First Results from NOvA

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Neutrino Oscillation

- A neutrino created with a specific lepton flavor (e, μ or τ) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies periodically as the neutrino travels in space.
- The neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are each a different linear combination of mass eigenstates (ν_1, ν_2, ν_3).

$$|\nu_\alpha>=\sum_i U^*_{\alpha i}\,|\,\nu_i>$$

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

$|\nu_\alpha>$, α = e (electron), μ (muon) or τ (tau) - flavor eigenstate
$|\nu_i>$, i=1, 2, 3 mass eigenstates with a definite mass m_i
$U_{\alpha i}$: an element of the PMNS mixing matrix

$$|\nu_i(L)>=e^{-im_i^2L/2E}|\nu_i(0)>$$

- As a neutrino propagates through space, the phases of the three mass states $|\nu_{i=1,2,3}>$ advance at different rates due to the differences in the neutrino masses.
- This results in a periodically changing mixture of mass states as the neutrino travels, so the probability of measuring a particular flavor state change accordingly.

$$P_{\alpha\to\beta}=|\langle\nu_\beta|\nu_\alpha(t)\rangle|^2=\left|\sum_i U^*_{\alpha i}U_{\beta i}e^{-im_i^2L/2E}\right|^2$$

Neutrino Oscillation

•For a certain travel distance (L) and energy (E), oscillation probability depends on squared mass differences $\Delta m^2_{ij}=m^2_i-m^2_j$ and parameters of the PMNS mixing matrix U

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U^*_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}L/4E)$$
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U^*_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}L/2E)$$

For anti-neutrinos,

$$P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = P(\nu_\alpha \to \nu_\beta, U^*)$$

(CPT invariant)

•In the case of CP violation $P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = P(\nu_\alpha \to \nu_\beta, U^*) \neq P(\nu_\alpha \to \nu_\beta, U)$, need a complex phase δ_{CP} in the mixing matrix U to describe the non-zero $\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})$

•For the three flavor case the PMNS matrix is most commonly parameterized by three real mixing angles θ_{12}, θ_{23} and θ_{13} *and a single complex phase* δ_{CP}

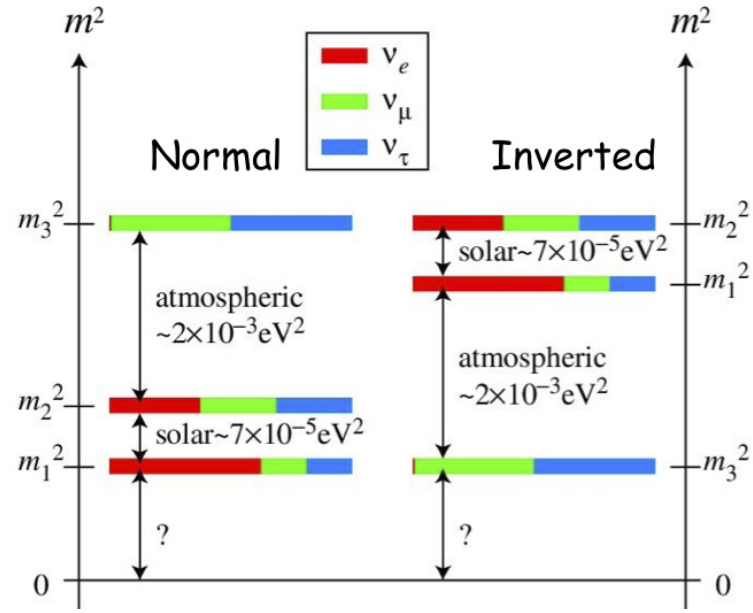
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Including two independent squared mass differences $\Delta m^2_{21}=m^2_2-m^2_1$ and $\Delta m^2_{31}=m^2_3-m^2_1$, for example, there are 6 free parameters that determine the neutrino oscillation.

Neutrino Oscillation Parameters

From previous neutrino oscillation experiments:

- we know that m_1 and m_2 are very close, but difference in m_3 and $m_{1,2}$ is much larger.
- $\sin^2 2\theta_{12}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{23}$ have been measured.

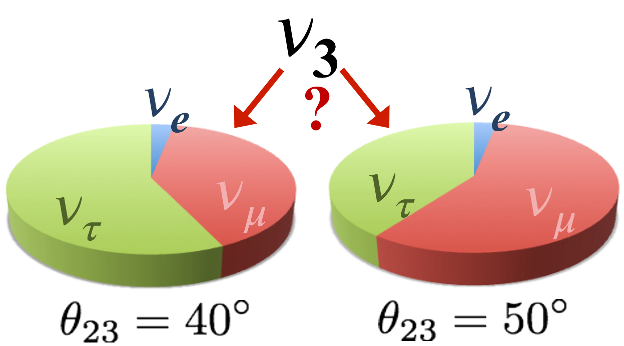


Fundamental questions remaining for long-baseline neutrino oscillation experiments:

- Mass hierarchy: $m_3 > m_{1,2}$ or $m_{1,2} > m_3$?
- CP phase δ_{CP}: whether neutrinos and antineutrinos behave the same way in oscillation?

$$P(\overline{\nu_\mu} \rightarrow \overline{\nu_e}) \neq P(\nu_\mu \rightarrow \nu_e)?$$

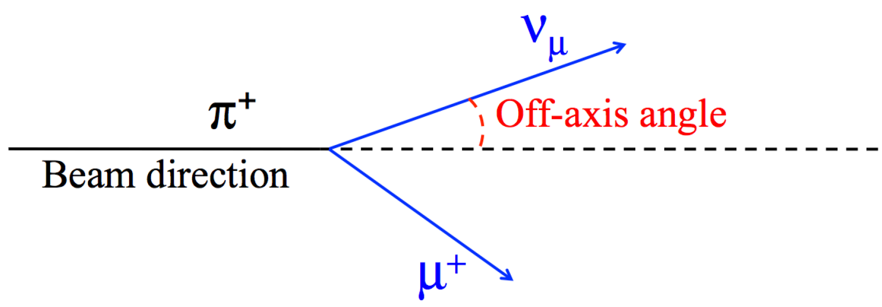
- Octant of θ_{23} : Is θ_{23} exactly 45°? Is ν_3 more strongly coupled to ν_τ or ν_μ?



NuMI Off-Axis ν_e Appearance Experiment

- NOνA is a 2-detector neutrino oscillation experiment, optimized for ν_e identification.
- Upgrading NuMI muon neutrino beam at Fermilab (700 kW).
- Construct a 14 kt liquid scintillator far detector at a distance of 810 km (Ash river, MN) to detect the oscillated beam.
- Functionally identical ~300 ton near detector located at Fermilab to measure unoscillated beam ν to estimate backgrounds in the far detector.

NuMI Off-Axis Beam

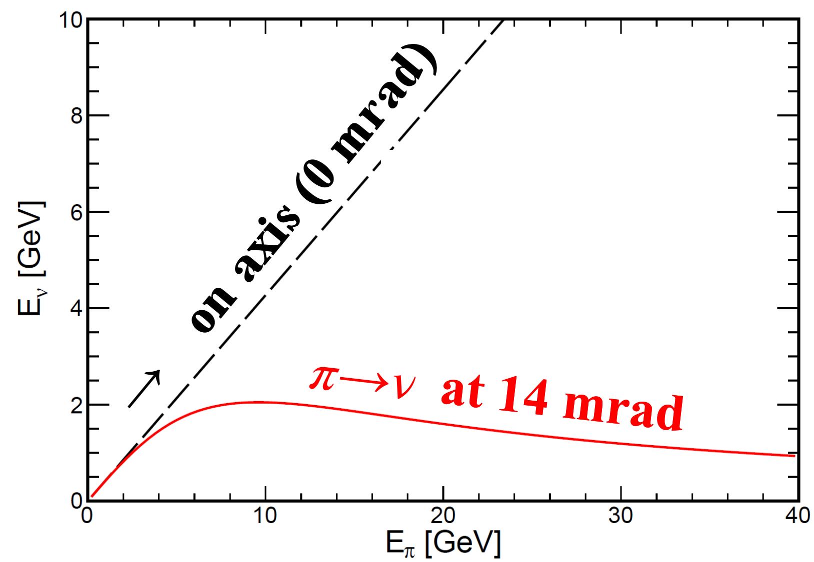


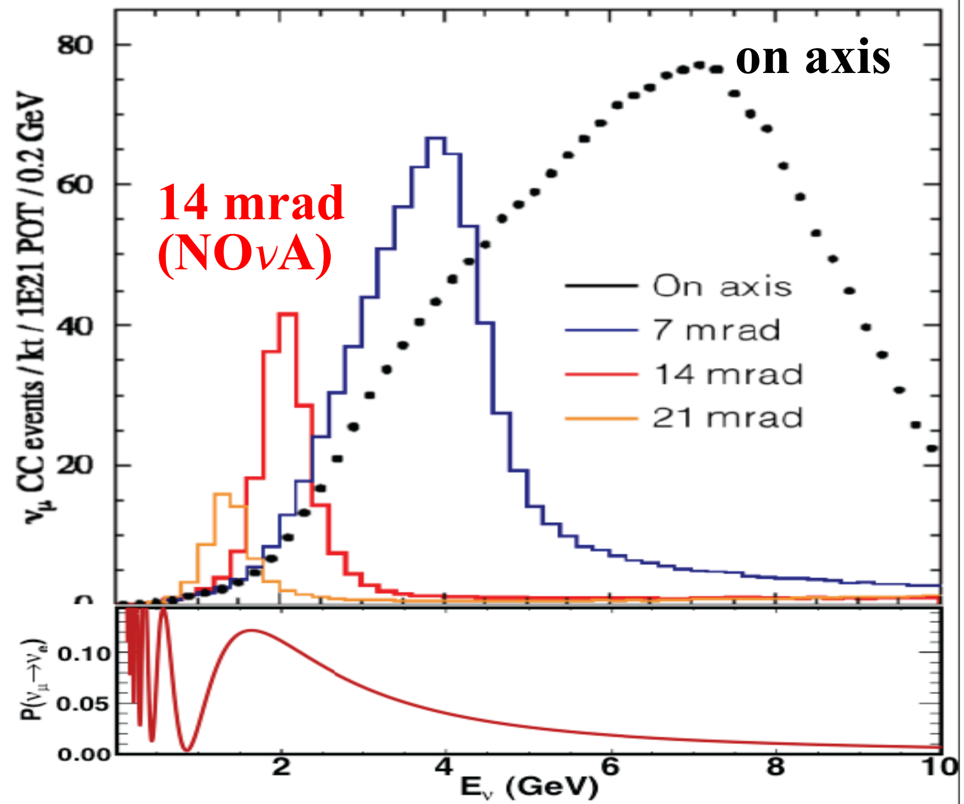
•NOνA detectors are sited 14 mrad off the NuMI beam axis

•Beam ν are produced by π and K decays. Neutrino energy depends on the decay angle and π/K energy

•With the medium-energy NuMI tune, yields a narrow 2-GeV spectrum at the NOνA detectors

•Reduces beam NC and ν_eCC backgrounds in the oscillation analyses while maintaining high ν_μ flux at 2 GeV for the oscillation signal





Neutrino Oscillation at NOvA

ν_μ disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m^2_{32} L/4E)$$

…to leading order

Improve precision on $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$

ν_e appearance:

When neutrinos travel through matter, their effective masses need corrections because they scatter on electrons (matter effect)

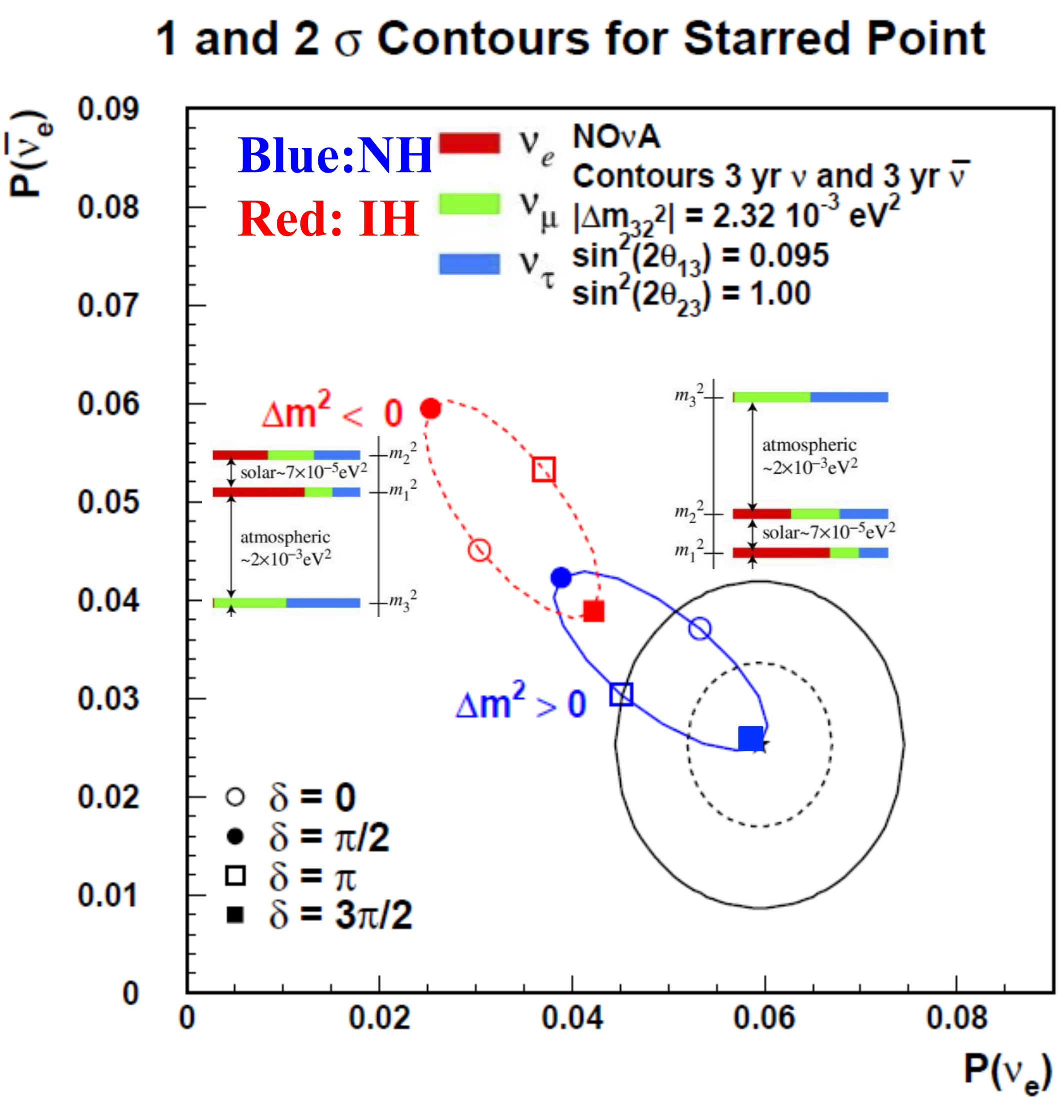
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$$

$$A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

Determine the sign of Δm^2_{31}, measure δ_{CP} and octant of θ_{23}

Physics Goals of NOvA



- Measuring ν_e appearance probability and ν_μ disappearance probability with ν_μ and anti-ν_μ beam.
- ν_e appearance:
  - Determine neutrino mass hierarchy.
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant.

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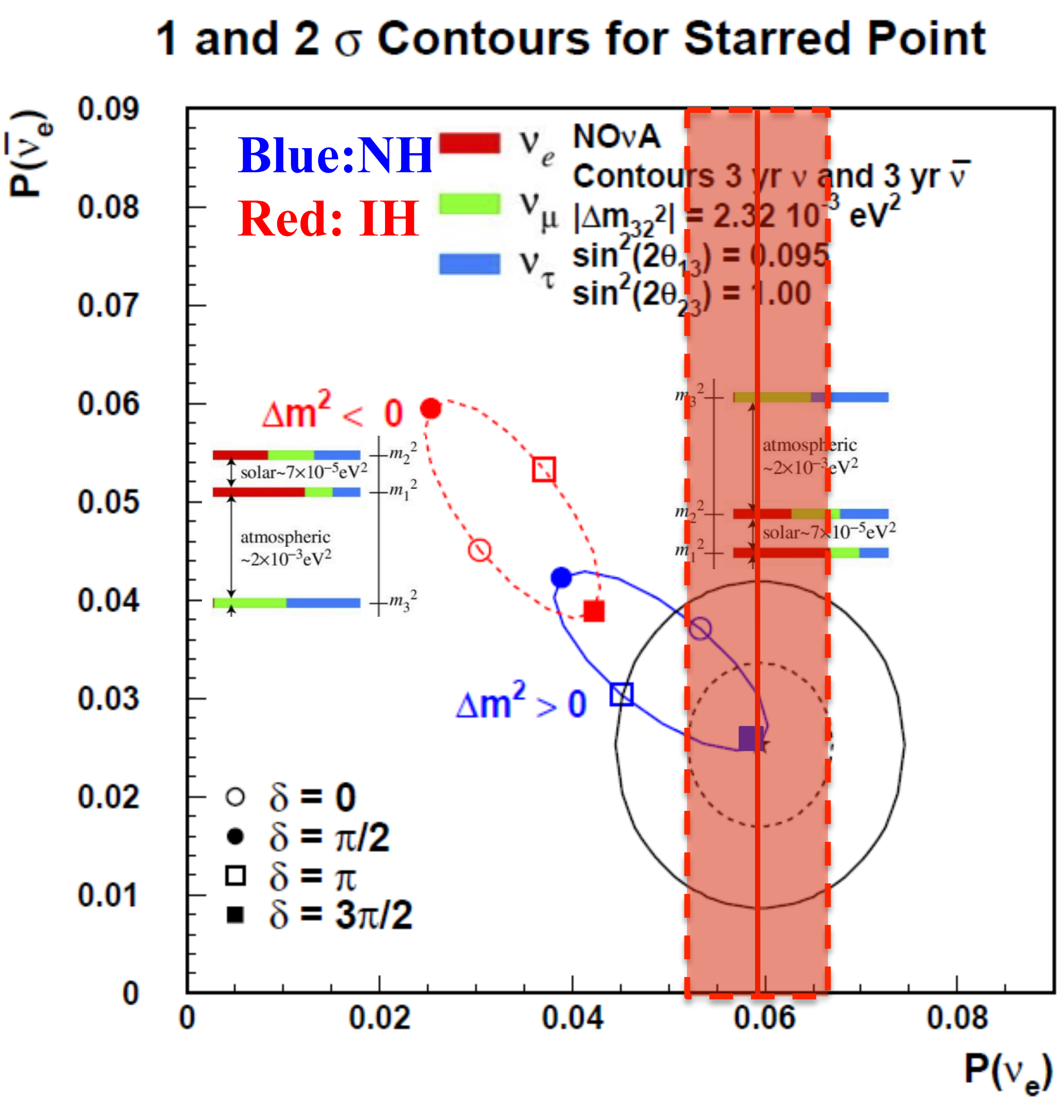
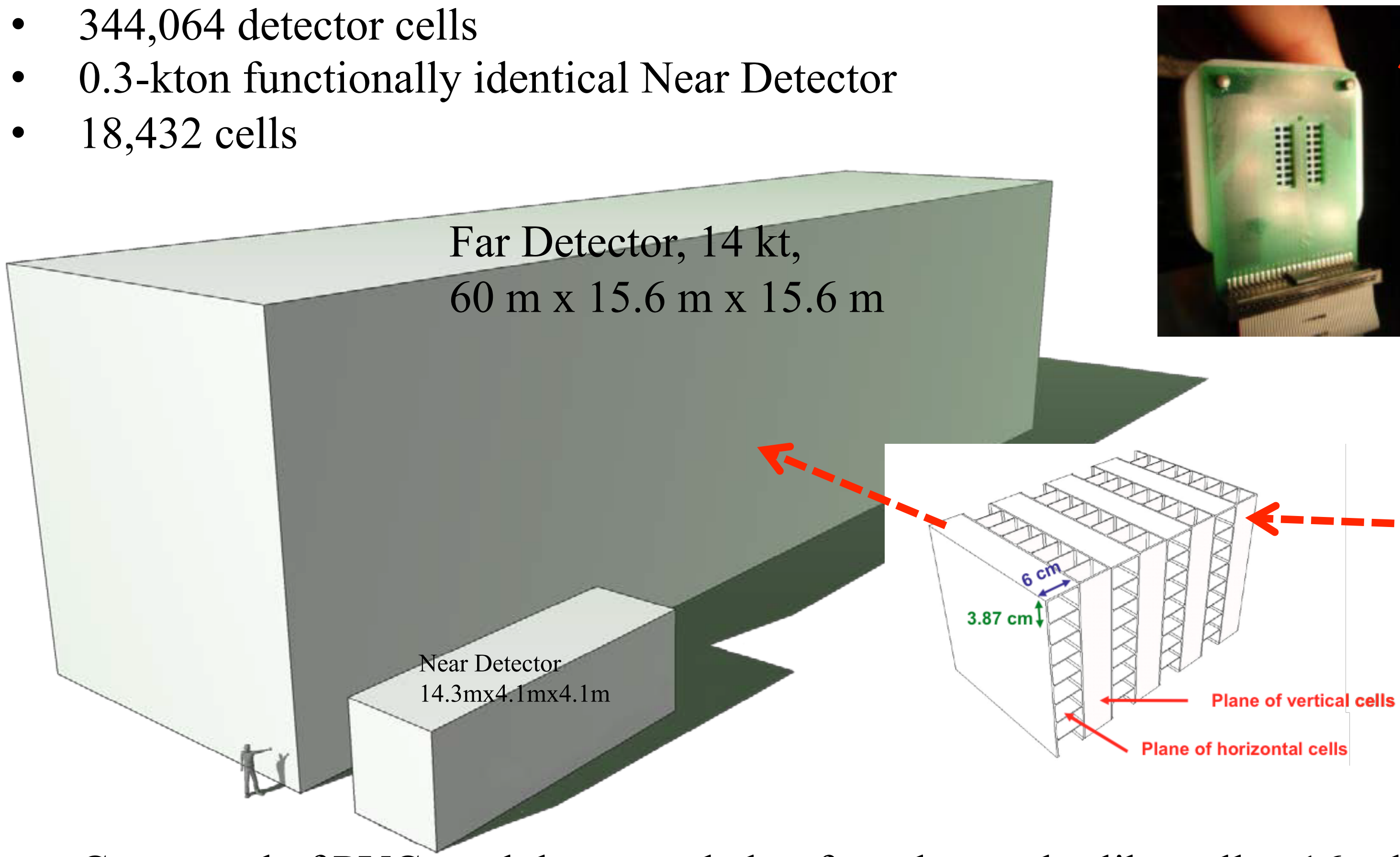
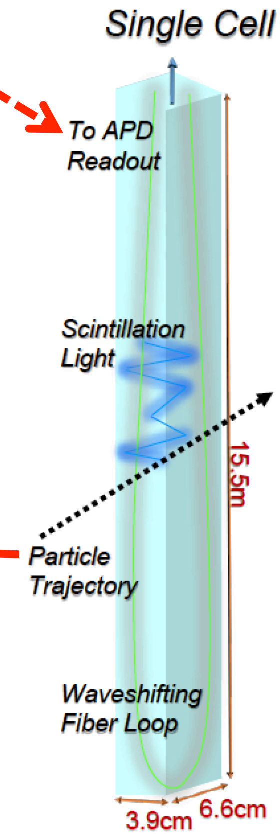


- Measuring ν_e appearance probability and ν_μ disappearance probability with ν_μ and anti-ν_μ beam.
- ν_e appearance:
  - Determine neutrino mass hierarchy.
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant.
- **For the first ν_e analysis we measure $\nu_\mu \rightarrow \nu_e$ with neutrino beam.**

The NOνA Detectors

- 14-kton Far Detector
- 344,064 detector cells
- 0.3-kton functionally identical Near Detector
- 18,432 cells

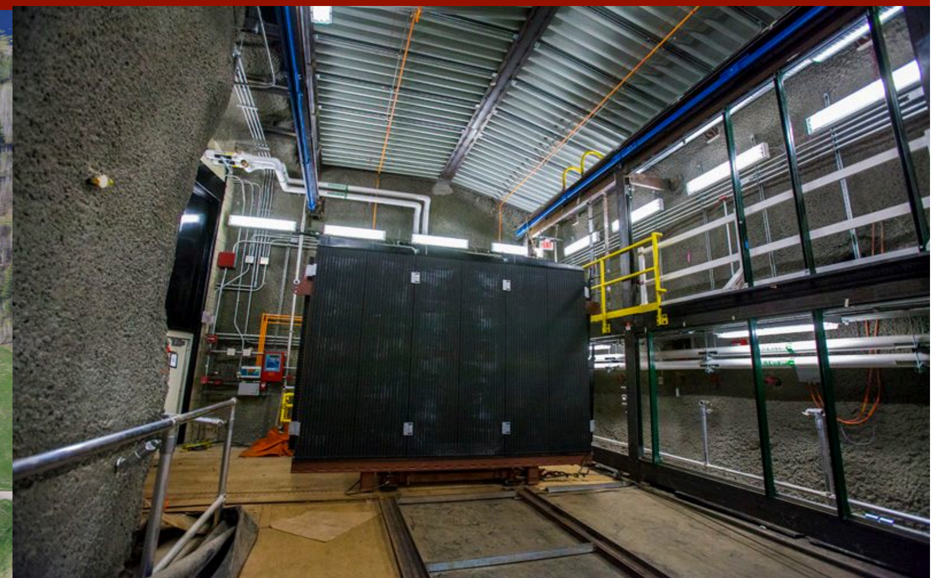


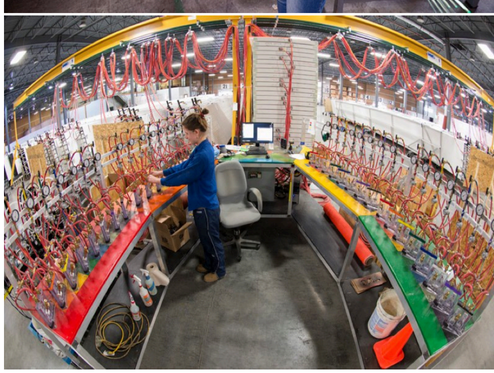


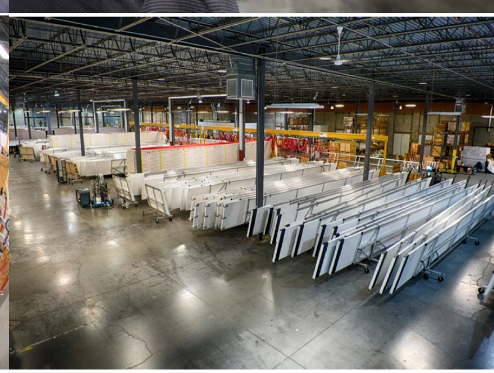
- Composed of PVC modules extruded to form long tube-like cells : 16m long in FD, 4m ND.
- Each cell is filled with liquid scintillator and has a loop of wavelength-shifting fiber routed to an Avalanche Photodiode (APD).
- Cells arranged in planes, assembled in alternating planes of vertical and horizontal extrusions.
- Each plane just 0.15 X_0. Great for e^- vs π^0 .

NOvA construction (2009-2014)

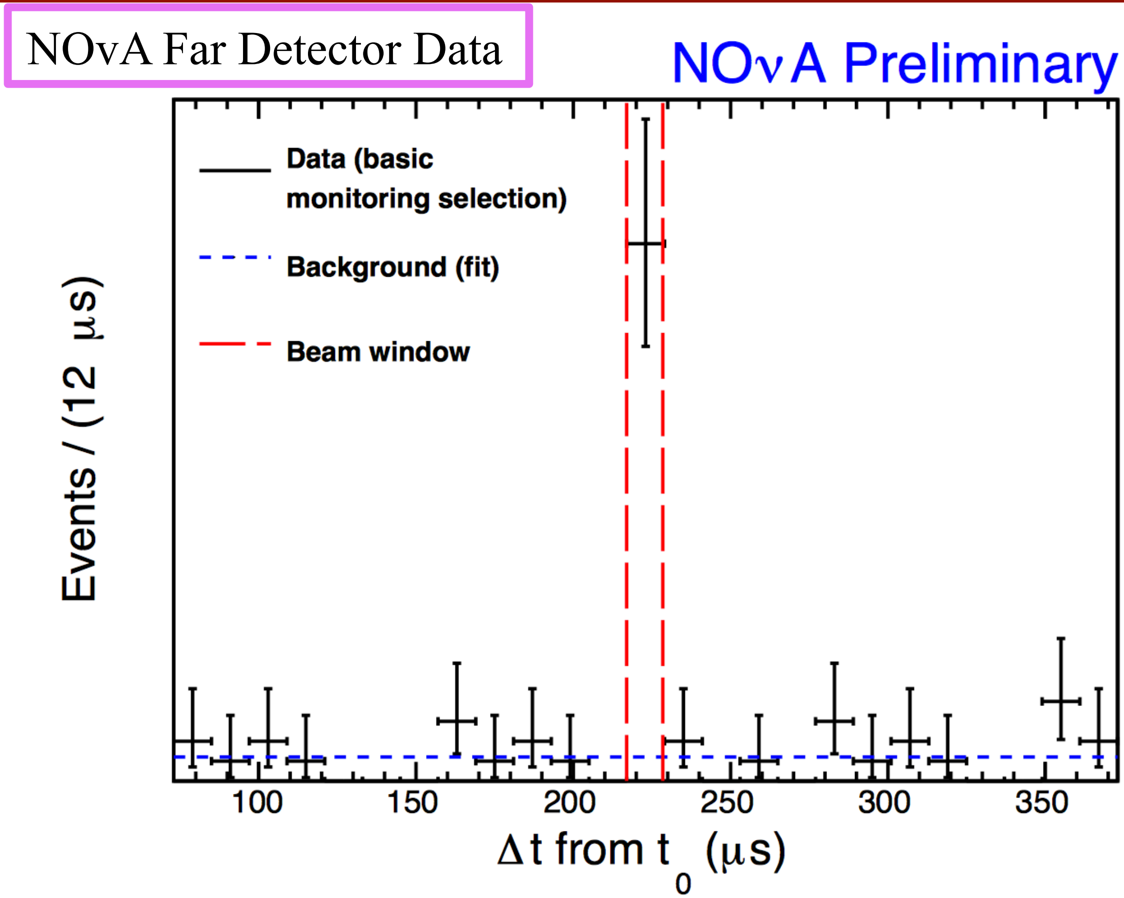
As of September 4th 2014, both far and near detectors are fully commissioned.

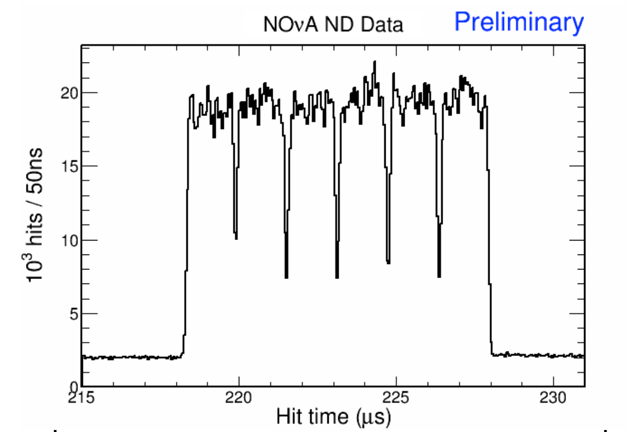


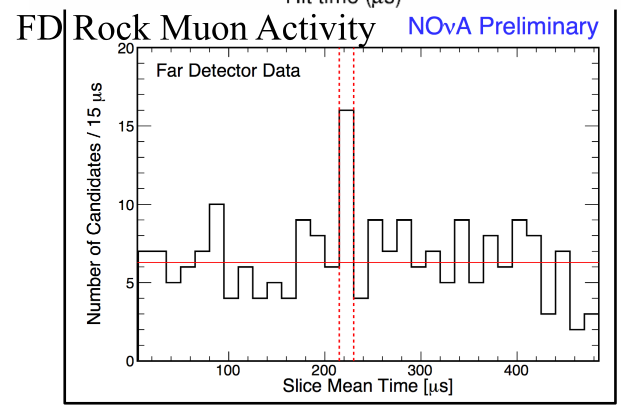




Far/Near Detector ν timing

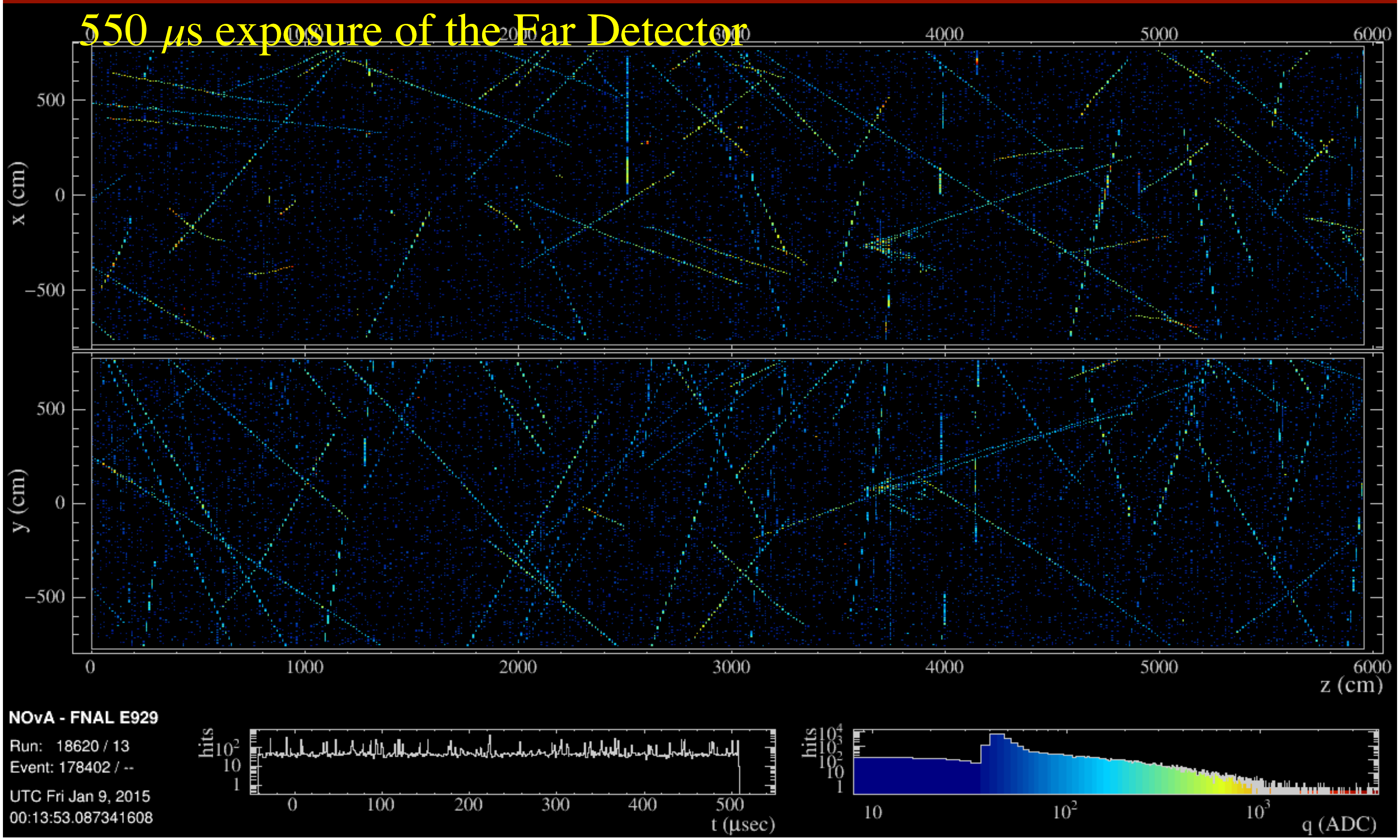






- Neutrino candidates were observed in both near and far detectors in 2014 summer.
- Far Detector neutrino candidates blow up of timing peak, showing agreement with expected spill times as measured at our Near Detector at FNAL.
- This demonstrates both FD & ND were completed.

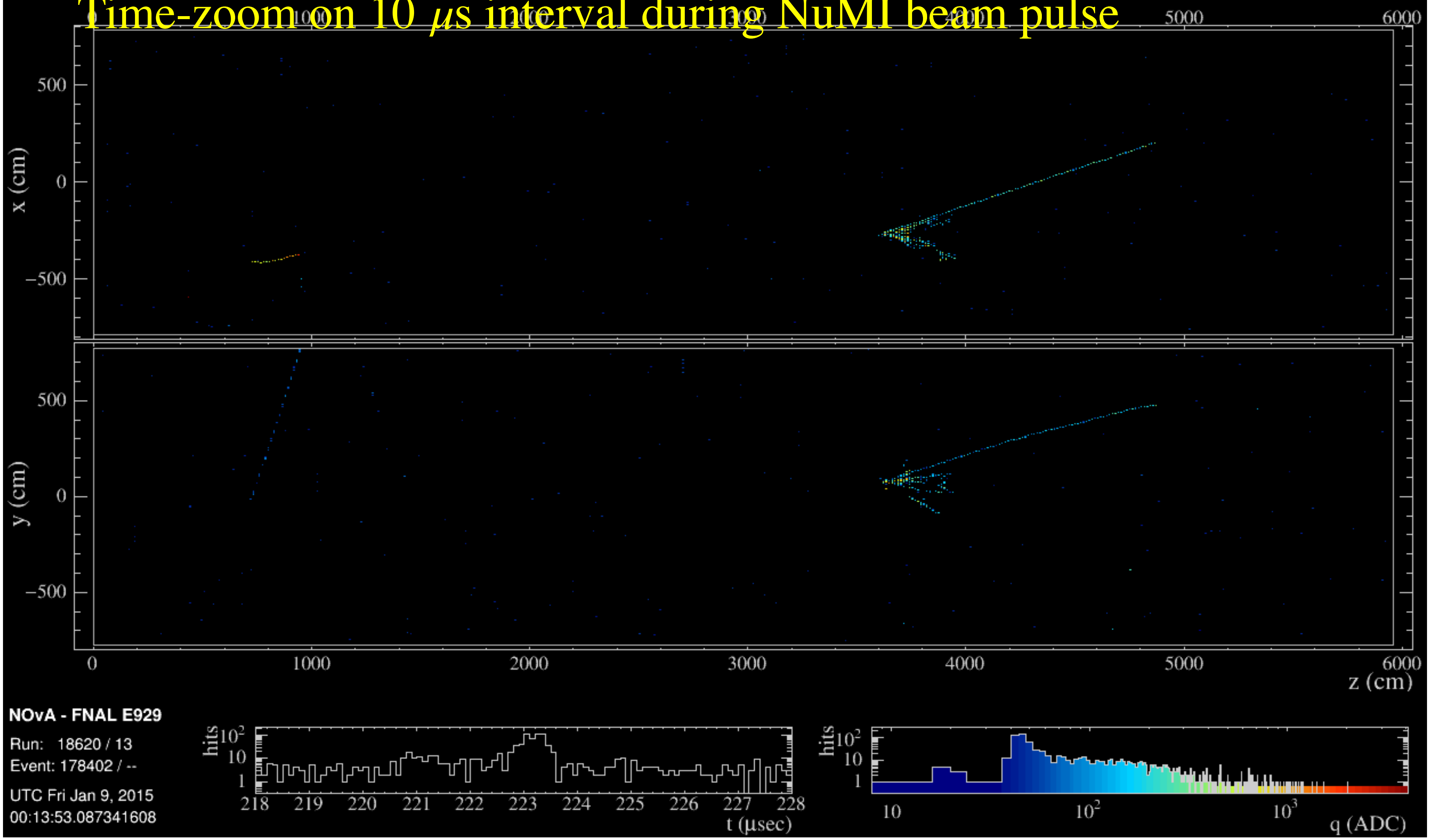
Event clustering



Because hits in a 550µs trigger window are a combination of cosmic and beam events, first step in reconstruction is to cluster hits by space-time coincidence

Event clustering

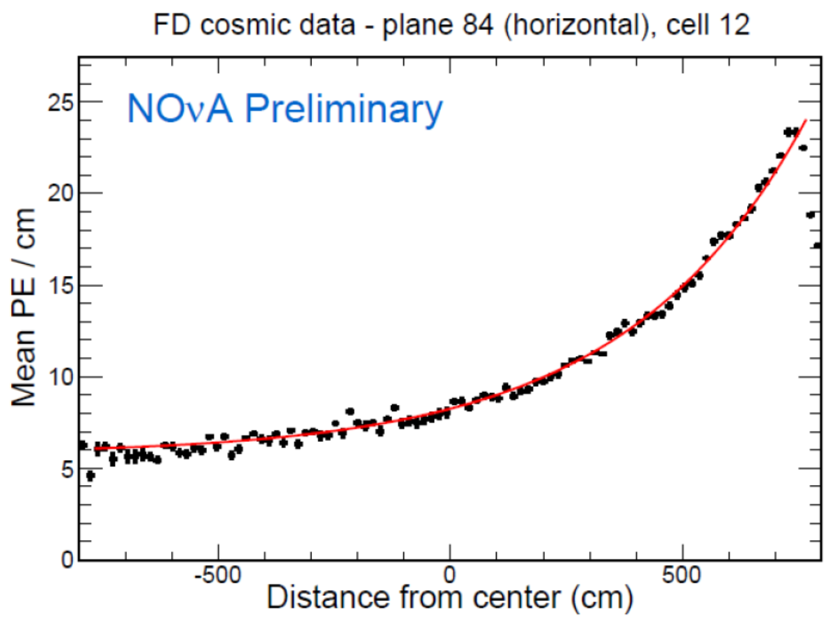
Time-zoom on 10 μs interval during NuMI beam pulse



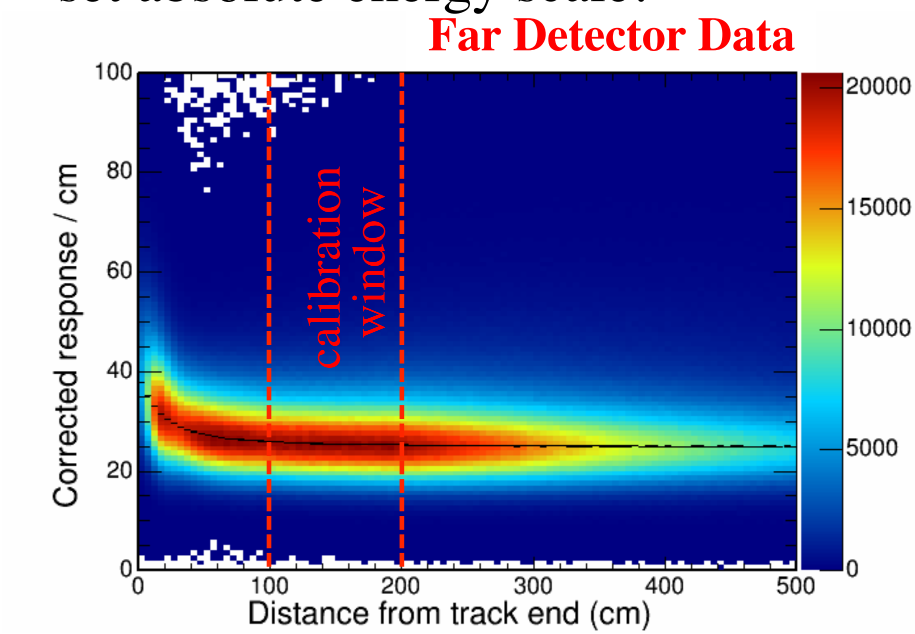
Event clusters that contain neutrino interactions can be correctly selected in the in the 10μs neutrino spill timing window

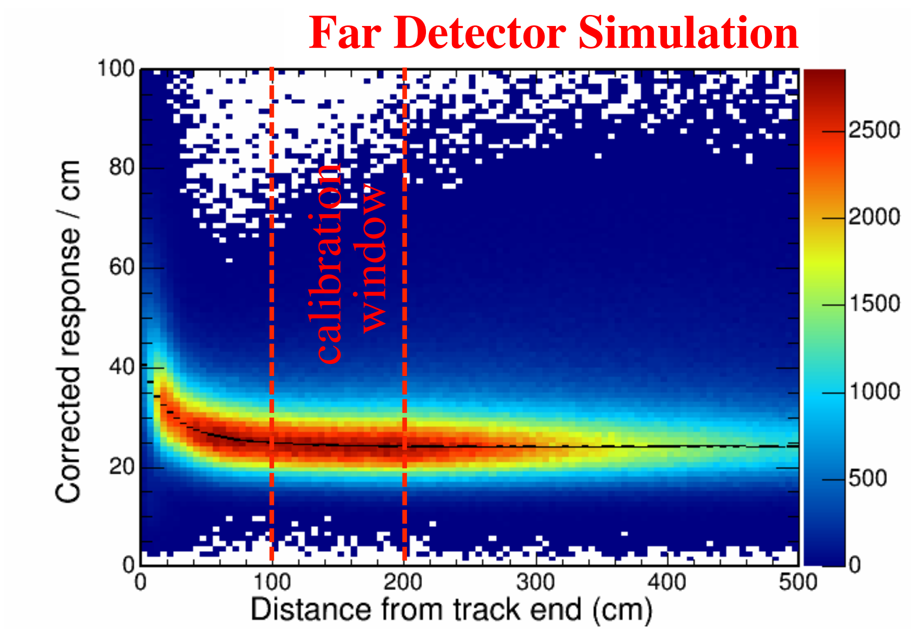
Calibration

- Use the MIP peak of cosmic muons to correct the attenuation in the WLS fiber.

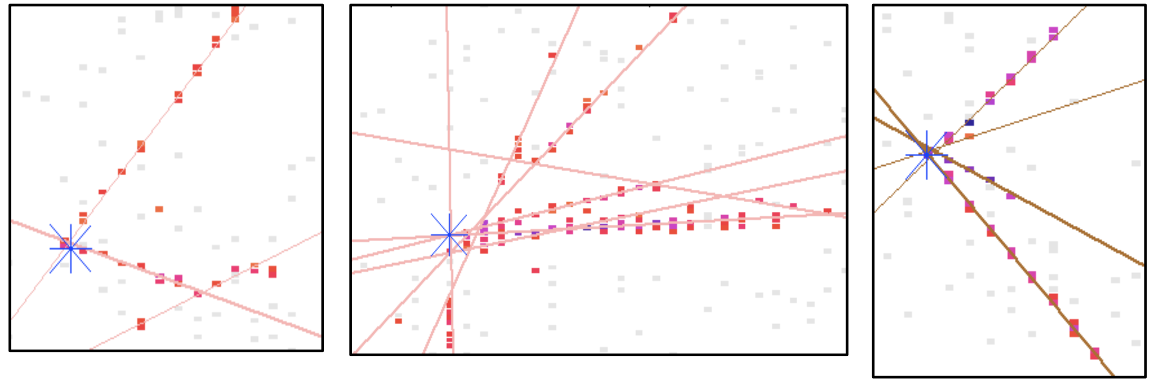


- Use stopping muons in cosmic rays to set absolute energy scale.

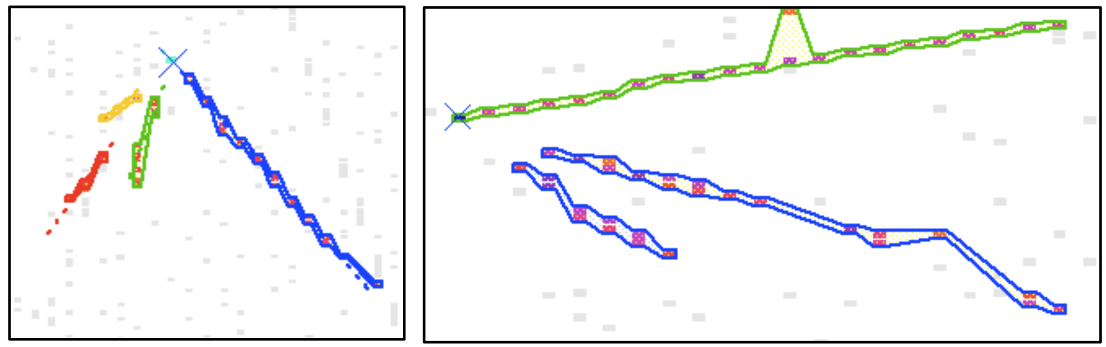




Reconstruction

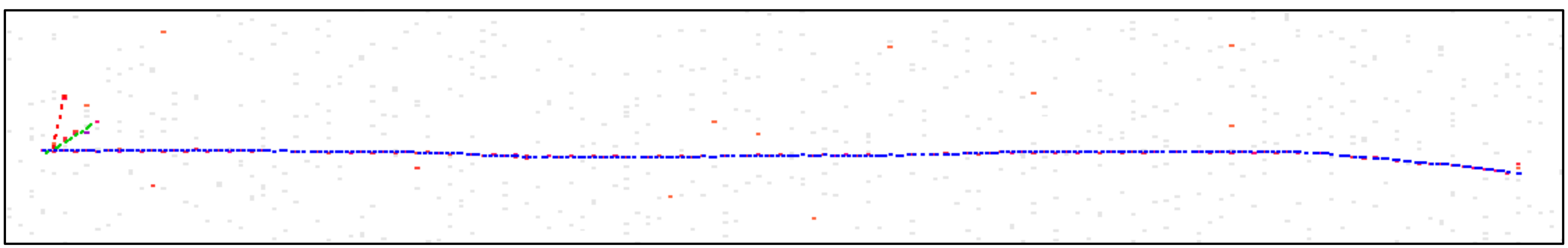


<u>Vertexing:</u> Find **lines of energy depositions** w/ Hough transform



<u>Shower Clustering:</u> Based on the vertex, prongs are determined by angular clustering.

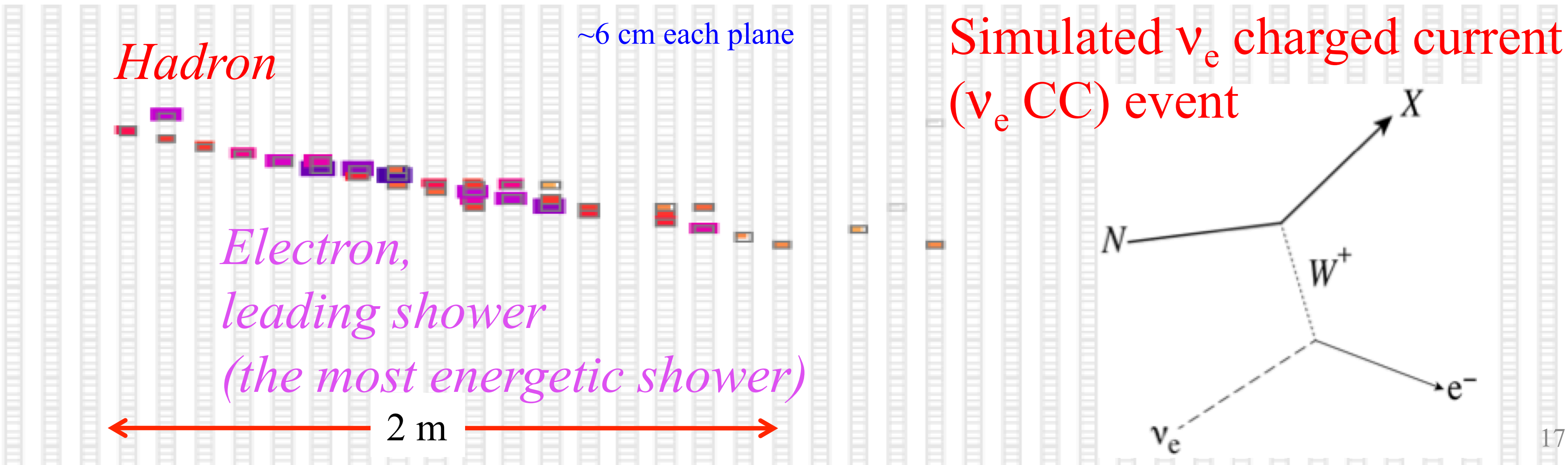
<u>Tracking:</u> Trace particle trajectories with **Kalman filter** tracker (below).
Also have a **cosmic ray tracker** that reconstructs cosmic tracks with high speed.



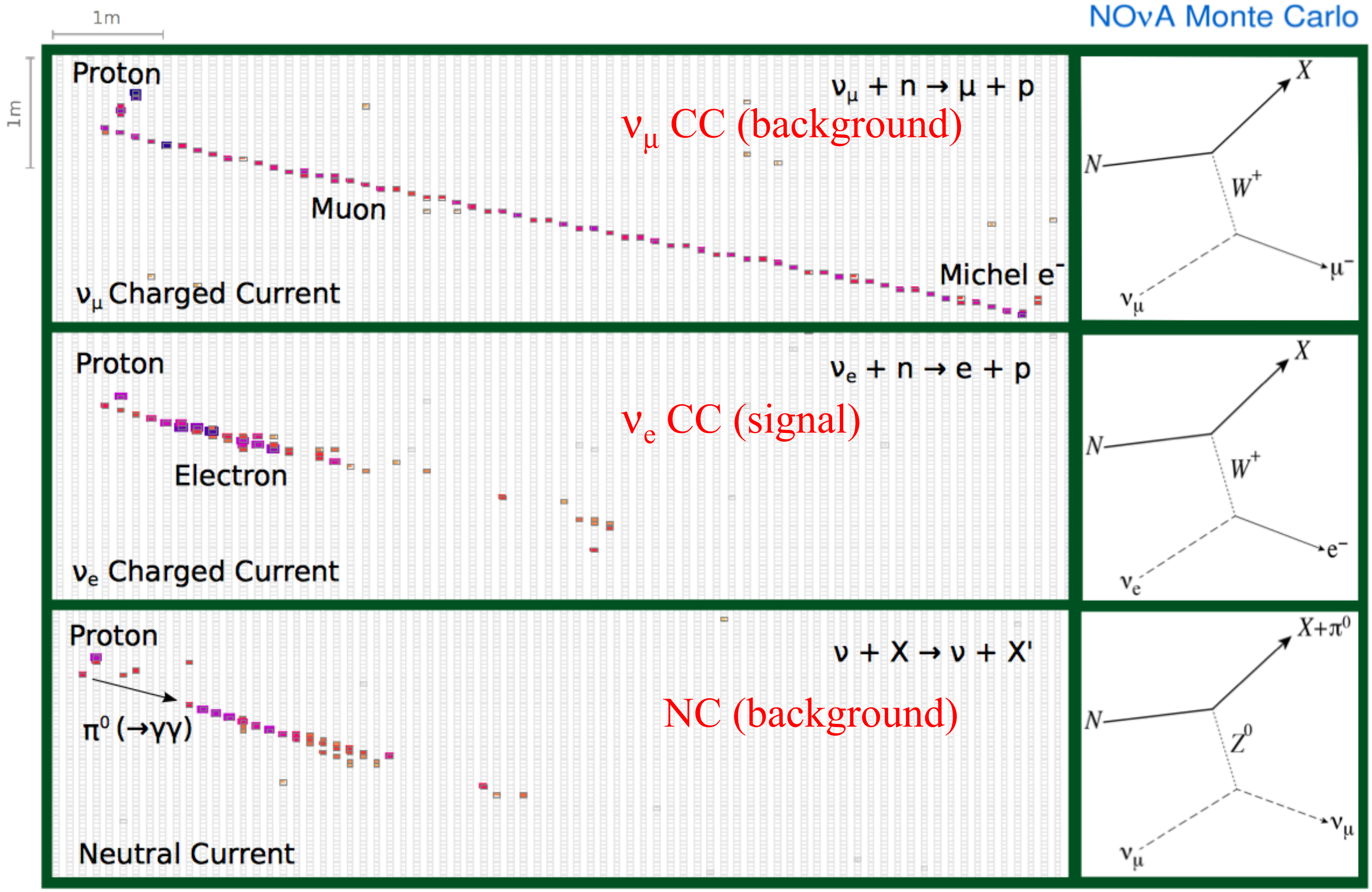
The first ν_e appearance analysis

- A cut-and-count analysis, with 1/13th of planned exposure.

- ν_e event reconstruction: clustering, calibration, reconstruct event vertex and prongs.
- ν_e identification: identify ν_e in $\nu_\mu \rightarrow \nu_e$ oscillation
  - LID: Artificial neural network using shower shape based likelihood for particle hypotheses. (Primary PID)
  - LEM: Matching events to a Monte Carlo library. (Cross check)
- Event selection, including cosmic rejection.
- Data driven extrapolation of background using ND data. Each background component: beam ν_e, NC, ν_μ CC is predicted in the FD.

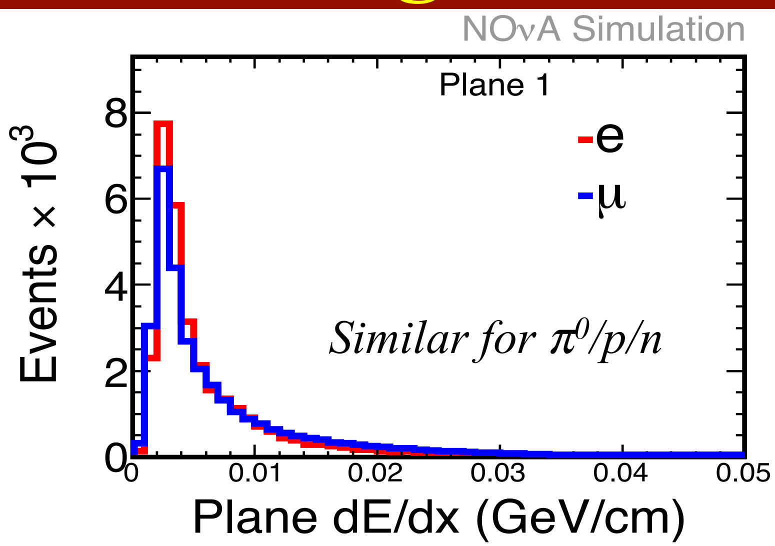


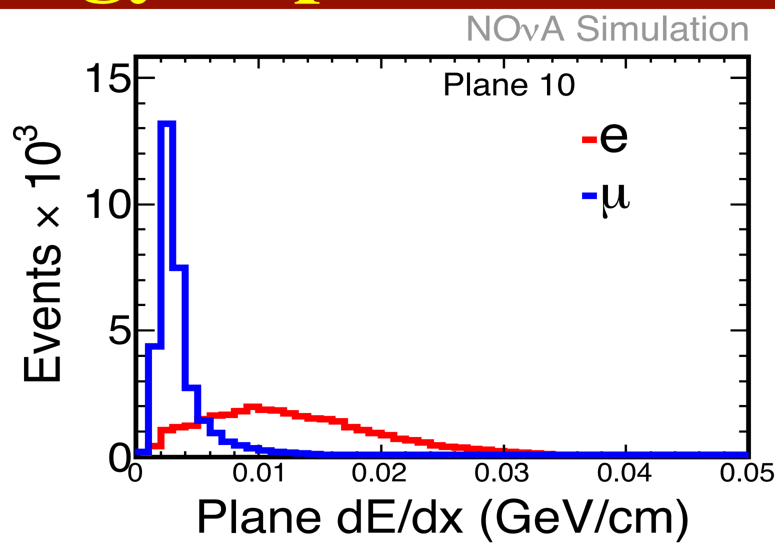
Neutrino Event Topology in NOνA

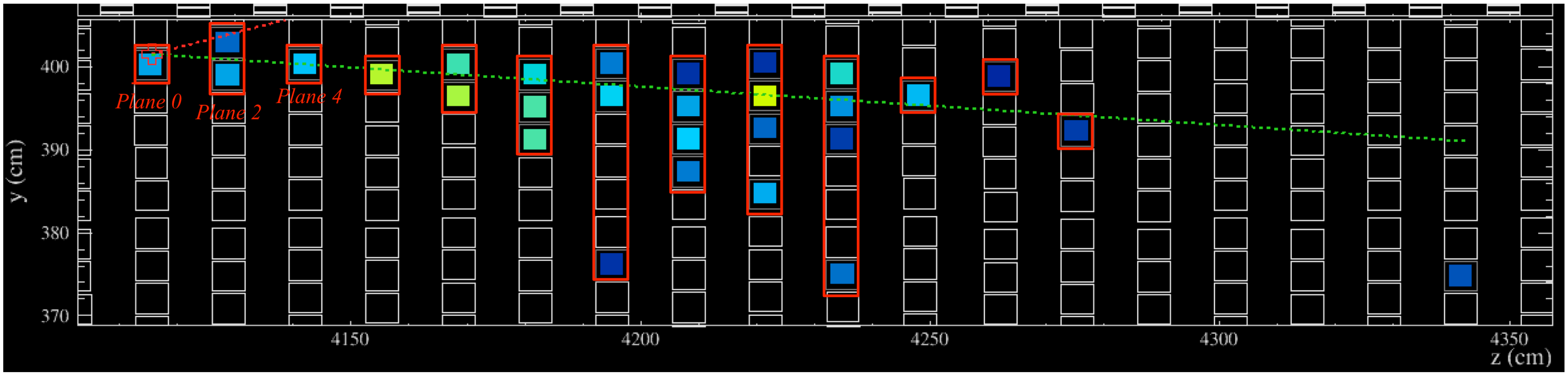


The muon is a long minimum ionizing particle (MIP) track, the electron ionizes in the first few planes then starts a shower and the photon is a shower with a gap in the first few planes.

Longitudinal energy deposition





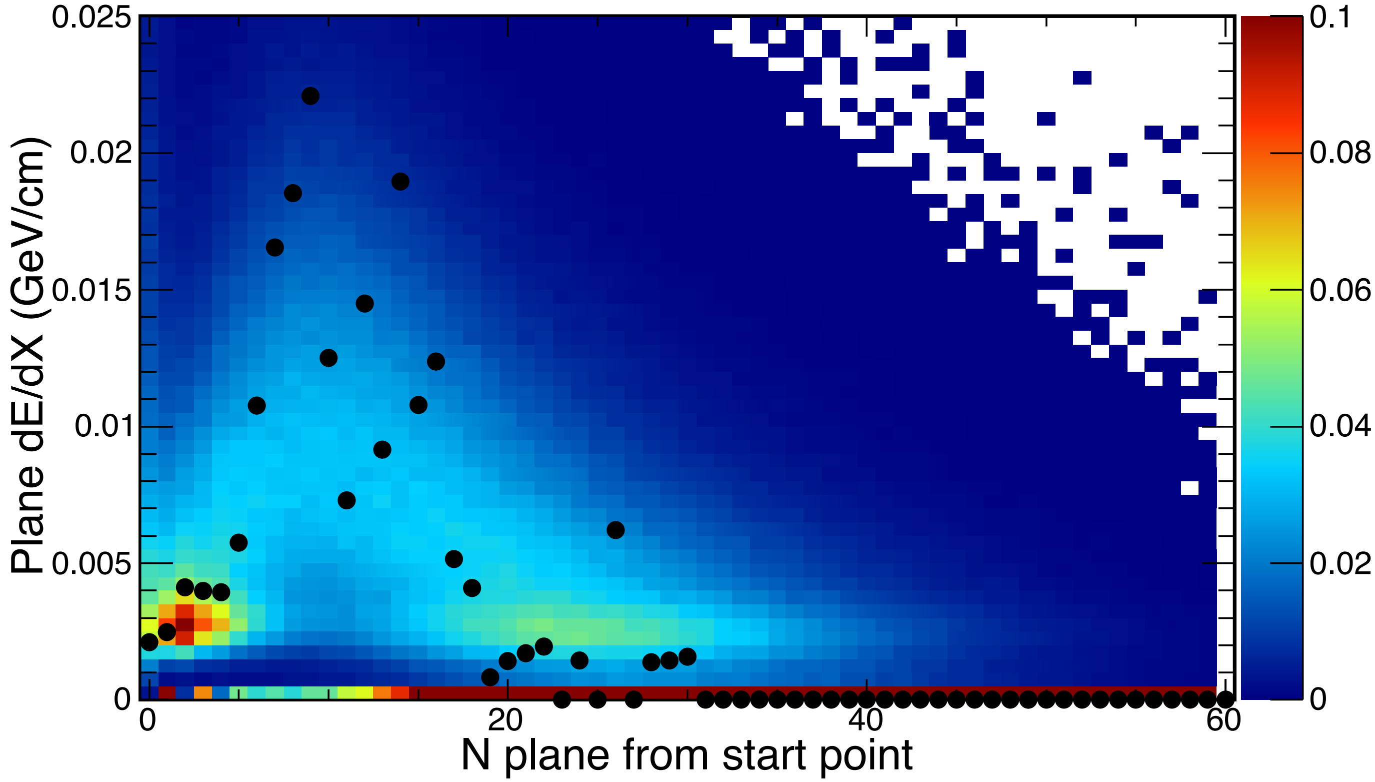


- Reconstructed prong energy profile, vertex and event topology go in to LID.
- For an unidentified particle, we compare its energy loss per length (dE/dx) with the expected dE/dx histograms by each longitudinal and transverse slice to construct the probability and likelihood for each particle hypotheses.

Probability Density Function (P.D.F) for plane dE/dx distributions and measured dE/dx in FD Data

Color: p.d.f. for dE/dx in each plane (e^- assumption)

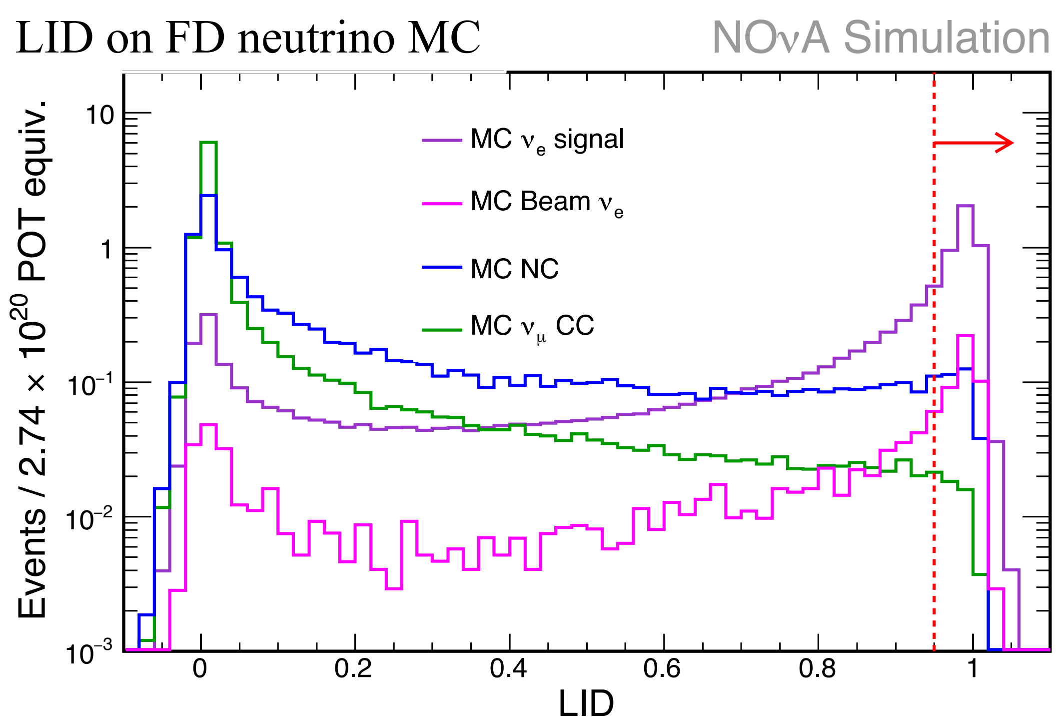
Points: measured dE/dx in each plane (example event)



- Summing over these longitudinal/transverse likelihoods we have overall longitudinal and transverse likelihoods for each type of particle.
- The difference of log-likelihoods indicates the identity of the particle, for example: LL(e/μ)=LL(e)-LL(μ).

Likelihood-based ν_e Identifier (LID)

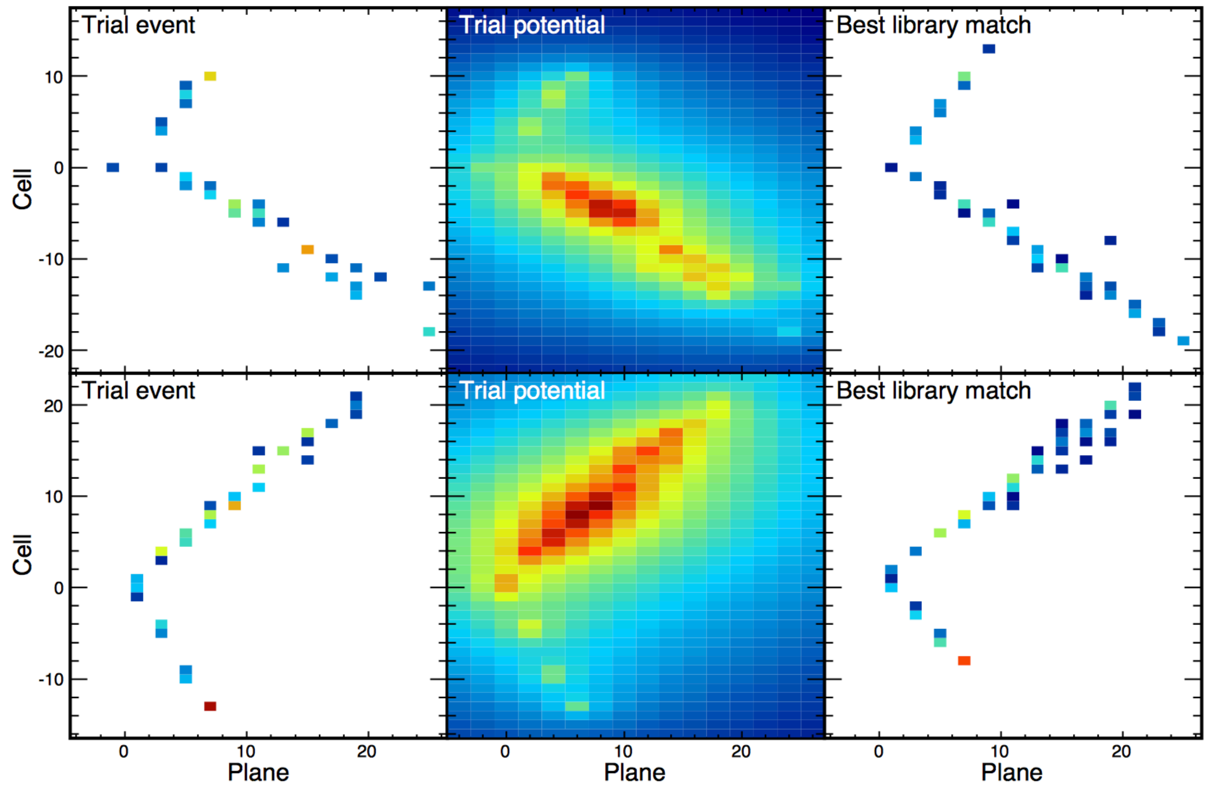
- Particle likelihoods for the leading shower, amongst other event topology variables, are used as inputs to an Artificial Neural Net (ANN) for the final PID.



- ν_e selection is LID>0.95, according to max. S/sqrt(B).
- Signal efficiency of 34% relative to the contained sample.
- Reject 99% of beam backgrounds.
- After all selection cuts, achieves a rejection of 1 in 10^8 for cosmogenic backgrounds.

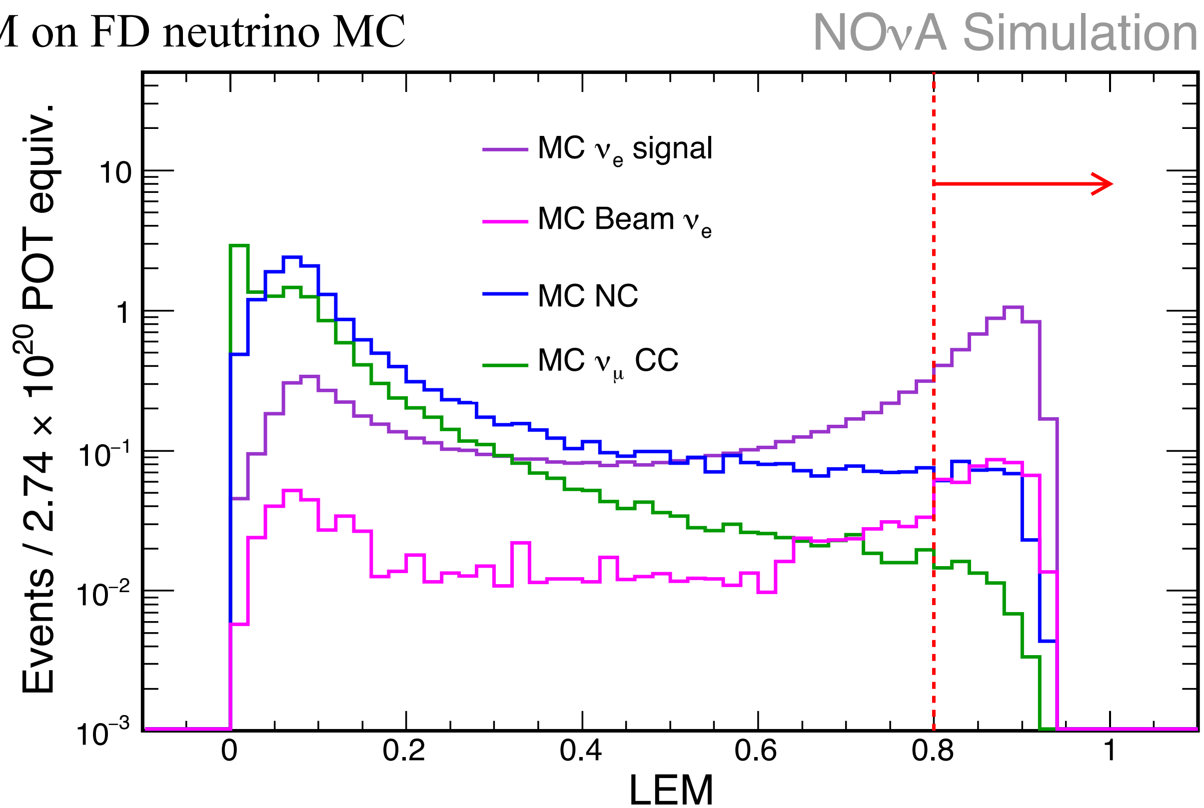
Library Event Matching ν_e Identifier (LEM)

- Compare an unknown trial event to an enormous **MC library**, using individual cell hits rather than high-level reconstructed variables.
- Extract **the pattern function (potential)** for the **trail event** by cell, including both position and charge information.
- Loop over all events in the library, place each event on the pattern function to calculate match value and record the **1000 best matching library events**.
- **Five matching goodness variables** based on the 1000 best matching events, along with the **calorimetric energy** of the trial event are trained in a BDT to form the PID (LEM).



Library Event Matching ν_e Identifier (LEM)

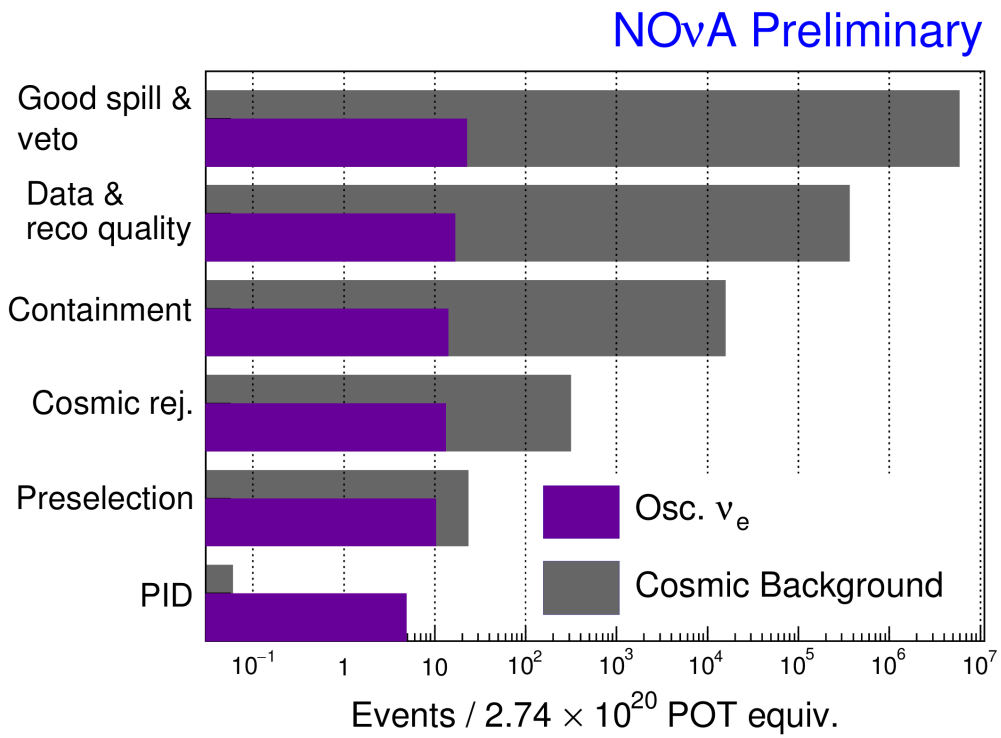
LEM on FD neutrino MC



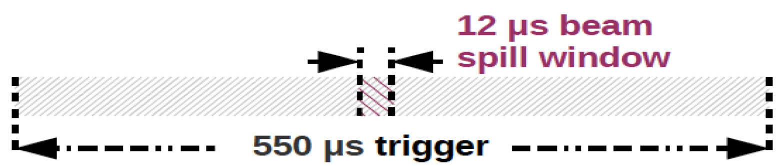
Both PIDs are very similar in the physics performance

- ν_e selection is LEM>0.8, according to max. FOM=S/sqrt(B).
- Signal efficiency of 36% relative to the contained sample.
- Similar rejection of beam and cosmic background.
- There is 62% overlap of selected signal events between the two PIDs.

Cosmic Ray Background Prediction



	Cosmic ray background
Good spill	21.9e6
Containment & data & reco quality	1.56e4
Cosmic rejection	312.16
ν_e Selection	0.06 (2)



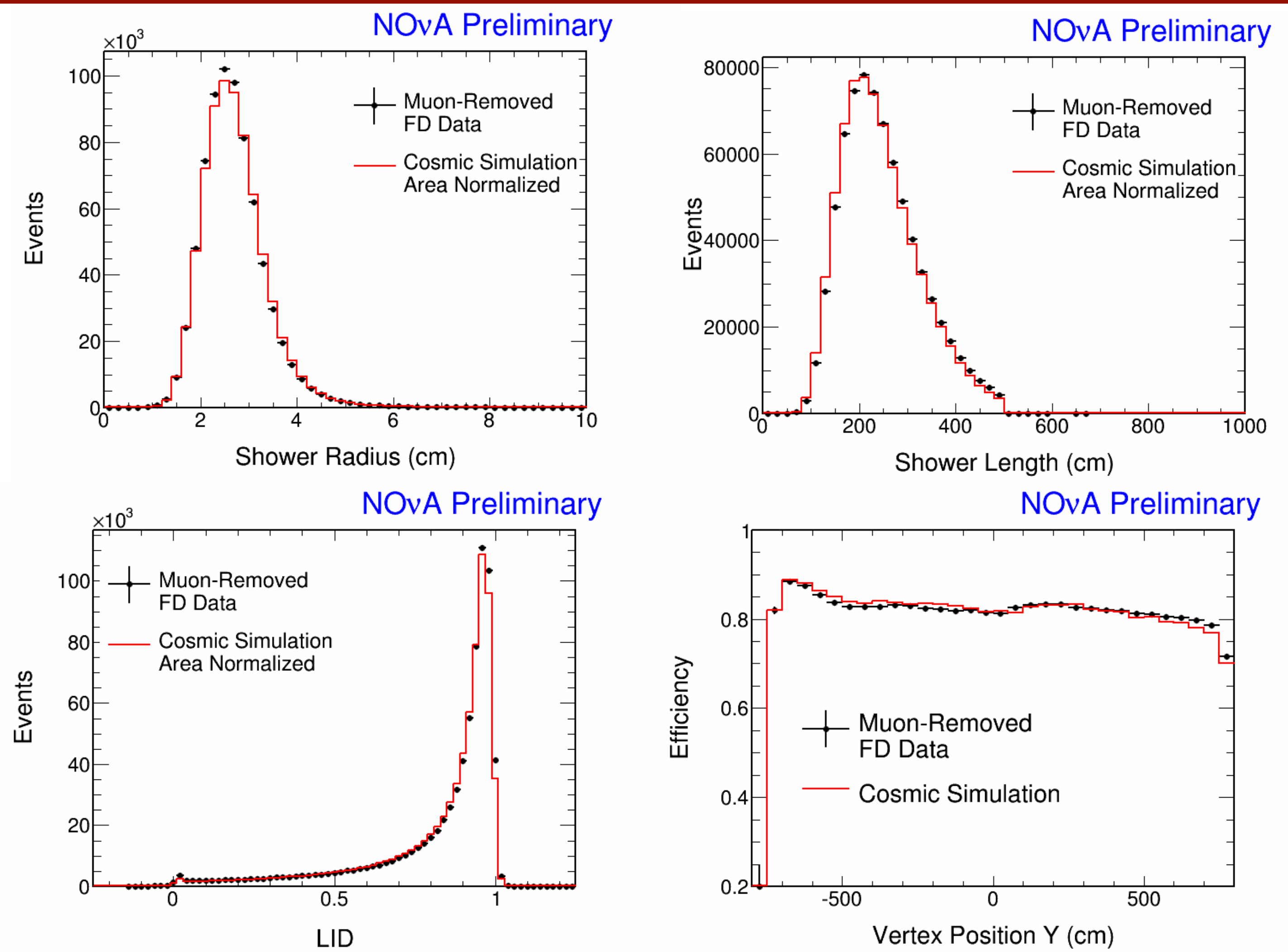
Because the NOvA FD is on surface, the rejection of cosmic rays is extremely important.

Three simple cuts are used to reject the cosmic induced backgrounds prior to PID

- P_t/P - force directionality of showers along the beam
- *Max Y hit position* – remove particles entering from the top of the detector
- Vertex Gap – assure reconstruction quality

Achieves 350 million to 1 cosmic rejection with cosmic rejection and and ν_e selection

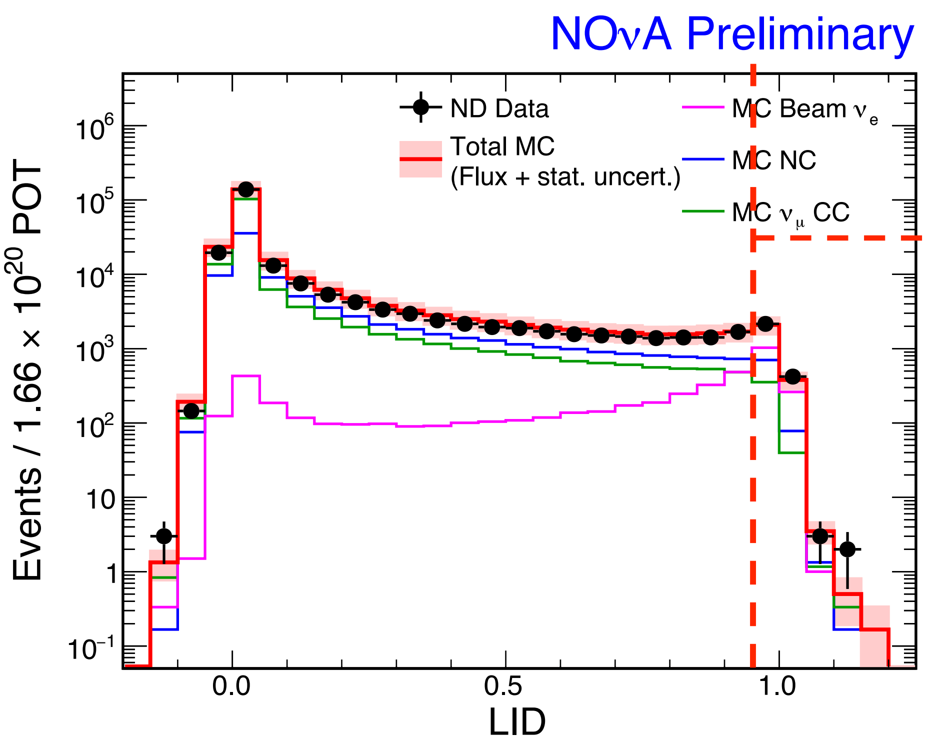
Data/MC for Brem Shower in cosmic rays

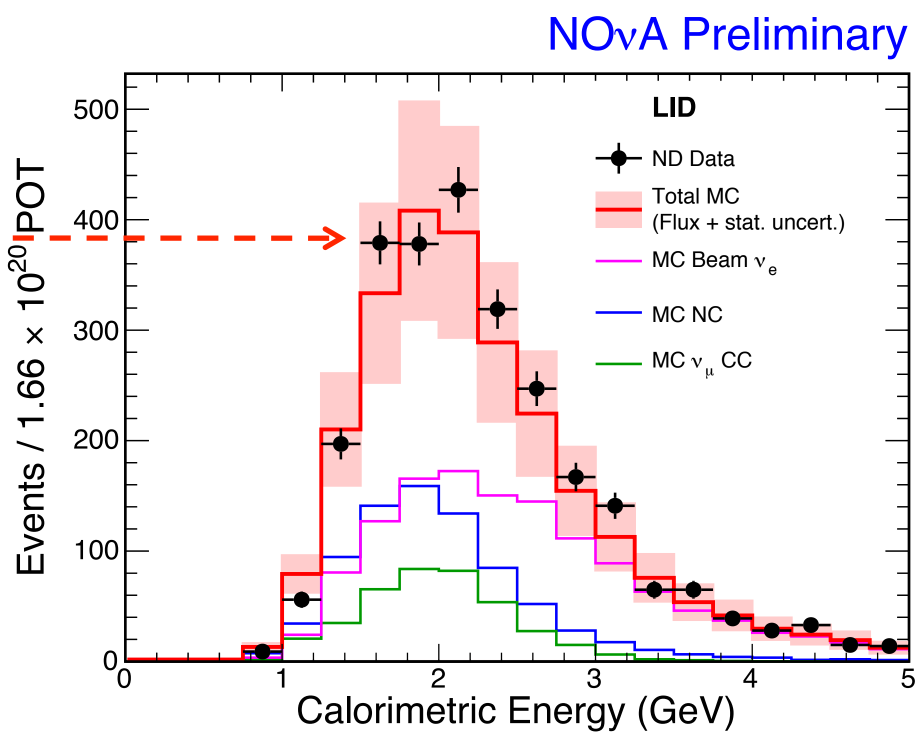


- Use muon removal technique to select signal-like Brem. shower in cosmic rays.
- Great agreement in reconstructed shower variables and LID.
- EM showers are well simulated by NOνA.

Near detector background

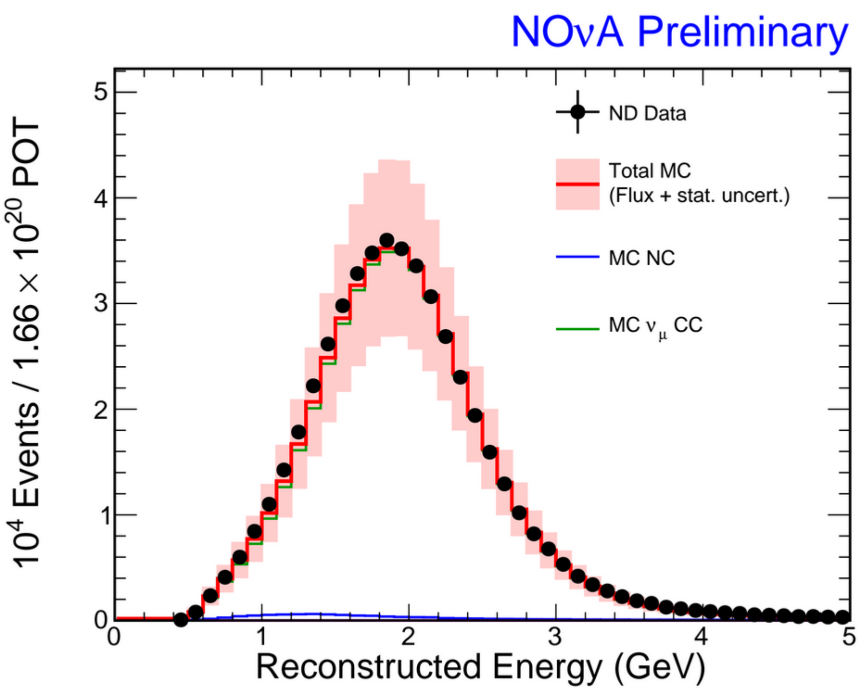
- Far Detector and Near Detector are functionally identical. Near detector is close to the beam (1 km), so in the ND, all PID selected events are background events.
- ND data gives a data-driven correction for the MC normalization in FD.
- Scale up each component in MC by the data/MC ratio improves the background prediction.

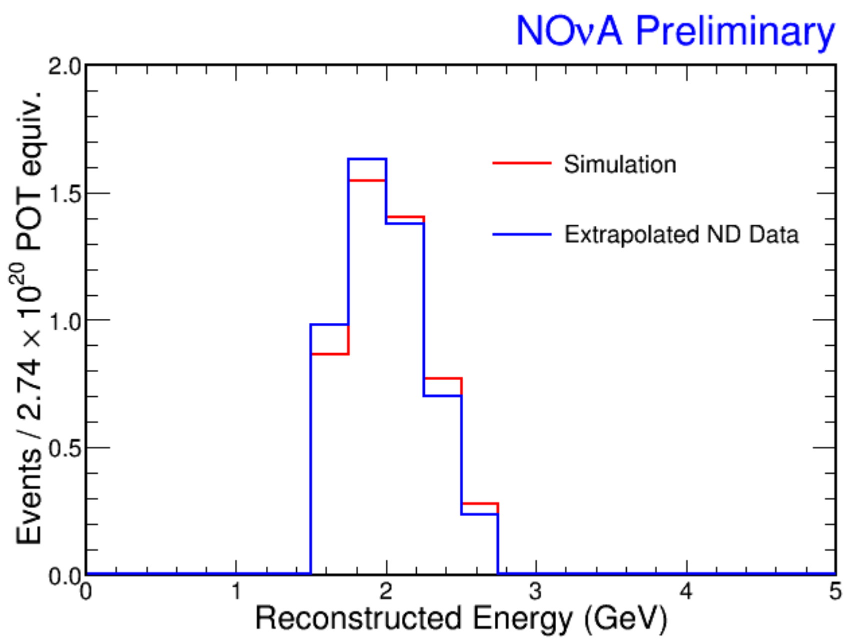




Near Detector ν_μ Spectrum for Far Detector Signal Prediction

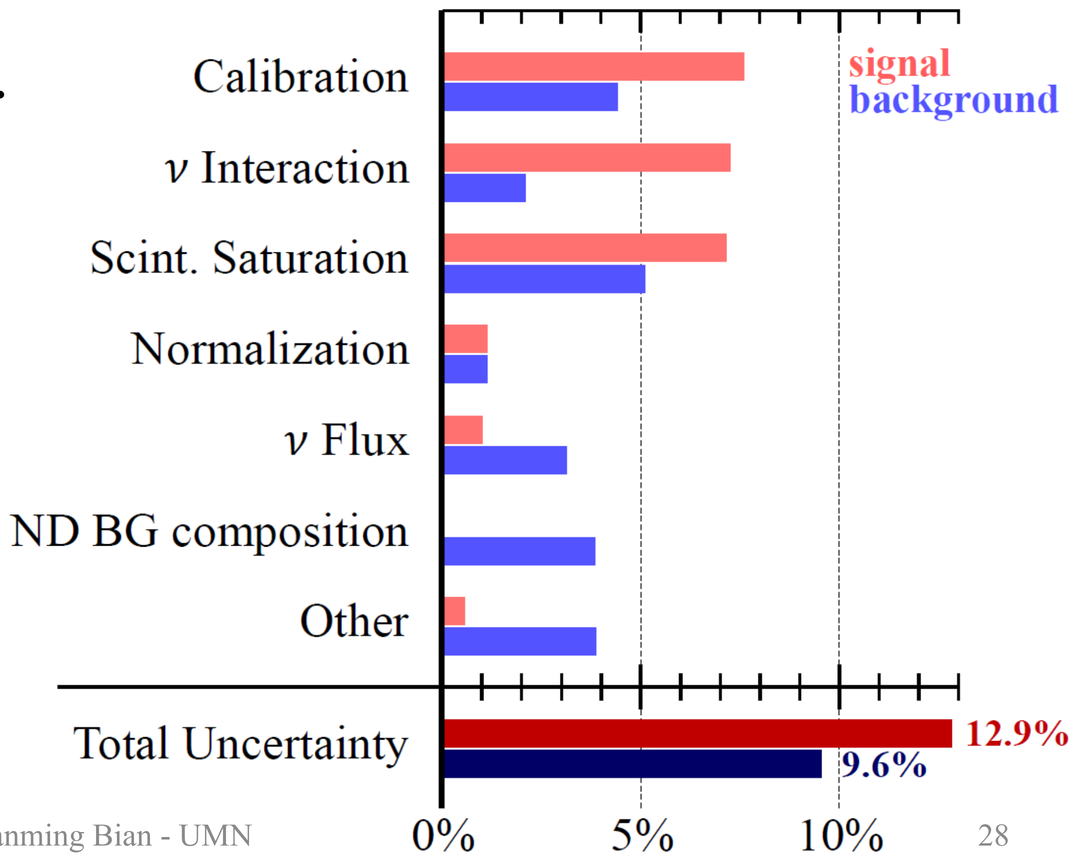
- The signal for the ν_e appearance analysis is ν_e from $\nu_\mu \rightarrow \nu_e$ oscillation, which does not appear in the Near Detector.
- The ND ν_μCC's allows us to predict our expected FD ν_eCC signal.





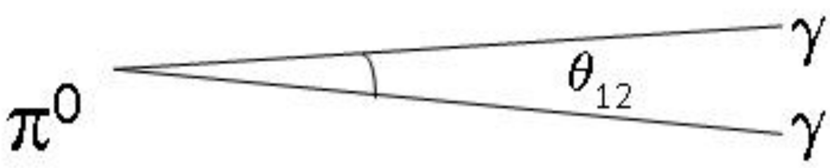
Systematic Errors

- A two detector experiment allows for the canceling or reduction of many systematic uncertainties such as beam flux and neutrino interaction modeling.
- The residual systematic uncertainties are evaluated by extrapolating our ND data with our nominal simulation and a systematically modified simulation
- For the appearance measurement, we consider a number of systematic effects
  - ***Calibration***
  - ***Non-linearity in Detector Resp.***
  - ***Neutrino interaction models***
  - ***ND background composition***
  - ***Overall normalization***
  - ***Beam uncertainties***
  - ***Others***

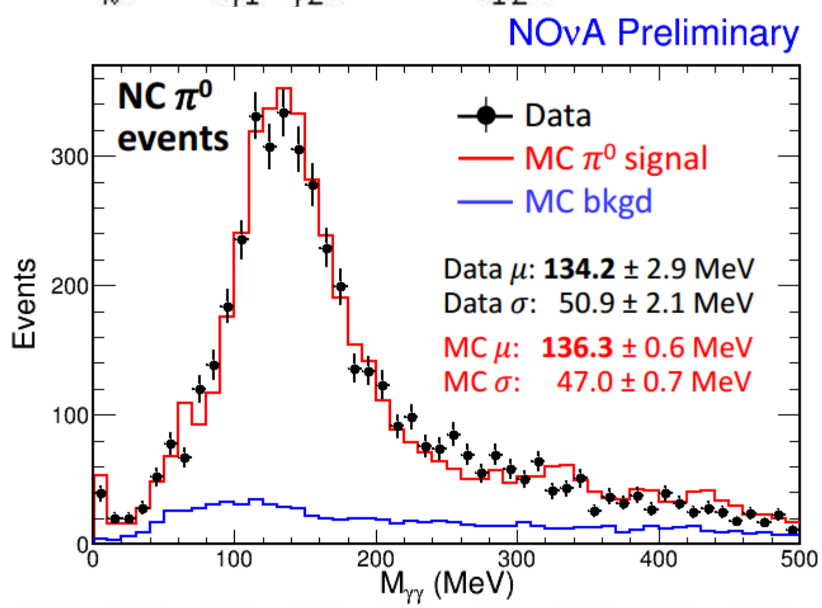


Systematic Error in Calibration

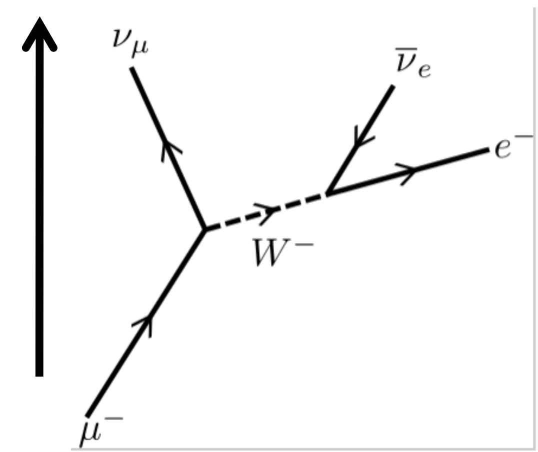
- Our calibration is built on dE/dx from stopping cosmic muons.
- Control samples for calibration uncertainty
  - π^0 mass peak in ND
  - Michel electrons in ND and FD

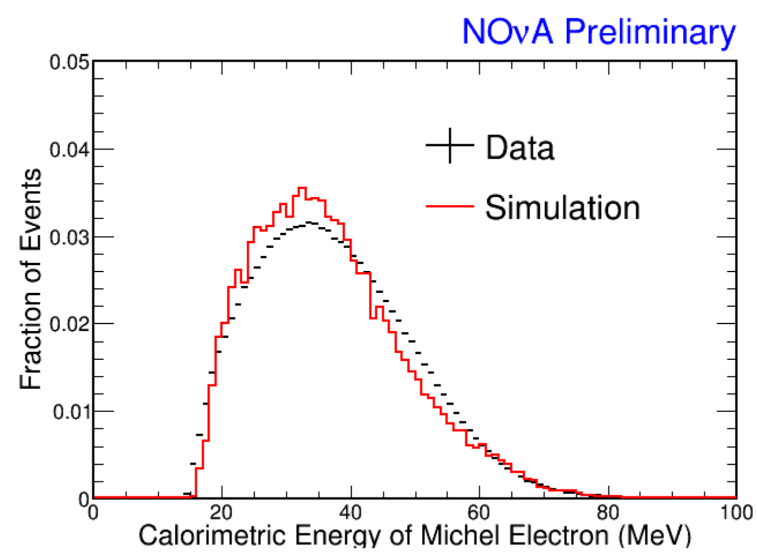


$$m^2_{\pi^0}=2E_{\gamma1}E_{\gamma2}(1-\cos\theta_{12})$$



Michel decay of muon





FD predictions with systematic uncertainties indicated

Background [0.01 events variation with relevant osc. parameters]

LID: **0.95 ± 0.09 events** [49% ν_e CC, 38% NC]
LEM: **1.01 ± 0.11 events** [46% ν_e CC, 40% NC]

2.74×10^{20} POT equiv.

Signal [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$]

LID: **5.62 ± 0.72 events**
LEM: **5.91 ± 0.65 events**

Signal [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$]

LID: **2.24 ± 0.29 events**
LEM: **2.34 ± 0.26 events**

→

Approx. totals (sig + bg)

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

LID: **6.6**
LEM: **6.9**

[IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$]

LID: **3.2**
LEM: **3.3**

Aside: Before unblinding, **two sidebands checks** –
(1) Near-PID (LID/LEM) sideband, and
(2) High-energy sideband

Results of both were **well within expectations**.

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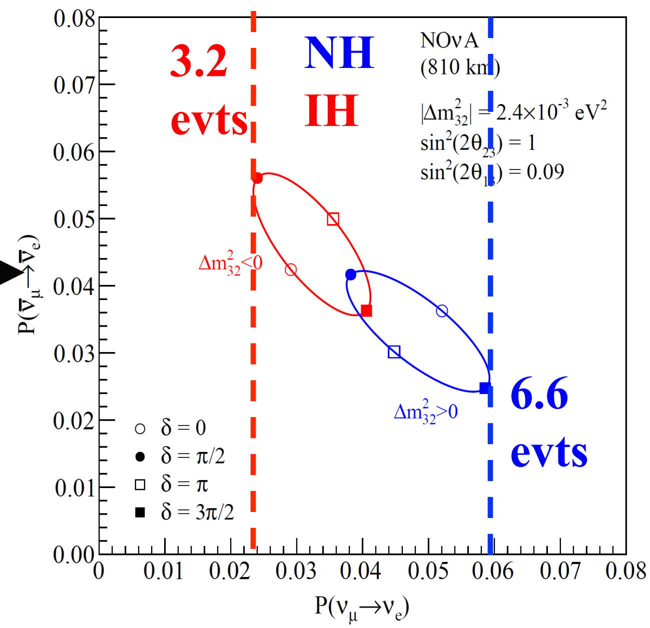


Aside: Before unblinding, **two sidebands checks** –

(1) Near-PID (LID/LEM) sideband, and

(2) High-energy sideband

Results of both were **well within expectations**.

FD data selected by LID

Background 0.94 ± 0.09 events [49% ν_e CC, 37% NC]

2.74×10^20 POT equiv.

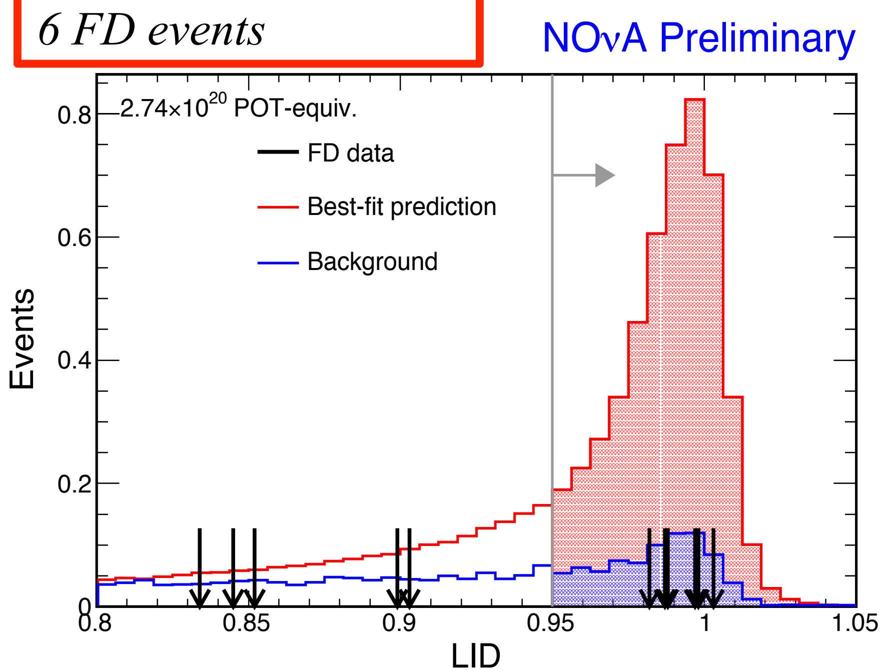
Signal [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$] **5.62 ± 0.72 events**

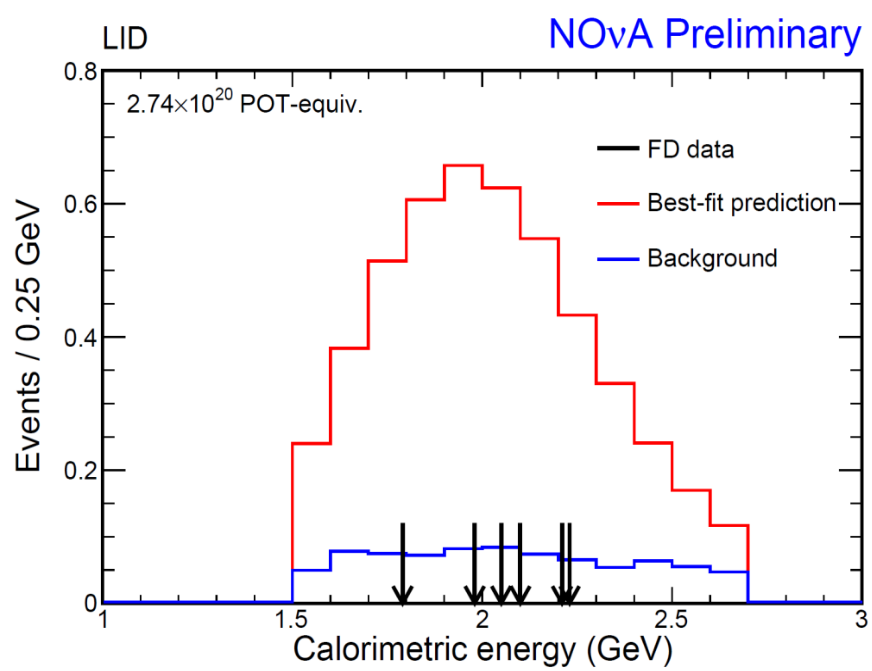
Signal [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$] **2.24 ± 0.29 events**

Sig+Bg [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$] **6.6 ± 0.7 events**

Sig+Bg [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$] **3.2 ± 0.3 events**

LID (Primary result)
6 FD events





FD data selected by LEM

Background 1.00 ± 0.11 events [46% ν_e CC, 40% NC]

2.74×10^{20} POT equiv.

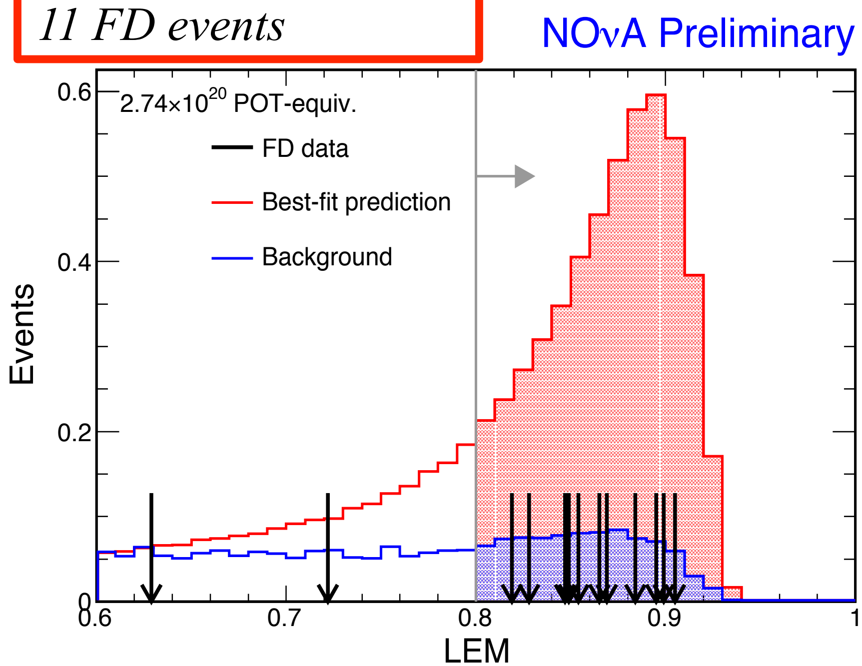
Signal [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$] **5.91 ± 0.65 events**

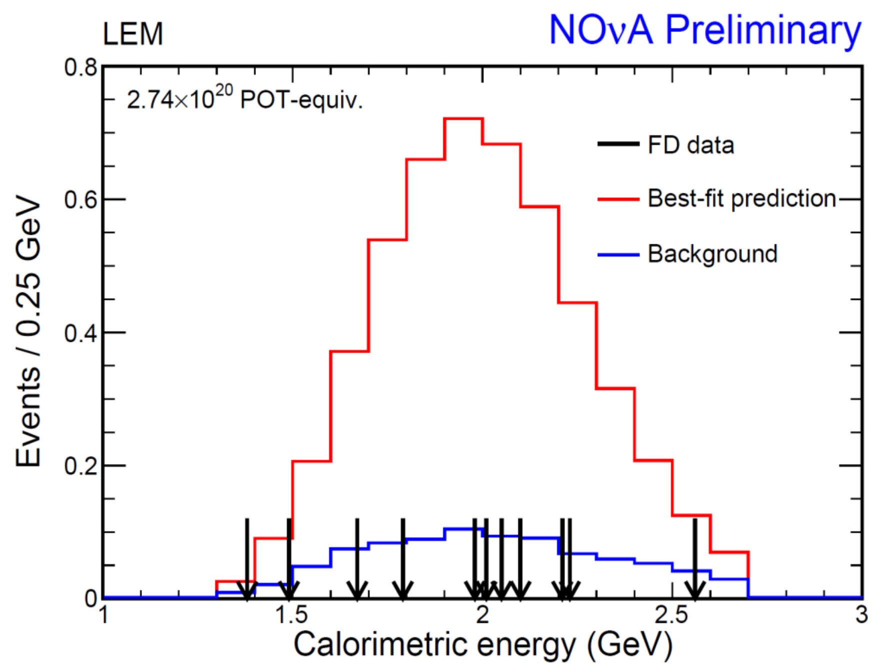
Signal [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$] **2.34 ± 0.26 events**

Sig+Bg [NH, $\delta = 3\pi/2$, $\theta_{23} = \pi/4$] **6.9 ± 0.7 events**

Sig+Bg [IH, $\delta = \pi/2$, $\theta_{23} = \pi/4$] **3.3 ± 0.3 events**

LEM
11 FD events

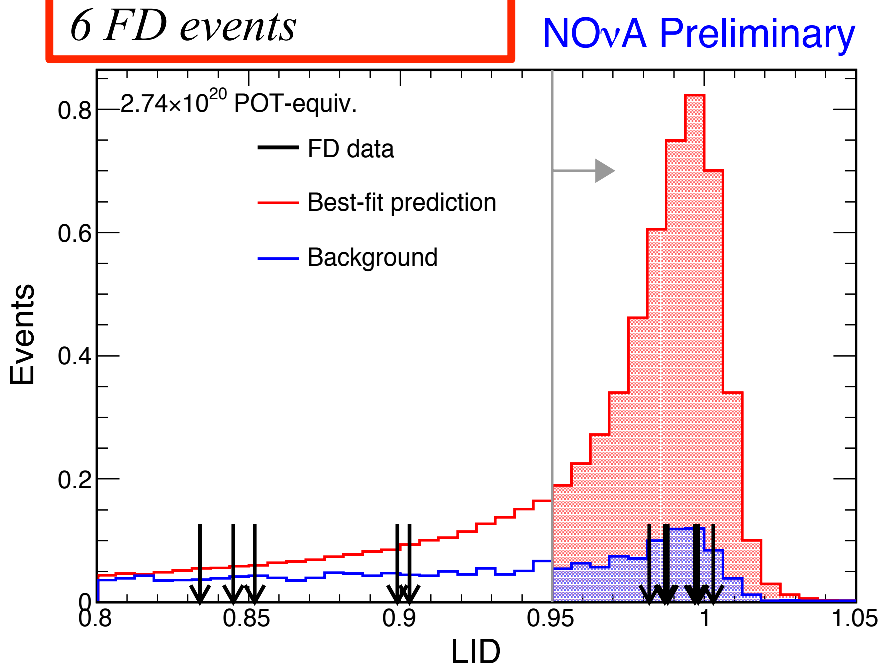




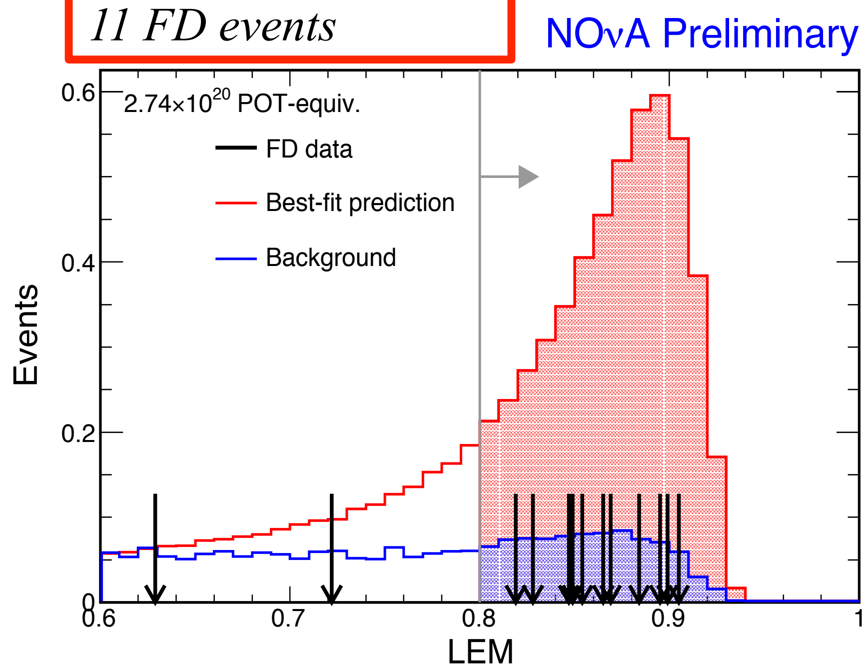
FD data selected by LID and LEM

- *In Data, the* ***(LID only)/(LEM only)/(LID&LEM)*** *events are* ***0/5/6***
- *Given Monte Carlo expected correlations, the observed event counts yield* ***a mutual p-value of 11%***

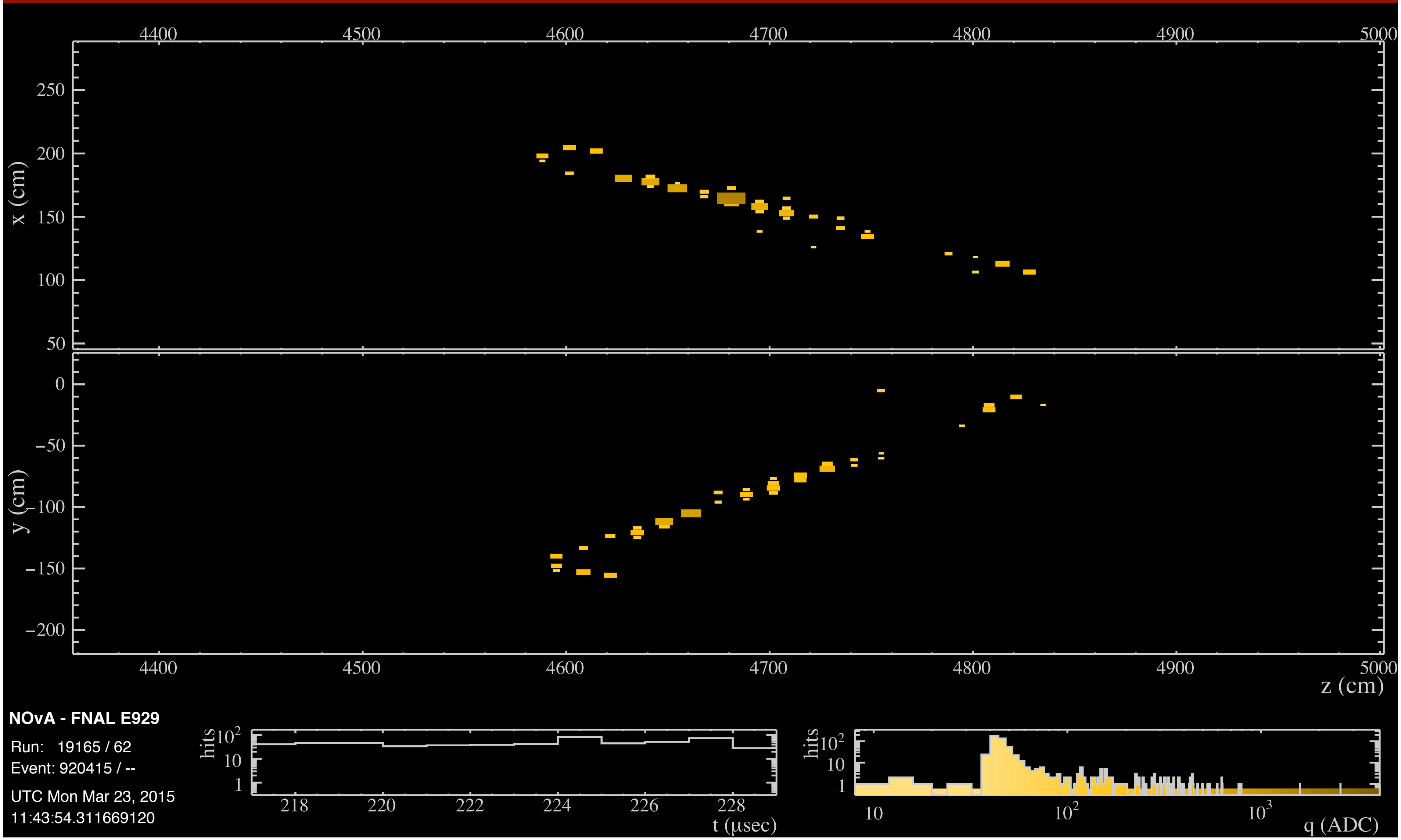
LID (Primary result)
6 FD events



LEM
11 FD events



Electron neutrino interaction candidate

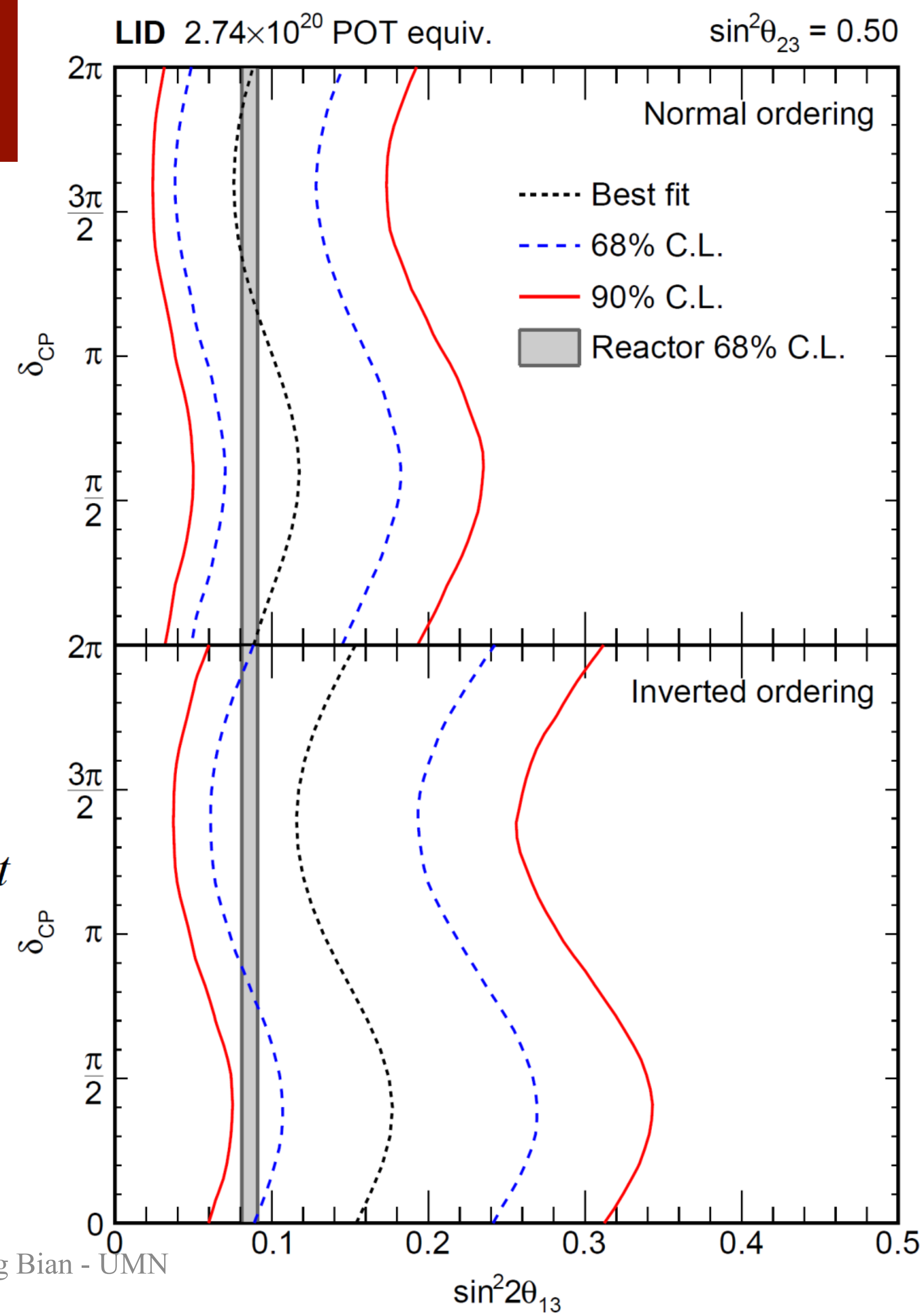


Results: Allowed region without reactor constraint

LID selected 6 ν_e candidates
3.3σ significance for ν_e appearance
(Primary Result)

For $(\delta_{CP}, \sin^2 2\theta_{13})$ allowed regions

- Feldman-Cousins procedure applied
- solar osc. parameters varied
- Δm^2_{32} varied by *new NOvA measurement*
- $\sin^2\theta_{23}$ held fixed at 0.5
  [contours for other values in backup]



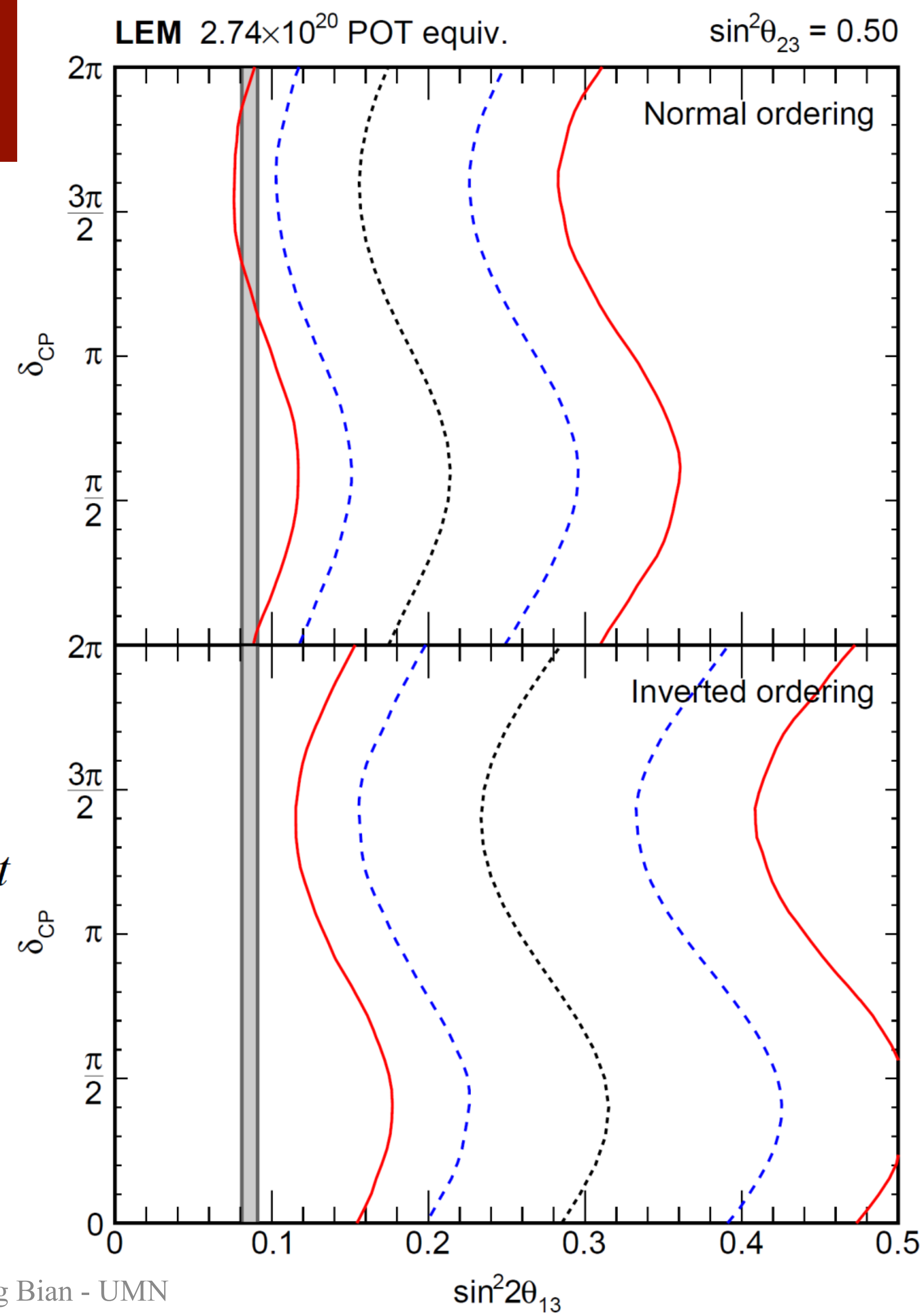
Results: Allowed region without reactor constraint

LEM selected 11 ν_e candidates
5.5σ significance for ν_e appearance

For $(\delta_{CP}, \sin^2 2\theta_{13})$ allowed regions

- Feldman-Cousins procedure applied
- solar osc. parameters varied
- Δm^2_{32} varied by *new NOνA measurement*
- $\sin^2\theta_{23}$ held fixed at 0.5
  [contours for other values in backup]

For LEM (n=11) the s-curves shift by a factor of 2 to the right increasing tension for the inverted mass ordering.



Results: Significance with reactor constraint

Applying global reactor constraint of
$\sin^2 2\theta_{13}$=0.086+-0.05

Same assumptions as previous page for Feldman-Cousins corrections

LID

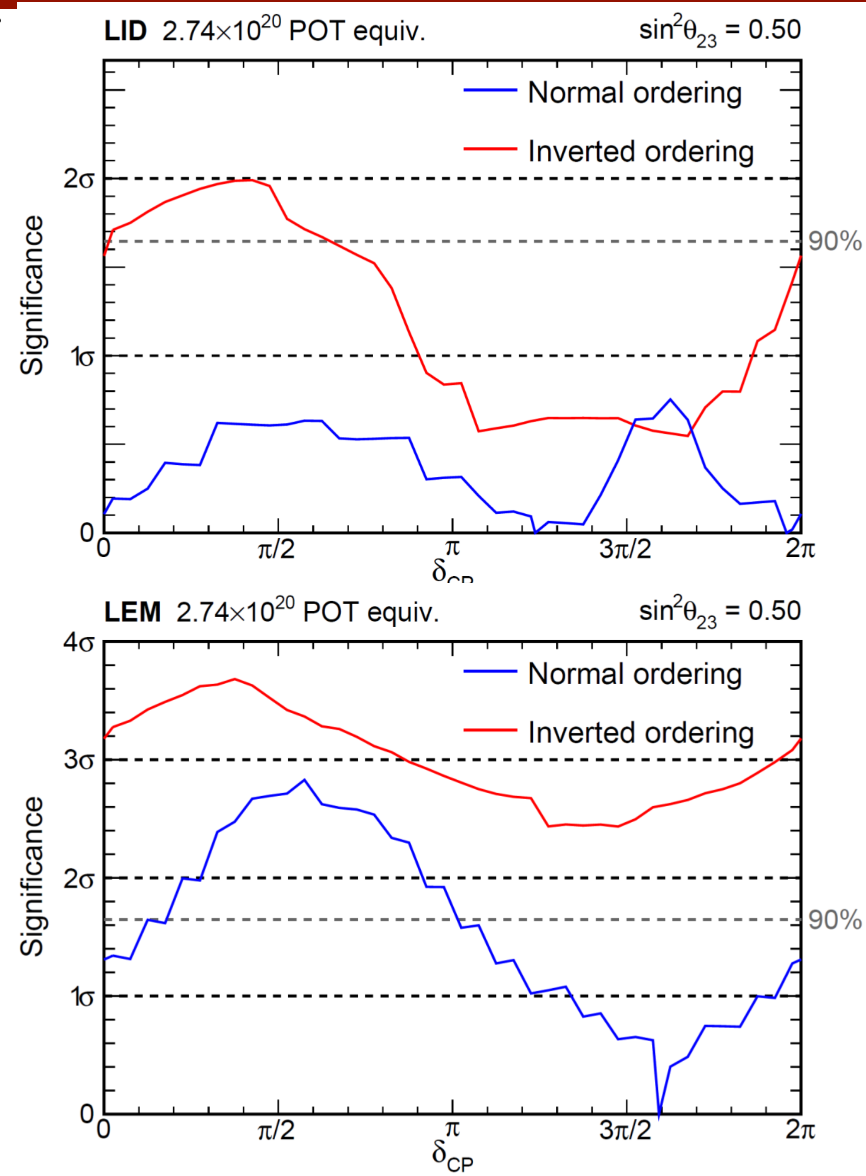
NH is favored within 1σ
For all $\sin^2\theta_{23}$ in [0.4,0.6]
IH for ∈ [0,0.8π] is mildly disfavored (>1σ)

LEM

IH is disfavored at >2.2σ
NH for δ ∈ [0, π] is mildly disfavored (>1σ)

LID, LEM Consistency:

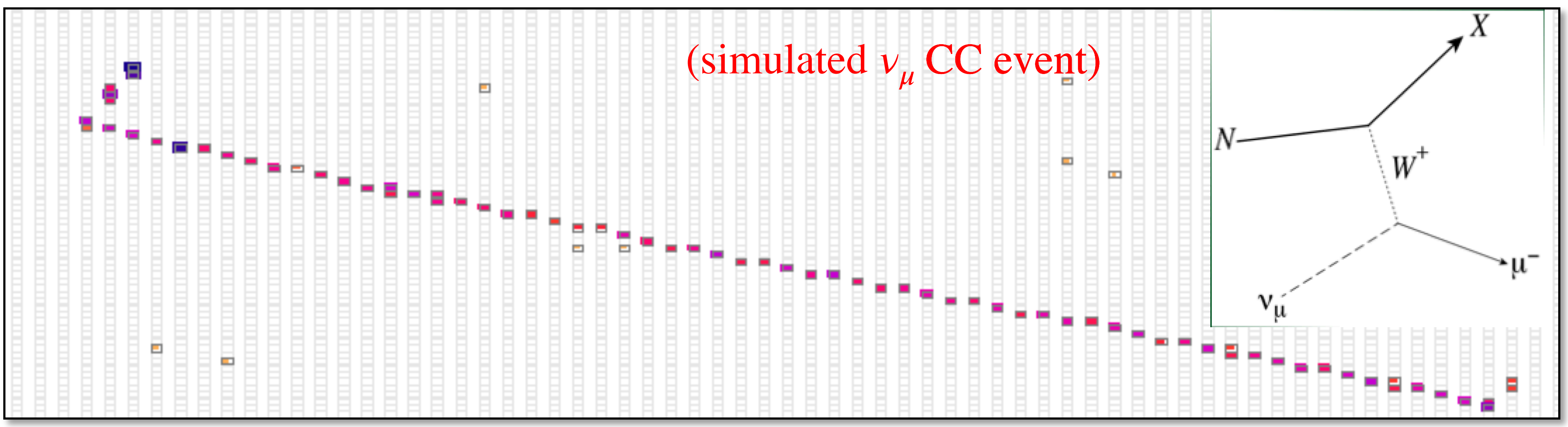
- *Both prefer normal ordering*
- *Both prefer δ_{CP} near 3π/2*



(Steps due to discrete nature of counting expt.)

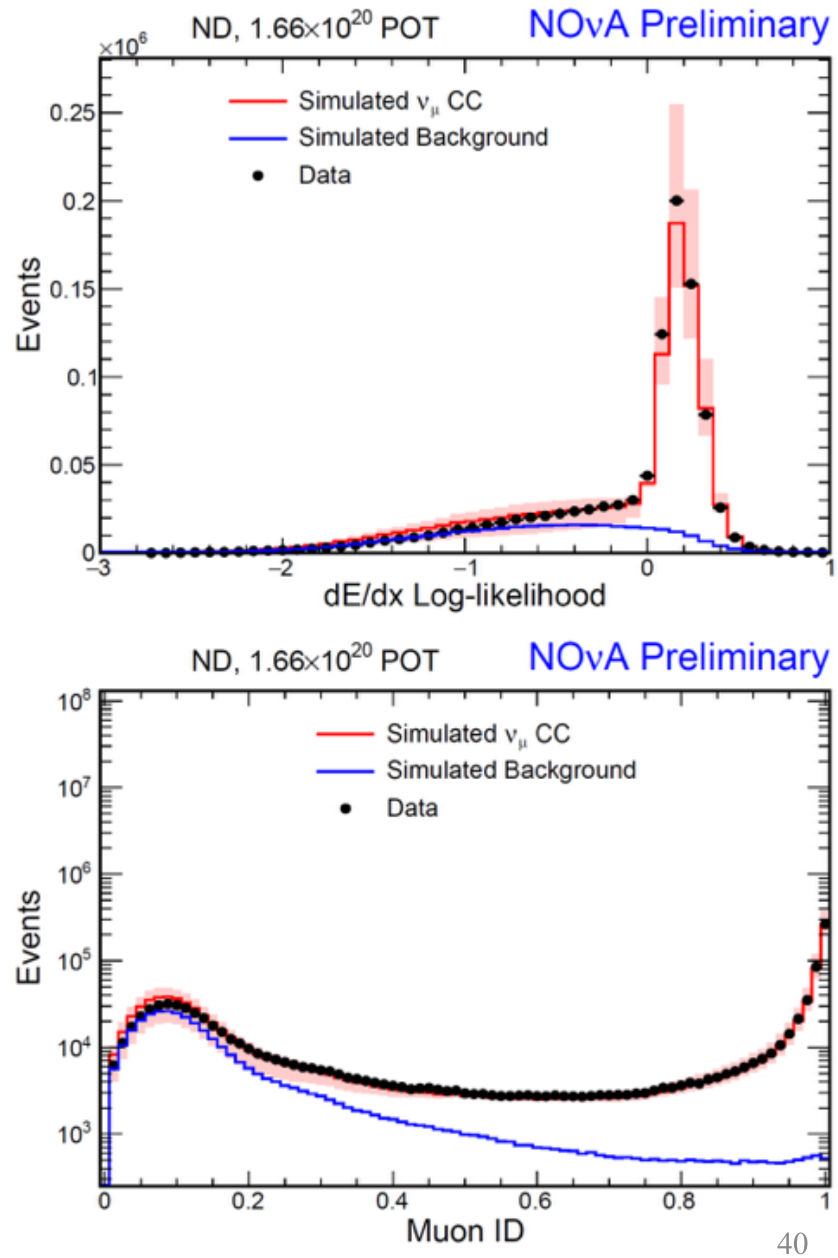
Muon Neutrino Disappearance

- We compare a prediction of the muon neutrino spectrum obtained from ND data with a FD measurement. Neutrino oscillations deplete the muon neutrino rate and distort its energy spectrum.
  - Identify contained ν_μ CC events in the Near Detector and Far Detector.
  - Measure their energies.
  - Extract oscillation information from differences between the Far and Near energy spectra



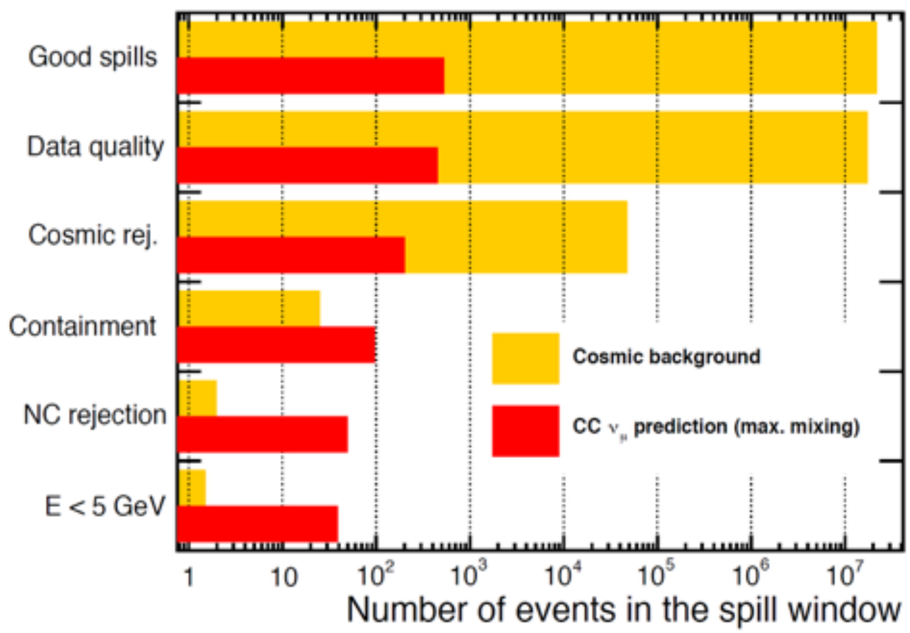
Muon Neutrino Selection

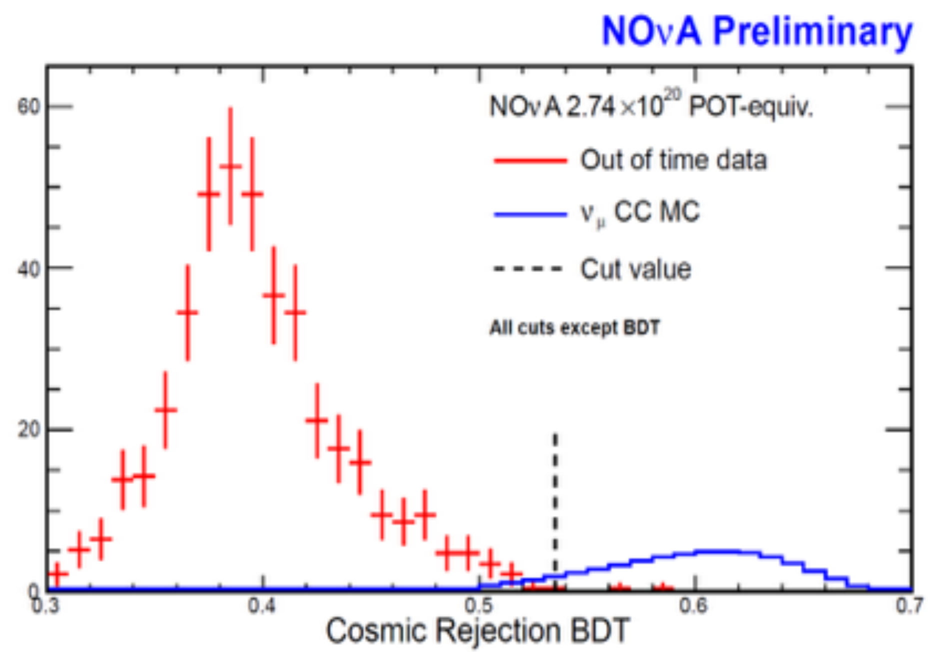
- We have developed a particle identification algorithm (k-nearest-neighbors) based on muon characteristics:
  - track length
  - dE/dx along the track
  - scattering along track
  - track-only plane fraction



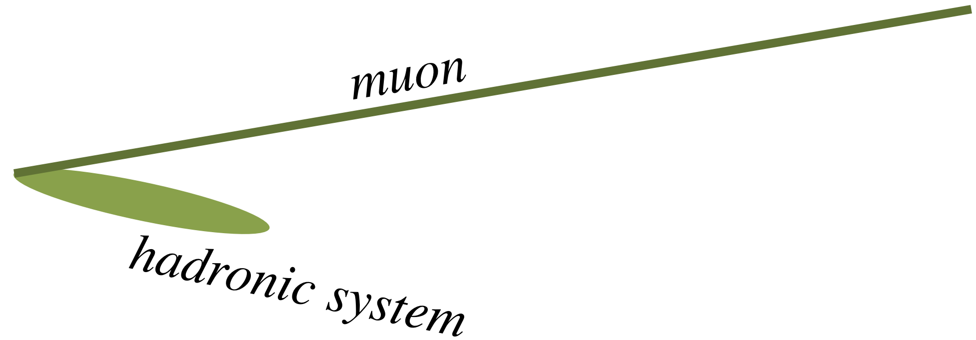
Cosmic Rejection For Muon Neutrinos

- Final cosmic background rate is measured directly from data taken concurrently with beam spill by using the out-of-time window.
- Selecting a narrow window around the 9.6 μsec spill gives a rejection factor of 10^5 track length.
- For the cosmic rejection of the muon neutrino disappearance analysis, we use a boosted decision tree algorithm based on reconstructed track direction, position, and length; and energy and number of hits in event.
- These event topologies gives a factor of 10^7 rejection.





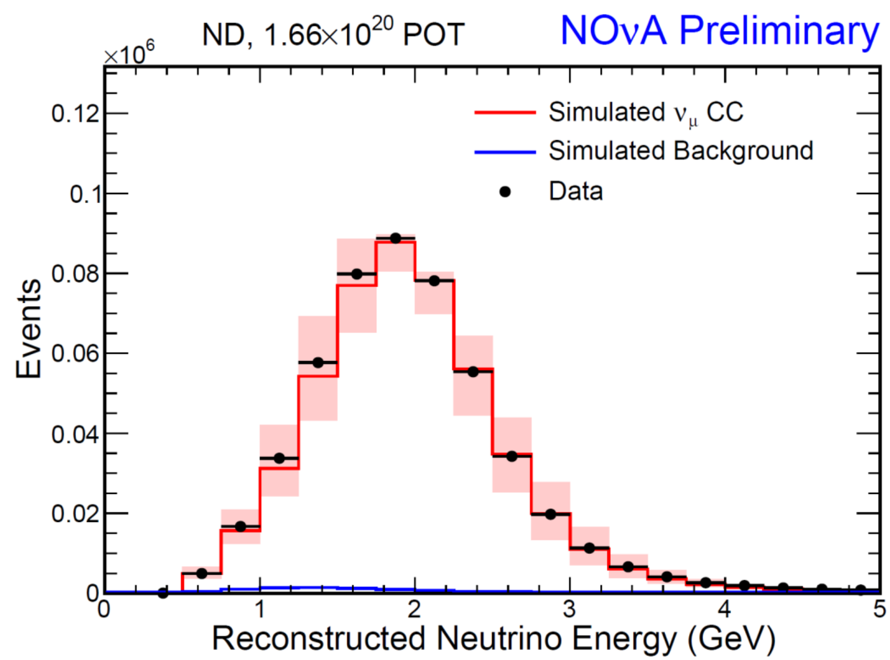
Muon Neutrino Energy



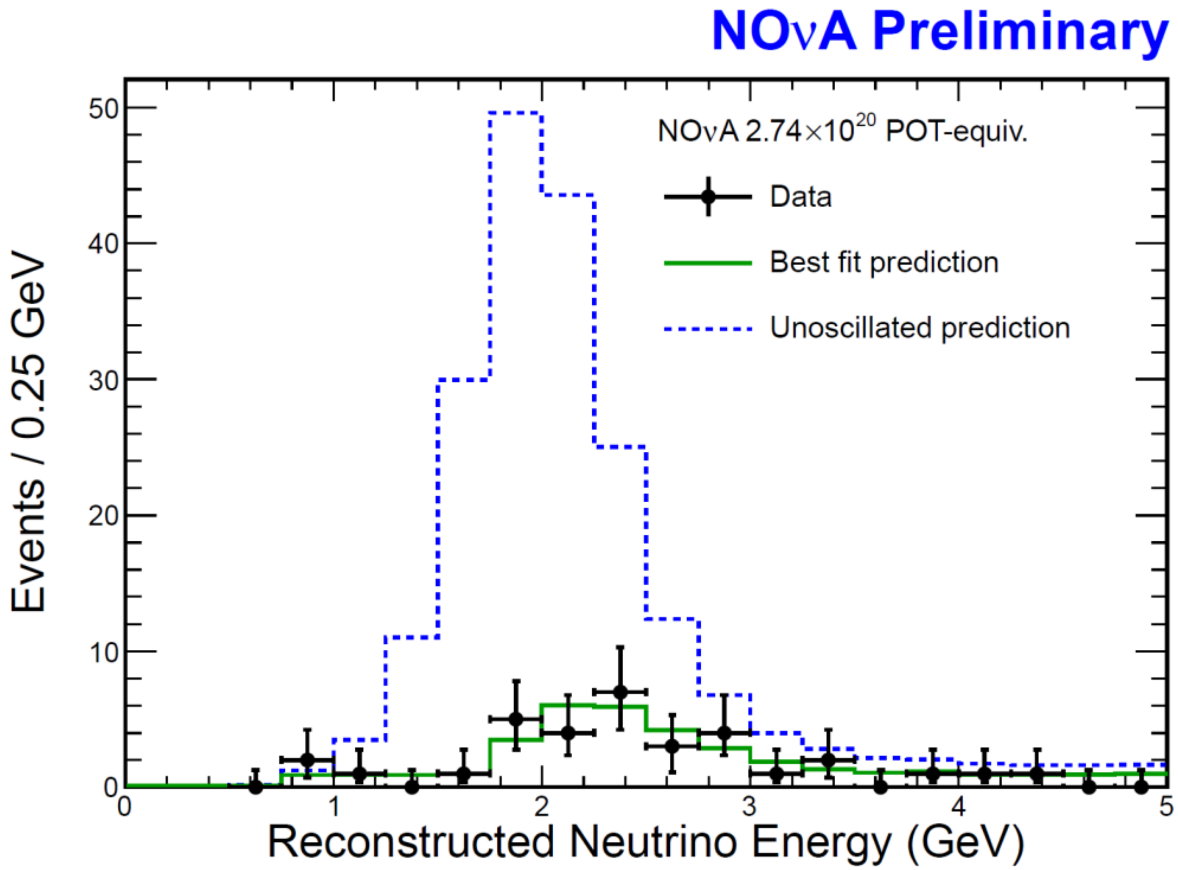
- Reconstructed muon track:
  track length → E_μ
- In the hadronic system:
  $\Sigma E_{\text{cell}} \rightarrow E_{\text{had}}$
- Reconstructed ν_μ energy is the sum of these two:

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

- *Energy resolution at beam peak ~7%*
- ND data is used to produce a data driven prediction in the FD

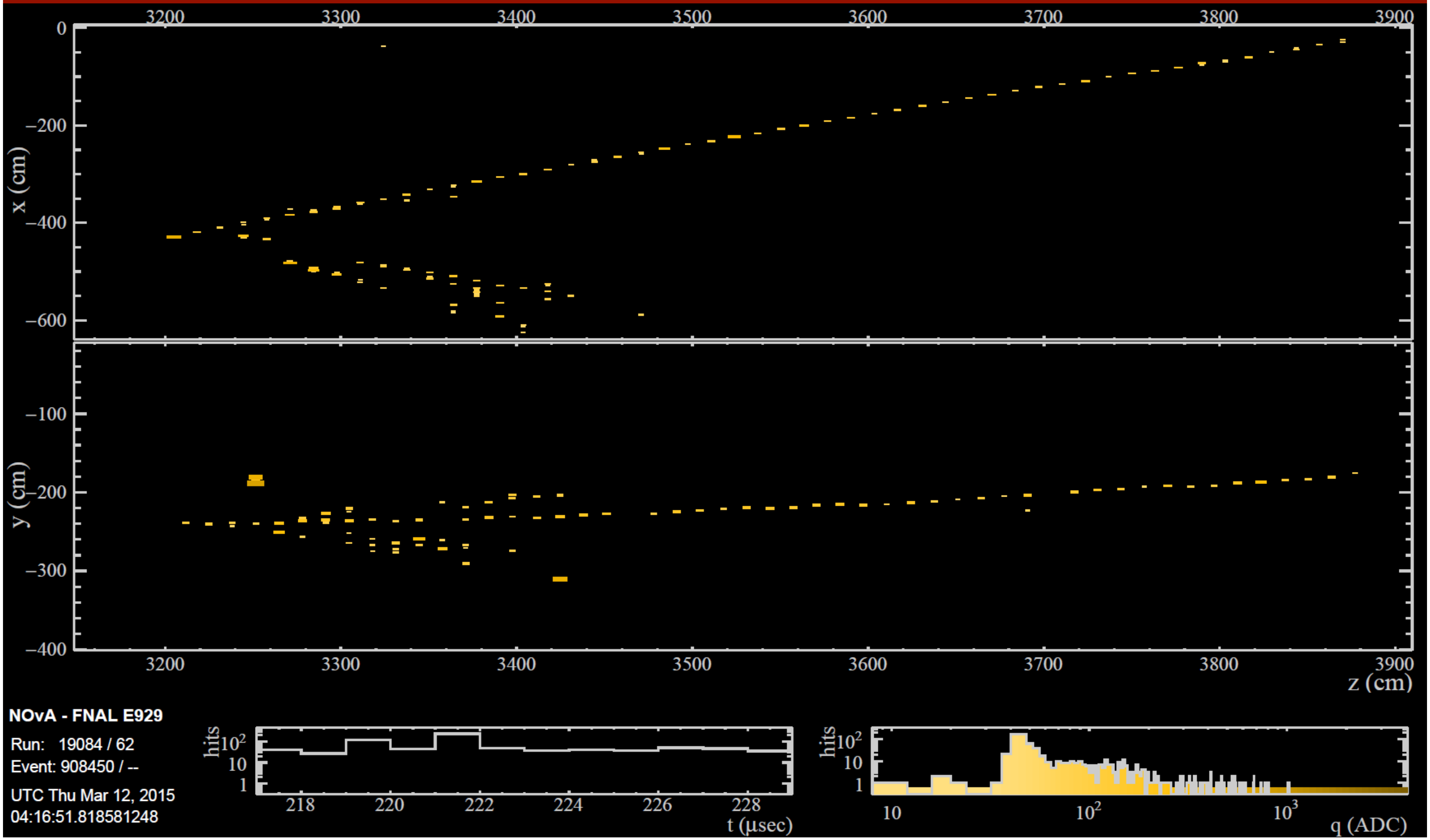


Muon Neutrino Energy Spectrum in FD



- We expect 201 events before oscillations.
- We observe 33 events.
- Muon neutrino disappearance observed.

Muon Neutrino Candidate in FD



Muon Neutrino Disappearance Results

- The spectrum is matched beautifully by the oscillation fit.
- Systematic uncertainties included in the fit as nuisance parameters: Hadronic neutrino energy, neutrino flux, absolute and relative normalization, neutrino interactions, NC background rate, multiple calibration and oscillation parameters.

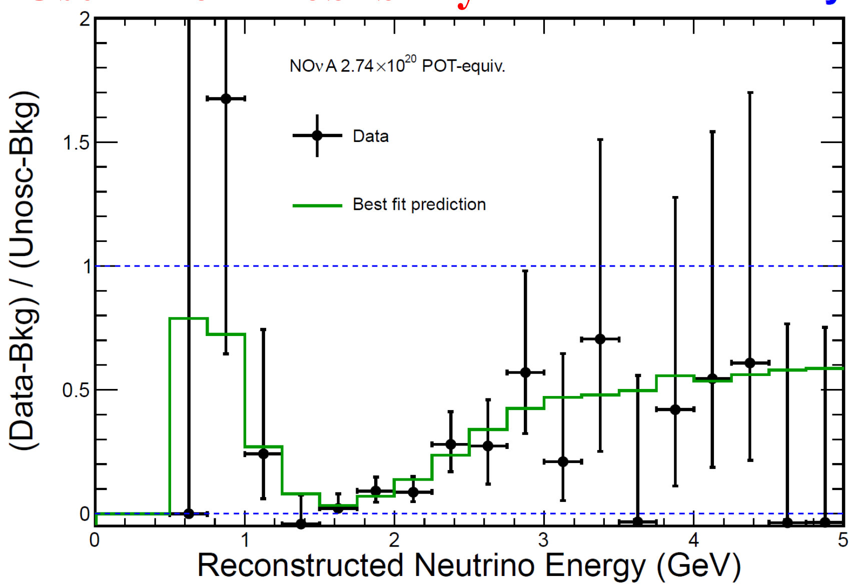
$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.16}_{-0.15}\ [\text{NH}] \\ -2.40^{+0.14}_{-0.17}\ [\text{IH}] \end{cases} \times 10^{-3}\ \text{eV}^2$$

(Errors are 1D profiles at 68% C.L.)

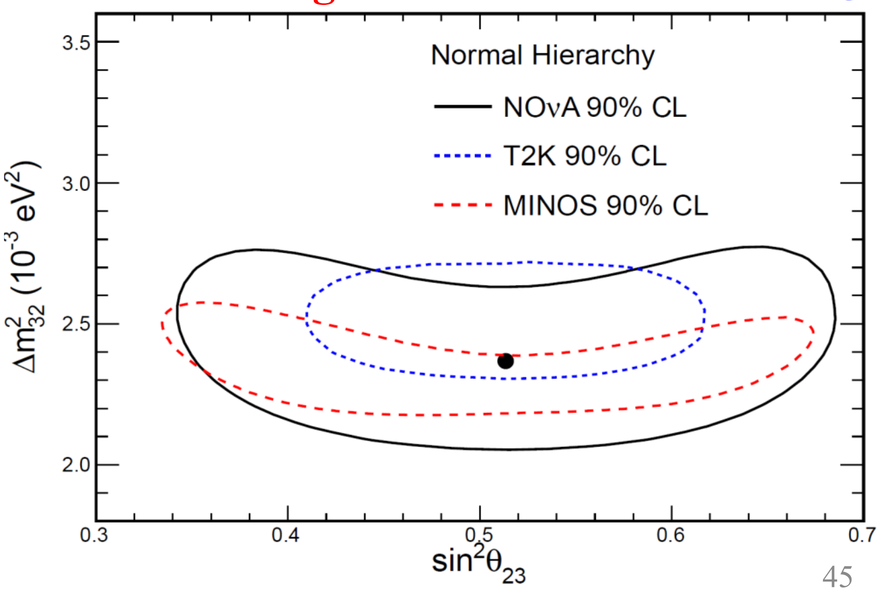
$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

- *7.6% of nominal NOνA exposure*
- *Allowed regions are consistent with MINOS and T2K*

Oscillation Probability NOνA Preliminary



Allowed region NOνA Preliminary



Summary

- NOvA observes electron neutrino appearance
  - ν_e appearance signal at 3.3σ for primary selector, 5.5σ for secondary selector.
  - Some preference for normal hierarchy
  - Only 1/13th of baseline NOνA exposure.
- NOvA observes muon neutrino disappearance
  - 6.5% measurement of $|\Delta m_{32}^2|$
  - θ_{23} consistent with maximal mixing (45^o)
- Beam returns in October, 2015
  - 400-500 kW running
  - Double the exposure by next summer
  - Lots more data to come