The Status of NOvA

Gavin S. Davies

Indiana University

for the NOvA Collaboration

Lake Louise Winter Institute
Fairmont Chateau Lake Louise
Alberta, Canada
February 15 – 21, 2015

NOvA Physics Goals

- Observe $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Measure θ_{13} via ν_e appearance
  - Determine the neutrino mass hierarchy
  - Search for neutrino CP violation
  - Determine the θ_{23} octant
- Observe $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
  - Precision measurements of $|\Delta m^2_{32}|$, θ_{23}
  - Over-constrain the atmospheric sector
- Broad Exotic Physics programme
  - Neutrino cross-sections at the Near Detector
  - Sterile Neutrinos
  - Supernova neutrinos (SNEWS) and Monopoles
  - Non-Standard neutrino Interactions (NSI)

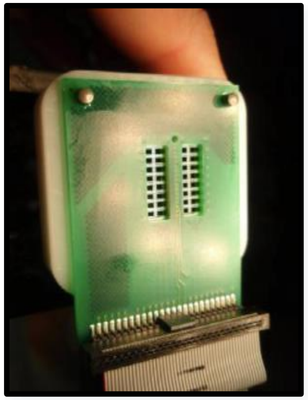
NOvA Experiment

- **N**uMI **O**ff-axis ν_e **A**ppearance experiment
- Over 200 scientists from 38 institutions and 7 countries

- 810 km baseline from Fermilab to Ash River, Minnesota
  - Long underground path to Far Detector leads to ~30% matter effects
- Two functionally identical detectors, optimised for ν_e identification
  - 14 kt liquid scintillator Far Detector on the surface at Ash River (3m of overburden)
  - A ~300 ton Near Detector (~100m underground) at Fermilab, 1 km from source
- Detectors placed 14 mrad off the NuMI beam axis

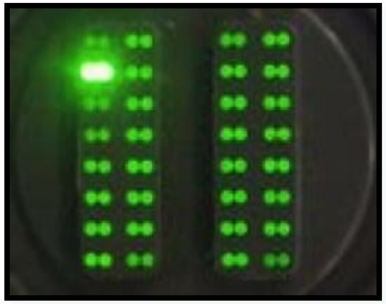
The NOvA Detectors

- 14-kton Far Detector (~3x MINOS)
  - 64% liquid scintillator by mass
- 0.3 kton Near Detector
  - 18,000 cells/channels.
- Each plane just 0.15 X_0. Great for e^- vs π^0 separation
  - Fine grained, low-Z, highly active, tracking calorimeters
  - WLS fibres looped in 4x6cm PVC cells

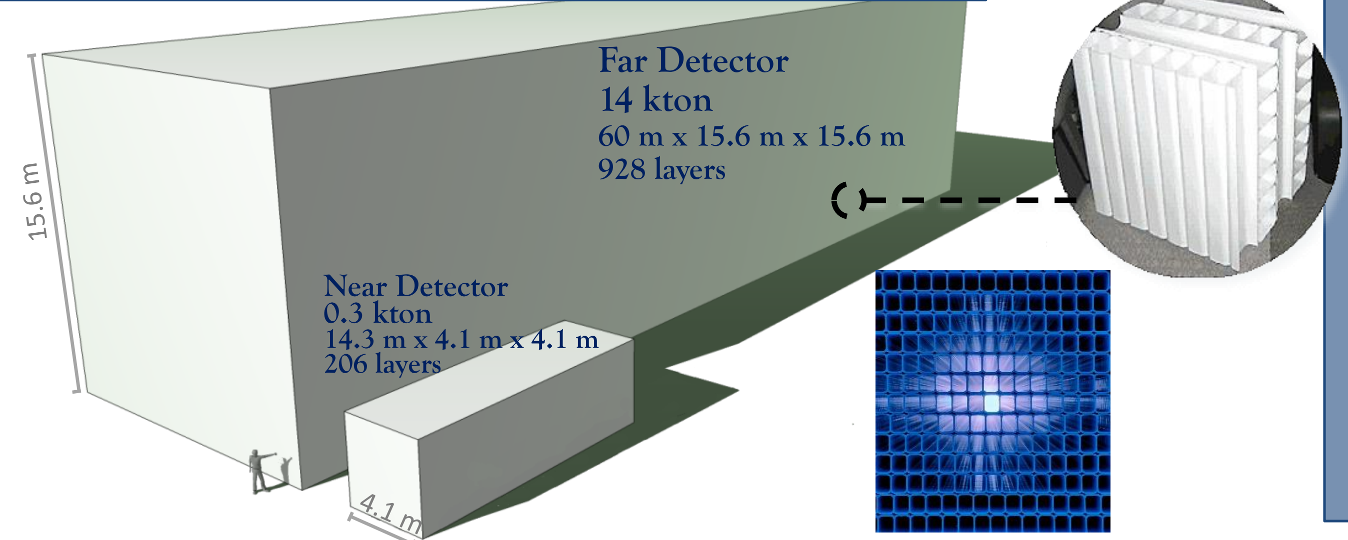


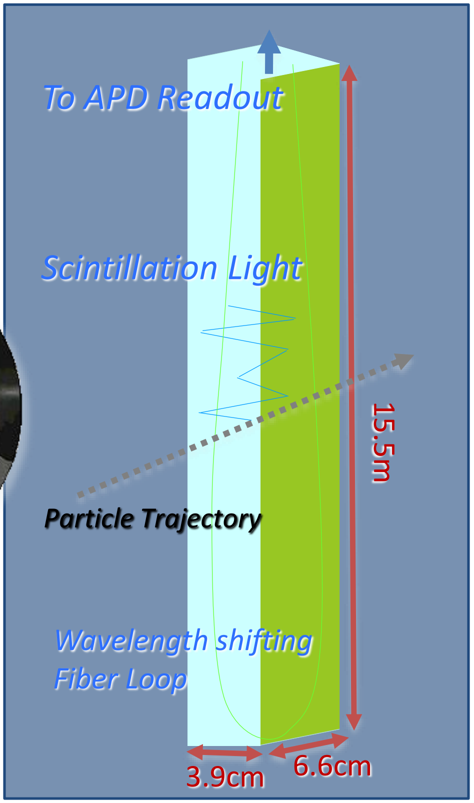
32-pixel APD

Fiber pairs from 32 cells



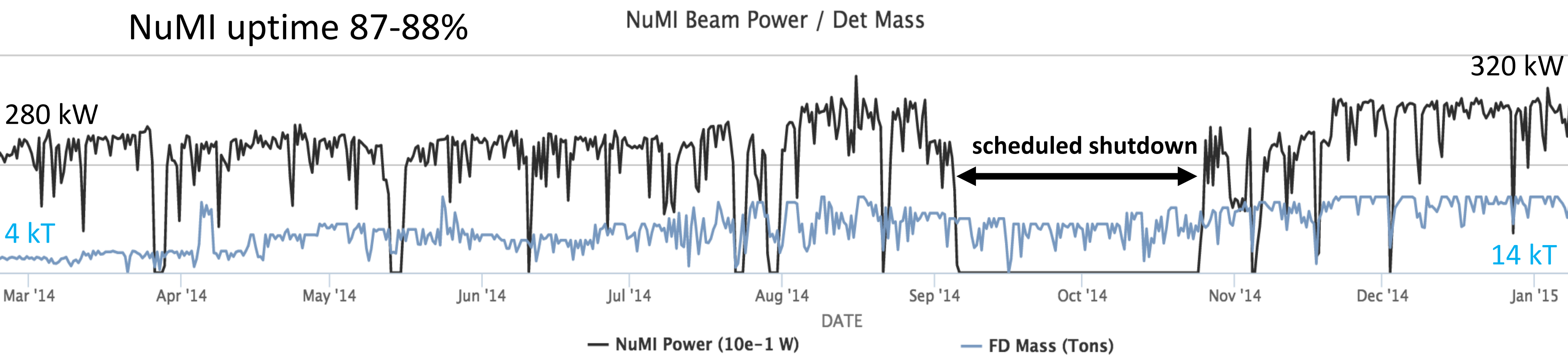
Extruded plastic (PVC) cells filled with 10.2 million litres of scintillator instrumented with λ-shifting fibre and APDs





2014 - 2015 NuMI beam delivery

NuMI uptime 87-88%



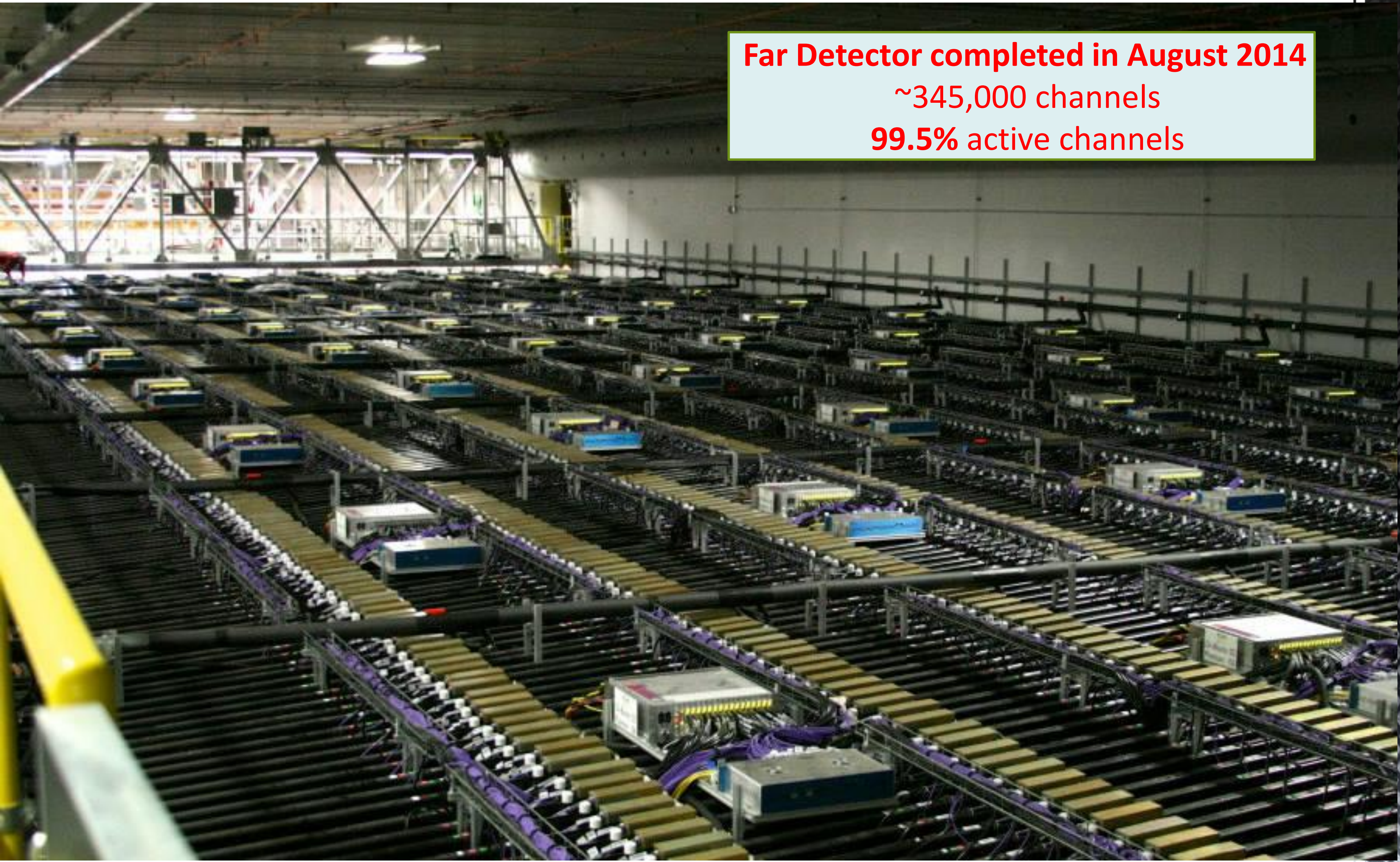
- First Analysis period: February 2014 to January 2015
  - Far Detector expanded from 4 to 14 kT during this period

- Detector instrumented in 64 plane segments (1 kT) allowing for physics data to be taken during construction

- Detector fully instrumented in August 2014,

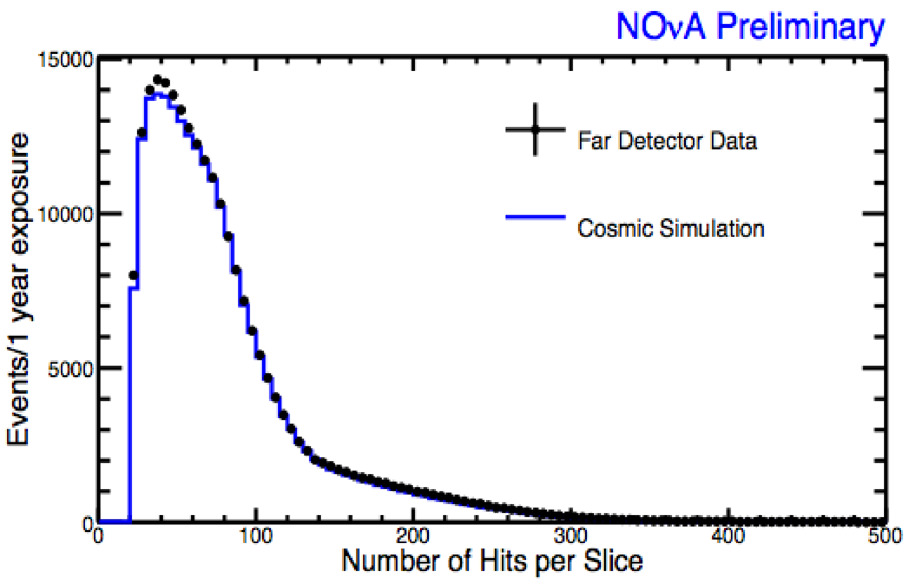
- Beam power increased from 280 to 320 KW
  - In total ~1.7 x 10^{20} POT collected (1/4 of a TDR year)

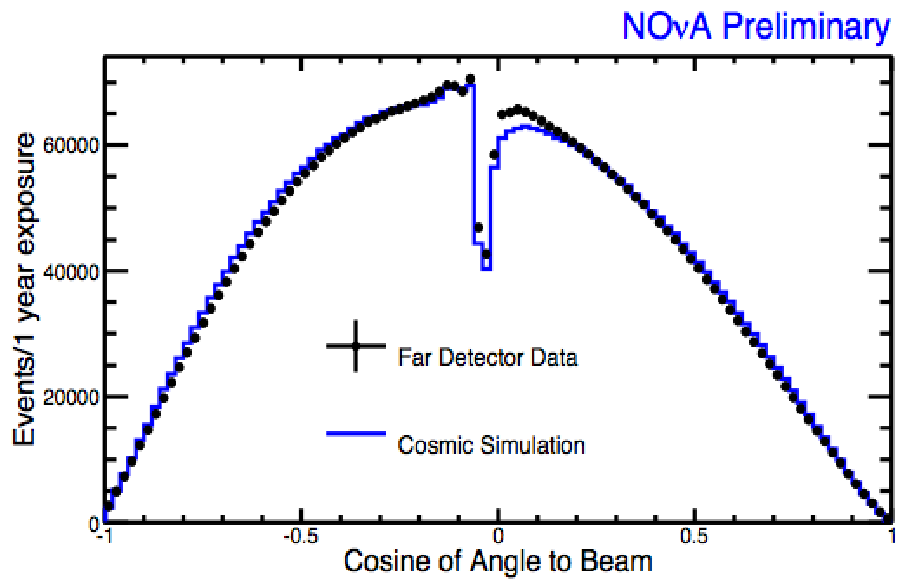
Far Detector



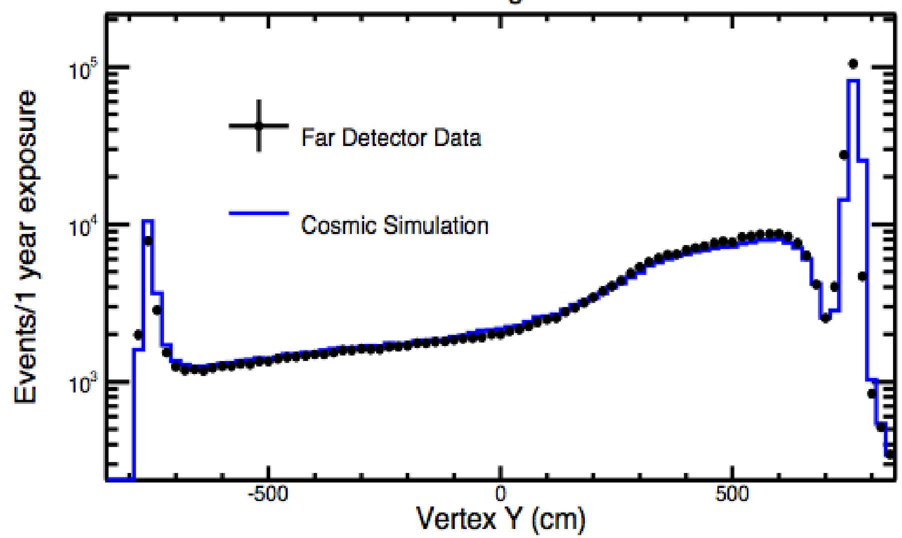
Far Detector completed in August 2014
~345,000 channels
99.5% active channels

Far Detector Cosmic Ray Data/Simulations





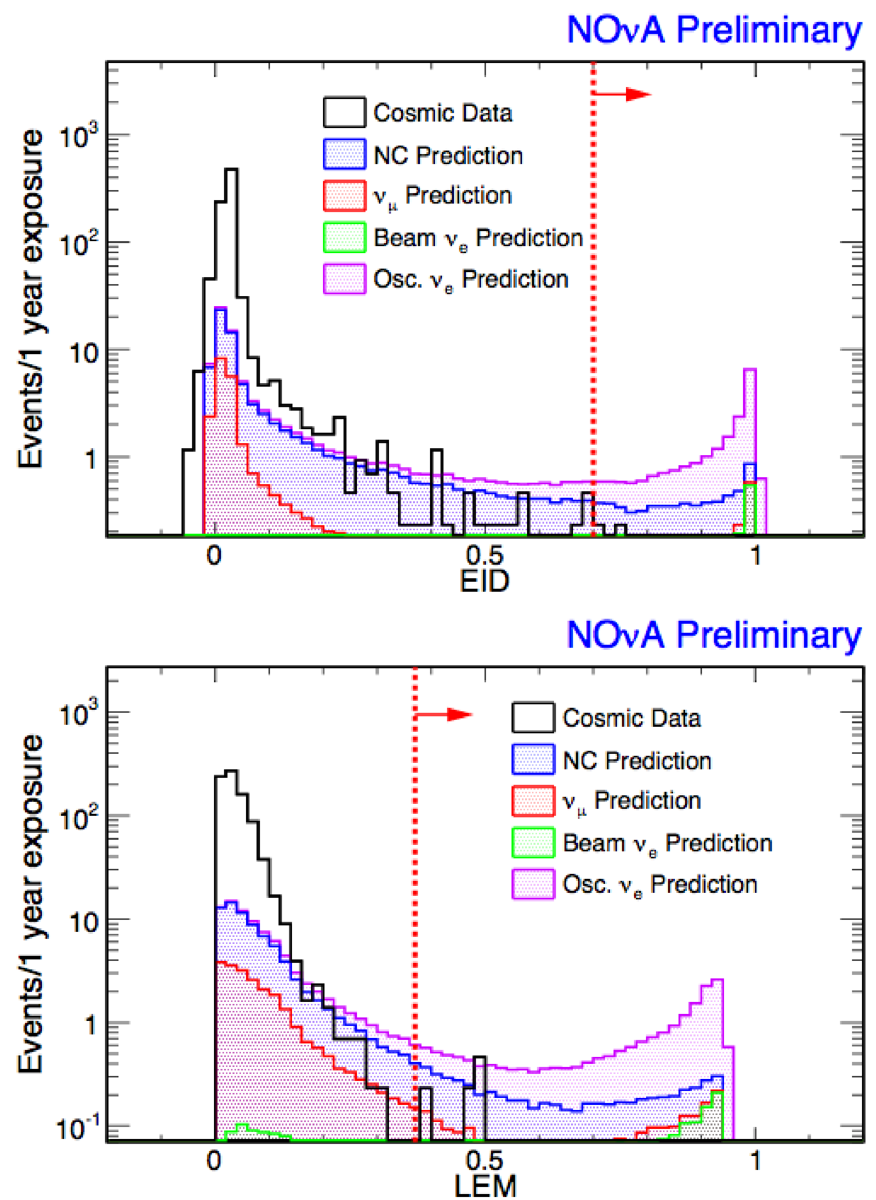
- Results from cosmic-ray fitter. Require 20 or more hits in event ("slice")
- Compare to CRY cosmic-ray simulation

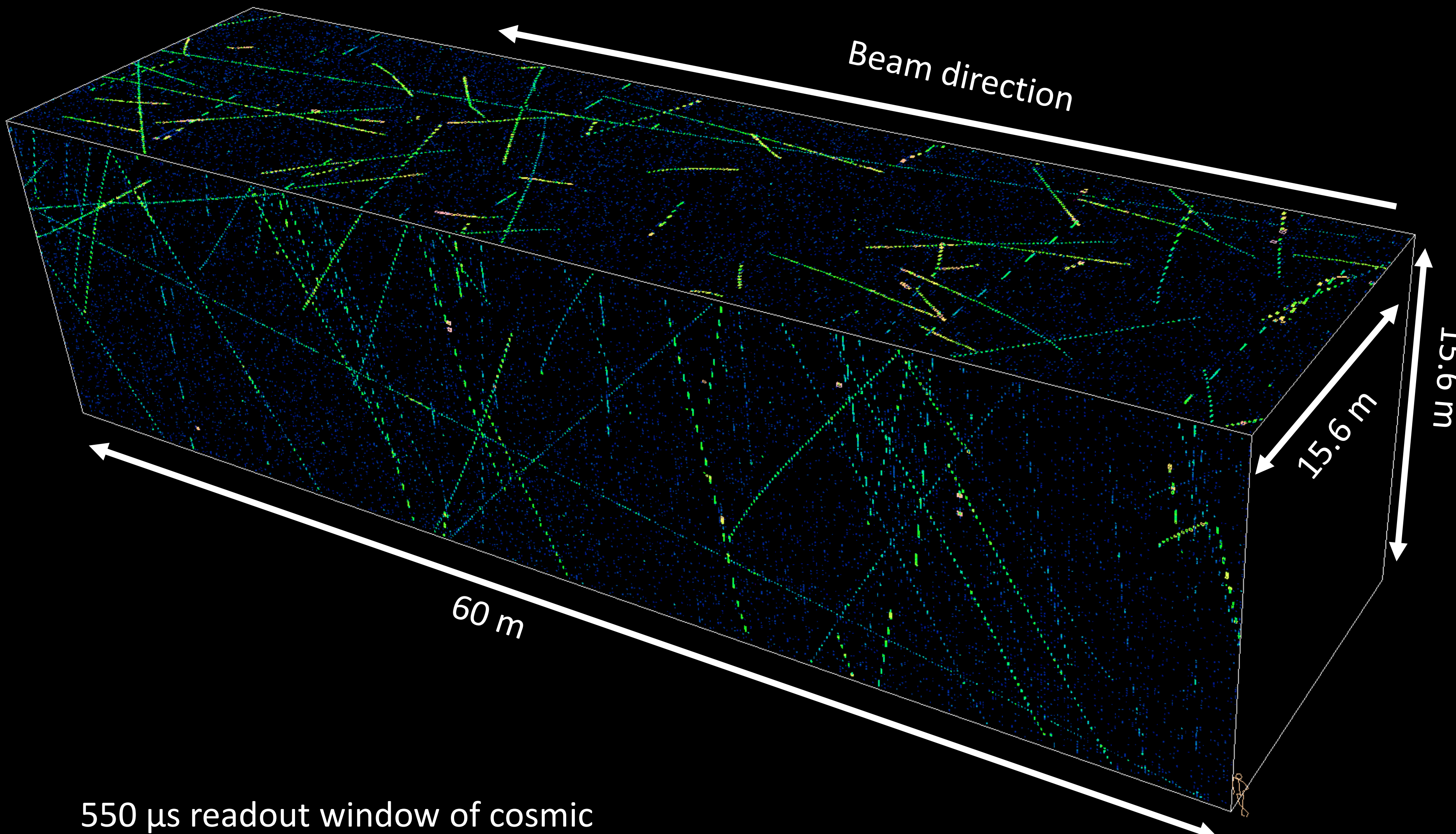


ν_e Event Selection

- Two methods:
  - "EID" (top) is a neural net evaluation of the shower longitudinal and transverse profile
  - "LEM" (bottom) matches the event topologies to large libraries of signal and background events.
- **Both achieve acceptable levels of rejection, with preselection, 40M:1 and 21M:1 against cosmic-rays recorded using the far detector**

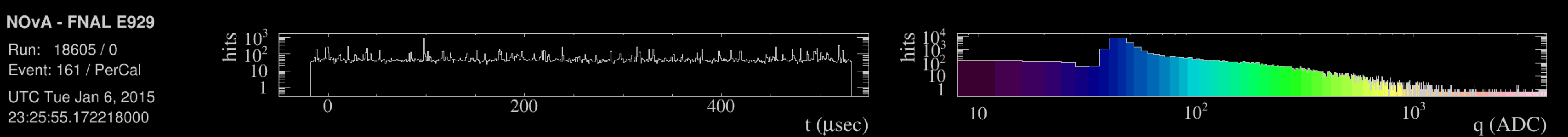
- Evaluation of performance on beam neutrinos awaits full analysis of near detector data



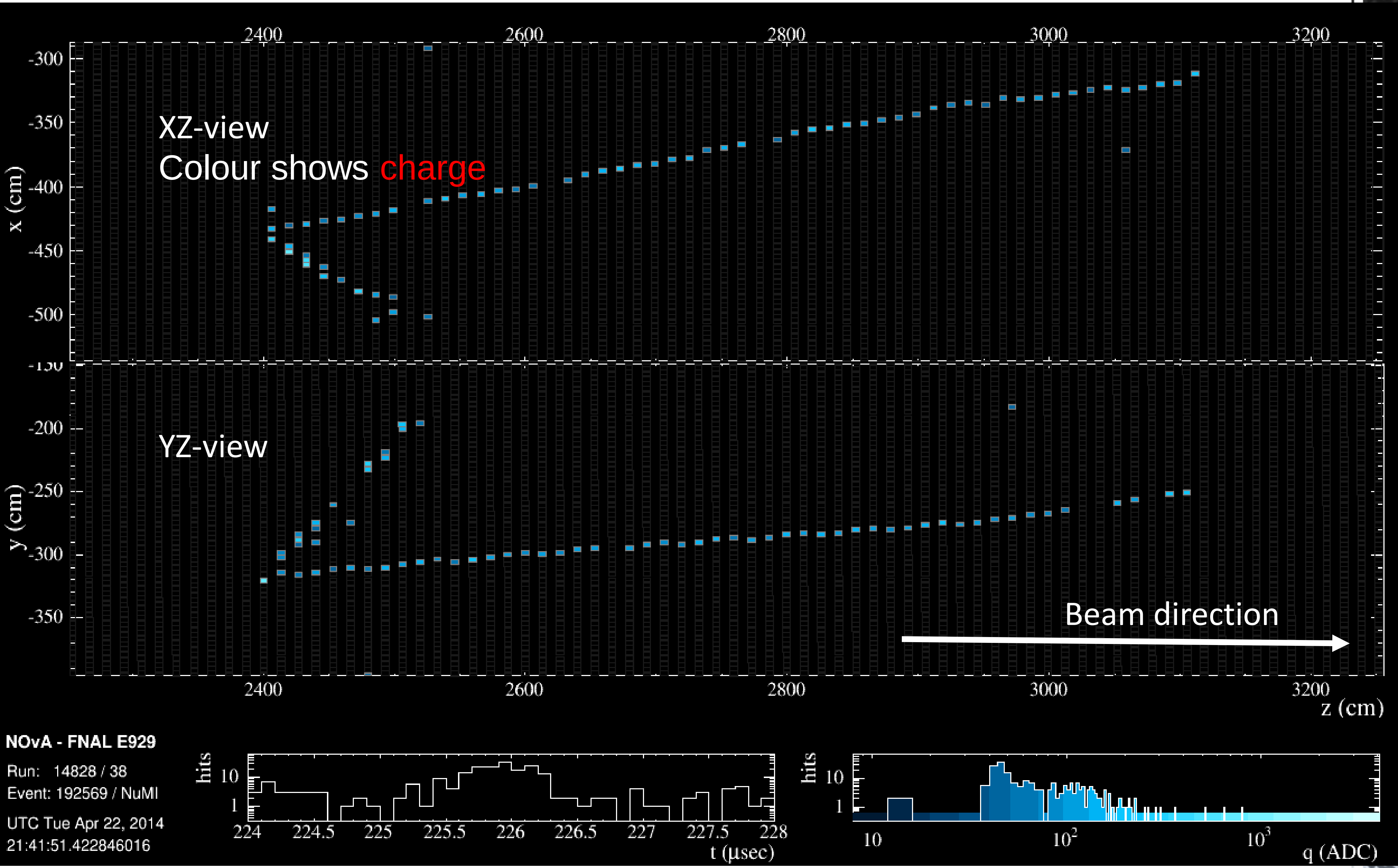


550 µs readout window of cosmic ray background at the Far Detector

Colour shows charge



ν_μ* Charged-Current Candidate (Far Detector)



*blind analysis, so no PID information

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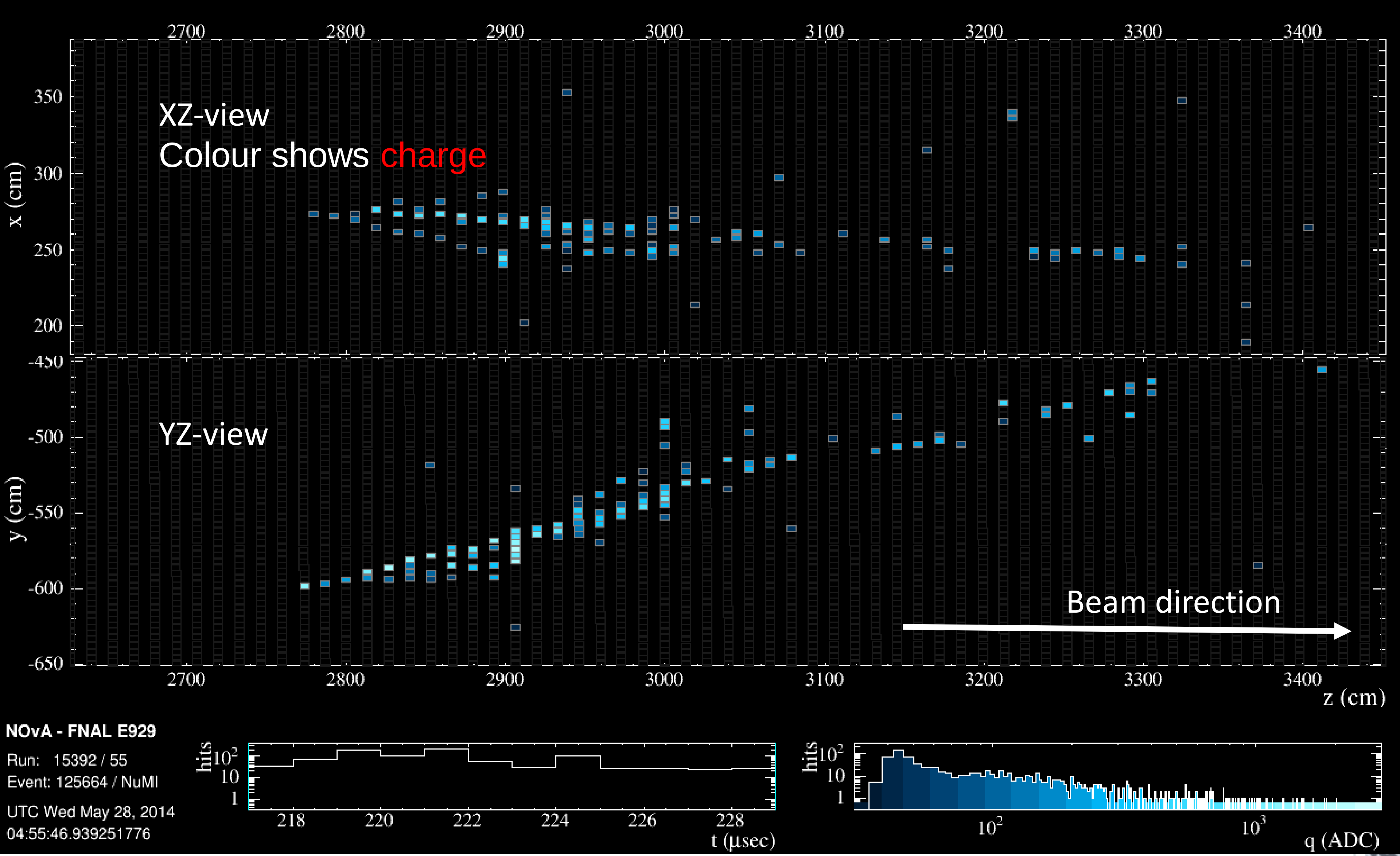
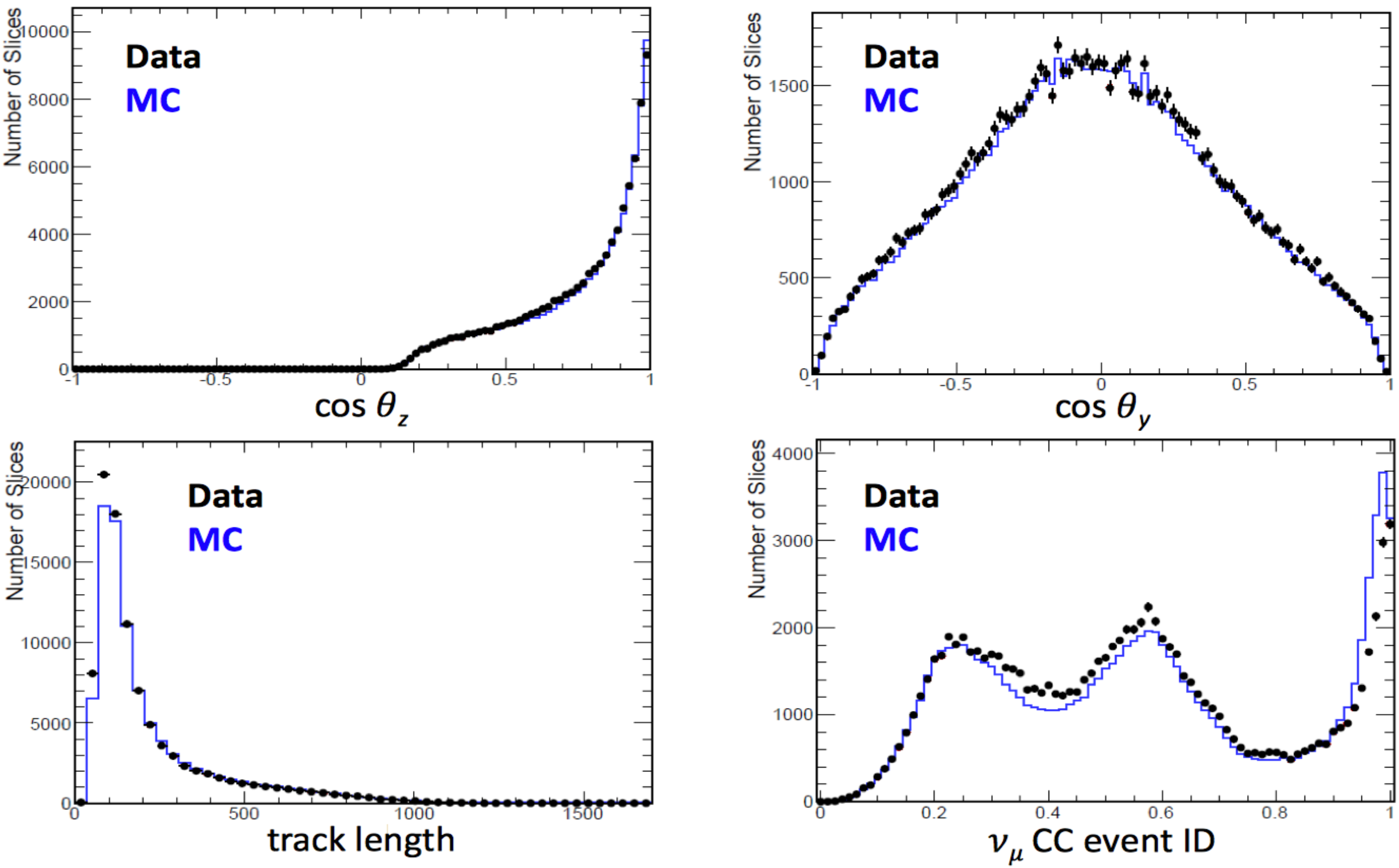


*blind analysis, so no PID information

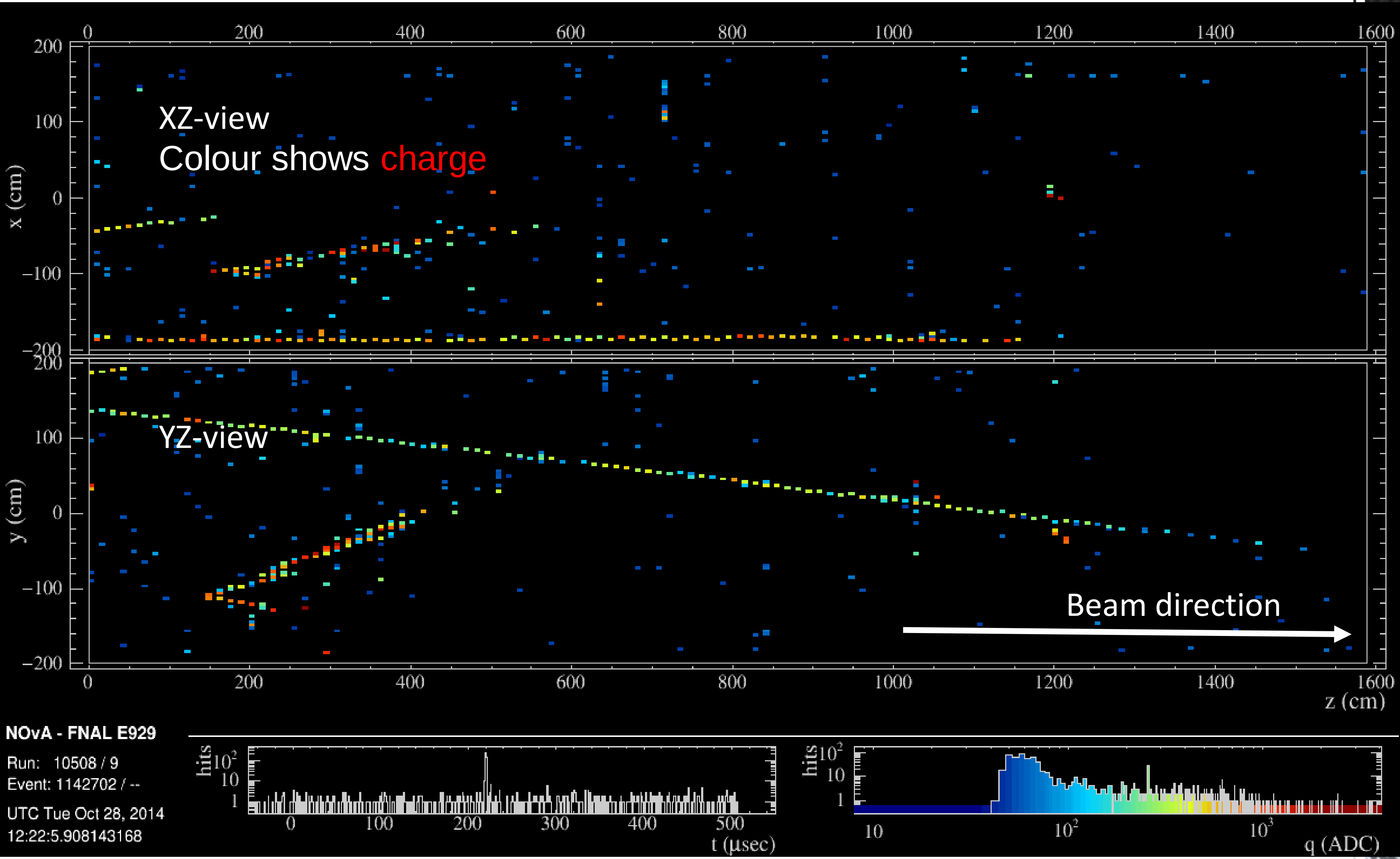
Near Detector

Near Detector completed in August 2014
99.4% active channels

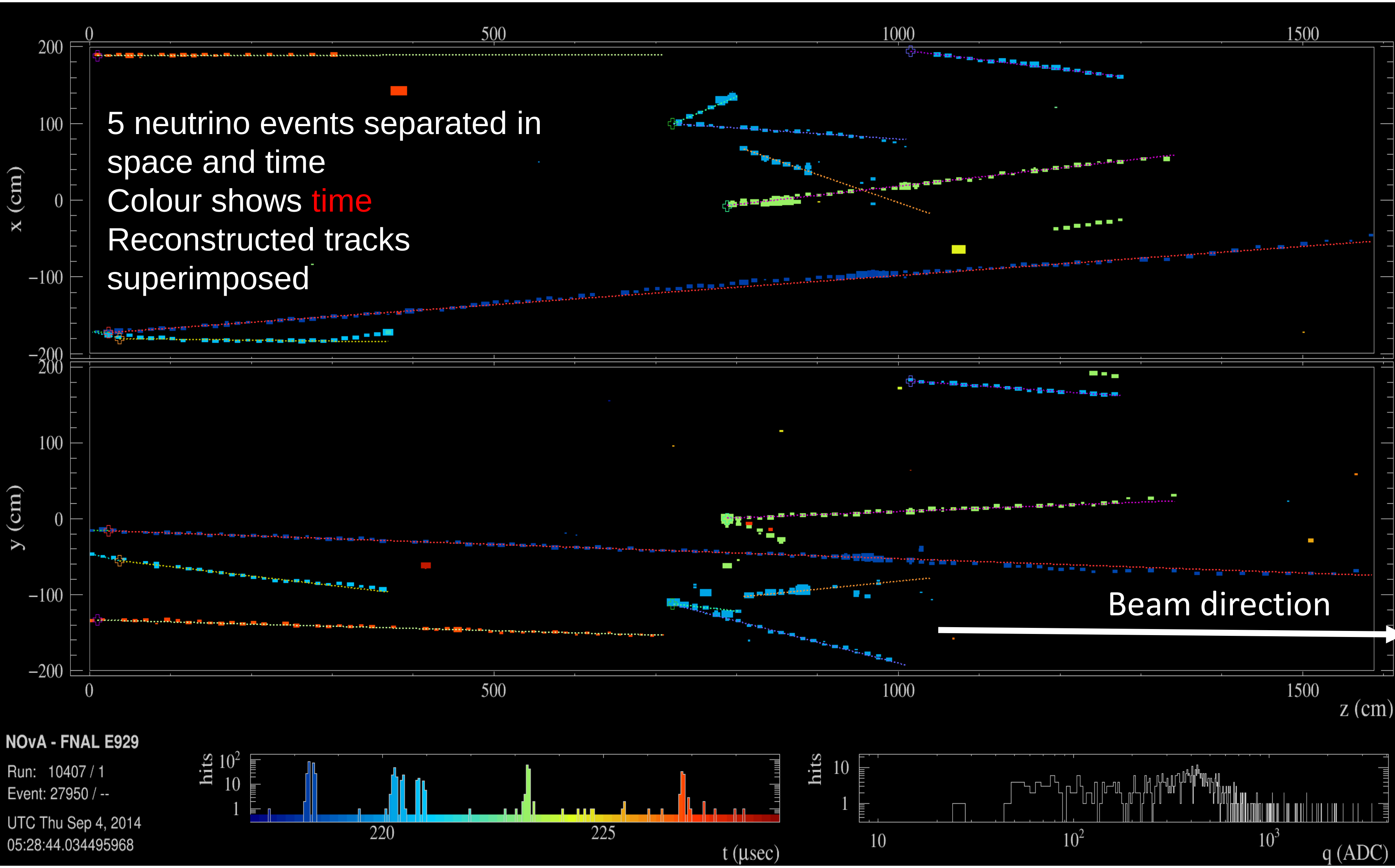
Near Detector Neutrino Distributions



550 µs Near Detector readout window



550 μs Near Detector beam spill

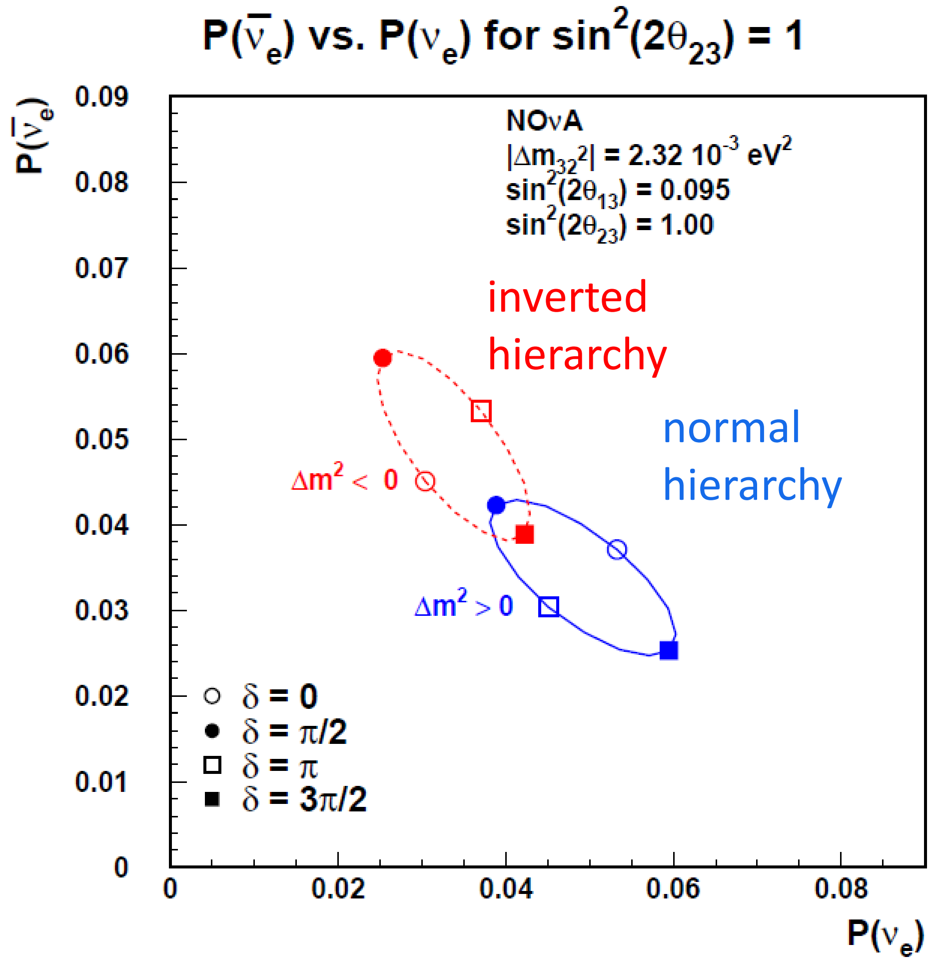


The ν_e Appearance Measurement

- To first order NOvA will measure:

  $P(\nu_\mu \rightarrow \nu_e)$ and

  $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ at 2 GeV



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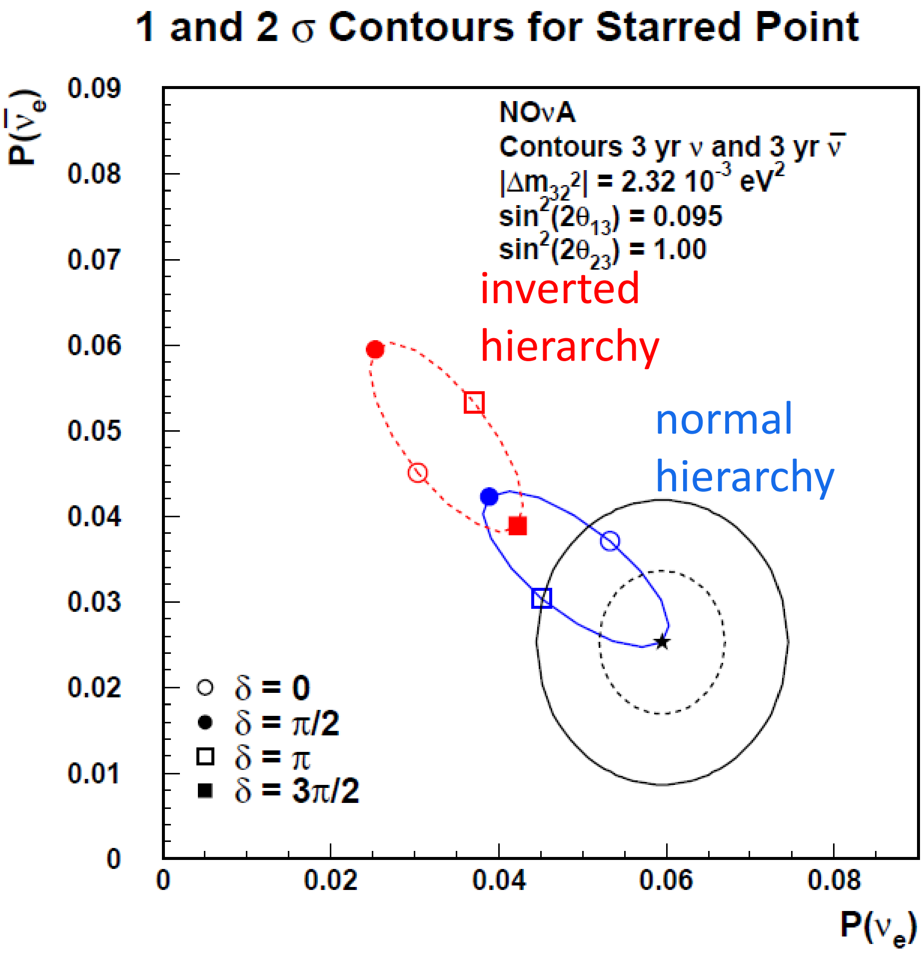
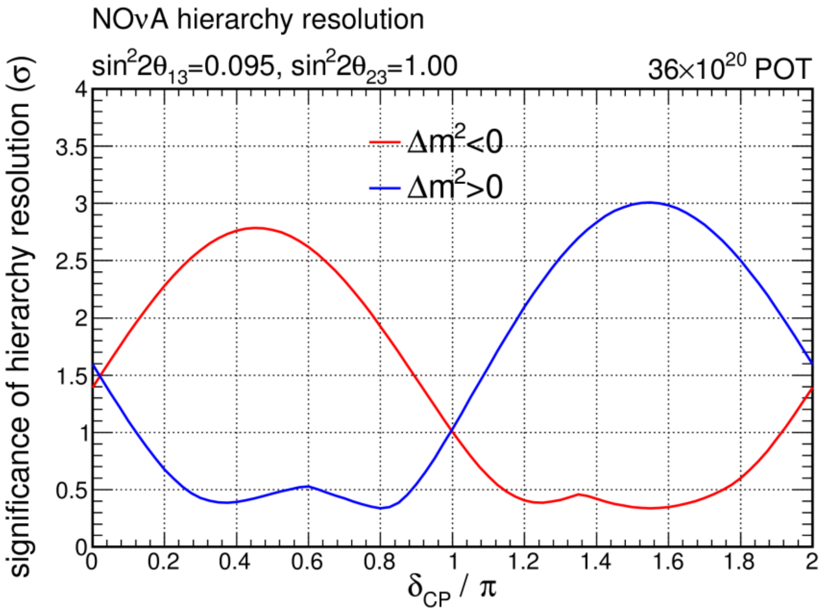
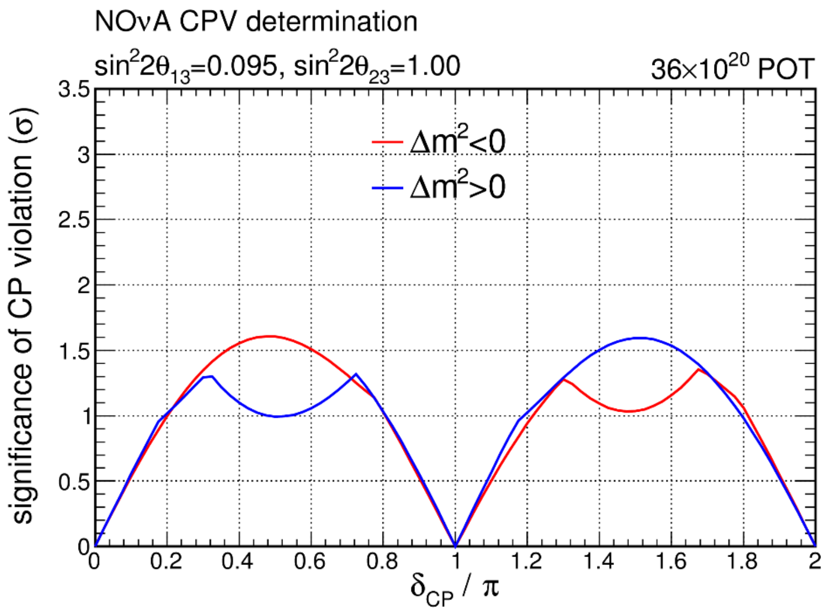
- Measurements give an allowed region in this space
- In this case all inverted hierarchy scenarios are excluded at > 2σ
- The measured probabilities depend on the mass hierarchy, θ_{23} octant, and δ_{cp}



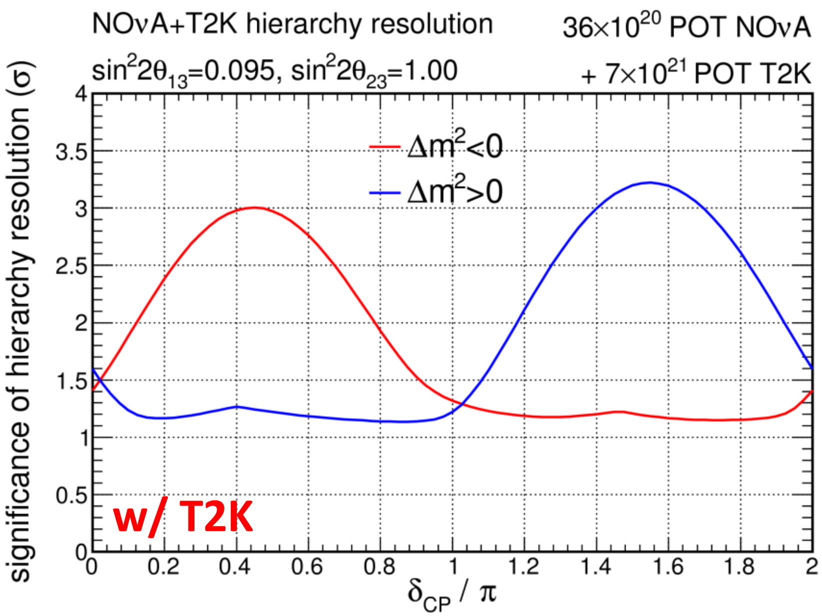
Mass Hierarchy/CPV resolution significance

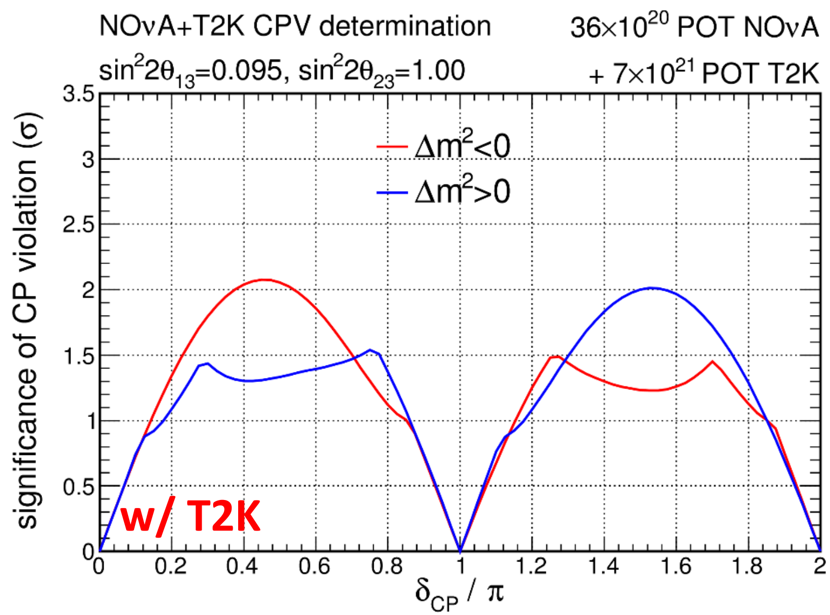




- Significance of mass hierarchy resolution using energy spectrum
- Energy fit provides improvement on the fully degenerate δ_{CP} values

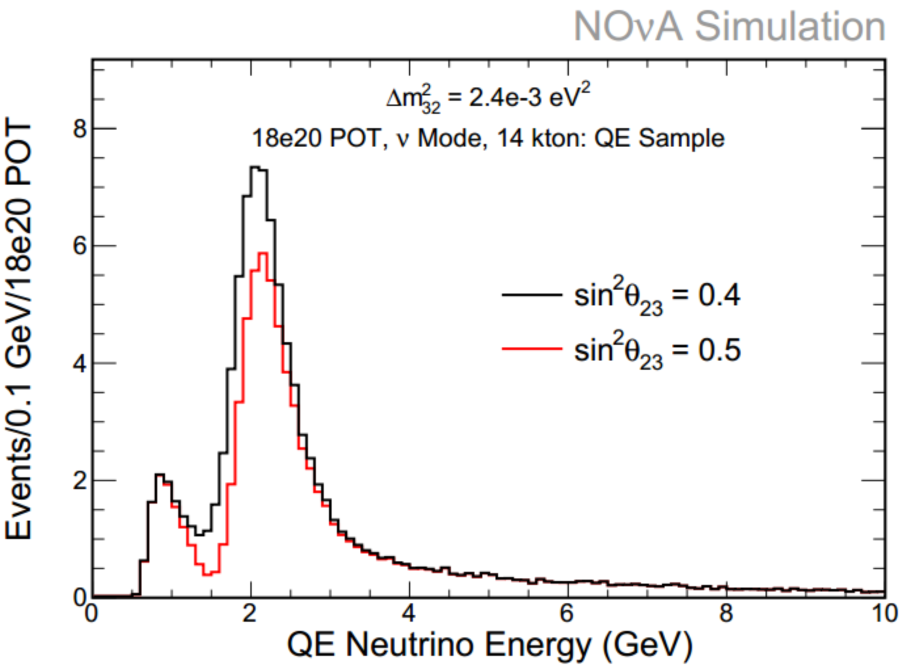
Mass Hierarchy/CPV resolution significance

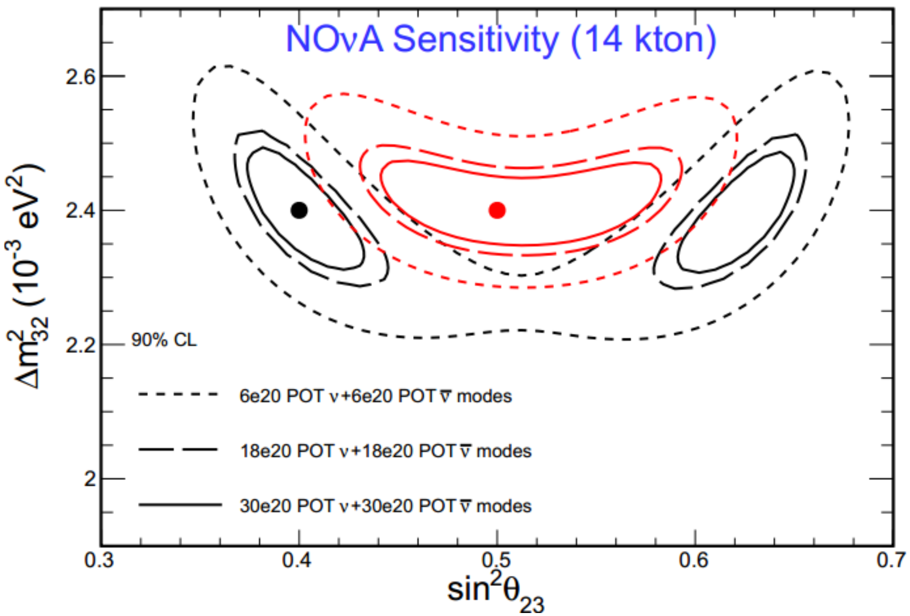




- Significance of mass hierarchy resolution using energy spectrum
- Energy fit provides improvement on the fully degenerate δ_{CP} values
- T2K baseline of 295 km; much smaller matter effects
  - But exactly the same kind of CP sensitivity

Full Reach of ν_μ Sensitivity



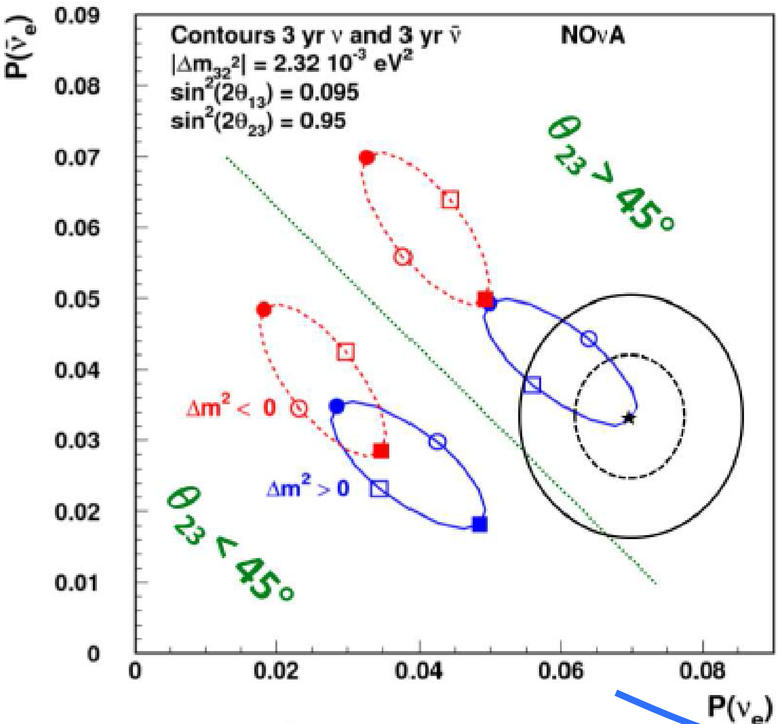


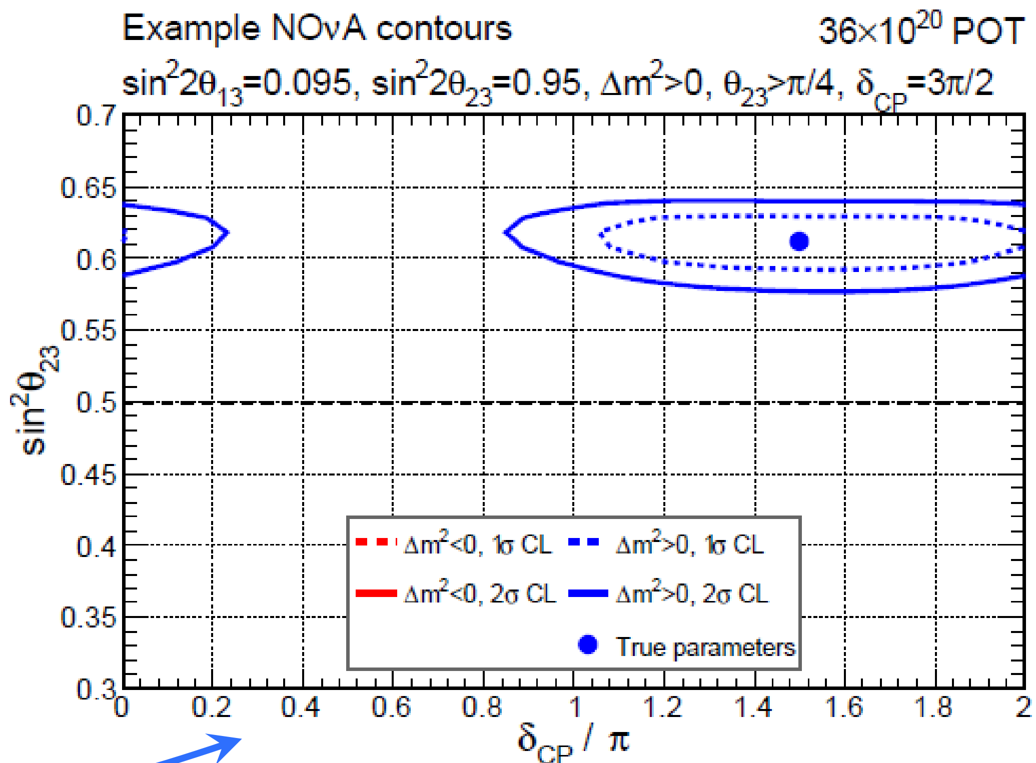
- Disappearance results are important to ν_e analysis and resolution of θ_{23} octant
- Fit quasi-elastic, non-QE and contained samples

- In 1+1 year can exclude maximal mixing at 90% if $\sin^2 2\theta_{23} = 0.95$
- In 3+3 years can achieve percent level uncertainty on atmospheric parameters

θ_{23} Octant Determination: $\nu_e + \nu_\mu$ analysis

- Expected contours for one example scenario using 3 years of data for each neutrino mode





Simultaneous hierarchy, CP phase, and θ_{23} octant information from NOvA

- In this favourable case we distinguish hierarchy and octant at > 2σ
- Rule out half of δ_{CP} space (2σ)

Summary

- Construction of NOvA experiment is complete; both Near and Far Detectors are recording high quality data with > 99% active channels

- Analysis of early data is underway with mature reconstruction and particle identification
  - Far Detector cosmic background rejection at the 40M:1 level achieved
  - Systematic errors are being finalised

- Best case hierarchy determination of 3σ, CPV discovery 1.5σ
- For sufficiently non-maximal θ_{23}, good chance to determine octant

- Beam power increased from 280 to 320 KW (Feb. 2014 – Jan. 2015)
  - In total ~1.7 x 10^{20} POT collected (1/4 of a TDR year)

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@NOvANuz

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Thank you for a great conference and stunning surroundings!

@NOvANuz

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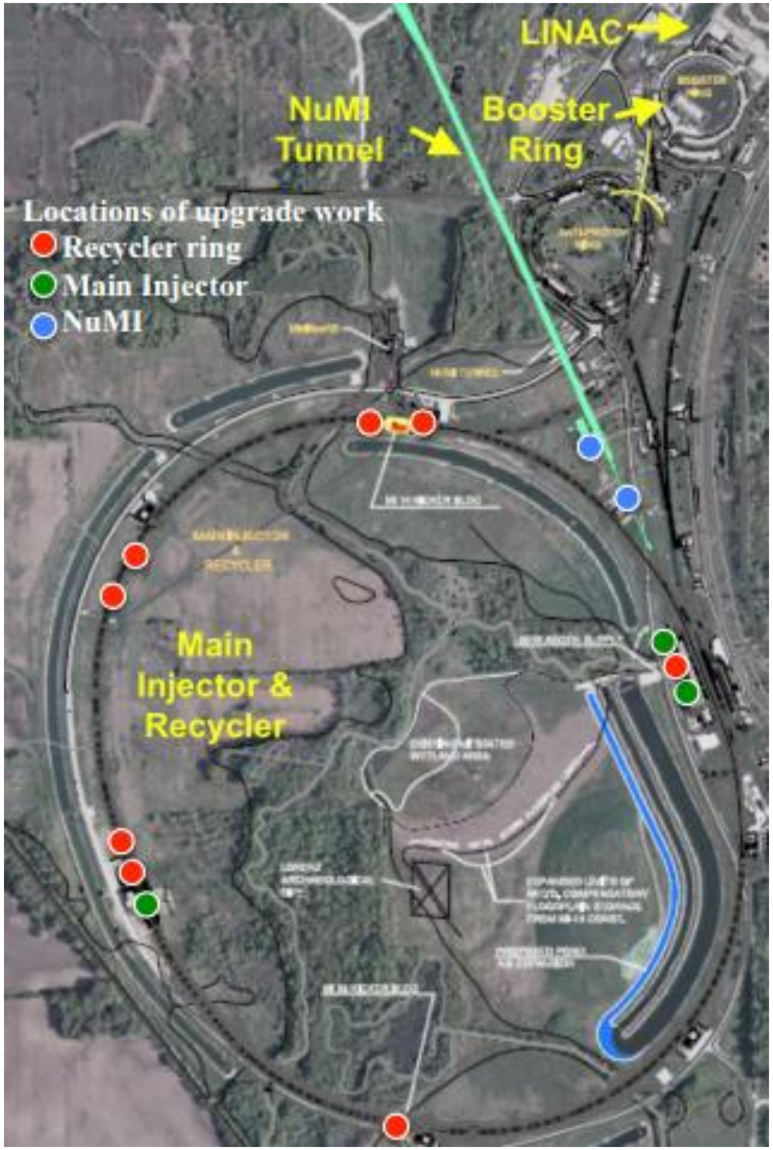
Backup

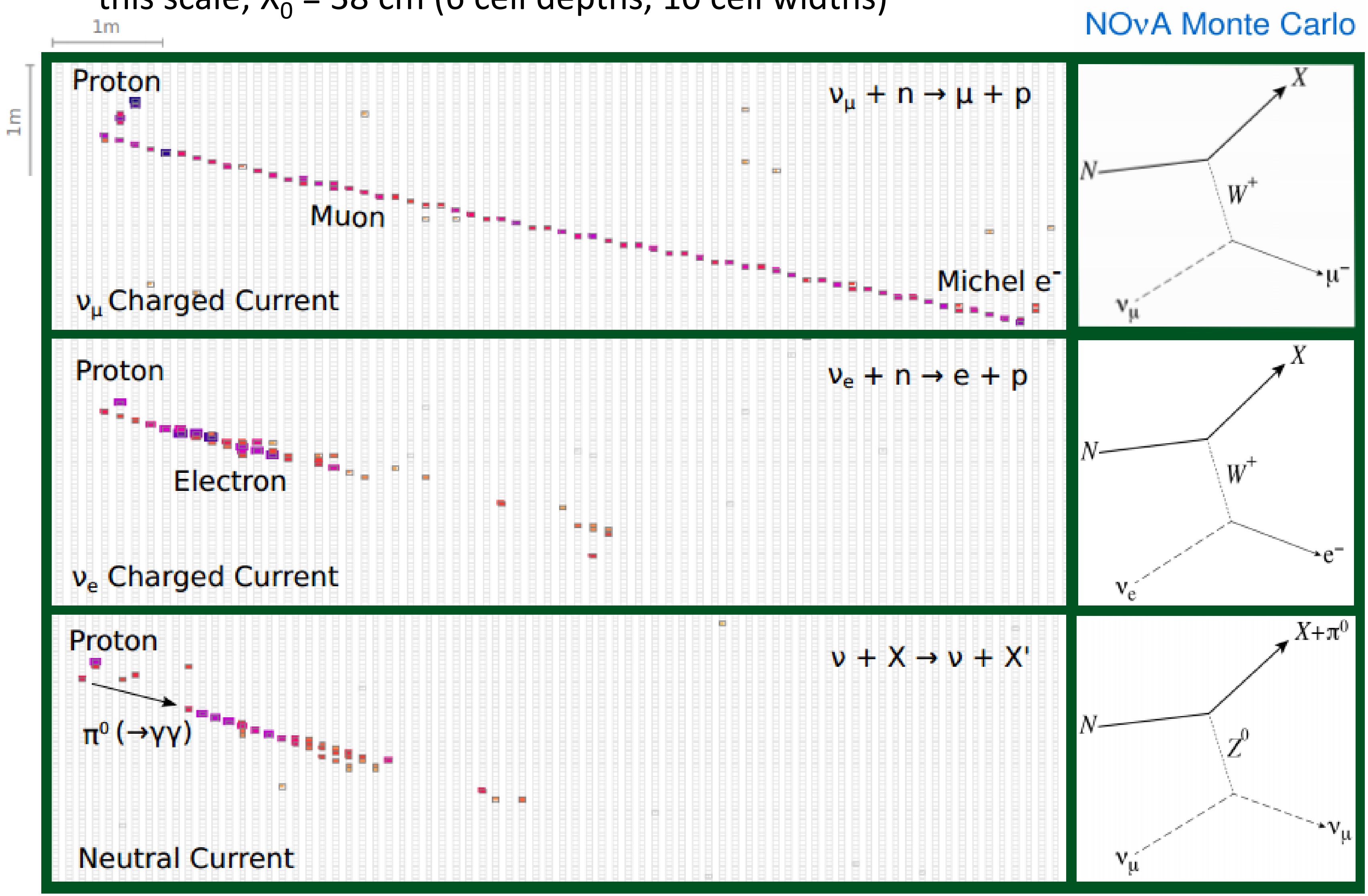
Accelerator and NuMI upgrades

- Fermilab has completed a series of upgrades to the Main Injector and Recycler rings to reduce the cycle time from 2.2 s to 1.3 s
- Intensity increased from 300 to 700 kW
- Neutrino beamline optimised for NOvA

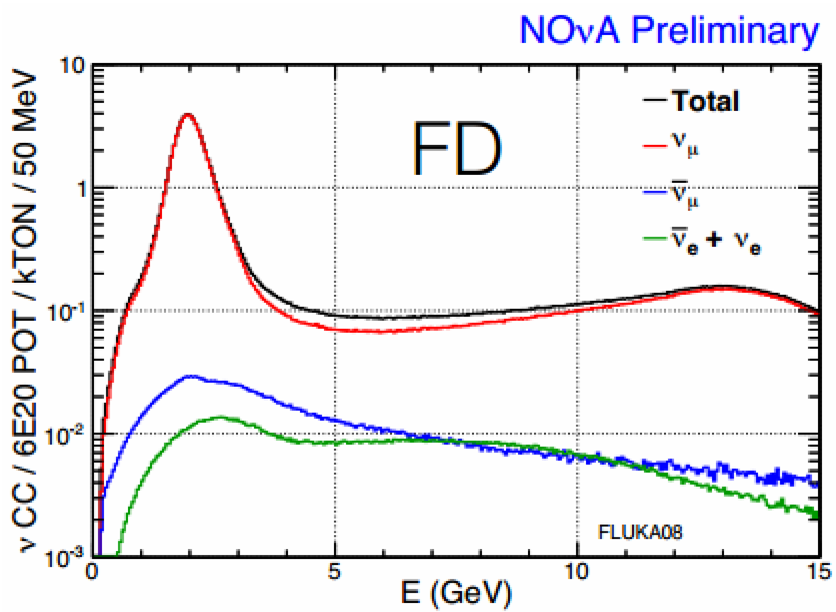


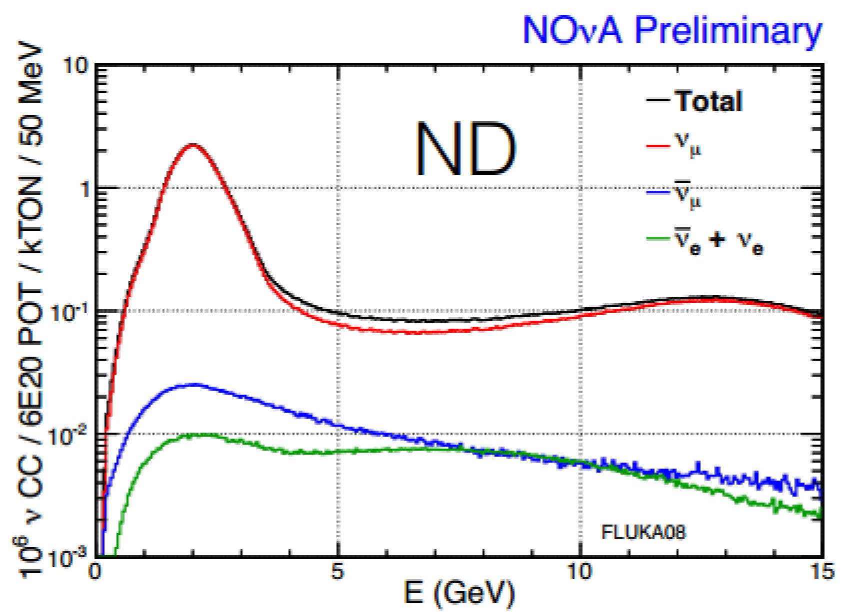
NOvA Neutrino Event Topologies

- NOvA has excellent spatial granularity for a detector of this scale; X_0 = 38 cm (6 cell depths, 10 cell widths)



Forward Horn Current Mode





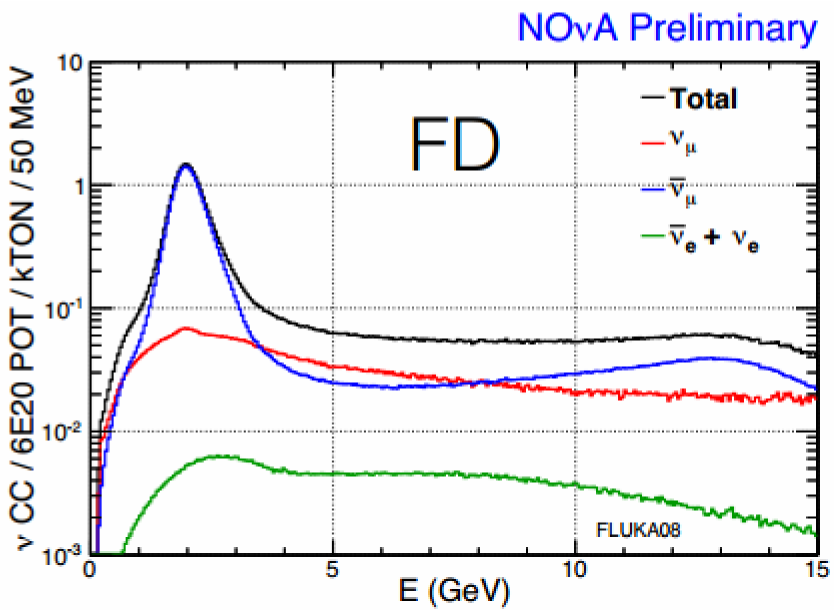
	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

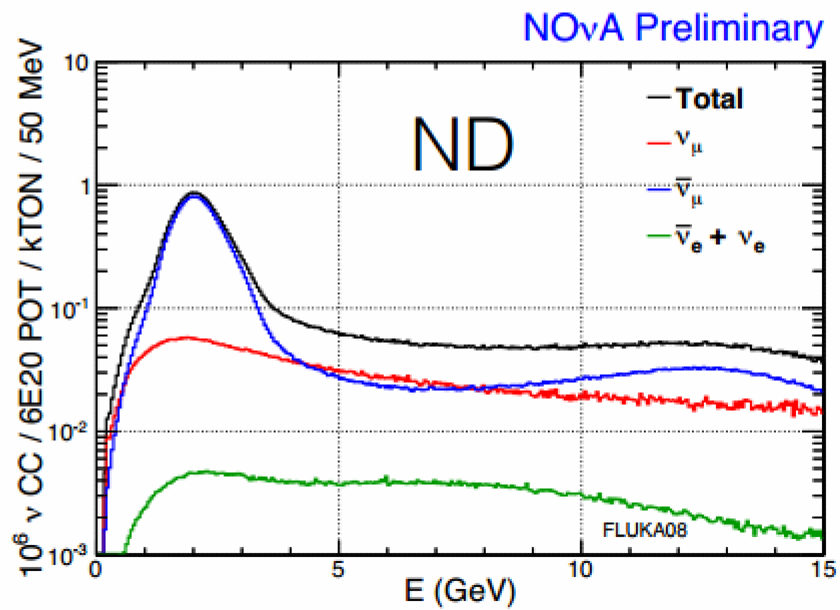
$\times 10^6$	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.6\%$

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.7\%$

Reverse Horn Current Mode





	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

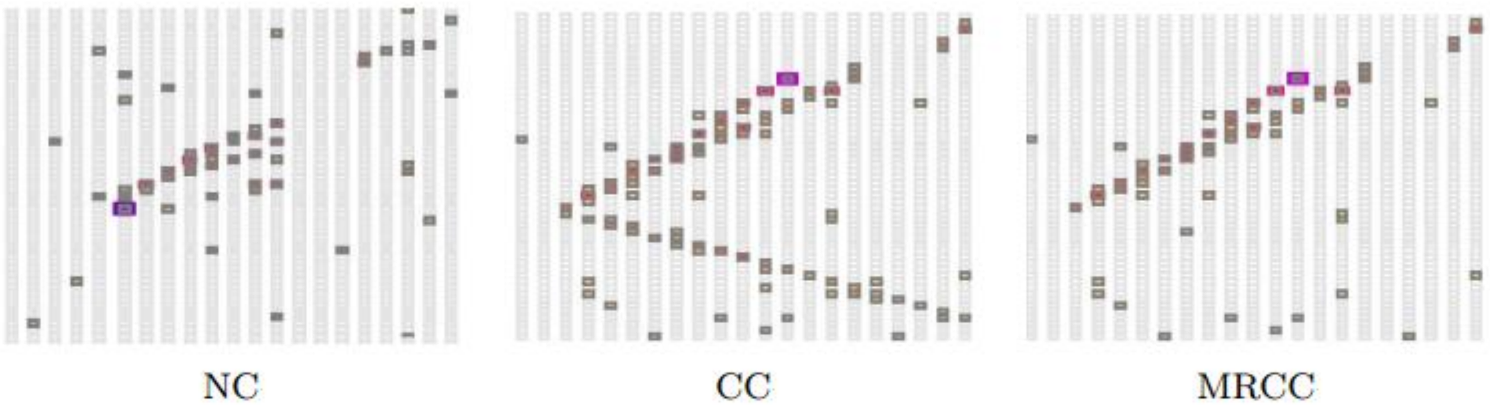
x10^6	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

[1,3]GeV: $(\nu_e + \overline{\nu}_e)/\nu_\mu = 0.8\%$

[1,3]GeV: $(\nu_e + \overline{\nu}_e)/\nu_\mu = 1.0\%$

Background Estimations using Near Detector

- Remove the muon track in a selected ν_μCC event and use the rest as a hadronic shower-only event
- Muon Remove Charged Current (MRCC) events give us a well understood sample of hadronic showers
- ν_μCC events without the muon look a lot like Neutral Current events, which are the main background to the ν_e analysis
- Well defined ν_μCC spectra, with well known efficiency and purity from the ν_μ disappearance analysis



Simulated events

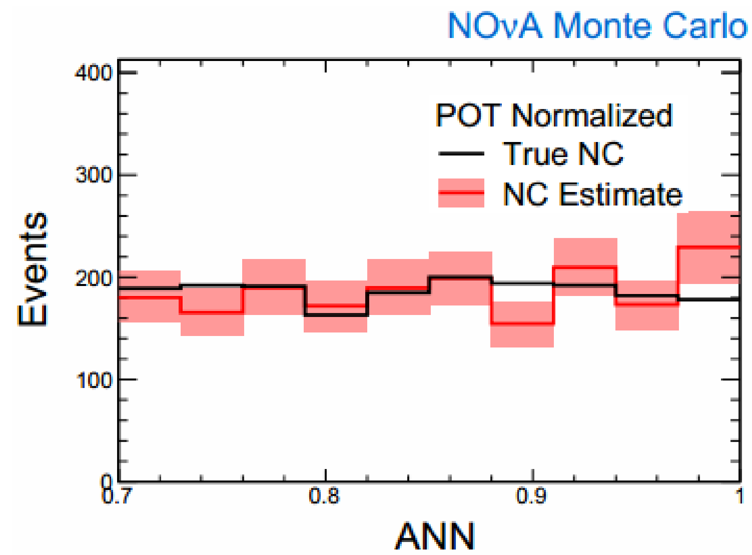
Using MRCC as a data-driven correction

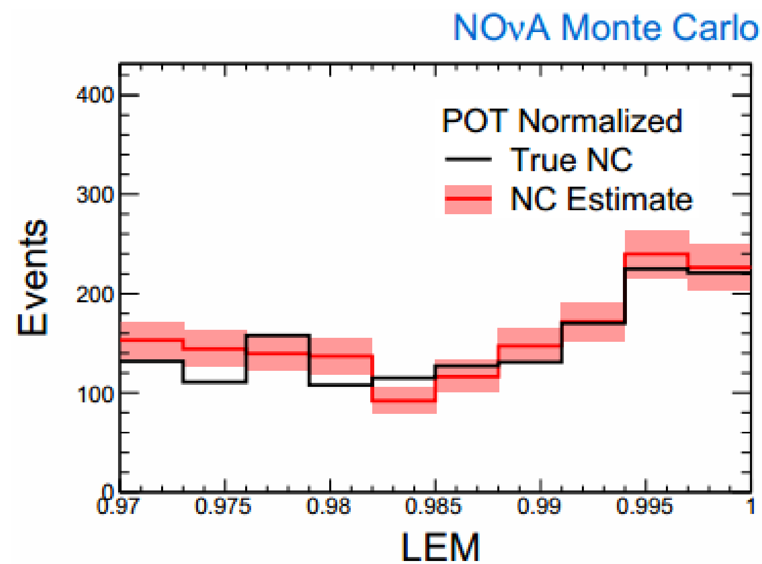
- We use the data/MC ratio from MRCC to obtain a data-driven correction that is applied to the standard NC events as a function of energy

$$NC^{BG} = \frac{NC^{MC}}{MRCC^{MC}} \times MRCC^{Data}$$

- Many systematic effects cancel in the ratio, resulting in a more accurate estimate of background

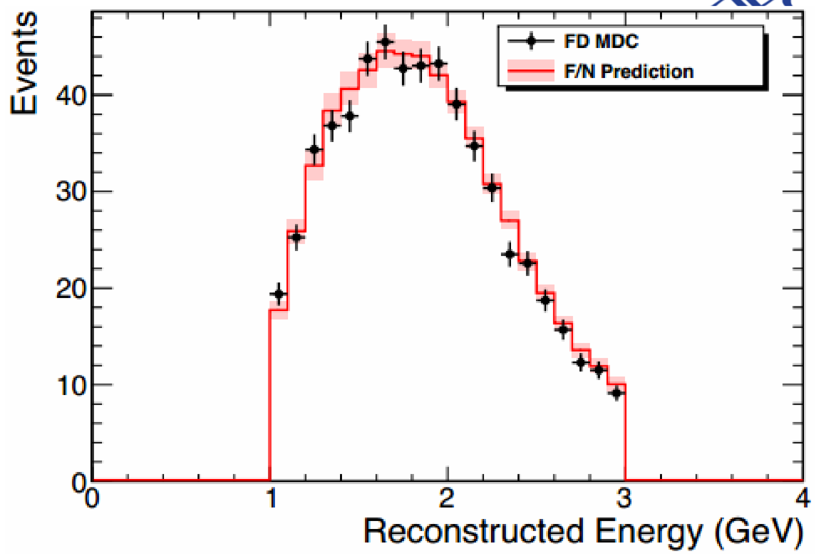
- Estimate Neutral Current background in psuedo-data on the right yields results consistent with MC truth

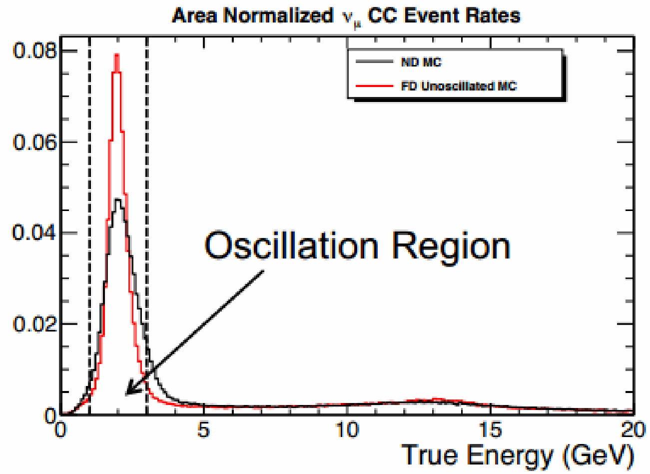


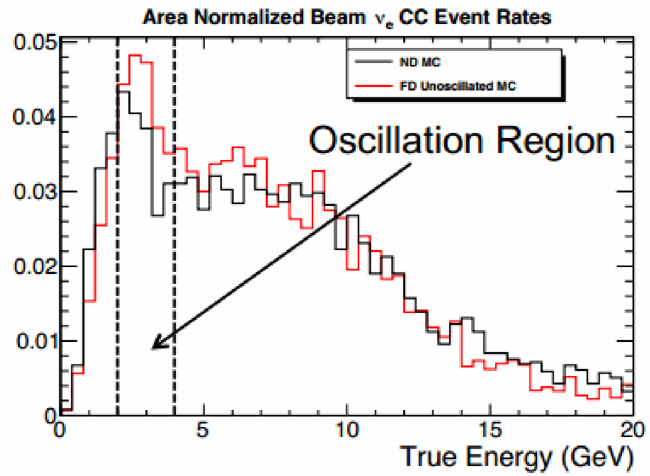


Predicting the Far Detector background

- The Near Detector ve selected NC and νμCC background components are corrected by the Far/Near MC ratio
- Far/Near ratio accounts for geometry, fiducial volume ratio, intensity, detector differences and oscillations







- Area normalized event rates demonstrate differences in detector spectra shapes. A F/N ratio can be made from the non-normalized versions. These spectra are the true events with no selections applied. The F/N ratios change when various selections or PIDs are applied

Electron-neutrino Appearance in NOvA

- NOvA measures the probability of ν_e appearance in a ν_μ beam

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

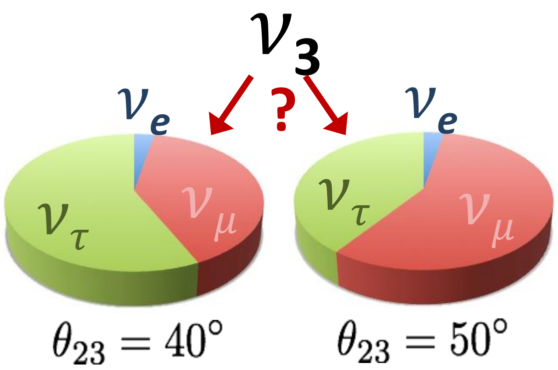
$$\overset{(+)}{-}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

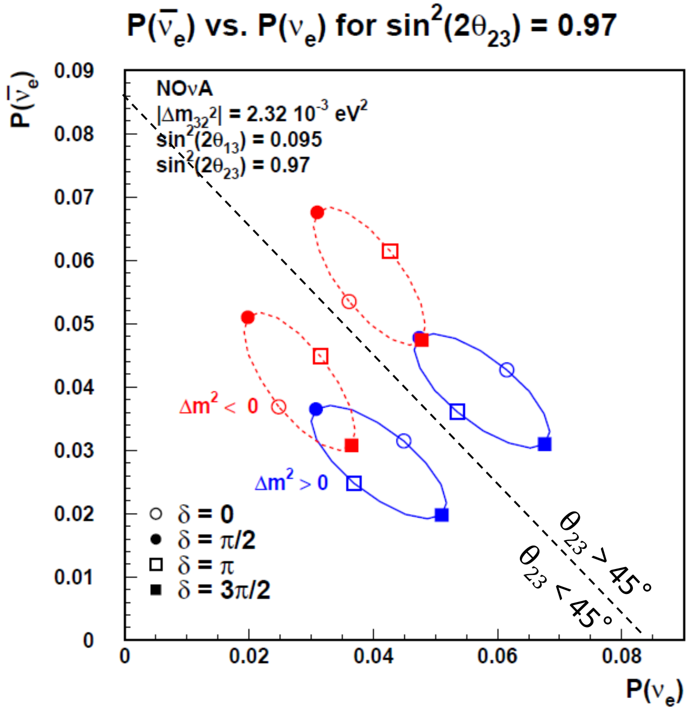
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$$

- **$\sin^2(2\theta_{13})$** can be accessed in long baseline searching for ν_e events
- **$\sin^2(2\theta_{13})$** has been measured which allows us to make measurements of δ_{CP}
- Note that we can gain information about the **θ_{23}** octant since **$\sin^2(\theta_{23})$** is a coefficient on the leading-order term above
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy, i.e the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running

Non-maximal $\sin^2 2\theta_{23}$





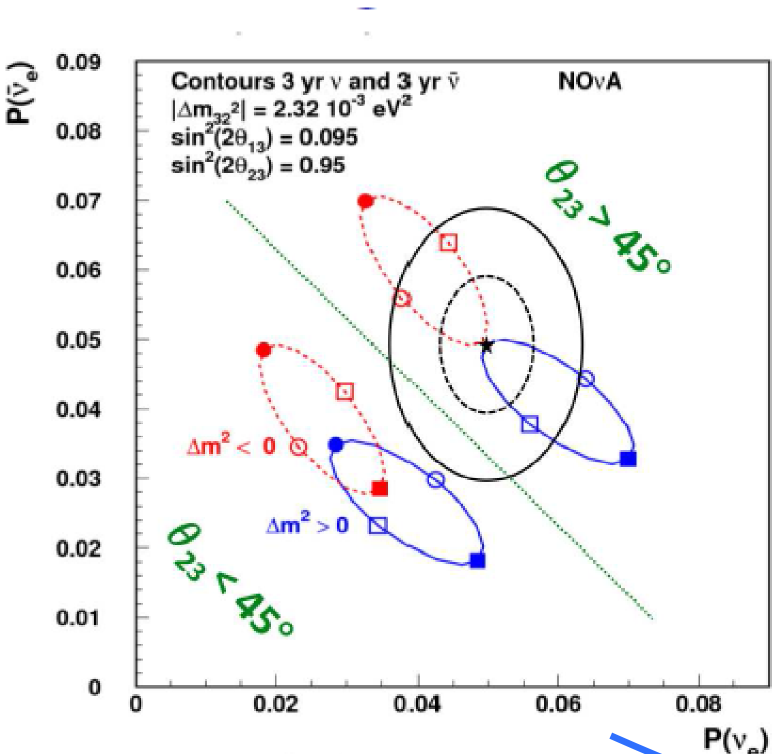
- If $\sin^2 2\theta_{23}$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than 45°
- The $\sin^2\theta_{23}$ is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments
- The $\sin^2 2\theta_{23}$ is measured via ν_μ disapperance

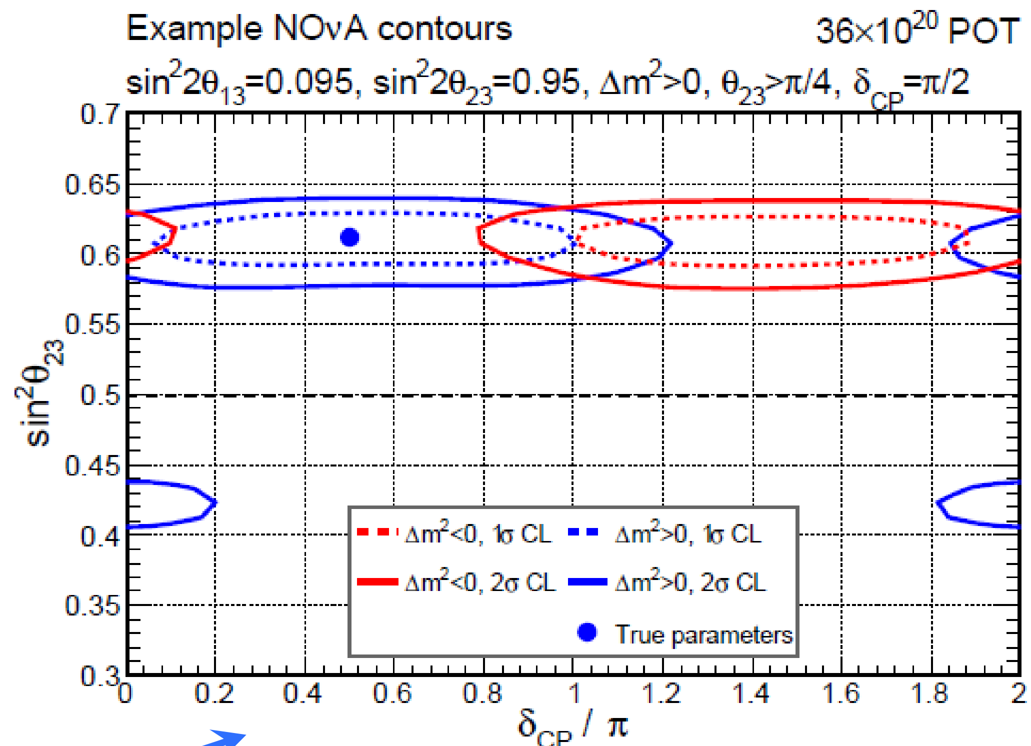
$$P(\nu_e) \propto \sin^2(\theta_{23})\sin^2(2\theta_{13})$$

$\Rightarrow$ ***θ_{23} octant sensitivity***

θ_{23} Octant Determination

- Expected contours for one example scenario using 3 years of data for each neutrino mode



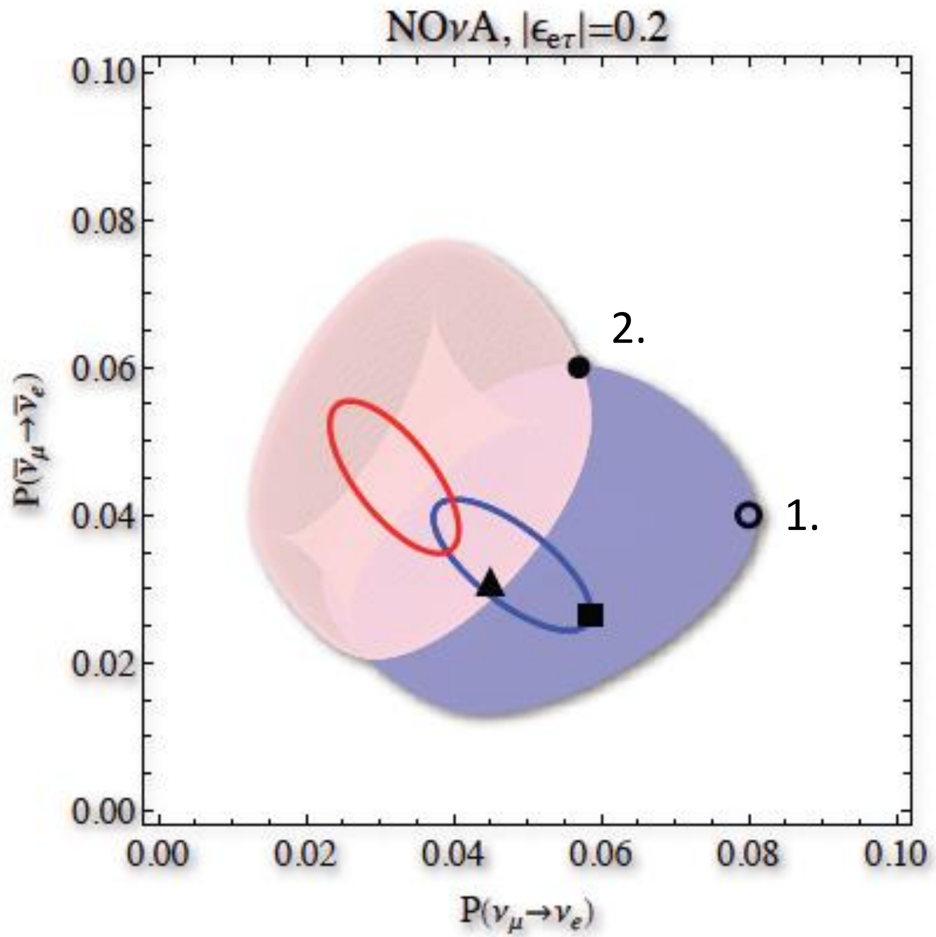


In "degenerate" cases, hierarchy and δ information is coupled. θ_{23} octant information is not

- Octant information mostly independent
- In this case ($\sin^2 2\theta_{23} = 0.95$, $\theta_{23} > \pi/4$) determine octant at better than 2σ for almost any δ and hierarchy

Non-Standard neutrino Interactions (NSI)

- NOvA bi-probability plots assume standard neutrino interactions
- Allowing for non-zero NSI in the e-τ sector, $|\epsilon_{e\tau}|$=0.2, expands the hierarchy regions significantly
- Consider qualitative possibilities:
  1. NSI and hierarchy determination
  2. NSI determination only



A. Friedland & I. Shoemaker
arXiv:1207.6642v1 [hep-ph]