Progress of the Electron-Neutrino Charged-Current Inclusive Cross-Section Measurement in the NOvA near detector

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Motivation

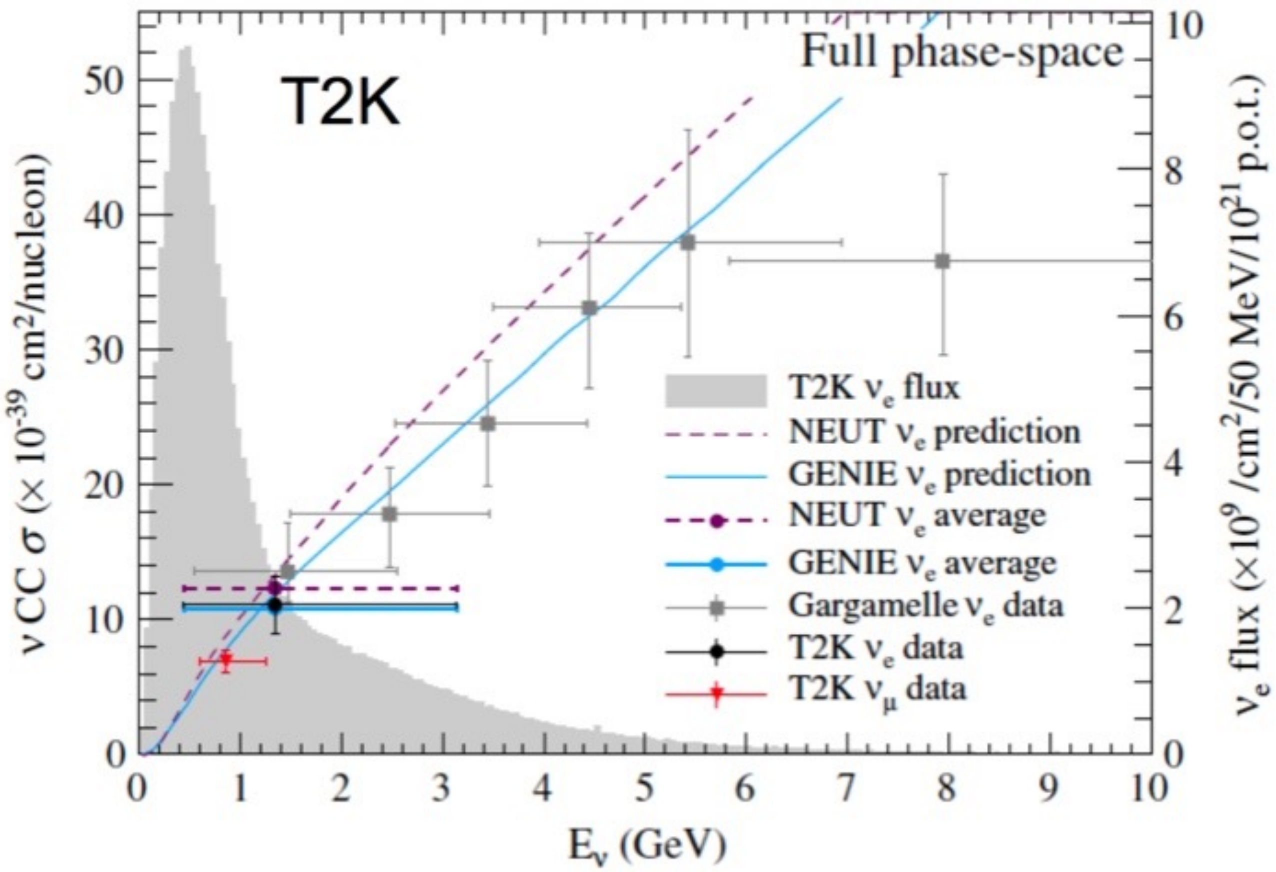
- **Precision** is becoming more important to the results of long baseline neutrino programs, with experiments looking to **reduce uncertainties to the percentage level**.
- Improving on the existing measurements of **neutrino cross sections** will play an important role in improving the precision of **oscillation analyses** and will influence future experiments.
- **The ν_e charged current (CC) inclusive cross-section** is a basic measurement that can be used to **directly tune simulations for the oscillation analysis**.
- In this talk, I am going to show the **current progress of the ν_e CC inclusive cross-section** measurement in the NOvA near detector

ν_e cross-section measurements from other experiments

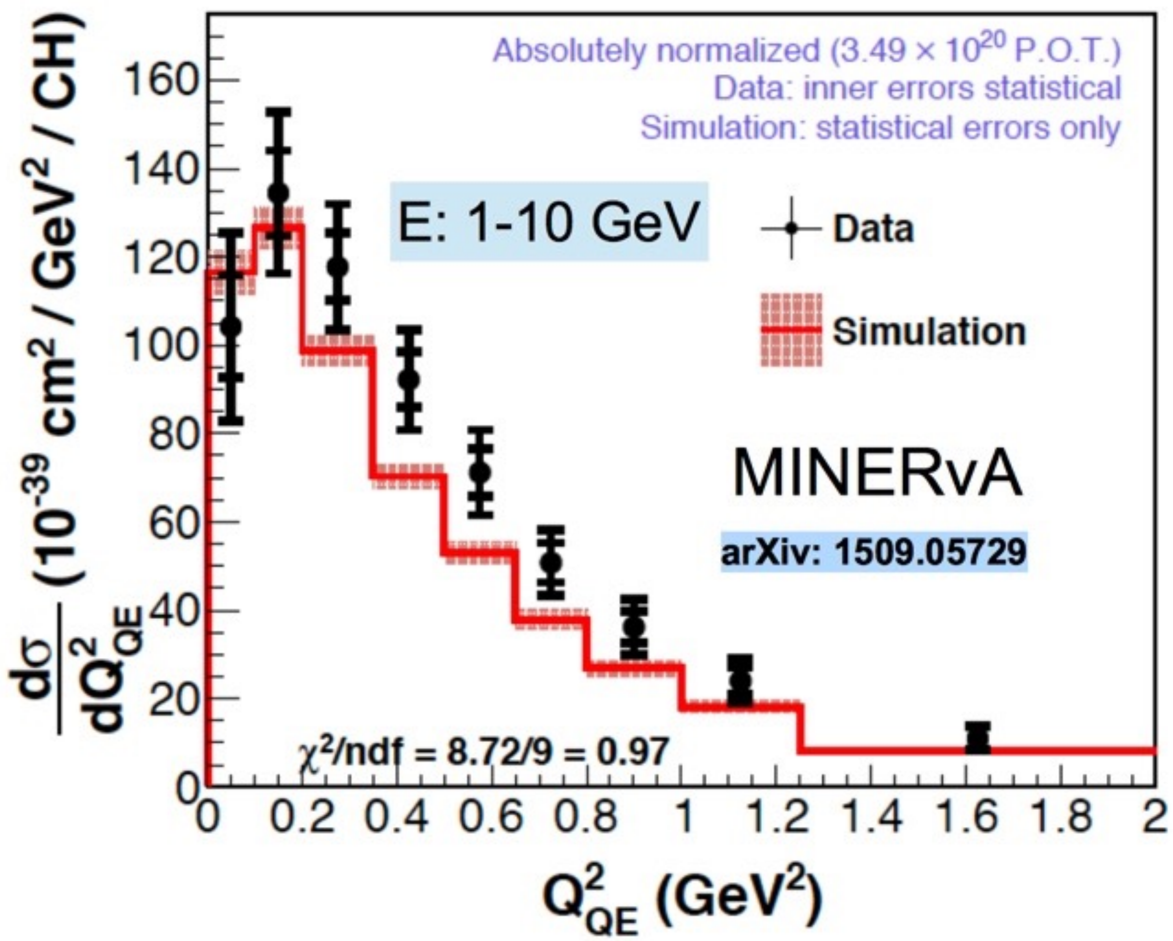
There are few ν_e cross-section measurements at the GeV scale.

Inclusive results

Gargamelle: Nucl. Phys. B133, 205 (1978)
T2K: PRL 113, 241803 (2004)

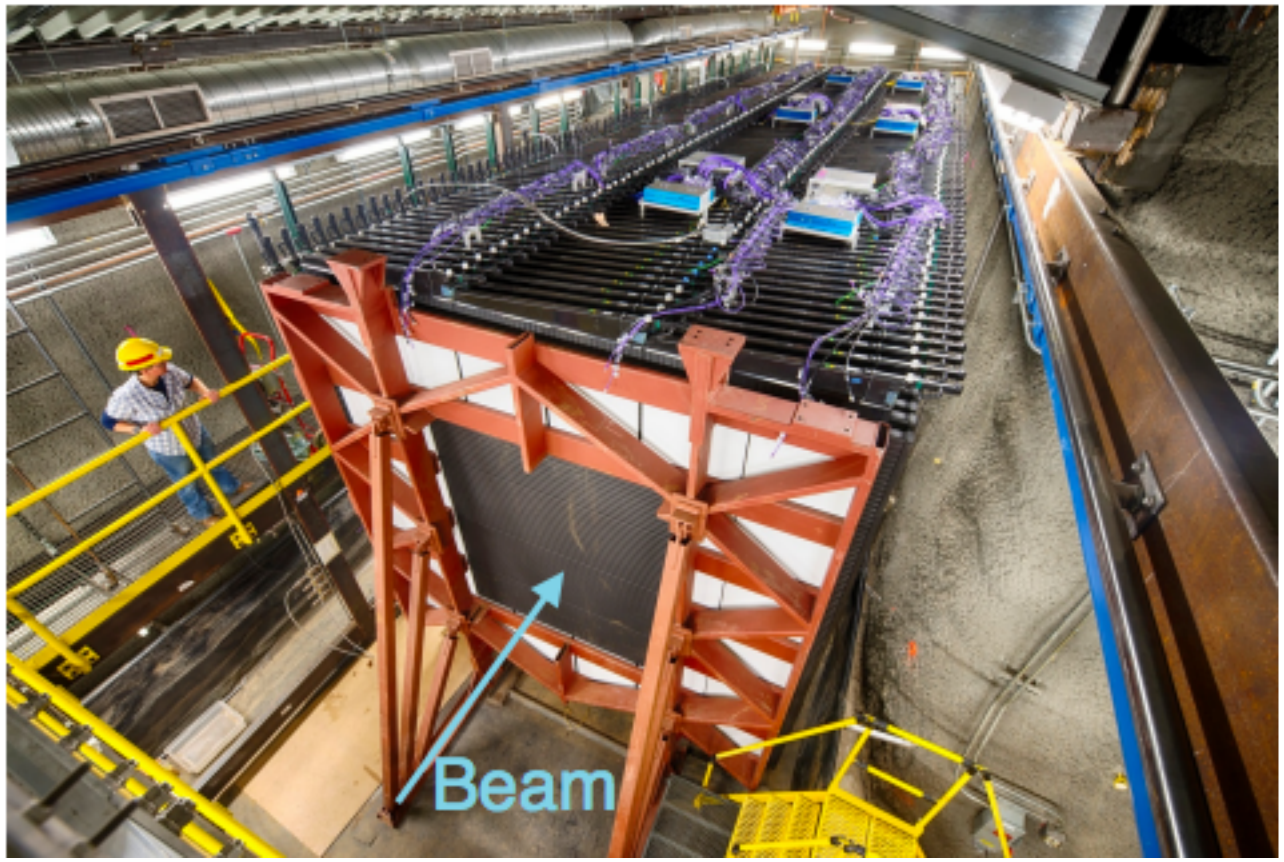


QE only results

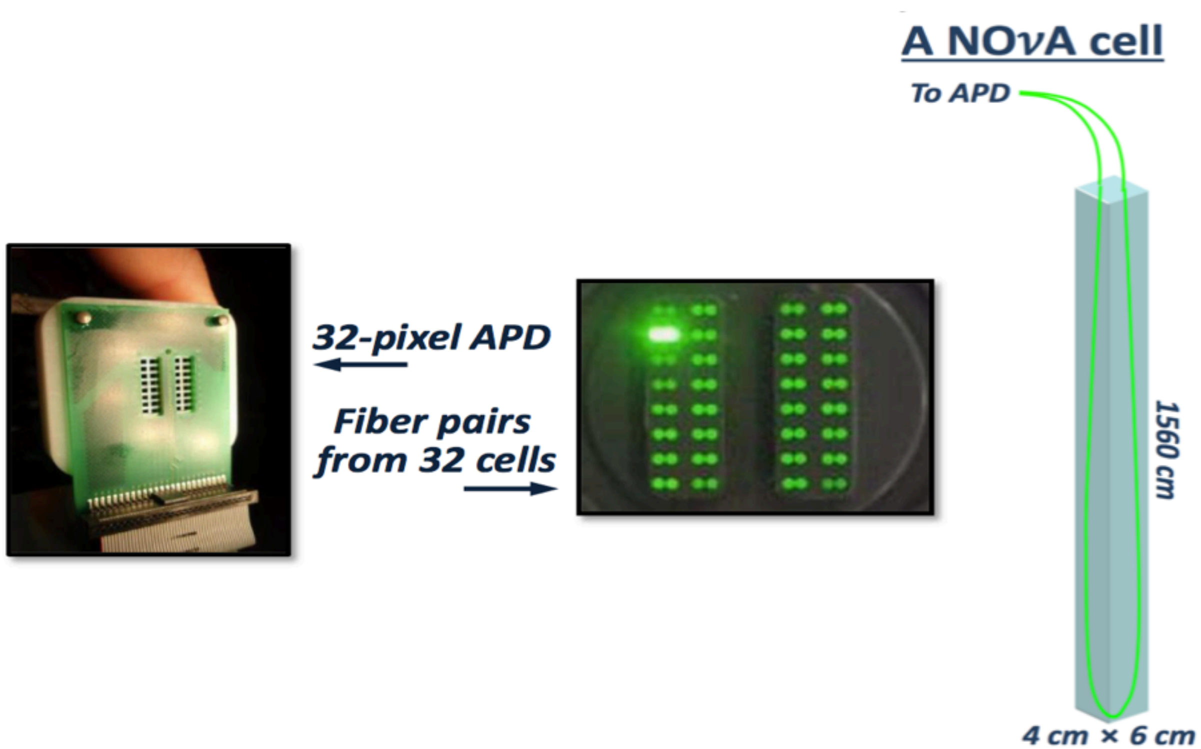


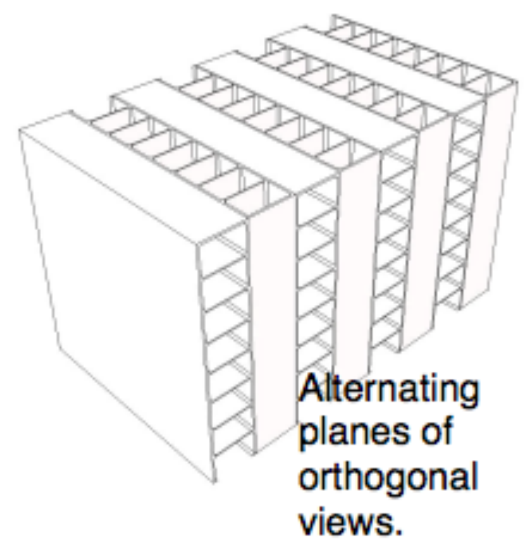
NOvA is making an inclusive cross-section measurement within a slightly higher energy range.

The NOvA Near Detector

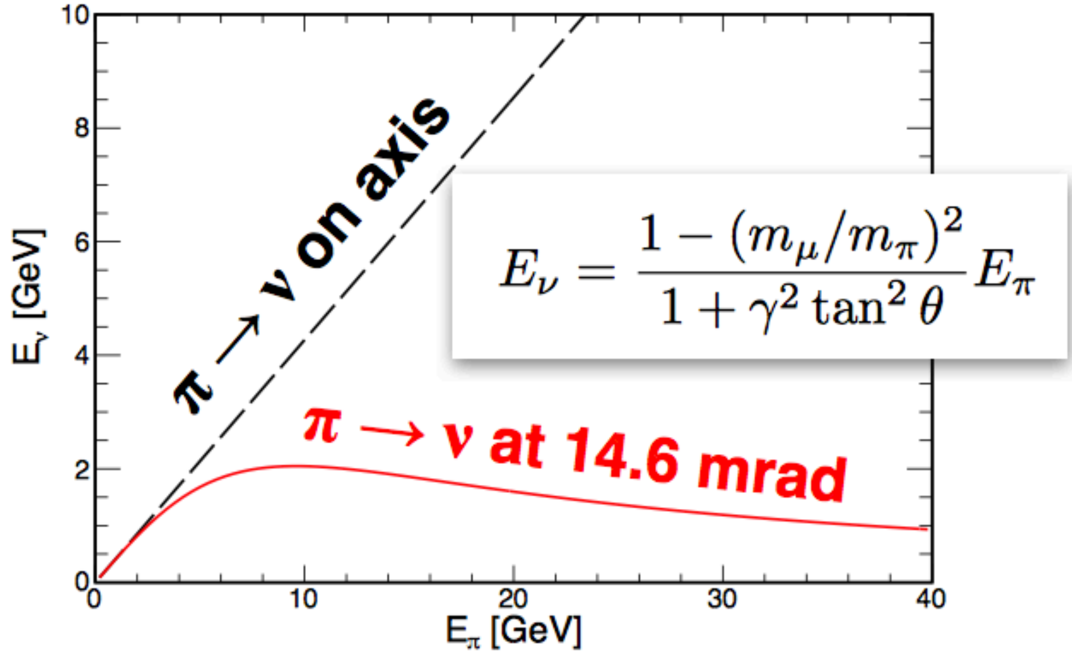


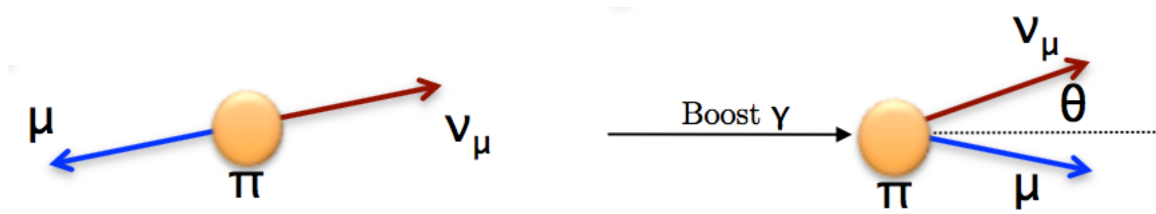
- off-axis, ~1km from target hall, ~100 m underground,
- Tracking calorimeter
- Low-Z ($X_0 \sim 0.3$m): 77% hydrocarbon by mass, 16% chlorine, 6% TiO_2;
- Muon catcher (steel + NOvA cells) at downstream end to range-out ~2 GeV muons;
- O(10) ns single hit timing resolution.





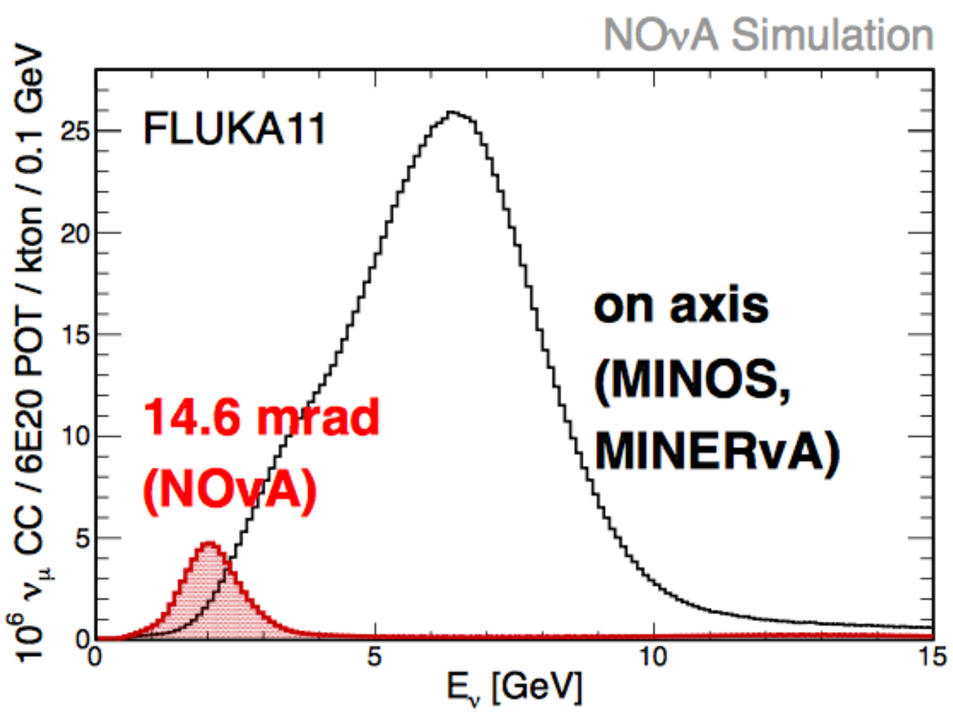
Neutrino Beam at NOvA

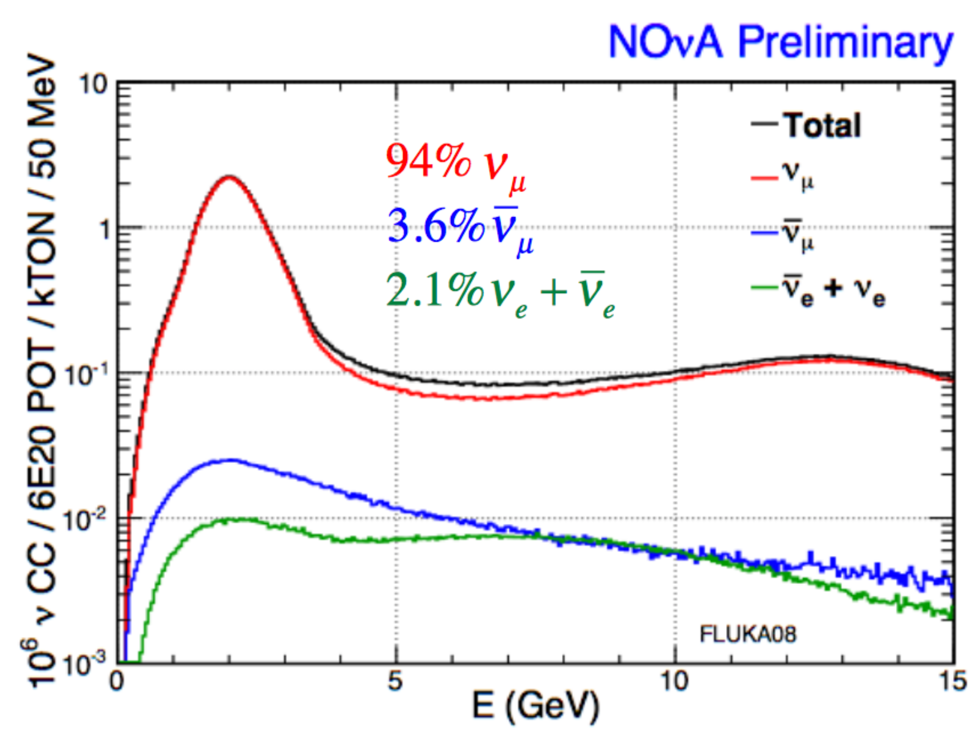




Pion rest frame   Lab frame

- Off-axis position results in:
  - narrow-band beam centered around 2 GeV
  - small flux shape uncertainties





Electron Neutrino flux is a small percent of the total flux, with a broad energy spectrum.

Cross-Section Measurement

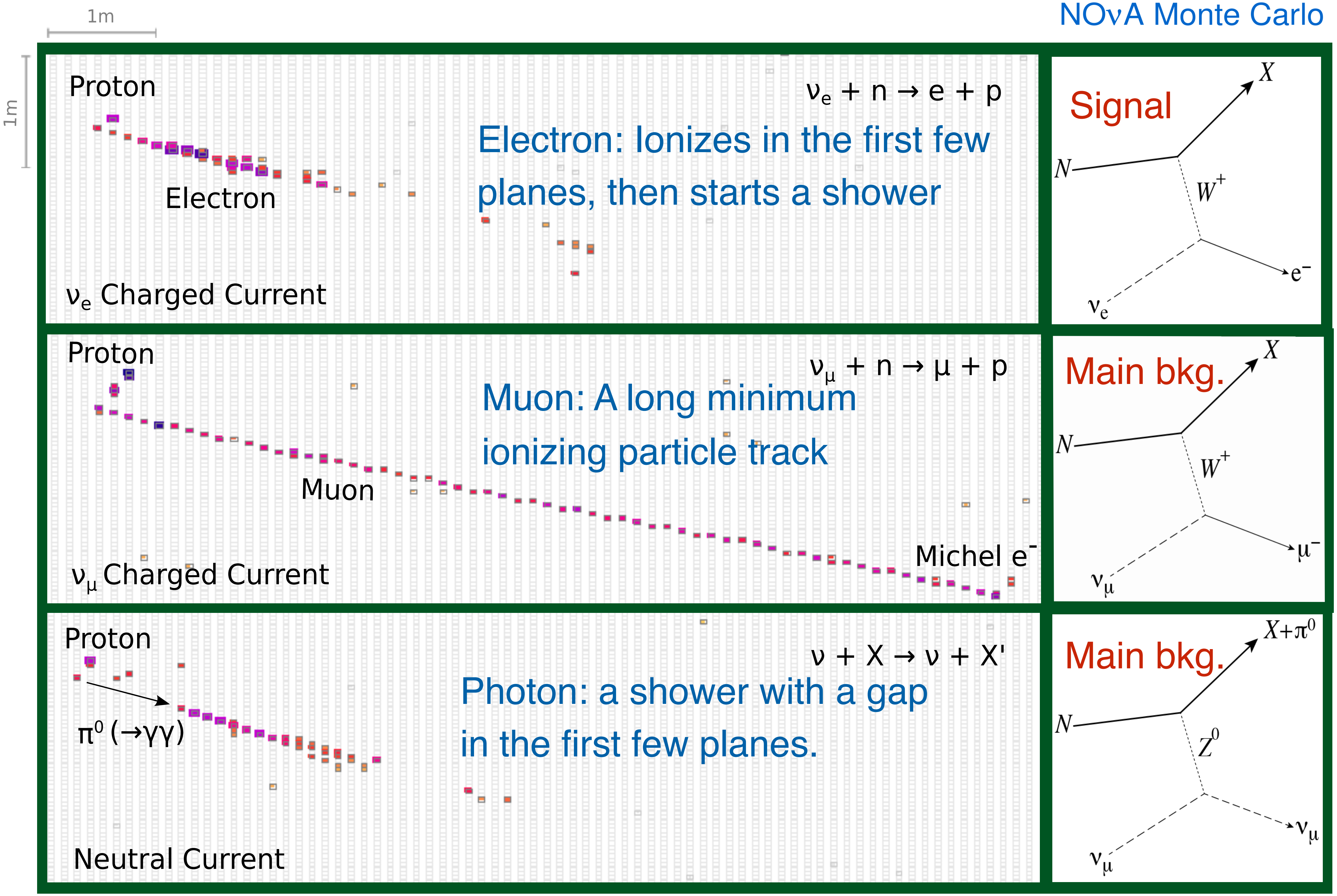
- The NOvA Near Detector (ND) provides an excellent opportunity for the measurement of various neutrino interactions

$$\sigma_k = \frac{\Sigma_j \, U_{kj} \left(N_j^{sel} - N_j^{bkg} \right)}{T \, \phi \, \varepsilon_k}$$

- N^{sel} is the number of selected data events
- N^{bkg} is the number of background events
- ε is the total event selection efficiency
- U is an unfolding matrix to unfolded to true space from reconstructed space
- Φ is the integrated neutrino flux
- T is the total number of nucleons in the target

Neutrino Interactions in the NOvA detector

NOvA Monte Carlo



Simulated Events With 2 GeV Neutrino Energy.

Event Selection

- A number of cuts are used to pre-select a sample of electron neutrino events;

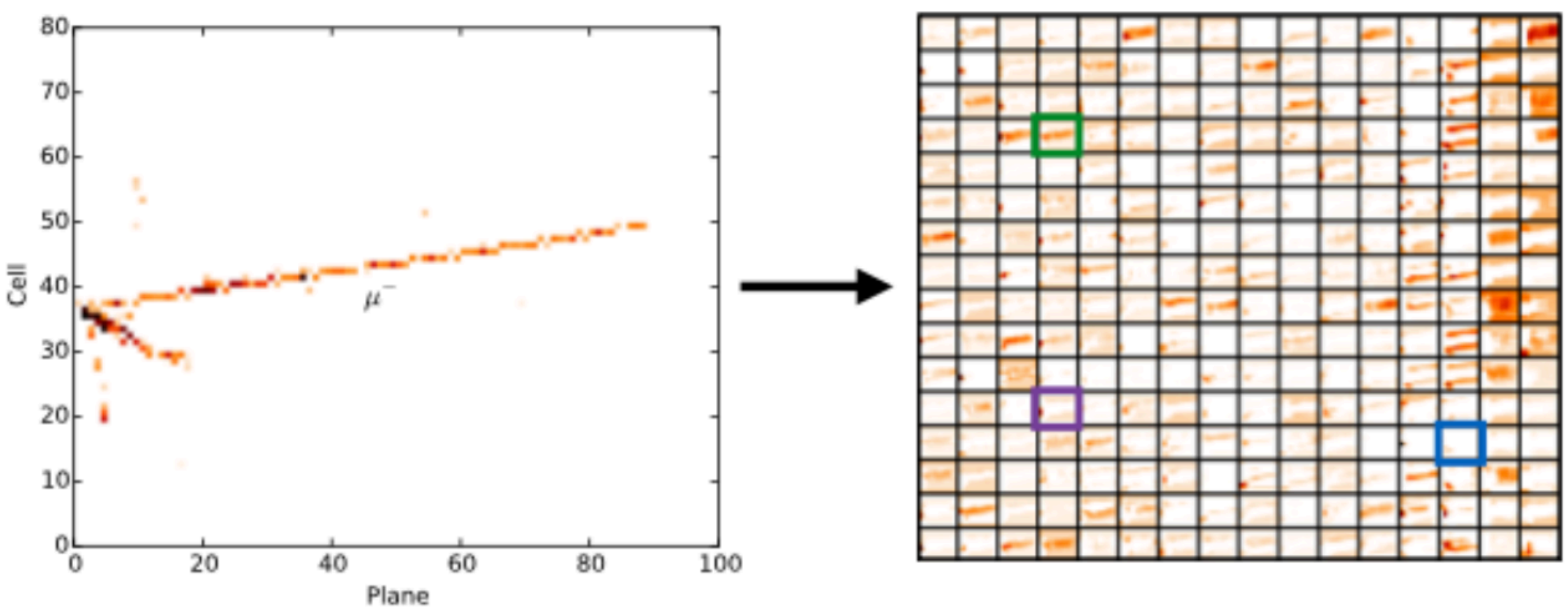
- The **final selection** is made using a technique based on deep learning to select ν_e CC events
  - Events are classified based on topology:
    - ν_e CC events can be identified through the presence of a shorter, wider shower
    - ν_μ CC events can be identified by the presence of long straight tracks
    - NC events lack a charged lepton in the final state and tend to only have activity from the nuclear recoil system
  - A series of image processing transformations are used to extract features that can be used to distinguish these different types of events

- A different PID (artificial neural network using shower shape based likelihood) has been studied as a cross-check in the final selection.

Event Selection with CVN

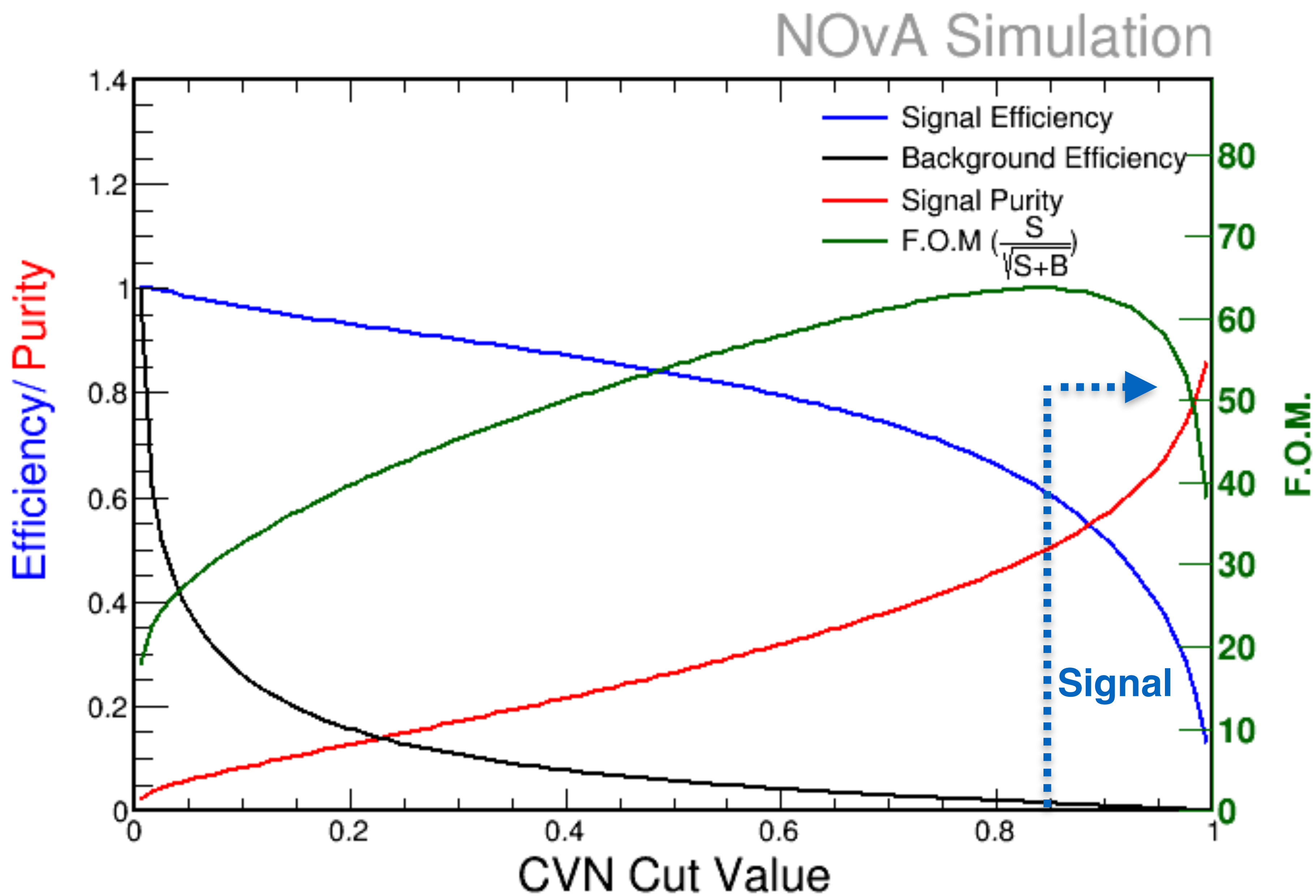
- Use progress in image processing technology via a convolutional neutral network (CNN), where a series of learned image filters are applied to hit map images to extract features associated with an interaction in our detector;

- Different filters highlight the topological features of the different types of neutrino interactions;



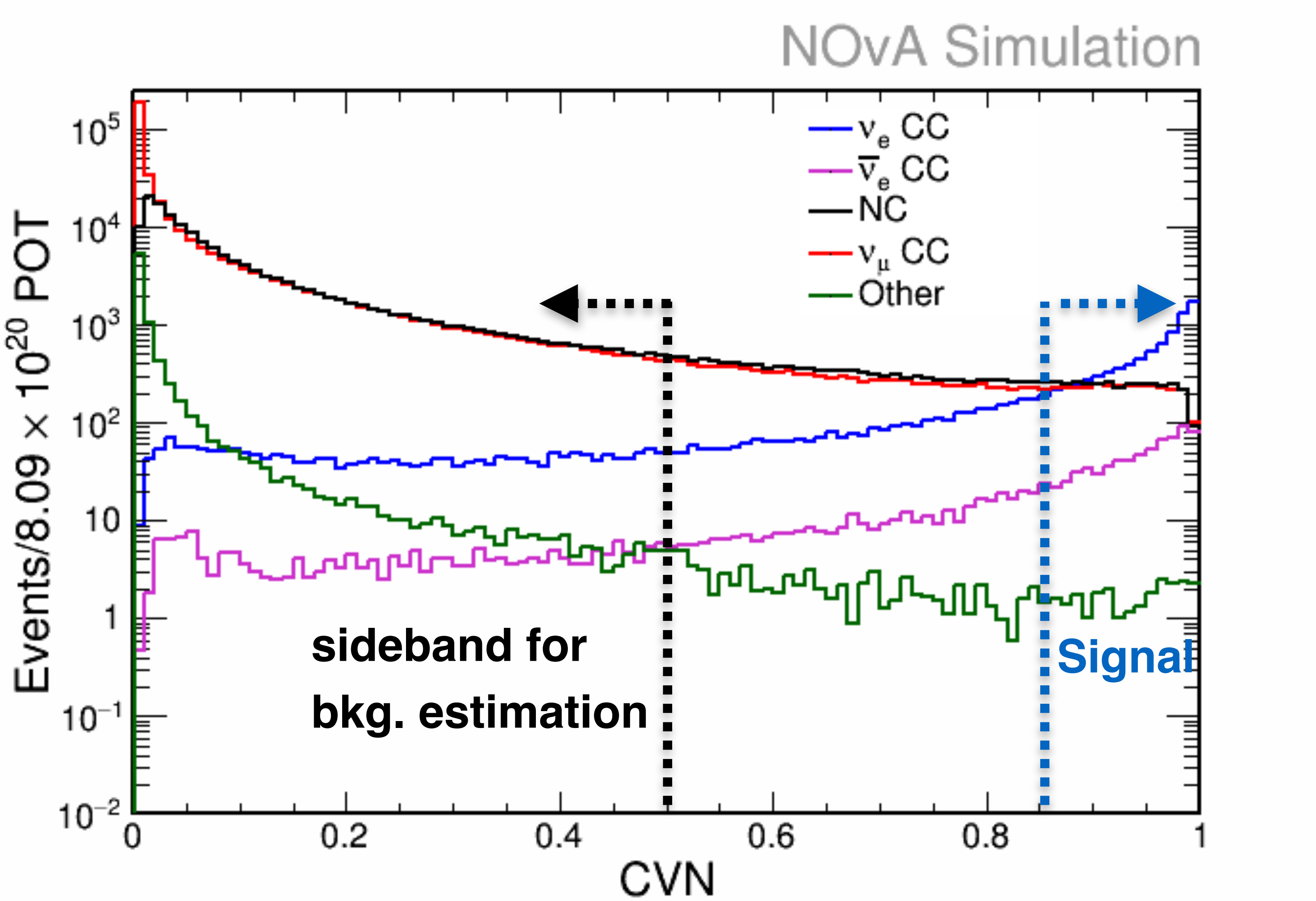
- A convolutional visual network (CVN) is then trained on these filters.

Efficiency and Purity - CVN



- Defining figure of merit (F.O.M.) as S/sqrt(S+B)
- Rough optimization of F.O.M. and signal efficiency is found with CVN ~0.85

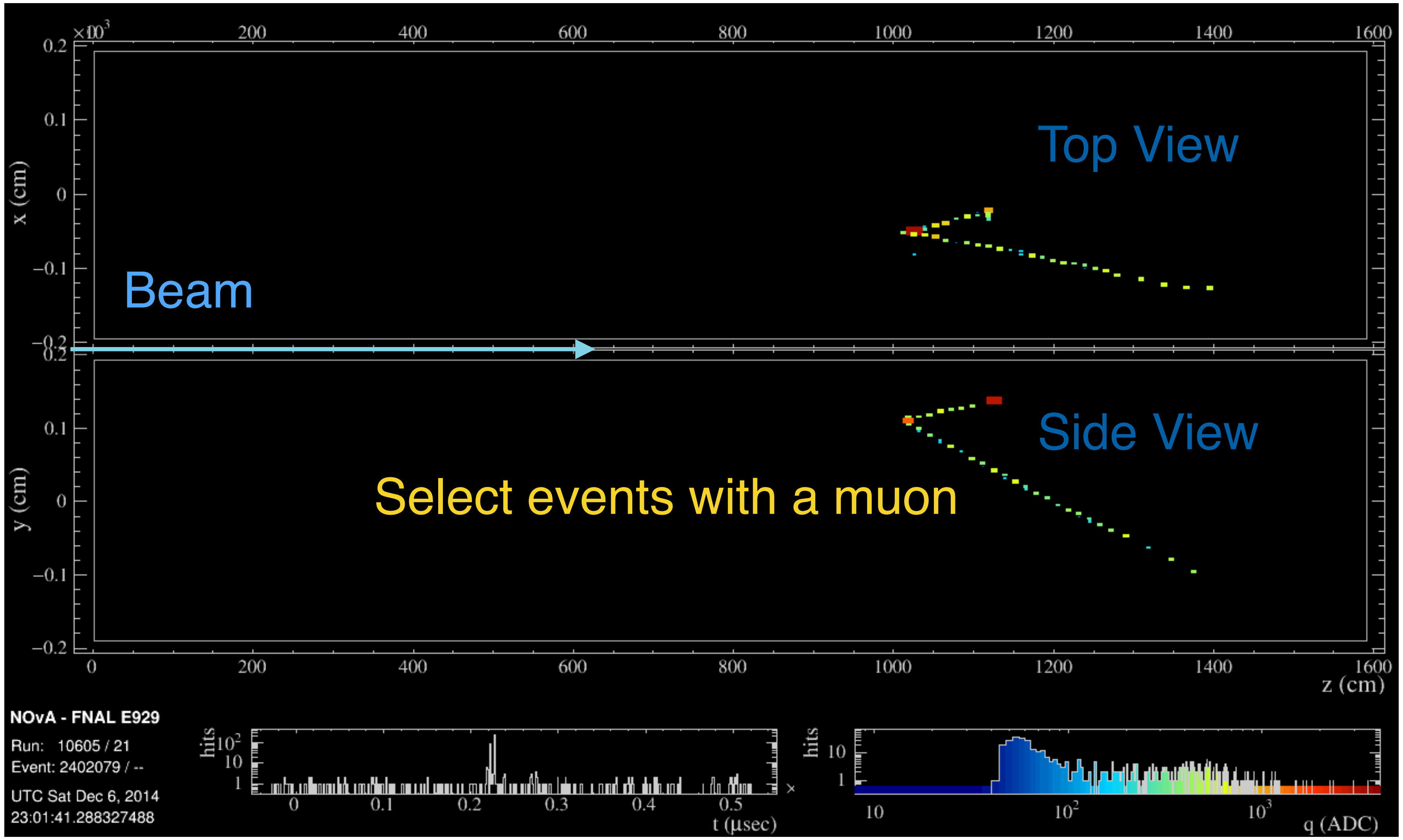
Event Selection and background estimation with CVN



Expected Event Fraction From Simulation		
Interaction	**Fraction(%)**	**Number**
ν_e CC	**51.2**	**10,446.70**
Anti - ν_e CC	**4.4**	**904.66**
ν_μ CC	**21.1**	**4,316.67**
NC	**23.0**	**4,691.16**
Other	0.18	37.67

- Events with CVN > 0.85 are selected as candidate ν_e CC events;
- A sideband is chosen with the CVN cut (e.g. CVN < 0.5) for the estimation of ν_μ CC and NC background;

Cross check with Muon Removed Electron (MRE) added Sample



- A special sample where the most likely muon candidates in events are removed and replaced with simulated electrons with the same energy;
- Comparing the selection of these events in our data and MC gives a powerful **data driven tool** to estimate the efficiency of the nue signal selection efficiency

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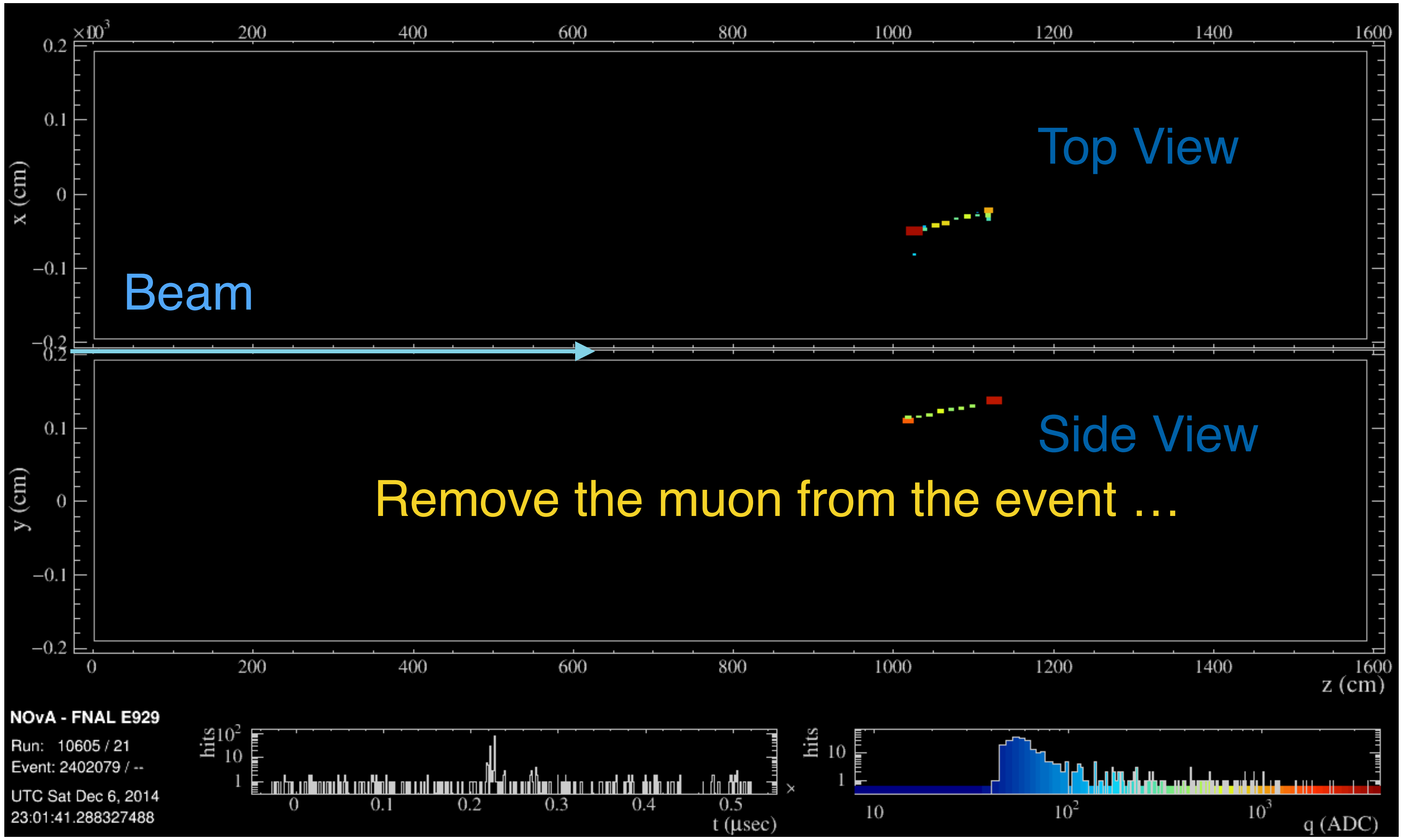

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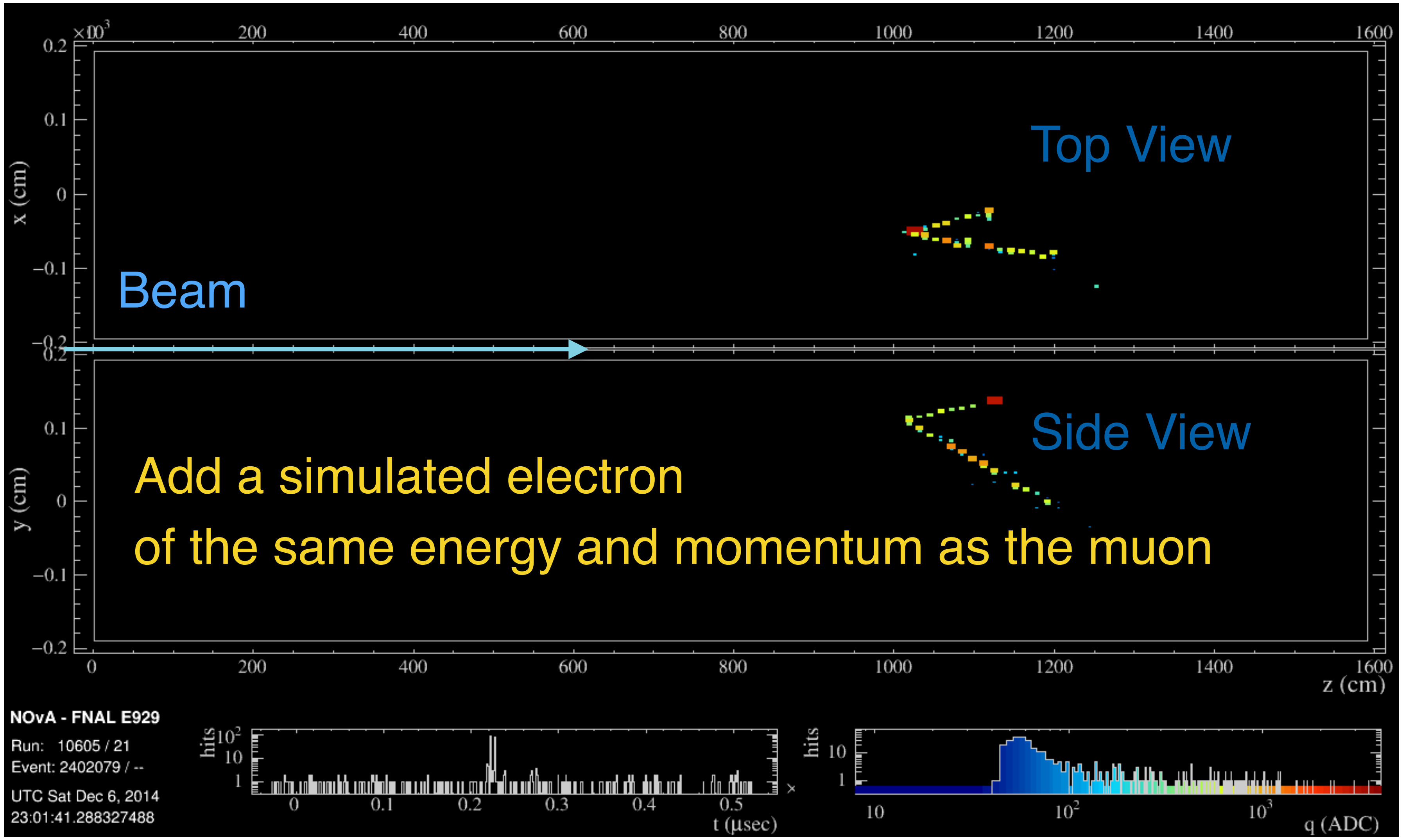

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Fermilab

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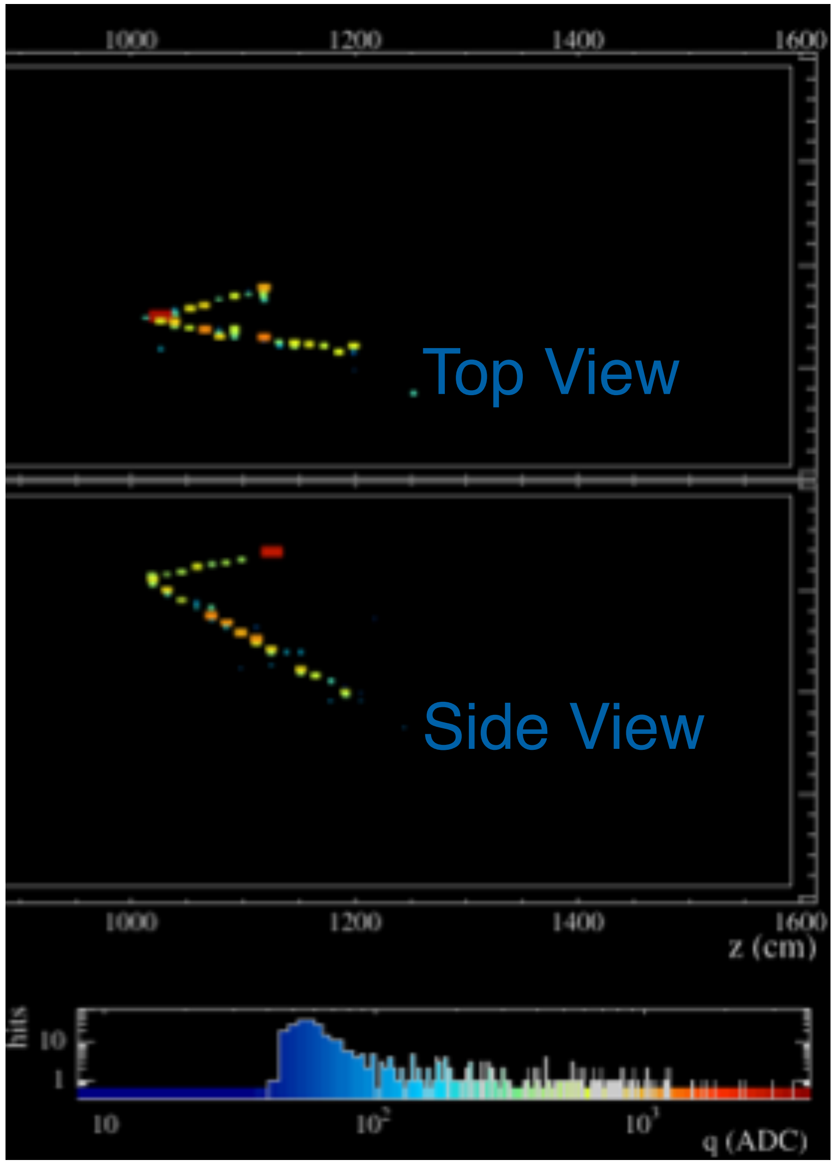
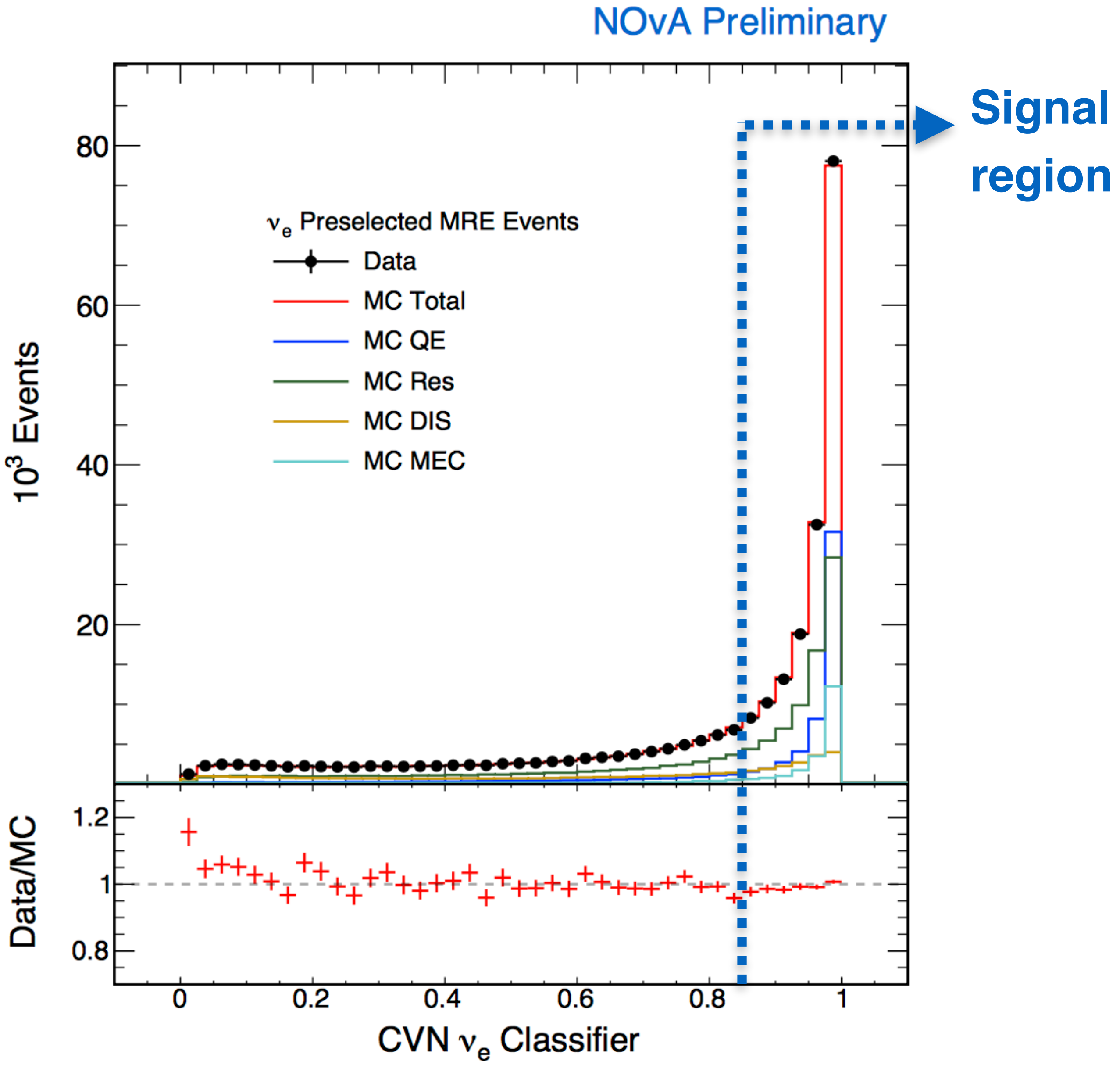
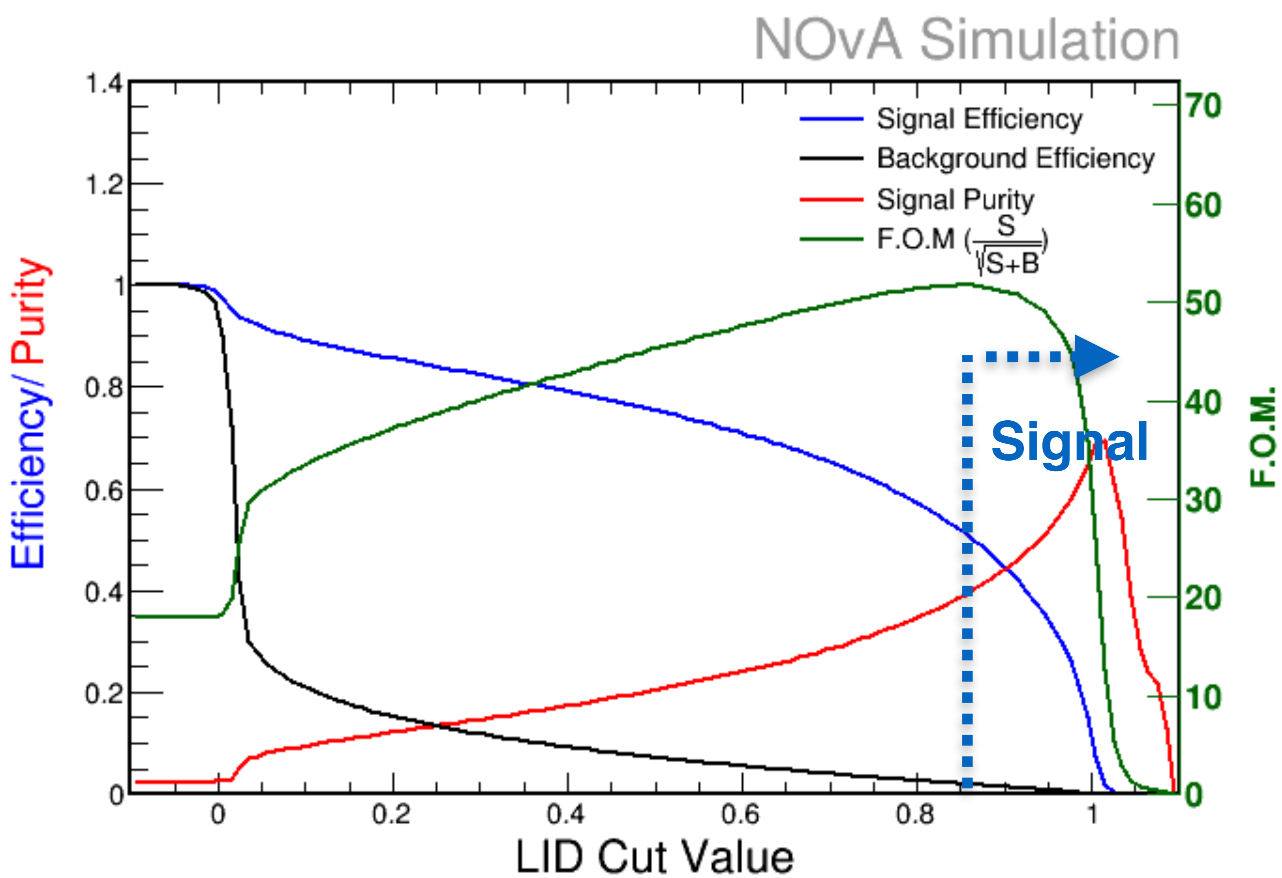
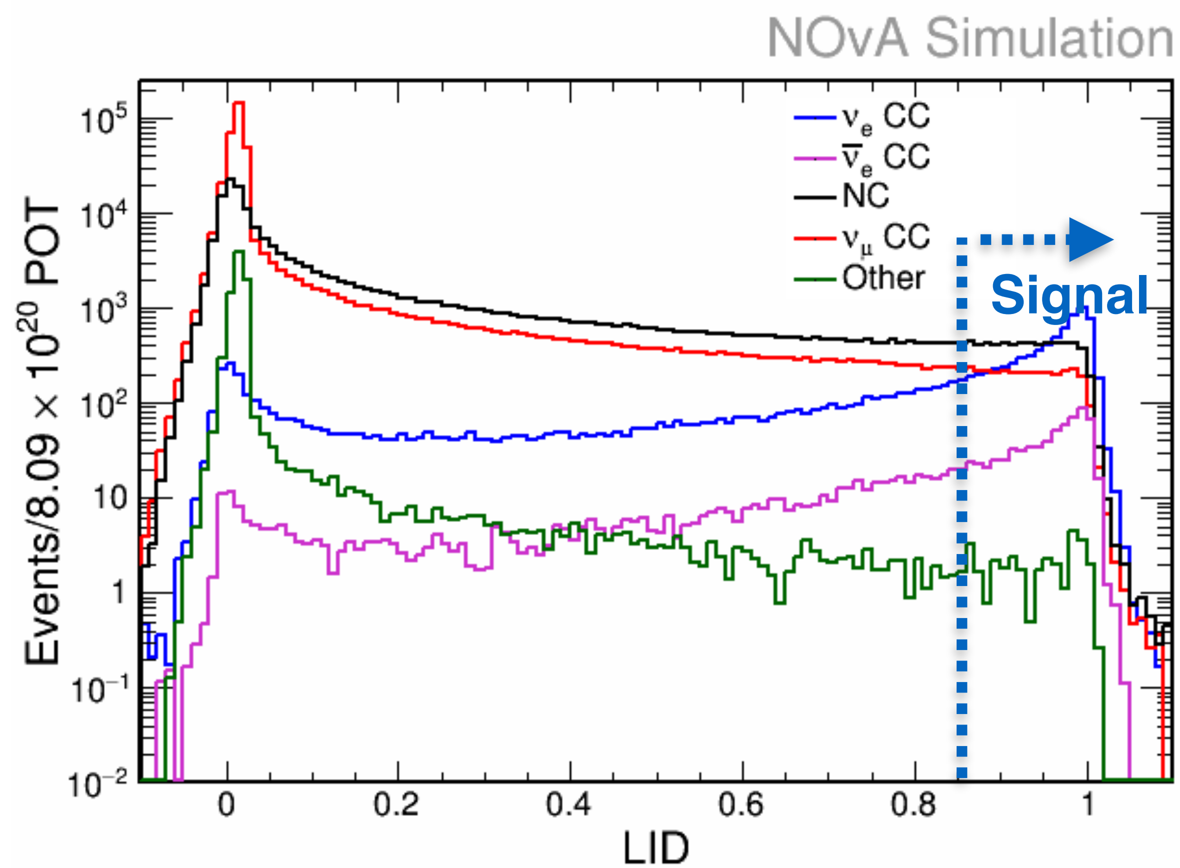




- MRE sample has similar kinematics as real ve CC events;
- It is data-driven so that we can compare MC with data and have an idea of how our simulation and event selection performs.
- MRE sample agrees well with simulation, especially in the signal region.

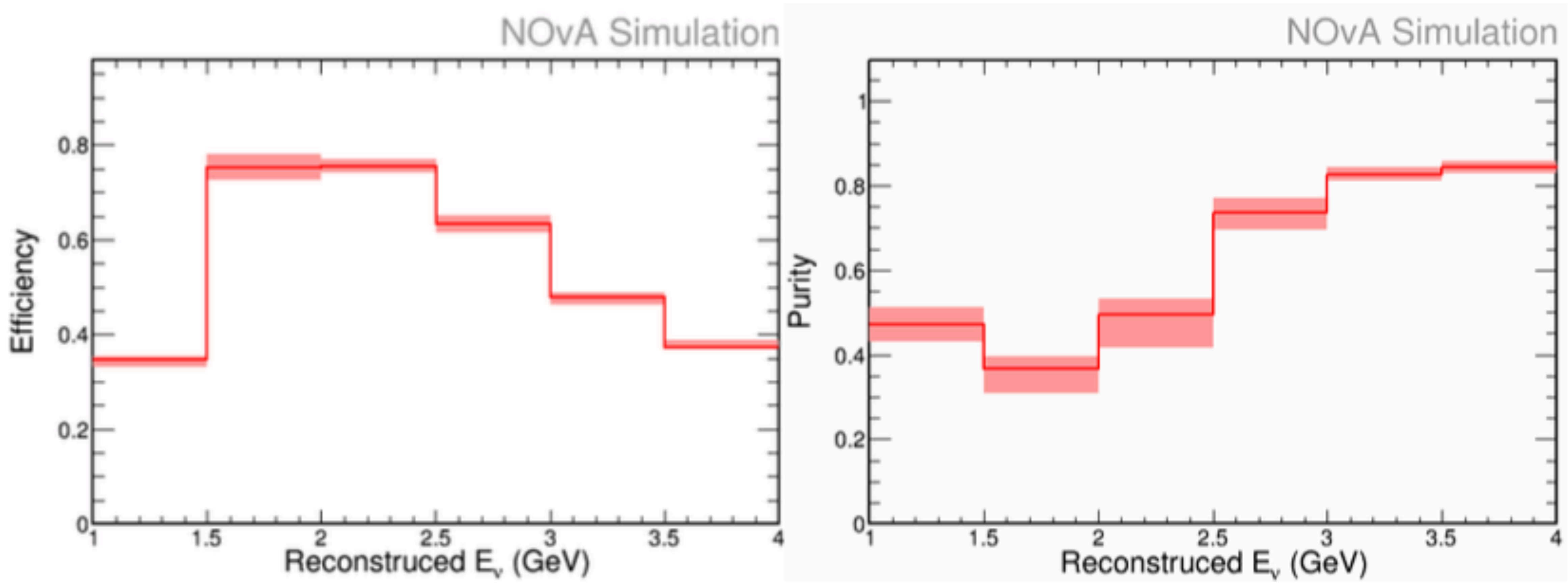
Event selection cross-check with LID





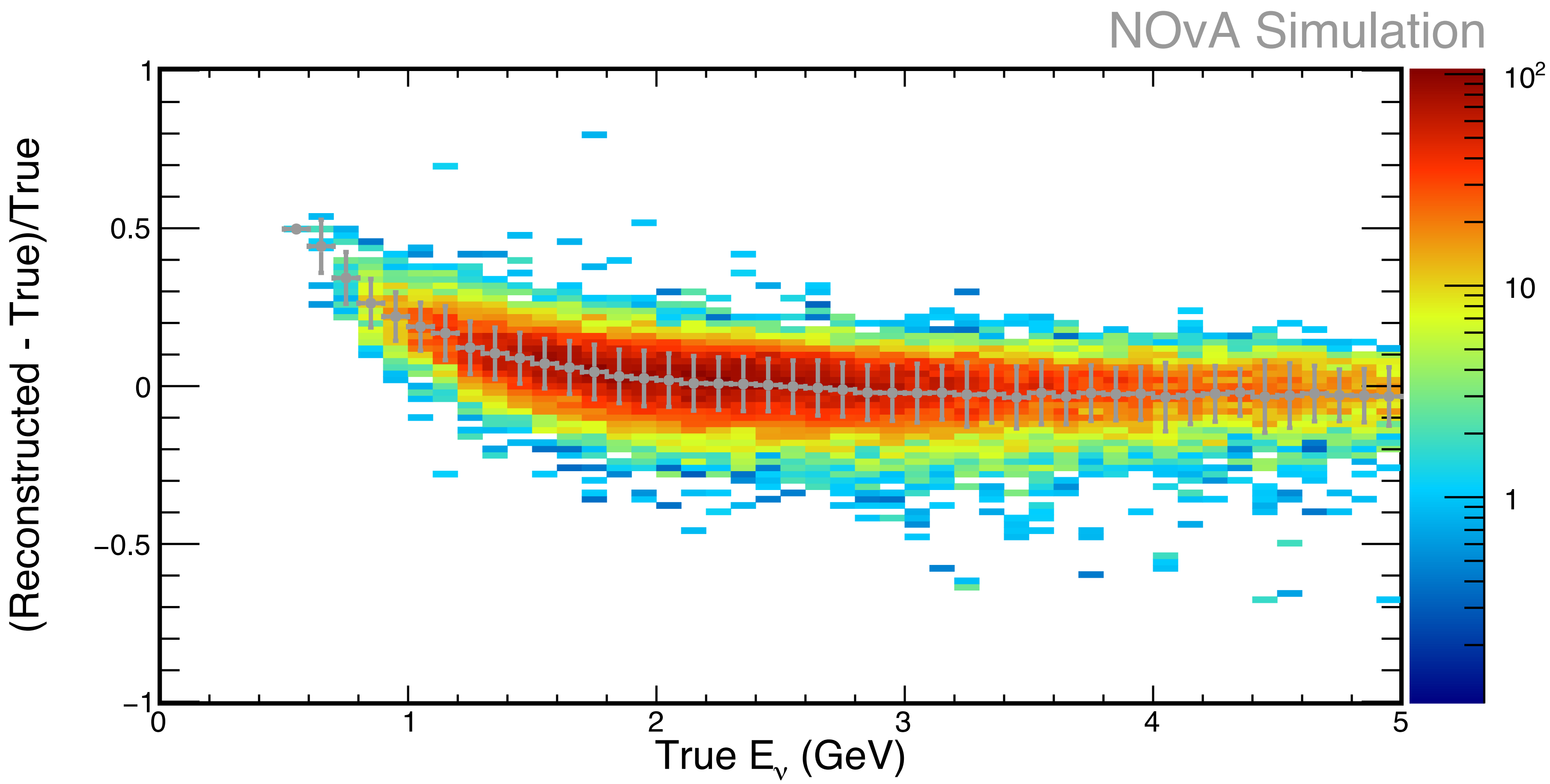
- LID: a traditional artificial neural network based on kinematic variables;
- the primary selector used by the NOvA 1st oscillation analysis;
- events with LID > 0.85 are selected as candidate ν_e CC events;
- LID provides a slightly lower signal efficiency (~10%) with similar power of background rejection.

Expected systematic uncertainties



- With the current event selection, we had a look at the expected dominant systematic uncertainties. The error bands in the plots includes:
  - Cross-section model
  - Final State Interaction (FSI)
  - Calibration
- Uncertainties on efficiency and backgrounds is between 5-10%;

Predicted Resolution and unfolding



- Markers show the mean and error bands show RMS of each slice of Reconstructed - True neutrino energy with respect to true neutrino energy;
- The predicted energy resolution is ~400 MeV averaged over the entire sample from 1 to 3 GeV in true Neutrino Energy;
- 0.5 GeV is the bin size to be chosen for unfolding and the final results.

Summary

- NOvA's high rate of neutrino interactions in the ND, off-axis narrow-band beam, and excellent tracking capabilities provide excellent opportunities to measure the inclusive ν_e charged current cross-section;

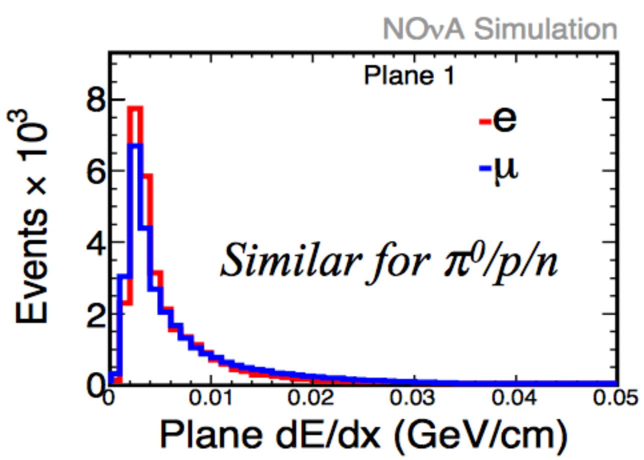
- We have done studies on event selection, background estimation, unfolding, systematic uncertainties etc for this measurement.

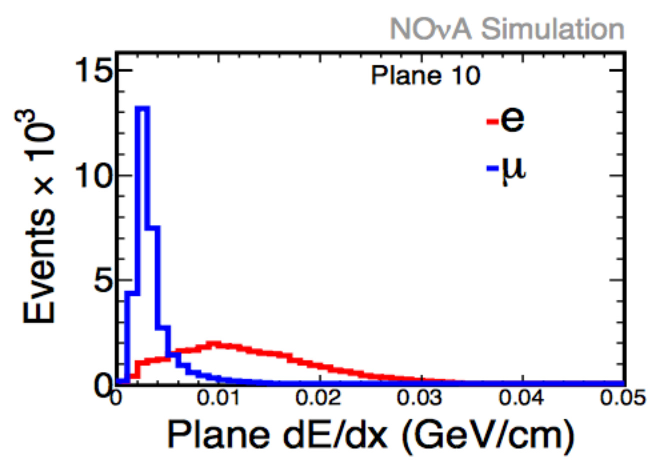
- NOvA has obtained 8×10^{20} POT neutrino (~3×10^{20} POT antineutrino) ND data set, aiming for results this year for systematics-limited (~10%) measurement.

- Stay tuned for results soon!

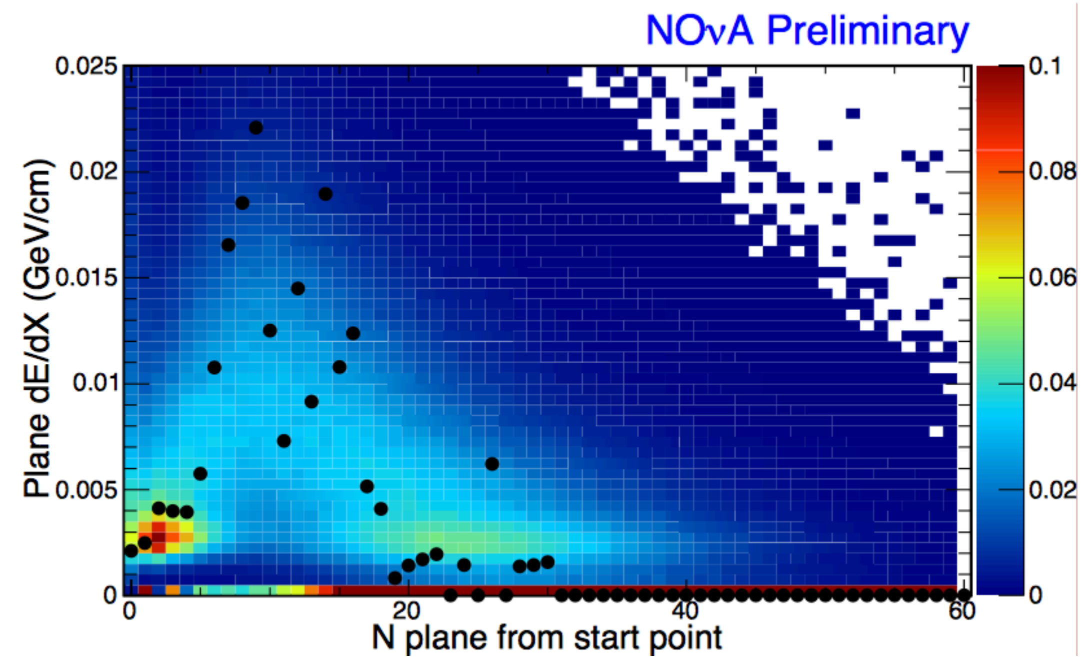
Backup

Event Selection - LID as a cross-check





Color: p.d.f. for dE/dx in each plane (e⁻ assumption)
Points: measured dE/dx in each plane (example event)



Reconstructed prong energy profile, vertex and event topology go in to LID;

- For an unidentified particle, we compare its energy loss per length (dE/dx)
- with the expected dE/dx histograms by each longitudinal and transverse slice to construct the probability and likelihood for each particle hypotheses.
- Summing over these longitudinal/transverse likelihoods we have overall longitudinal and transverse likelihoods for each type of particle.
- The difference of log-likelihoods indicates the identity of the particle, for example: LL(e/μ)=LL(e)-LL(μ).