WHAT STARTS HERE CHANGES THE WORLD

Electromagnetic Response Studies in the NOvA Test Beam

Presented on behalf of the NOvA Collaboration

Panoramic Image of the (late) NOvA Test Beam Detector and Beamline
(Credit to Alex Sousa)

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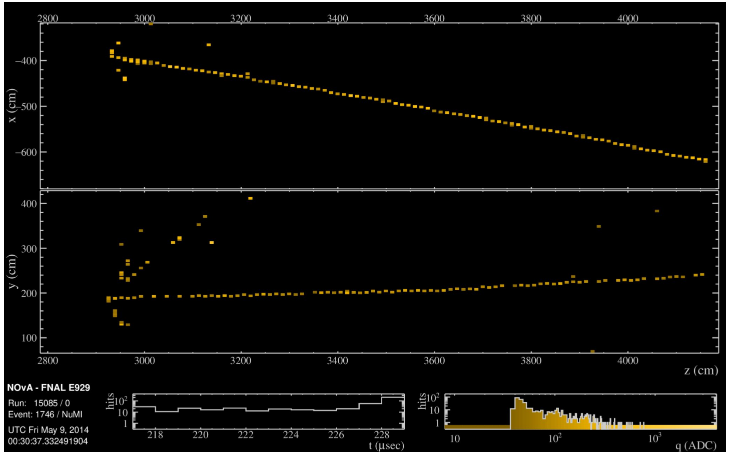
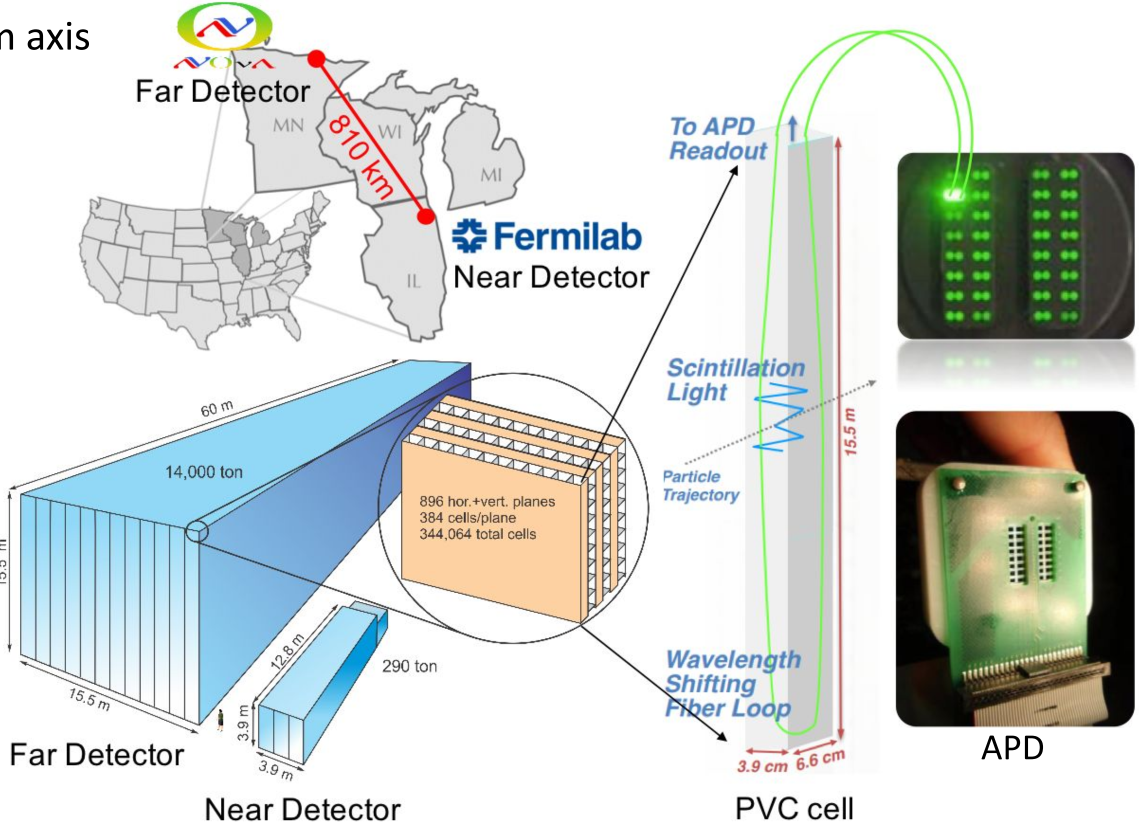
NuFact 2024
Argonne NATIONAL LABORATORY

NOvA – NuMI Off-Axis ν_e Appearance

- 2 Detectors 14.6 mrad (~0.8°) off beam axis
  - Near Detector (Fermilab)
  - Far Detector (Ash River, MN)
- ν_μ (or anti-ν_μ) provided by NuMI
- Measure ν_μ disappearance and ν_e appearance at FD

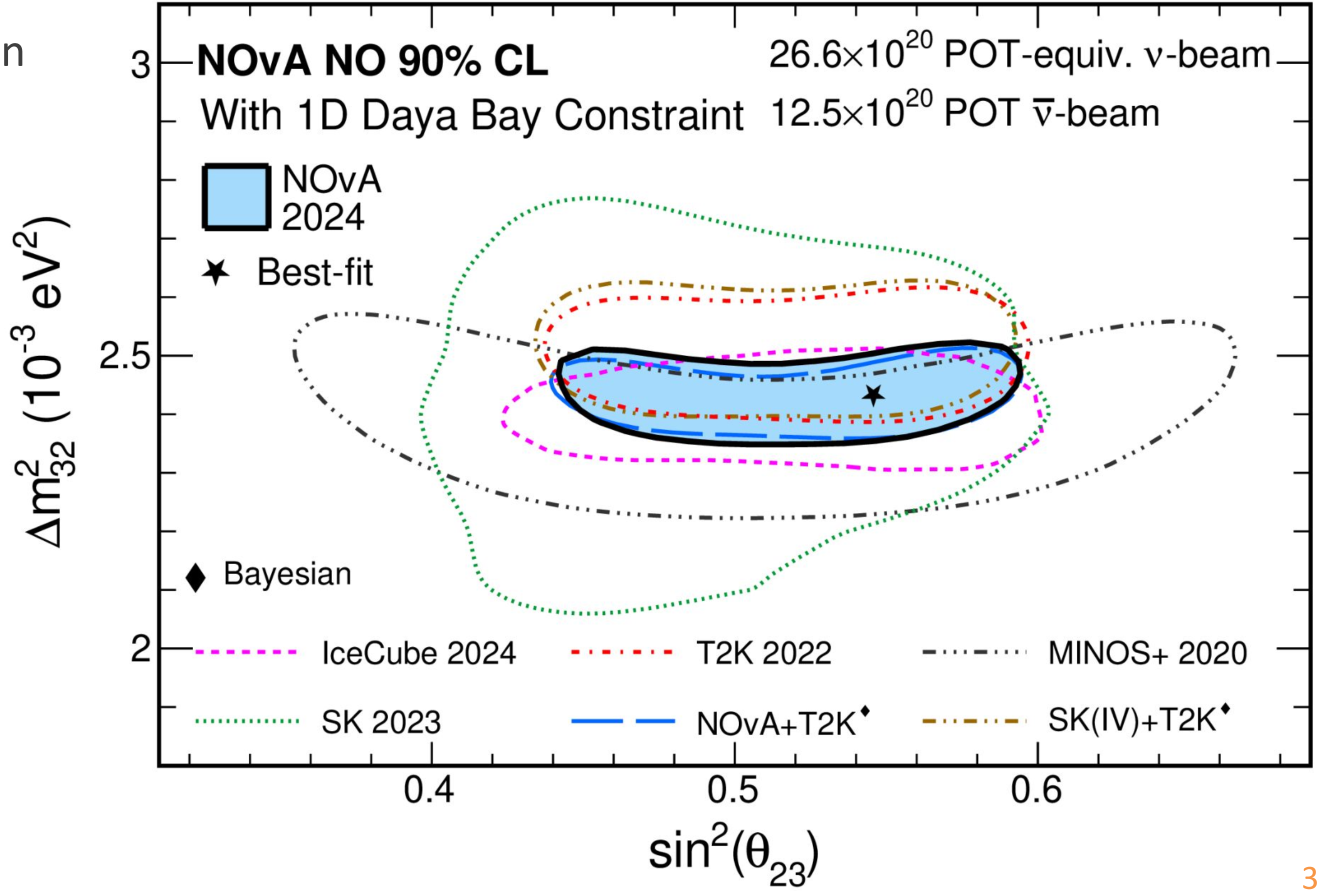




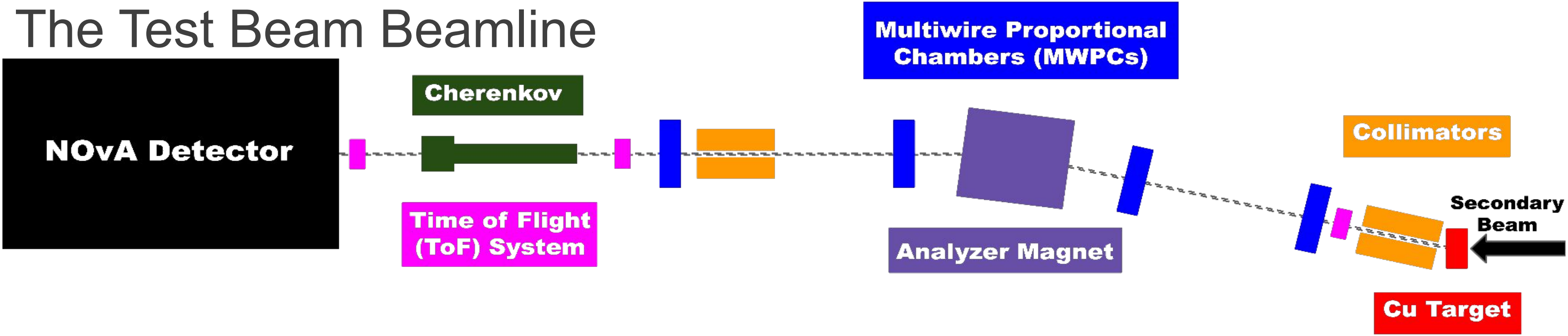
NOvA – Recent Results

- NOvA is a world-leader in neutrino oscillation parameter measurements
- Improving NOvA's uncertainties benefits the reach of neutrino physics globally
- Launched Test Beam program in 2019 to better understand calibration-related systematics

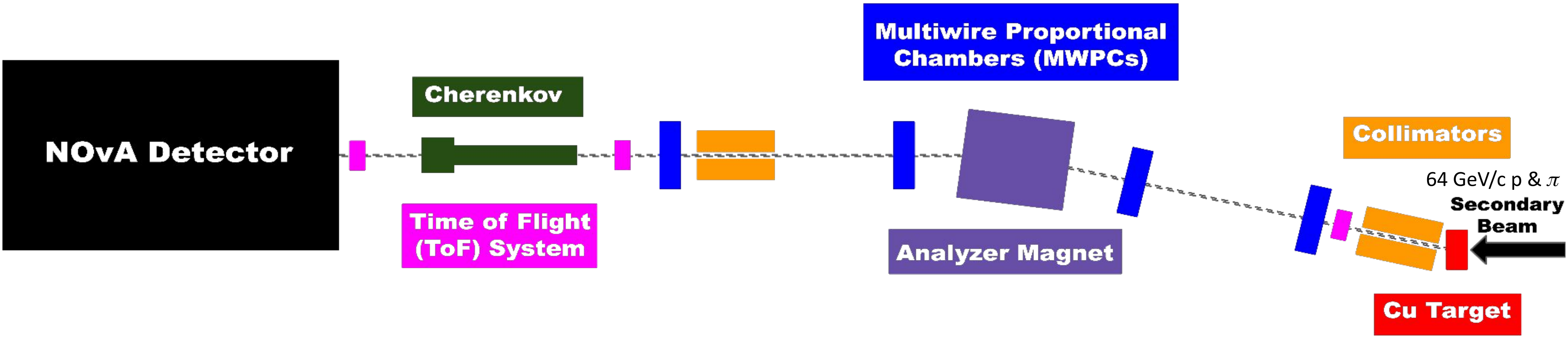
NOvA Preliminary



The Test Beam Beamline

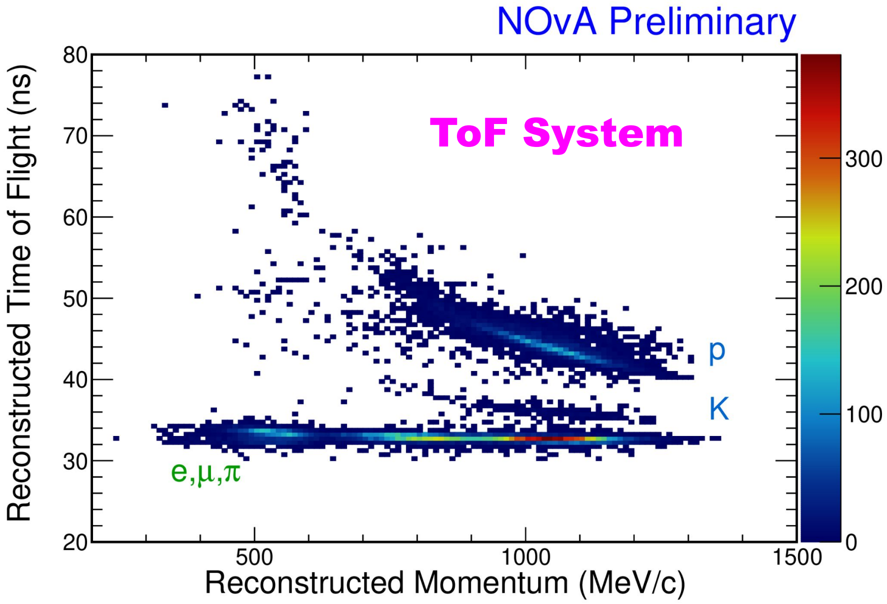


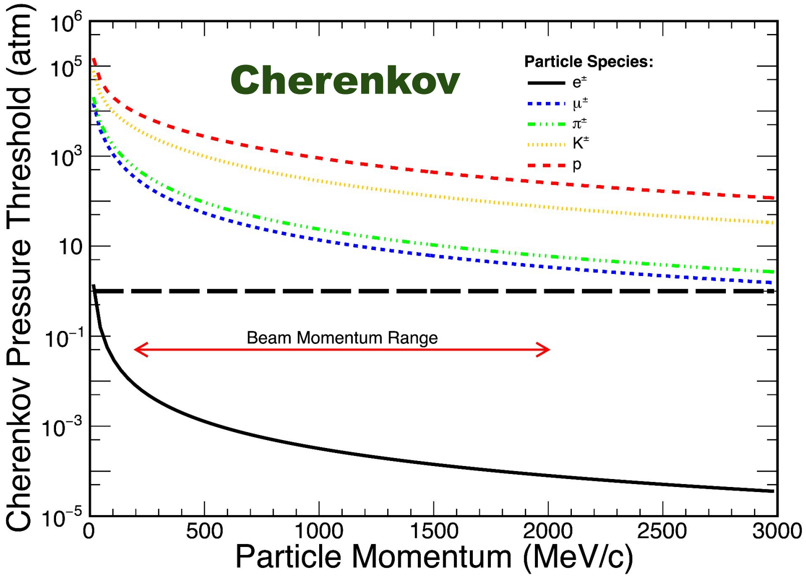
The Test Beam Beamline



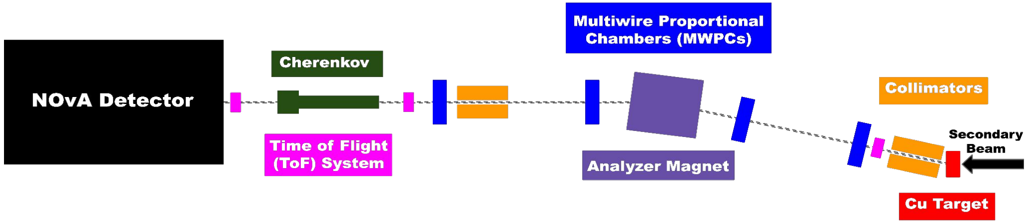
1. 64 GeV/c hadronic beam interacts with **Cu Target** producing 0.2 - 2 GeV spray (p, $K^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$)
2. Particles far from the ideal beamline path (------) are filtered out using **Collimators**
3. Momentum determined by **Magnet** & **MWPCs** (Measures bend angle through known B-Fields)
4. First PID performed by **ToF System** (p, $K^{\pm}$, or "fast" particle)
5. Out of "fast" particles ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$), **Cherenkov** tags $e^{\pm}$ separately from $\pi^{\pm}/\mu^{\pm}$
6. Particles of known **species** and **momentum** enter the **NOvA Detector**

Electron Selection





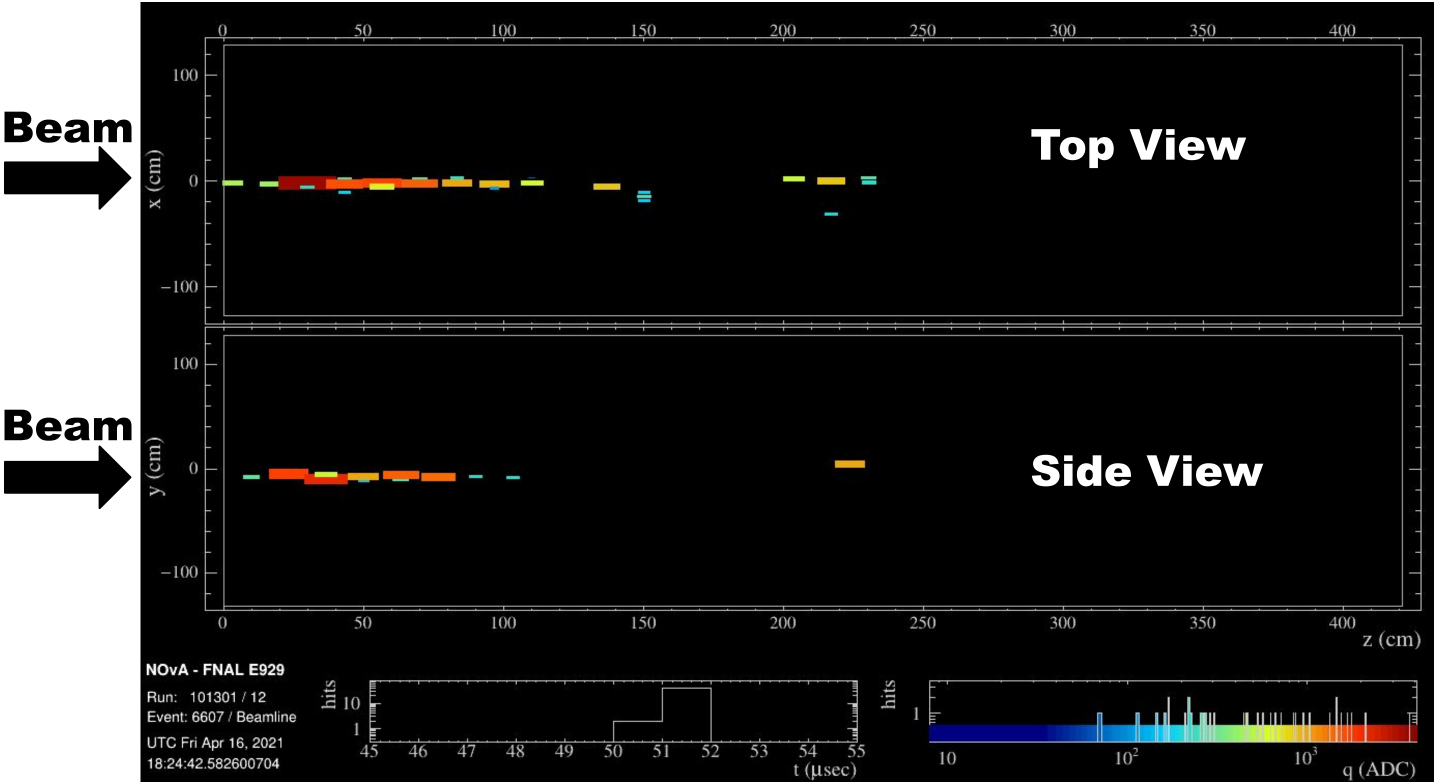
- ToF discriminates p & K from $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$
  - ~32 ns ToF for fast particles
- 1 atm CO_2 is above the Cherenkov pressure threshold only for $e^{\pm}$ in Mom. range
- Allows discrimination of $e^{\pm}$ vs. $\mu^{\pm}$/ $\pi^{\pm}$



NOvA Test Beam Detector

Example electron candidate event display
ToF: 32.6 ns
Reco. Momentum: 1070 MeV/c

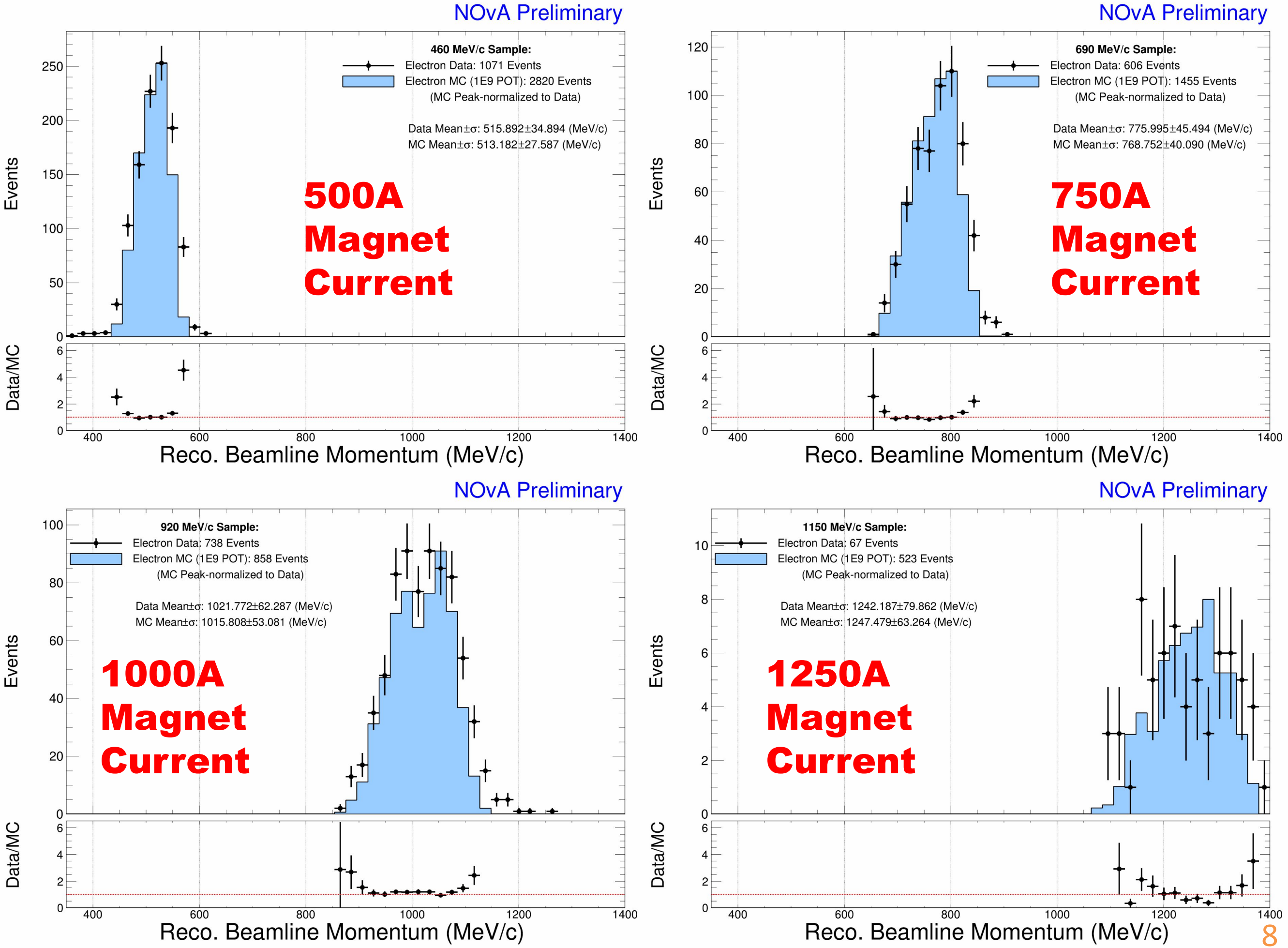
- ND & FD technology
- TB: 63 planes; 30 tons
- ND: 214 planes; 300 tons
- FD: 896 planes; 14 ktons



Electromagnetic Energy Response Measurement

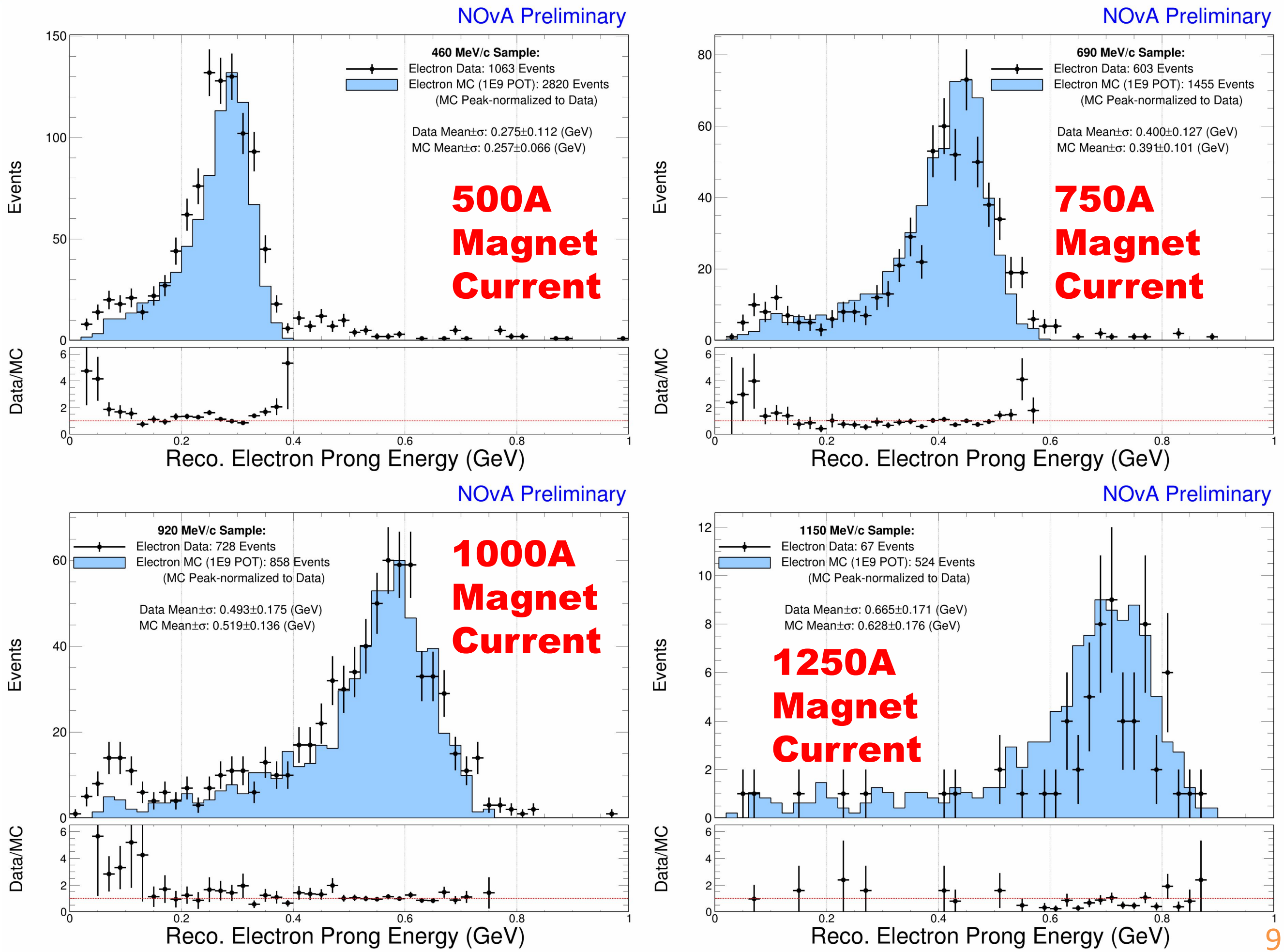
Goal:

- Associate calorimetric response of NOvA hardware to beamline momentum measurements
- Incorporate into electron reconstruction
  - ν_e appearance measurements



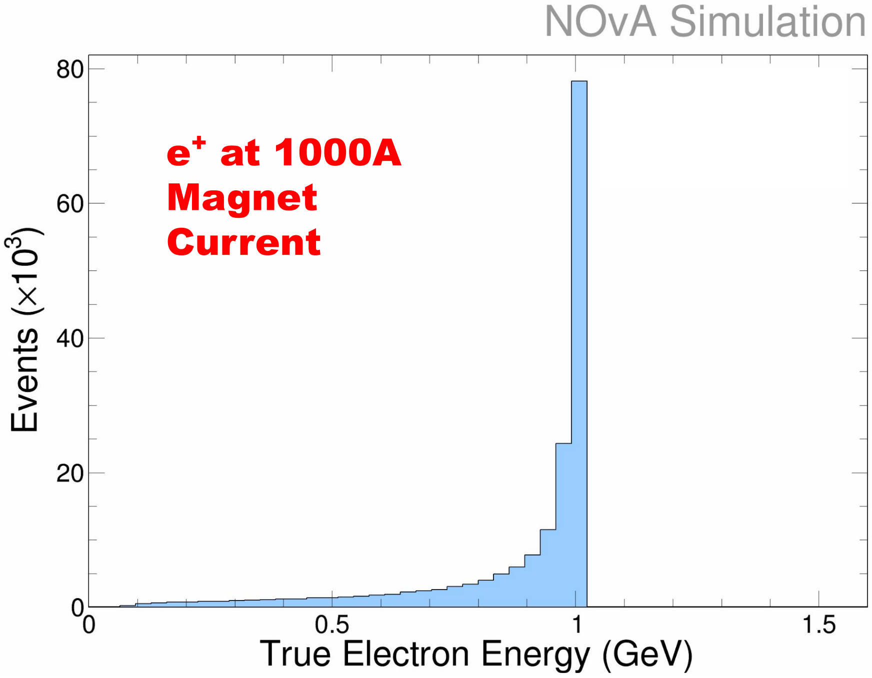
Electron Energy Spectrum in the NOvA Detector

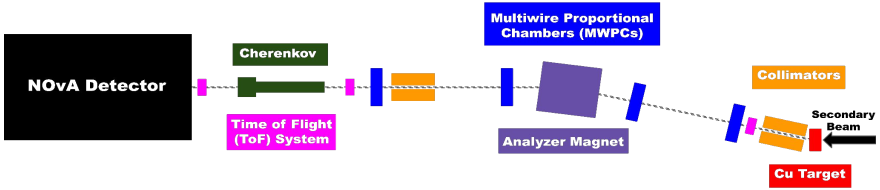
- Low-energy tail in electron energy spectrum in data and MC
- High-energy tail in data only
  - Background μ from MCenter beam target



Energy Loss in Beamline Materials – Simulation

- Simulated 1 GeV e^+ in the Test Beam
  - 1000 A magnet current
  - Plotted true e^+ energy at NOvA Detector face
- Electrons lose energy via matter interactions
  - Stochastic process
  - Radiative losses occur primarily in beamline scintillators (ToF modules)

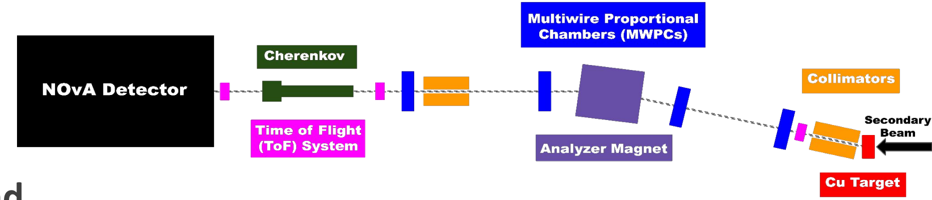


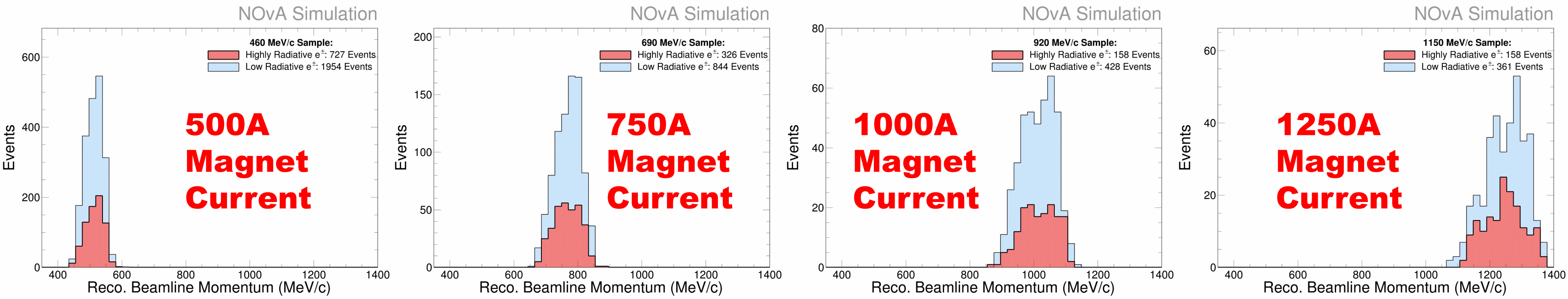


Investigating Beamline Energy Loss

1. Simulated more electrons in the Test Beam beamline
2. Split reconstructed events
   a. >15% beamline energy loss → Highly radiative
   b. <15% beamline energy loss → Low radiative
3. Looked for properties that could be used to separate these events in data

Due to where the energy losses occur, highly radiative and low radiative events look identical in BL momentum





Idea: Use Event Topology Characteristics to Filter Events

- Need to look for the least-biased way to filter events with significant energy loss in the beamline
- Looked for reconstructed quantities that can be used to aid separation
  - **Found several with promise!**

kNN Classifier Algorithm:

1. Choose any number of variables that can aid separation
2. Choose a dimensionless normalization for each variable
3. Choose a value for k

kNN requires no training!

To use:

$$P(\text{class}) = \frac{\#\text{ of class in } k \text{ nearest neighbors}}{k}$$

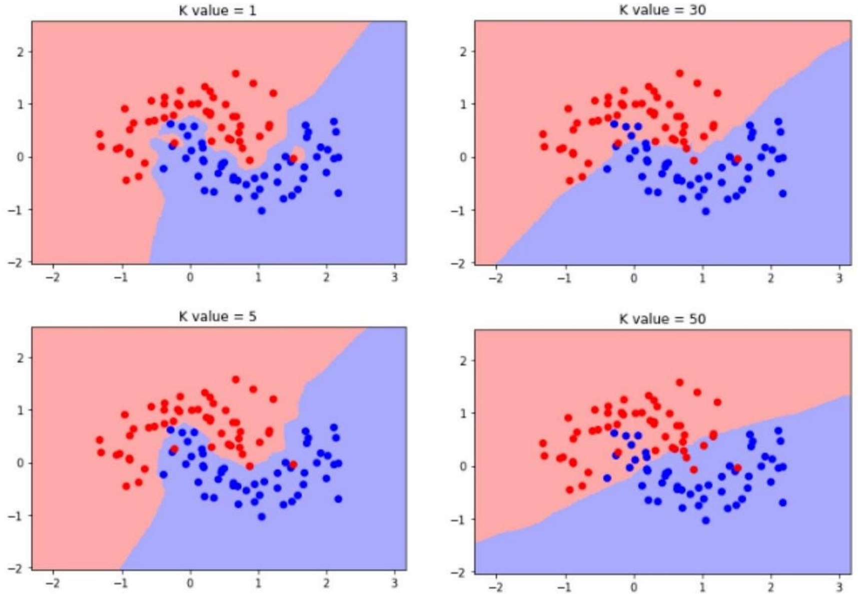
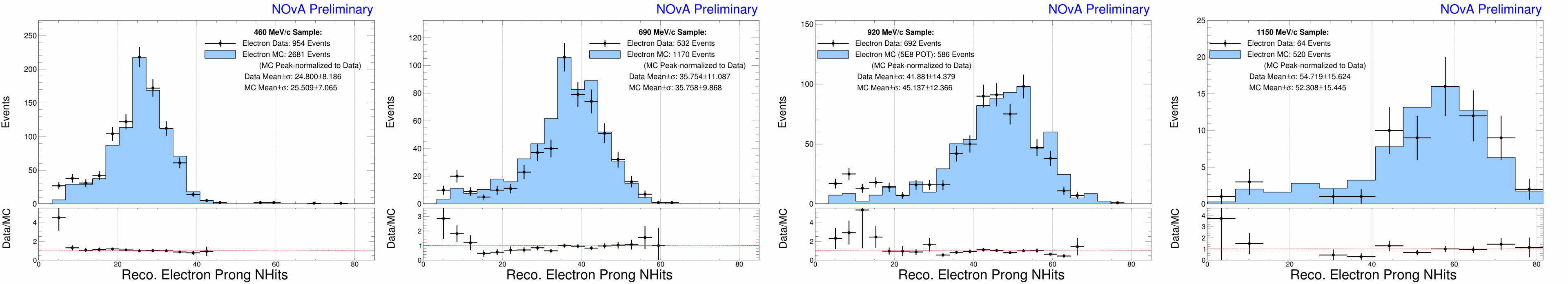


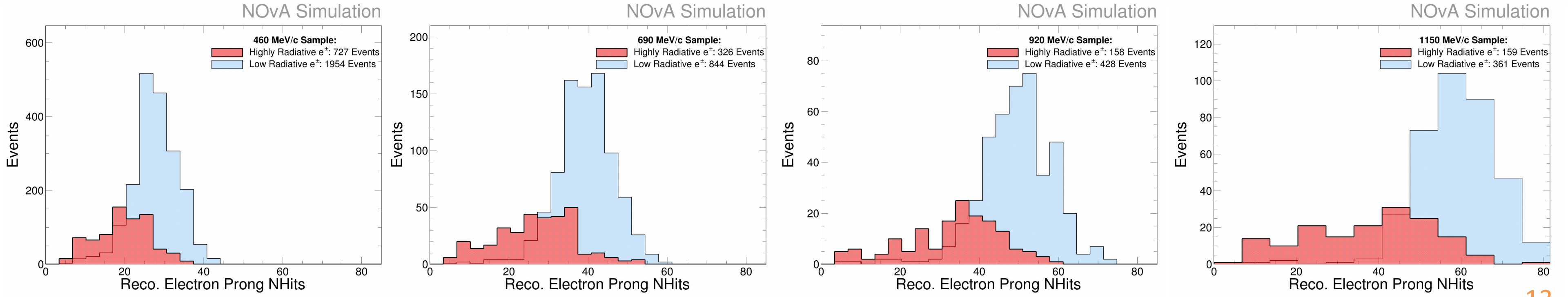
Image Credit

Topological Event Properties in NOvA – NHits

- Reconstructed number of cell hits assigned to electron prongs

Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right

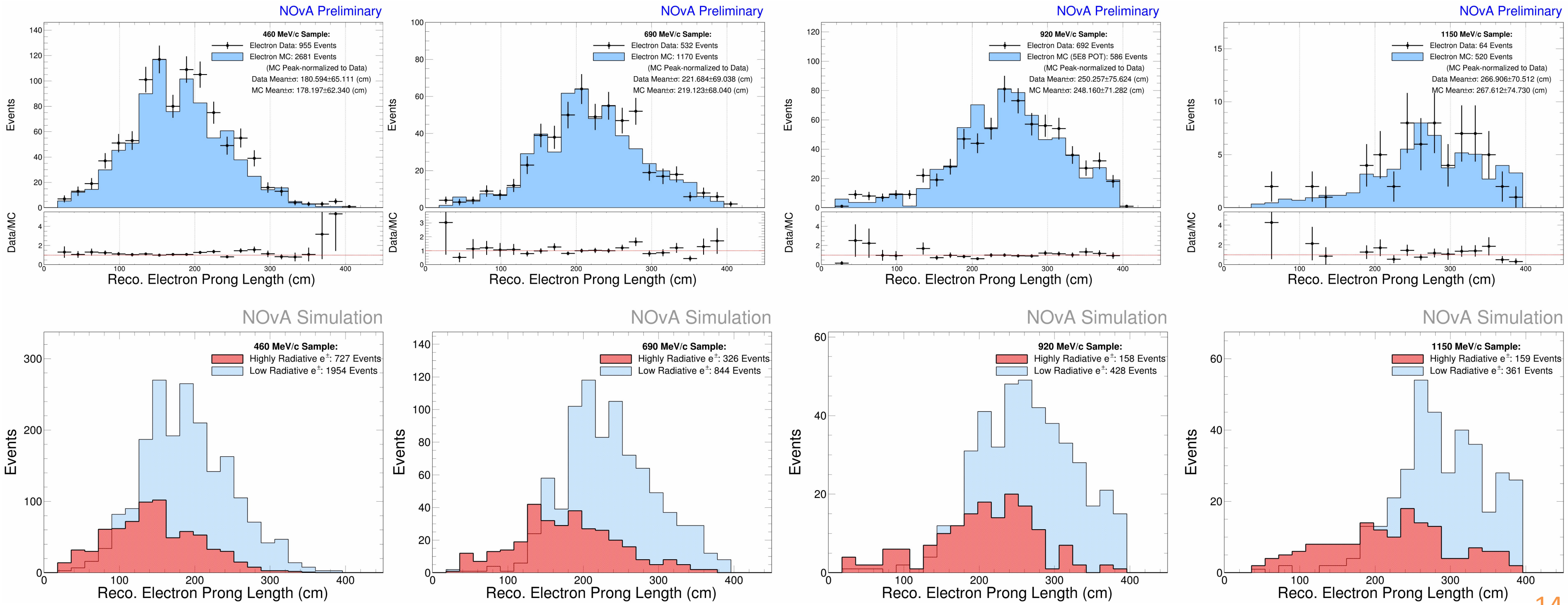




Topological Event Properties in NOvA – Prong Len.

- Reconstructed length of electron prongs

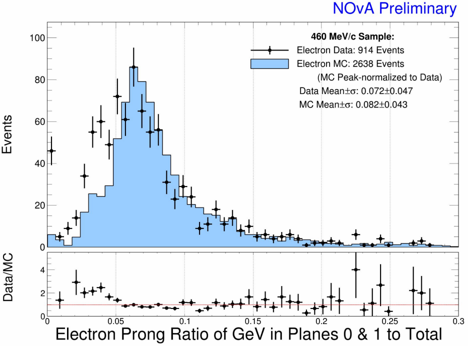
Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right

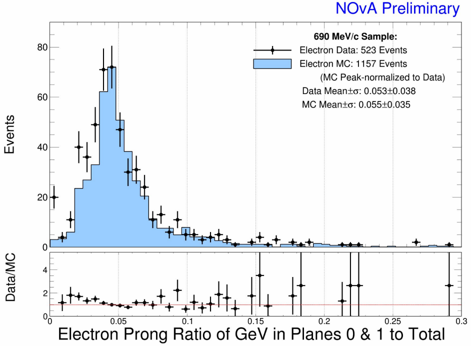


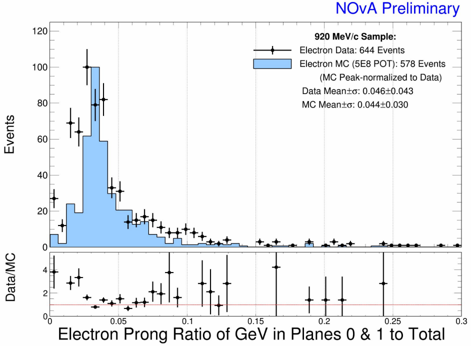
Energy Ratio – Planes 0 & 1 to Total

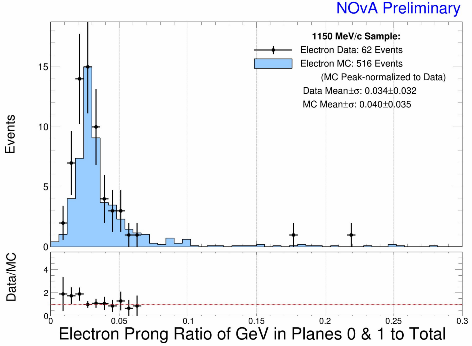
- Reconstructed ratio of energy in planes 0 & 1 to total
- Reconstructed energy near the beginning of tracks as a fraction of the total track energy

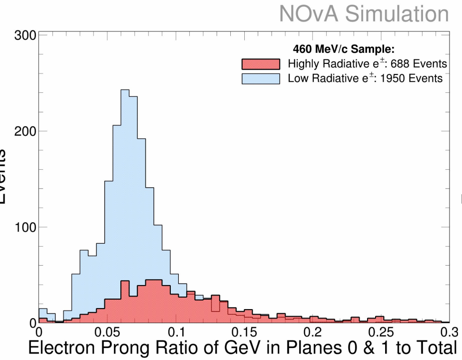
Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right

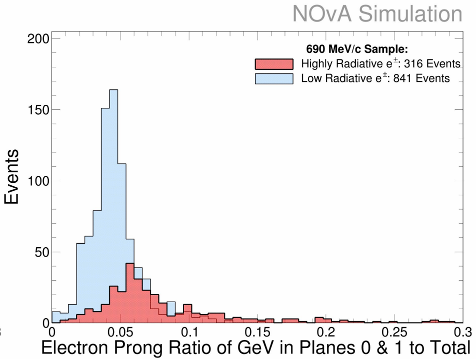


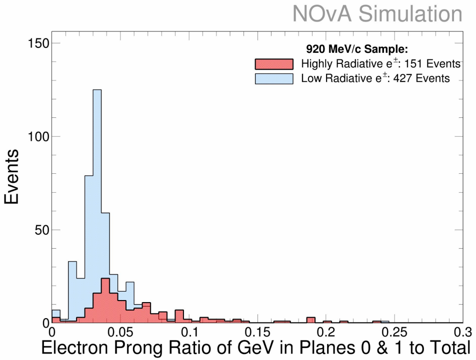


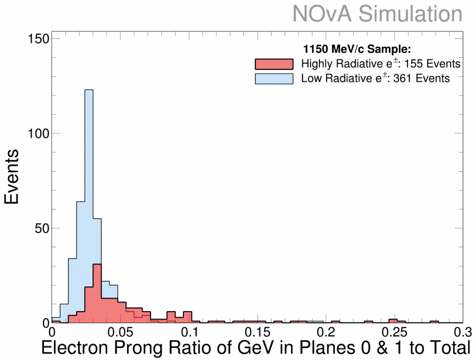




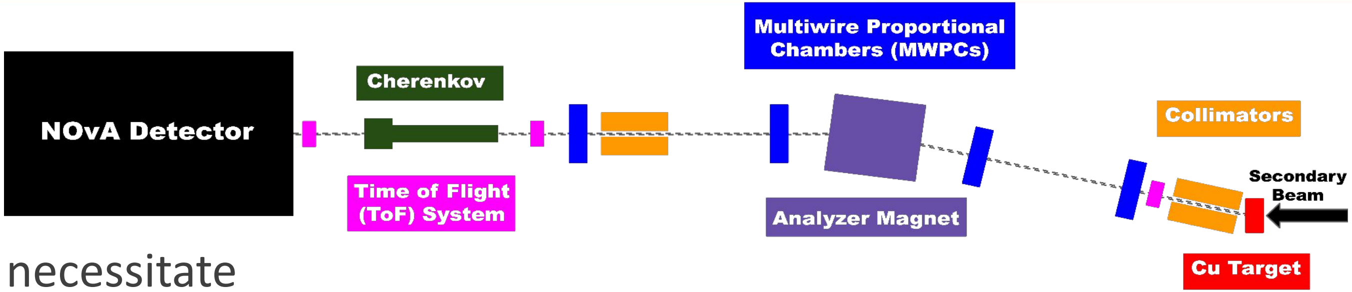






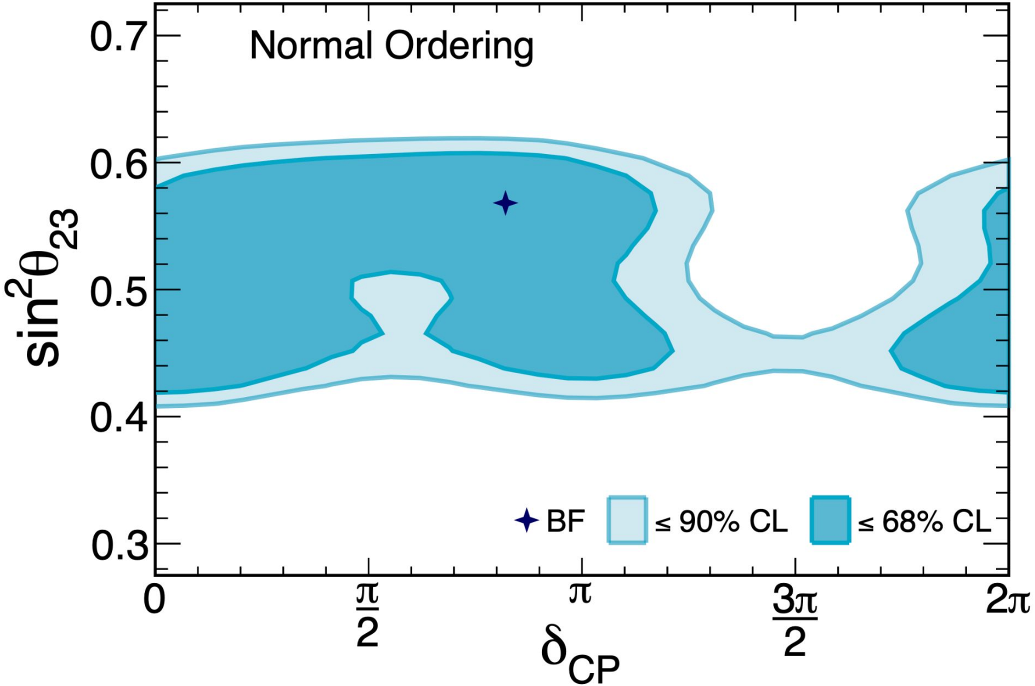


Summary & Plans



- Beamline energy losses necessitate careful selection of $e^{\pm}$
  - Topological properties of electromagnetic tracks could assist selection
  - Preliminary tests have shown promising results!

- Recent results NOvA which Test Beam can improve even further!



Thanks for Listening!

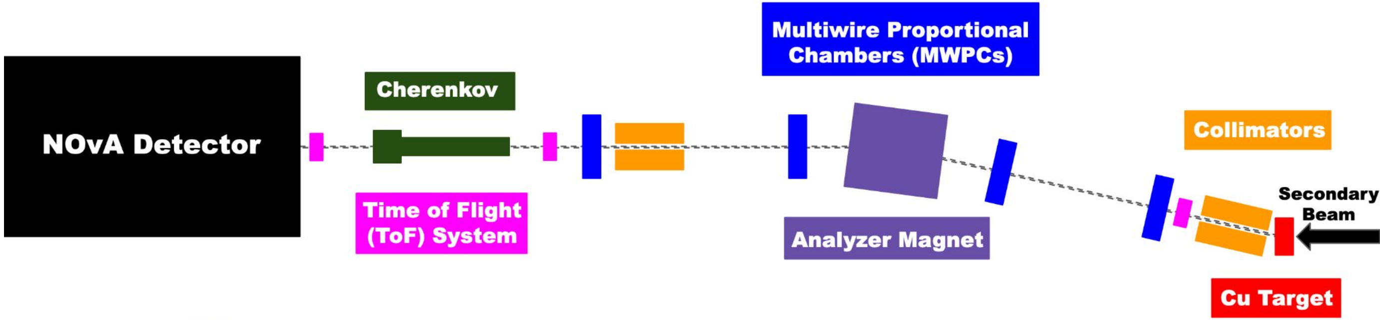
Questions?

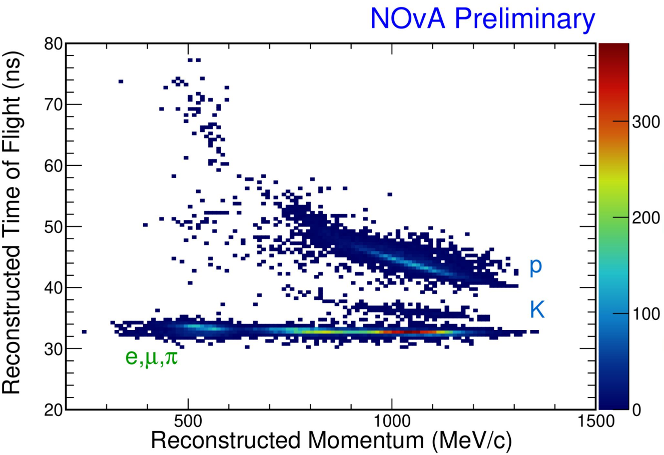
All photos graciously provided by the NOvA Collaboration

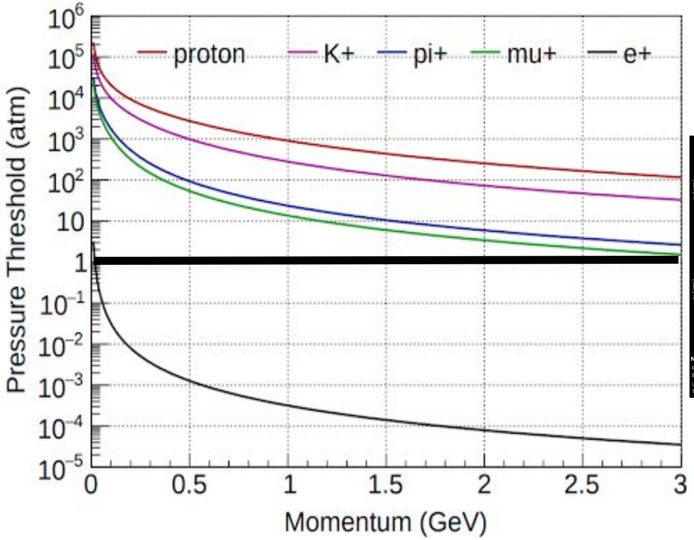
Test Beam Electron Selection

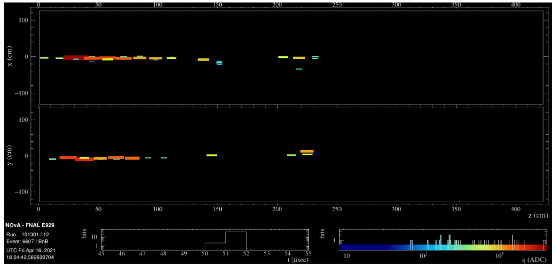
Electrons are identified using the ToF system, the Cherenkov Detector, and the NOvA Detector

- ToF of ~32 ns
- Cherenkov Activity
- Reco. Electron Prong





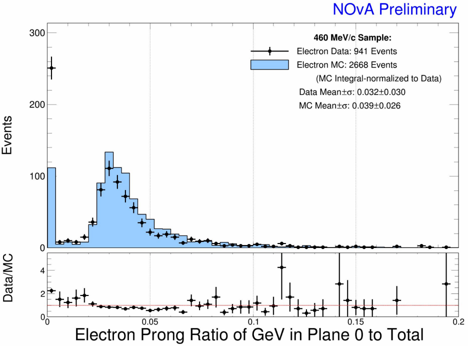


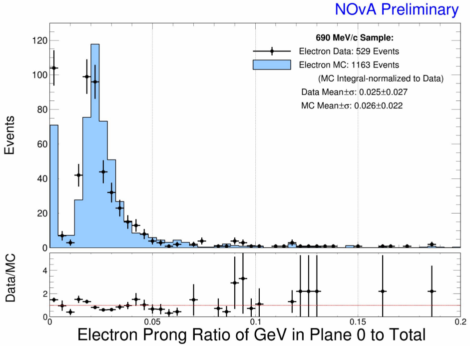


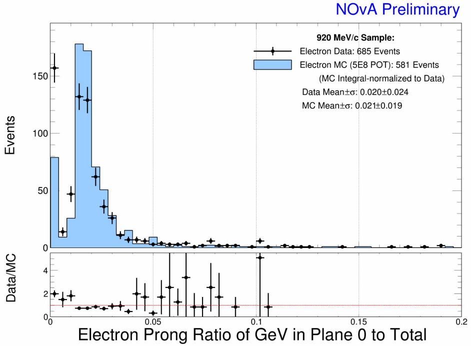
Energy Ratio – Plane 0 to Total

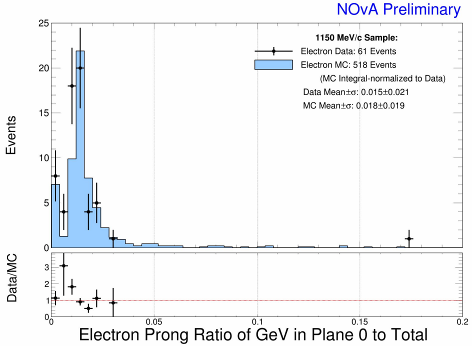
- Reconstructed ratio of energy in plane 0 to total
- Track energy location ratios have some discrepancies – number of events with 0 reco hits in plane 0

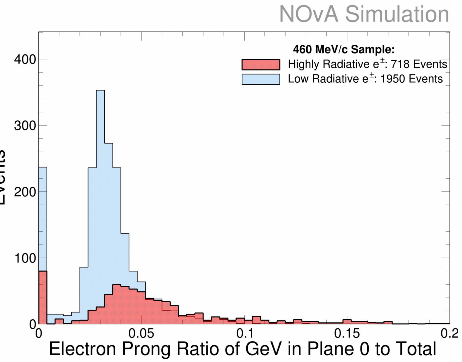
Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right

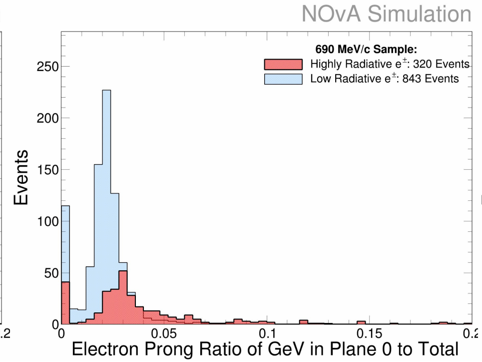


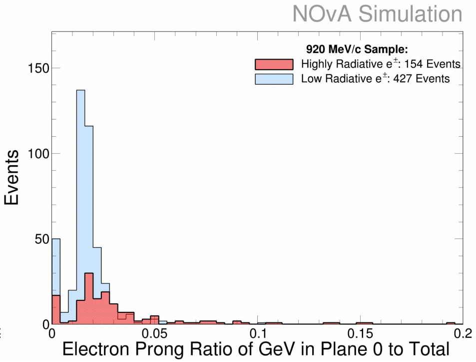


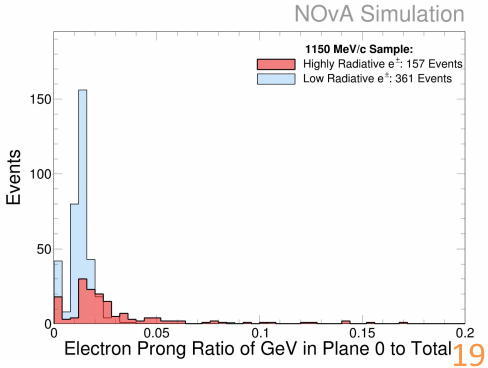




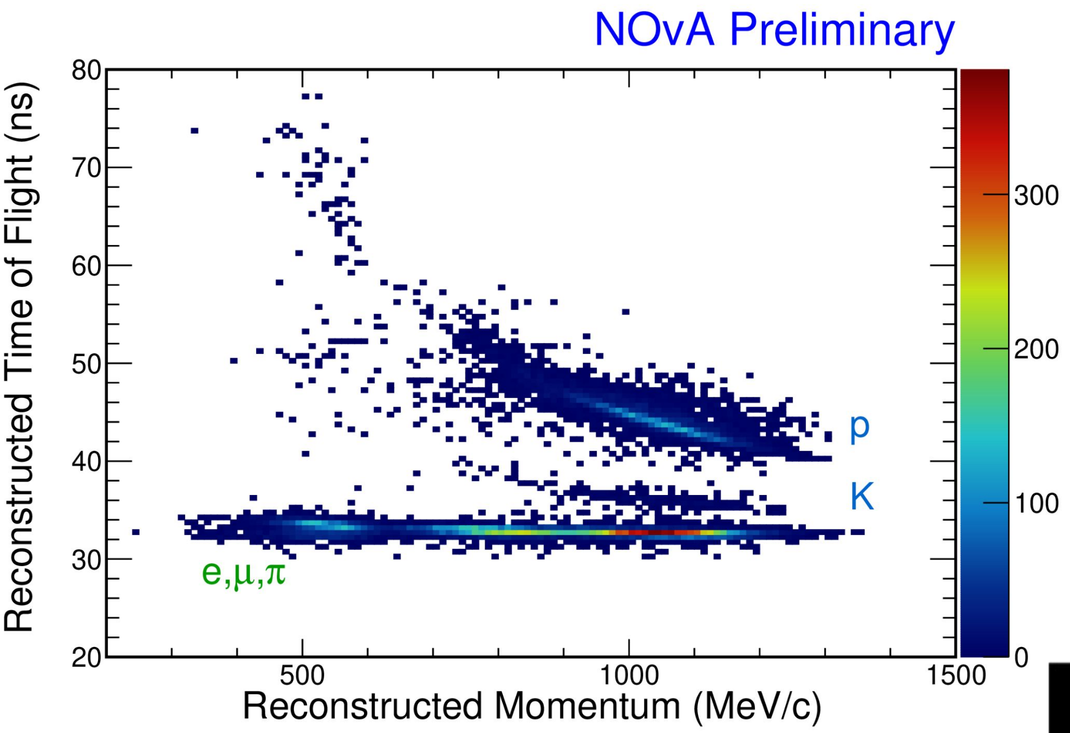




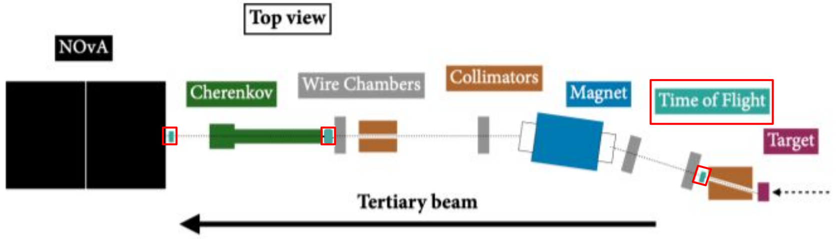




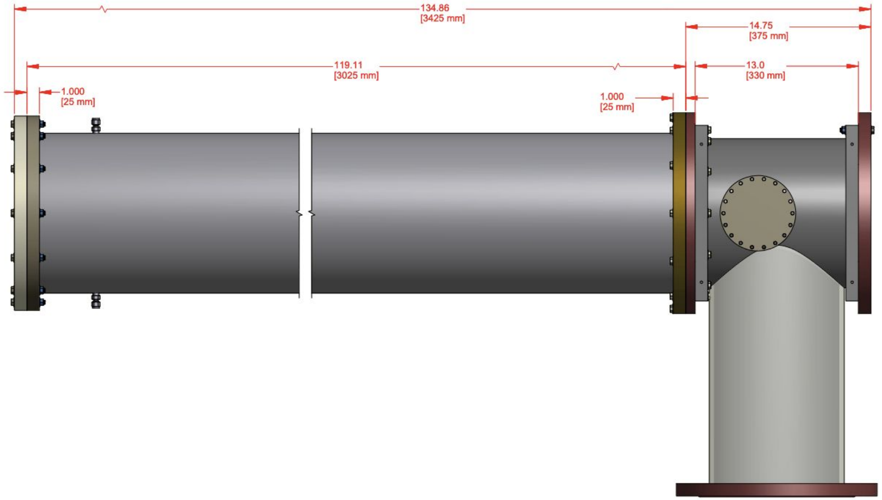
Time of Flight (ToF) System

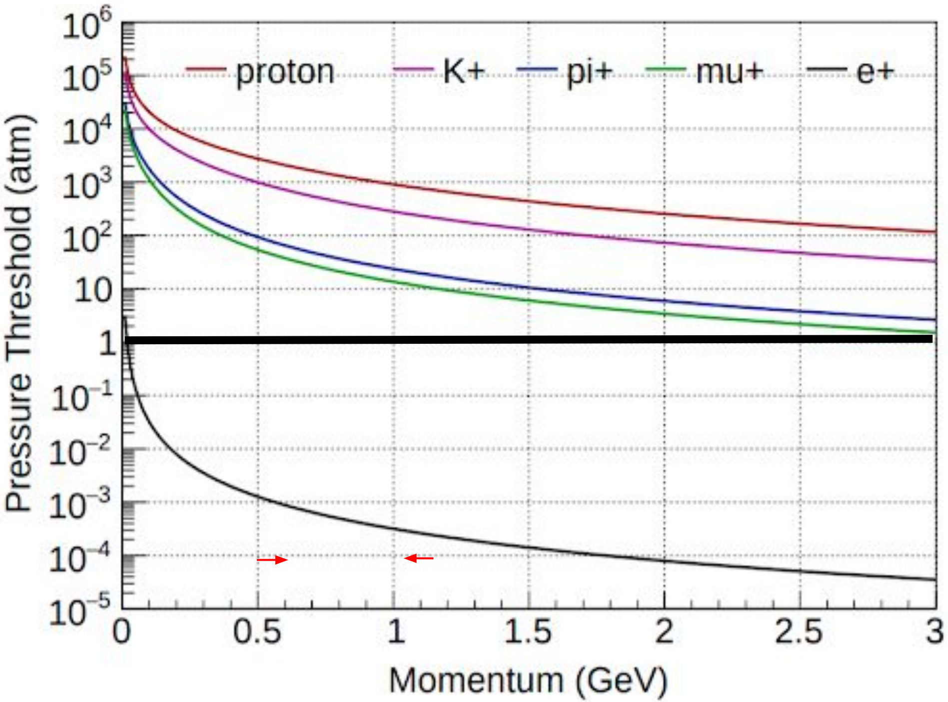


- Each ToF module made of a scintillator block surrounded by 4 PMTs
- 9.9 m path length → 33 ns time difference for v ≅ c
- Resolves p and K from "fast particles" in relevant momentum range: (500-1150) MeV/c

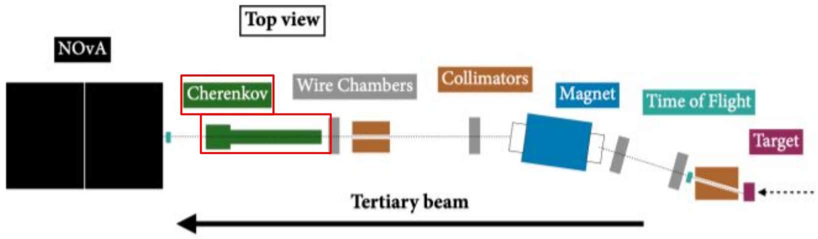


Cherenkov Detector



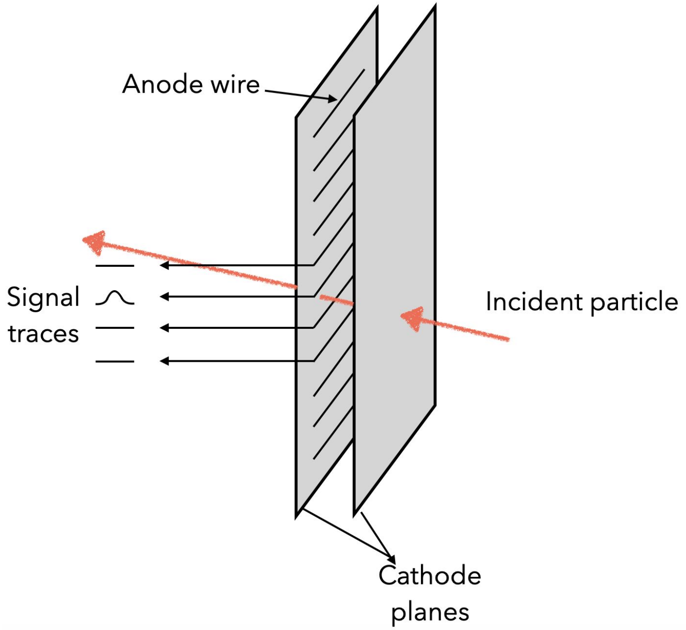


- Designed and built at UT Austin
- Contains CO_2 at a pressure of 1 atm
  - Tuned so only electrons will be above the Cherenkov threshold in the relevant momentum range
- Cherenkov light is reflected by an angled mirror and detected by a PMT in the lower arm



Multi-Wire Proportional Chambers (MWPCs)

Wire Chamber

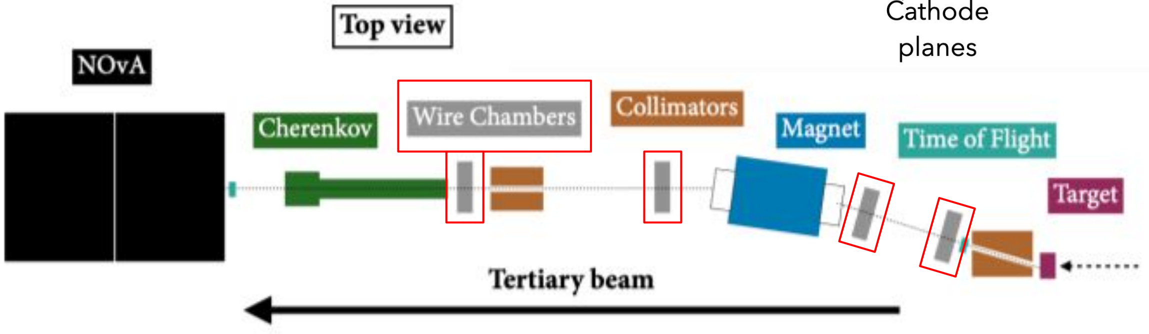


- Connecting hit points of the 2 sets of modules upstream and downstream of the magnet gives 2 tracks
- Angle between tracks gives momentum reconstruction

128 Wires per plane
- 1mm pitch

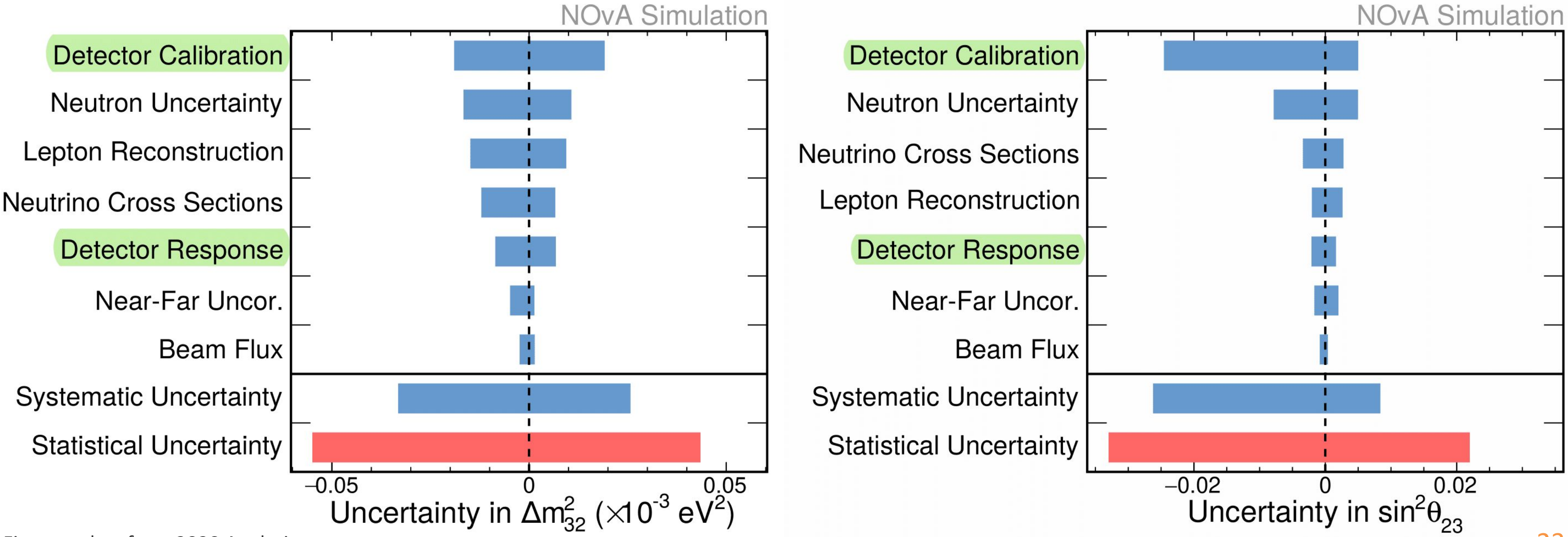
2 planes per module
4 modules
- 2 Upstream
- 2 Downstream

Reconstructed momentum accuracy of ~1-3%



NOvA Test Beam – Motivation

- **Better understanding of Systematic Uncertainties**
- Beamline-measuring components measure particles before they enter a scaled-down NOvA detector
- Looking at e, μ, $\pi^{\pm}$, $K^{\pm}$, and p → ***not neutrinos***
- Understand uncertainty associated with Detector Calibration and Detector Response (NOvA-specific terms)

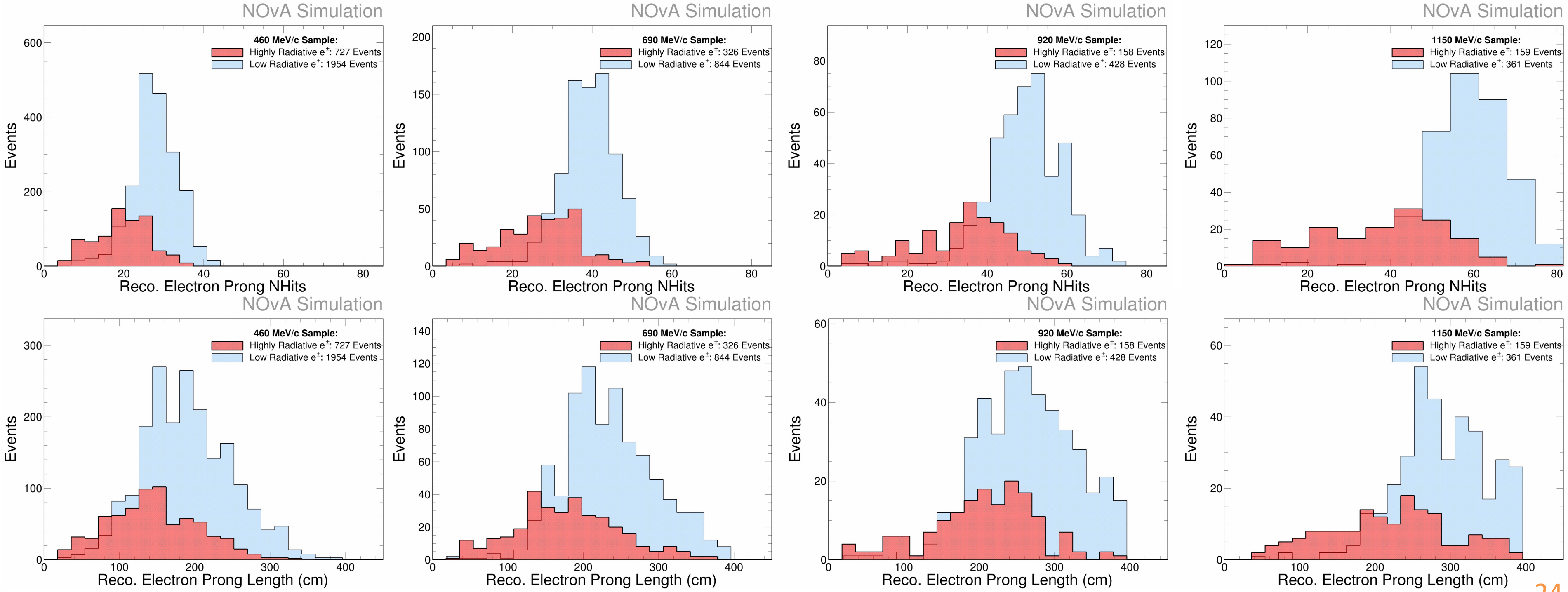


Figures taken from 2020 Analysis

Topological Event Properties

- No single topological is sufficiently separated in these samples to use 1D cuts
- Plan to use a number of topological properties to inform a kNN binary classifier
- Prong length and number of reconstructed hits in particular show separation potential

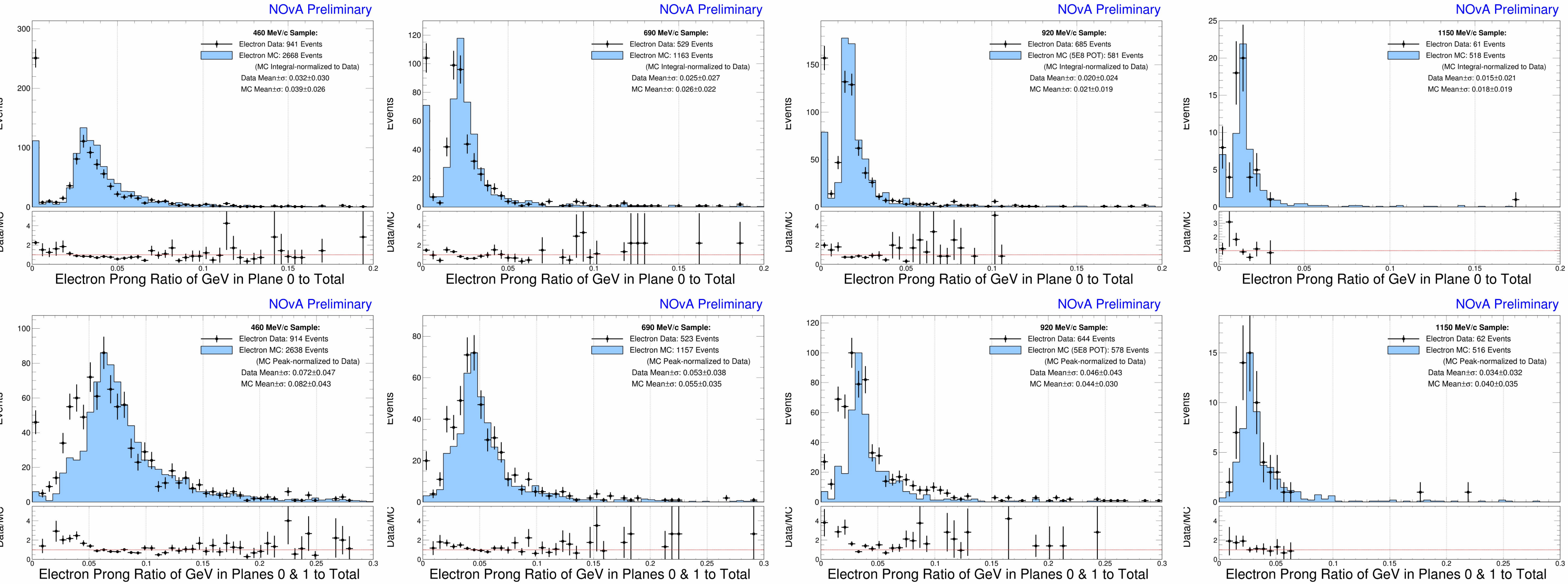
Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right



Topological Event Properties – Data/MC Comparisons

- Track energy location ratios have some discrepancies

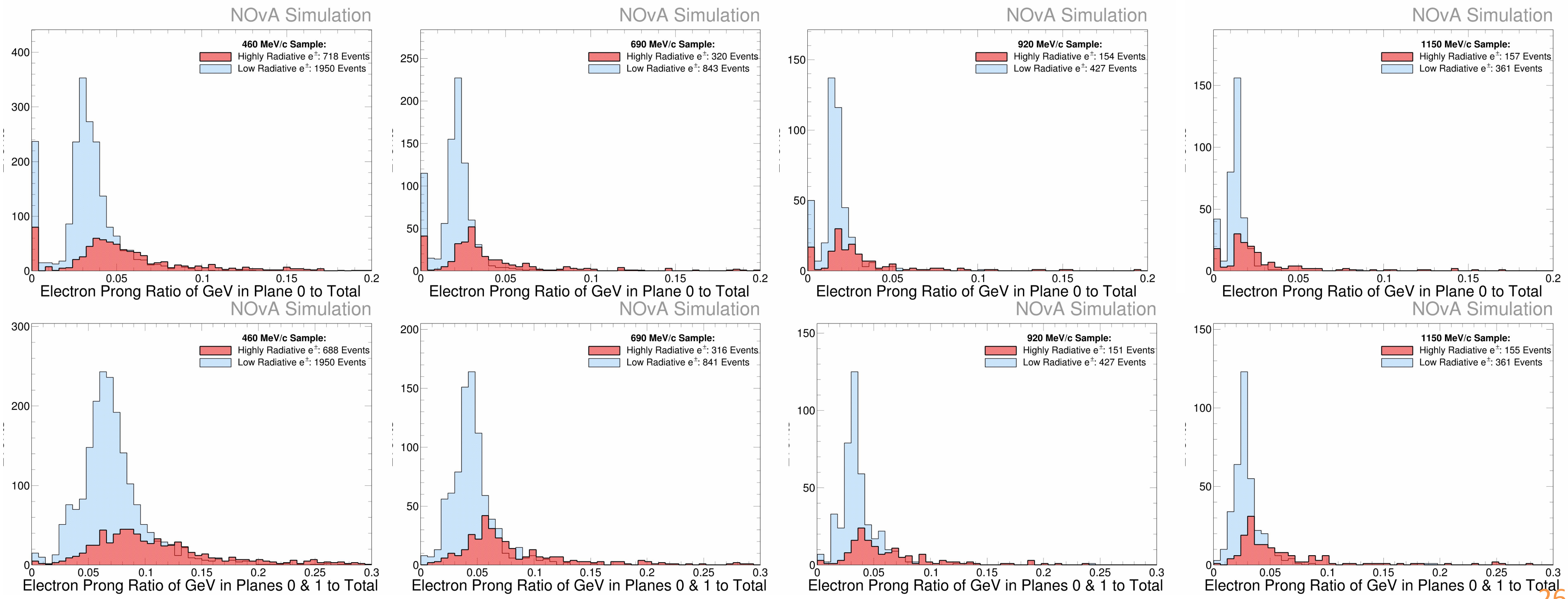
Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right



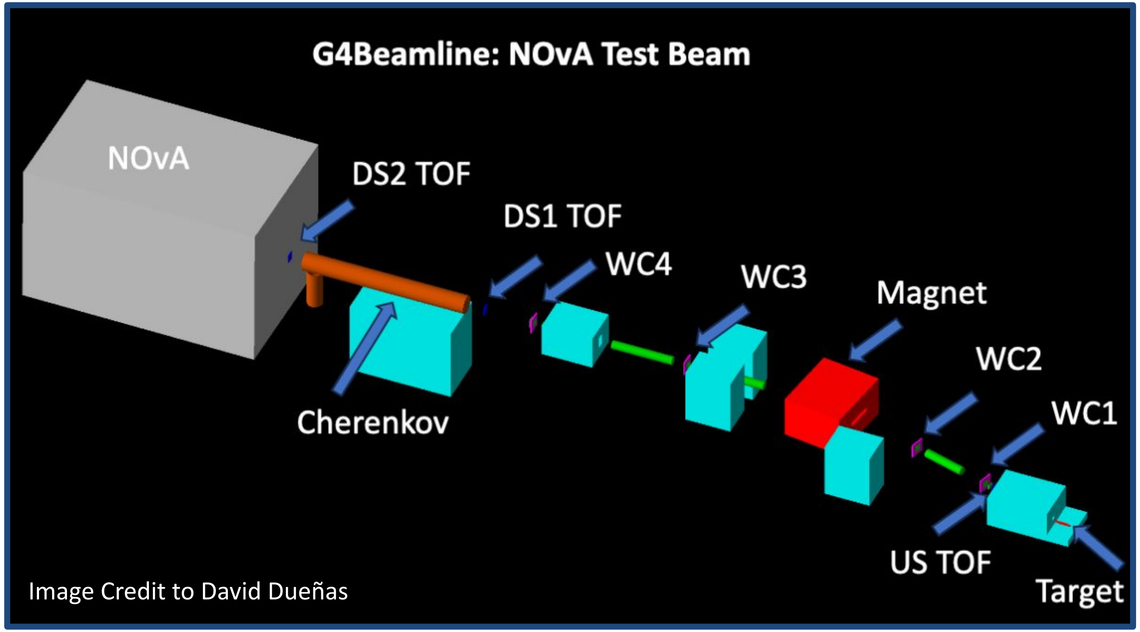
Topological Event Properties

- Reconstructed energy near the beginning of tracks as a fraction of the total track energy also shows promise
  - Looked at 1st plane/total & 1st 2 planes/total

  Simulated magnetic current settings 500A, 750A, 1000A, 1250A left-to-right



Test Beam Electron Simulation



Ordinarily, we simulate the 64 GeV/c hadronic beam interaction with the target

- **Inefficient for electrons**

Alternative Simulation Paradigm:

1. Simulate beamline particles downstream of the target
2. Simulate beamline interactions and detector responses
3. Simulate response of the NOvA Detector