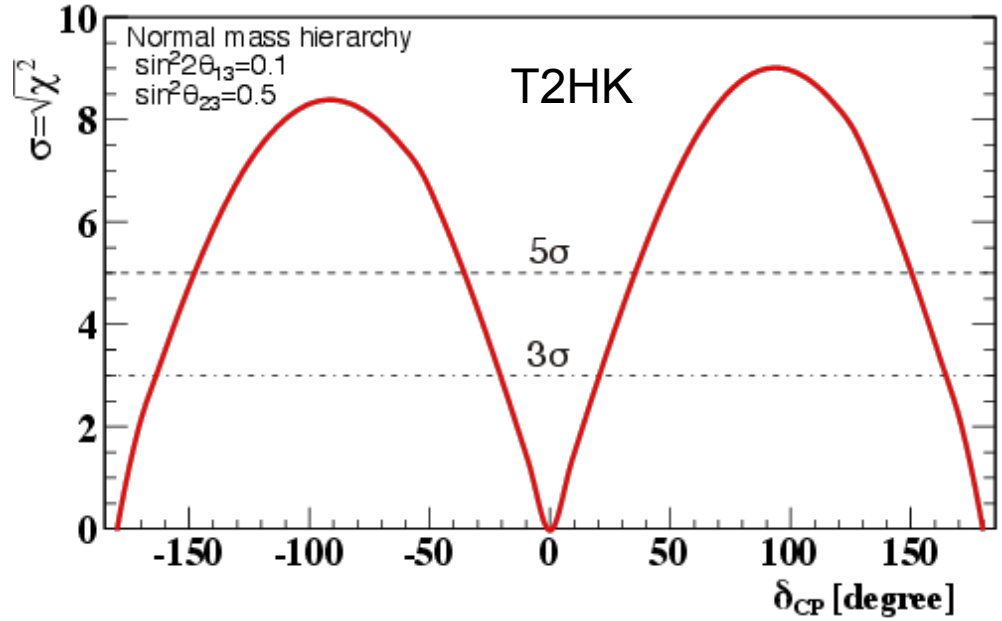
(380kton fiducial)

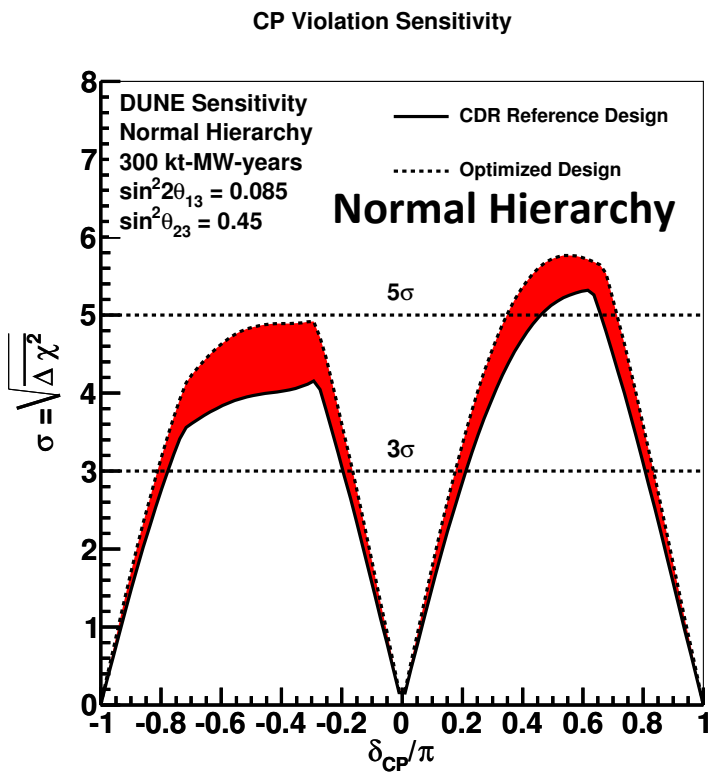
x10

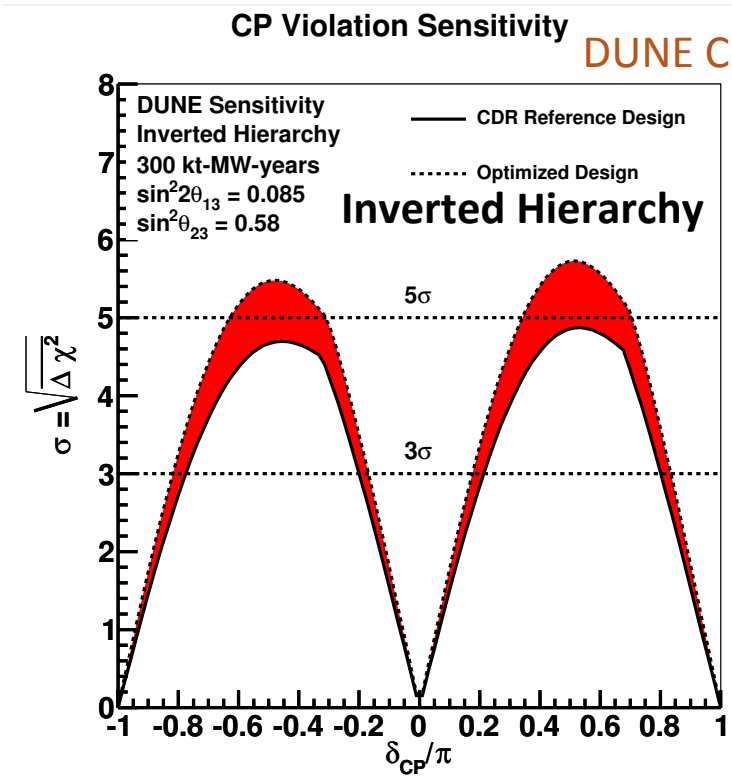
(x20 fiducial mass)

arXiv:1109.3262
arXiv:1309.0184
PTEP 2015,053C02

CP Sensitivity







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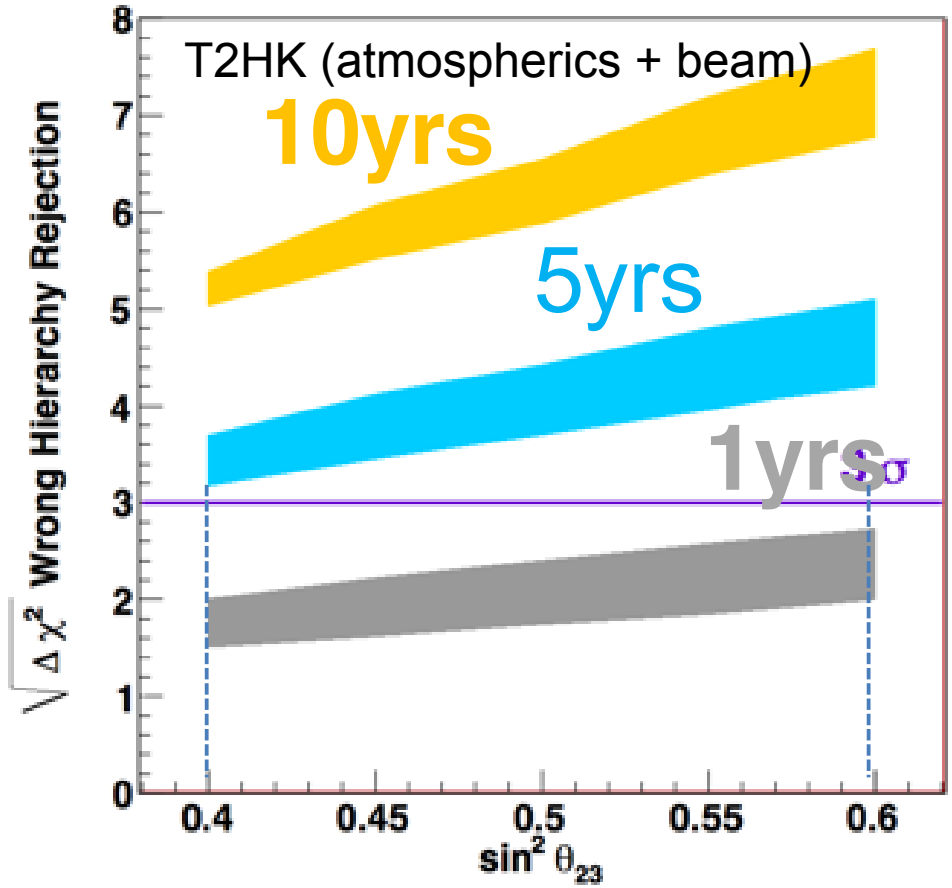
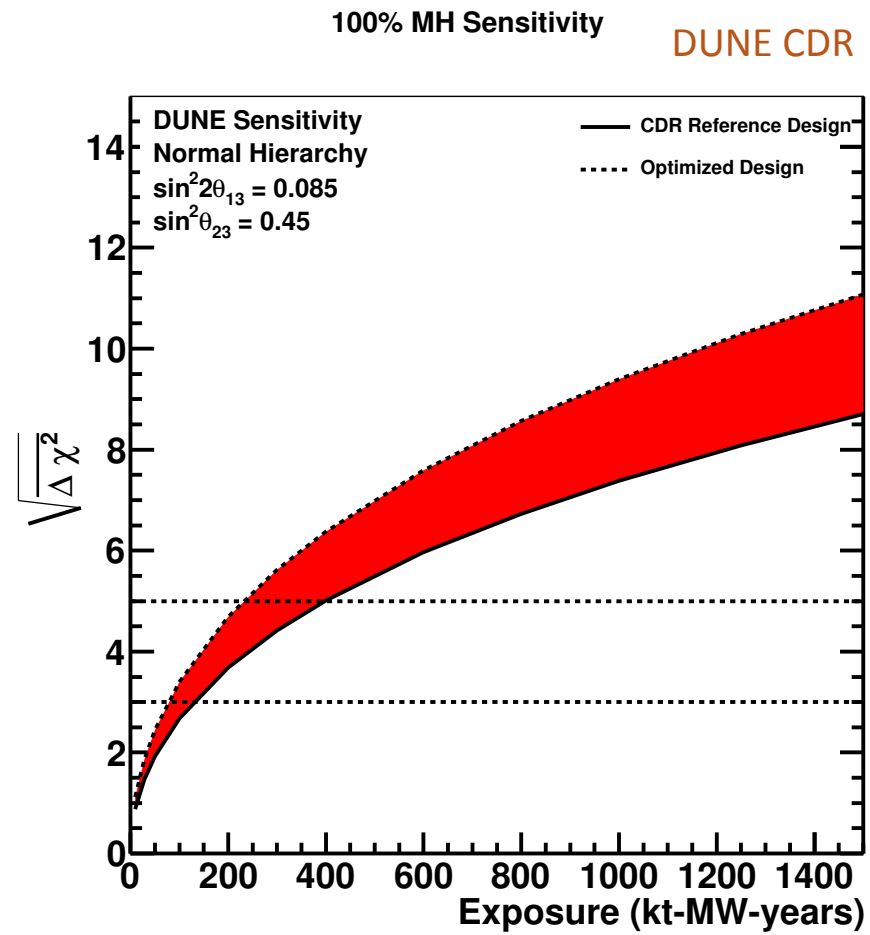
MH Sensitivity





Pros and Cons

(Very complementary projects!)

DUNE

- Long 1300 km baseline
  - excellent MH measurement
  - access to 2nd oscillation max with greater CP asymmetry
- Wide band beam
  - see more effects of oscillation
  - good sensitivity to non-standard effects (test 3 neutrino paradigm)
- Exquisite detector imaging
  - high eff. and pur.
  - lower stats
  - Perhaps lower systematics

HyperK

- Huge detector
  - high statistics
  - excellent early CPv sensitivity
  - limited information on hadronic recoil system
- Short-baseline
  - much smaller matter effects
  - need to know mass hierarchy
  - (use atmospheric neutrinos)
- Narrow band beam
  - less background to reject
  - less energy information

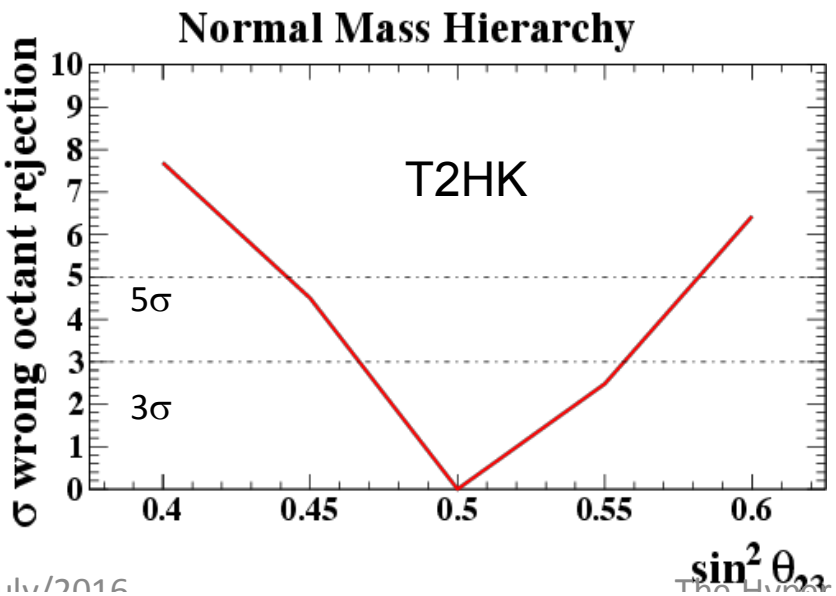
Conclusions

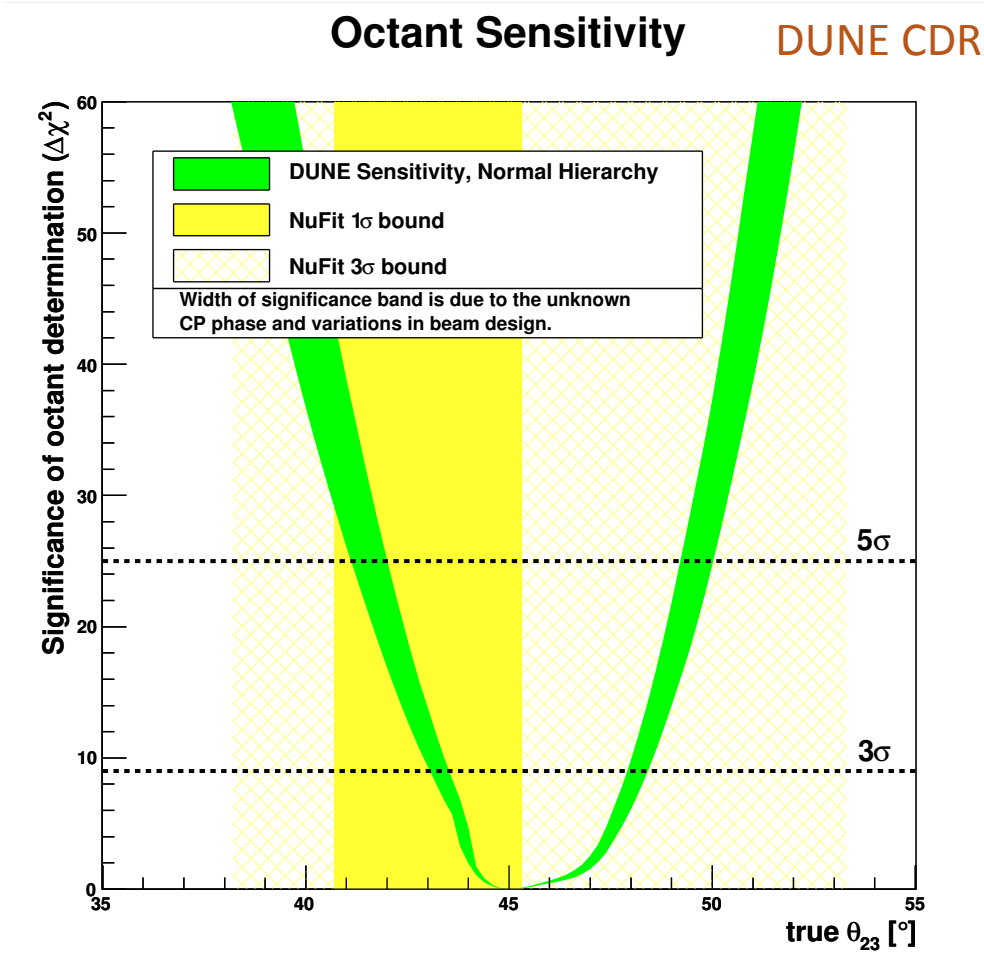
- Discovery of non-zero θ_{13} has opened the door to a 2nd golden age of neutrino oscillation physics
- New NOvA results (exclude IH, 0.4, pi/2 at 3σ)
- New T2K antineutrino result
- Emerging CPv trends in global data?

- Discovery of CPv requires new expts
- DUNE and HyperK are very complementary
- Stay tuned!

Backup slides

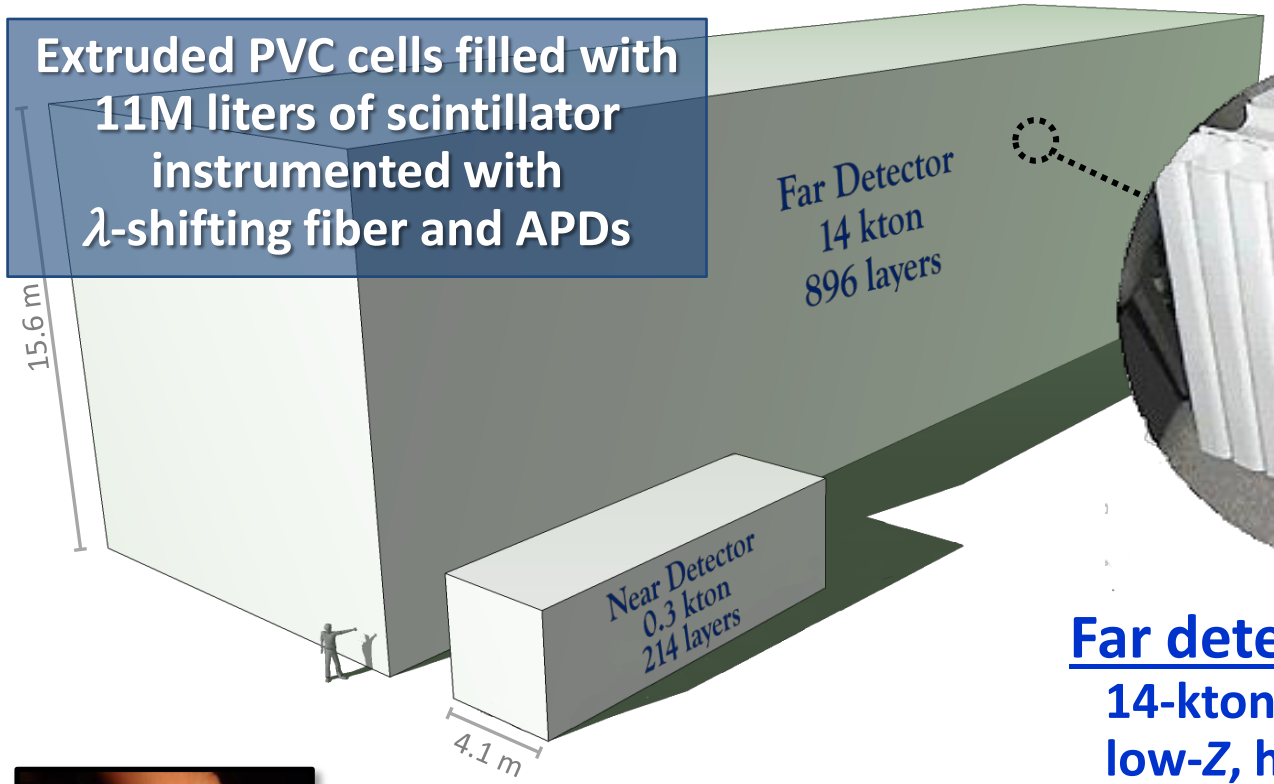
Octant Sensitivity



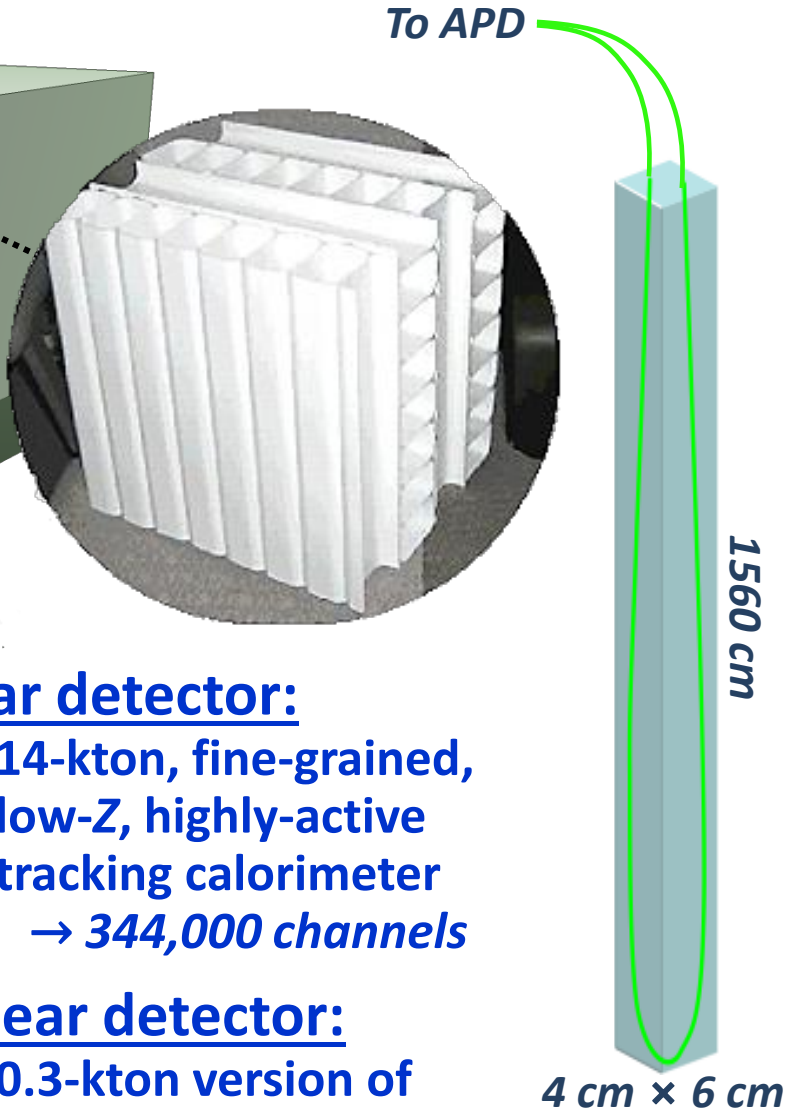


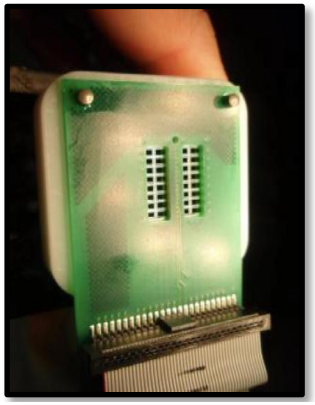
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



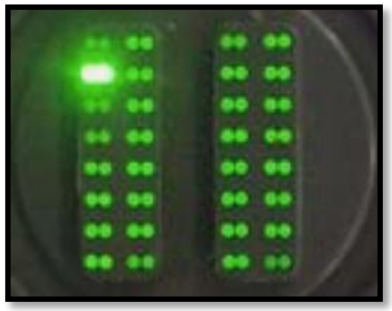
A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ *344,000 channels*

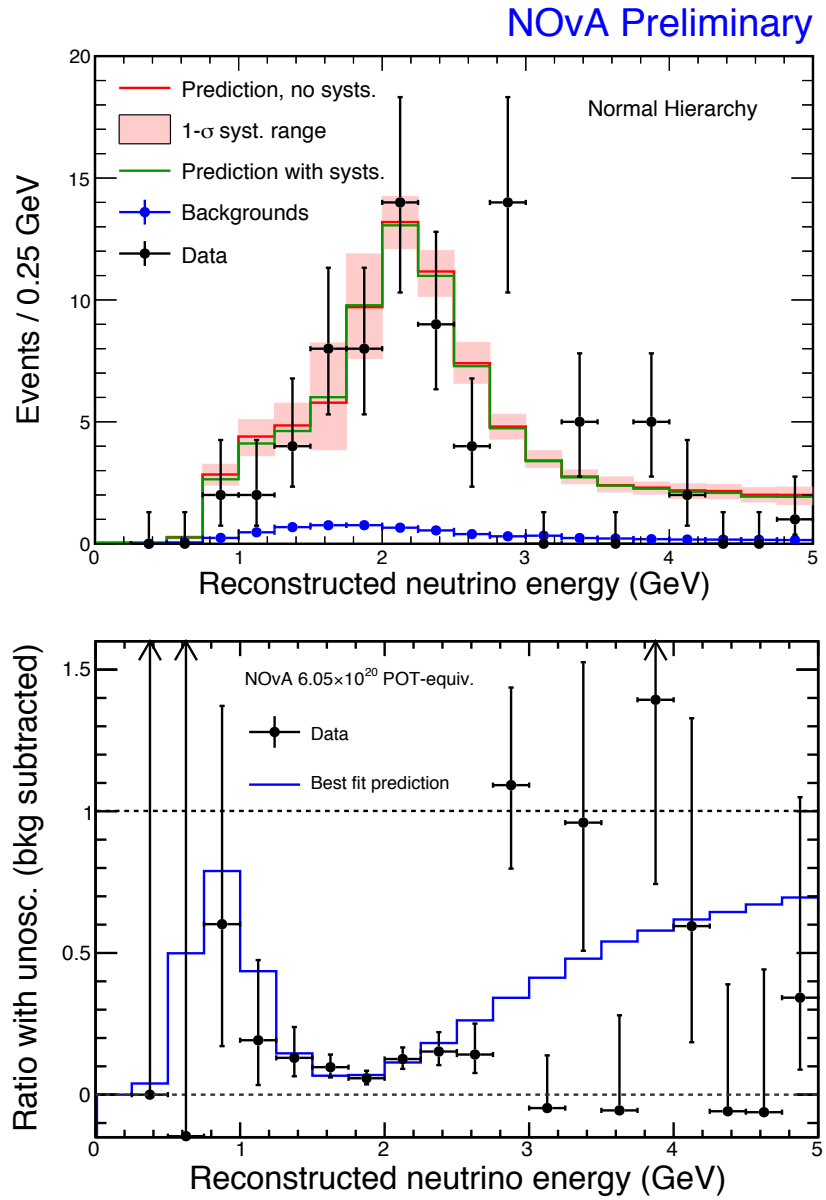
Near detector:

0.3-kton version of the same
→ *20,000 channels*

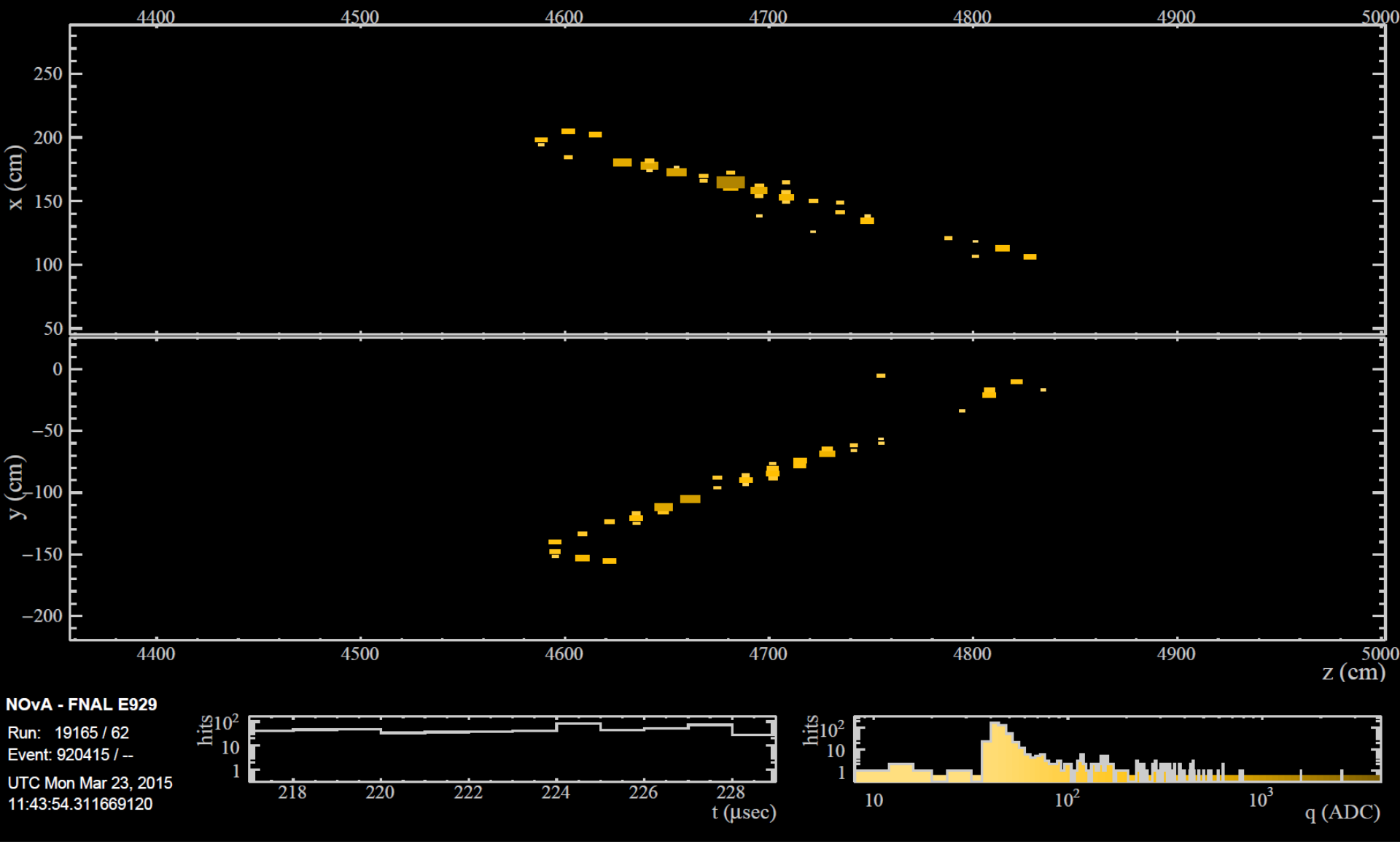
78 events observed in FD

- 473±30 with No Oscillation
- 82 at best oscillation fit
- 3.7 beam BG + 2.9 cosmic

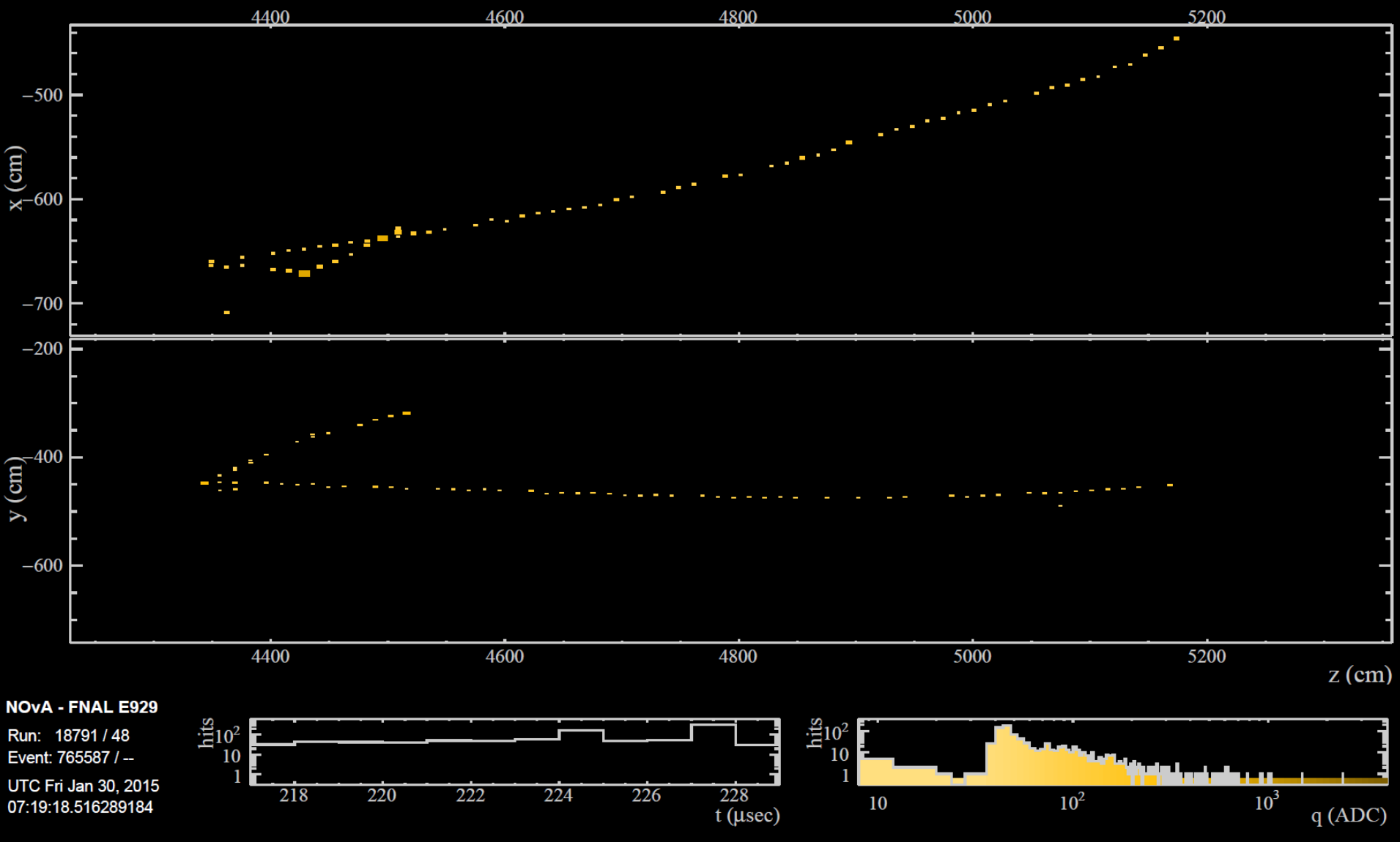
χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



Far Detector selected ν_e CC candidate



Far Detector selected ν_μ CC candidate

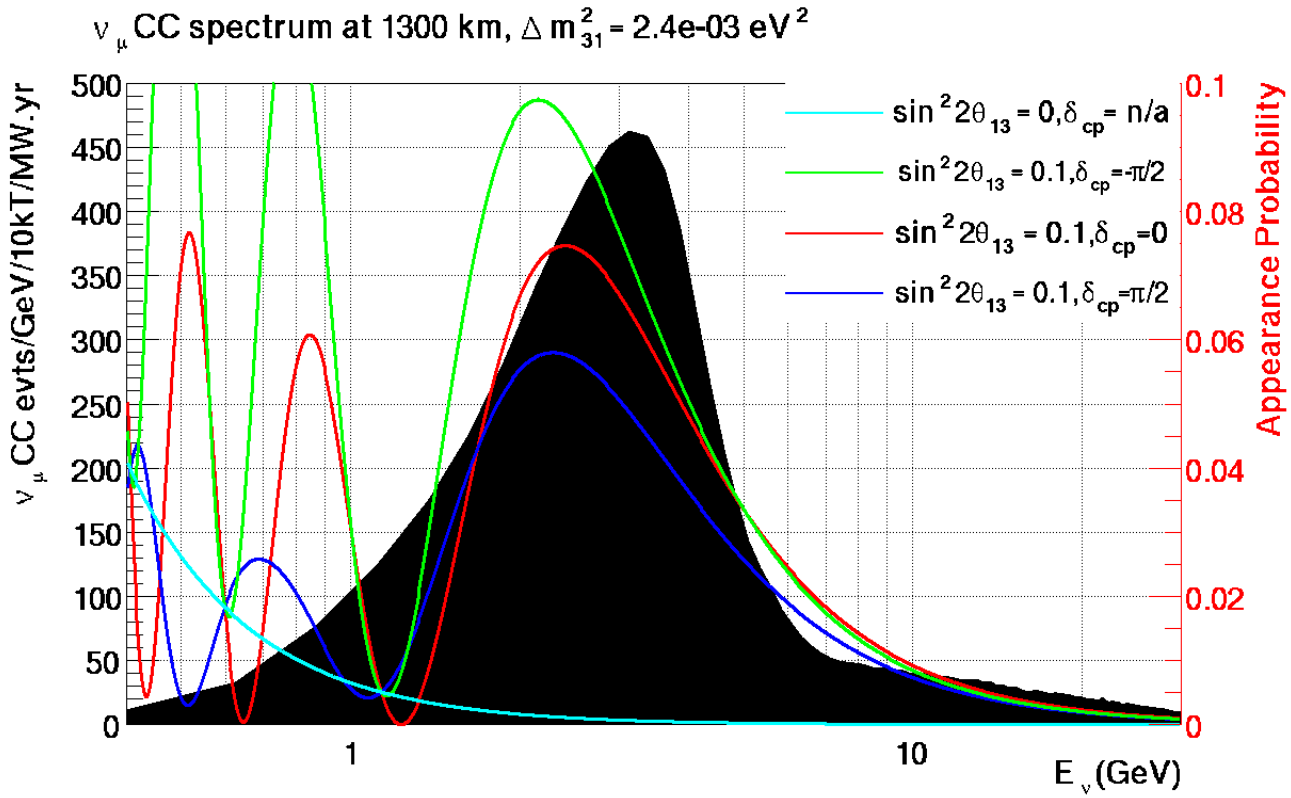


ν_e APPEARANCE

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 + \alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} - \alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

$$a = G_F N_e \sqrt{2}$$

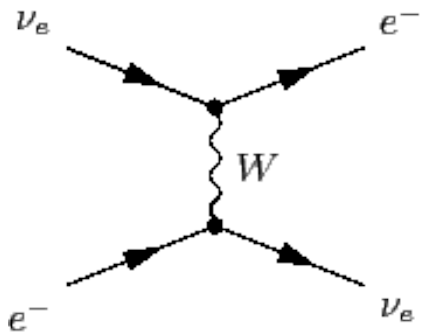
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



- $\sin^2(2\theta_{13})$ determines size of event sample
- δ_{CP} affects amplitude and phase of oscillation
- δ_{CP} dependence larger at 2nd oscillation maximum

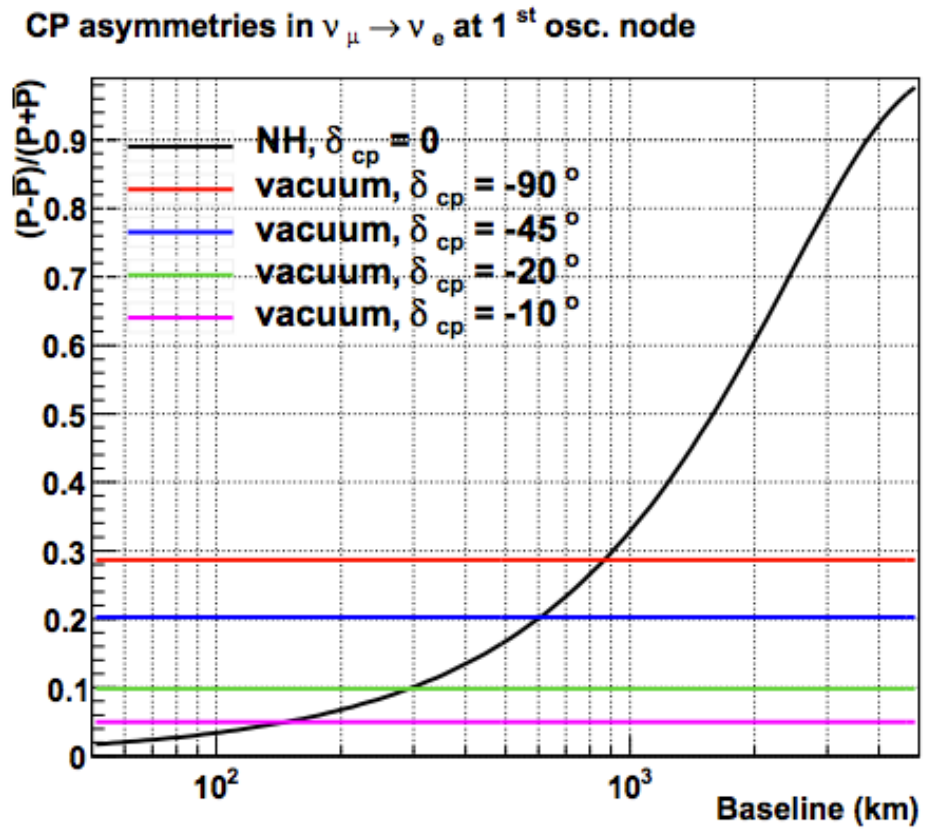
Matter Asymmetry

Charged-current coherent forward scattering on electrons:



Occurs only for neutrinos

- Normal hierarchy: matter effect enhances neutrino oscillation and suppresses antineutrino oscillation
- Inverted hierarchy: matter has opposite effect



M. Bishai

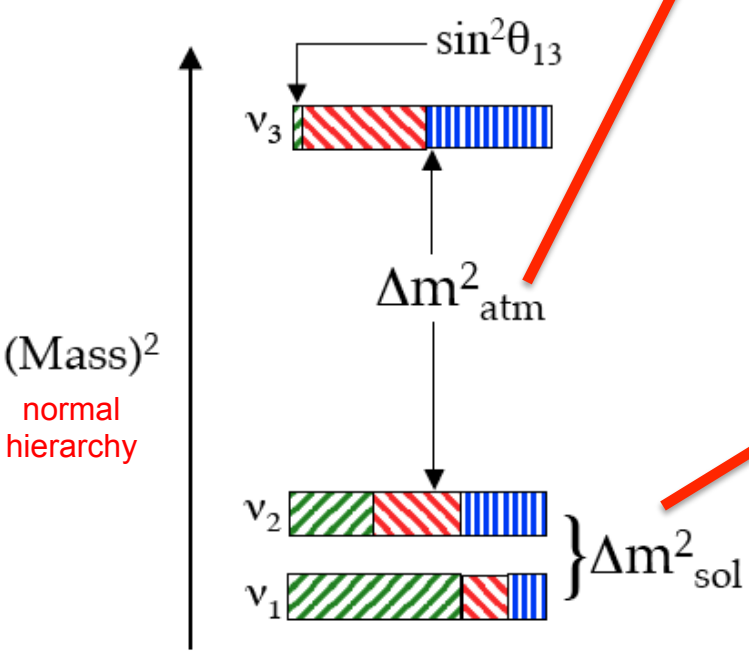
Matter asymmetry very important for long-baseline experiments!

Theory Overview

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

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

Subdominant term



$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV