Current Program and Projections

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Second International Meeting for Large Neutrino Infrastructures
Fermilab, April 20-21, 2015

Fermilab APPEC

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

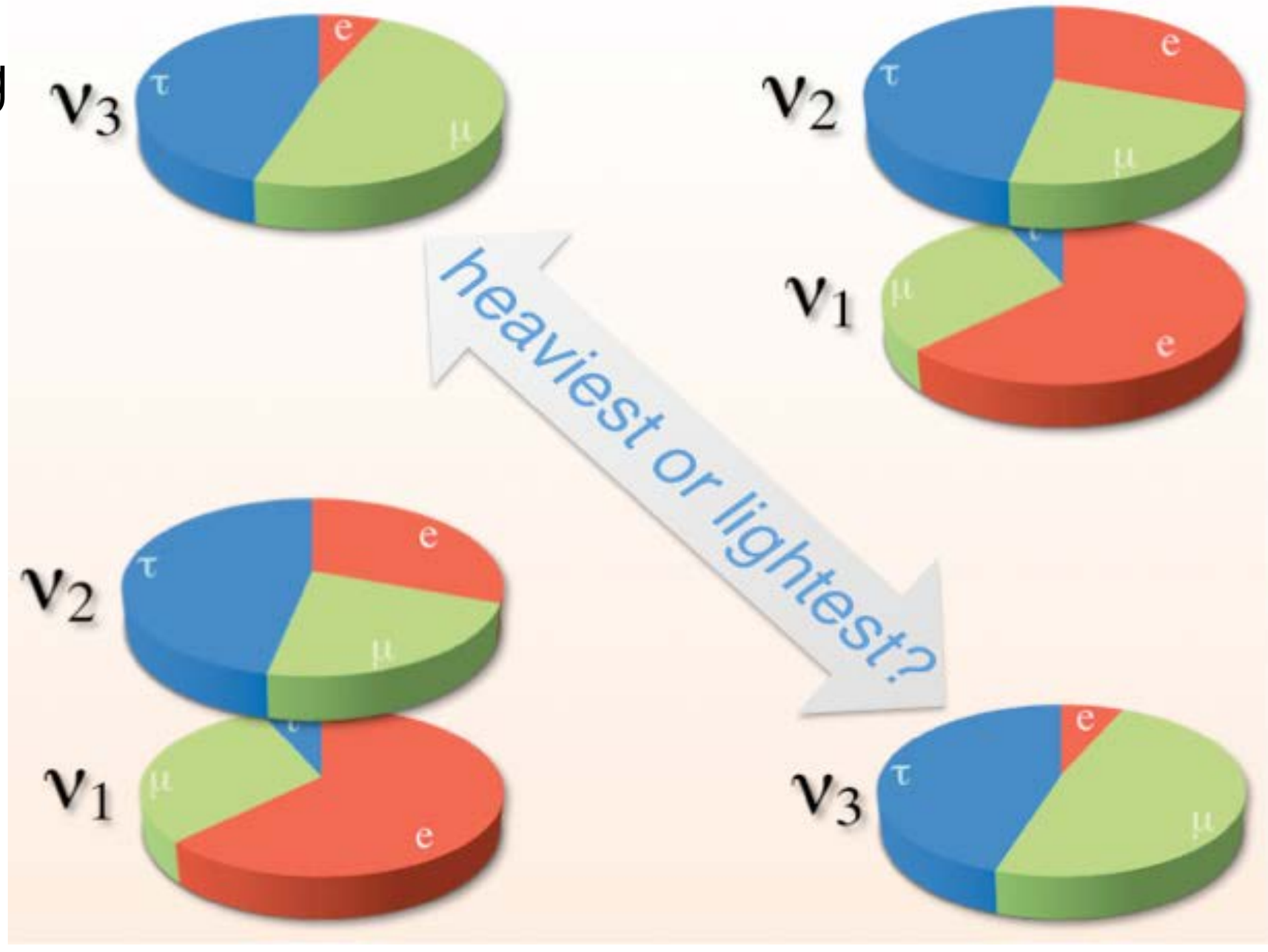
$\Delta m^2_{21} \simeq 8 \times 10^{-5}\ \mathrm{eV}^2$

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

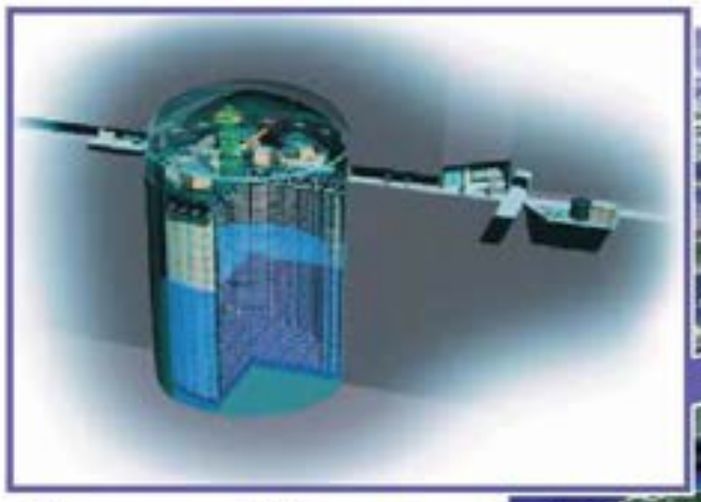
solar and reactor

Next Questions In Neutrino Physics

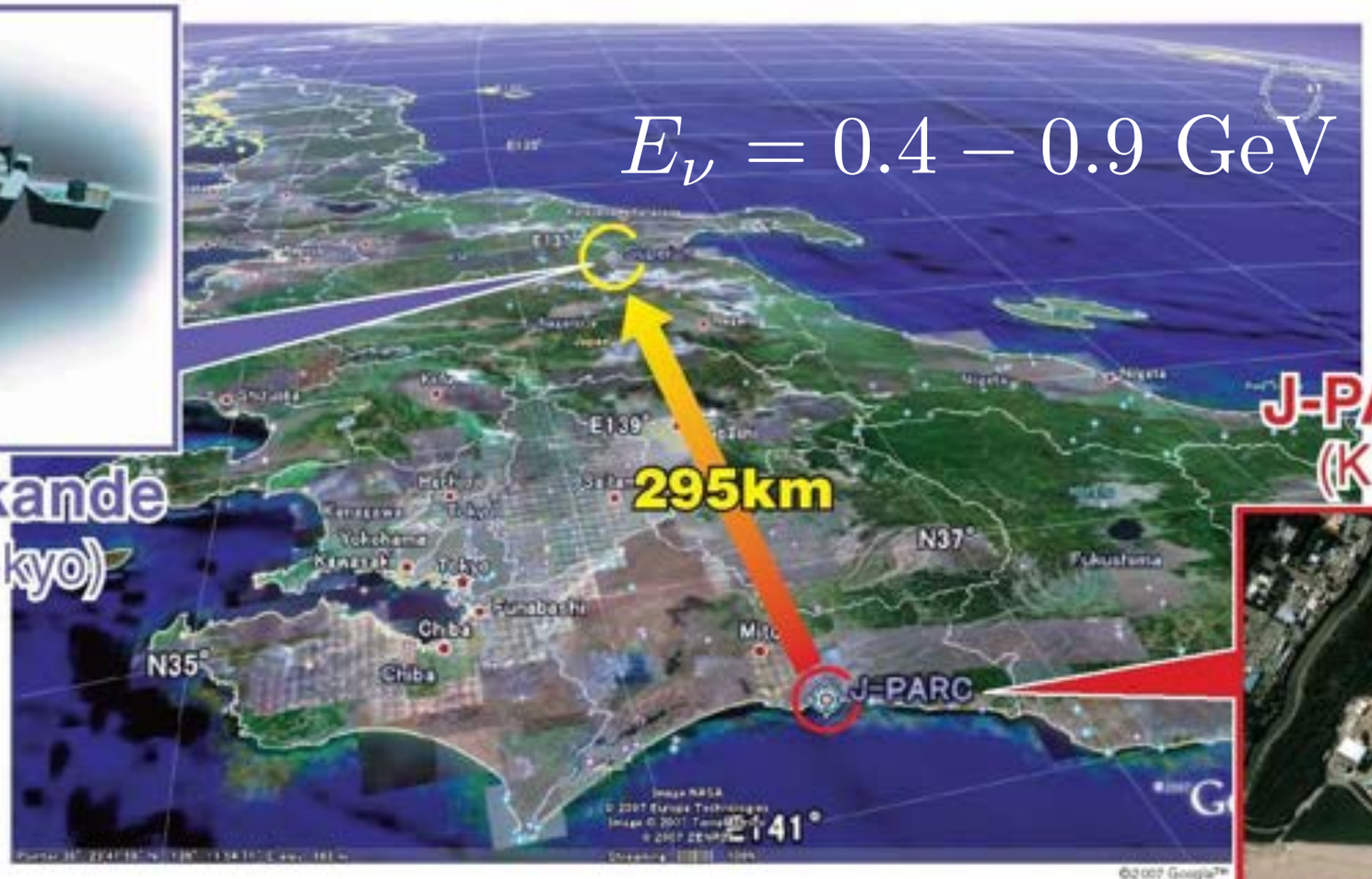
- Mass ordering
- Nature of ν_3 "θ_{23} octant"
- Is CP violated?
- Is there more to this picture?



T2K Experiment



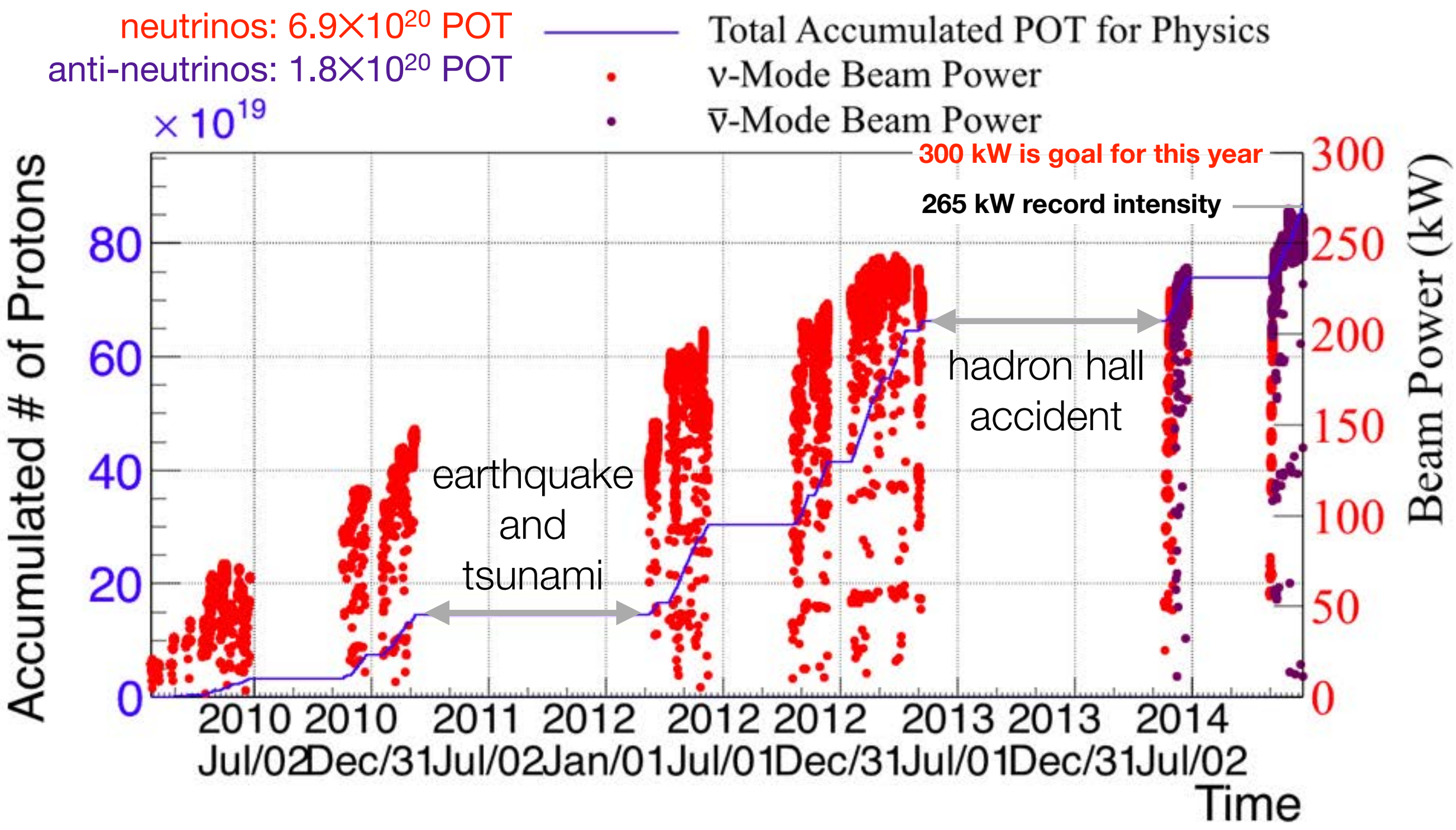
Super-Kamiokande
(ICRR, Univ. Tokyo)

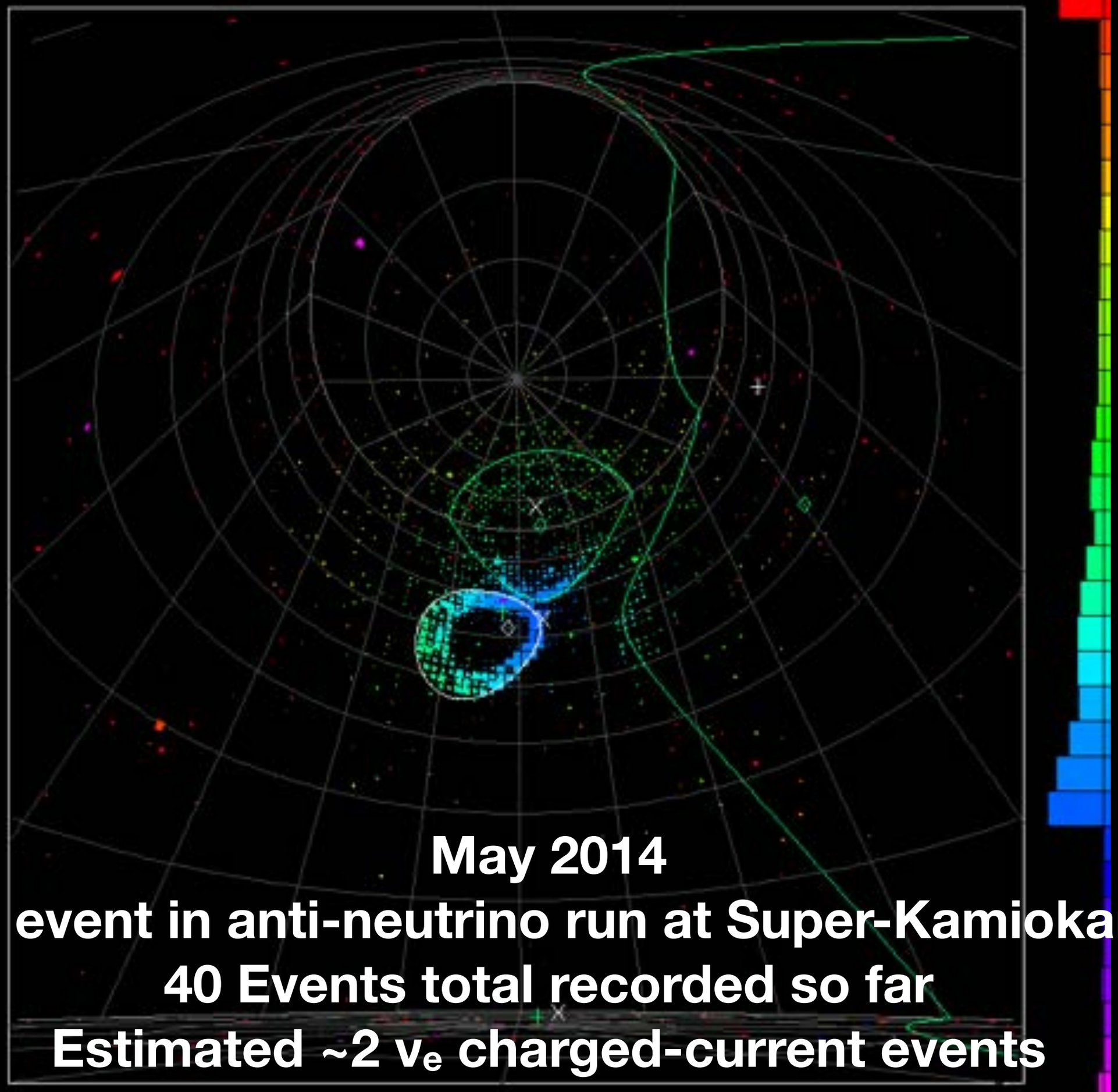


J-PARC Main Ring
(KEK-JAEA, Tokai)

T2K Beam Delivery

Total: 8.7×10^{20} POT
neutrinos: 6.9×10^{20} POT
anti-neutrinos: 1.8×10^{20} POT





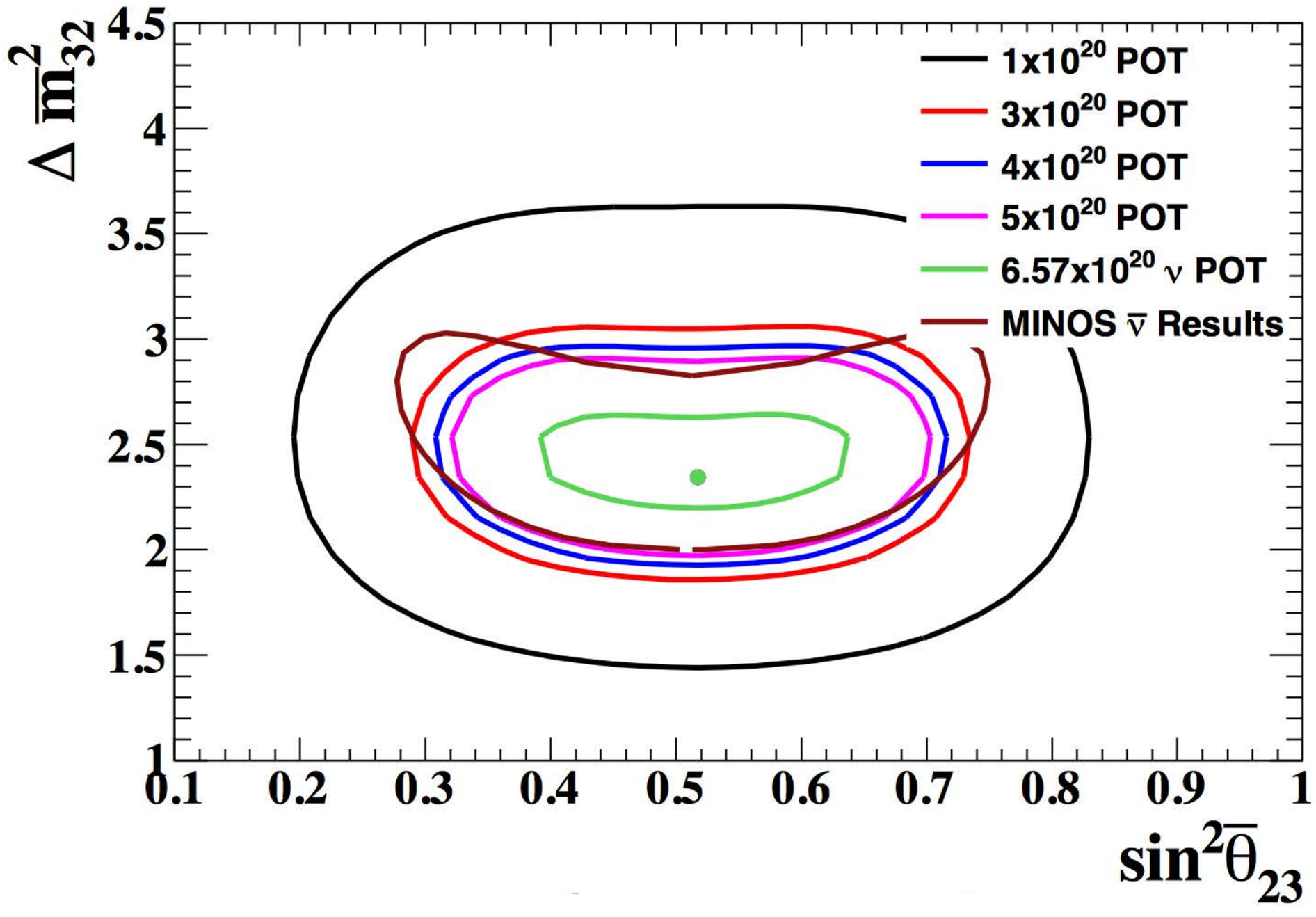
May 2014

First event in anti-neutrino run at Super-Kamiokande

40 Events total recorded so far

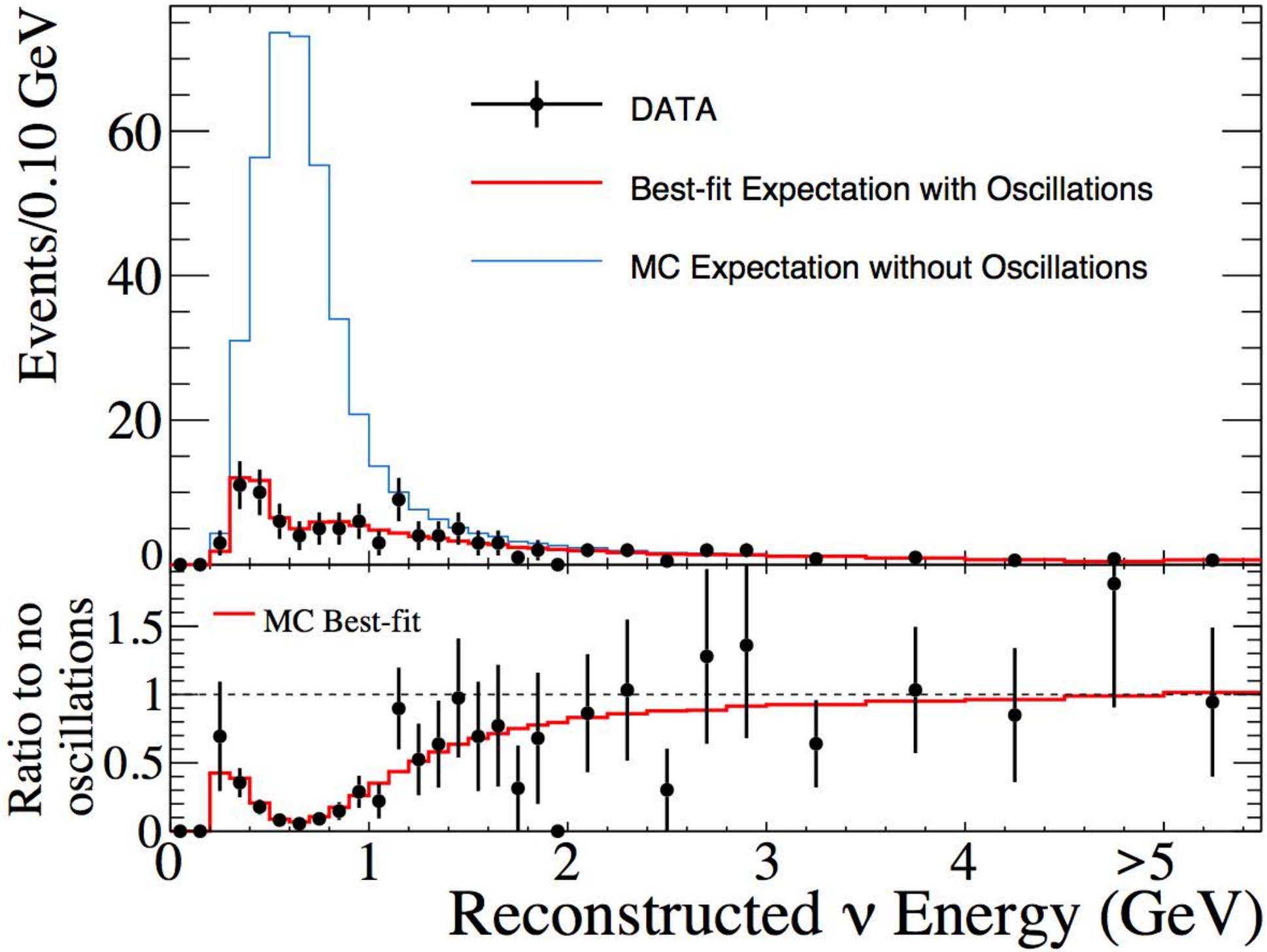
Estimated ~2 ν_e charged-current events

T2K
$\bar{\nu}_\mu$ charged-current sensitivity

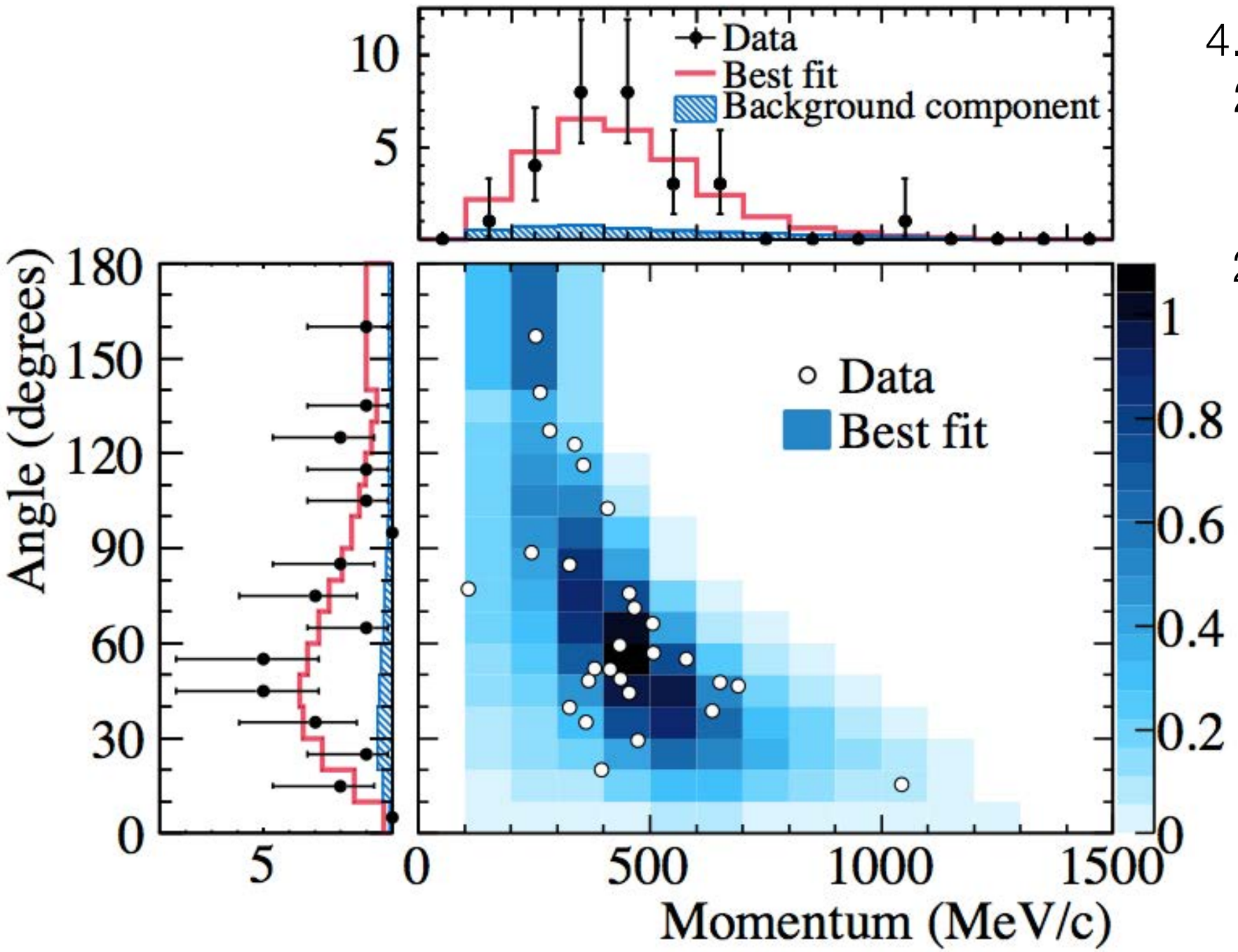


T2K will catch up to MINOS at ~3e20 POT

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

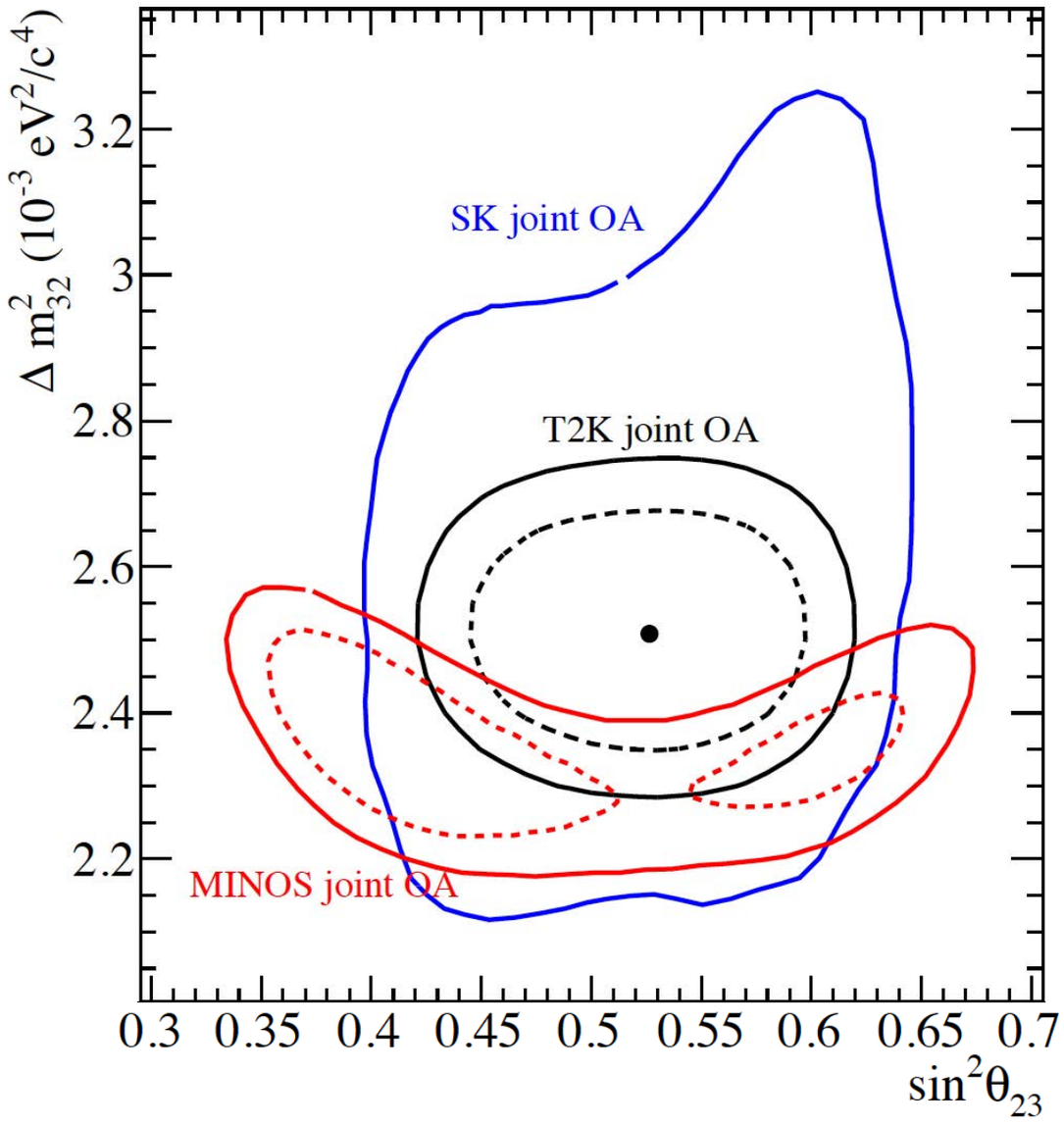
$\sin^2 2\theta_{13}=0.1$

$\delta_{CP} = 0$

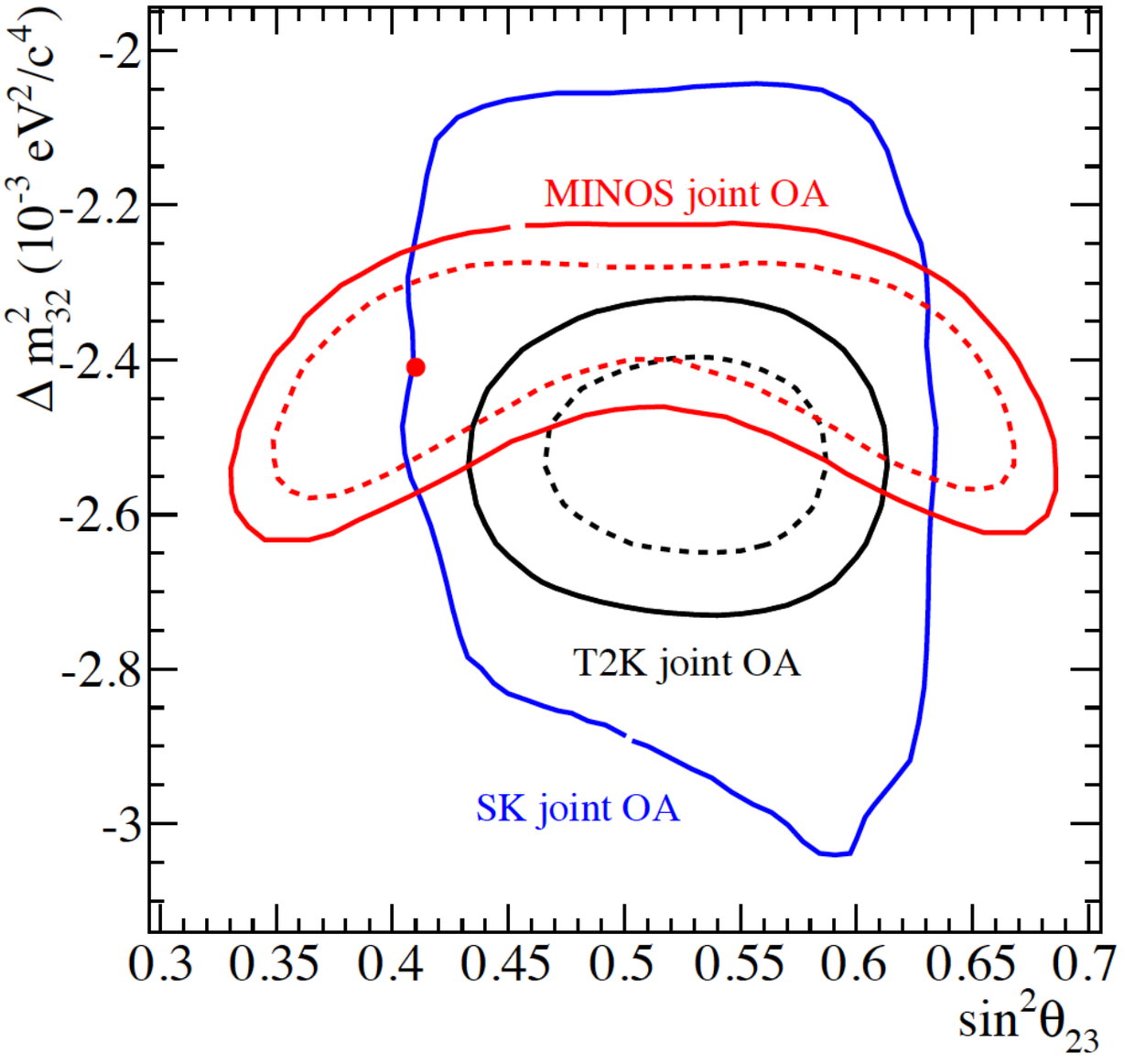
$\sin^2\theta_{23} = 0.5$

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

Normal Mass Ordering



Inverted Mass Ordering



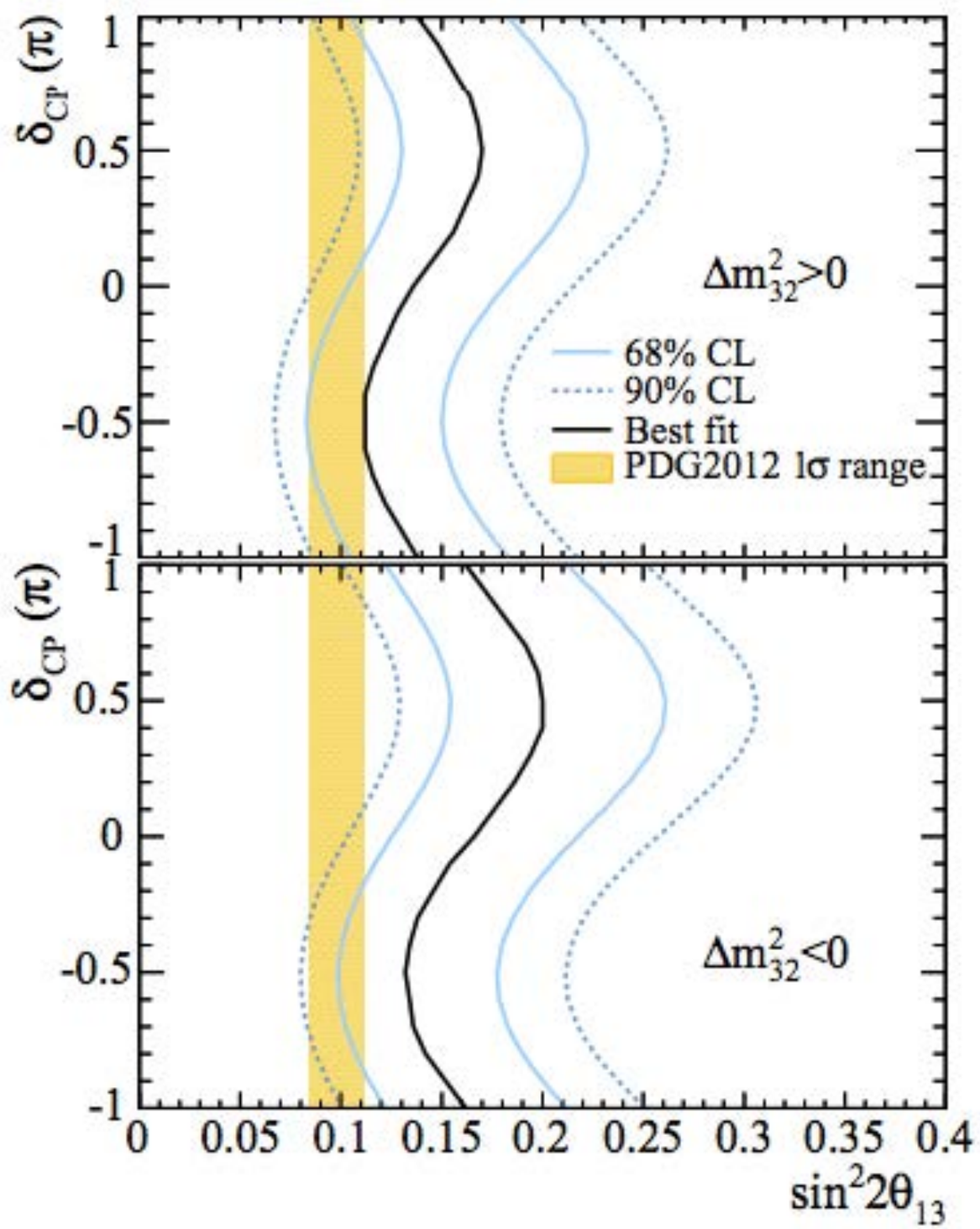
Normal hierarchy: $\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$

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 $\sin^2\theta_{23}=0.5$, $\delta_{CP}=0$, and normal hierarchy (top), and inverted hierarchy (bottom)

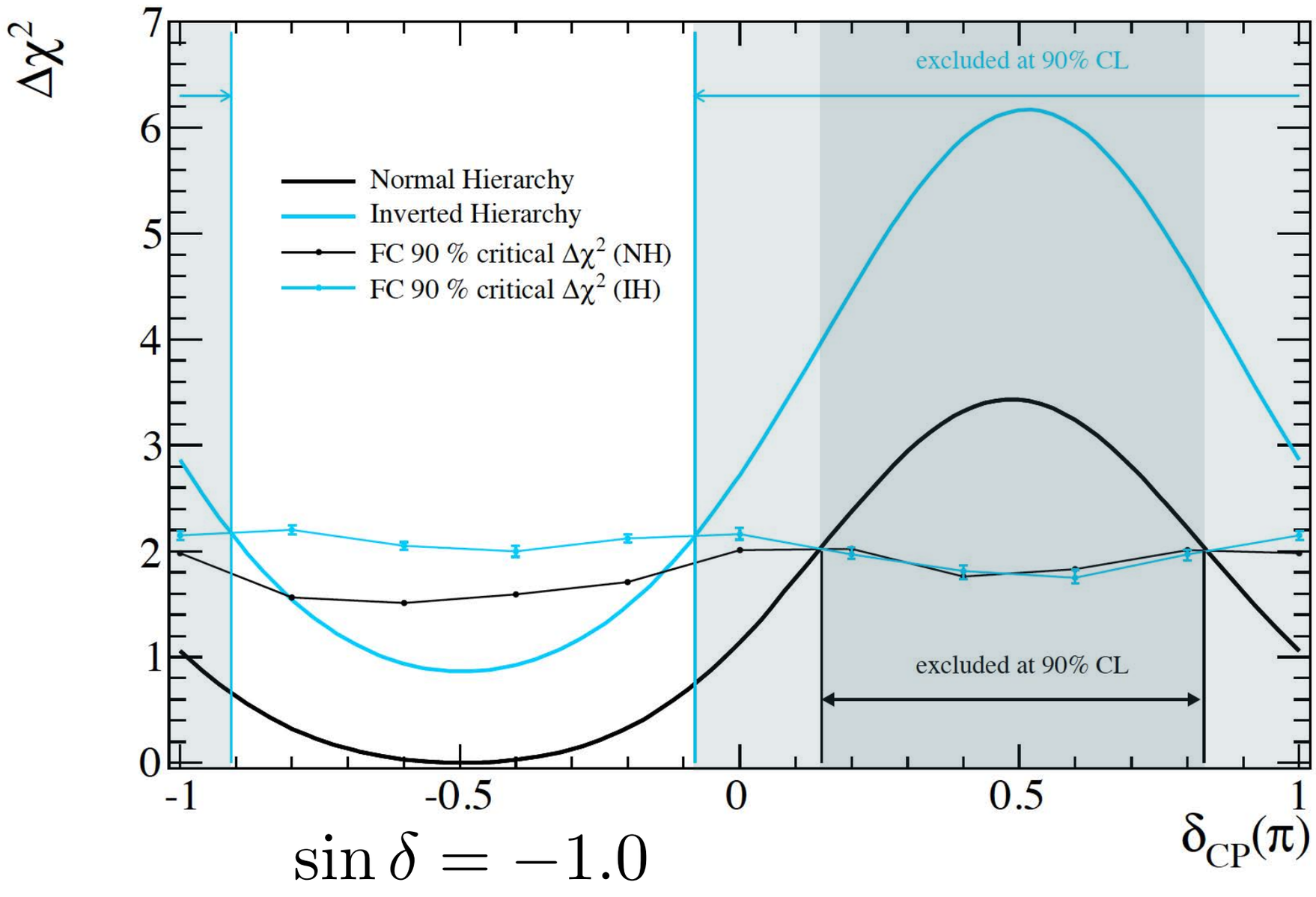


Consistent at 90% CL (1.6σ)

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

- normal hierarchy
- $\theta_{23}>45^o$
- $\delta_{CP}=-\pi/2$ (aka $3\pi/2$)

Combining T2K with Reactors



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.

Note: This goes in opposite direction from MINOS global fit which has slight preference for inverted hierarchy and $\theta_{23}<45^o$

Fermilab NuMI Beam

NOvA

$L = 810$ km

$E_\nu = 1.8 - 2.5$ GeV

MINOS and MINOS+

$L = 735$ km

$E_\nu = 2 - 5$ GeV

$E_\nu = 4 - 9$ GeV

NOvA Far Detector

MINOS Far Detector

Minnesota

Wisconsin

Ontario

Milwaukee

Fermilab

Chicago

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]%
θ23 octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

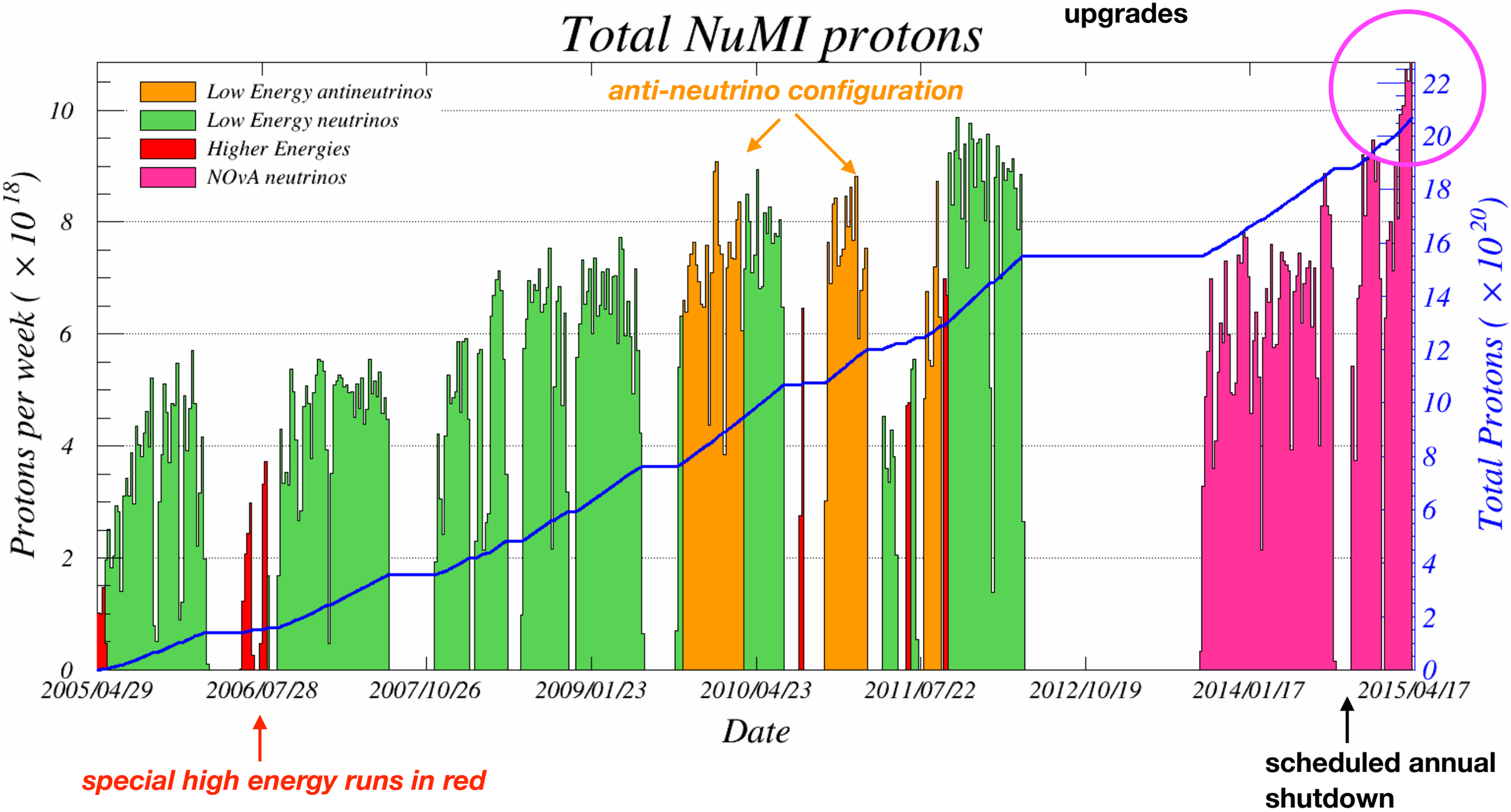
Nota bene:

- 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 ±2σ range found by a recent global fit (PRD 90, 093006)

MINOS

NOvA

shutdown for NOvA intensity upgrades



NuMI has reached a peak of 453 kW operation

Routinely running at 400 - 410 kW

Excellent efficiency: 87% in NOvA era compared to 64% during MINOS era

Getting NuMI to 700 kW

700 kW requires:

✅ 1.33 s second ramp time

✅ Slip-stacking in recycler ring

☐ **12 Booster batches in recycler.**

Currently circulating 8 batches

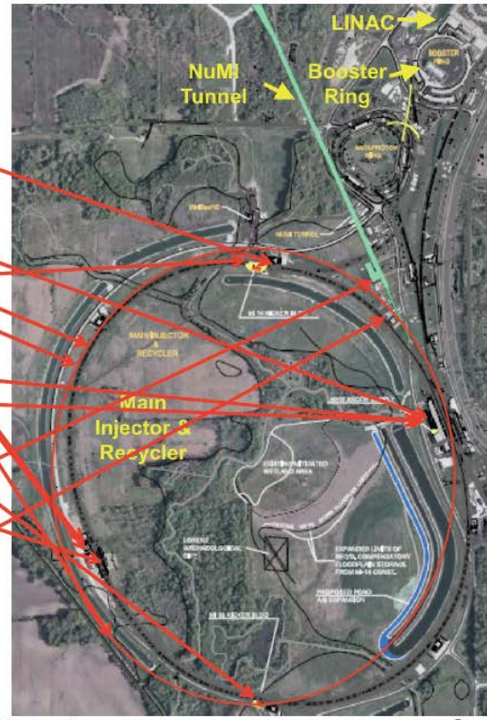
☐ **9 Hz operation of Booster ring**.

Currently at 7.5 Hz. Cavity refurbishment continues. Could have enough cavities for 15 Hz operation of Booster summer 2015

Taken together NuMI should reach 700 kW in another year. On track to deliver 3e20 POT this year.

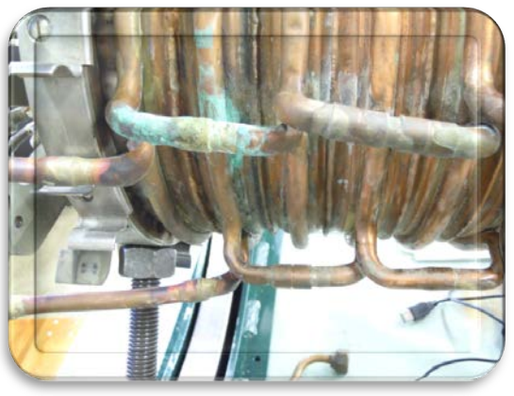
Accelerator and NuMI Upgrades

- Recycler Ring, RR (WBS x.0.1)
  - New injection line into RR
  - New extraction line from RR
  - New 53 MHz RF system
  - Instrumentation Upgrades
  - New abort kickers
  - Decommissioning of pbar components
- Main Injector (WBS x.0.2)
  - Two 53 MHz cavities
  - Quad Power Supply Upgrade
  - Low Level RF System
- NuMI (WBS x.0.3)
  - Change to medium energy ν beam configuration (new target, horn, configuration)
  - Cooling & power supply upgrades
- Beam Physics (WBS 1.0.4 Complete)
  - Beam Simulations & Evaluation of Proton Plan

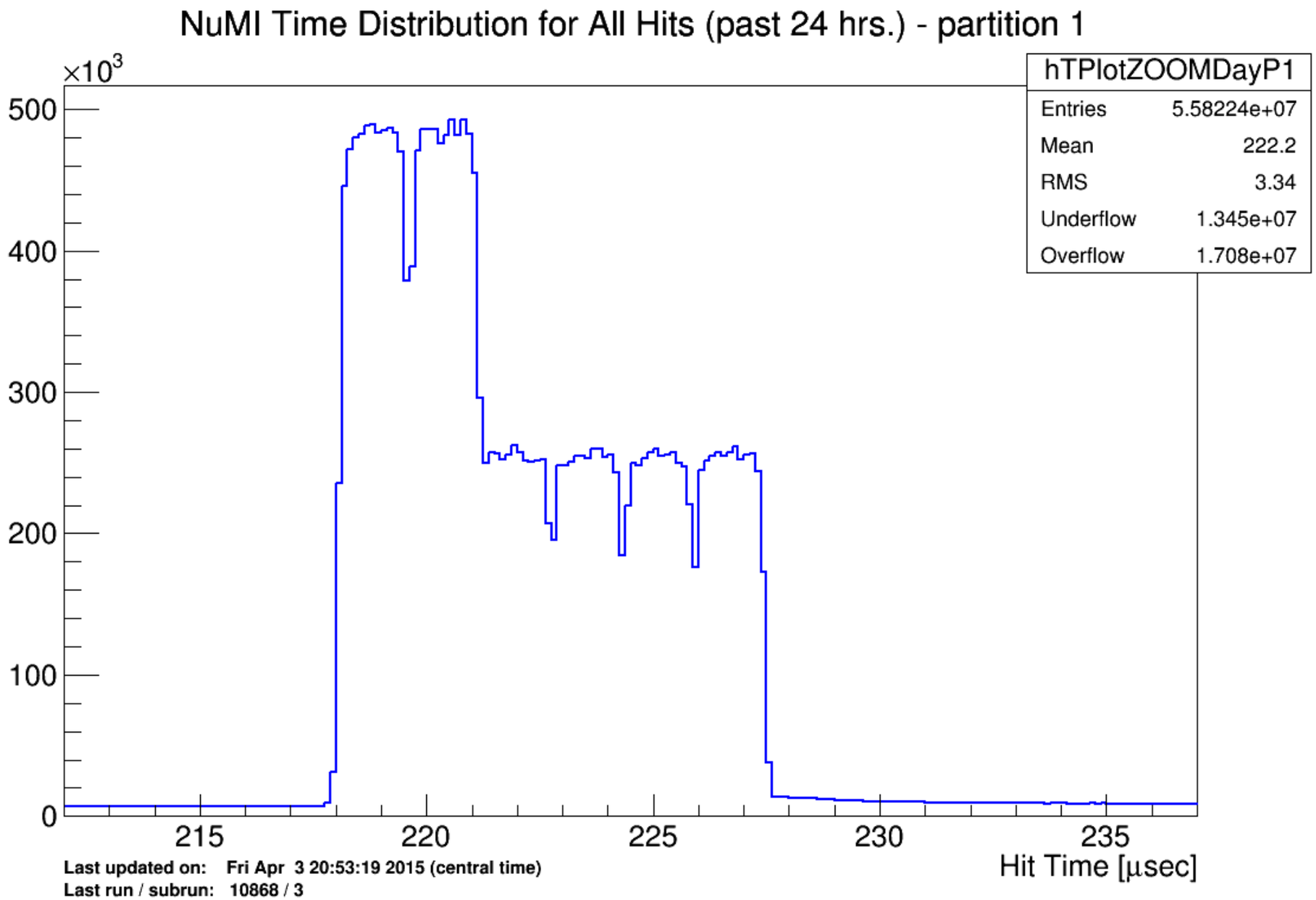


Nearly every sector of Main Injector opened during upgrades

Booster tuner “findings”

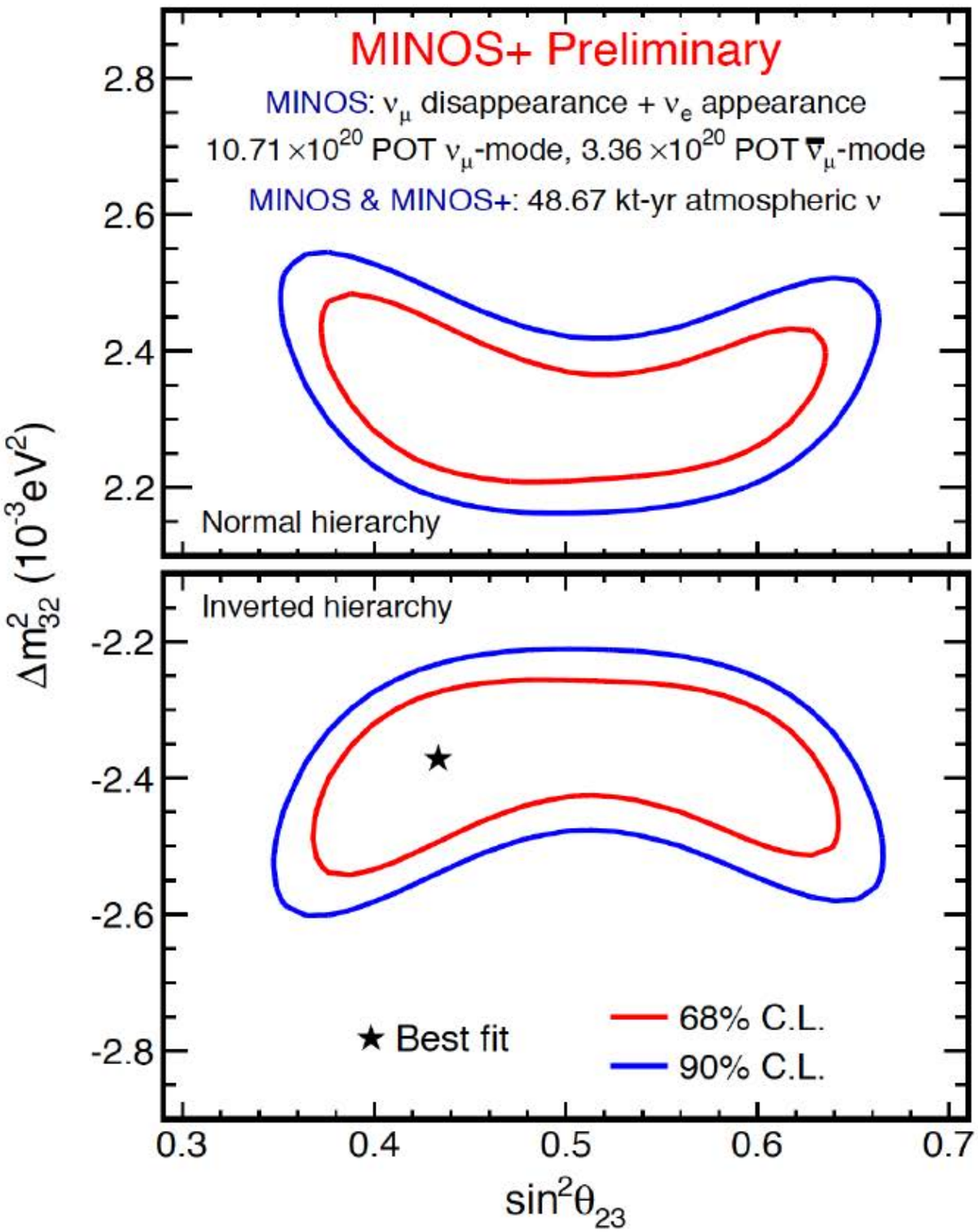


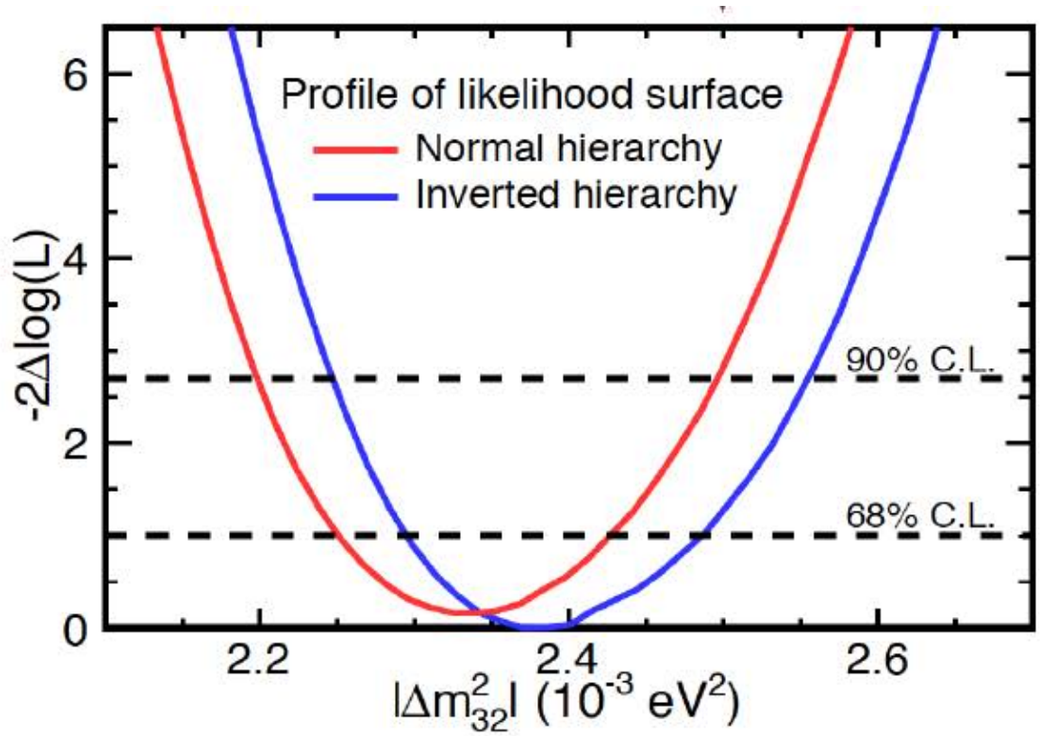
Slip stacking in the recycler ring as seen by NOvA near detector

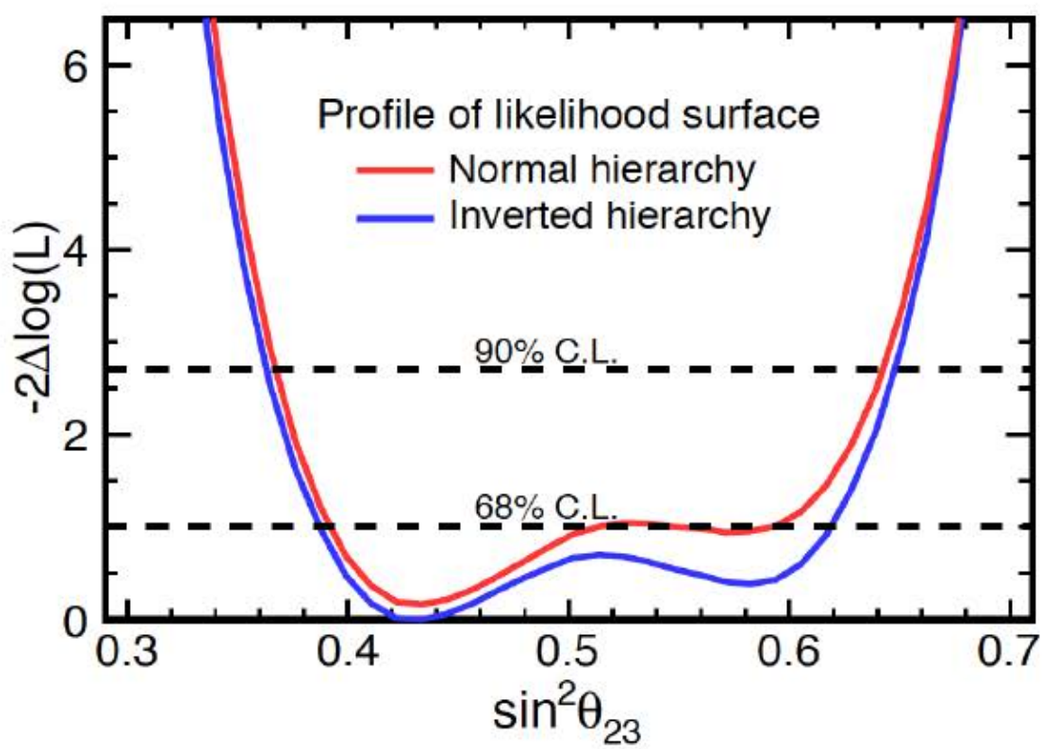


MINOS(+)

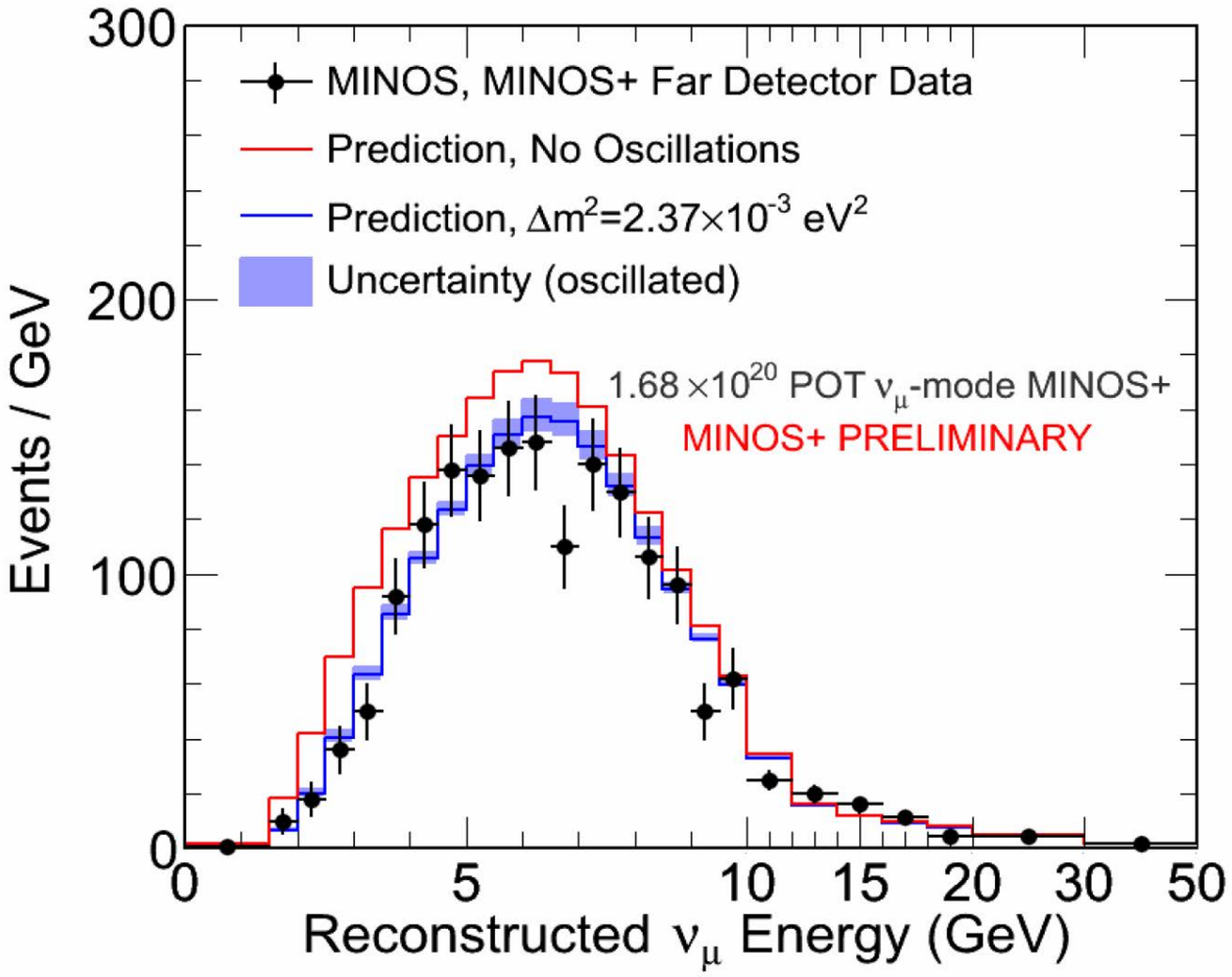
Combined fit to beam and atmospheric neutrinos



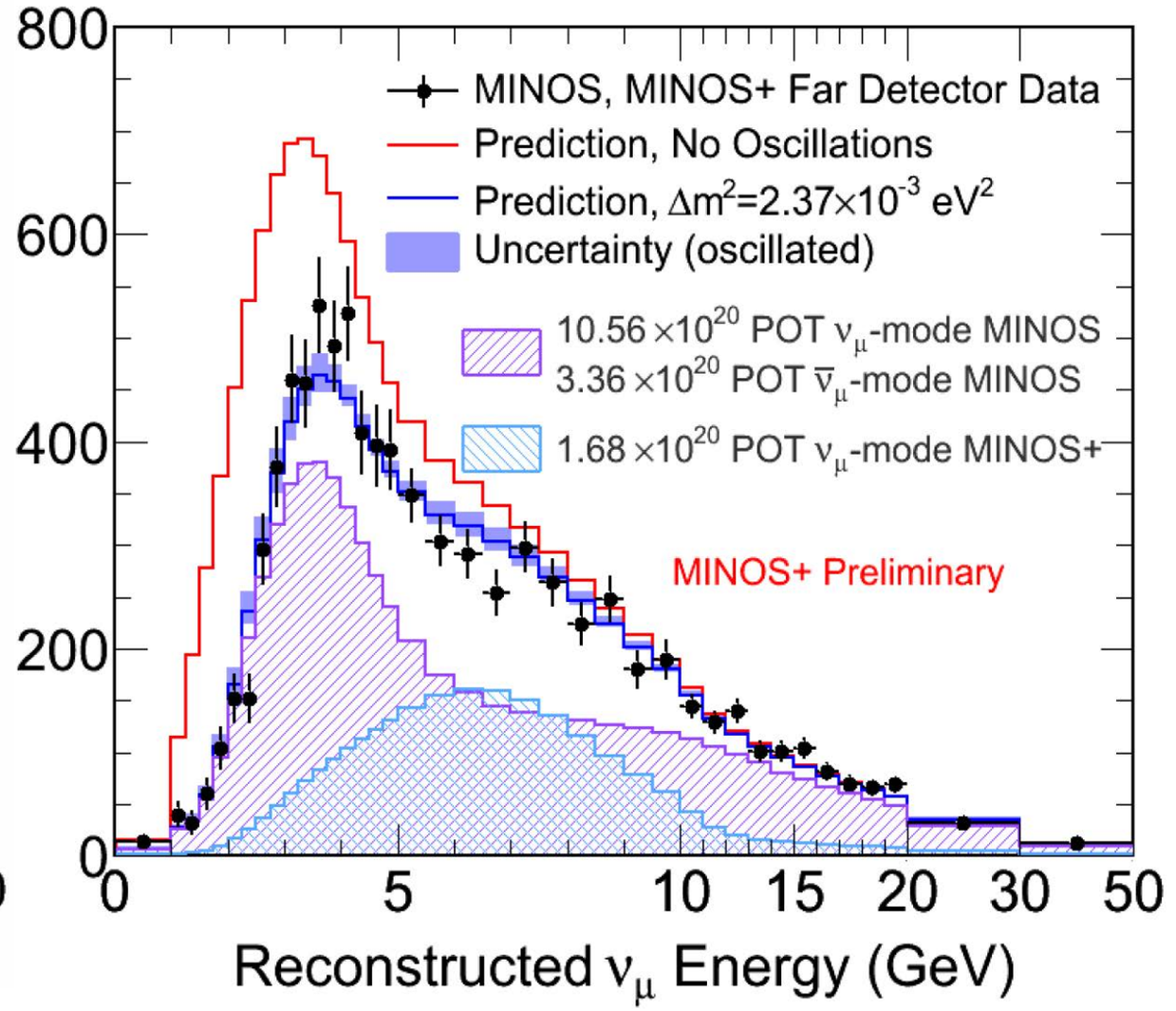




MINOS$^+$ and **MINOS/MINOS$^+$** Combination ν_μ Charged-Current Spectra at L=735 km



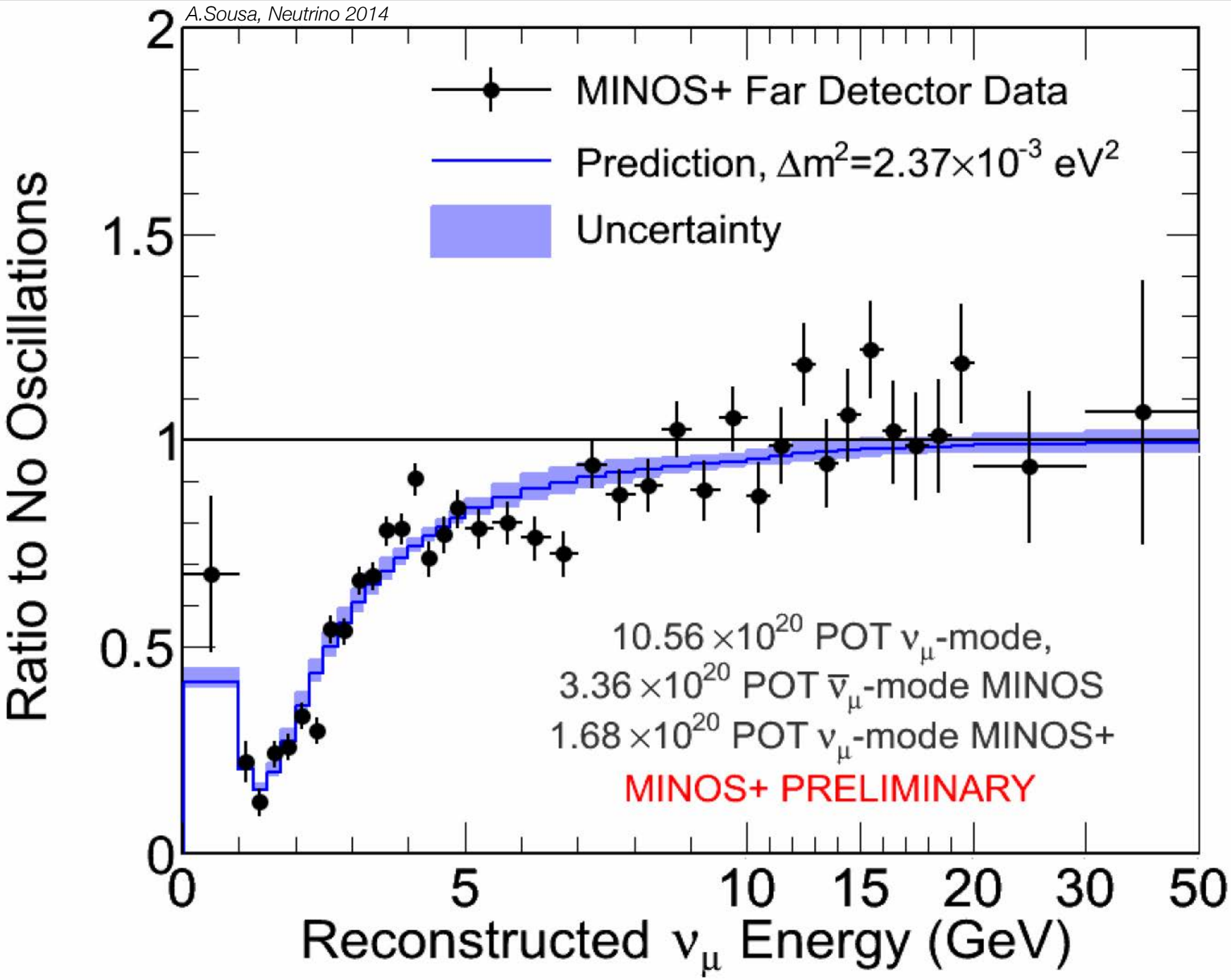
MINOS$^+$



MINOS + MINOS$^+$

Combine MINOS with MINOS+ data

$$P(\nu_\mu \to \nu_\mu) \text{ vs. } E \text{ for } L = 735 \text{ km}$$



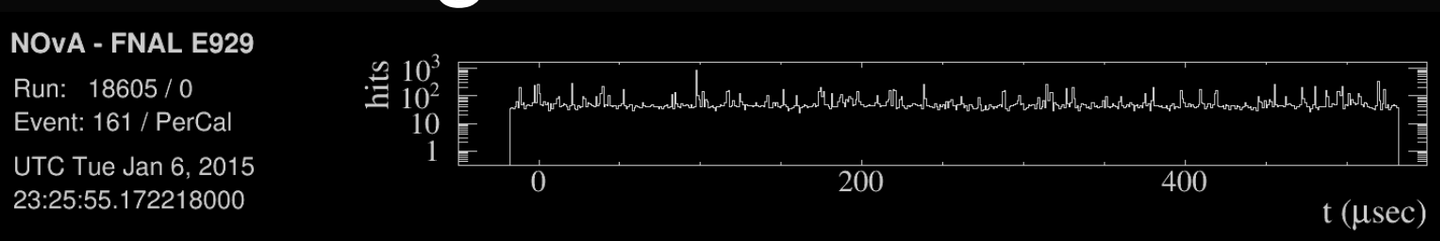
NOvA Far Detector

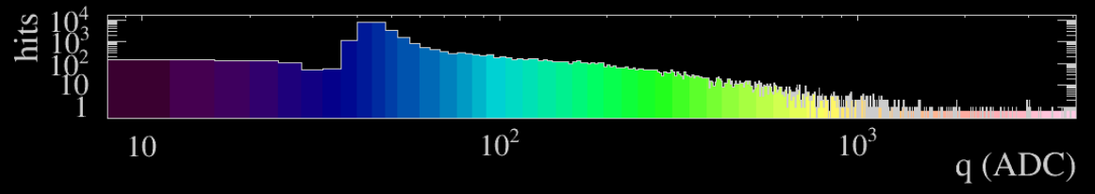
NOvA Far Detector completed in July 2014
On time, under budget!

60 m

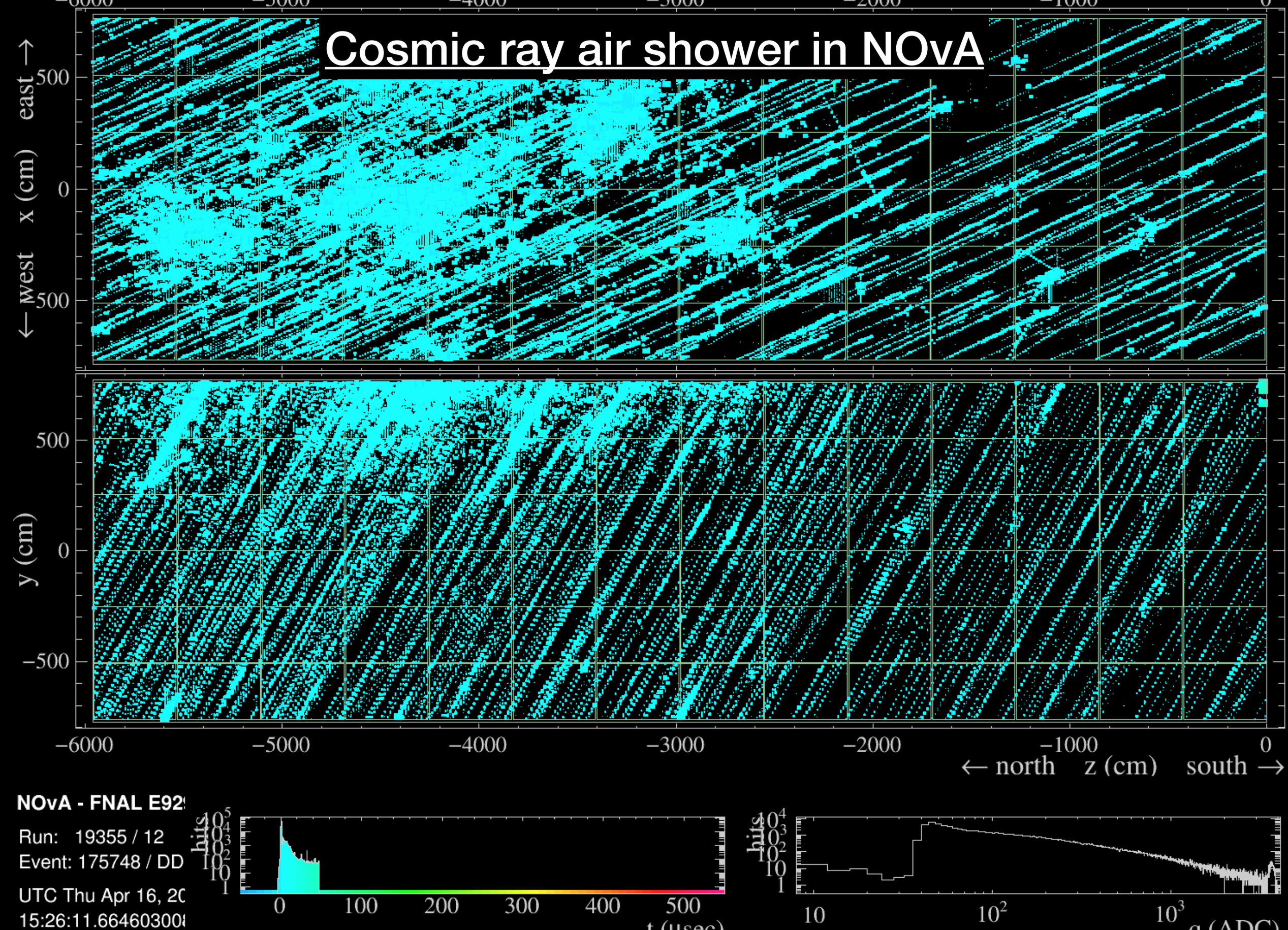
15.6 m

Running with >99% active channels and >95% uptime





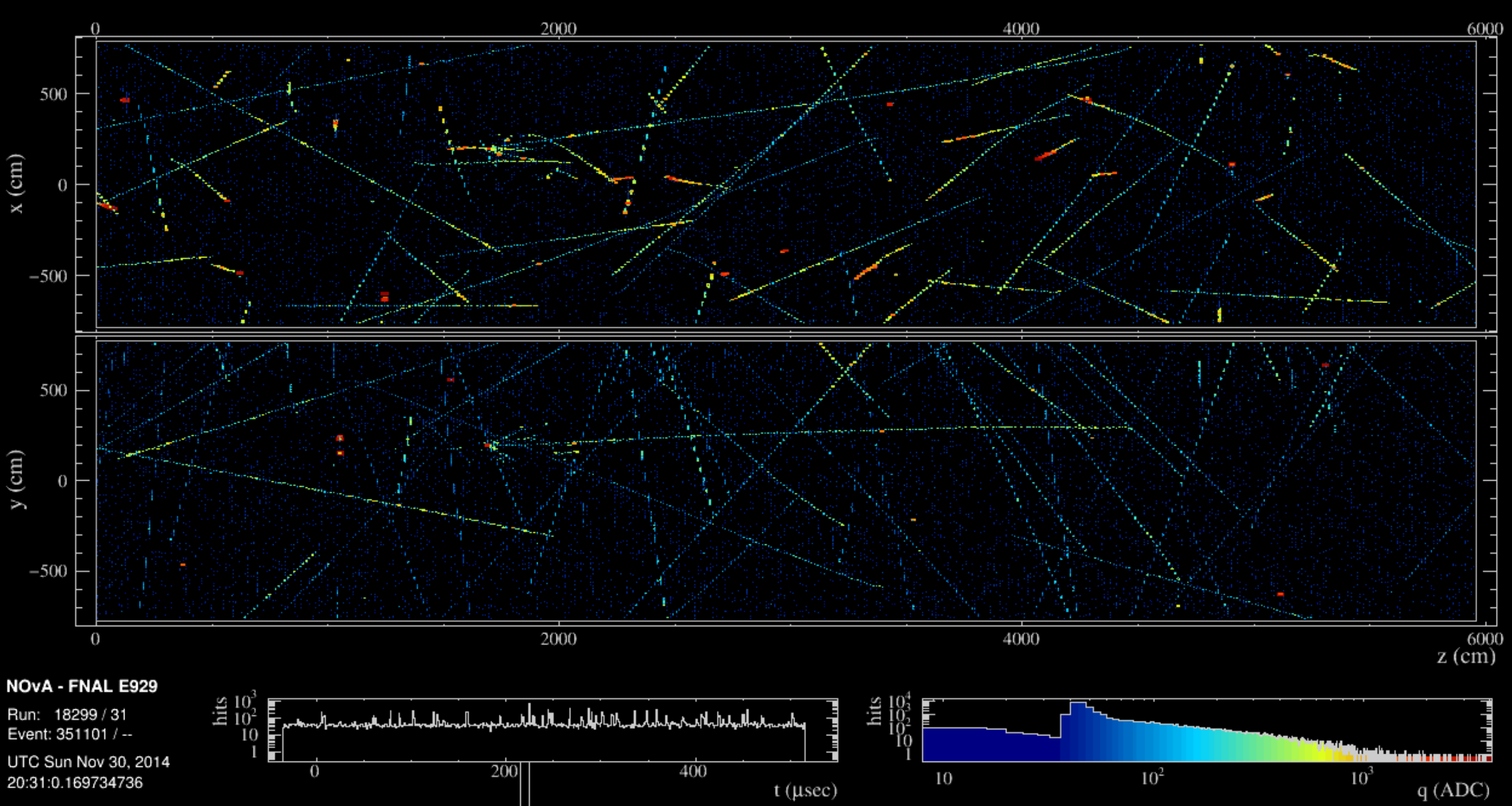
Cosmic ray air shower in NOvA



NOvA - FNAL E92

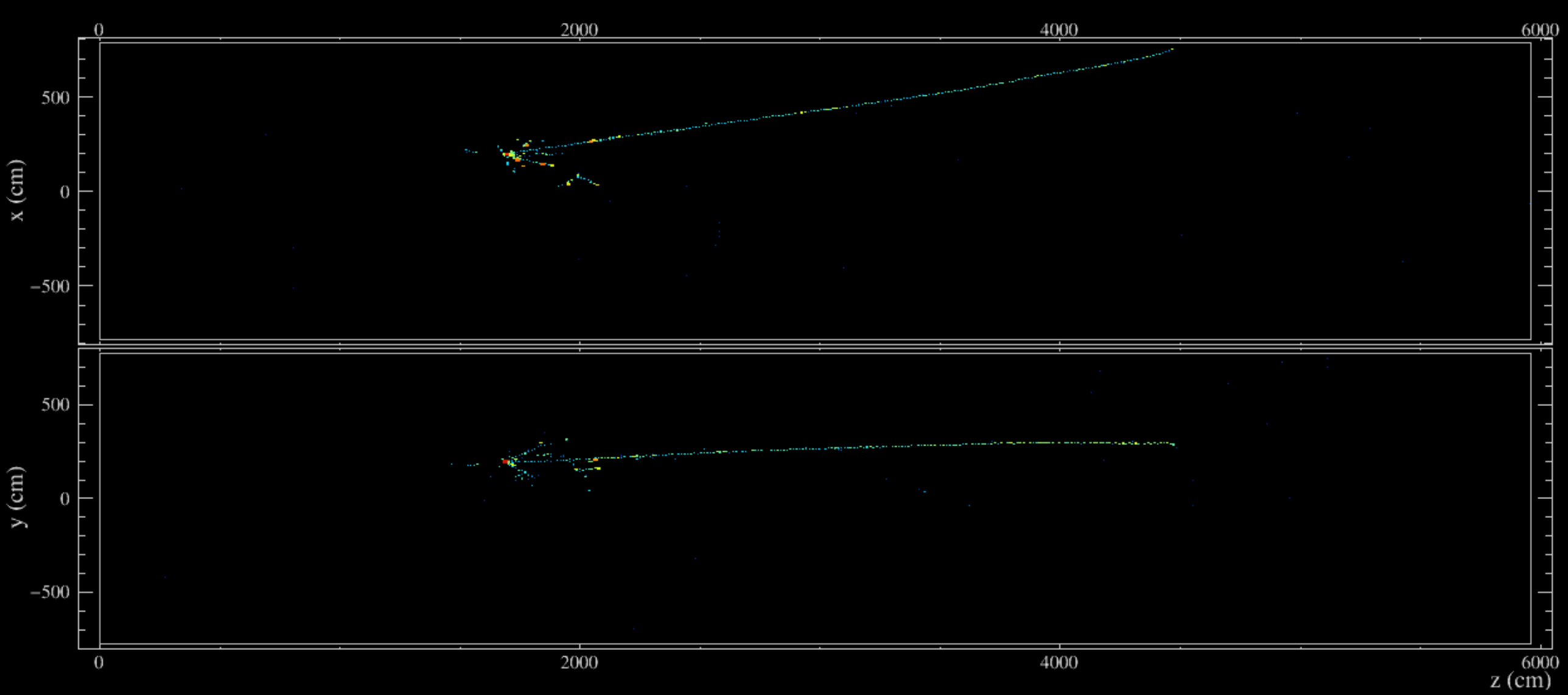
Run: 19355 / 12
Event: 175748 / DD

UTC Thu Apr 16, 2(
15:26:11.66460300(



10 μsec NuMI Time Window

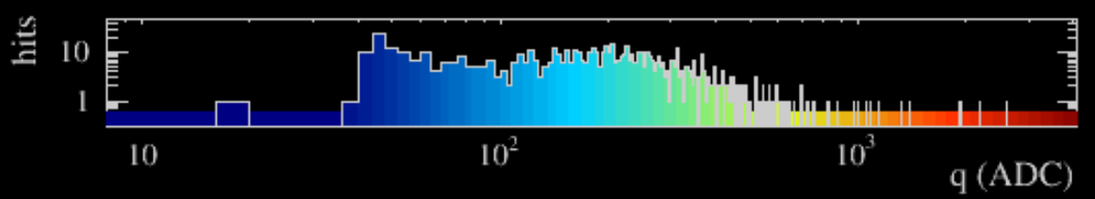
NOvA Far Detector Data



NOvA - FNAL E929

Run: 18299 / 31
Event: 351101 / --

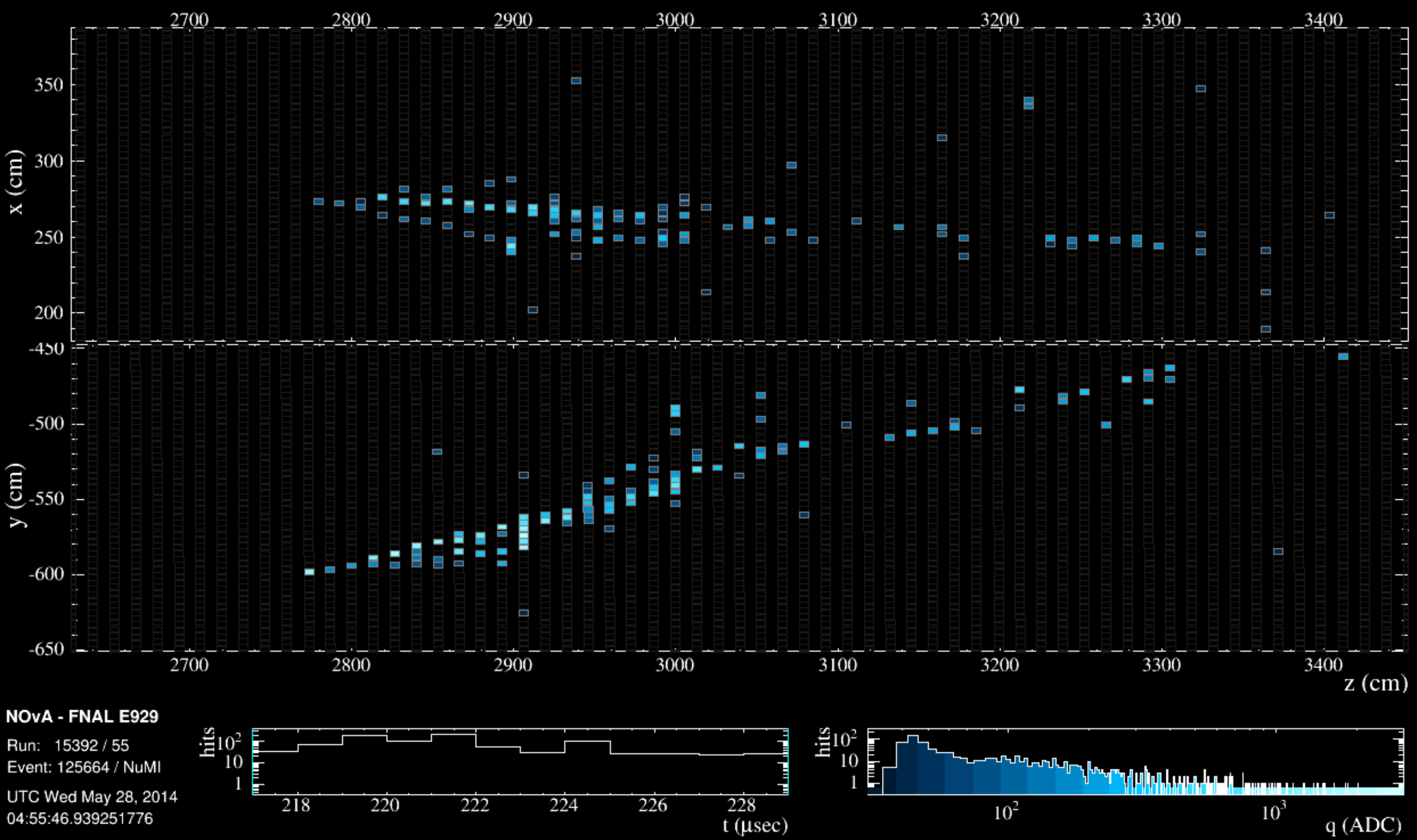
UTC Sun Nov 30, 2014
20:31:0.169734736



neutrino event raw time window

Neutrinos detected in NOvA operating on the surface

NOvA ν_e* Charged-current candidate



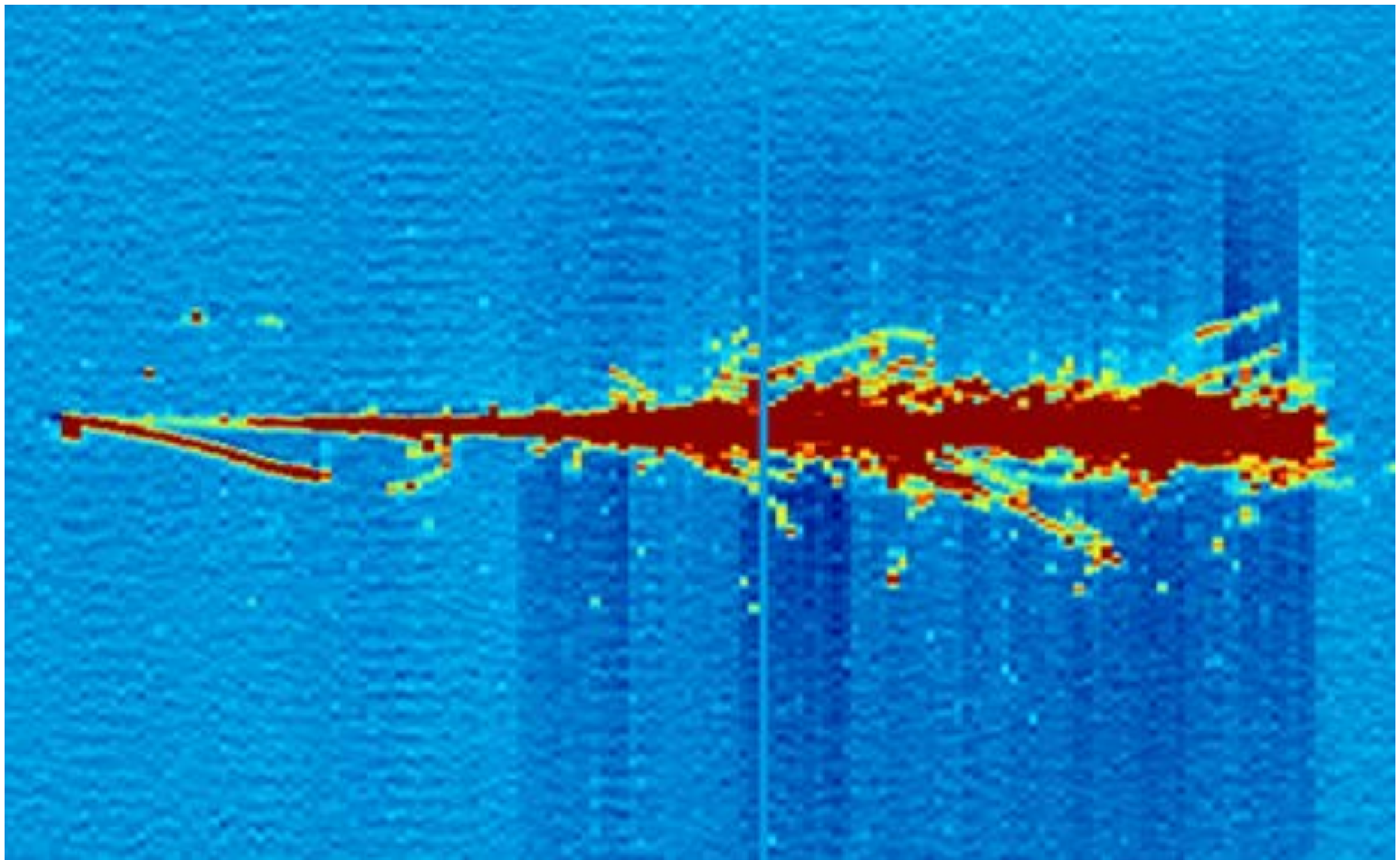
NOvA - FNAL E929

Run: 15392 / 55
Event: 125664 / NuMI

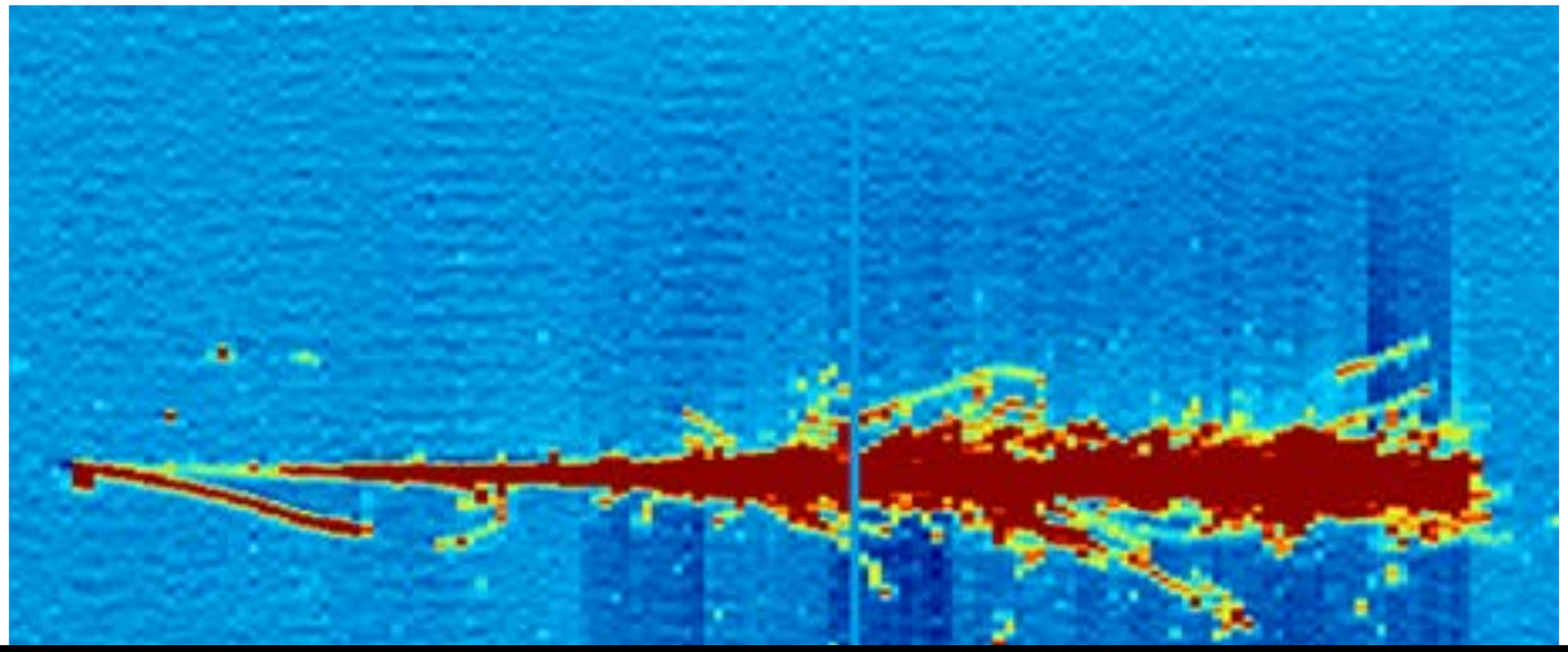
UTC Wed May 28, 2014
04:55:46.939251776

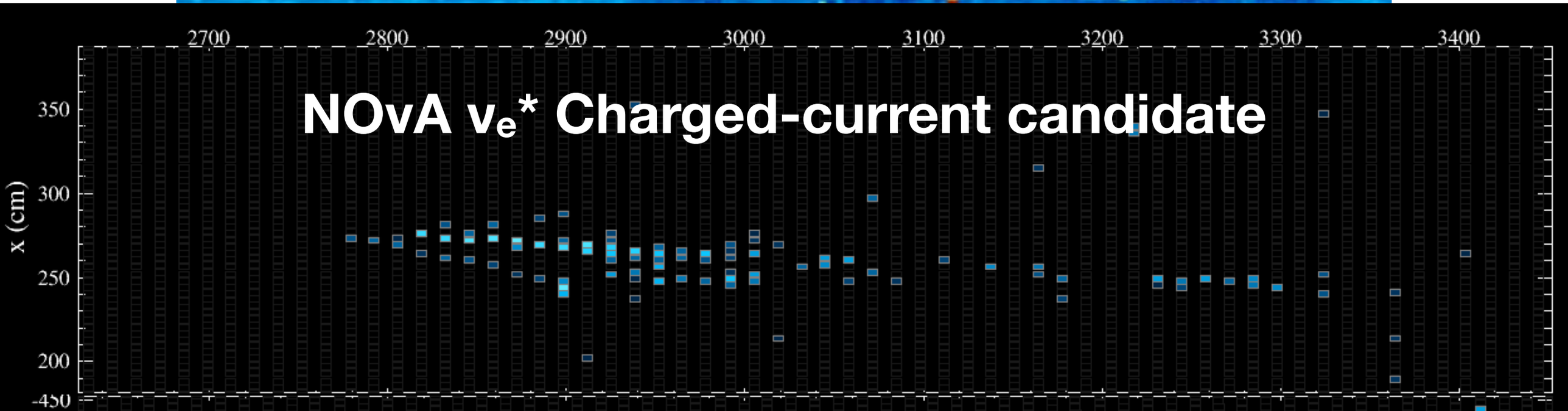
* particle IDs blinded until analysis finalized

ArgoNeuT ν_e Charged-current candidate



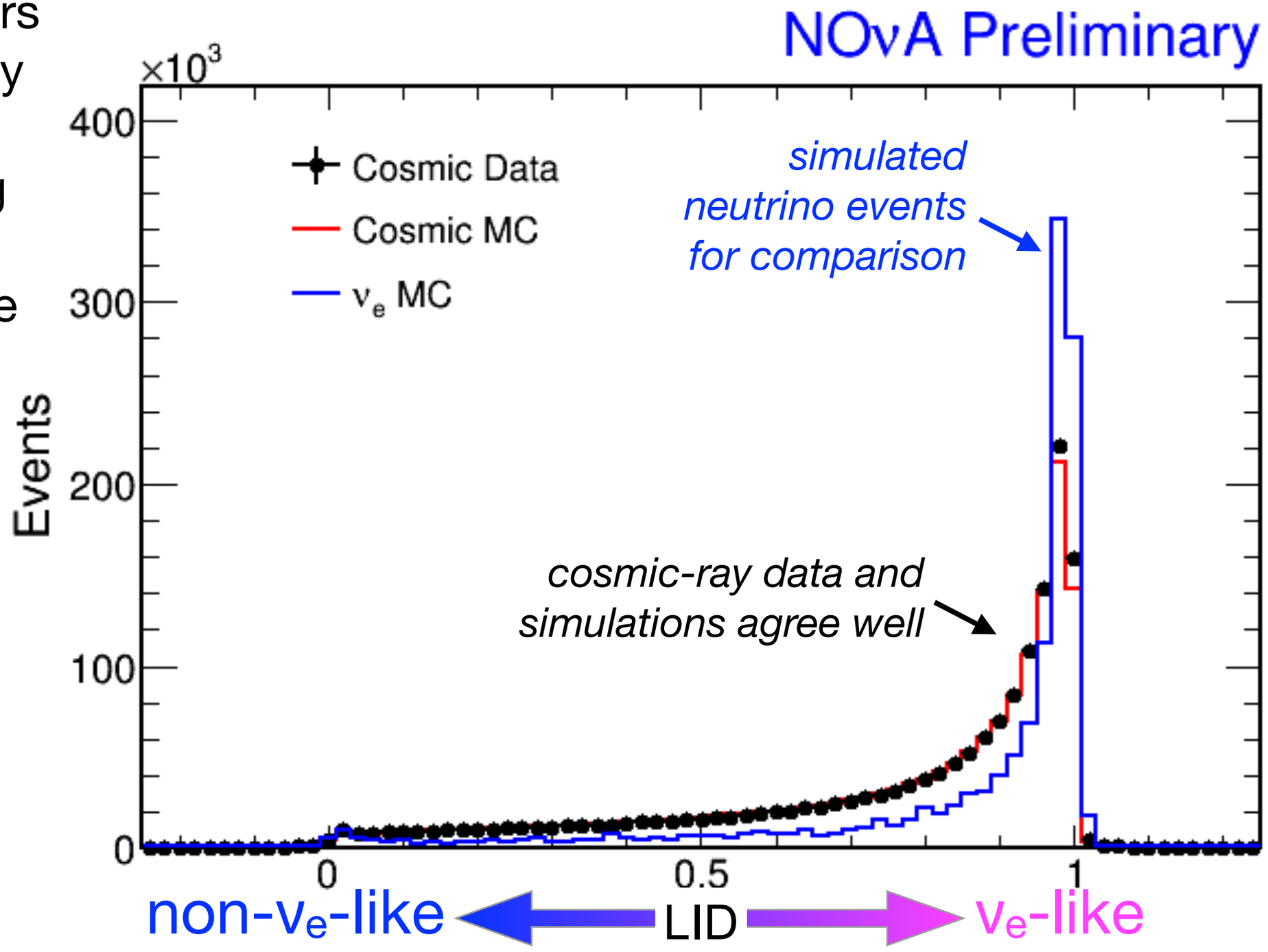
ArgoNeuT ν_e Charged-current candidate



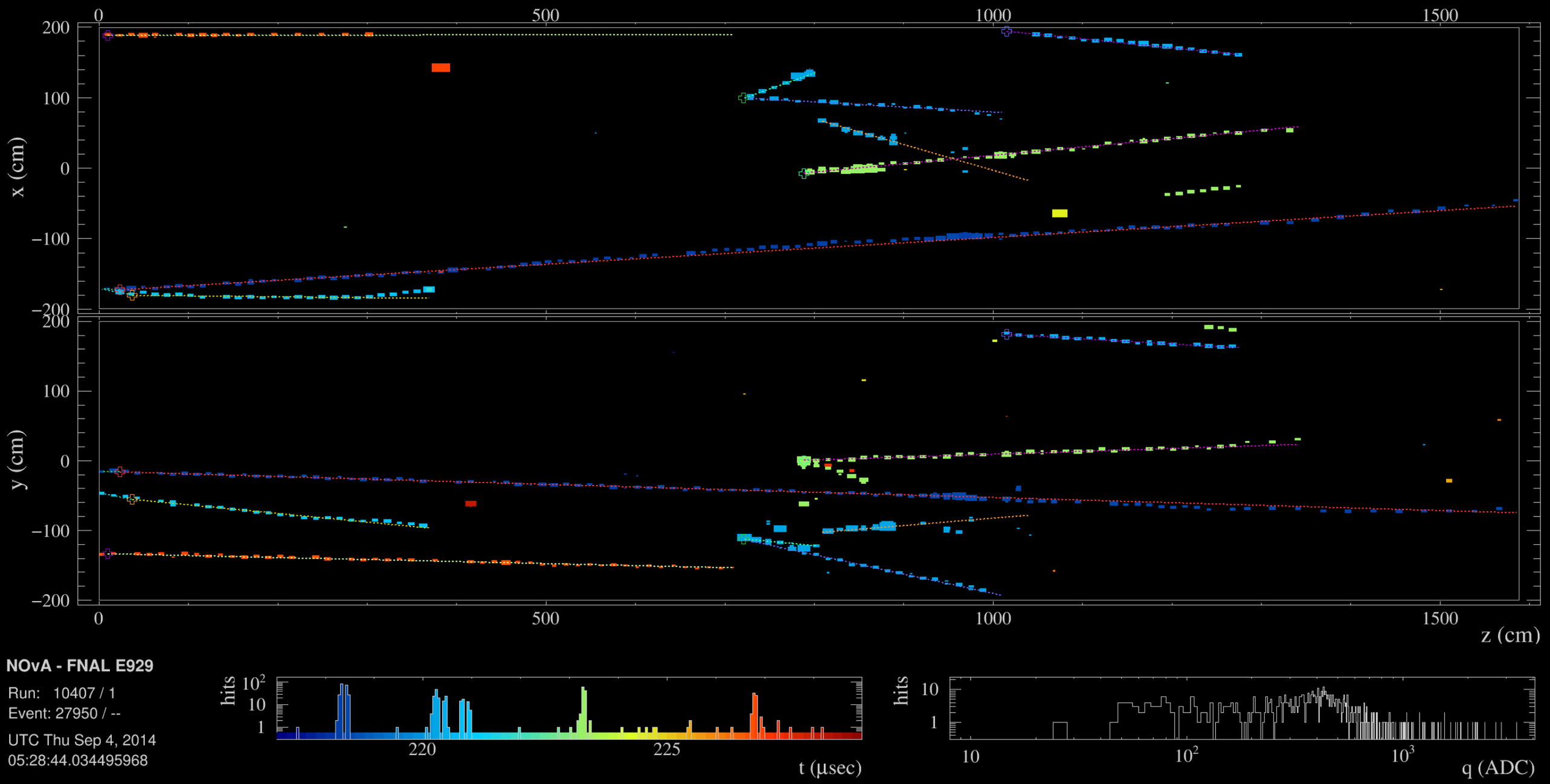


NOvA: Particle ID at Far detector

Using real electron showers from cosmic-ray muons bremsstrahlung to tune up electron particle ID at the far detector

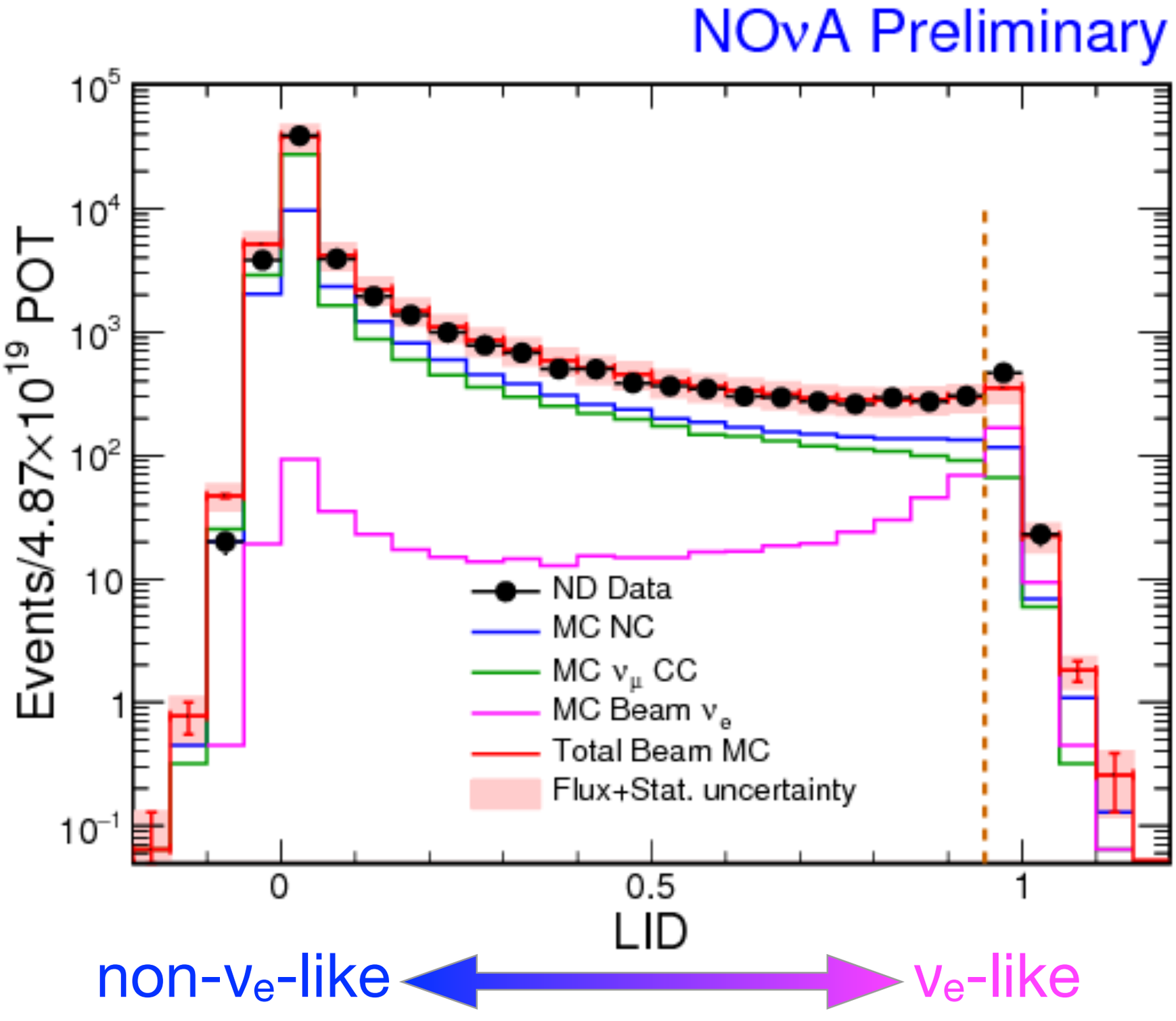


Near Detector Event Display

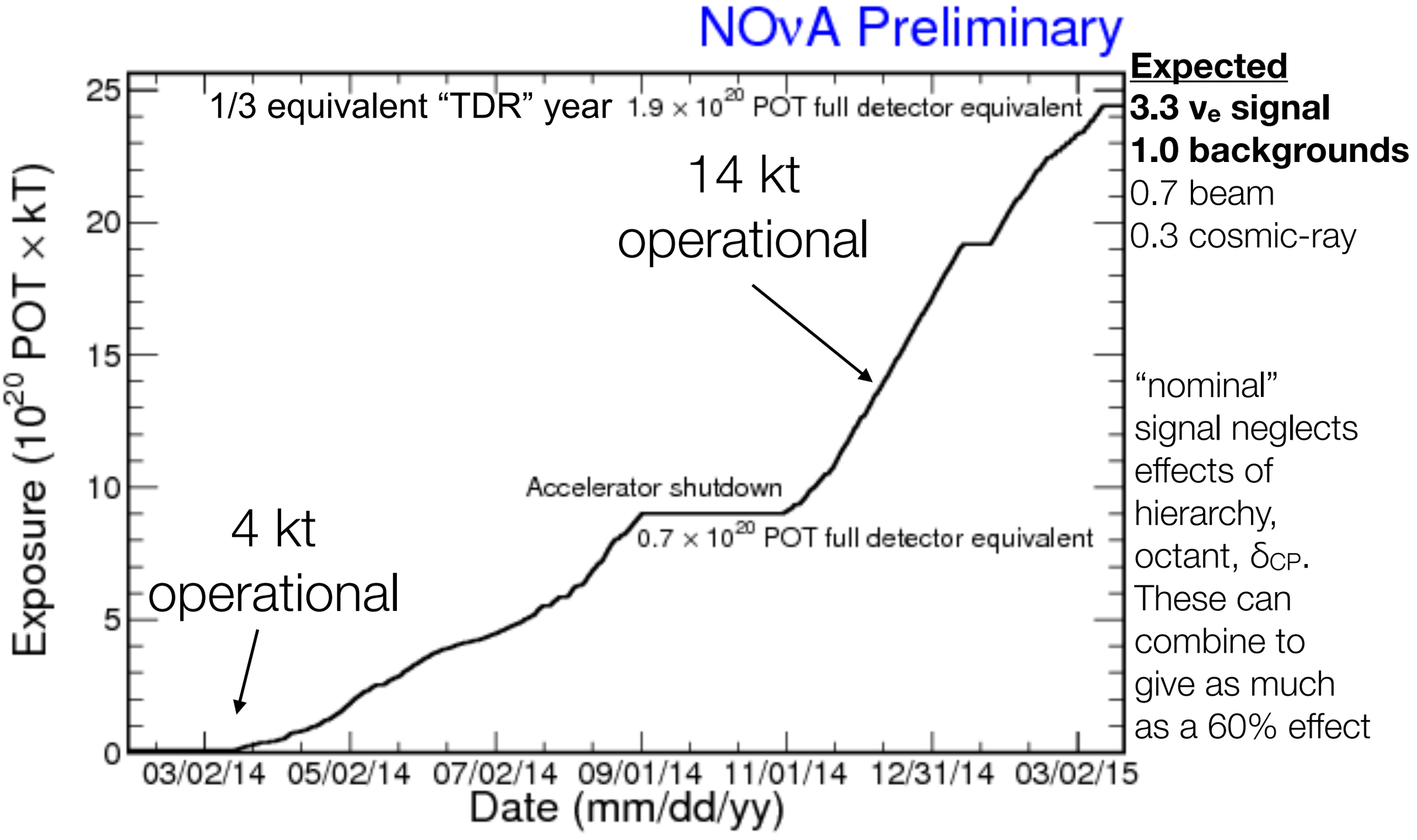


Colors show time
reconstructed tracks and vertices superimposed

NOvA:
Particle Identification in Near Detector

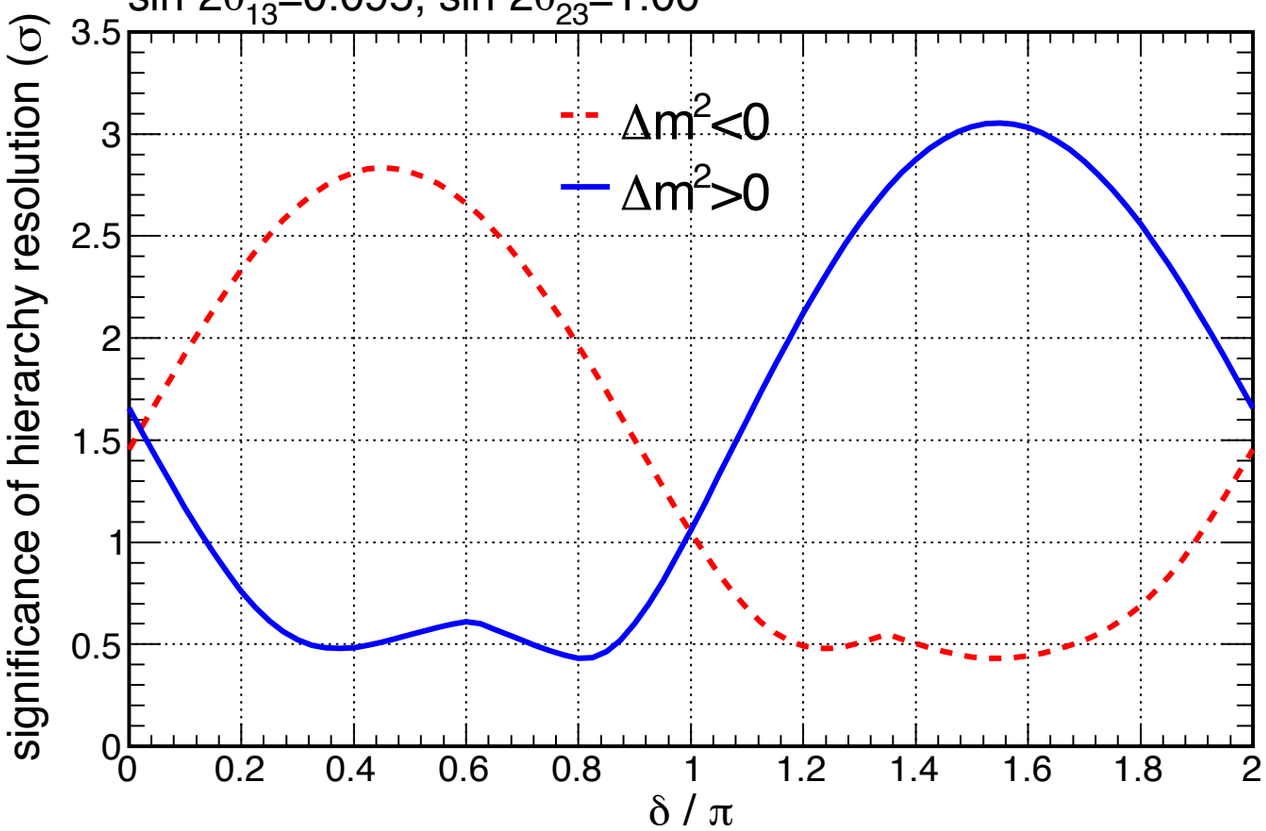


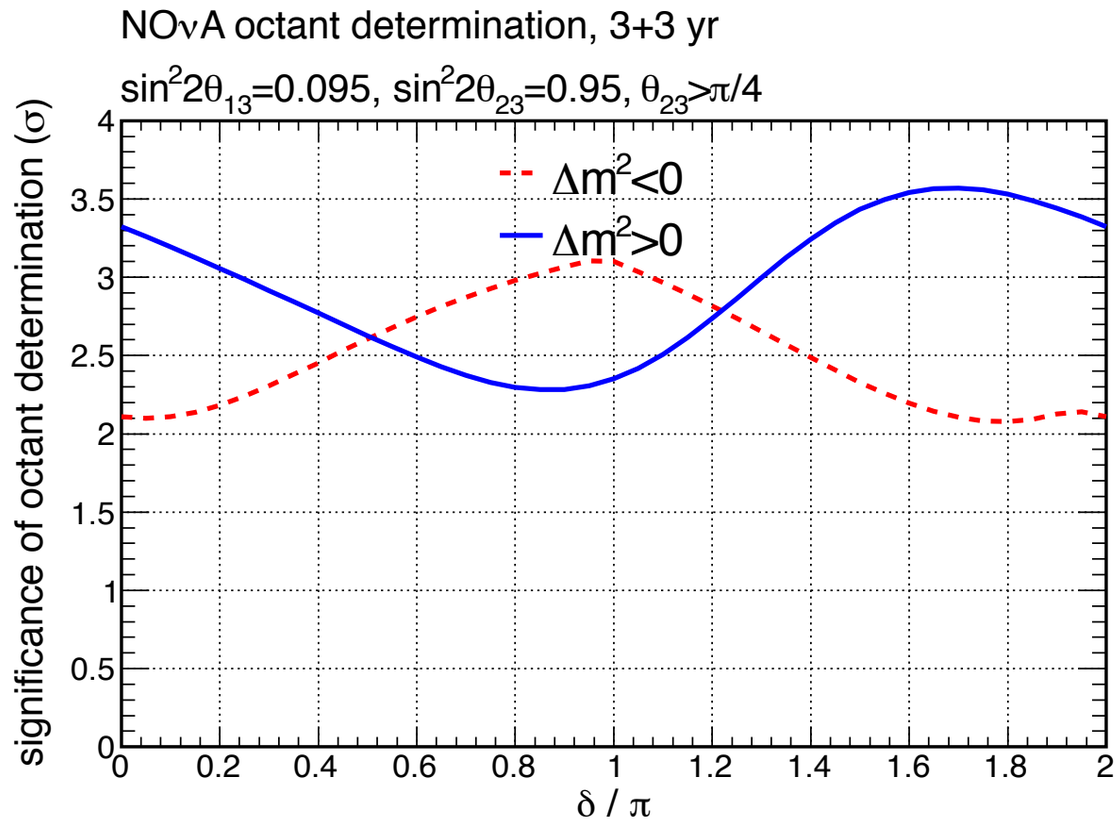
NOvA:
First data set

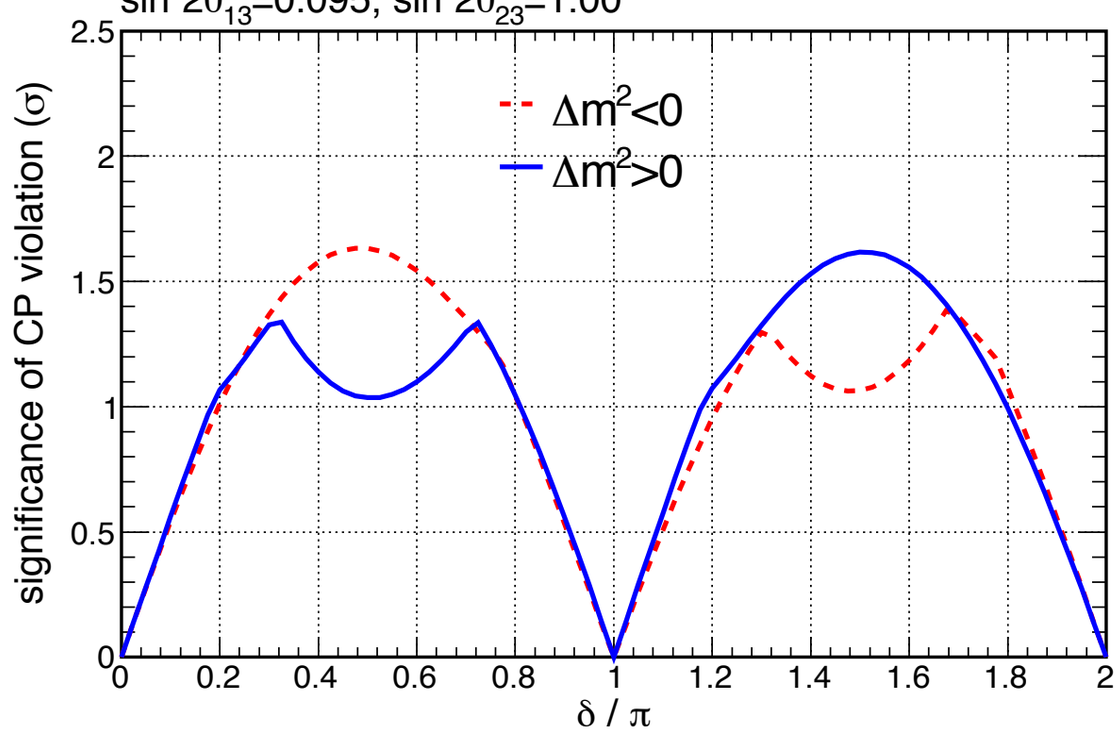


"nominal" signal neglects effects of hierarchy, octant, δ_{CP}. These can combine to give as much as a 60% effect

NOvA Projected Sensitivities for "Next Questions"

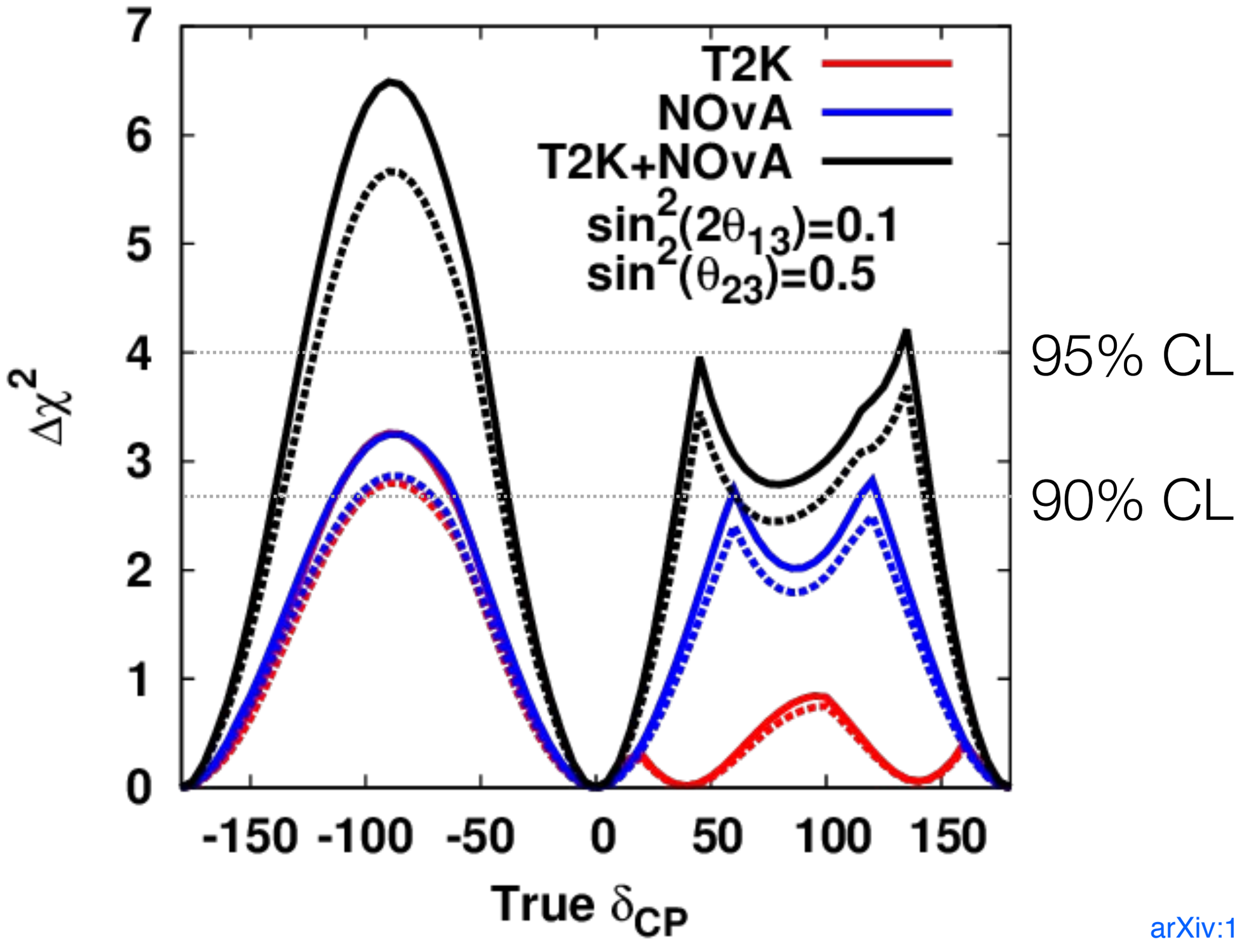






Combining NOvA and T2K

Potential for 95% CPV evidence this generation



95% CL

90% CL

arXiv:1409.7469

Summary of the current program

MINOS

- Best measurement of Δm^2_{23}
- Exploring non-PMNS effects in oscillation
- Constraints on sterile searches in combination with reactor data
- Non-standard neutrino interactions
- **MINOS+** will extend these searches

T2K

- $>7\sigma$ observation of $\nu_\mu \rightarrow \nu_e$ oscillations
- "excess" over reactor expectations are favorable for future but inconclusive
- Now best measure of θ_{23} mixing

NOvA

- Detectors completed - operating at >95% efficiency
  - **14 kiloton, highly segmented detector**
  - **longest baseline**
  - **highest intensity beam**
- Recorded first neutrinos at far detector and millions of events at near detector
- Verified detector performance on surface
- First results months away
- Run plan: Neutrinos for first 6e20 (1.5 years) then make decision about anti-neutrinos

Combinations of current generation can reach 95% CL CP violation