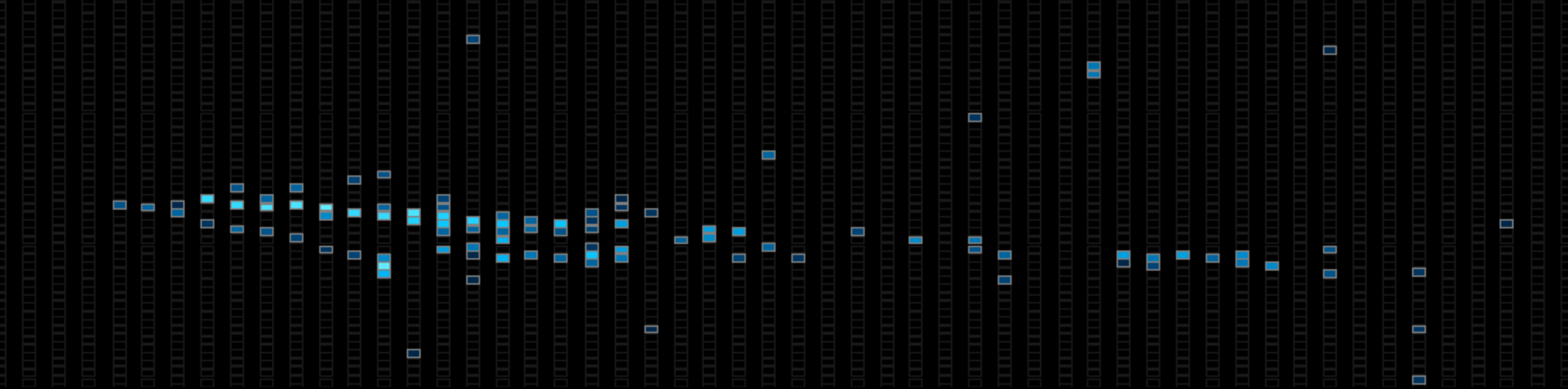


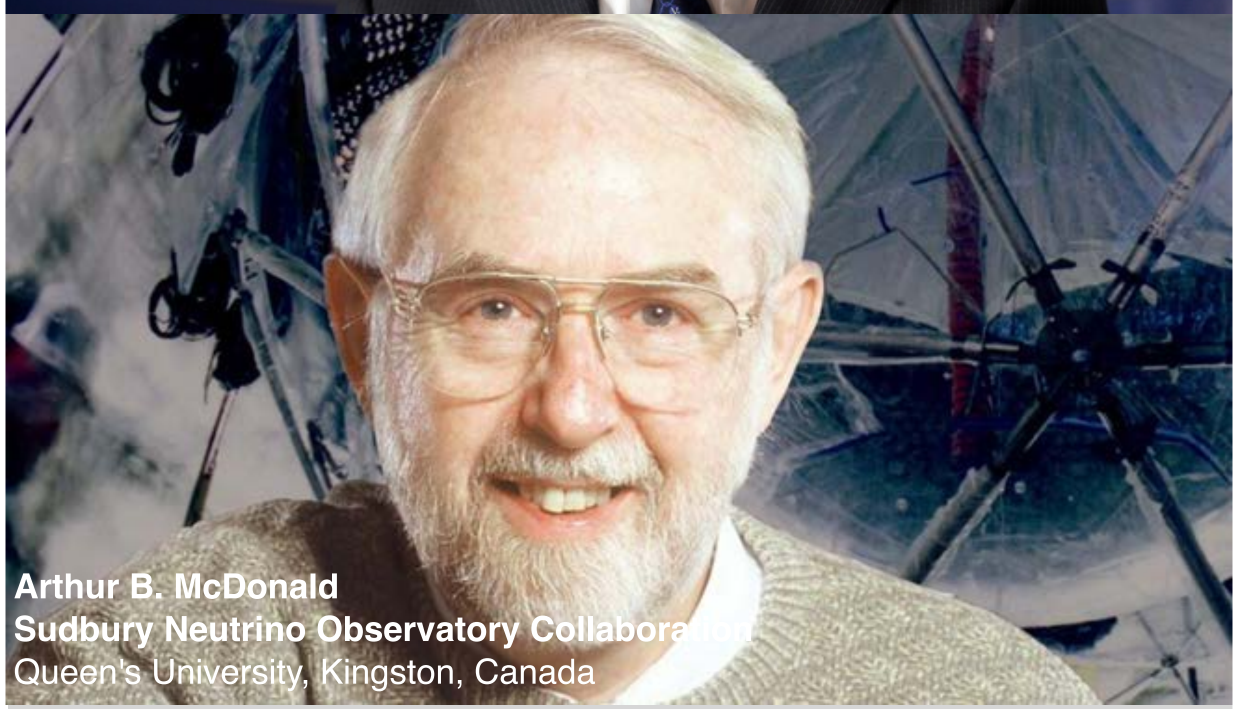
Accelerator-based Neutrino Experiments

Mark Messier
Indiana University

2016 Aspen Winter Conference on Particle Physics
January 14, 2016

ASPEN CENTER FOR PHYSICS

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan



Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

2015 Nobel Prize in physics “for the discovery of neutrino oscillations, which shows that neutrinos have mass”

<u>Mass found in elusive particle; Universe may never be the same</u>

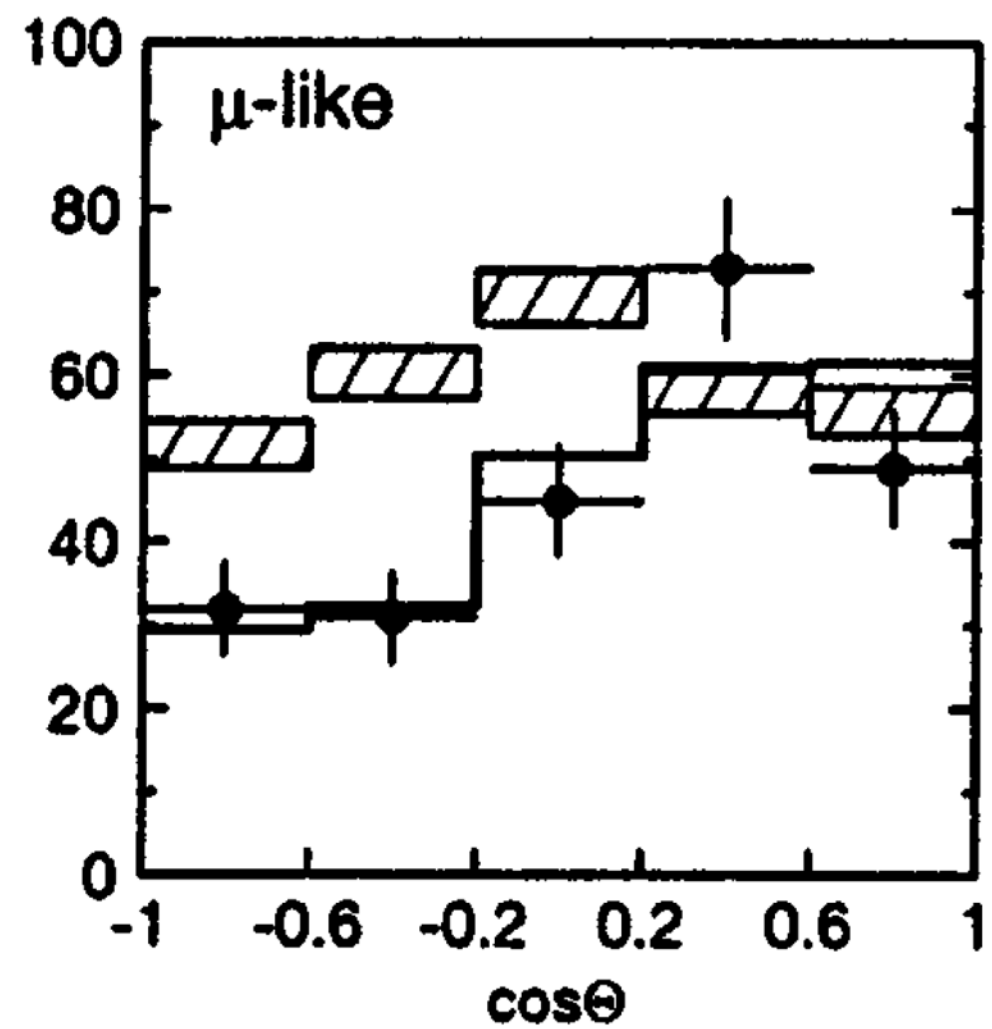
New York Times, page 1, June 5, 1998

Evidence for oscillation of atmospheric neutrinos,

Phys.Rev.Lett.81:1562-1567,1998

4600+ citations to date

#24 all time, #4 experimental



Neutrino oscillations

$$\left|\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\left|\begin{array}{c}\nu_1\\ \nu_2\\ \nu_3\end{array}\right\rangle$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

$$|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2| \simeq 2\times 10^{-3}\ \mathrm{eV}^2$$

$$\nu_\mu \longrightarrow \nu_\mu$$
$$\nu_\mu \longrightarrow \nu_\tau$$

atmospheric and long baseline

$$\Delta m^2_{31} \simeq \Delta m^2_{32}$$

$$\nu_e \longrightarrow \nu_e$$
$$\nu_\mu \longrightarrow \nu_e$$

reactor and long baseline

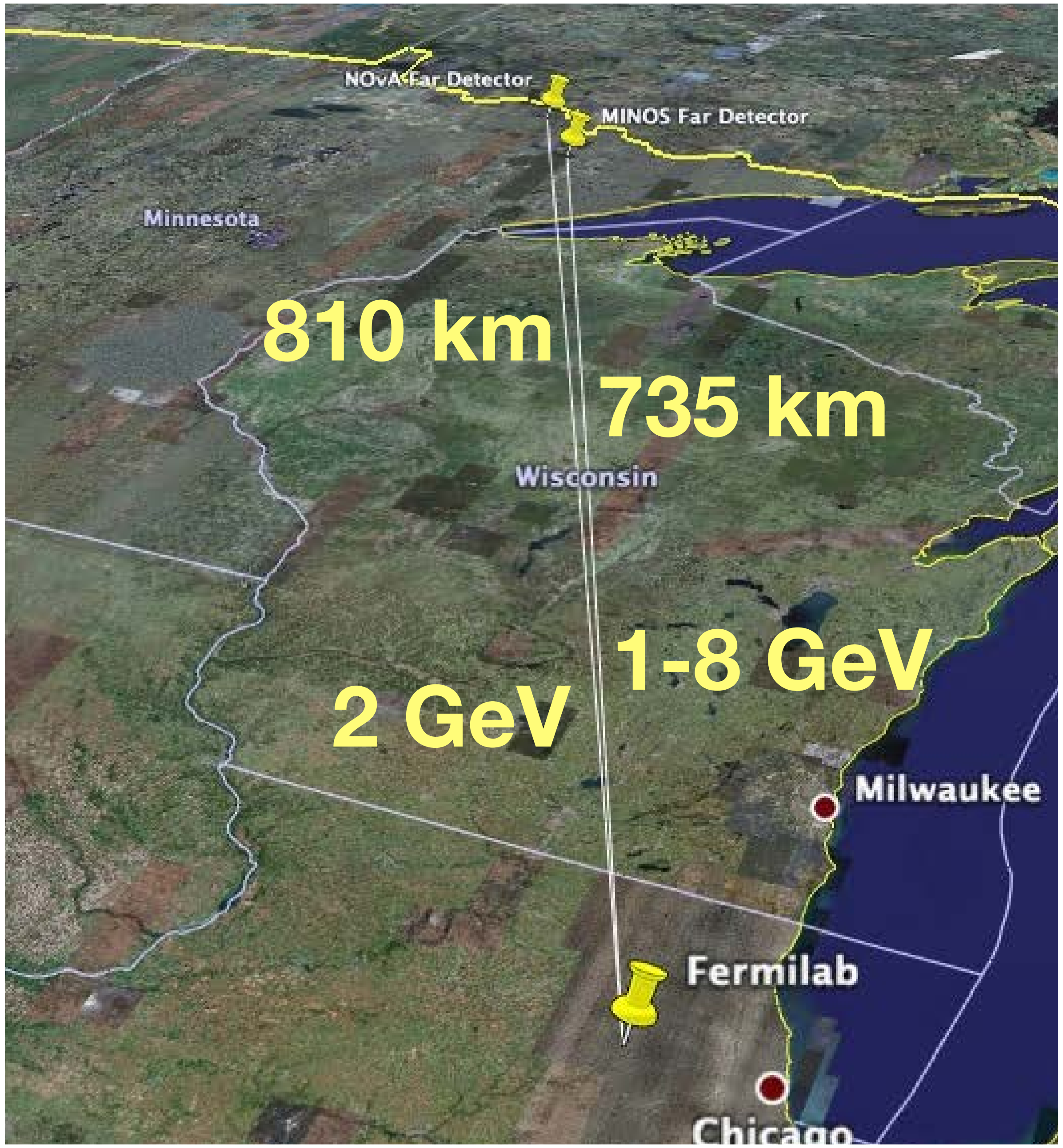
$$\Delta m^2_{21} \simeq 8\times 10^{-5}\ \mathrm{eV}^2$$

$$\nu_e \longrightarrow \nu_e$$
$$\nu_e \longrightarrow \nu_\mu + \nu_\tau$$

solar and reactor

Long Baseline Experiments

MINOS and NOvA



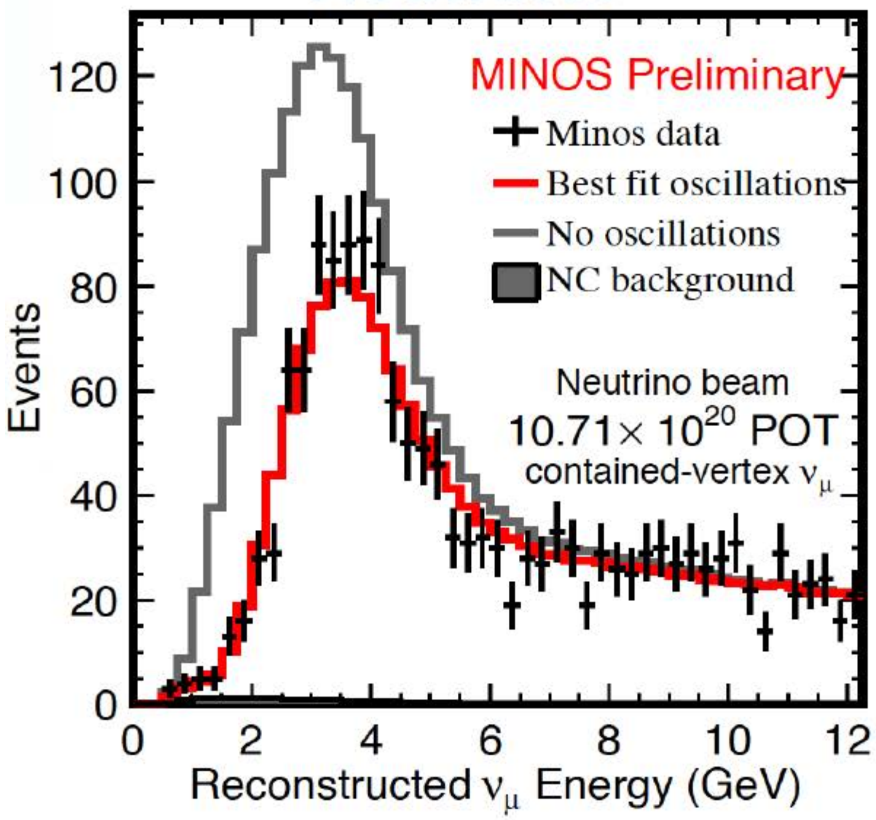
T2K

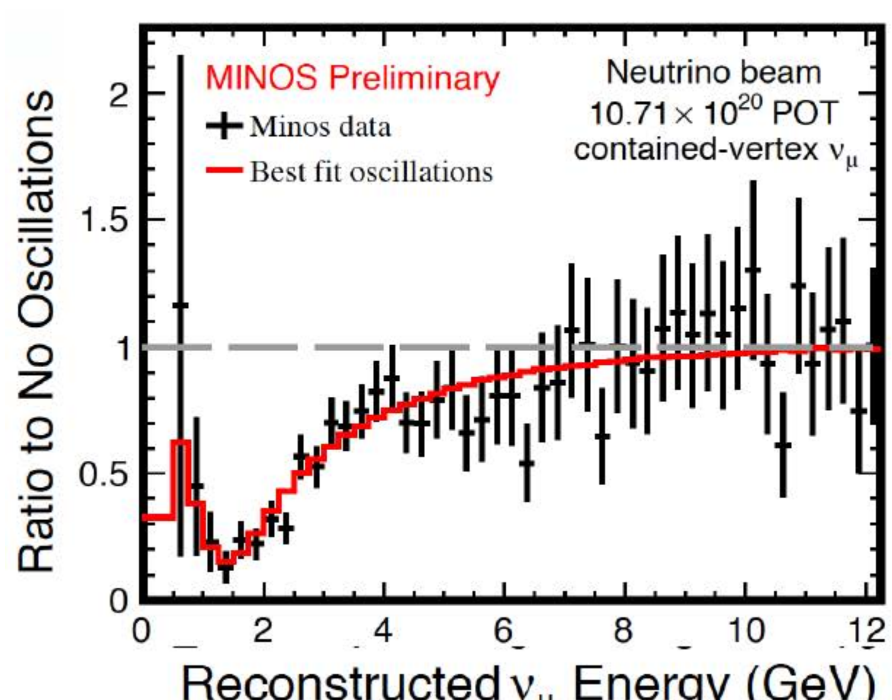
MINOS

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$

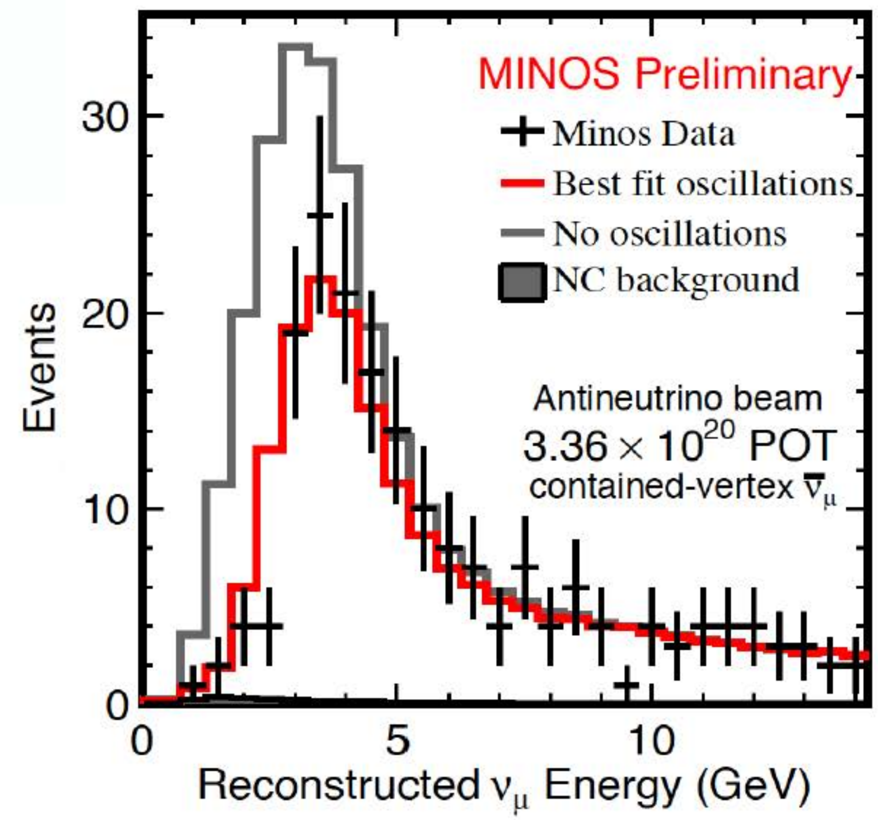
$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

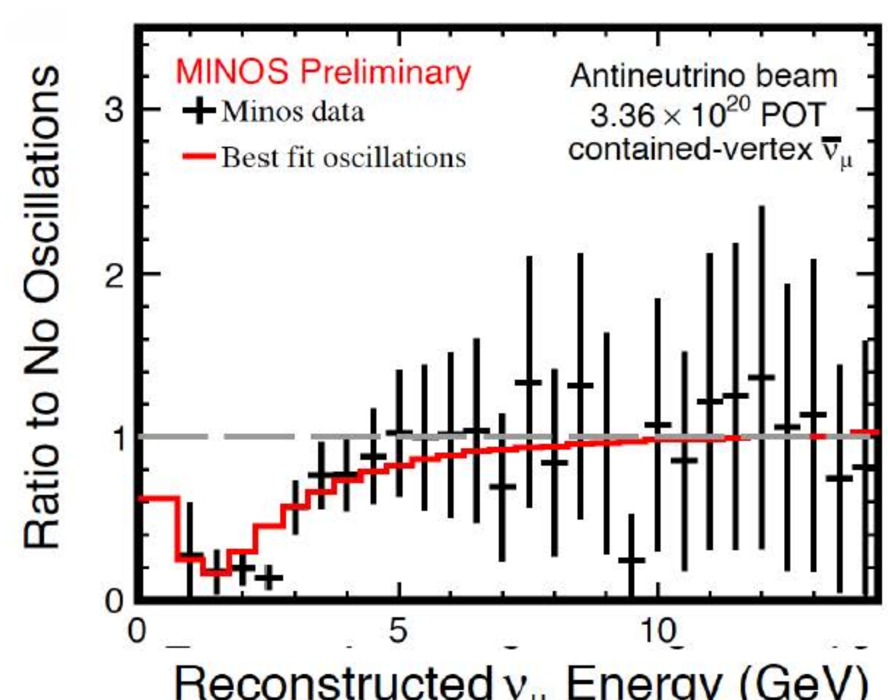
Neutrinos





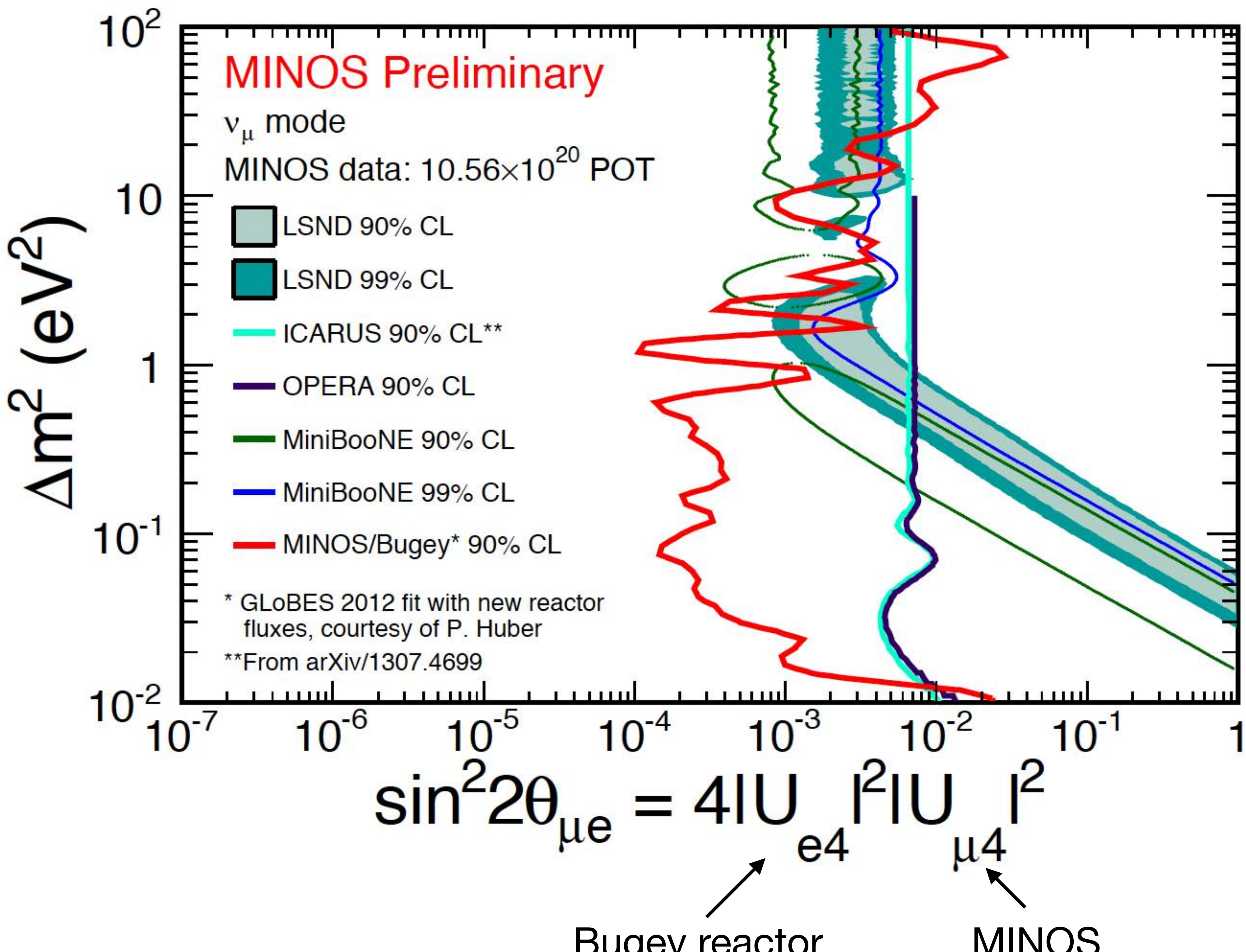
Antineutrinos

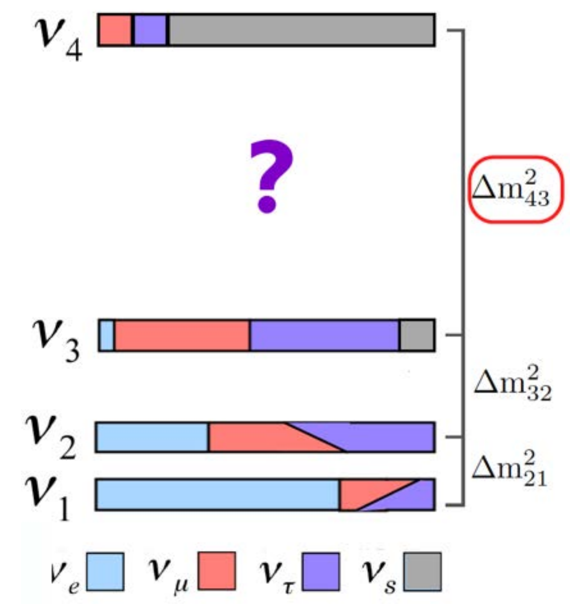




backgrounds	69.1	10.5
"nominal" signal at $\theta_{13} = 0.1$	+26.0	+3.1
total:	**95.1**	**13.6**
Observed	**88**	**12**

MINOS
Fit to sterile neutrino oscillations in 3+1 model

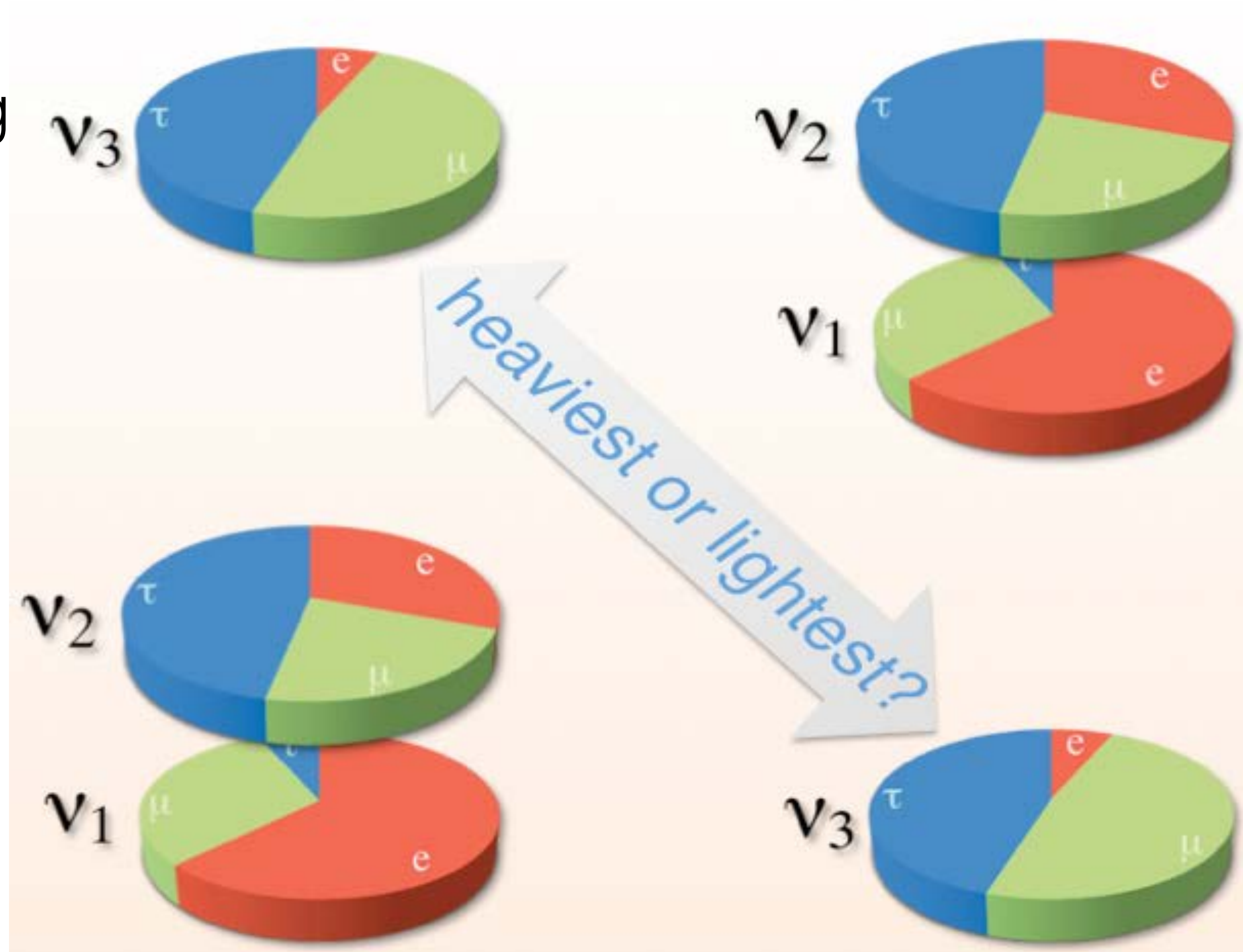




Use 3+1 model to relate MINOS and Bugey limits on active neutrino disappearance to the rate of $\nu_\mu \rightarrow \nu_e$ at short baseline

Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



Neutrino oscillations

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

In vacuum:

$$P(\nu_\mu \to \nu_e) = |2U_{\mu 3}^* U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U_{\mu 2}^* U_{e2} \sin\Delta_{21}|^2$$

$$\Delta_{32} \equiv \frac{1.27\Delta m_{32}^2[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27 \cdot 2.32\times 10^{-3}\cdot 810}{2.1} \simeq 1.1$$

For NOvA: $$\Delta_{31} \equiv \frac{1.27\Delta m_{31}^2[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} \simeq \Delta_{32}$$

$$\Delta_{21} \equiv \frac{1.27\Delta m_{21}^2[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27 \cdot 7.58\times 10^{-5}\cdot 810}{2.1} \simeq 0.04$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq |\sqrt{P_{\mathrm{atm}}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\mathrm{sol}}}|^2 \\ &= P_{\mathrm{atm}} + P_{\mathrm{sol}} + 2\sqrt{P_{\mathrm{atm}}P_{\mathrm{sol}}}\,(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta) \end{aligned}$$

"$-$" : ν

"$+$" : $\bar{\nu}$

$$P_{\mathrm{atm}} \equiv \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

long baseline experiments measure this combination

$$P_{\mathrm{sol}} \equiv \cos^2\theta_{23}\cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Neutrino oscillations

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

In matter:

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\rm atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2$$
$$= P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} \, (\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

$$\sqrt{P_{\rm atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

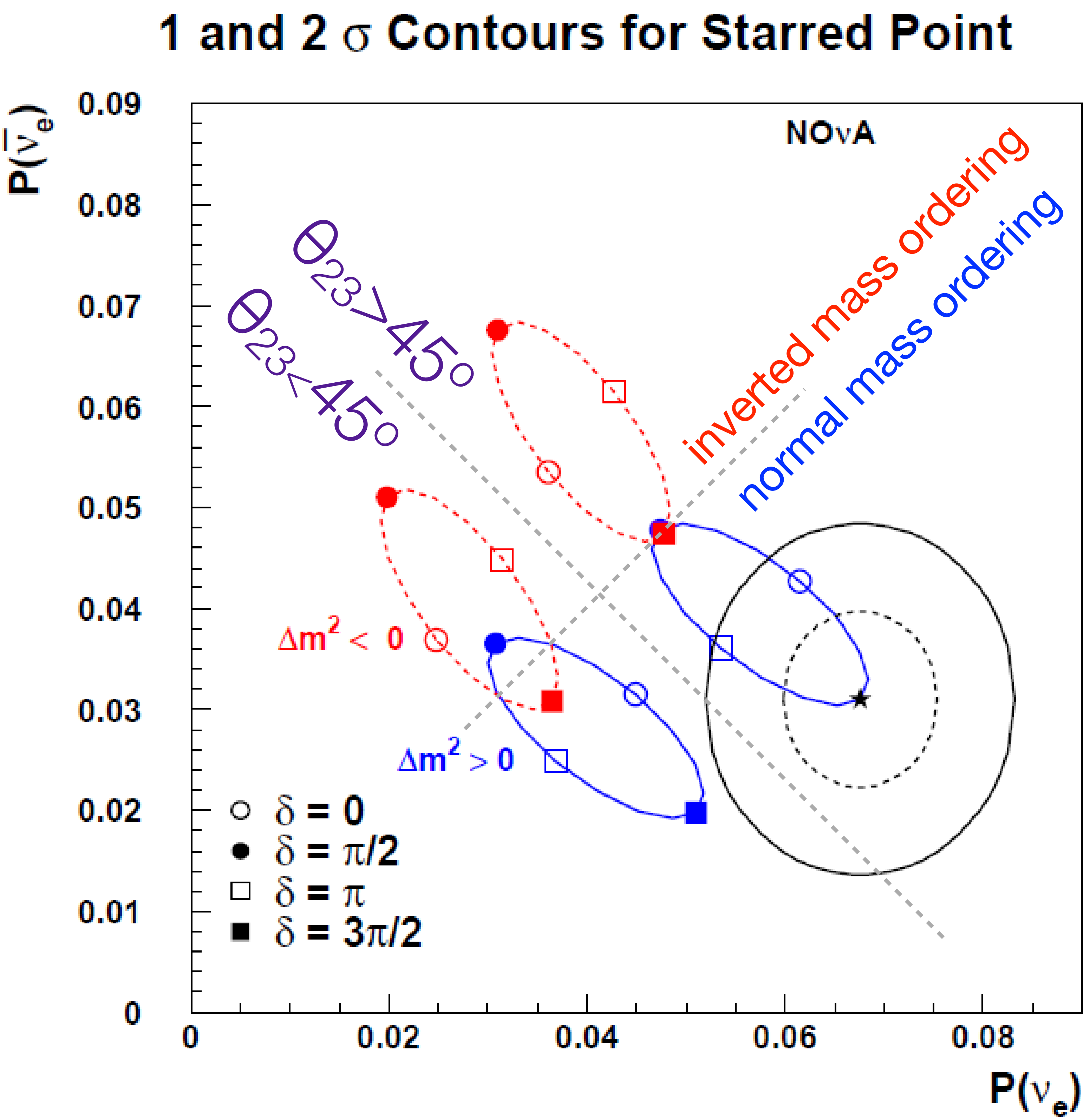
dependence on relative sign of ***Δ_{31}*** *and* ***a***

$$\sqrt{P_{\rm sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$
$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

Neutrino oscillations



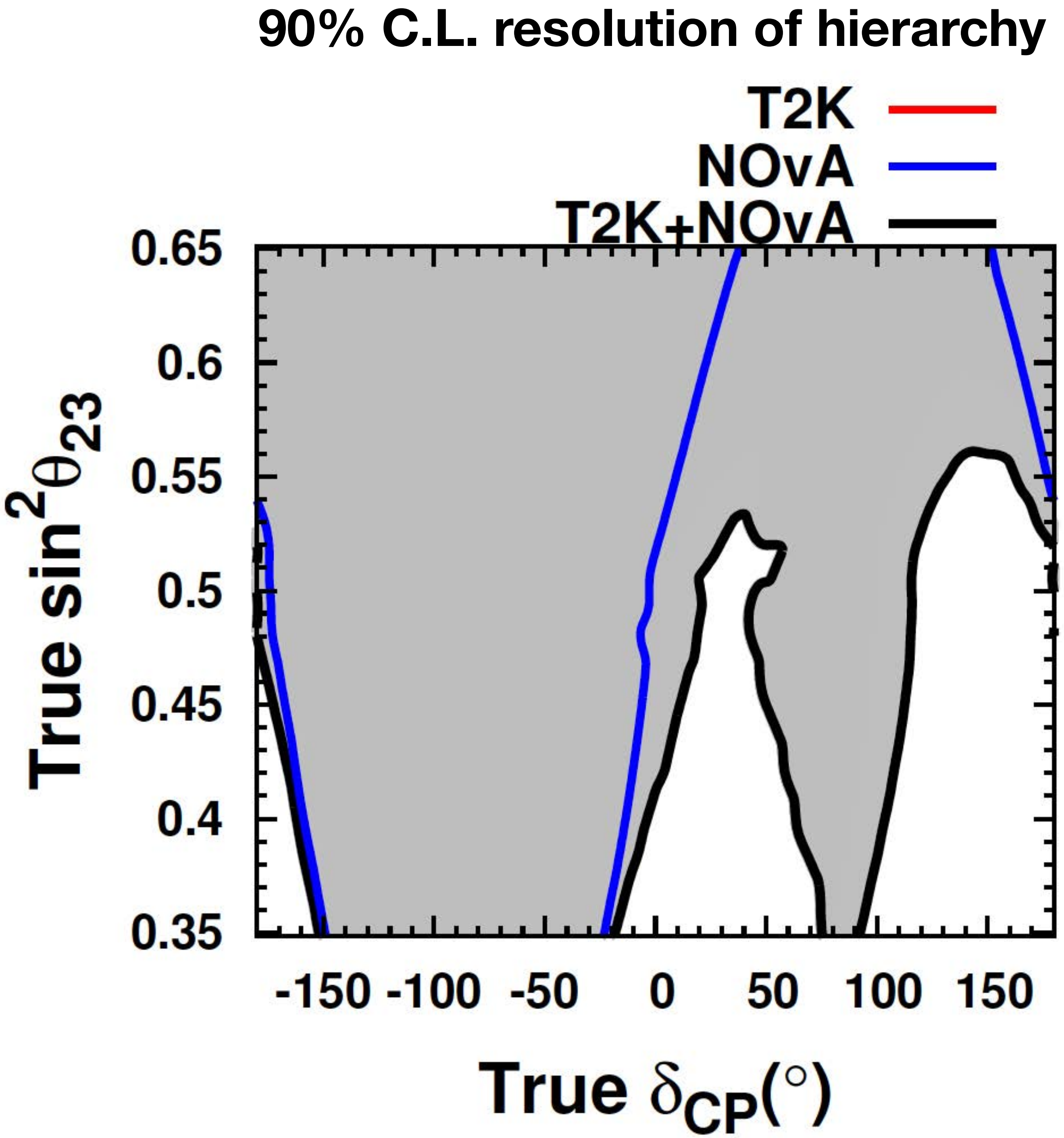
Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics parameters

Factor	Type	Inverts for $\overline{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

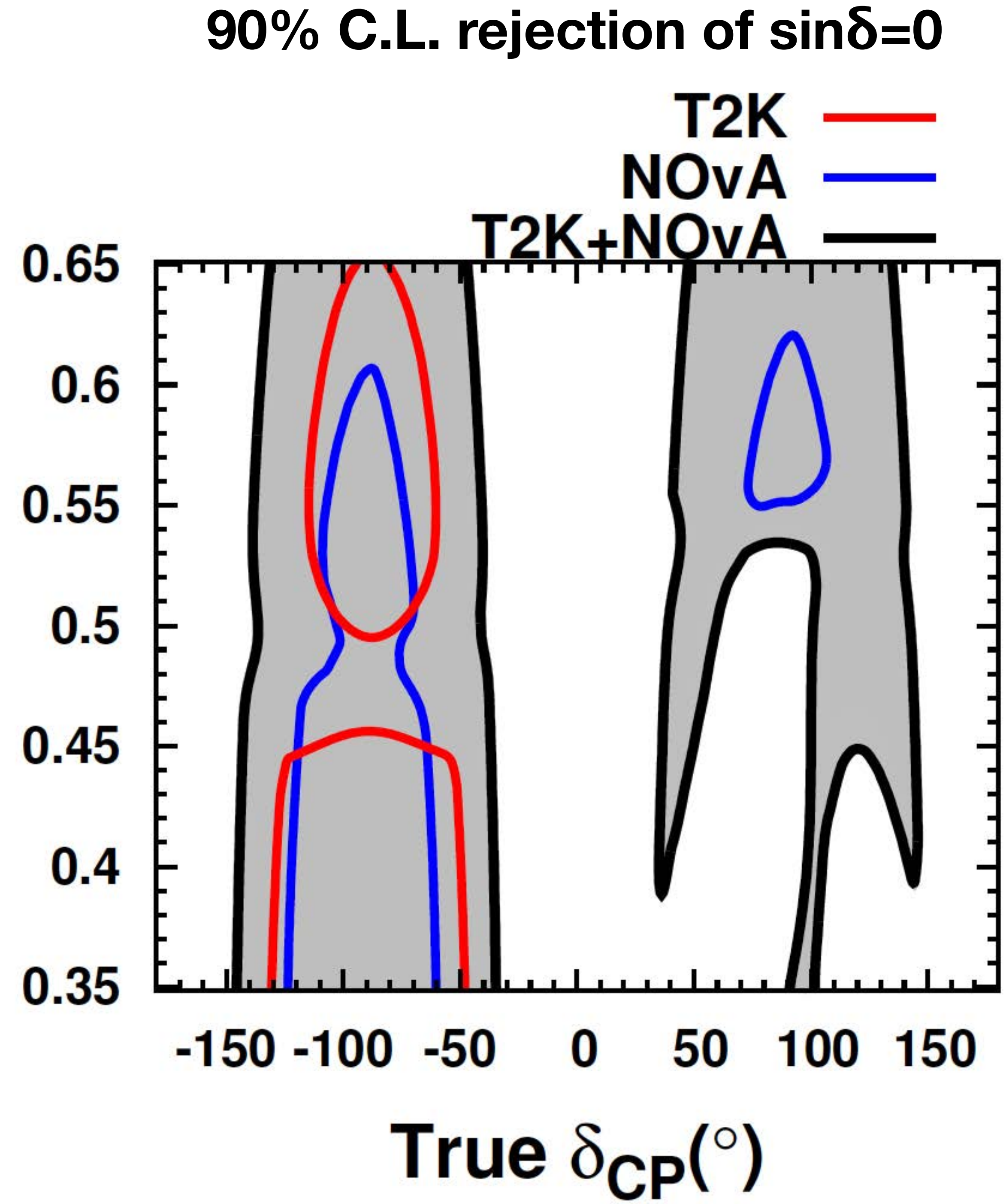
Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the $\pm 2\sigma$ range found by a recent global fit (PRD 90, 093006)

Projected Daya Bay+T2K+NOvA sensitivity by end of current runs



(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



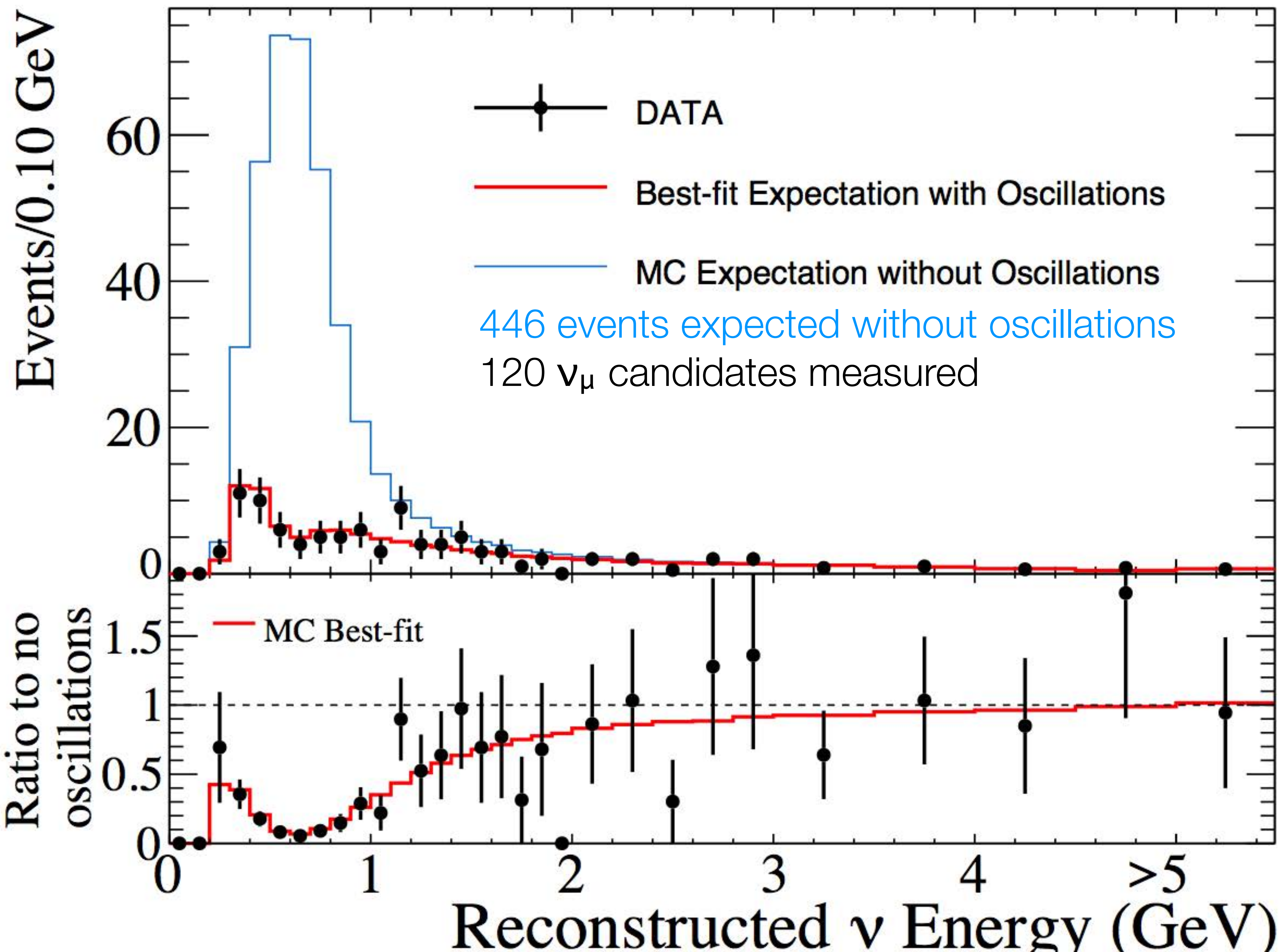
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH

arXiv:1409.7469v2 [hep-ex] 10 Feb 2015

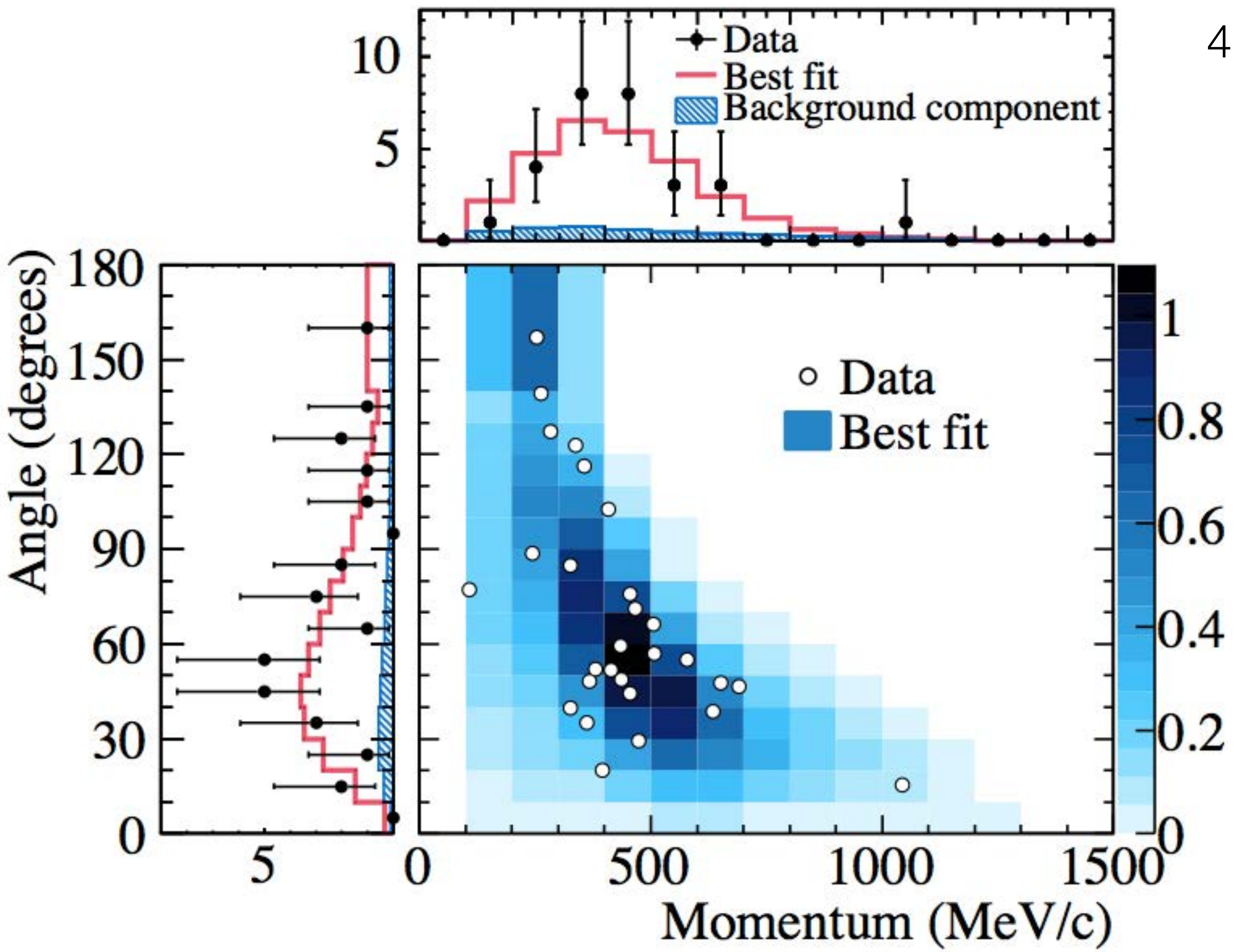
T2K

7e20 POT in neutrino mode (2009 - 2012)
4e20 POT in anti-neutrino mode (2013 - current)
350 kW peak power

T2K
ν_μ charged-current spectra



T2K
Electron neutrino signal events

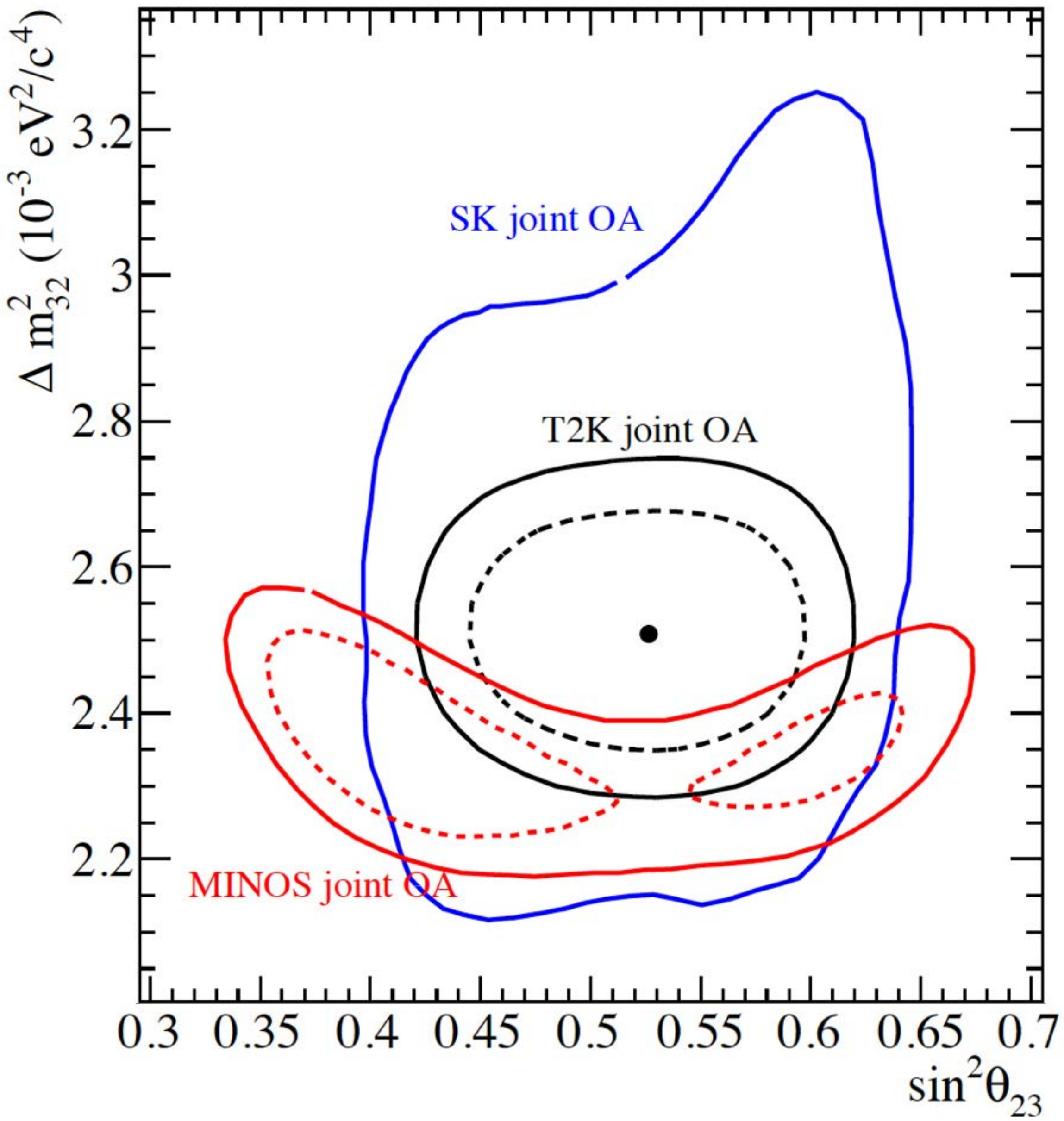


4.92 ± 0.55 background
28 events observed
7.3σ observation

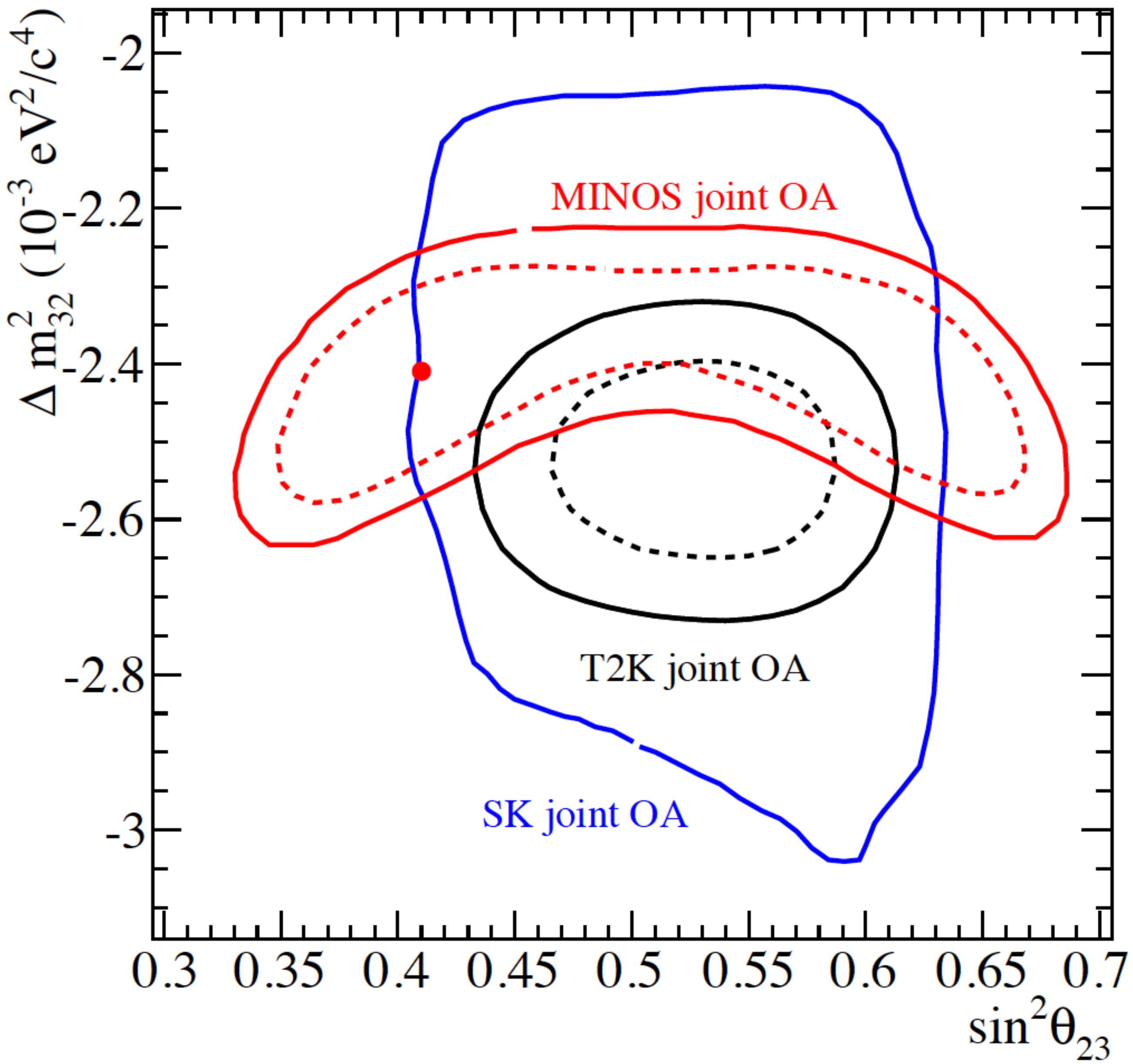
21.6 events expected
$\sin^2 2\theta_{13}=0.1$
$\delta_{CP} = 0$
$\sin^2\theta_{23} = 0.5$

T2K
$\sin^2\theta_{23}$ result

Normal Mass Ordering



Inverted Mass Ordering



Normal hierarchy: $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

Inverted hierarchy: $\sin^2\theta_{23} = 0.511 \pm 0.055$

arXiv:1502.01550v2

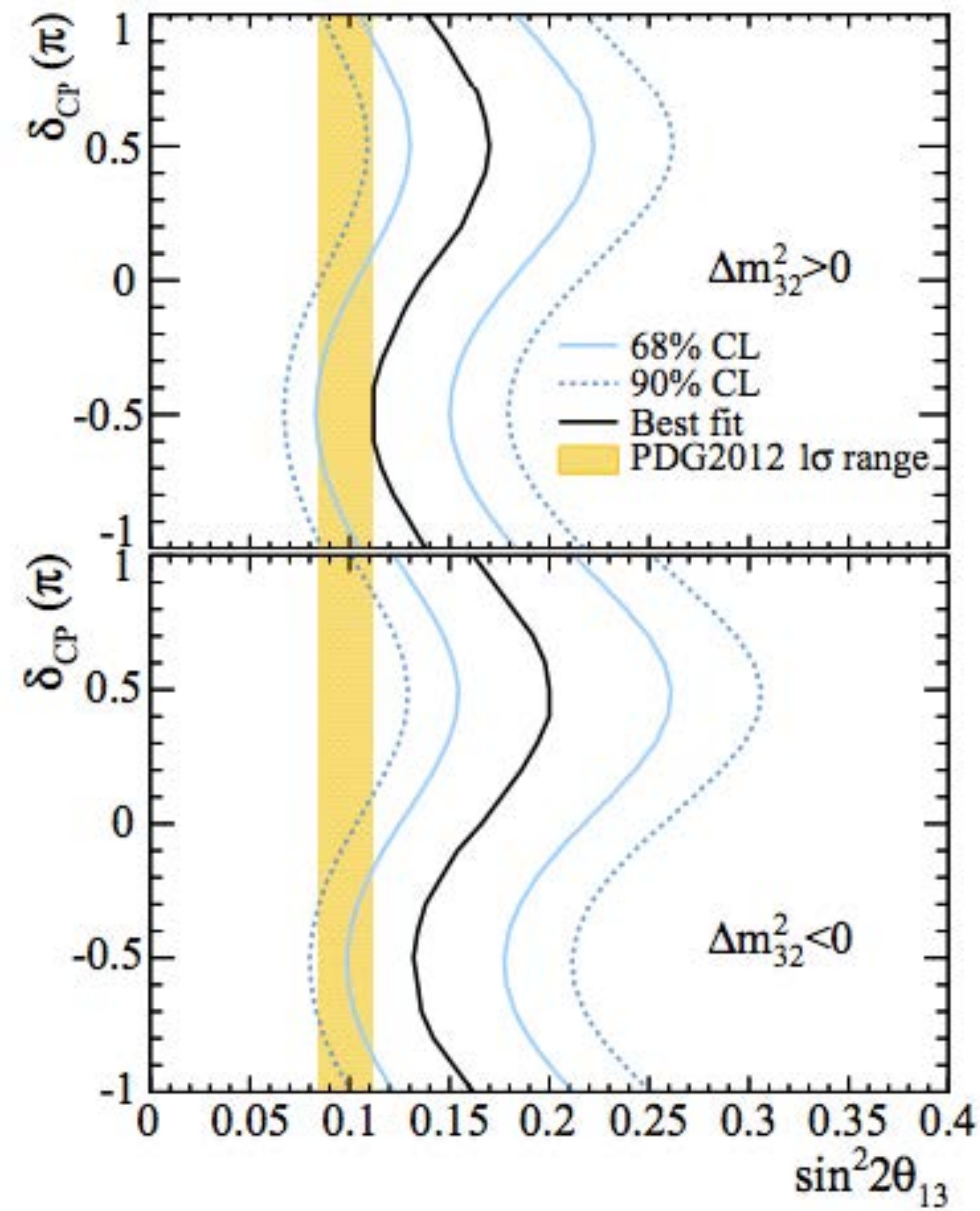
Comparing T2K results with reactors

T2K $\sin^2 2\theta_{13}$ result computed assuming $\sin^2\theta_{23}$=0.5, δ_{CP}=0, and normal hierarchy (top), and inverted hierarchy (bottom)

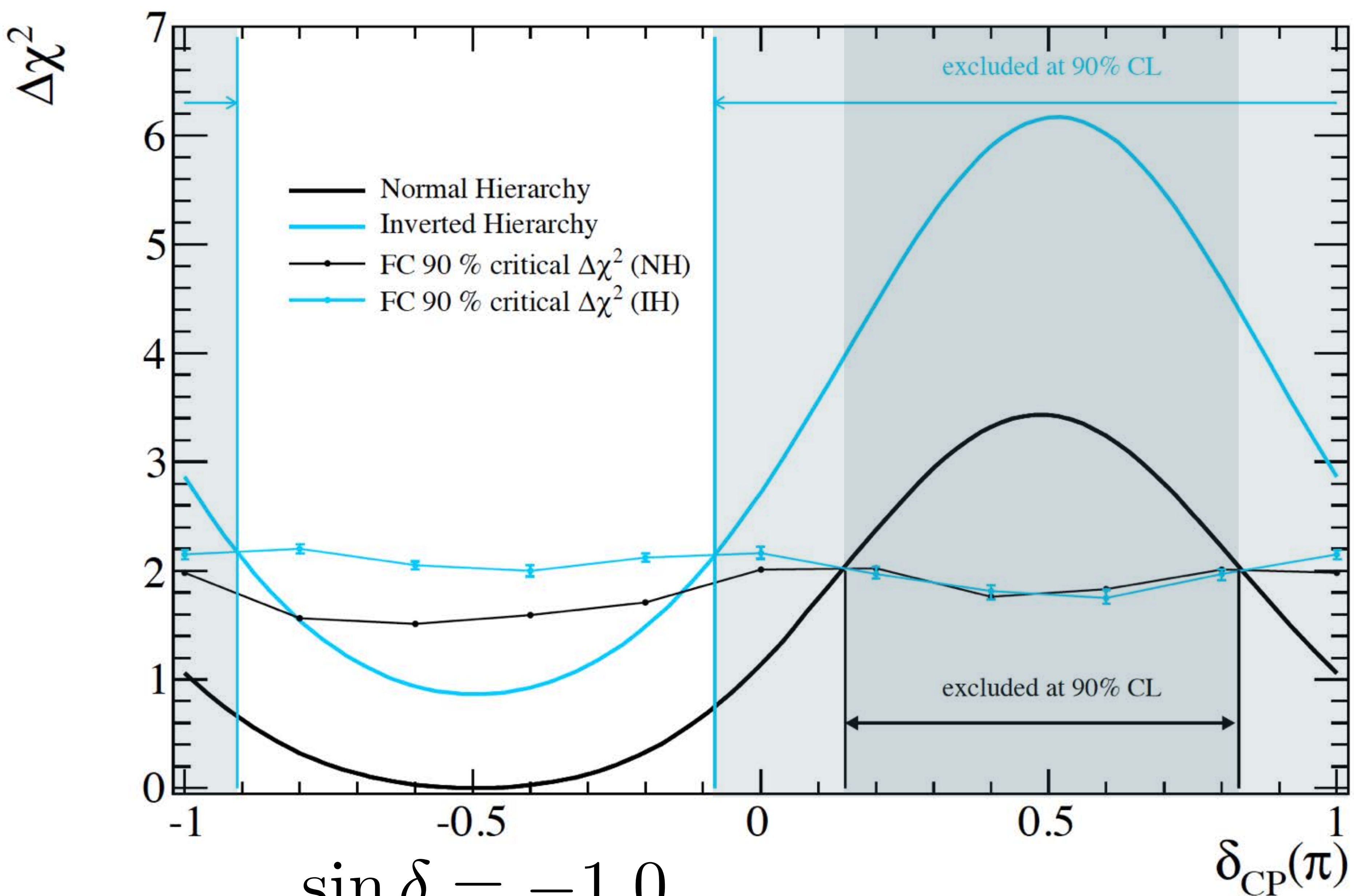
Consistent at 90% CL (1.6σ)

…but excess seen by T2K nudges all remaining unknowns in direction to increase rates

- normal hierarchy
- θ_{23}>45^o
- δ_{CP}=-π/2 (aka 3π/2)



Combining T2K with Reactors

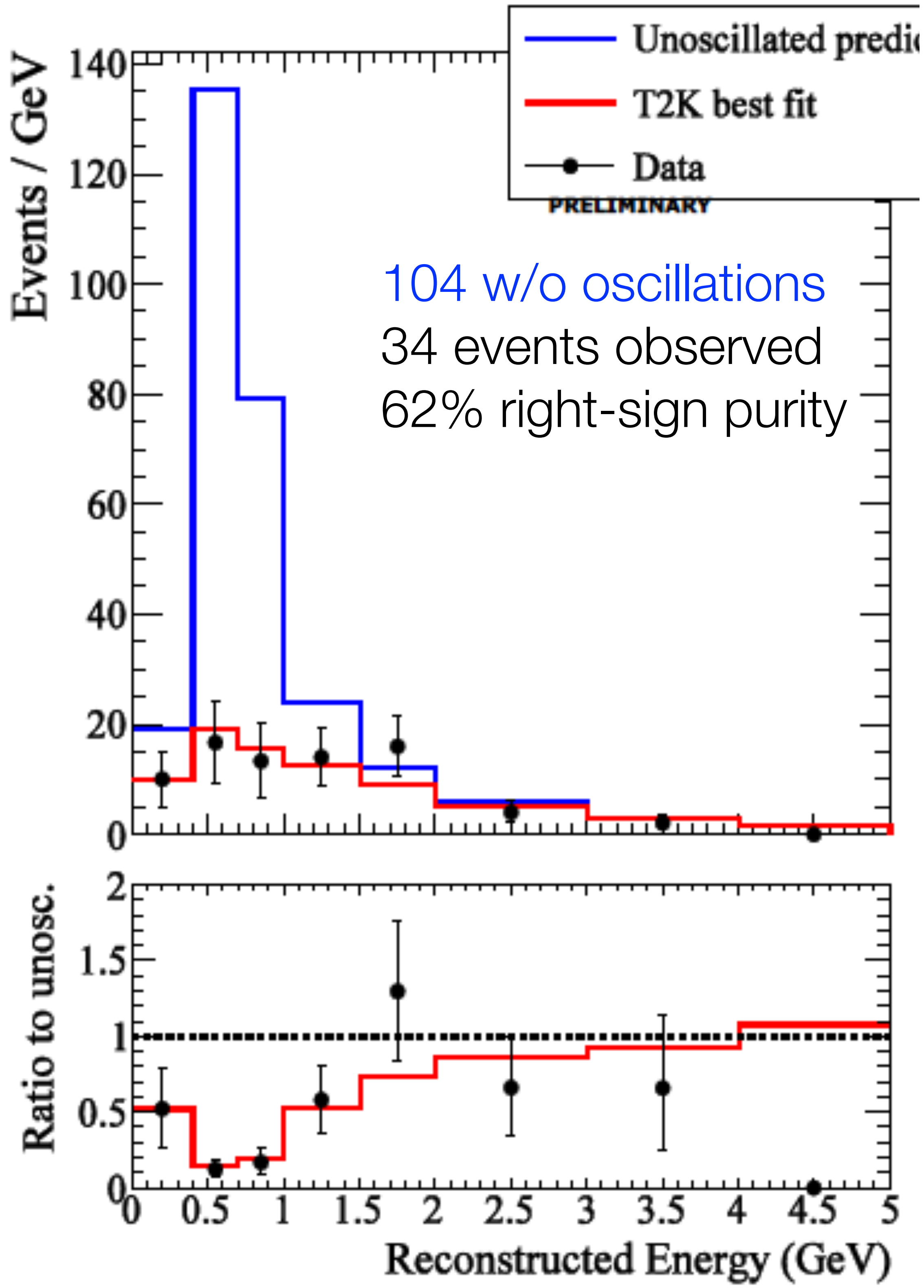


$$\sin\delta = -1.0$$

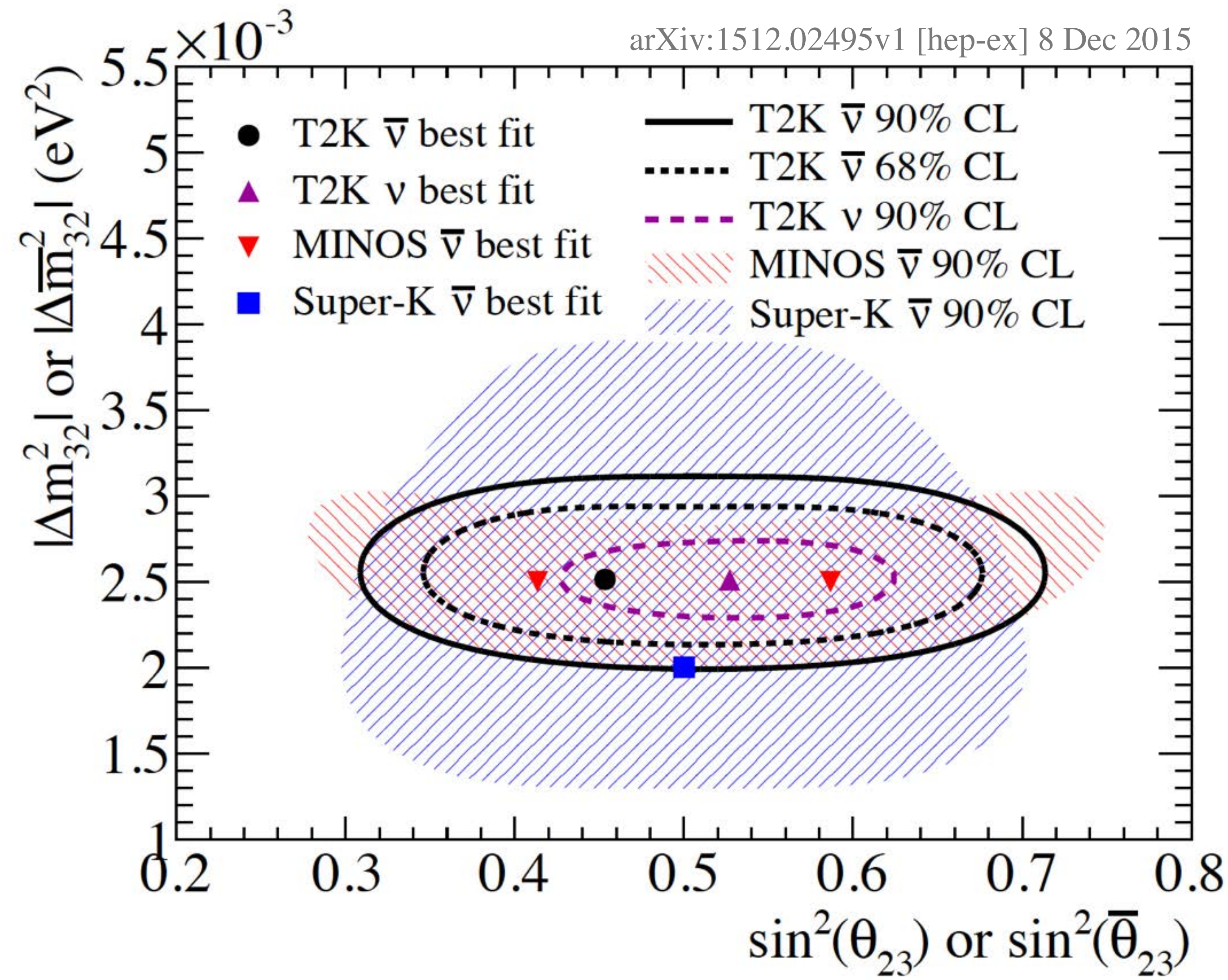
The tension with reactors gives some early sensitivity to δ_{CP}

T2K data prefers the normal hierarchy with $\delta_{CP}<0$ at ~90% C.L.

T2K Antineutrino Results

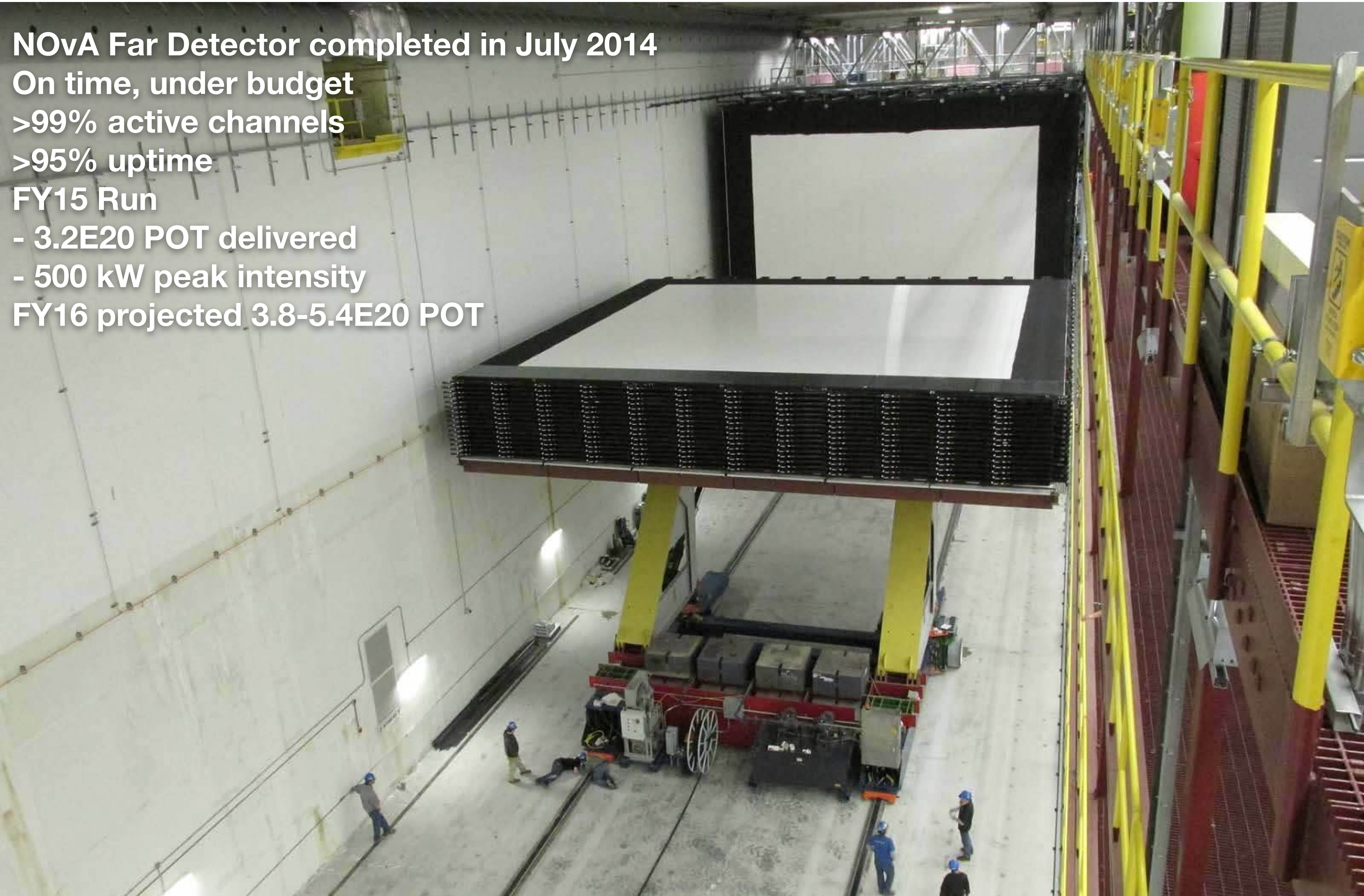


104 w/o oscillations
34 events observed
62% right-sign purity



Also sees 3 e-like events on background of 1.8 in antineutrino running

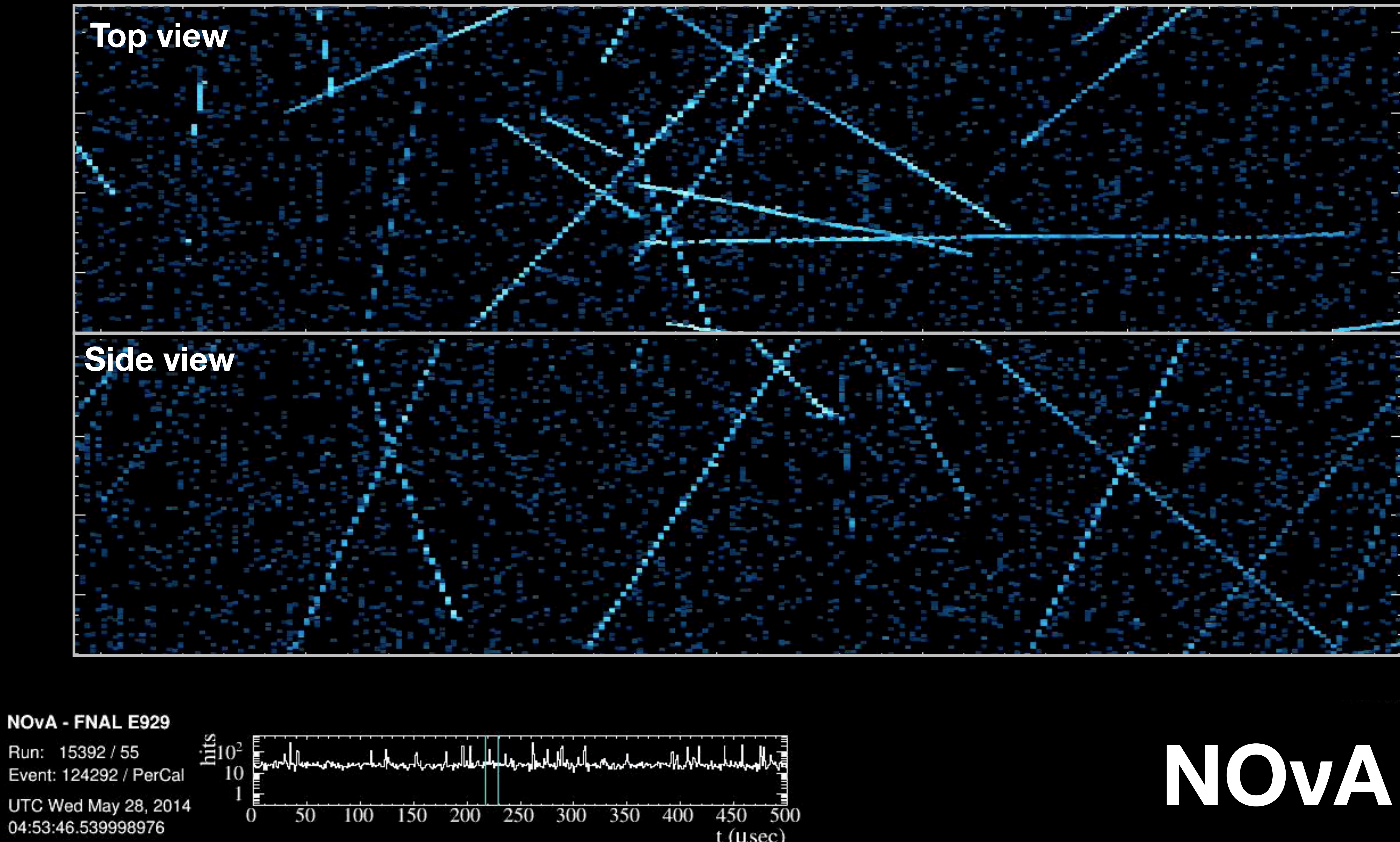
NOvA



NOvA Far Detector completed in July 2014
On time, under budget
>99% active channels
>95% uptime
FY15 Run
- 3.2E20 POT delivered
- 500 kW peak intensity
FY16 projected 3.8-5.4E20 POT

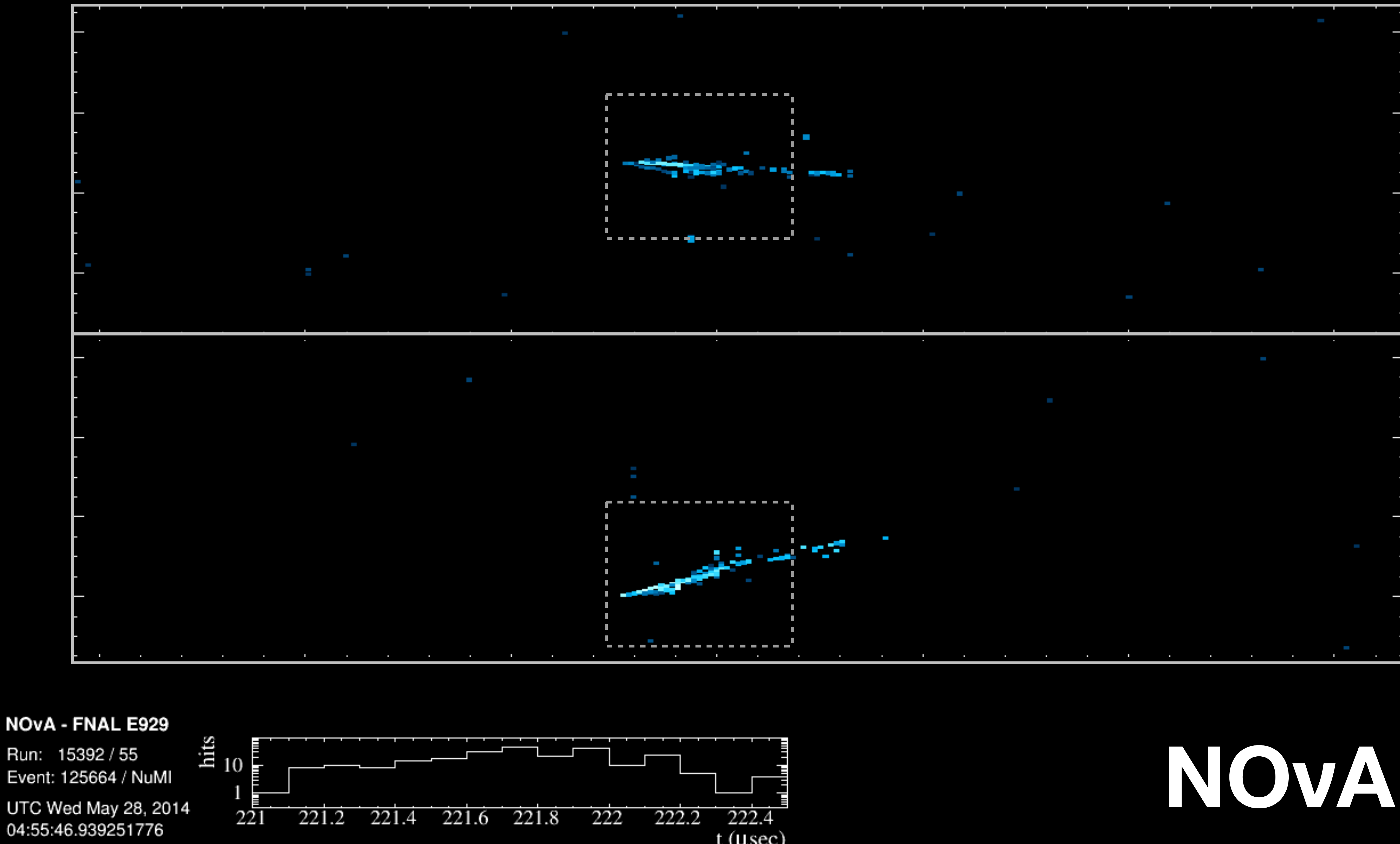
NOvA Far Detector Laboratory

Ash River Trail, Minnesota, USA



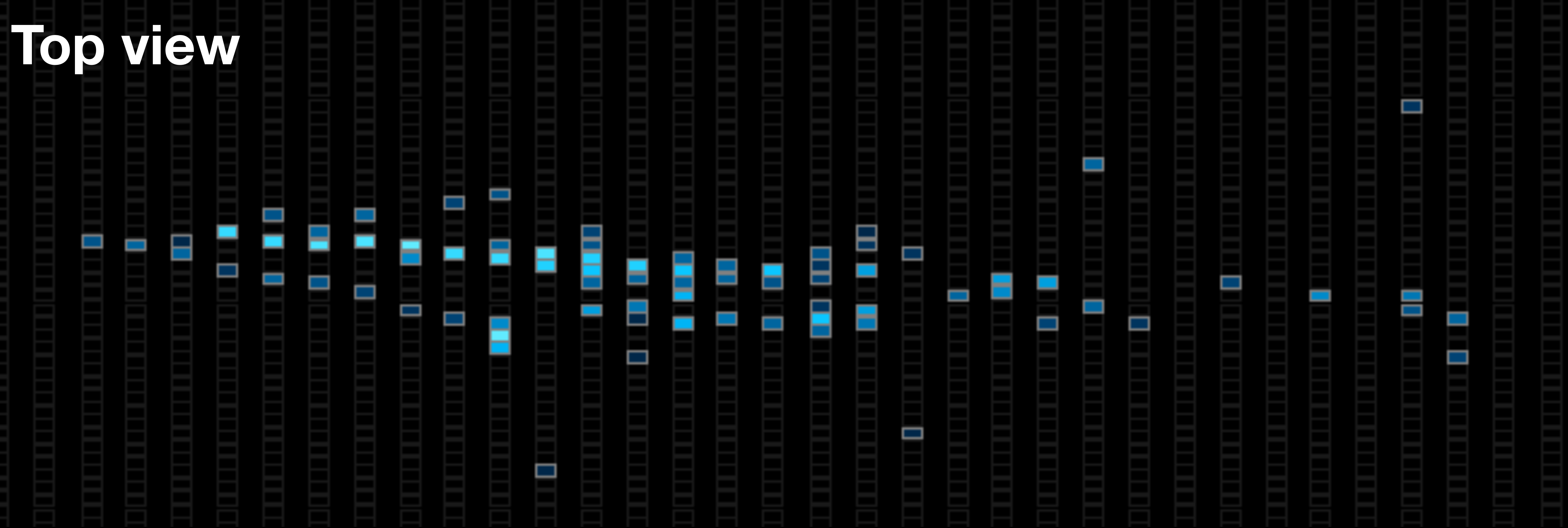
Top view
Side view
NOvA - FNAL E929
Run: 15392 / 55
Event: 124292 / PerCal
UTC Wed May 28, 2014
04:53:46.539998976
hits
10^2
10
1
0
50
100
150
200
250
300
350
400
450
500
t (μsec)

NOvA

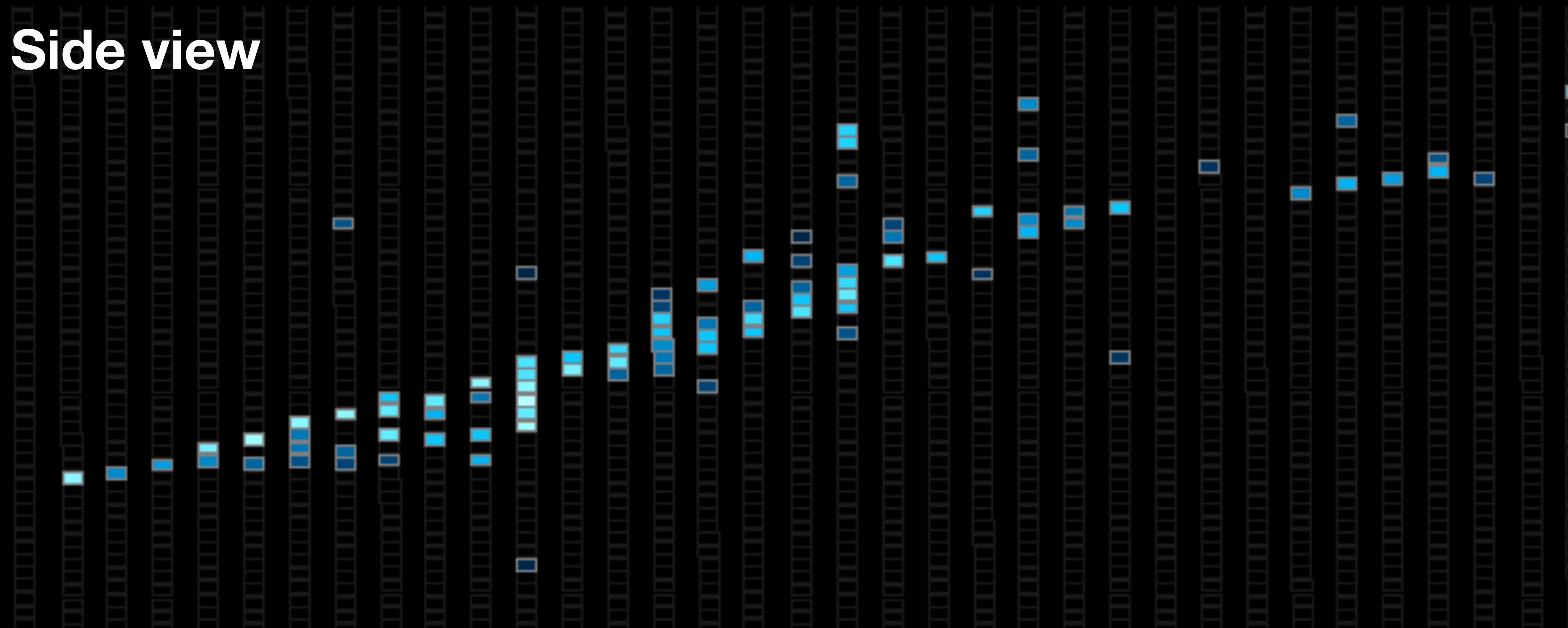

NOvA - FNAL E929
Run: 15392 / 55
Event: 125664 / NuMI
UTC Wed May 28, 2014
04:55:46.939251776
hits
10
1
221
221.2
221.4
221.6
221.8
222
222.2
222.4
t (μsec)

NOvA

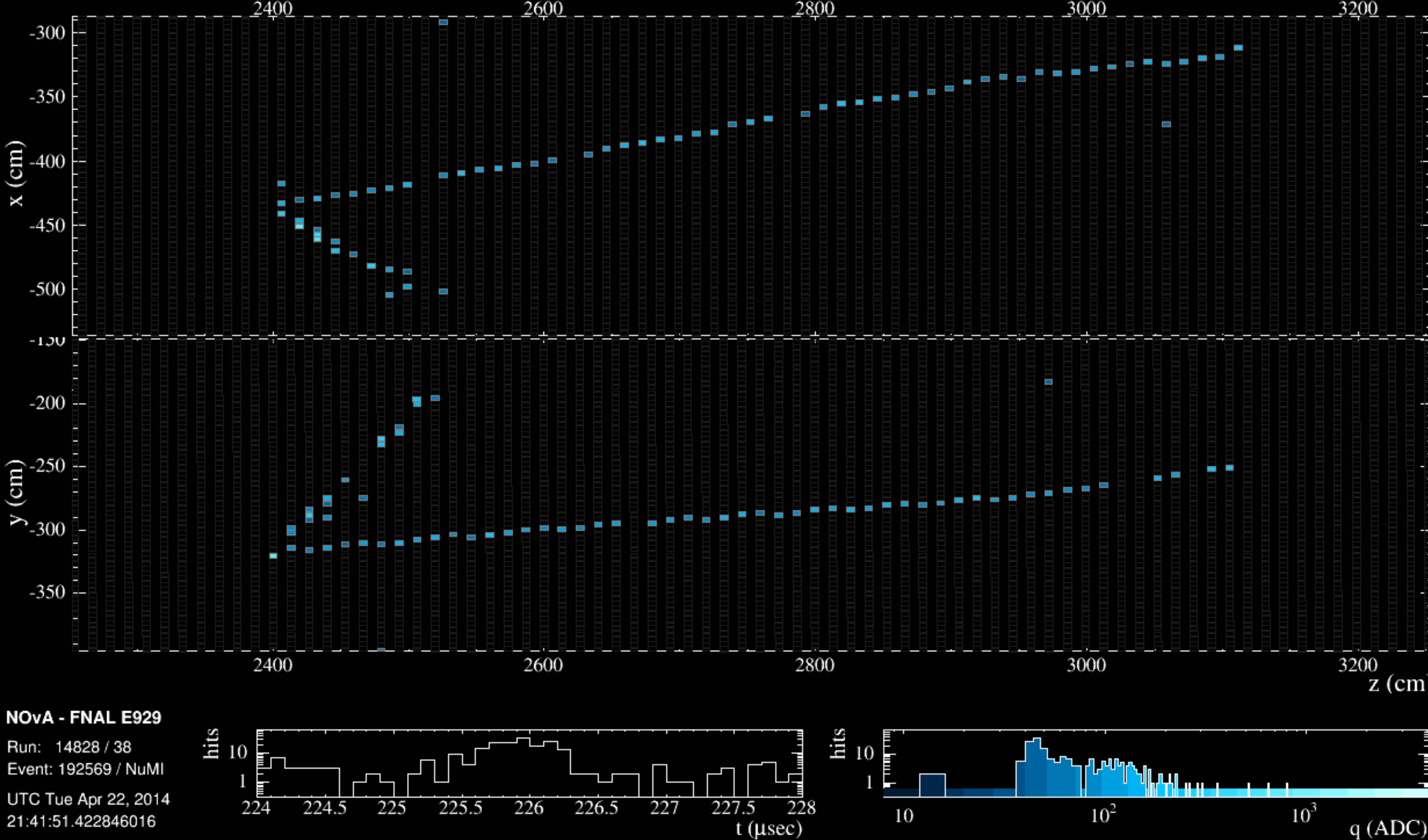
Top view

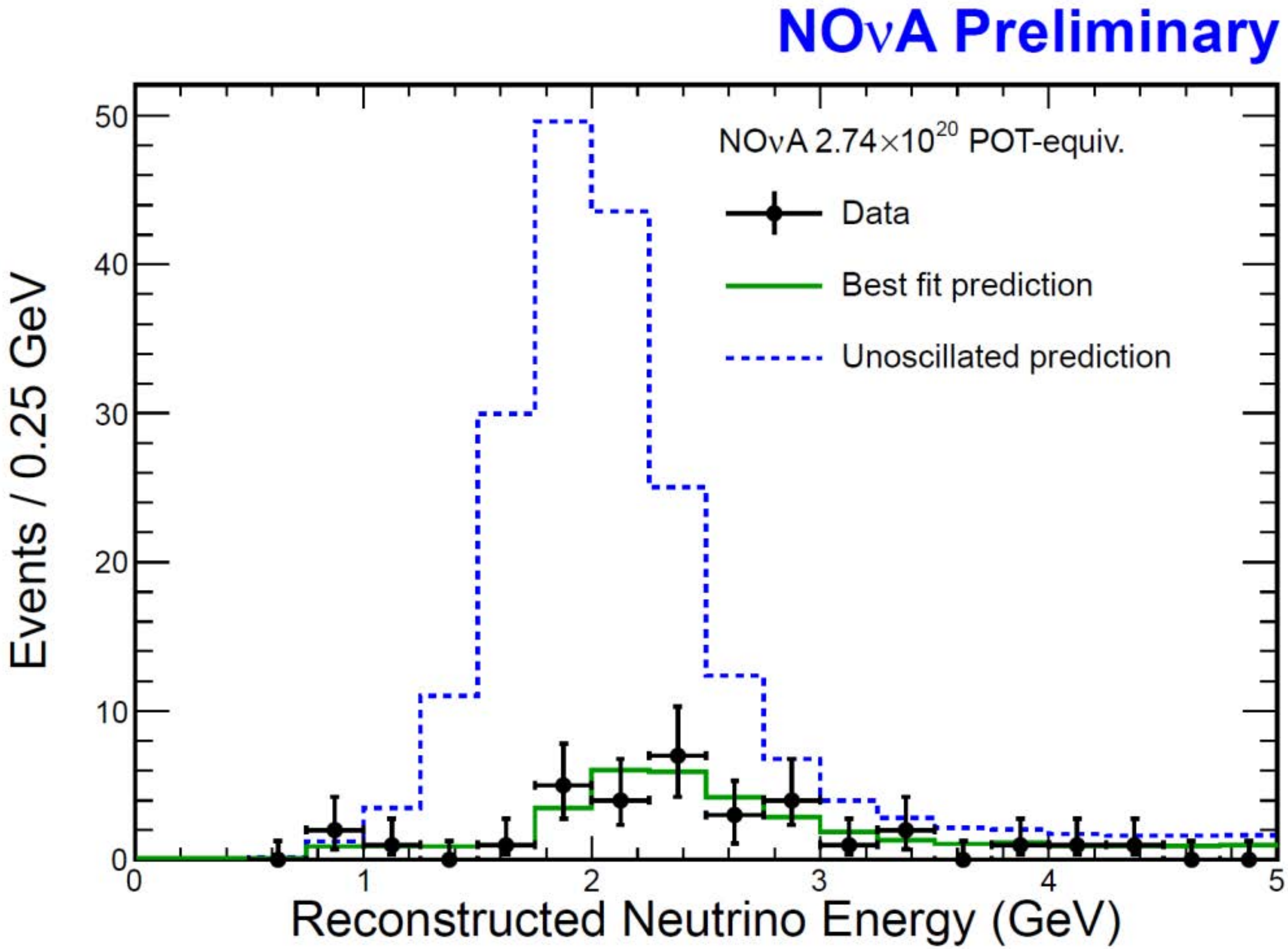


Side view



NOvA ν_μ Charged-current candidate





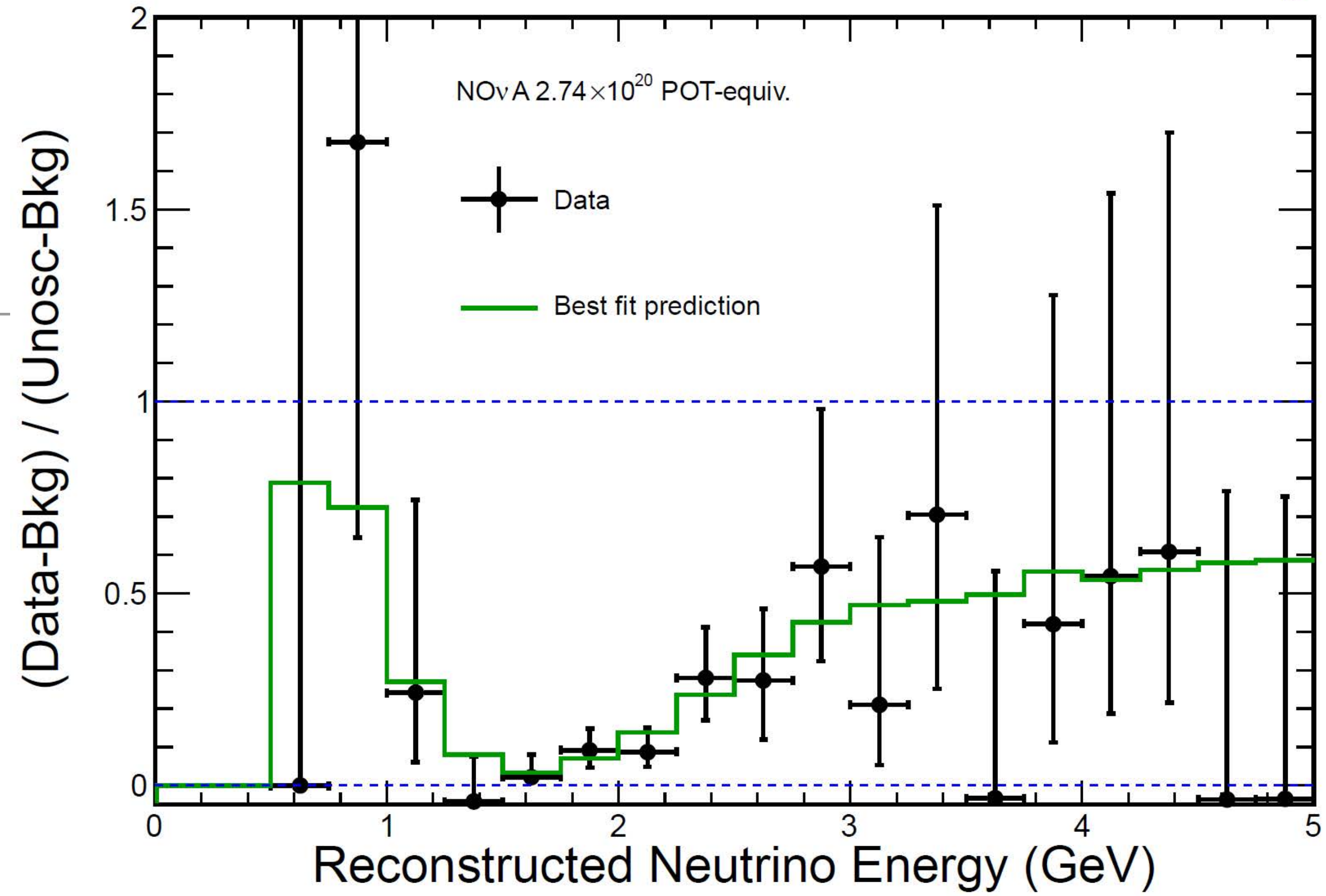
NOvA Far detector muon neutrino spectrum

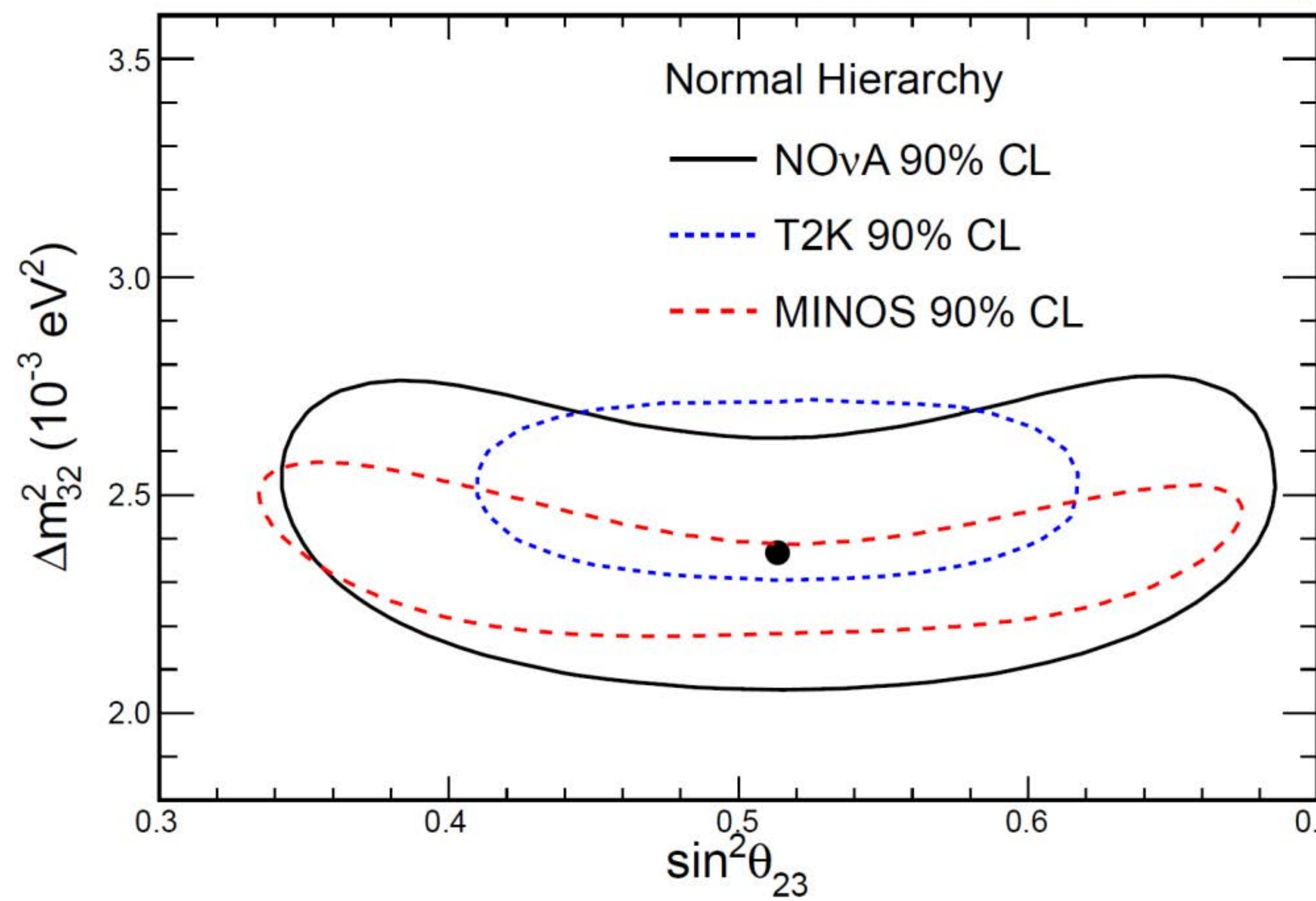
201 events expected before oscillations
33 events observed

NOvA
ν_μ Disappearance

$$\Delta m^2_{32} = +2.37^{+0.16}_{-0.15} \text{ [normal ordering]}$$
$$\Delta m^2_{32} = -2.40^{+0.14}_{-0.17} \text{ [inverted ordering]}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

NOvA Preliminary

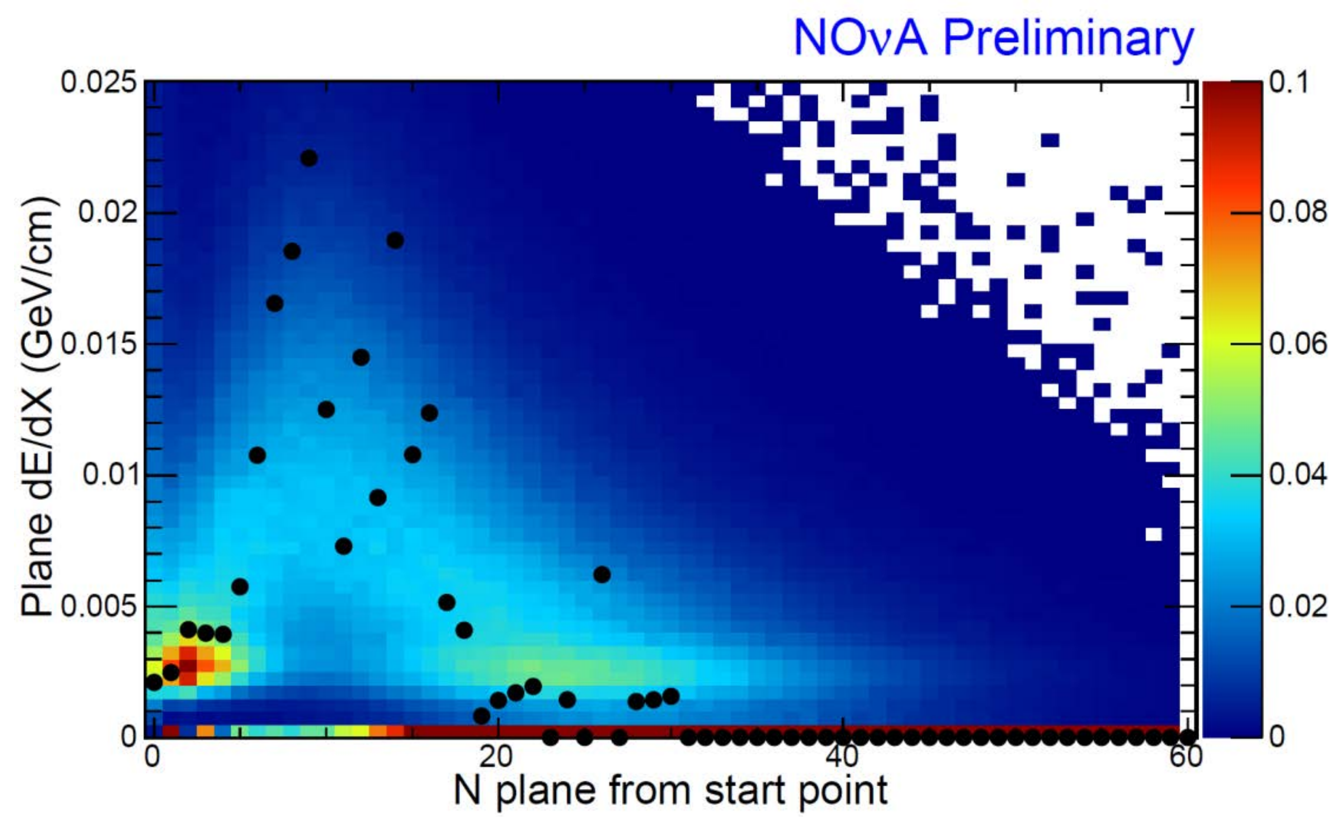




ν_e Identification in NOvA

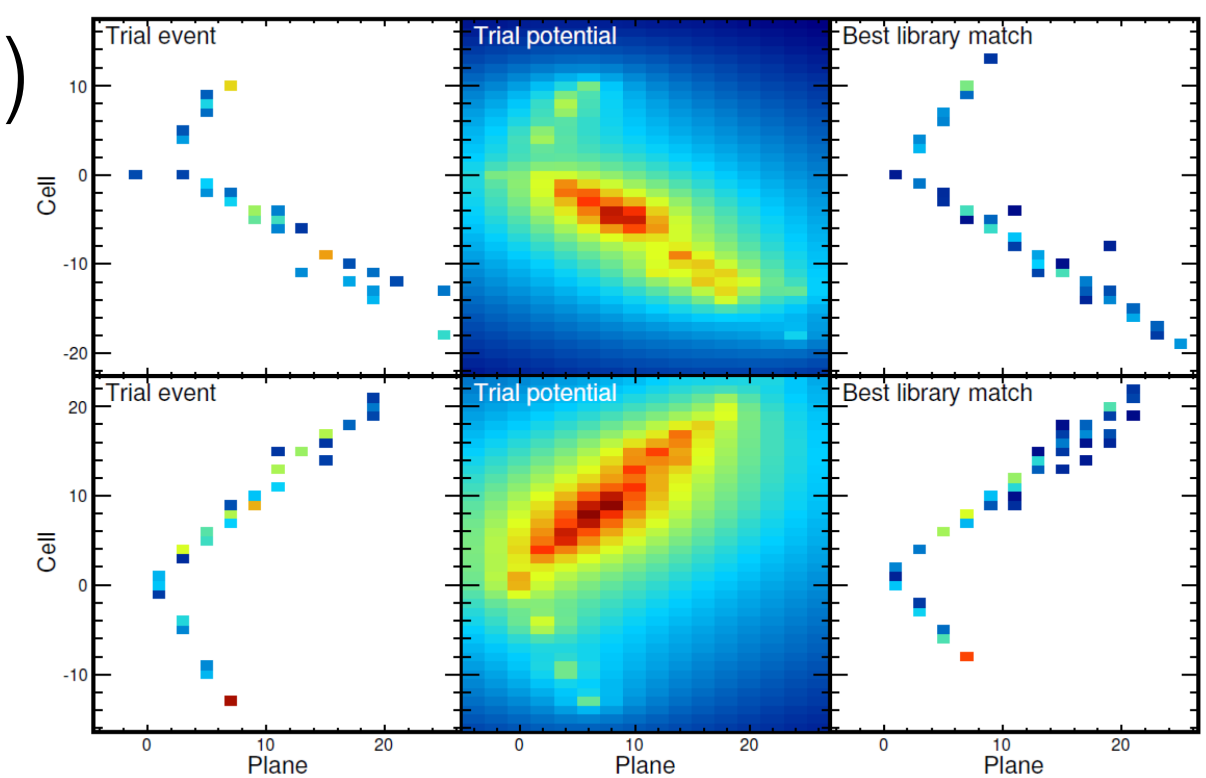
Likelihood Identifier ("LID")

Tests event longitudinal and transverse shower dE/dx profiles against probability density functions for e/μ/π/p hypotheses



Library Event Matching ("LEM")

Tests entire event topology against a large library of simulated neutrino signal and background events. Assigns event characteristics according to top matches.



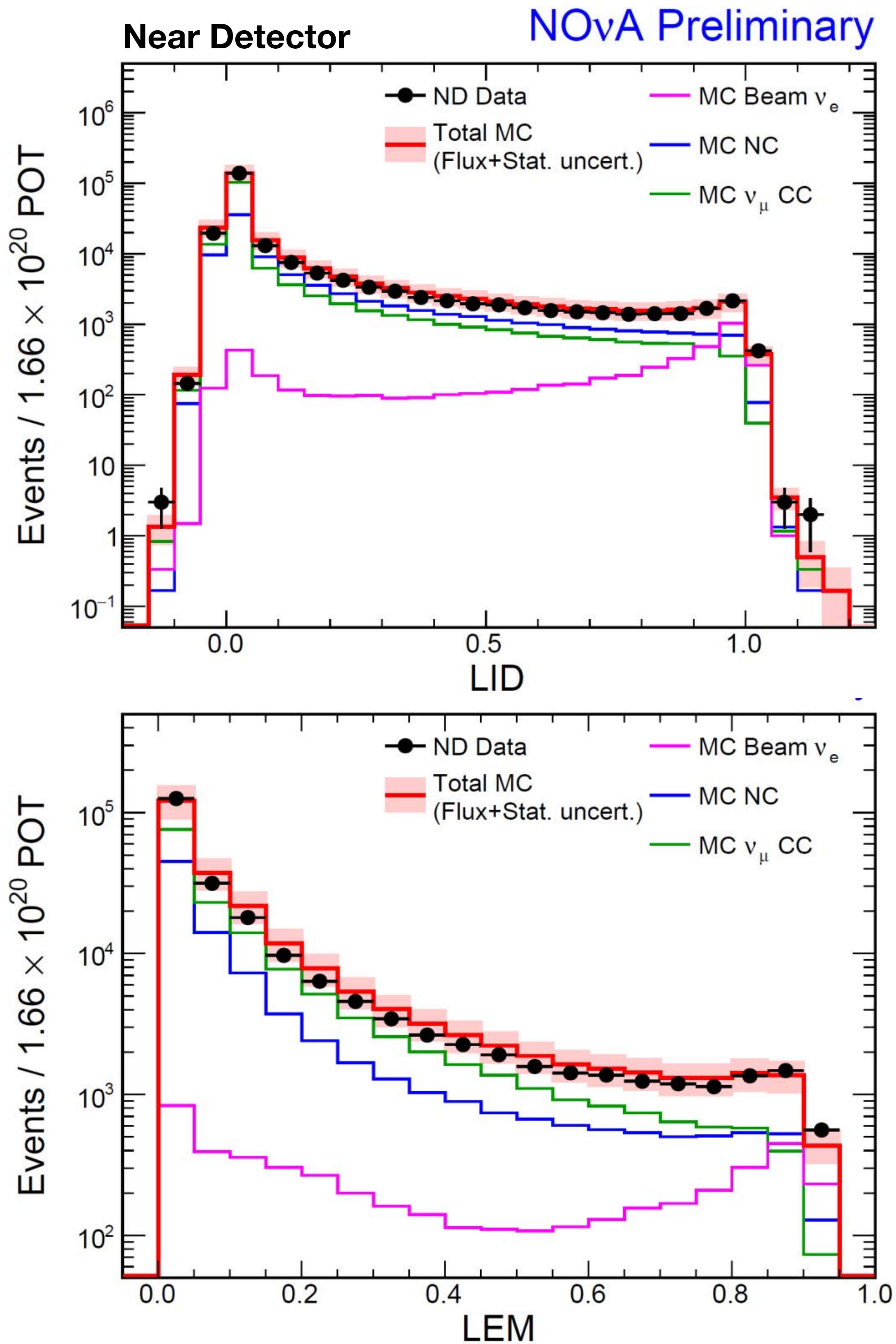
NOvA ν_e Selection

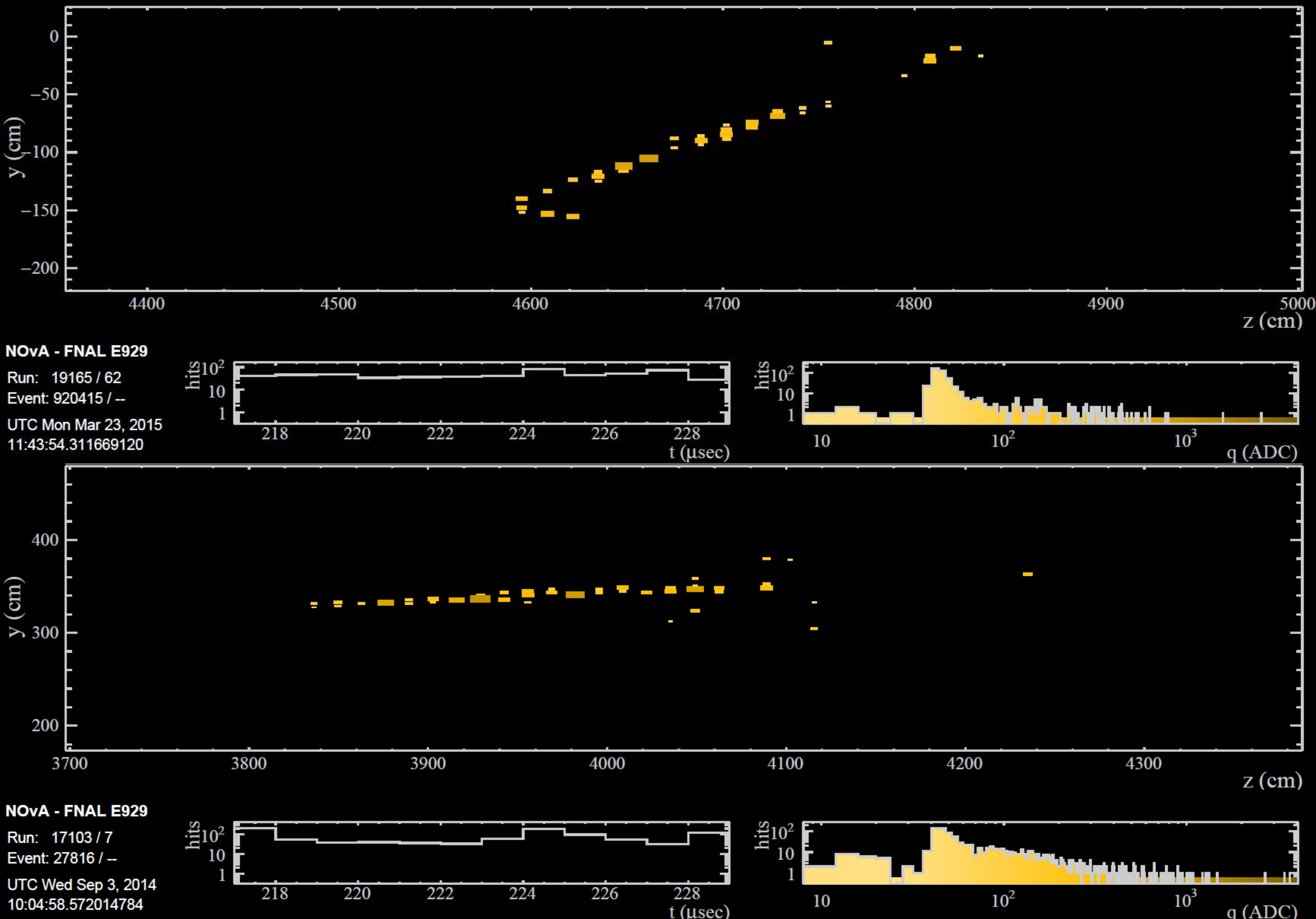
Based on near detector measurements predict:

1 ± 0.1 background events

2 ± 0.3 signal [IH $\delta_{CP}=\pi/2$]
6 ± 0.7 signal [NH $\delta_{CP}=3\pi/2$]

at far detector for $\sin^2\theta_{23}=0.5$



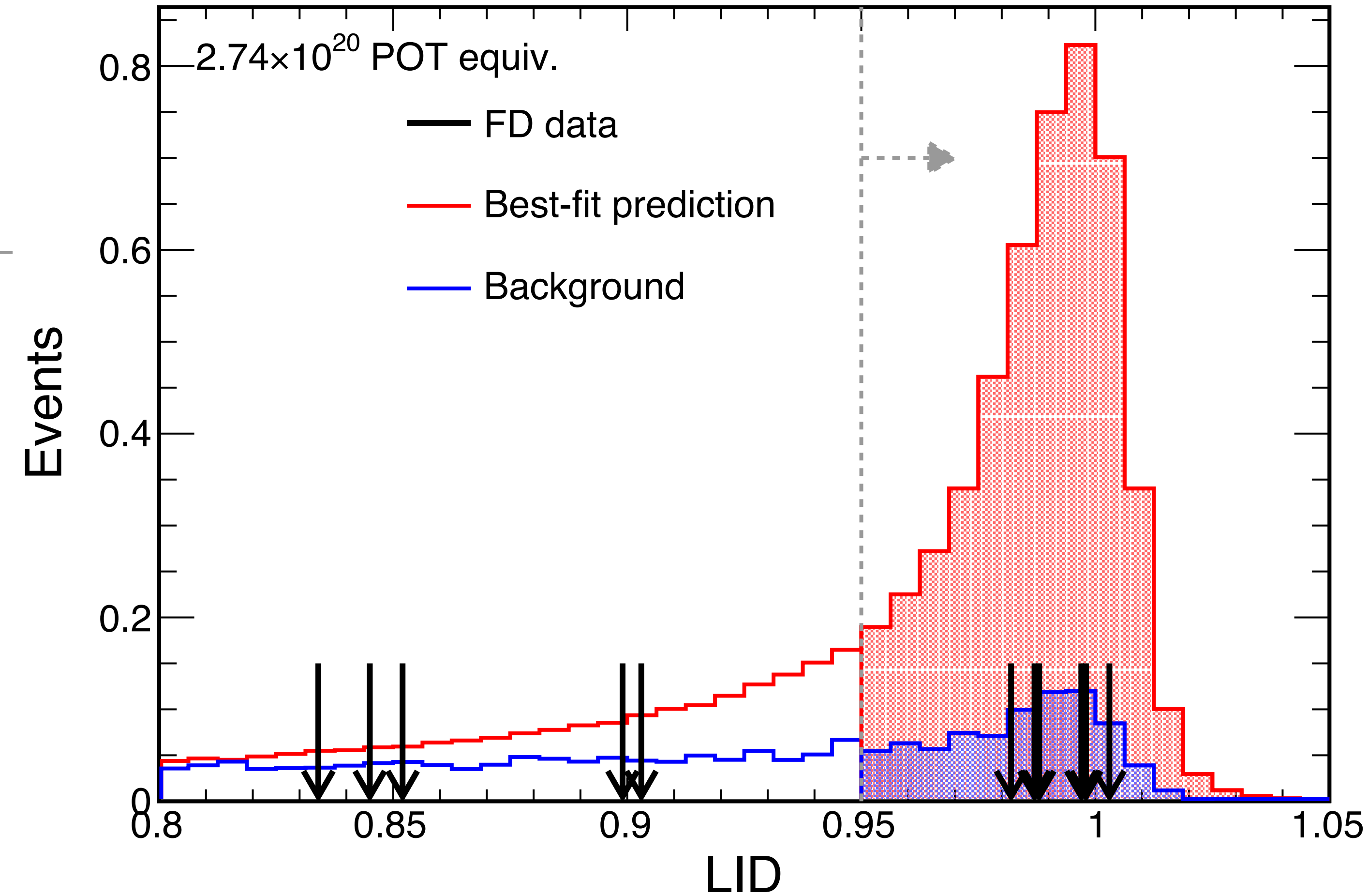


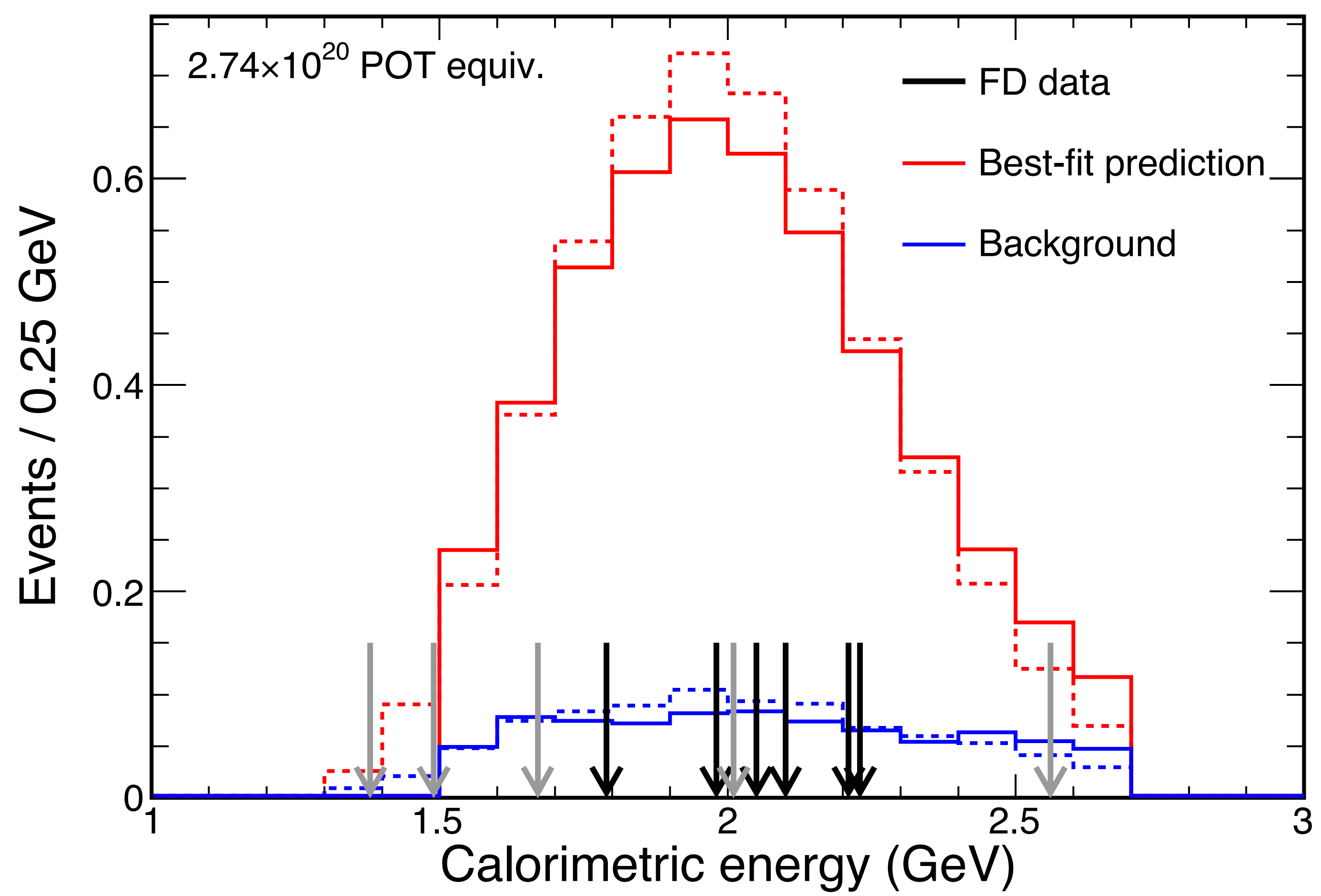
Two NOvA ν_e Candidates

NOvA Electron Neutrino Appearance

- These select **6 (LID)** and **11 (LEM)** events. All 6 of the LID events are selected by LEM. Expected **background is 1 event** for each. These are **3.3σ** and **5.5σ** significant excesses over background.
- LID and LEM have 60% overlap, determined from simulation and checked in NOvA near detector. The P-value for selecting the combination (11:6/5/0) is 11%.
- Top plot shows the LID particle IDs for the 11 selected events. The LID&LEM events are to the right of the dashed line. The 5 LEM-only events are shown to the left. Bottom plot shows the energy spectrum of the 11 events. LID are in black, LEM in gray.

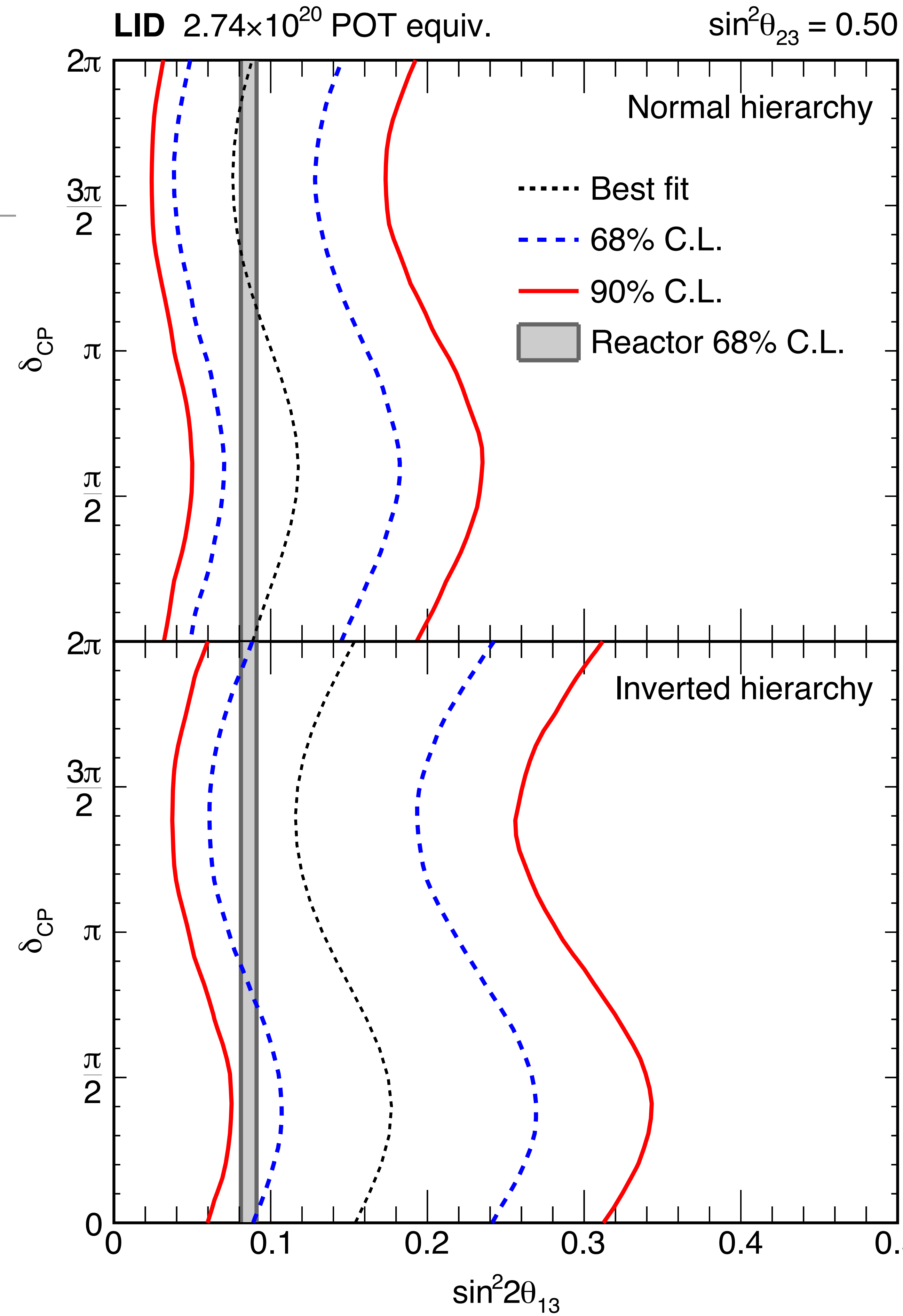
NOvA Preliminary





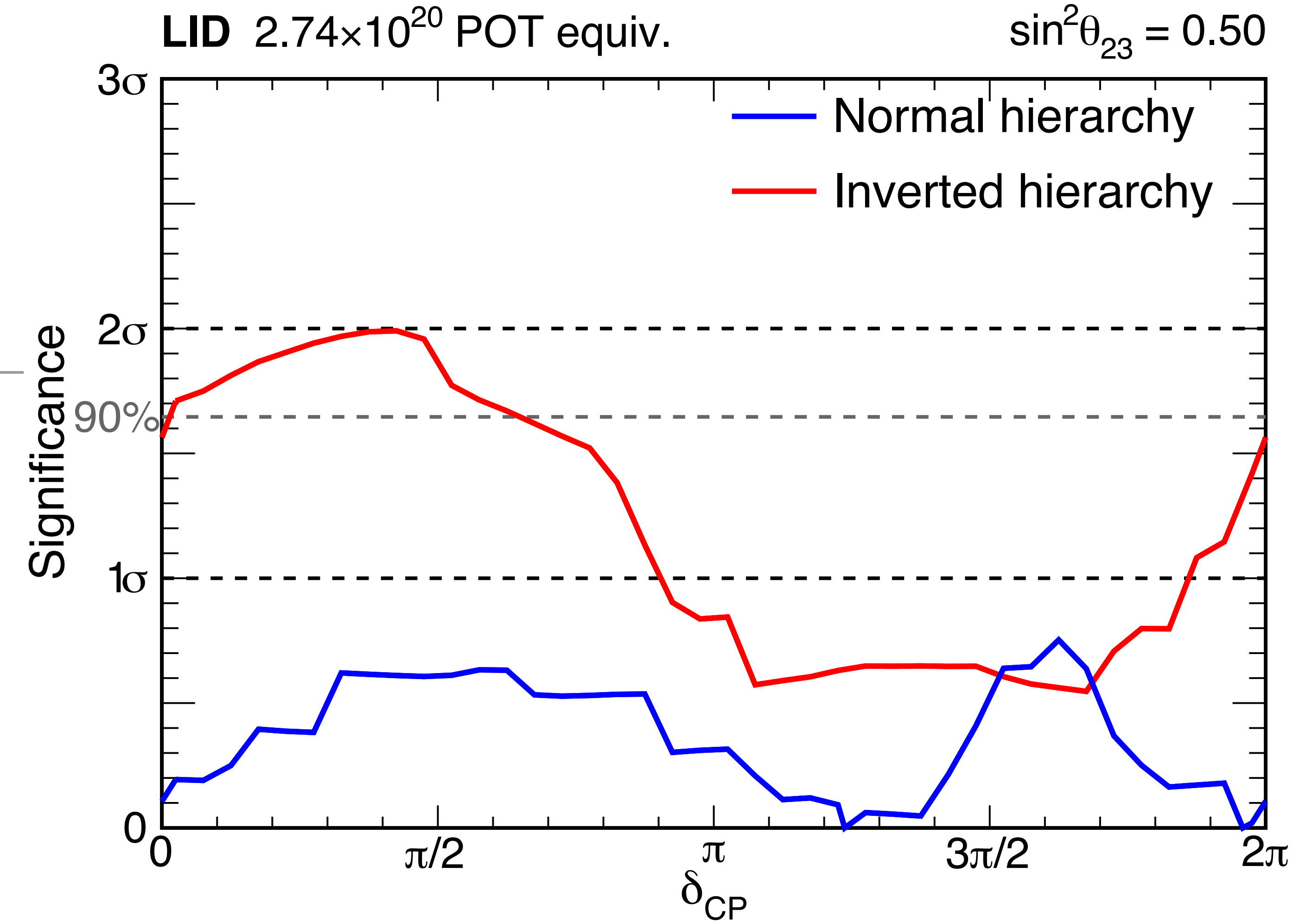
NOvA Electron Neutrino Appearance

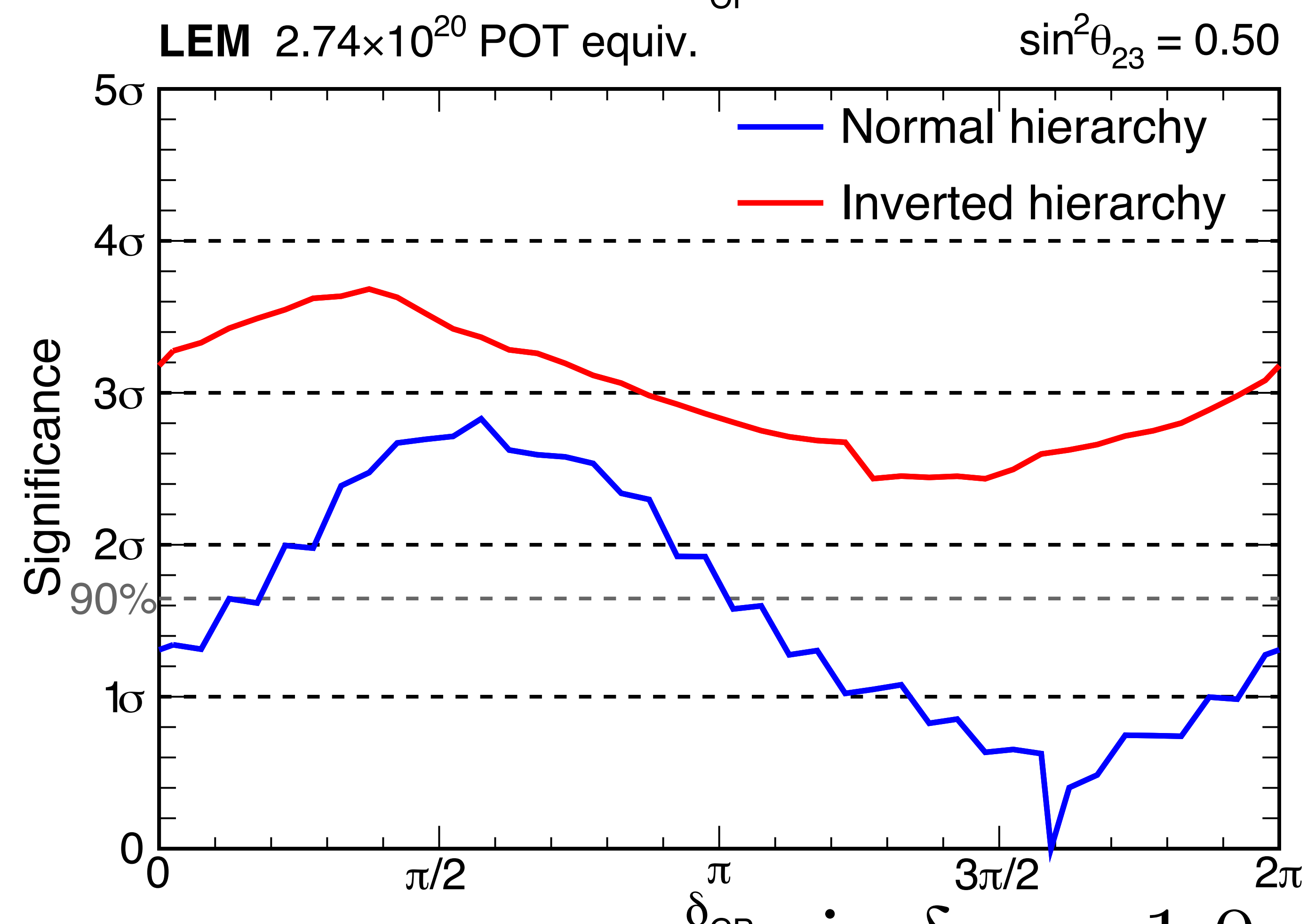
- Results show good consistency between NOvA (s-cuves) and reactor experiments (gray band) for normal (top) and inverted mass ordering (bottom).
- Agreement is ~1σ better for the normal ordering
- This plot is for LID selector (n=6). For LEM (n=11) the s-curves shift ~x2 to the right increasing tension for the inverted mass ordering. See next page.



NOvA Electron Neutrino Appearance

- If we take the reactor measurement of θ_{13} as an input we can ask how well the NOvA event counts fit to particular choices of the mass ordering and δ_{CP}
- Both LID and LEM prefer normal mass ordering with δ_{CP} between π and 2π
- For LID (n=6, top plot) there is some tension with the inverted hierarchy especially for δ_{CP} near π/2
- For LEM (n=11, bottom plot) the inverted hierarchy is everywhere disfavored at 2σ
- ***Beware of trials factor of choosing to only look at LEM results*** - true answer is most likely somewhere in between top and bottom results. We will have roughly x2 more data to report at Neutrino in July, 2016
- A further note: The jagged contours are a result of small-number statistics





$\sin\delta = -1.0$

Summary

Measurements using atmospheric neutrinos, reactor neutrinos and long-baseline neutrinos form a consistent picture

- Large θ_{23} ($0.4 < \sin^2\theta_{23} < 0.6$)
- Precisely known $\theta_{13} = 8.4^o$
- Consistent hints favoring
  - $\pi<\delta_{CP}<2\pi$
  - normal mass ordering
- First data from NOvA strengthens this picture with more data to come