First Neutrino Oscillations Results from NOvA

Heavy Quarks and Leptons 2016

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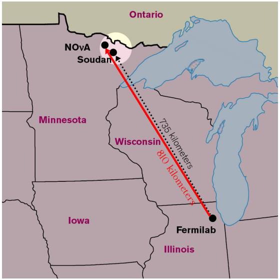
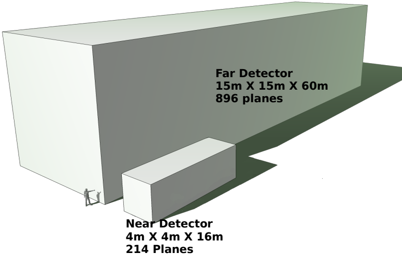
Fermilab

May 23, 2016

The NOvA Experiment

- NOvA (NuMI Off-axis ν_e Appearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - Two functionally identical detectors





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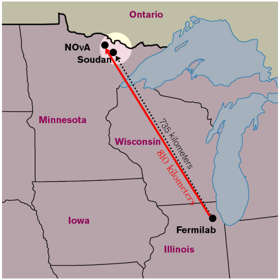

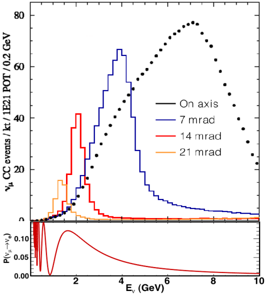

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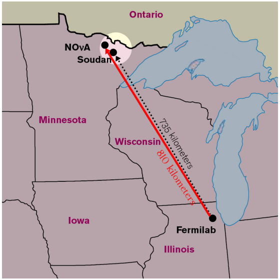
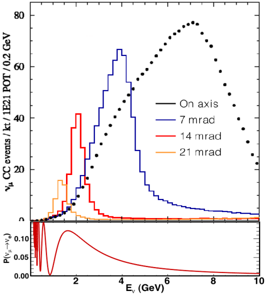
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - Two functionally identical detectors
  - 14 mrad off-axis from the beam
- Measure standard oscillations in channels:
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_e(\bar{\nu}_e)$ (appearance)
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\mu(\bar{\nu}_\mu)$ (disappearance)
- First data from February 2014 to May 2015, with 2.74 $\times 10^{20}$ of full-detector equivalent POT, 7.6% of exposure planned for full life of NOvA





- NuMI beam can run in neutrino as well as anti-neutrino
- To first order, NOvA measures $\nu_\mu \to \nu_e$ and $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillation probabilities at 2 GeV

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

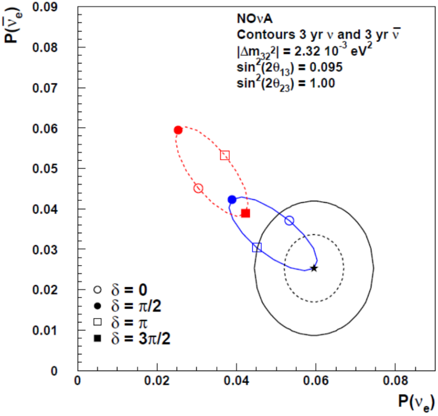
$$P_2 = \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

$$P_3 = \overset{(+)}{-} J \sin\delta \sin \frac{\Delta m^2_{32} L}{4E}$$

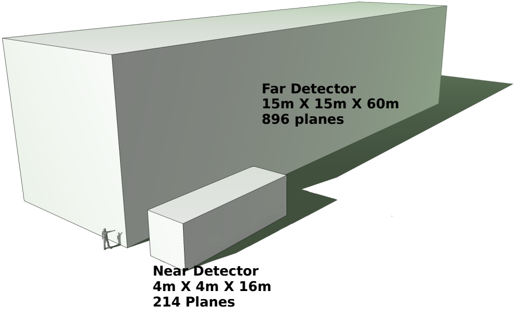
$$P_4 = J \cos\delta \cos \frac{\Delta m^2_{32} L}{4E}$$

$$J = \cos\theta_{31} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{21} \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

1 and 2 σ Contours for Starred Point



- Tracking calorimeters

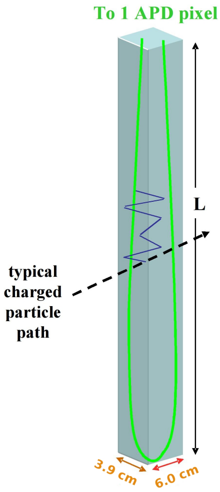


Far Detector (FD)

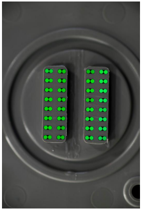
- 14 kt, $\gtrsim$ 344,000 channels
- On surface
- 810 km from source

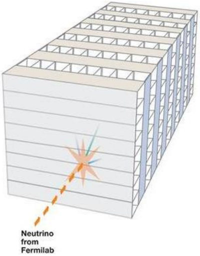
Near Detector (ND)

- 0.3 kt, $\gtrsim$ 20,000 channels
- 100 m below surface
- 1 km from the NuMI



- Composed of PVC modules extruded to form long tube-like cells : 15 m long in FD, 4 m ND
- 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

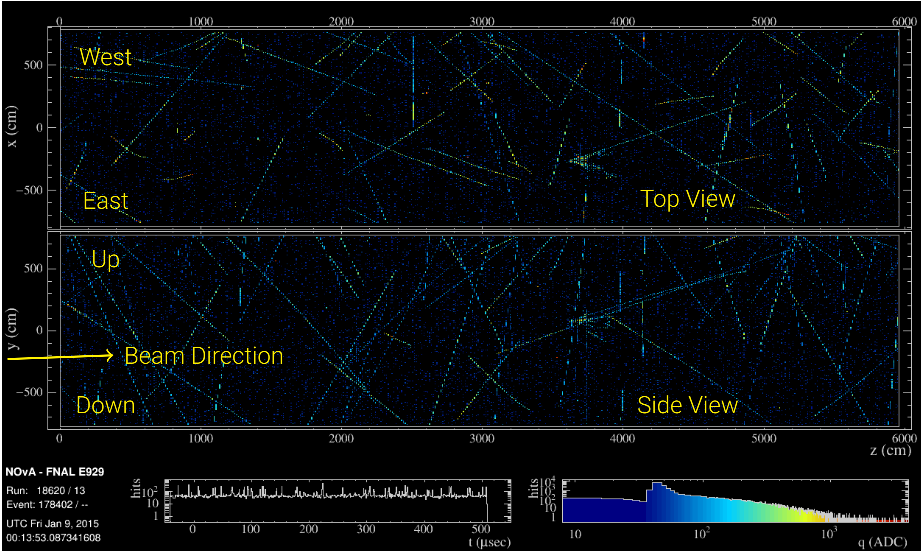




Far Detector

Far Detector Data

* Trigger window is 500 μs, neutrino spill only lasts 10 μs



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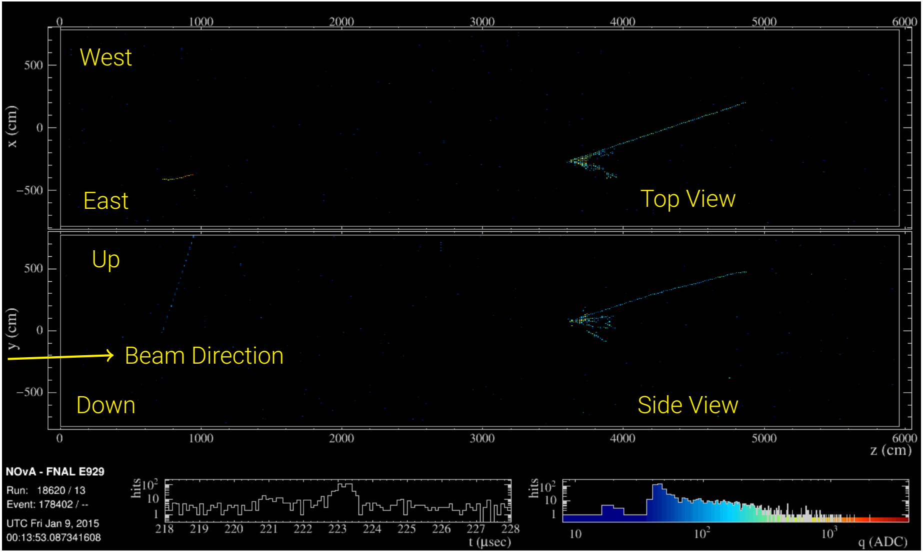

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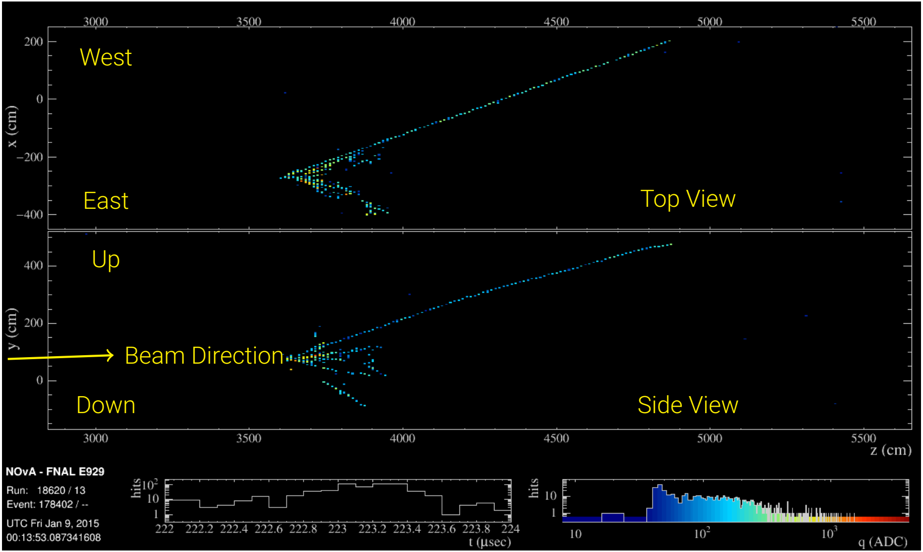
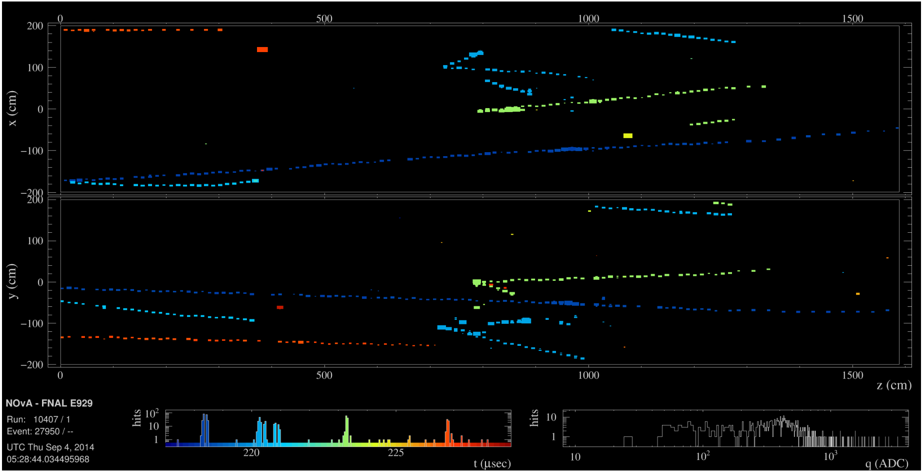
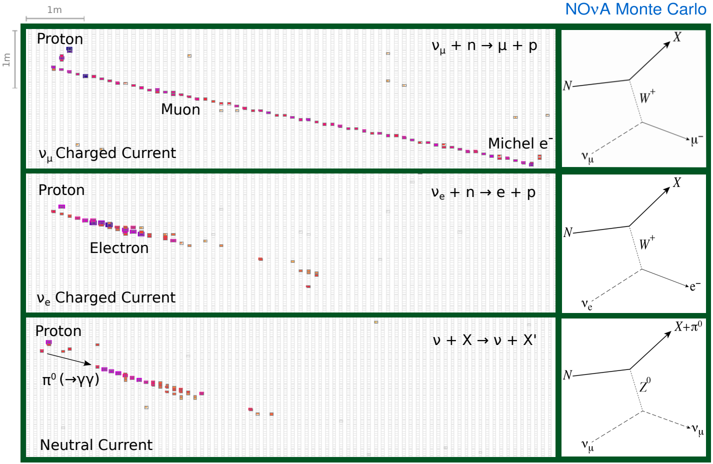




NOvA - FNAL E929
Run: 10407 / 1
Event: 27950 / --
UTC Thu Sep 4, 2014
05:28:44.034495968
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

Neutrino Events In NOvA

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



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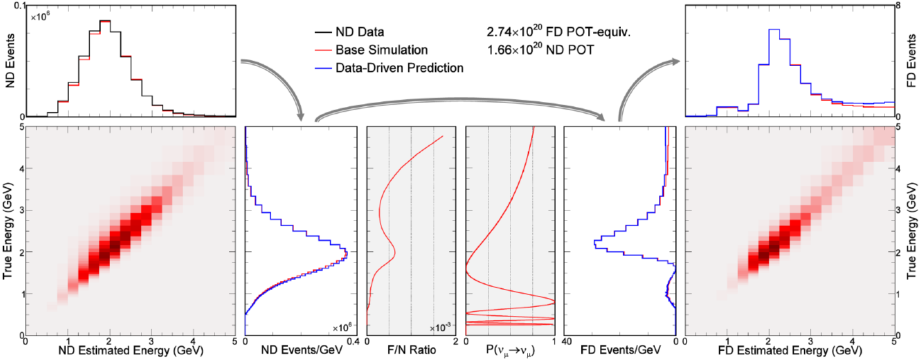
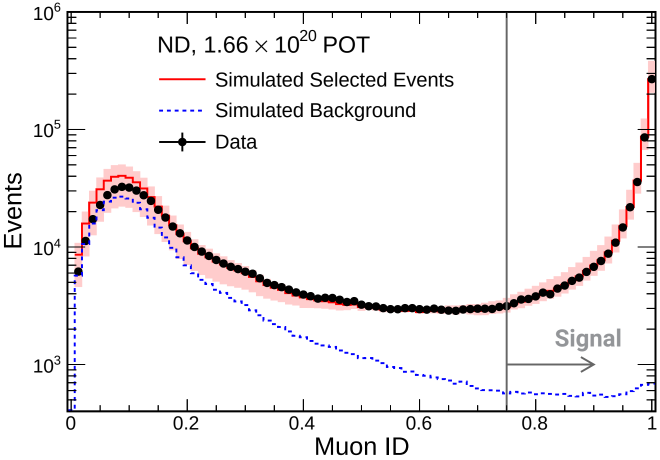
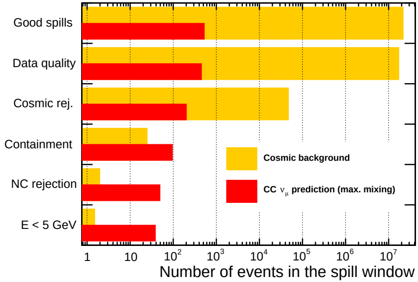
- Use Near Detector data to constrain the signal and backgrounds expected in the Far Detector
- Systematic errors, like flux, interaction cross-section, detector modeling etc cancel to a large extent in extrapolation



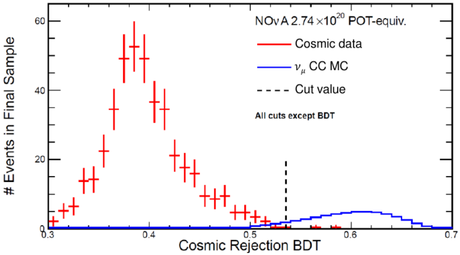
ν_μ Disappearance Analysis

Combine input variables in a k-Nearest Neighbor algorithm
ν_μ selection purity of $> 95\%$





Cosmic rejection BDT based on muon direction, position, length, number of hits in slice and energy



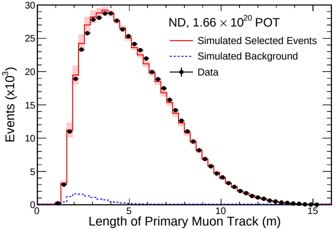
Rejection factor of 10^7 achieved with event topology

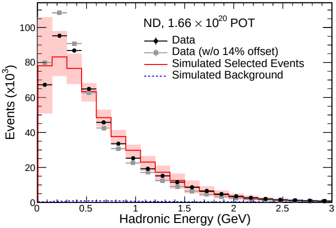
Expect 1.4 cosmic background events on an expected oscillated signal count of 30-35 signal events!

Final background measured directly form beam-off FD data

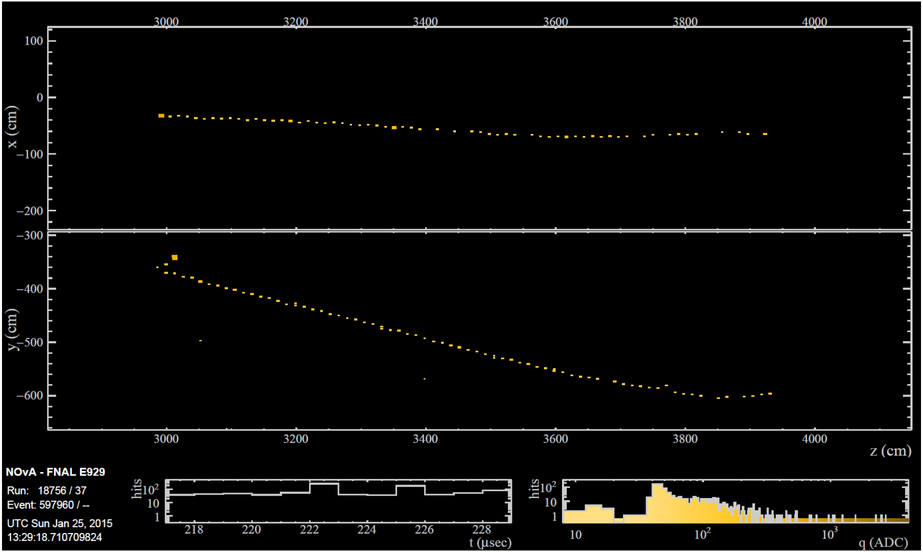
Systematics

- Most systematics are negligible in F/N ratio
- ND data exhibits smaller hadronic energy than simulation, though muons agree well
- Calibrate hadronic energy response in simulation to data
- Assign a 14% uncertainty on E_{had} scale $\Longrightarrow \sim$ 5% error on E_ν
- Other systematics evaluated: neutrino flux, neutrino interaction models, absolute and relative calibration, oscillation parameter uncertainty





Far Detector ν_μ Candidates



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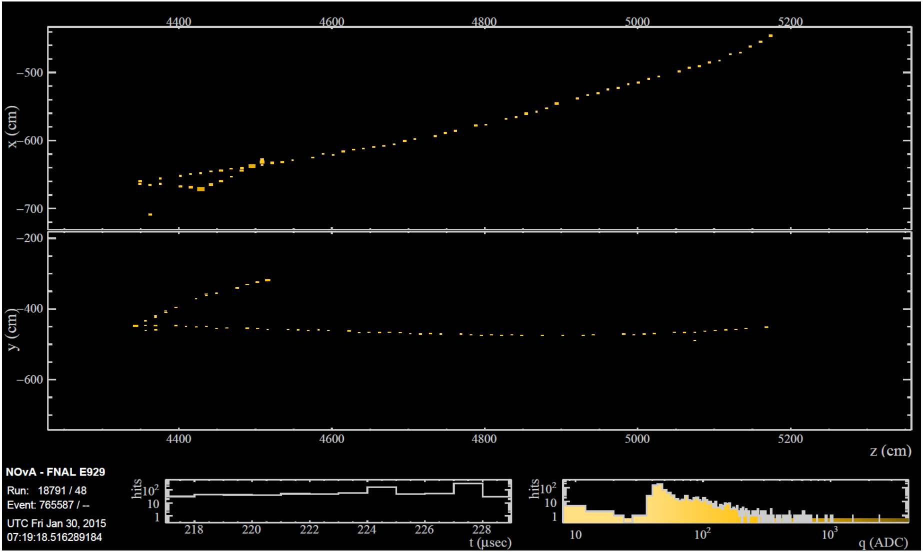
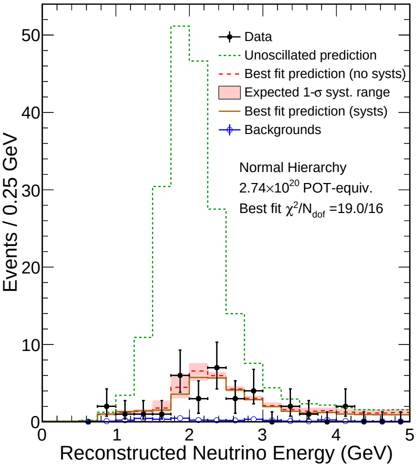
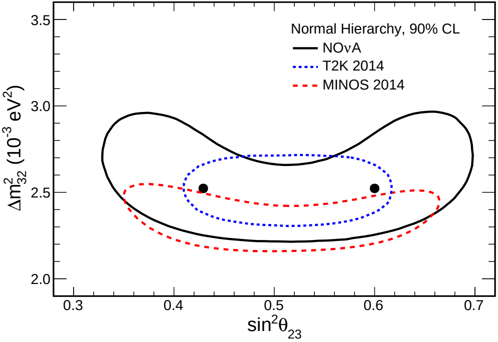


Disappearance Result



- Expected 201 events in the absence of oscillations (with 2 beam neutrino background and 1.4 cosmics)
- Observed 33 events
- Clear observation of ν_μ disappearance!

Disappearance Result



- Normal Hierarchy
  - $\Delta m^2_{32} = (2.52^{+0.20}_{-0.18}) \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23}$ in the 68% CL range $[0.38, 0.65]$. Best fits 0.43 and 0.60
- Inverted Hierarchy
  - $\Delta m^2_{32} = (-2.56 \pm 0.19) \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23}$ in the 68% CL range $[0.37, 0.64]$. Best fits 0.44 and 0.59
- Recently published: Phys. Rev. D 93, 051104(R)

ν_e Appearance Analysis

Identifying Electron Neutrinos: LID

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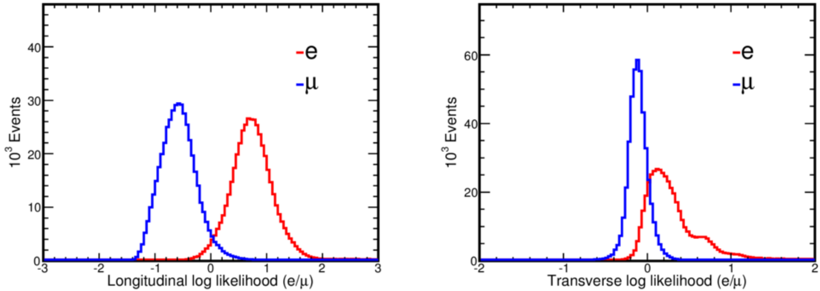
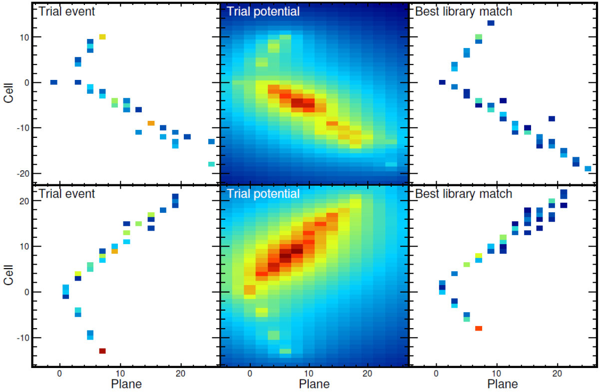
- Likelihood-based ν_e identification (LID)
- Checks if leading shower is electron-like
- Uses energy deposited per path-length (dE/dx) in a plane to identify particles
- dE/dx measured in longitudinal and transverse directions



Identifying Electron Neutrinos: LEM

Spatial pattern of energy deposition matched against library of 10^8 simulated events

Properties of best-matches are input to a decision tree



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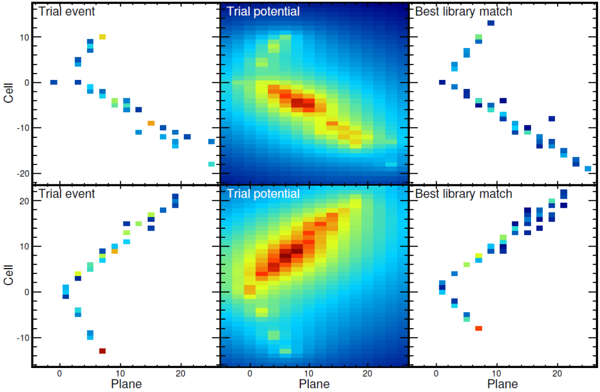
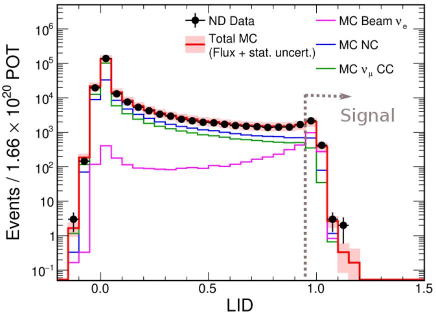


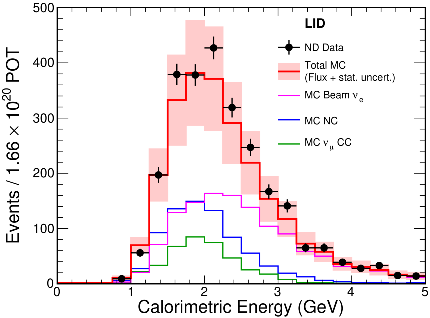
LID and LEM have nearly identical performance.

Signal efficiency wrt preselection is 35%, with 62% overlap in signal between the two IDs

Primary PID: the more traditional LID

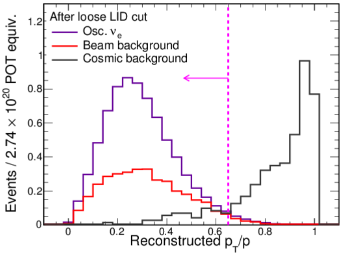
⁎ LID and neutrino energy distributions in ND data and simulation

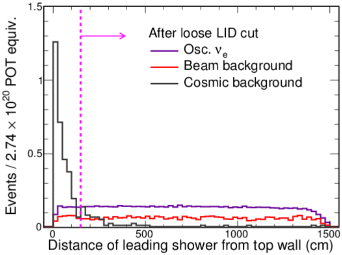


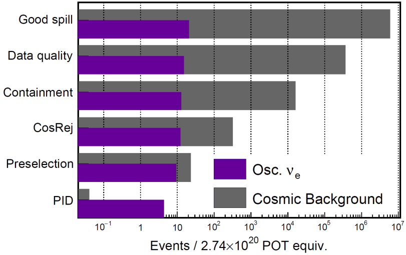


7% excess in ν_e selected ND data, extrapolated to FD background prediction

Cosmic Rejection







Simple cuts reject downward directed events and those too close to detector edges

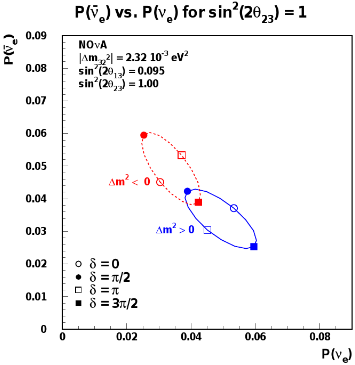
Rejection achieved at 1 part in **10^8**
Expected cosmic background is **0.06** event!

Final FD Prediction

	Signal	Syst	Bg	Syst	Tot Events
IH, $\delta = \pi/2, \theta_{23} = \pi/4$	2.48	0.41	1.01	0.11	3.49
NH, $\delta = 3\pi/2, \theta_{23} = \pi/4$	6.25	1.01	0.99	0.11	7.24

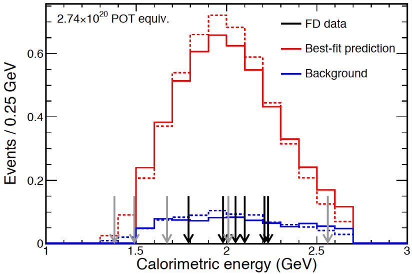
Cut and count analysis

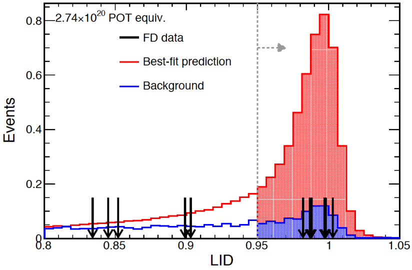
PID cut optimized to maximize $s/\sqrt{b}$



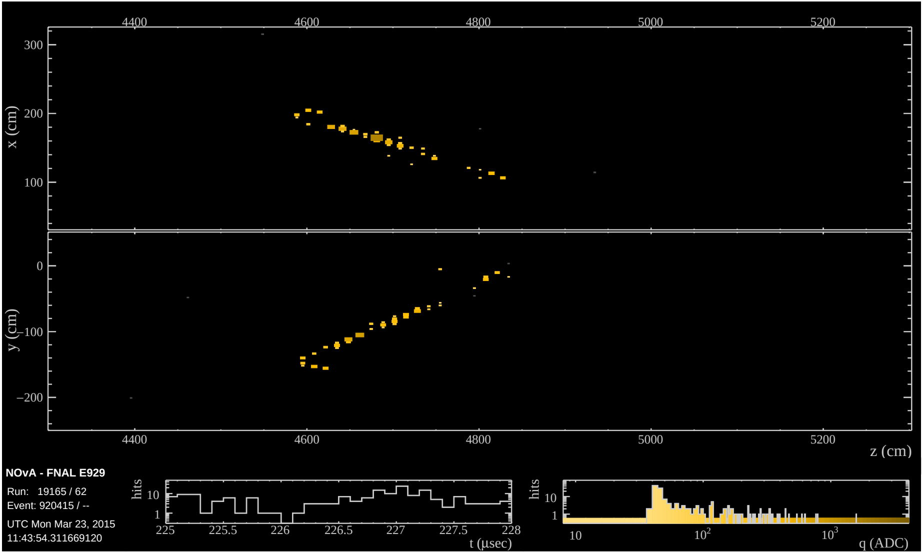
Result

- Observation in FD
  - LID: 6 ν_e candidates, significance of ν_e appearance: 3.3 σ
  - LEM: 11 ν_e candidates, significance of ν_e appearance: 5.3 σ
- None appear to be obvious cosmic rays or neutrino background
- 7.8% probability of observing a less likely LID-LEM overlap

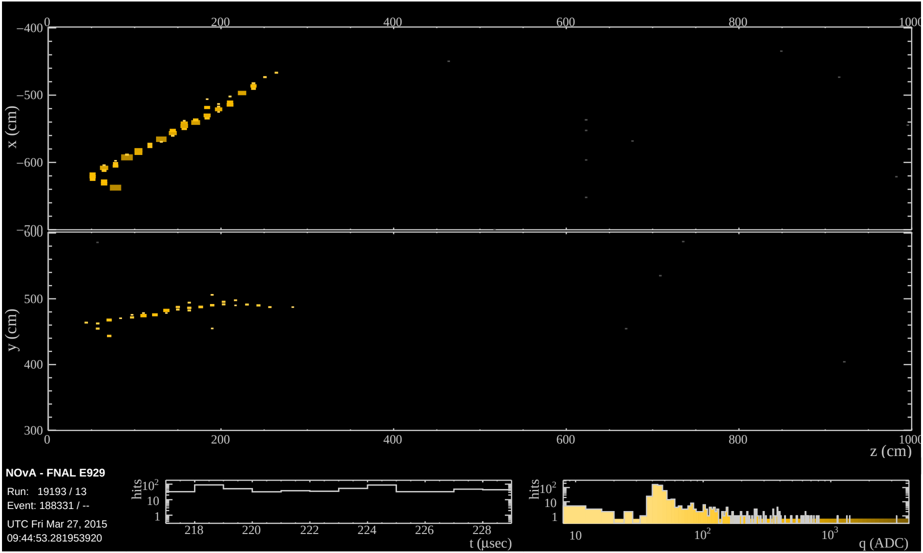


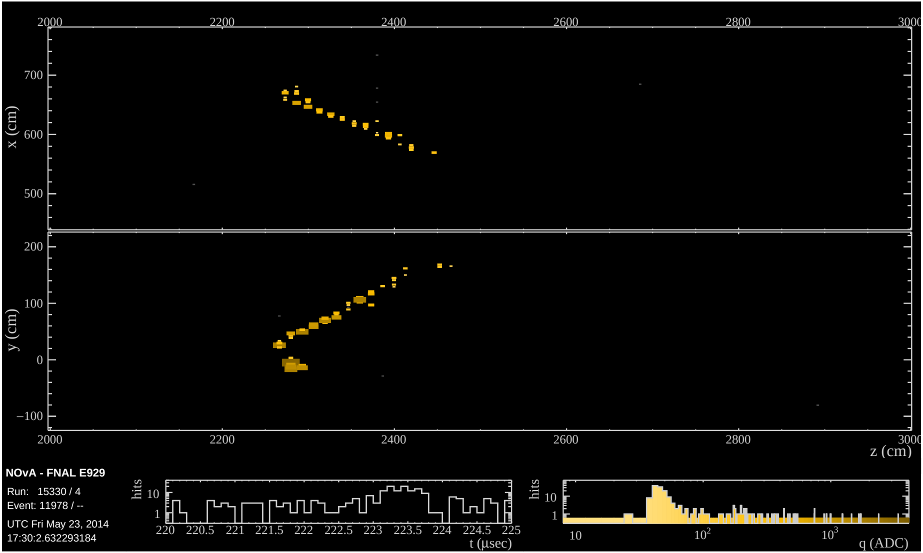


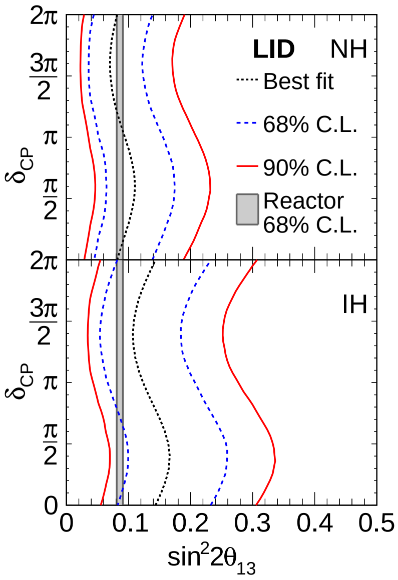
ν_e Signal Events



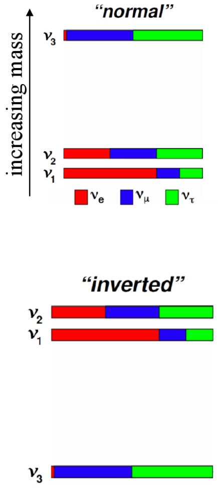
ν_e Signal Events



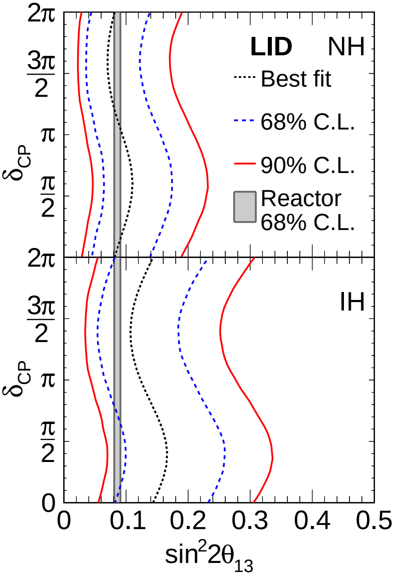

NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
x (cm)
y (cm)
z (cm)
hits
t (µsec)
q (ADC)



LID NH
Best fit
68% C.L.
90% C.L.
Reactor 68% C.L.
IH
δ_{CP}
2π
$\frac{3\pi}{2}$
π
$\frac{\pi}{2}$
0
0.1
0.2
0.3
0.4
0.5
$\sin^2 2\theta_{13}$

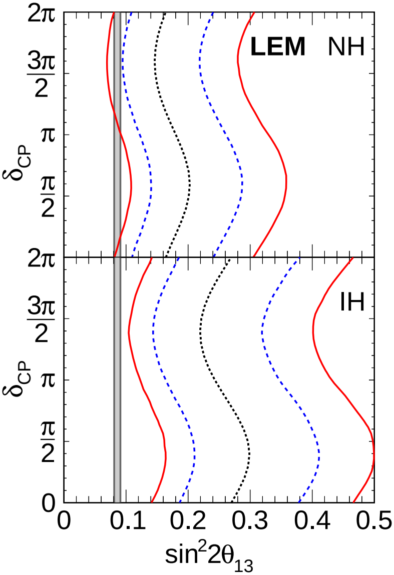


increasing mass
"normal"
ν_3
ν_2
ν_1
ν_e ν_μ ν_τ
"inverted"
ν_2
ν_1
ν_3



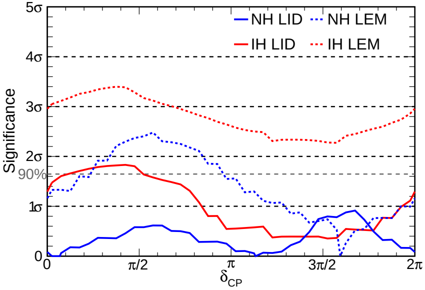
- Feldman-Cousins procedure
- Solar oscillation parameters varied
- Δm^2_{32} varied according to NOvA ν_μ disappearance result
- $\sin^2\theta_{23} = 0.5$

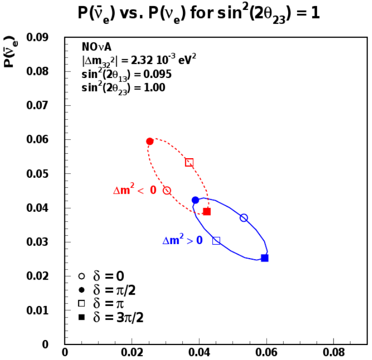
θ_{13} vs CP Violation



- Feldman-Cousins procedure
- Solar oscillation parameters varied
- Δm^2_{32} varied according to NOvA ν_μ disappearance result
- $\sin^2\theta_{23} = 0.5$
- LEM observation has some tension with reactor results

- Additional reactor constraint of $\sin^2 2\theta_{13} = 0.086$
- Inverted hierarchy is disfavoured at 90% CL in the range $0.1\pi < \delta_{CP} < 0.5\pi$
- With secondary selector, LEM, all values of δ_{CP} are disfavoured at 90% for inverted hierarchy
- Paper published in PRL (Phys. Rev. Lett. 116, 151806)





Conclusions

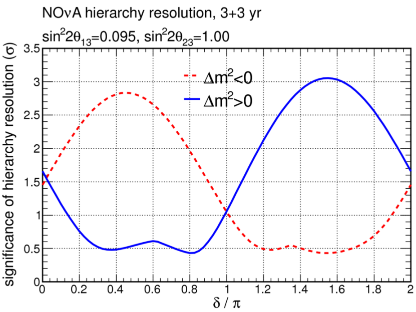
- First oscillation results from NOvA with 8% planned exposure already competitive
- ν_μ disappearance results consistent with MINOS and T2K
- ν_e appearance result consistent with reactor neutrinos, disfavours $0.1\pi < \delta_{CP} < 0.5\pi$ for Inverted Hierarchy at 90% CL

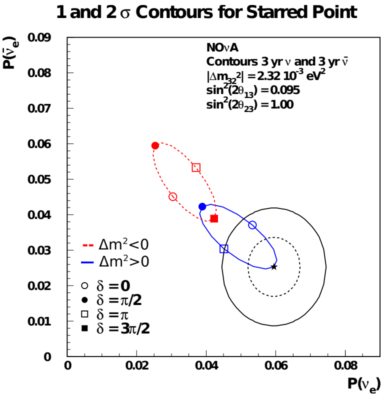
- Later this year: new oscillation results with more than 2x the data
- Plus: new analysis techniques being developed
- Disappearance result with reduced systematics
- Sterile neutrino, many x-sec and other exotic physics analyses in progress too!

- Thank you!

Back Up

NOvA Sensitivity to Mass Hierarchy





* Mass hierarchy resolution at $\sim 3\sigma$ in the best case

Normal Hierarchy
Inverted Hierarchy

NOvA Sensitivity to CP Violation

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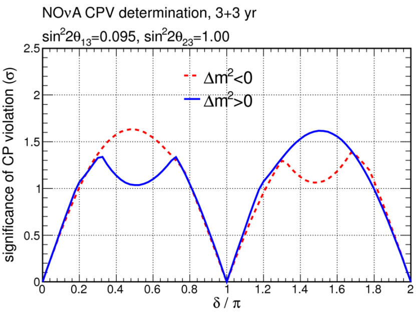
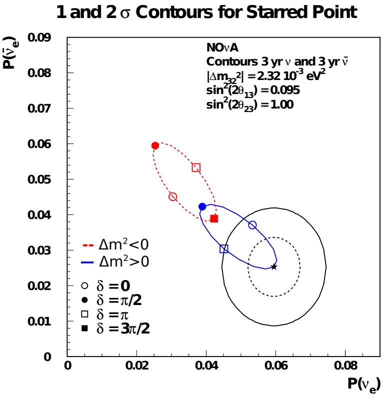
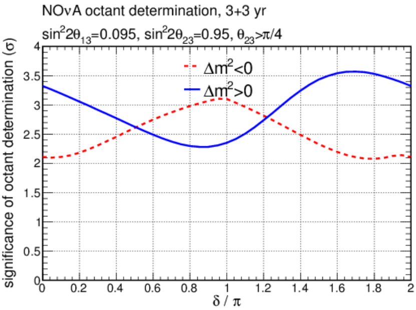


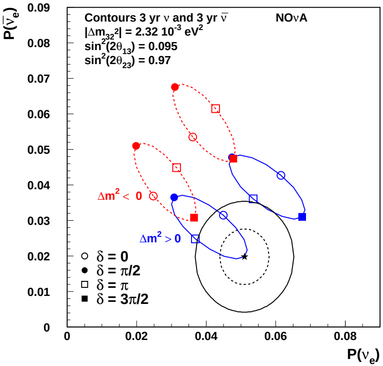


- CP violation phase determination at $> 1.5\sigma$ in the best case

Normal Hierarchy
Inverted Hierarchy

NOvA Sensitivity to θ_{23} Octant





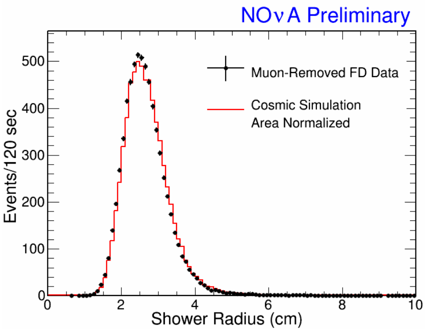
* θ_{23} octant determination at $\sim 3\sigma$

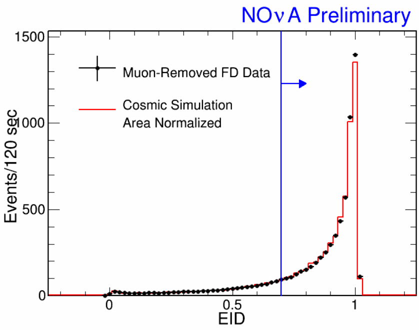
Normal Hierarchy

Inverted Hierarchy

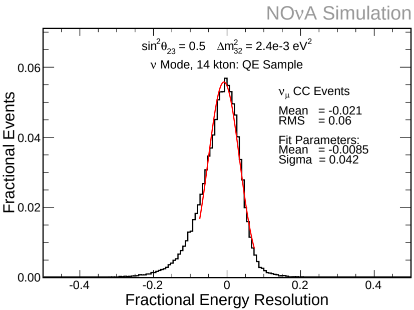
Fermilab

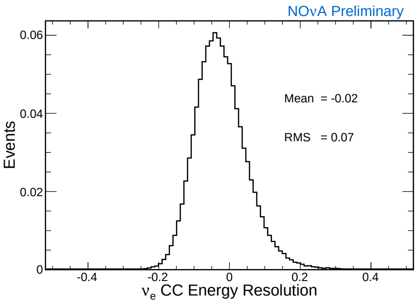
- EM shower validation in FD
- Isolate brem-showers in cosmic-ray muons by muon-removal



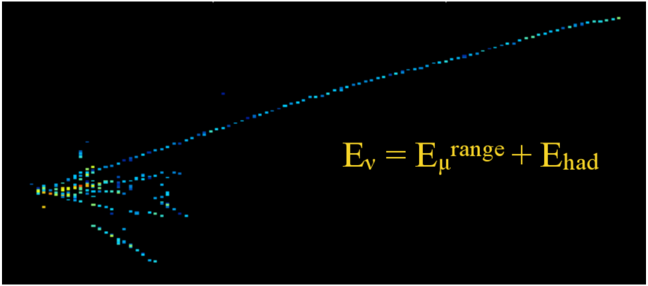


* Reconstructed neutrino energy in FD





- Muon energy reconstructed from range
- Hadronic system: $\sum_{cell} E_{visible} \implies E_{had}$
- Neutrino energy is the sum of the two
- Energy resolution $\sim$ 7% at beam peak



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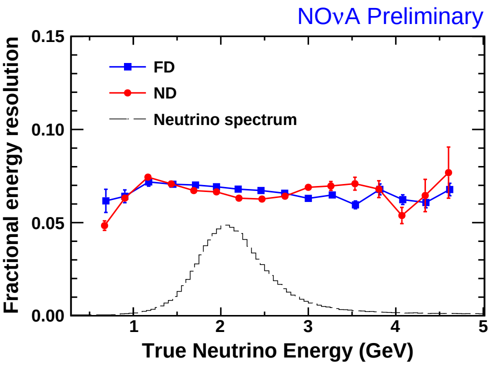
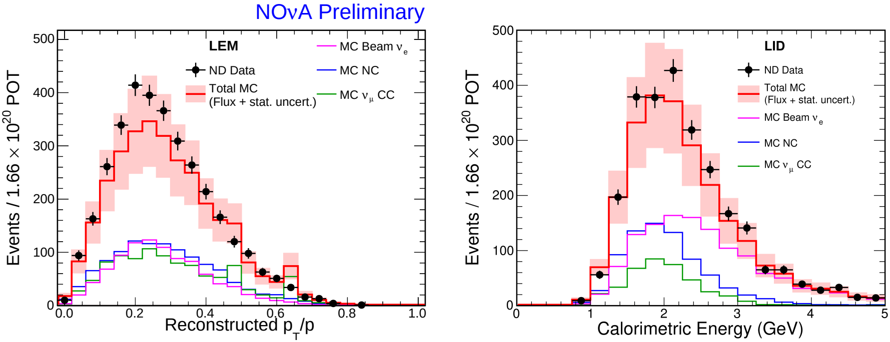
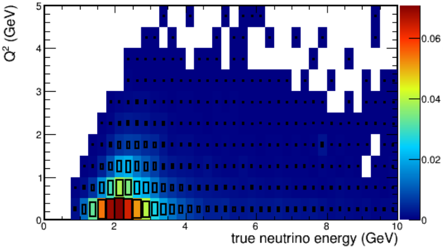


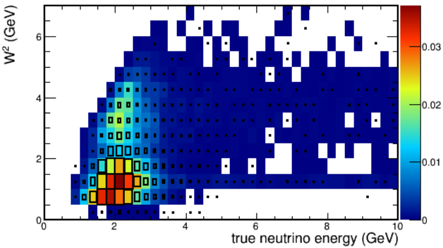
LID, LEM Performance in ND

- Data and simulation agree well for LID and LEM selected events in the ND
- See a 7% excess in ND data over MC



Extrapolation can work..





LID selected backgrounds are similar in ND and FD

ν_e Systematics