Status of the NOvA Experiment

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NuMI Off-Axis ν_e Appearance Experiment

NOvA is a long-baseline neutrino oscillation experiment located 14 mrad off-axis from the NuMI beam designed to measure:

ν_e appearance

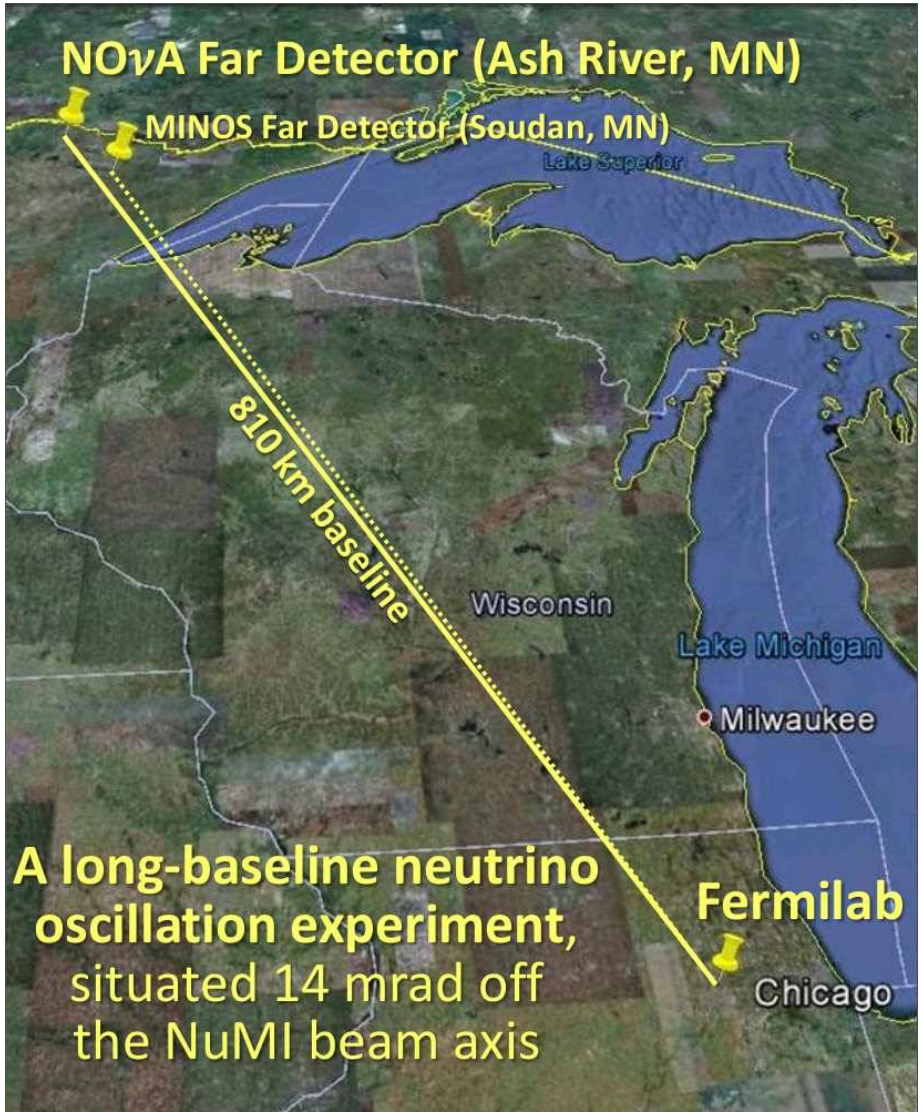
- Mass hierarchy
- CP violation
- θ_{23} octant

ν_μ disappearance

- Improved precision on $|\Delta m^2_{32}|$ and θ_{23}

Others

- Steriles
- Cross sections
- Supernovae
- Exotics



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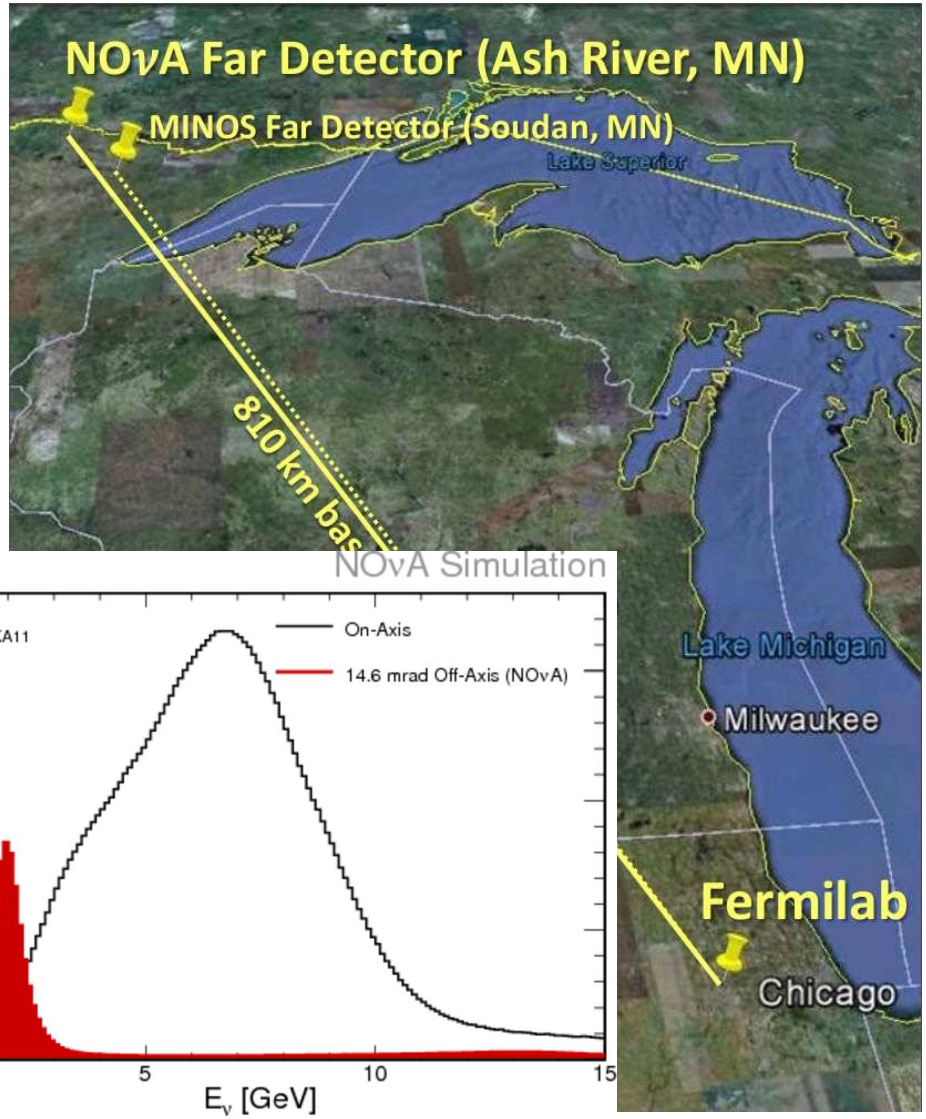
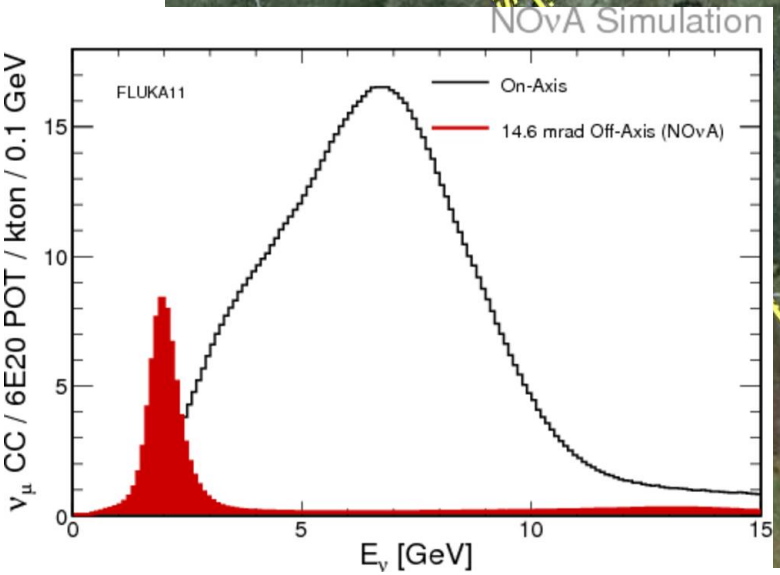
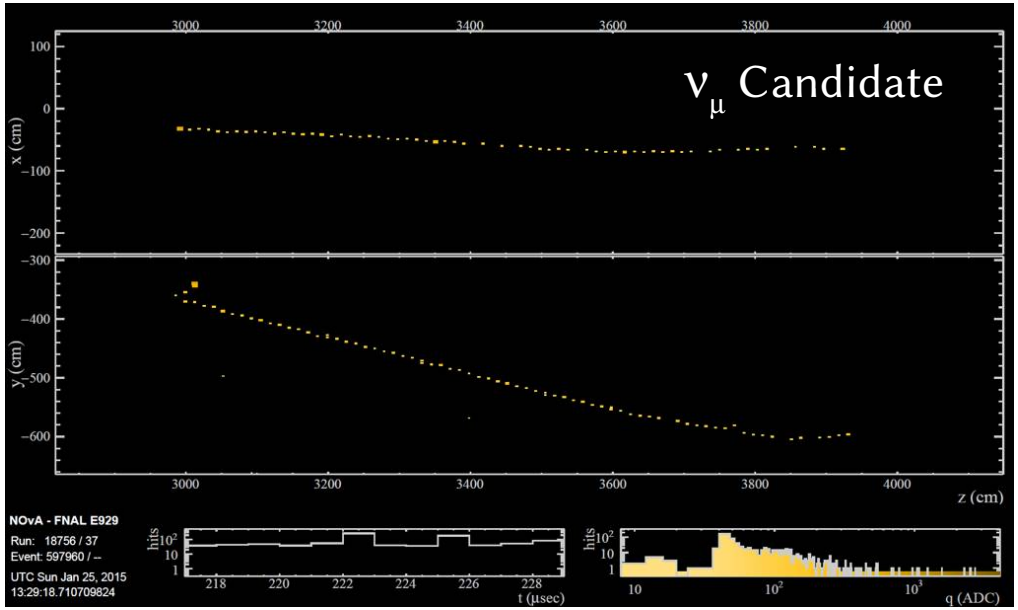
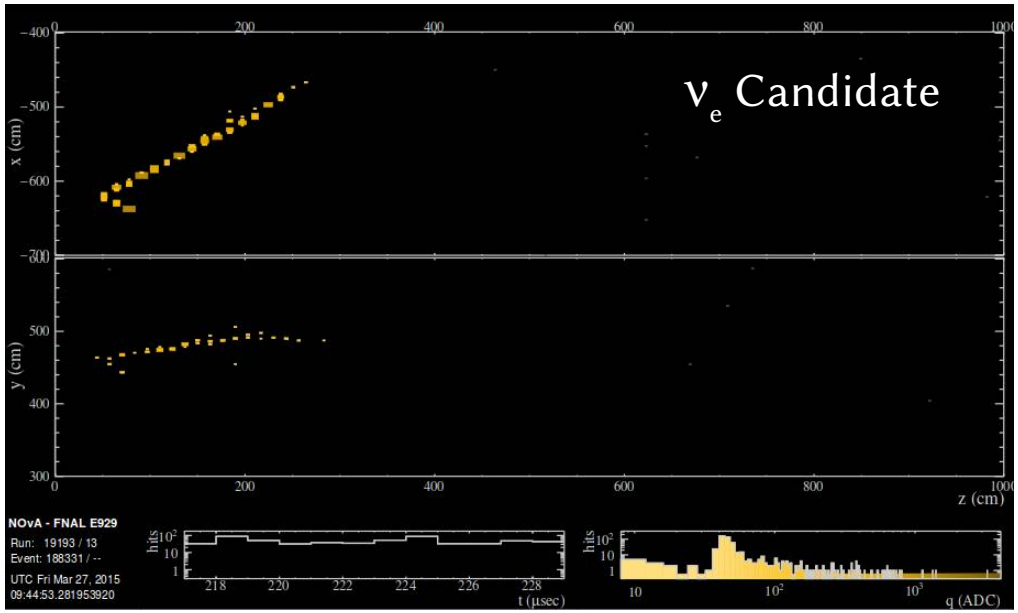




NOvA Analyses Overview

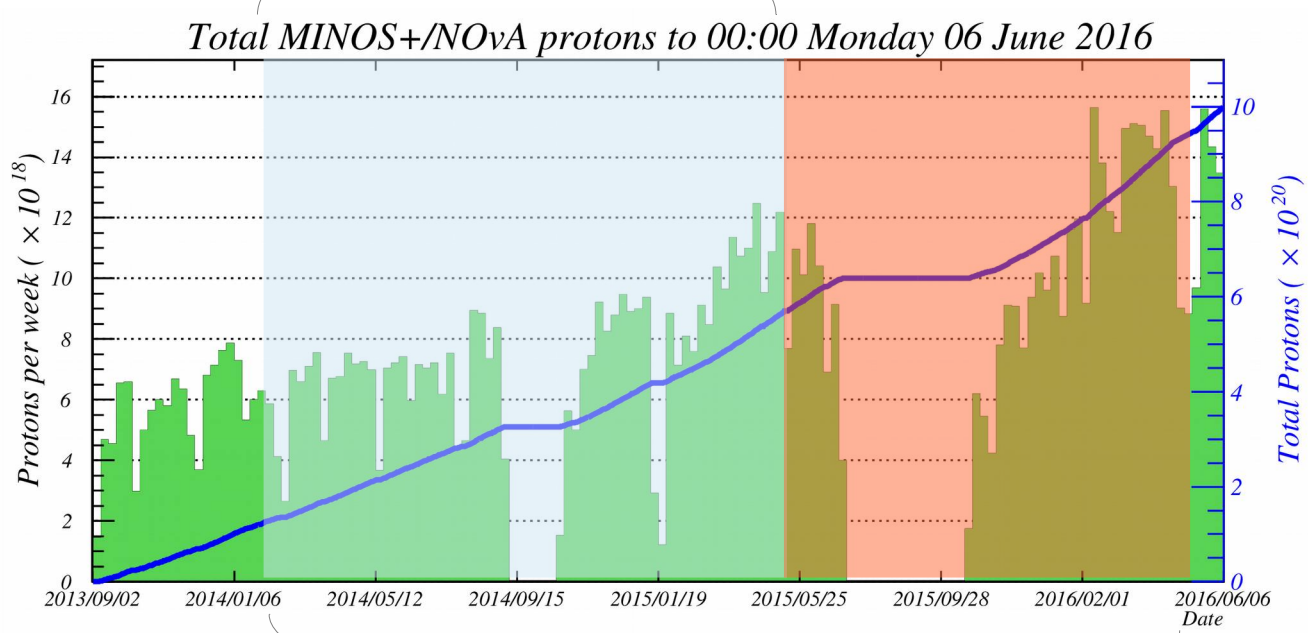
- Measure the ν_μ and ν_e rates and spectra at the Near Detector.
- Use these measurements to correct the prediction of the Far Detector.
  - Two detector technique helps control correlated flux and cross-section systematic uncertainties.
  - Helps us understand the intrinsic ν_e component of the beam.
- Look for a deficit of muon neutrinos and an excess of electron neutrinos at the Far Detector.
- In this talk:
  - Describe published 1st analysis results.
    - ν_μ disappearance: Phys. Rev. D93, 051104(R)
    - ν_e appearance: Phys. Rev. Lett. 116, 151806
  - Show analysis improvements to be used for the 2nd analyses coming this summer.





NuMI Beam Performance

1st Analysis: 6 Feb. 2014 – 15 May 2015
→ 2.74 x 10^{20} POT



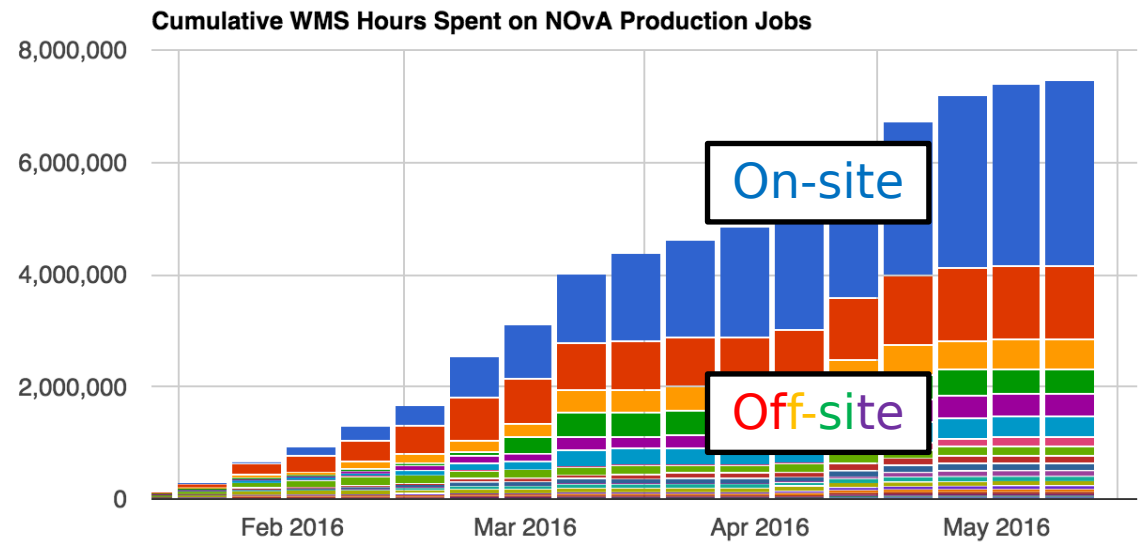
2nd Analysis: 6 Feb. 2014 – 2 May 2016
→ 6.05 x 10^{20} POT

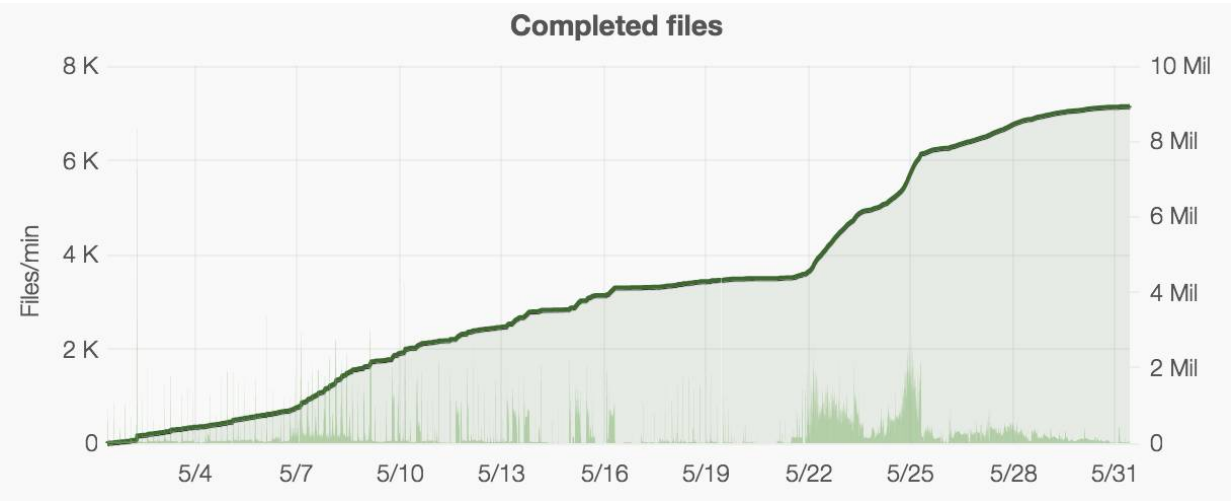
- Data taking started while detector was still under construction.
  - All exposures are in full detector mass equivalents.
- ~95% Far Detector efficiency.
  - Thanks to major DAQ improvements by the Real Time Applications group, this has improved to ~98%!
- Recently reached full design power: 700 kW!

Thanks to the Accelerator Division!

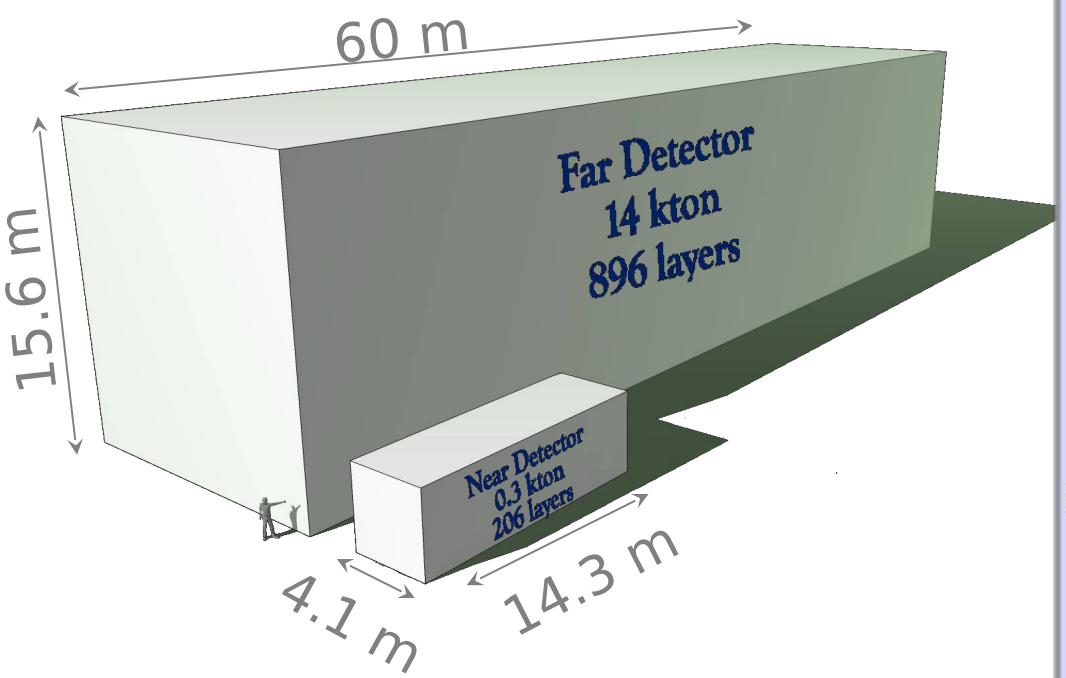
Computing for the 2nd Analysis

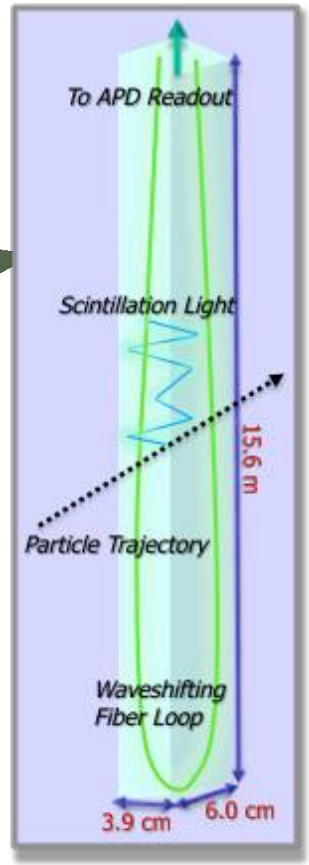
- Lots of CPU
  - 7 million CPU hours for simulation and reconstruction.
    - Averages to 2400 jobs running non-stop.
- Enormous data handling
  - Cataloging 7 PB of data.
- Excellent support – **Thanks to the SCD!**



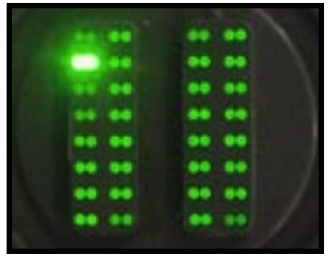


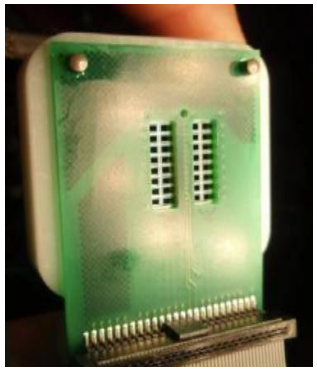
NOvA Detector Design





Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells.





Wavelength shifting fibers carry light out of the cells to APDs.

Far detector (FD)

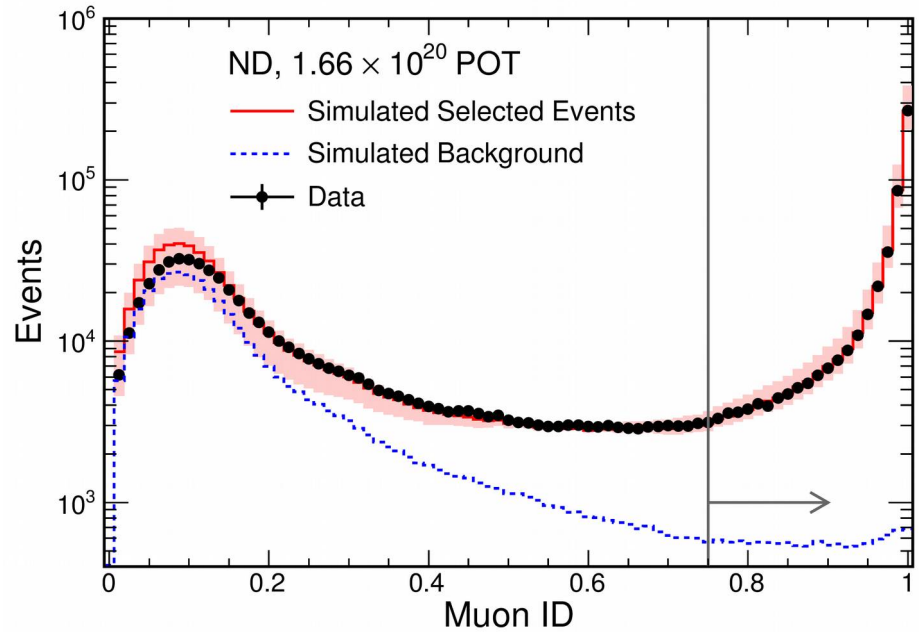
- 14 kton
- 65% active mass
- ~344,000 channels

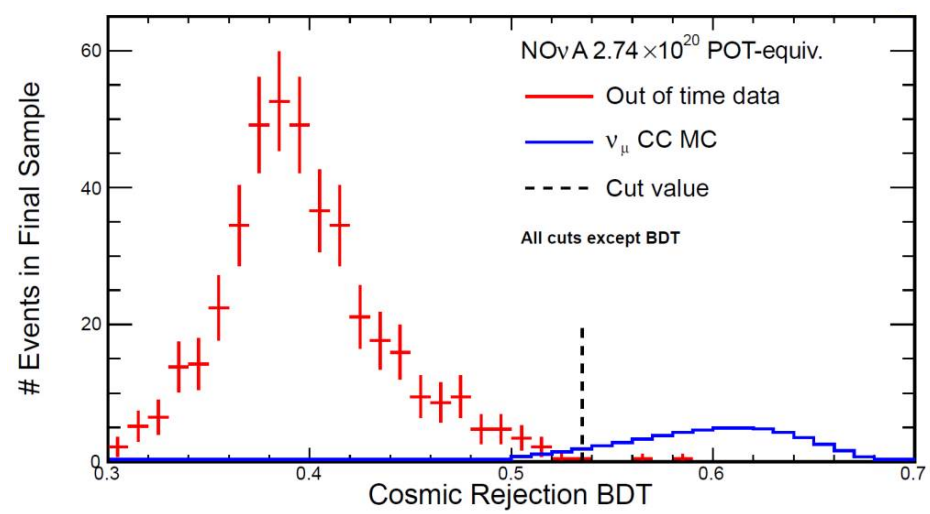
Near detector (ND)

- 0.3 kton
- Functionally equivalent to FD for systematic uncertainty reduction
  - Faster electronics
  - Muon catcher to contain muons
- ~20,000 channels

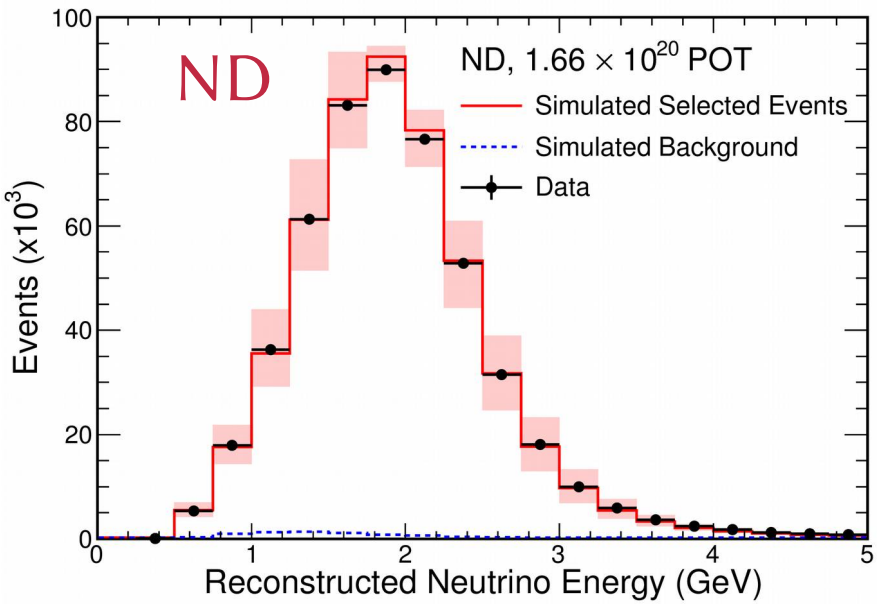
ν_μ Disappearance

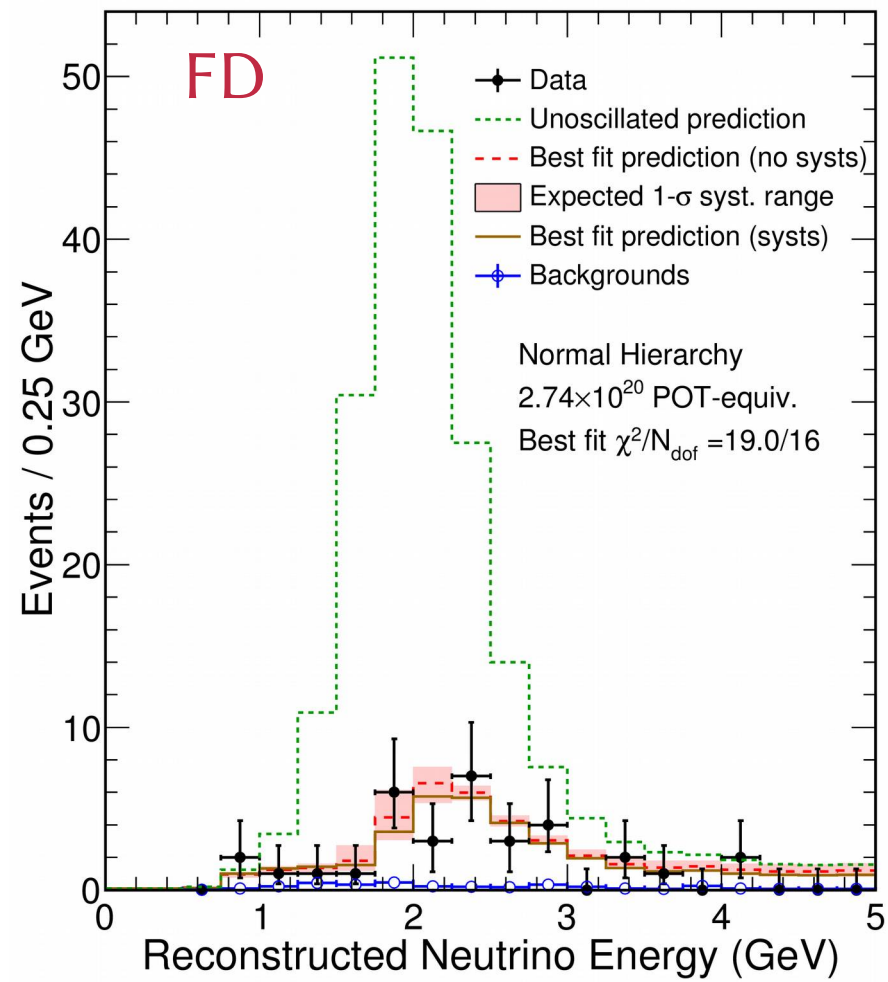
- Require that events are contained.
- Separate muon from pion tracks with a 4 variable k-nearest-neighbor classifier to identify muon tracks.
  - Excellent data/MC agreement in final muon id for selected ND ν_μ candidates.
- Cosmic background is estimated using out-of-time data.
- Selecting a narrow window around the 9.6 μs spill gives a 10^5 rejection factor.
- Using a boosted decision tree trained to reject cosmic-like topologies achieves a 10^7 rejection factor.





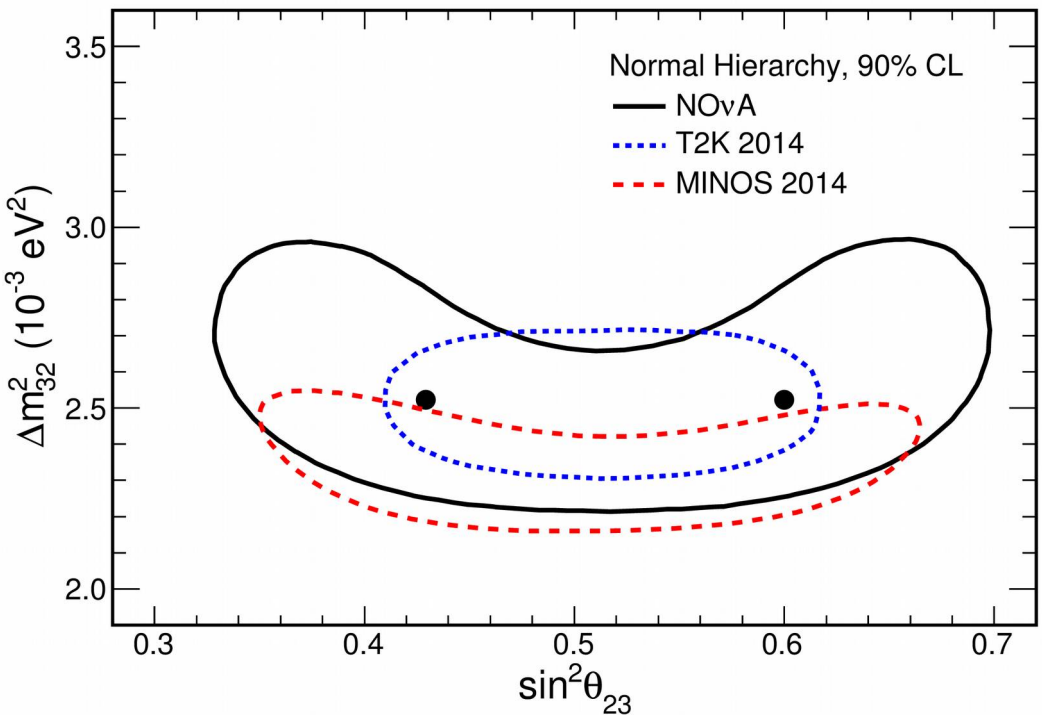
ν_μ Selected Spectrum: 1st Analysis





- 201 events predicted without oscillation
  - 2 beam background and 1.4 cosmic events.
- 33 events observed.
- Clear observation of ν_μ disappearance.

ν_μ Disappearance Result: 1st Analysis



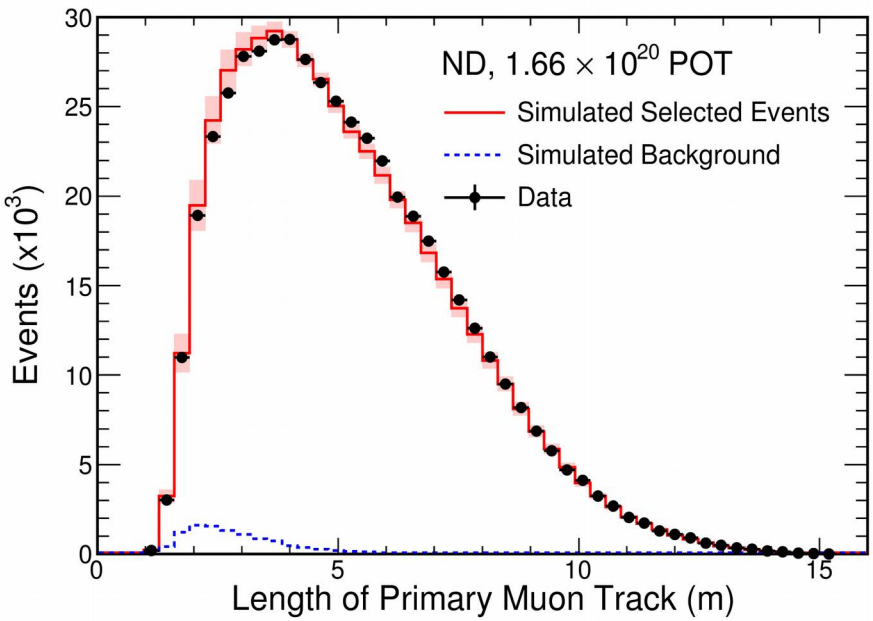
$$\Delta m^2_{32} = 2.52^{+0.20}_{-0.18} \times 10^{-3}\mathrm{eV}^2$$

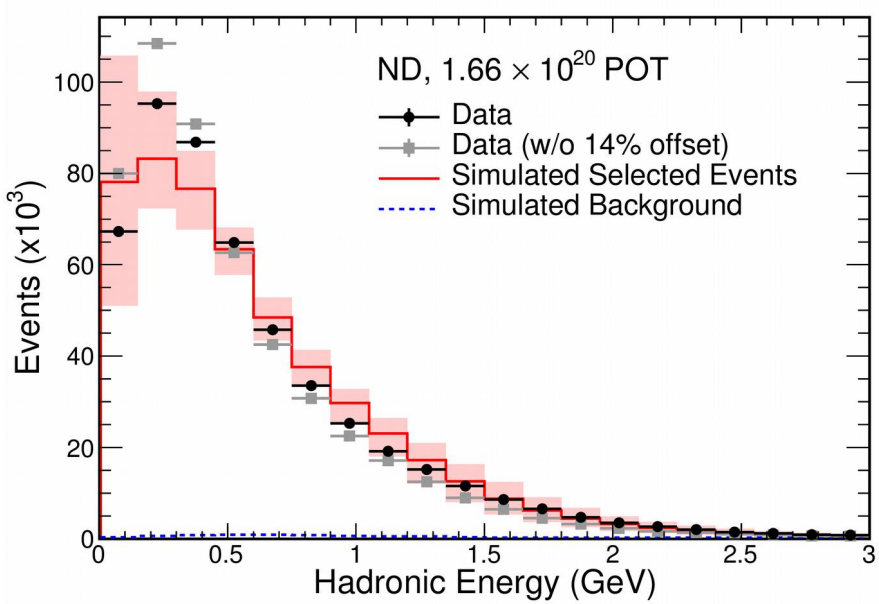
$\sin^2\theta_{23}$ in the 68% C.L. range [0.38, 0.65] with best fits 0.43 and 0.60.

Already competitive with only 8% of nominal exposure!

Published in Phys. Rev. D93, 051104(R)

ν_μ Improvements - Hadronic Energy



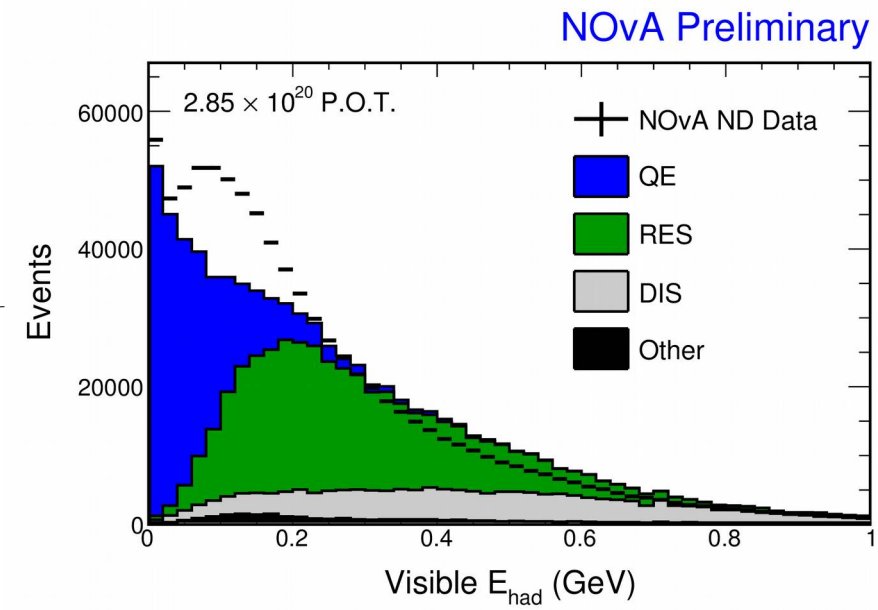


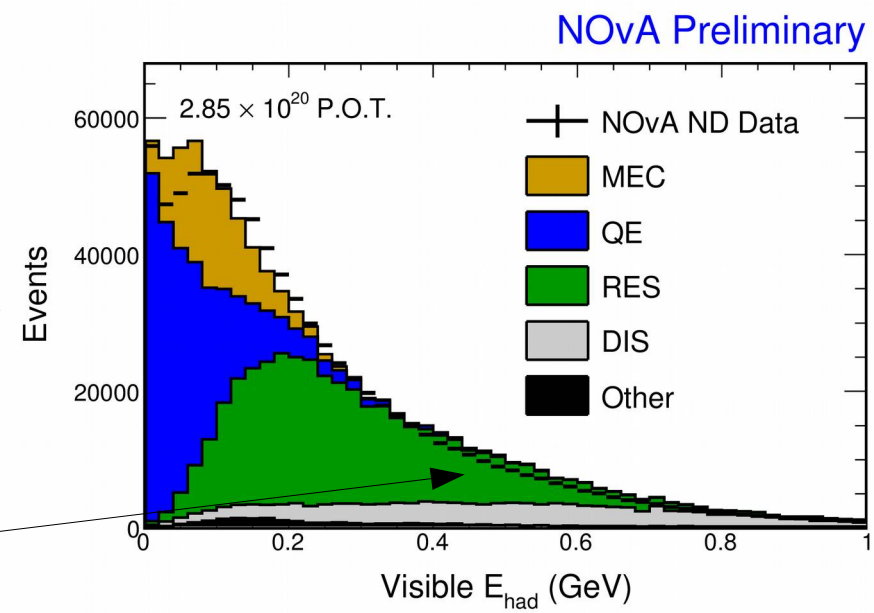
- Good data/MC agreement for selected muons, but 14% more energy in MC hadronic system compared to data.
- 1st analysis: recalibrate hadronic energy to make the peak of the total reconstructed neutrino energy distribution agree in data and MC.
  - 5% overall neutrino energy scale uncertainty.
- 2nd analysis: improve the cross section model
  - Add and tune a multinucleon component.
  - Reduce single nonresonant pion production (arXiv:1601.01888).

Modeling Multinucleon Processes

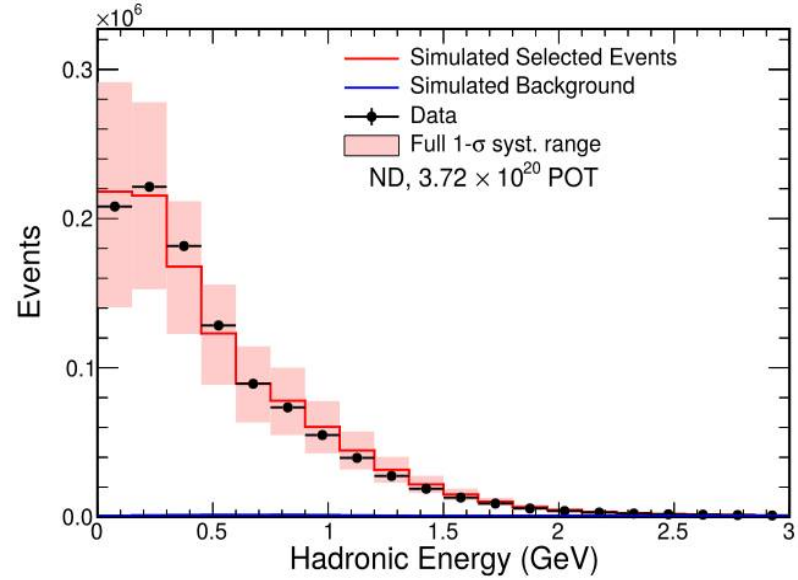
- NOvA simulates neutrino interactions using the GENIE generator.
- GENIE 2.10.4 includes a new, optional empirical MEC (meson exchange current) model.
  - Tuned to reconcile MiniBooNE and NOMAD's quasi-elastic cross-section measurements.
- Constrain this empirical model using the observed excess in ND data.
  - Greatly improves agreement a low E_{had}

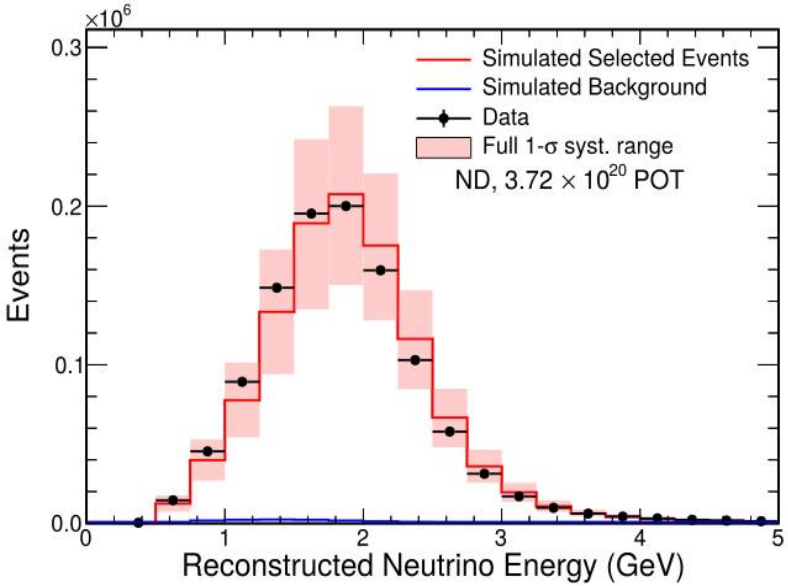
Reducing the single nonresonant pion production component improves agreement in the tail.

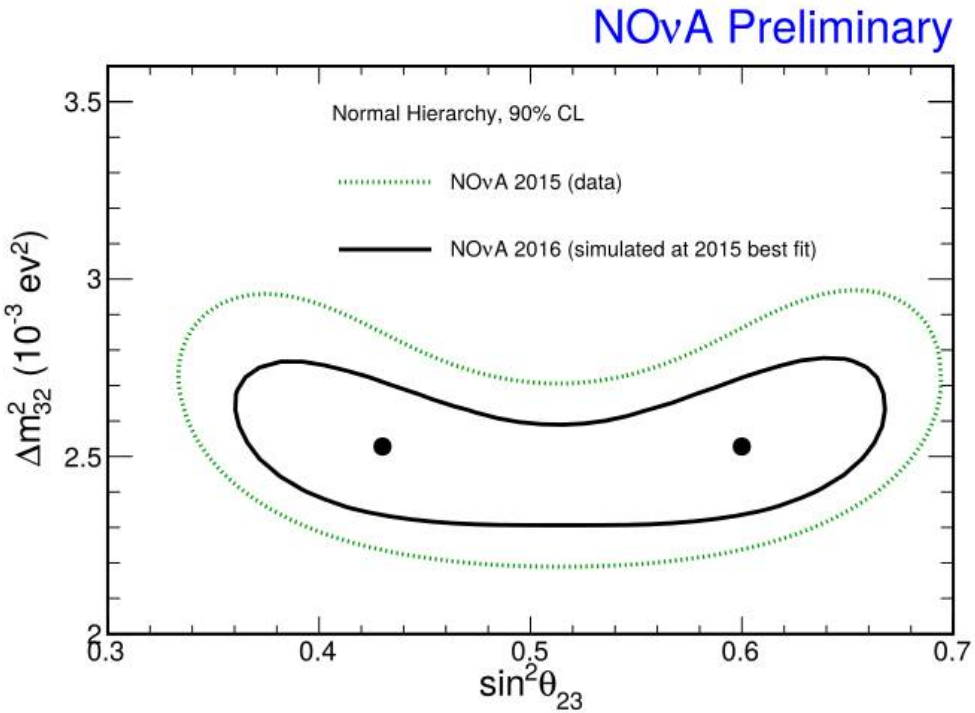




ν_μ Disappearance Sensitivity: 2nd Analysis



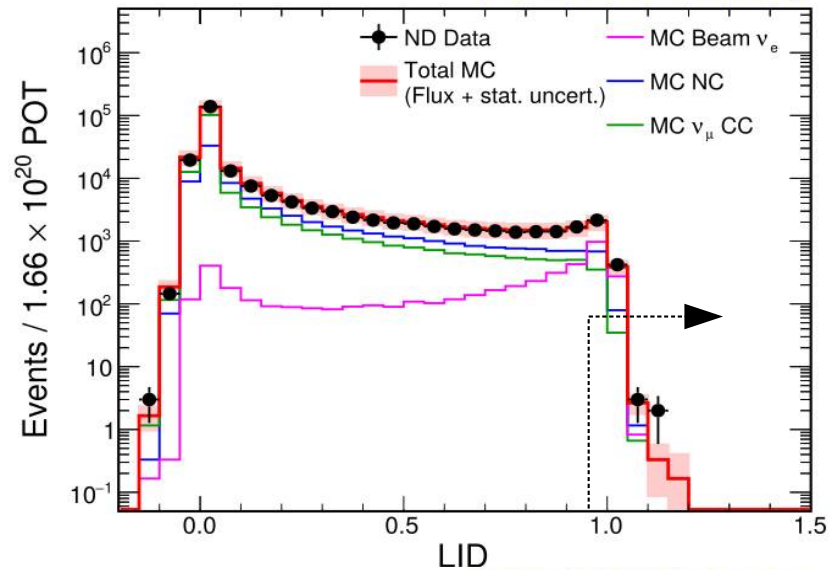


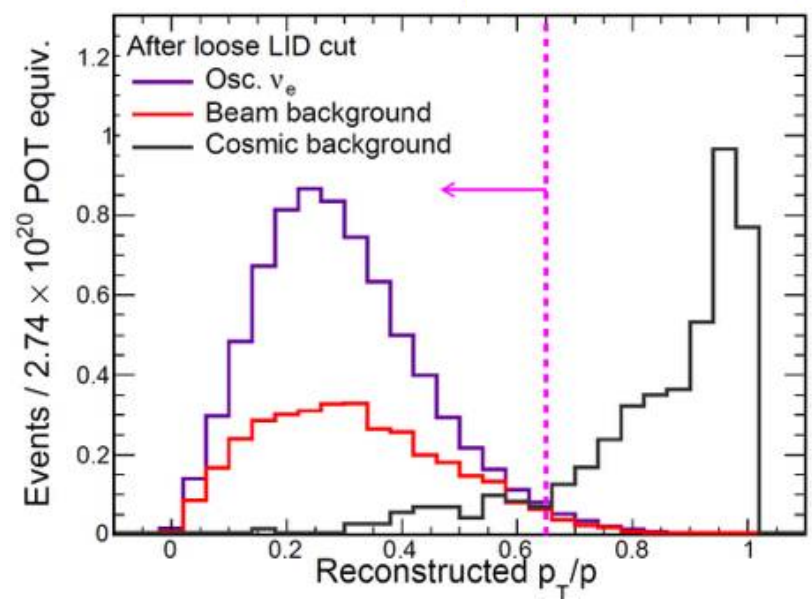


- After improving the cross section model, E_{had} has better data/MC agreement.
- E_{reco} data/MC disagreement reduced from 5% to 2%.
- Reduced E_{had} disagreement ⟶ reduced overall systematic uncertainty.

ν_e Appearance: 1st Analysis

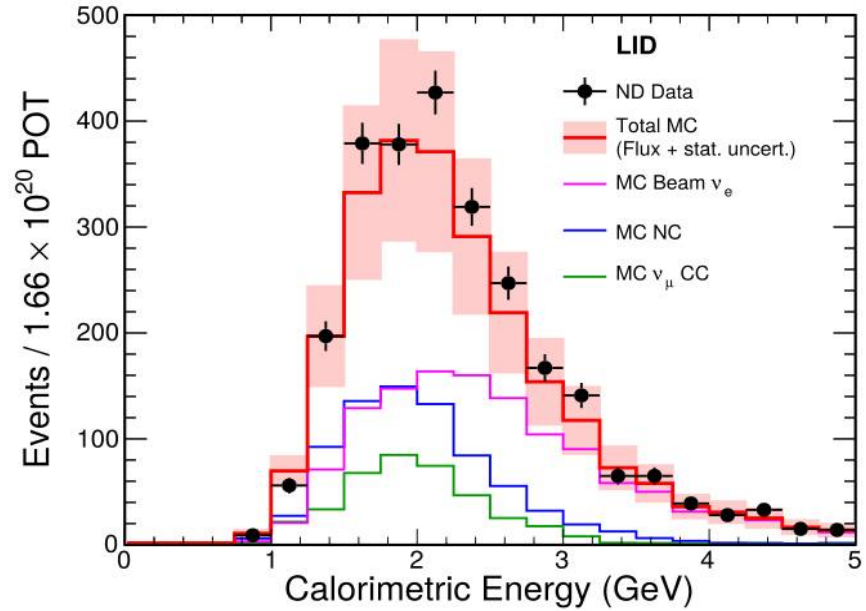
- Two selectors:
  - Likelihood ID (LID)
    - Based on transverse and longitudinal dE/dx likelihoods calculated for various particle hypotheses.
  - Library Event Matching (LEM)
    - Uses properties of best matches between the event and a library of simulated signal and background events.
- Both selectors have similar purity and efficiency.
- LID was chosen to be the primary selector before looking at data.
- Cosmic rejection using topological variables like p_T/p.
- ν_e selectors + topological cuts achieves better than 1 part in 10^8 cosmic ray rejection.
  - Expect 0.06 cosmic events to pass cuts.

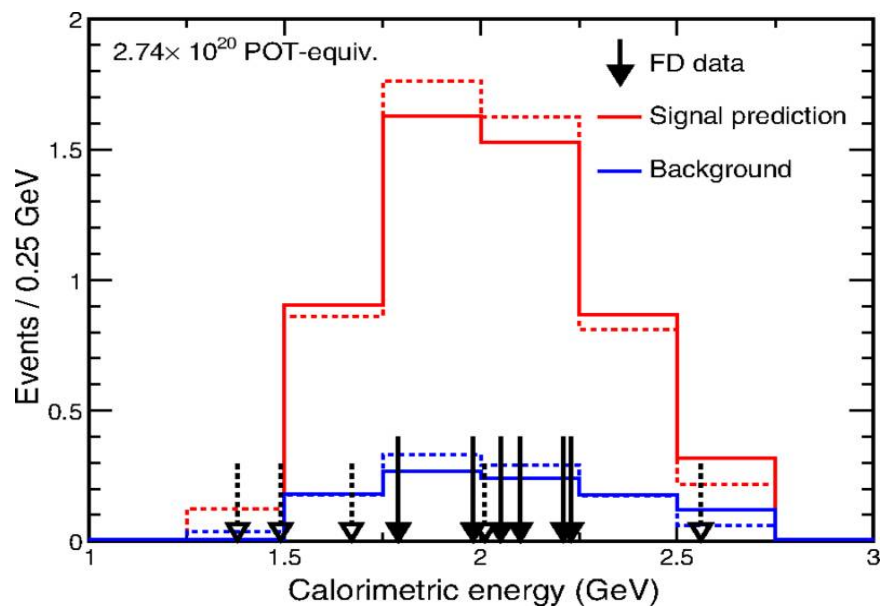




ν_e Selected Events: 1st Analysis

- Good data/MC agreement for the ND energy spectrum.
- Data selects ~5% more events than MC.
- Use simulated Far/Near ratio bin-by-bin to extrapolate ND data.
  - Predicted oscillated ν_e from ND ν_μ events.
  - Extrapolate beam ν_e and NC events to predict FD beam backgrounds.
- Predict 0.94 ± 0.09 background events
- Signal depends on parameters:
  - **Minimal for IH, $\delta_{CP} = \pi/2 \rightarrow 2.4 \pm 0.3$**
  - **Maximal for NH, $\delta_{CP} = 3\pi/2 \rightarrow 6.0 \pm 0.8$**





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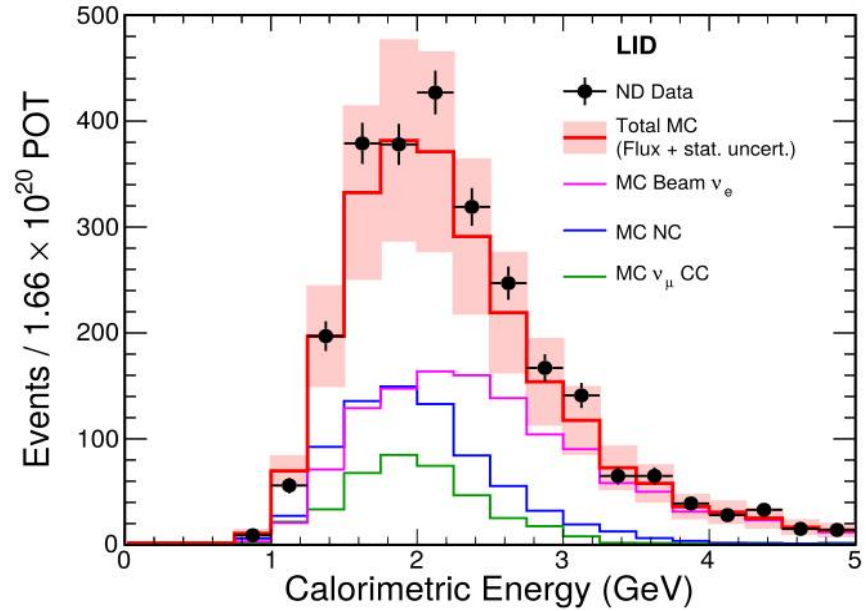
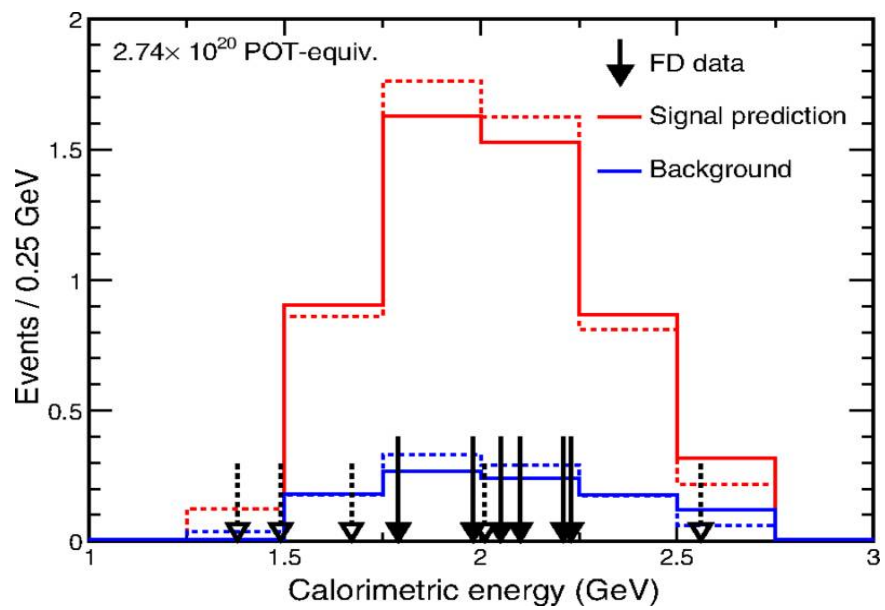
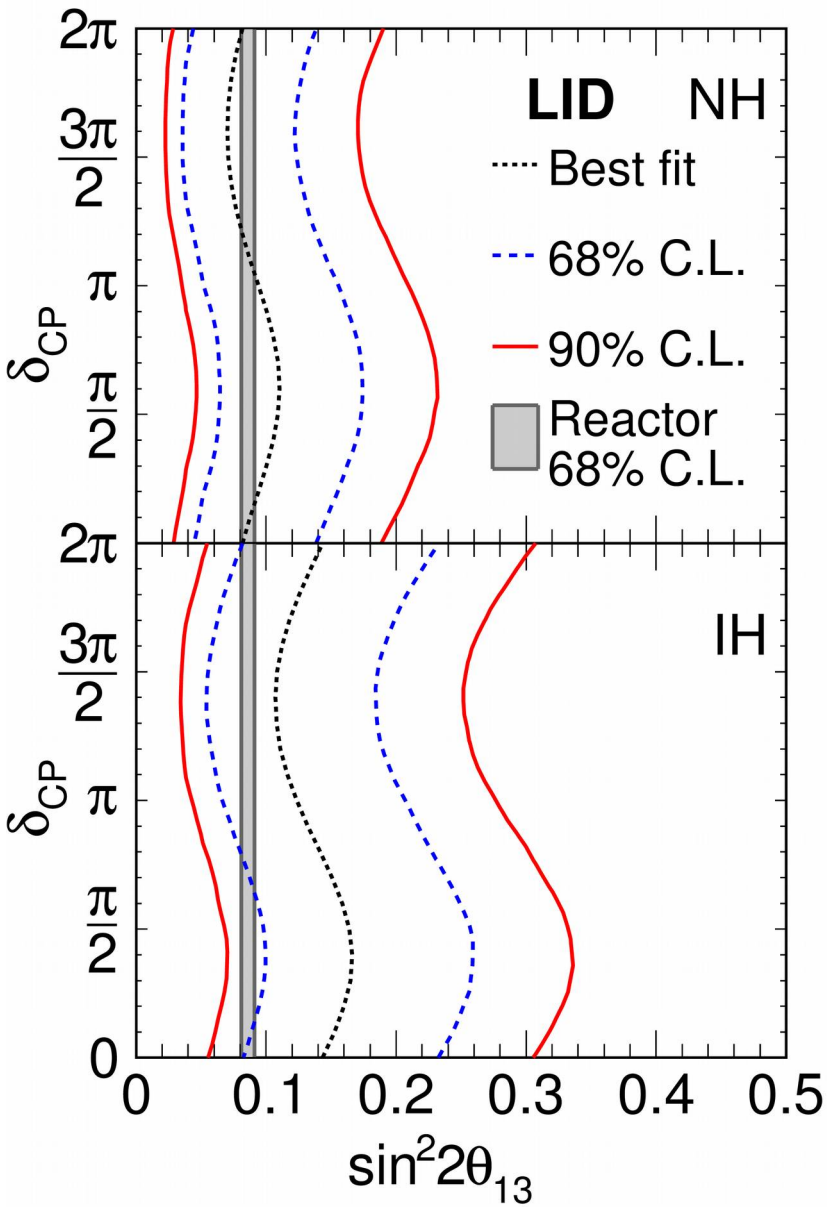
  - Minimal for IH, $\delta_{CP} = \pi/2 \longrightarrow 2.4 \pm 0.3$
  - Maximal for NH, $\delta_{CP} = 3\pi/2 \longrightarrow 6.0 \pm 0.8$
- **Observed 6 ν_e candidates (11 for LEM)**
  - Significance of appearance = 3.3σ (5.3σ for LEM).





ν_e Results: 1st Analysis

- Good consistency between NOvA (s-curves) and reactor experiments (gray band) for normal and inverted hierarchies.
  - Agreement is ~1σ better for normal hierarchy.

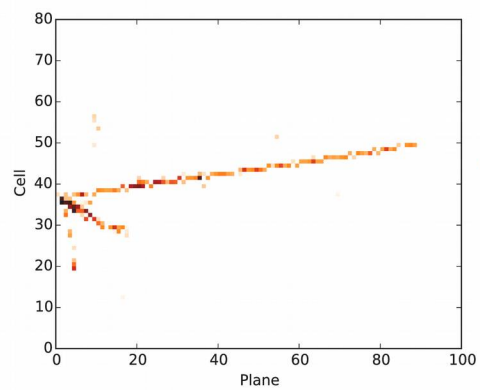


Published in Phys. Rev. Lett. 116, 151806

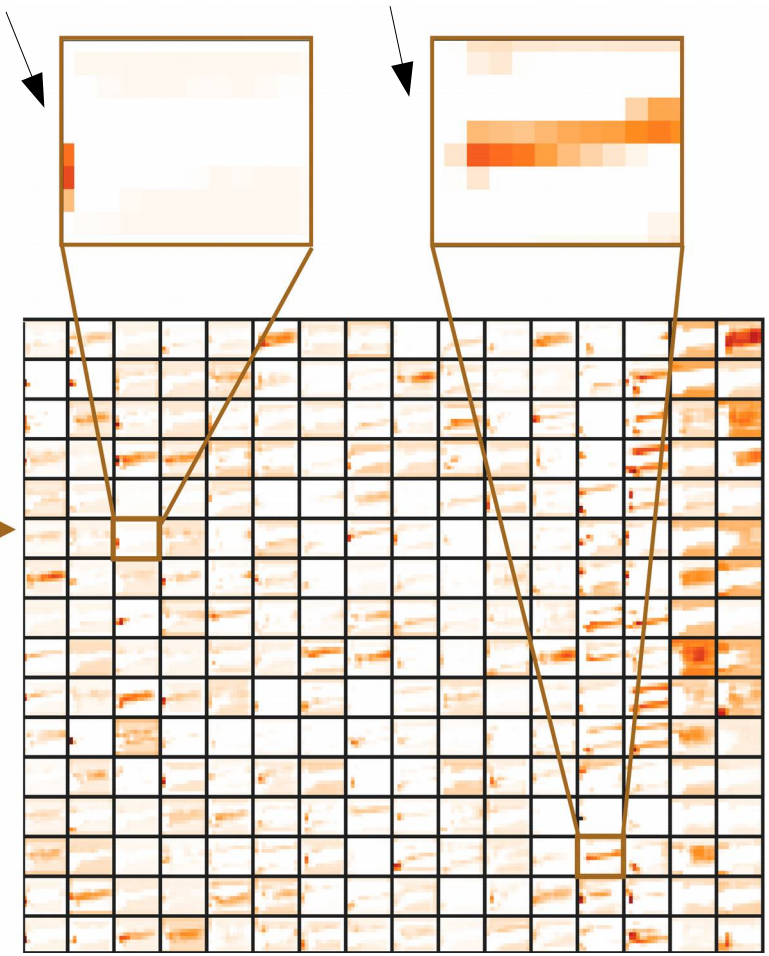
A New Deep-Learning Selector (CVN)

- Simulation studies suggested that LID and LEM only overlapped by 62%.
  - Suggested that there was still efficiency to be gained.
- Use all information in each event with tools from the computer vision community.
  - Convolutional Visual Network (CVN) based on the GoogLeNet architecture.
- Trained on GPUs on the Wilson cluster at Fermilab ⟶ made possible by the support of the SCD.

Treat each event as an image with cells as pixels and charge as color value



Individual learned filters are sensitive to physics: e.g. hadronic activity or muon tracks.

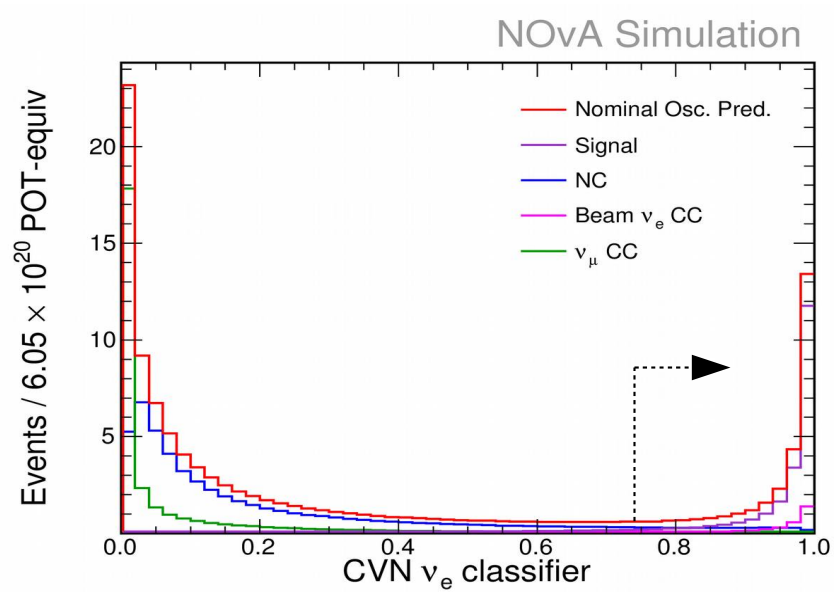


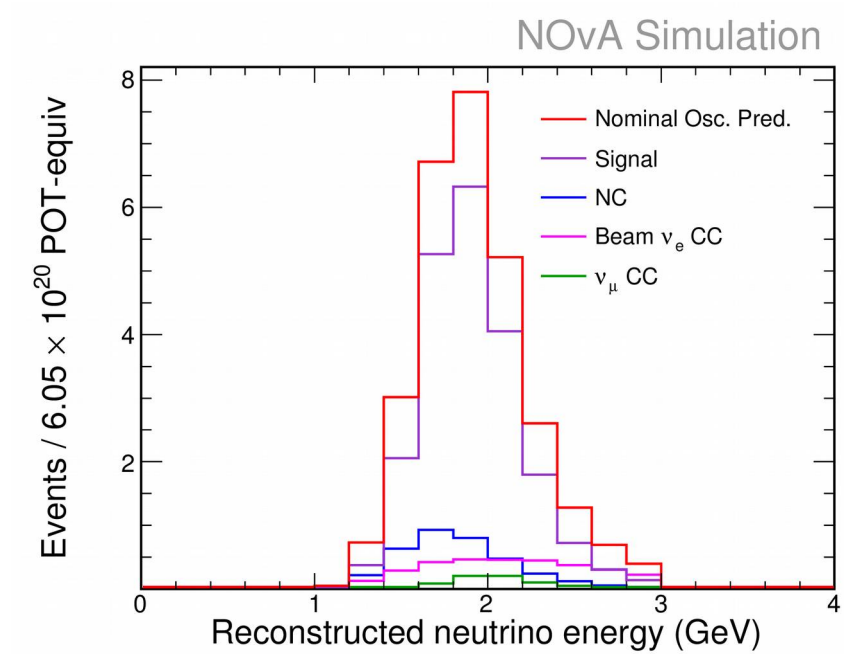
Convolutional layers learn filters to optimally extract features from the data.

arXiv:1604.01444 (submitted to JINST)

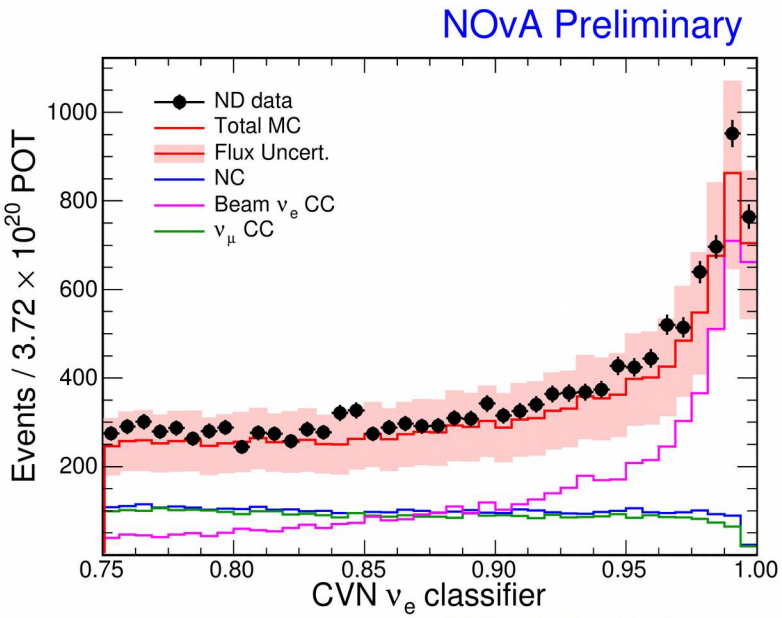
CVN as a ν_e Selector

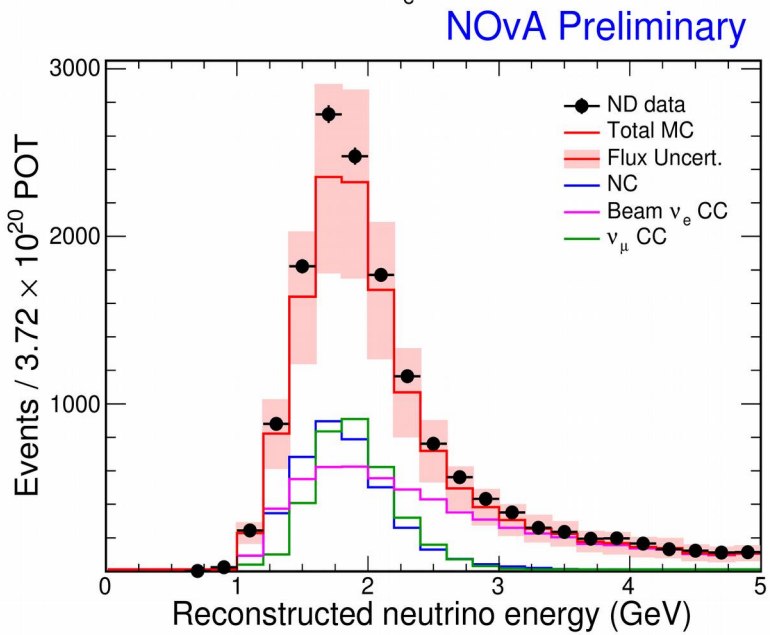
- CVN is trained to separate different neutrino flavors and interaction types.
  - Really a multiclassifier.
  - Different outputs can be used in a variety of analyses.
- The ν_e CC classifier output is a powerful PID.
  - 40% higher efficiency than 1st analysis event classifiers with similar purity.
- More details can be found in arXiv:1604.01444 (submitted to JINST).





ν_e Appearance Sensitivity: 2nd Analysis



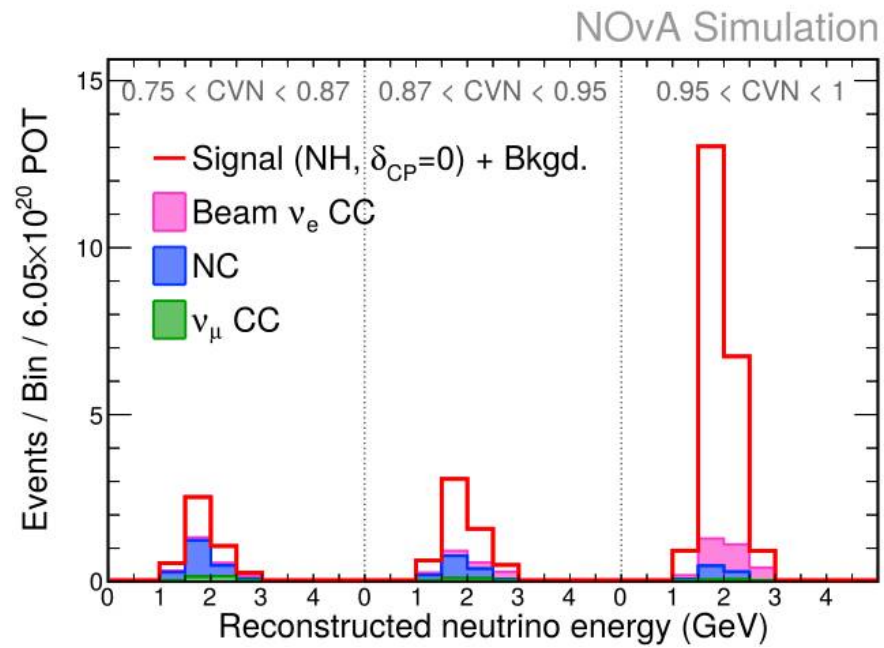


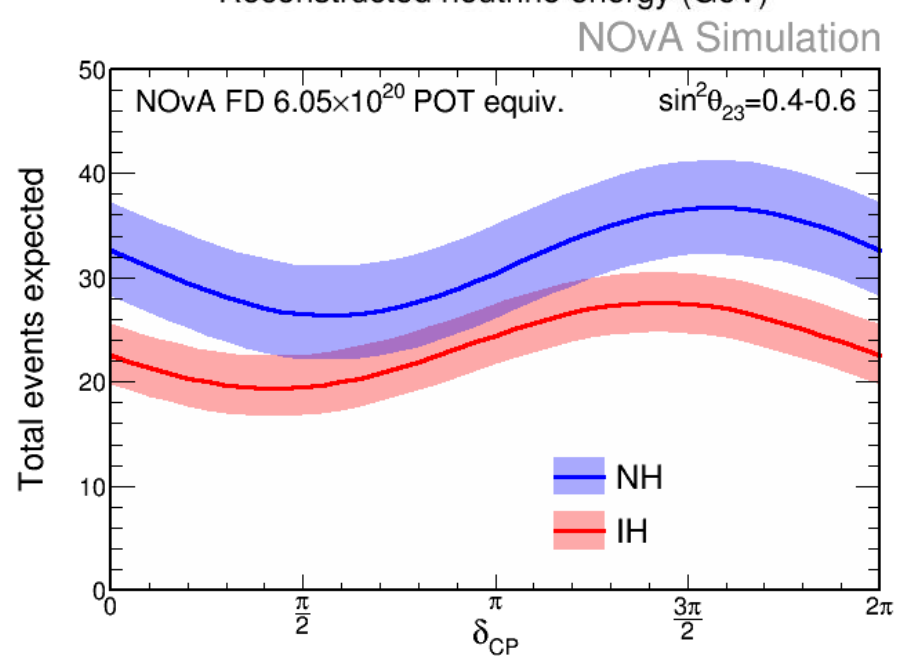
- Good data/MC agreement for the ND CVN output and ND reconstructed energy.
- Doubled dataset, improved selection efficiency, and loosening energy cuts doubles the sensitivity to ν_e appearance.

	Signal (NH, δ_{CP} = $3\pi/2$)	Beam Bkg	Cosmic Bkg	S/sqrt(B)
1st Ana (LID)	6.0	0.94	0.06	6
2nd Ana (CVN)	21.3	3.11	0.05	12

Further ν_e Appearance Improvements

- Move from a counting experiment to a shape fit.
  - Binned in both reconstructed neutrino energy and CVN.
  - Improve signal acceptance by adding in lower-purity CVN bins.
- Improve the reconstructed energy by taking into account the EM and hadronic fractions of each event.
- Improve the FD spectrum prediction using new ND data decomposition techniques.





Summary

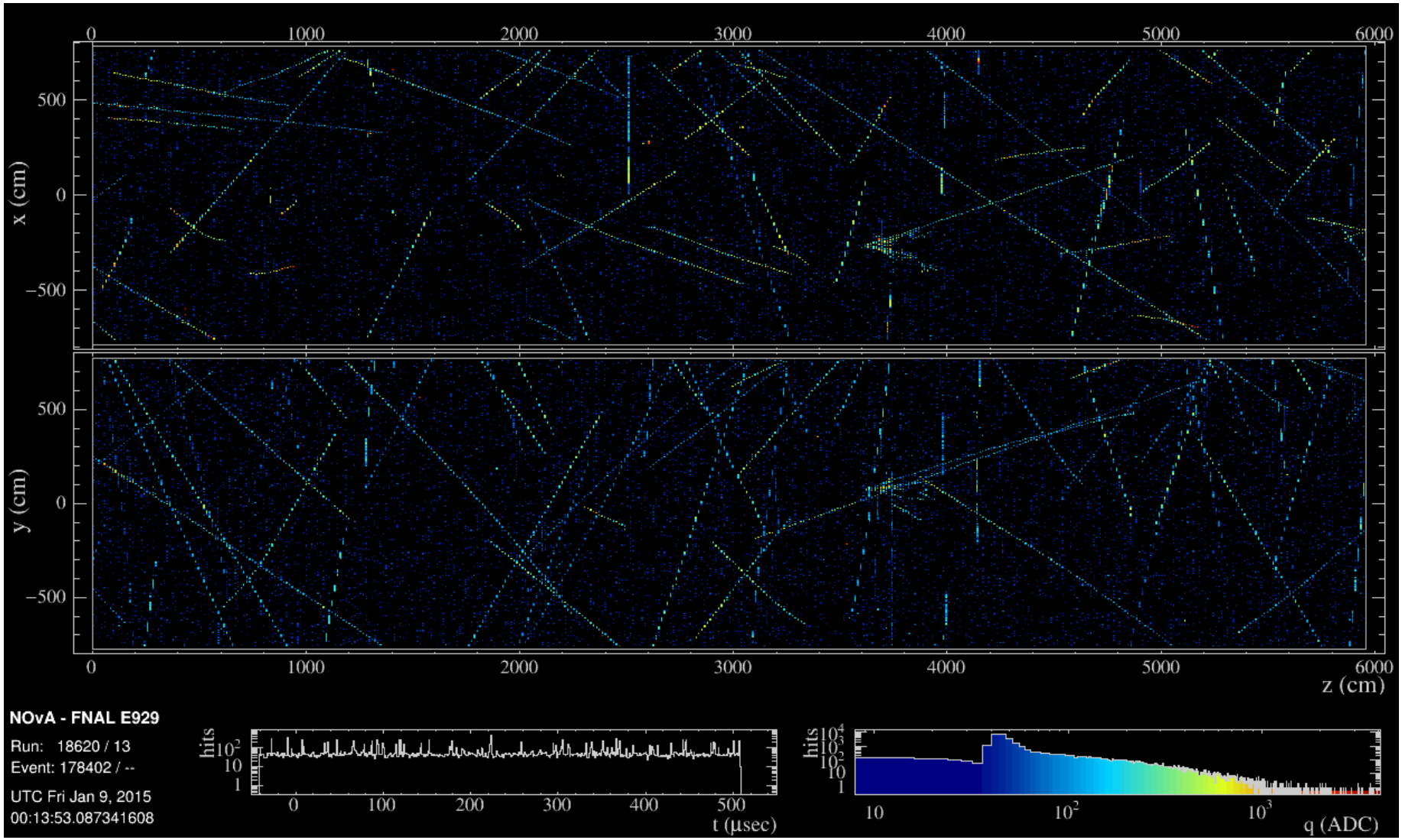
- We have analyzed our first dataset for both ν_μ disappearance and ν_e appearance.
  - Made a 7.5% measurement of Δm^2_{32} and a θ_{23} measurement consistent with maximal mixing.
  - Observed a ν_e appearance signal at 3.3σ significance for our primary selector.
    - Consistent with hints of the normal hierarchy and $\pi < \delta_{cp} < 2\pi$
- We have doubled our dataset and made significant improvements to both the ν_μ disappearance and ν_e appearance analyses.
  - In particular, improving hadronic energy data/simulation agreement and ν_e event selection.
- **Stay tuned for NOvA's 2nd analysis results!**

Thank you!

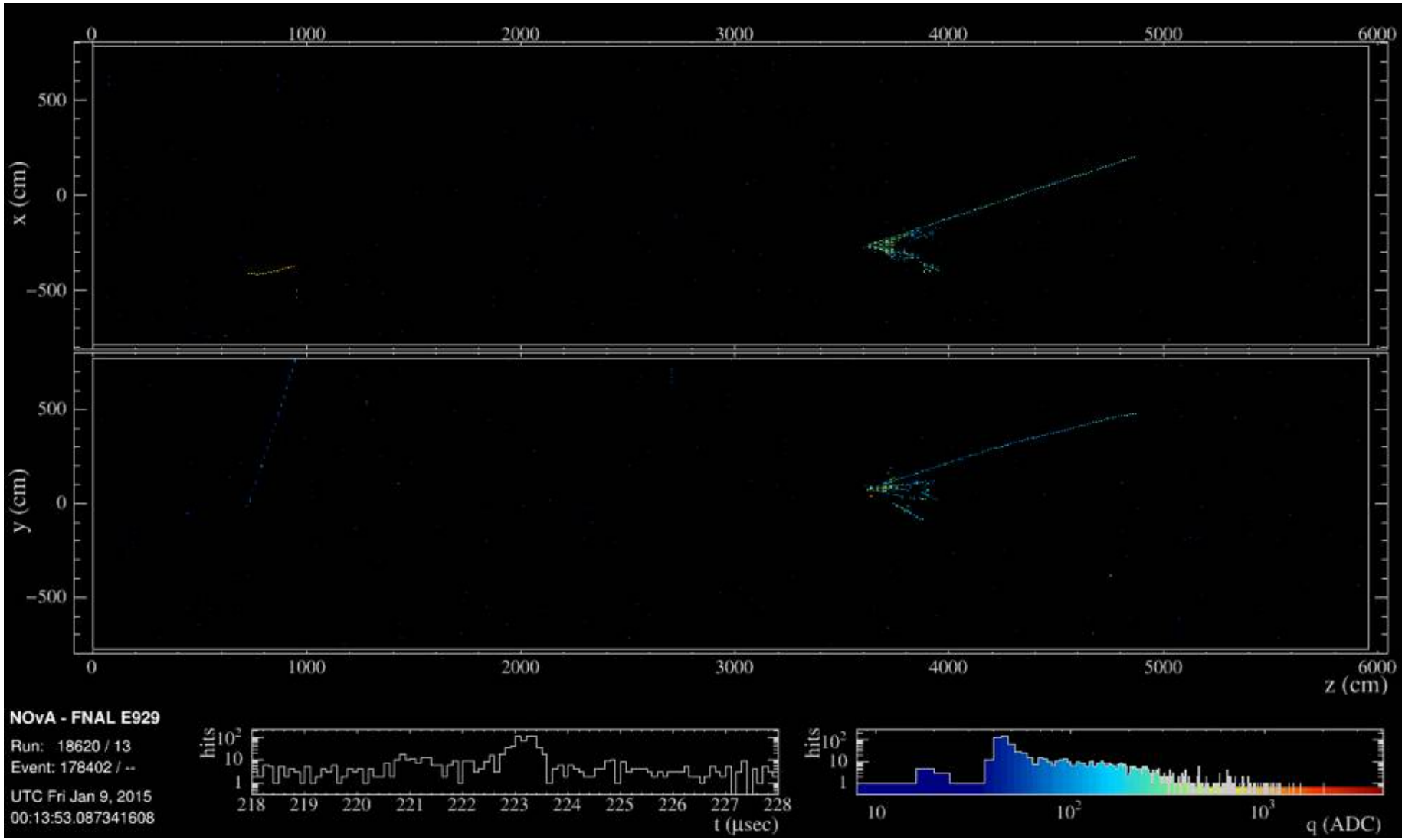
- New Perspectives Talks and Posters:
  - J. Sepulveda-Quiroz "NOvA in 10 minutes"
  - J. Vasel "Finding Neutrinos: The Design of the NOvA Timing and Synchronization System"
  - K. Maan "Data-Driven Constraint on the Total Neutrino Flux using ν_e Elastic Scattering in the NOvA Near Detector"
  - G. Brunetti "Measurement of ν_μ Induced Neutral Current π^0 Production Cross Section with the NOvA Near Detector"
  - S. Kasetti "Sterile Neutrino Oscillations At the NOvA Near Detector"
  - P. Singh "Attenuation Calibration of the NOvA Detectors"
  - J. Sepulveda-Quiroz "The Muon Neutrino Disappearance Analysis at NOvA"
  - S. Yang "Search for Sterile Neutrino Mixing Through Neutral Current Disappearance at NOvA"
  - J. Wolcott "Constraining GENIE using NOvA Internal and External Data"
  - B. Behara "Measurement of ν_μ Induced Neutral Current π^0 Production Cross-Section with NOvA Near Detector"

Backup Slides

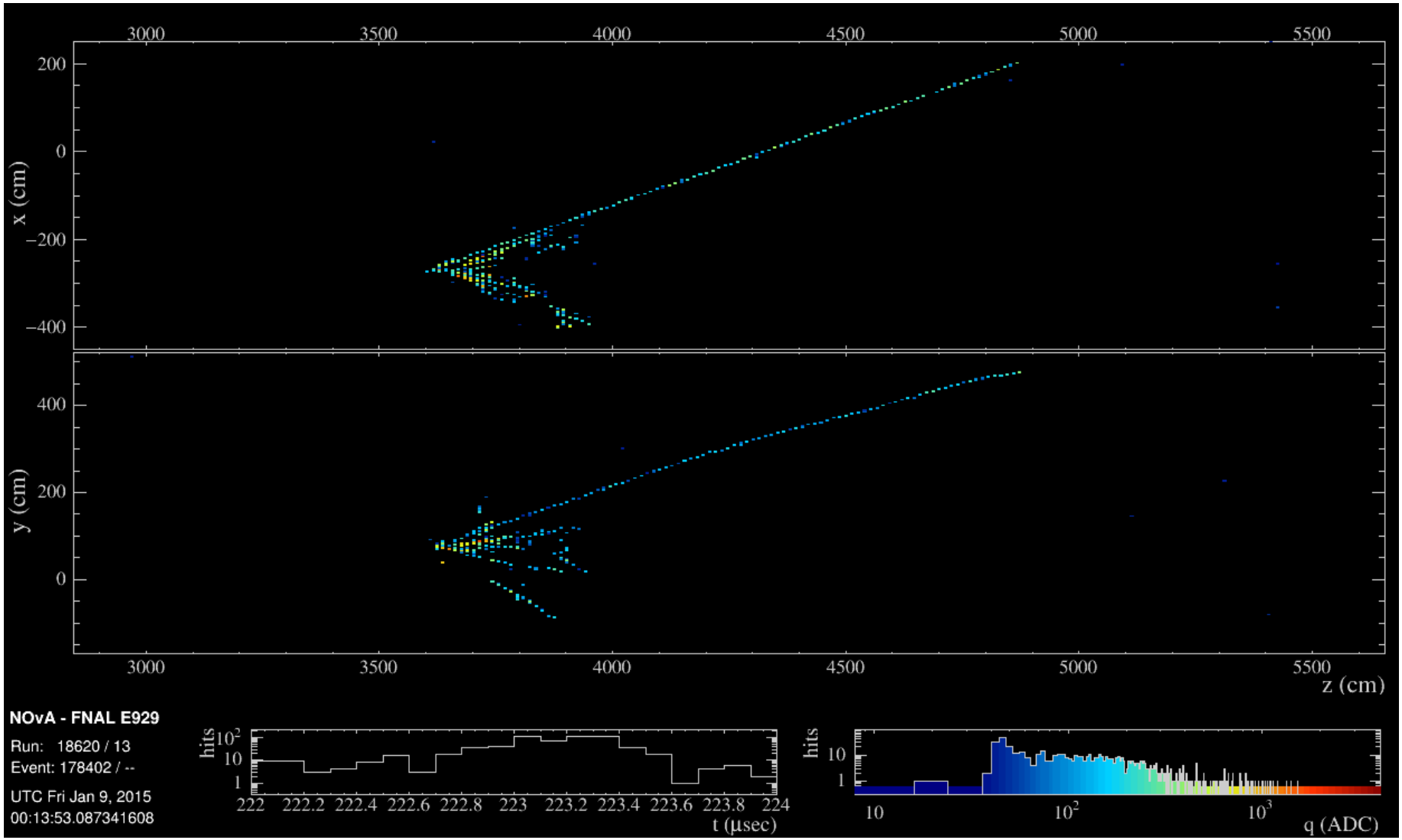
550 μs Far Detector Exposure



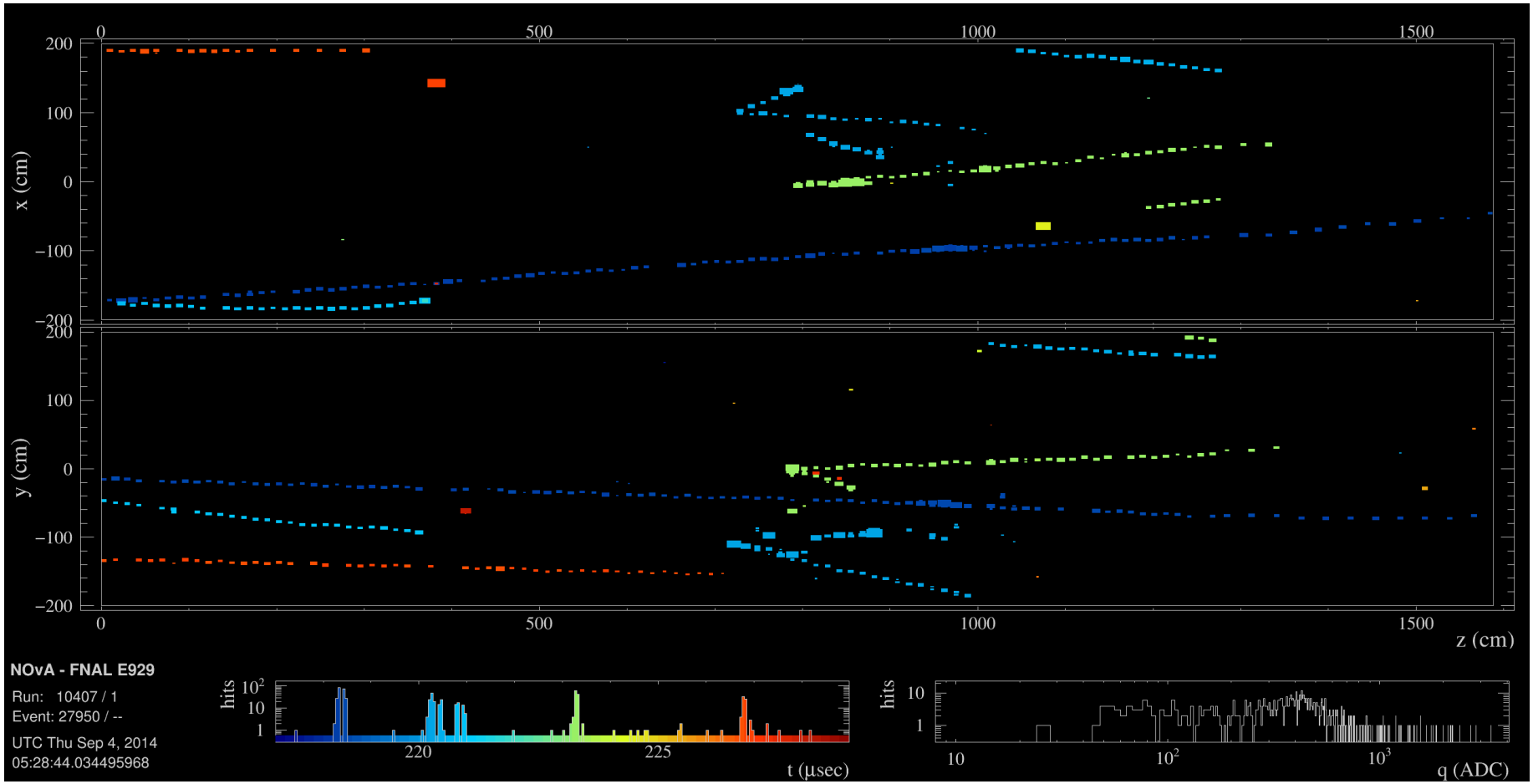
Zoomed in on 9.6 μs Beam Window



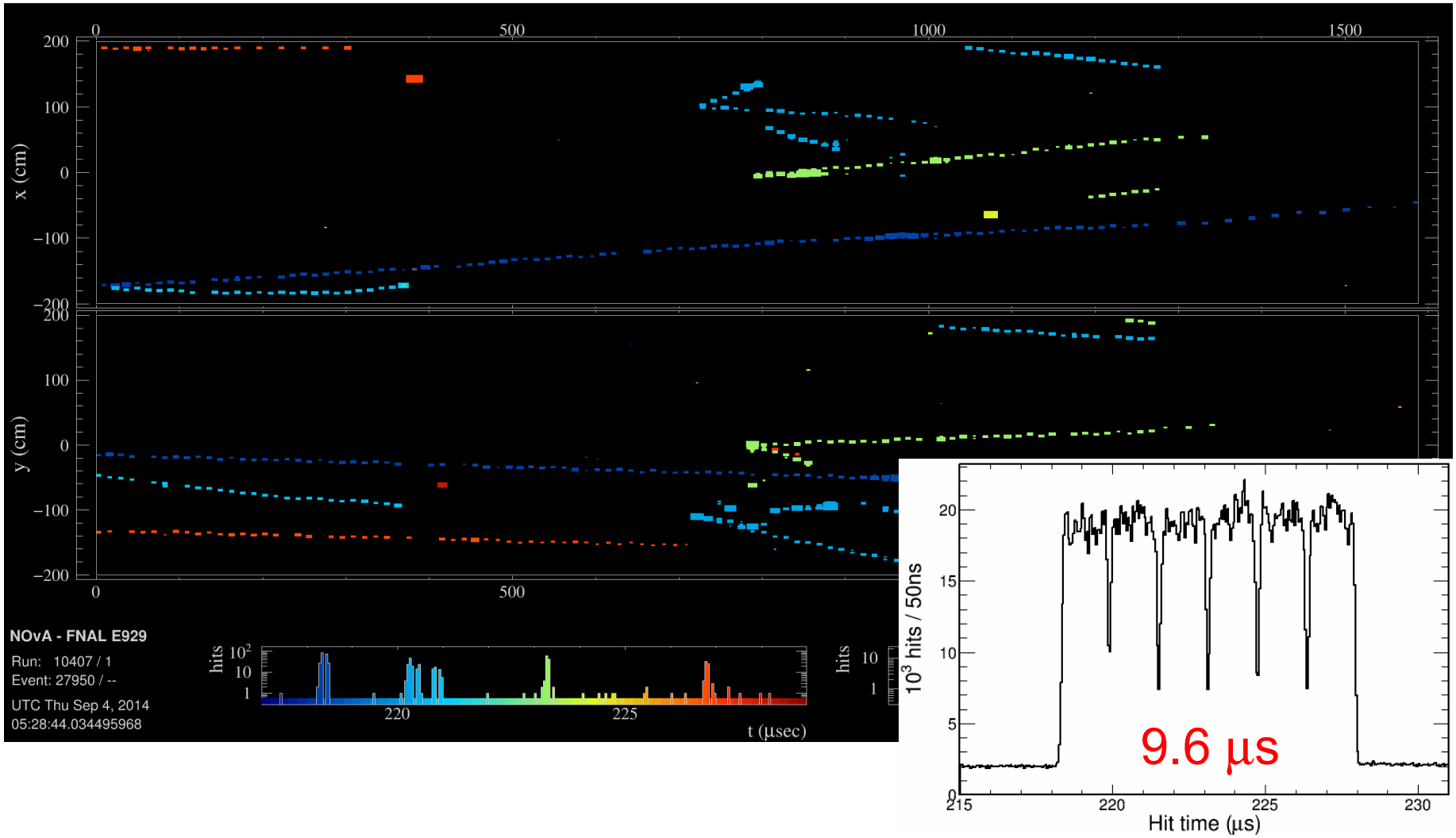
Zoomed in Spatially



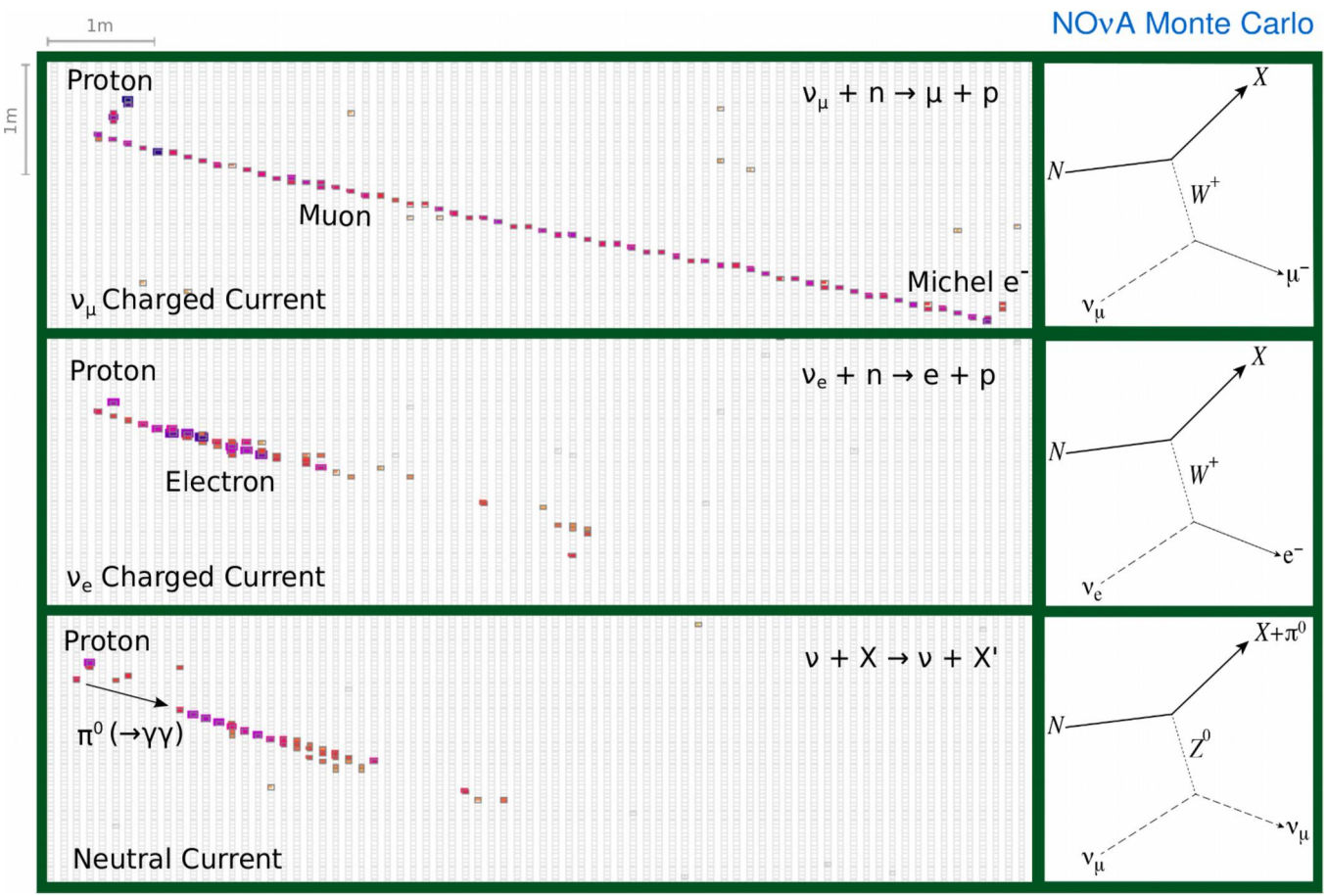
Neutrinos in the Near Detector



Neutrinos in the Near Detector

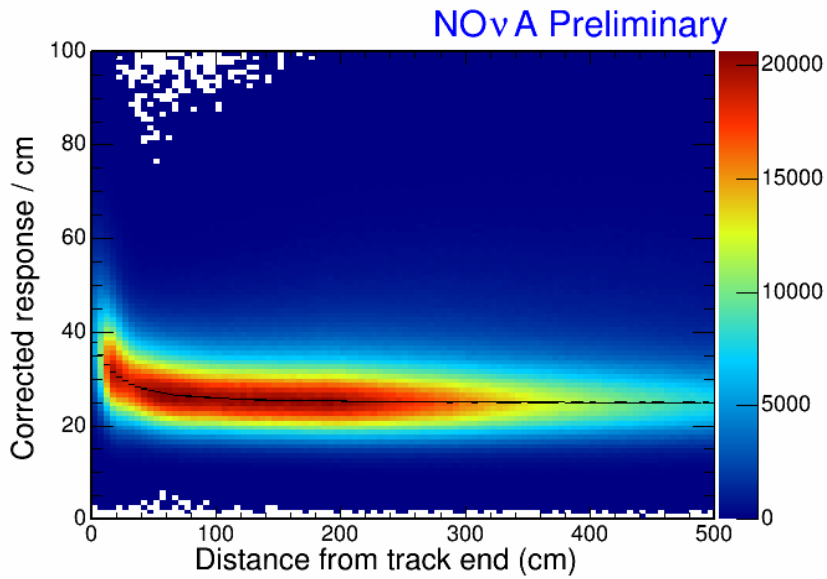


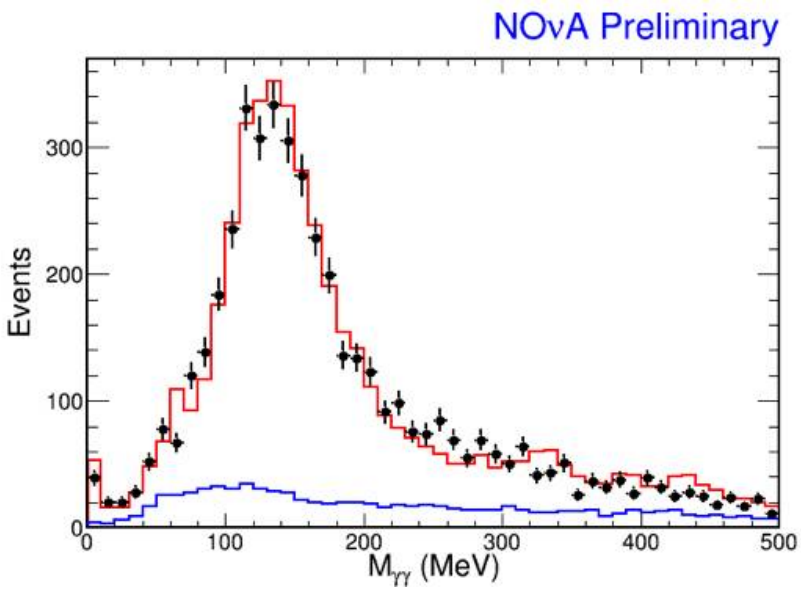
Event Topologies



- Excellent spatial granularity.
- Muons look like long tracks
- Low Z material (0.15 X_0 per plane) allows for seeing the development of electron showers.
- NC can look very similar to electron showers, but there is sometimes a gap between the start of the event and the beginning of the π^0 shower.

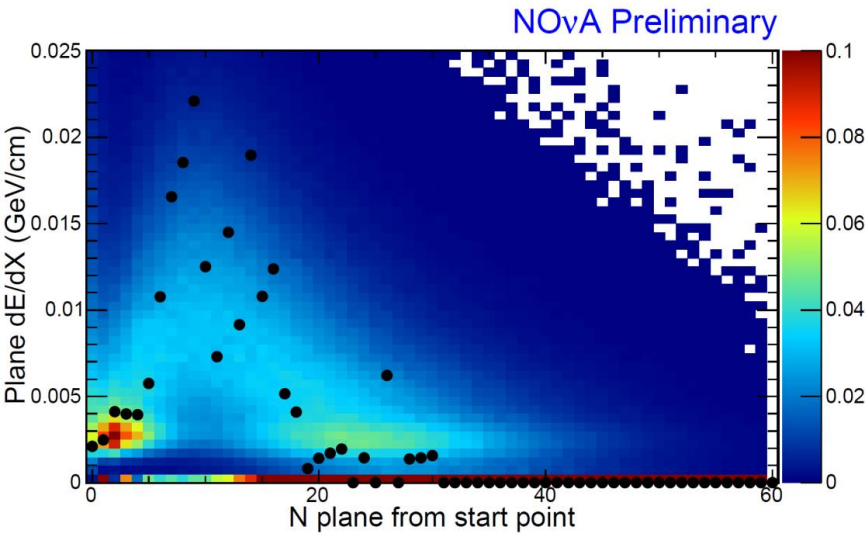
Calibration

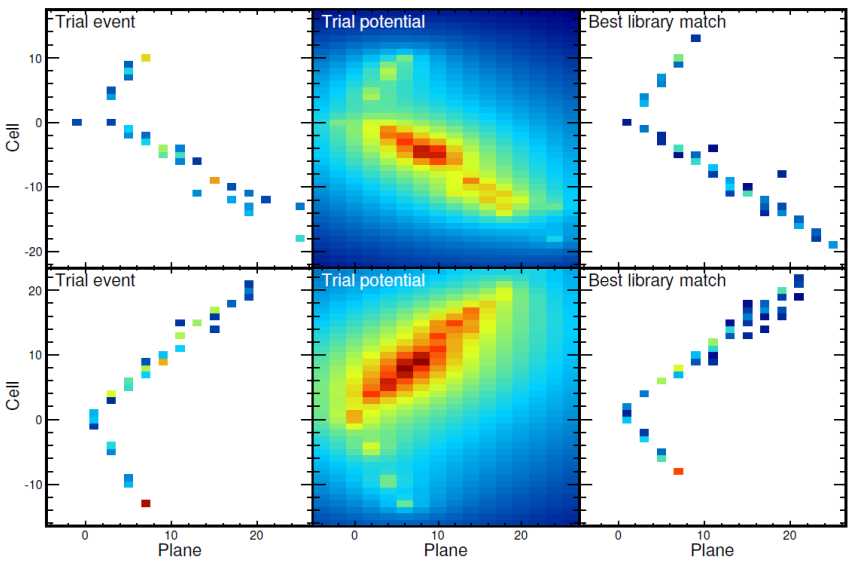




- Use cosmic muons to determine channel-to-channel and attenuation calibrations.
- Use stopping muons as a standard candle for setting the absolute energy scale.
- Multiple cross-checks:
  - cosmic muon dE/dx
  - beam muon dE/dx
  - Michel e^- spectrum
  - **π^0 mass**
  - hadronic shower energy per hit
- All samples agree within 5%.

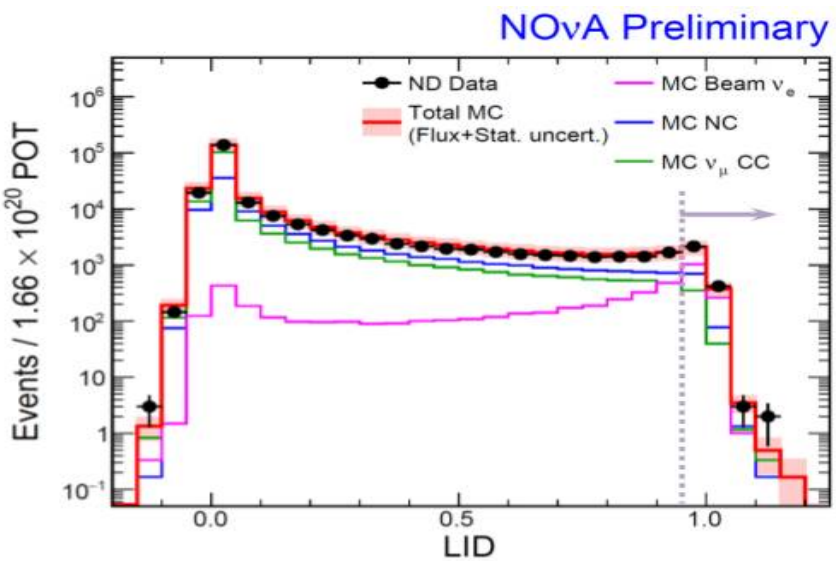
ν_e Selection

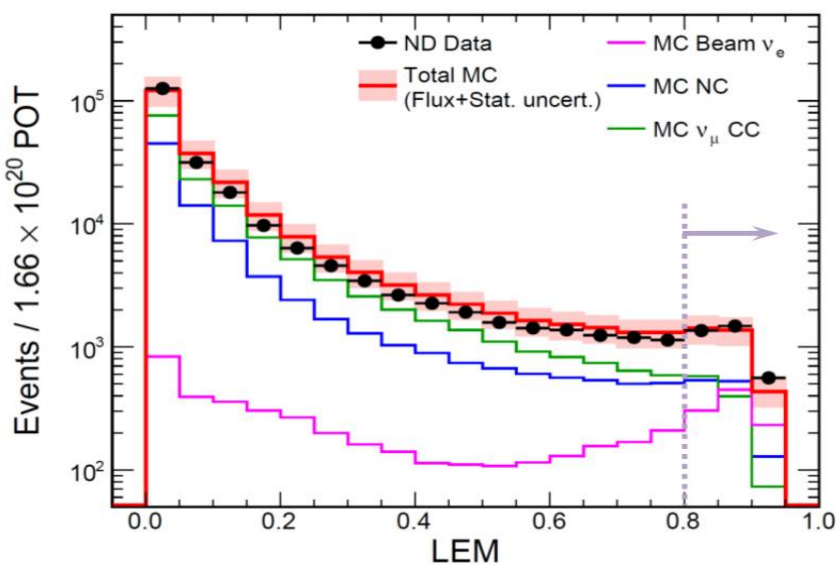




- LID
  - Calculates transverse and longitudinal dE/dx likelihoods for various particle hypotheses.
  - These, plus topological features, are fed into a standard neural network
- LEM
  - Finds best matches to a library of simulated events.
  - Properties of the best matches are fed into a decision tree.

ν_e Selection

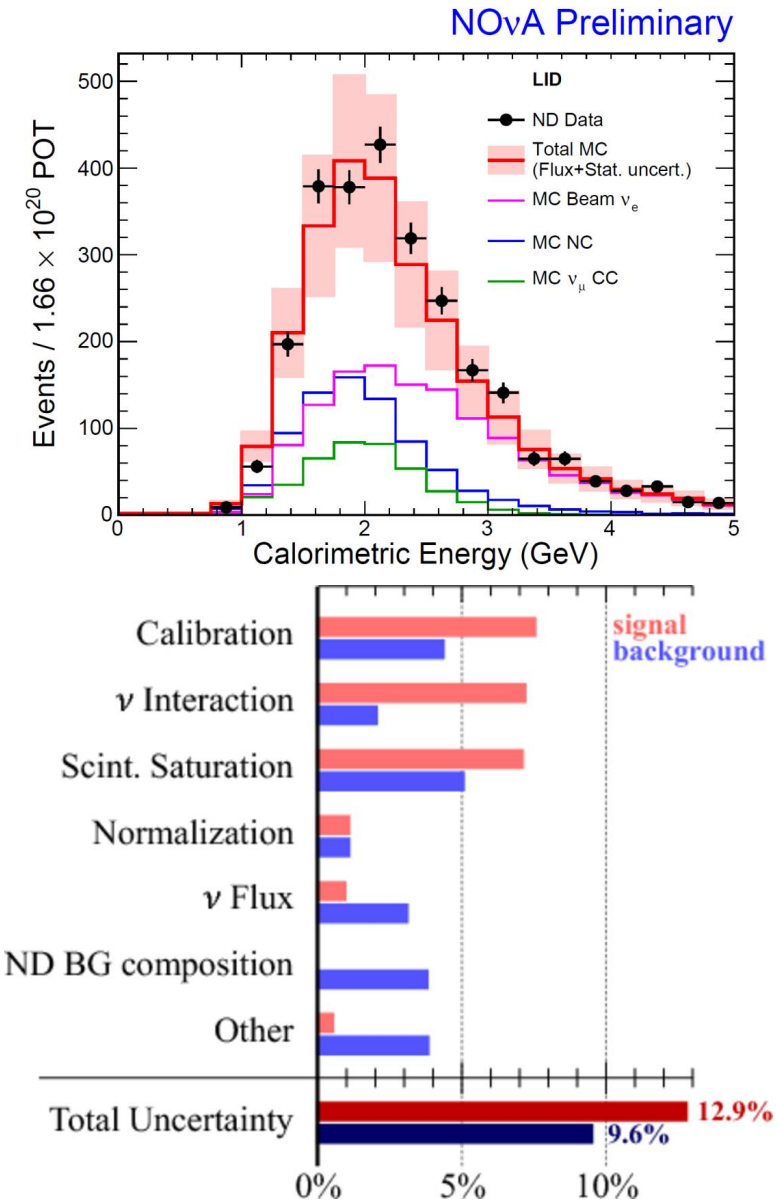




- LID
  - Calculates transverse and longitudinal dE/dx likelihoods for various particle hypotheses.
  - These, plus topological features, are fed into a standard neural network
- LEM
  - Finds best matches to a library of simulated events.
  - Properties of the best matches are fed into a decision tree.

Good data/MC agreement over the full PID range for both selectors.

FD Prediction



- Good data/MC agreement for ND energy spectrum.
- Data selects ~5% more events than MC.
- Use simulated Far/Near ratio bin-by-bin to extrapolate ND data.
  - Predicted oscillated ν_e from ND ν_μ events.
  - Extrapolate beam ν_e and NC events to predict FD beam backgrounds.
- FD cosmic rate determined from out of time FD data.
- Most systematics assessed by modifying the Near and Far MC and calculating the variation in the prediction.

Signal and Background Predictions

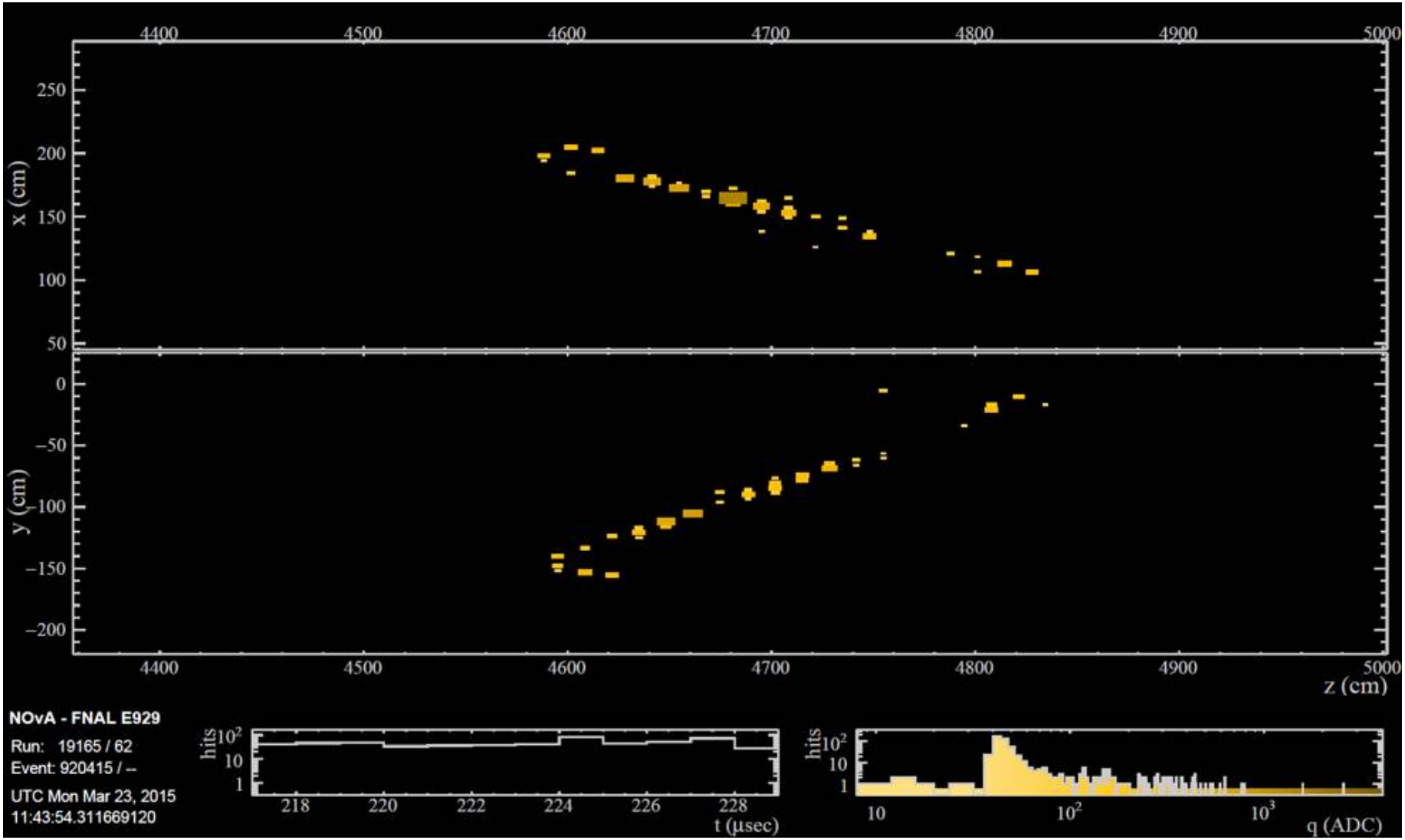
- Background prediction for both selectors is ~1 event with 10% systematic uncertainty.
- Selected backgrounds are dominated by beam ν_e and neutral current events.
  - Beam ν_e events are irreducible – can only be exclude if they are outside our chosen energy window.
  - Most selected neutral current events contain an energetic π^0.
- Signal prediction depends on chosen oscillation parameters.
- Both selectors have ~same performance. Prior to unblinding, decided to show results using both selectors, but use the more traditional LID as our primary selector.

	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	0.94 ± 0.09	0.47	0.36	0.05	0.02	0.06
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

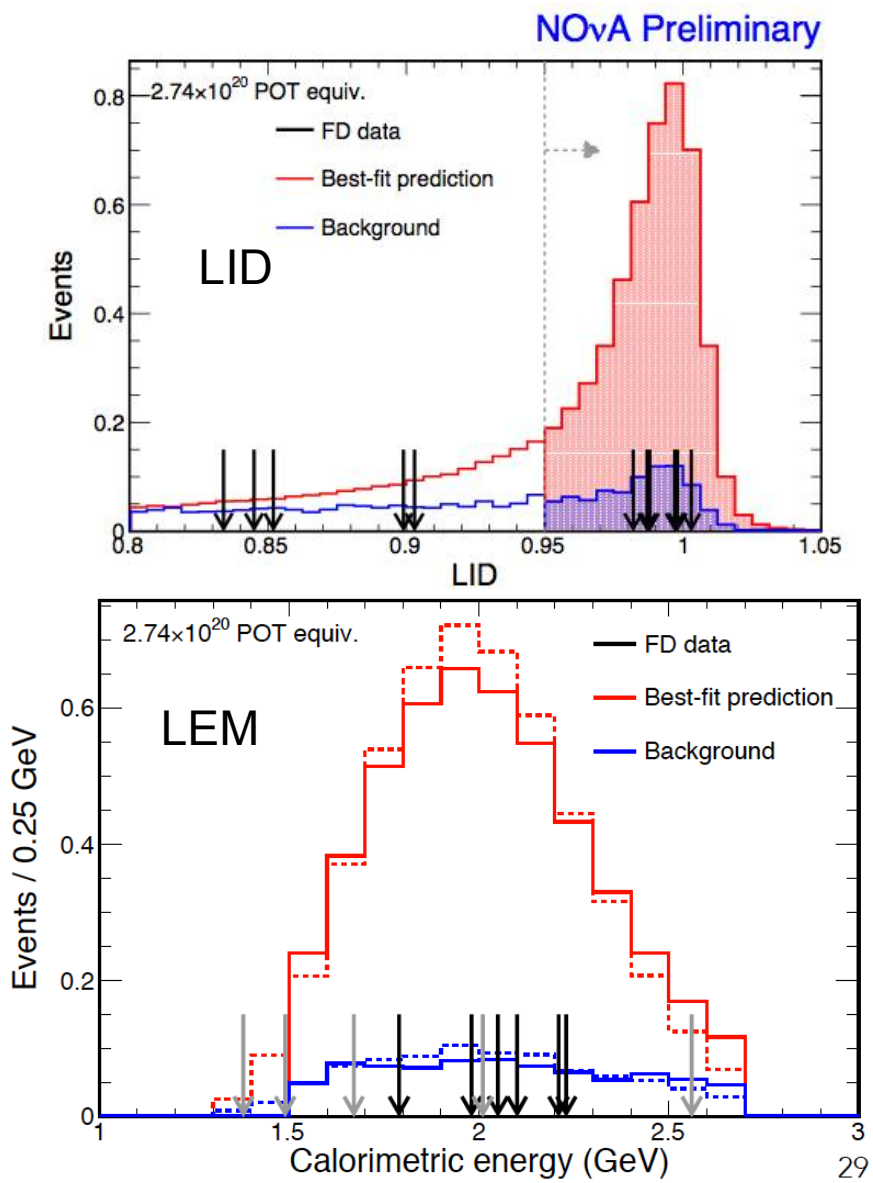
Signal prediction:
Chosen parameters reflect the outer range of possible results.

	NH, δ_{CP}= 3π/2	IH, δ_{CP} = π/2
LID	5.62 ± 0.72	2.24 ± 0.29
LEM	5.91 ± 0.59	2.34 ± 0.23

Selected ν_e Candidate

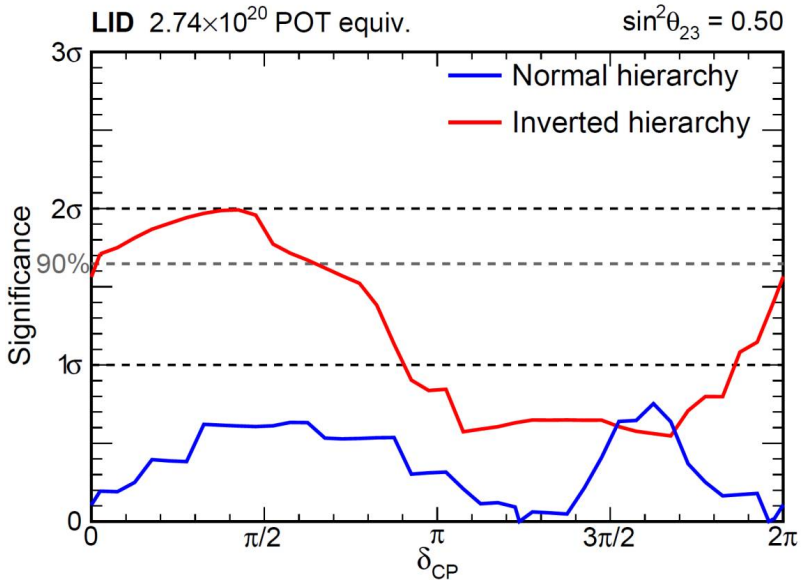


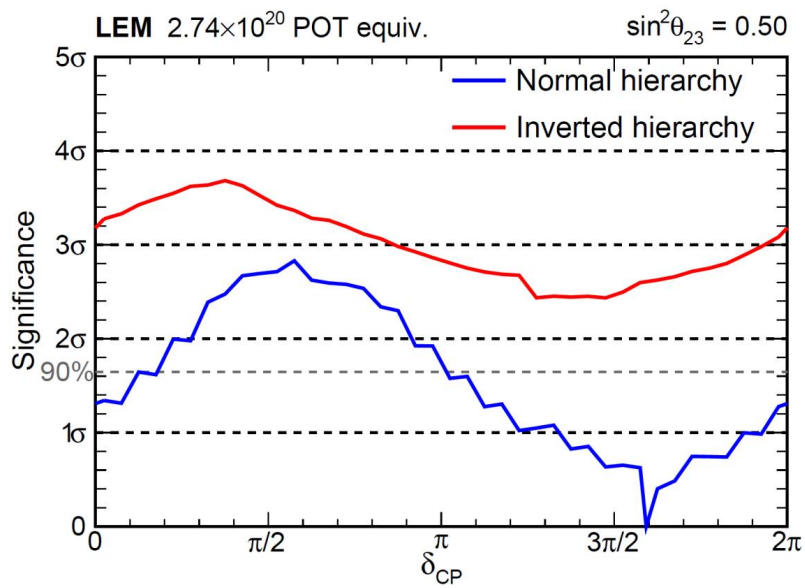
Selected Events



- LID selects 6 events
  - 3.3σ significance for ν_e appearance.
- LEM selects 11 events
  - 5.5σ sigificance for ν_e appearance.
- All 6 LID events are also selected by LEM.
  - Trinomial probability of selecting this combination (11:6/5/0) is 9.2%.

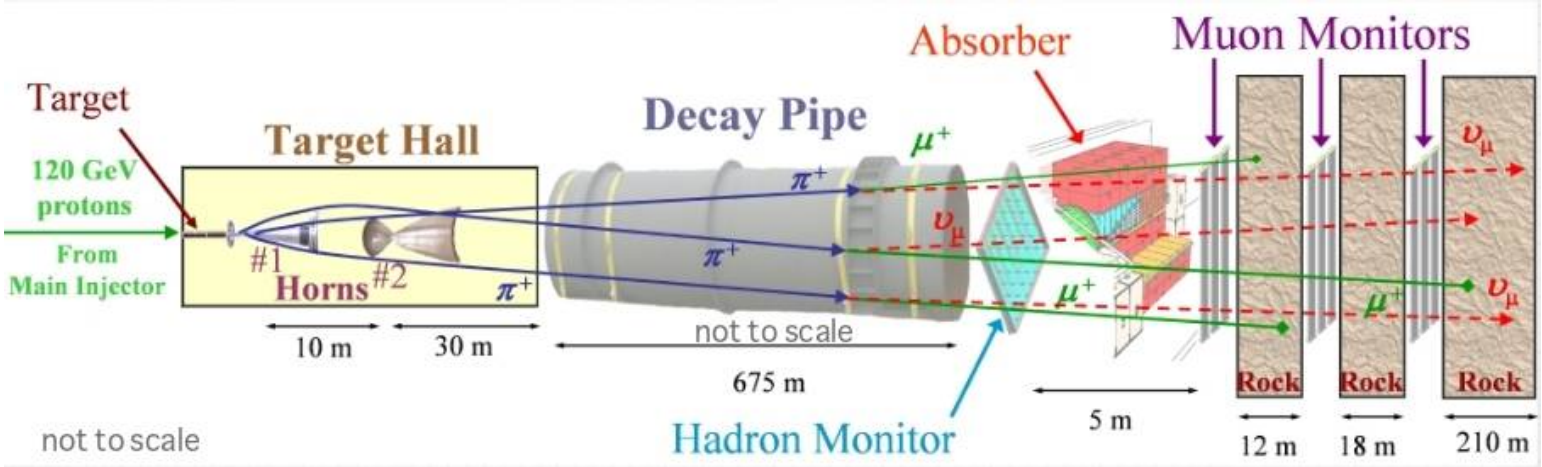
ν_e Results





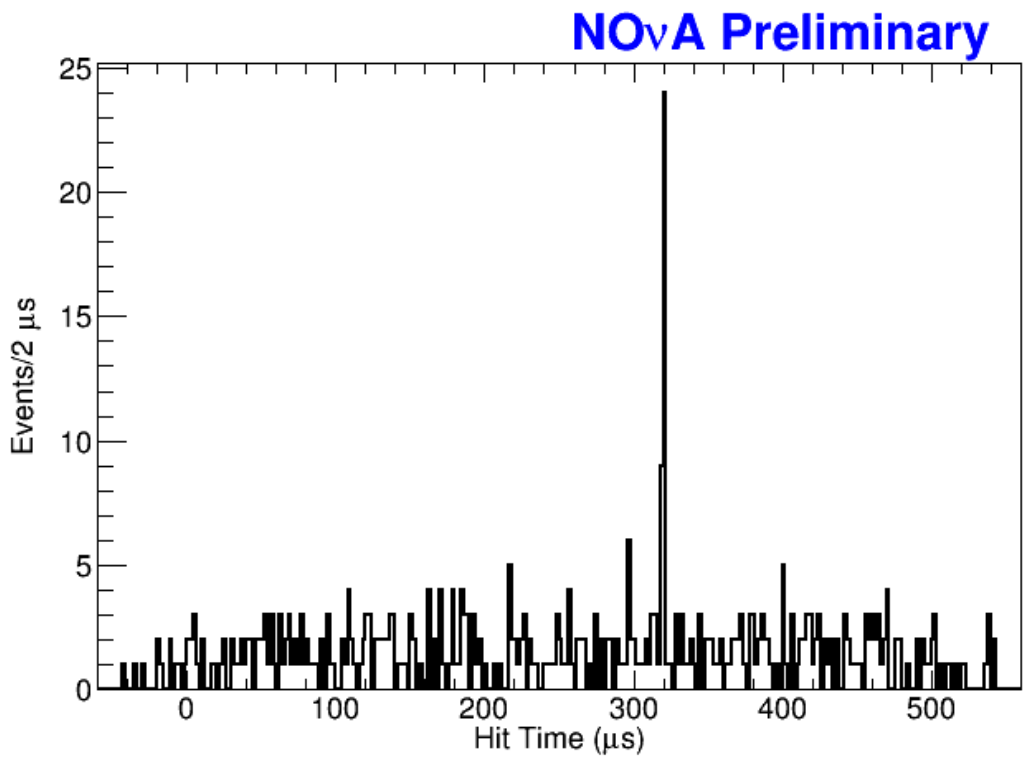
- Apply the global reactor constraint of $\sin^2 2\theta_{13} = 0.086 +/- 0.05$ to eliminate the θ_{13} axis.
- Explore compatibility with mass hierarchy and δ_{CP} using Feldman-Cousins.
- Jagged shape due to the discrete nature of counting experiment.
- Disfavor IH for $0 < \delta_{CP} < 0.6\pi$ at 90% CL with primary selector.
- Both selectors prefer NH, both prefer δ_{CP} near $3\pi/2$.

NuMI Beam



- Protons from the Main Injector at 120 GeV strike a graphite target.
- The resulting pions and kaons are focused by two magnetic horns.
- The particles travel down a decay pipe, decaying to produce neutrinos.
- At the end, all remaining hadrons and muons are absorbed by rock leaving a beam entirely composed of neutrinos.
  - The neutrinos are almost entirely muon neutrinos.

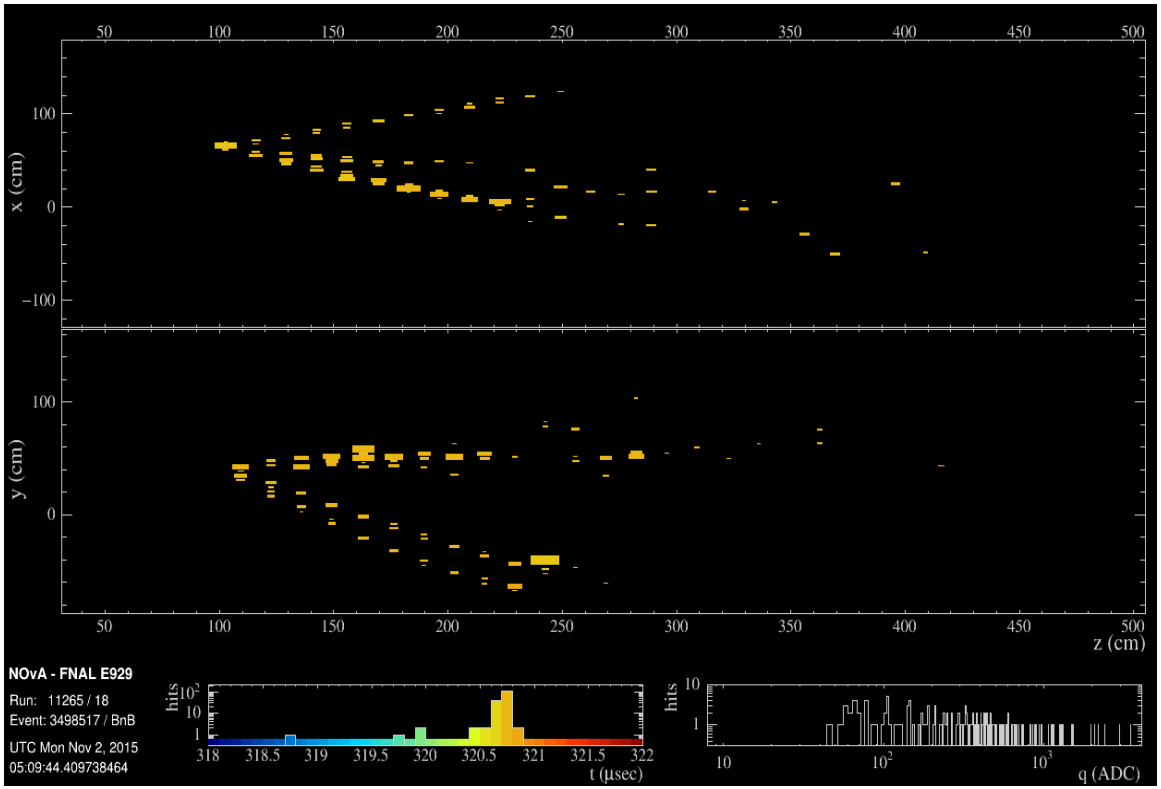
Booster Neutrinos



A significant timing peak can be seen in BNB triggered events.

- The booster neutrino beam (BNB), serving MicroBooNE, turned on mid-October.
- With a new trigger, the NOvA near detector is able to see these events.
- These events have a lower peak energy (~1.4 GeV) than NuMI neutrinos (~2 GeV).
- They have ~same L/E as neutrinos seen by MiniBooNE.
- NOvA may be able to study the MiniBooNE low energy excess.

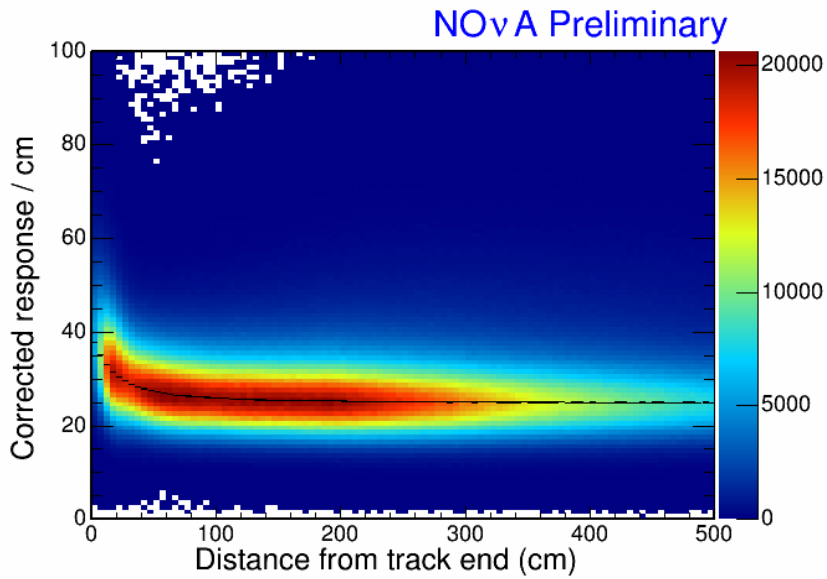
Booster Neutrinos

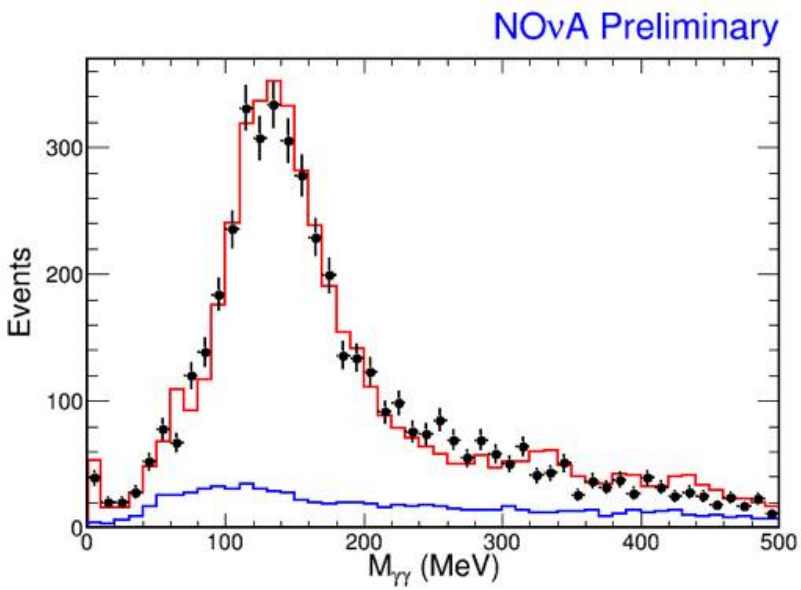


A BNB neutrino event in the NOvA near detector captured by the new BNB trigger.

- The booster neutrino beam (BNB), serving MicroBooNE, turned on mid-October.
- With a new trigger, the NOvA near detector is able to see these events.
- These events have a lower peak energy (~1.4 GeV) than NuMI neutrinos (~2 GeV).
- They have ~same L/E as neutrinos seen by MiniBooNE.
- NOvA may be able to study the MiniBooNE low energy excess.

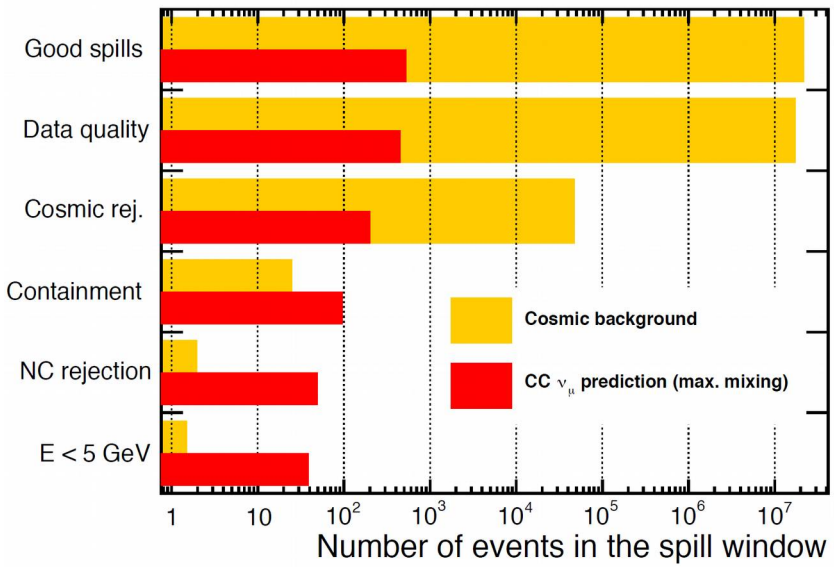
Calibration

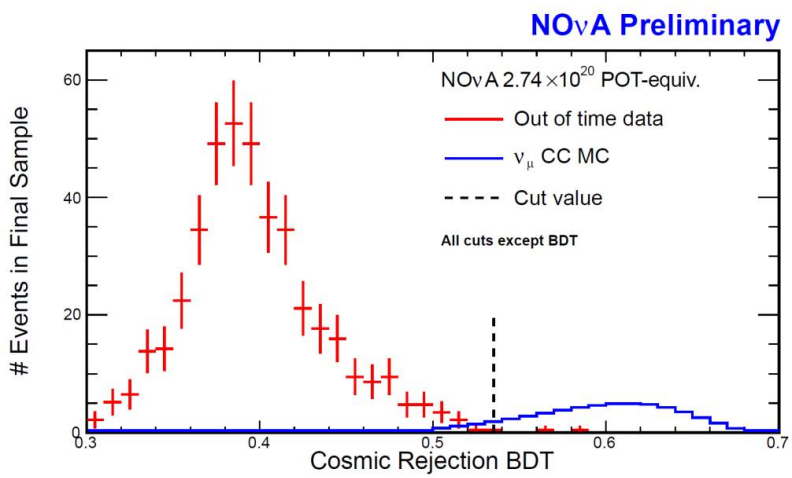




- Use cosmic muons to determine channel-to-channel and attenuation calibrations.
- Use stopping muons as a standard candle for setting the absolute energy scale.
- Multiple cross-checks:
  - cosmic muon dE/dx
  - beam muon dE/dx
  - Michel e^- spectrum
  - **π^0 mass**
  - hadronic shower energy per hit
- All samples agree within 5%.

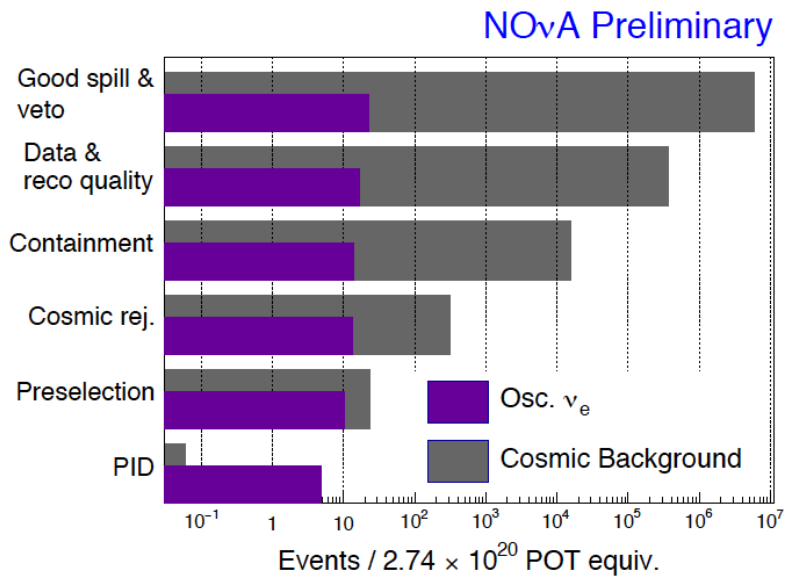
Cosmic Rejection for ν_μ

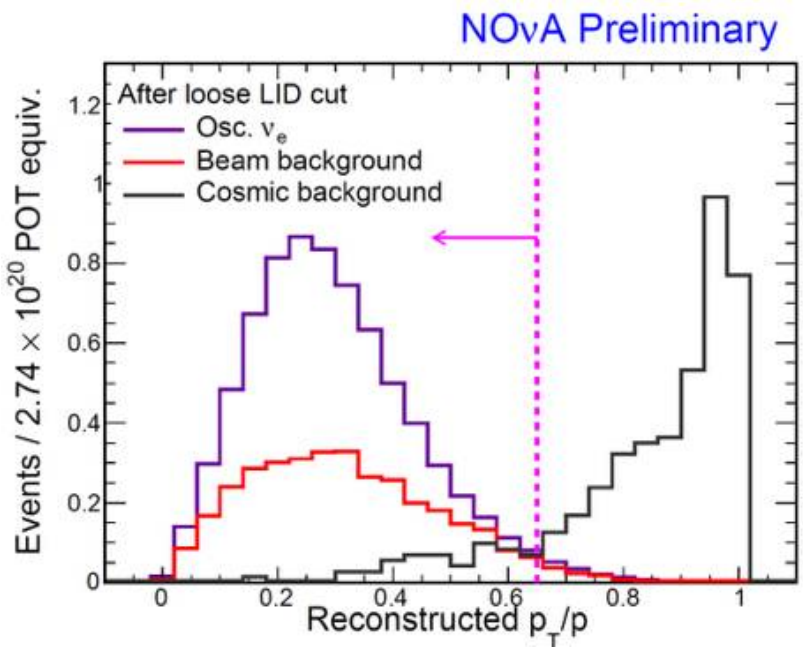




- Cosmic background rate is measured using the out-of-time window in data.
- Selecting a narrow window around the 9.6 μs spill gives a rejection factor of 10^5.
- 10^7 rejection factor reached by using a boosted decision tree to reject cosmic-like topologies based on:
  - Track direction, position, and length; energy and number of hits in the event.

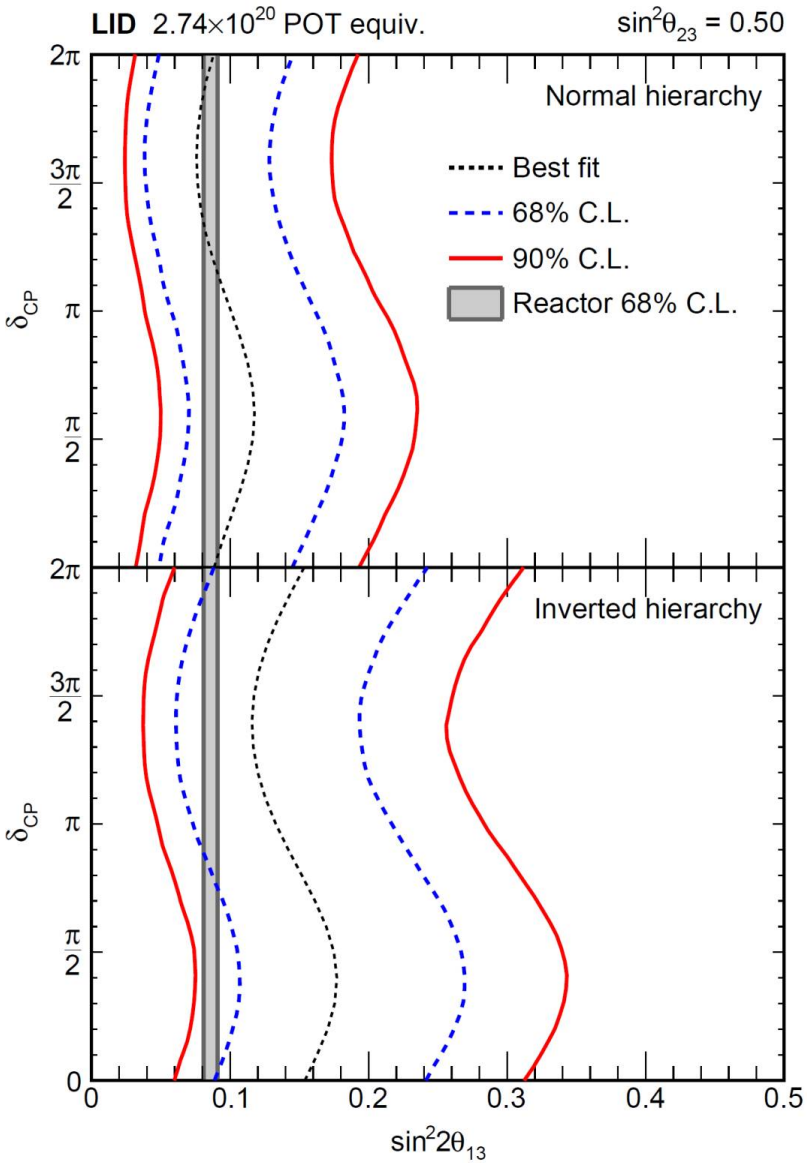
Cosmic Rejection for ν_e





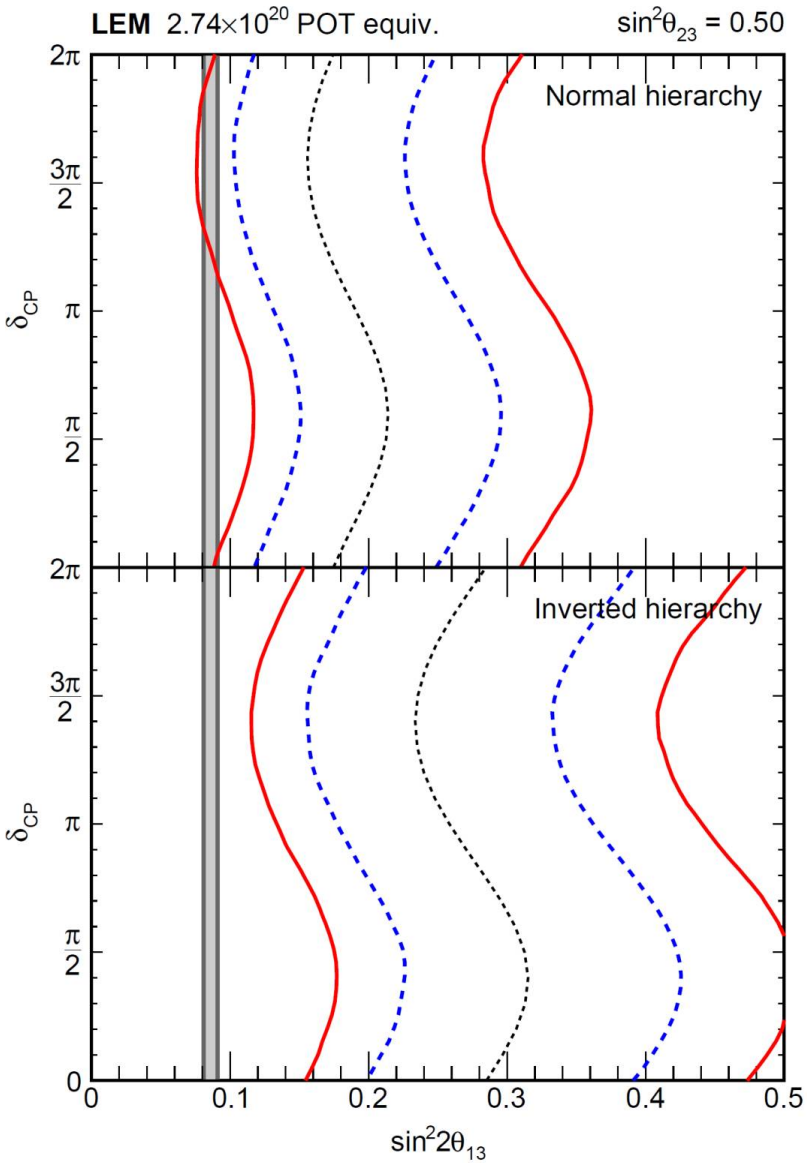
- Containment cuts.
- Topological cuts, such as p_T/p.
- The ν_e selectors provide additional rejection power to achieve better than 1 part in 10^8 rejection of cosmic ray interactions.
- We expect 0.06 cosmic events to pass our cuts.

ν_e LID Results



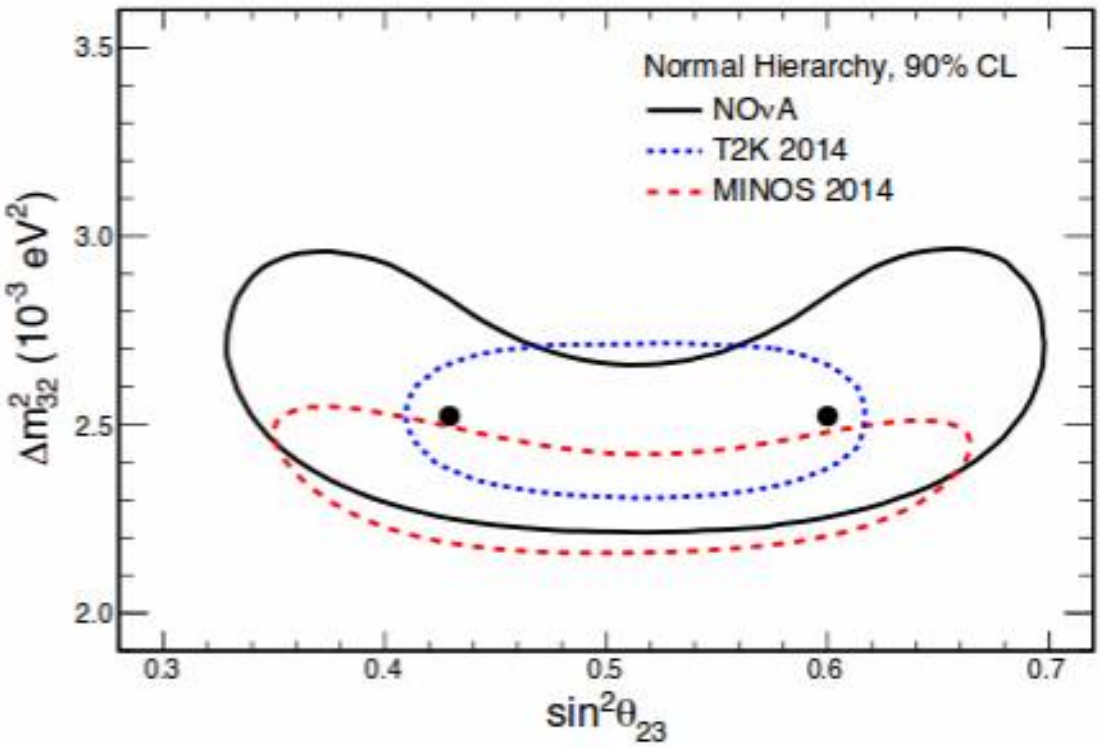
- Results consistent between NOvA and reactor experiments for both NH and IH.
- Agreement is ~1σ better for NH.

ν_e LEM Results



- Curves are shifted right ~2x
- LEM has tension with the reactor experiments in both hierarchies.

ν_μ Disappearance Result: 1st Analysis



Normal Hierarchy

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

$\sin^2\theta_{23}$ in the 68% C.L. range [0.38, 0.65] with best fits 0.43 and 0.60

Inverted Hierarchy

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

$\sin^2\theta_{23}$ in the 68% C.L. range [0.37, 0.64] with best fits 0.44 and 0.59

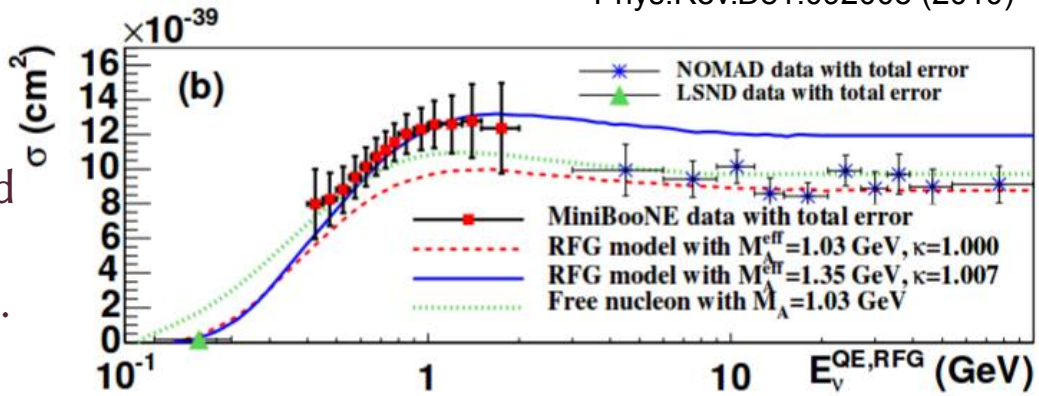
Already competitive with only 8% of nominal exposure!

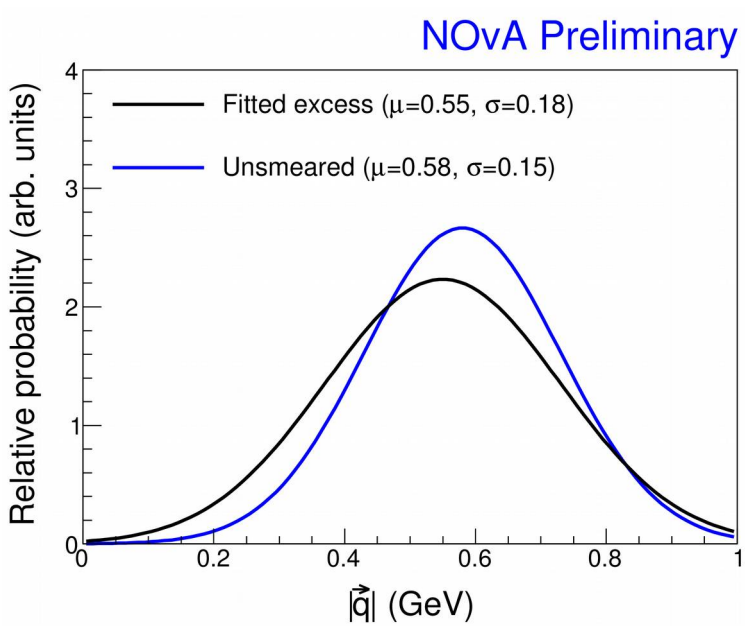
Published in Phys. Rev. D93, 051104(R)

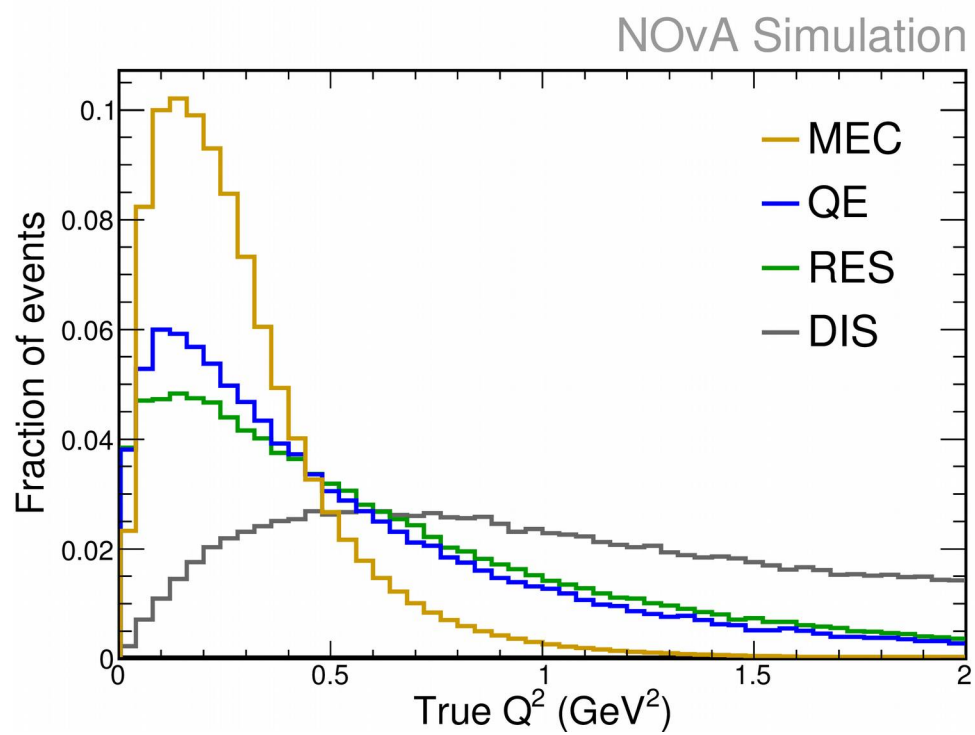
Meson Exchange Currents

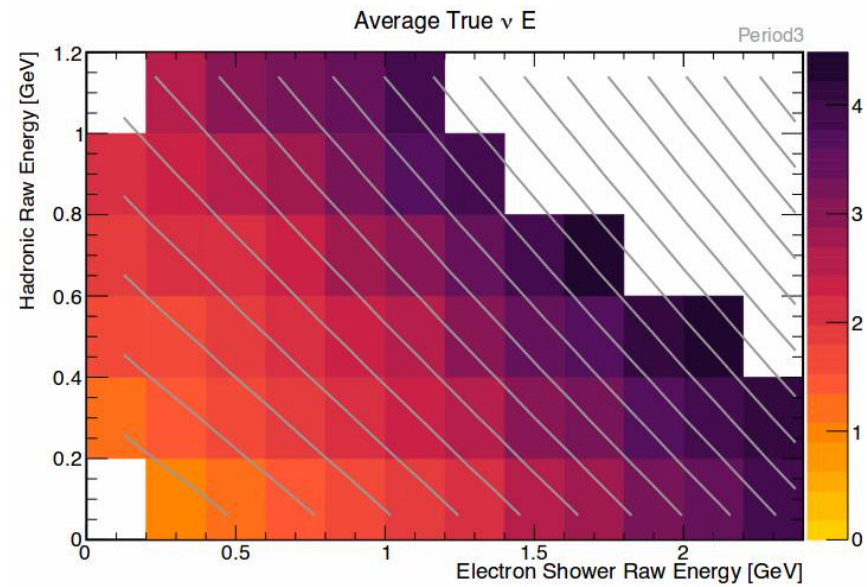
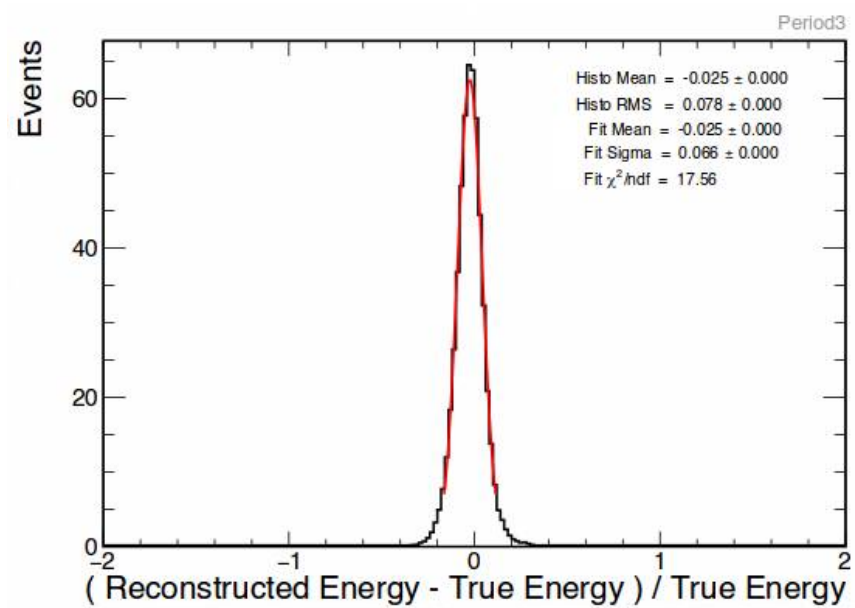
- MiniBooNE and NOMAD observed inconsistent quasi-elastic cross sections.
  - Possibly due to unmodeled scattering off of correlated nucleon pairs in the nucleus.
- GENIE has an empirical MEC model designed to reconcile MiniBooNE's QE cross section measurement with free nucleon cross section.
- Use this model, but reweight it using NOvA ND data.

Phys.Rev.D81:092005 (2010)







Energy Estimation

- Response of the detector is different for hadronic and EM deposits.
- Perform a quadratic fit to true neutrino energy as a function of measured hadronic and EM energy.
- Resulting energy resolution is 7% ⟶ 22% improvement over 1st analysis energy estimation.