First oscillation results from NOvA

IOP, 22nd March 2016

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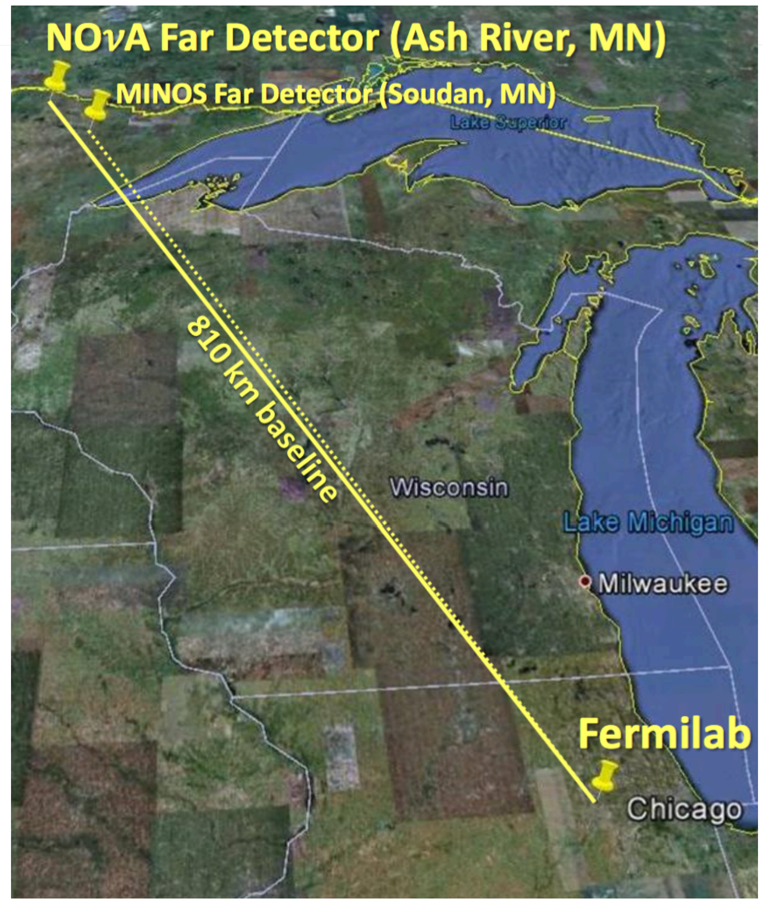


Outline

- Neutrino oscillations
- NOvA detectors
- Why off-axis?
- muon neutrino disappearance
  - energy estimation
  - near to far energy extrapolation
  - results
- electron neutrino appearance
  - results

long baseline neutrino oscillations

ν_μ disappearance

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

experimental data is consistent
with unity → "maximal mixing"

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 \theta_{23} \underbrace{\sin^2 2\theta_{13}} \sin^2(\Delta m^2_{32} L/4E)$$

Daya Bay reactor experiment:

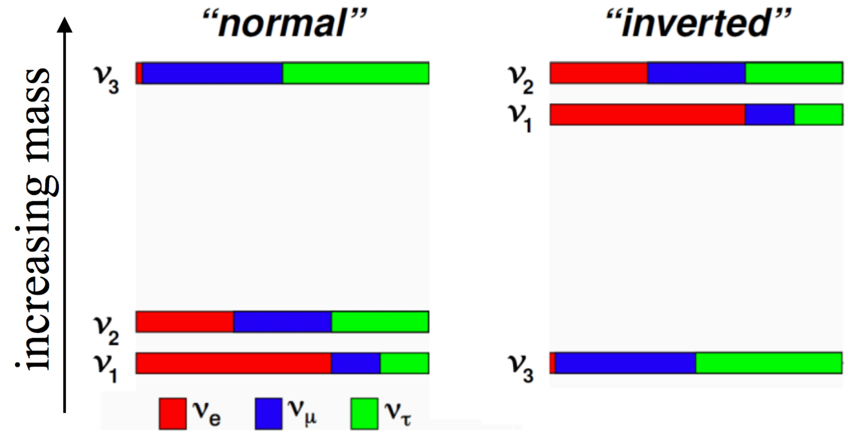
$$\sin^2(2\theta_{13}) = 0.084 \pm 0.005$$

… + potentially large neutrino ***CP*** *and* ***matter effect*** *modifications*

long-baseline neutrino oscillations

$$\theta_{13} > 0 \implies \nu_\mu \to \nu_e$$

Makes feasible long-baseline measurements of:



neutrino mass hierarchy

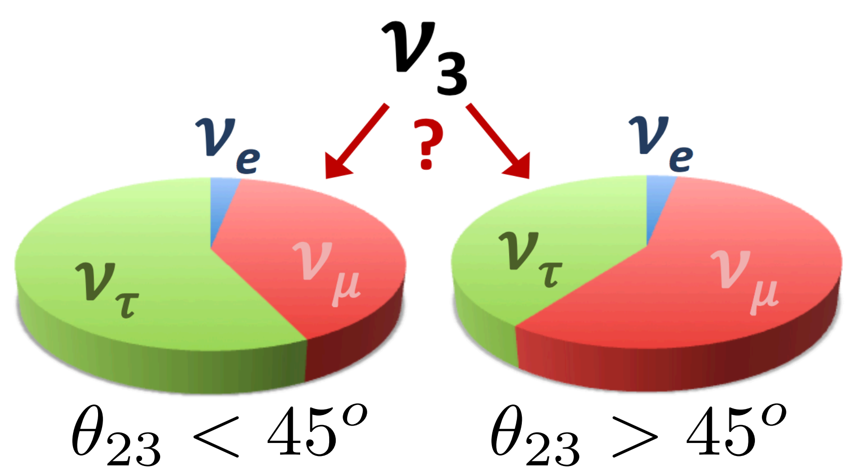
via matter effects that enhance (suppress) electron neutrino appearance if the hierarchy is normal (inverted).

CP violation

via dependence of $P(\nu_\mu \to \nu_e)$ on CP phase δ

ν_3 flavour mixing

via leading-order factor $\sin^2(\theta_{23})$



NOvA detectors

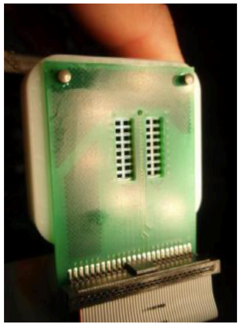
Two functionally identical detectors

- fine grained
- low Z
- highly active tracking calorimeters

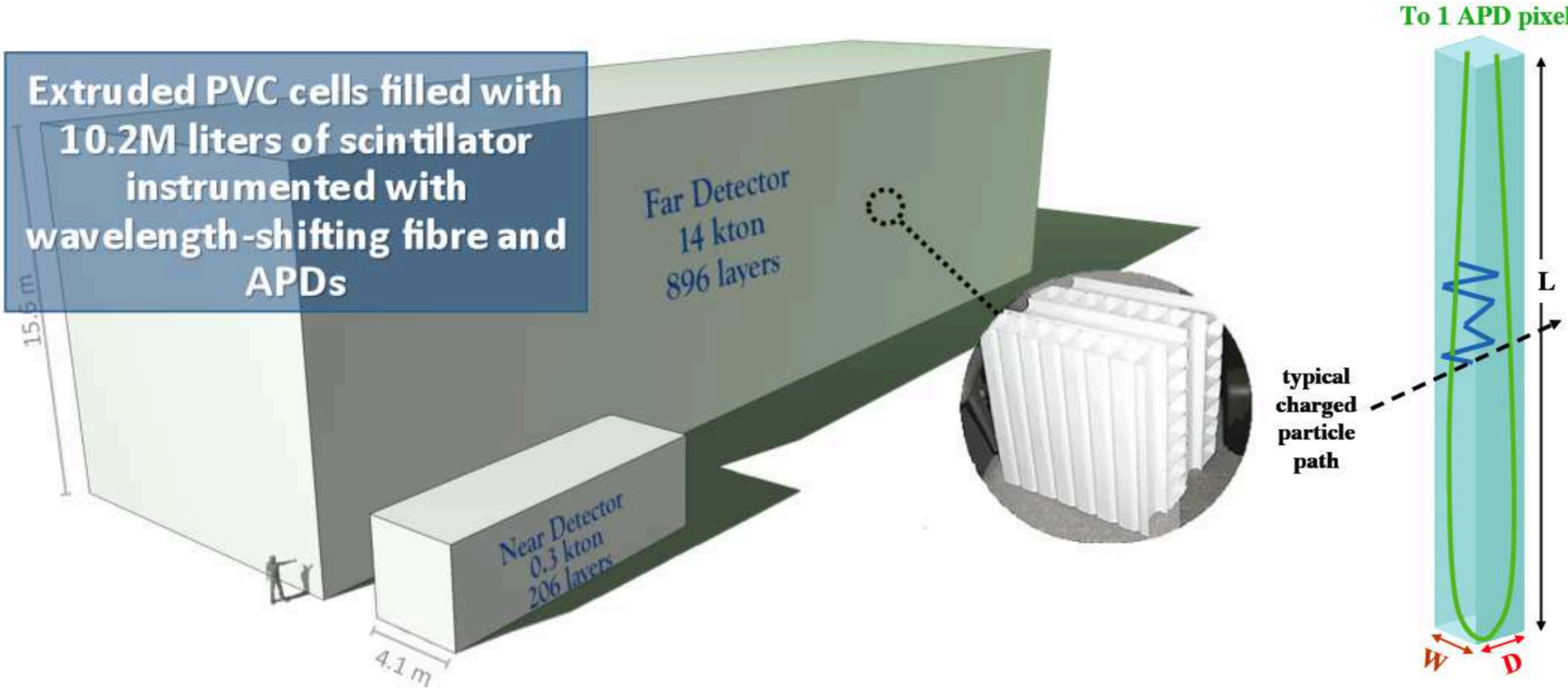
14kt far detector is 8.8kt of liquid scintillator held in 5.2kt of PVC cells

→ 63% active scintillator / 37% PVC

32-pixel APD



32 fibre pairs from 32 cells



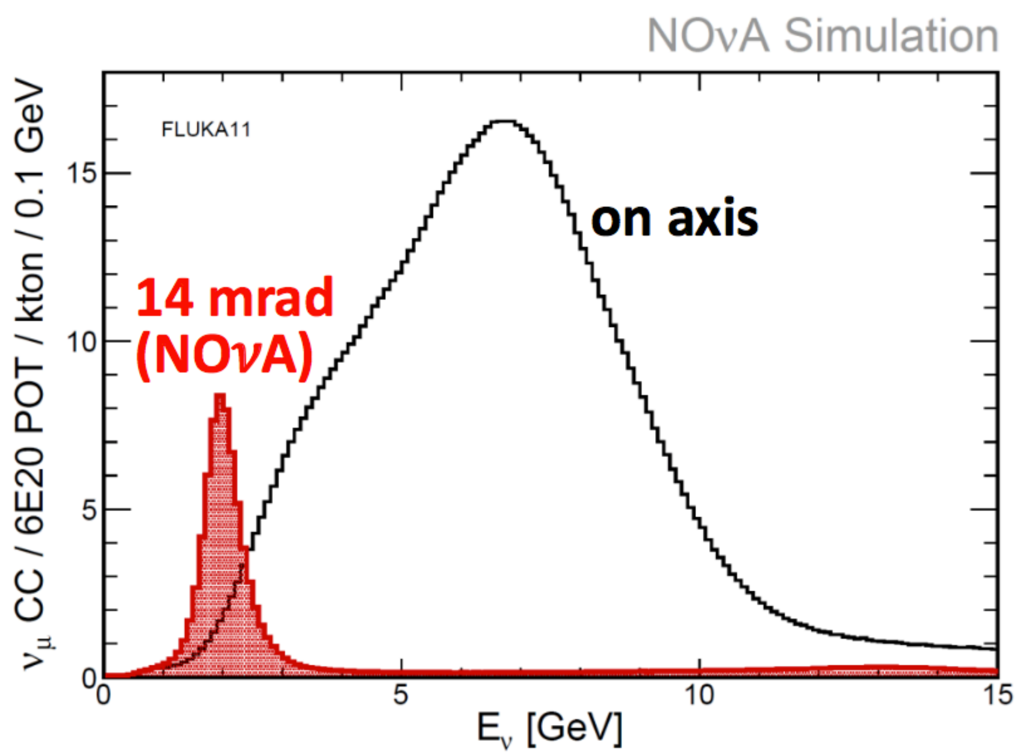
NuMI off-axis beam

NOvA detectors are sited 14 mrad off the NuMI beam axis

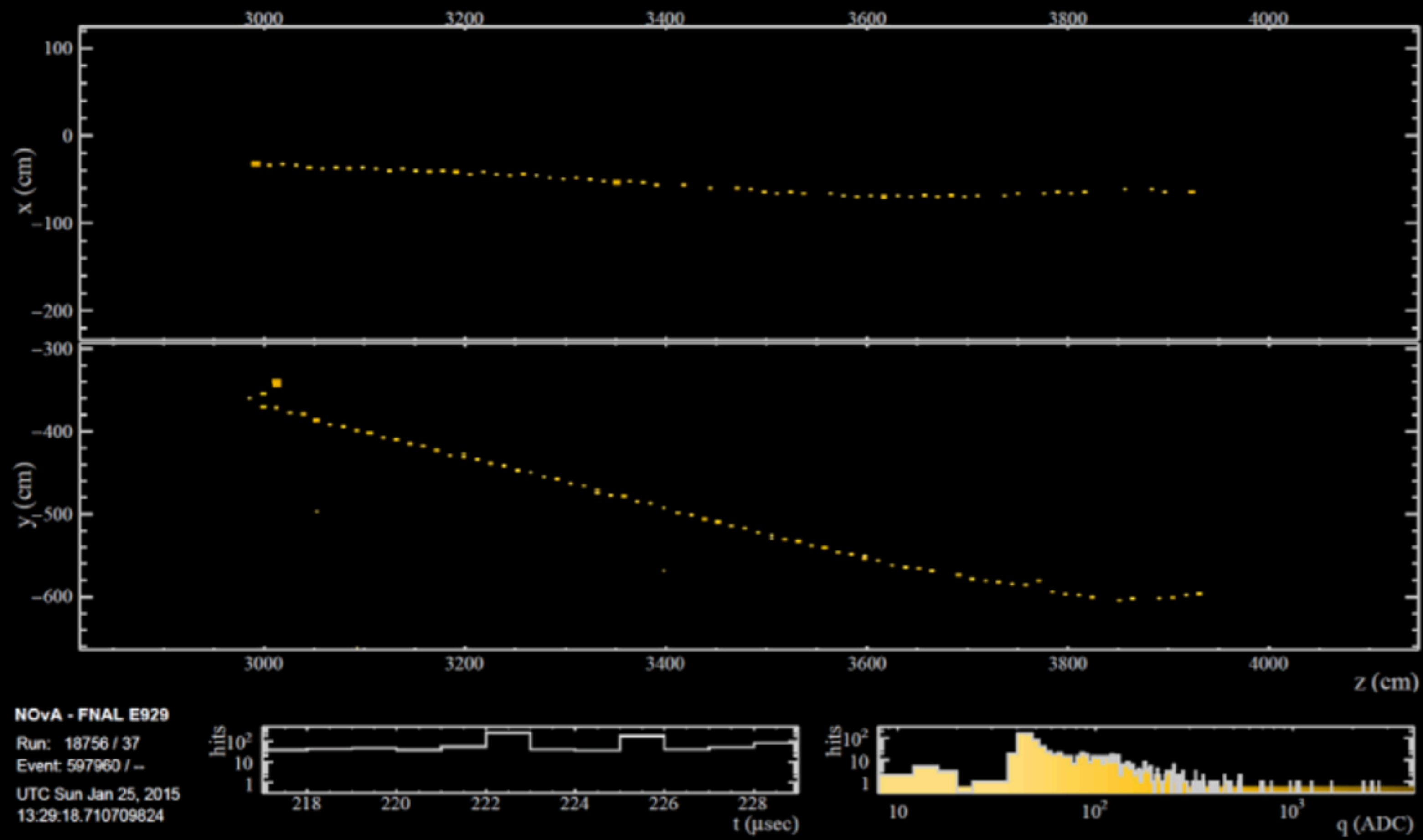
→ Reduced NC and nue CC backgrounds for oscillation analyses

The medium-energy NuMI tune yields a narrow 2 GeV neutrino spectrum at the NOvA detectors

→ Enhances neutrino flux in region of the first oscillation maximum



Muon neutrino disappearance



Select and measure the **energy** of **contained muon neutrino charged current** events in each detector

Measure oscillation parameters using the difference between the **near and far energy spectra**

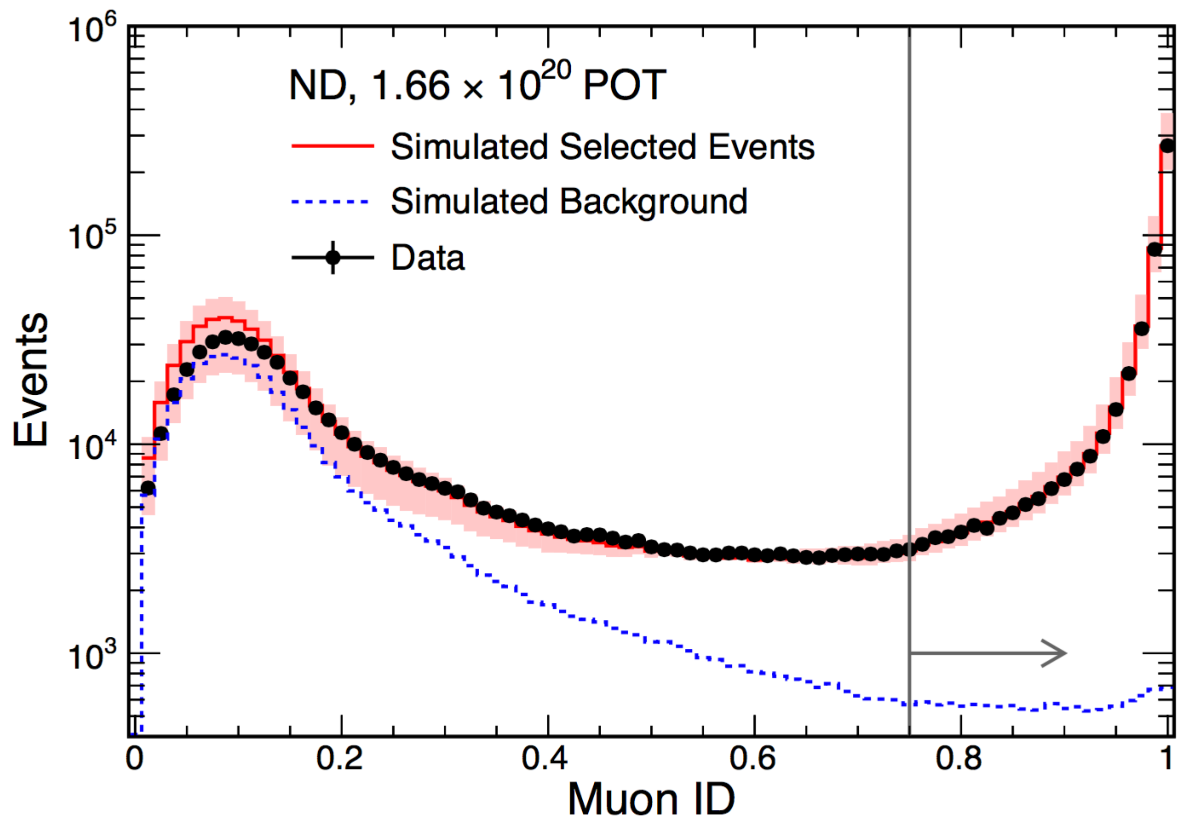
University of Sussex

Muon neutrino CC selection

<u>Muon ID</u>
muons identified using a k-nearest-neighbour algorithm with four input variables:

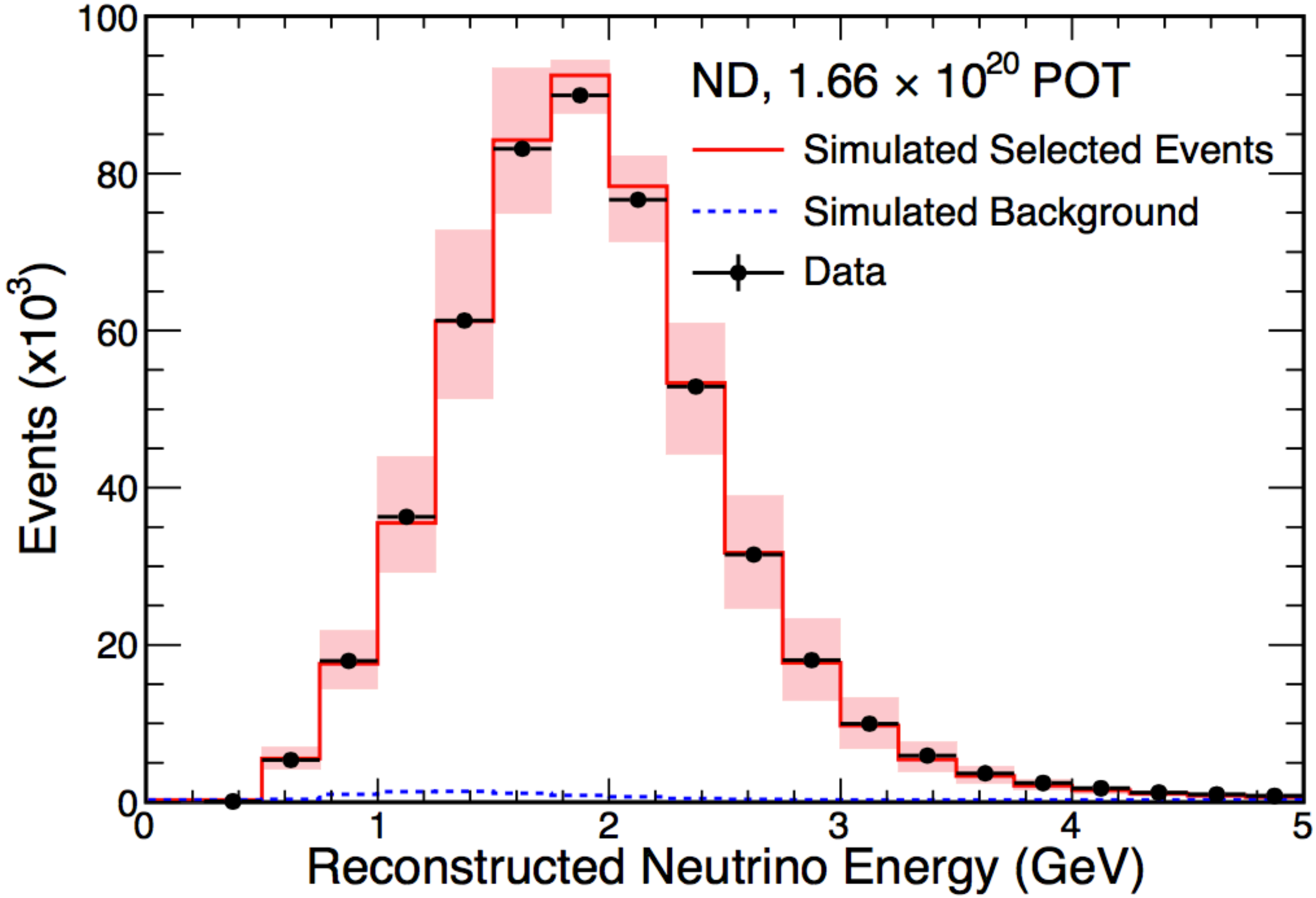
- track length
- dE/dx along track
- scattering along track
- track-only plane fraction

Select events with Muon ID > 0.75



Muon neutrino disappearance

About 0.5 M events selected in the **near detector**.
Energy spectrum extrapolated to the far detector…

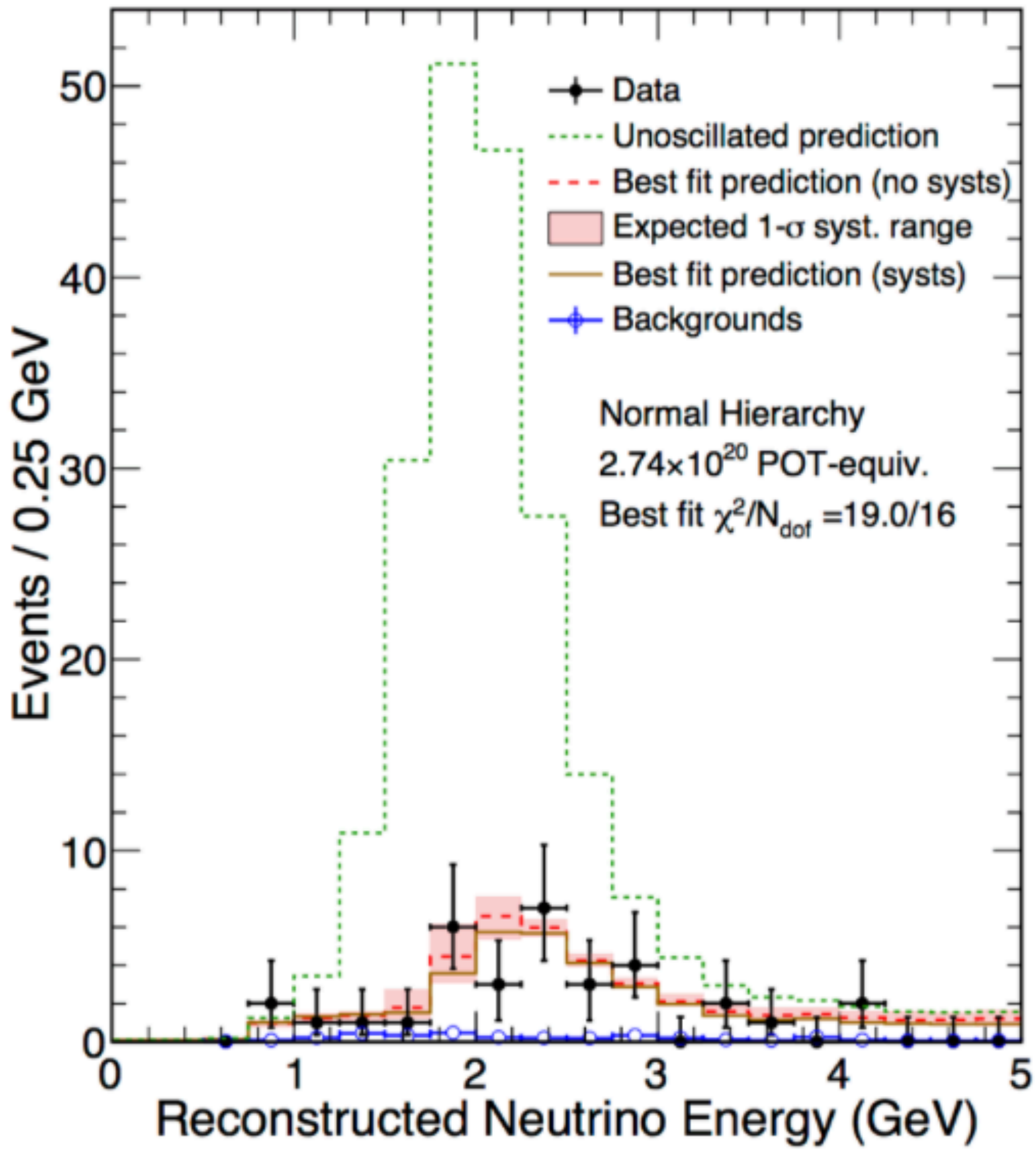


Muon neutrino disappearance

33 events selected in the Far Detector

In absence of neutrino oscillations, would **expect 212** events

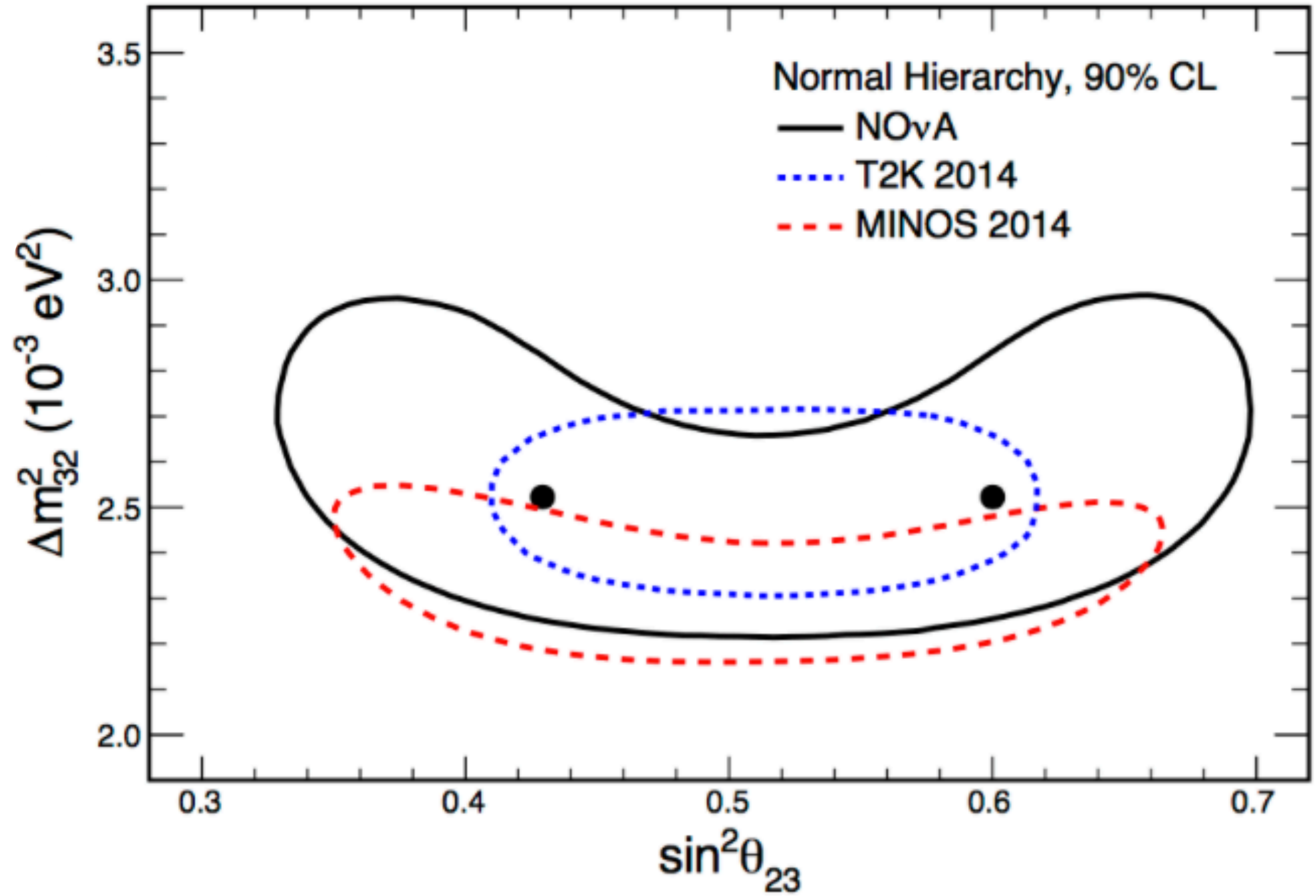
→ **Clear observation of ν_μ disappearance**



Muon neutrino disappearance

NOvA allowed regions are consistent with MINOS and T2K

NOvA results already competitive with just 7.6% of nominal exposure



Normal hierarchy:

$$\sin^2\theta_{23} : 0.38 - 0.65$$

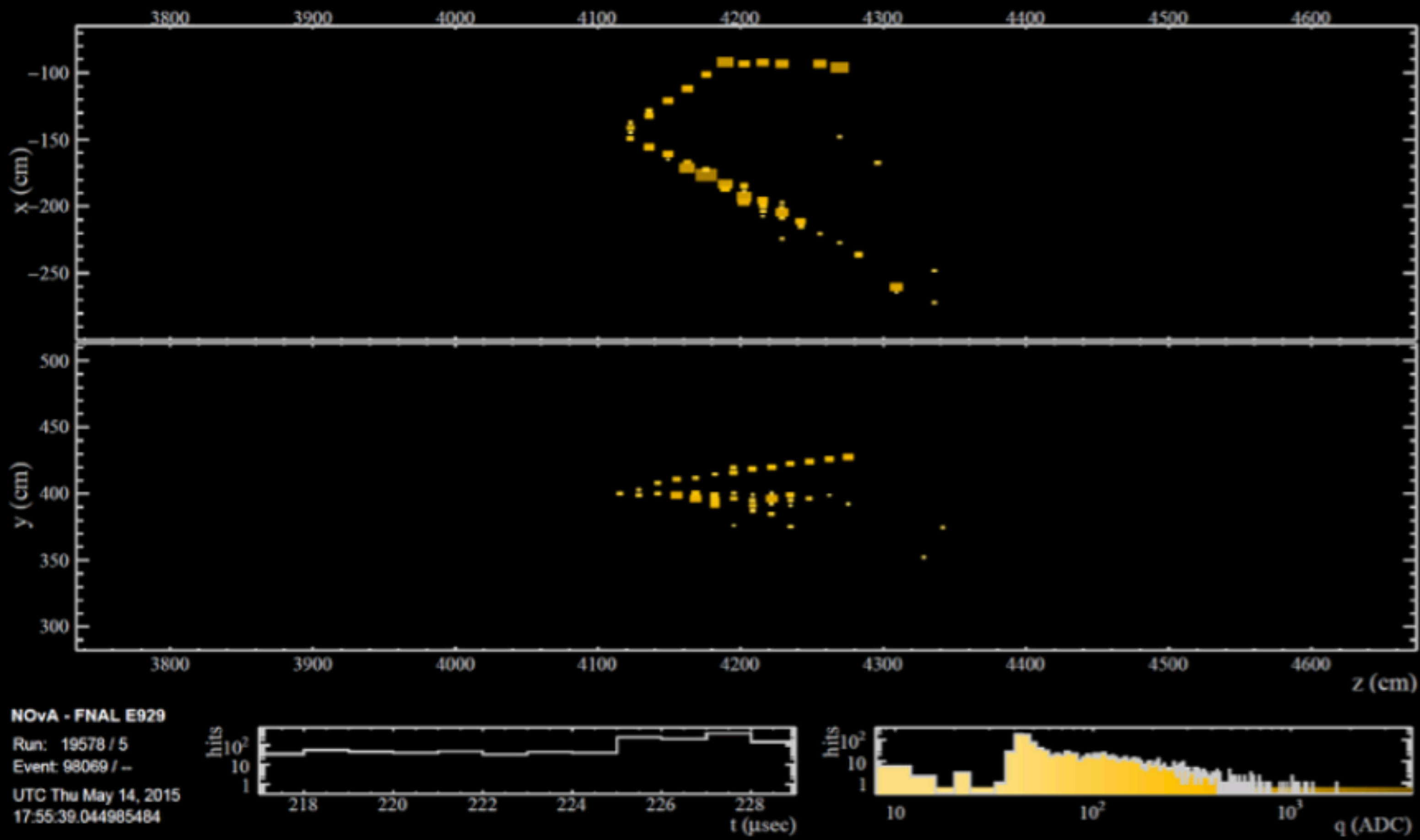
$$\Delta m^2_{32} = (2.52^{+0.20}_{-0.18}) \times 10^{-3}\mathrm{eV}^2$$

Inverted Hierarchy:

$$\sin^2\theta_{23} : 0.37 - 0.64$$

$$\Delta m^2_{32} = (-2.56^{+0.19}_{-0.19}) \times 10^{-3} eV^2$$

Electron neutrino appearance



Use near detector electron neutrino CC candidates to predict beam background in the far detector

Oscillation parameters found by counting number of far detector electron neutrino events above predicted background

Electron neutrino event selection

Two independent electron neutrino selection methods:

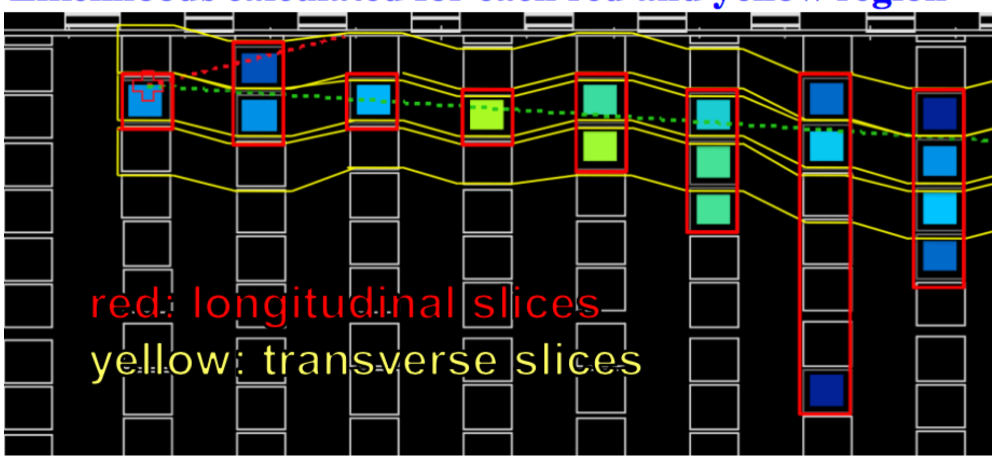
Likelihood Identification (LID)

(chosen as primary selection prior to un-blinding)

dE/dx likelihoods calculated for longitudinal and transverse slices of leading shower under multiple particle hypotheses

Likelihoods feed an artificial neutral network along with kinematic and topological info: e.g., energy near vertex, shower angle, vertex-to-shower gap

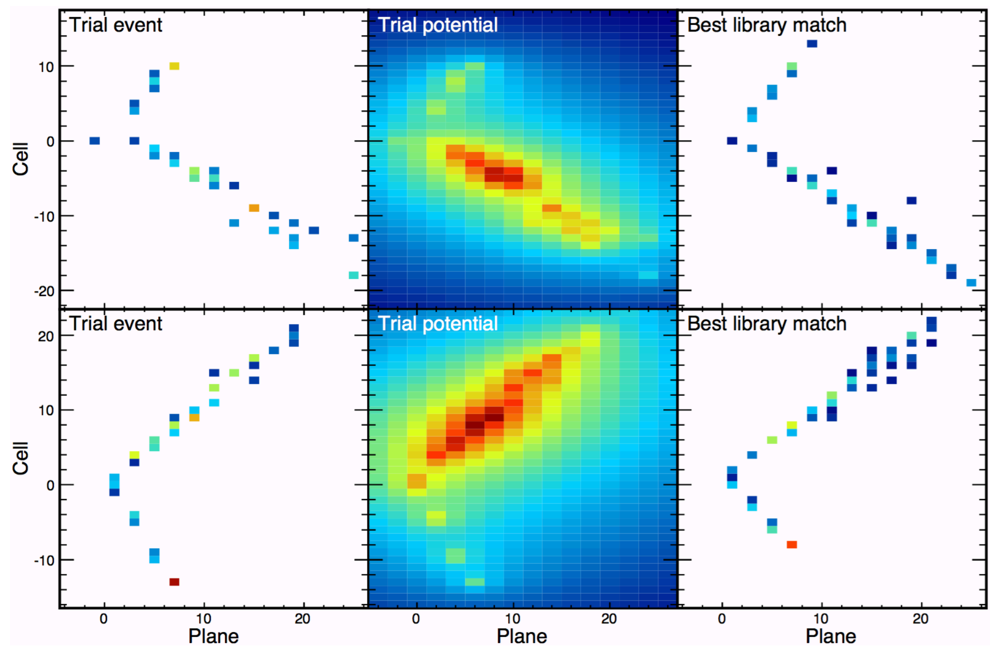
Likelihoods calculated for each red and yellow region



Library Event Matching (LEM)

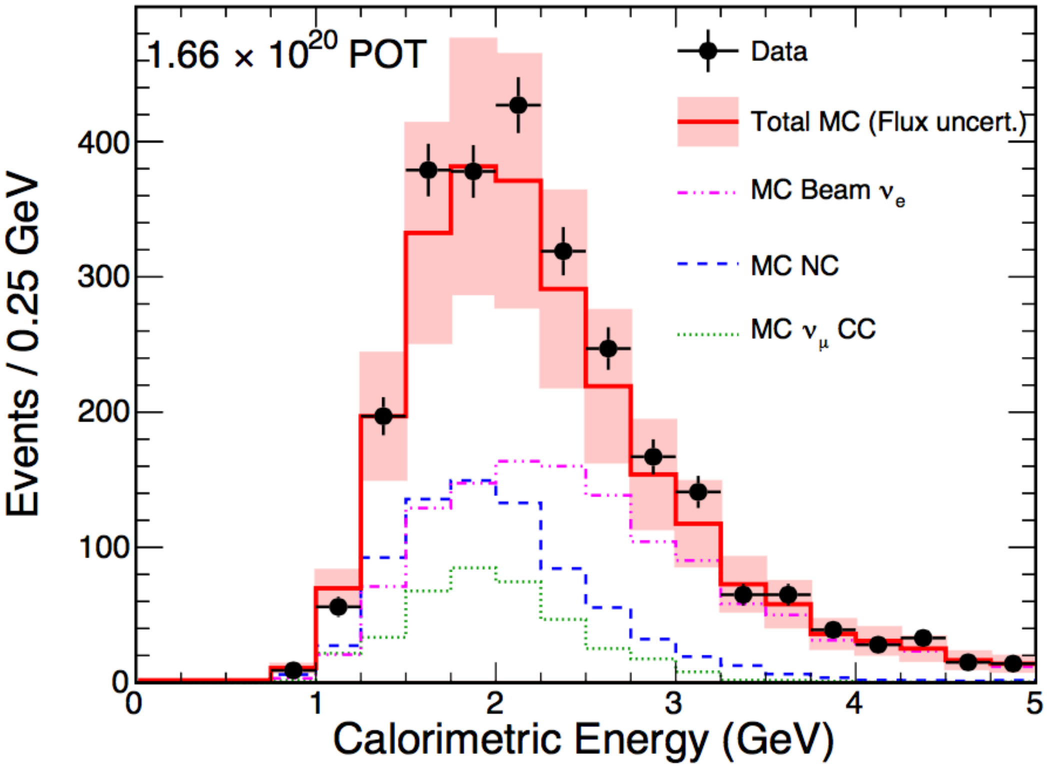
Spatial pattern of energy deposition is compared to ~10^8 simulated events

Properties of the best matched library events are put into a decision tree to form a discriminant

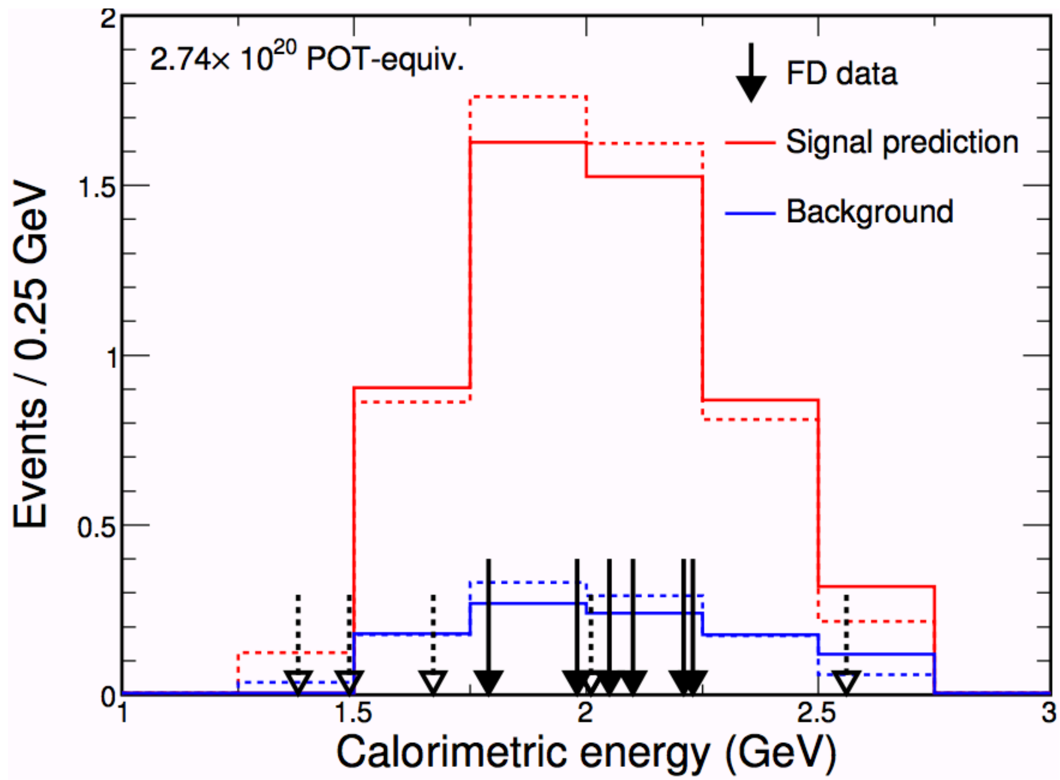


Electron neutrino appearance

ND LID selected events



FD selected events



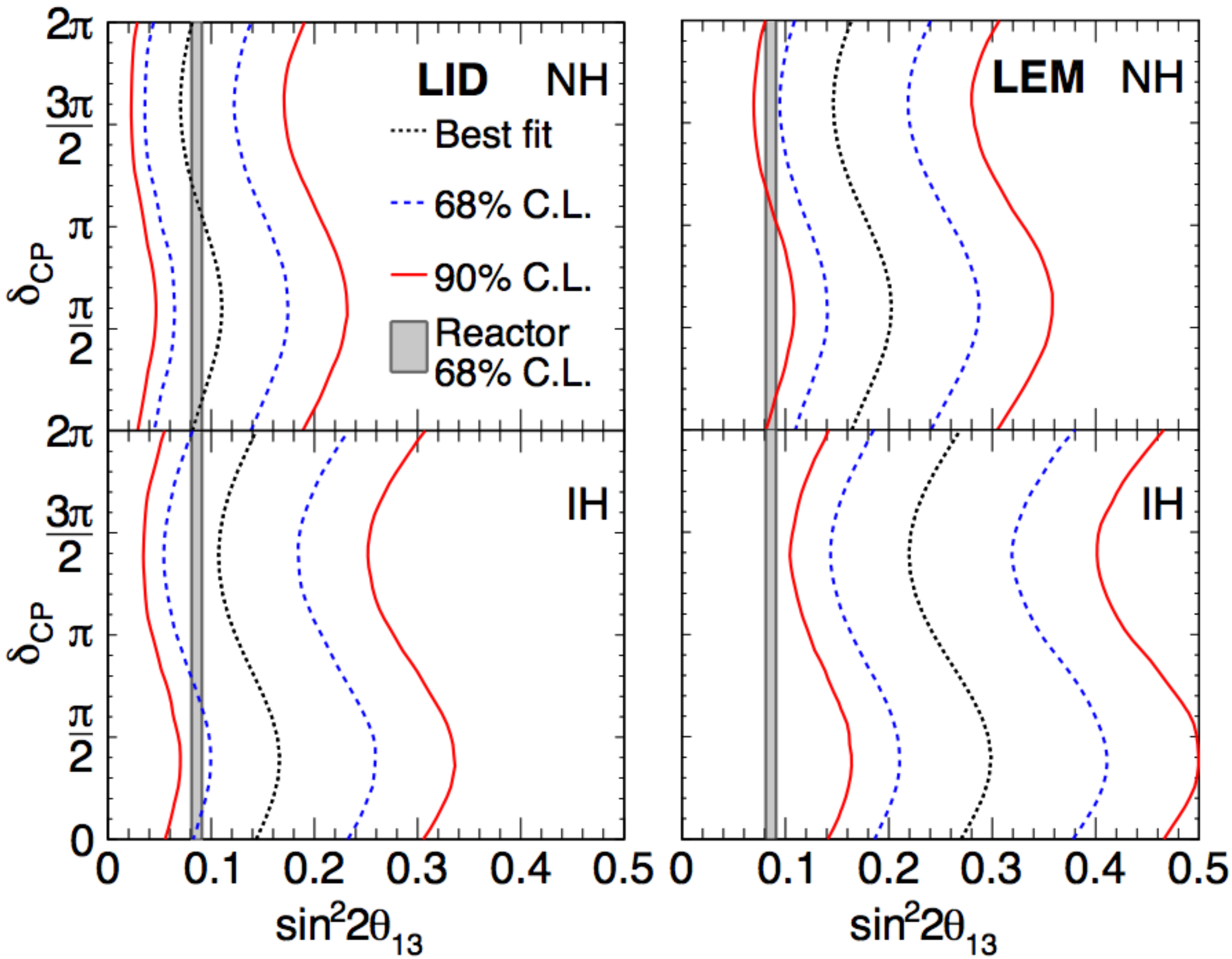
~1 background ν_e candidate event expected

LID → solid
LEM → dotted

6 ν_e candidate events observed (LID)

3.3σ significance for ν_e appearance

Electron neutrino appearance



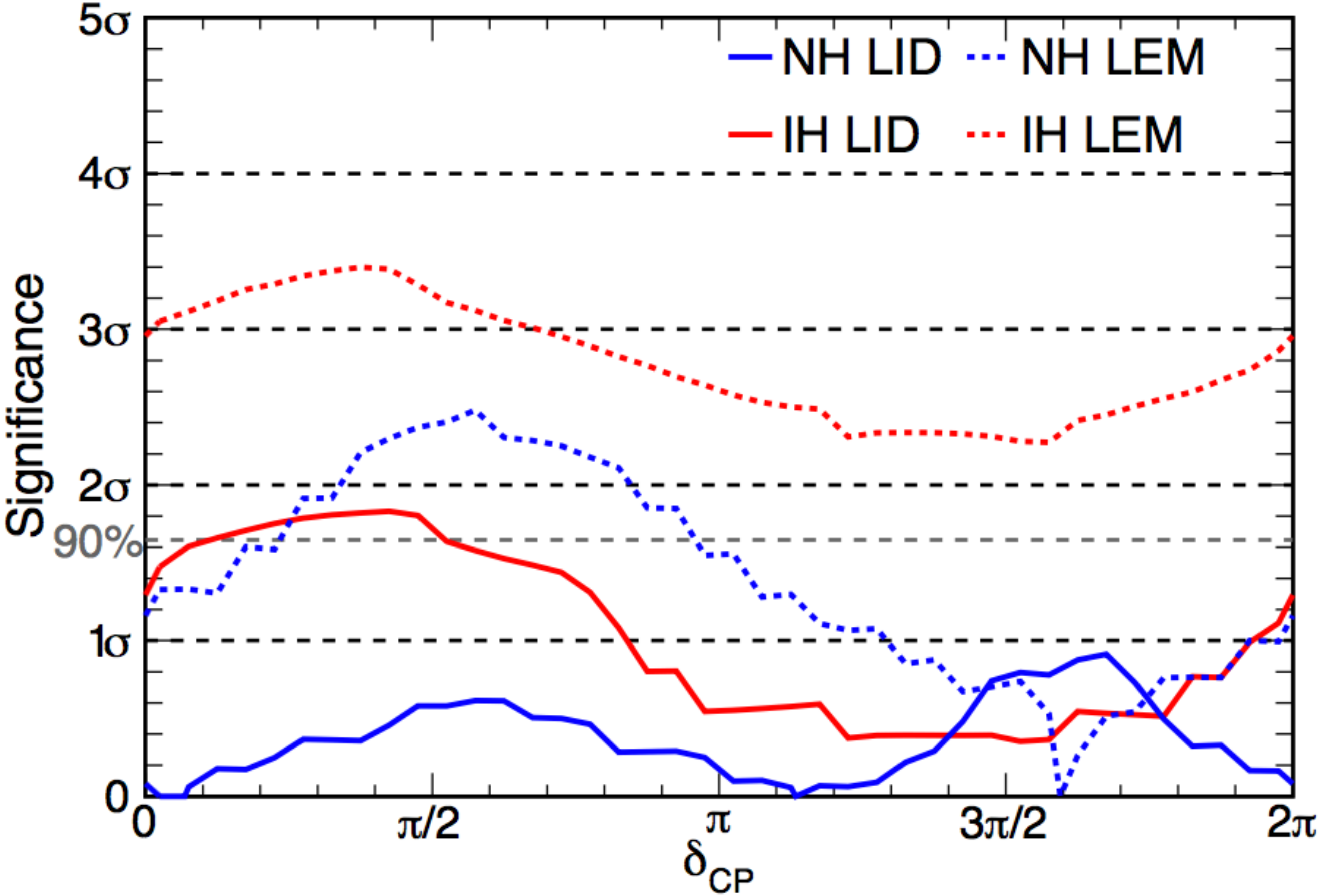
For $(\boldsymbol{\delta_{CP}}, \mathbf{sin^2 2\theta_{13}})$ allowed regions

- Feldman-Cousins procedure applied
- solar osc. parameters varied
- Δm^2_{32} varied by *new NOvA measurement*
- $\sin^2\theta_{23}$=0.5

For LID:

IH for $\delta \in [\,0, 0.8\pi\,]$ is mildly disfavored (>1σ)

Electron neutrino appearance



Summary

With 2.74 x 10^{20} POT-equiv. exposure:

- Clear muon neutrino disappearance signature
- 8% measurement of atm. mass splitting, and θ_{23} measurement consistent with T2K, MINOS and maximal mixing

- Electron neutrino appearance signal at 3.3σ
- At max. mixing, disfavour IH for $\delta : [0, 0.6\pi]$
- 2^{nd} result with double the statistics planned for the summer

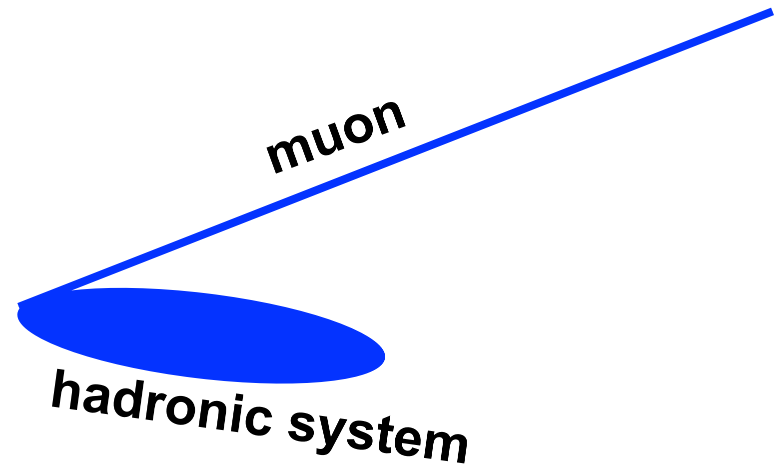
nue first results: P. Adamson et al. [NOvA Collaboration], arxiv/1601.05022 [hep-ex]
numu first results: P. Adamson et al. [NOvA Collaboration], arxiv/1601.05037 [hep-ex]
LEM: C. Backhouse, R. B. Patterson, arXiv:1501.00968v2 [physics.ins-det]

Backup

Energy estimation

Reconstructed muon energy found from track length:

$$length \rightarrow E_\mu$$

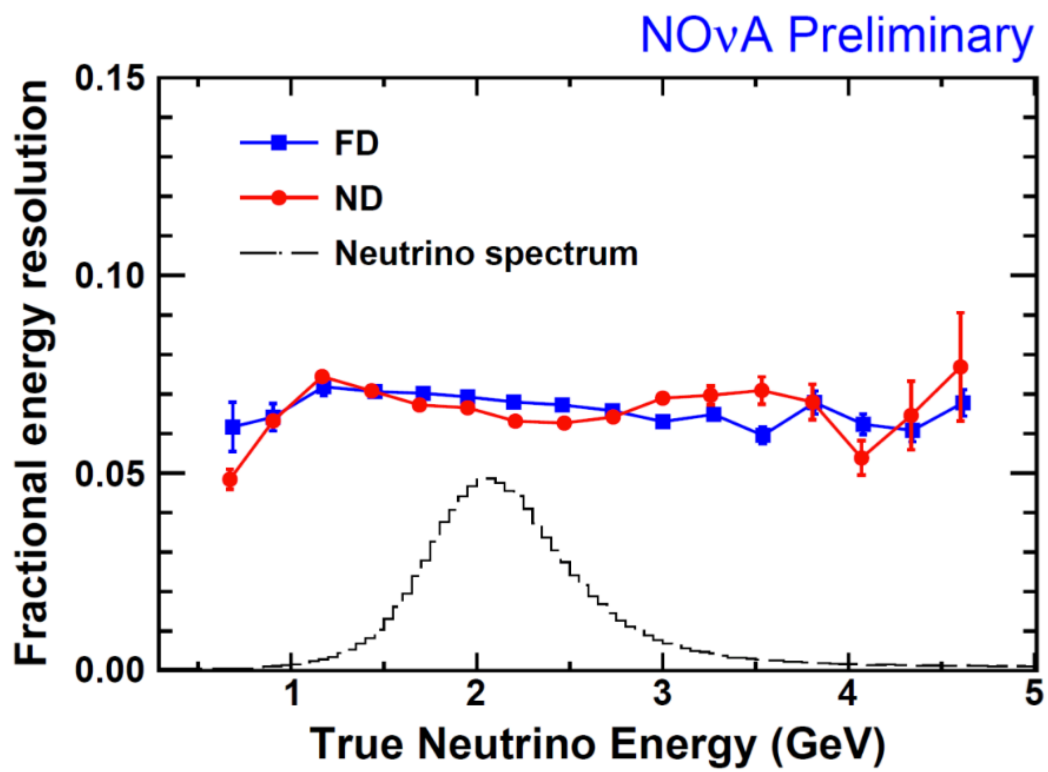


Hadronic energy:

$$\sum_{cells} E_{visible} \rightarrow E_{had}$$

Reconstructed neutrino energy:

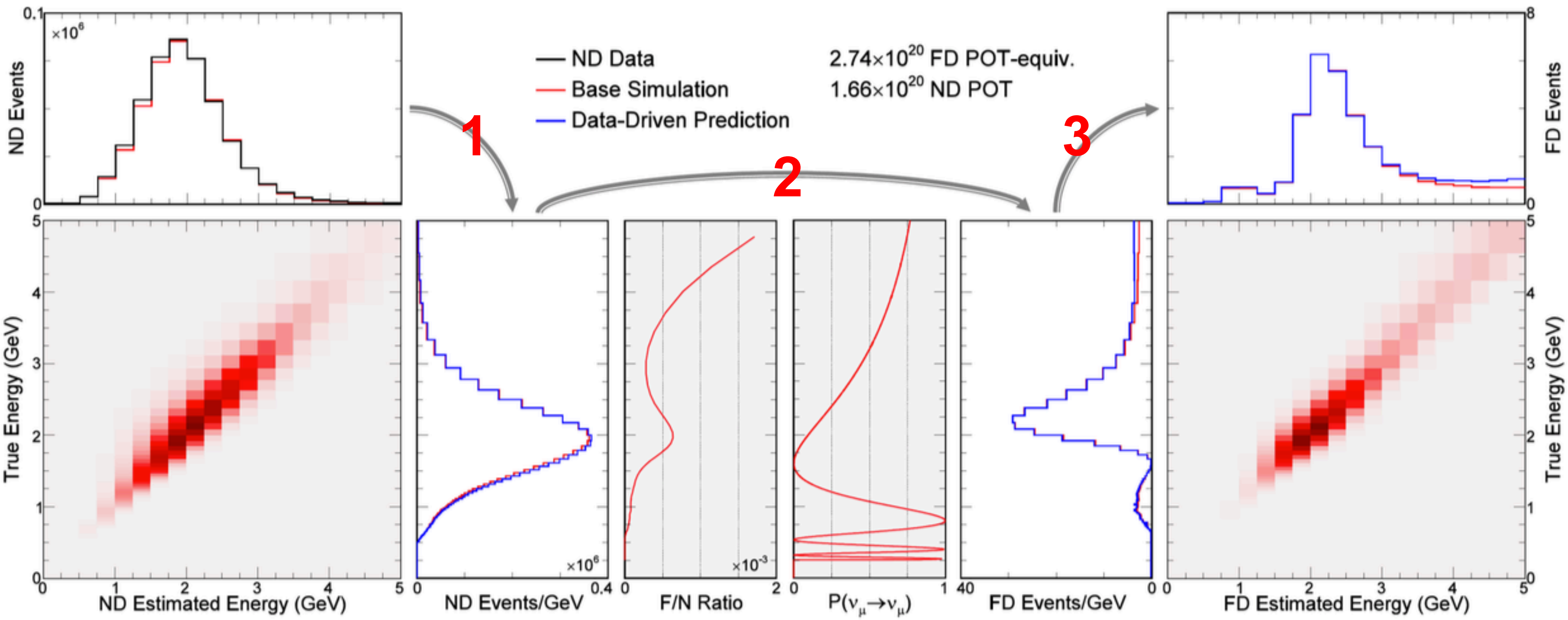
$$E_\nu = E_\mu + E_{had.}$$



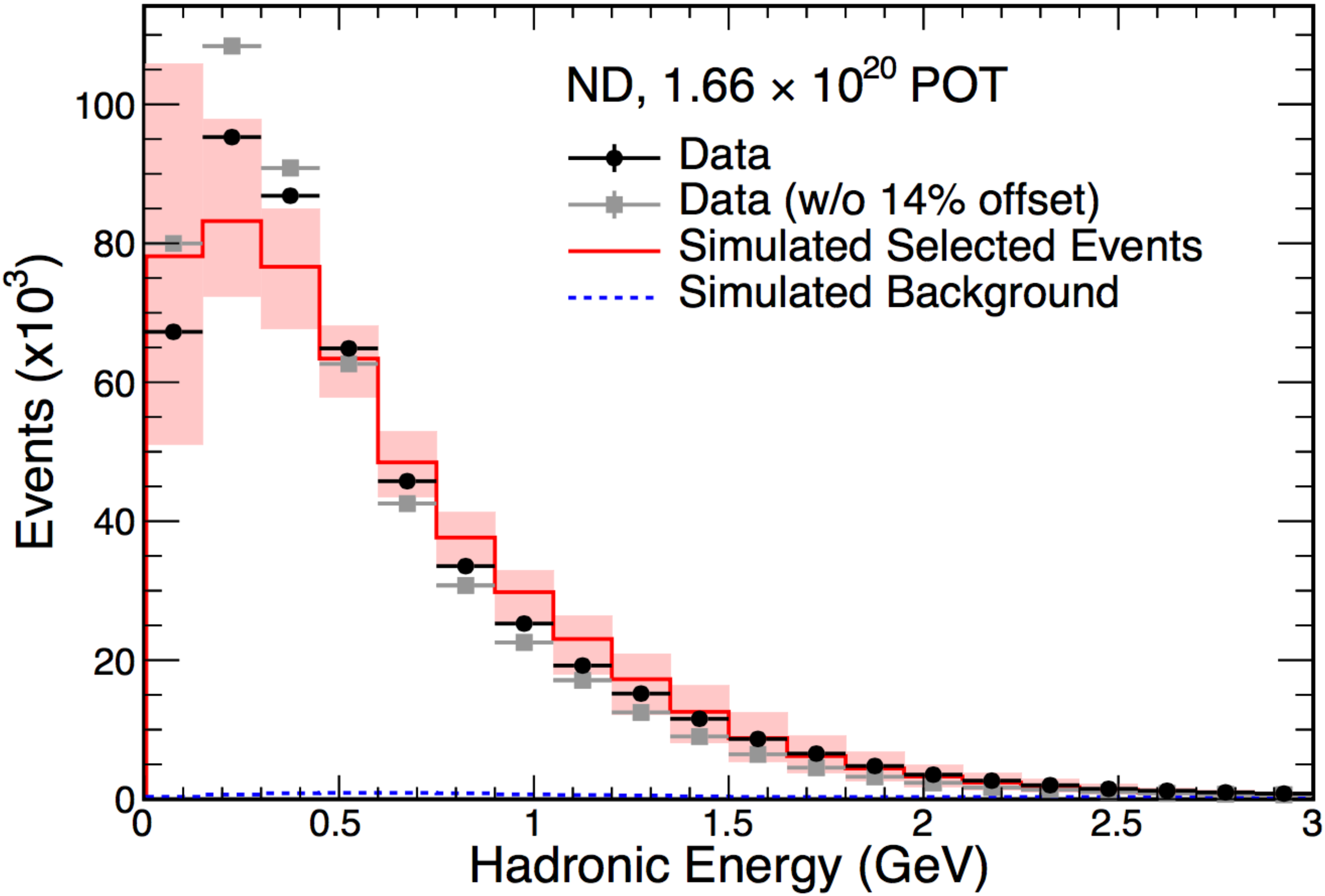
energy resolution at beam peak ~7%

Far detector prediction

1. Estimate underlying true energy distribution of selected ND events
2. Multiply by expected Far/Near event ratio and $\nu_\mu \rightarrow \nu_\mu$ survival probability as a function of energy
3. Convert FD true energy distribution into predicted FD reco. energy distribution

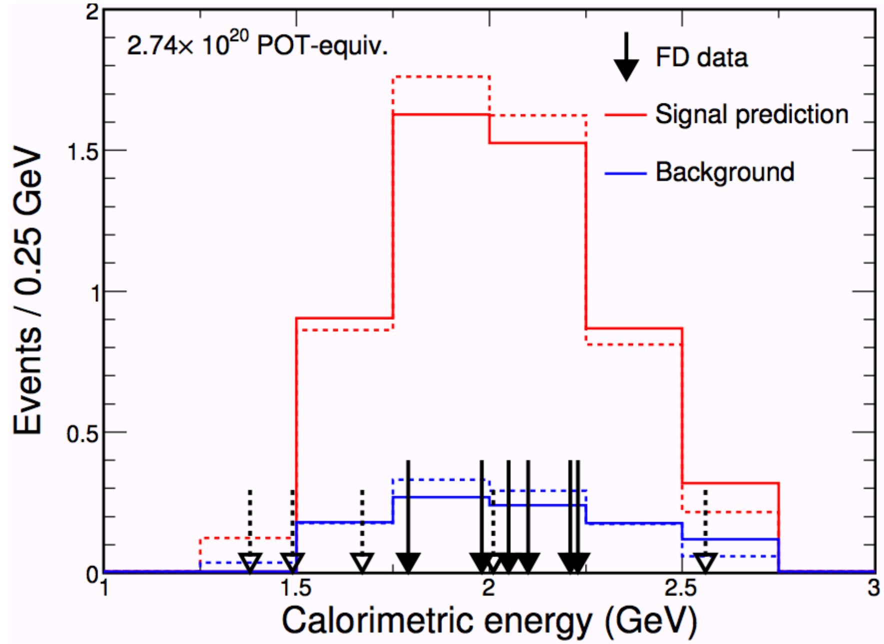


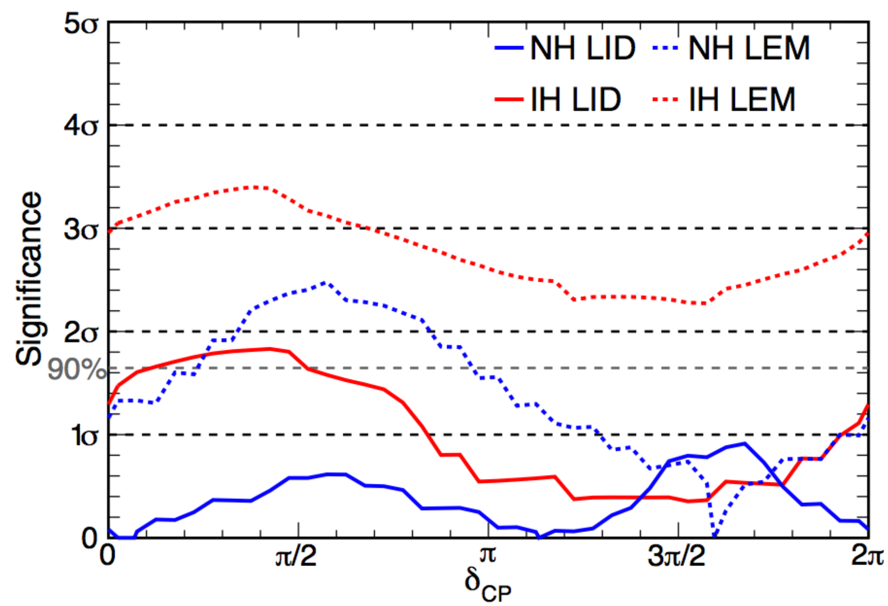
Systematic uncertainties



Electron neutrino appearance
LID – LEM consistency

- Both prefer normal hierarchy
- All 6 events selected by LID are also selected by LEM which selects 11
- Using the trinomial distribution and the number of simulated events that overlap between the selectors,
  - We compute the probability of observing this overlap configuration (or a less likely one) as 7.8%





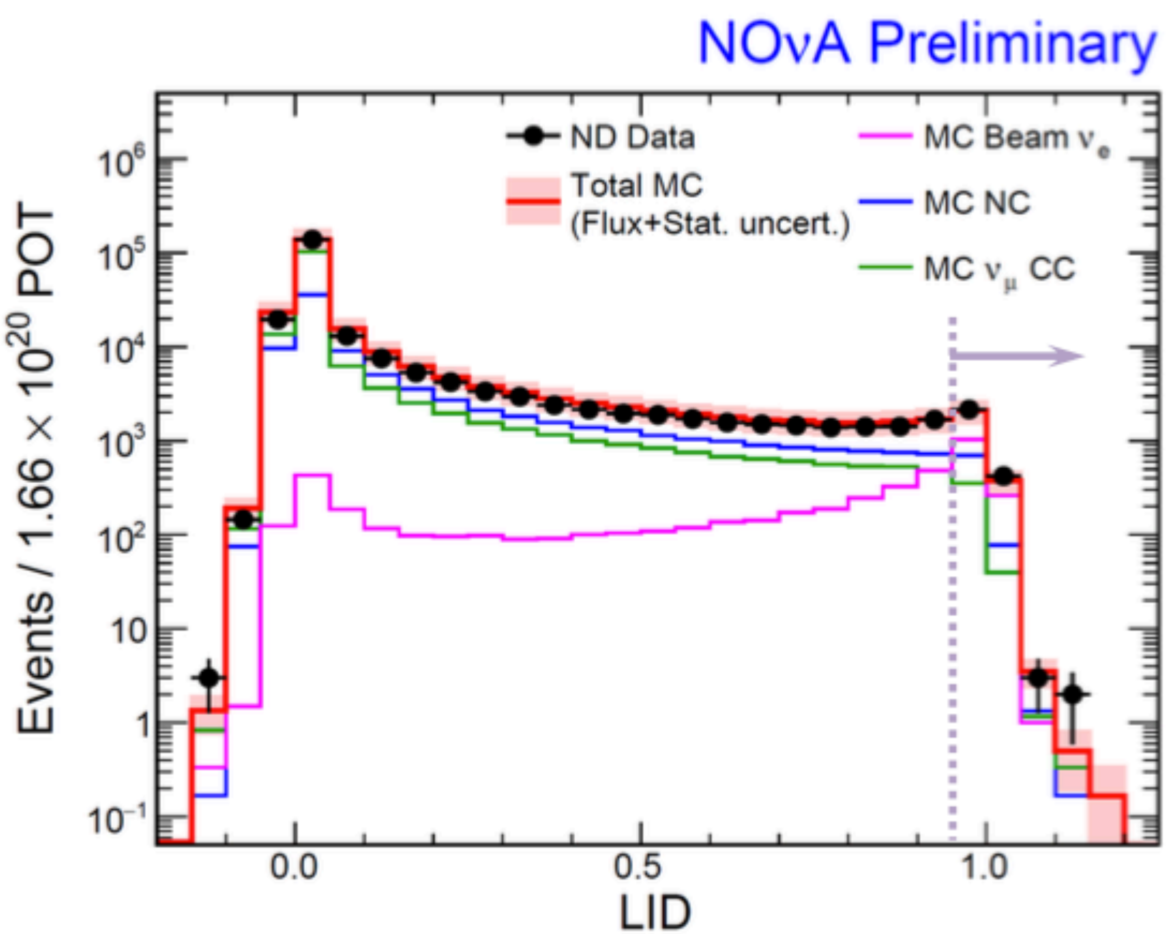
Electron neutrino CC event selection

LID: Likelihood Identification

dE/dx likelihoods calculated for longitudinal and transverse slices of leading shower under multiple particle hypotheses

Likelihoods feed an artificial neural network along with kinematic and topological info:

e.g. energy near vertex, shower angle, vertex-to-shower gap



Electron neutrino cross-section