Cosmic Muon Induced EM Showers in the NOνA Detectors

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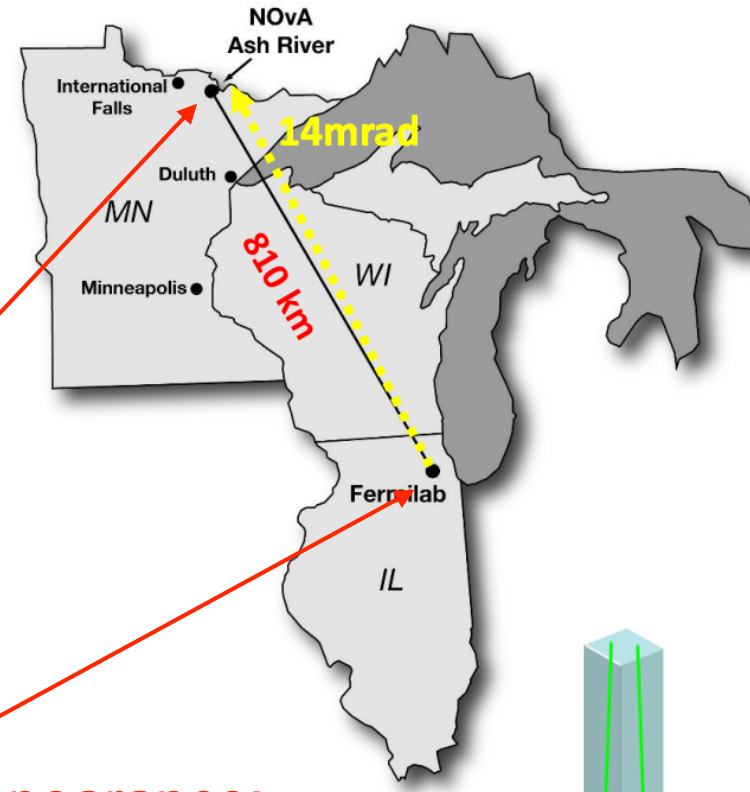
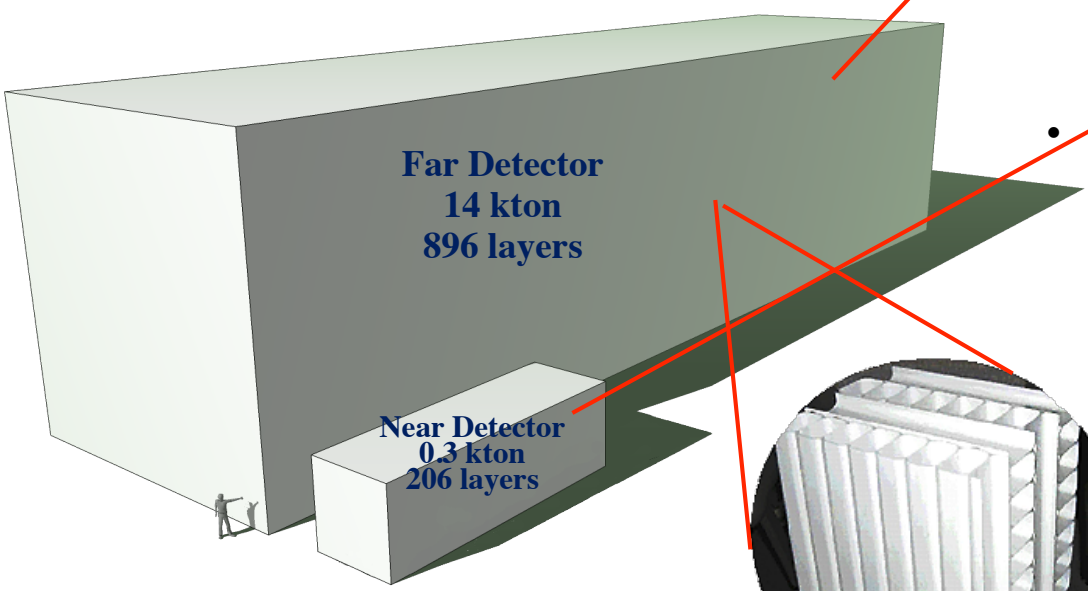
Outline

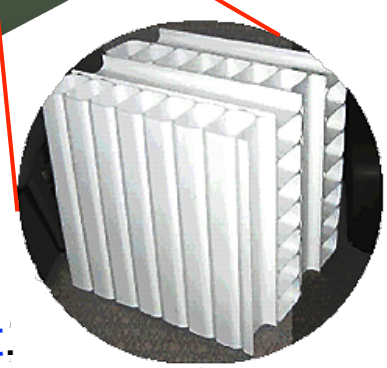
- Brief introduction to NOνA.
- A Muon-Removal technique is developed to get a pure EM shower sample from FD cosmic data.
- Those samples can be used to characterize the EM signature and provide checks of the MC simulation, PID algorithms, and calibration across the NOνA detectors.

NOνA Detectors

- NOνA (NuMI Off-axis ν_e Appearance) is a long-baseline neutrino oscillation experiment on NuMI beam at Fermilab.
- Two liquid-scintillator detectors.
  - Far: 14 kton, 15.6mX15.6mX59.8m, 810 km from source, on the surface (Cosmic!).
  - Near: 0.3 kton, 4.2mX4.2mX15.8m, 1 km from source, underground.

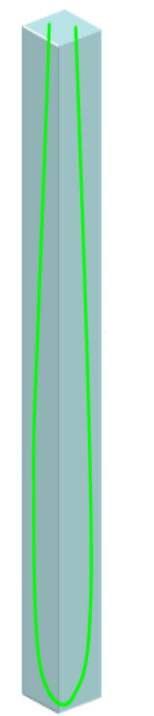




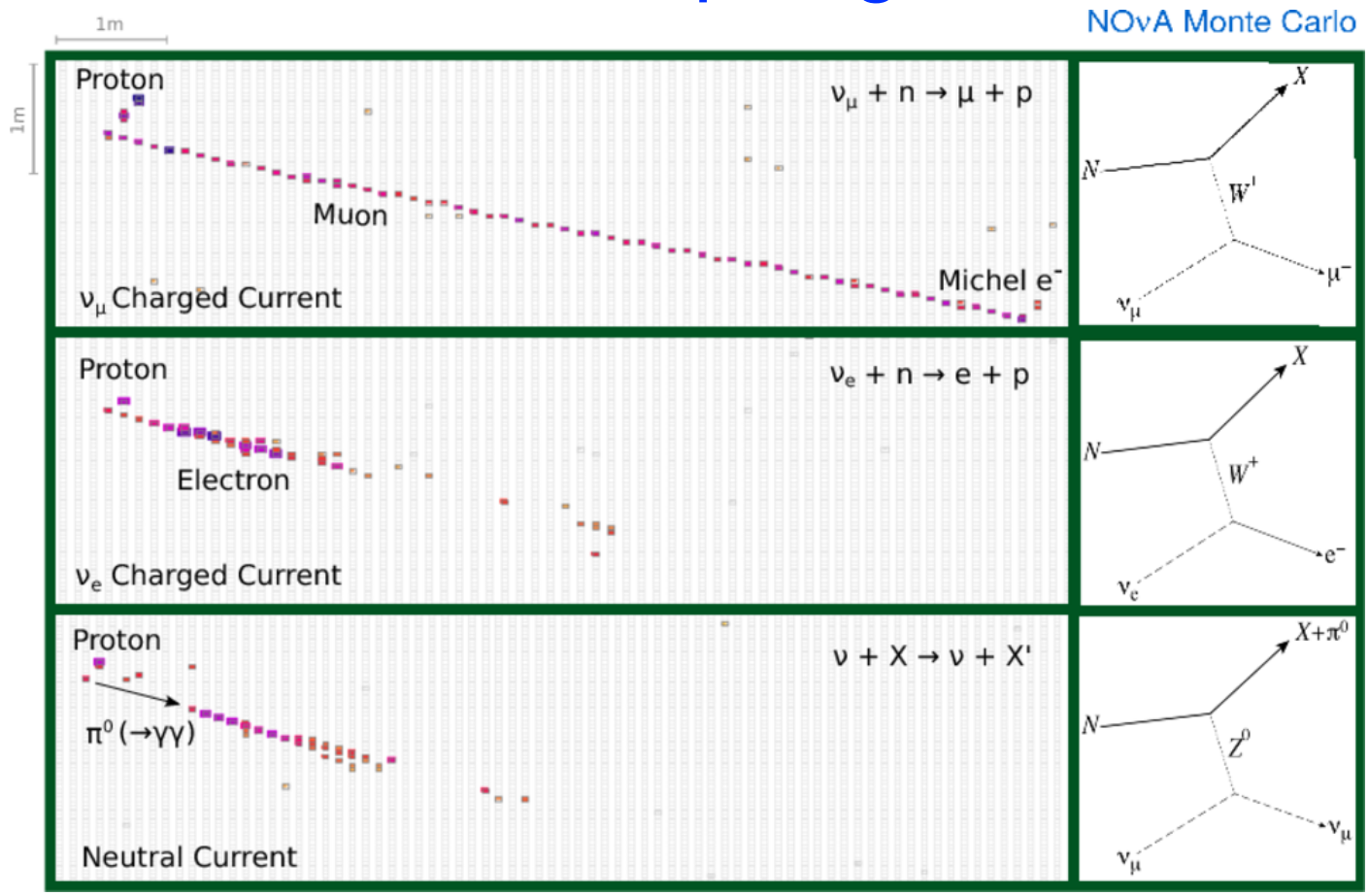


Far detector is huge:
calibration (attenuation) is important.

- ν_e Appearance:
  Low-Z, fine-grained (1 plane ~ $0.15X_0$), highly-active tracking calorimeter, optimized for EM shower reconstruction.



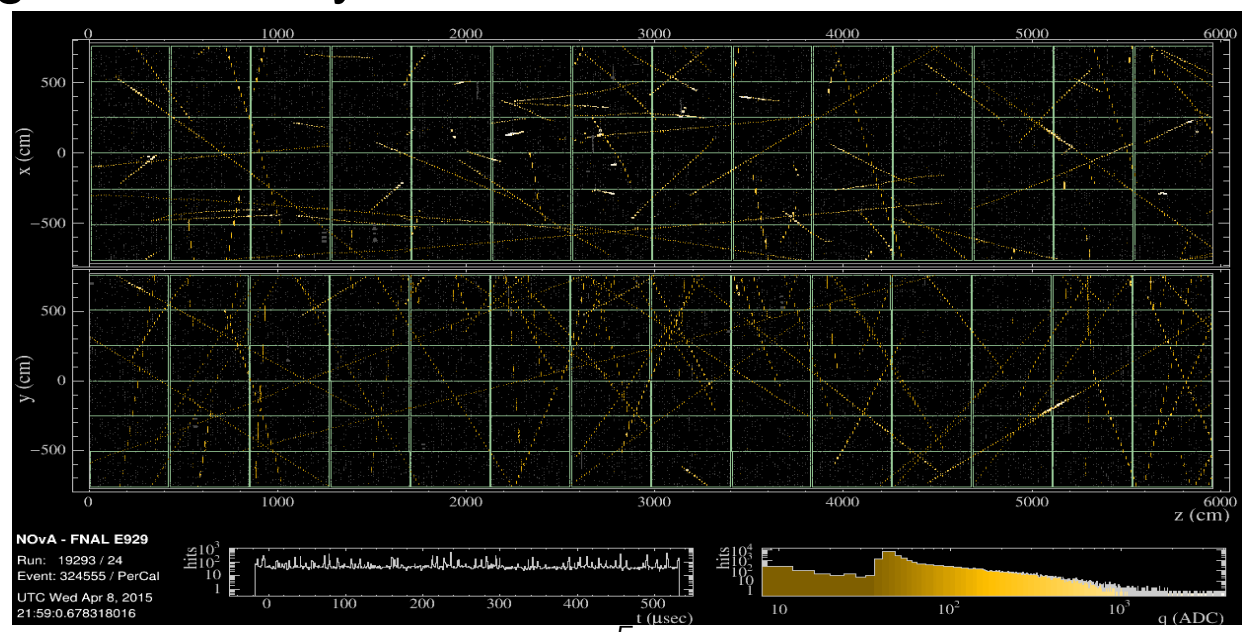
Event Topologies



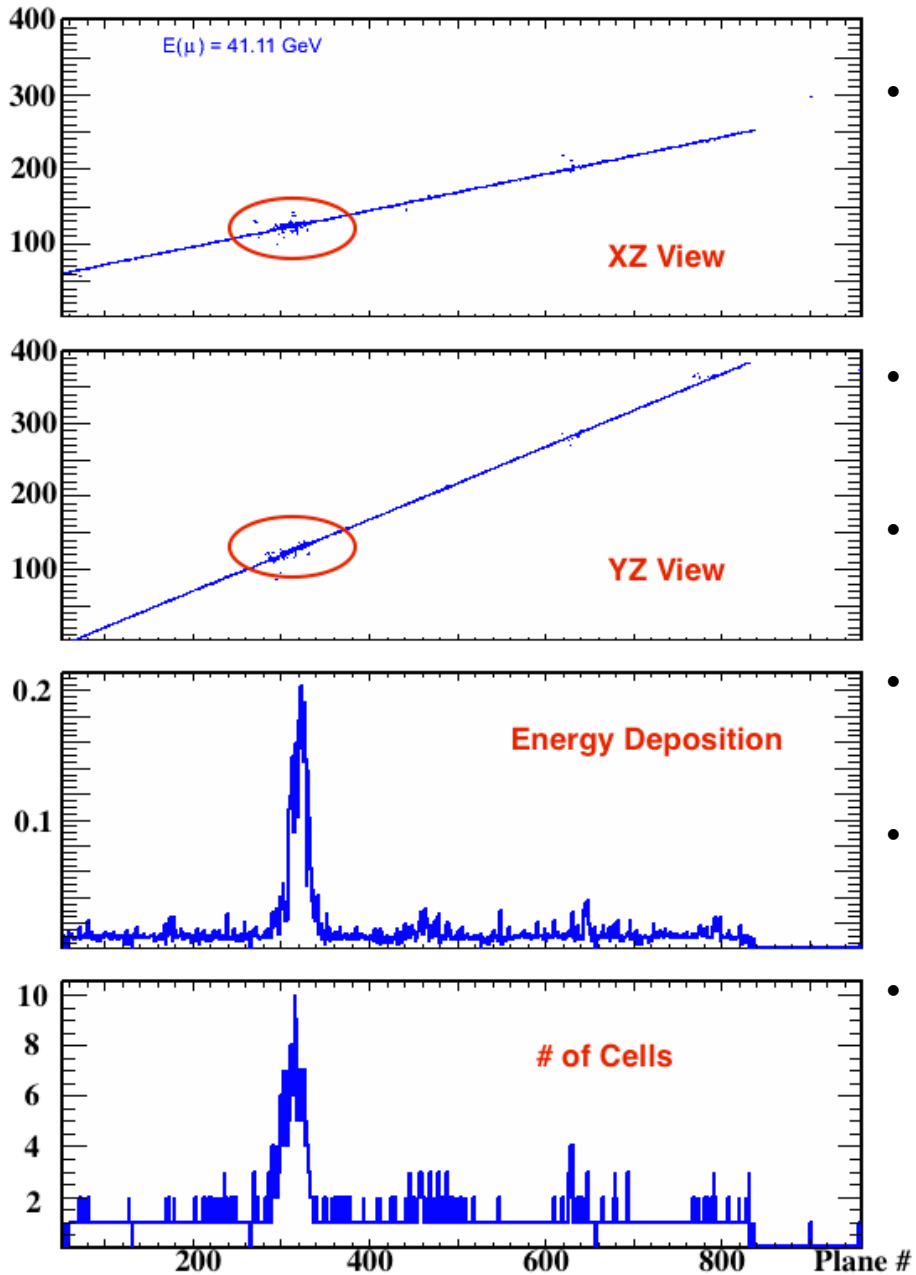
- NOvA find ν_e signal by EM showers induced by electrons from charged current ν_e interactions.
- It is important that EM showers are corrected modeled in MC.
- We need a data-driven method to benchmark EM shower modeling and PID algorithms for NOvA.

Cosmic Muons in The Far Detector

- NOvA far detector is on surface: cosmic ray muons are abundant (148 kHz).
- Muons undergo bremsstrahlung (Brem) radiation by emitting an energetic photon.
- Cosmic Brem showers make background to ν_e signal. (See T. Xin's talk)
- Also provide statistically rich sample of pure EM shower from data:
  - Check EM shower modeling.
  - Check PID algorithms.
  - Check signal efficiency across the detector.

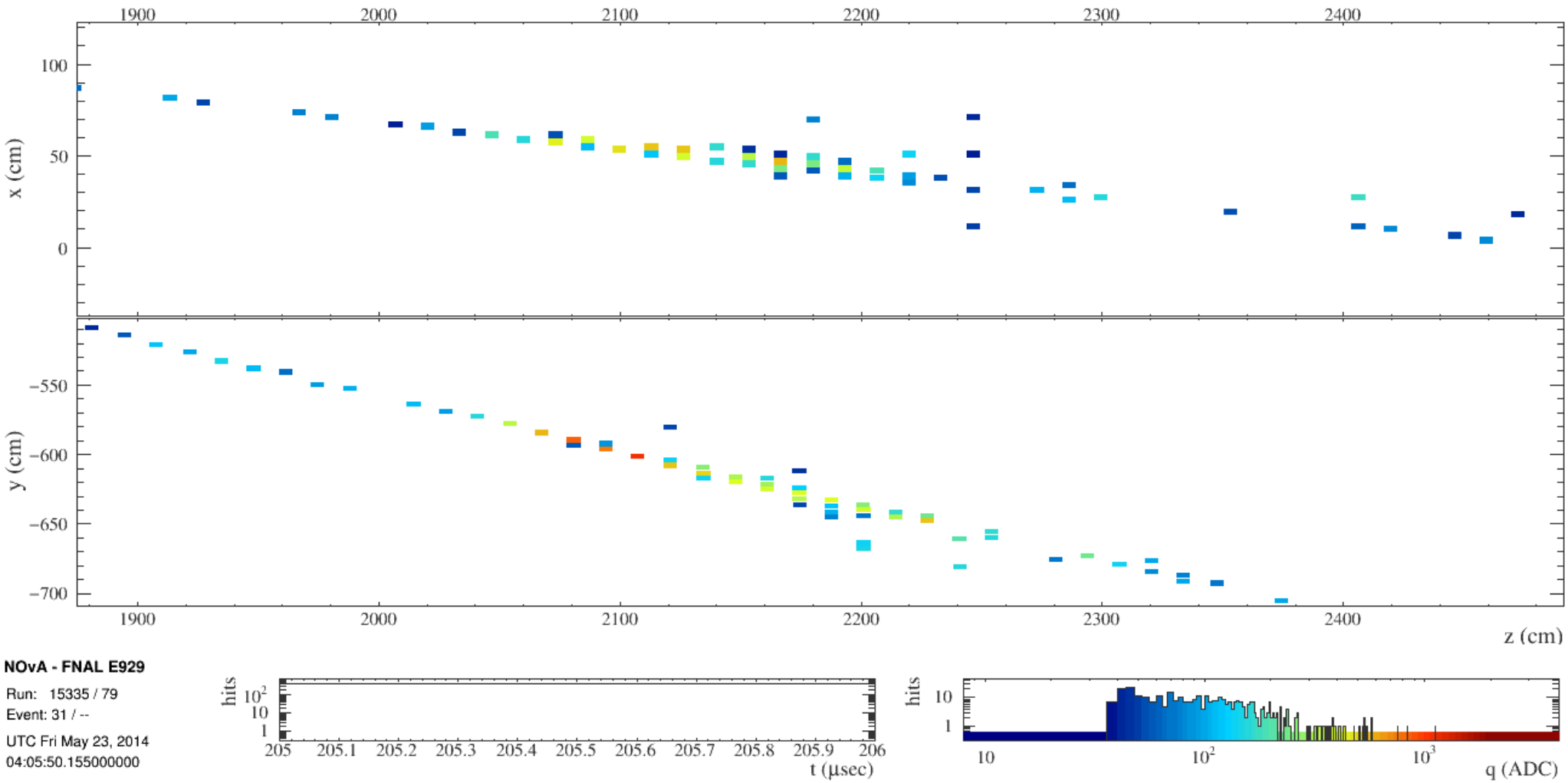


Shower Finding and Muon-Removal



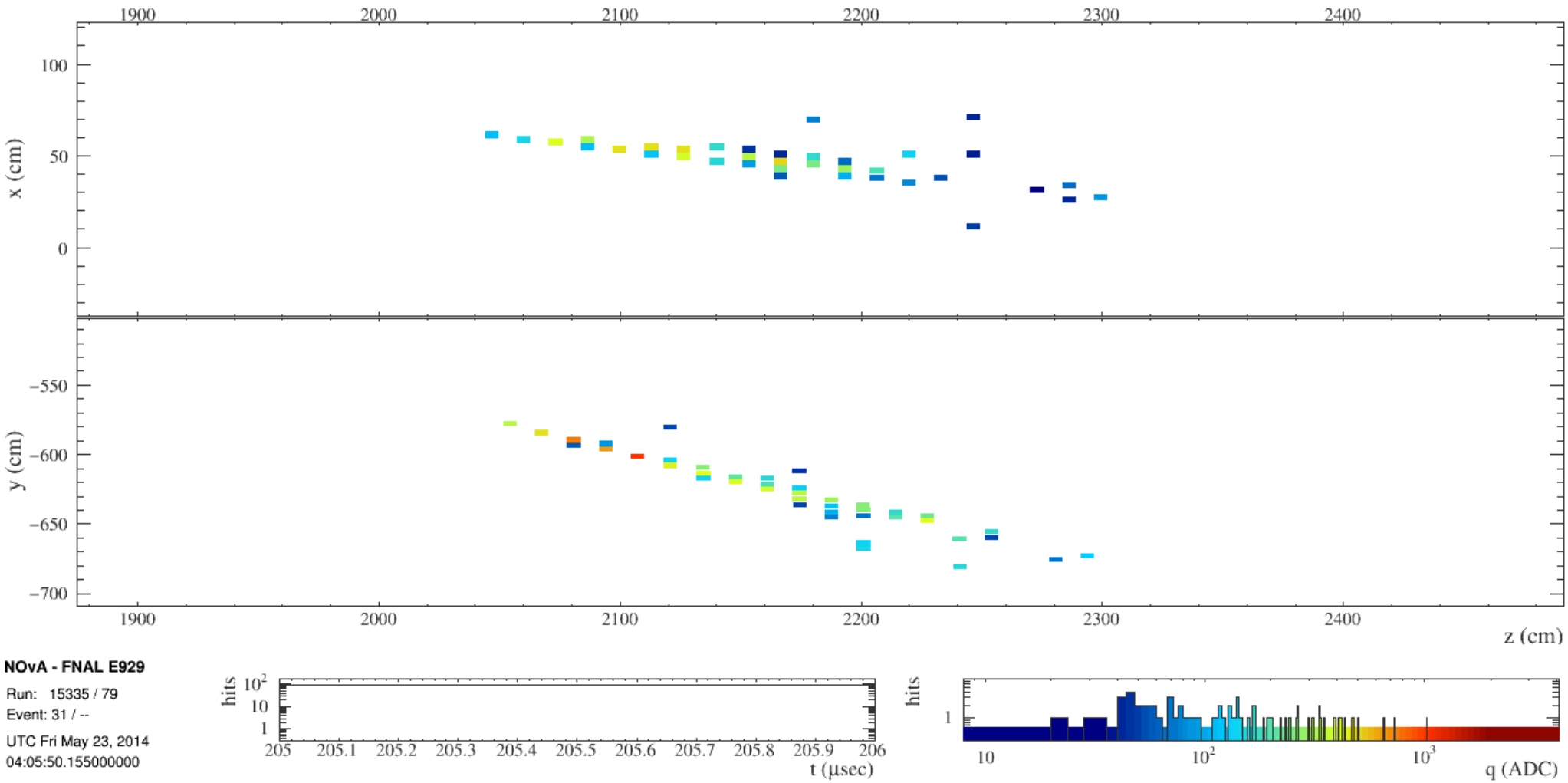
- An algorithm based upon energy deposition along the muon tracks is developed to identify the Brem showers.
- Muon is an minimum ionization particle (MIP).
- Brem showers deposit much more energy: define the shower region.
- Remove all muon hits outside of the shower region.
- Remove the muon MIP from shower hits inside the shower region.
- Re-run standard ν_e reconstruction and PIDs.

Cosmic Brem in Event Display



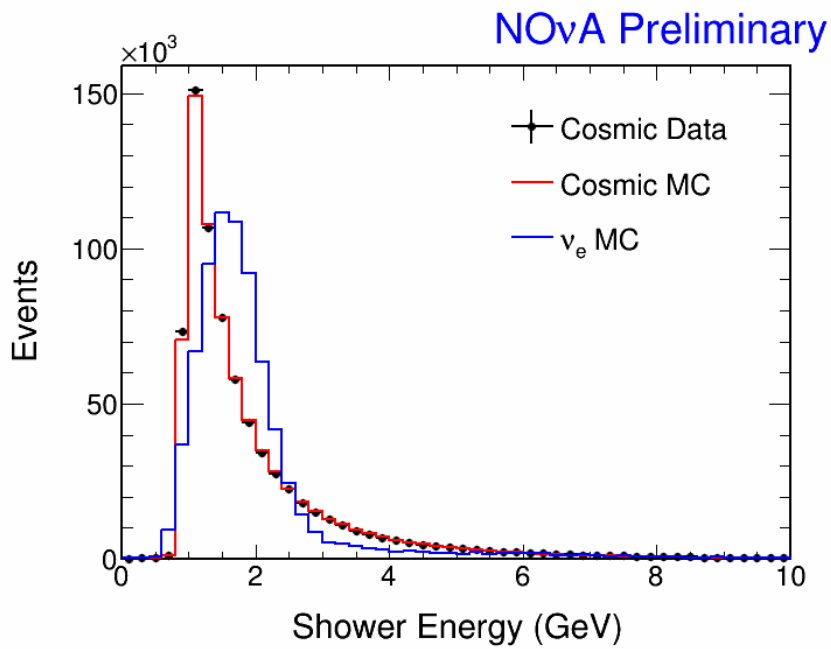
Event display of a cosmic muon candidate with Electromagnetic (EM) Bremsstrahlung (Brem) Shower from NOvA FD simulation.

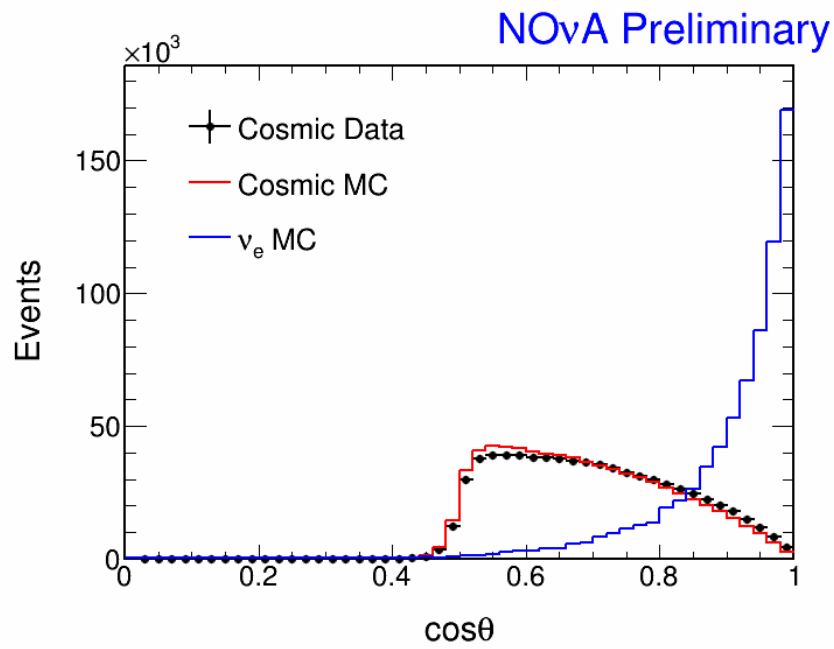
Cosmic Brem in Event Display



Event display of hits of the EM shower after the removal of hits associated with the muon track.

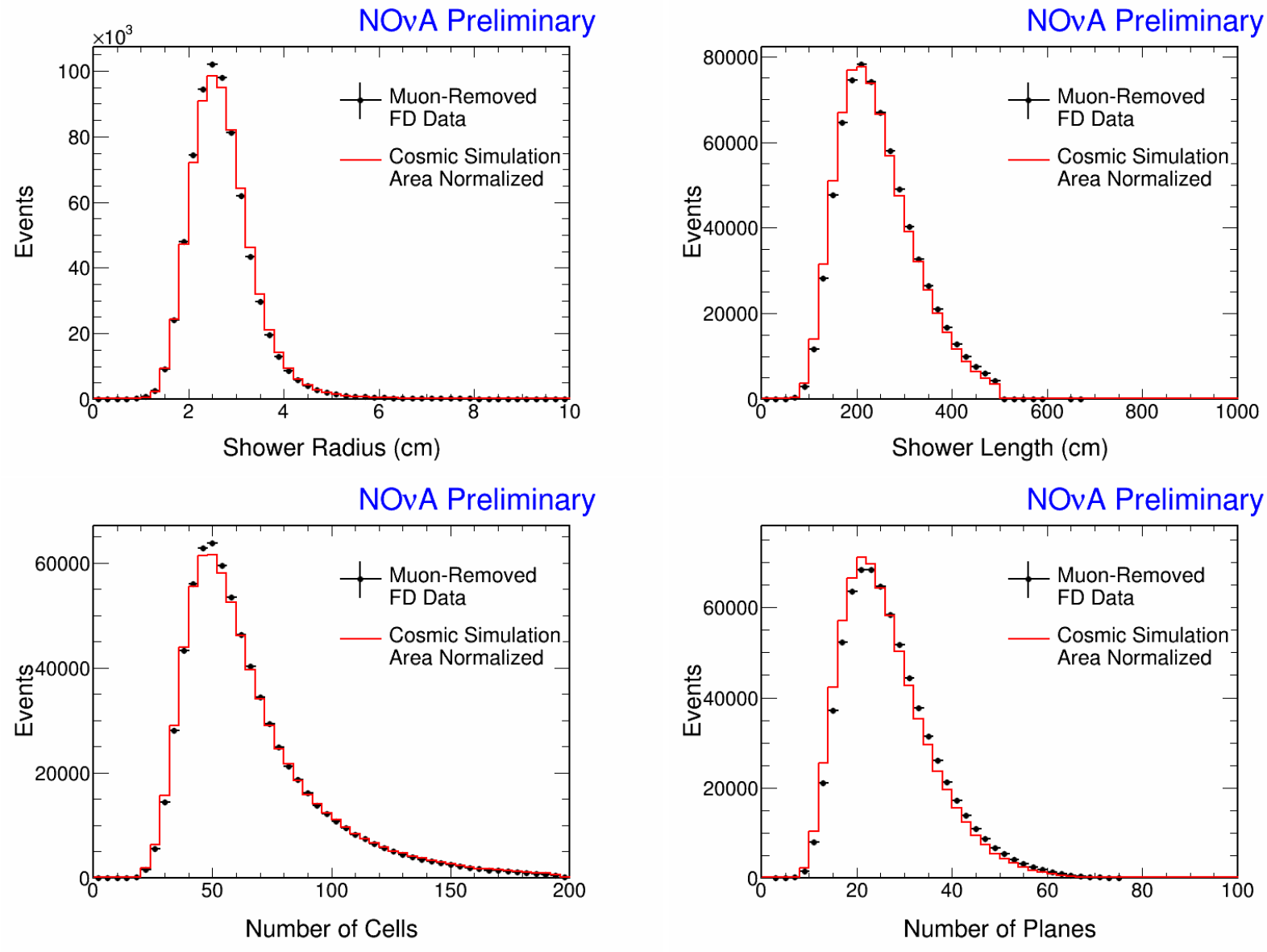
Brem Shower





- Good data/MC agreement in shower energy and angle.
- Cosmic Brem showers do not have exactly the same energy and angle distribution as ν_e showers.
- It does cover the ν_e region.
- Can be used to check data/MC agreement and PID efficiency for ν_e analysis.

Brem Shower

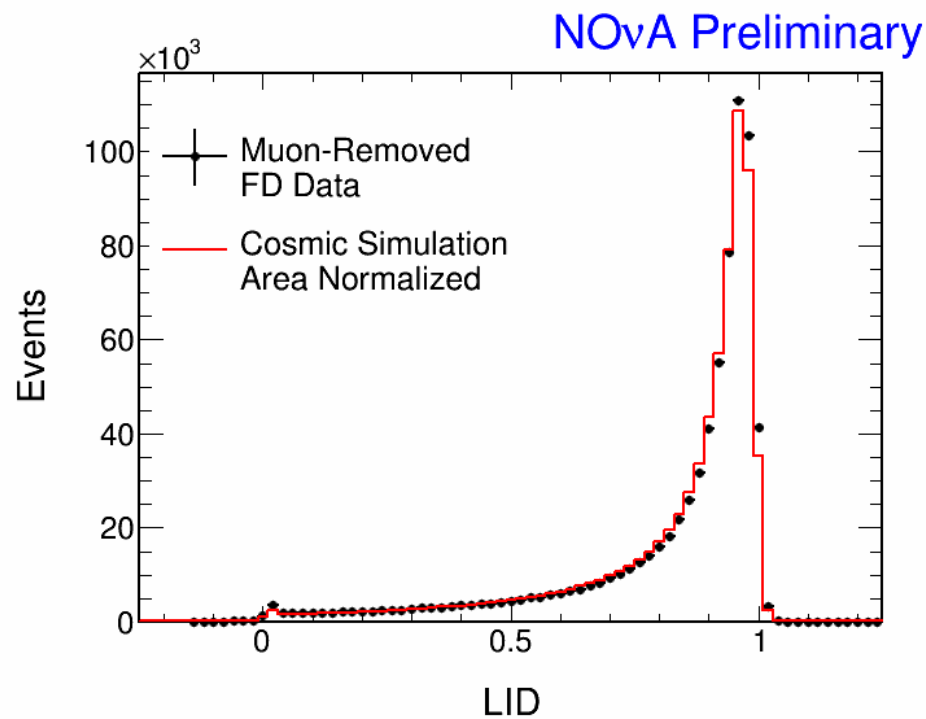


- Great agreement in reconstructed shower variables.
- EM showers are well simulated by NOνA.

Particle Identification: LID

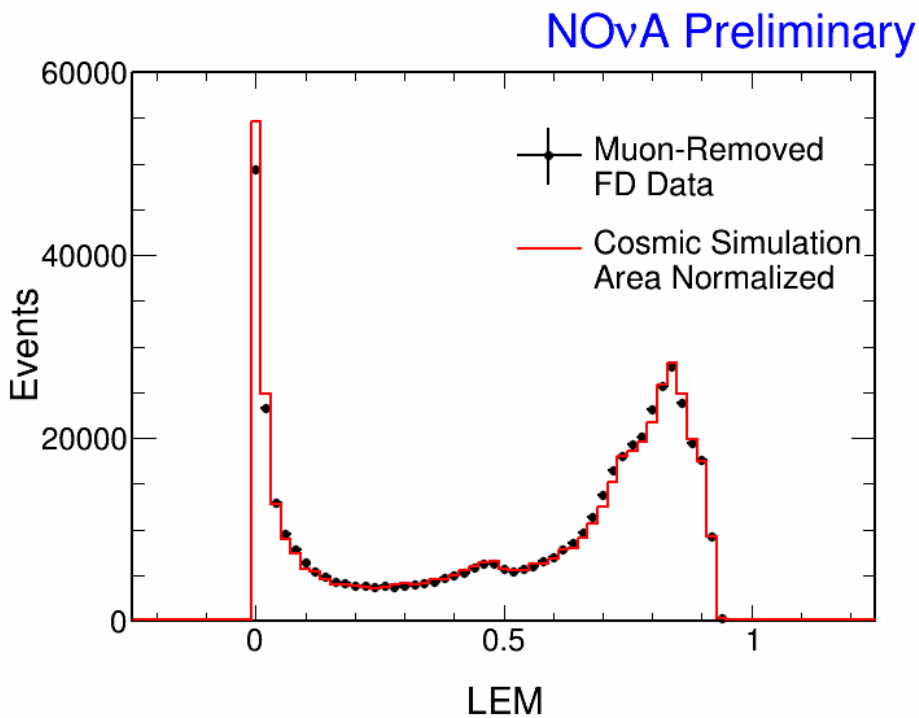
- Likelihood Based ν_e Identifier (LID)
  - Uses the dE/dx of a particle to compute the likelihoods that the candidate particle is an electron.
  - The likelihood variables are used as input to an Artificial Neural Network to construct a particle ID along with other topological information about the event.
  - Used as the primary PID algorithm for the ν_e appearance analysis.
  - More details see talk by J. Bian.

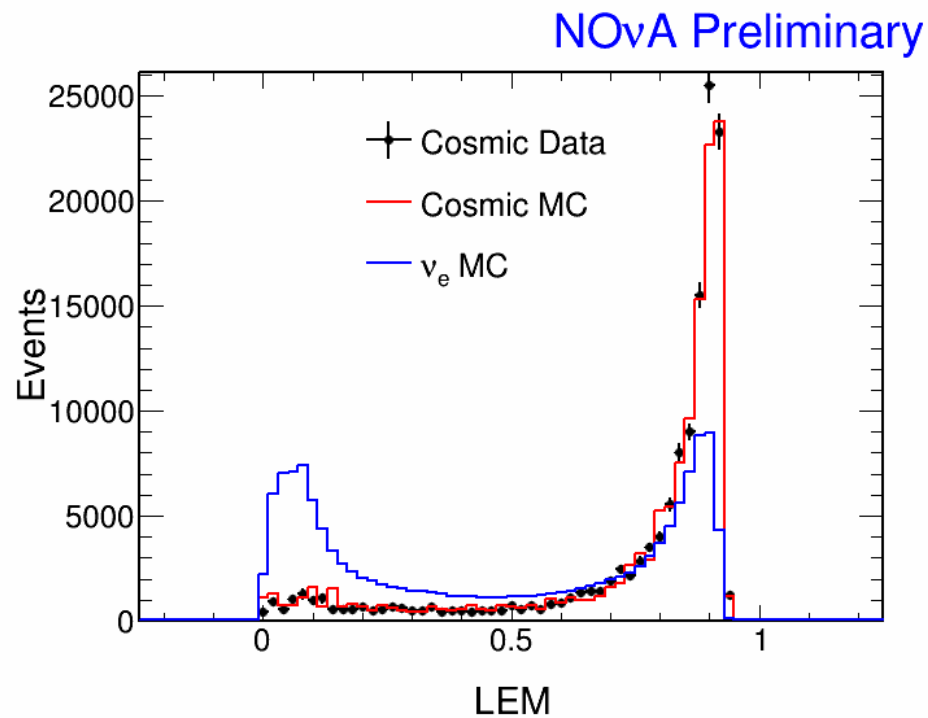
- LID see most of the cosmic Brem showers as signal-like.
- Good data and MC agreement in likelihood variables and LID.



Particle Identification: LEM

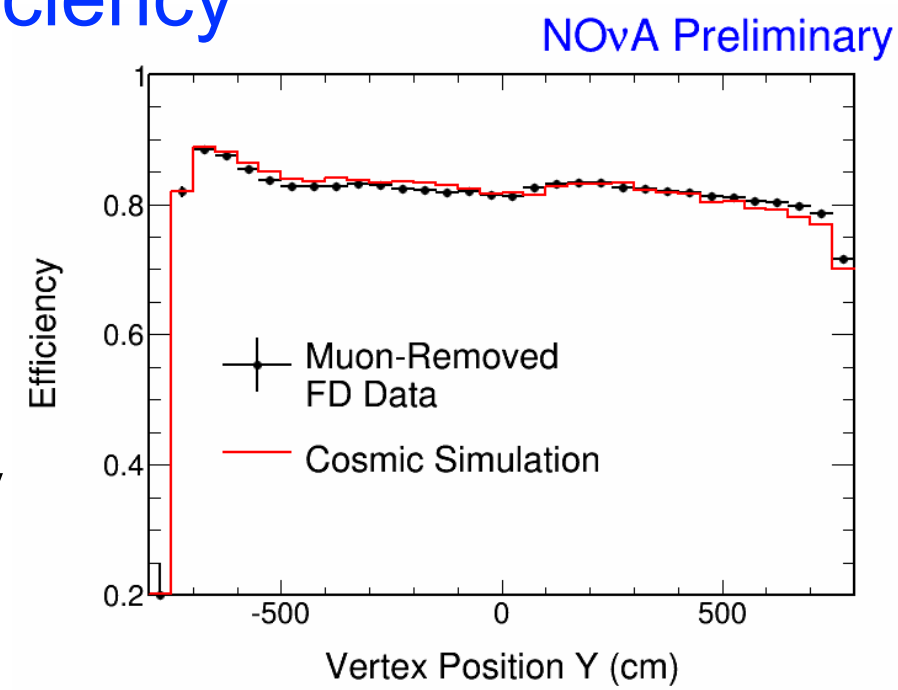
- Library Event Matching (LEM)
  - Compare an unknown trial event to a library of known event from MC.
  - Used as a cross-check PID algorithm (More details see talk by J. Bian).
- LEM sees good agreement between data and MC for Cosmic Brem.
- Cosmic Brem showers are not all signal-like in LEM due to difference in angle and energy from ν_e events.
- A re-weight in energy and angle is able to correct the difference: Signal-like, still good data/MC agreement.

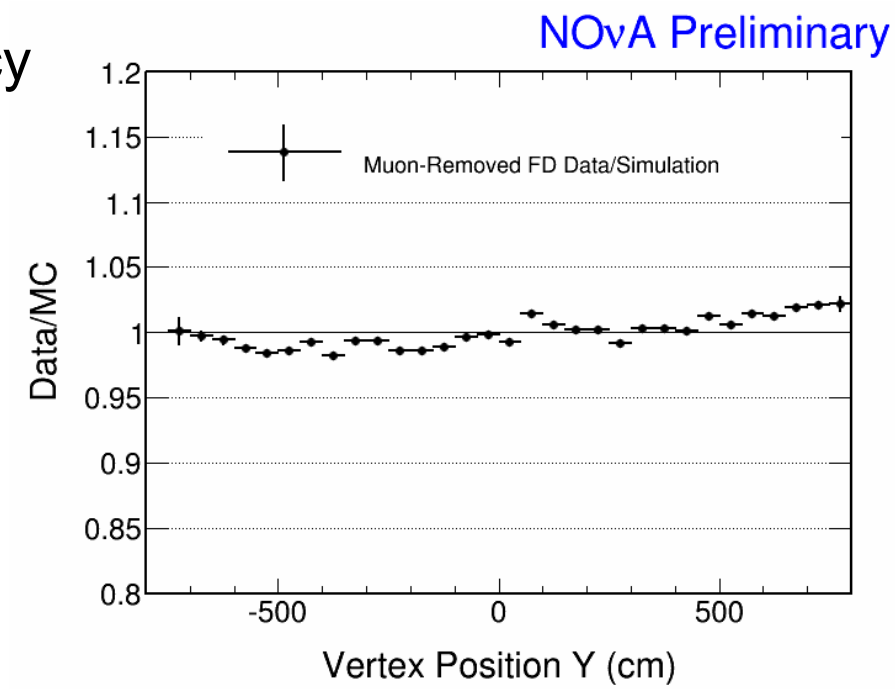




PID Efficiency

- NOνA has a huge far detector: calibration such as attenuation is important.
- We do a check using PID efficiency as function of vertex position (distance from readout),
- LID and LEM efficiency as function of vertex position shows consistency across the detector and good agreement between data and MC with in 5%.
- Calibration effect is under control.





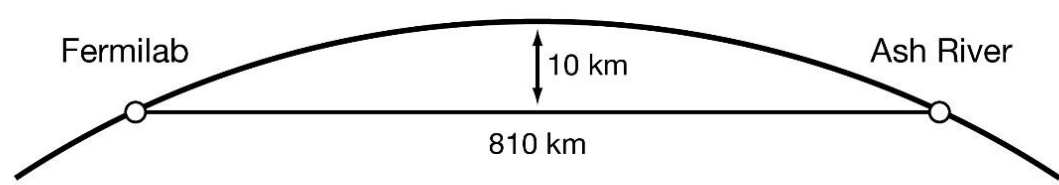
Conclusion

- We find cosmic muon induced EM showers, and remove the muons to get a pure EM shower sample from cosmic data.
- A data-driven method to benchmark EM shower modeling and PID algorithms.
- Good data and MC agreement: EM showers are well simulated in NOνA MC.
- Consistent PID efficiency across the detector indicates calibration effects are under control.

Backup Slides

NOvA Experiment

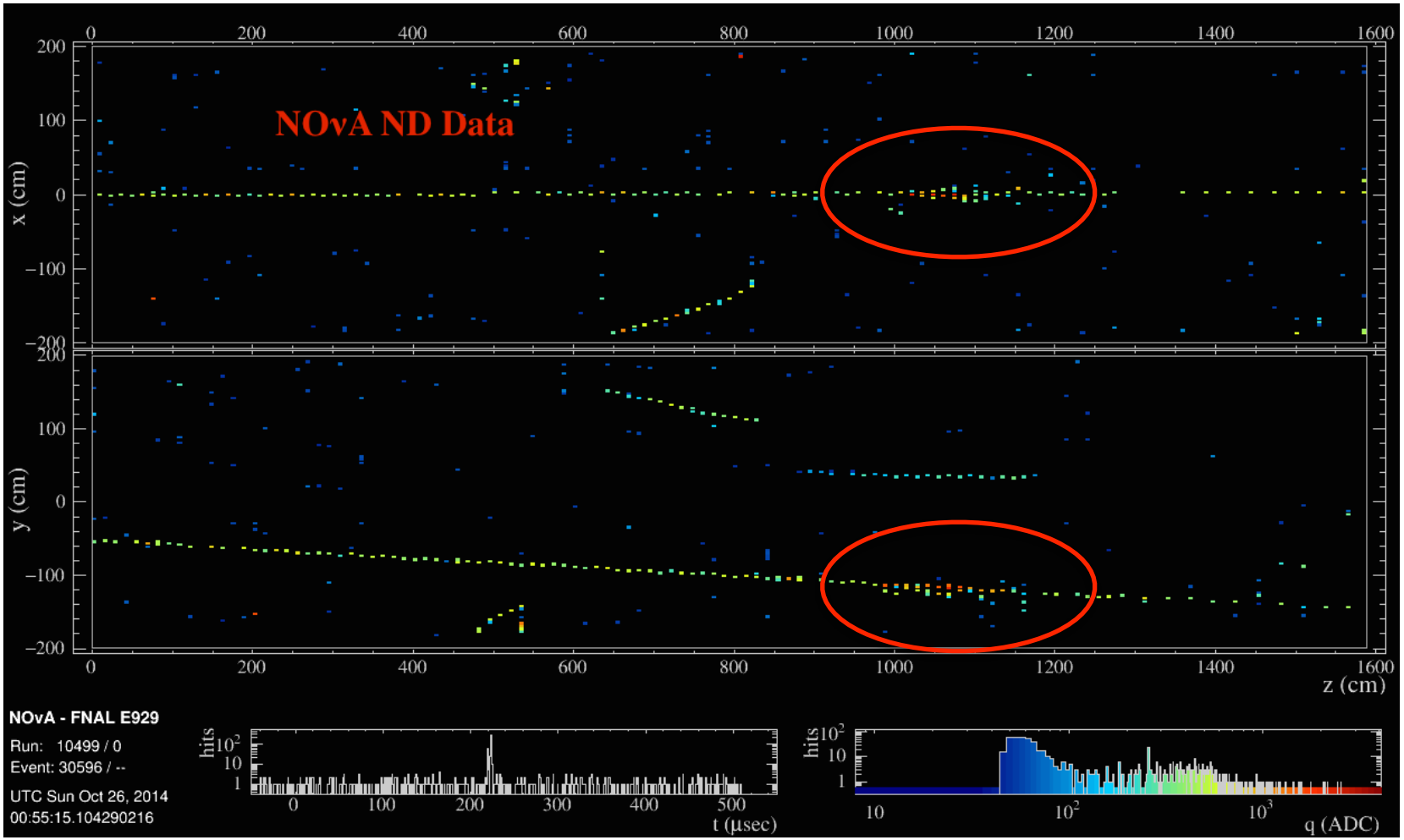
- NOvA (NuMI Off-axis ν_e Appearance) is a long-baseline neutrino oscillation experiment on NuMI beam at Fermilab.
  - NuMI (Neutrinos at Main Injector) beam: mostly ν_μ.
  - 14 mrad off-axis: Narrow band flux centers around 2 GeV.
- Detectors:
  - Far: 14 kton, 810 km from source.
  - Near: 0.3 kton, 1 km from source.
- Physics goals:
  - Measure mixing angles.
  - Determine the mass hierarchy.
  - Search for CP violation.



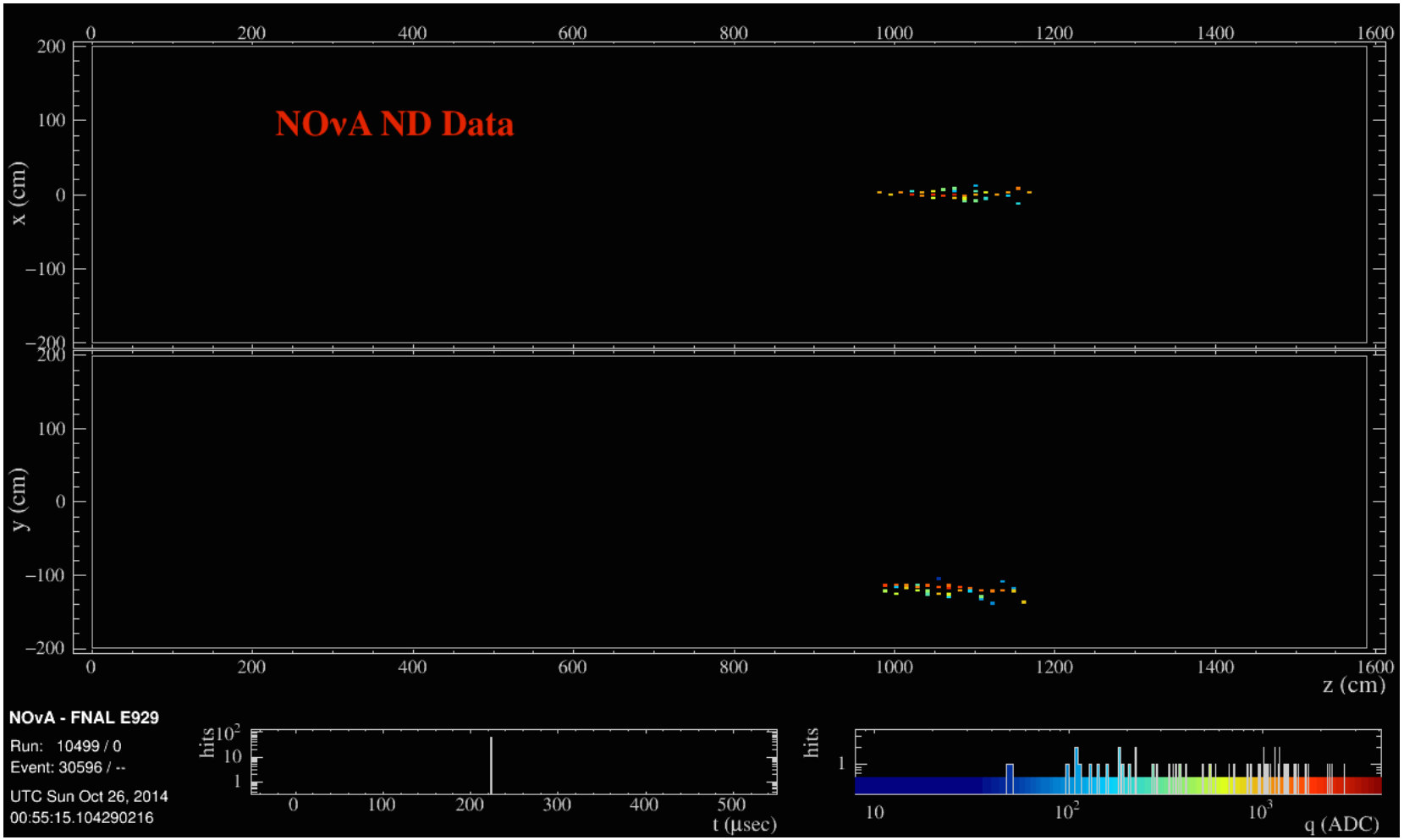
Rock Muons In The Near Detector

- There is not as many energetic cosmic ray muons in nova ND which is underground.
- Rock muons are abundant.
- Neutrinos interact with rock around ND via charged current interactions and produce muons that entering the detector.
- Mouns undergo bremsshulang radiation and generate EM showers.
- EM shower samples to benchmark EM showers for ND physics topics: NuE cross-section, Nu-E elastics scattering, coherent π^0…

Rock Muon Showers In Event Display

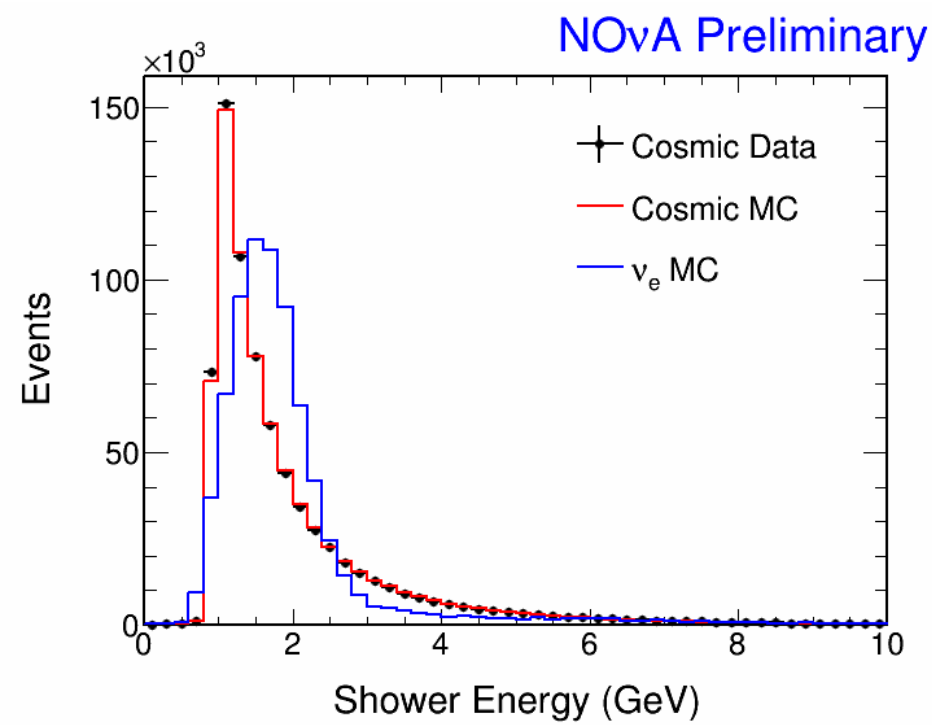


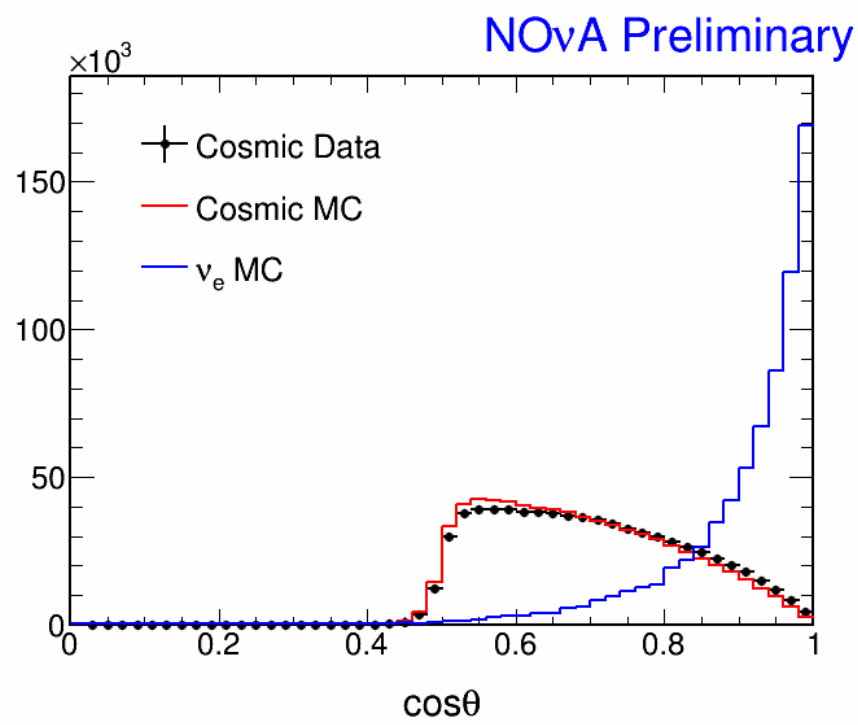
Rock Muon Showers In Event Display



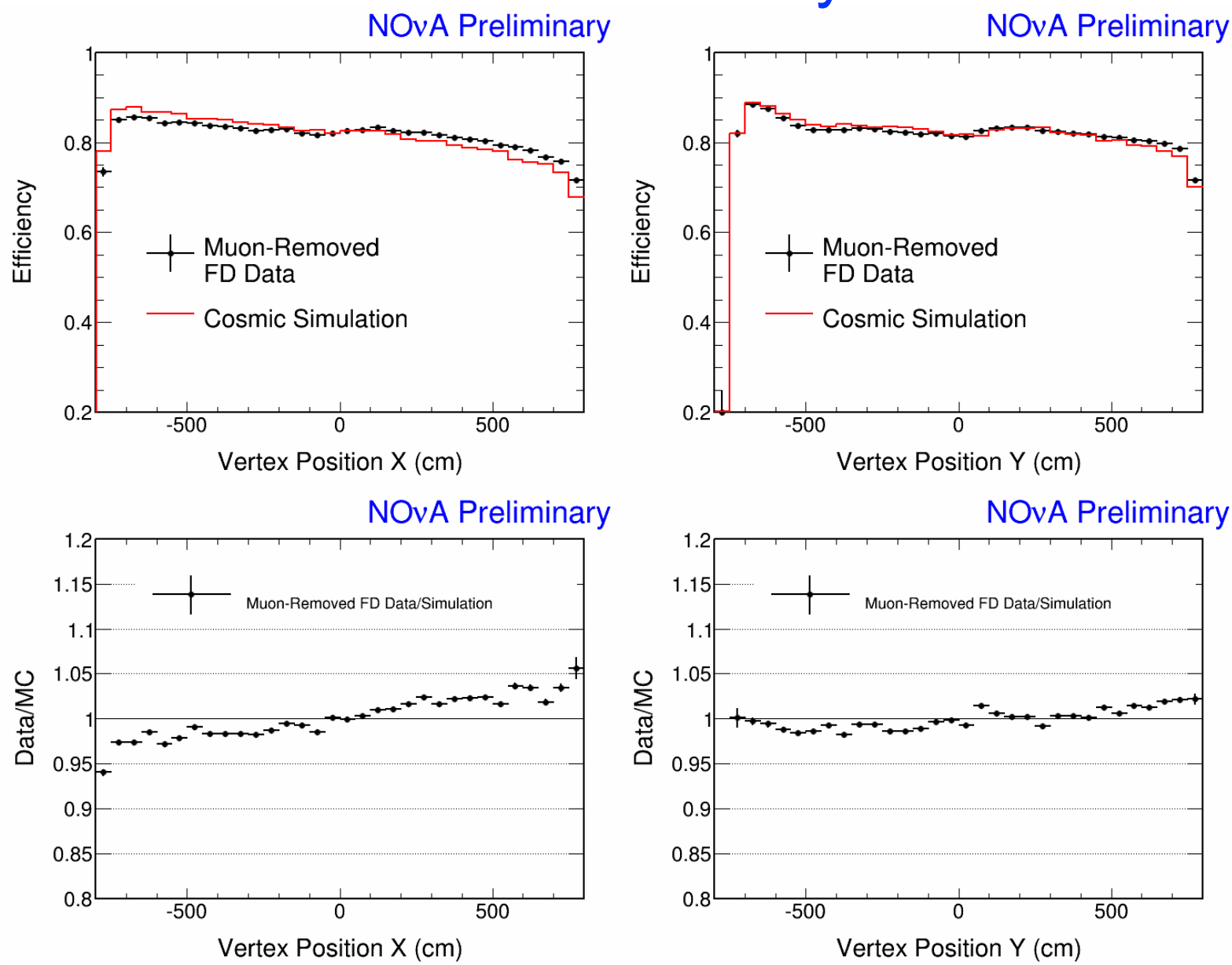
Re-Weight Method

- Cosmic Brem does not have the same energy and angle distribution as ν_e events.
- LEM is sensitive.
- We developed a ν_e-reweight method to correct the difference.



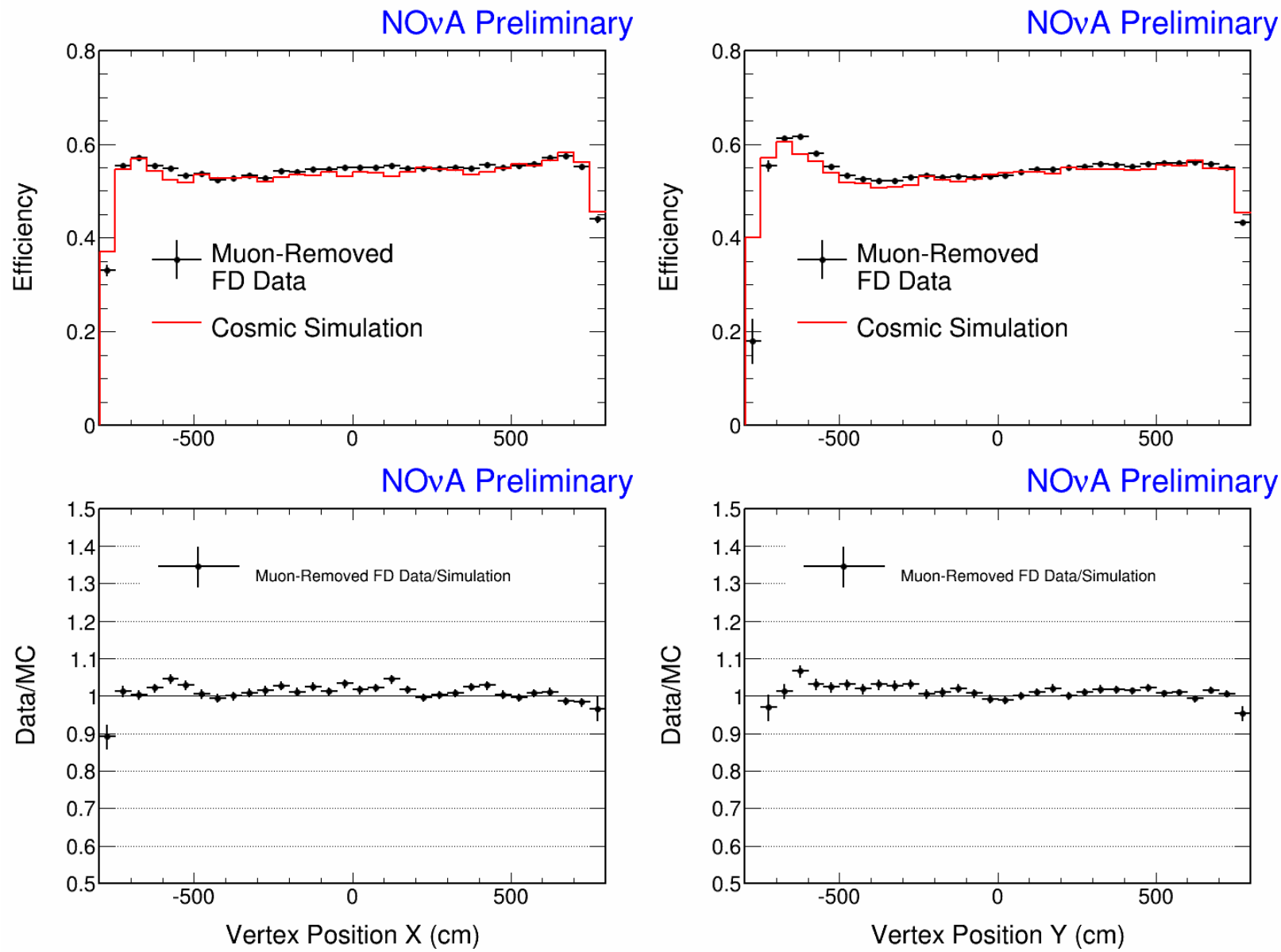


LID Efficiency



- LID efficiency as function of vertex position shows consistency across the detector and good agreement between data and MC with in 5%.

LEM Efficiency



- PID efficiency as function of vertex position shows good agreement between data and MC with in 5%.