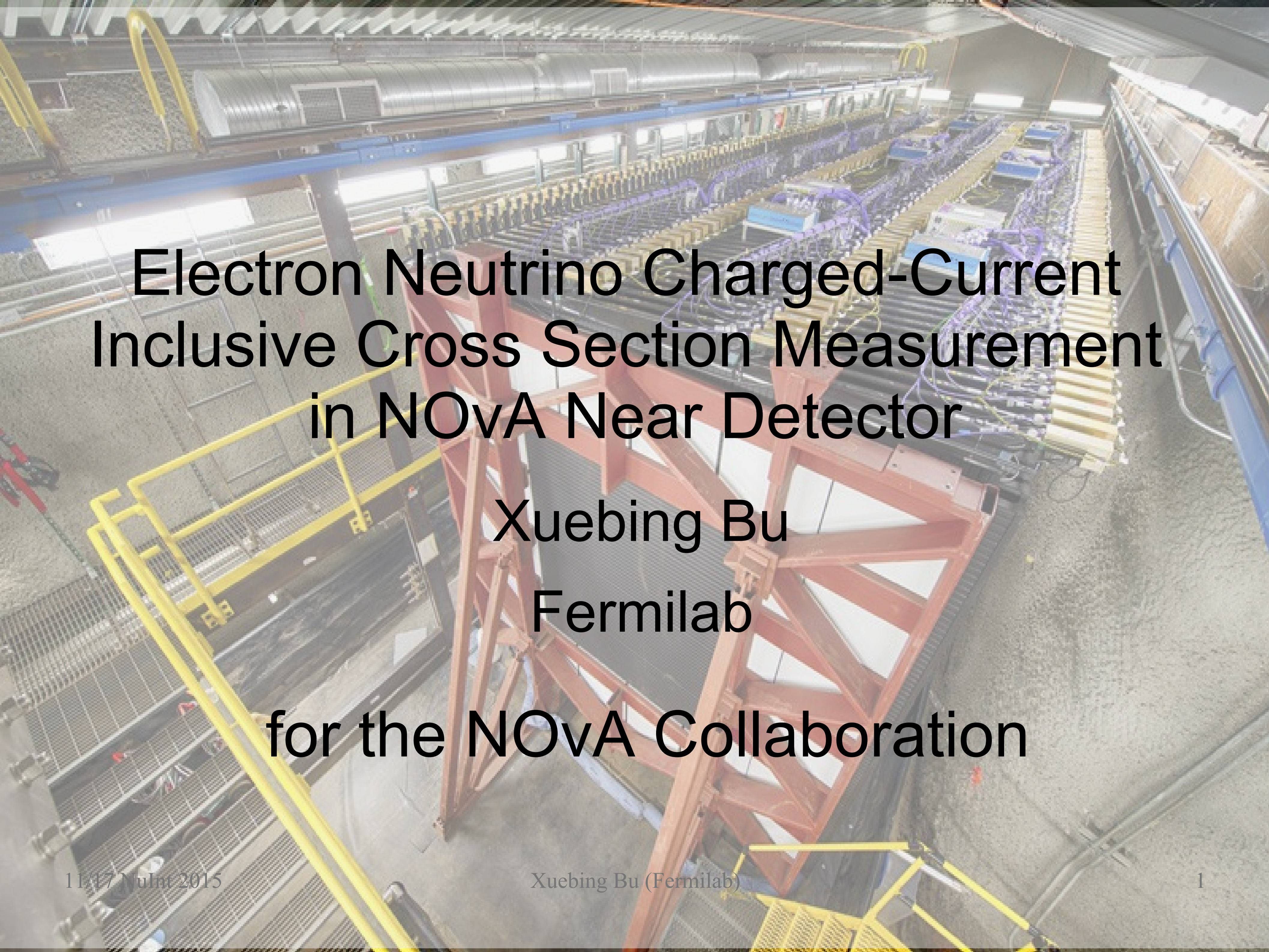


Electron Neutrino Charged-Current Inclusive Cross Section Measurement in NOvA Near Detector

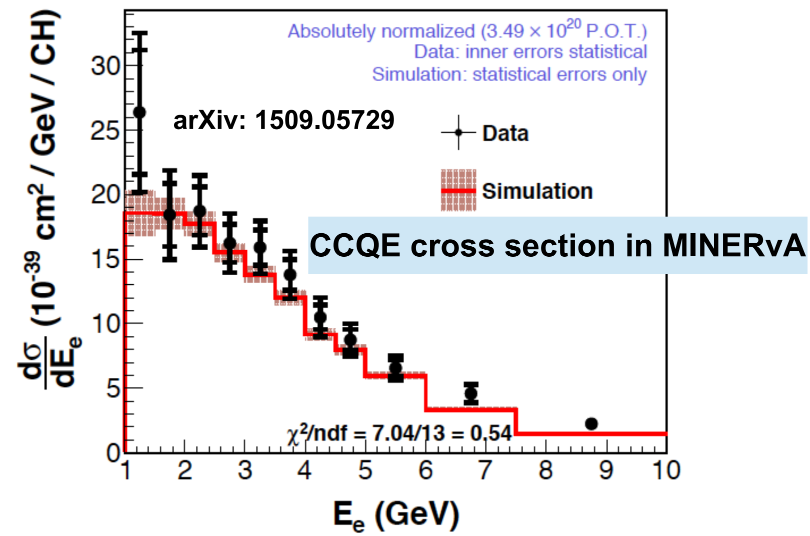
Xuebing Bu

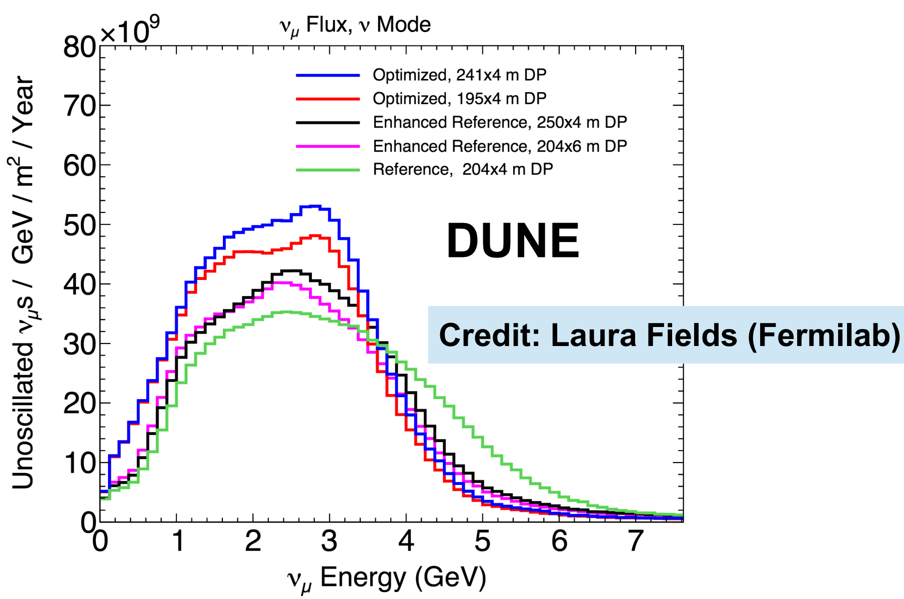
Fermilab

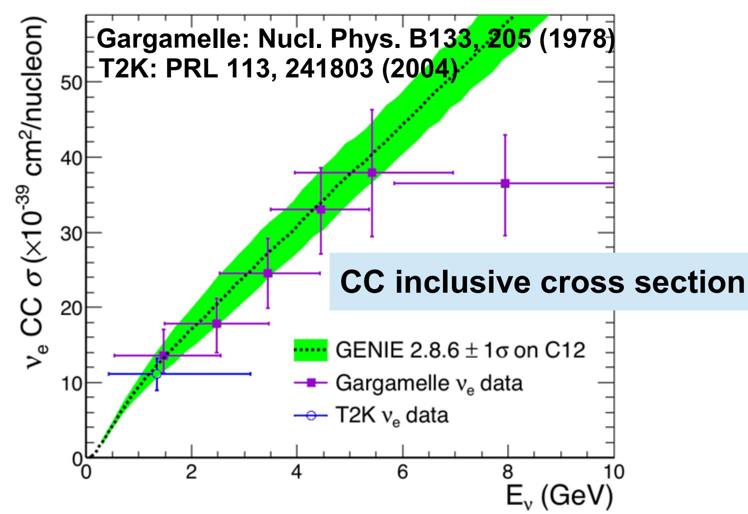
for the NOvA Collaboration

Introduction

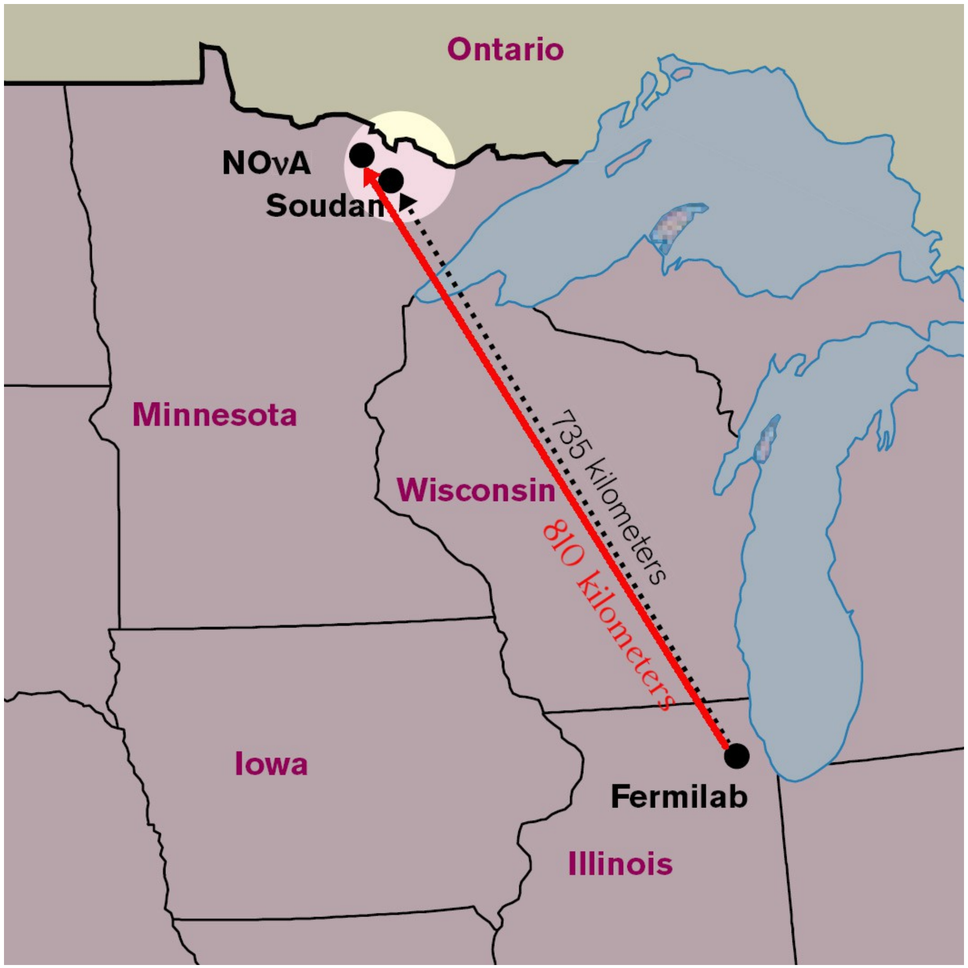
- There are very few electron neutrino cross section measurements at GeV scale.
- Beam electron neutrino is irreducible background for the electron neutrino appearance analysis.
- Measuring and knowing the electron neutrino inclusive cross section, in particular in the 1 – 3 GeV energy region is important for long-baseline experiment, like DUNE.







NOvA Experiment

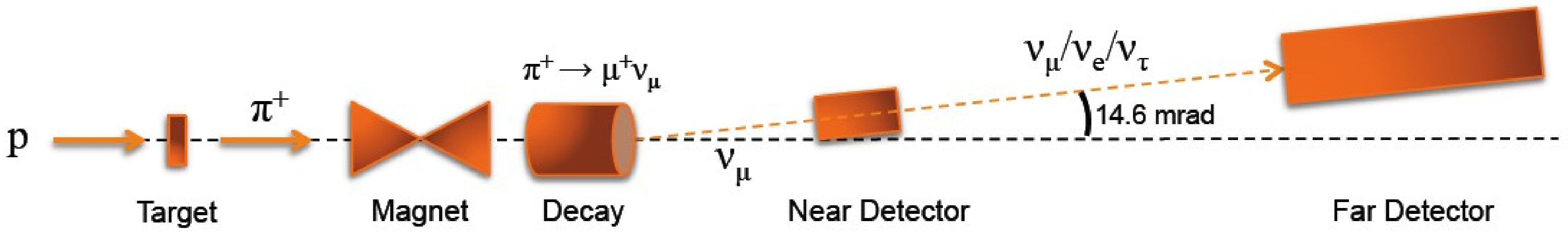


- Long-baseline experiment with two detectors
- Physics goals
  - $\nu_e/\bar{\nu}_e$ appearance
  - $\nu_\mu/\bar{\nu}_\mu$ disappearance
  - ND cross section
  - Exotics search

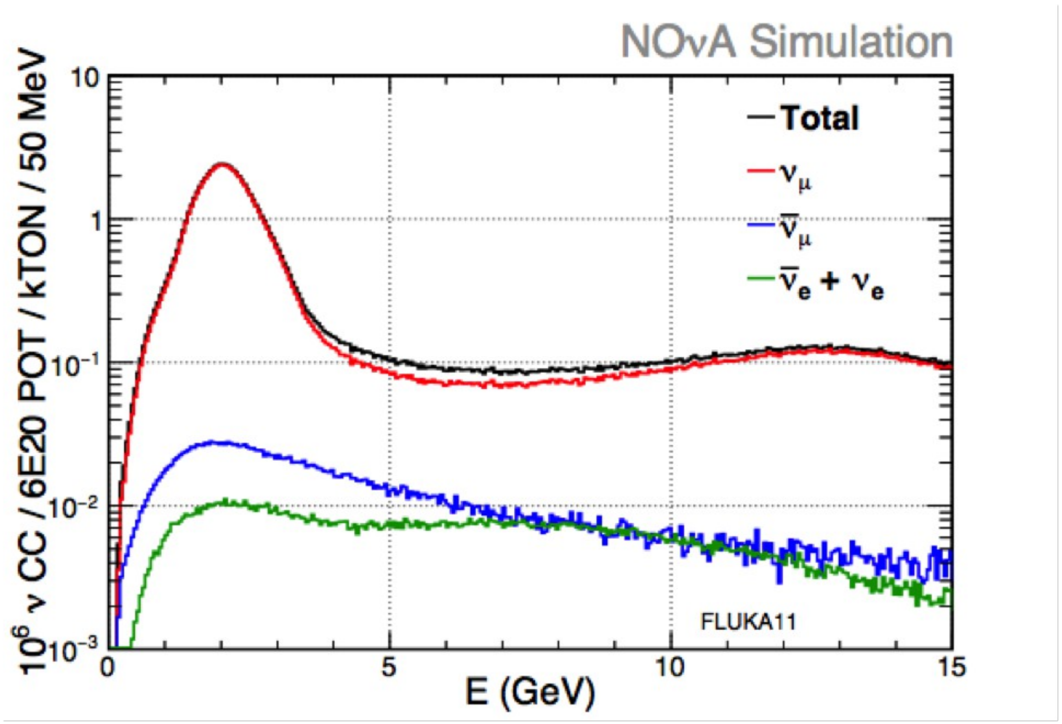
NOvA Collaboration

200+ scientists and engineers
from 38 institutions, 7 countries

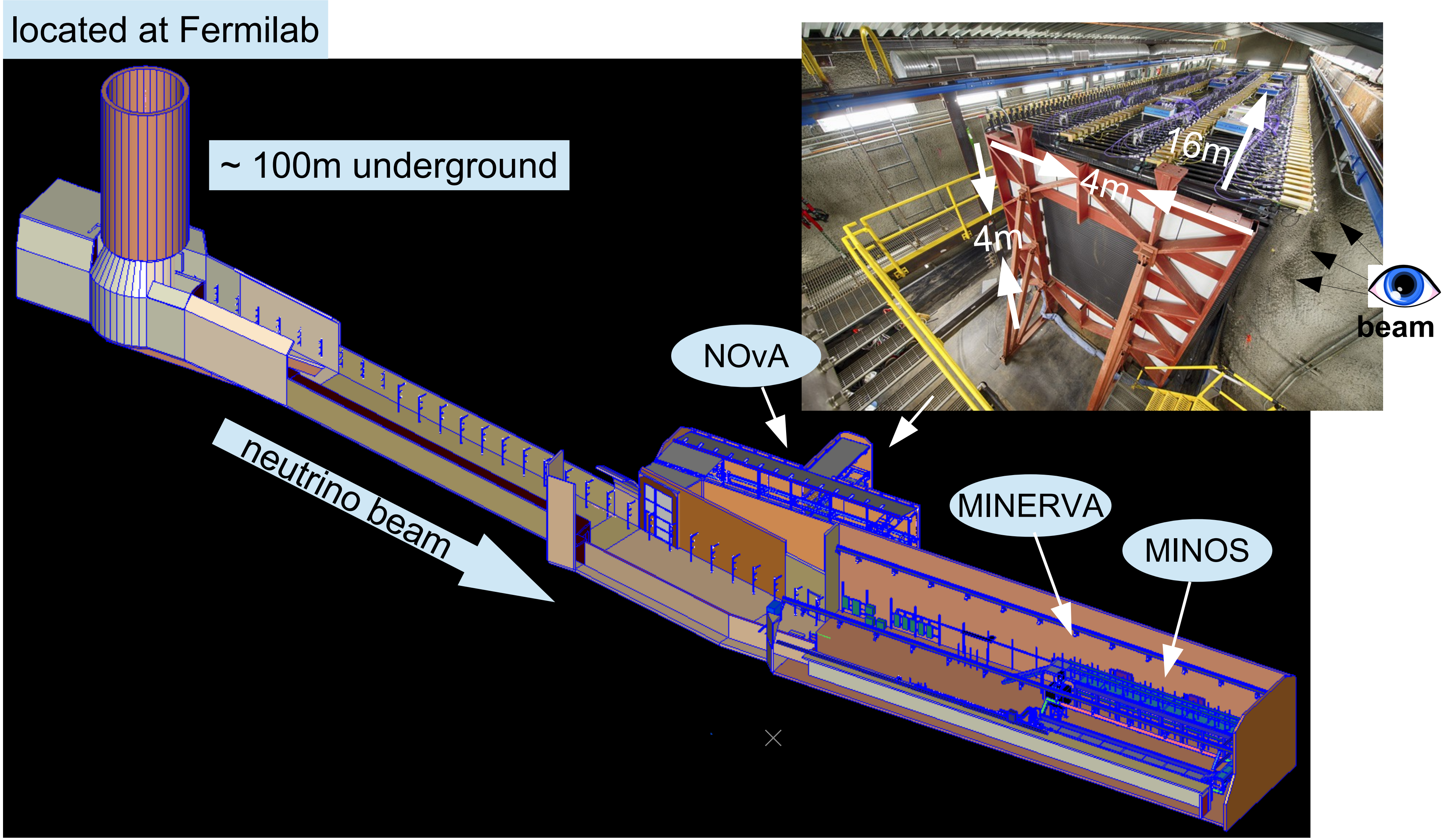
NuMI Beam



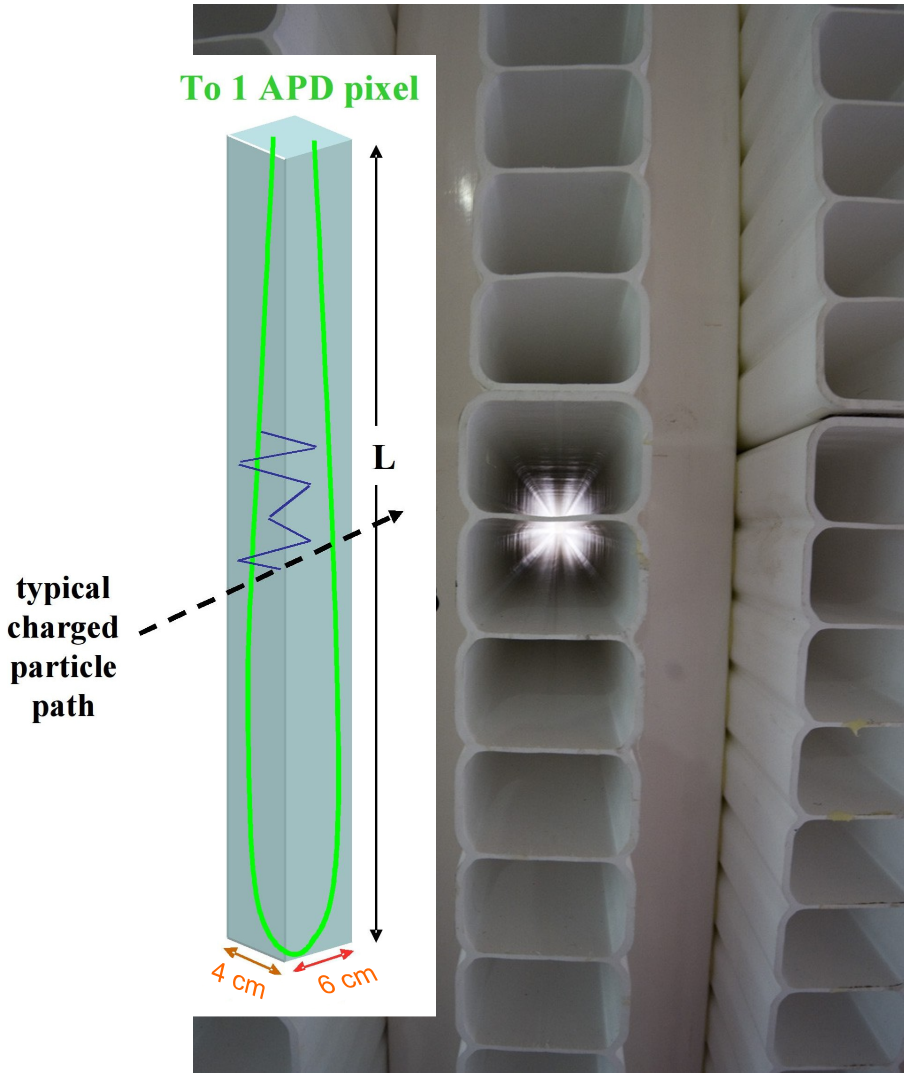
- Detectors are installed by being off beam axis
  - Narrow band beam peaked at 2 GeV
  - Near maximum oscillation
  - Reduced NC background
- Electron neutrino flux counts ~1% of total flux.



Near Detector



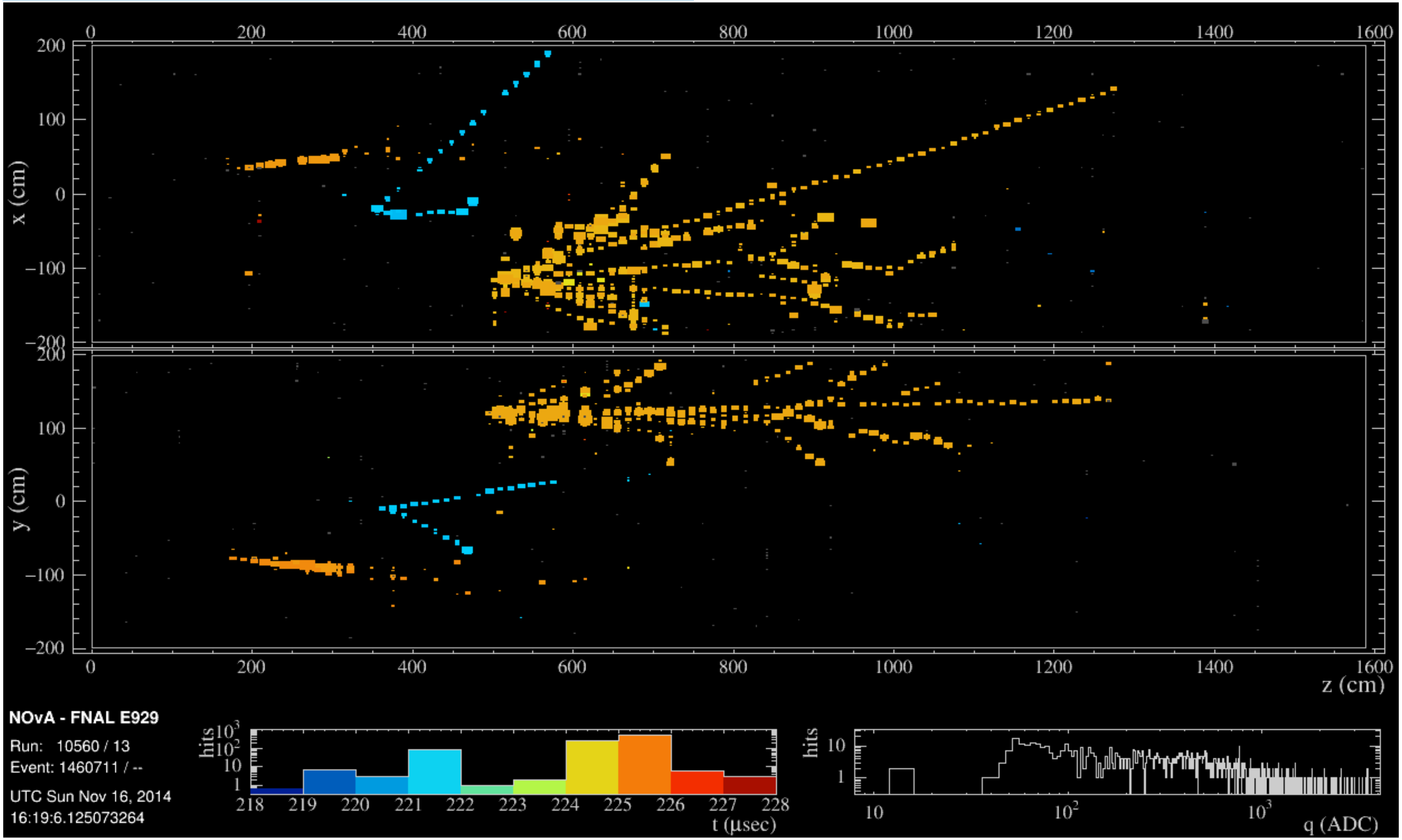
Detector Technology



- PVC cells (long tube), each cell contains one wavelength-shifting fiber, and filled with scintillator oil. Read out by avalanche photo-diode
- Planes are layered in orthogonal views
- Near Detector:
  - 300 ton
  - 20K channels
  - low Z and high-active tracking calorimeter

Near Detector data event

All hits recorded in a beam spill at ND.



Analysis overview

- We select nue CC inclusive events to measure the inclusive cross section in 4 energy bins from 1 to 3 GeV.

# of selected data events
Similar selection cuts as nue appearance analysis plus a customized shower based PID.

# of background events
Normalization determined from 2 sideband samples.

$$\sigma = \frac{N_{data} - N_{bkg}}{\phi \cdot T \cdot \epsilon_{eff}}$$

Integrated flux
Using external data from NA49 and MIPP to constrain the hadron production uncertainty.

# of nucleons

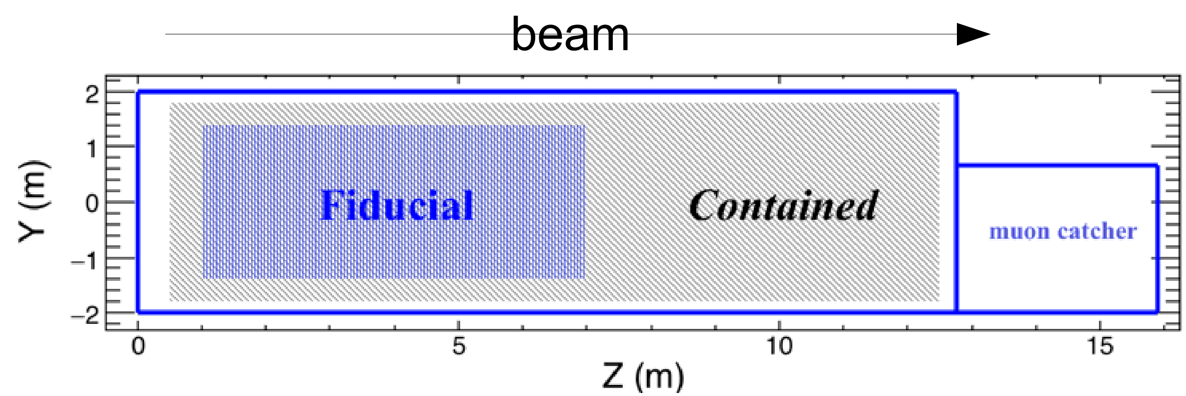
Event selection efficiency
Measured from GENIE MC events,
Using muon induced EM showers to validate the shower selection efficiencies in both data and MC.

Data and MC samples

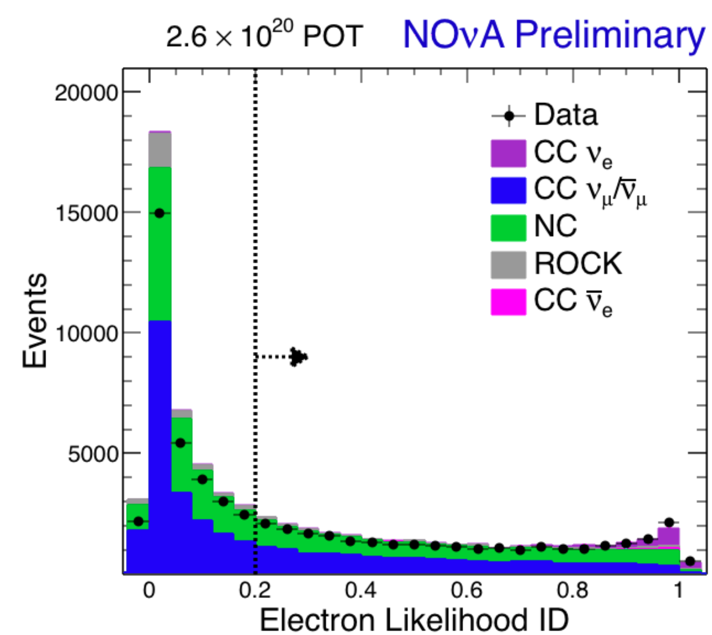
- Data
  - Collected between November 2014 and June 2015
  - 2.6E20 proton-on-target.
- MC
  - Hadron generator: FLUKA v2011
  - Beam simulation: FLUGG v2009
  - Detector simulation: GENIE (R-2_8_6)

Event selection — Preselection

- Fiducial cuts
  - |Vx/Vy|<140cm
  - 100<Vz<700cm

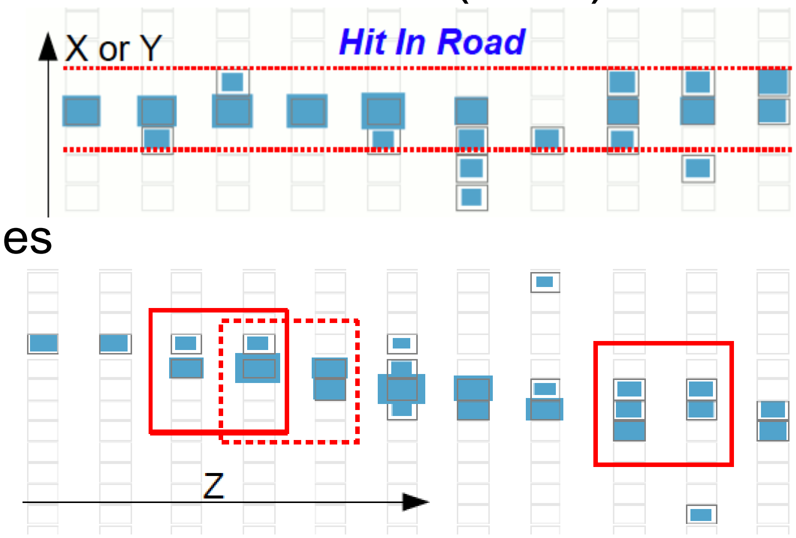


- Select contained EM shower with
  - 150 < shower length < 500cm
  - shower energy < 3.5GeV
  - Fraction of MIP hits < 0.35
  - EM likelihood ID (LID) > 0.2



Event selection — Shower based PID

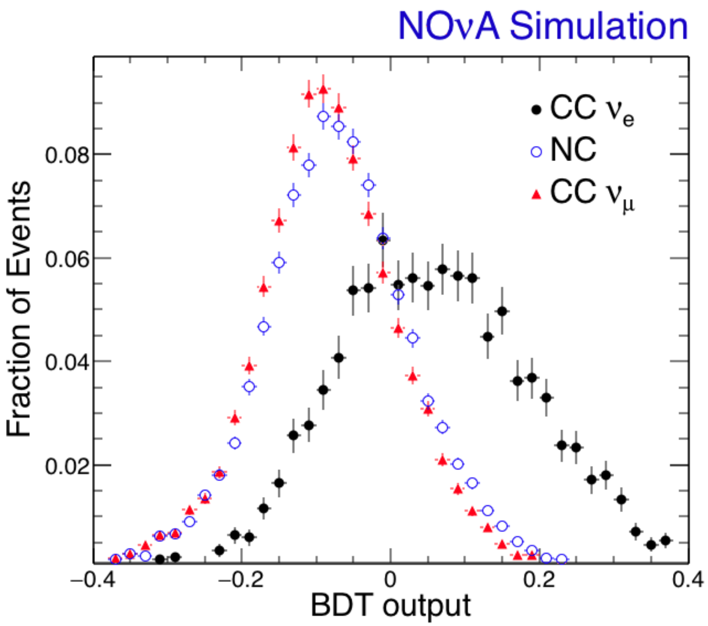
- To reduce background further, we build a new PID completely based on shower properties.
- We use 7 input variables to train the Boosted Decision Tree(BDT):
  - Fraction of MIP hits in sub-leading prong
  - Fraction of energy in ±4cm transverse road
  - Maximal fraction of energy in 6-continuous planes
  - Fraction of energy in first 10 planes
  - Fraction of energy in 2nd, 3rd and 4th plane.

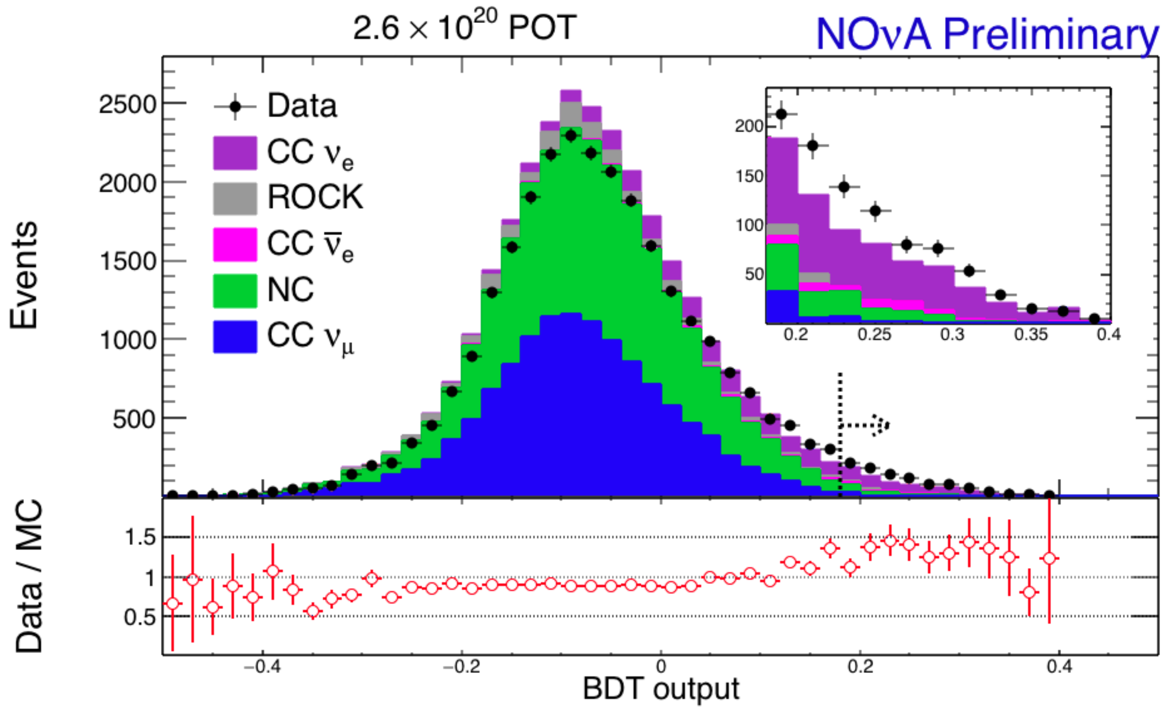


NOvA Simulation

- We test its performance showers from muon bremsstrahlung. These energetic rock muons are from the muon neutrino interactions with rock.

BDT output distributions

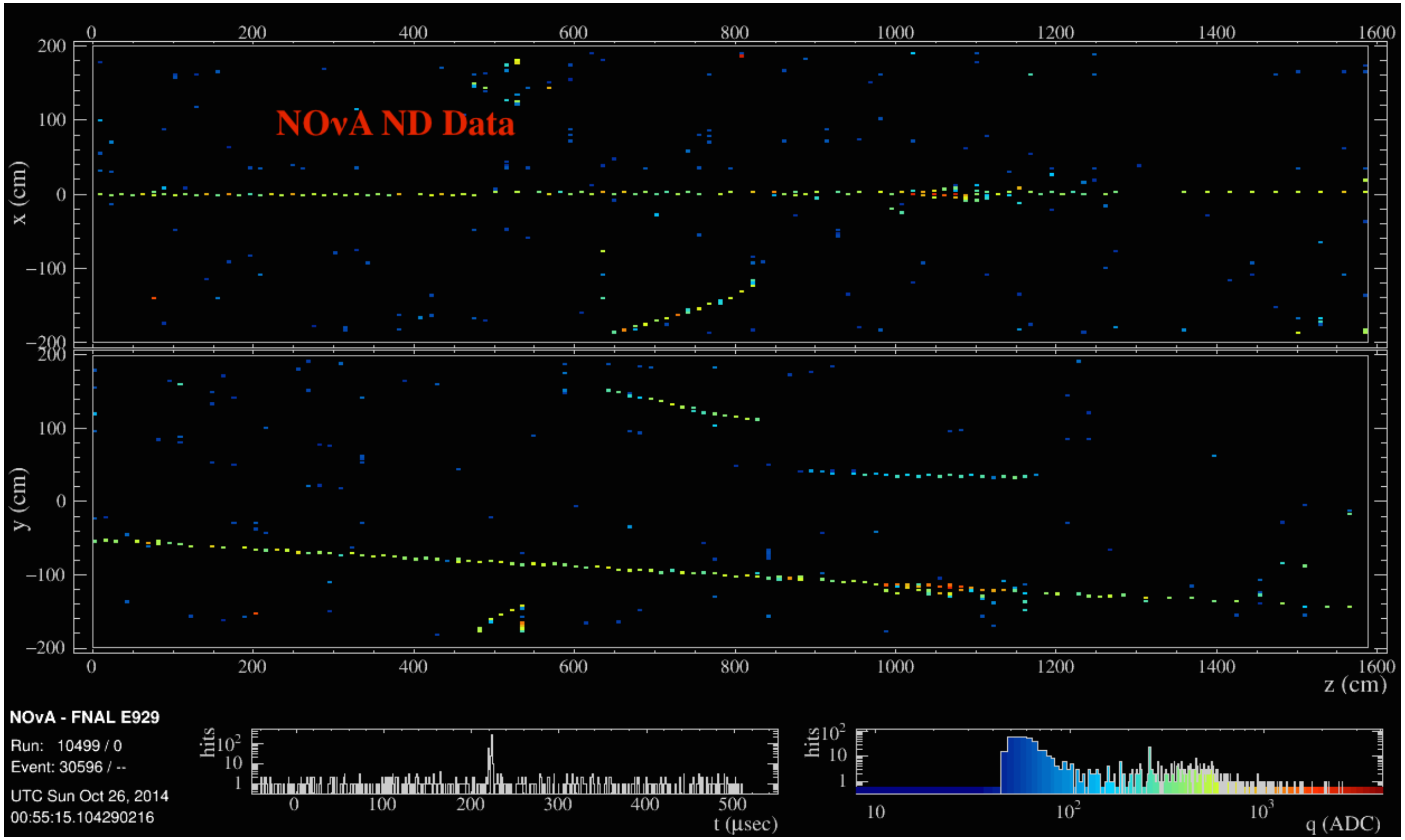




Left plot shows the shape distributions of BDT output for the nue CC signal and numu CC and NC background.
Right plot shows the BDT output distributions after event selection from data, signal and various backgrounds.
All events are selected with preselection cuts.

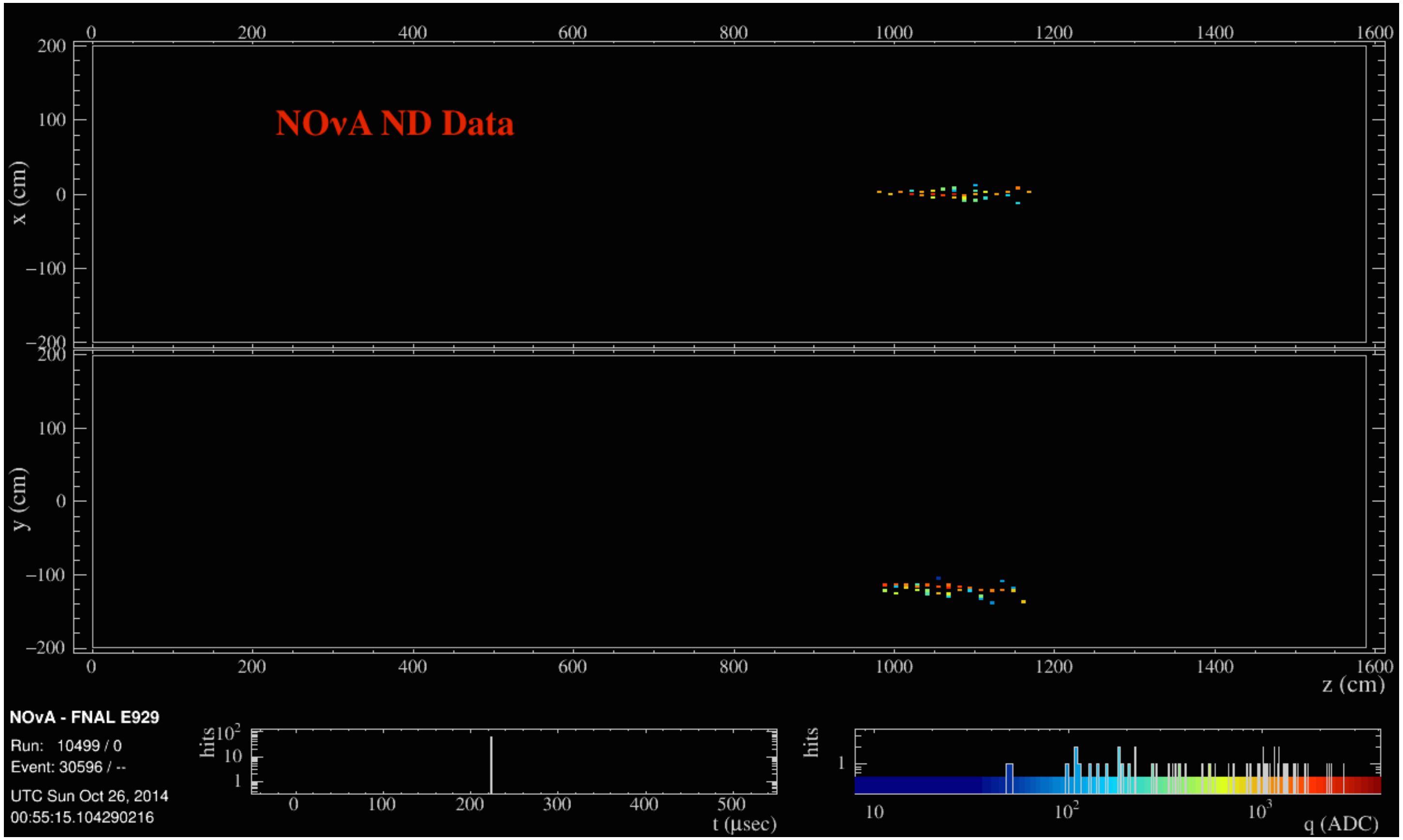
Rock muon induced EM showers

- We select EM showers from muon bremsstrahlung by removing the muon activity.

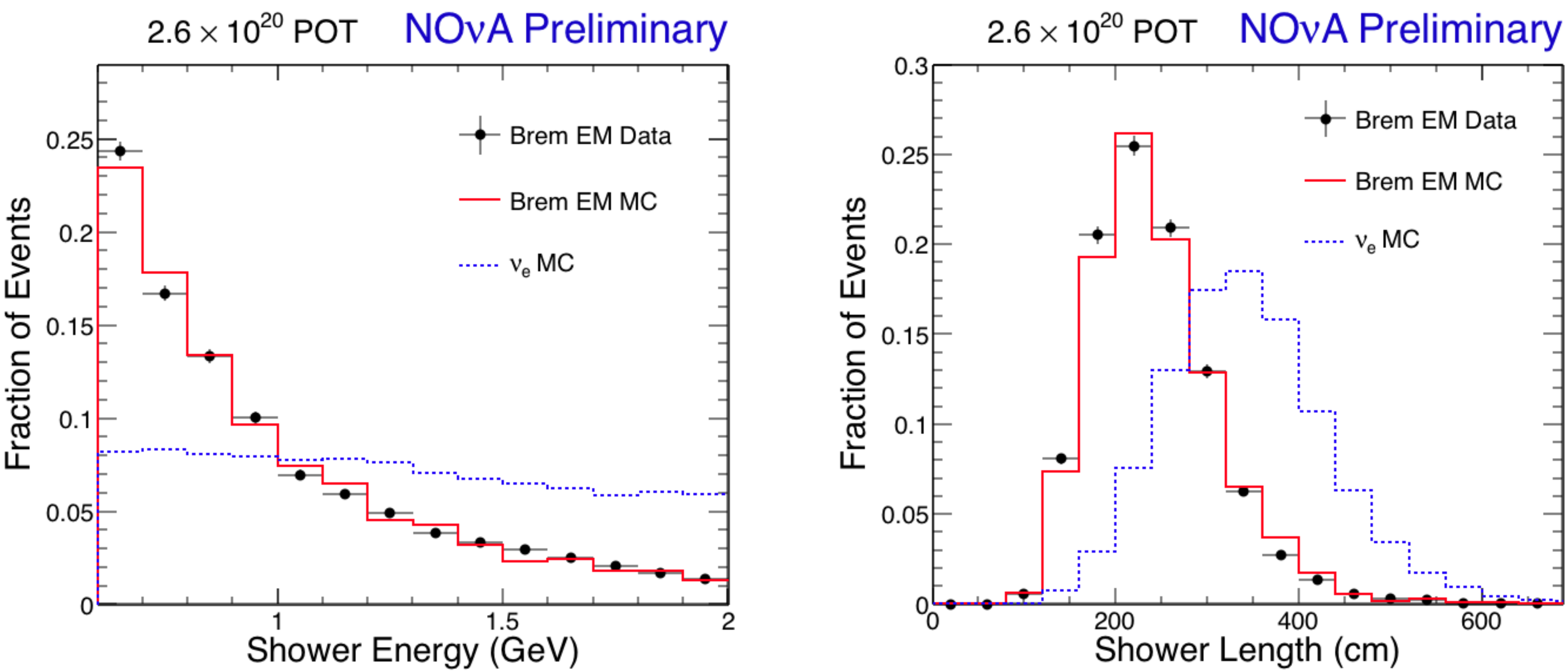


Rock muon induced EM showers

- We select EM showers from muon bremsstrahlung by removing the muon activity.

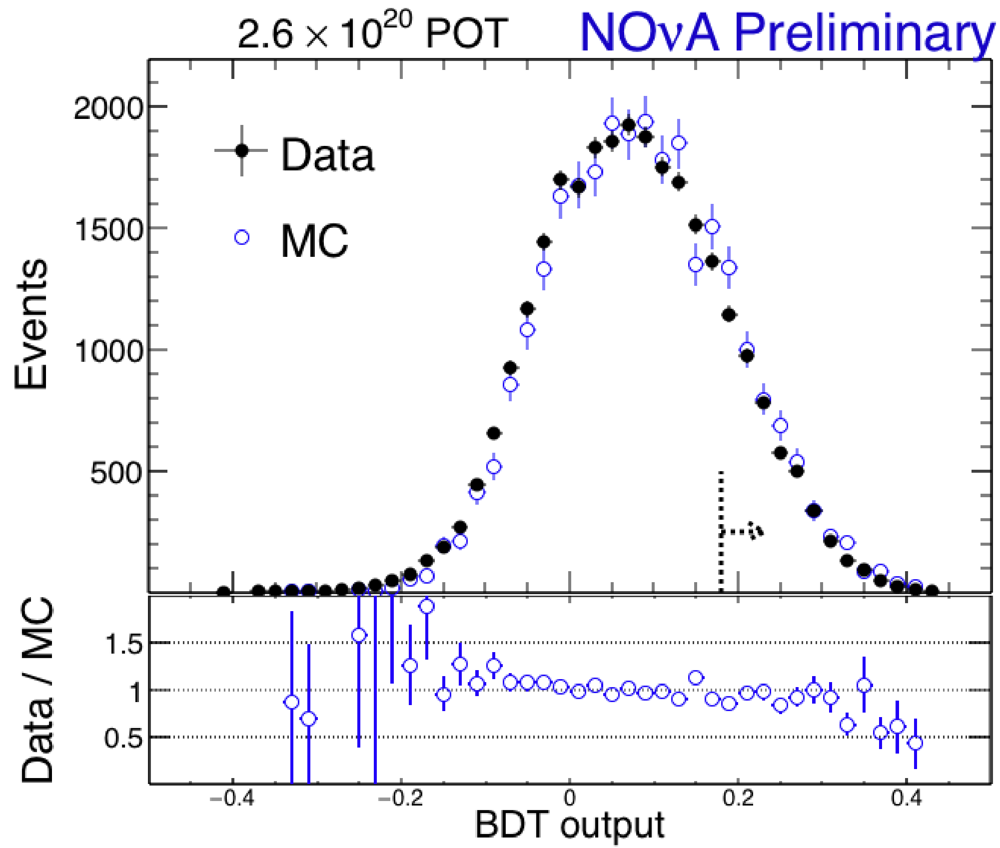


Rock muon induced EM showers



Distributions for shower energy and length
from Brem. EM data and MC, and nue signal MC.
There is decent agreement between Brem. EM data and MC.
Brem. EM showers have similar shower properties as the nue signal events.

Rock muon induced EM showers



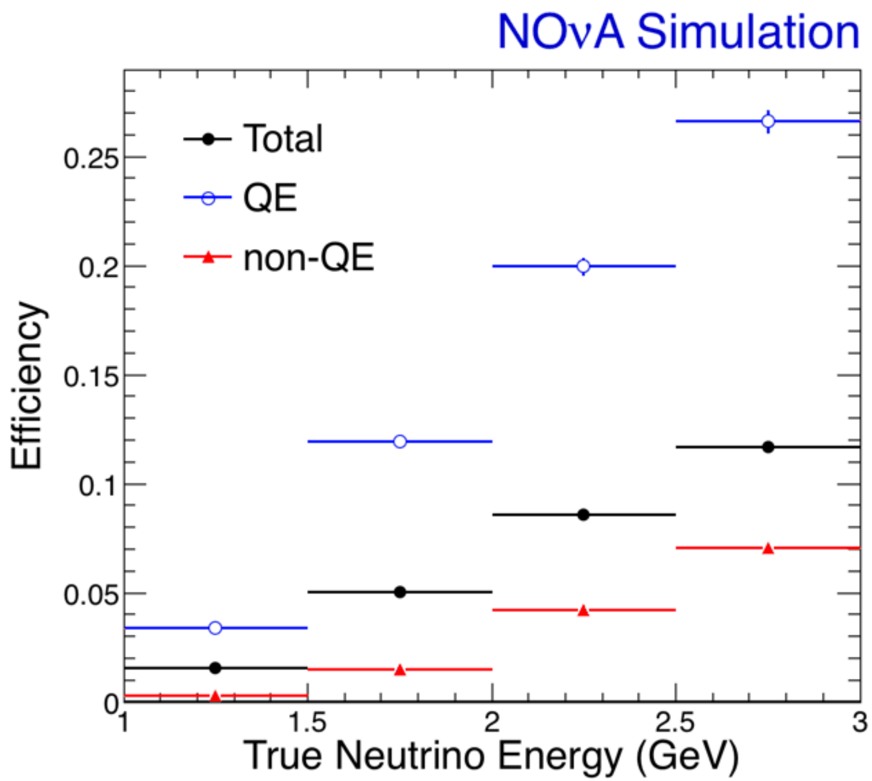
Excellent agreement between data and MC for the shower-based PID.
MC is normalized to no. of data events.
All events are selected with preselection cuts.

Event selection efficiency

- Defined as

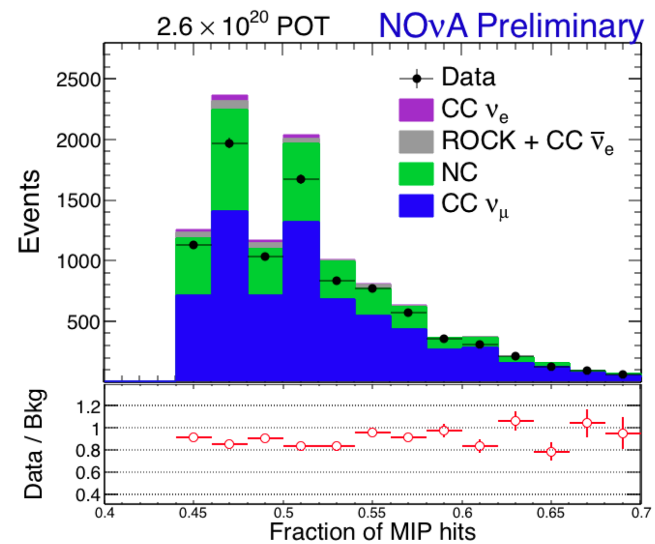
$$\frac{\text{Number of signal events passing all event selection cuts}}{\text{Number of signal events in true fiducial volume}}$$

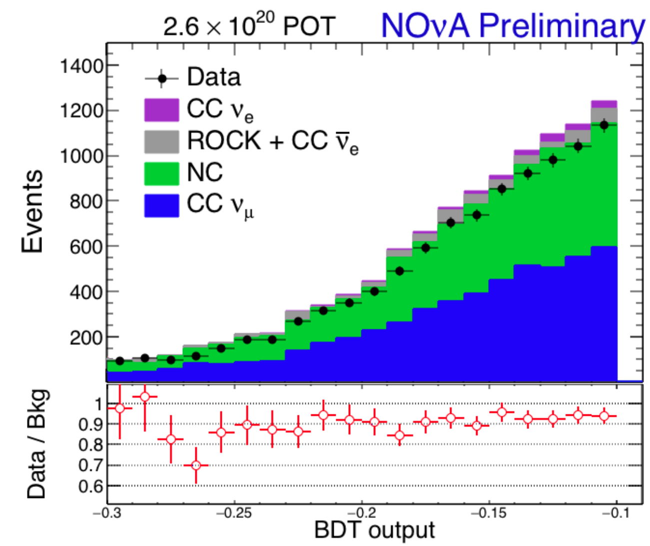
- The GENIE MC events are used to measure the efficiency.
- Shower selection is studied using the Brem. EM showers, 5% uncertainty is assigned based on the data and MC comparison.
- For GENIE cross section uncertainties, the dominant is from CC QE normalization, the effect is 5%.
- For detector modeling, comparing GEANT4 physics lists QGSP, QGSC, and FTFP, no visible effect.



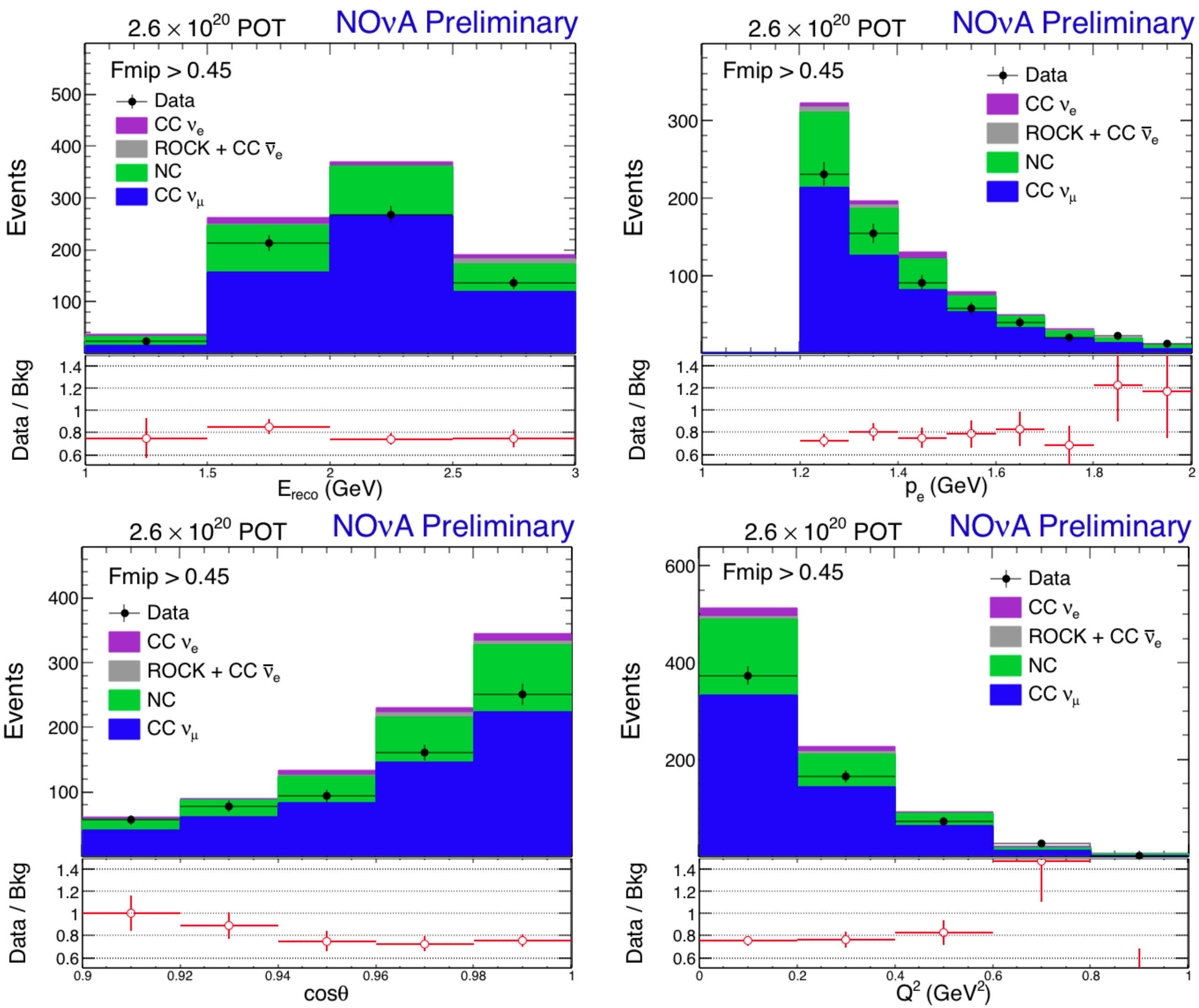
Background normalization

- We select 2 sideband samples to study the background normalization
  - Events with high fraction of MIP hits
    - Passed all Preselection cuts except reversing the cut on fraction of MIP hits
    - Dominated by numu CC and NC
    - Add Pe>1.2 GeV and cosθ>0.9 to select the events in the similar kinematic region as the sample in signal region
  - Event with BDT < -0.1
    - Passed all Preselection cuts
    - Dominant by numu CC and NC
    - Add Pe>1.2 GeV and cosθ>0.9 to select the events in the similar kinematic region as the sample in signal region





Background normalization – fraction of MIP hits>0.45

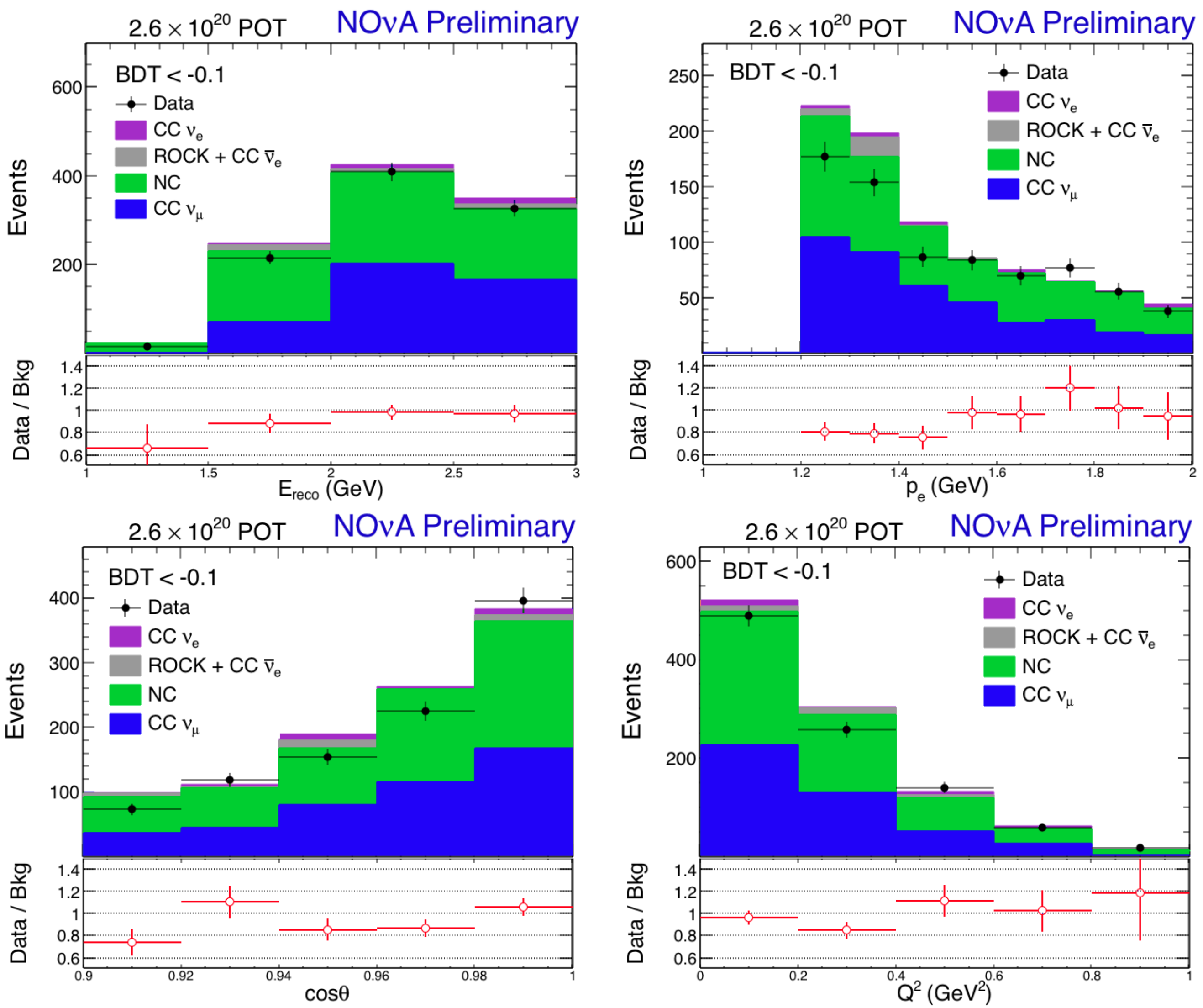


The distributions for Ereco, Pe, cosθ, and Q2 from Fmip>0.45 sample.

This sideband sample has different ratio for numu CC over NC by comparison with signal region.

The data over background ratio is ~0.8.

Background normalization – BDT<-0.1



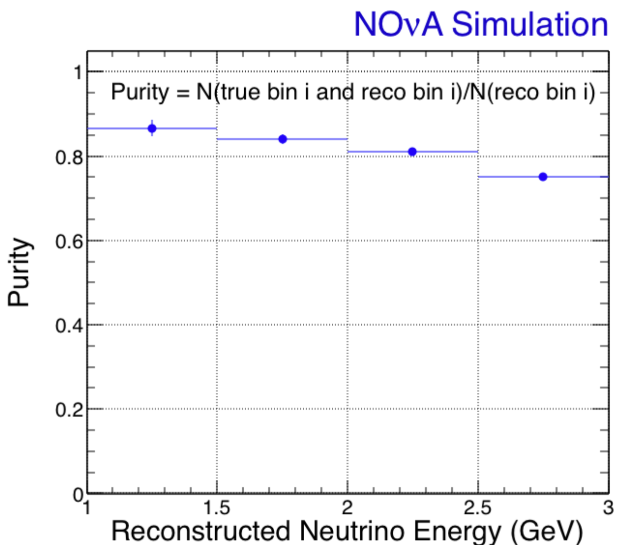
The distributions for Ereco, Pe, cosθ, and Q2 from BDT<-0.1 sample.

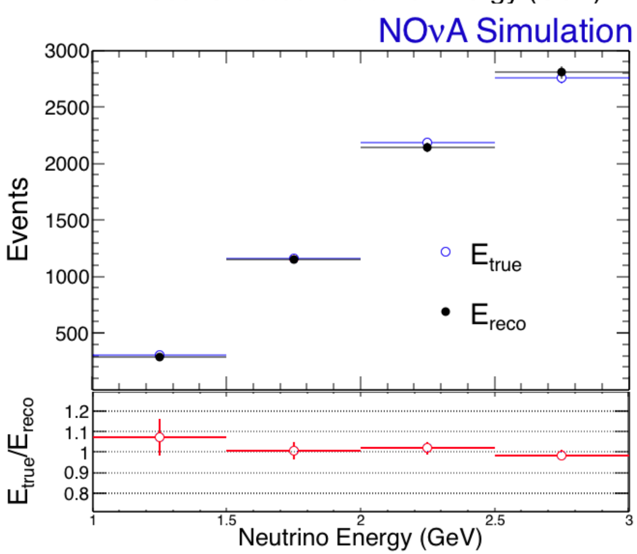
This sideband sample has similar ratio for numu CC over NC by comparison with signal region.

Conservatively, we use 0.95±0.2 as the background normalization factor. This 21% uncertainty will be propagated to be ~10% uncertainty on final cross section.

Bin-by-bin migration

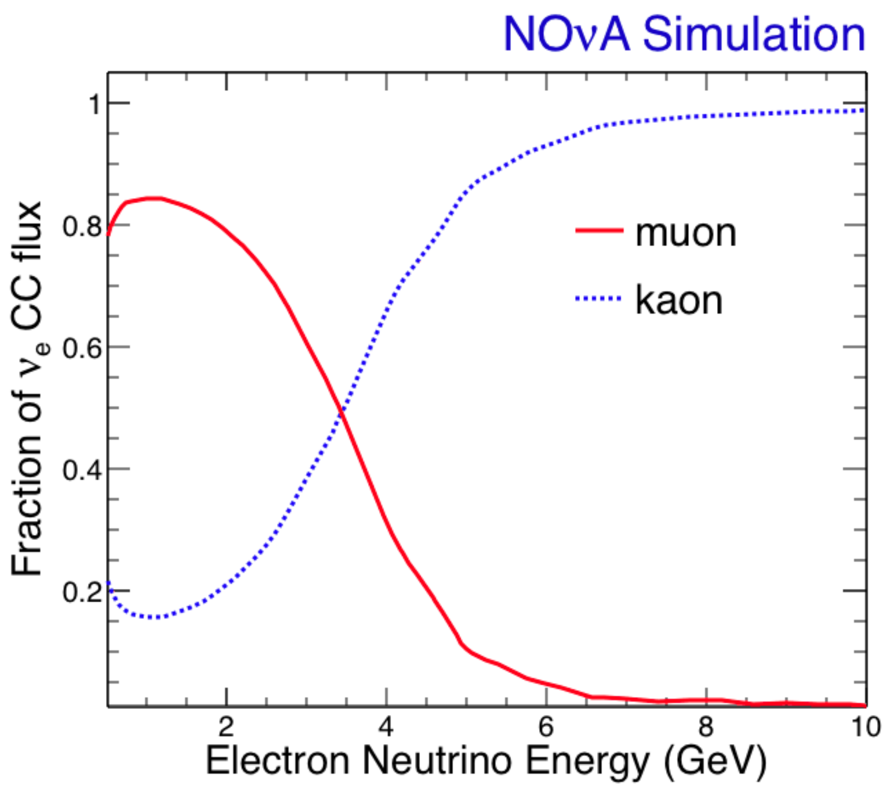
- Experimental effects lead to event migration outside a given bin at generated level. The magnitude of the effect depends on the bin size relative to the energy resolution.
- Our energy resolution is ~5% across the whole energy region.
- Given the good energy resolution, and large bin size (0.5GeV), we directly correct the reconstructed energy spectrum to match true.





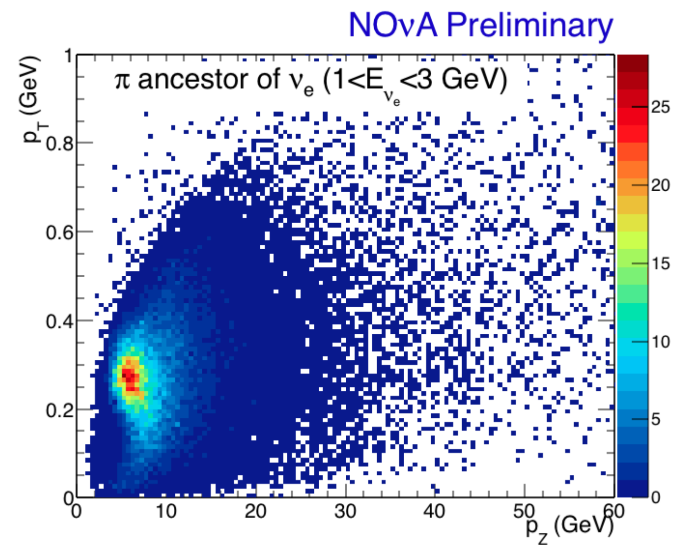
Electron neutrino flux

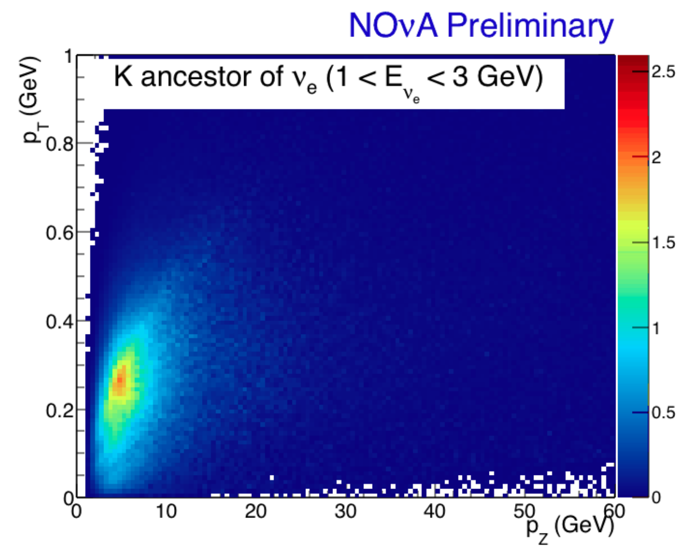
- The dominant contribution to electron neutrino flux in 1 – 3 GeV region is from muon and kaon. Kaon dominates in the high energy region.
- The fraction of neutrino flux from secondary mesons is ~55%.



Flux uncertainty

- Two major uncertainties
  - Beam transport: horn current, beam spot, B field
  - Hadron production
    - Using external data (see below table)
    - For region not covered by external data, assigning conservative systematic uncertainty





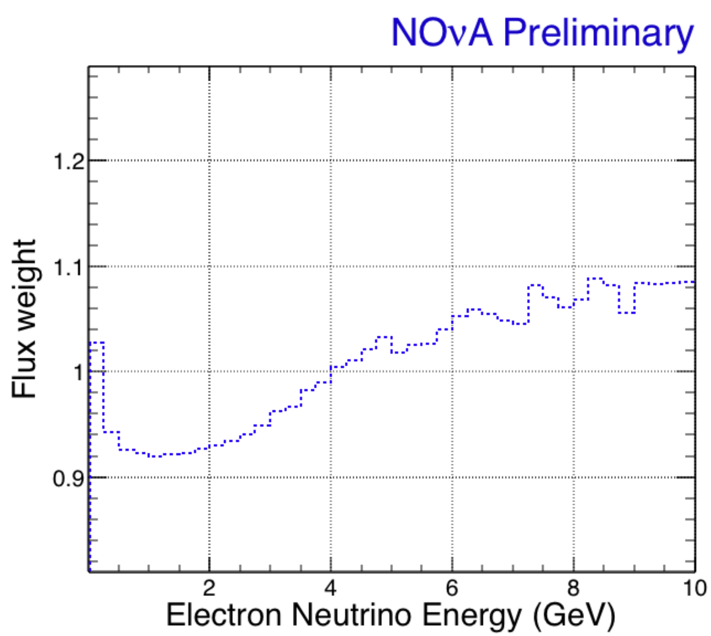
Experiment	data type	p_T range (GeV)	x_F range	target	proton energy (GeV)
NA49	pion production	$0-2$	$0-0.5$	thin Carbon	158
NA49	kaon production	$0-1$	$0-0.2$	thin Carbon	158
MIPP	kaon/pion ratio	$0-2$	$0.2-0.5$	thin Carbon	120
MIPP	pion production	$0-2$	$0-0.5$	thick Carbon	120

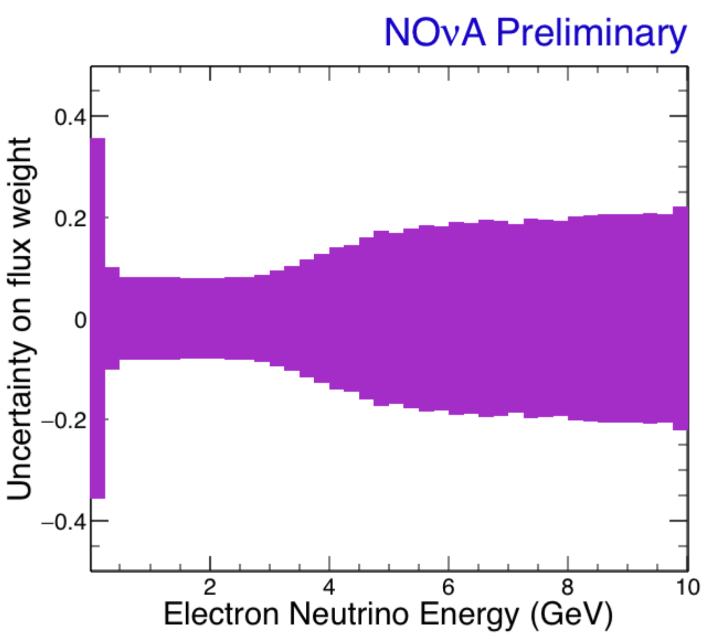
NA49 pion cross section: Eur. Phys. J. C49 (2007)
NA49 kaon cross section: G. Tinti Ph.D. Thesis
MIPP kaon/pion ratio: A. Lebedev Ph.D. Thesis

MIPP pion yield: Phys. Rev. D 90, 032001 (2014)

Hadron production uncertainty

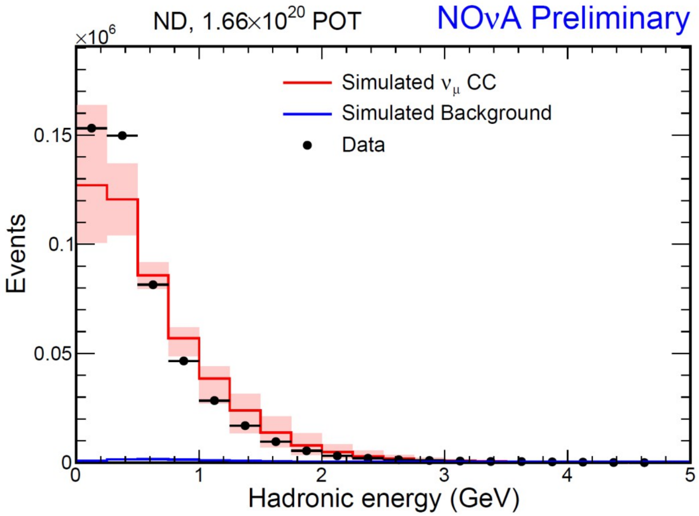
- We use the external data results from NA49 and MIPP experiments to constrain the hadron production uncertainty. The uncertainty of using the low energy NuMI beam target (MIPP) pion yield on the medium energy target (NOvA) has been taken into account.
- We reduce the electron neutrino flux by 5 – 8% in 1 – 3 GeV energy region, the corresponding uncertainty is about 10%.

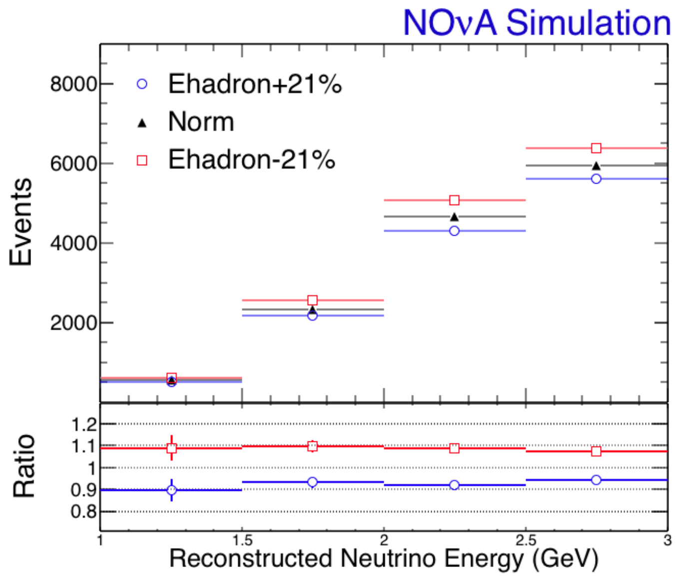




Hadron Energy

- There is discrepancy for hadronic energy between data and MC. A 21% uncertainty has been assigned to cover that discrepancy.
- We shift the hadronic energy up and down 21% event-by-event to quantify the effect. There is 6 – 10% change on the total energy.
- We also cross-checked with selected nue events in sideband samples. It confirms the 21% uncertainty is large enough to cover existed discrepancy between data and MC.





Uncertainties

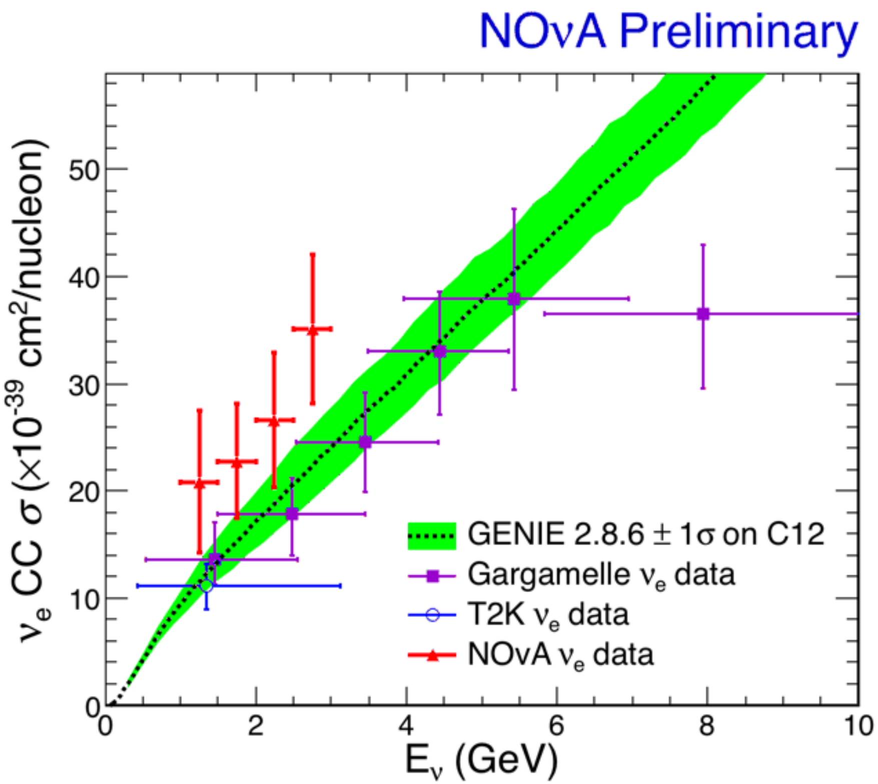
- Dominant systematics in order
  - Flux uncertainty
  - Background normalization
  - Hadron energy
  - Event selection efficiency

- Statistical and systematic uncertainties in each energy bin:

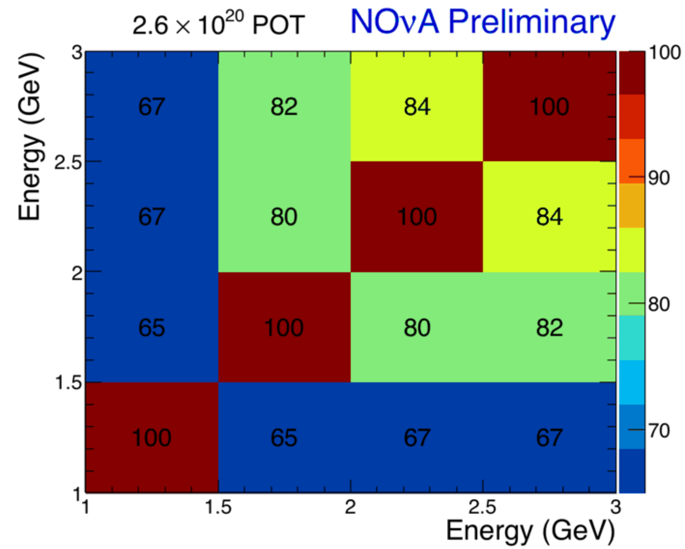
Energy	Statistical Uncertainty	Systematic Uncertainty
1 – 1.5 GeV	22.6%	22.4%
1.5 – 2 GeV	11.8%	20.4%
2 – 2.5 GeV	10.3%	21.5%
2.5 – 3 GeV	6.8%	18.7%

We are already systematic-limited now.
For general systematic studies at NOvA,
please see Dr. Muether's talk at yesterday Systematics session.

Results



Bin to bin correlation matrix:



Mass weight of detector component:

C12	Cl35	H1	Ti48	O16	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

The measured inclusive cross section from Gargamelle, T2k, and NOvA as shown. There is also shown the predicted cross section for nue on carbon from GENIE. There is large correlation between the energy bins for NOvA results (see Top table). Our detector material is dominant by the carbon, chlorine, and hydrogen.

Other measurements

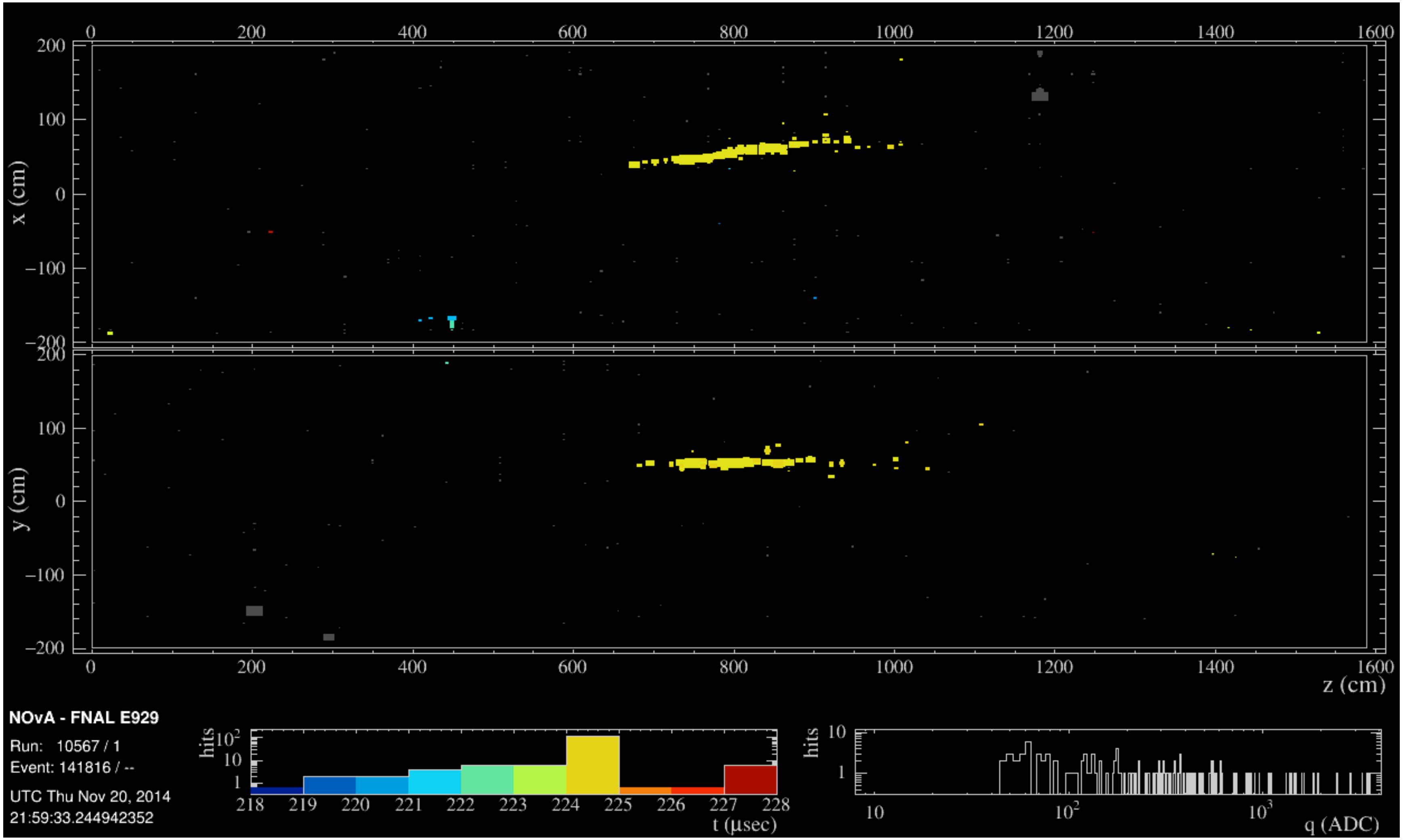
- Besides this analysis, we also have other measurements in our ND
  - Muon neutrino charged-current inclusive cross section
  - Coherent pion production cross section
  - Charged pion production cross section
  - Neutrino on atomic electron scattering production

Summary

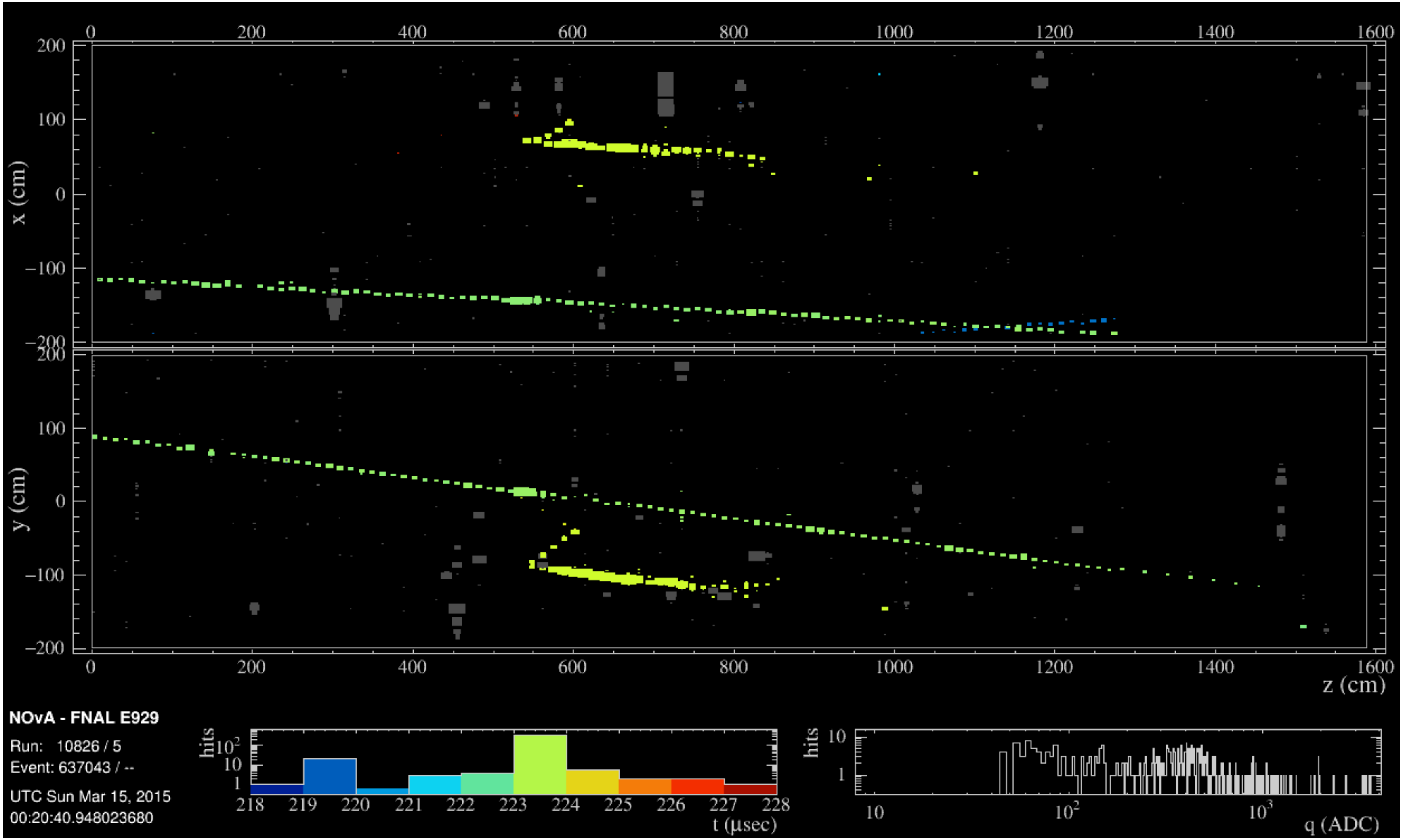
- We measured the electron neutrino inclusive cross section in 1 – 3 GeV energy region using data with 2.6E20 POT.
- Other measurements, including the inclusive cross section for muon neutrino is under way.
- Stay tuned !

Back-up

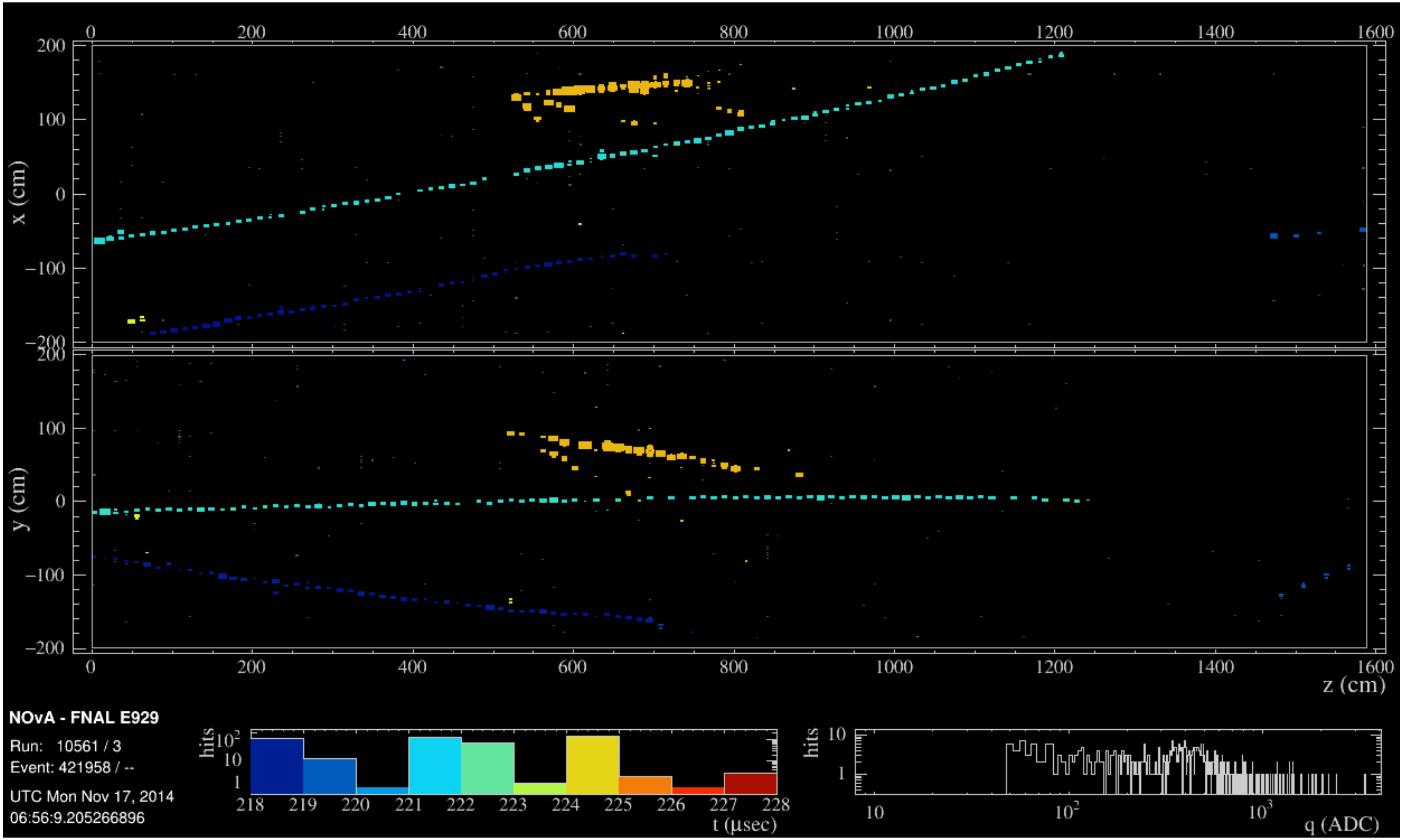
Event display for nue candidate in data



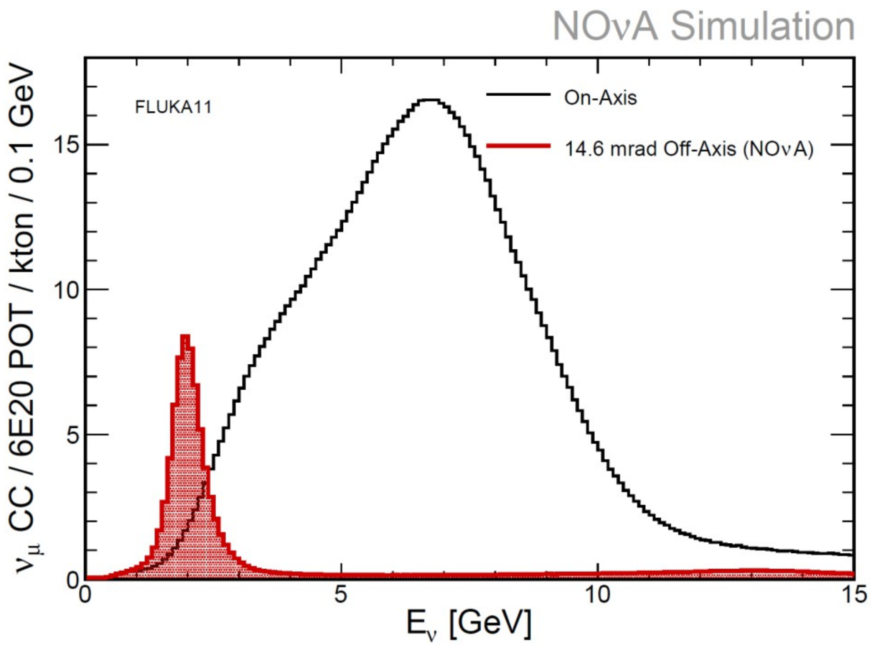
Event display for nue candidate in data

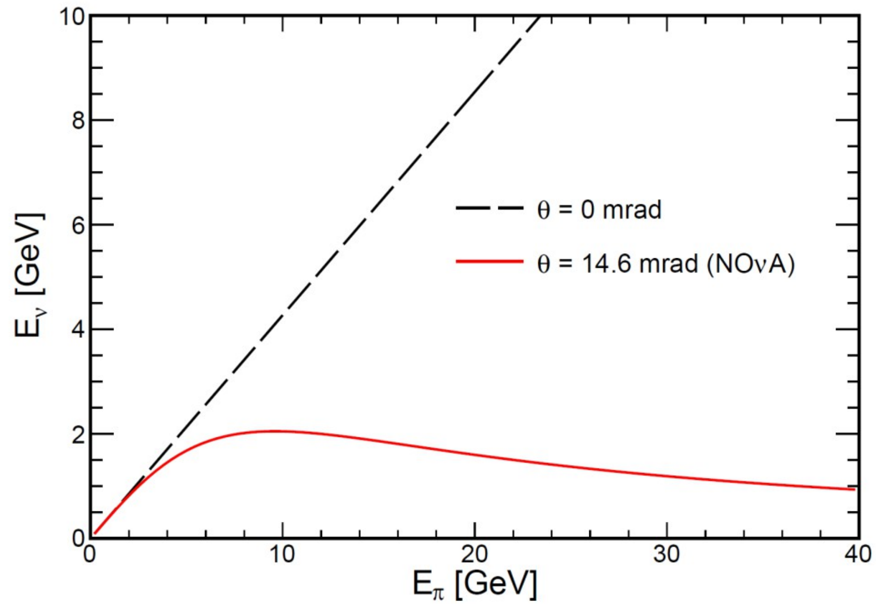


Event display for nue candidate in data

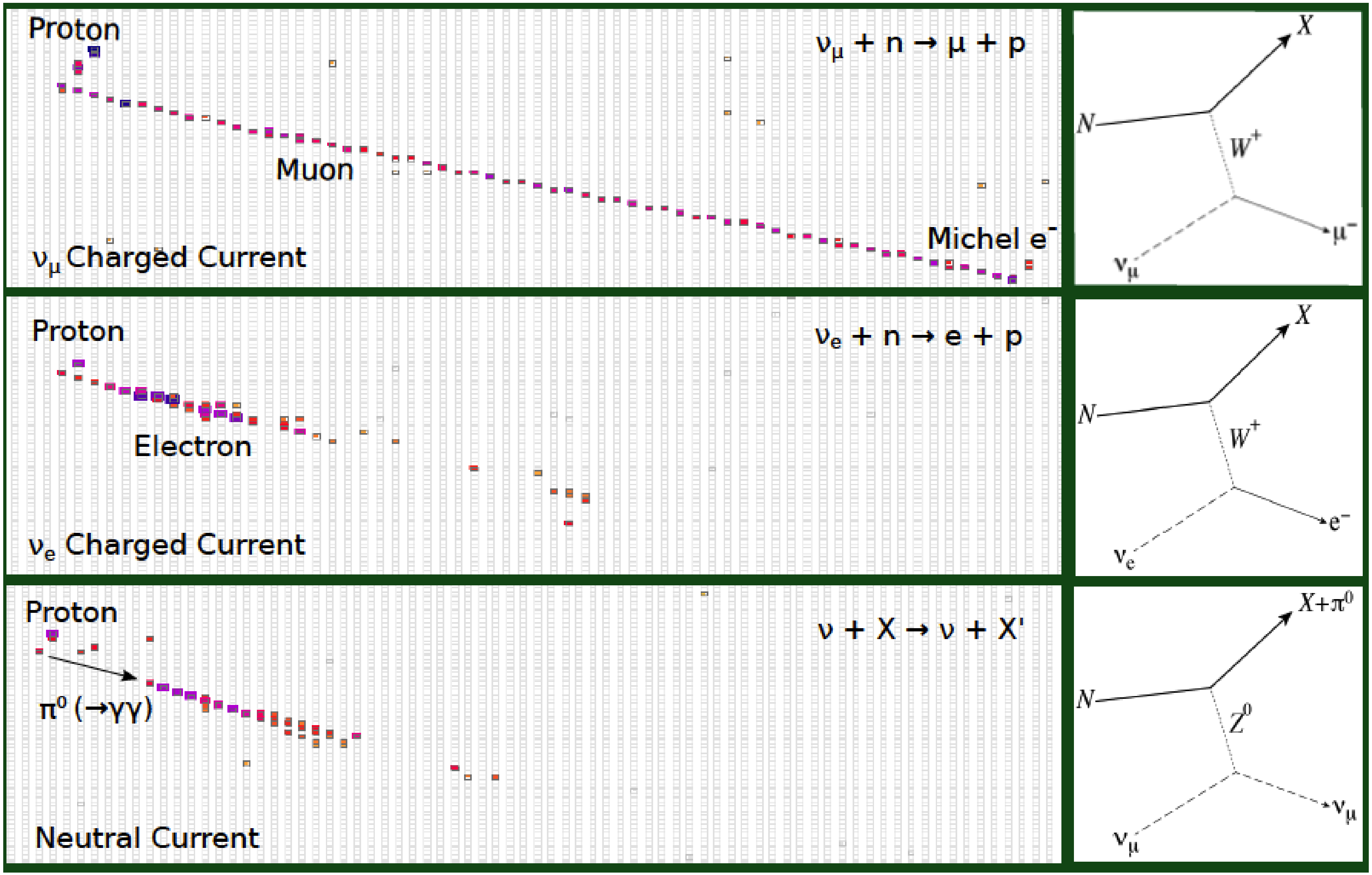


Off-axis beam

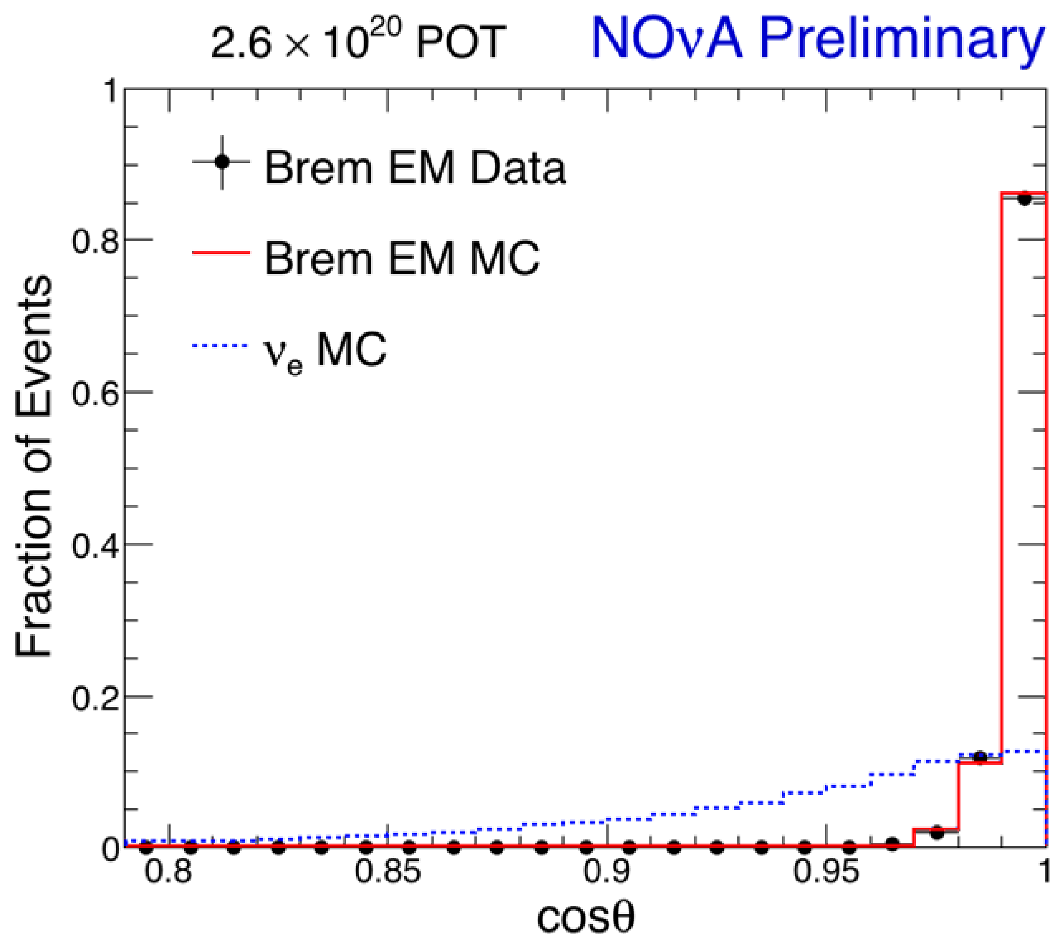




MC event topologies

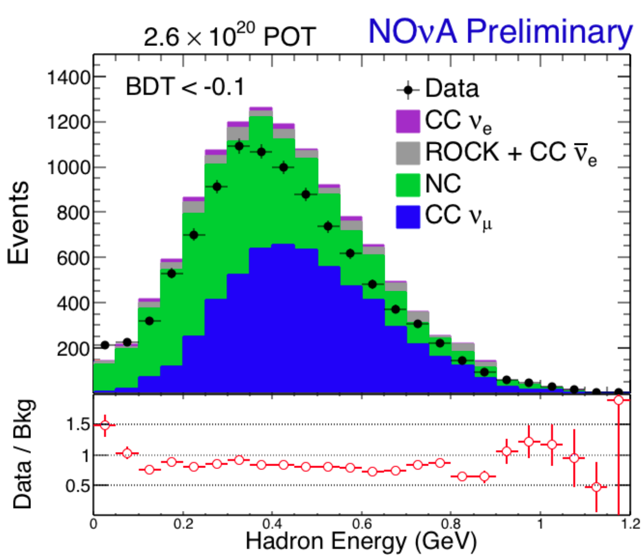


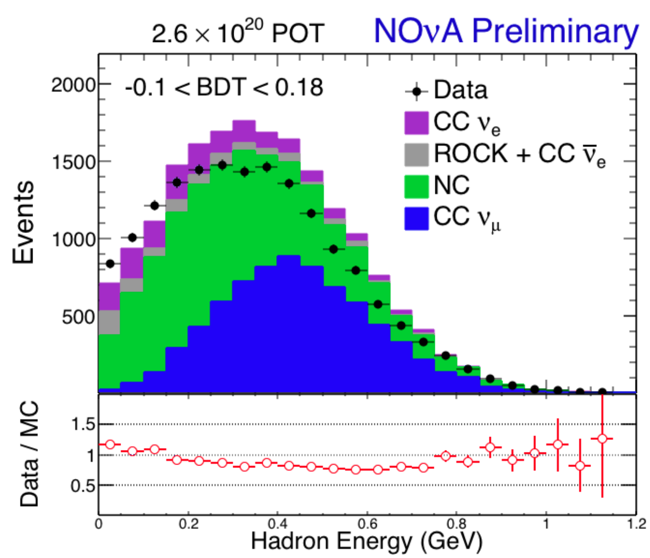
Shower angle

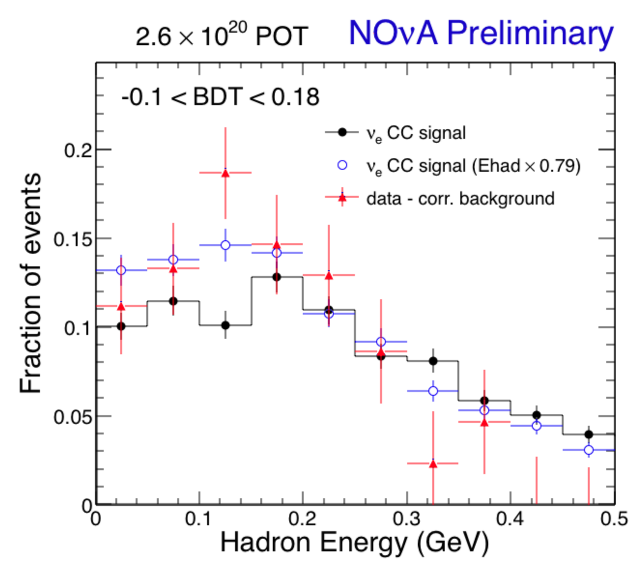


Hadron Energy

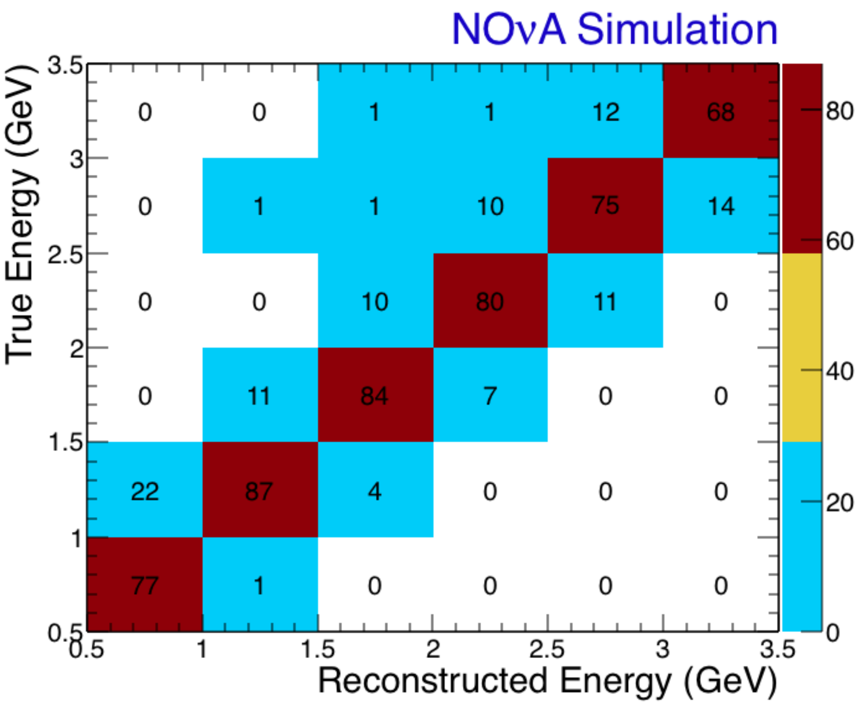
- We use events in sideband region with BDT<0.18 to study the hadron energy. We split these events further to background dominant sample (BDT<-0.1) and signal-included sample (-0.1<BDT<0.18).
- We derive the data/background correction using the background sample, and then apply these correction to the background in the signal-included sample.
- Then we compare the background subtracted data with the signal MC prediction in the signal-included sample (see right plot). The KS test results for the default and Ehad-shifted MC signal give 0.019 and 0.185 respectively.

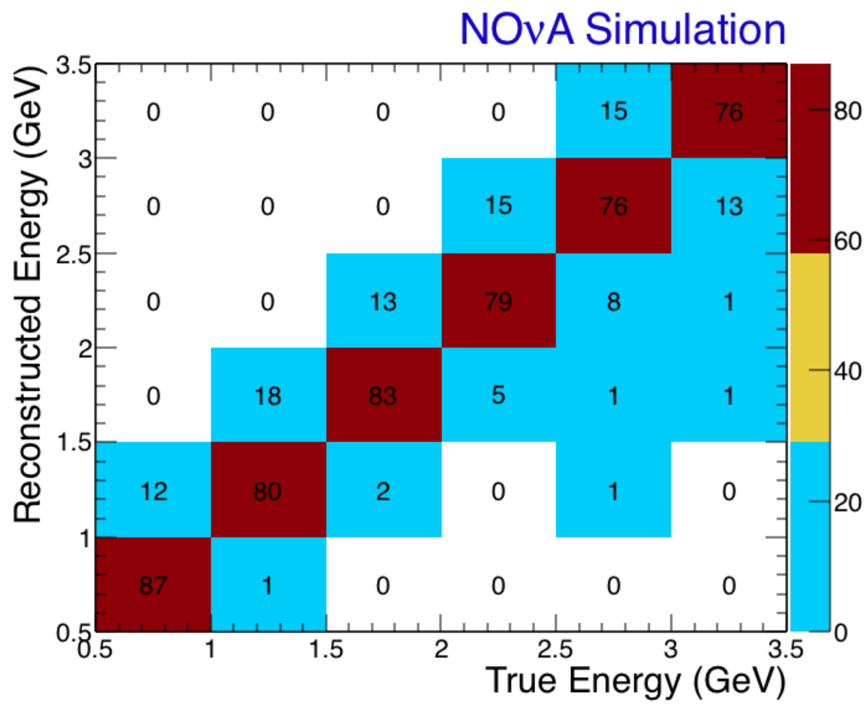




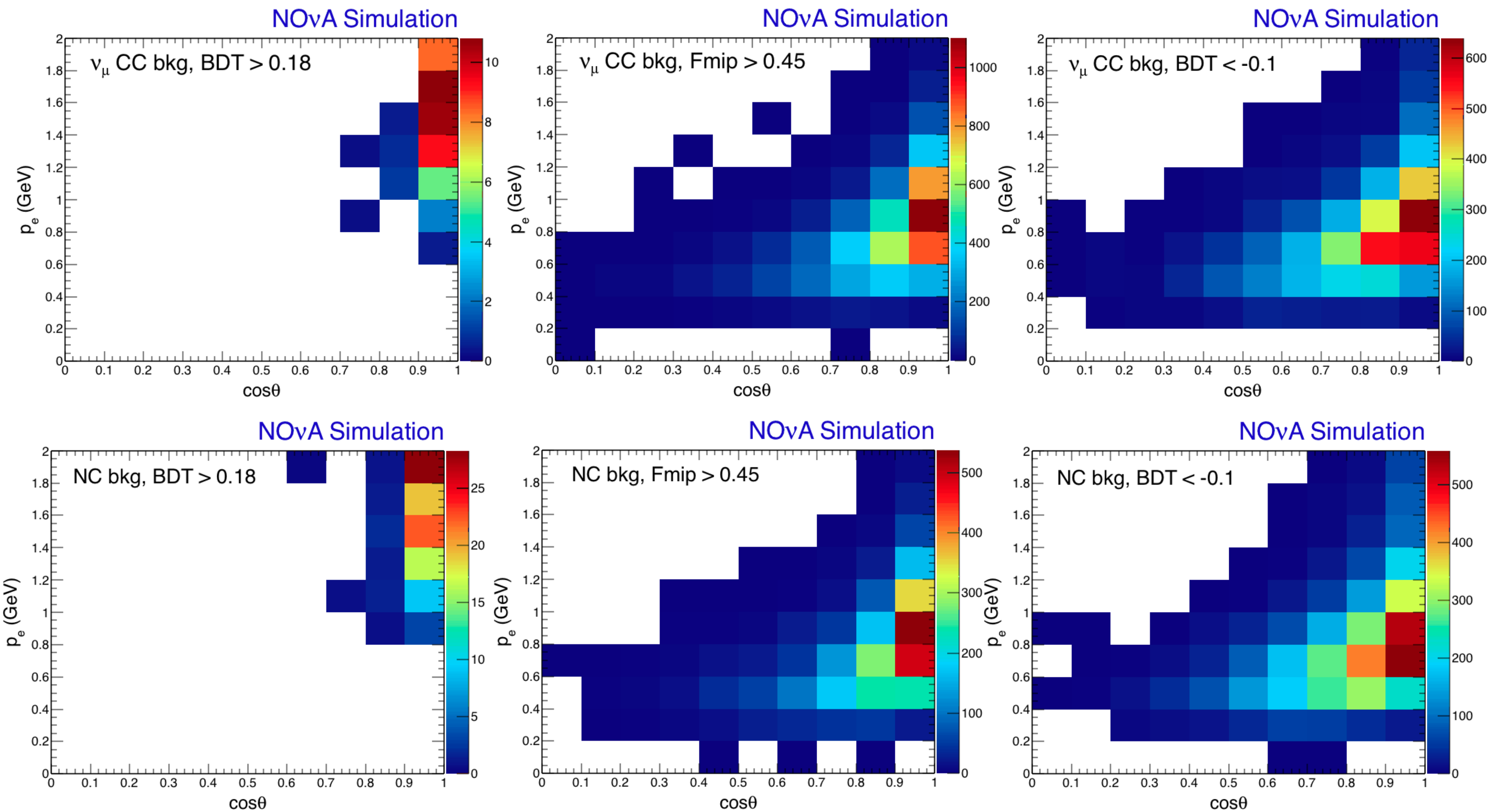


Migration matrix



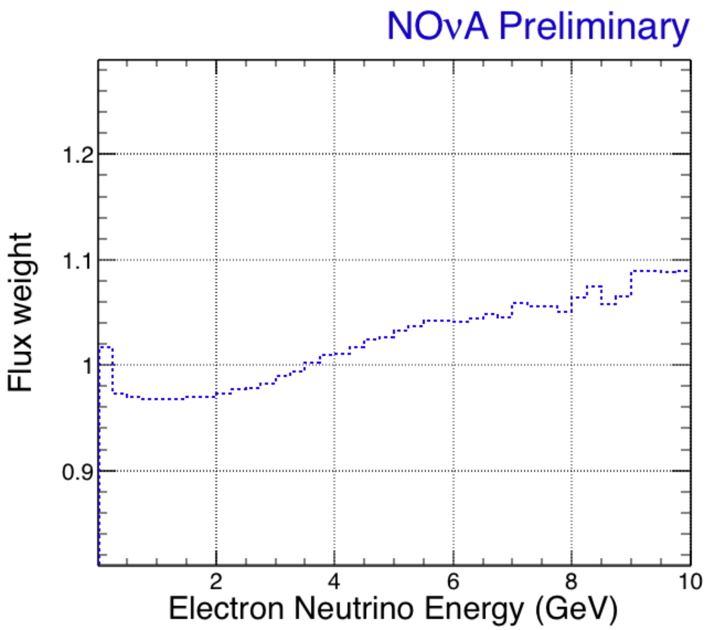


Pe vs. cosθ for numu CC and NC background



Hadron production Uncertainty

- We also derive the hadron production uncertainty without using the MIPP pion yield results. And apply the results from NA49 for pion cross section to the events from secondary pions only.
- The trend is similar as using MIPP results, to reduce the flux in 1 – 3 GeV energy region by 3%, the uncertainty is almost same.



GENIE 2.8.6 Prediction