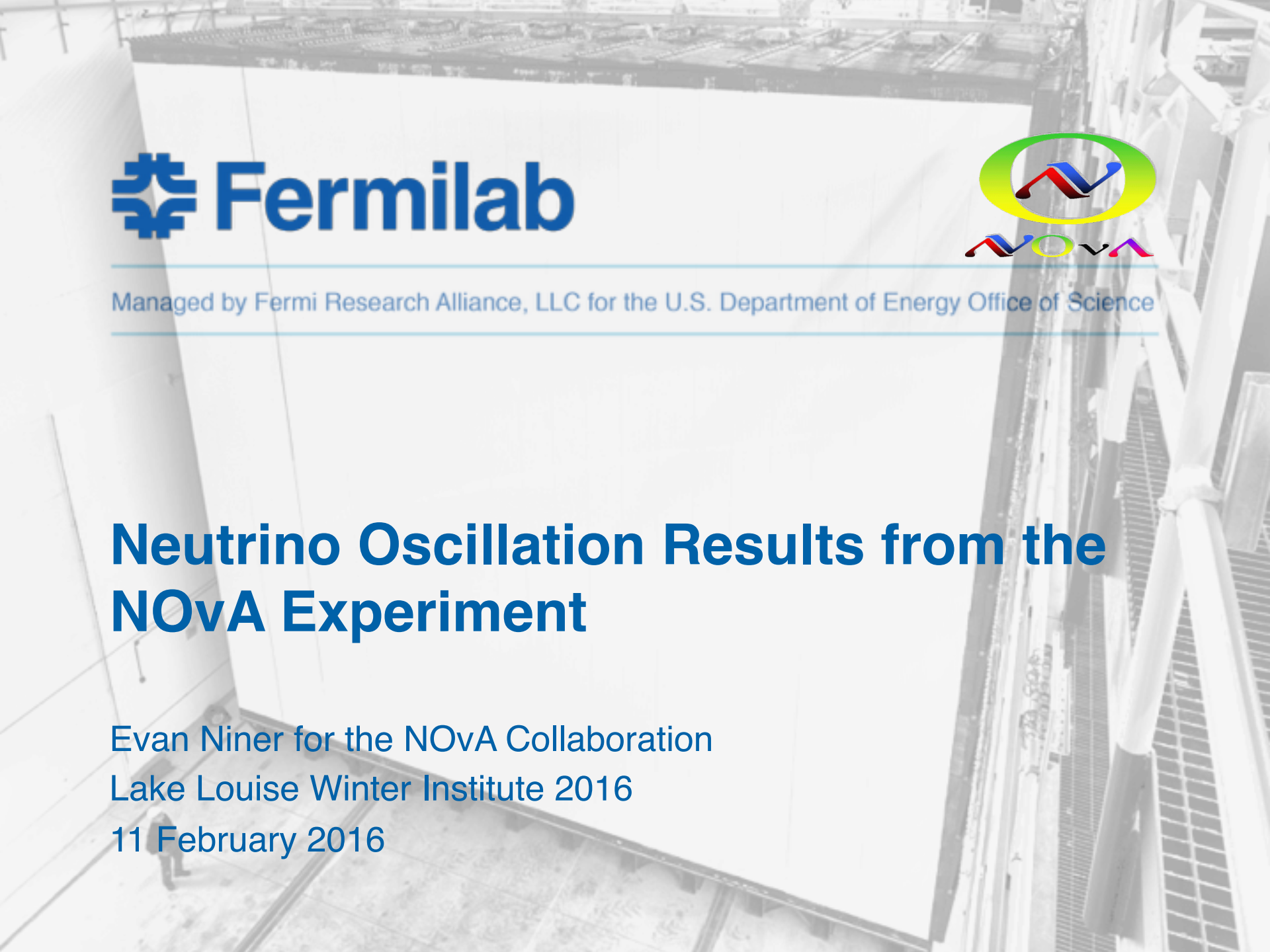

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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Neutrino Oscillation Results from the NOvA Experiment

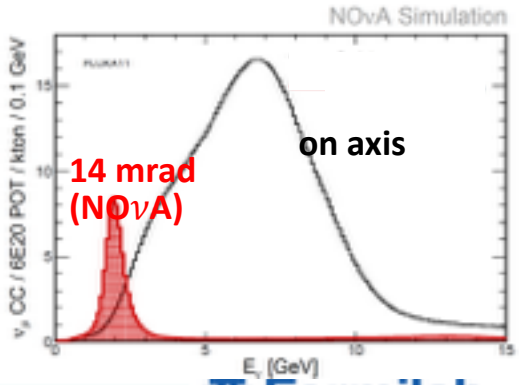
Evan Niner for the NOvA Collaboration

Lake Louise Winter Institute 2016

11 February 2016

NuMI Off-axis ν_e Appearance Experiment

- Two functionally identical detectors 809 km apart and 14 milli-radians off-axis from NuMI beam.
- Narrow-band off-axis muon neutrino beam centered at 2 GeV.
- Neutrino and anti-neutrino beam modes.
- Measure θ_{13}, θ_{23}, mass hierarchy, and δ_{cp}
- First analysis data from February 2014 to May 2015.
- 3.45x10^{20} protons-on-target (POT) accumulated.
  - Full-detector equivalent 2.74x10^{20} POT (7.6% planned exposure)



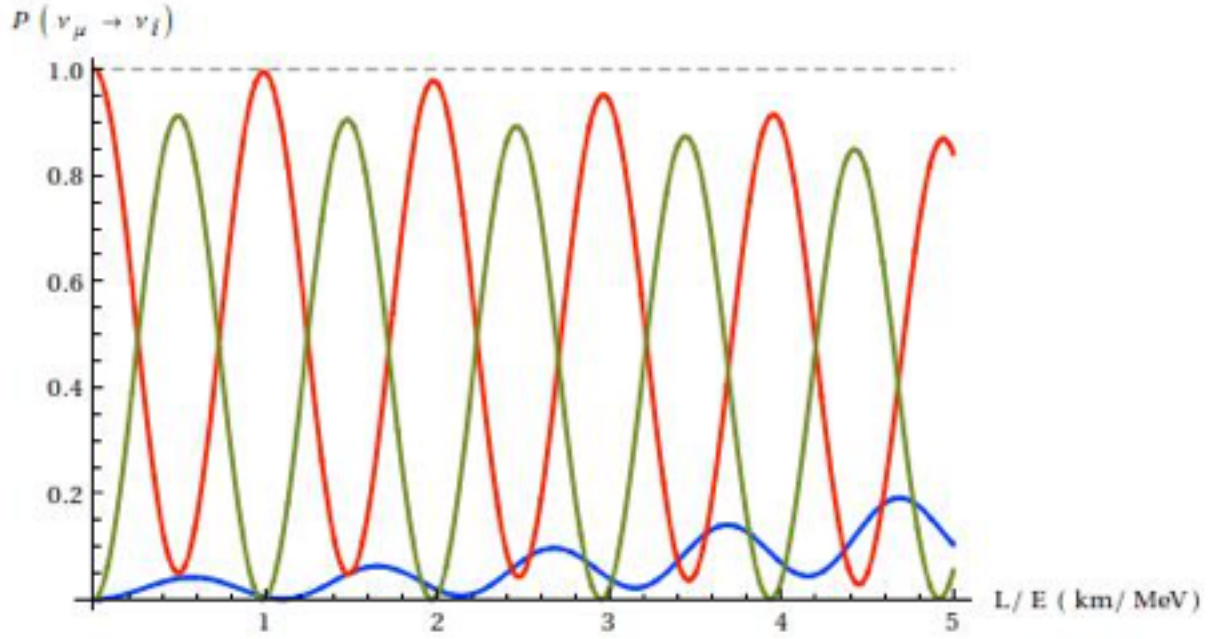
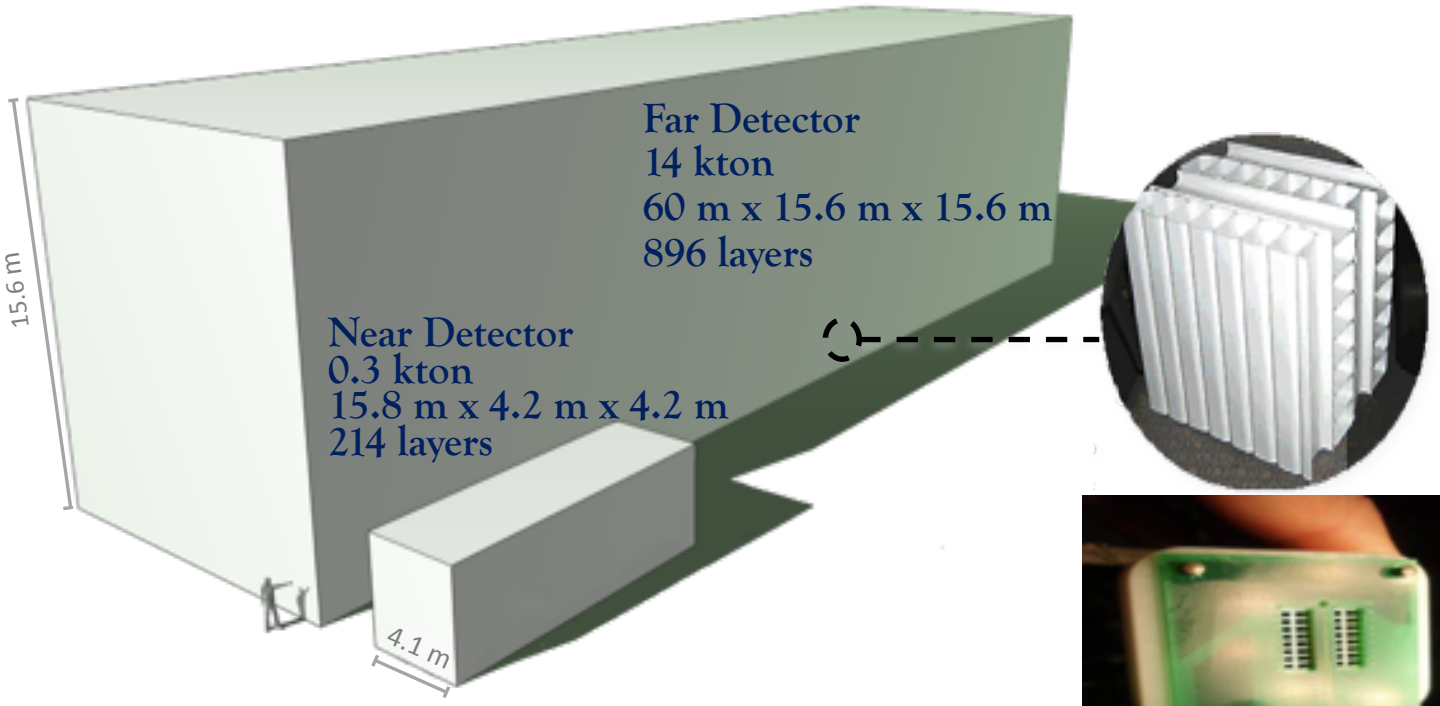


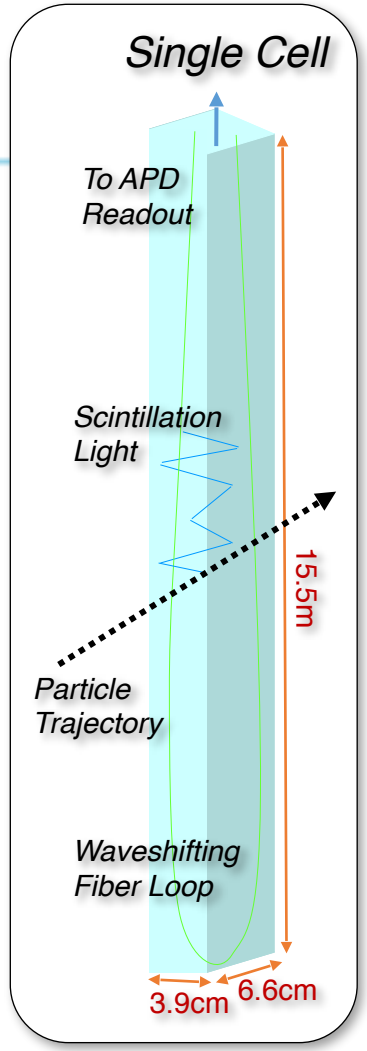
Image from: http://invisibles.eu/outreach/entry/ceaseless-transformation-three-neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

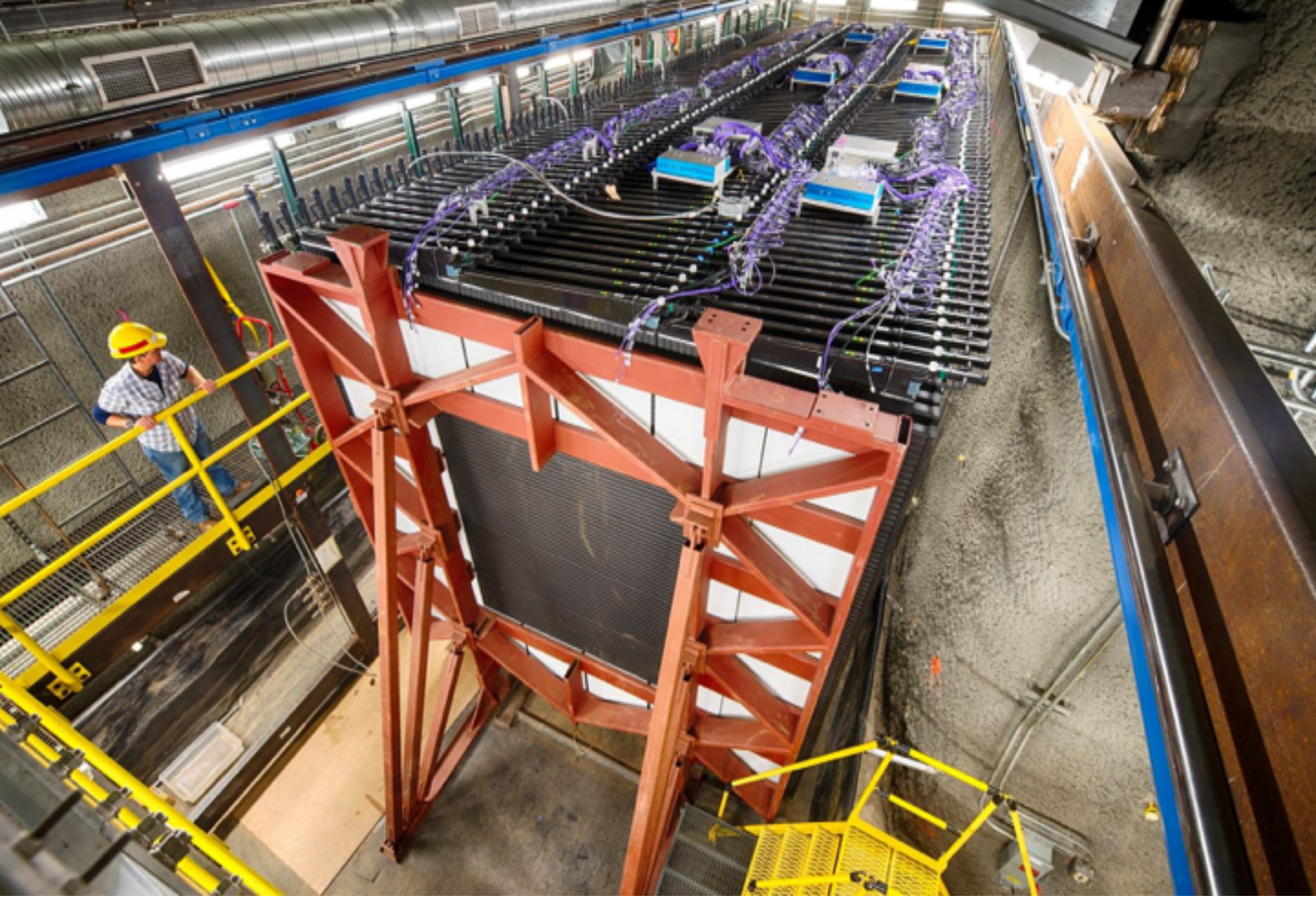
$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_e$	$\nu_e \rightarrow \nu_\mu + \nu_\tau$
atmospheric and long-baseline	reactor and long-baseline	solar and reactor

NOvA Design



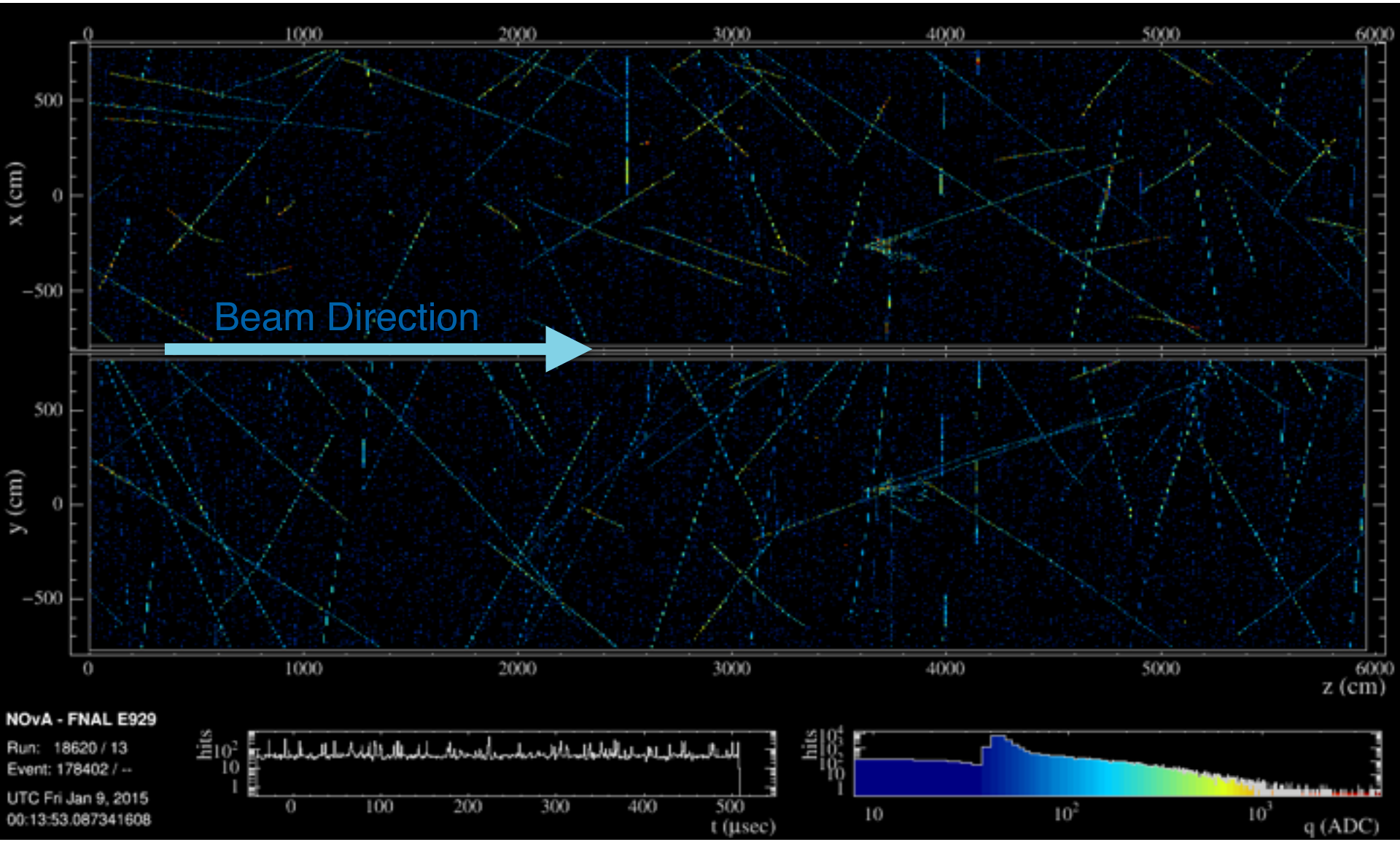


- Functionally identical detectors made of planes of extruded plastic PVC cells.
- Each cell filled with liquid scintillator, light collected in a wavelength shifting fiber, coupled to APD.
- Low-z design enhances electron/photon separation.
- Near Detector has 10 steel planes at downstream end to range out muons.



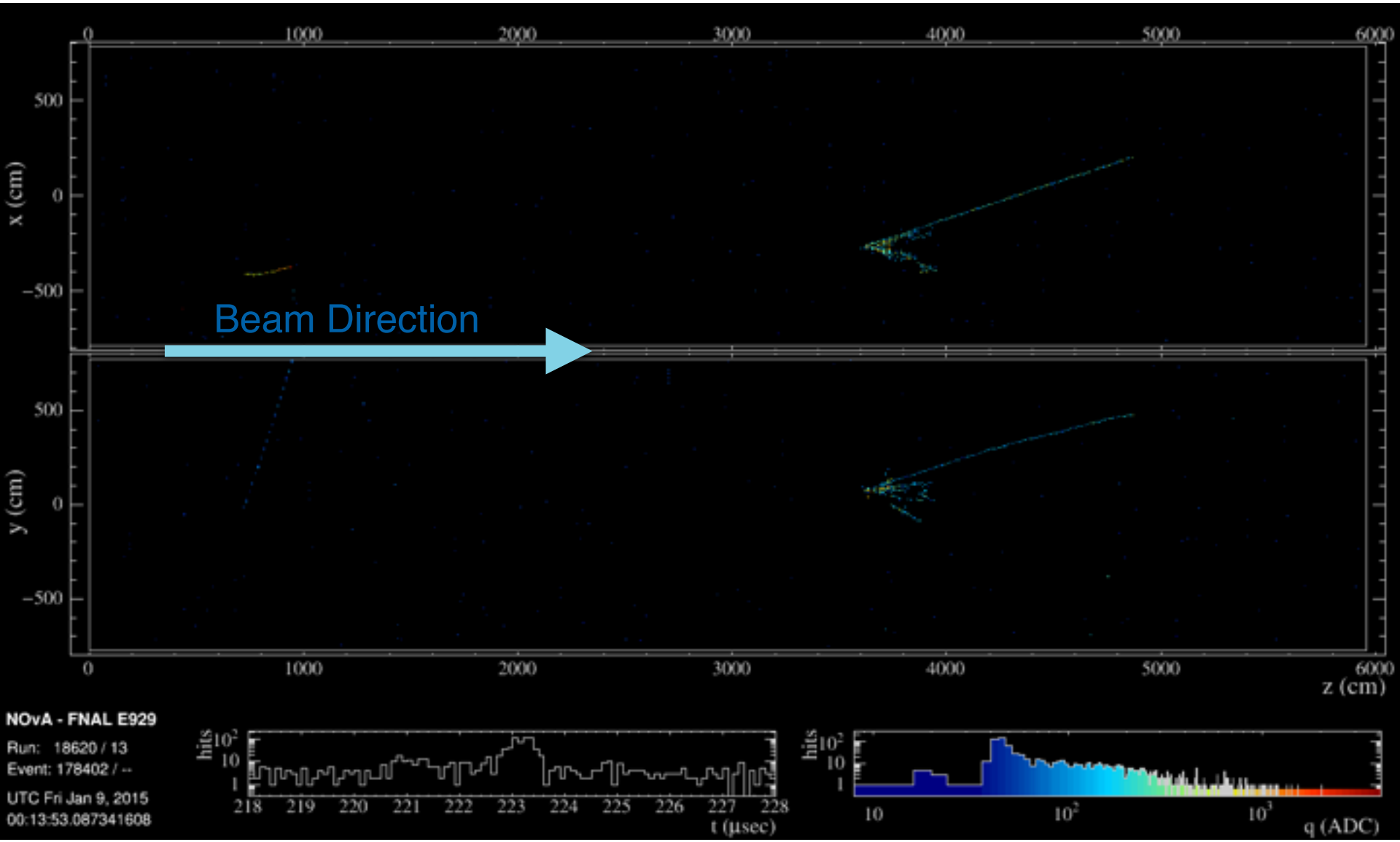
Far Detector 550 μs Readout Window

Cell hits colored by charge deposition



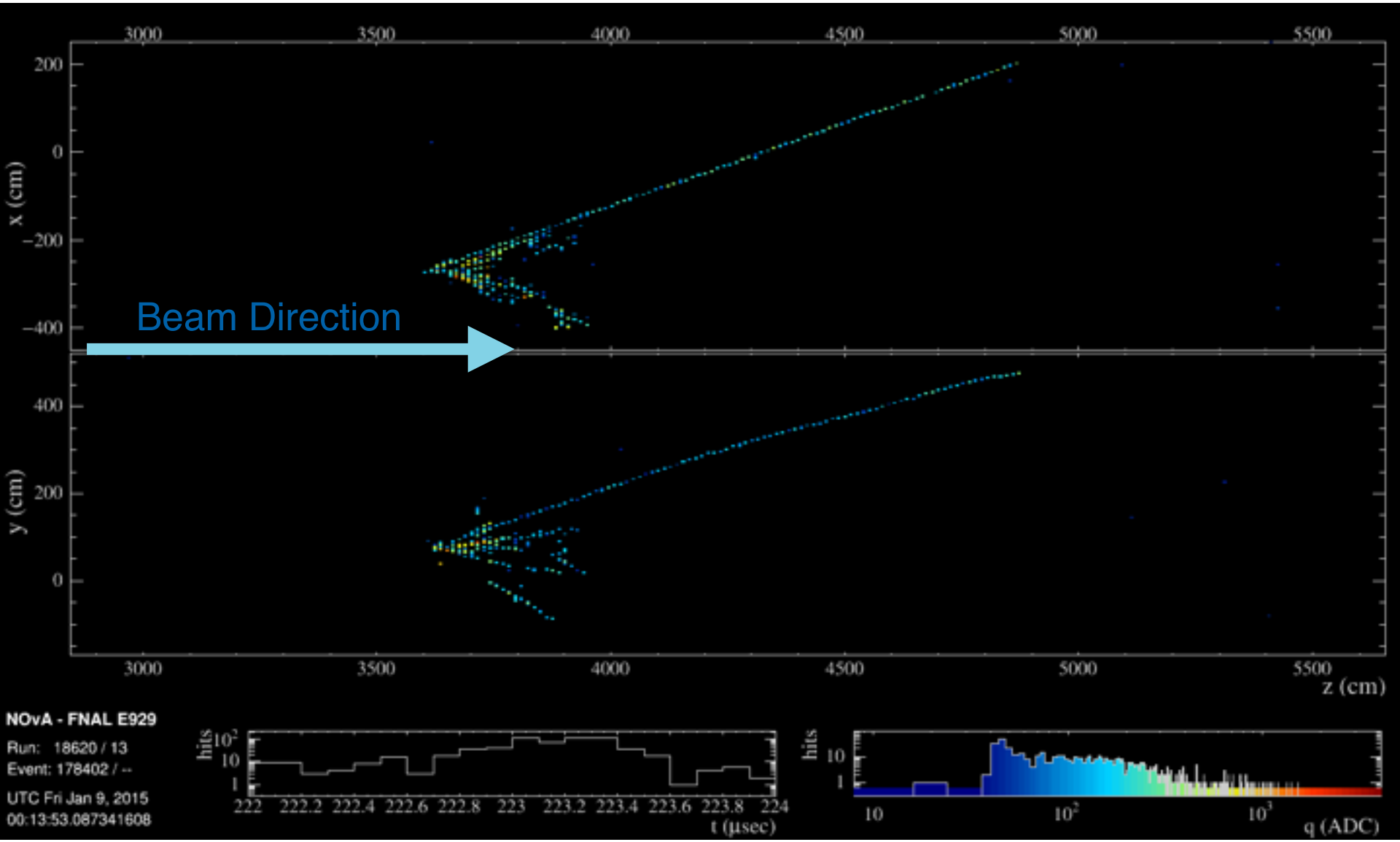
Far Detector 10 μs NuMI Beam Window

Cell hits colored by charge deposition



Far Detector Neutrino Interaction

Cell hits colored by charge deposition



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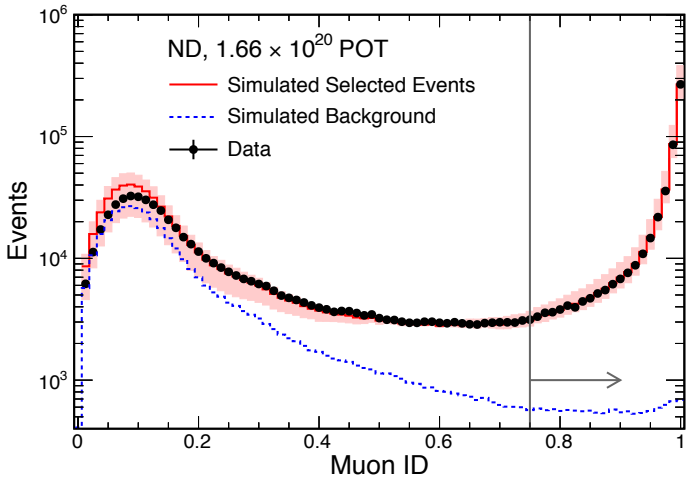
Muon Neutrino Disappearance Analysis

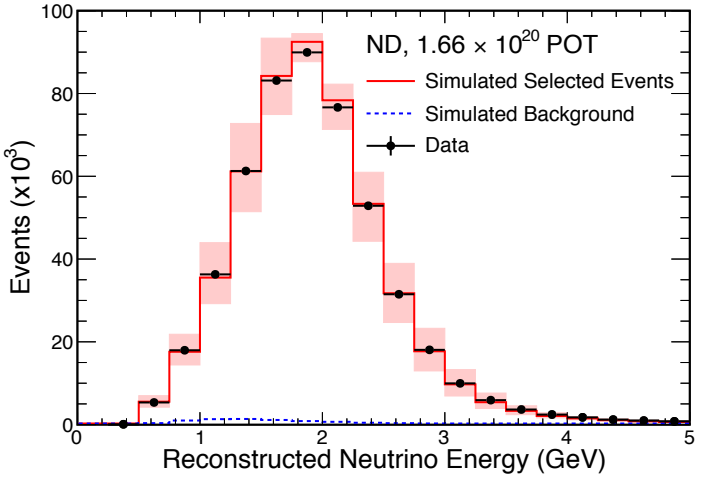
Muon Neutrino Disappearance Analysis

- Use ND selected ν_μ's to extrapolate FD prediction, reduces systematics.
- Cosmic ray backgrounds rejected by factor 10^7.
- 99% percent reduction of neutral current events.



kNN based on track length, dE/dx, multiple-scattering, fraction of overlapping hadronic energy.

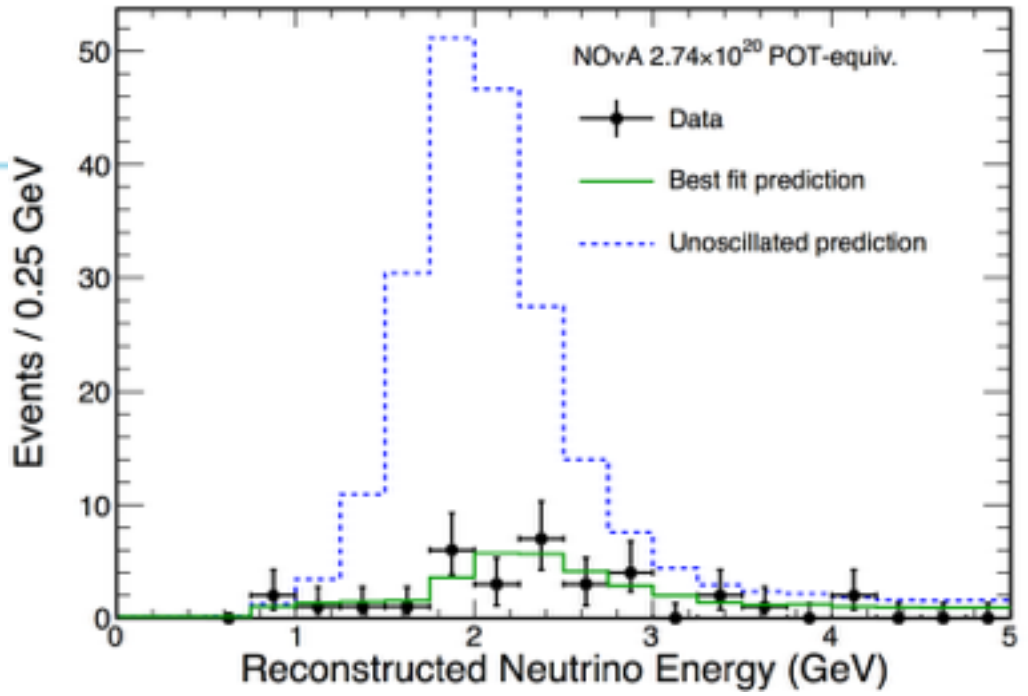
Energy spectrum in Near Detector with 14% hadronic energy correction, equivalent to 6% neutrino energy shift.

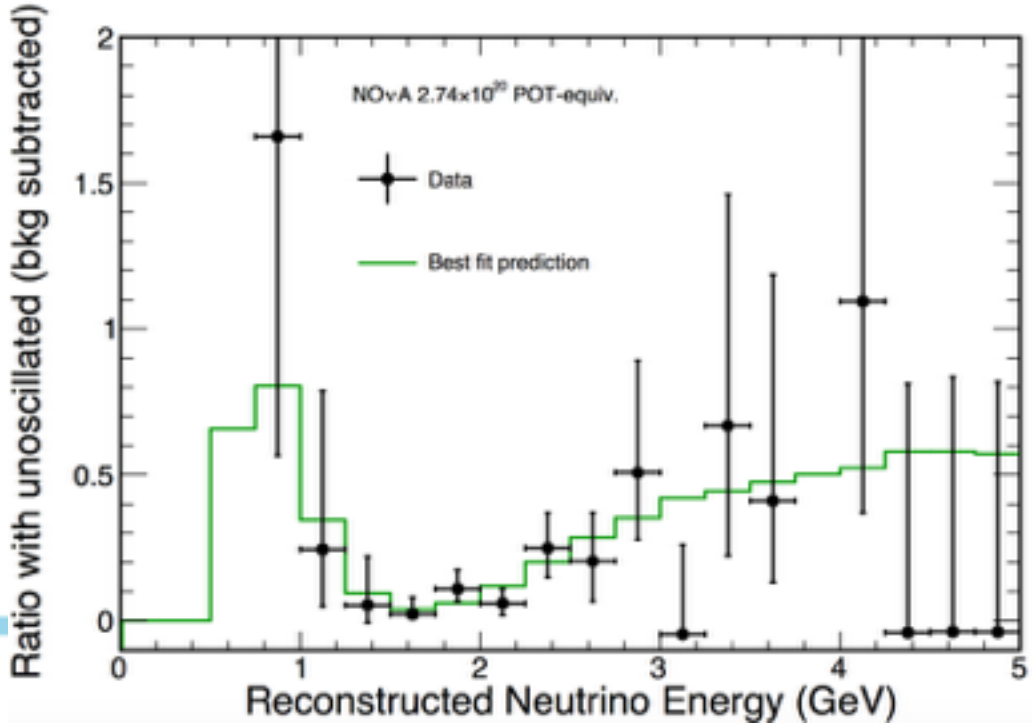


ν_μ Spectrum

- 211.8 ± 12.5 (syst.) events predicted in the absence of oscillations.

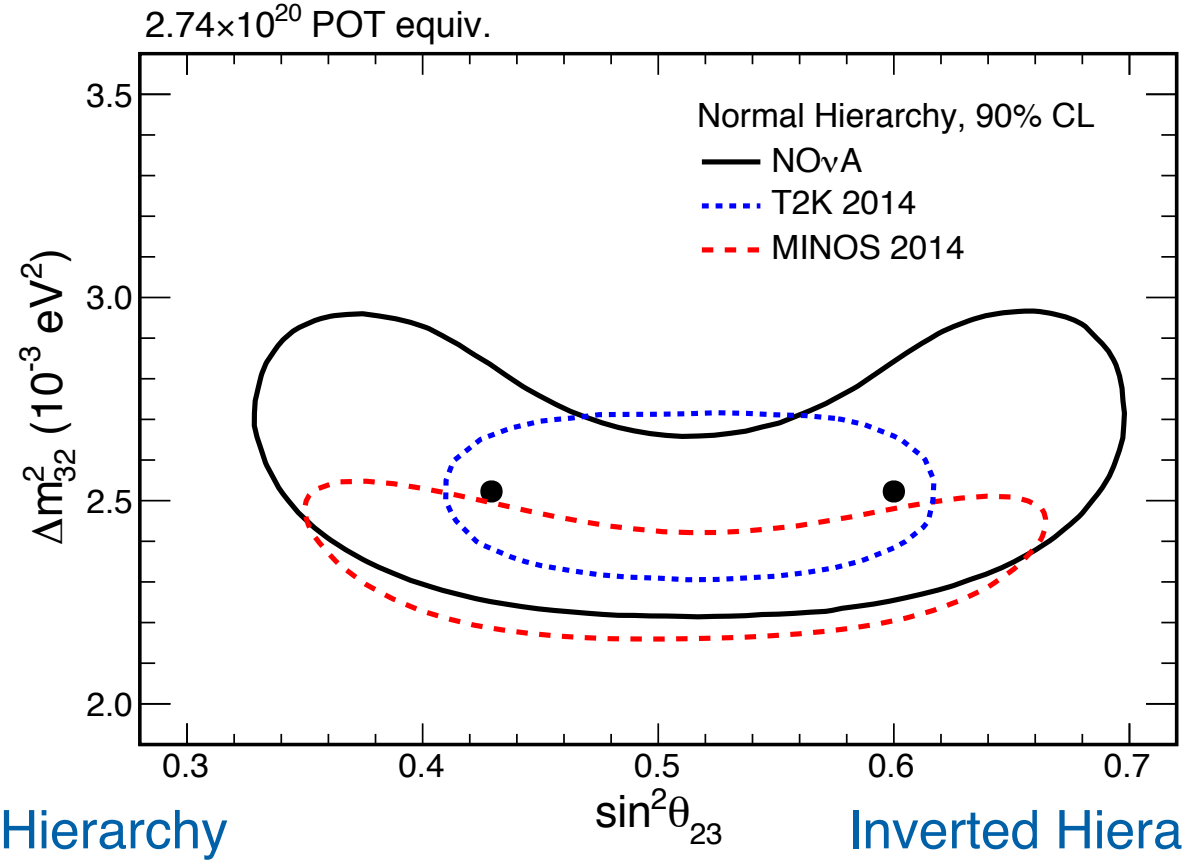
- 33 candidate events between 0 and 5 GeV observed.





Best Fit Oscillation Parameters

arXiv:1601.05037



Normal Hierarchy

$$\Delta m^2_{32} = \left(2.52^{+0.20}_{-0.18}\right) \times 10^{-3}\text{eV}^2$$

$$\sin^2\left(\theta_{23}\right) = [0.38, 0.65]$$

(68% CL)

Degenerate best fit points at 0.43 and 0.60

Inverted Hierarchy

$$\Delta m^2_{32} = (-2.52 \pm 0.19) \times 10^{-3}\text{eV}^2$$

$$\sin^2\left(\theta_{23}\right) = [0.37, 0.64]$$

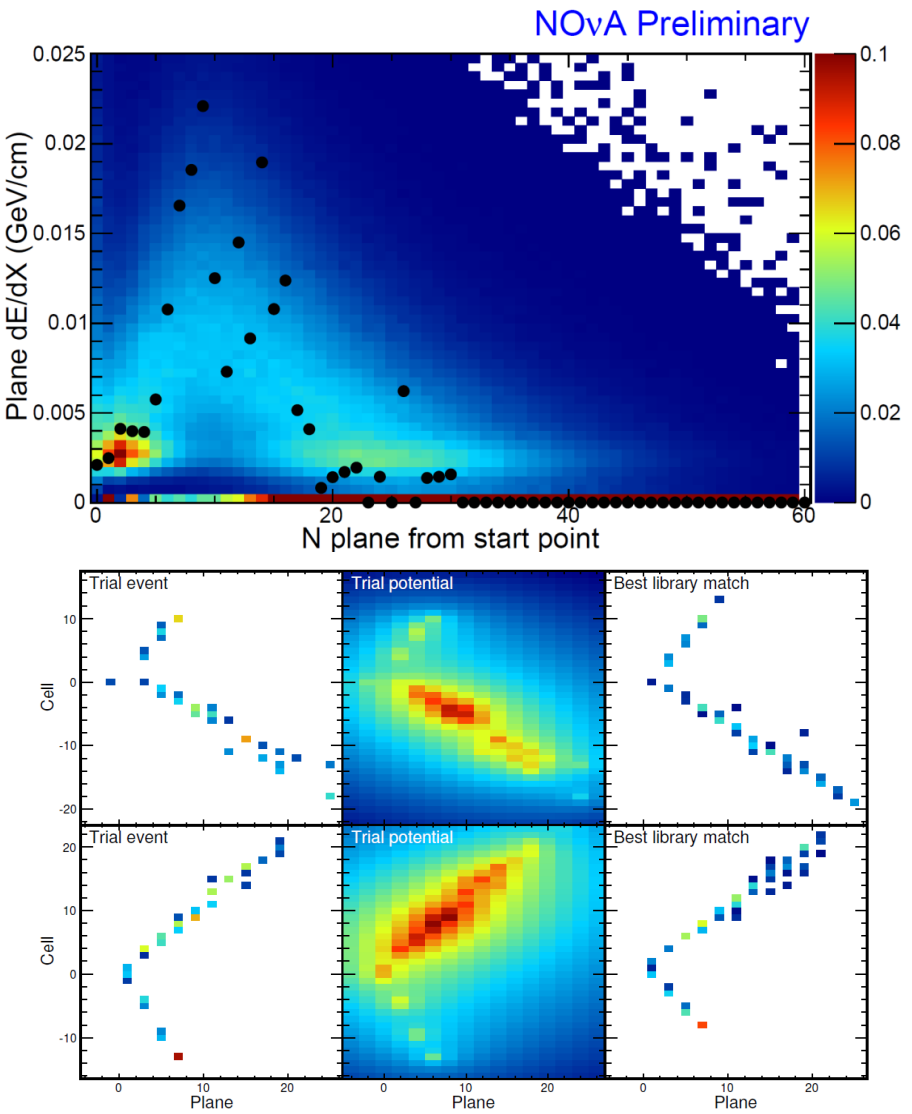
(68% CL)

Degenerate best fit points at 0.44 and 0.59

Electron Neutrino Appearance Analysis

ν_e Identification

- Likelihood Identifier (LID)
  - Compare longitudinal and transverse dE/dx in leading shower to template histograms for e/p/n/μ/$\pi^{\pm}$/π^0/γ.
  - Build neural net from these inputs and reconstructed quantities.
- Library Event Matching (LEM)
  - Compares input event to simulated event library.
  - Properties from most similar events fed into decision tree.
- 62% event overlap between selectors.
- LID chosen before unblinding as primary selector.



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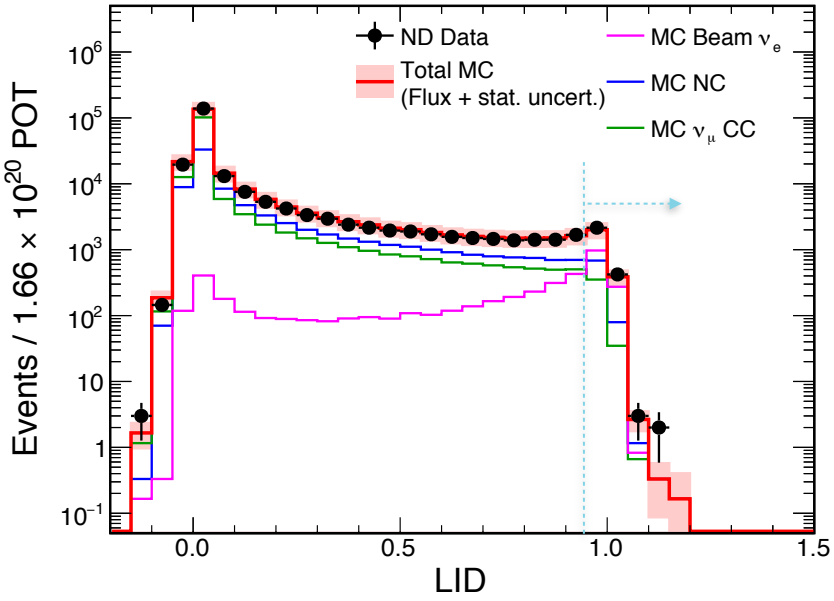
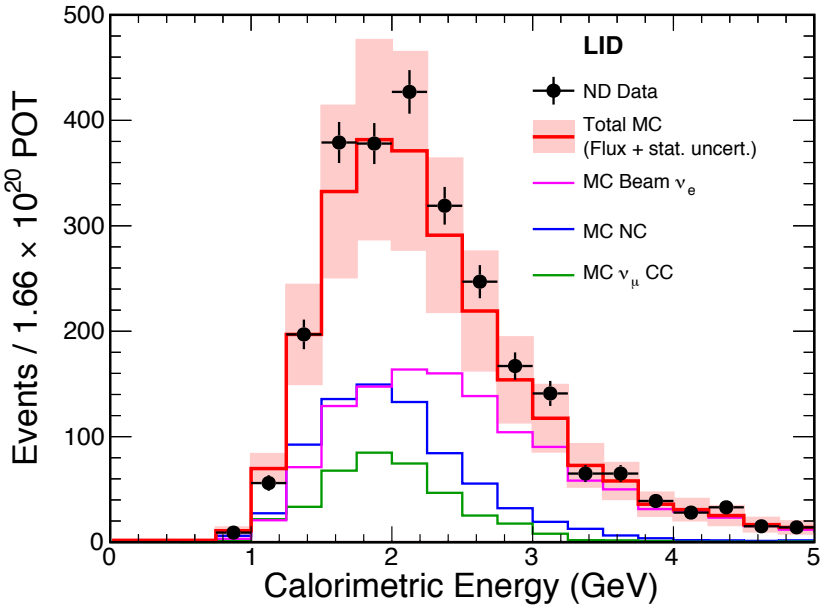
ν_e Appearance Analysis Strategy

- FD background prediction extrapolated from ND
  - ND selects ~7% more background in data relative to simulation.
- Combination of containment, topology and event classifier achieve cosmic rejection factor >10^8. Effective FD fidicual volume of 10 kT.
- "Cut and count" analysis between 1.5 and 2.7 GeV in FD for the primary selector.

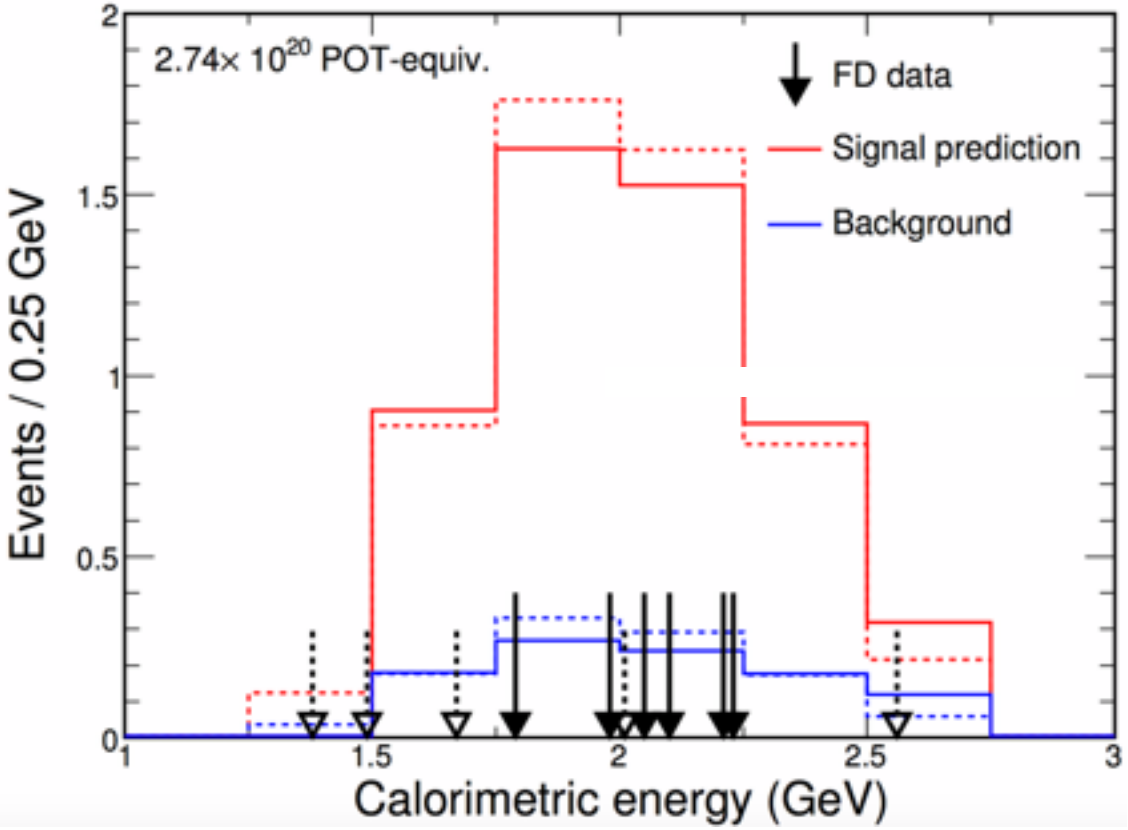




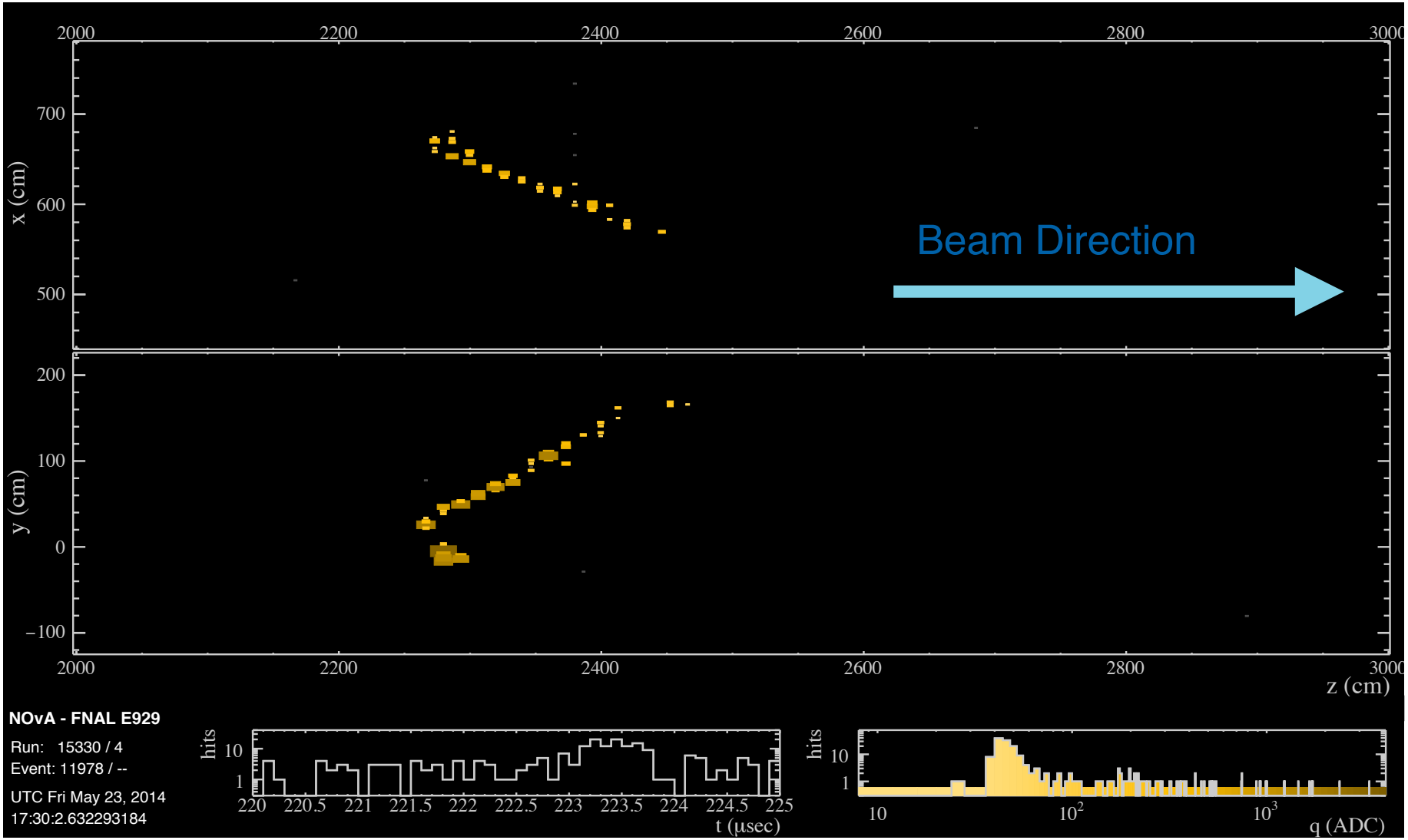
ND energy spectrum with LID>0.95

ν_e Appearance Analysis Results

- LID observed 6 events on a background prediction of 0.99±0.11(syst), 3.3σ excess.
- LEM observed 11 events on a background of 1.07±0.14(syst), 5.3σ excess.
- All LID events in LEM set.
- 7.8% probability of this overlap configuration or one less likely.

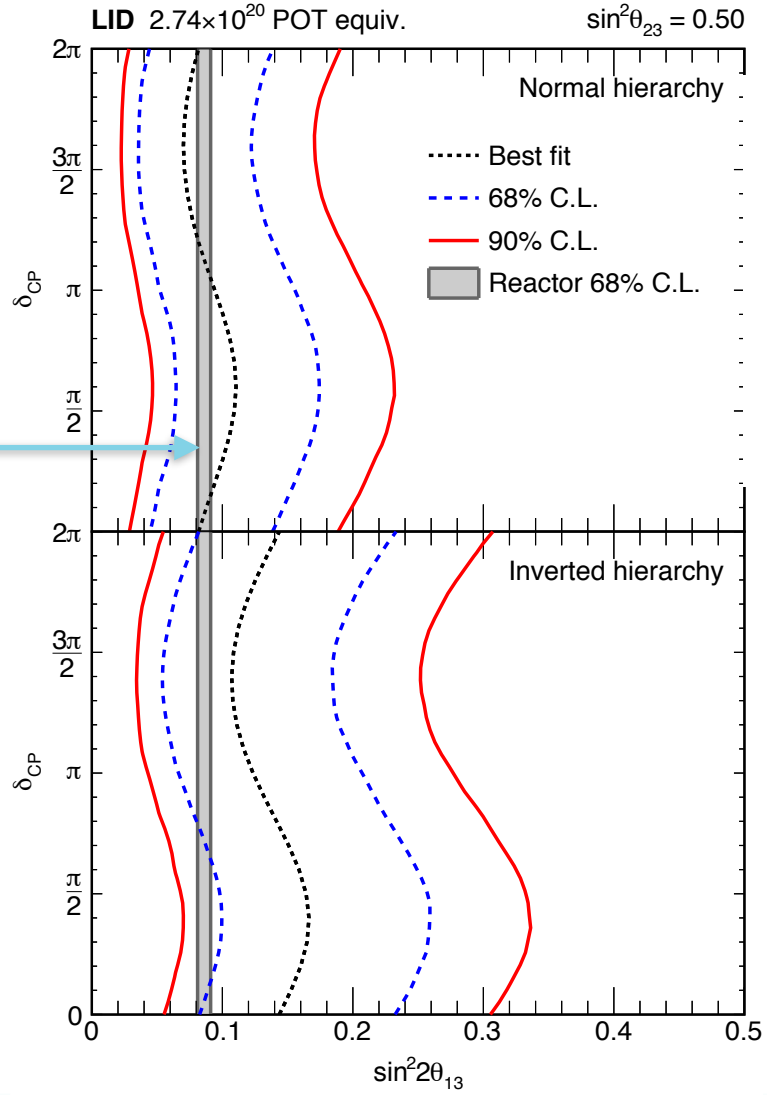


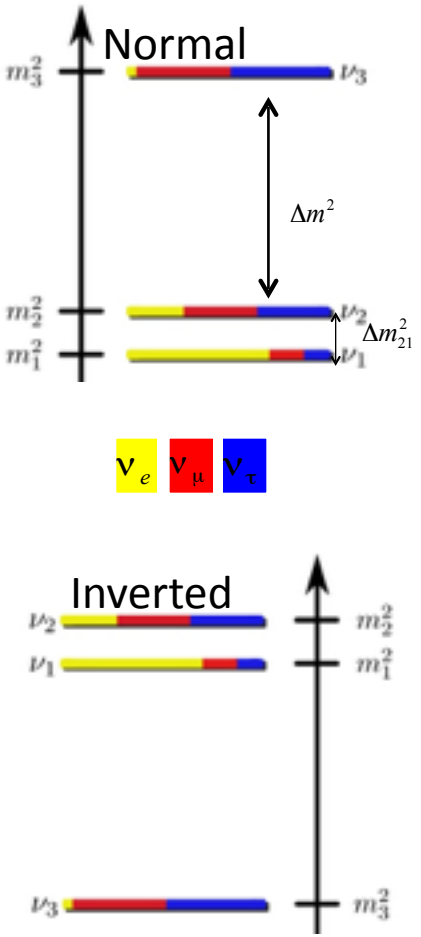
Far Detector ν_e CC candidate



ν_e Appearance Analysis Results

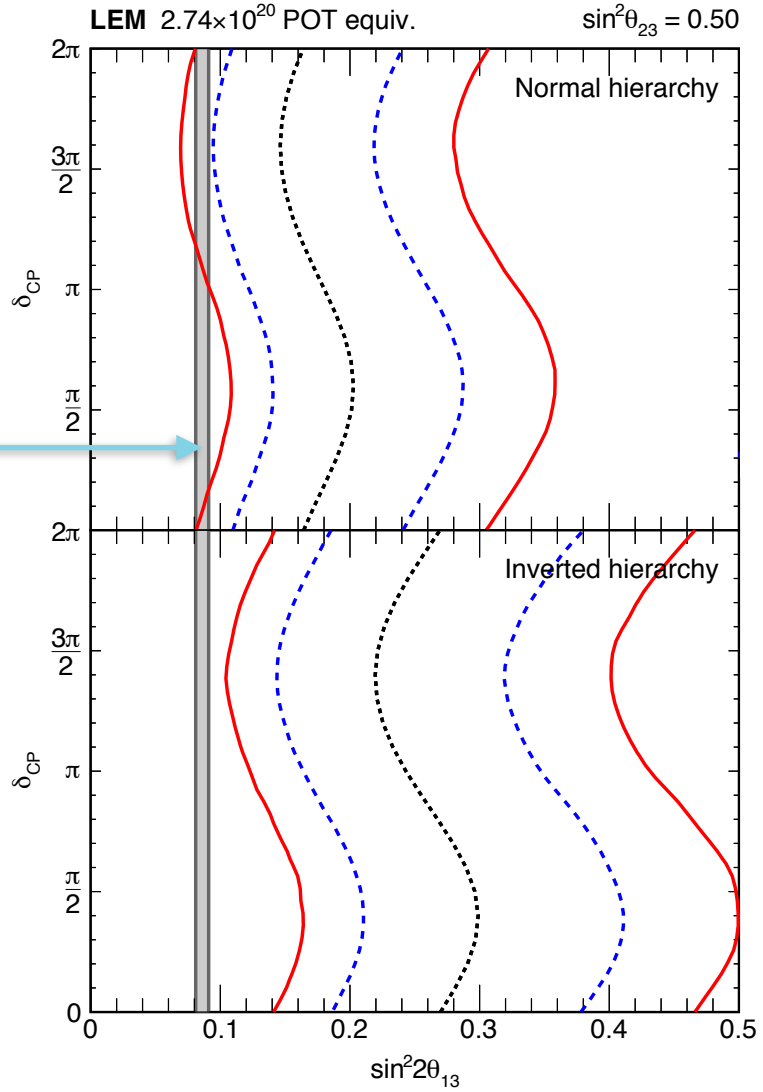
Global best fit from reactor experiments

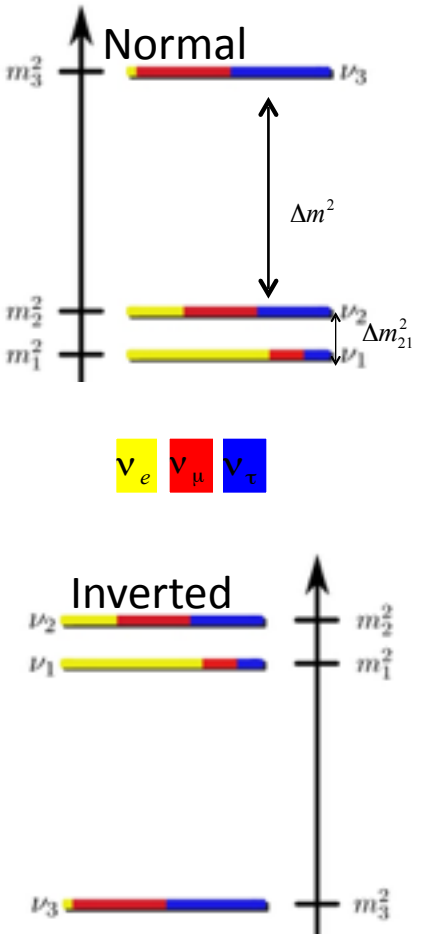




ν_e Appearance Analysis Results

Global best fit from reactor experiments

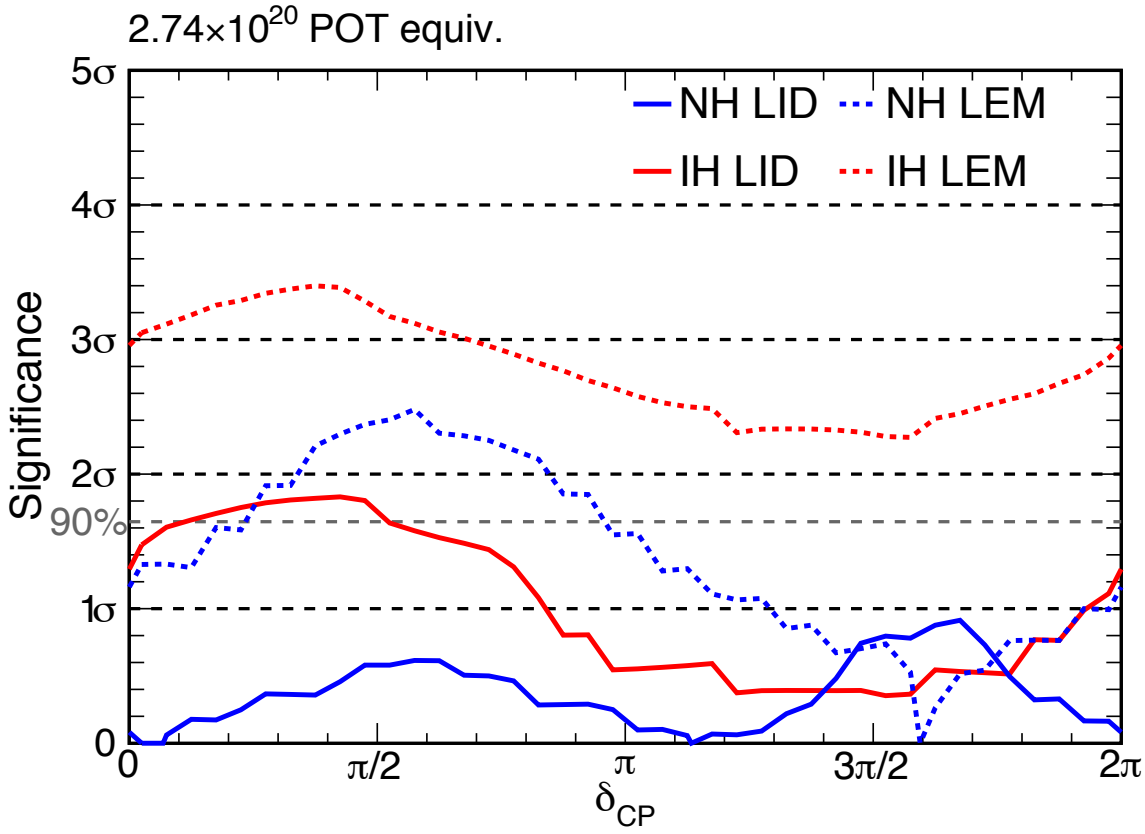




Significance with Reactor Constraint

arXiv:1601.05022

- Apply global reactor constraint
  - $\sin^2\theta_{13}=0.086\pm0.05$
- Marginalize over θ_{23}.
- Both selectors weakly prefer normal mass hierarchy and $\pi<\delta_{cp}<2\pi$.
- This preference is consistent with T2K (arXiv:1502.01550)



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Summary

- First oscillation results from NOvA program with 7.6% of planned exposure.
- ν_μ disappearance results consistent with MINOS and T2K.
- ν_e appearance results hint at normal mass hierarchy and $\pi<\delta_{cp}<2\pi$, consistent with T2K.
- Near Detector cross section studies in progress with ν_e CC and coherent π^0 results shown at NuINT, publications in progress.
- Expect to produce second analysis with double the statistics in 2016.
- Stay Tuned!

Thank You

ν_e Appearance Oscillation Probability

$$P(\nu_\mu \to \nu_e) \approx \left|\sqrt{P_{atm}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{sol}}\right|^2$$

$$= P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

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

Depends on relative sign of "a" and Δ_{31}

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

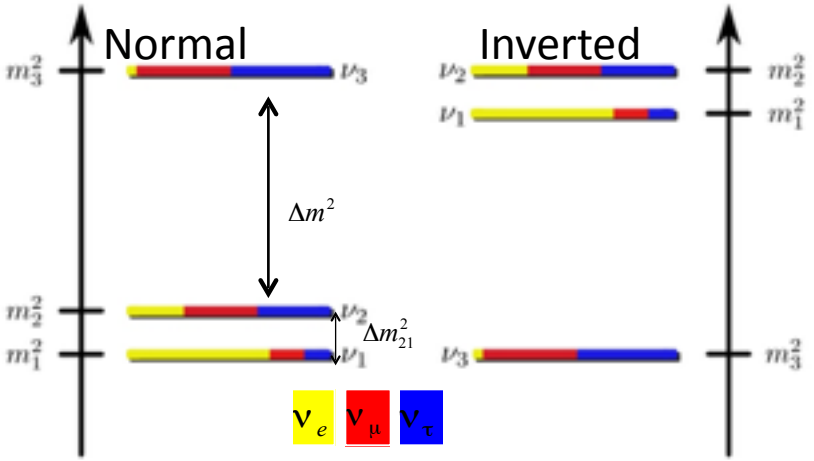
aL=0.08 for L=295km T2K baseline
aL=0.23 for L=810km NOvA baseline

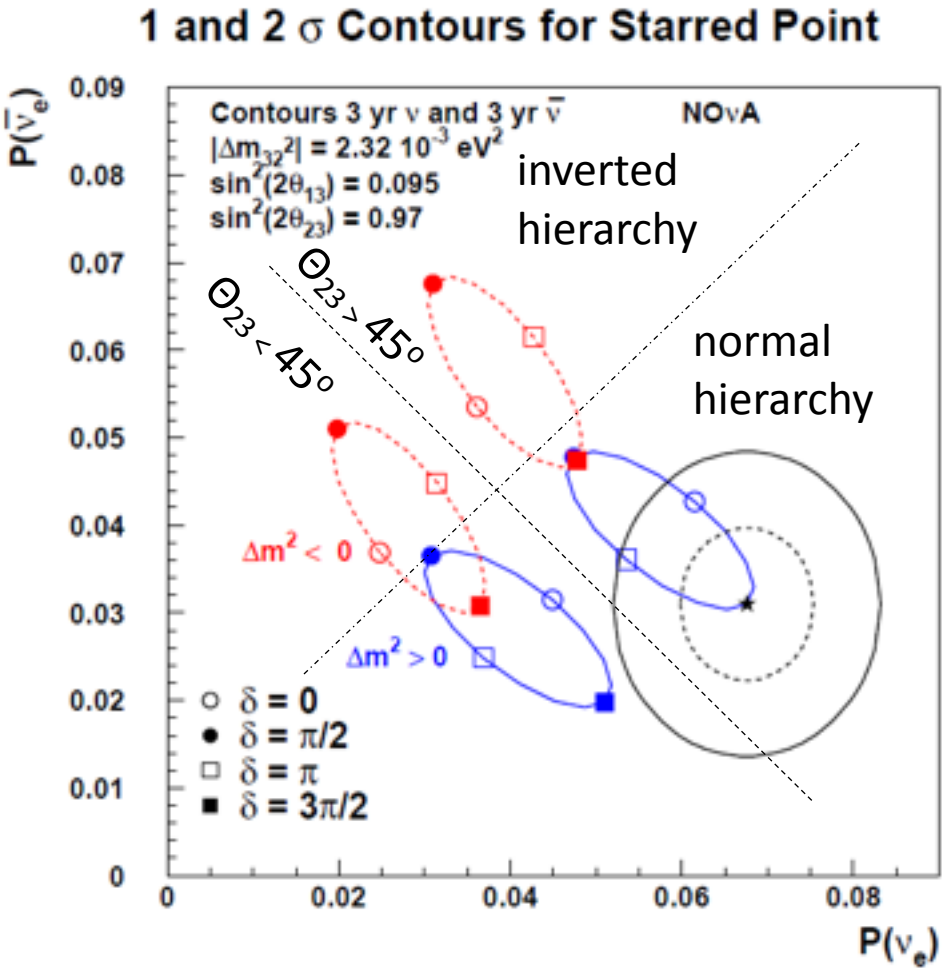
$$a = \frac{G_F N_e}{\sqrt{2}} \approx \frac{1}{3500km}$$

Oscillation probability is sensitive to: mass ordering, CP violating phase, and θ_{23} octant.

Relation of Oscillation Parameters in NOvA

- NOvA makes a measurement of the oscillation probabilities:
  - $P(\nu_\mu \rightarrow \nu_e)$
  - $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$
- The measured probabilities depend on the mass hierarchy, θ_{23} octant, and δ_{cp}.



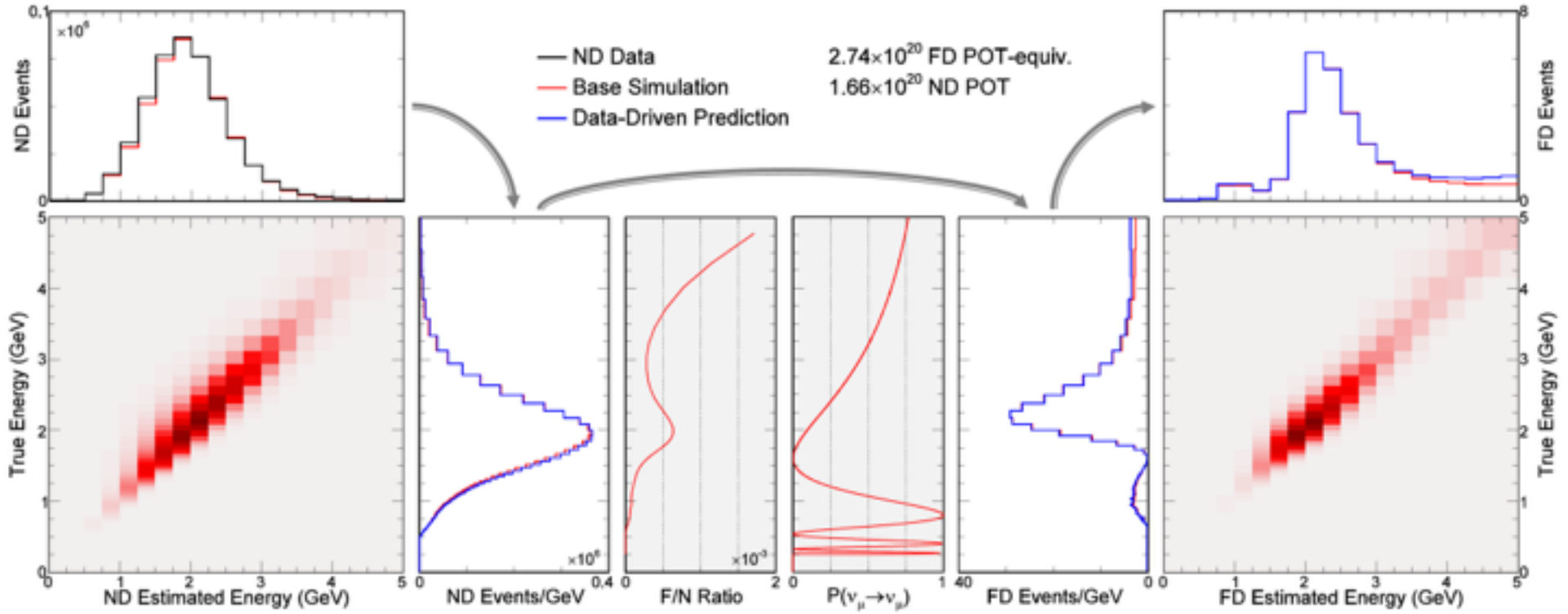


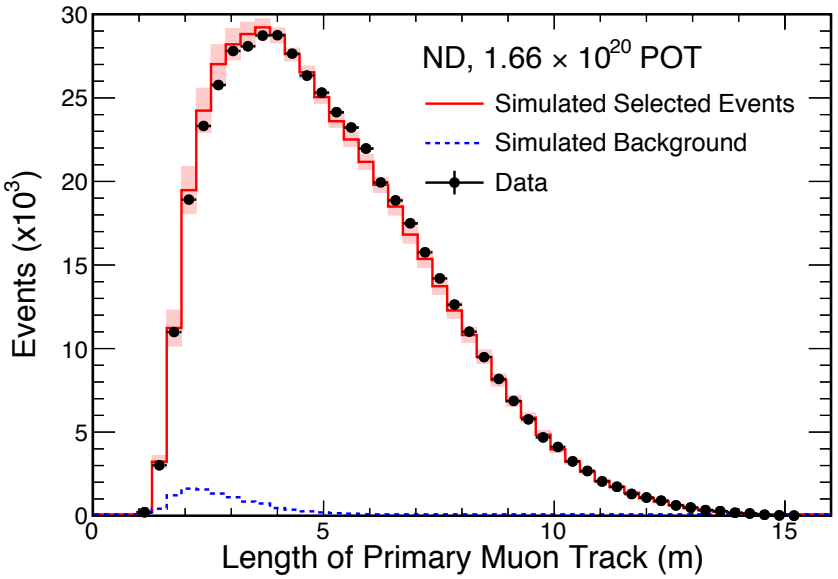
(1) Estimate the underlying **true energy distribution** of selected ND events

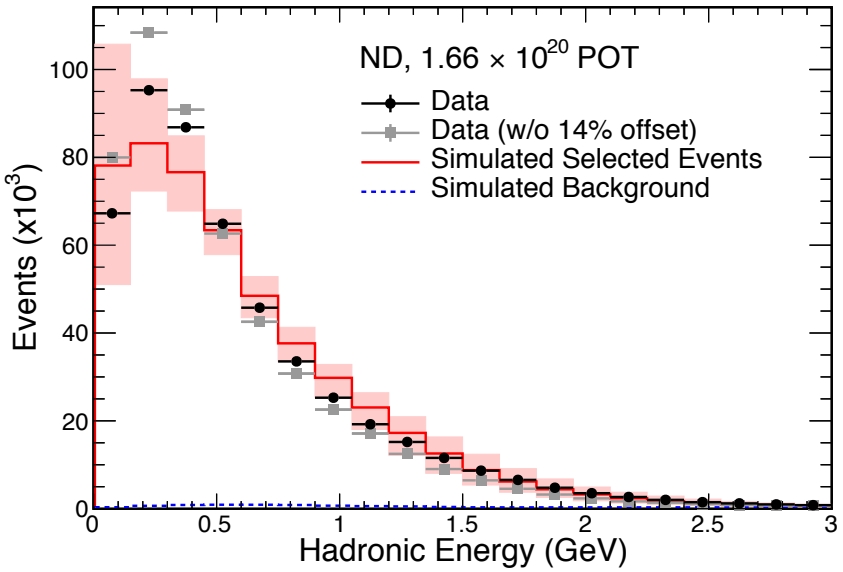
(2) Multiply by expected **Far/Near event ratio** and $\nu_\mu \rightarrow \nu_\mu$ **oscillation probability** as a function of true energy

(3) Convert FD true energy distribution into **predicted FD reco energy distribution**

Systematic uncertainties assessed by **varying all MC-based steps**

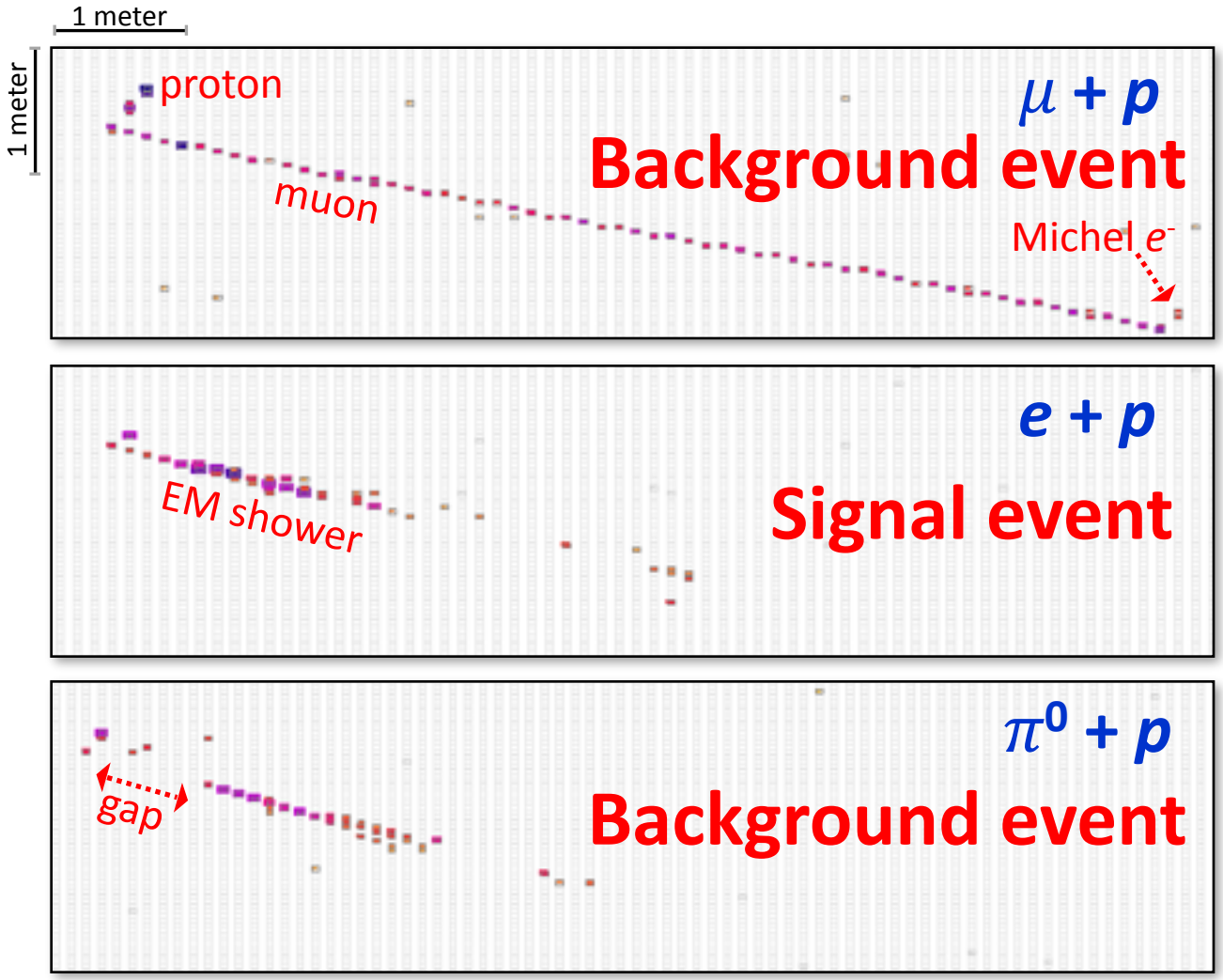


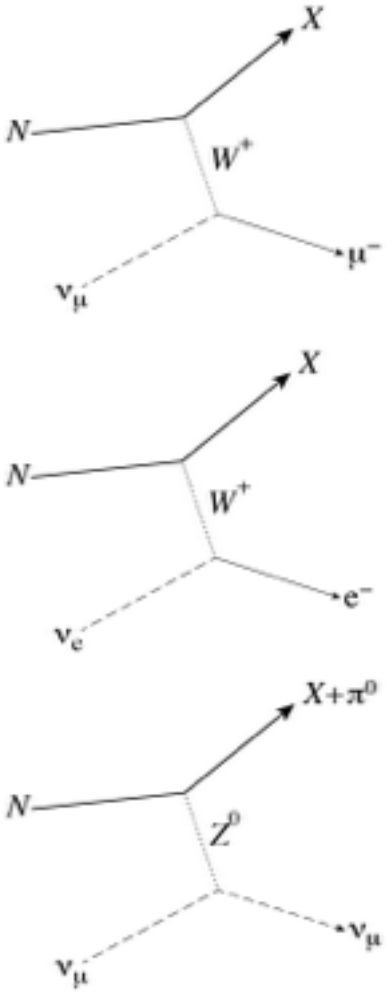




$$E_\nu = E_\mu + E_{\text{hadrons}}$$

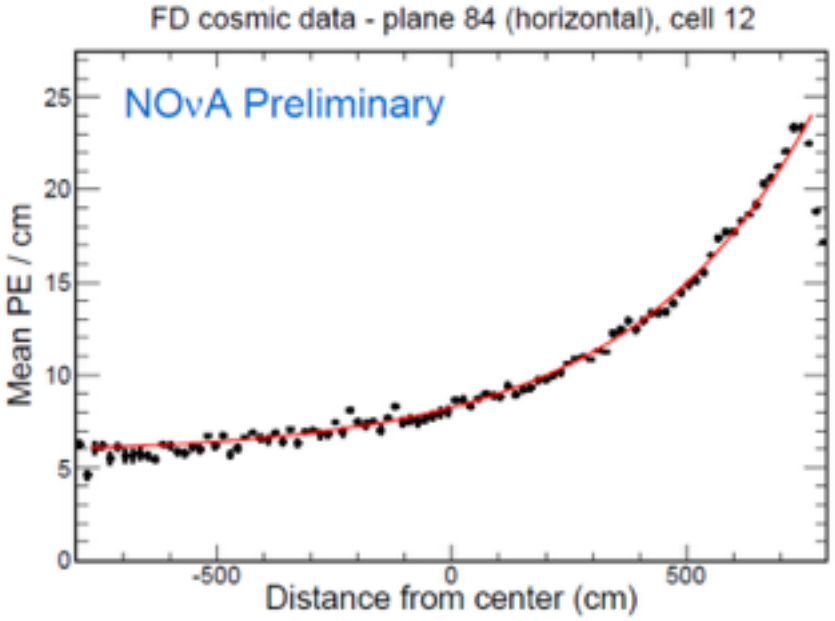
- Muon variables in agreement
- Best fit to hadronic energy prefers 14% increase in data

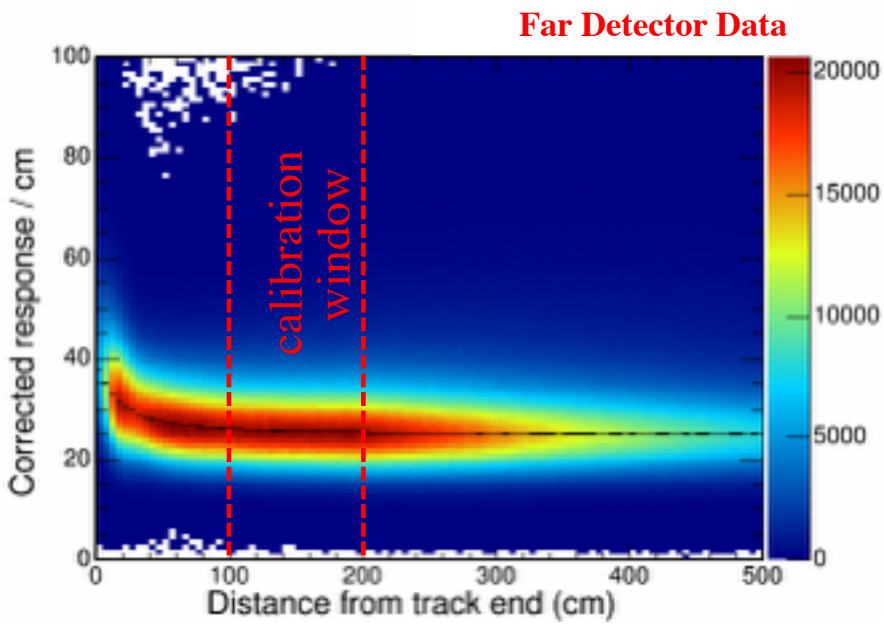


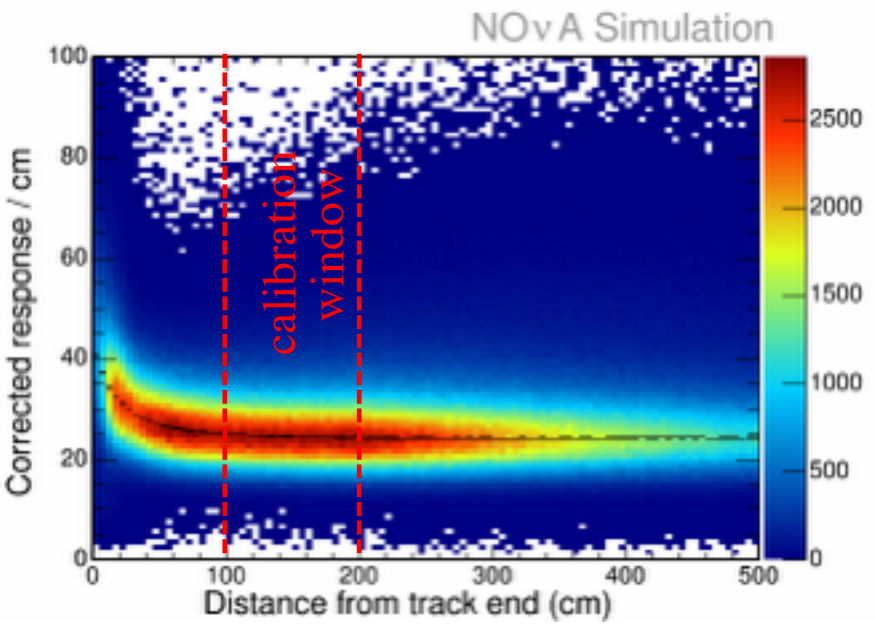


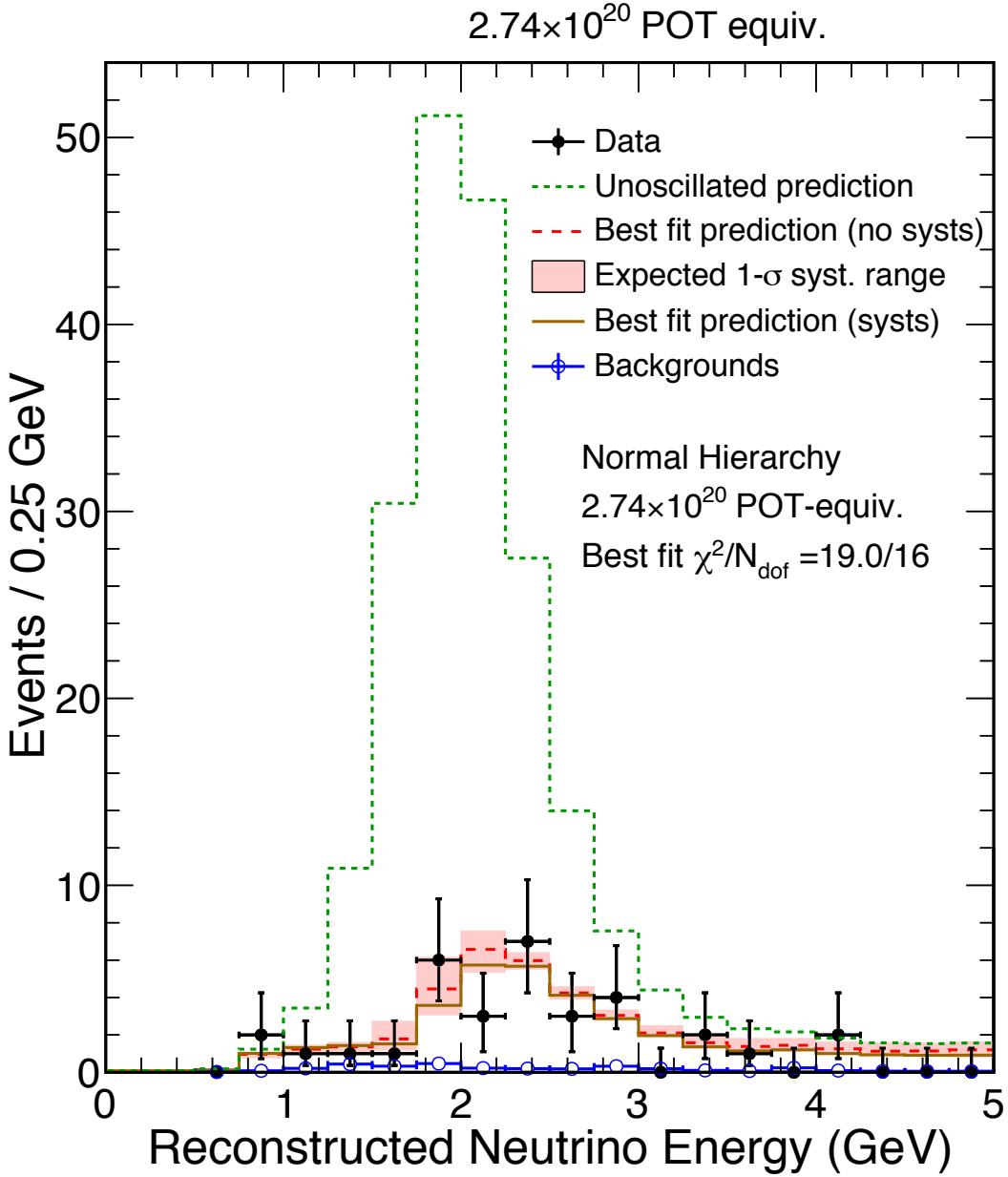
1 radiation length = 38cm (6 cell depths, 10 cell widths)

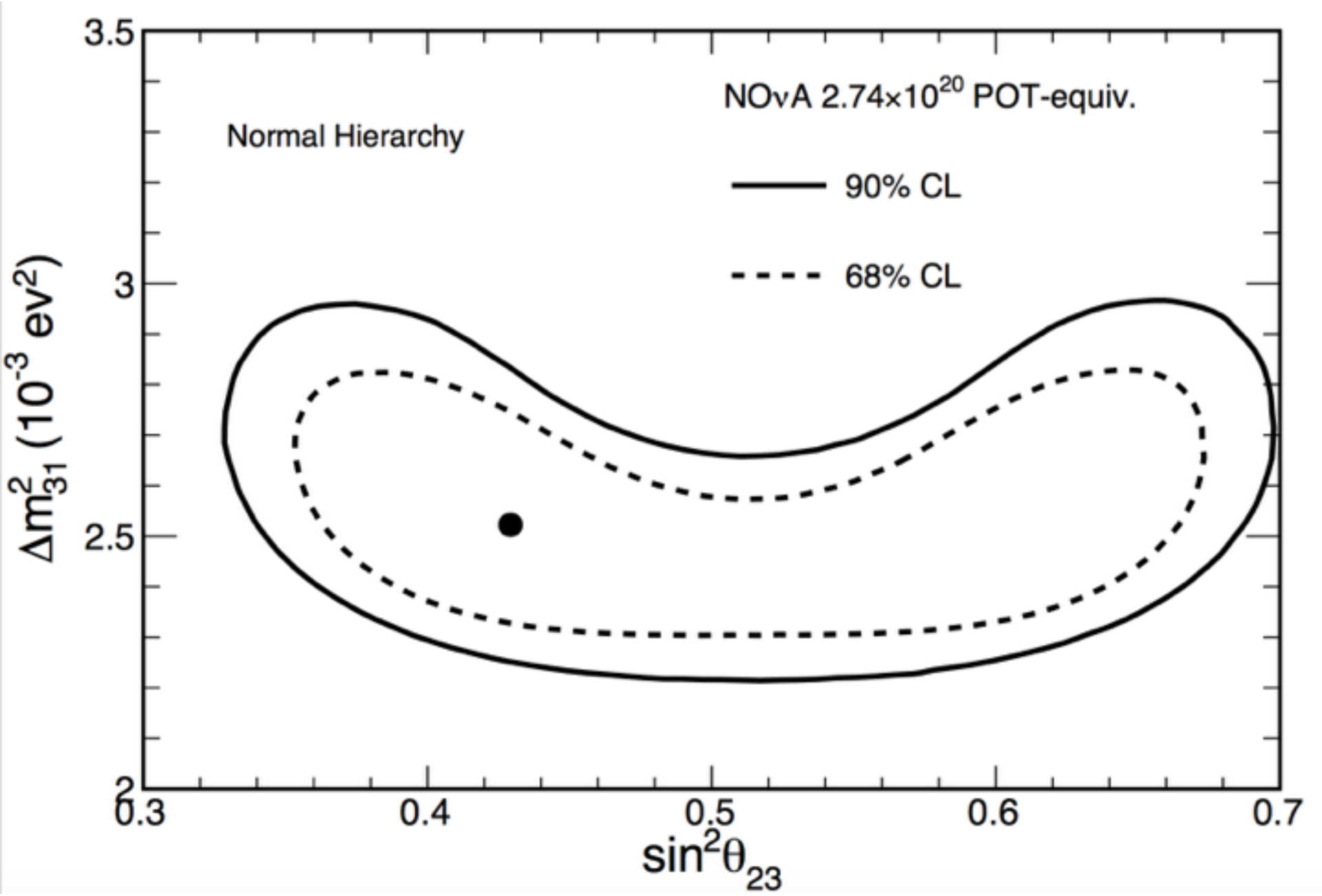
- Correct for attenuation in each cell using through-going cosmic muons (right)
- Set absolute energy scale using stopping muons in data and tuned Monte Carlo (below)

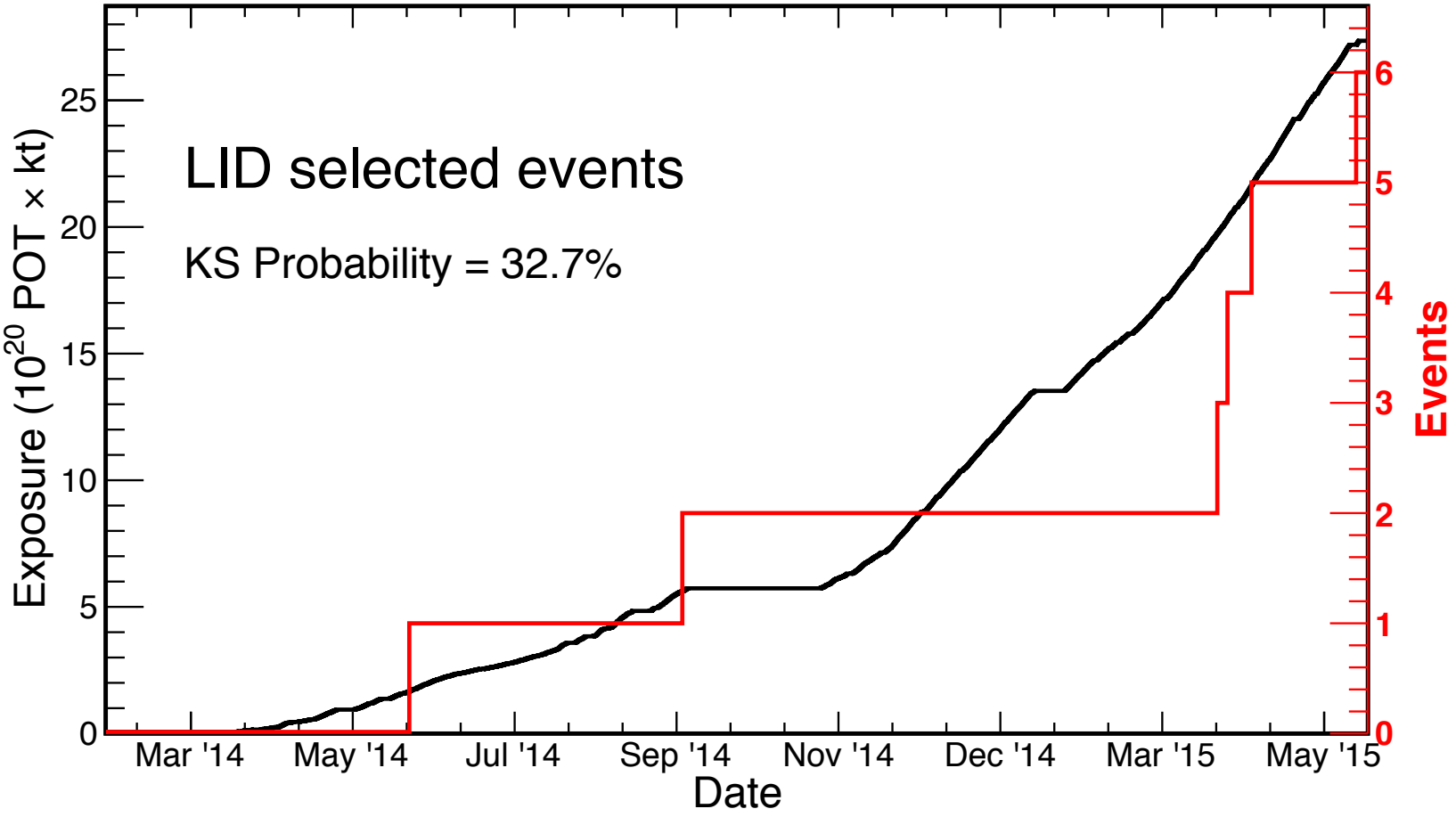


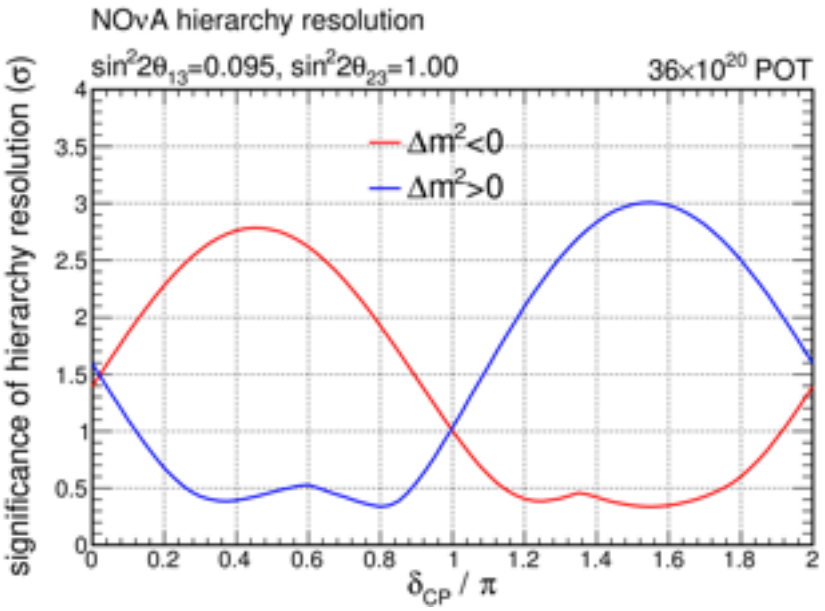


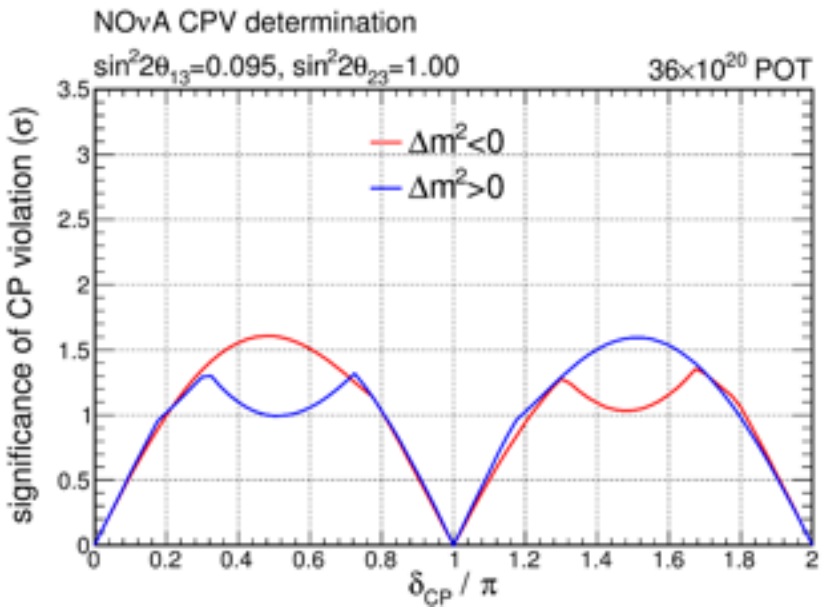



2.74×10^20 POT equiv.
Data
Unoscillated prediction
Best fit prediction (no systs)
Expected 1-σ syst. range
Best fit prediction (systs)
Backgrounds
Normal Hierarchy
2.74×10^20 POT-equiv.
Best fit χ²/N_dof =19.0/16
Events / 0.25 GeV
Reconstructed Neutrino Energy (GeV)
0
10
20
30
40
50
0
1
2
3
4
5

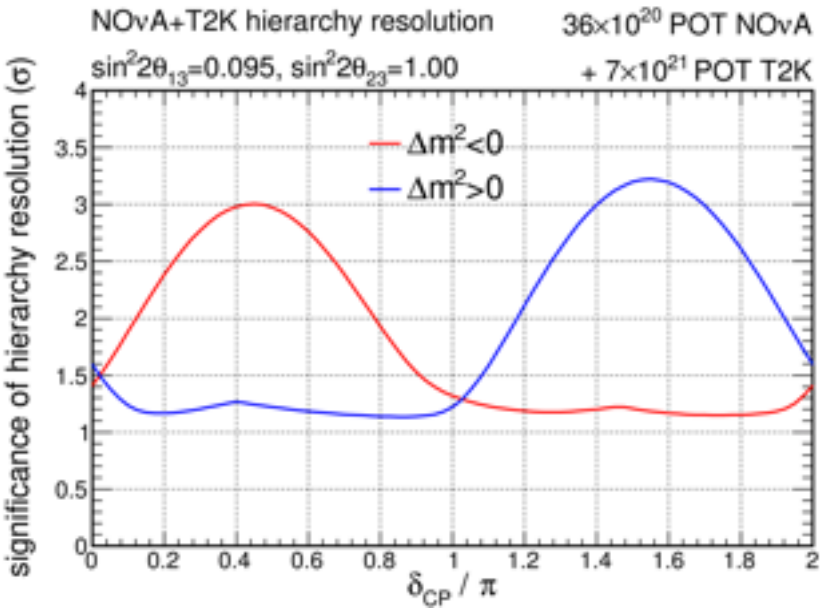

NOvA 2.74×10^20 POT-equiv.
Normal Hierarchy
90% CL
68% CL
Δm²31 (10⁻³ ev²)
sin²θ23
3.5
3
2.5
2
0.3
0.4
0.5
0.6
0.7

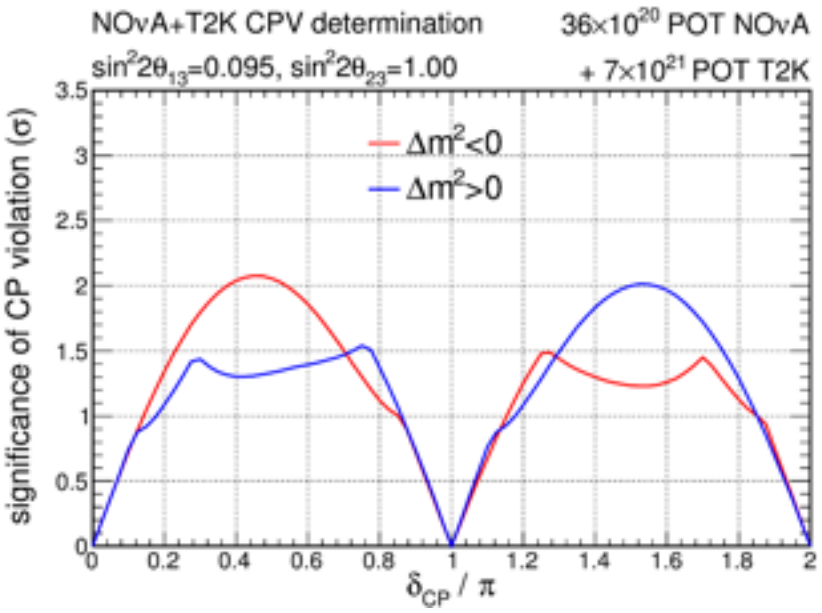

LID selected events
KS Probability = 32.7%
Exposure (10^{20} POT × kt)
Events
Date
0
5
10
15
20
25
0
1
2
3
4
5
6
Mar '14
May '14
Jul '14
Sep '14
Nov '14
Dec '14
Mar '15
May '15



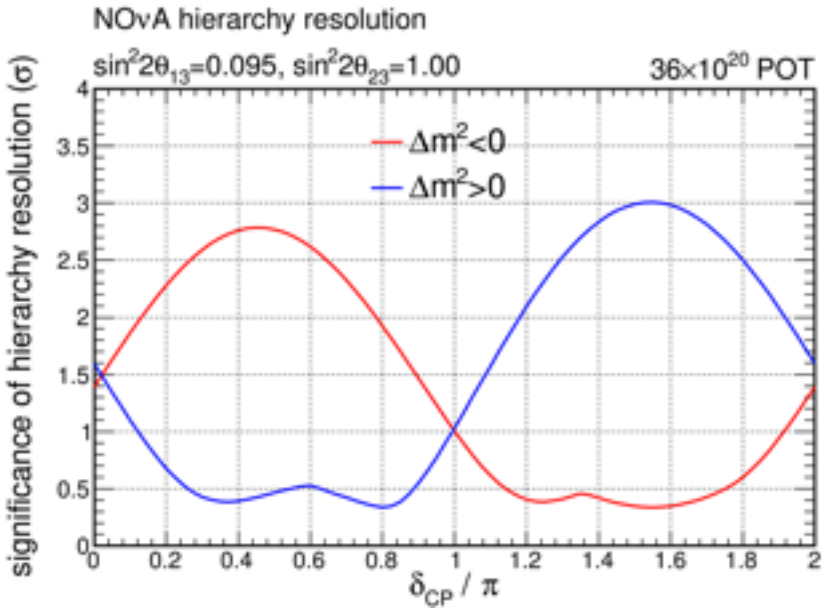


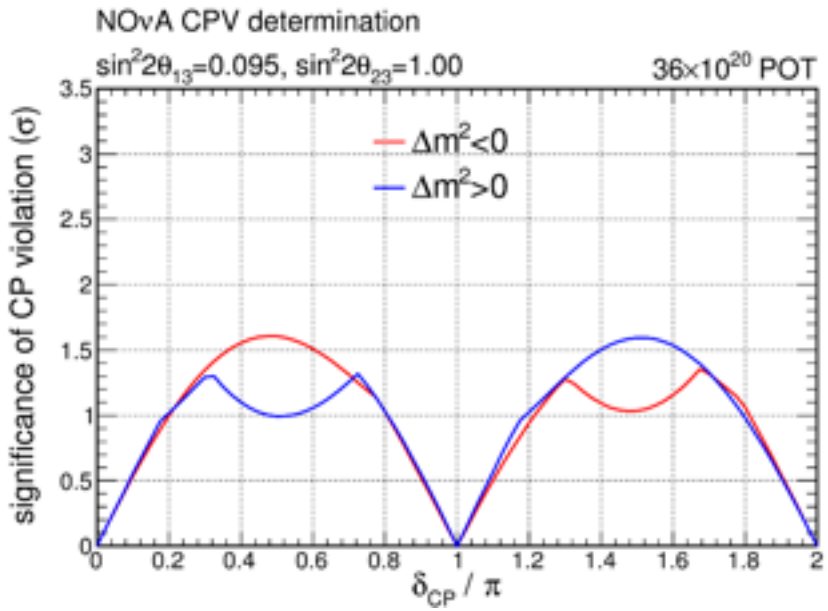
Double-click to edit

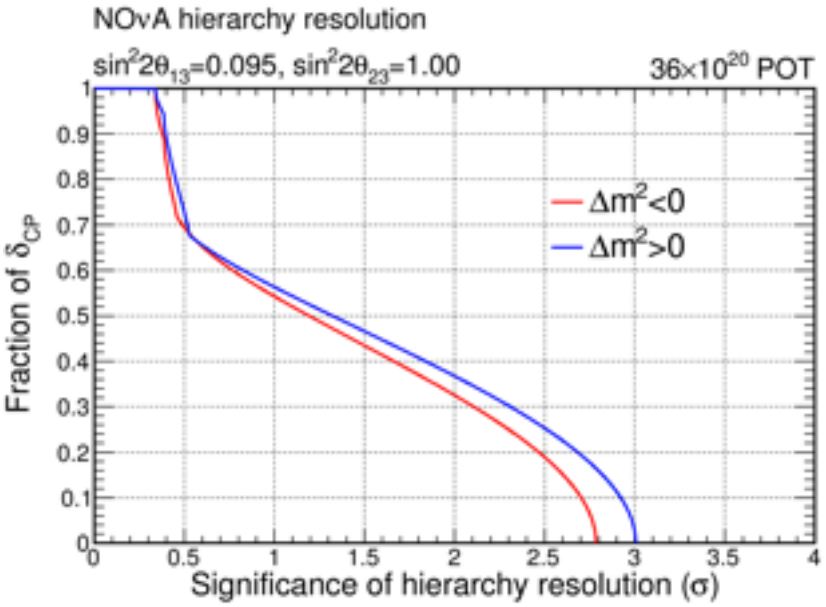




Double-click to edit


NOvA hierarchy resolution
sin²2θ13=0.095, sin²2θ23=1.00
36×10²⁰ POT
Δm²<0
Δm²>0
significance of hierarchy resolution (σ)
δCP / π


NOvA CPV determination
sin²2θ13=0.095, sin²2θ23=1.00
36×10²⁰ POT
Δm²<0
Δm²>0
significance of CP violation (σ)
δCP / π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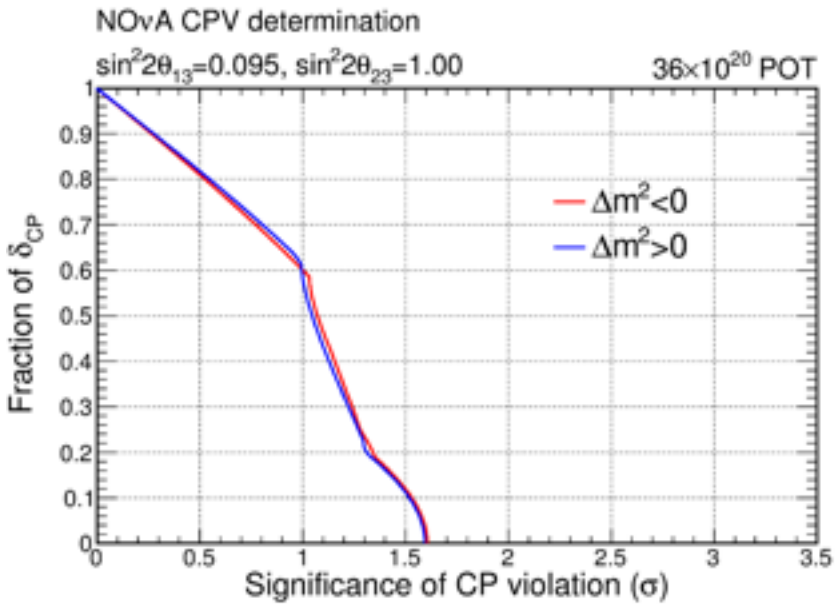
Significance of hierarchy resolution (σ)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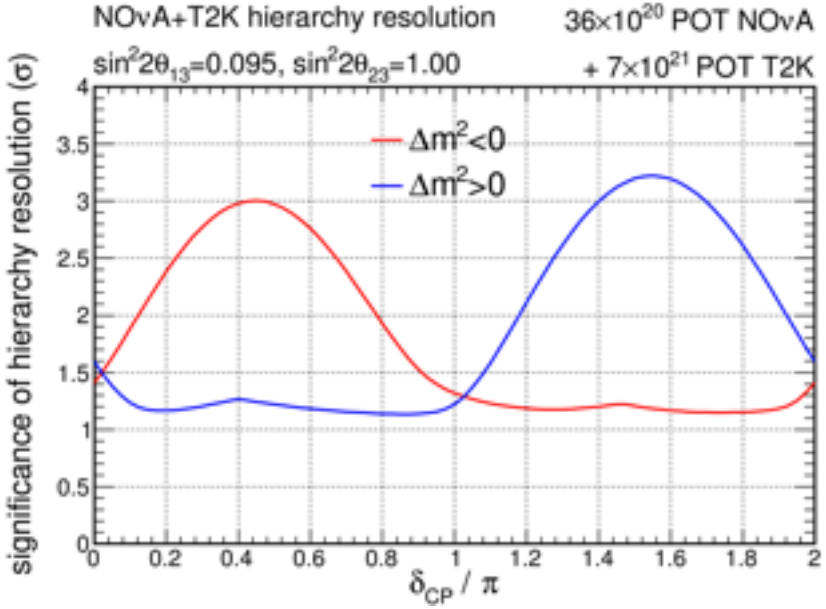
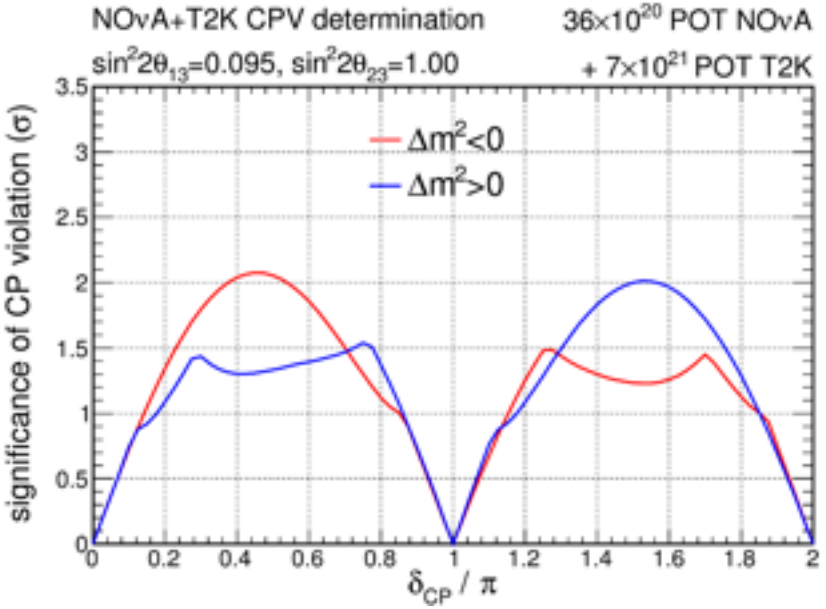

NOvA+T2K hierarchy resolution
36×10^20 POT NOvA
sin^2 2θ13=0.095, sin^2 2θ23=1.00
+ 7×10^21 POT T2K
Δm^2<0
Δm^2>0
significance of hierarchy resolution (σ)
δCP / π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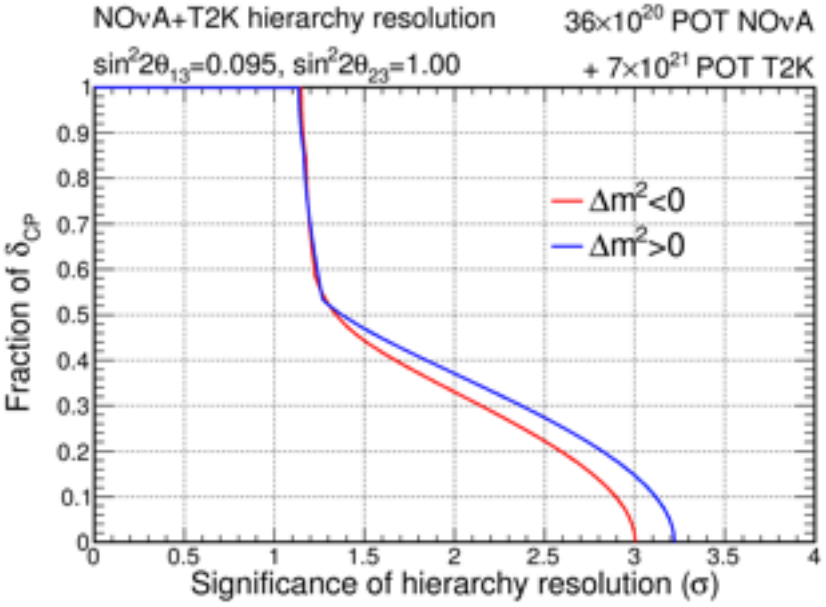
δCP / π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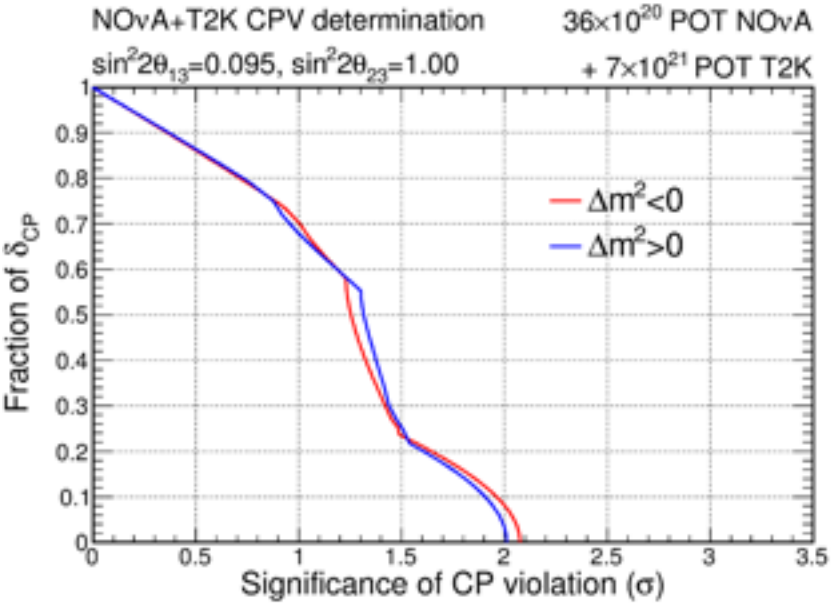
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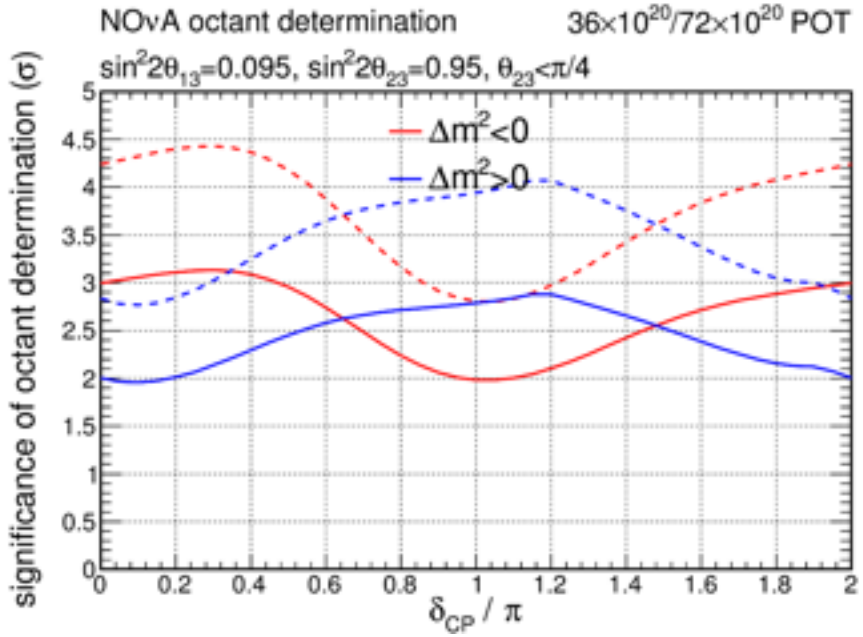
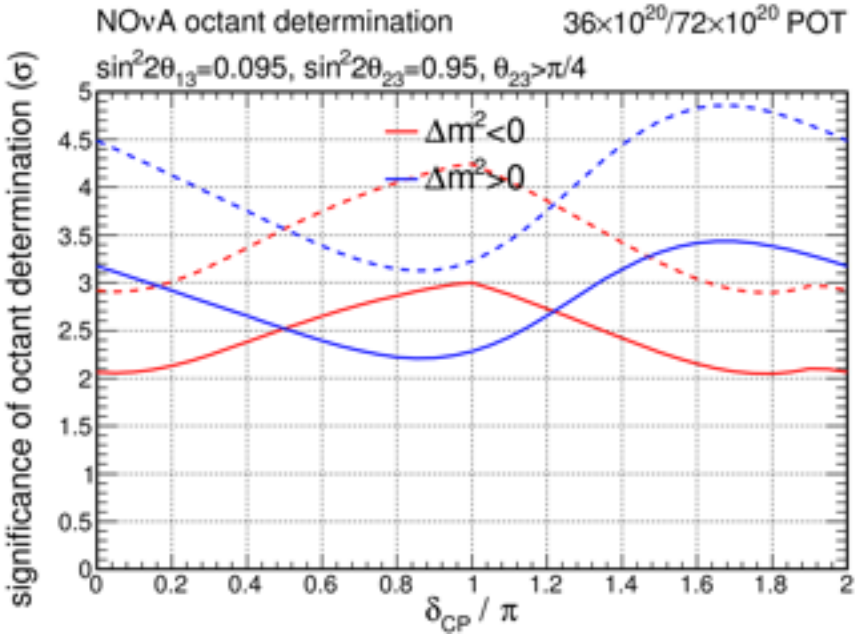

NOvA octant determination
36×10^20/72×10^20 POT
sin^2 2θ13=0.095, sin^2 2θ23=0.95, θ23<π/4
Δm^2<0
Δm^2>0
significance of octant determination (σ)
δCP / π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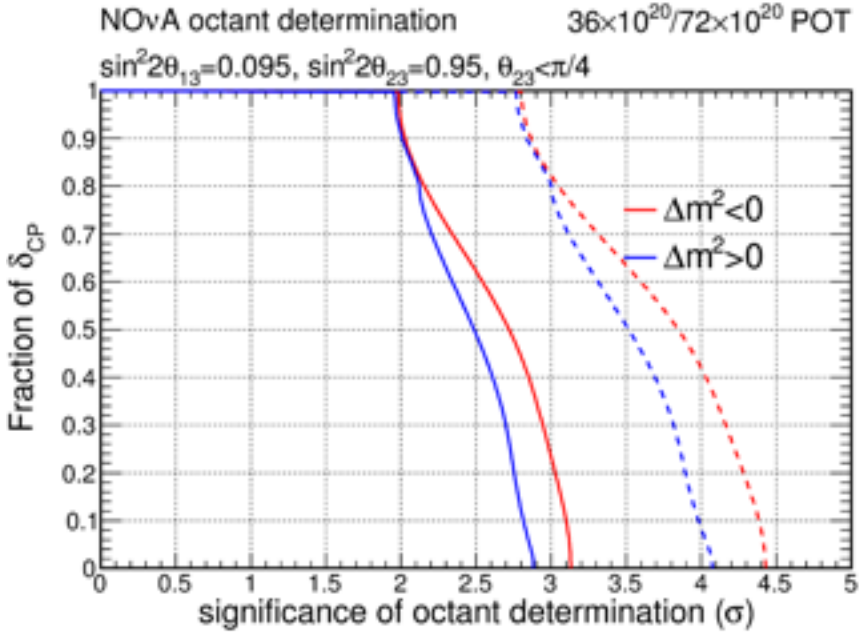
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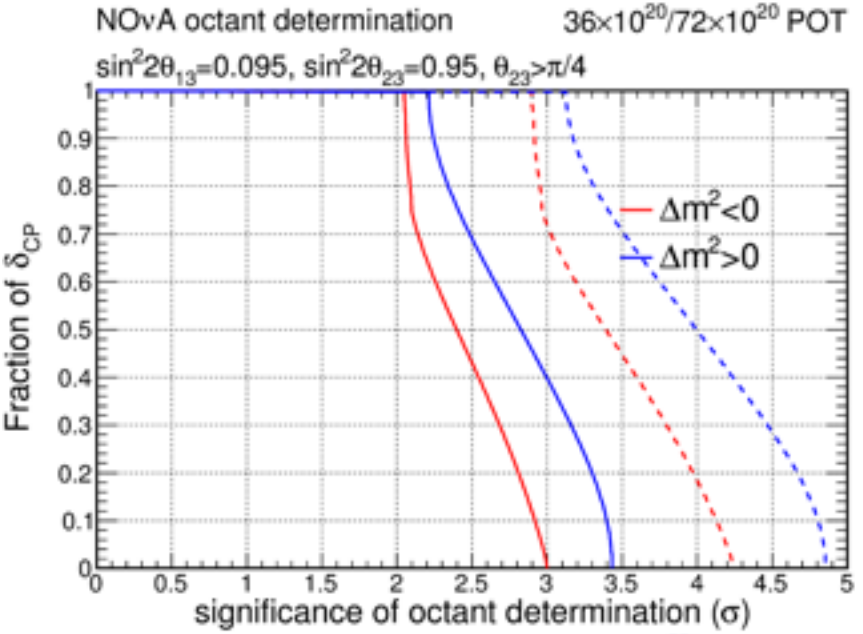
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