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First Results and Prospects of the NOvA Experiment

Peter Shanahan

Colloquium Prague V15

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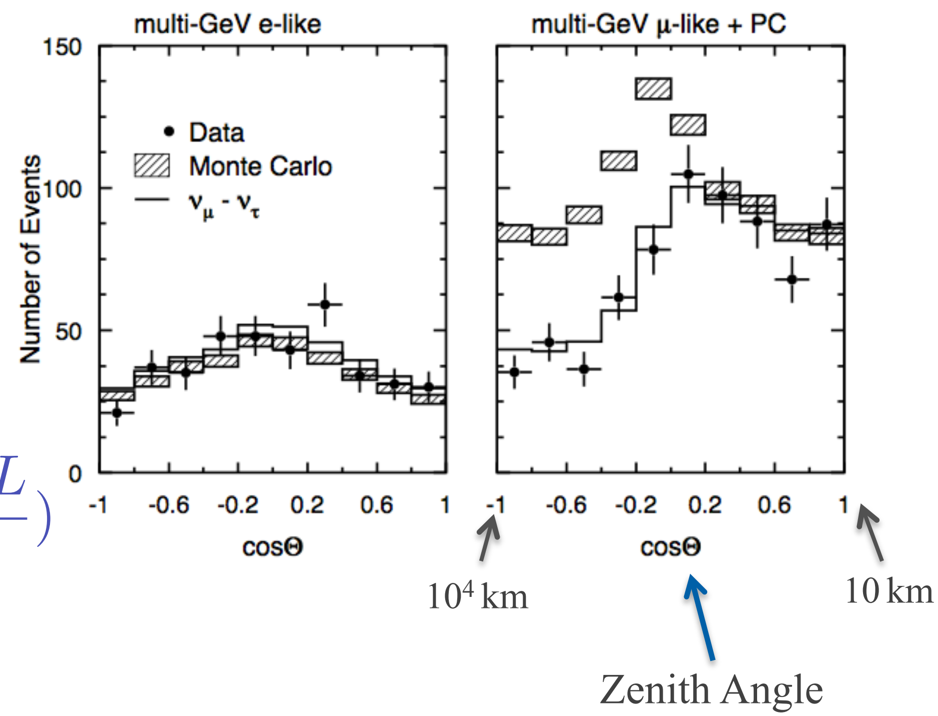
Super-Kamiokande – 1st observation of ν_μ Disappearance

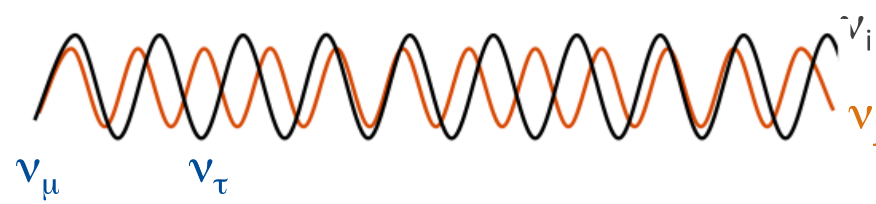
- 2 flavor model
  - Mixing of 2 mass eigenstates by angle θ
  - Survival probability over distance L at energy E

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$



Note degeneracies in P:
$\Delta m^2 \rightarrow -\Delta m^2$
$\theta - \pi/4 \rightarrow \pi/4 - \theta$

  - $\Delta m^2 \sim 2.5 \times 10^{-3}\ eV^2$
  - $\theta \sim 45^o$



3-flavor Neutrino Mixing - PNMS Matrix

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

Phase δ changes sign for anti-neutrino

Majorana Phases, not detectable in oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{13} \equiv \cos\theta_{13}, etc.$$

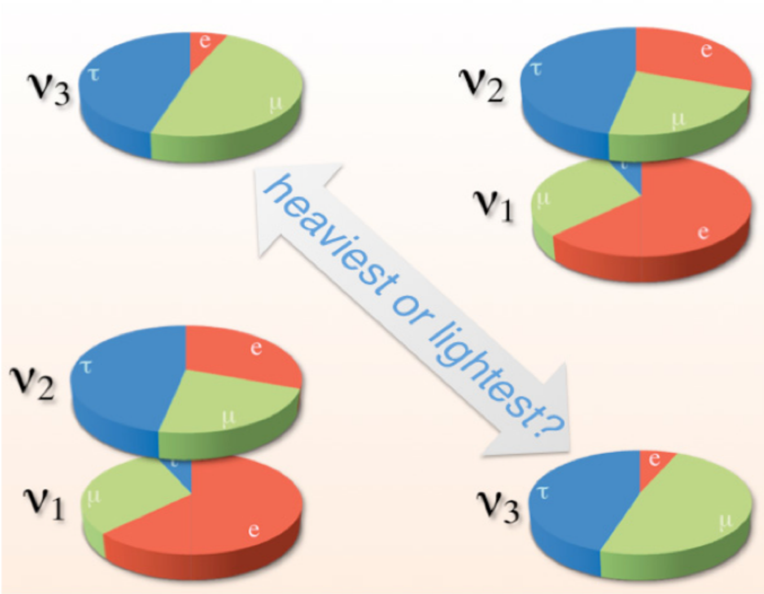
First measured in Atmospheric ν_μ disappearance

θ_{13} first measured in reactors – Daya Bay, Reno, Double Chooz

First measured in Solar ν_e disappearance – SNO & Reactors - KAMLAND

The Current Questions

- The last 15 years have seen tremendous progress
  - $sin^2(2\theta_{23})$, Δm^2_{ATM}, $sin^2(\theta_{12})$, Δm^2_{21}, $sin^2(2\theta_{13,})$ now well measured
- Unanswered questions include
  - Leptonic CP violation: $sin(\delta_{CP})\neq 0$?
  - Mass Ordering:
    - $m_3>m_2,m_1$ or $m_3<m_2,m_1$
  - θ_{23}: Maximal? $\theta_{23}=45^o$
  - θ_{23} octant: if not maximal, is $\theta_{23} <45^o$ or $\theta_{23} >45^o$ (is ν_3 more ν_τ or ν_μ?)



- Is there more to the picture than 3-flavor mixing?

Long Baseline $\nu_\mu \rightarrow \nu_e$ Appearance Probability

- $P(\nu_\mu \rightarrow \nu_e) \cong P_{Atm} + P_{\sin\delta} + P_{\cos\delta} + P_{Sol}$ *DUNE Science Report and References*

$$P_{Atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2[(A-1)\Delta]}{(A-1)^2}$$

$$P_{Sol} = \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}$$

$$P_{\sin\delta} = \alpha 8 J_{CP} \sin\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)} N$$

$$P_{\cos\delta} = \alpha 8 J_{CP} \cot\delta_{CP} \cos\Delta \sin(A\Delta) \frac{\sin[(1-A)\Delta]}{A(1-A)}$$

δ_{CP} and A change sign for $\bar{\nu}$

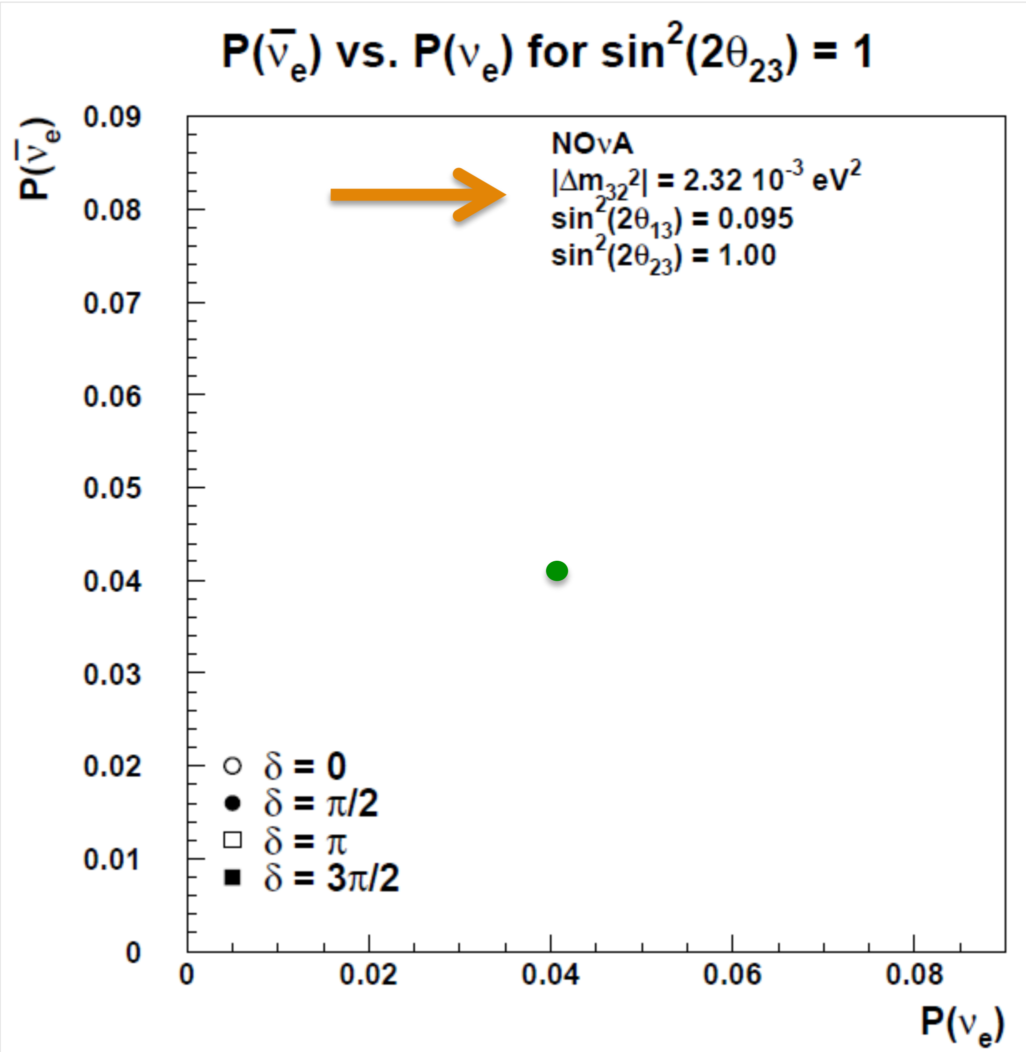
A depends explicitly on (sign of) Δm^2_{31}

$\Delta = \Delta m^2_{31} L/4E$ $\quad A = \sqrt{2} G_F N_e 2E/\Delta m^2_{31}$ $\quad \alpha = |\Delta m^2_{21}|/|\Delta m^2_{31}|$

$J_{CP} = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta_{CP}/8 \approx 0.03 \sin(\delta_{CP})$

Jarlskog Invariant

Long Baseline $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



Comparison of neutrino and anti-neutrino appearance for a specific baseline and energy

Assuming

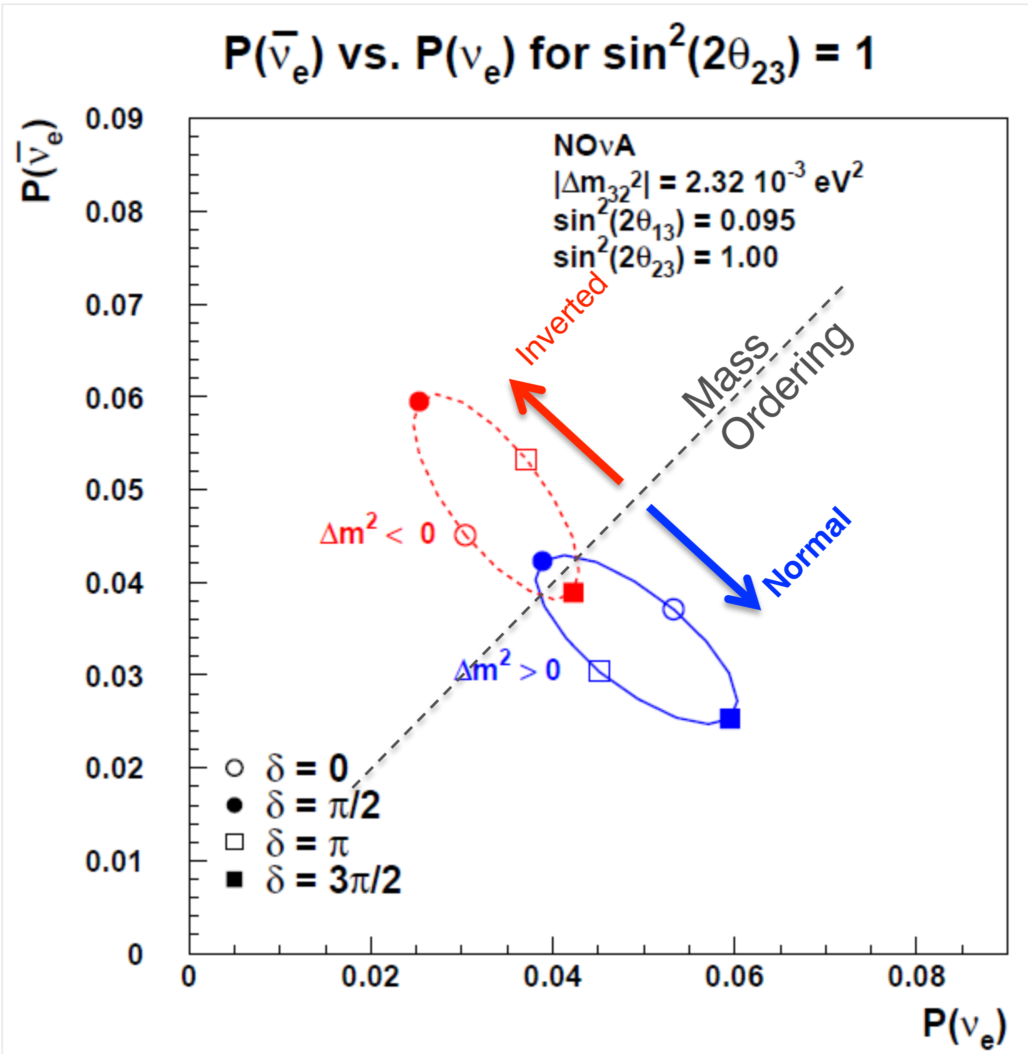
-No matter effect

-No CP Violation

-Maximal θ_{23}

-Not terribly exciting…

Long Baseline $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



CP Violation

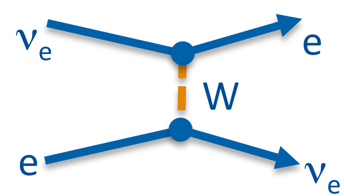
-Probabilities vary on an ellipse with δ_{CP}

Mass Ordering

-Matter (MSW) effect due to presence of electrons in matter

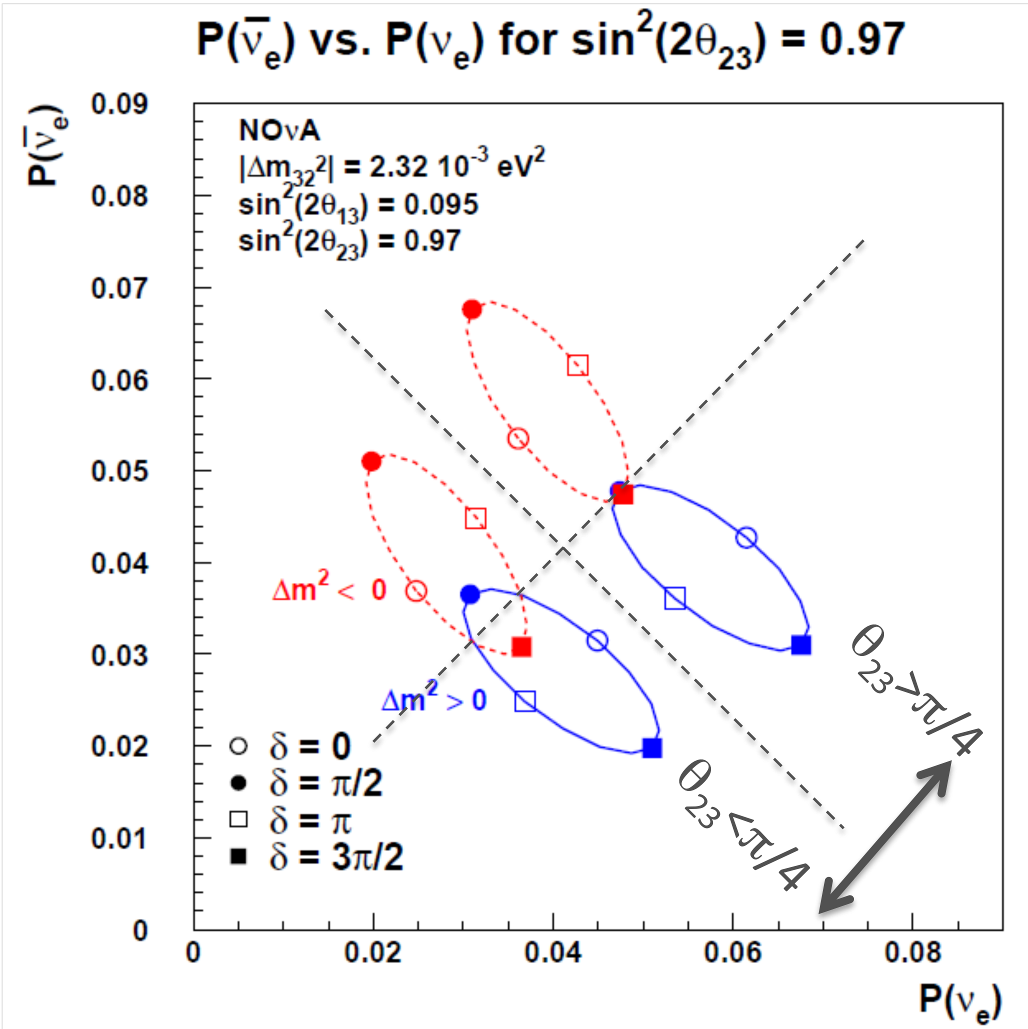
-~30% effect for NOνA, 11% for T2K

$\sqrt{2}G_F N_e 2E/\Delta m^2_{31}$



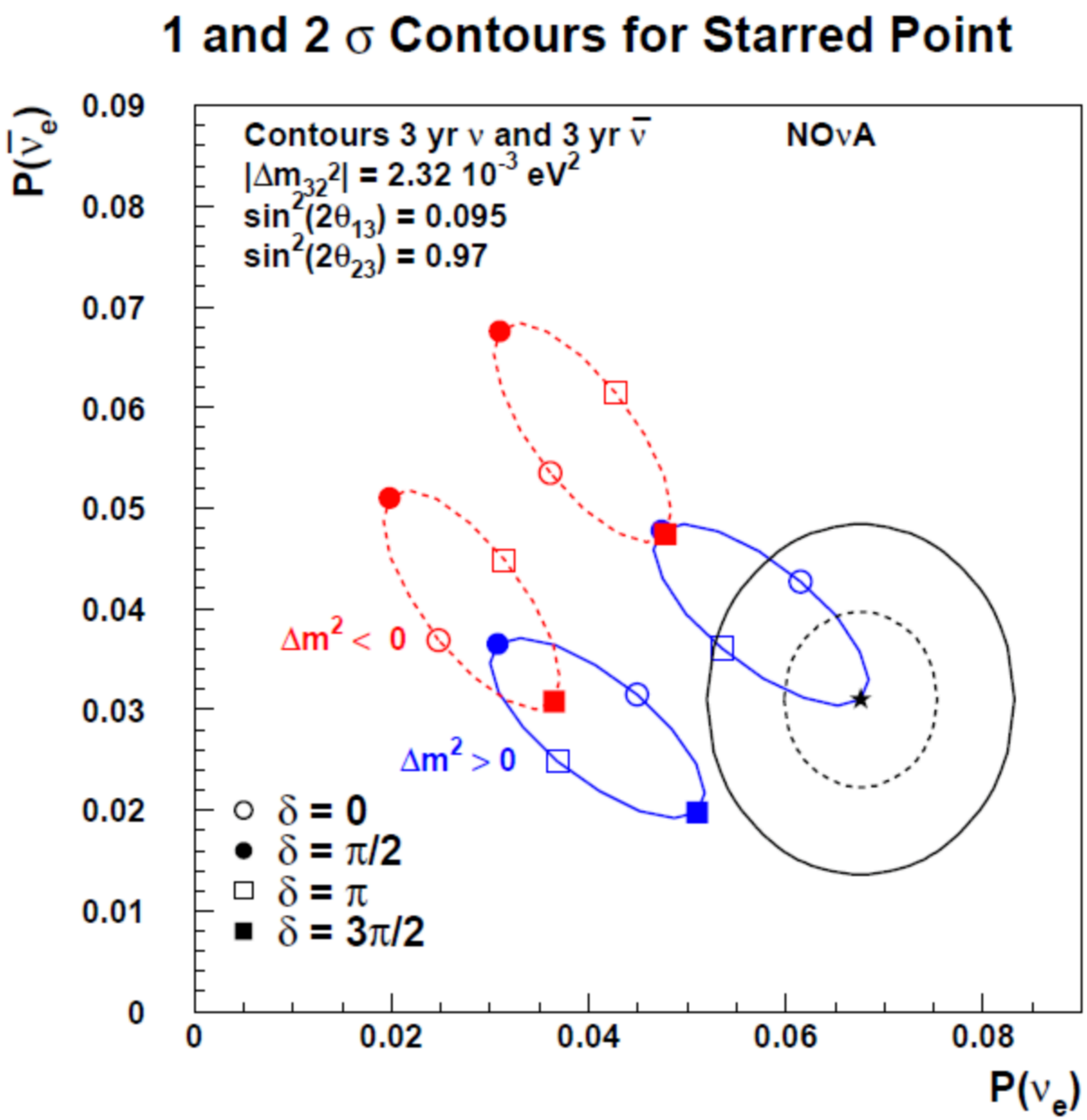
Shown for Maximal θ_{23}

Long Baseline $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



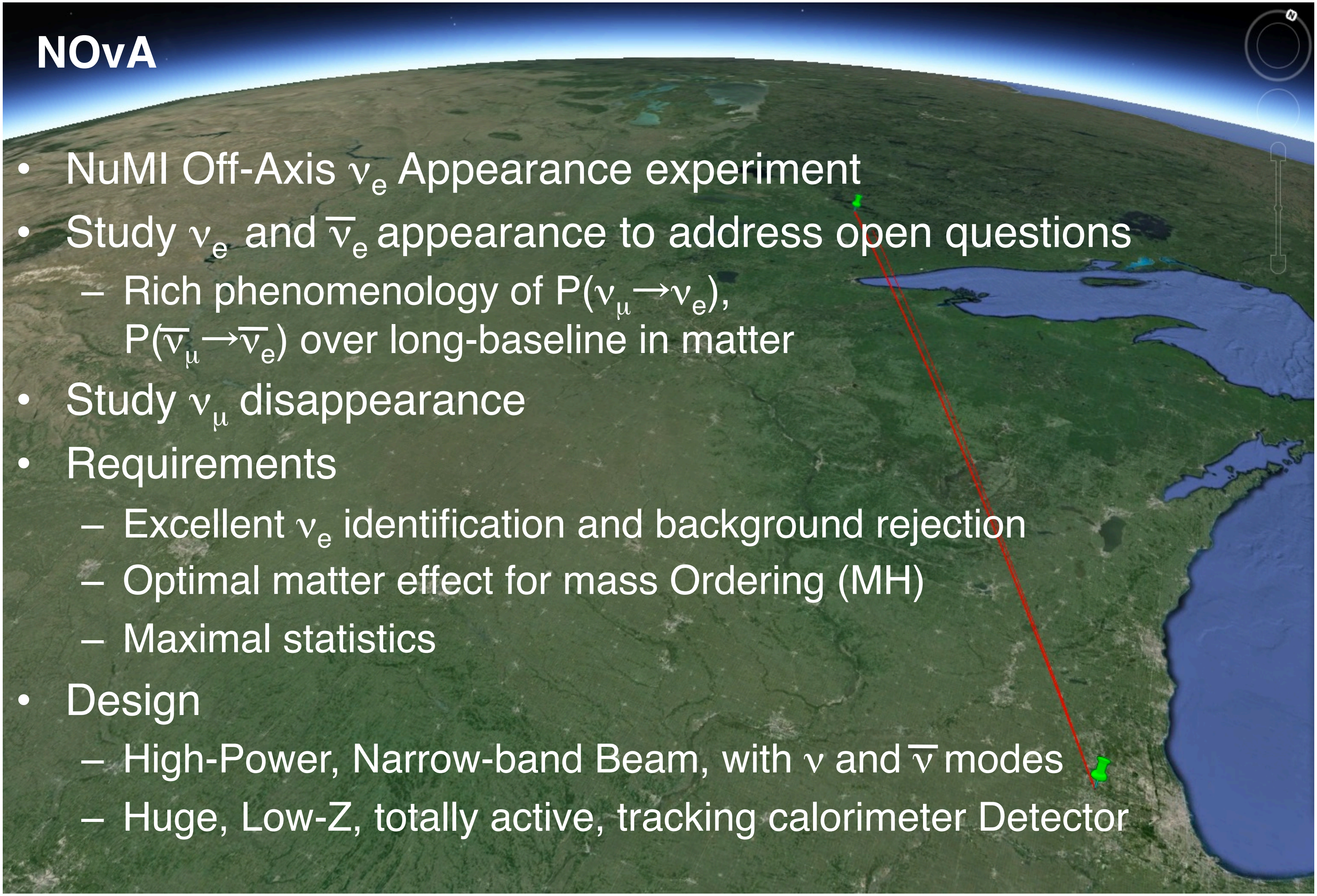
θ_{23} Octant from $\sin^2(\theta_{23})$ in leading term of $P(\nu_\mu \rightarrow \nu_e)$, $P(\nu_\mu \rightarrow \nu_e)$

Long Baseline $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



Hypothetical measurement corresponding to most favorable parameter values.

NOvA



- NuMI Off-Axis ν_e Appearance experiment
- Study ν_e and $\overline{\nu}_e$ appearance to address open questions
  - Rich phenomenology of $P(\nu_\mu \rightarrow \nu_e)$, $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ over long-baseline in matter
- Study ν_μ disappearance
- Requirements
  - Excellent ν_e identification and background rejection
  - Optimal matter effect for mass Ordering (MH)
  - Maximal statistics
- Design
  - High-Power, Narrow-band Beam, with ν and $\overline{\nu}$ modes
  - Huge, Low-Z, totally active, tracking calorimeter Detector

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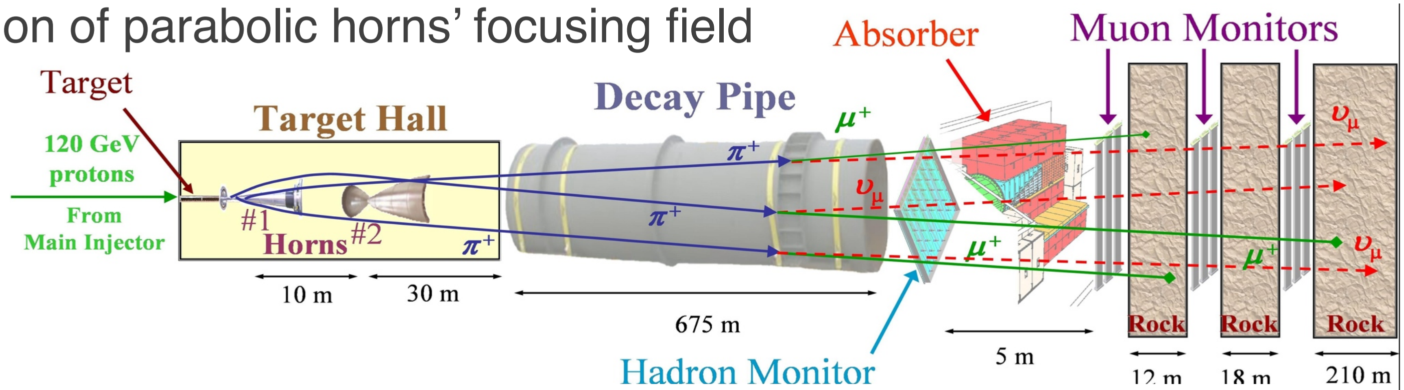
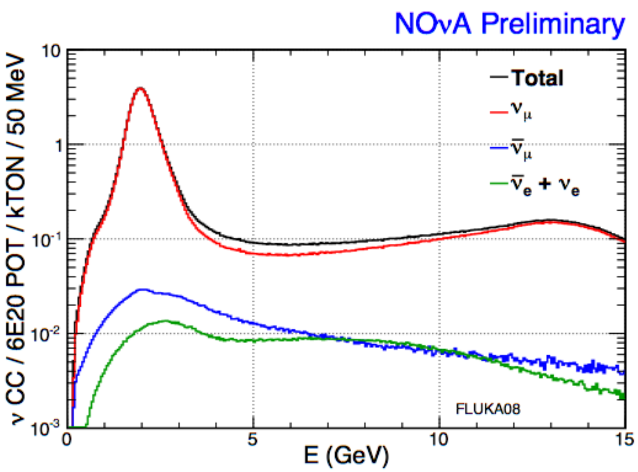
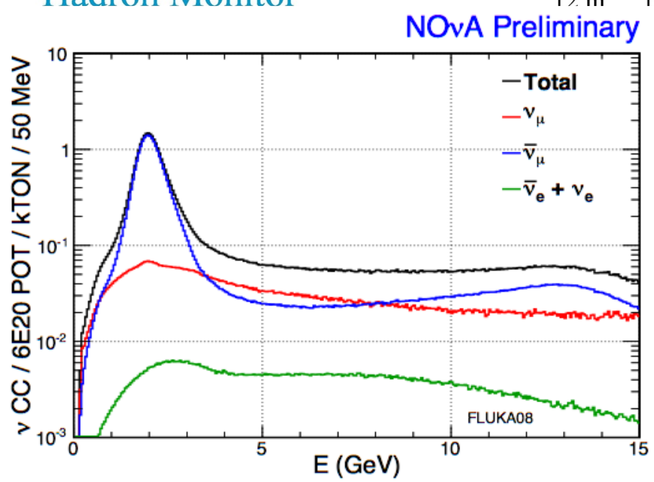
NuMI Beam

- High beam power
  - NuMI/accelerator upgrade was a major part of the NOvA project
  - 520 kW achieved in June 2015. Expect 700 kW in coming year.
- ν and $\bar{\nu}$ beam modes
  - Direction of parabolic horns' focusing field



Neutrino mode:
~1% wrong-sign





Anti-neutrino:
~7% wrong-sign

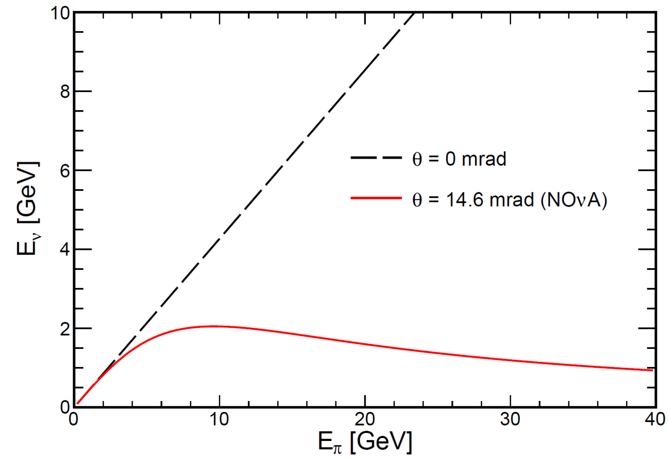
Location

Simulation

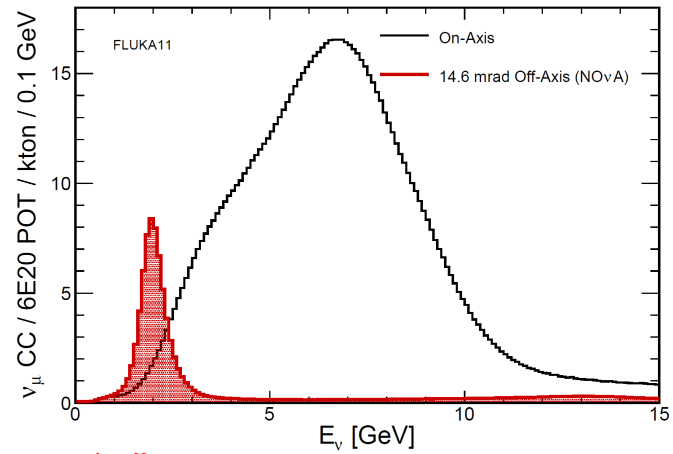
- 14 mrad (11km) off the NuMI beam axis
  - Pion 2-body decay kinematics

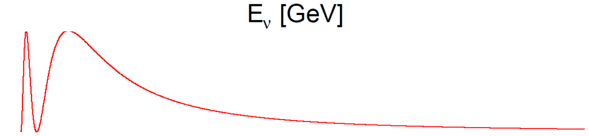
$$E_{\nu} = \frac{0.43 E_{\pi}}{1 + \gamma^2 \theta^2}$$

    - Neutrino spectrum peaks around 1st oscillation maximum
    - High energy tail suppressed: reduces Neutral Current π^0 background
- As far as possible from Fermilab for maximum matter effect/Mass Ordering sensitivity
  - 810 km



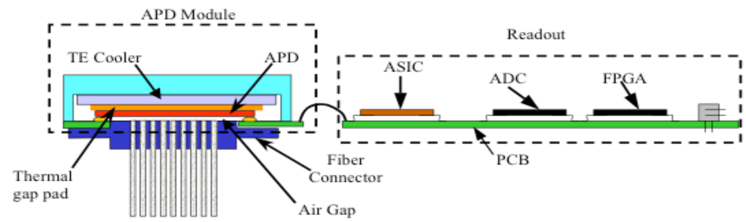
NOνA Simulation

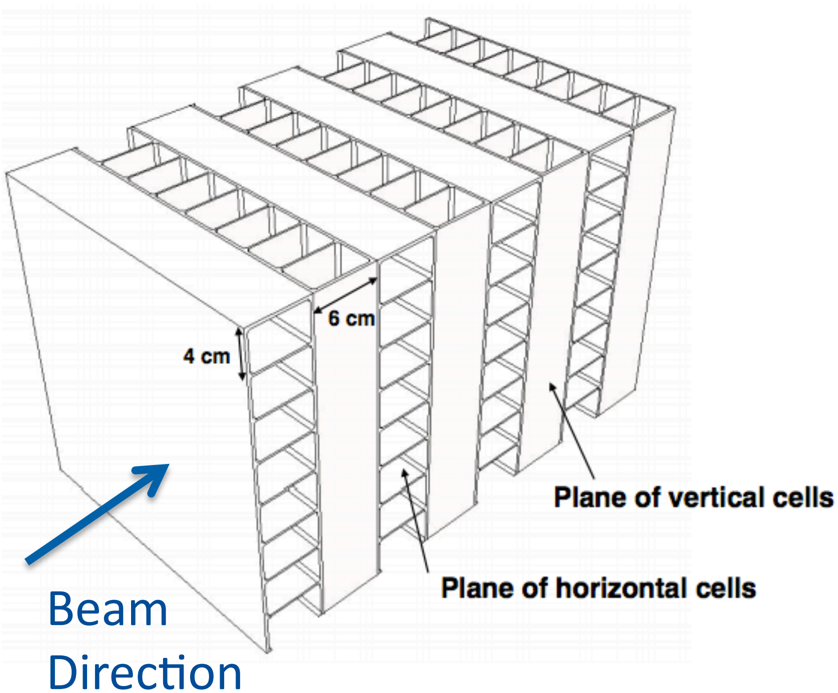




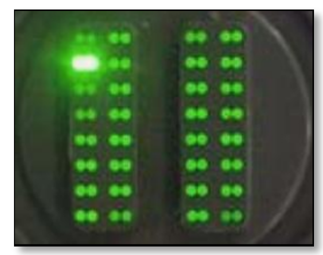
NOvA Detector Technology

- Low-Z tracking Calorimeter
  - PVC Cell Structure
  - Mineral oil + 5% pseudocumene

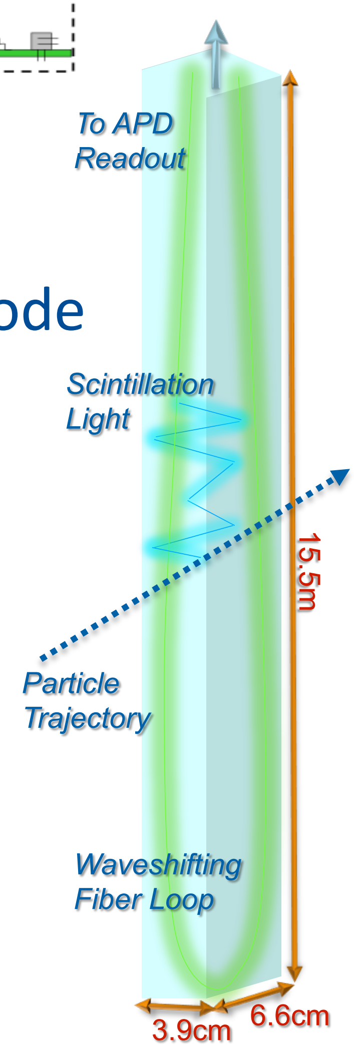




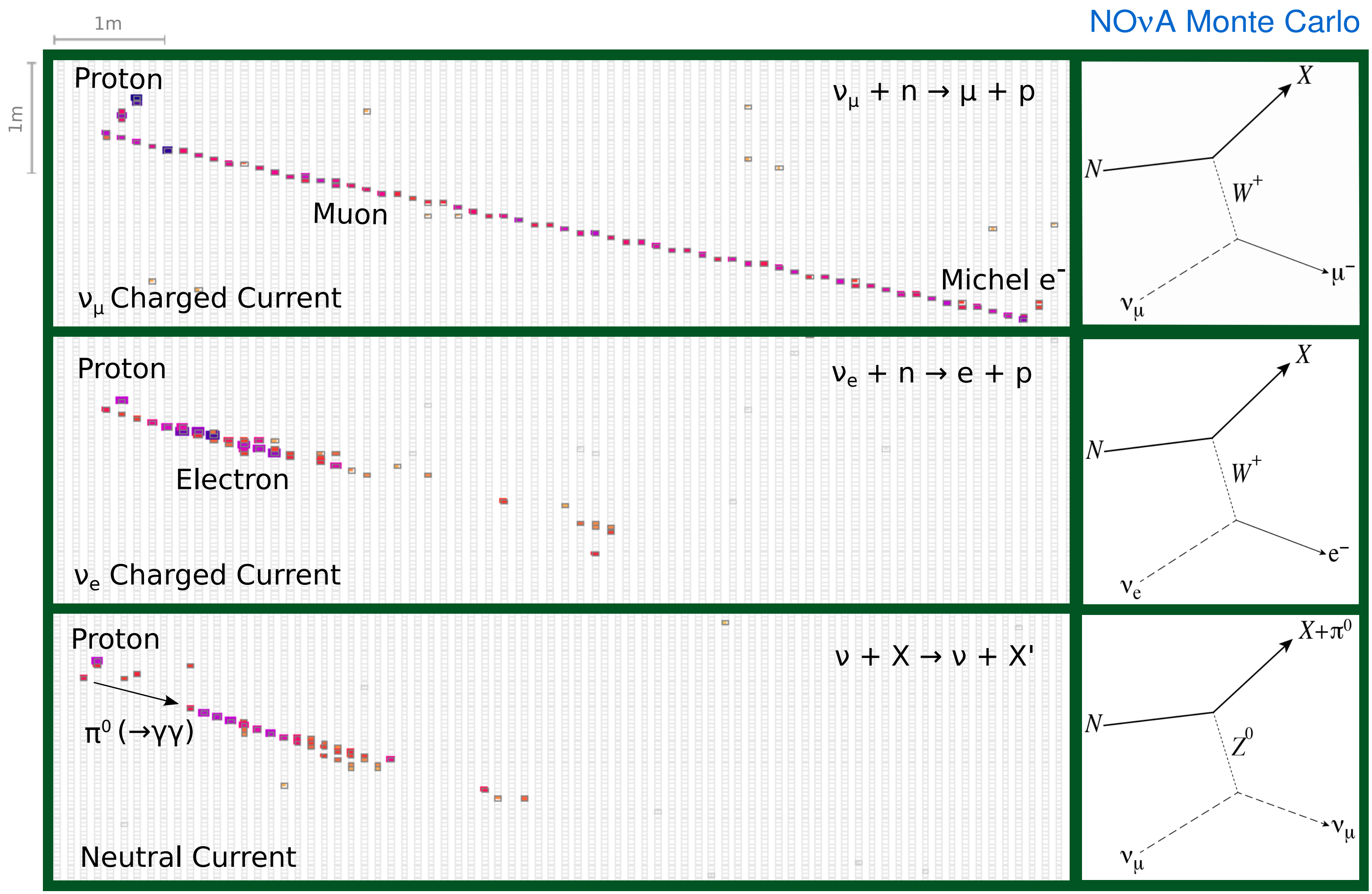
32 cells per Avalanche Photo Diode



- ~6 planes per radiation length
  - Excellent Electro-magnetic shower characterization

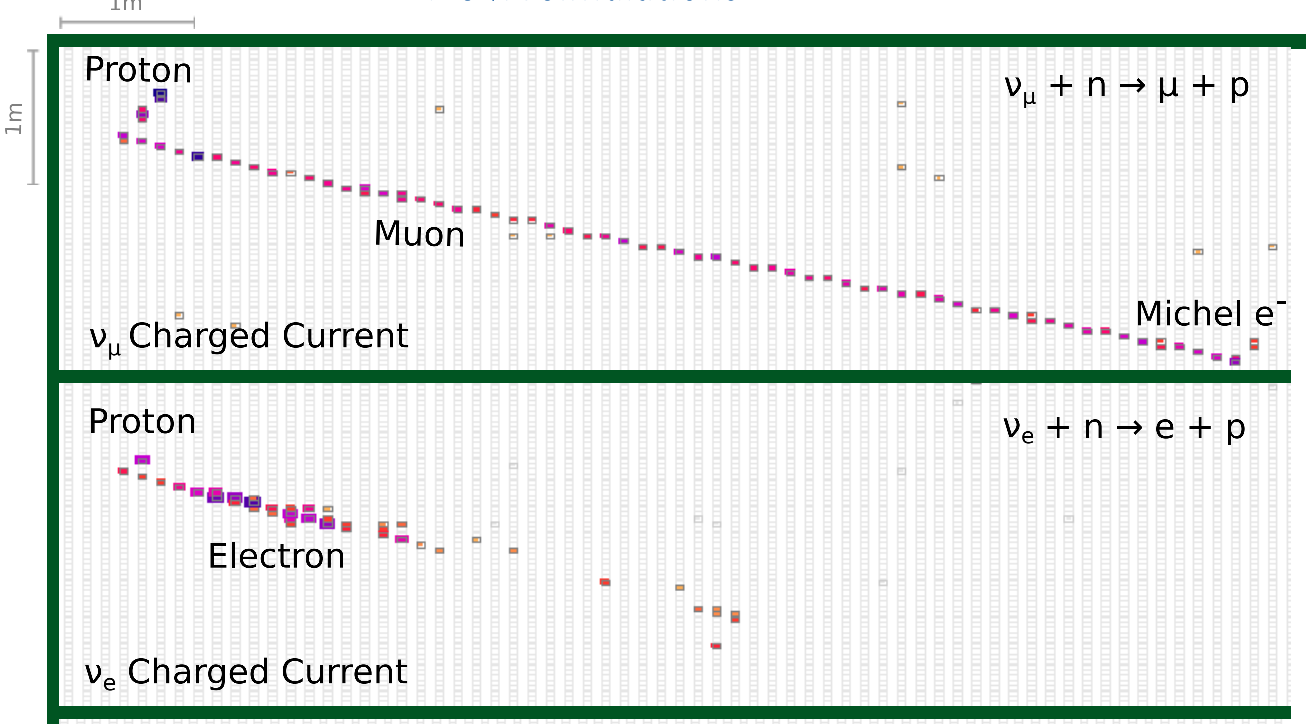


Event Topologies in NOνA

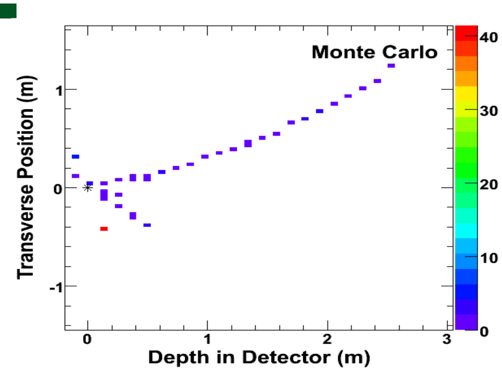


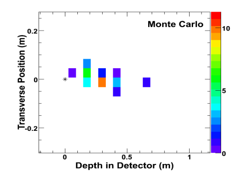
Event Topologies in NOνA vs. MINOS

NOνA Simulations



MINOS Simulations





Compare to representative event topologies in MINOS iron-scintillator tracking calorimeter optimized for ν_μ charged current

How Big a Detector Is Needed?

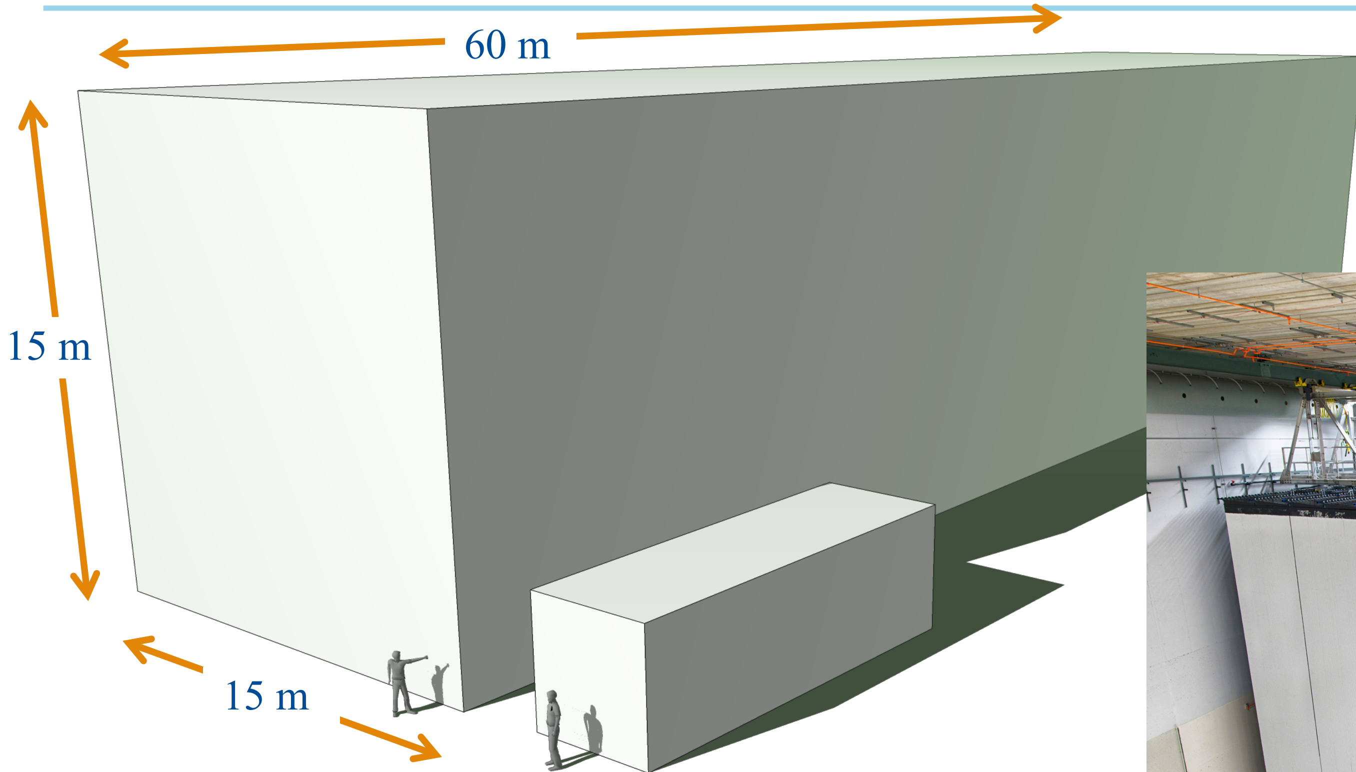
- For a very rough estimate, assume…
- we can get $O(10^{13})$ pion decays per second in our beamline decay pipe
- Neutrinos in area A=1 cm^2 per decay at z=810 km, θ=14mr

$$F = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

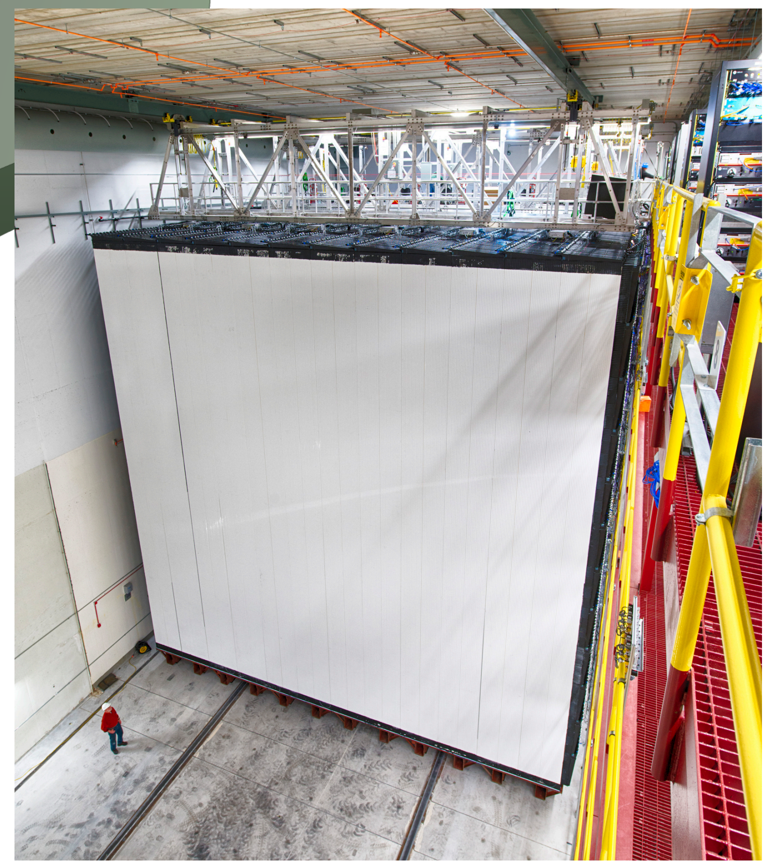
  – Where $\gamma = E_\pi / m_\pi = 100$ as representative
  – $F = 5\times10^{-14}$ ν/decay/cm^2
- Neutrino flux = $10^{13} \times 5\times10^{-14}$ = 0.5 /cm^2/sec
- Cross section 10^{-38} cm^2/nucleon.
- For O(1) interaction/day, need
  – $(10^{-38}$ cm^2/nucleon x 0.5/cm^2/sec x 10^5 sec/day$)^{-1}$ = 2×10^{33} nucleons or 3.3 kt

Of course, simulations provide a more reliable number…

NOvA Detectors



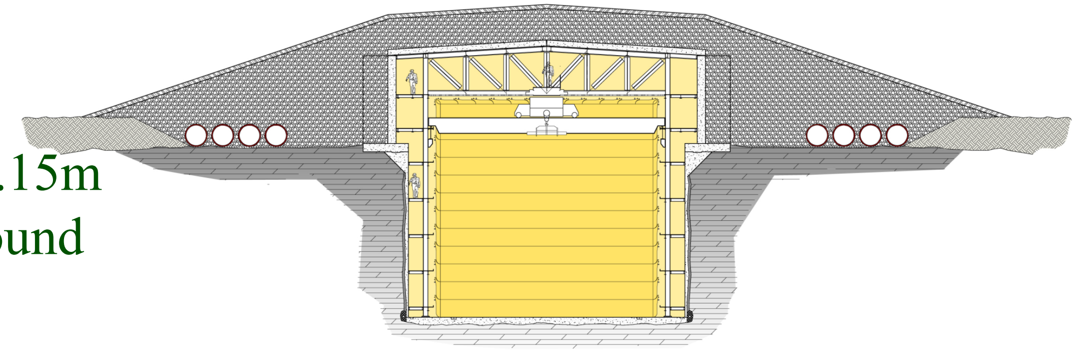
- Far Detector
  - 14 kT
  - 896 planes



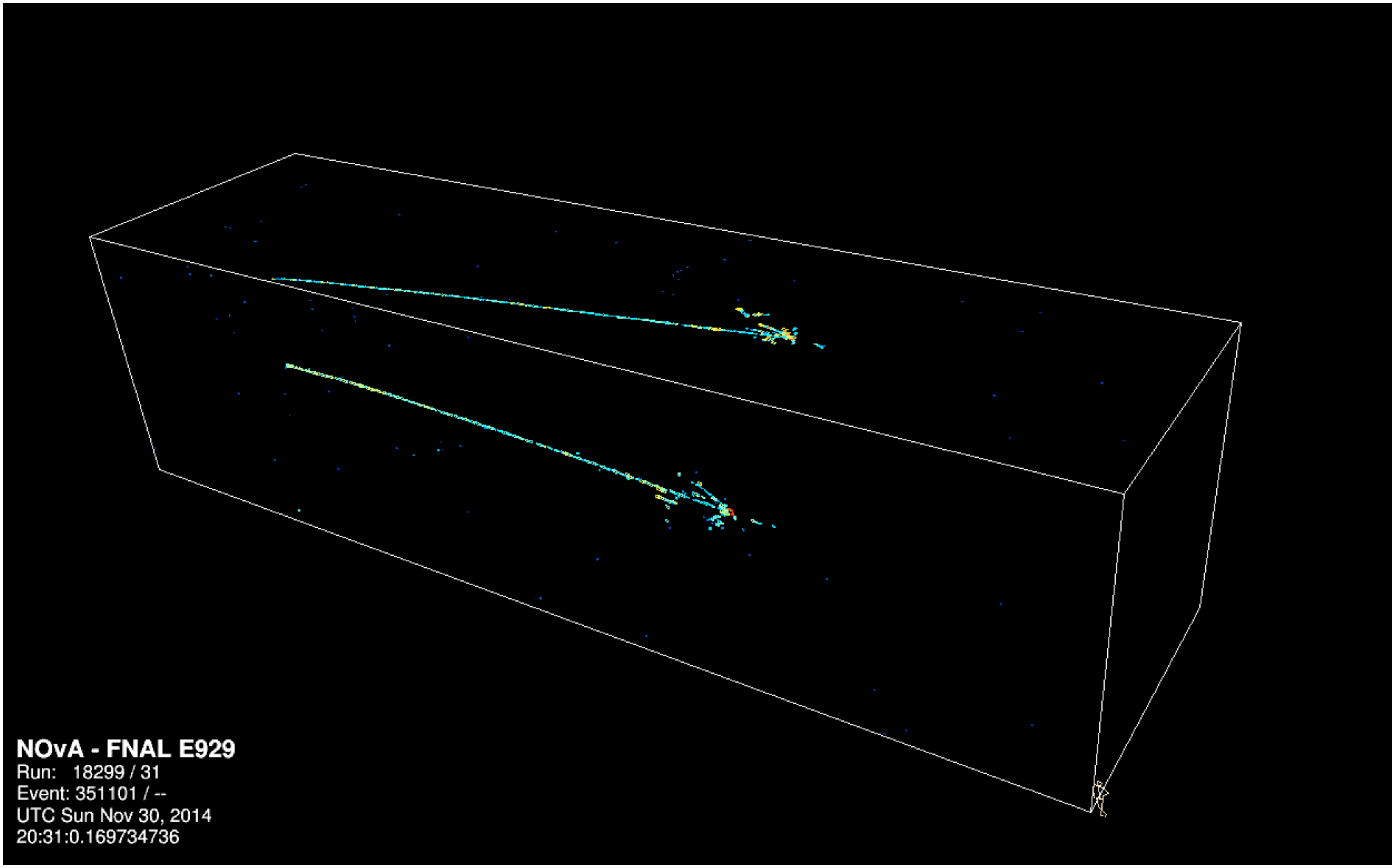
- Near Detector
  - 293 tons
  - 192 planes, plus a muon catcher with 10 planes of iron

Far Detector

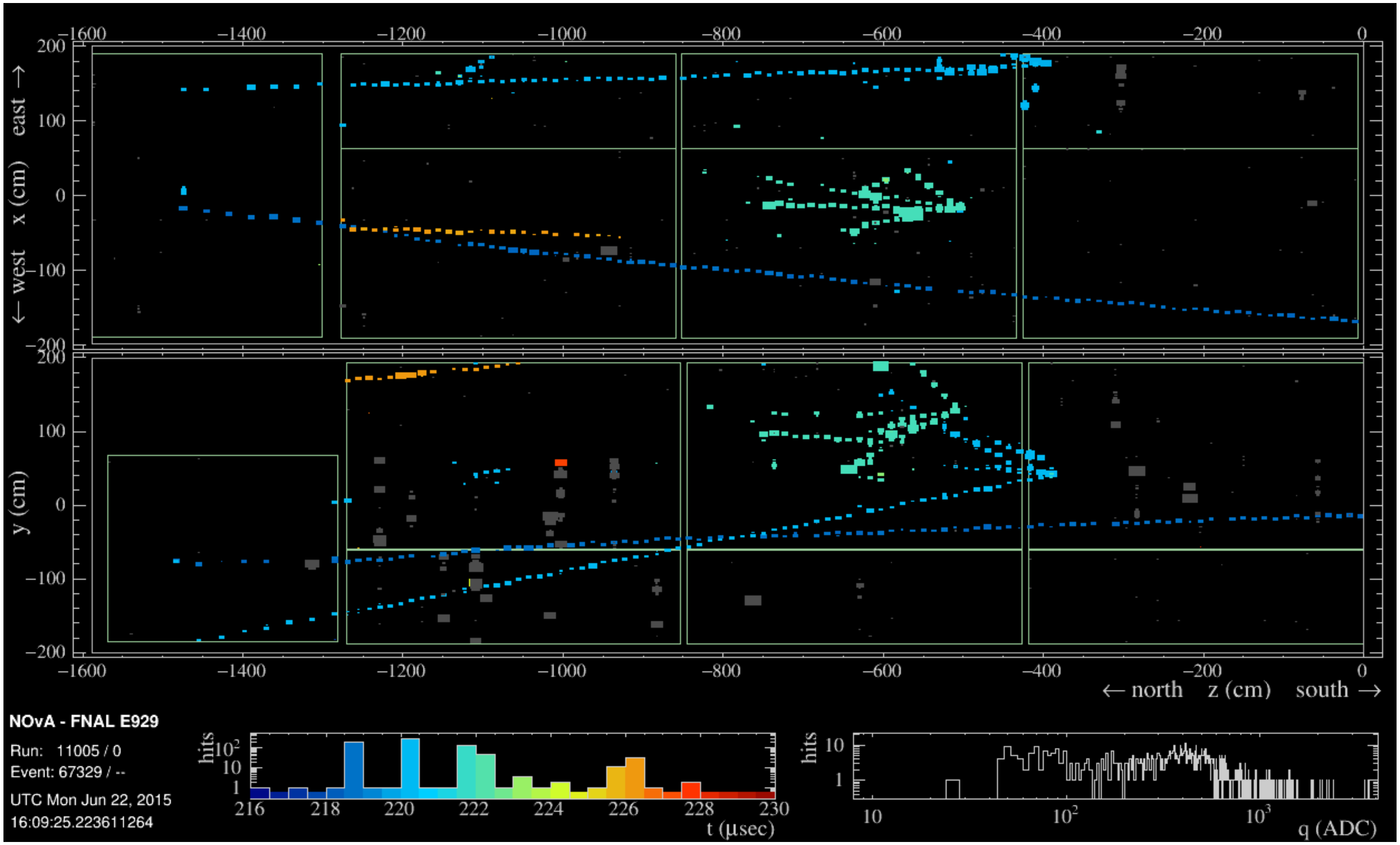
– Detector is mostly below grade
– Overburden: 1.37m concrete + 0.15m Barite ($BaSO_4$) for cosmic background reduction



NOvA Far Detector ν_μ Candidate

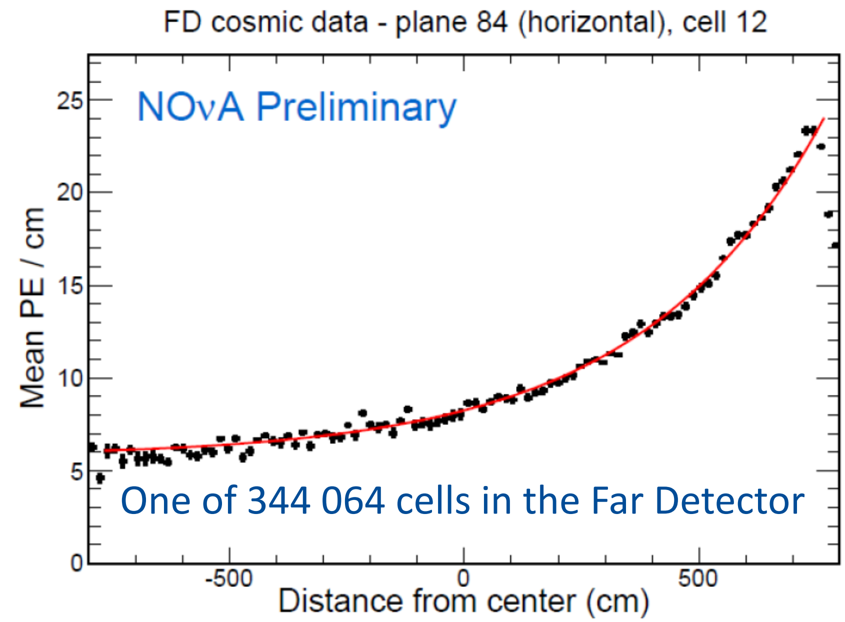


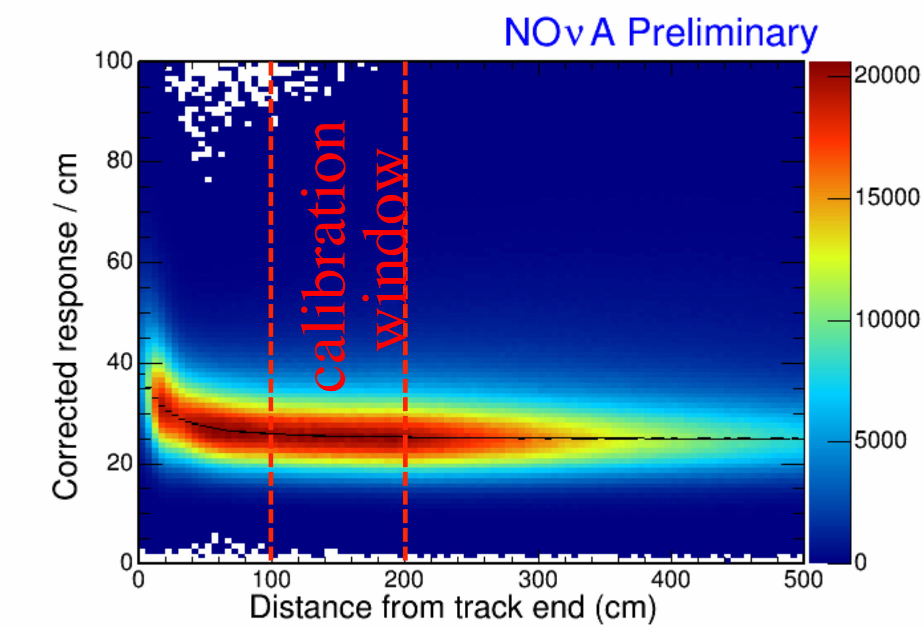
NOvA Near Detector – Typical NuMI Spill



Calibration

- MIP energy deposition of cosmic muons used to correct attenuation in Wavelength Shifting Fiber

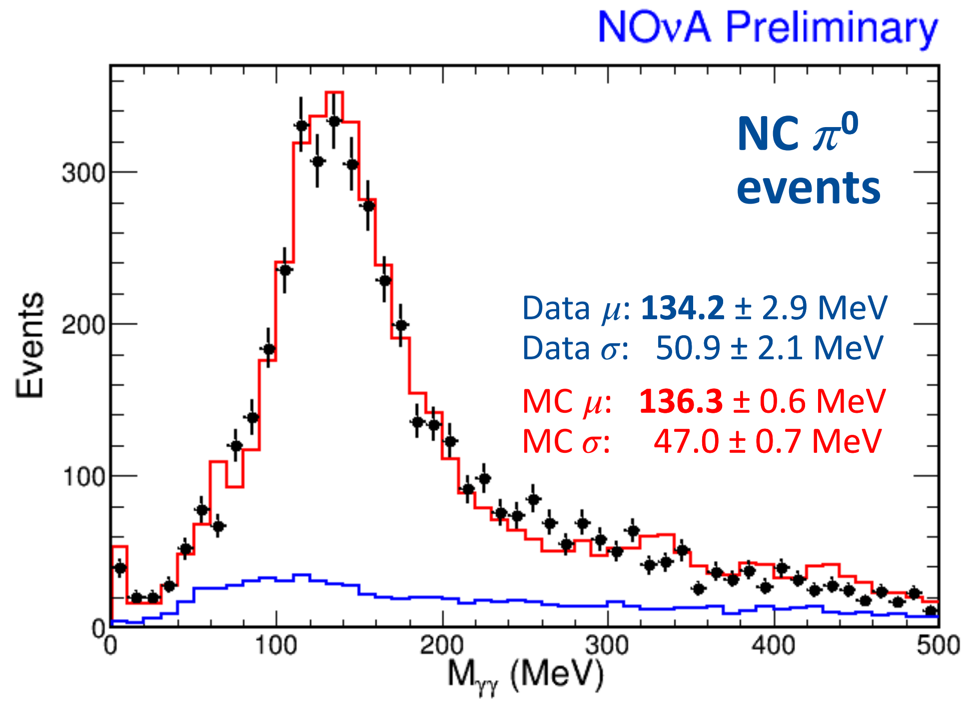


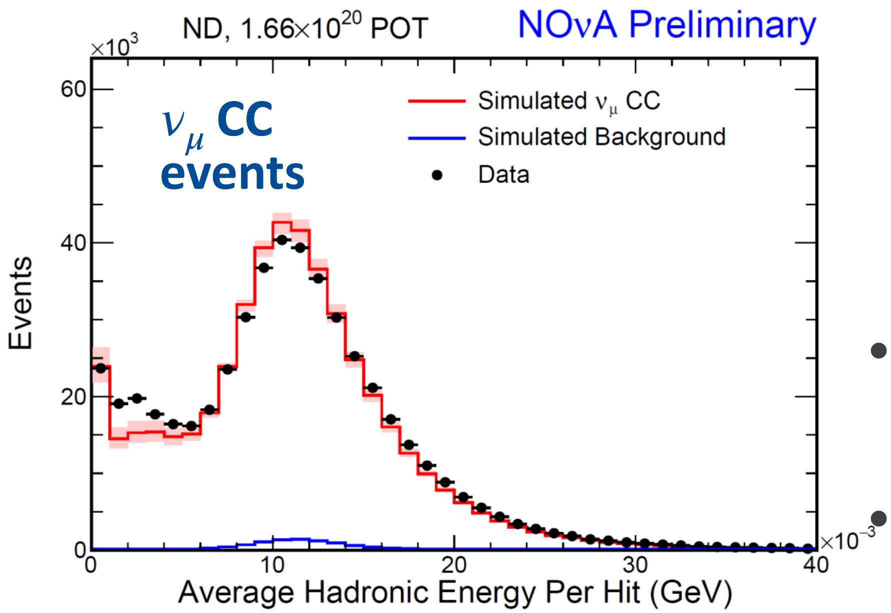


- Stopping muons provide absolute energy scale

Probing the energy scale calibration

- Reconstructed π^0 mass
  - $m^2_{\pi^0}=2E_{\gamma1}E_{\gamma2}(1-\cos(\theta_{\gamma\gamma}))$





- Energy deposition of hadronic hits
- All checks agree to within 5%

ν_μ Disappearance Analysis

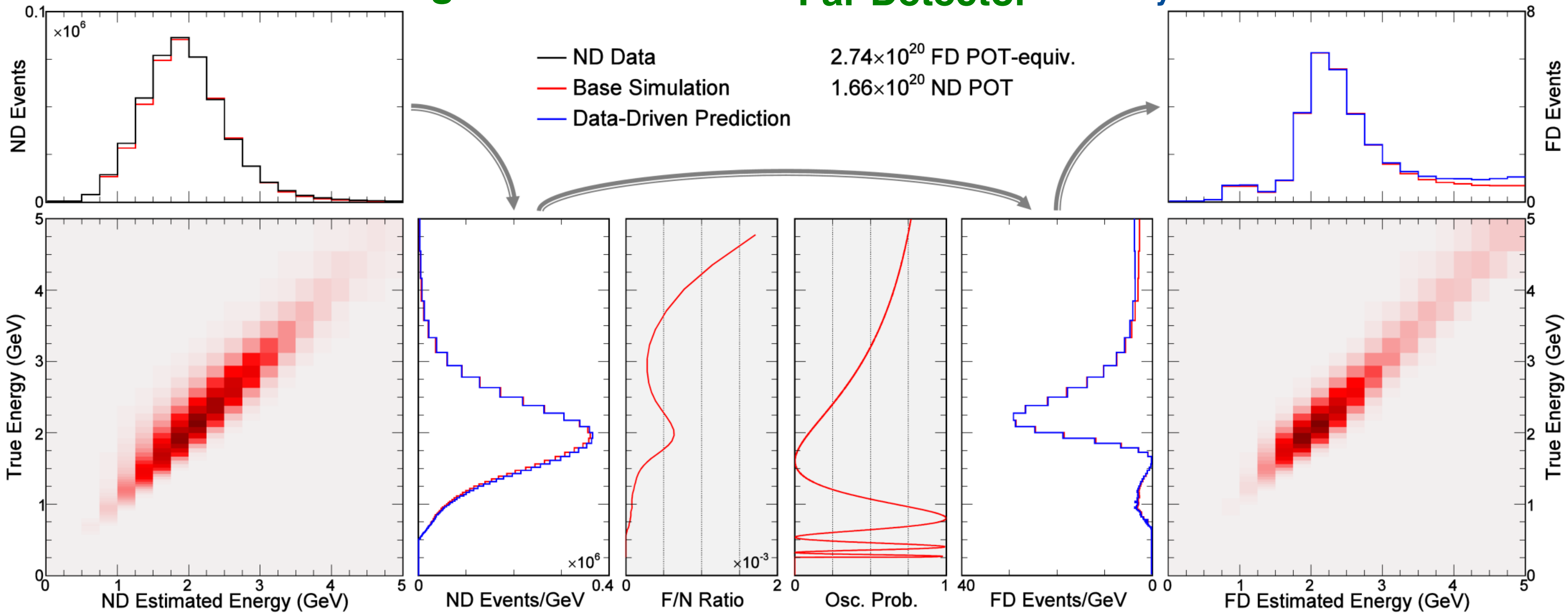
Observe Near Detector Interaction Spectrum

Relate to true signal spectrum using simulation

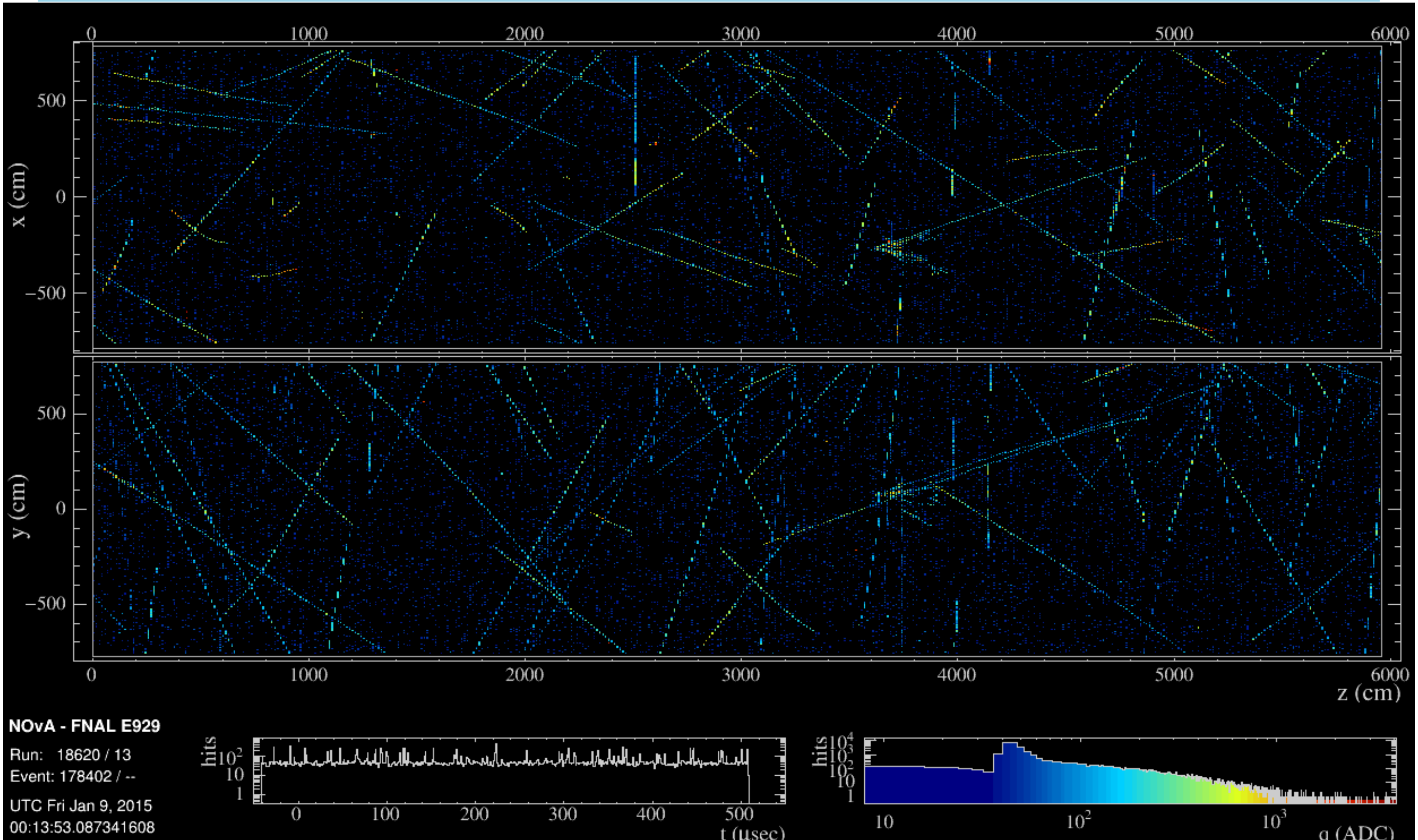
Predict Oscillated true spectrum in Far Detector

Compare Predicted Far Detector Interaction Spectrum to Observed

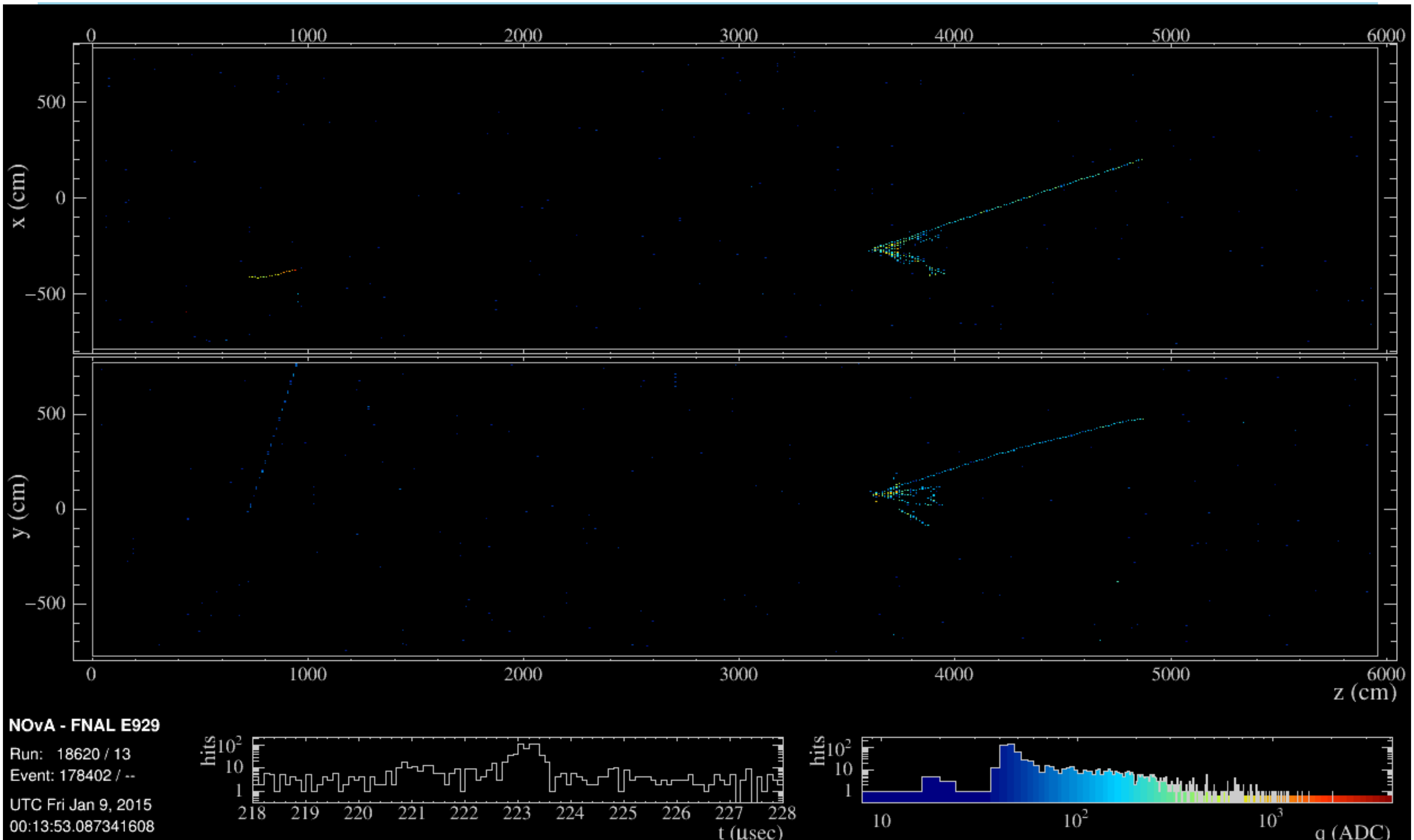
Blind Analysis - only look at FD data after understanding all systematic uncertainties



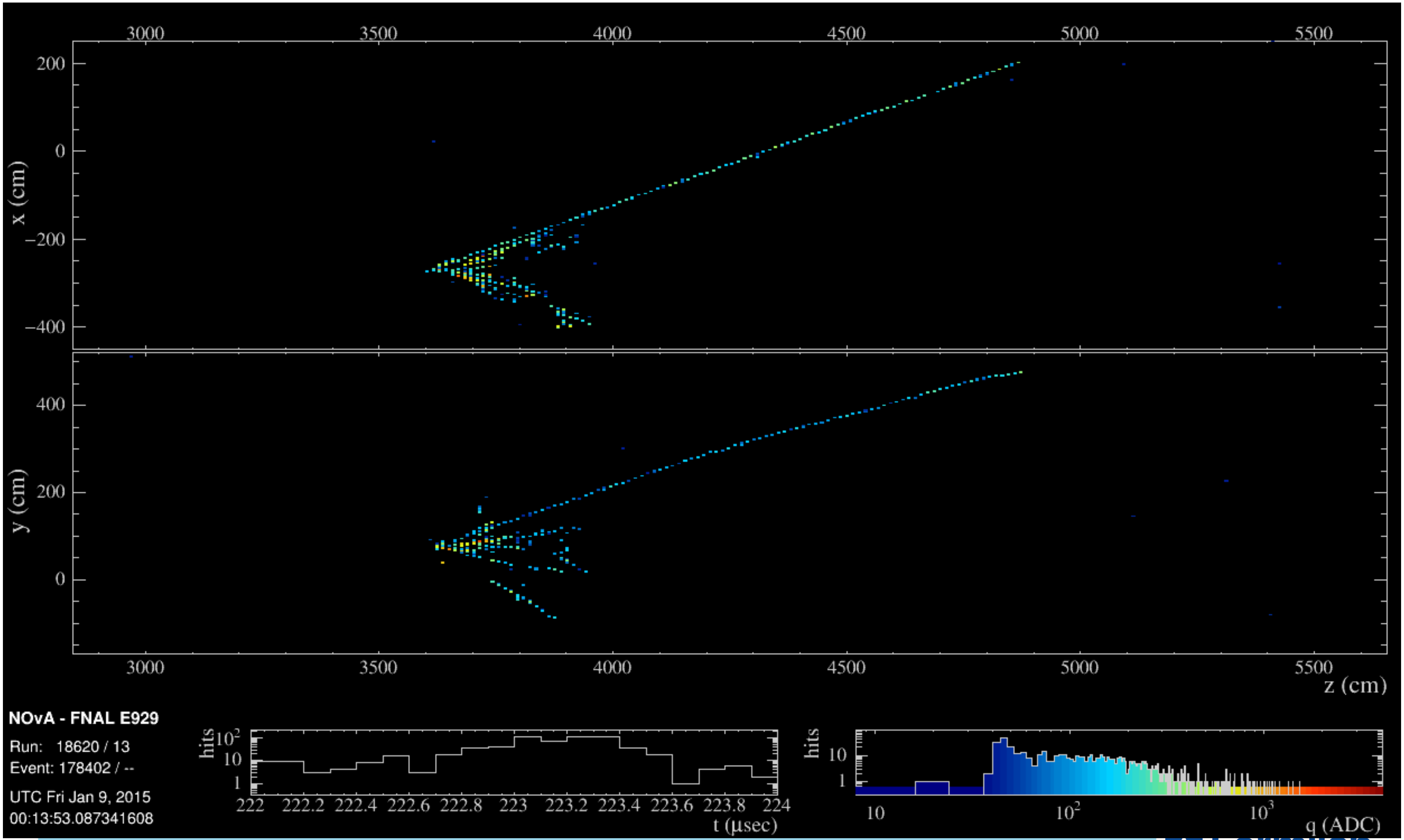
550 μs NOvA Far Detector Beam Trigger Window



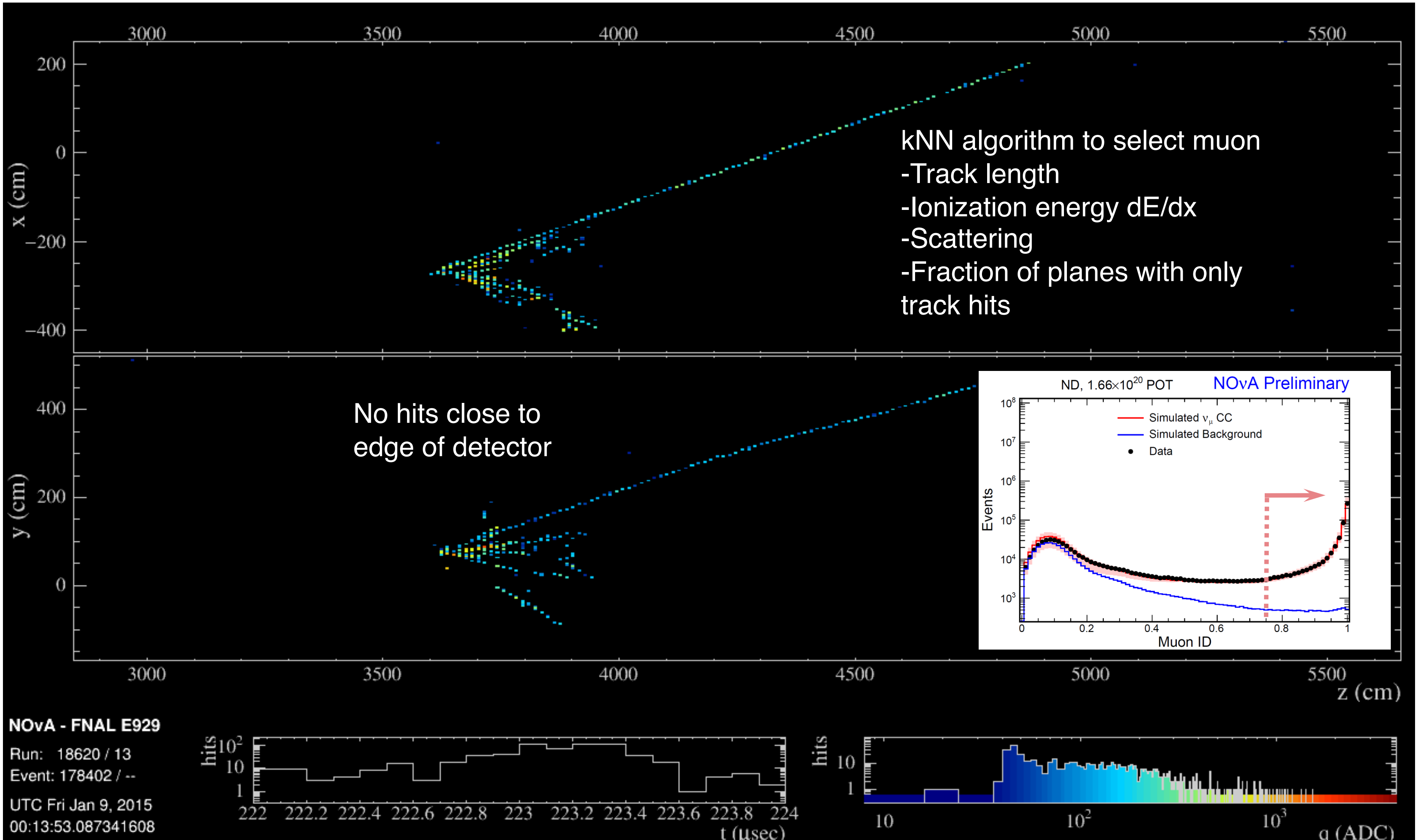
10 μs NOvA Far Detector Window around Beam Spill



Zoomed NOvA Far Detector Neutrino Event



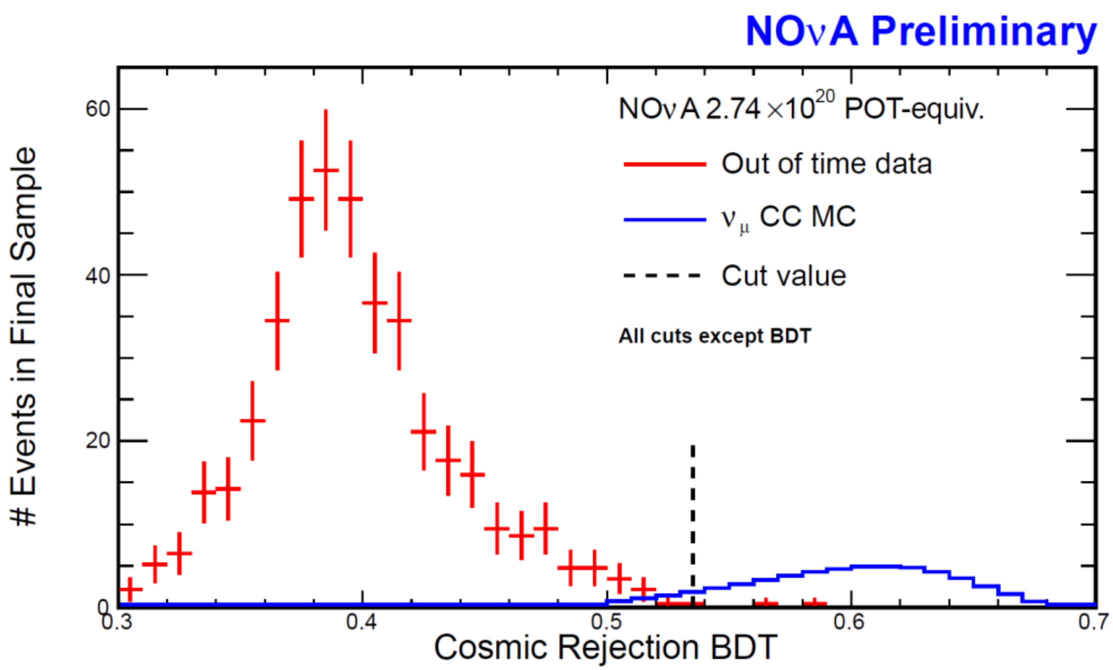
ν_μ Charged Current Event Selection



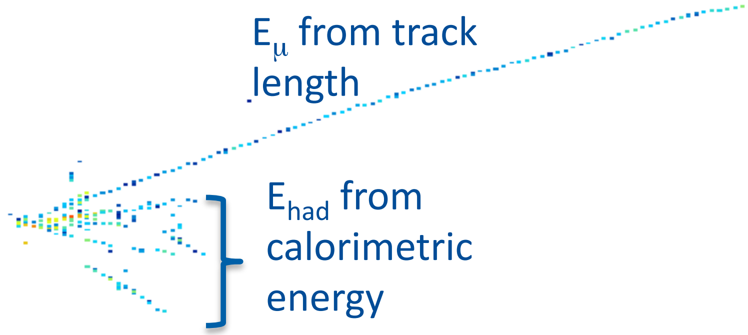
Cosmic Ray Background Rejection

- Cosmic ray rejection
  - 10^5 from beam timing
  - 10^7 from event topology
    - Number of hits, energy, track length, position, direction

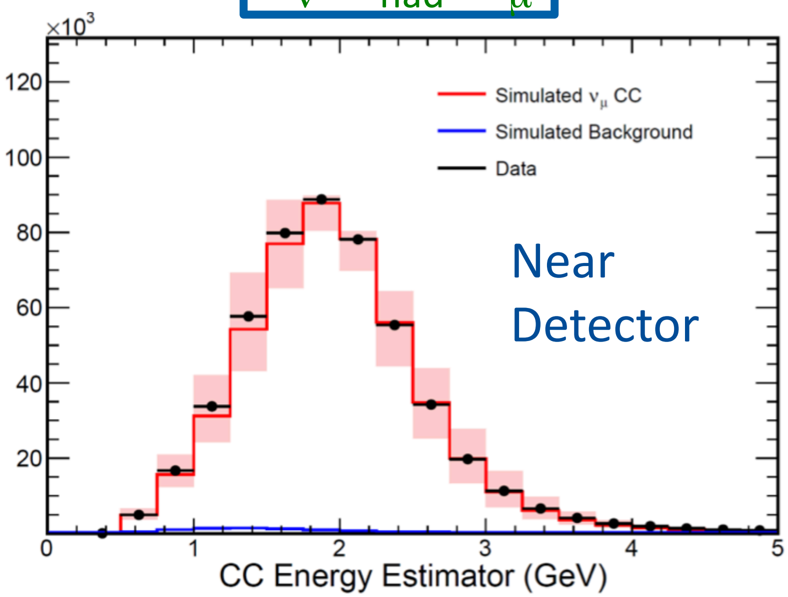
Cosmic rejection measured with out-of-time data



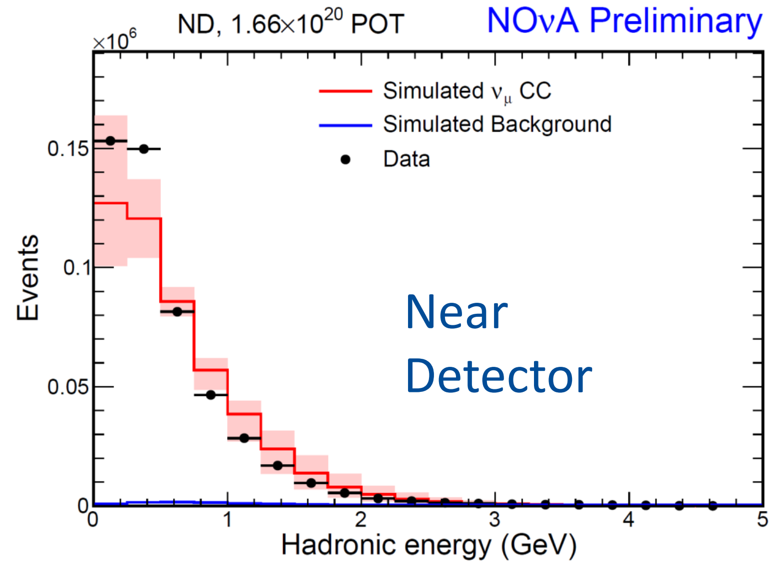
Neutrino Energy Determination



$E_\nu = E_{had} + E_\mu$



Tuned E_ν for ν_μ CC events

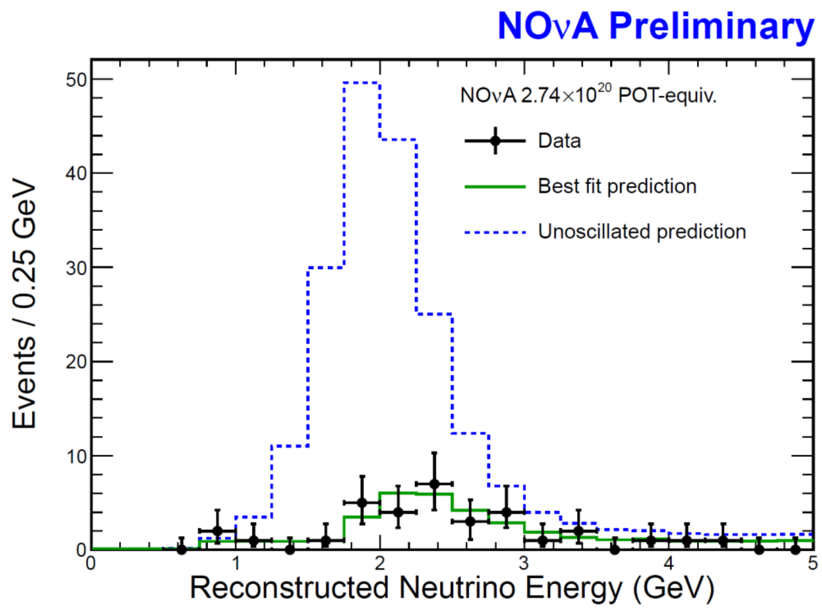


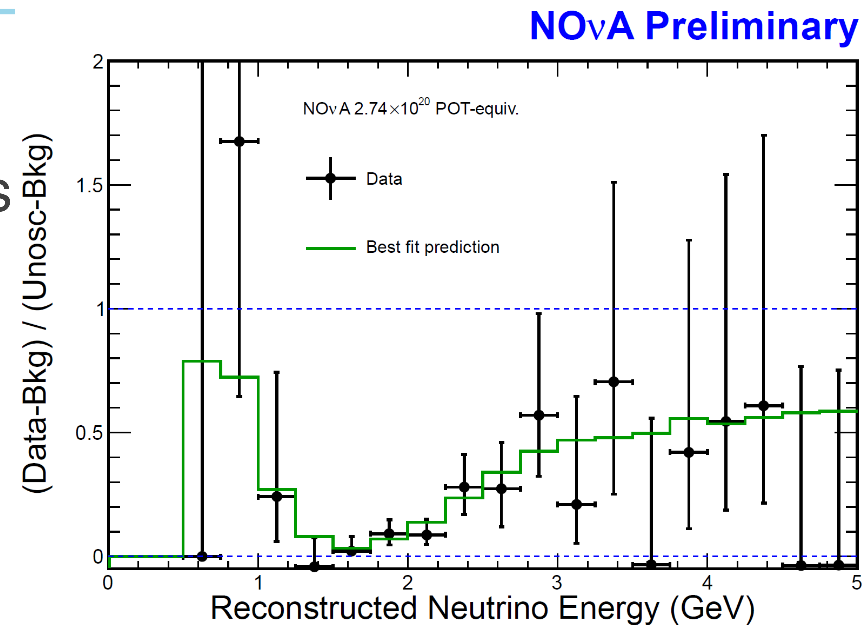
E_{had} tuned in Near Detector to give better agreement between Data and MC

- 21% uncertainty in E_{had}
- 6% in E_ν

Far Detector Oscillation Results

- 33 Events selected in 0-5 GeV
  - 201 expected without oscillations
  - Background: 2.0 beam, 1.4 cosmic





Clear observation of $\nu_\mu \rightarrow \nu_\mu$ disappearance

Spectrum is well matched by oscillation fit for Δm^2 and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

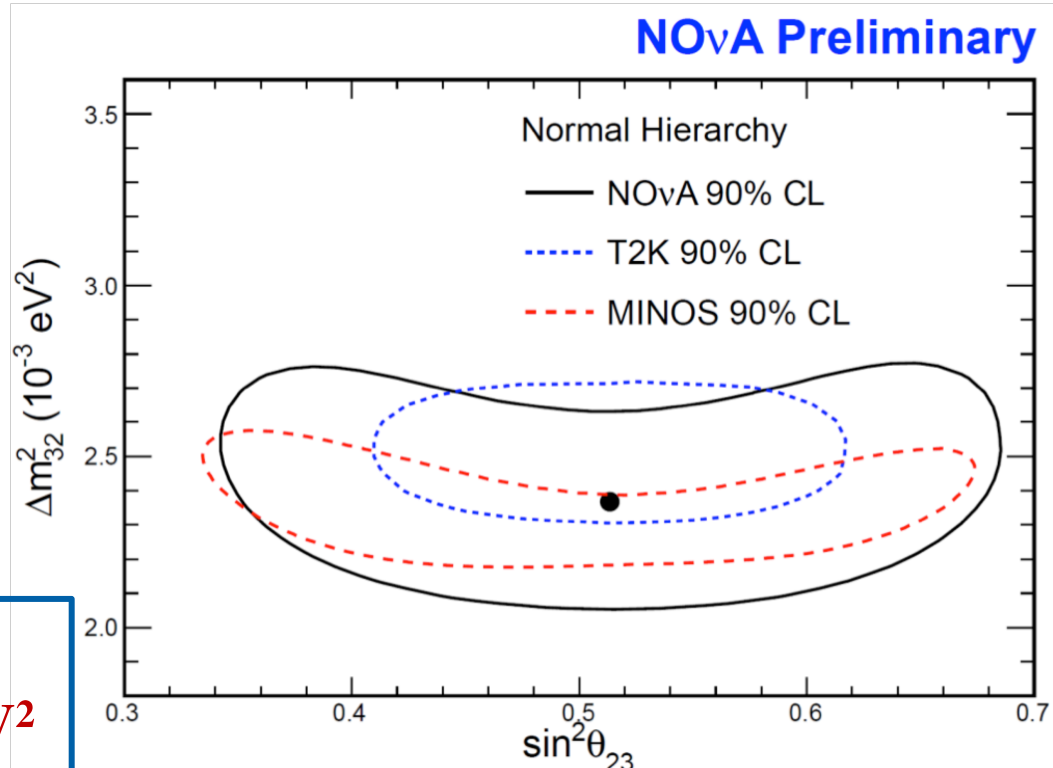
NOνA Results

- NOνA allowed region in (Δm^2, $\sin^2\theta_{23}$)

- Best fit

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.18}_{-0.15} \text{ [NO]} \\ -2.40^{+0.14}_{-0.17} \text{ [IO]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

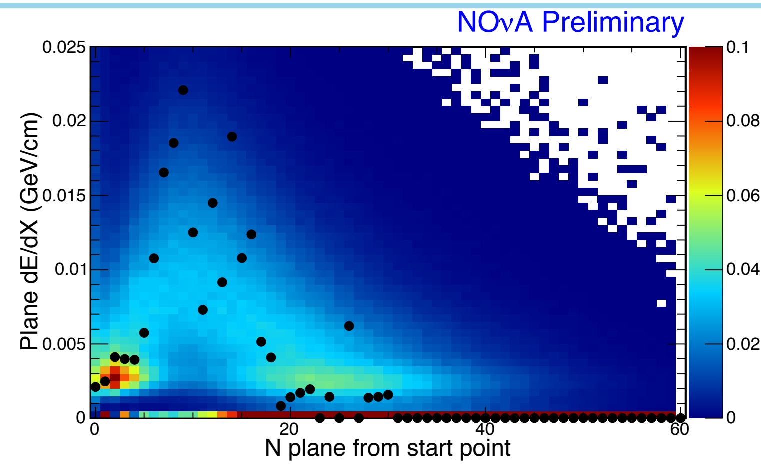
$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$



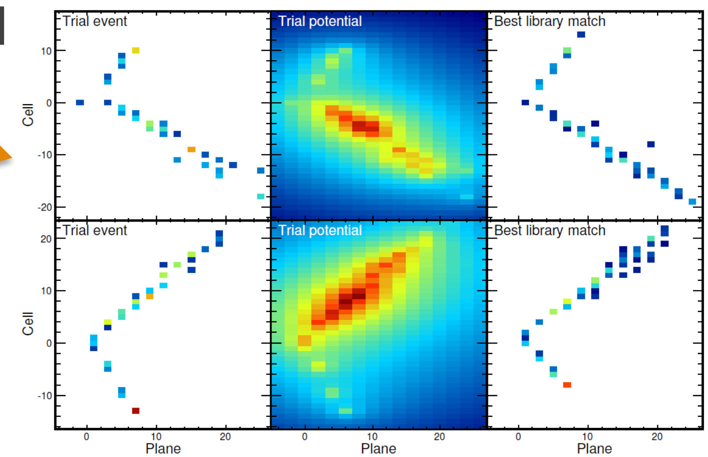
These results are from 7.6% of planned exposure

ν_e Appearance

- Identify ν_e candidates
  - Basic pre-selection
  - Multivariate ν_e selectors
    - LID – Likelihood ID: Electron shower shape likelihood- based ANN



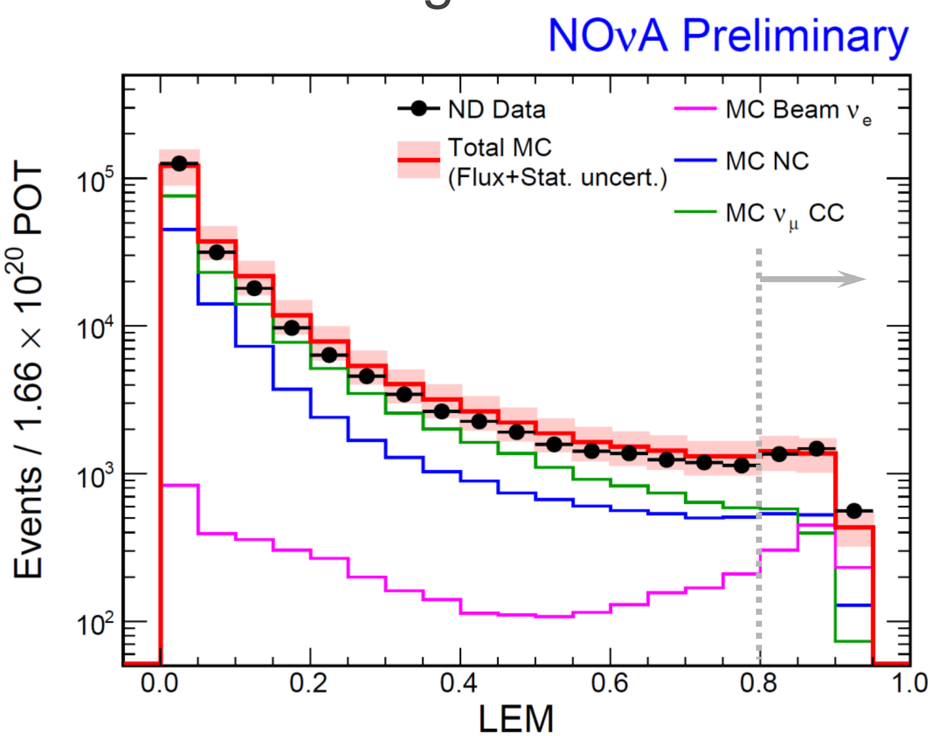
    - LEM – Library Event Matching: based on match of spatial pattern of event to library of 10^8 simulated events

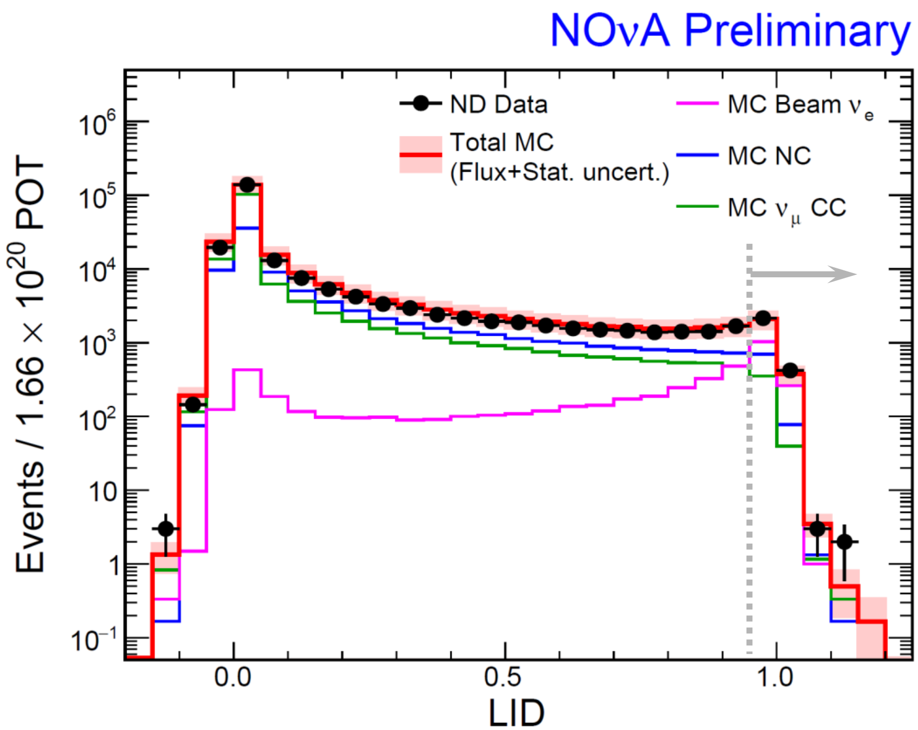


- Use Near Detector to predict Far
  - Beam backgrounds, $\nu_\mu \rightarrow \nu_e$ signal
- Characterize cosmic backgrounds in Far Detector timing sidebands
- Counting experiment: Interpret Far Detector excess as $\nu_\mu \rightarrow \nu_e$

Selector Performance

- Overall performance and sensitivity identical
  - Chose more traditional LID as primary prior to unblinding

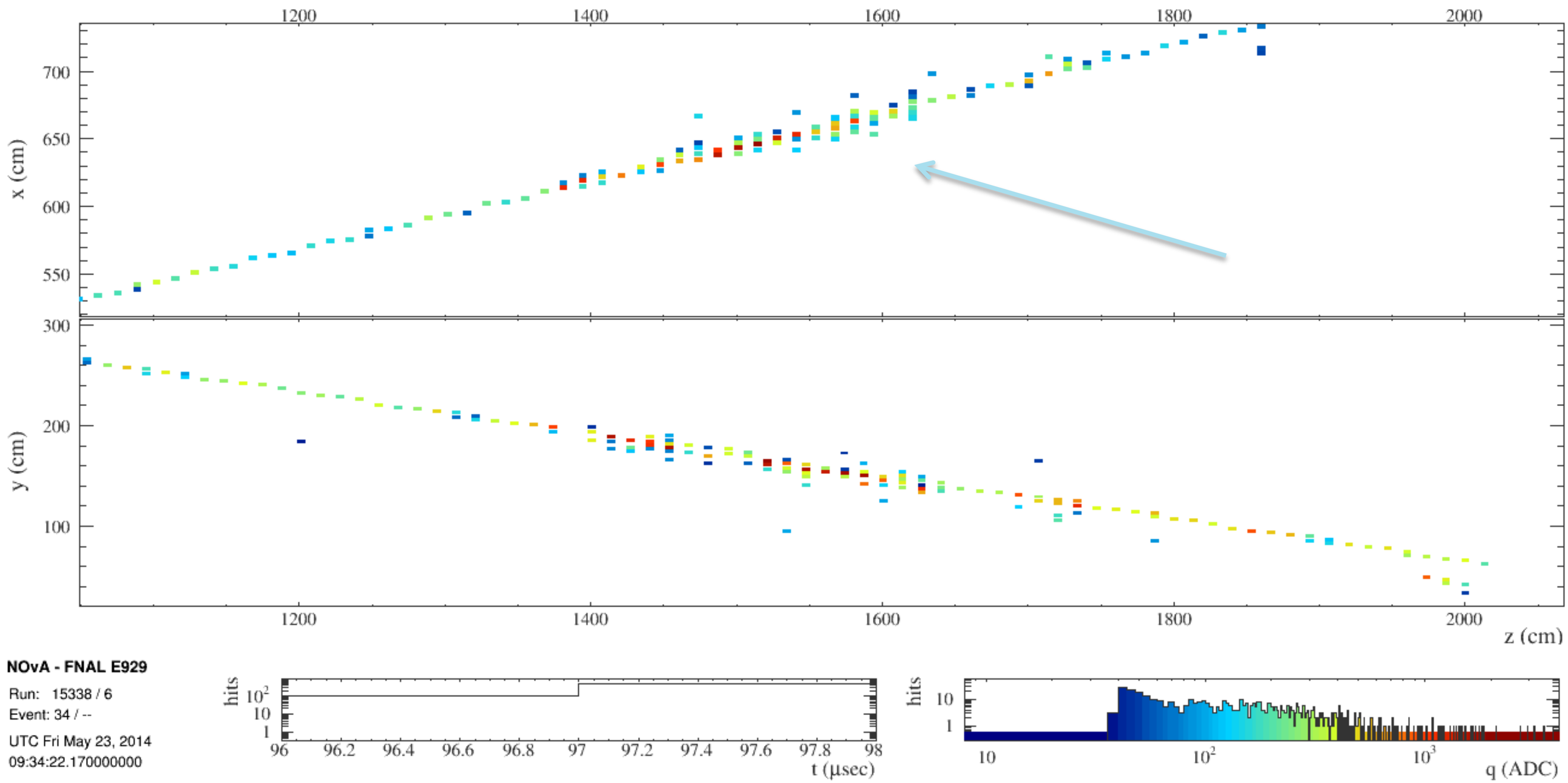




- 35 % signal efficiency (starting with contained events)
- 62% expected overlap between LID and LEM

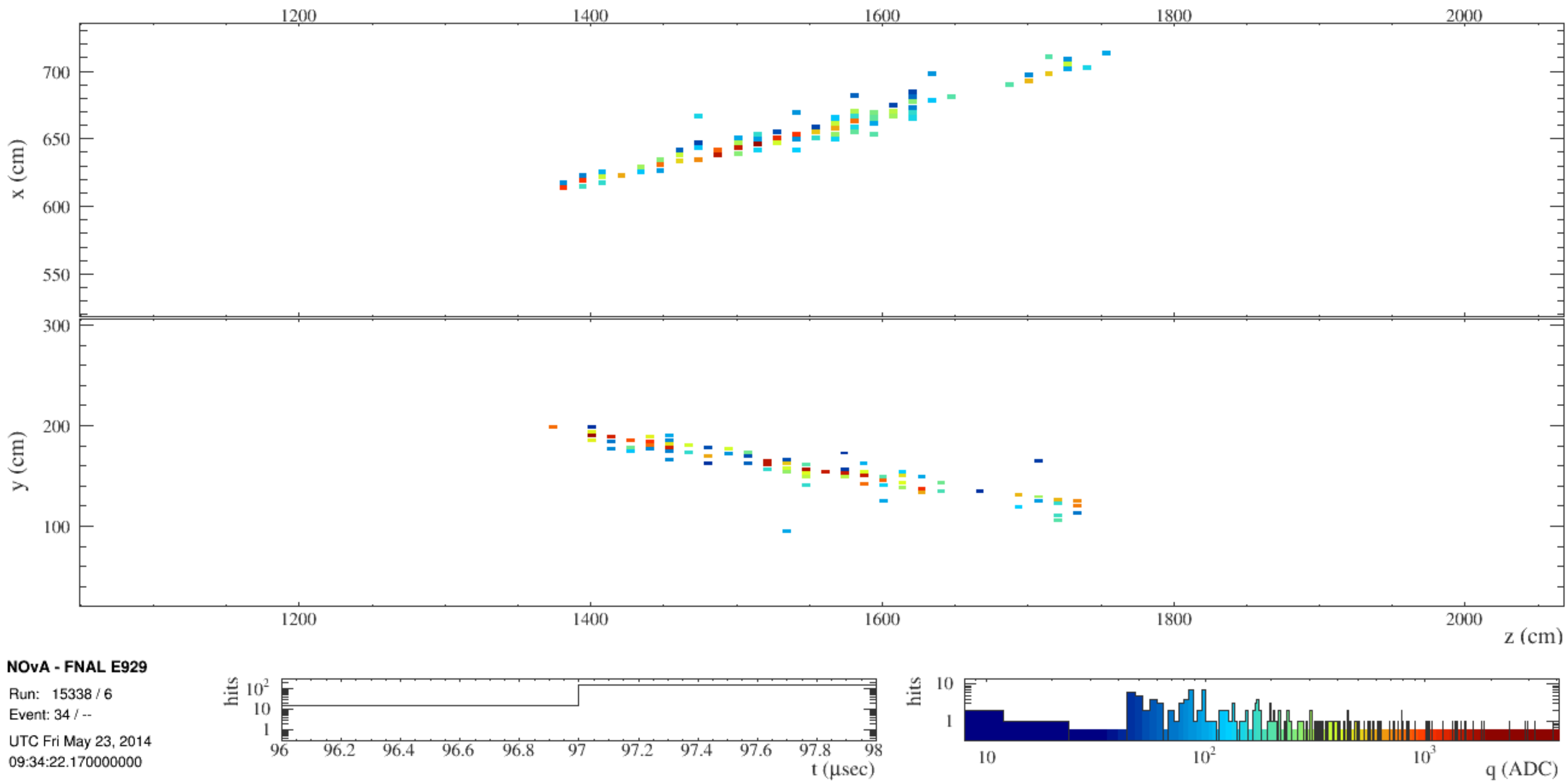
Fermilab

Checking Selector Performance with Cosmic-ray induced showers

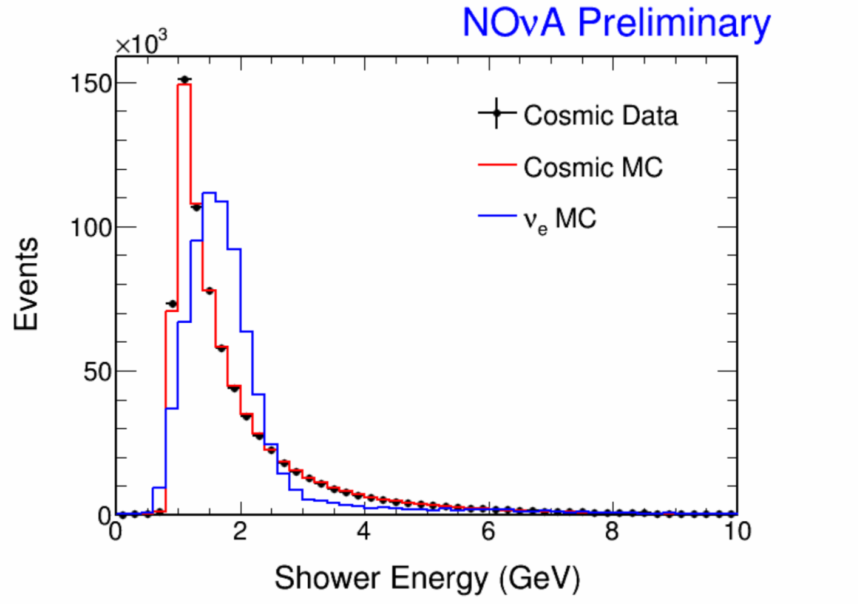


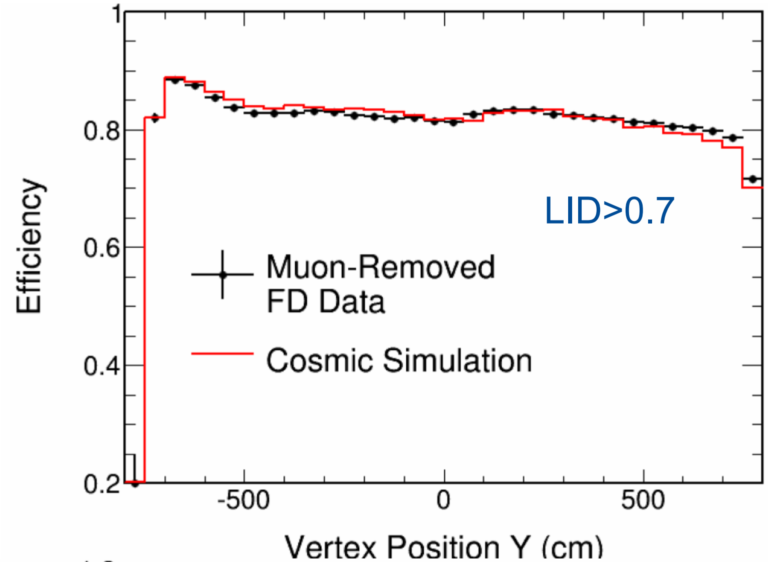
Fermilab

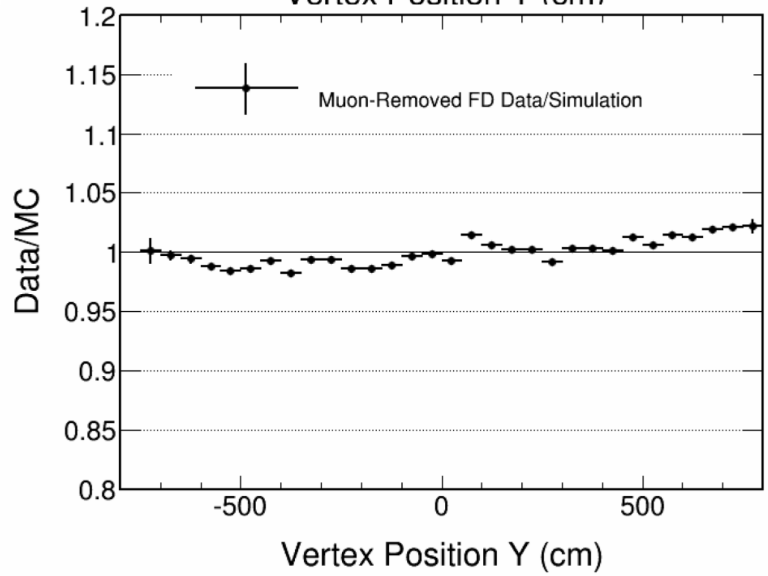
Cosmic-ray induced shower with muon removed



Cosmic Bremsstrahlung Energy & Efficiency



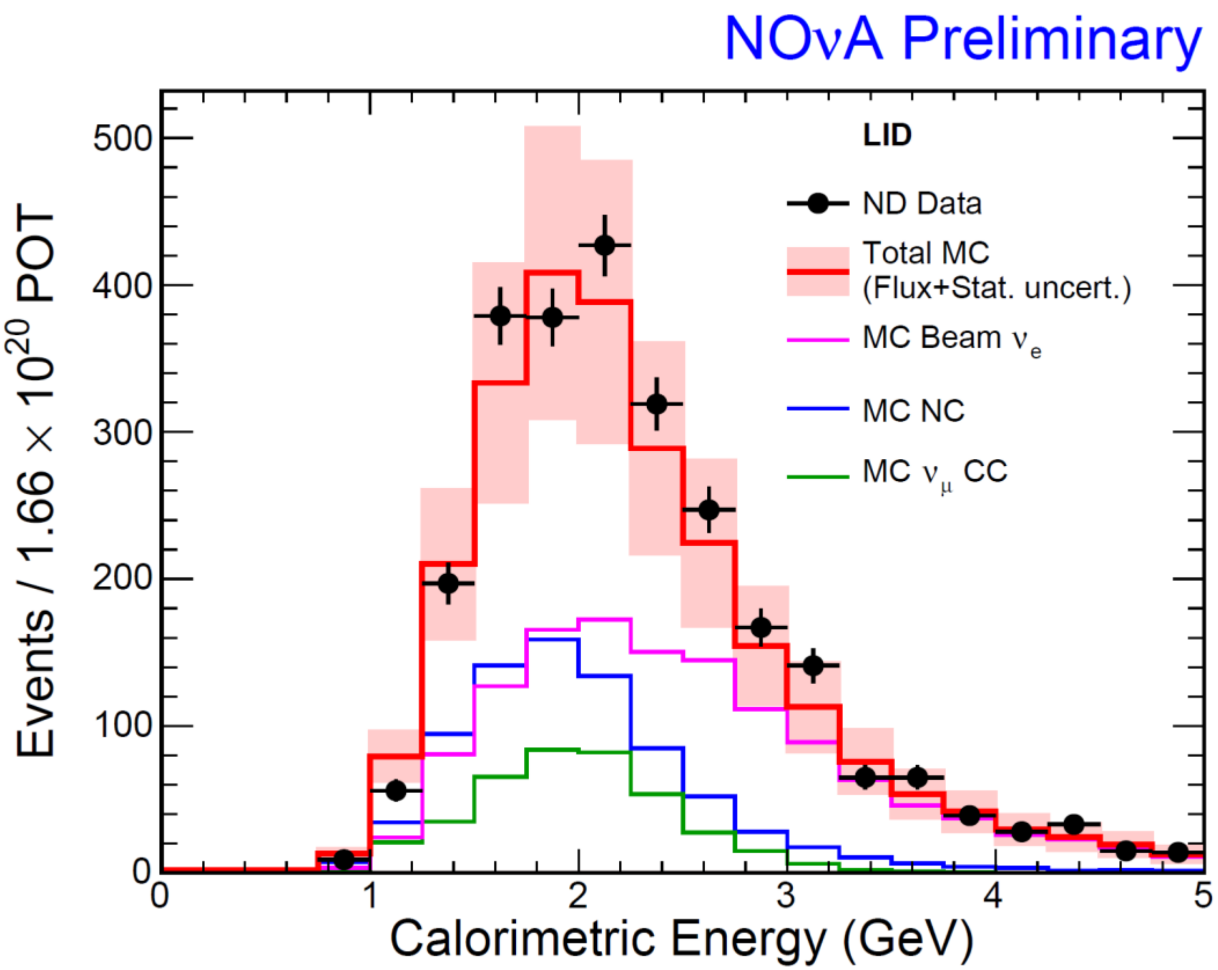




Data-driven check on performance of electron identification algorithms

Selected ν_e Candidate Energy Spectrum

- LID Selection – Near Detector



Far Detector ν_e Prediction for Two Scenarios

Predicted Signal:

$[\,I.O.,\ \delta = \pi/2,\ \ \theta_{23} = \pi/4]$

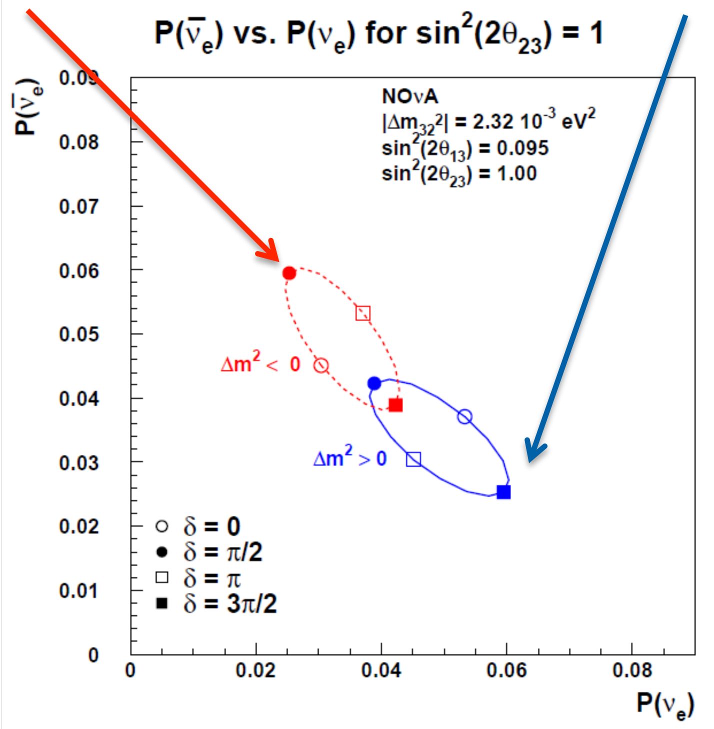
2.24 ± 0.29 events

2.34 ± 0.26 events

$[\,N.O.,\ \delta = 3\pi/2,\ \ \theta_{23} = \pi/4\,]$

LID: **5.62 ± 0.72 events**

LEM: **5.91 ± 0.65 events**



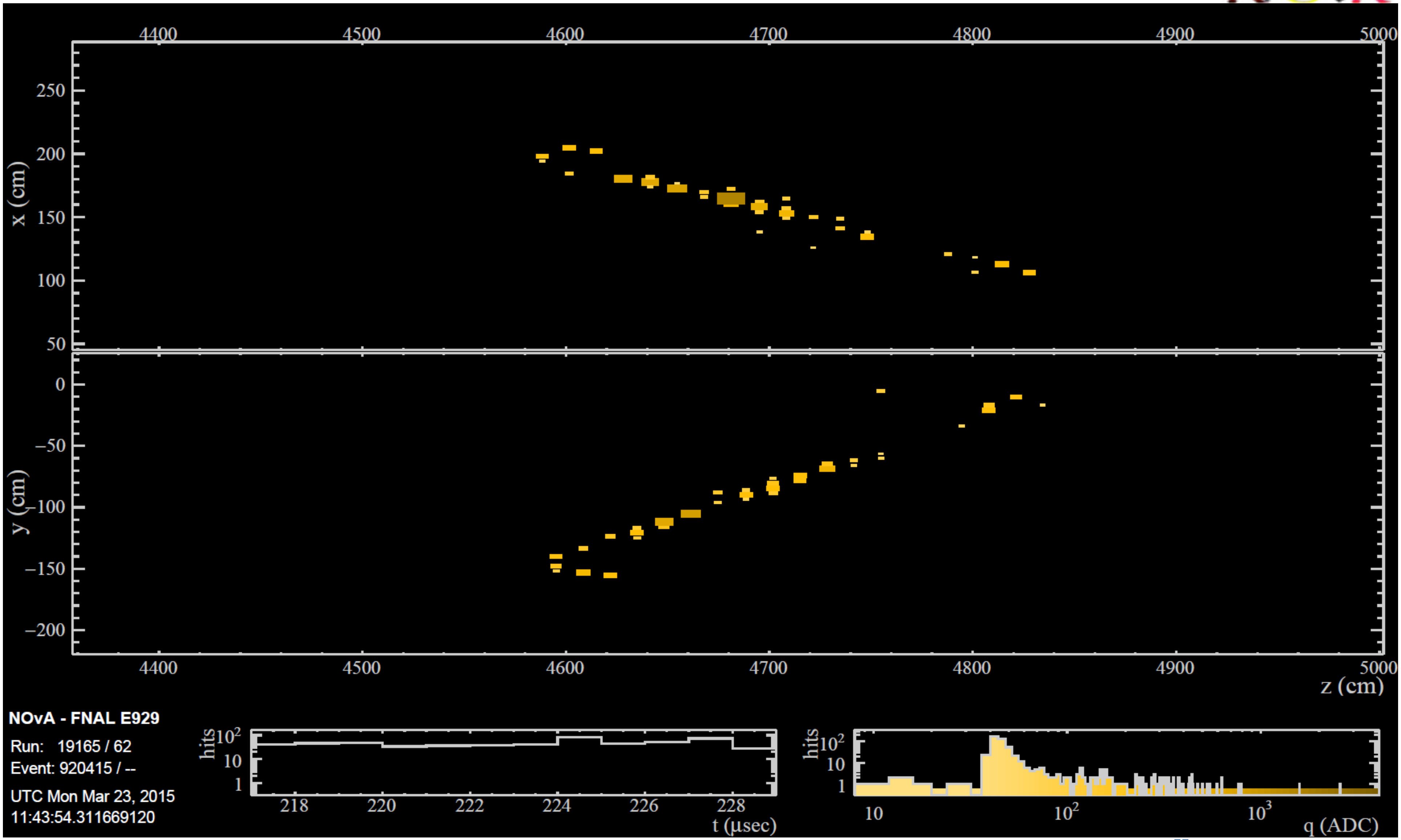
- Backgrounds
  - NC reduced by 99.3%
  - Cosmic rejection10^8:1
    - Expected cosmic bg 0.06 events
    - Measured with beam-off

Background

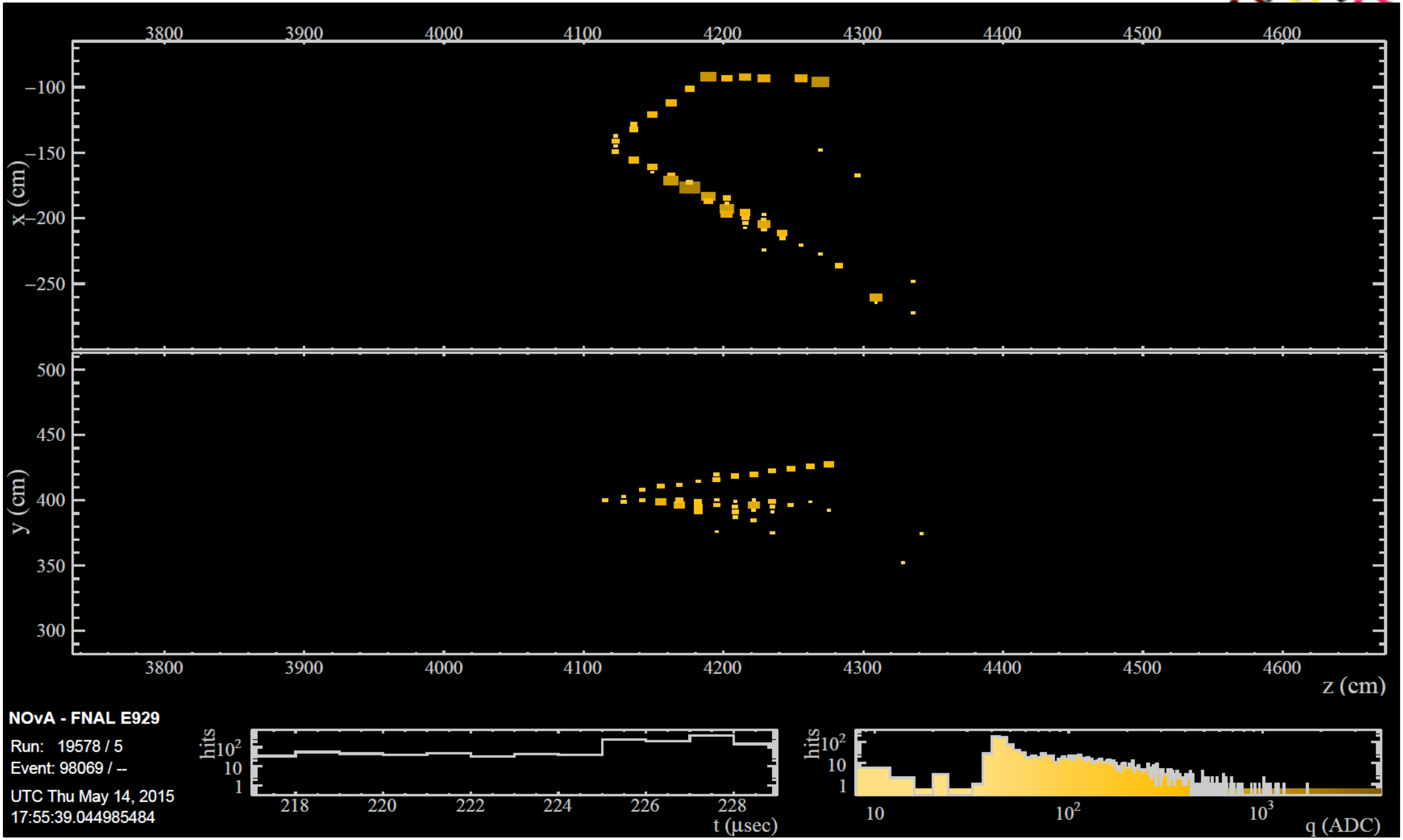
LID: **0.95 ± 0.09 events** [49% ν_e CC, 38% NC]

LEM: **1.01 ± 0.11 events** [46% ν_e CC, 40% NC]

Far Detector Selected ν_e CC Candidate

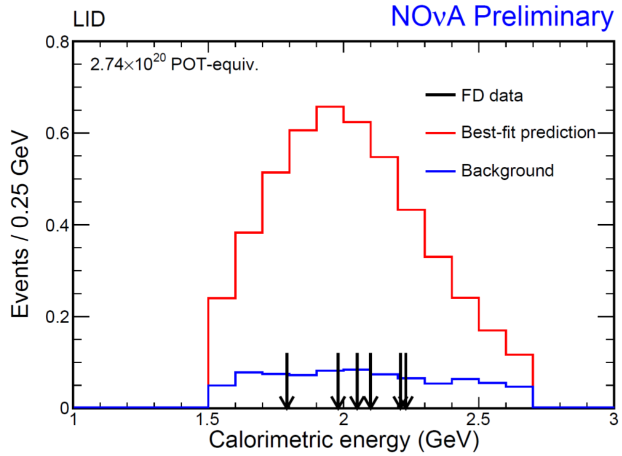


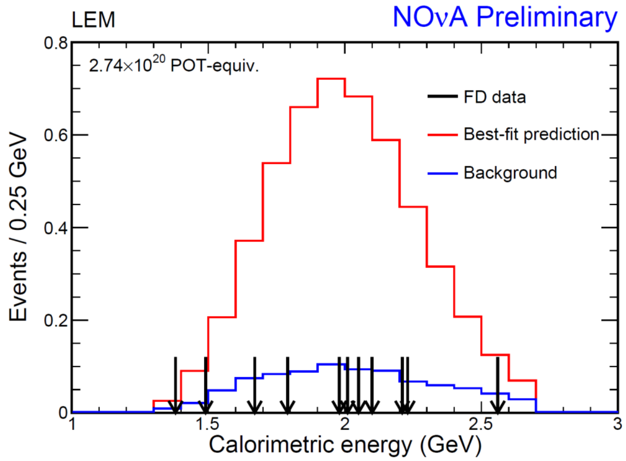
Far Detector Selected ν_e CC Candidate

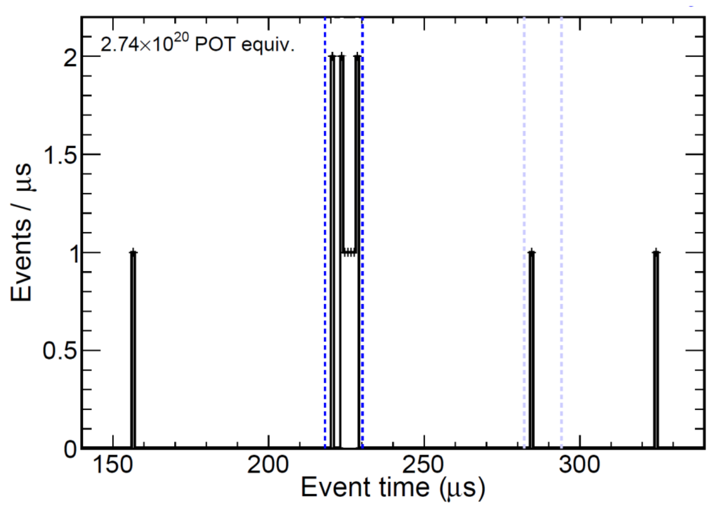


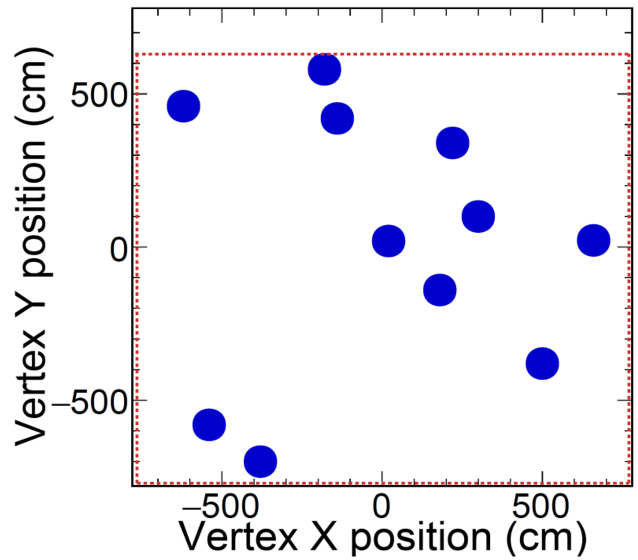
ν_e Candidate Events in the Far Detector

- LID: 6 ν_e candidates
  - 3.3σ significance
- LEM: 11 ν_e candidates
  - 5.5σ significance
- All LID events are selected by LEM
  - Mutual p-value 10%



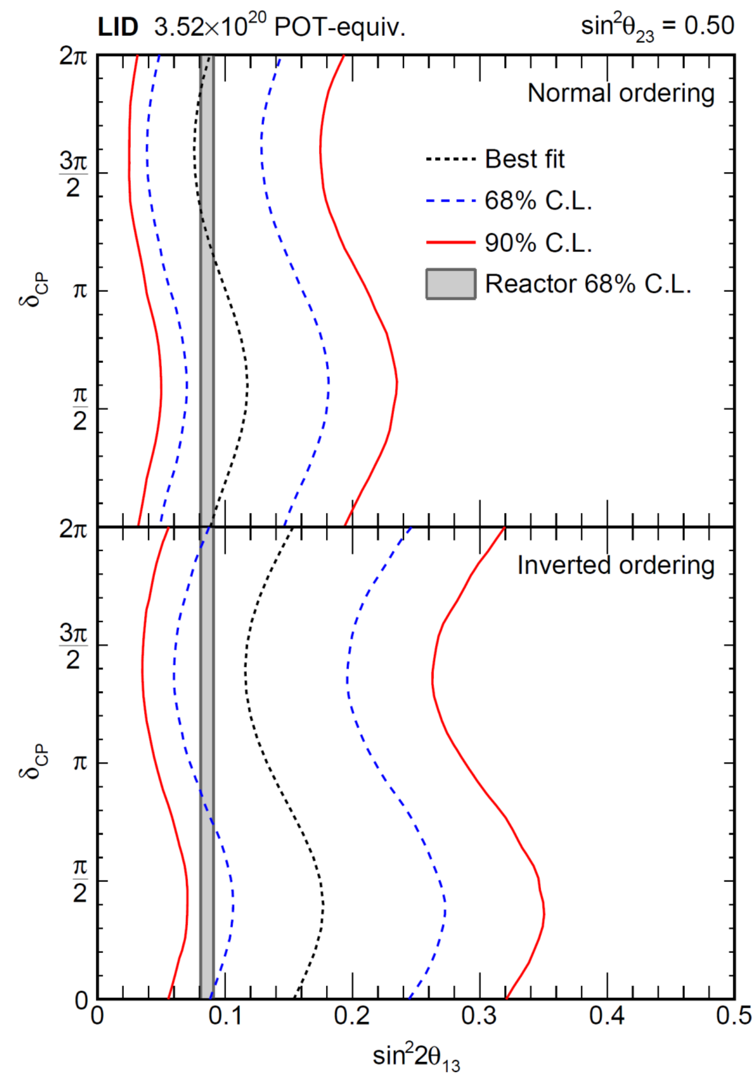






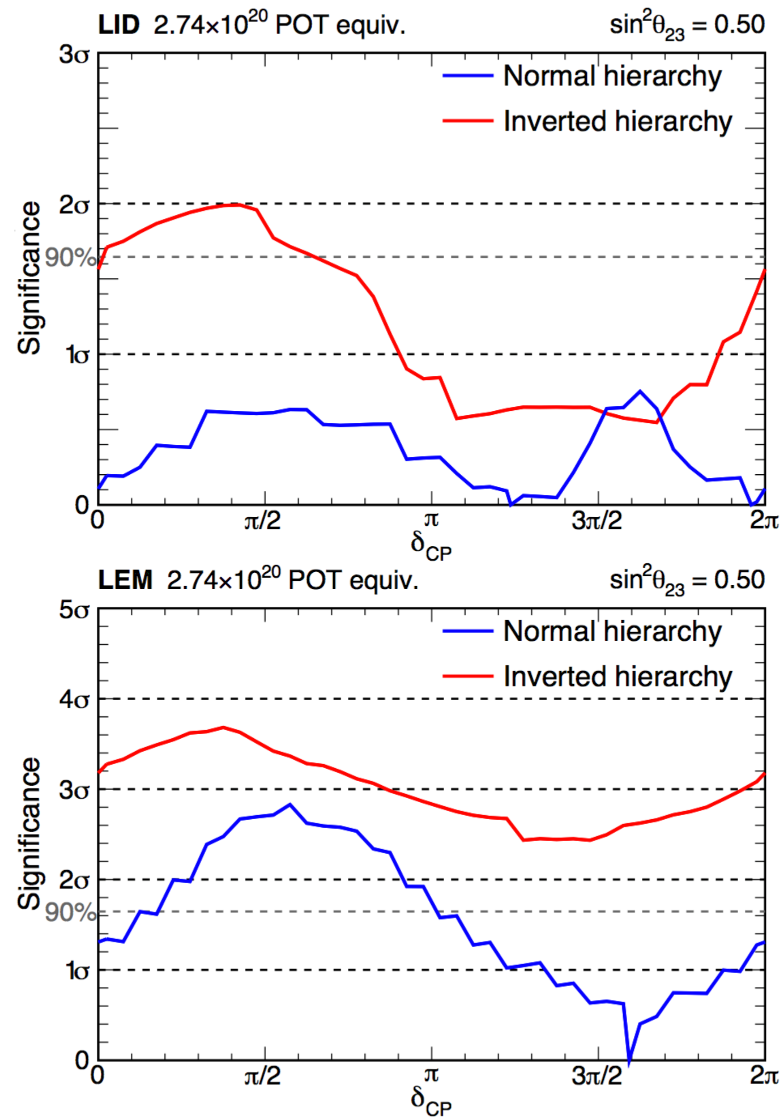
NOvA ν_e Appearance Result (LID)

- δ_{CP}, $\sin^2\theta_{13}$ allowed regions
  - Feldman-Cousins contours
  - $\sin^2\theta_{23}$ fixed at 0.5
  - Marginalized over other parameters



δ_{CP} , Mass Ordering Significance with Reactor Constraint

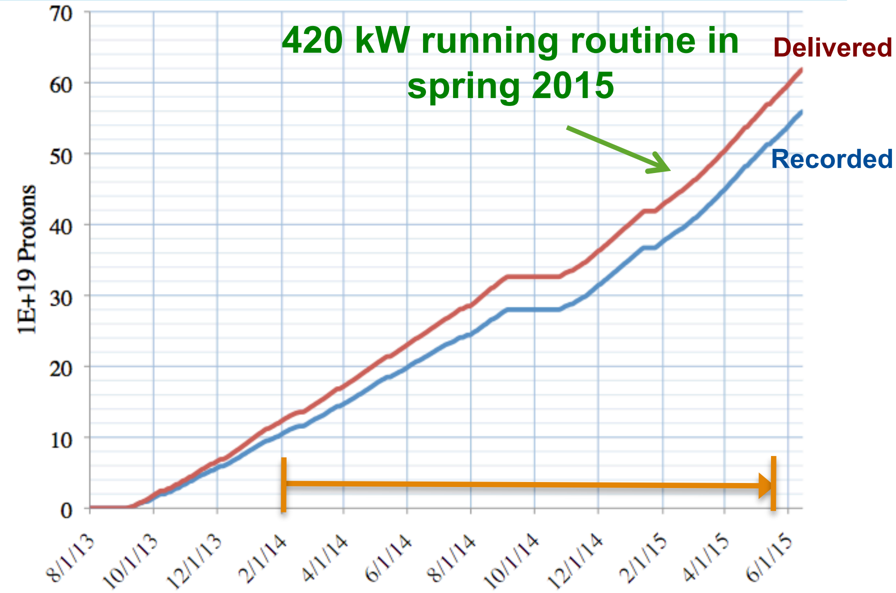
- Apply global reactor constraint
  - $\sin^2\theta_{13}=0.086 \pm 0.05$
- Significant Feldman-Cousins corrections
- Both LID and LEM prefer normal mass ordering with $\pi<\delta_{CP}<2\pi$
  - LID has some tension for Inverted Ordering near $\delta=\pi/2$
  - LEM disfavors Inverted Ordering at 2σ



Fermilab

Prospects

- Excellent performance in first year
  - Typical beam powers of 420 kW, but accelerator uptime has been higher than assumed
  - Detector up-times of greater than 95%



- Beam resumed in October following annual shutdown
  - Working back to 521 kW achieved shortly before shutdown
- 700 kW may be possible before Summer 2016
  - May require several more months depending on need for additional collimation in former anti-proton recycler
- Possible switch to anti-neutrino mode in mid-2016

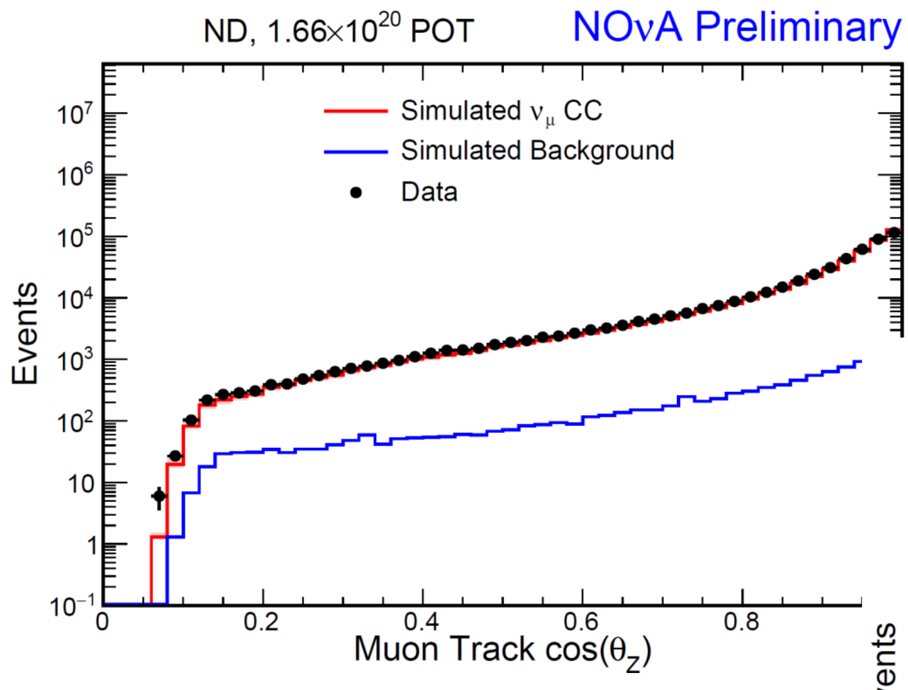
Summary

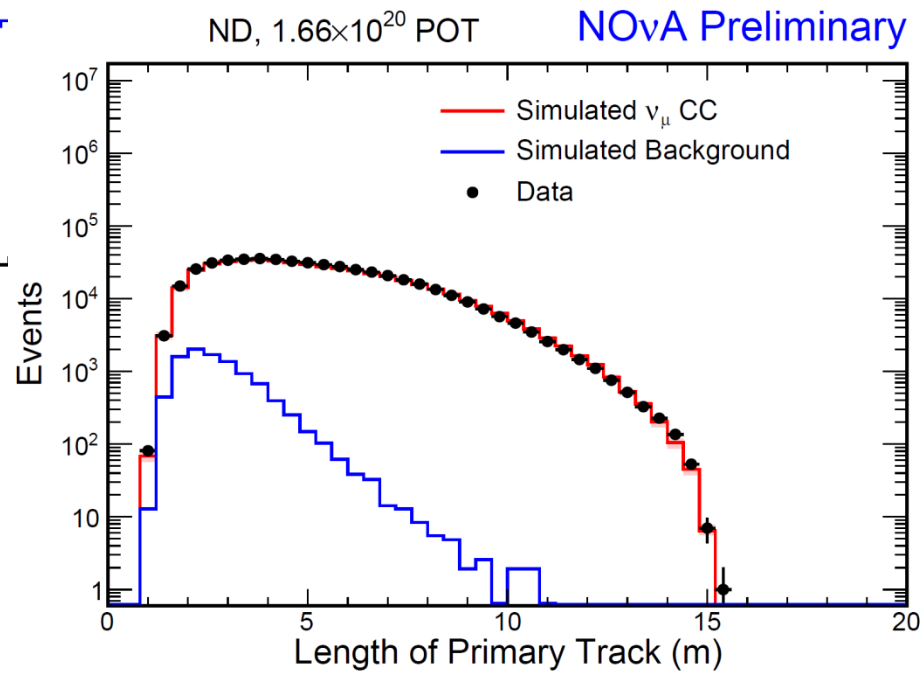
- NOνA has produced its first oscillation results within a year of starting formal operations
  - Using less than 8% of planned exposure
- Compelling sensitivity for ν_μ disappearance
- Same hints as T2K in favor of Normal Mass Ordering and CP violating enhancement of ν_e appearance
- Beam has resumed, aiming for 700 kW
- First NOνA neutrino interaction results expected soon
- Looking forward to updates on oscillation analyses at Neutrino2016 in July

Děkuji!

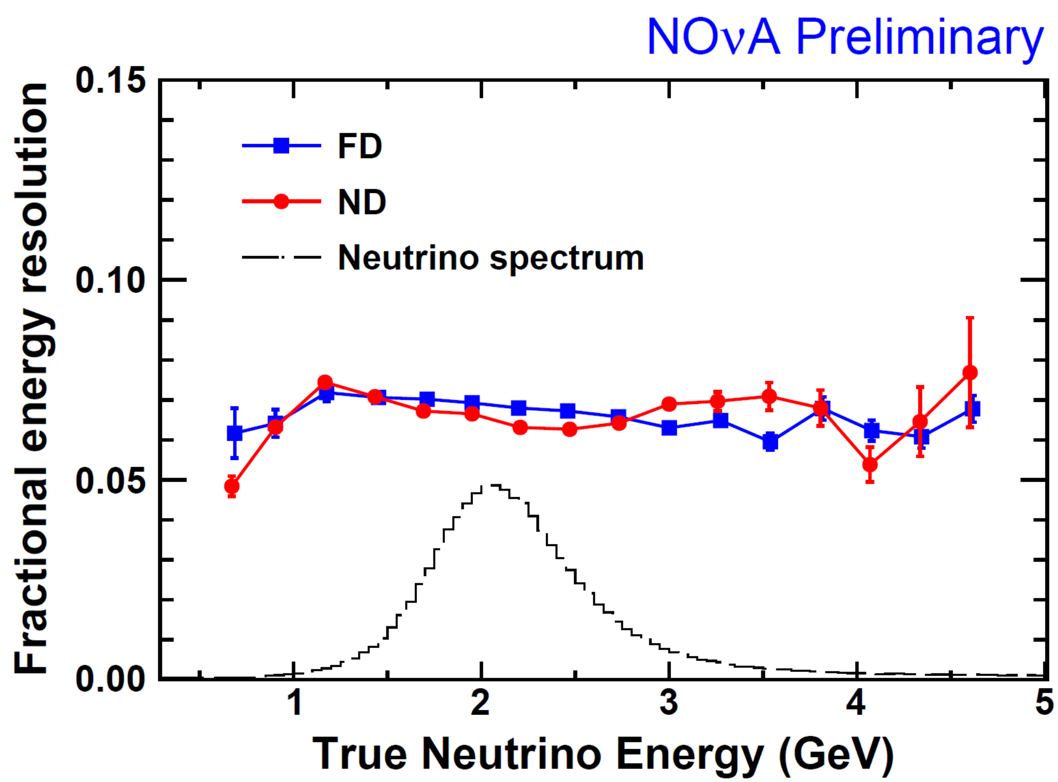
Backups

ν_μ Kinematic Variables

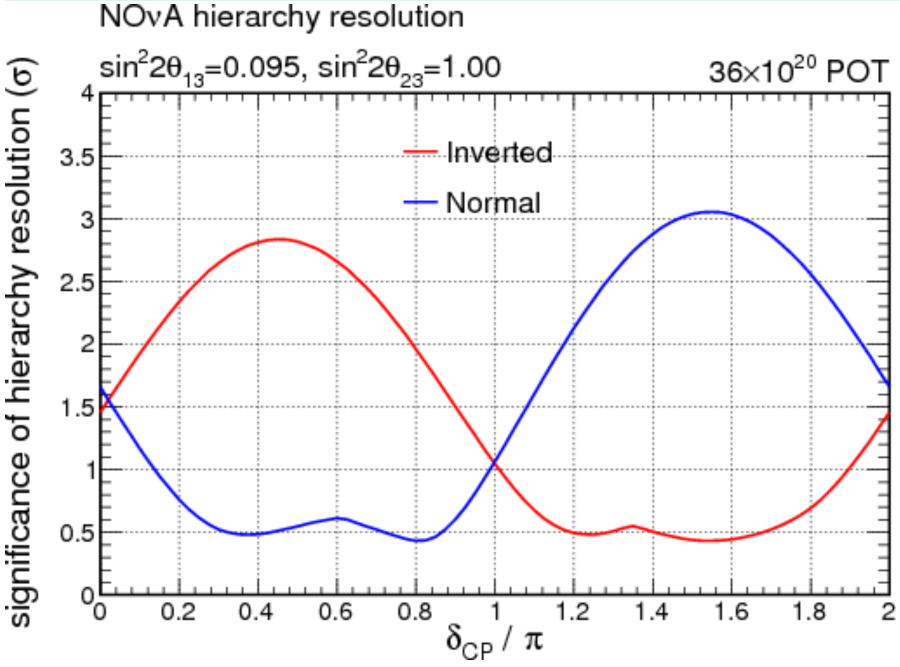


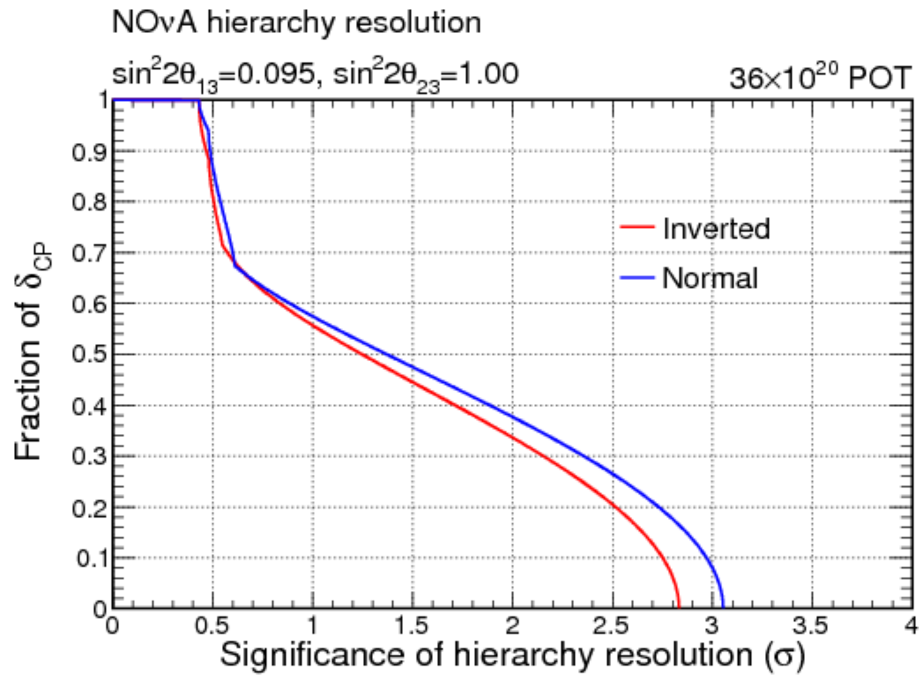


ν_μ Energy Resolution

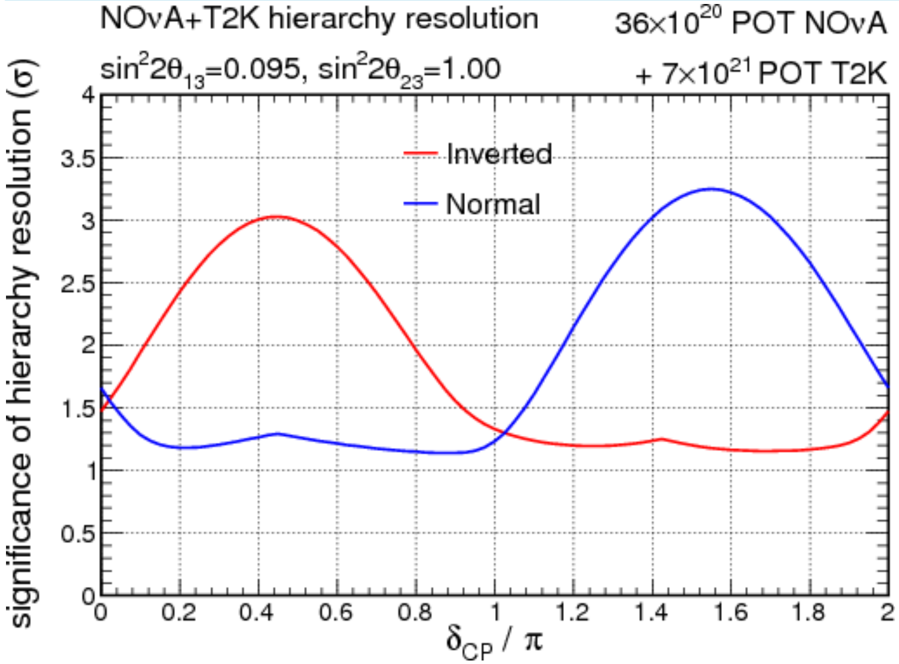


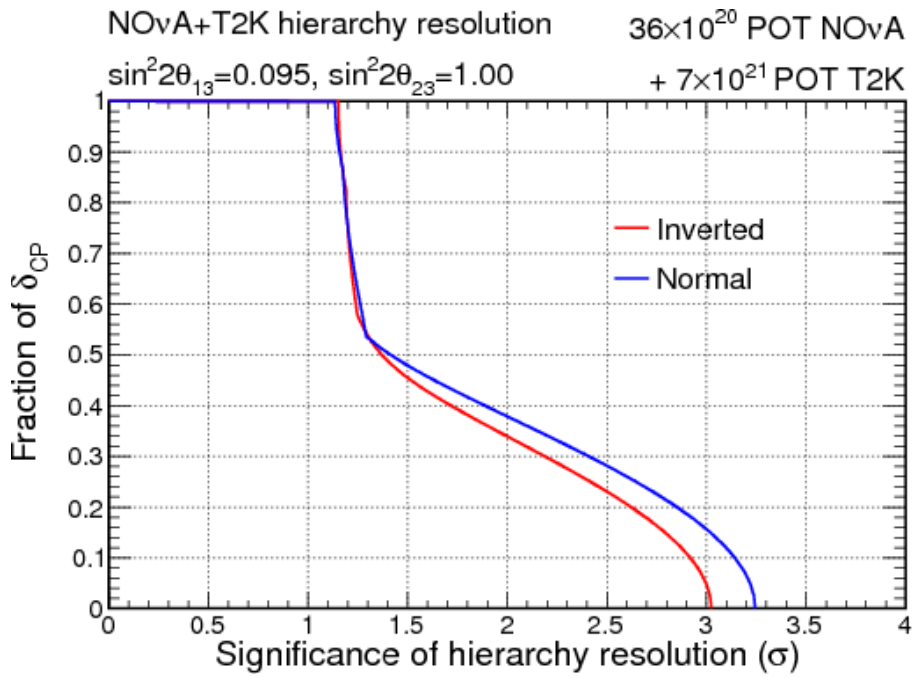
Mass Hierarchy – NOvA



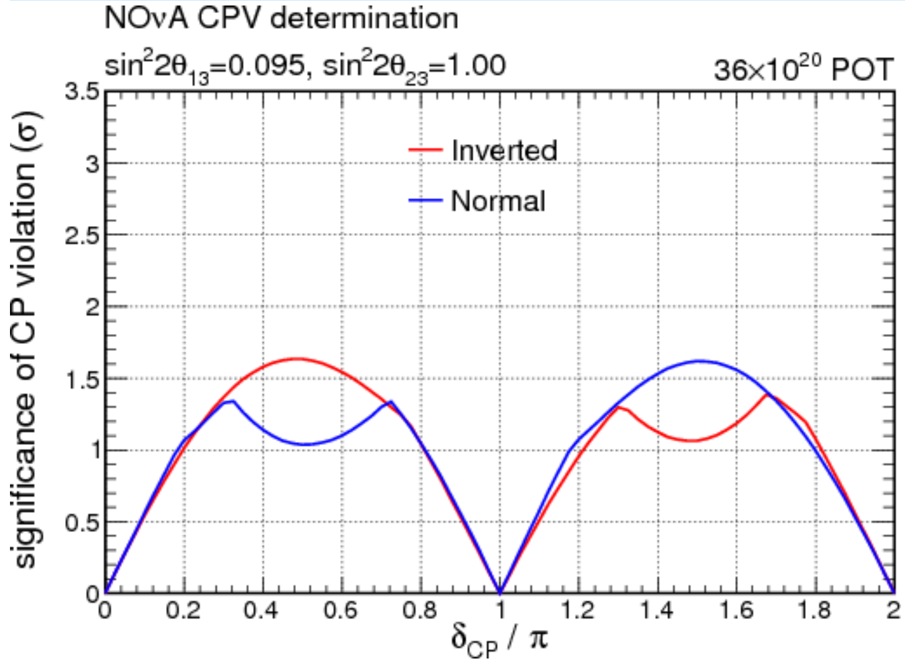


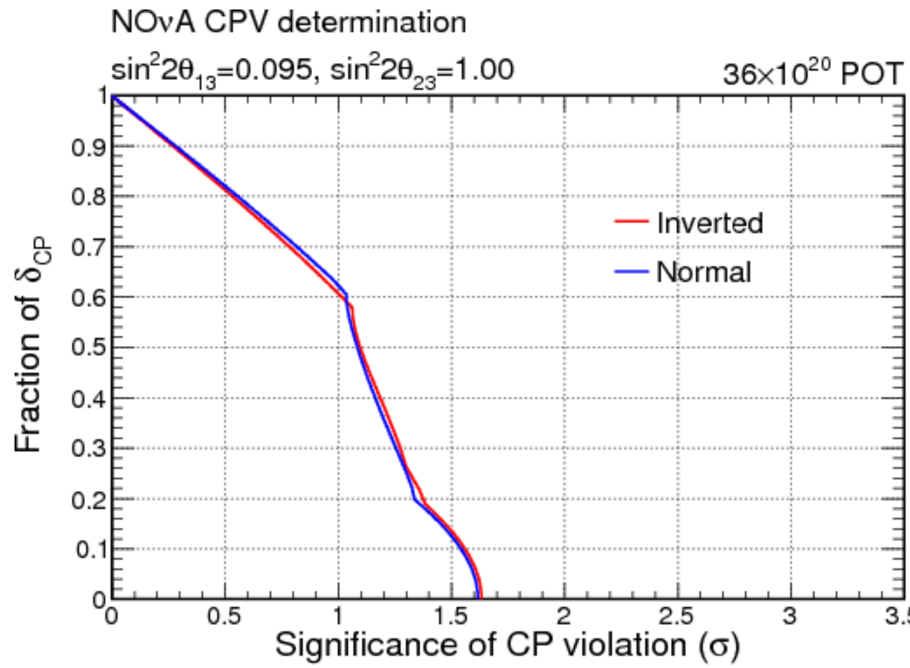
Mass Hierarchy – NOvA+T2K



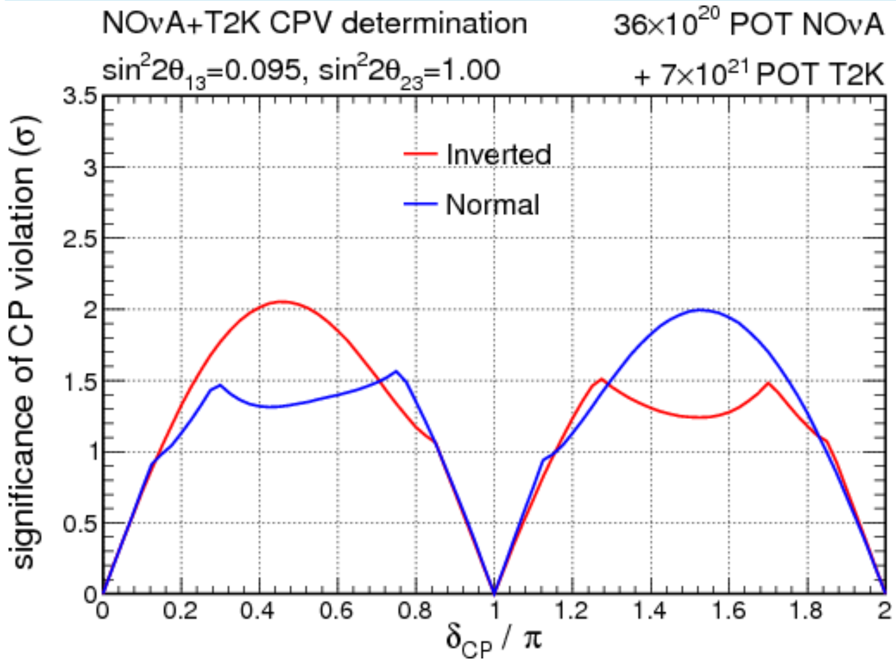


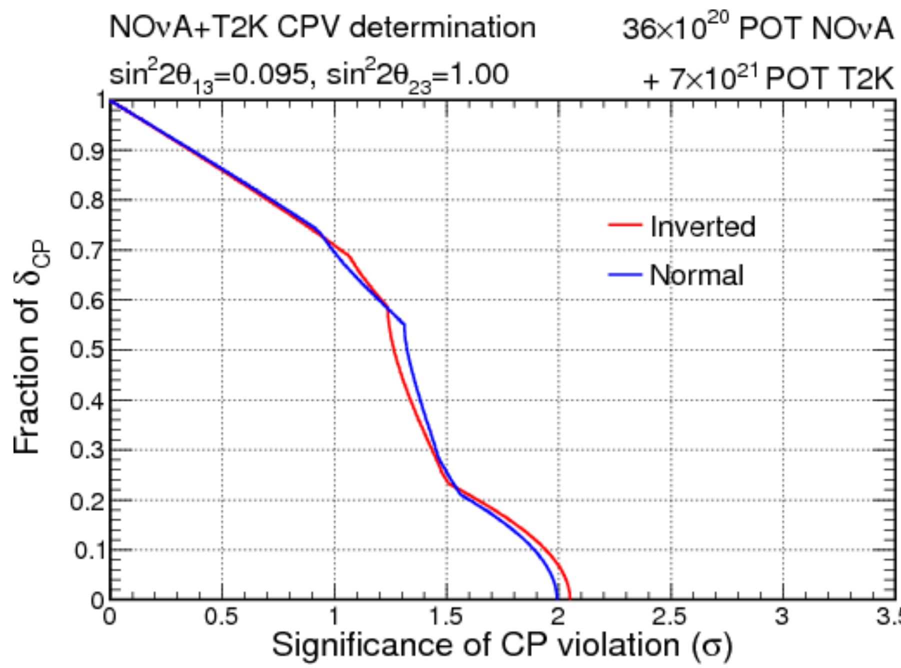
CP Violation – NOvA



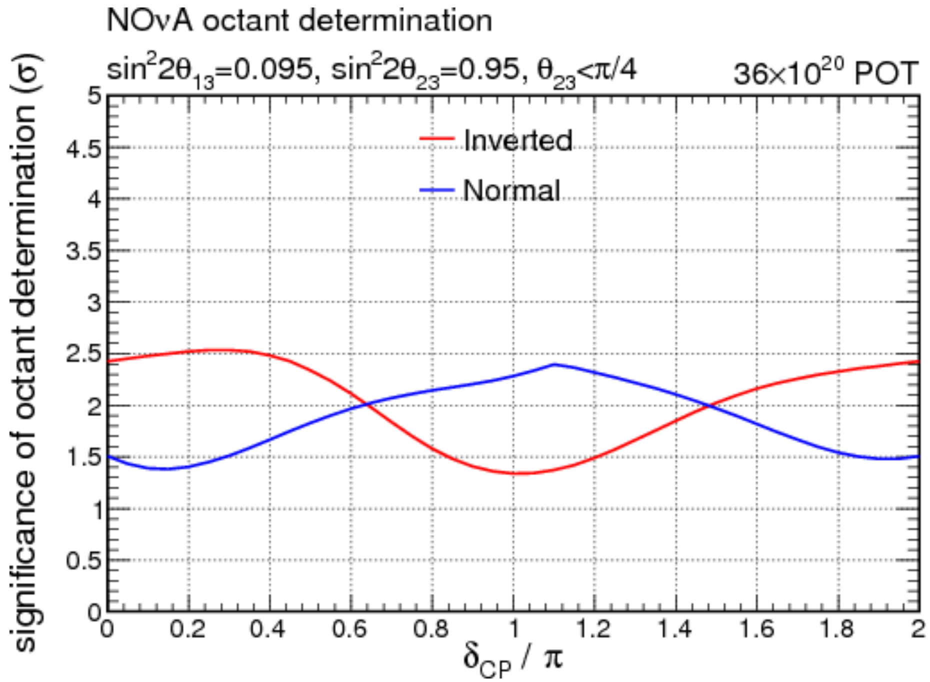


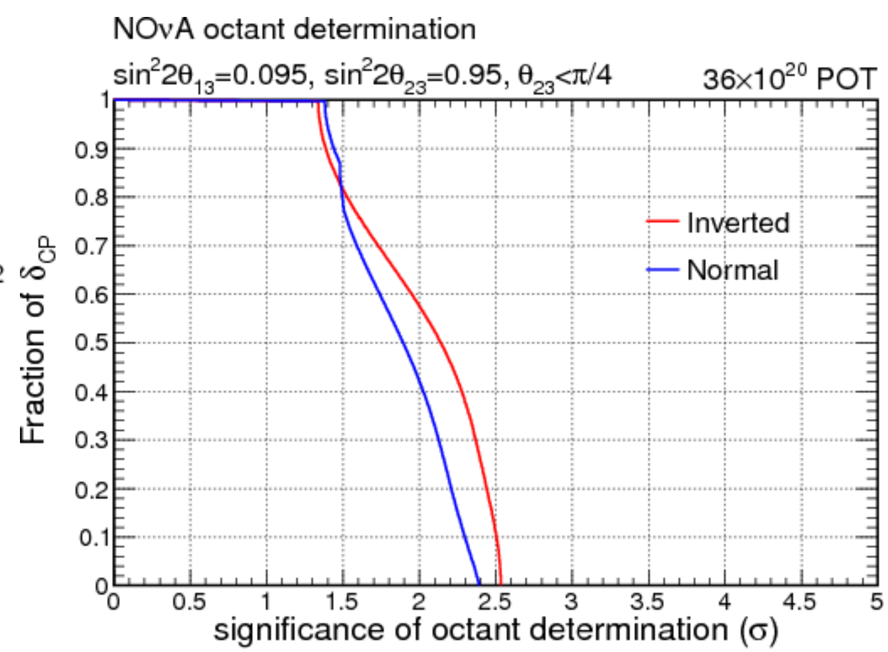
CP Violation – NOvA+T2K





θ_{23} Octant - NOvA





NOvA Disappearance

6 Nominal Design Years