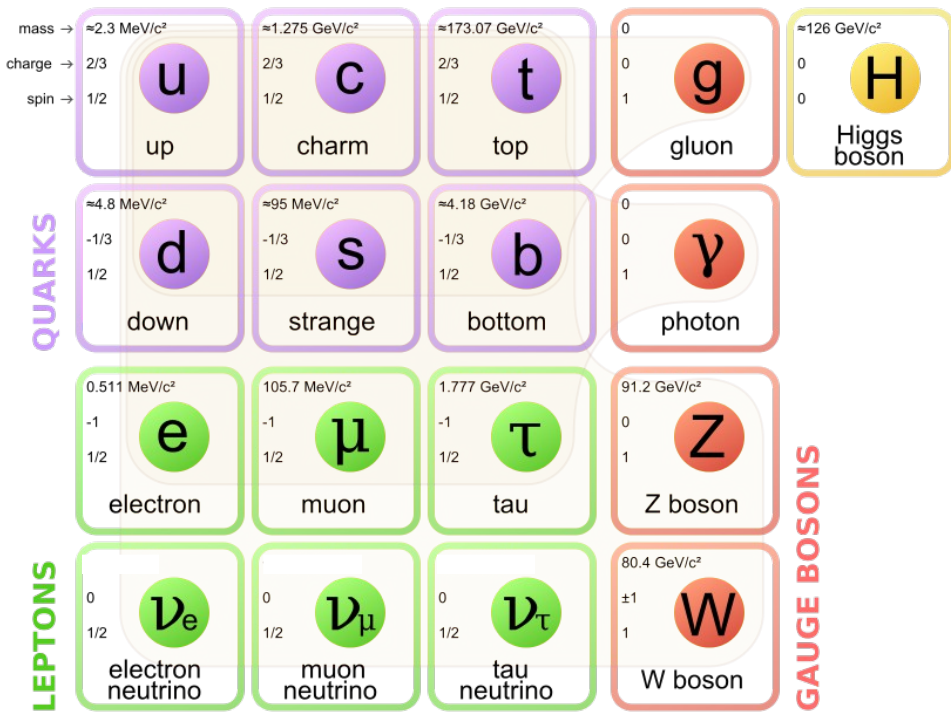
Electron Neutrino Charged-Current Inclusive Cross Section Measurement in NOvA

Xuebing Bu

Fermilab

for the NOvA Collaboration

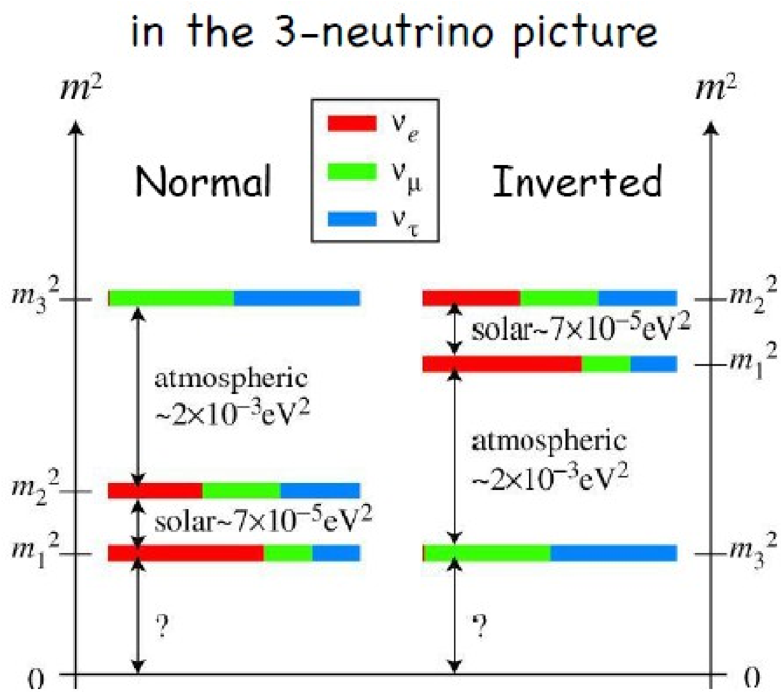
Elusive neutrinos



Standard Model
of elementary particles

- Puzzles for neutrinos
  - Small mass
  - Mass ordering
  - Relationship between neutrino and anti-neutrino: are they the same particle ?
  - CP violation
  - Number of flavors

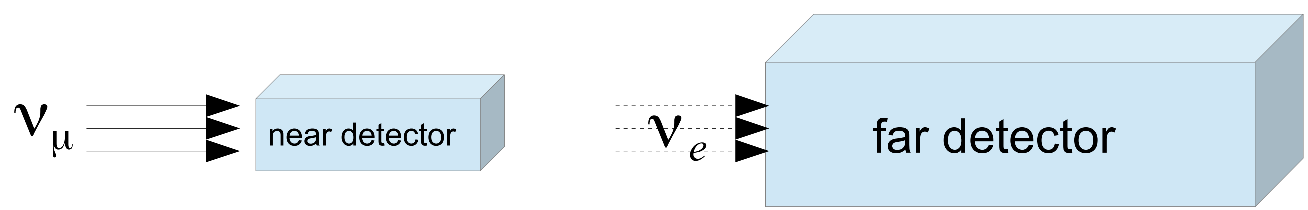
Mass ordering



- Oscillation experiments can give detailed information on the difference between mass values.
- Solving this mass ordering puzzle is a major goal for NOvA.

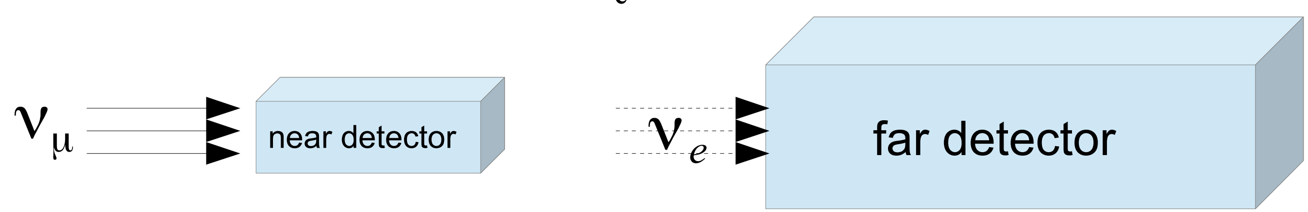
Long-baseline neutrino oscillation experiments

- To solve the puzzles of mass ordering and CP violation, long baseline neutrino experiments usually use muon neutrino beam to study electron neutrino appearance with two detectors.
- The near detector is used to understand the beam composition and predict the backgrounds in the far detector.



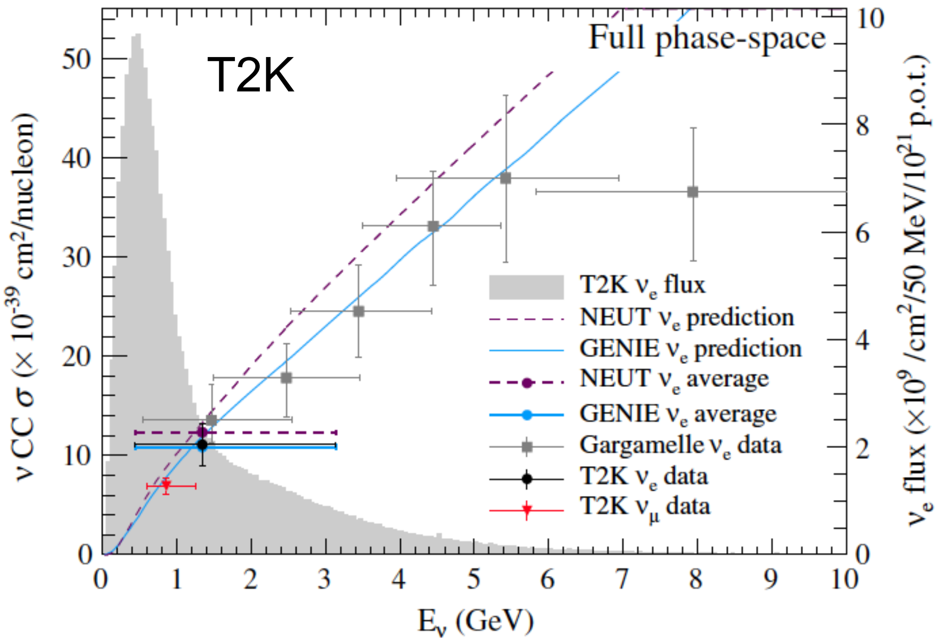
Long-baseline neutrino oscillation experiments

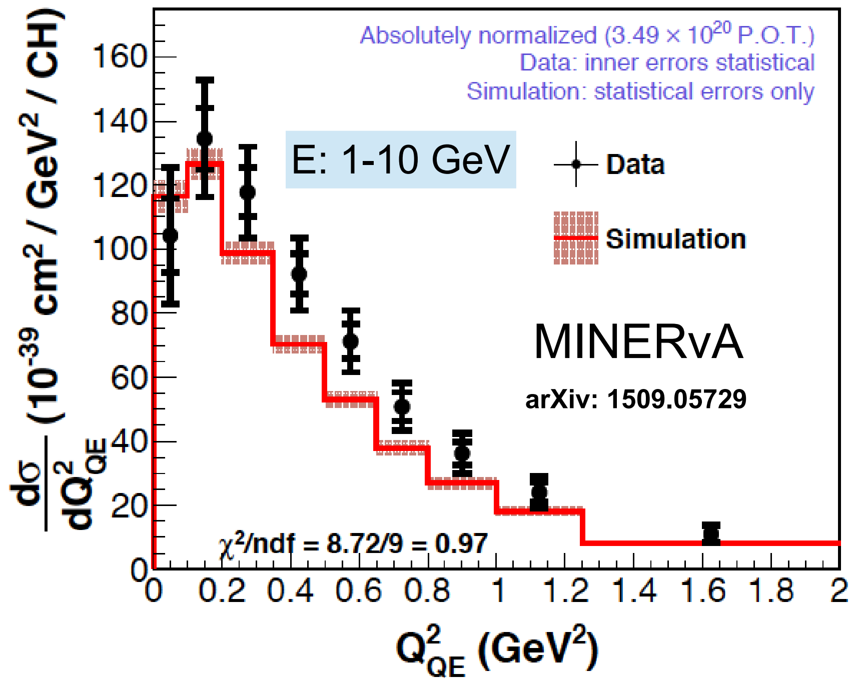
- CP violation sensitivity is achieved by comparing the ν_e and anti-ν_e appearance rate in a far detector
  - Flux produced through oscillations, and not present in the initial flux at a near detector.
  - Knowing ν_e cross section is necessary to determine CP violation with high precision in future oscillation experiments.
- Intrinsic beam ν_e is a irreducible background for ν_e appearance analysis, and the flux is not fully cancelled between near detector and far detector.
- A direct measurement of ν_e cross section is important.



Electron neutrino cross section measurements

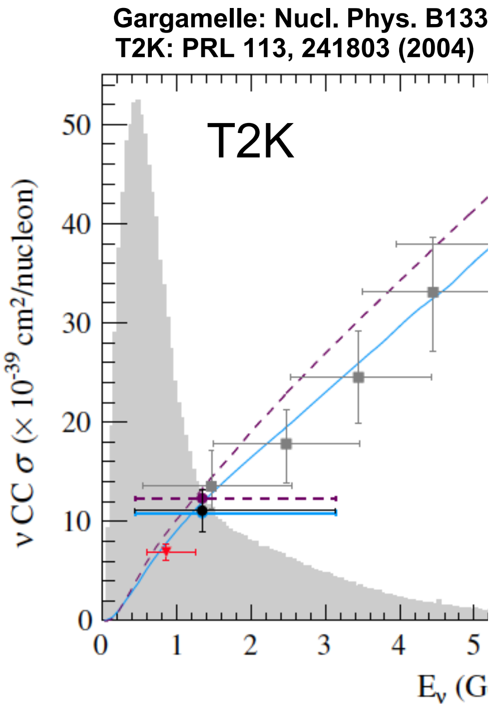
Gargamelle: Nucl. Phys. B133, 205 (1978)
T2K: PRL 113, 241803 (2004)

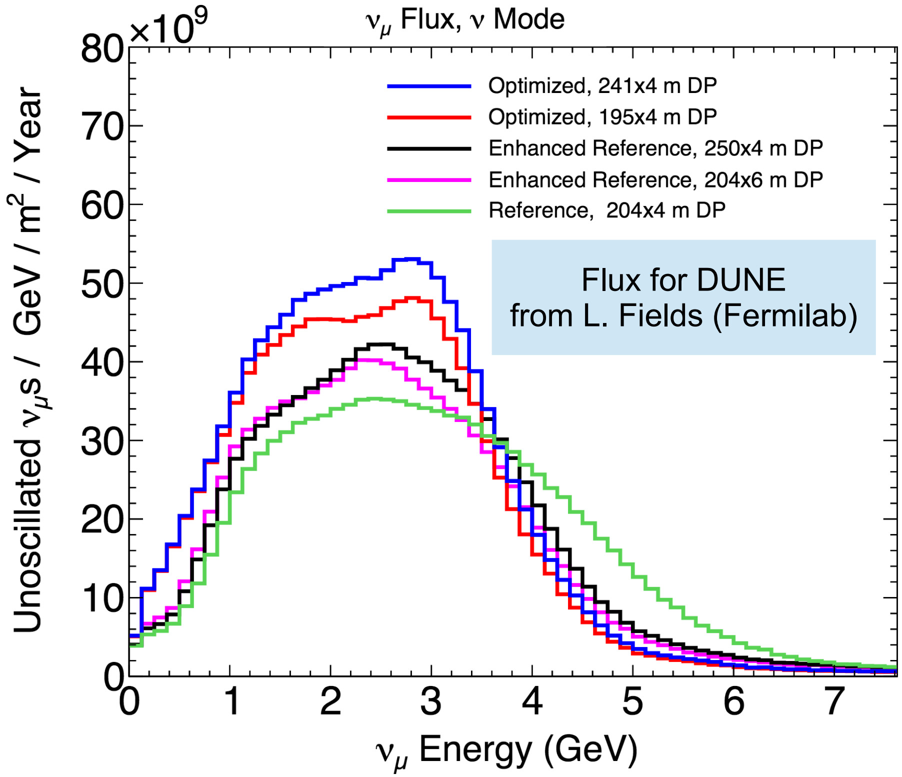


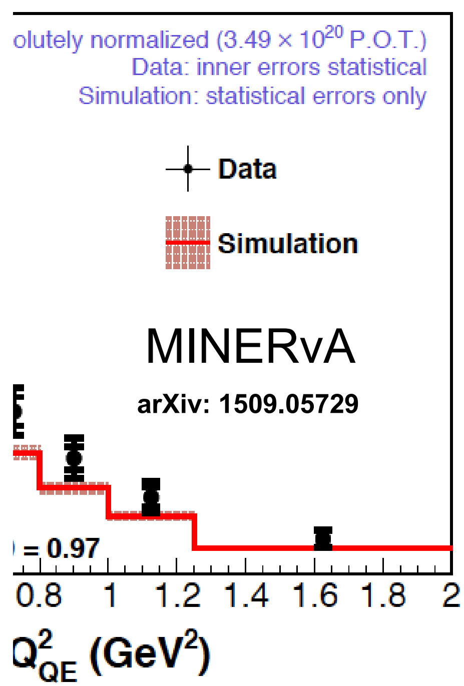


There are very few electron neutrino cross section measurements at GeV scale.

Electron neutrino cross section measurements

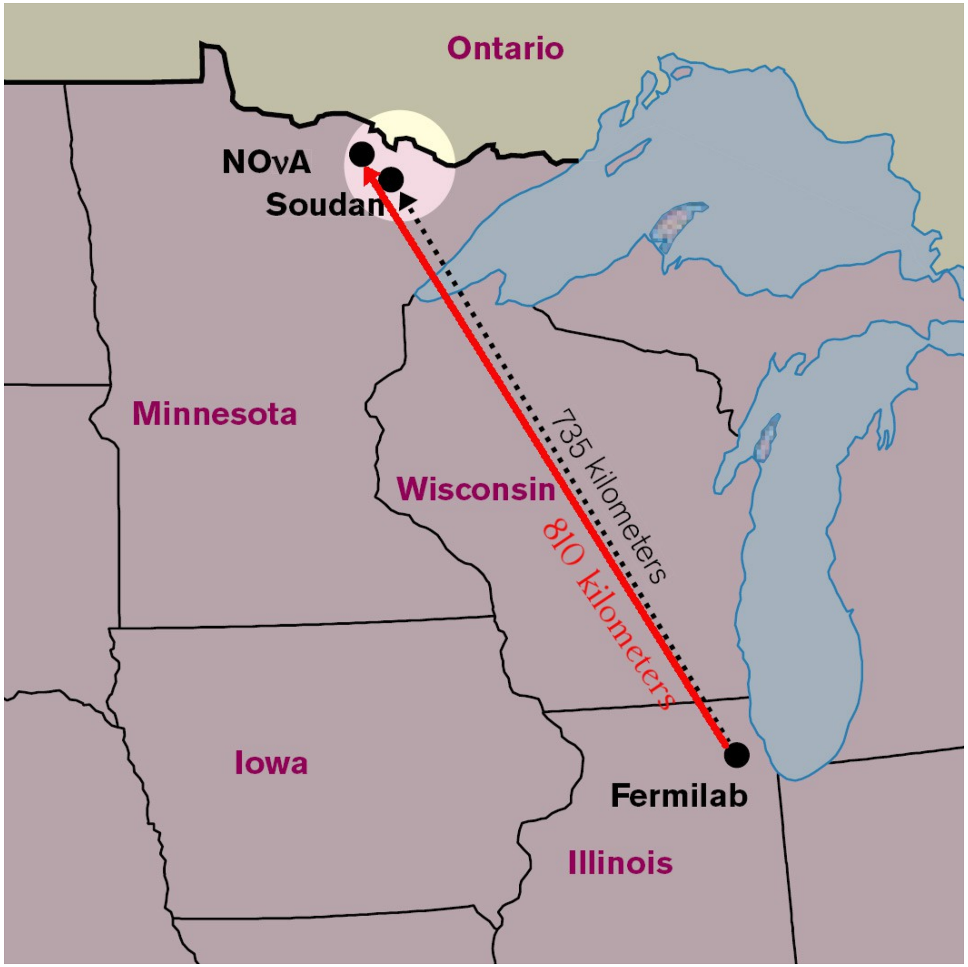






There are very few electron neutrino cross section measurements at GeV scale. Knowing the cross section in few GeV energy region is important for long-baseline experiments, like DUNE.

NOvA Experiment

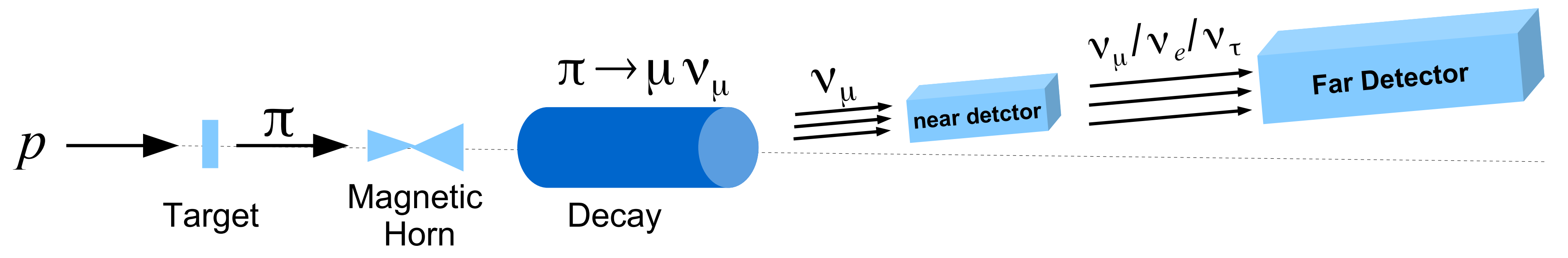


- Long-baseline experiment with two functionally identical detectors
- Physics goals
  - Appearance $\nu_\mu \rightarrow \nu_e, \overline{\nu}_\mu \rightarrow \overline{\nu}_e$
  - Disappearance $\nu_\mu \rightarrow \nu_\mu, \overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$
  - Sterile neutrino
  - Near Detector cross section
  - Exotics phenomena

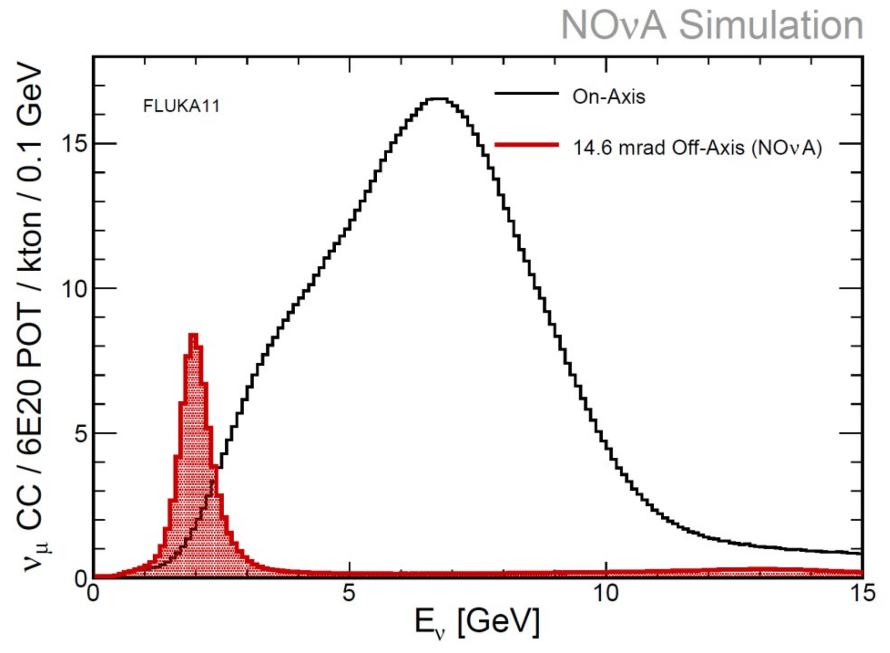
NOvA Collaboration

200+ scientists and engineers
from 39 institutions, 7 countries

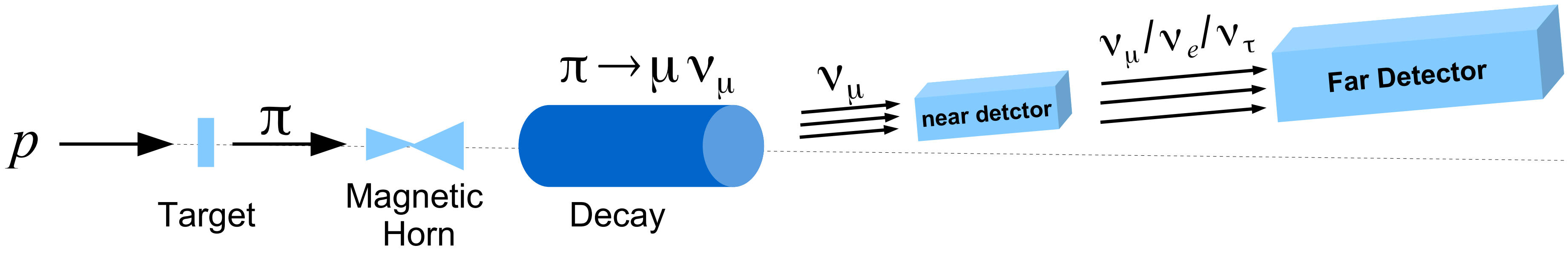
NuMI Beam



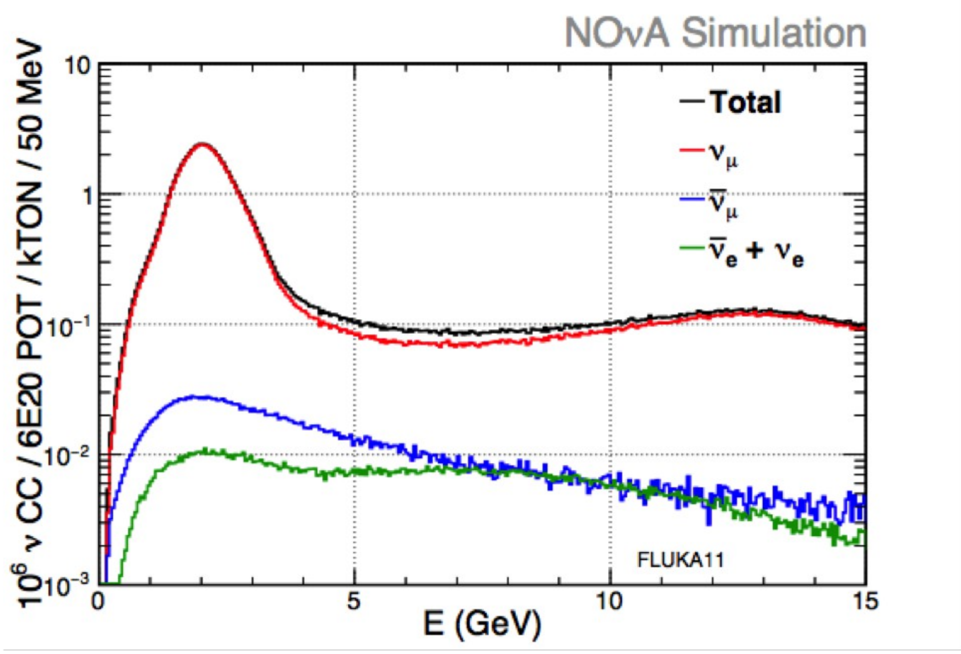
- Detectors are off beam axis
  - Narrow band beam peaked at 2 GeV.



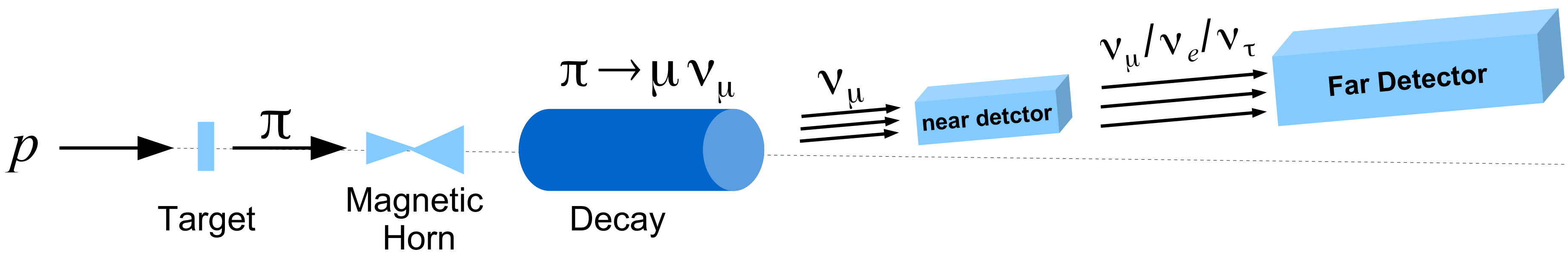
NuMI Beam



- Detectors are off beam axis
  - Narrow band beam peaked at 2 GeV.
  - Electron neutrino flux is ~1% of total with broad energy spectrum.

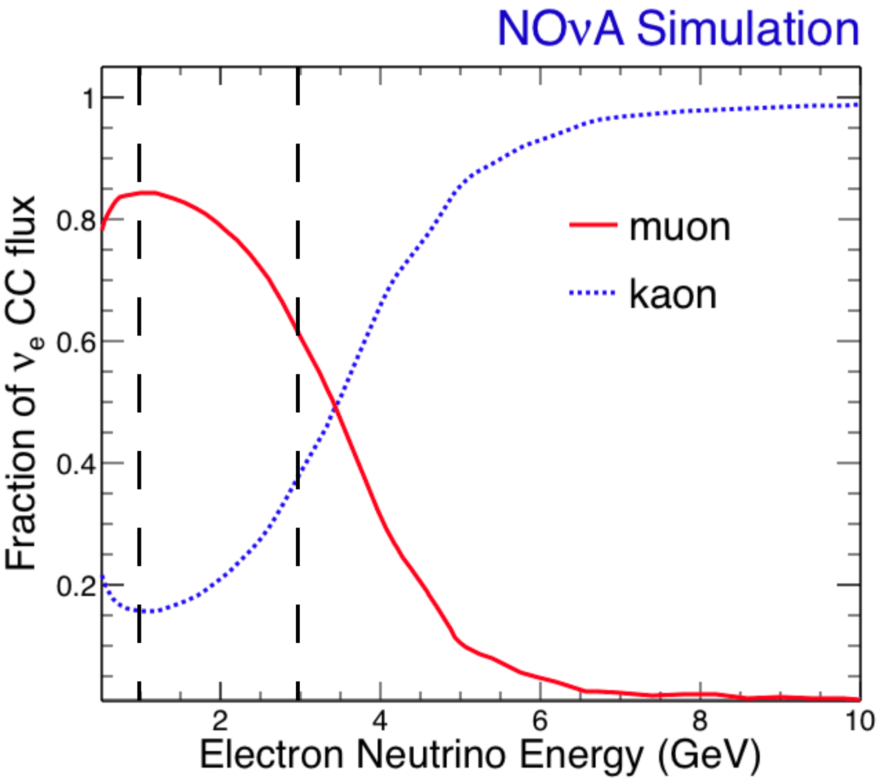


NuMI Beam

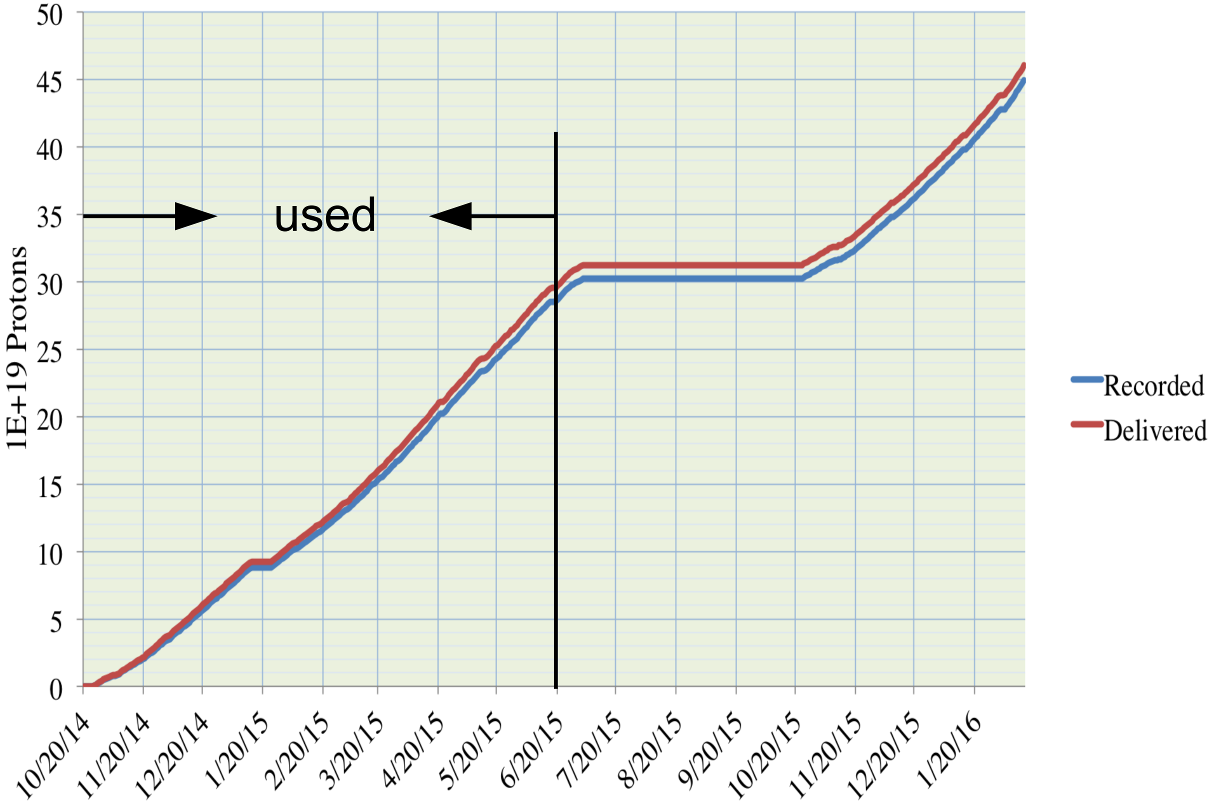


- Detectors are off beam axis
  - Narrow band beam peaked at 2 GeV.
  - Electron neutrino flux is ~1% of total with broad energy spectrum.
  - Electron neutrino are mainly from decay of muons and kaons.

$$\begin{cases} \pi^+ \rightarrow \mu^+ \rightarrow \nu_e + e^+ + \bar{\nu}_\mu \\ K^+ \rightarrow \nu_e + e^+ + \pi^0 \\ K_L^0 \rightarrow \nu_e + e^+ + \pi^- \end{cases}$$



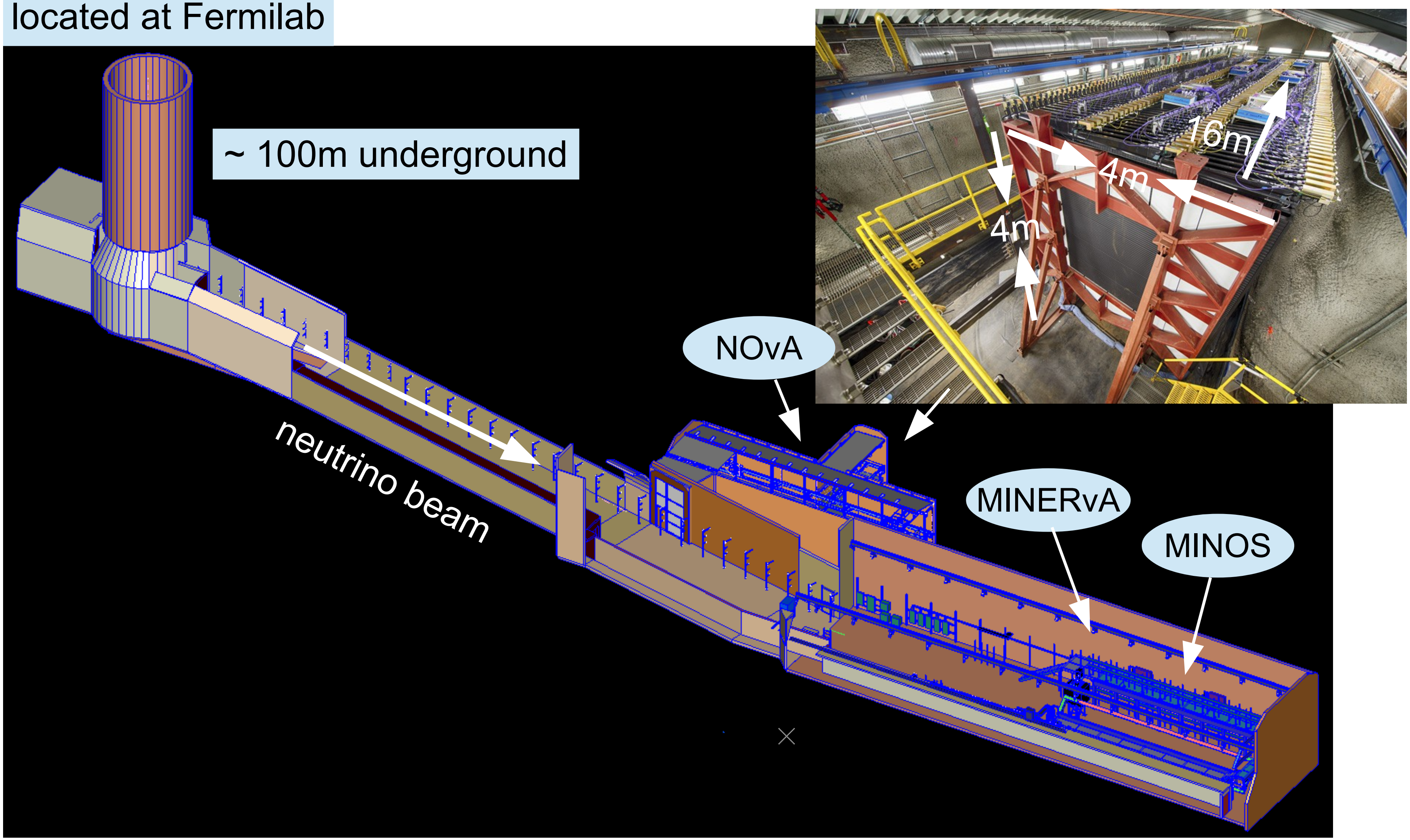
NuMI Beam status



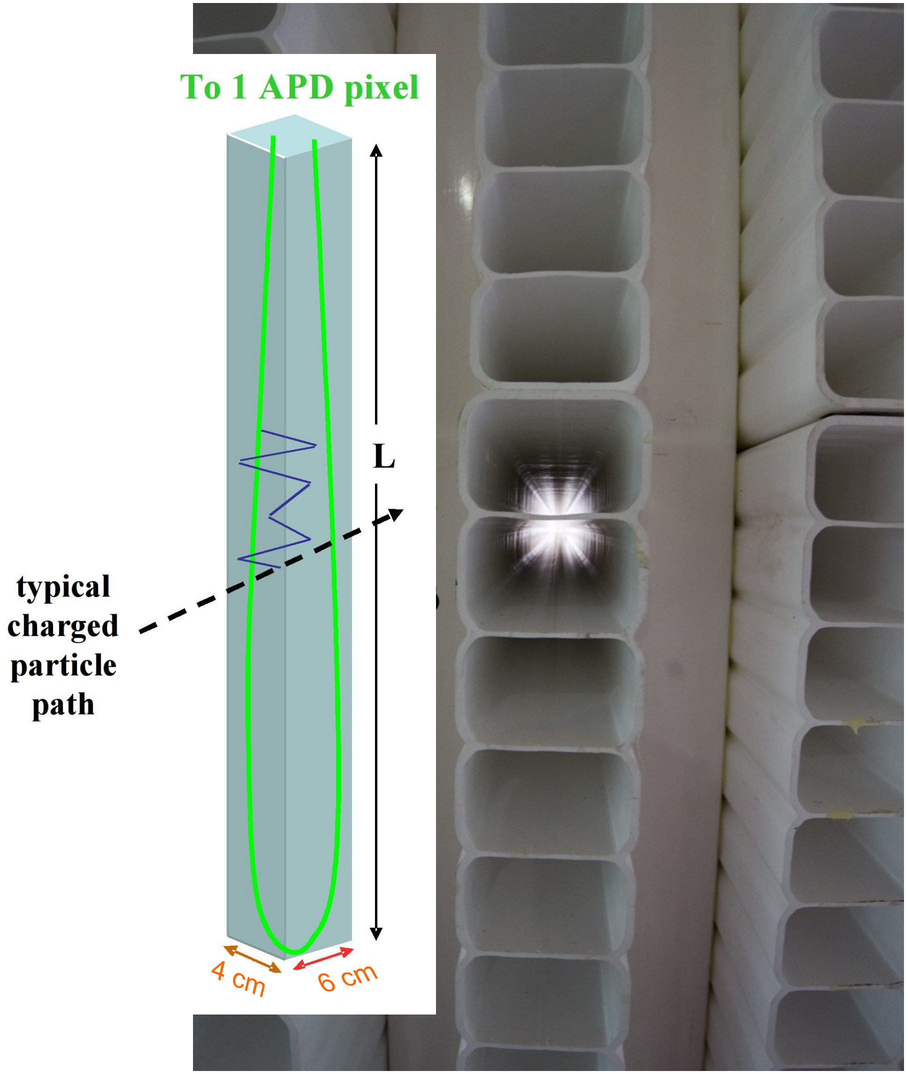
Data collected from an exposure of 2.6E20 protons-on-target are used in this analysis.
There are major updates last summer towards to 700 kW operation.
Current beam power stays around 500 kW with a peak at **570 kW** !

Near Detector

located at Fermilab

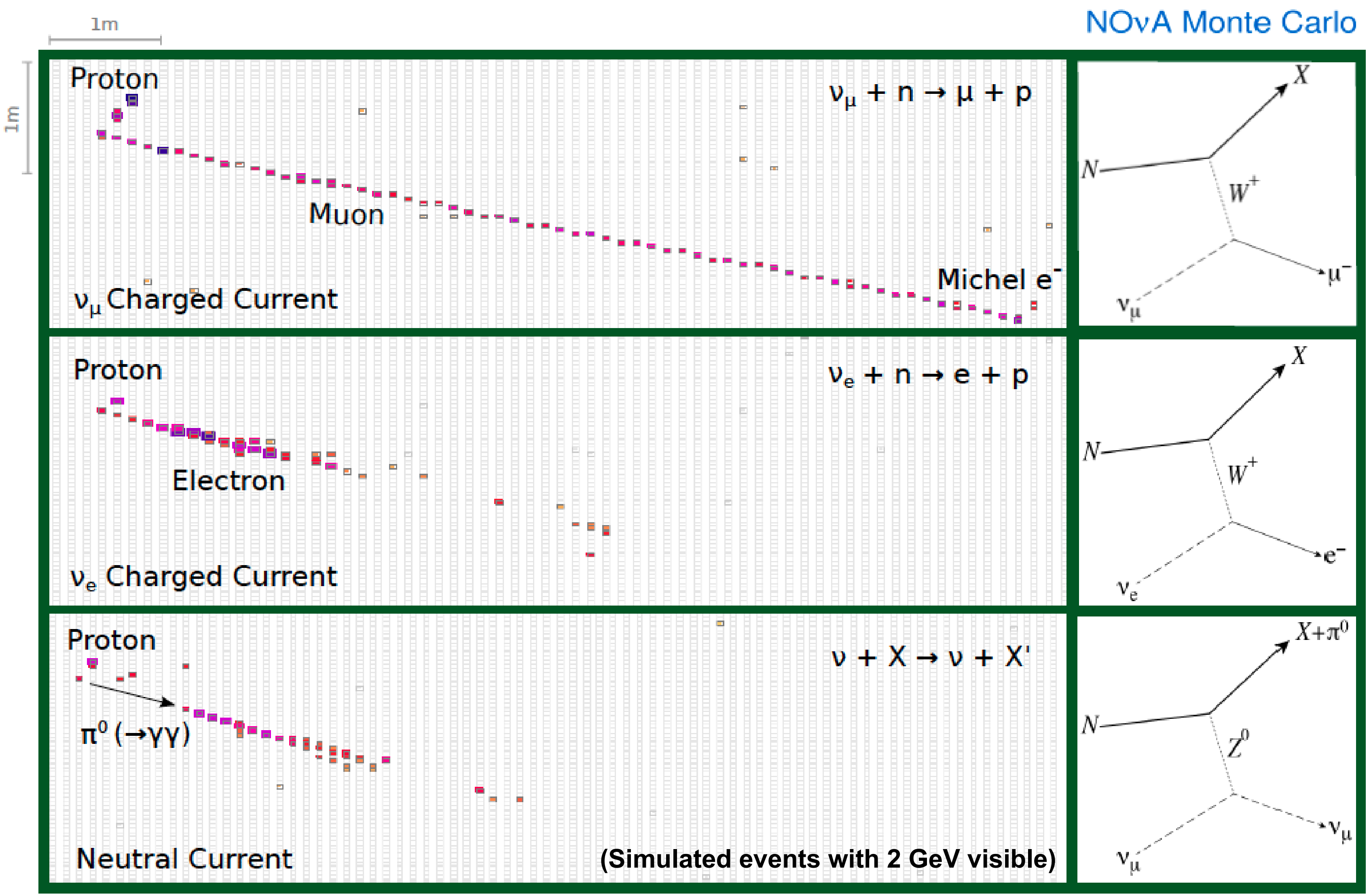


Detector Technology



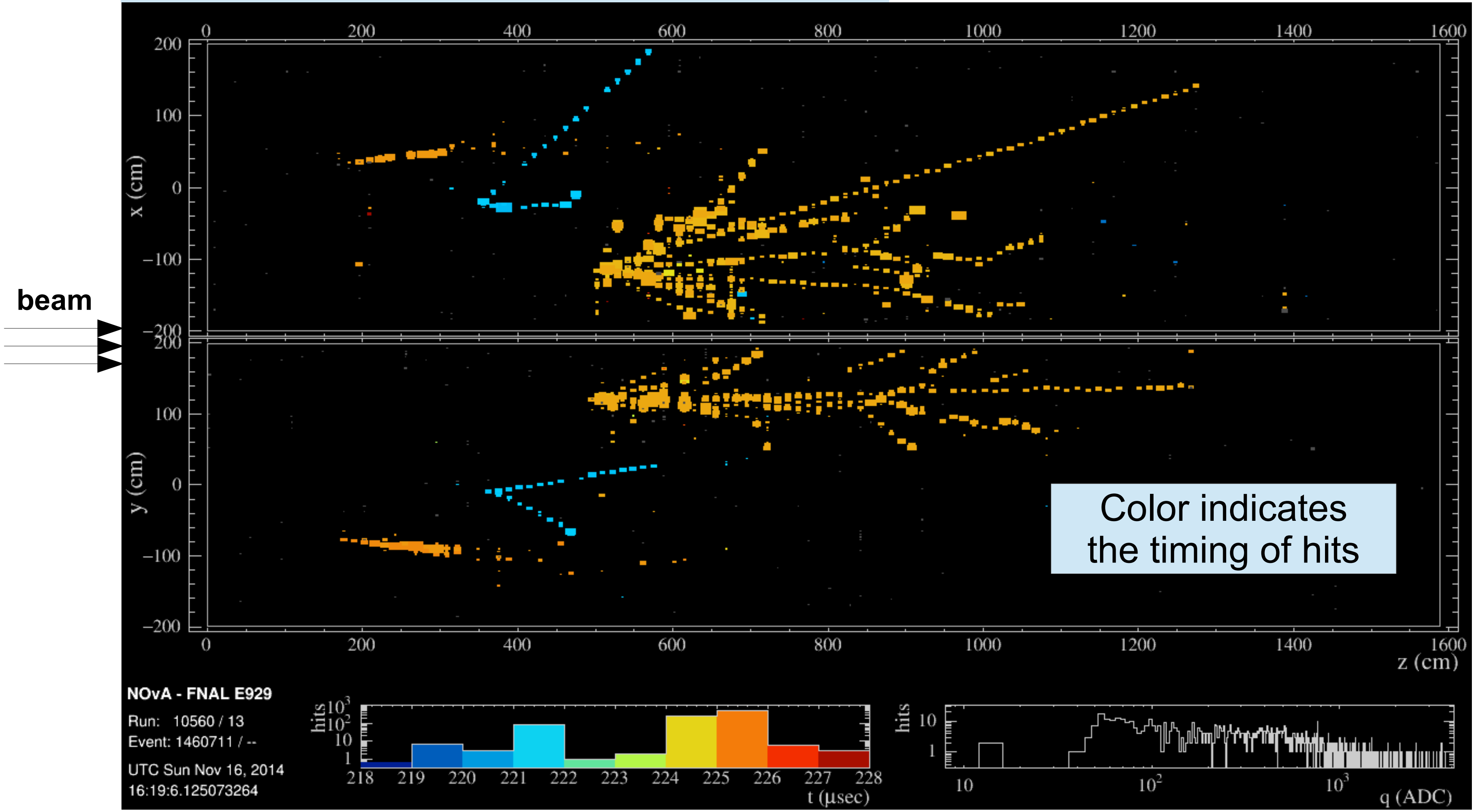
- PVC cells, each cell contains one loop of wavelength-shifting fiber, and filled with scintillator oil. Read out by avalanche photo-diode
- Planes are layered in orthogonal views
- Near Detector:
  - 193-ton fully active + 97-ton muon catcher
  - 20K channels
  - low Z and high-active tracking calorimeter

MC topologies



Near Detector data event

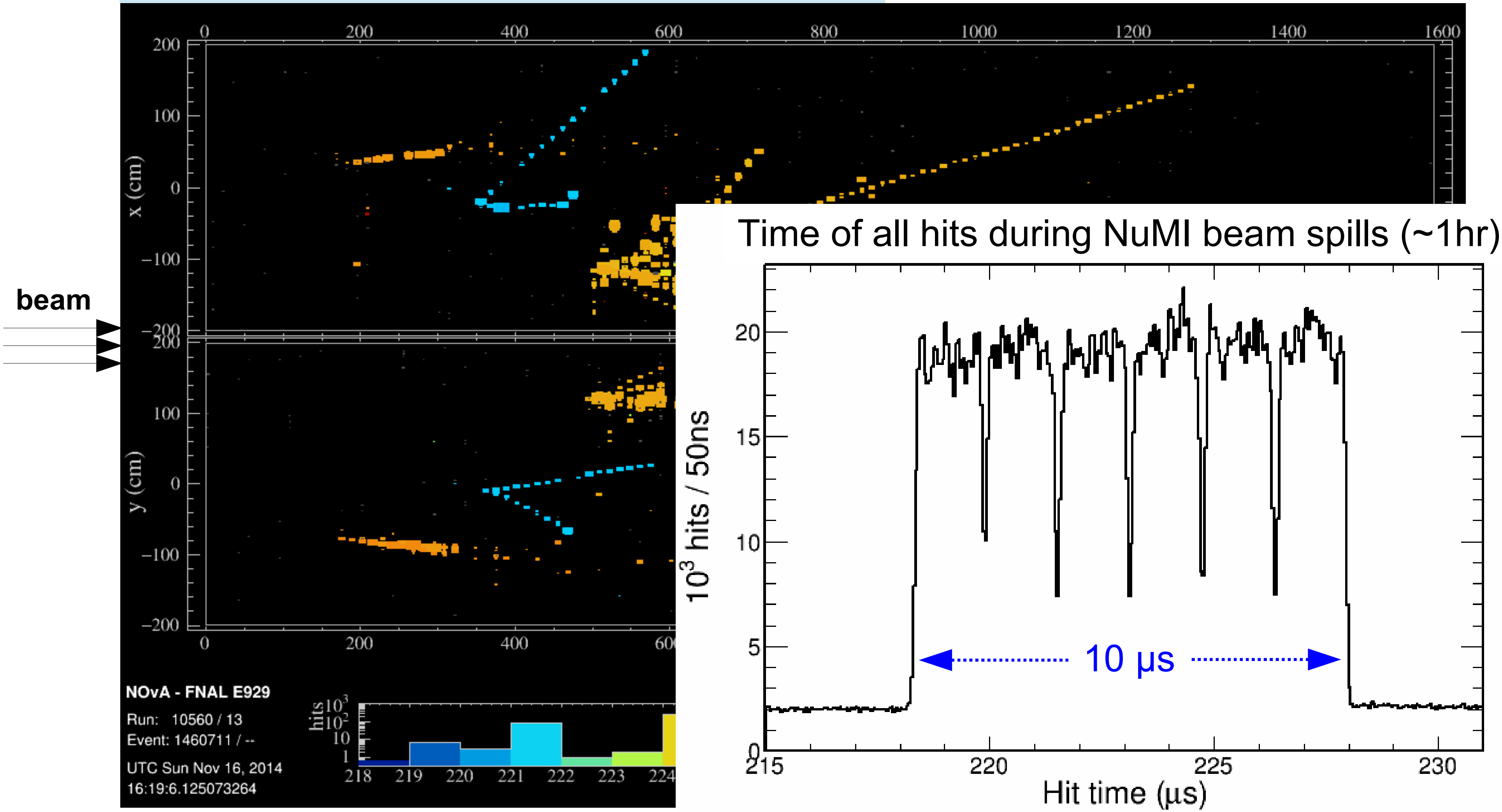
All hits recorded in a 10 μs beam spill at ND.



Color indicates the timing of hits

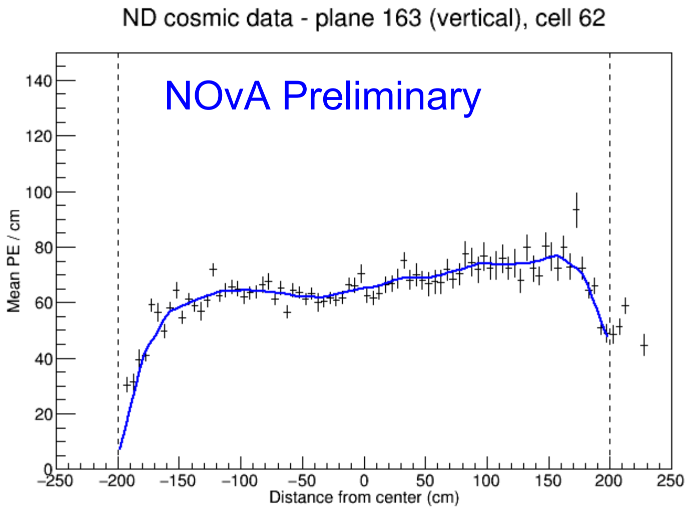
Near Detector data event

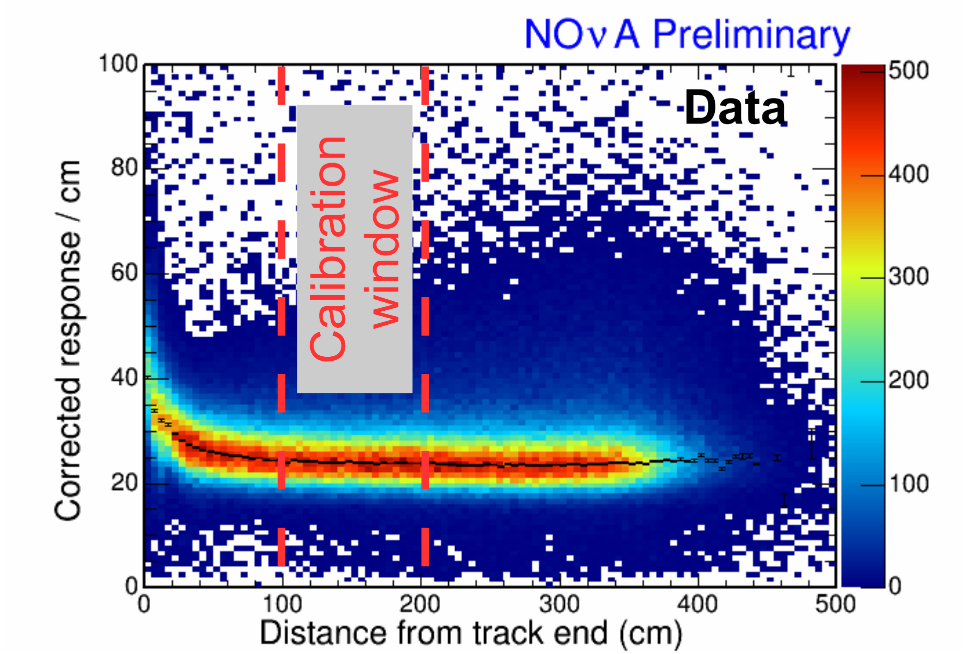
All hits recorded in a 10 μs beam spill at ND.

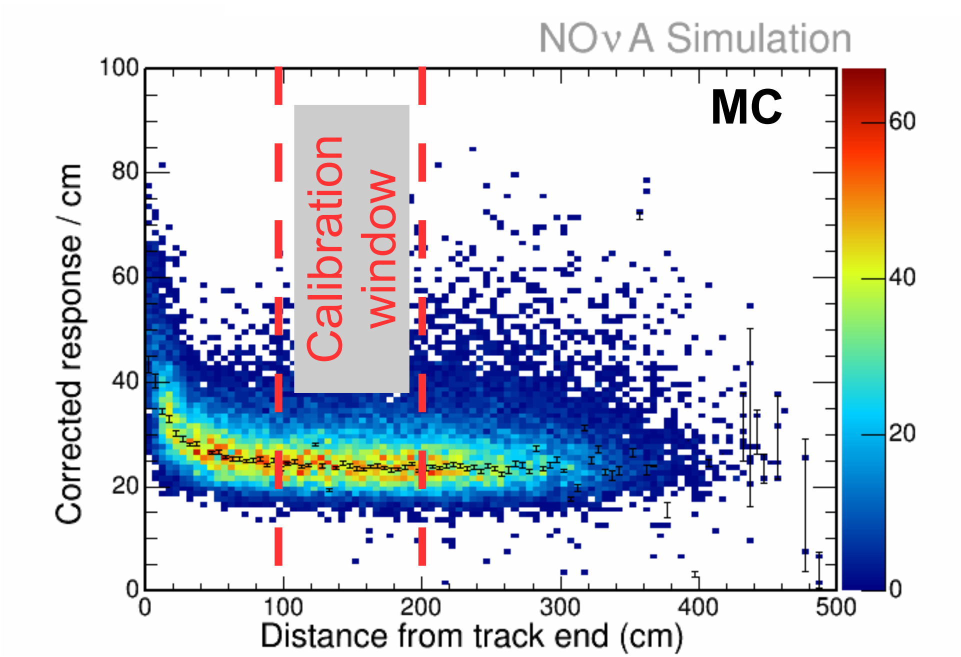


Calibration

- Attenuation correction for WLS fiber using cosmic data.
- Stopping muons are used as standard candles to set absolute energy scale.

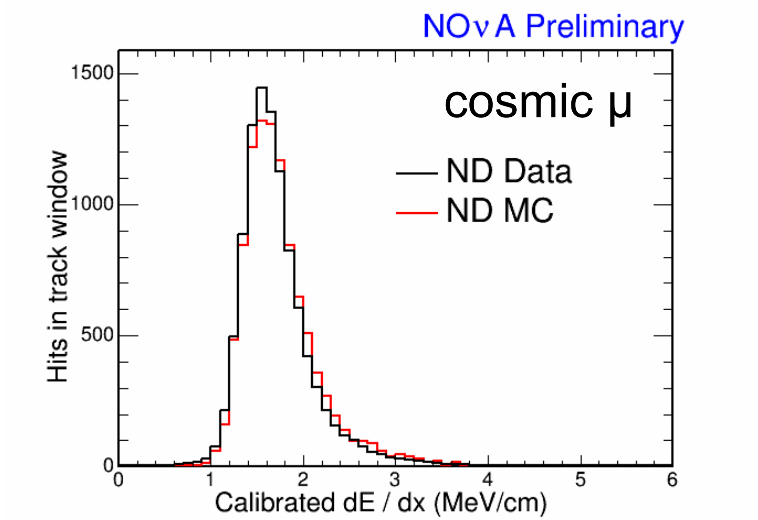


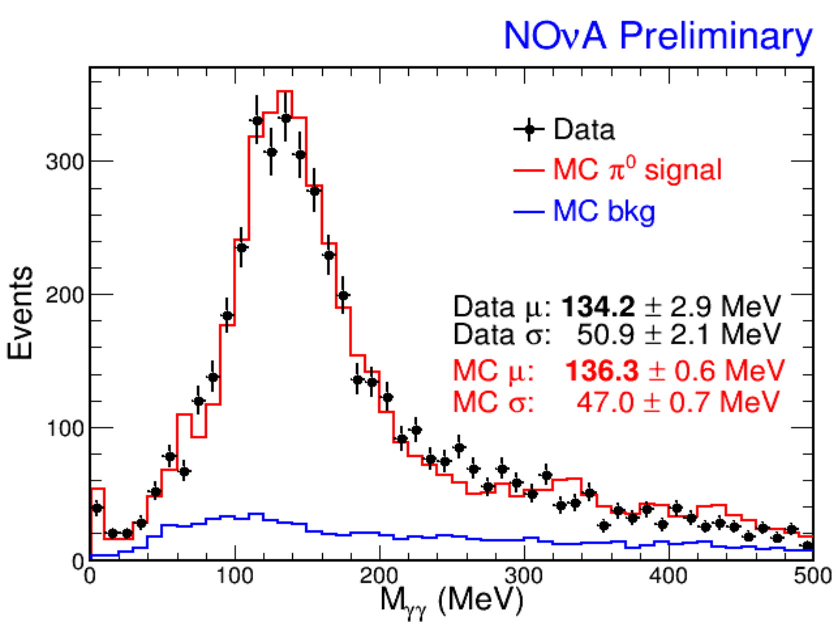


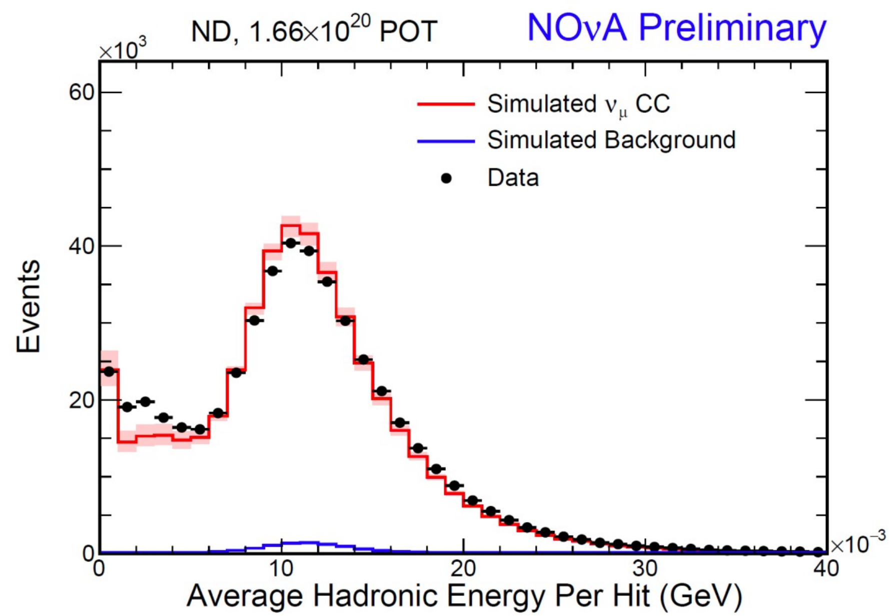


Calibration

- Multiple cross-checks for energy scale
  - Cosmic μ dE/dX
  - Horizontal μ from beam neutrino
  - π^0 invariant mass
  - Hadron energy per hit
- All results agree within 5%.

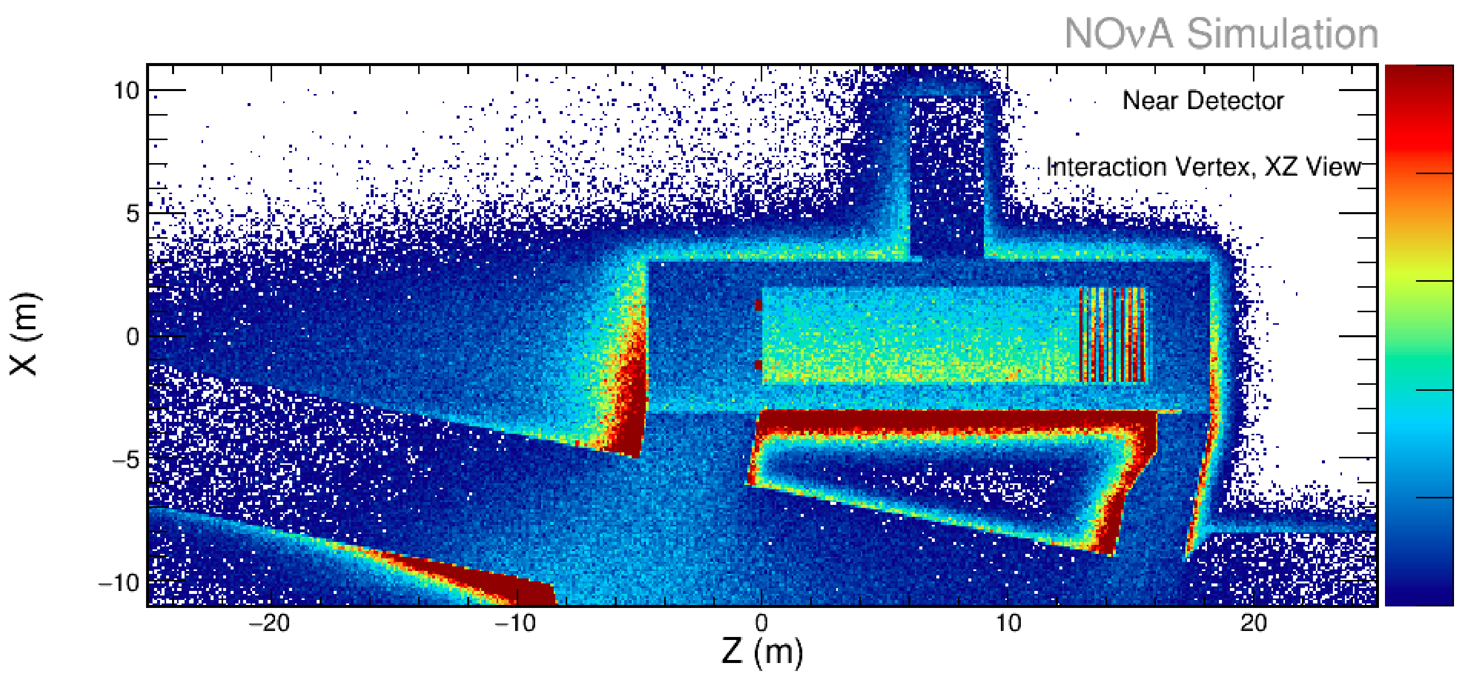






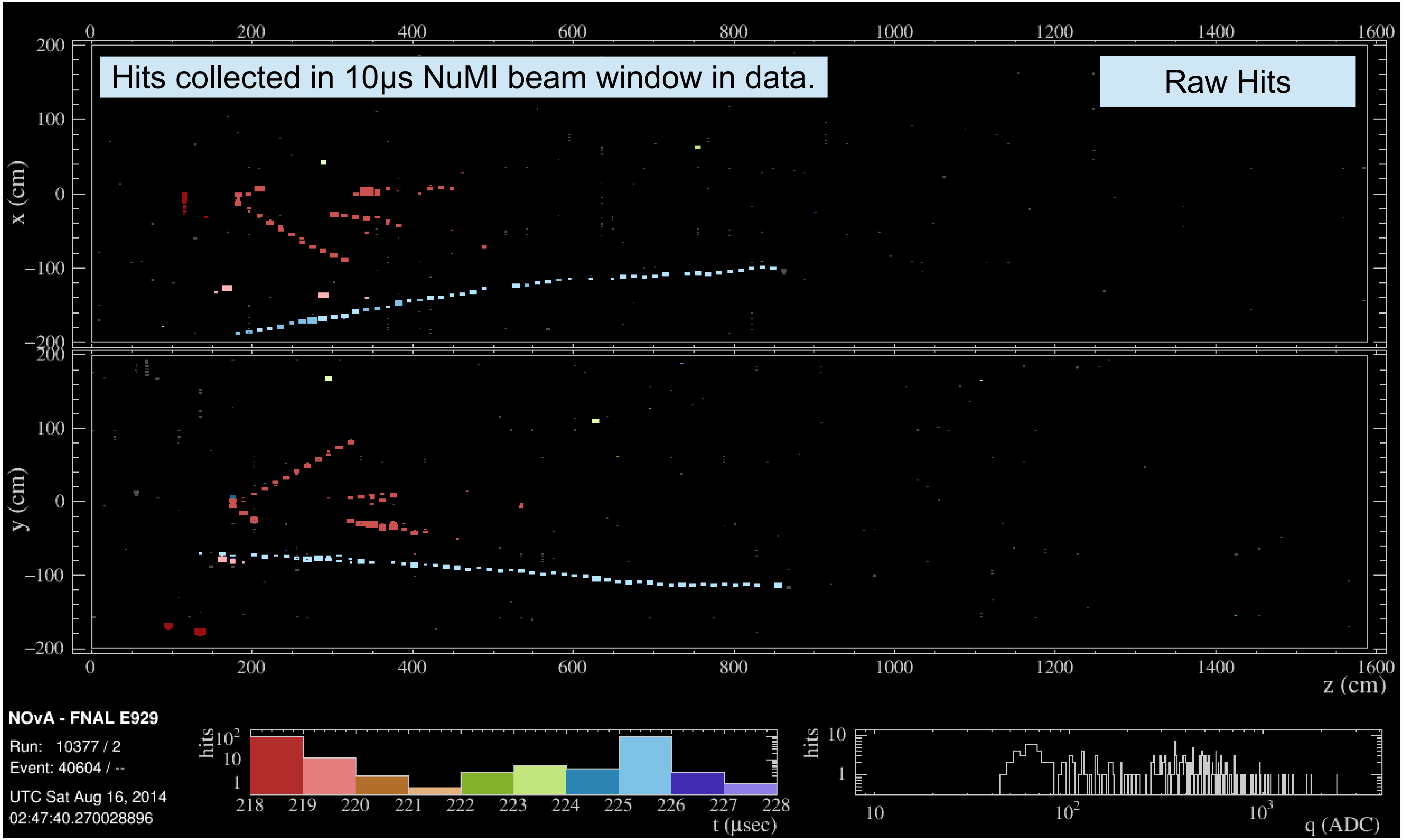
Simulation

- Beam flux: FLUKA v2011 + FLUGG v2009
- Neutrino interactions modeling: GENIE v2.8.0
- Detector simulation: GEANT 4.9.6
- Readout electronics and DAQ: custom simulation

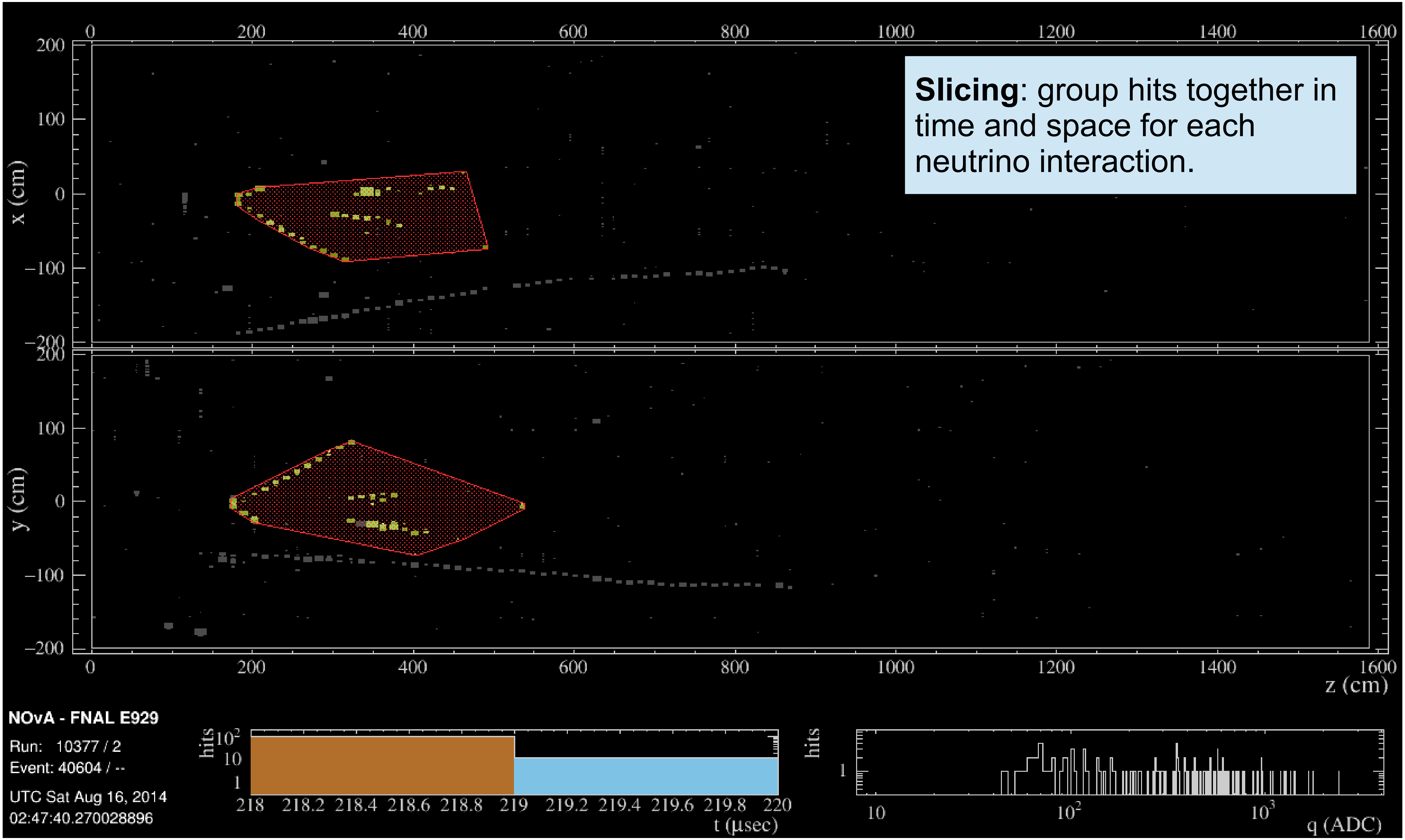


Simulation: Locations of neutrino interactions that produce activity in the Near Detector

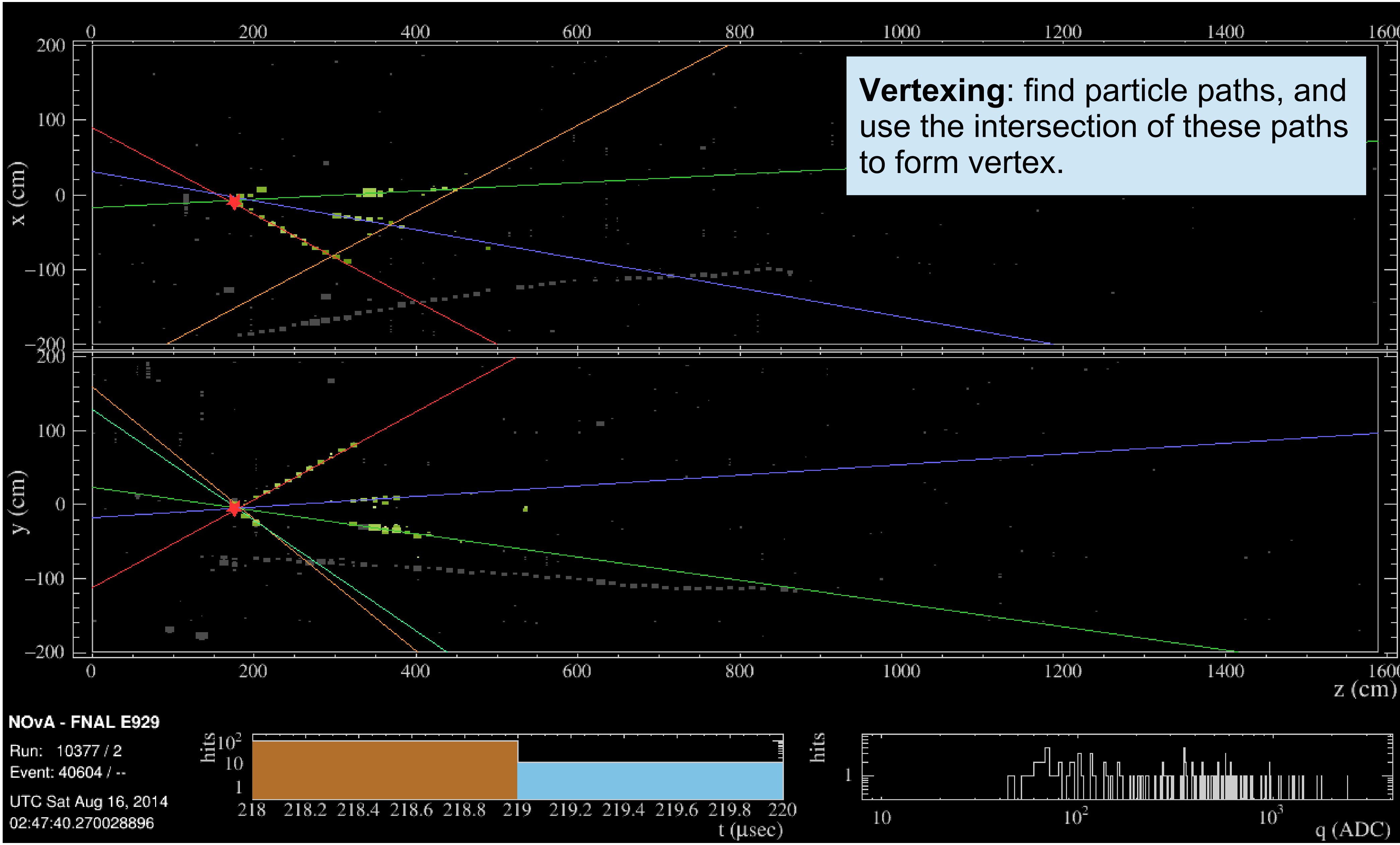
Reconstruction



Reconstruction



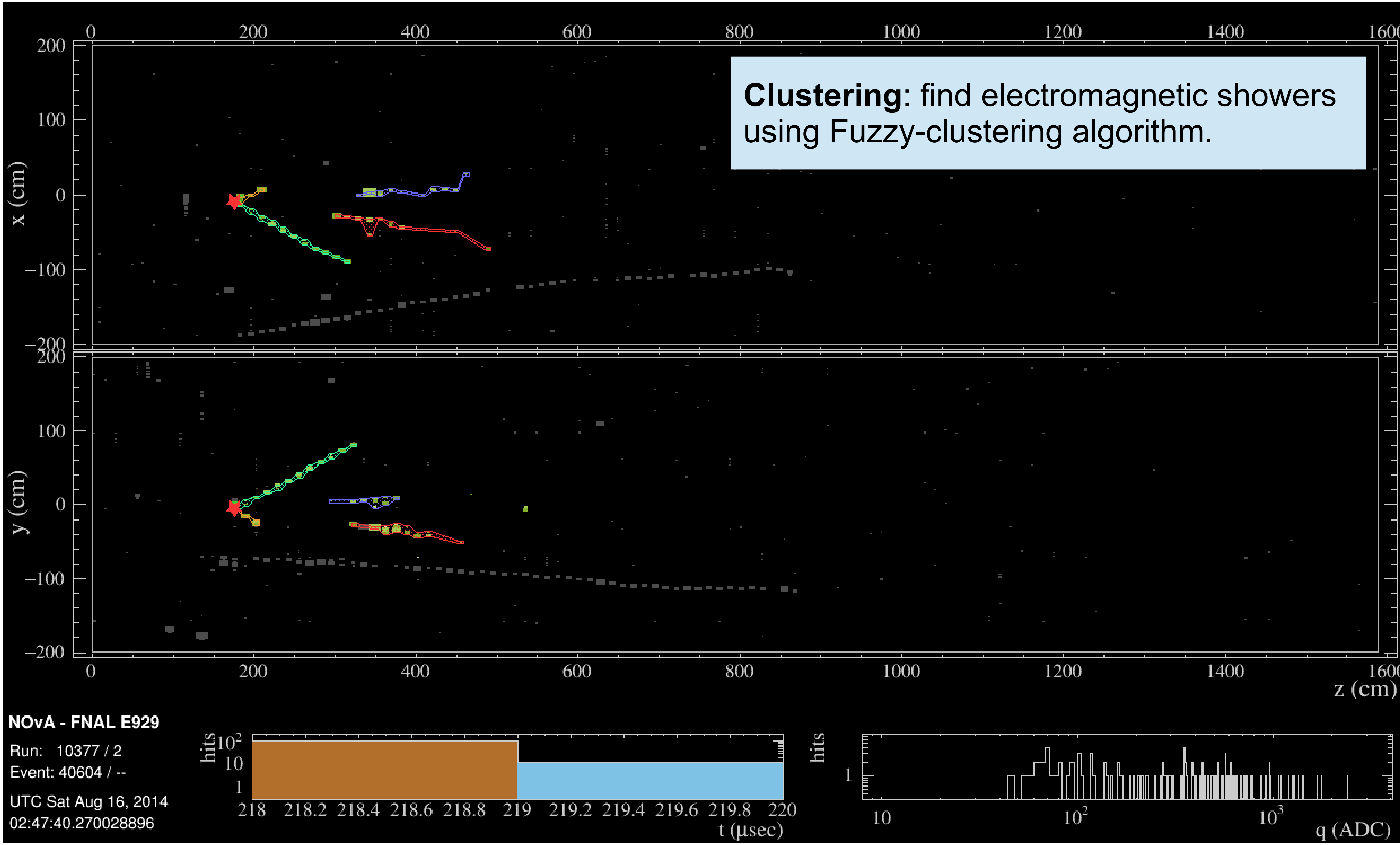
Reconstruction



Vertexing: find particle paths, and use the intersection of these paths to form vertex.

Reconstruction

Clustering: find electromagnetic showers using Fuzzy-clustering algorithm.



Analysis overview

- We select ν_e CC inclusive events to measure the inclusive cross section per nucleon in the energy range 1 to 3 GeV.

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

# of background events
Normalization determined from 2 sideband samples.

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

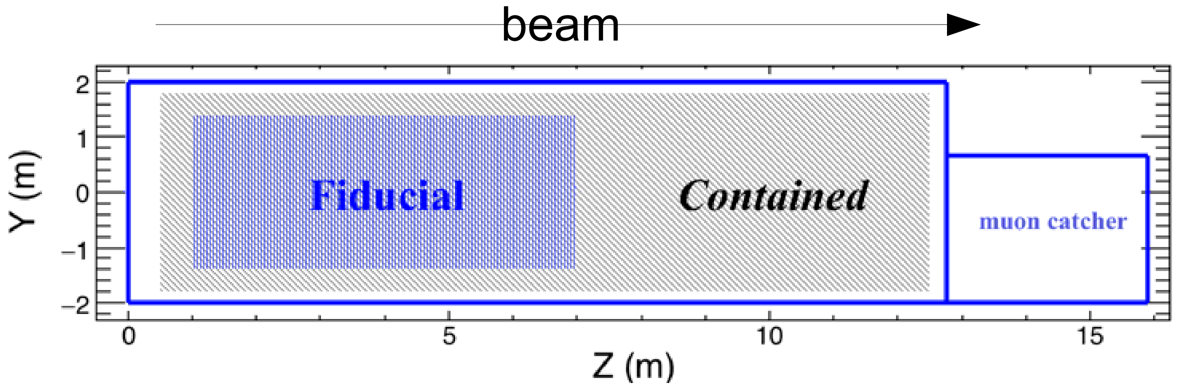
Integrated flux
Using external data from NA49 and MIPP to constrain the hadron production uncertainty.

# of nucleons

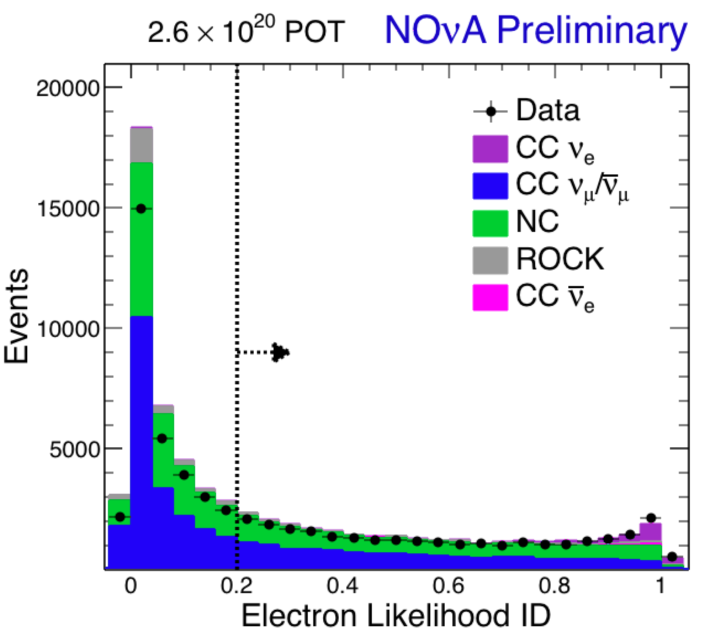
Event selection efficiency
Measured from GENIE MC events,
Using muon induced EM showers to validate the shower selection efficiencies in both data and MC.

Event selection — Preselection

- Fiducial cuts
  - $|V_x/V_y|<140cm$
  - $100<V_z<700cm$

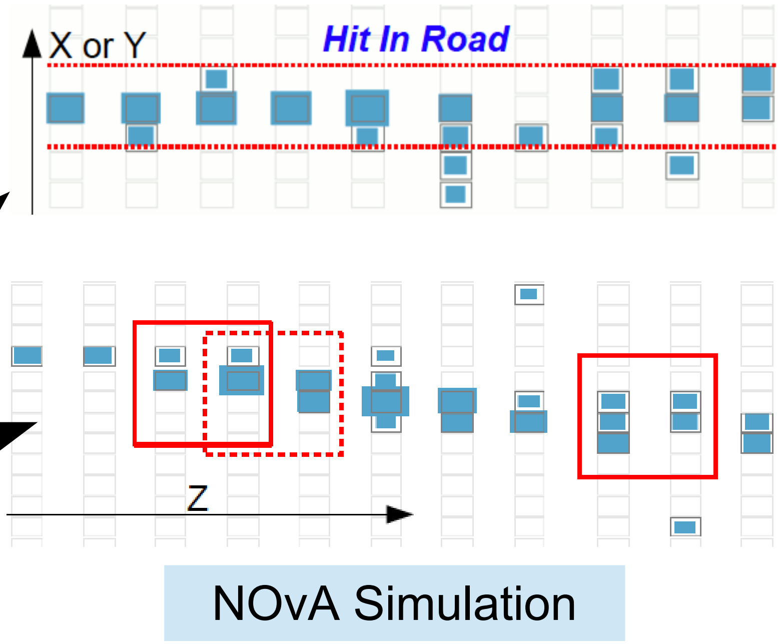


- Select contained EM shower with
  - 150 < shower length < 500cm
  - shower energy < 3.5GeV
  - Fraction of MIP hits < 0.35
  - EM likelihood ID (LID) > 0.2

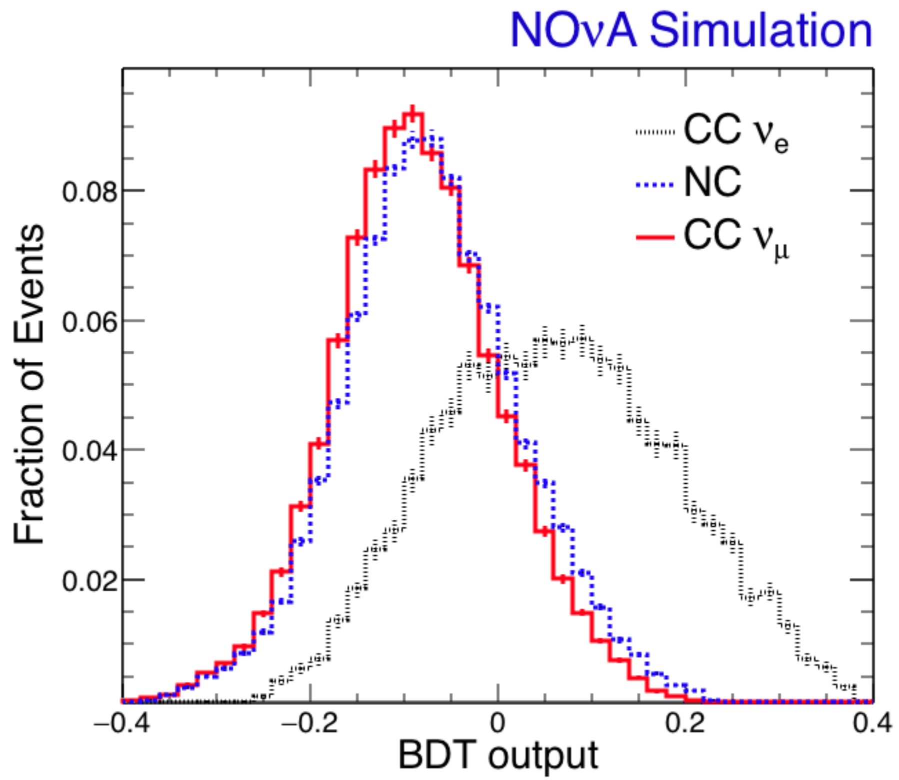


Event selection — Shower based PID

- 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.

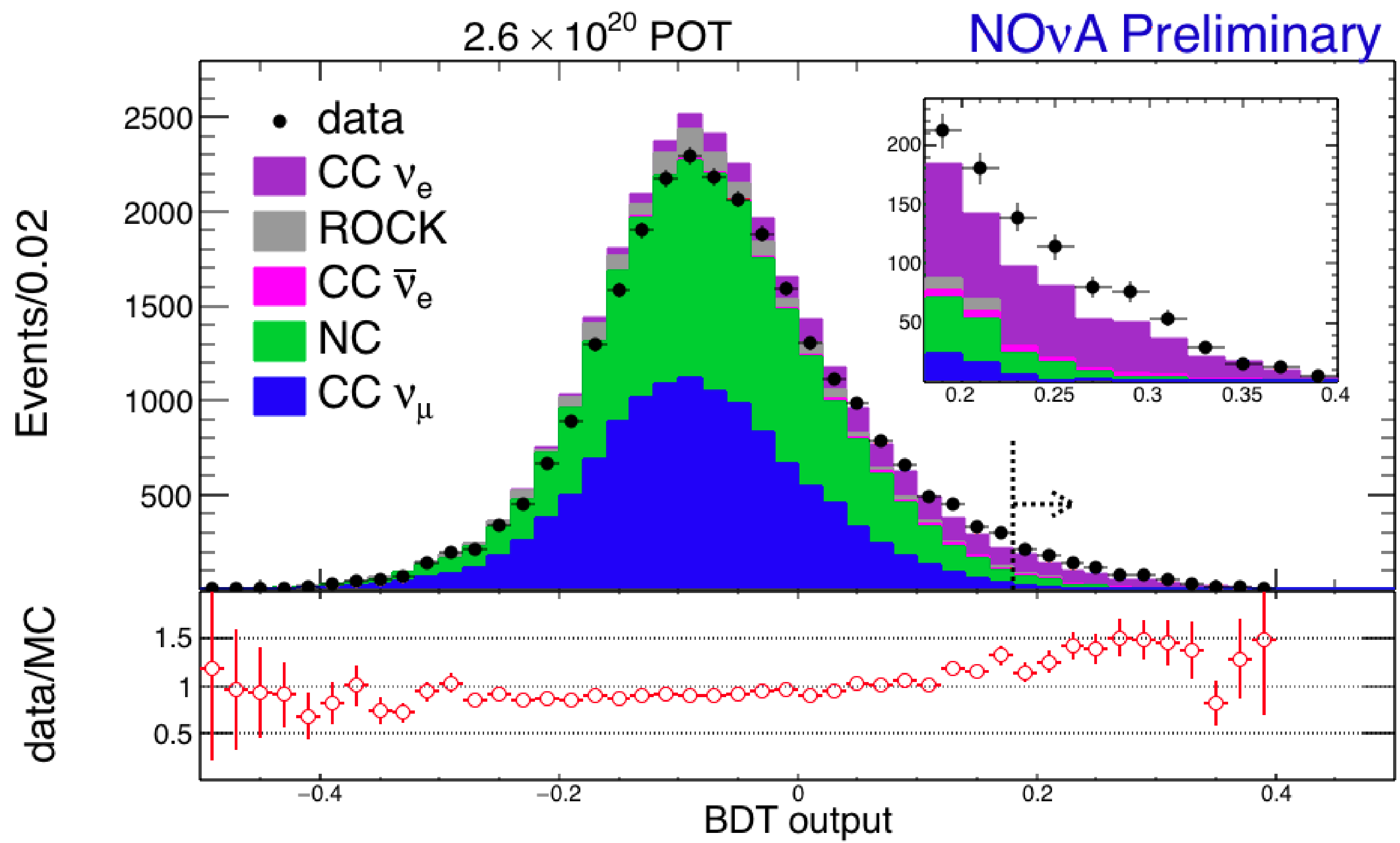


BDT output distributions



The shape distributions of BDT output for the ν_e CC signal and ν_μ CC and NC background after preselection.

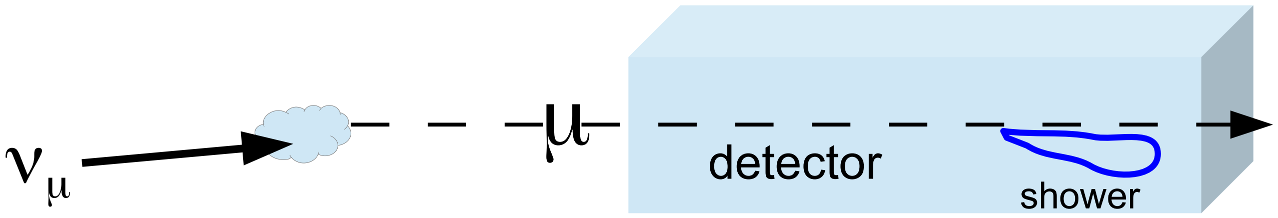
BDT output distributions



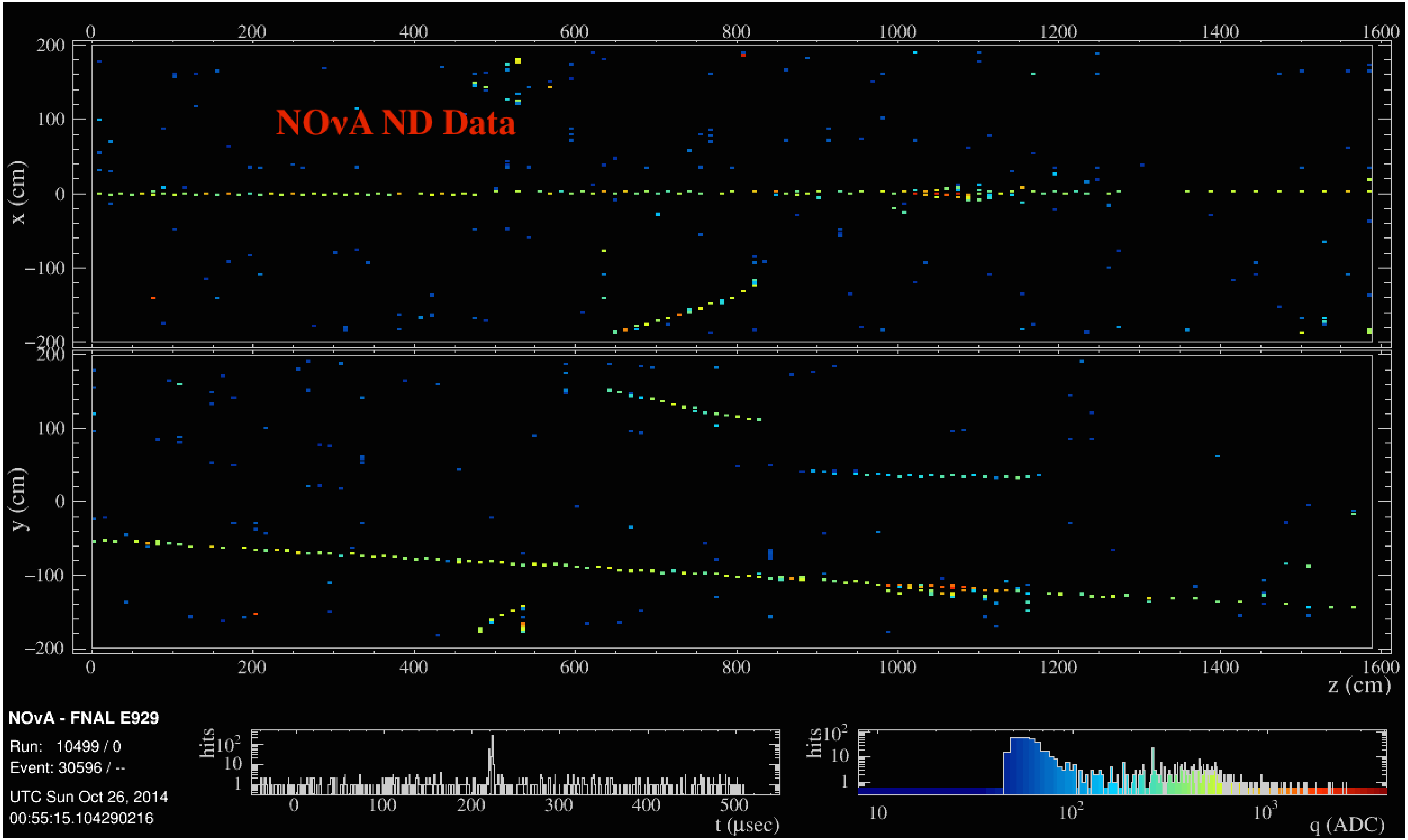
The BDT output distributions for data, signal and various backgrounds. All events are selected with preselection cuts.

Select EM showers from brem. muon

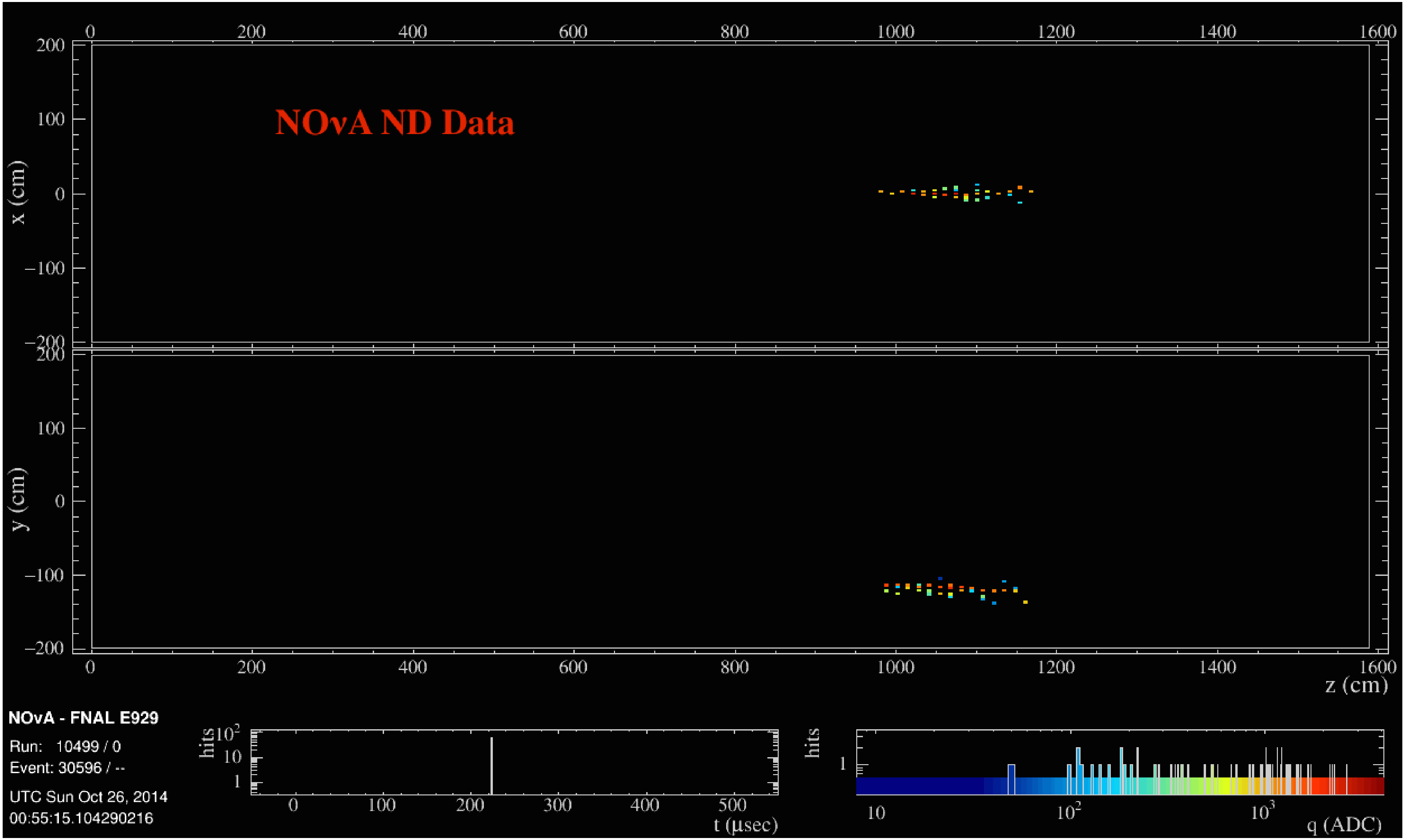
- Data-driven method to select EM showers to confirm the shower reconstruction and PID.
- We select EM showers from bremsstrahlung muons, which are produced from muon neutrino interactions in the rock upstream of the detector.



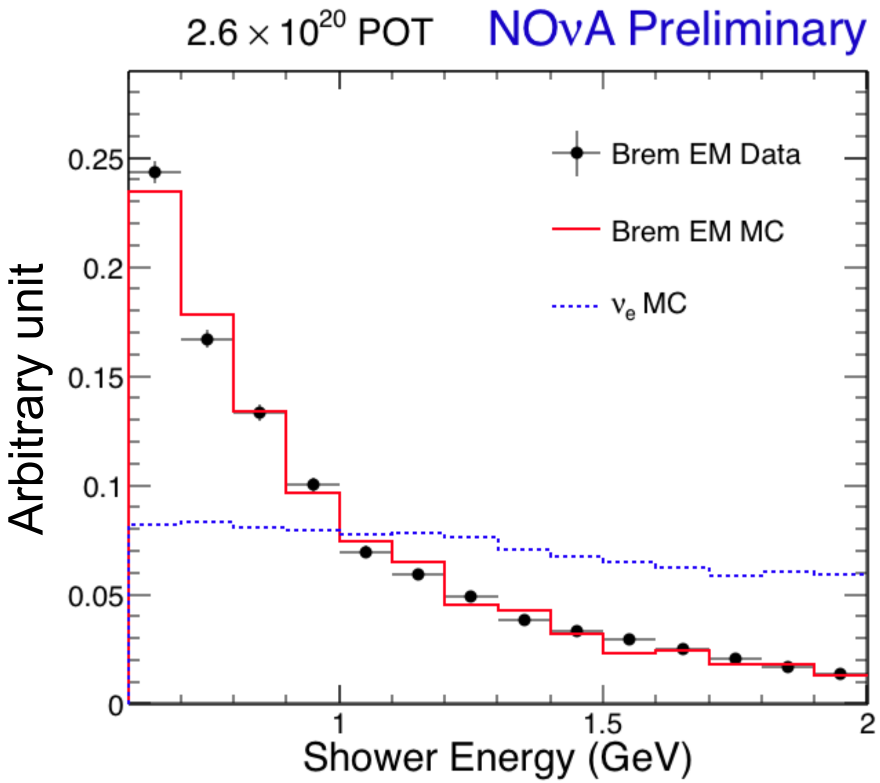
EM showers from brem. muon

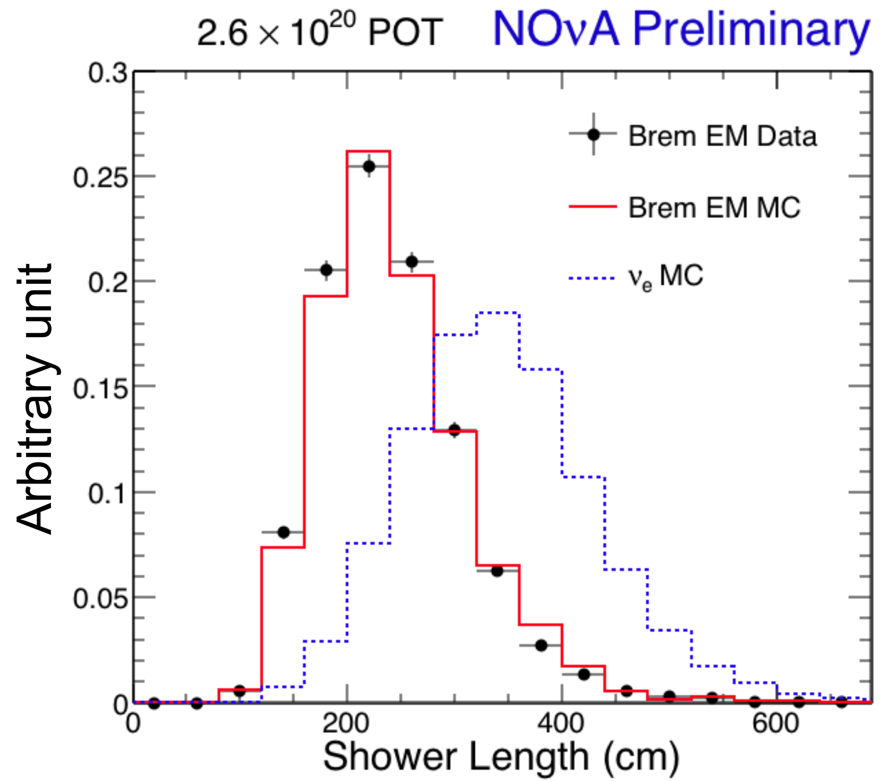


EM showers from brem. muon



Rock muon induced EM showers

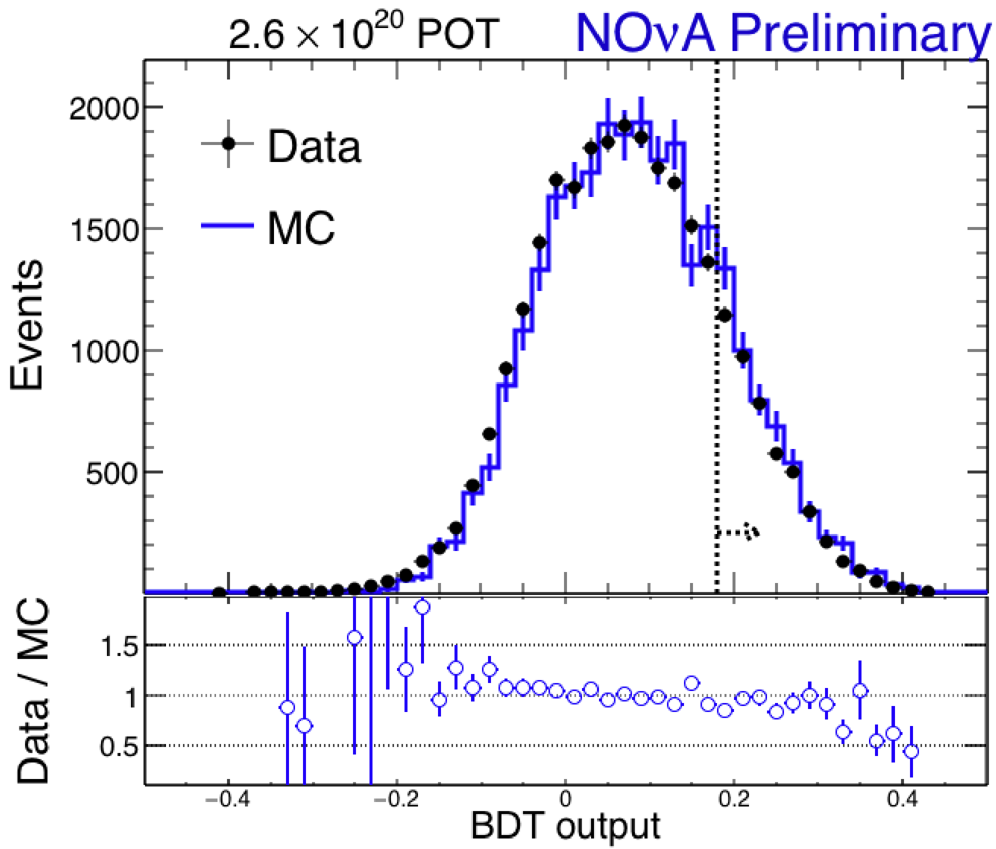




Distributions for shower energy and length from Brem. EM data and MC, and ν_e signal MC.

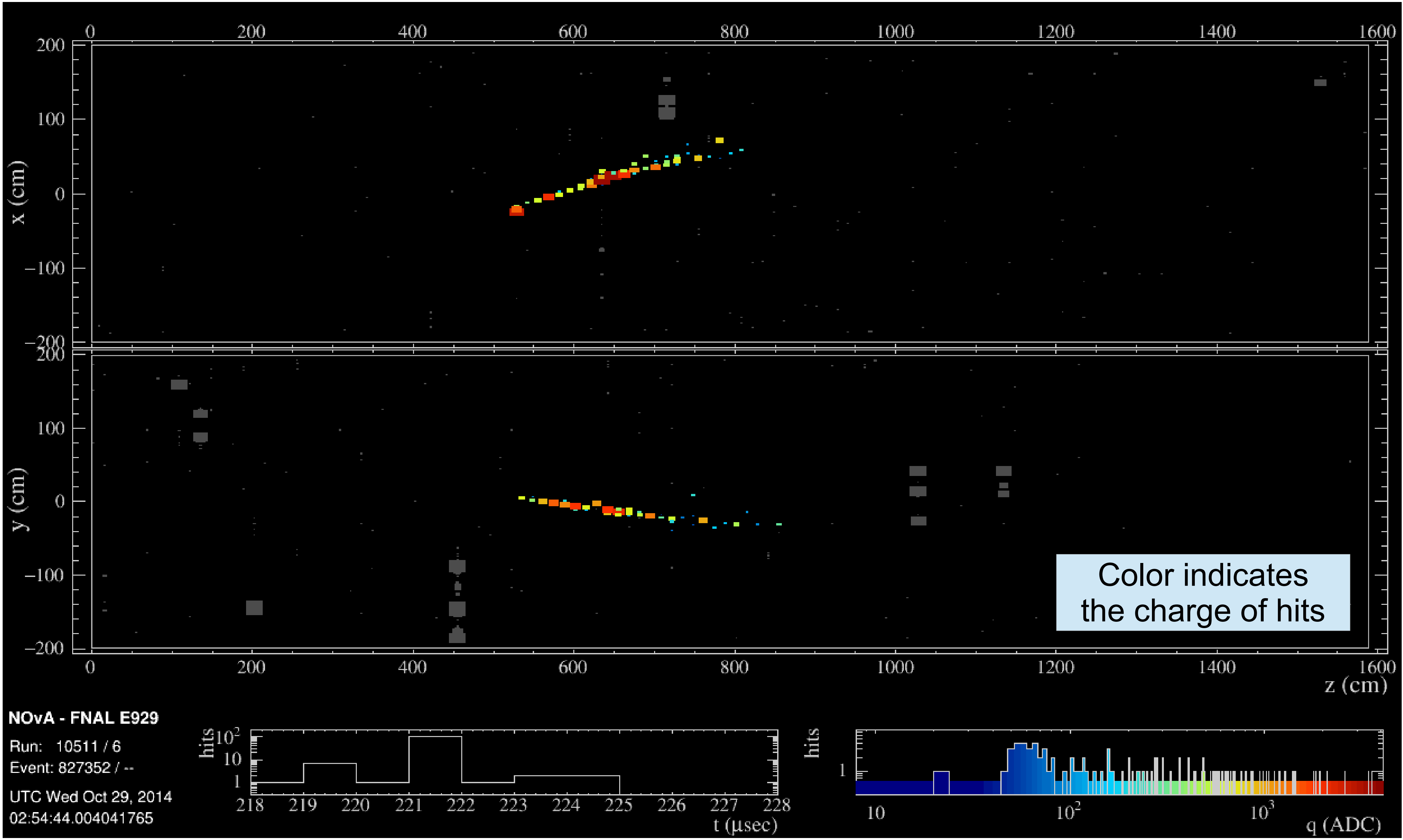
There is decent agreement between Brem. EM data and MC.
Brem. EM showers have similar shower properties as the ν_e signal events.

Rock muon induced EM showers

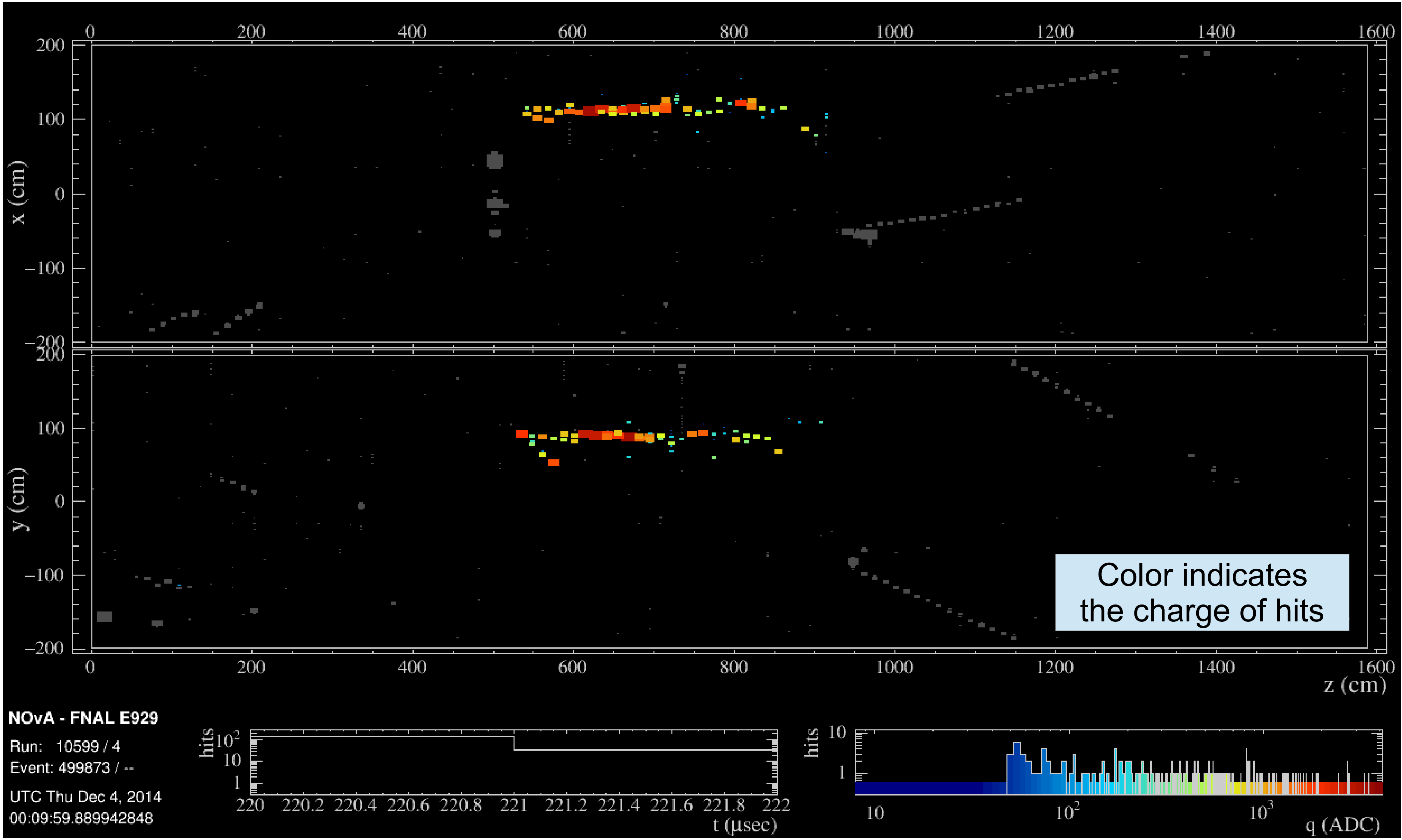


Excellent agreement between data and MC
for the shower-based PID.
MC is normalized to no. of data events.
All events are selected with preselection cuts.

Selected ν_e candidates in data



Selected ν_e candidates in data



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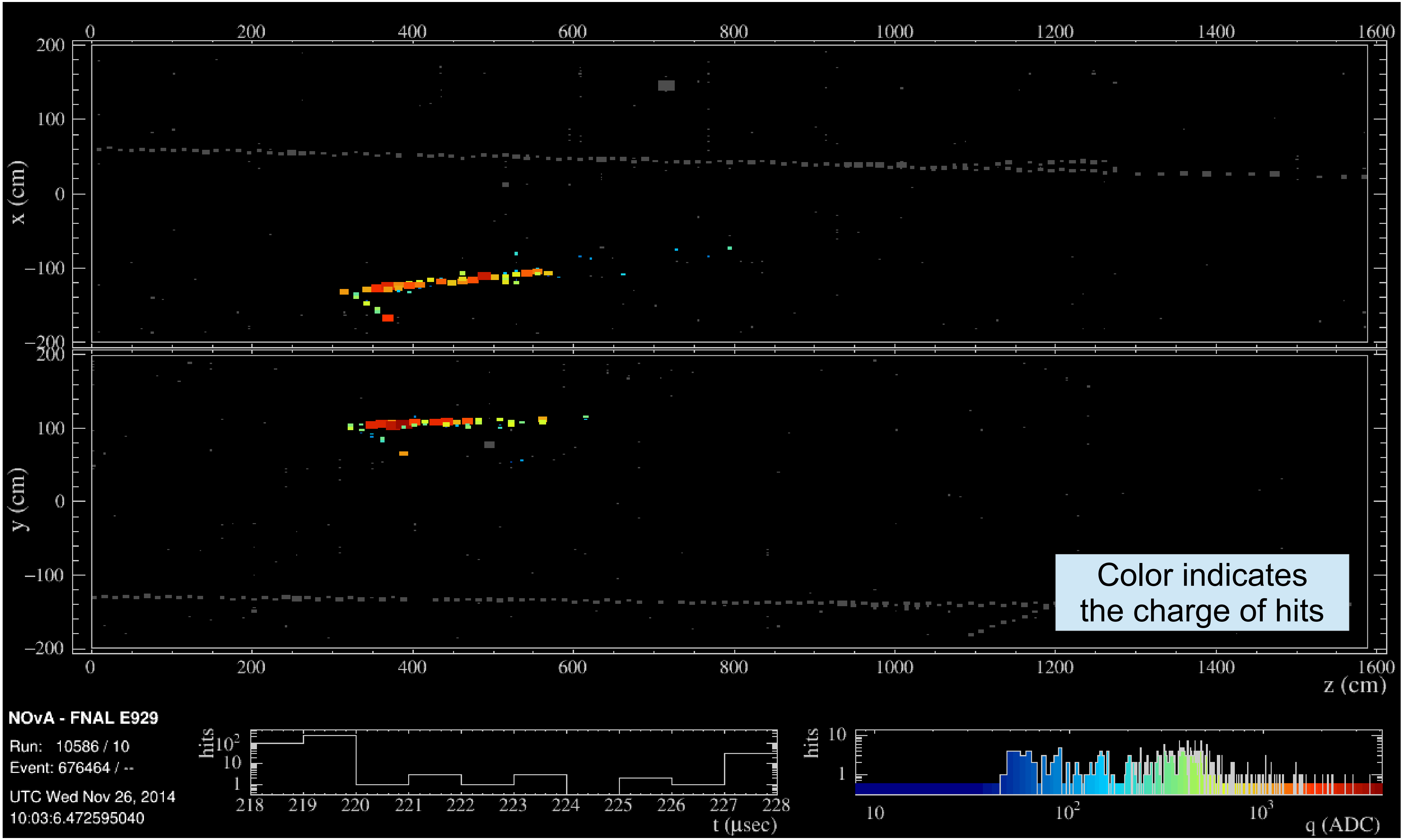
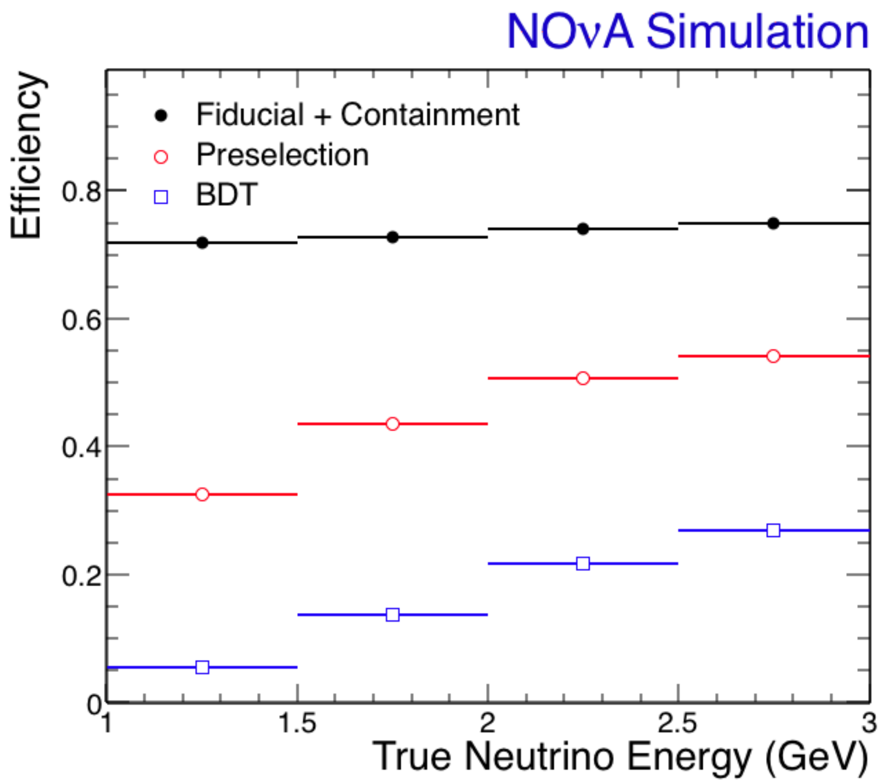


Event selection efficiency

- Defined as

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

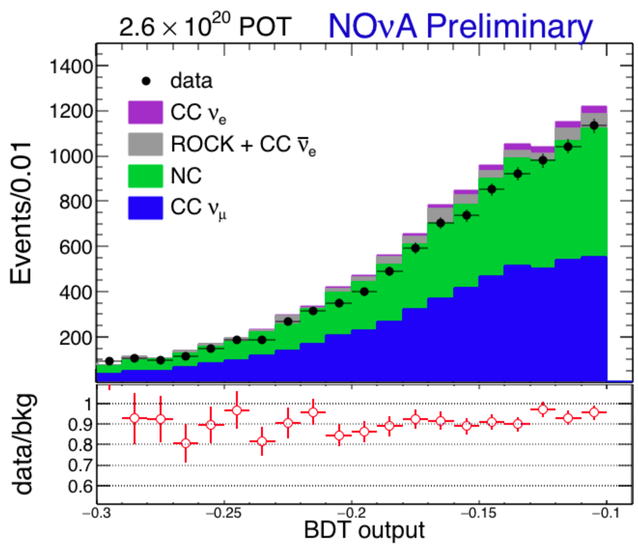
- The GENIE MC events are used to measure the efficiency.
- Shower selection is studied using the Brem. EM showers, 5% uncertainty is assigned based on the data and MC comparison.
- There is 5% uncertainty for the sample compositions of QE, DIS, and RES.
- For detector modeling, comparing GEANT4 physics lists QGSP, QGSC, and FTFP, no visible effect.



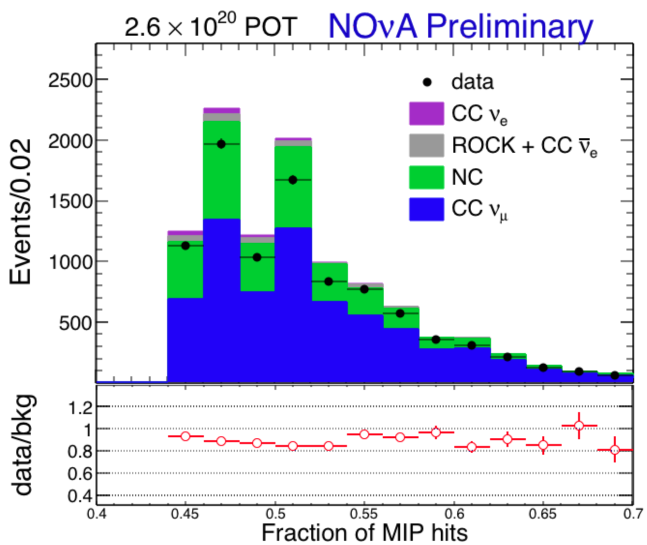
Background normalization

- We select 2 sideband samples to study the background normalization
  - Dominated by ν_μ CC and NC
  - Add p_e>1.2 GeV and cosθ>0.9 to select the events in the similar kinematic region as the sample in signal region

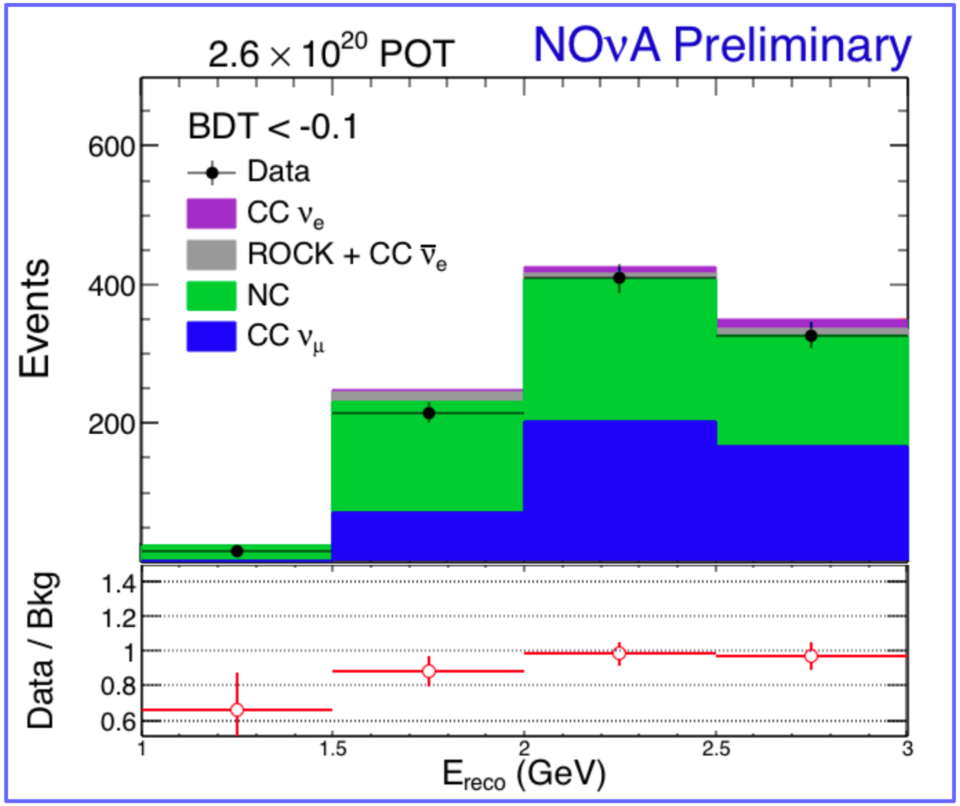
- Events with BDT < -0.1
  - Passed all Preselection cuts

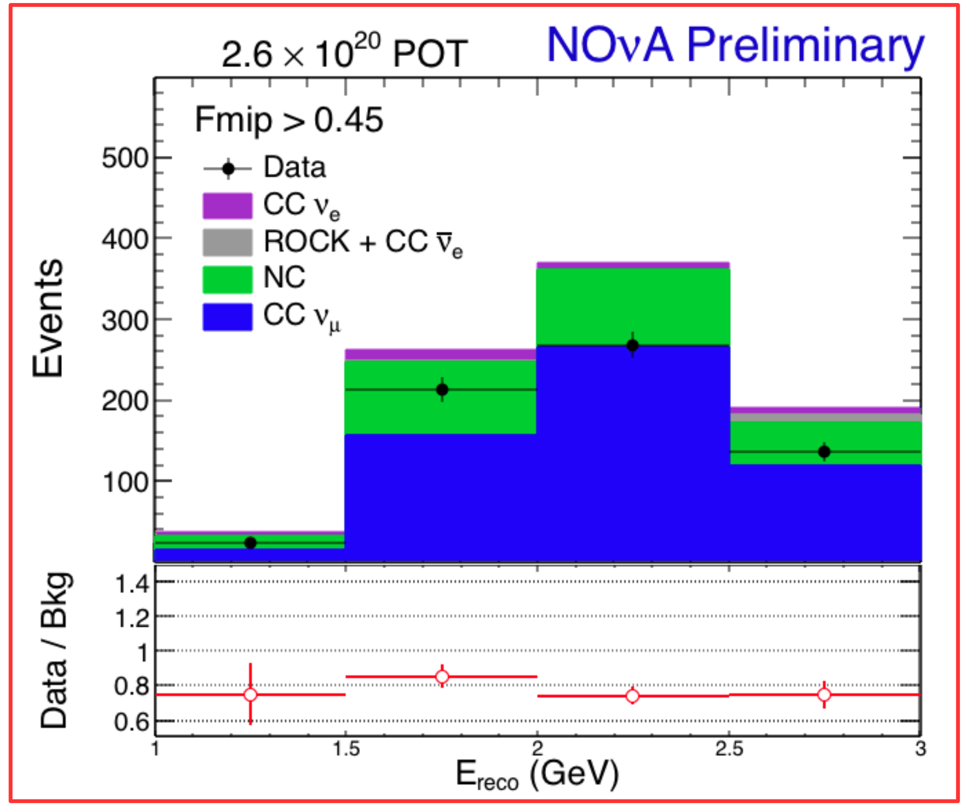


- Events with *Fmip* > 0.45
  - Passed all Preselection cuts except the *fraction of MIP hits*



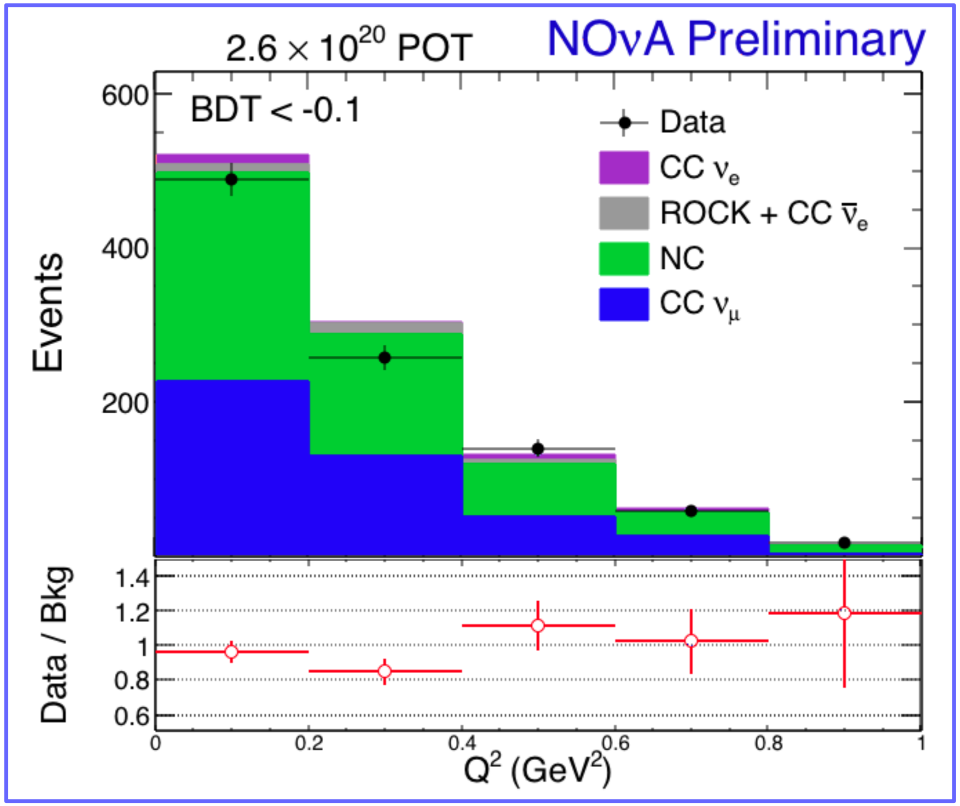
Background normalization

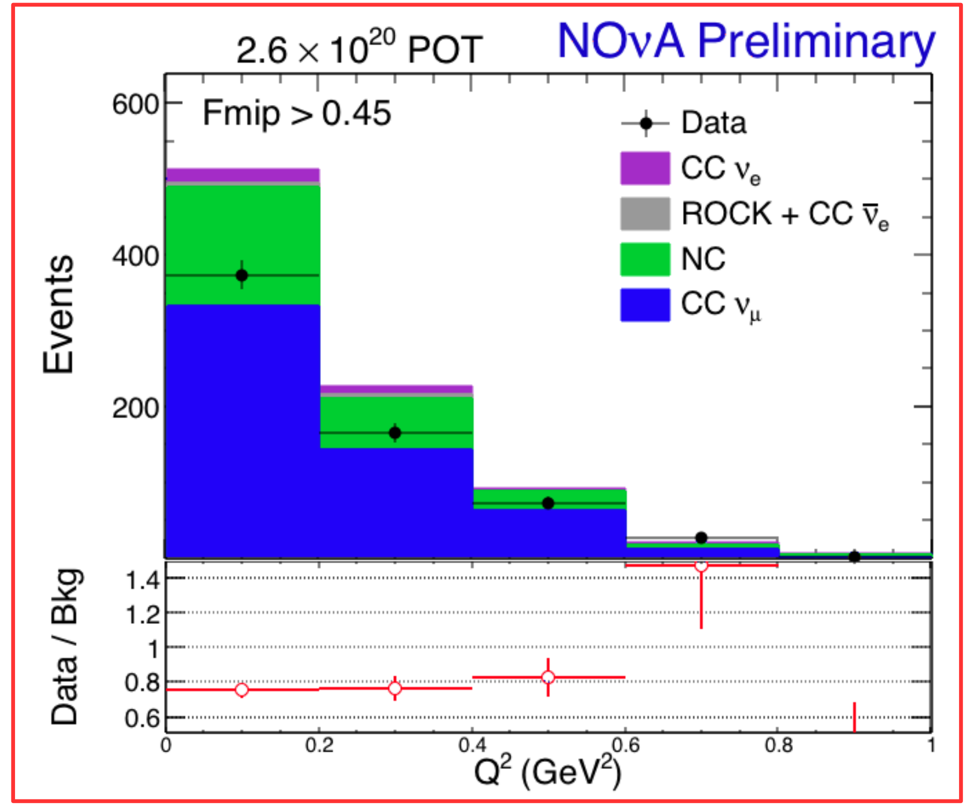




Reconstructed energy distributions from sideband samples.
Left plot for the main sideband sample with low BDT output,
which has similar ratio for ν_μ CC over NC as in signal region.
0.95±0.2 is used as the background normalization factor.

Background normalization

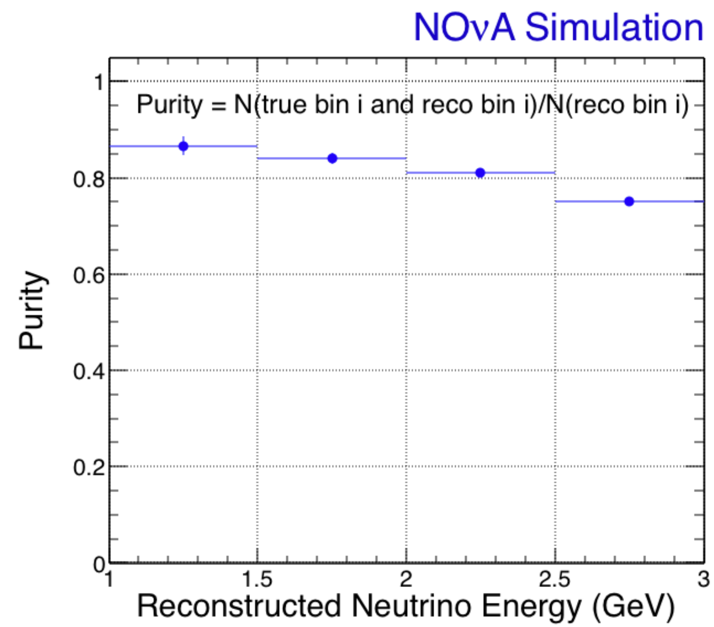


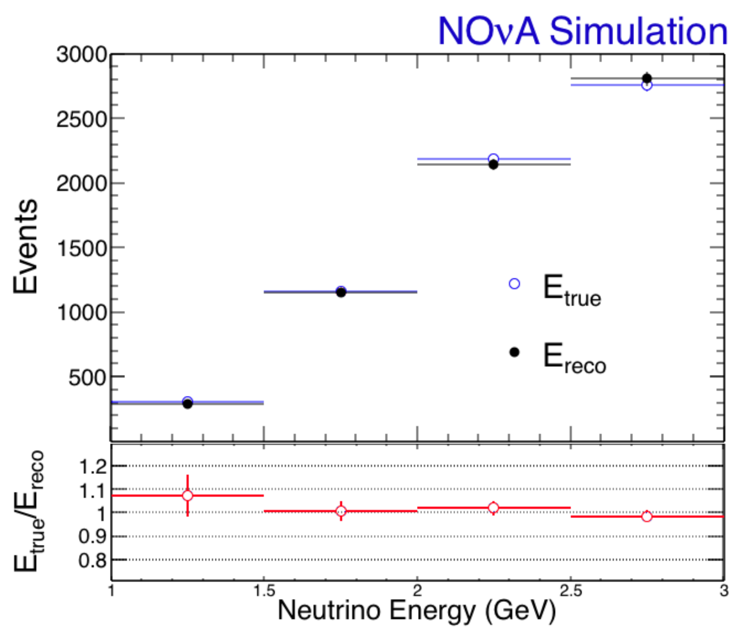


Invariant 4-momentum transfer squared distributions from sideband samples.
0.95±0.2 is used as the background normalization factor.
This 21% uncertainty will be propagated to be ~10% uncertainty on final cross section.

Unfolding

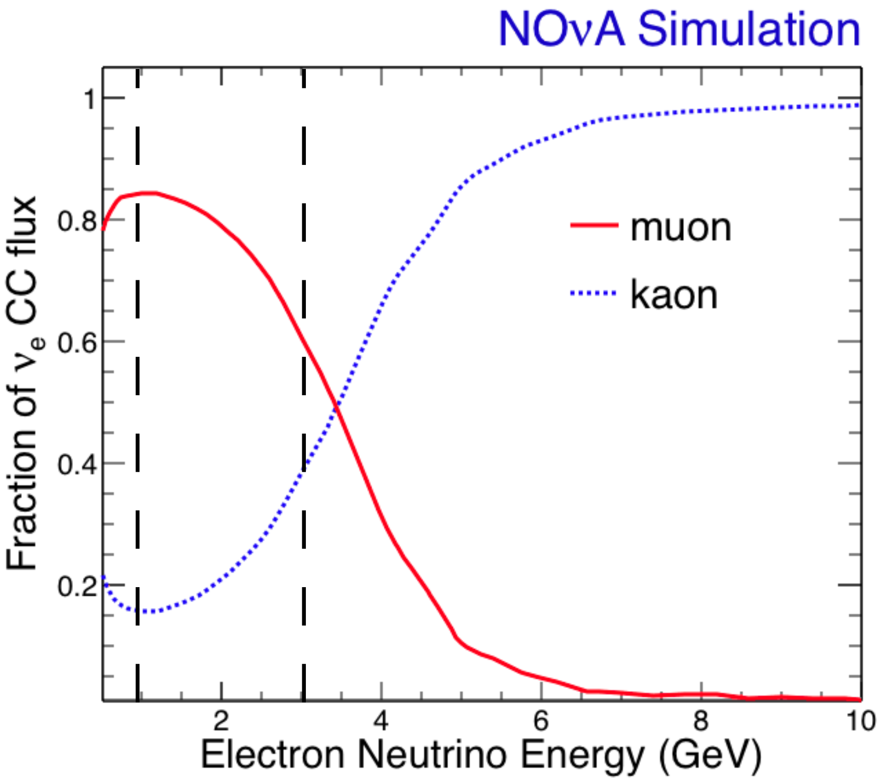
- Experimental effects lead to event migration outside a given bin at generated level. The magnitude of the effect depends on the bin size relative to the energy resolution.
- Given the good energy resolution (~5%), and large bin size (0.5GeV), we directly correct the reconstructed energy spectrum to match true.
- Ensemble test with 200 statistically independent ν_e samples are used to estimate the systematic uncertainty to be 4%.





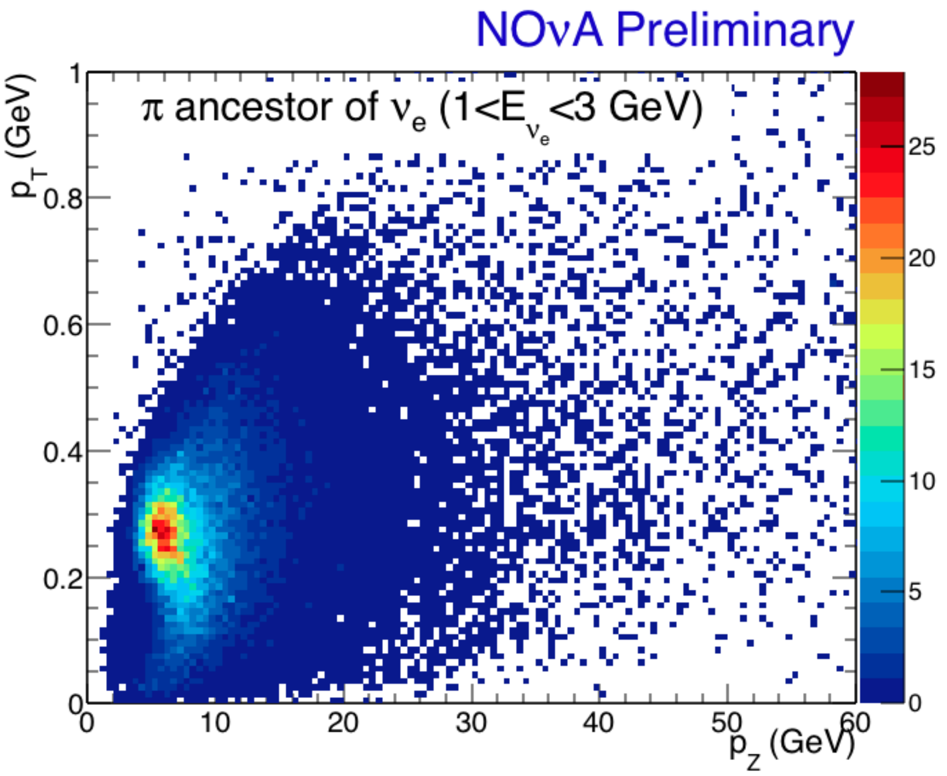
Electron neutrino flux

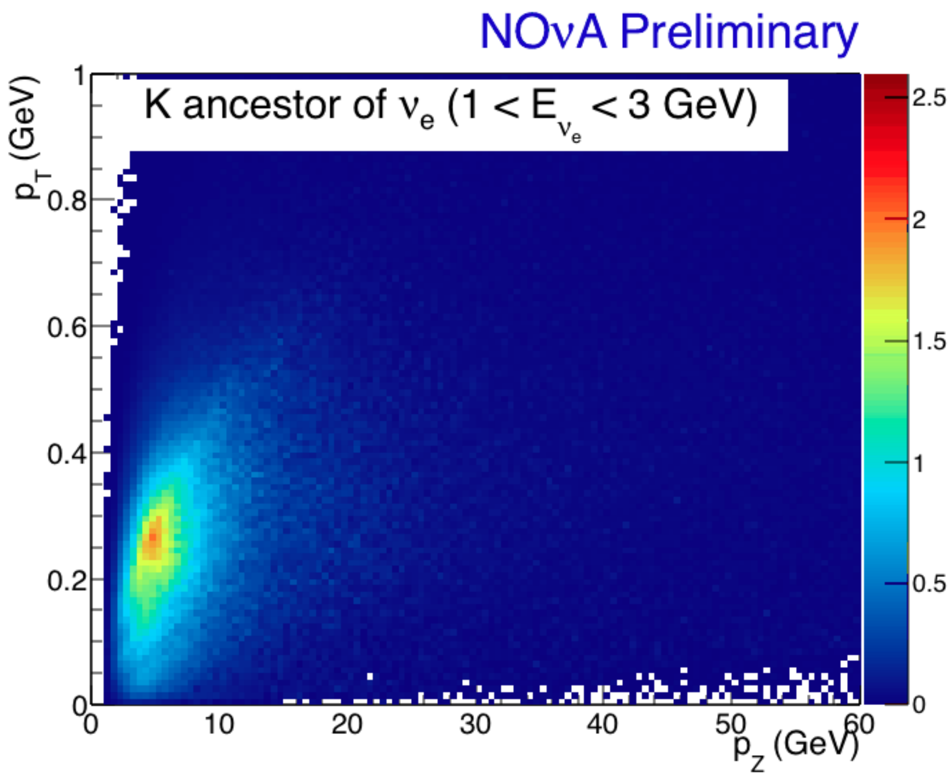
- The dominant contribution to electron neutrino flux in 1 – 3 GeV region is from muons and kaons. Kaon dominates in the high energy region.
- The fraction of neutrino flux from secondary mesons is ~55%.



$P \to \pi(\to\mu)/K \to \nu_e$	55%
$P \to X \to \pi(\to\mu)/K \to \nu_e$	45%

Electron neutrino flux





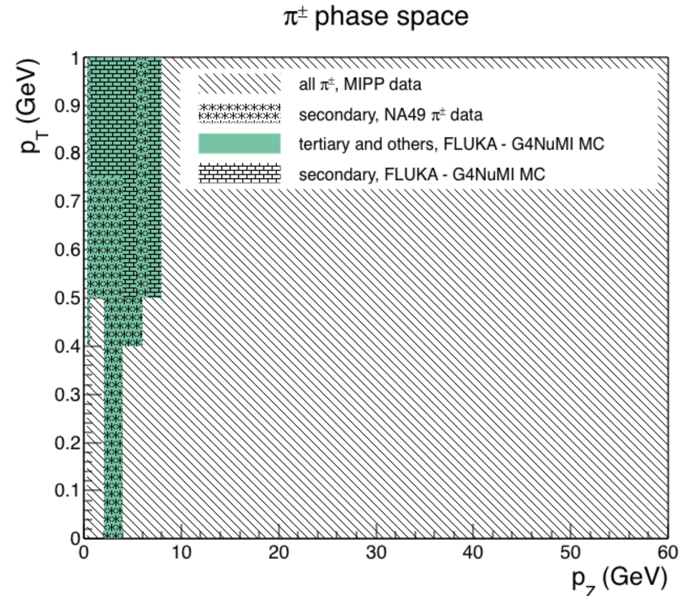
In 1—3 GeV energy region, our flux majorly locates within $p_T < 0.5$ GeV, $4 < p_Z < 15$ ($0.03 < x_F < 0.125$)

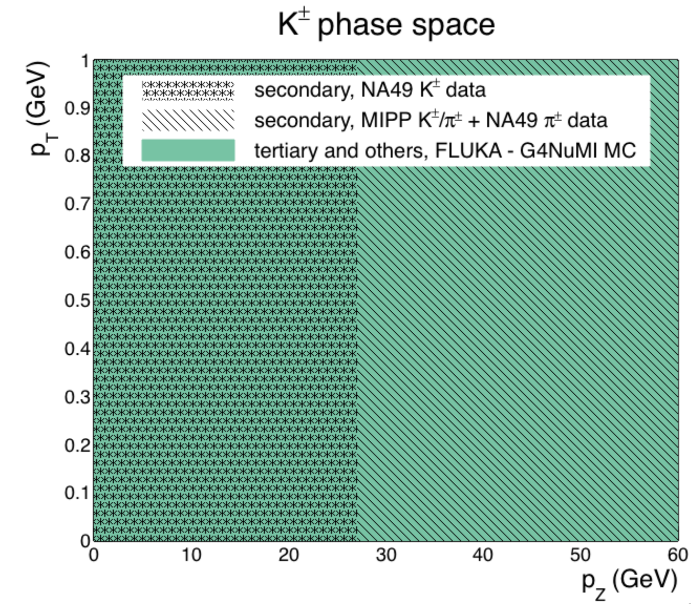
Flux uncertainty

- Two major uncertainties
  - Beam transport (5%)
    - horn current, horn positions, beam direction, beam spot size, and magnetic field
  - Hadron production
    - Using external data (see below table)
    - Conservative systematic uncertainty is assigned for the region not covered by data.

Data	p_T range (GeV)	p_z range (GeV)	Carbon Target	Proton energy (GeV)
NA49 pion	0 - 2	0 - 60	thin	158
NA49 kaon	0 - 1	0 - 27	thin	158
MIPP kaon/pion ratio	0 - 2	27 - 60	thin	120
MIPP pion	0 - 2	0 - 60	thick	120

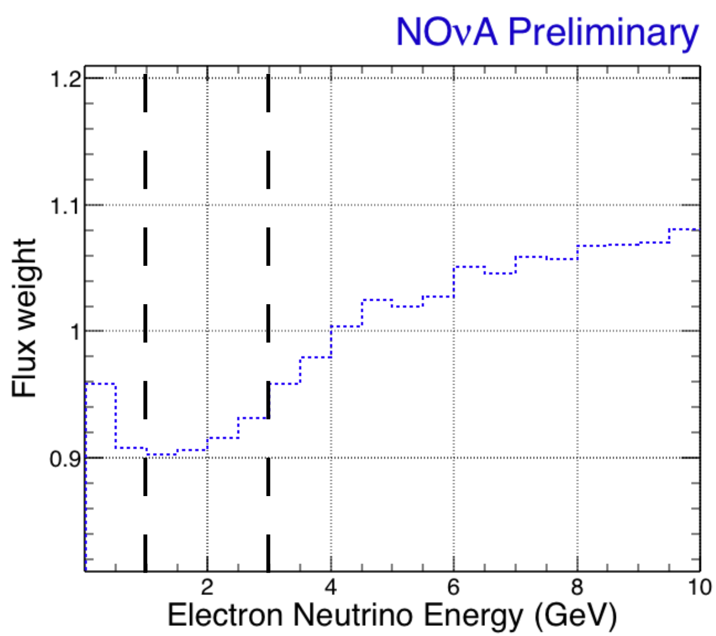
NA49 pion cross section: Eur. Phys. J. C49 (2007)
NA49 kaon cross section: G. Tinti Ph.D. Thesis
MIPP kaon/pion ratio: A. Lebedev Ph.D. Thesis
MIPP pion yield: Phys. Rev. D 90, 032001 (2014)

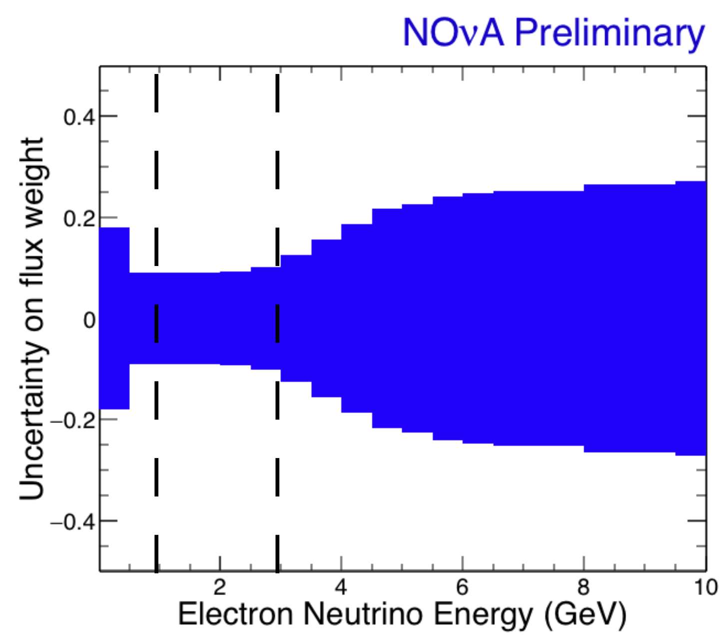




Hadron production uncertainty

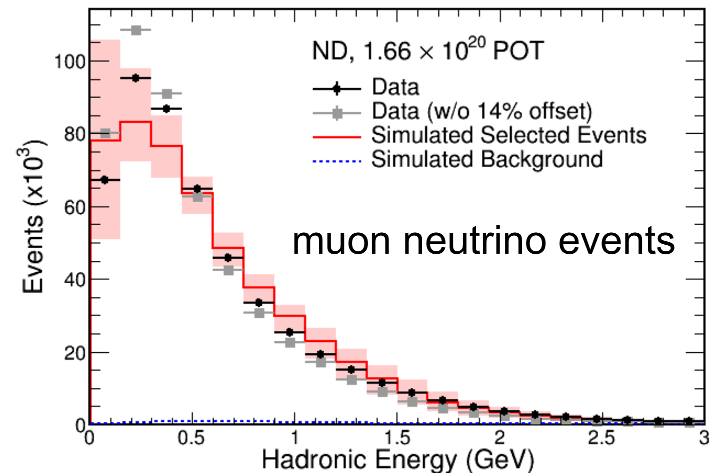
- We use the external data results from NA49 and MIPP experiments to constrain the hadron production uncertainty. The uncertainty of using the low energy NuMI beam target (MIPP) pion yield on the medium energy target (NOvA) has been taken into account.
- We reduce the electron neutrino flux by 5 – 10%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

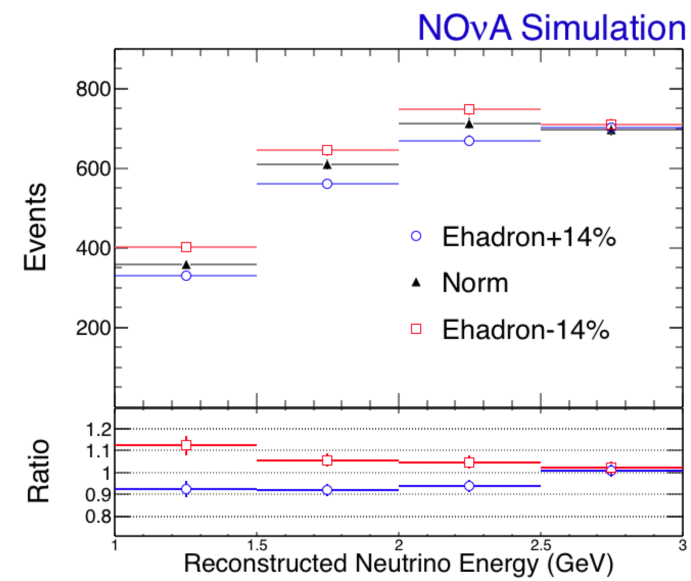




Hadron Energy

- There is 14% uncertainty for hadronic energy scale measured from muon neutrino samples.
- We shift the hadronic energy up and down 14% event-by-event to quantify the effect. There is 2 – 10% change on the total energy.
- We also cross-checked with selected nue events in sideband samples. It confirms the 14% uncertainty is large enough to cover existed difference between data and MC.

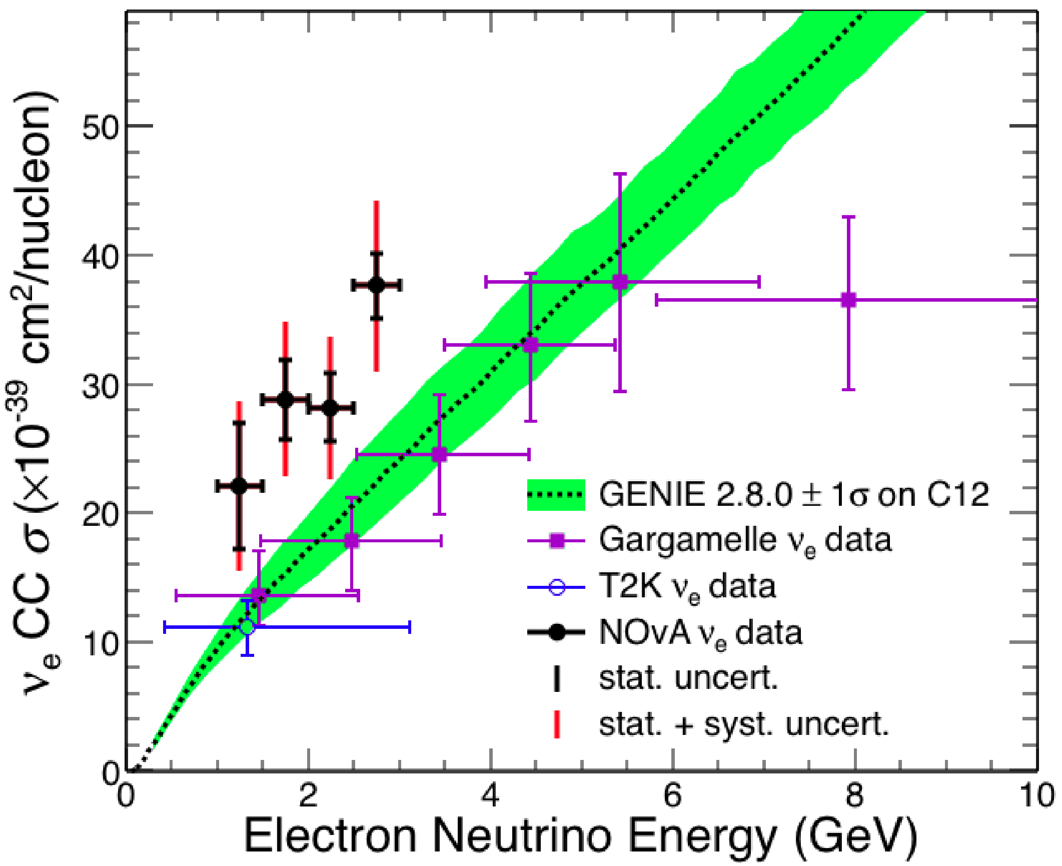




Uncertainties

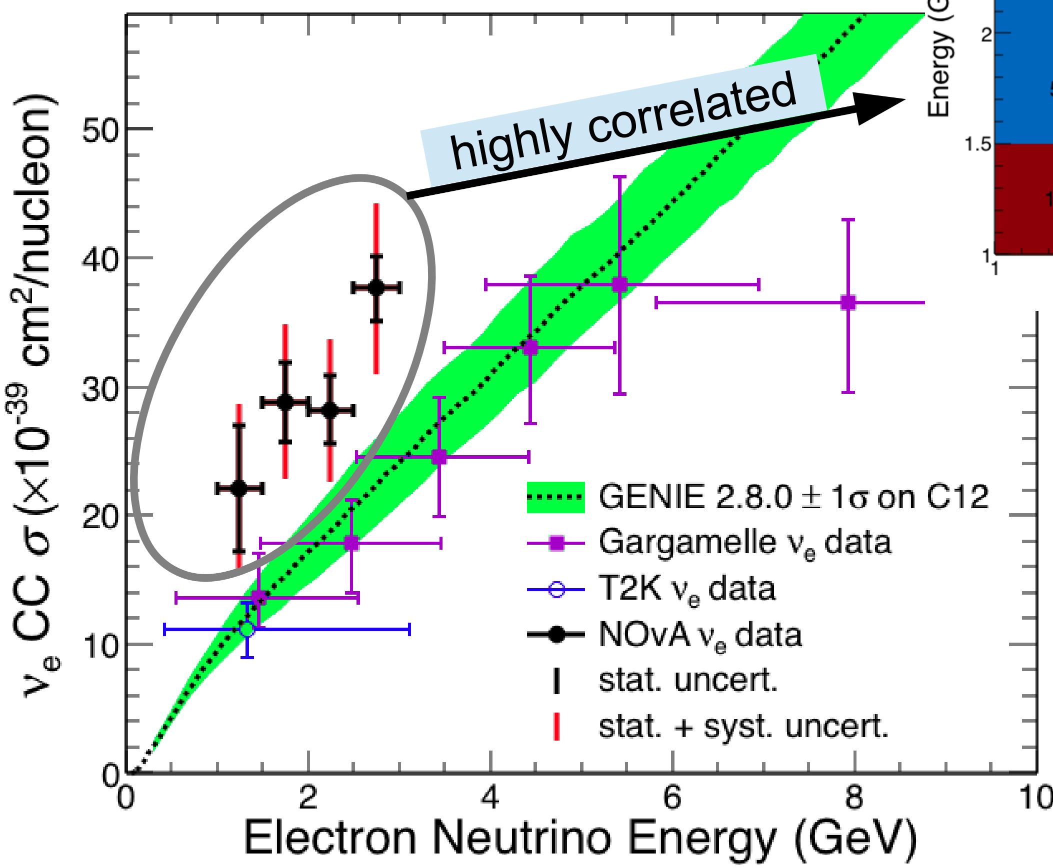
Uncertainty (%)	1 – 1.5 GeV	1.5 – 2 GeV	2 – 2.5 GeV	2.5 – 3 GeV
Flux	10	11	11	12
Background subtraction	11	8	9	6
Hadron energy	10	7	5	2
Event selection	7	7	7	7
Others	5	5	5	5
Total systematic	20	18	17	16
Statistical	22	11	9	7

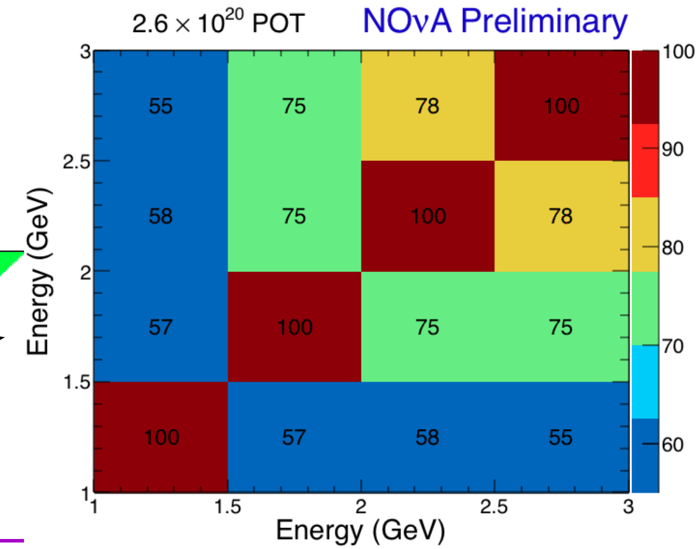
Results



Electron neutrino charged-current inclusive cross section as a function of electron neutrino energy.

Results





Electron neutrino charged-current inclusive cross section as a function of electron neutrino energy.

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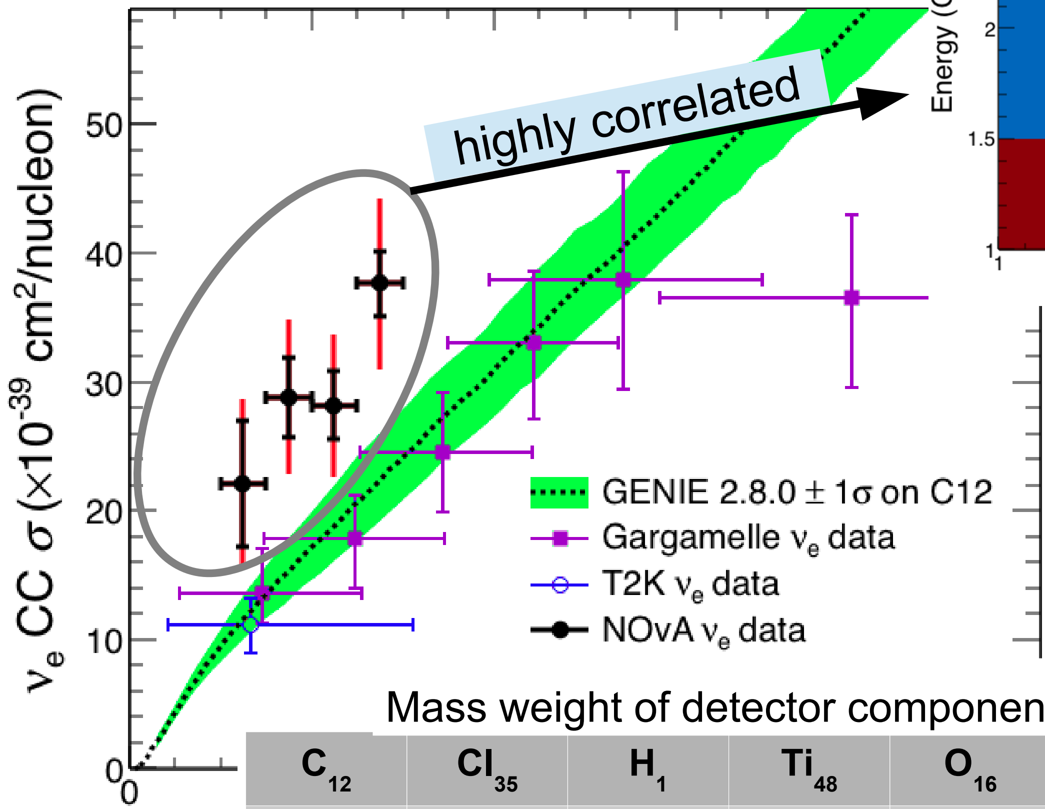
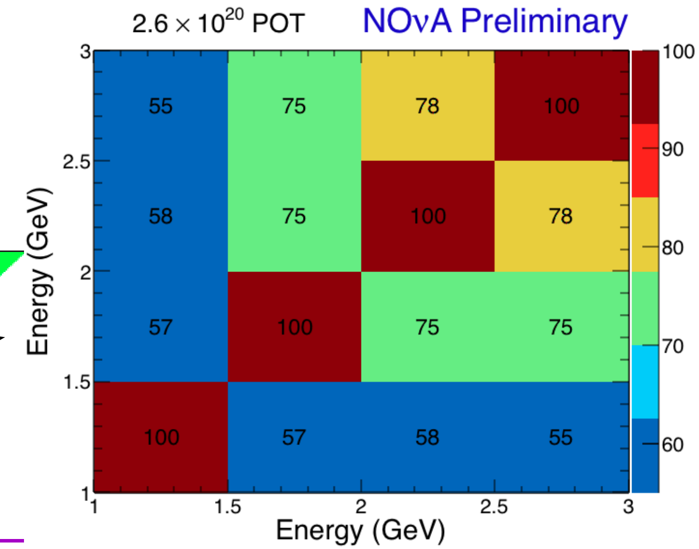


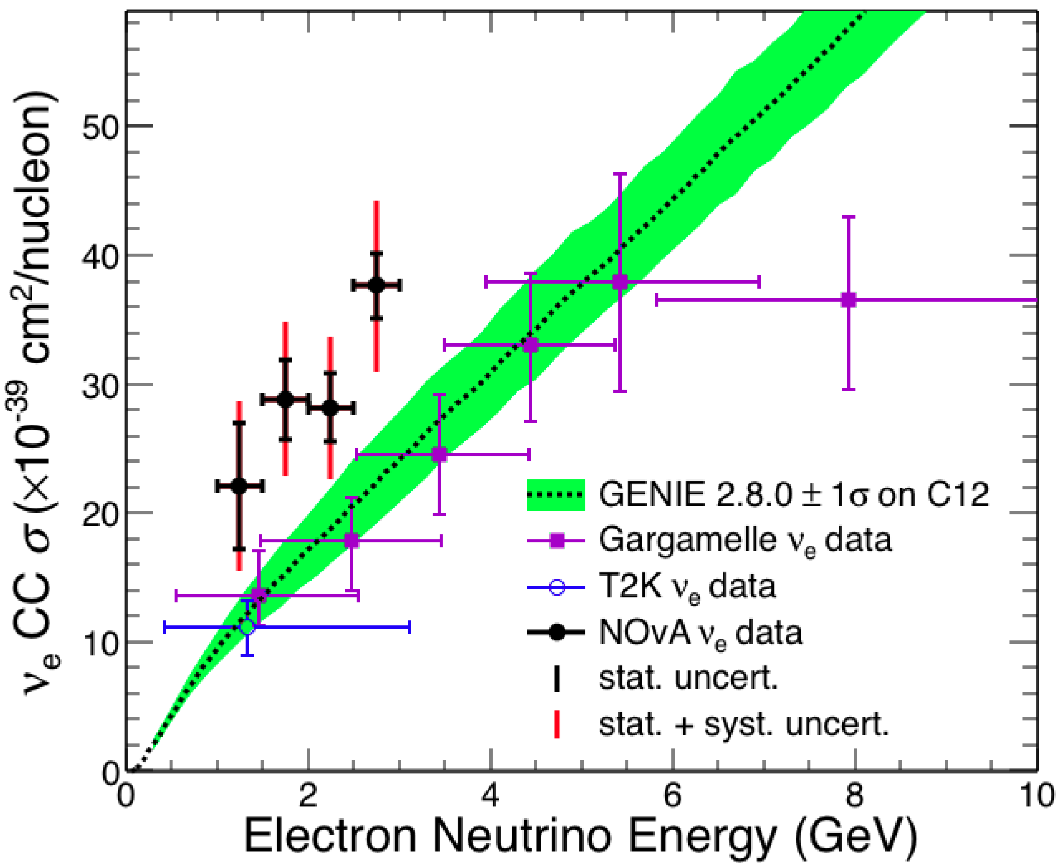


Mass weight of detector component:

C_{12}	Cl_{35}	H_1	Ti_{48}	O_{16}	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

From GENIE, the carbon-only prediction and the prediction for the actual composition of NOvA detector agree to within 2%.

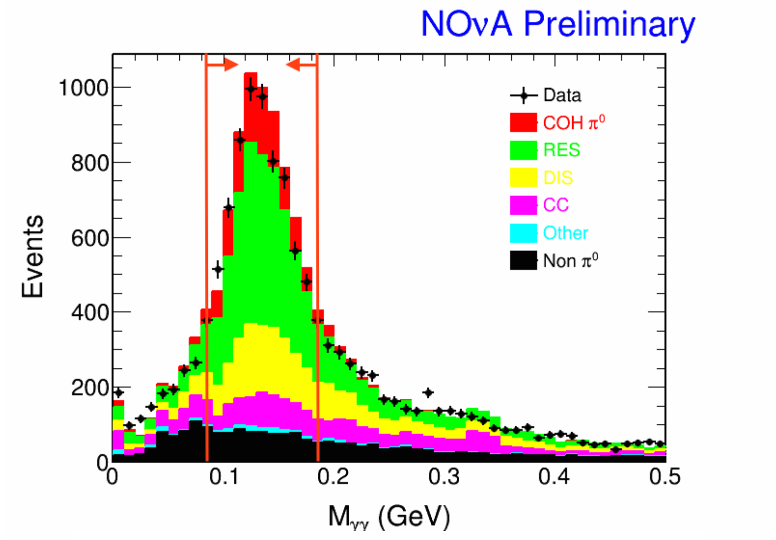
Results

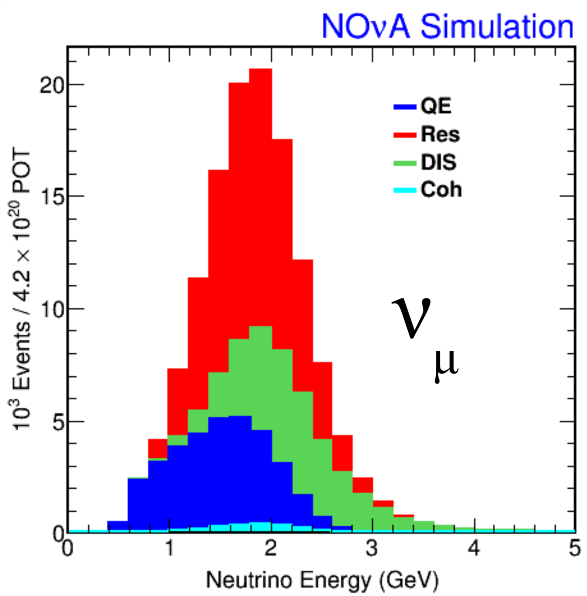


The measured per-nucleon cross section is >50% higher than GENIE prediction, but agree within 1.5σ.

Other measurements

- Other measurements under way
  - NC coherent π^0 production
  - ν_μ CC inclusive cross section
  - ν-e scattering
  - ν_μ CC π^0
  - Many more...





Summary

- We measured the electron neutrino charged-current inclusive cross section in 1 – 3 GeV energy region using data with an exposure of 2.6E20 POT. The paper is under preparation for publication.
- The measured per-nucleon cross section is >50% higher than GENIE prediction, but agree within 1.5σ. The results show the indication of increasing the cross section.
- Other measurements, including the inclusive cross section for muon neutrino are under way.

Back-up

Neutrino mixing matrix and mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Atmospheric and accelerator neutrino:

$$\sin^2\theta_{23} = 0.42^{+0.08}_{-0.03}, \quad \Delta m^2_{31} \approx \Delta m^2_{32} = 2.35^{+0.12}_{-0.09} \times 10^{-3} \ eV^2$$

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- Solar and reactor neutrino:

$$\sin^2\theta_{12} = 0.312^{+0.018}_{-0.015}, \quad \Delta m^2_{21} = 7.58^{+0.22}_{-0.26} \times 10^{-5} \ eV^2$$

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- Midterm:

$$\sin^2\theta_{13}=0.092\pm0.0016(stat.)\pm0.005(syst.)$$ (DayaBay)

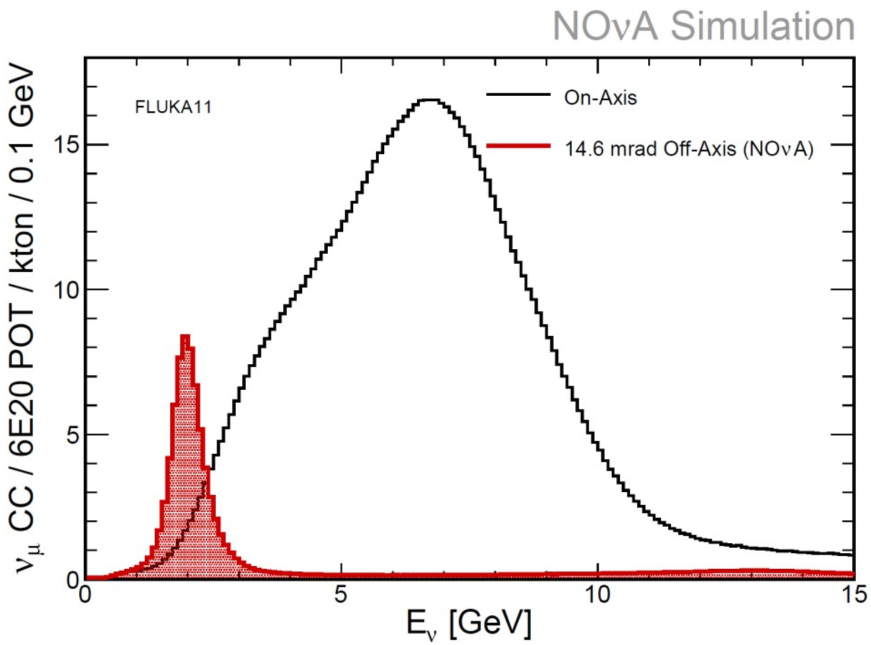
$$\sin^2\theta_{13}=0.140^{+0.038}_{-0.032}\quad\left(0.170^{+0.045}_{-0.037}\right)$$ (T2K)

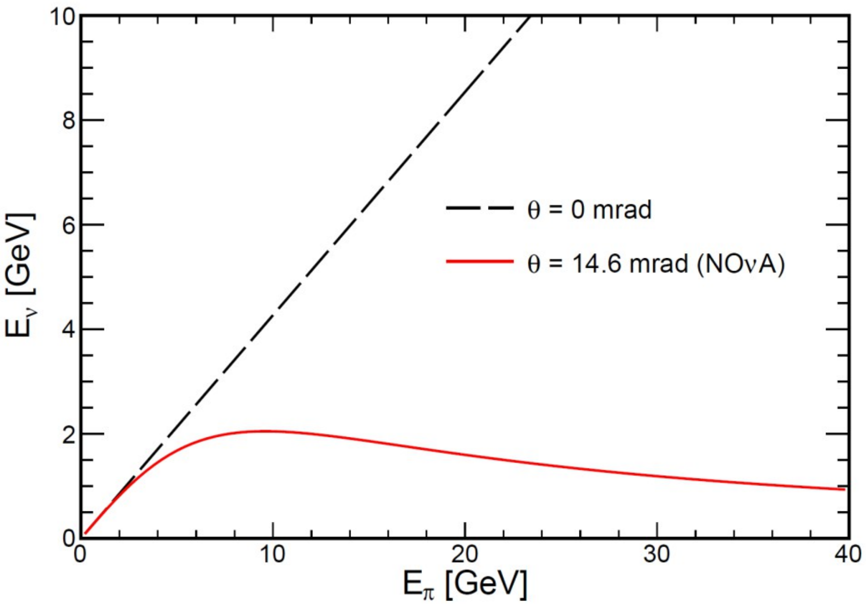
CP violation phase δ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

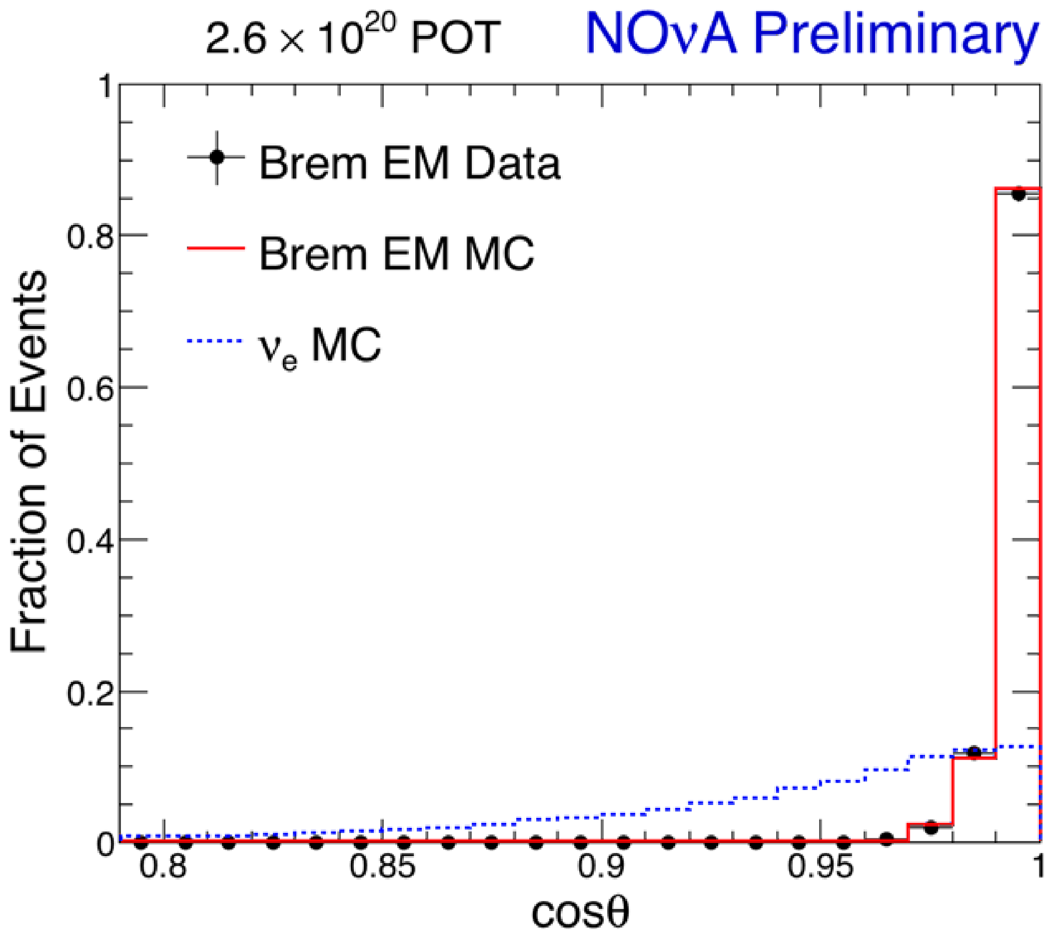
- The neutrino mixing parameter δ is unknown.
- Neutrino oscillations are likely to play important role in future CP studies, as a dynamically-generated matter-antimatter asymmetry for the universe requires additional sources of CP violation beyond the observations in quark sector of Standard Model.

Off-axis beam

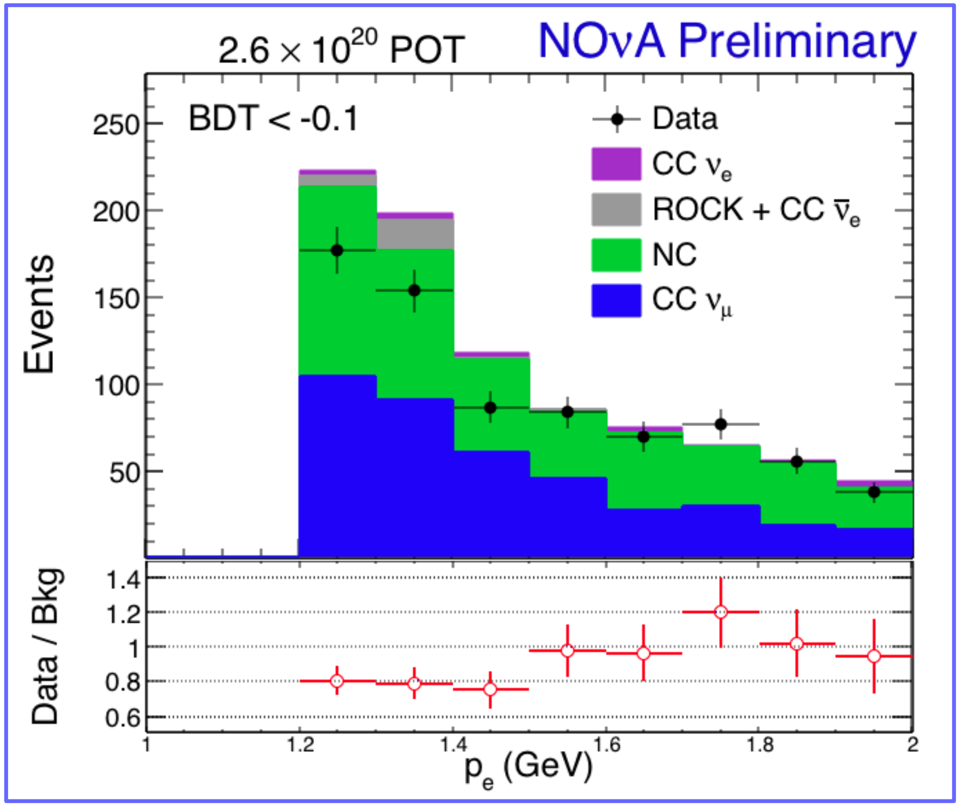


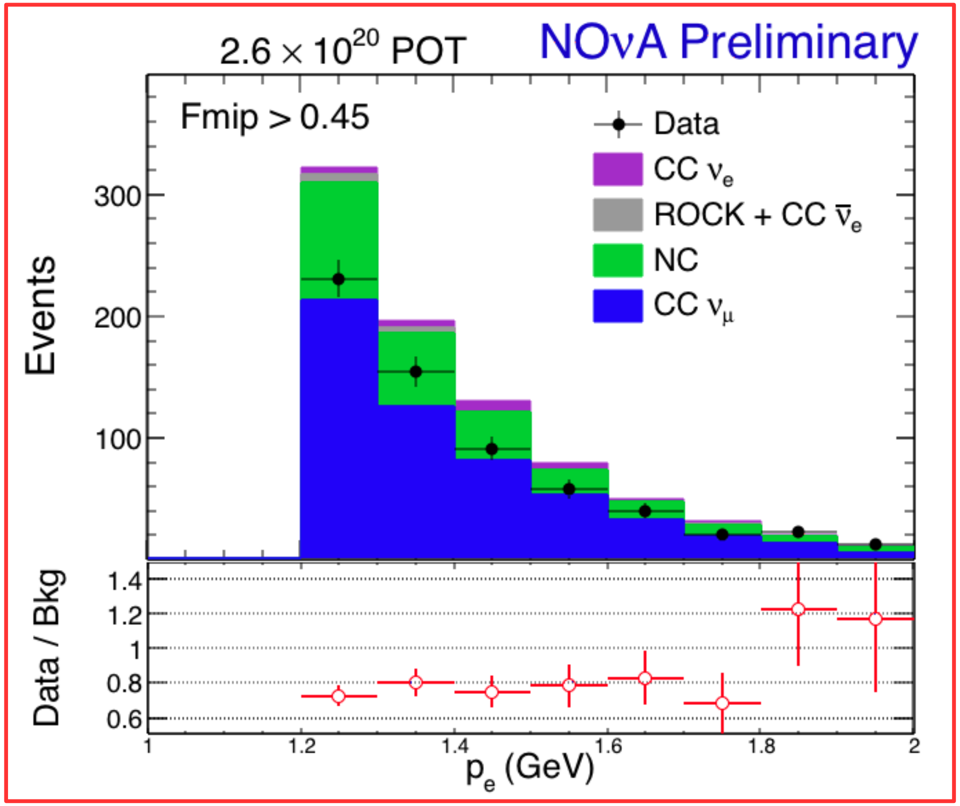


Shower angle



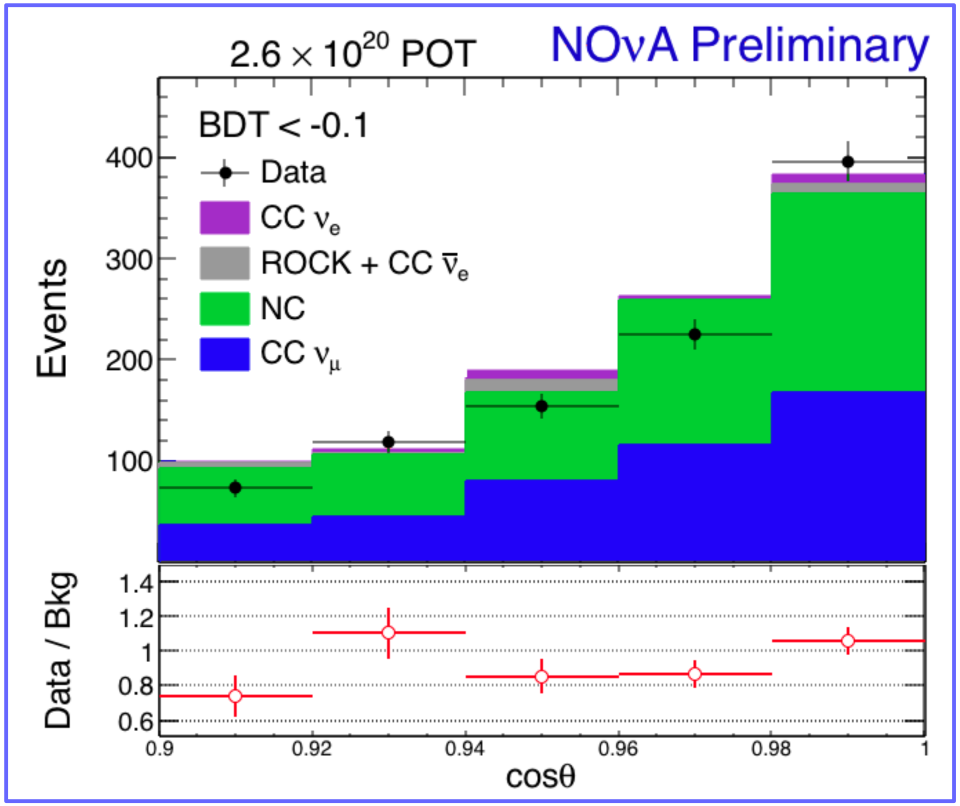
Background normalization

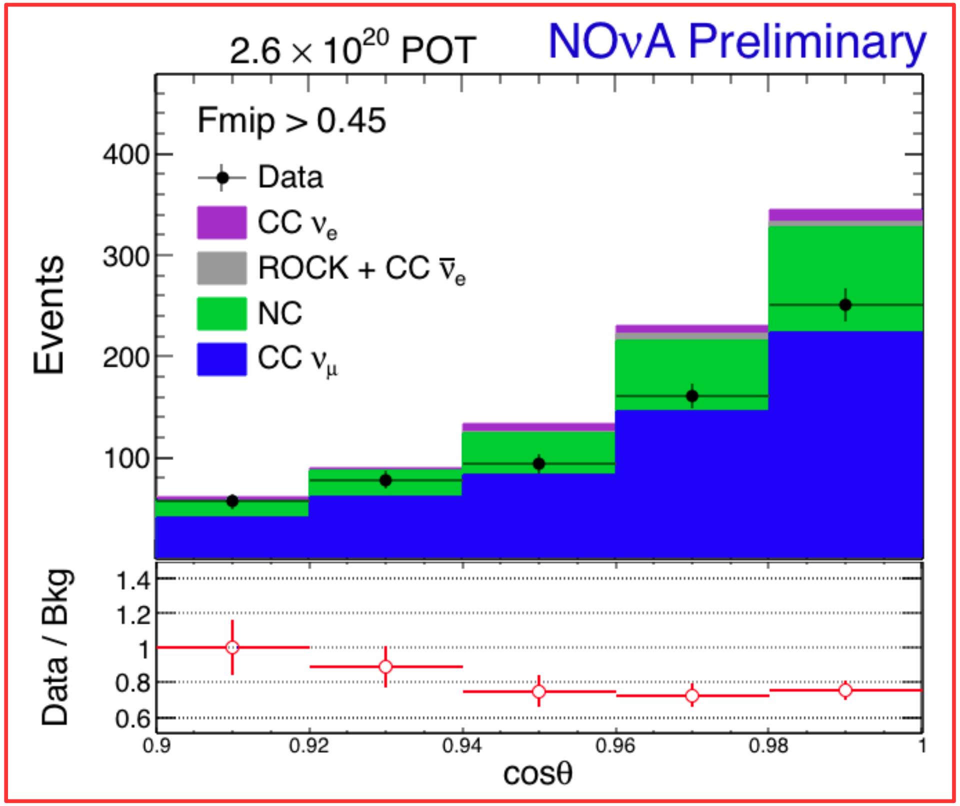




Electron momentum distributions from sideband samples.
0.95±0.2 is used as the background normalization factor.
This 21% uncertainty will be propagated to be ~10% uncertainty on final cross section.

Background normalization





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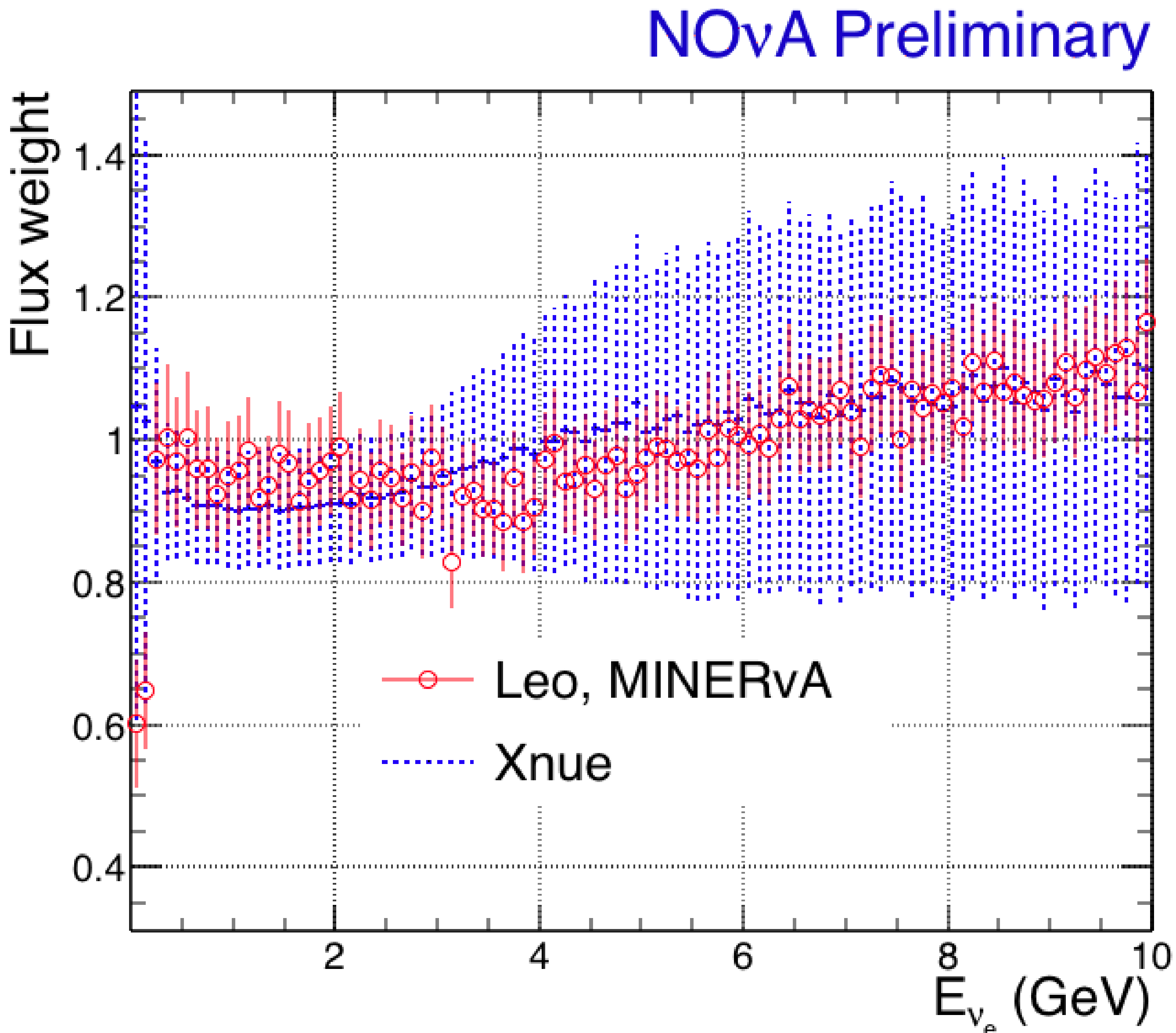
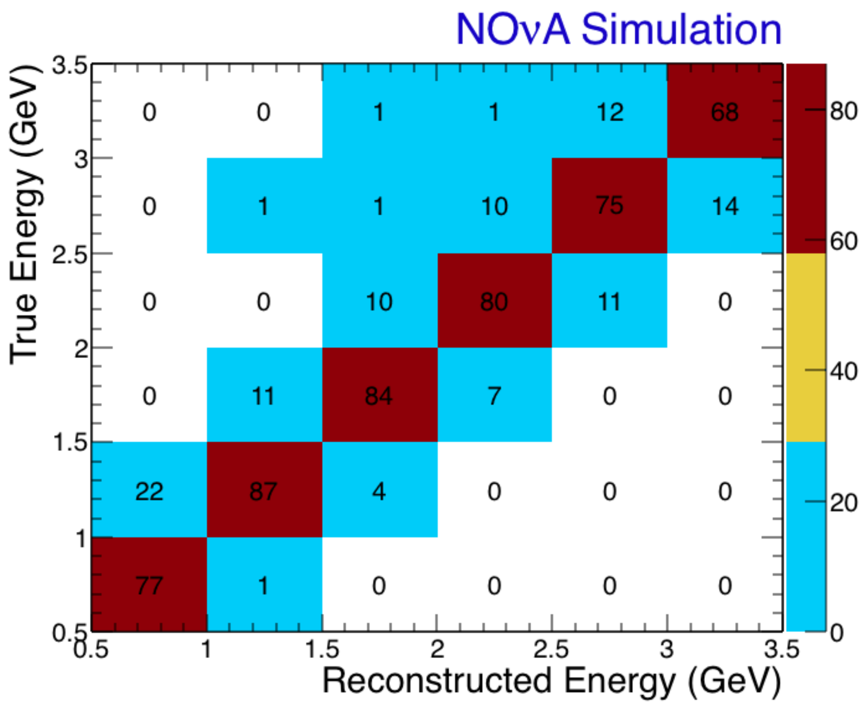
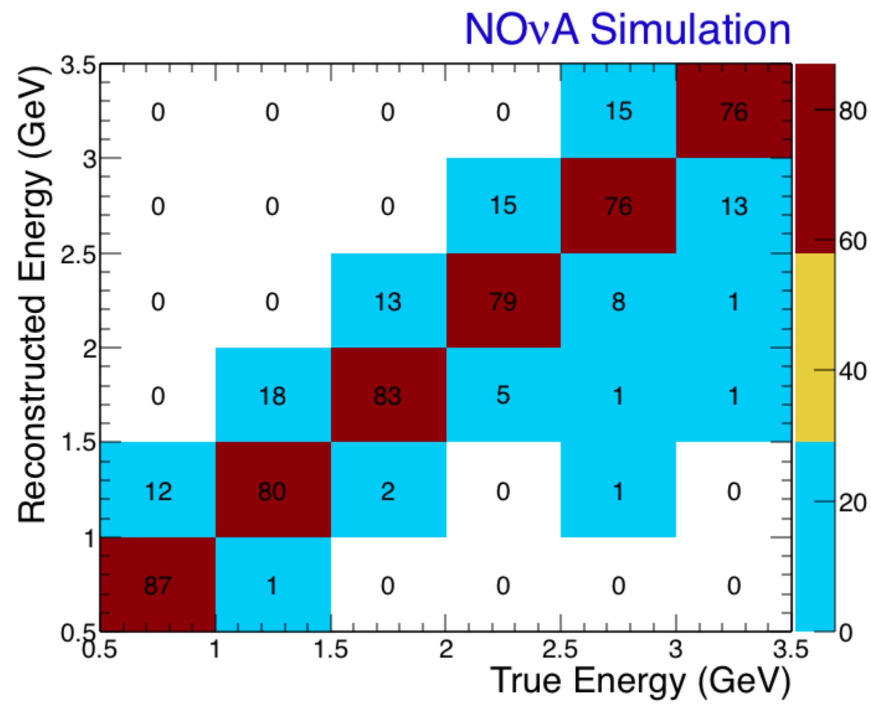
Flux weight and uncertainty



Migration matrix





Pe vs. cosθ
for numu CC and NC background