Electron Neutrino Appearance in NOνA

New Perspectives, 2014

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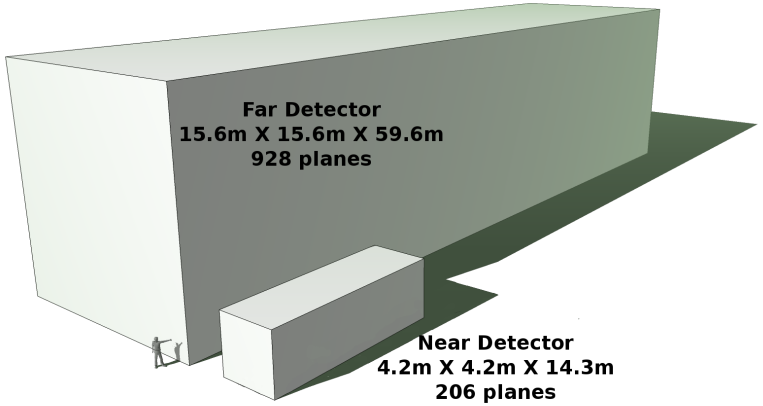
The NOνA Experiment

* NOνA (NuMI Off-axis ν_e Appearance) is a neutrino oscillation experiment
  * Baseline of 810 km
  * Source of neutrinos: NuMI (Neutrinos at Main Injector) beam of mostly ν_μ
  * Two functionally identical detectors
  * 14 mrad off-axis from the beam



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  - Baseline of 810 km
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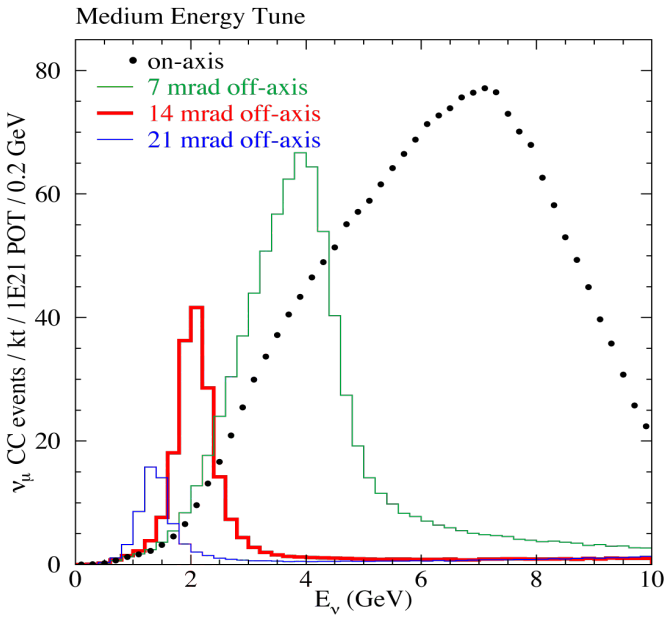
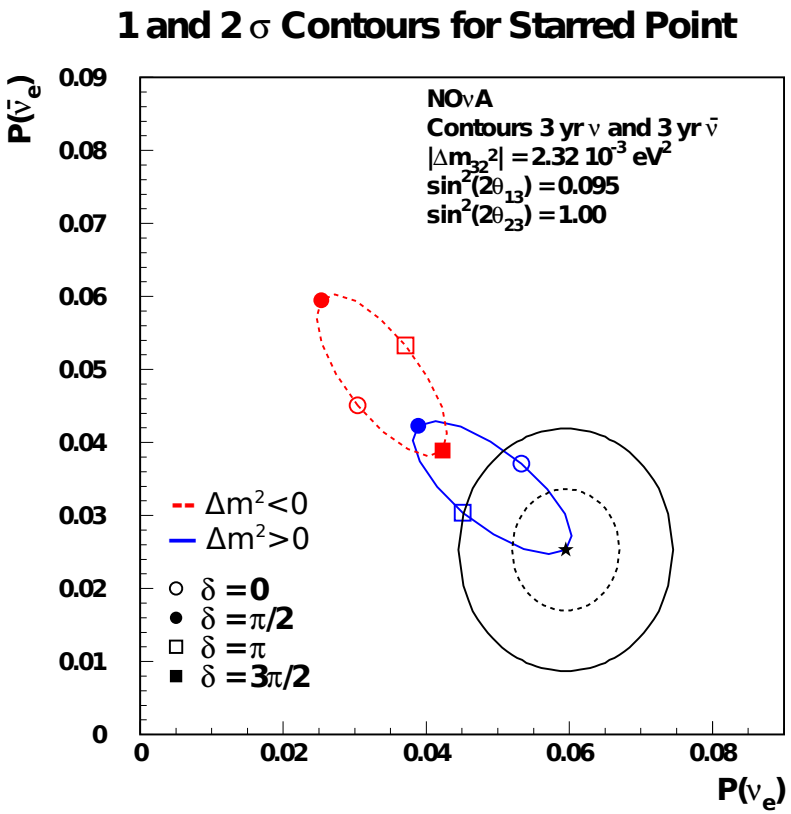
  - Two functionally identical detectors
  - 14 mrad off-axis from the beam
- Oscillation channels accessible to NOνA :
  - $\boldsymbol{\nu_\mu(\bar{\nu}_\mu)}$ **to** $\boldsymbol{\nu_e(\bar{\nu}_e)}$ (appearance)
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\mu(\bar{\nu}_\mu)$ (disappearance)



Parameters Accessible to NOνA Through ν_e Appearance

- The long baseline of NOνA allows for large matter effect
  - ν_e have a *slightly* different Hamiltonian than $\bar{\nu}_e$ due to interactions with electrons
  - This difference is **sensitive to mass hierarchy**: is mass state ν_3 heavier than ν_1, ν_2?
- NuMI beam can run in neutrino as well as anti-neutrino mode. Makes us sensitive to
  - **CP violation** in neutrino sector
  - $\boldsymbol{\theta_{23}}$ **octant**: Is $\boldsymbol{\theta_{23}}$ *exactly* **45**$^\circ$, slightly more or slightly less?



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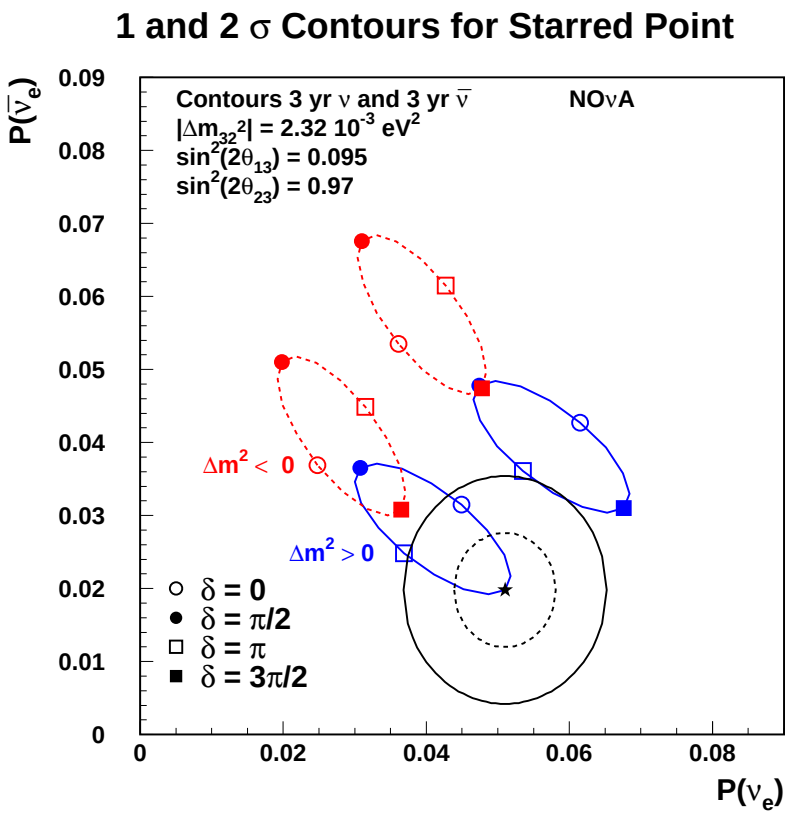

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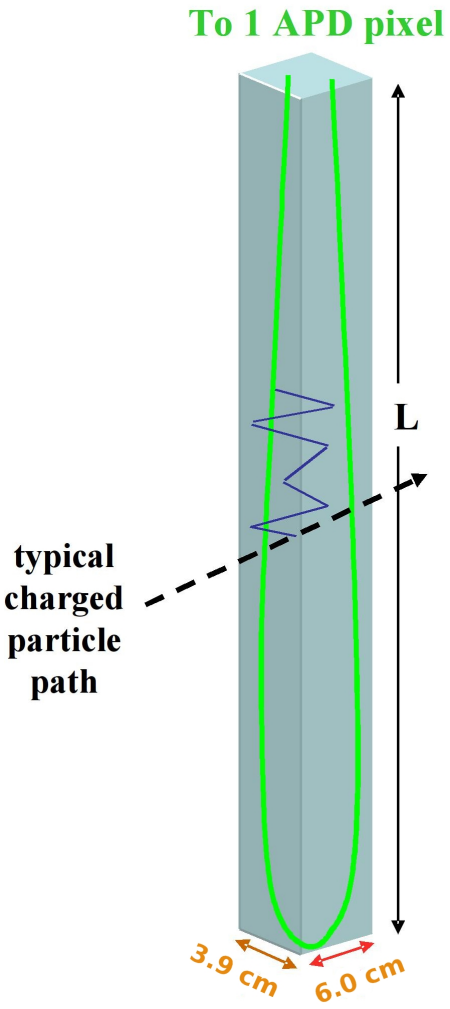
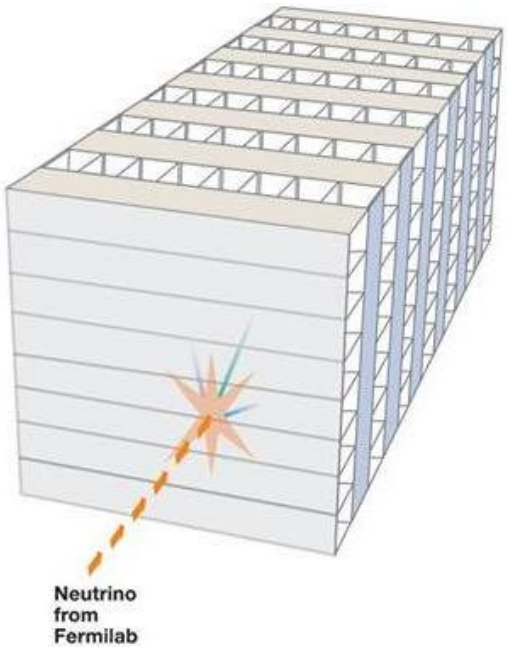
NOνA Detector Design

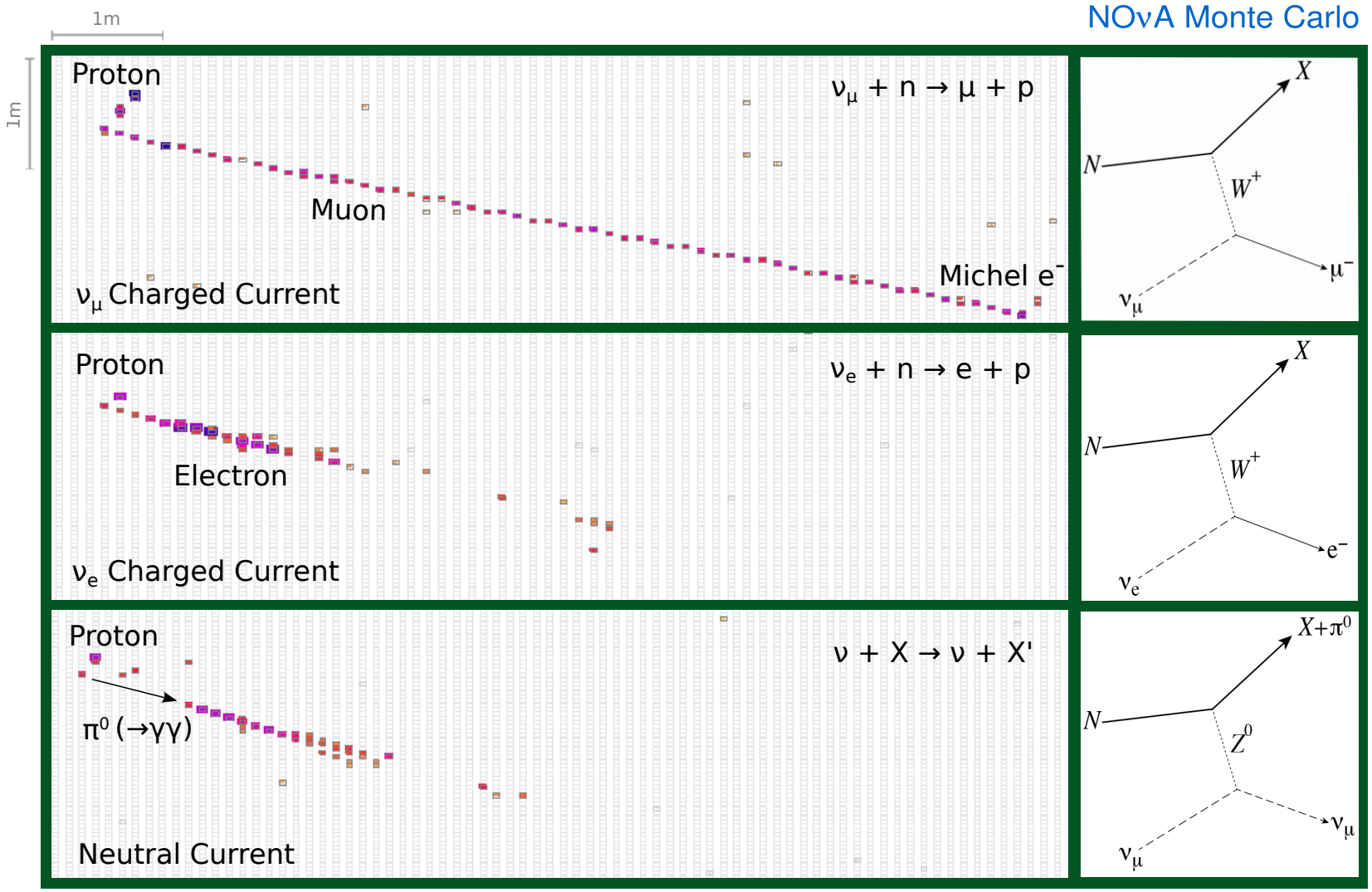


- Composed of PVC modules extruded to form long tube-like cells
- Each cell is filled with liquid scintillator
- Optical fiber loop carries scintillation light to a pixel on an Avalanche Photo Diode (APD)
- Cells arranged in planes, with alternating planes perpendicular in orientation



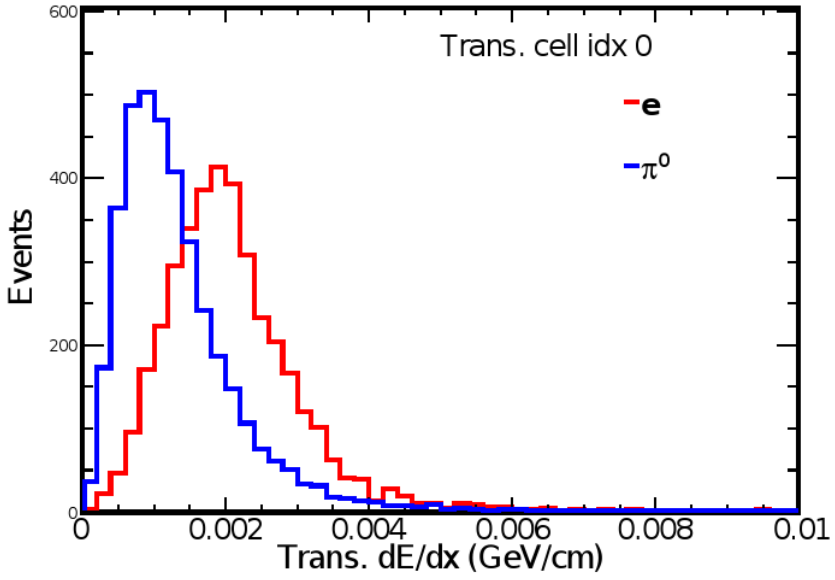
Neutrino Event Topology In NOνA

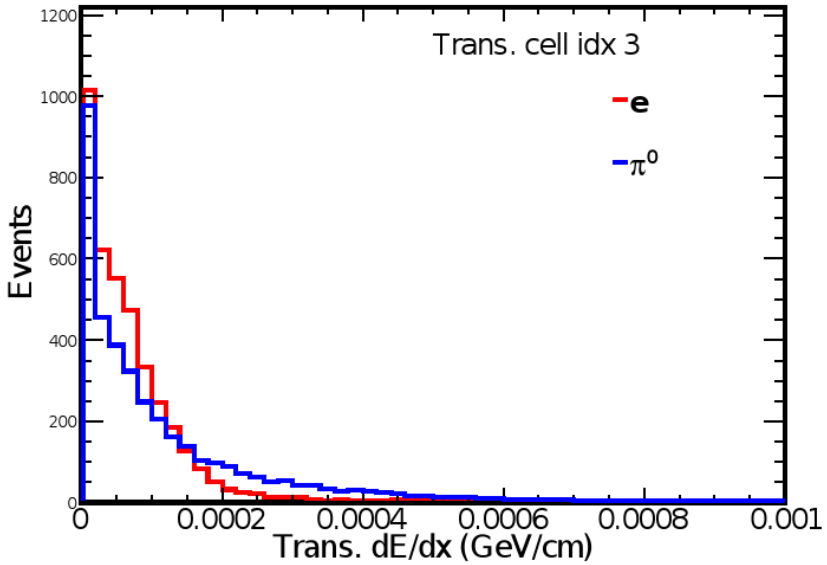
- Low-Z material, each plane samples $\sim$ 0.18 radiation-lengths
- Molière radius is $\sim$ 10 cm, 2.5 NOνA cells



Identifying Electron Neutrinos

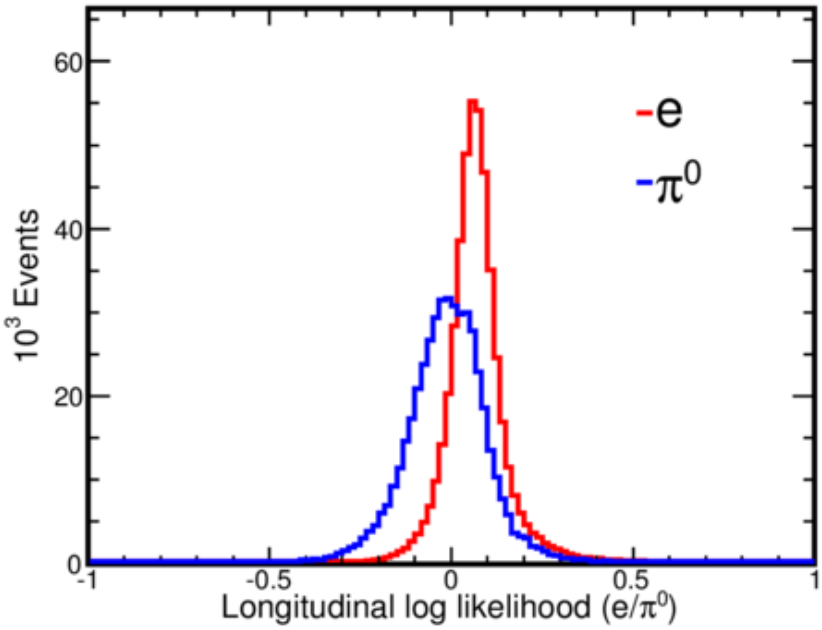
- Fine grained structure of NOνA allows multiple samples of information along particle's trajectory
- One of the ν_e PIDs in NOνA , the EID, uses energy deposited per path-length (dE/dx) in a plane to identify particles
- Simulation is used to make expected distributions for each particle hypothesis

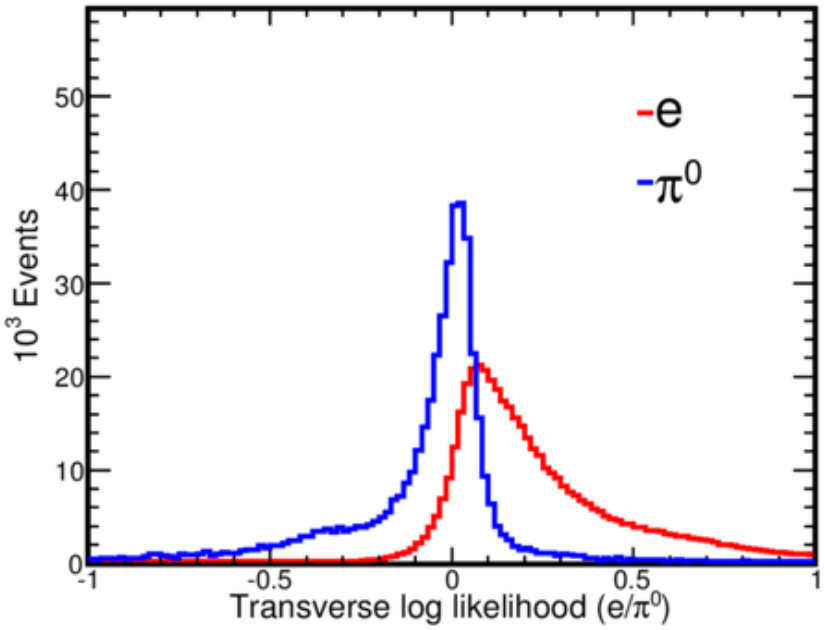




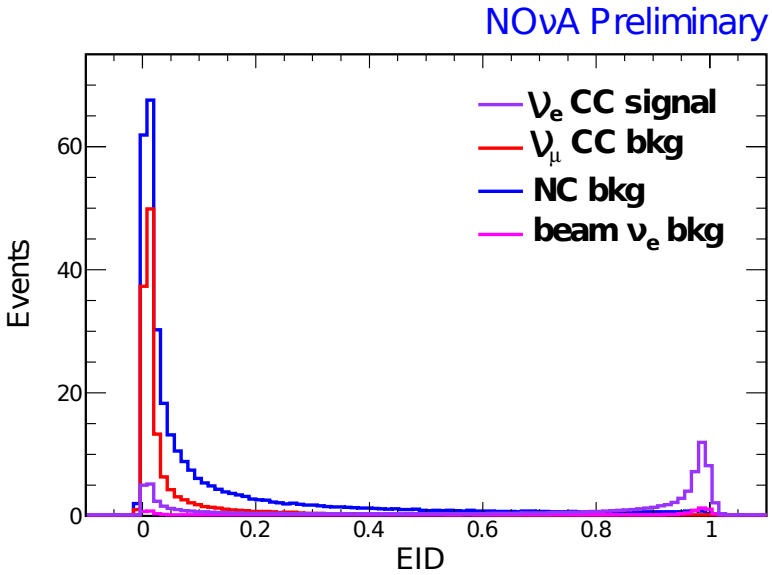
Identifying Electron Neutrinos

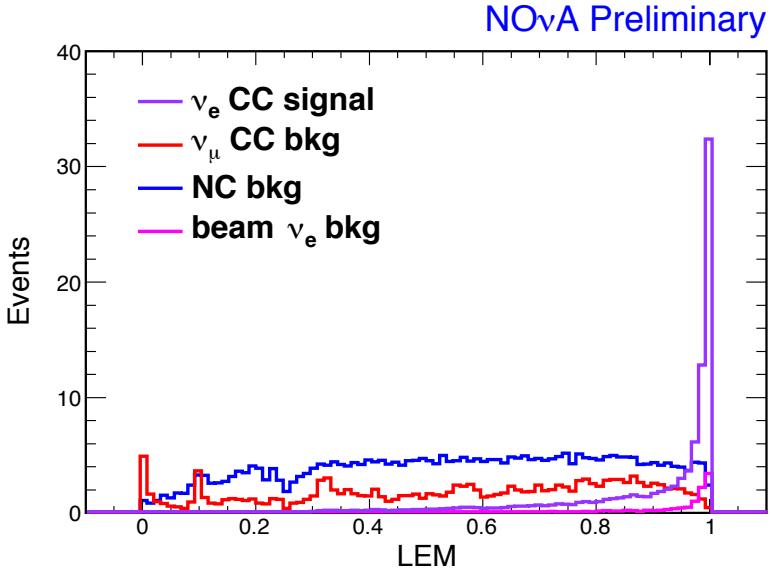
- An unidentified particle deposits energy E_i in the ith plane, the probability for, say, an electron is $P_i(e)$
- We construct log-likelihood(LL) by summing probabilities over all planes
- The difference of log-likelihoods indicates the identity of the particle, eg $LL(e) - LL(\pi^0)$
- LLs, amongst other variables, are used as inputs to a Artificial Neural Net (ANN) for the final PID





Performance of PIDs



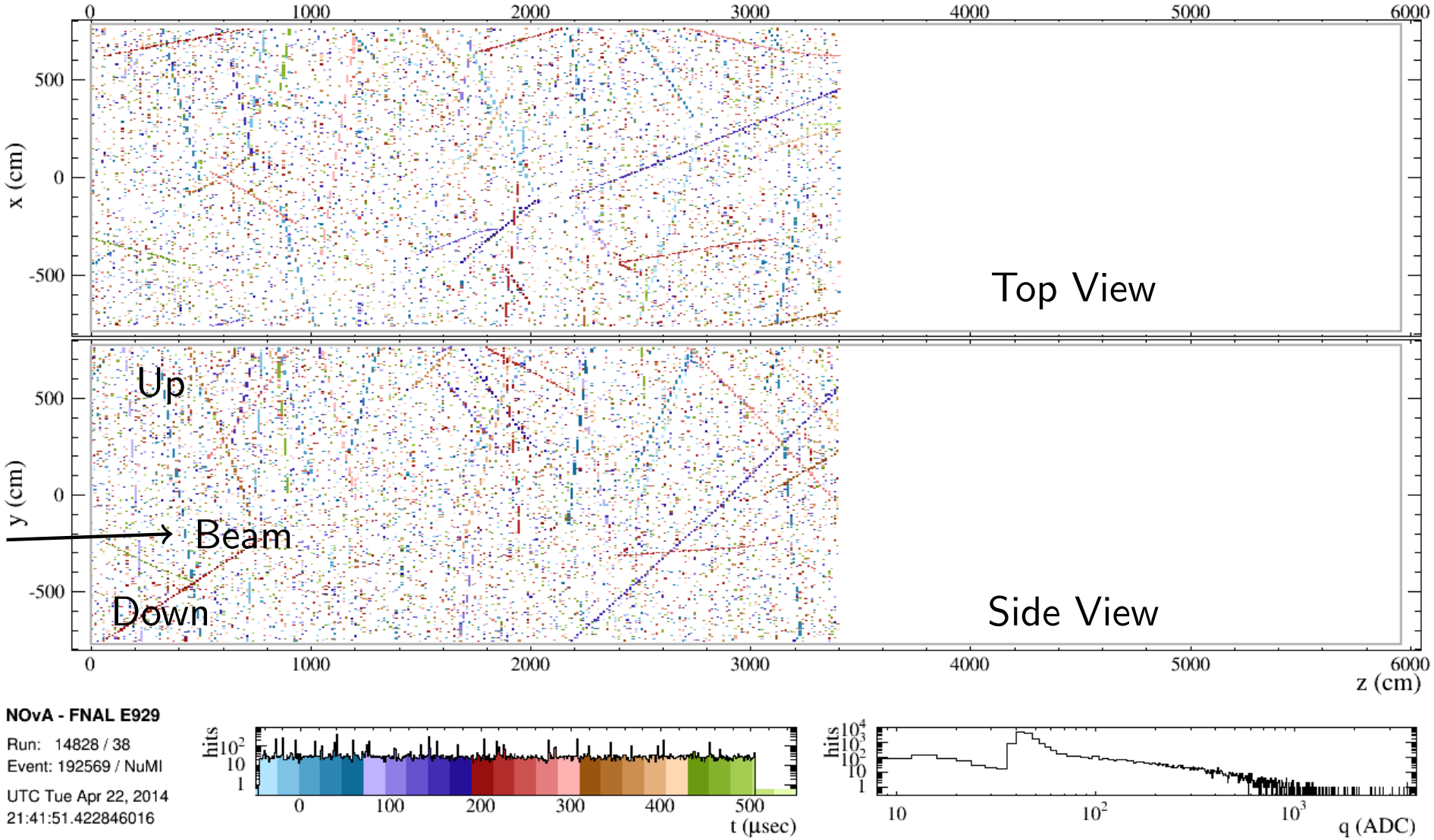


- An independent PID algorithm, LEM, matches candidate event against a vast library of signal and background events
- PIDs obtain similar performance
- Signal and background levels after one year of nominal exposure

PID	ν_e Signal	ν_μ CC	NC	Beam ν_e CC
EID	13.9	0.7	3.9	1.5
LEM	14.0	1.1	3.5	1.5

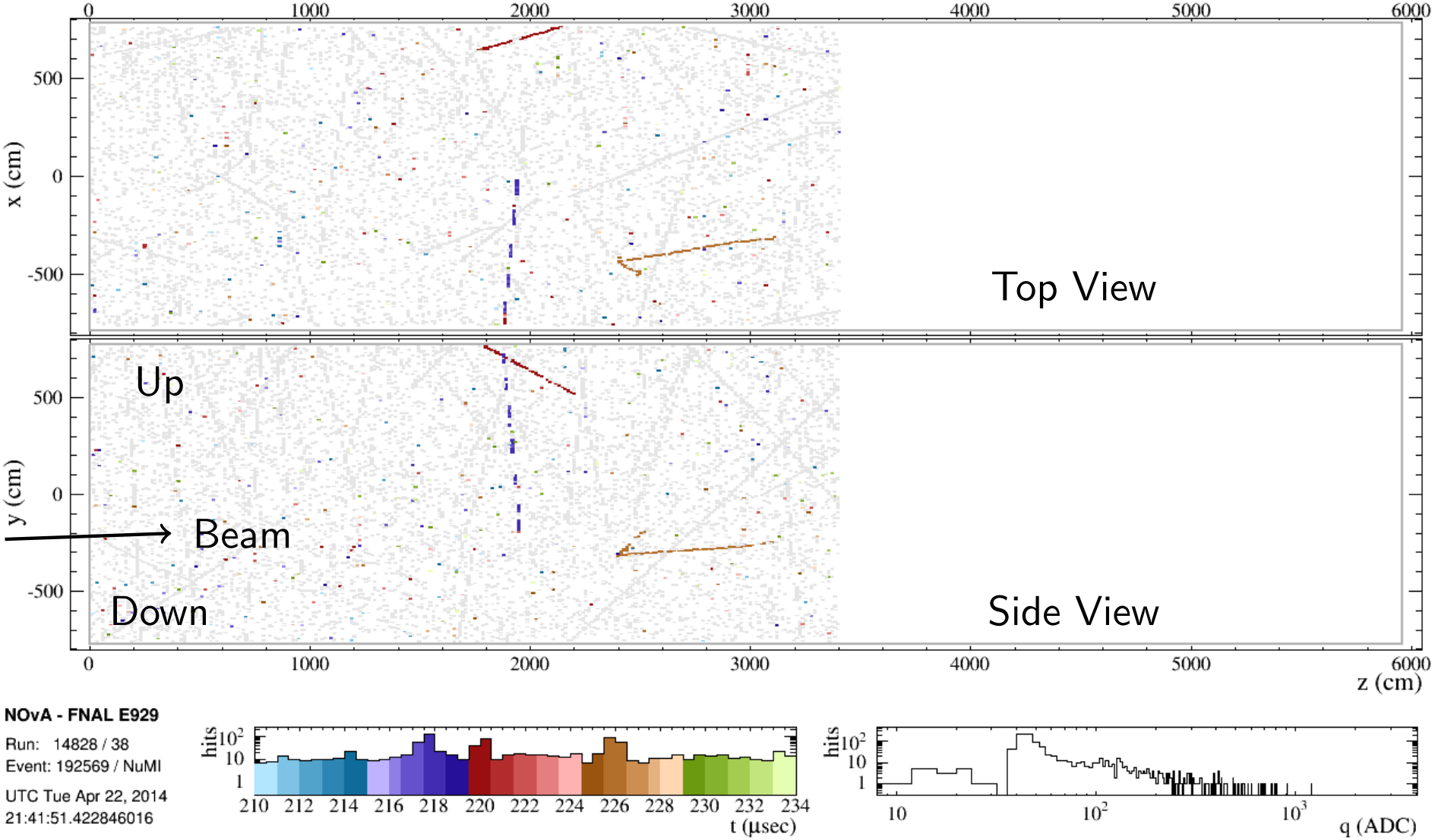
Cosmic Background

* Far Detector is on surface, cosmic flux is $\sim 100kHz$ for the full detector



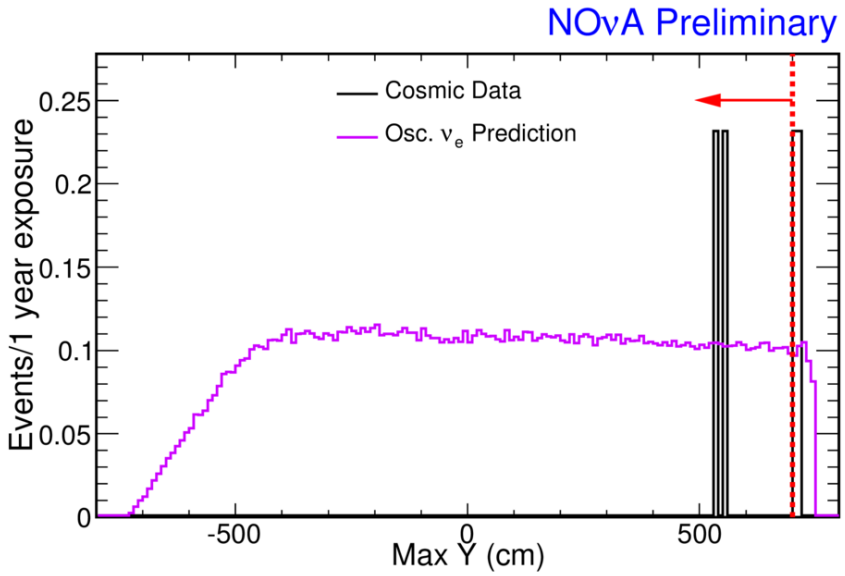
Cosmic Background

* Beam spills are 10μs long. Small live-time causes a large suppression of cosmics



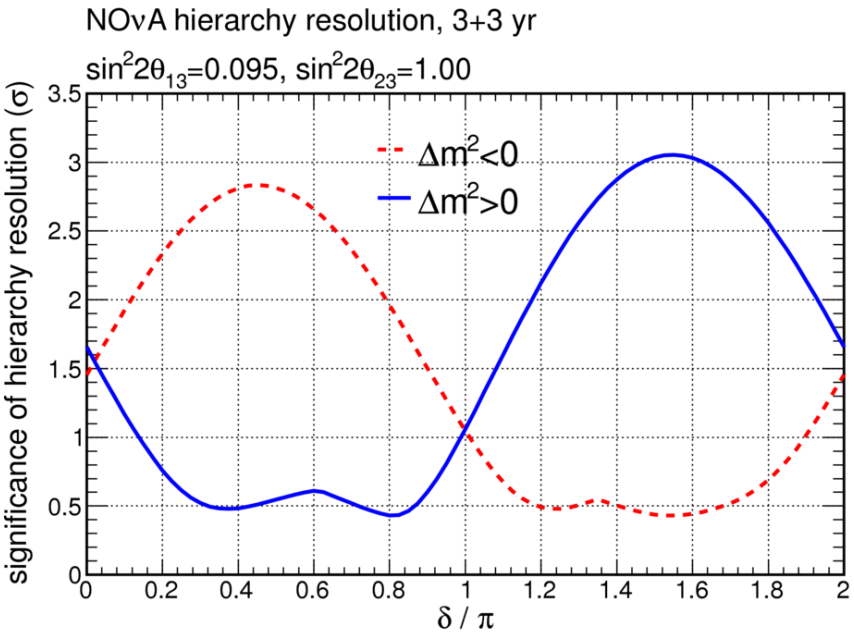
Cosmic Rejection

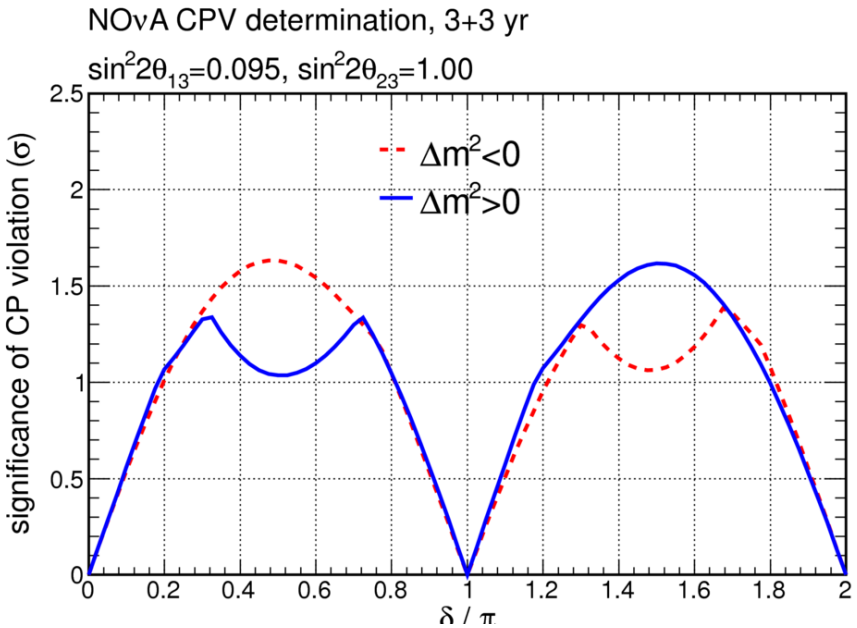
- Geometry of electron neutrino events is very different from cosmics
- Simple cuts remove most of the cosmic background
- Rejection achieved at the level of ~ 2 cosmic events in 3 years of beam

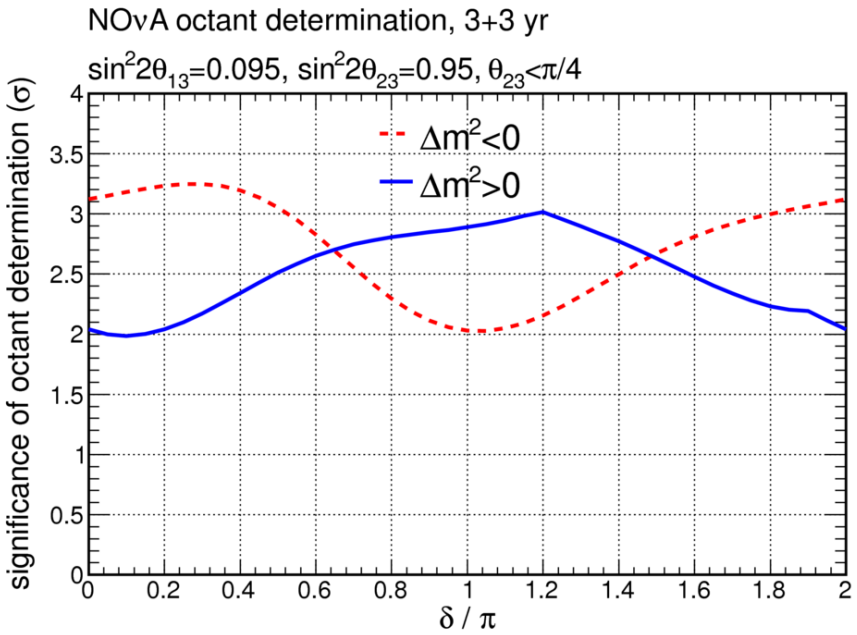


- Cosmic rejection cuts:
  - Beam spill timing
  - Fiducial and pre-selection
  - Transverse momentum fraction, $p_T/p < 0.6$
  - Max-Y < 700 cm
  - Gap from vertex < 150cm
  - EID > 0.7

NOνA Sensitivities







- Mass hierarchy resolution at $\sim 3\sigma$ in the best case
- CP violation phase determination at $> 1.5\sigma$ in the best case
- θ_{23} octant determination at $\sim 3\sigma$

Concluding Remarks

* The ν_e appearance analysis chain is in place to produce oscillation results
* We can reject cosmic background to a negligible level, about 2 events for 3 years of beam
* NOνA has unique capability of resolving neutrino mass-hierarchy and determining CP violation phase and the octant θ_{23} - *Stay tuned!*