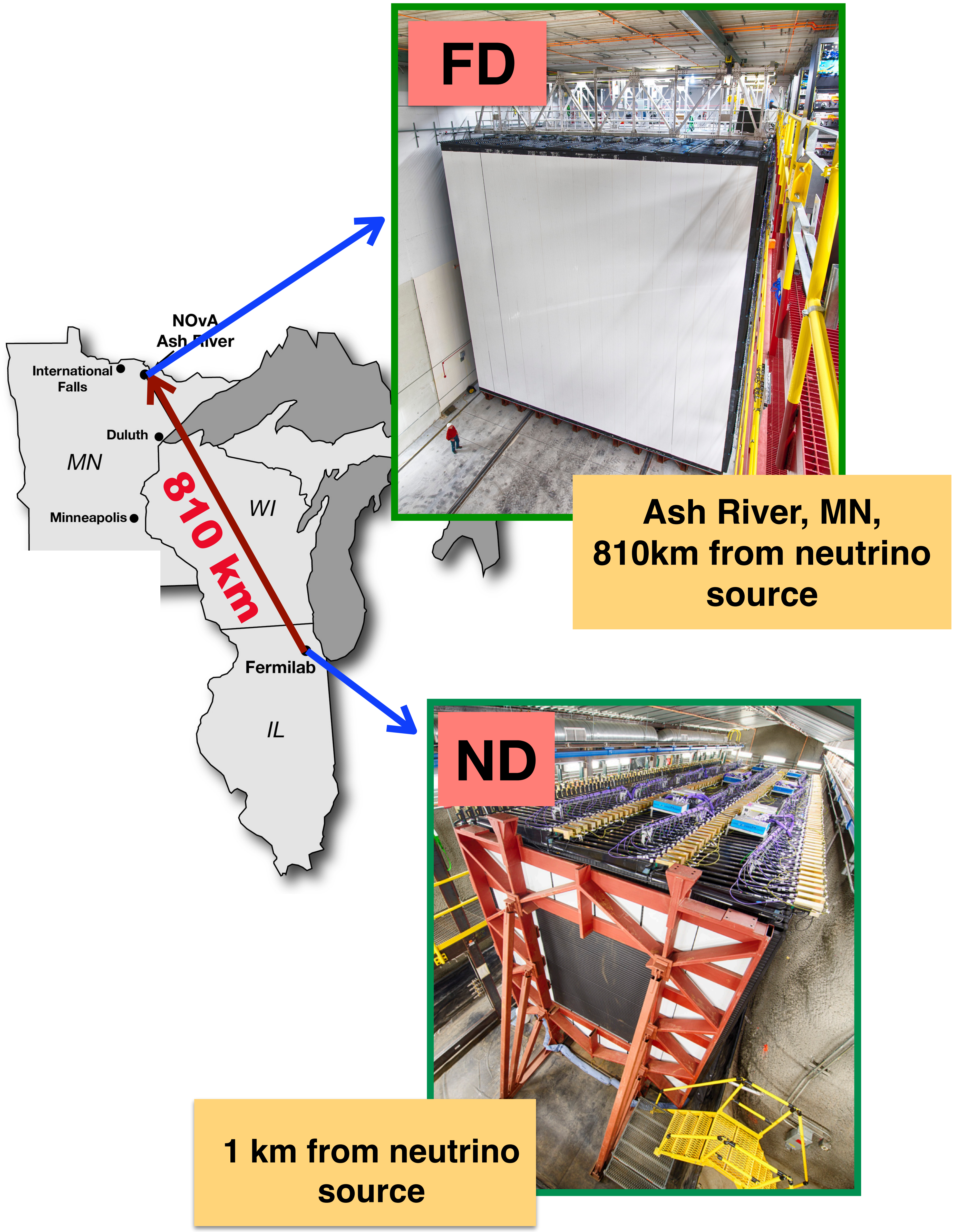
Status of Triple Differential $\bar{\nu}_{\mu}$ CC Inclusive Cross-section Measurement in the NOvA Near Detector

Prabhjot Singh, on behalf of the NOvA Collaboration

IoP 2022 - Joint APP/HEPP Conference
6 April 2022

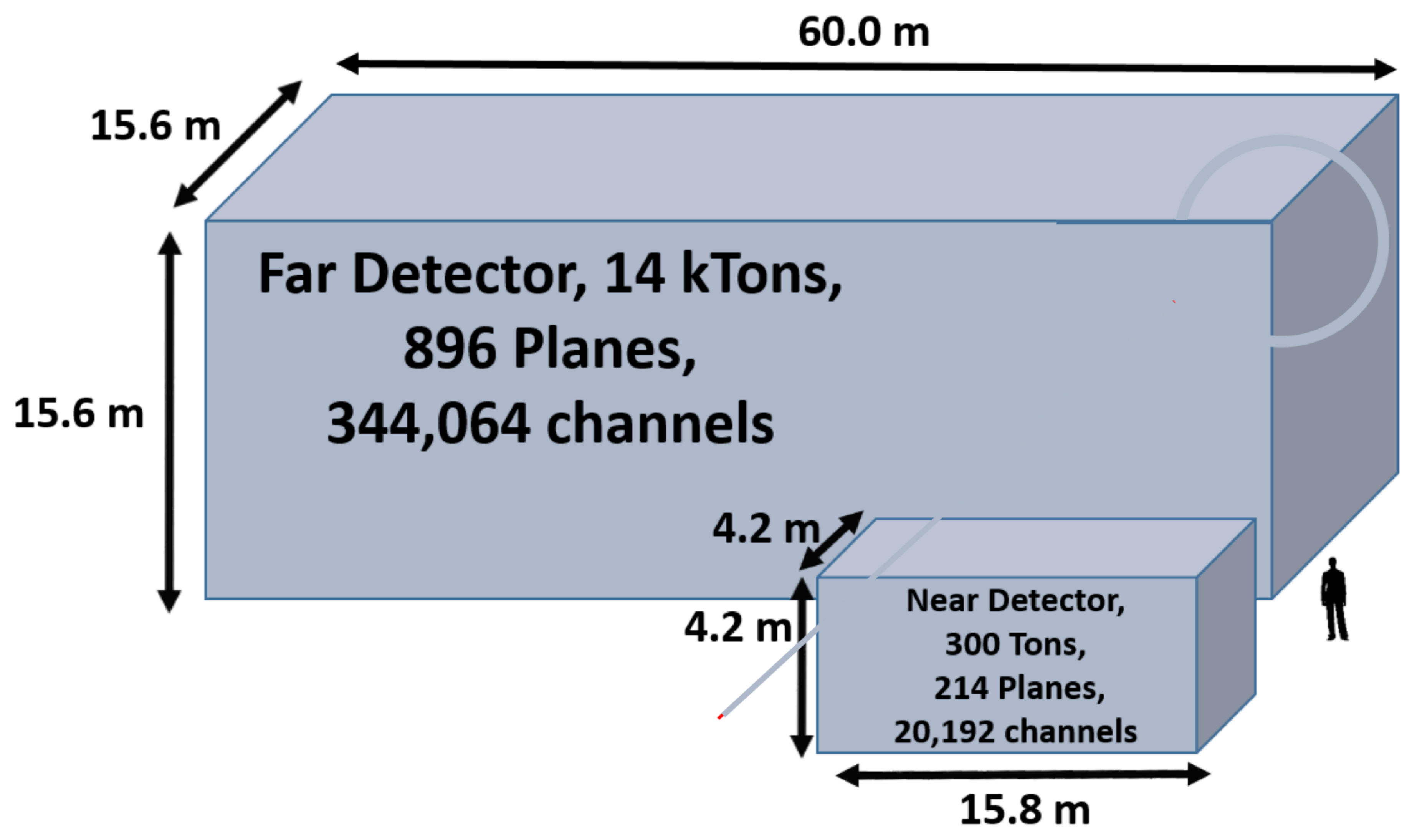
The NOvA Experiment

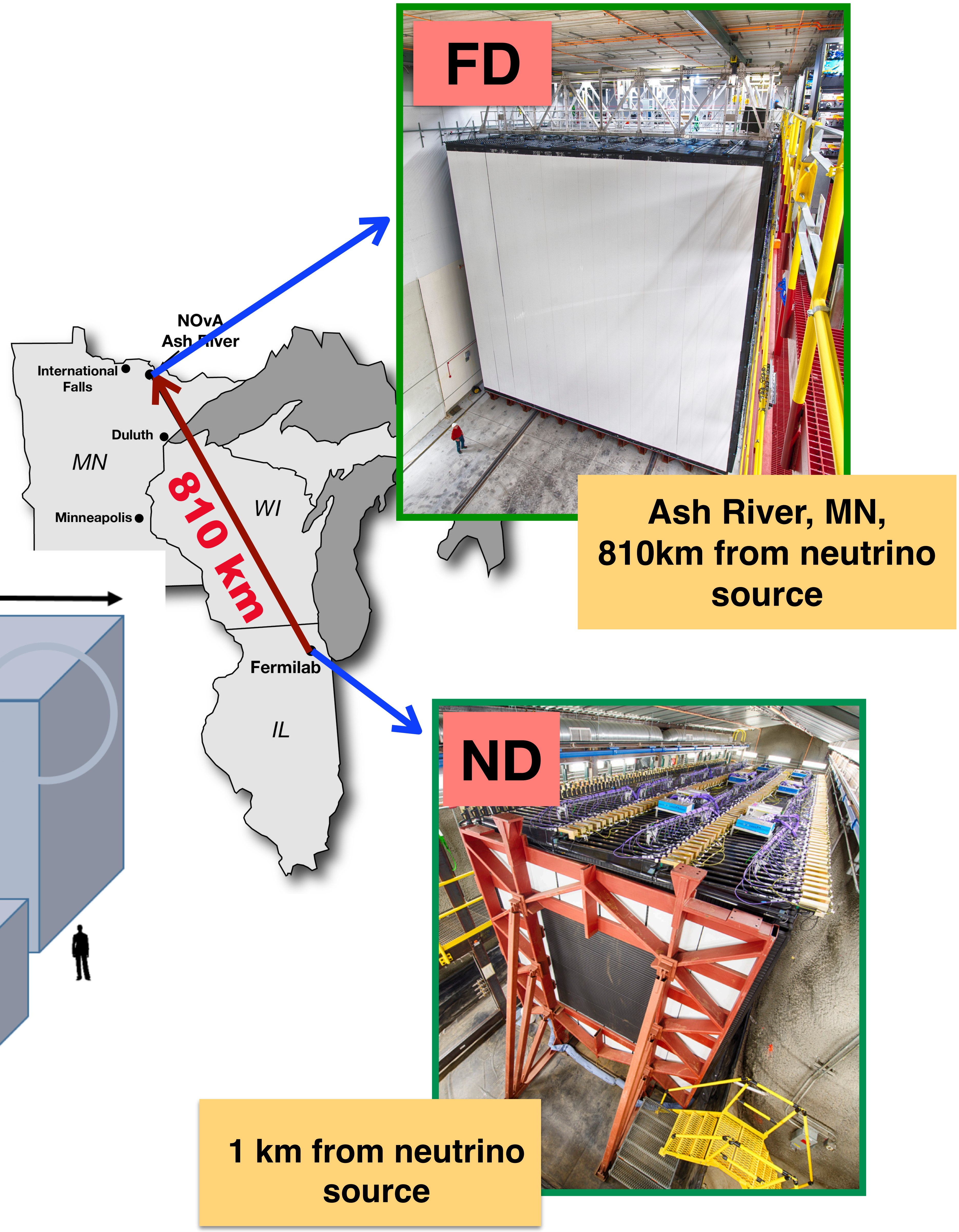
- NOvA is a long-baseline two-detector neutrino oscillation experiment



The NOvA Experiment

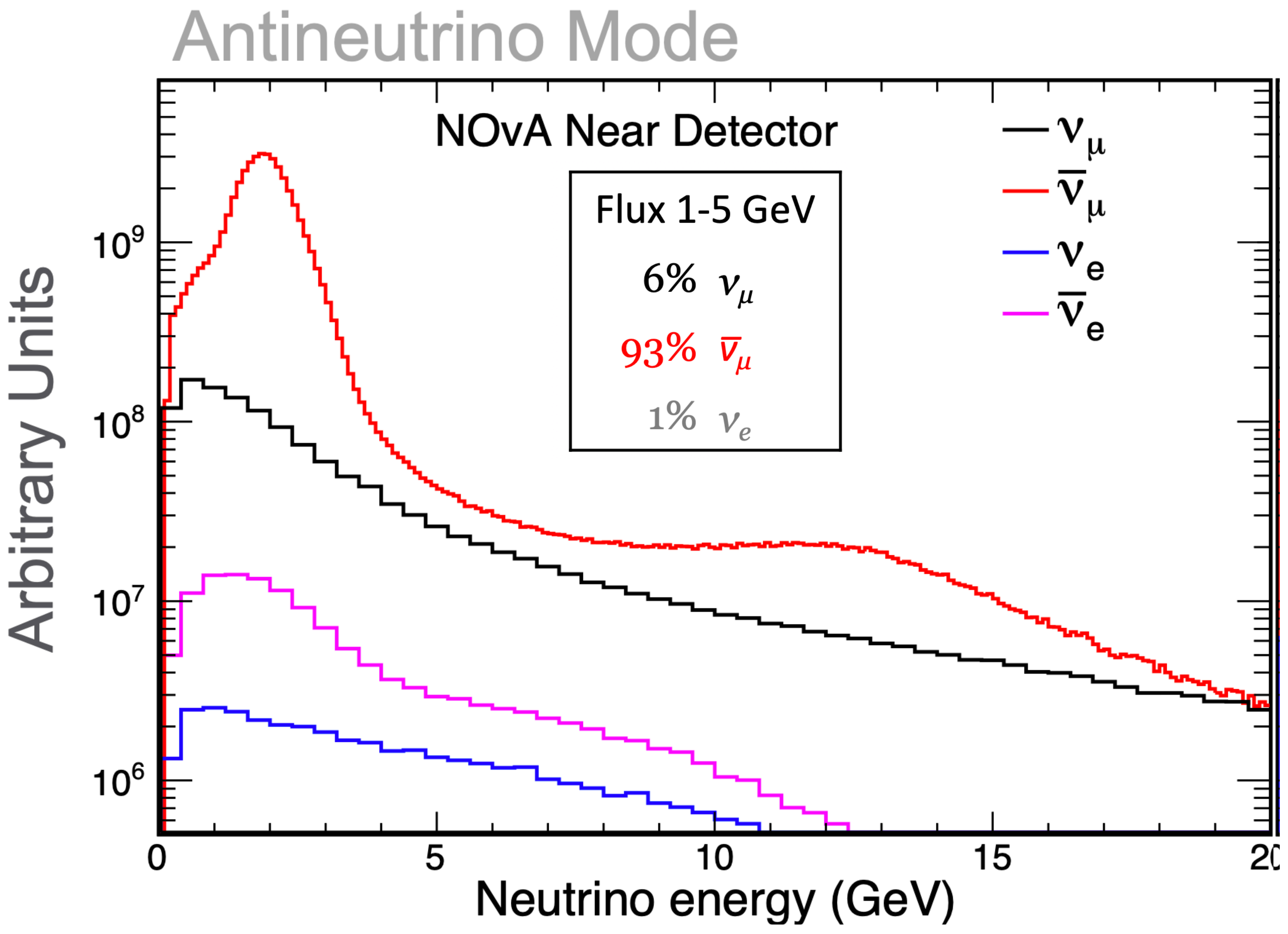
- NOvA is a long-baseline two-detector neutrino oscillation experiment
- Both detectors filled with liquid scintillator and composed of 77% CH_2, 16% chlorine, 6% TiO_2 by mass

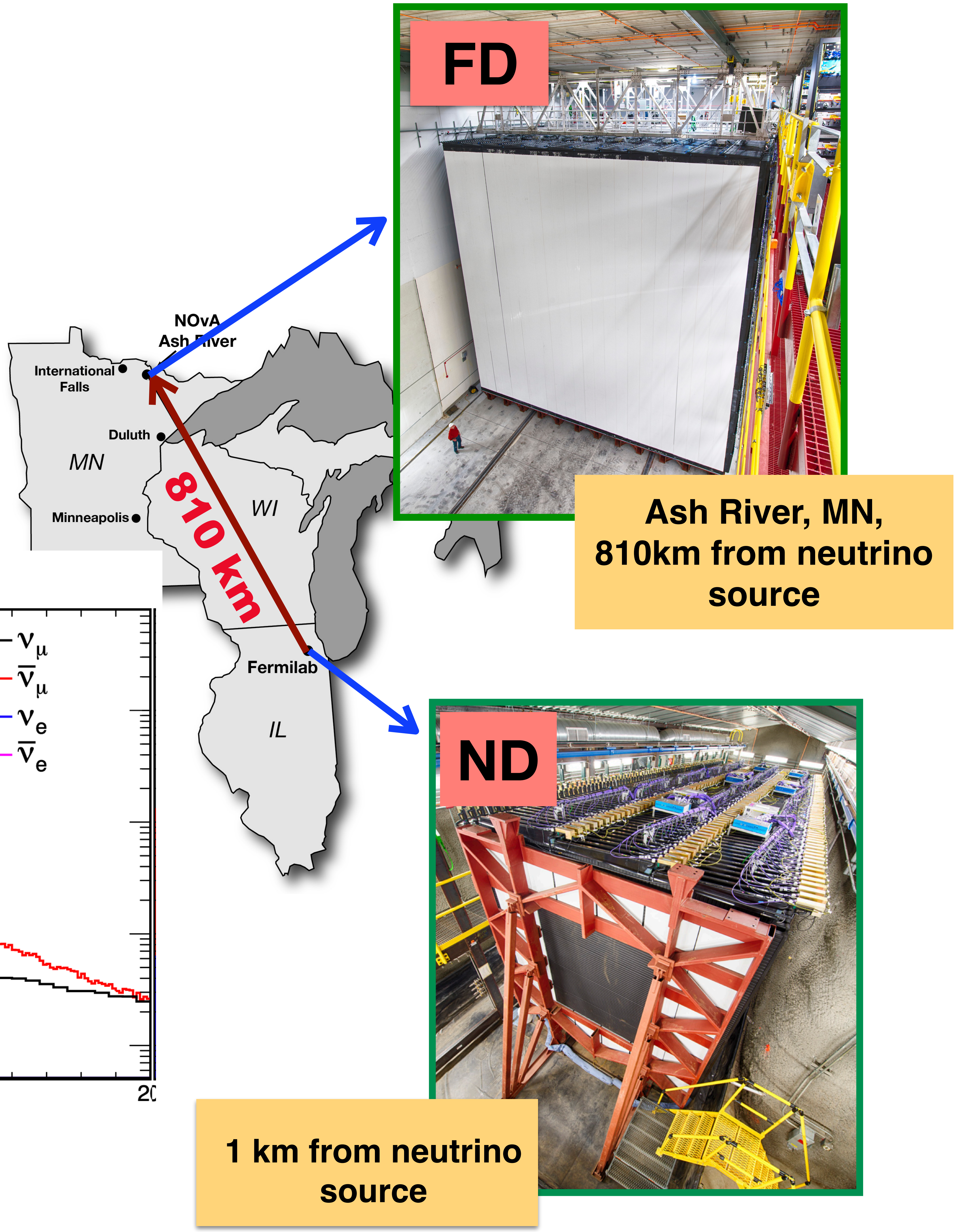




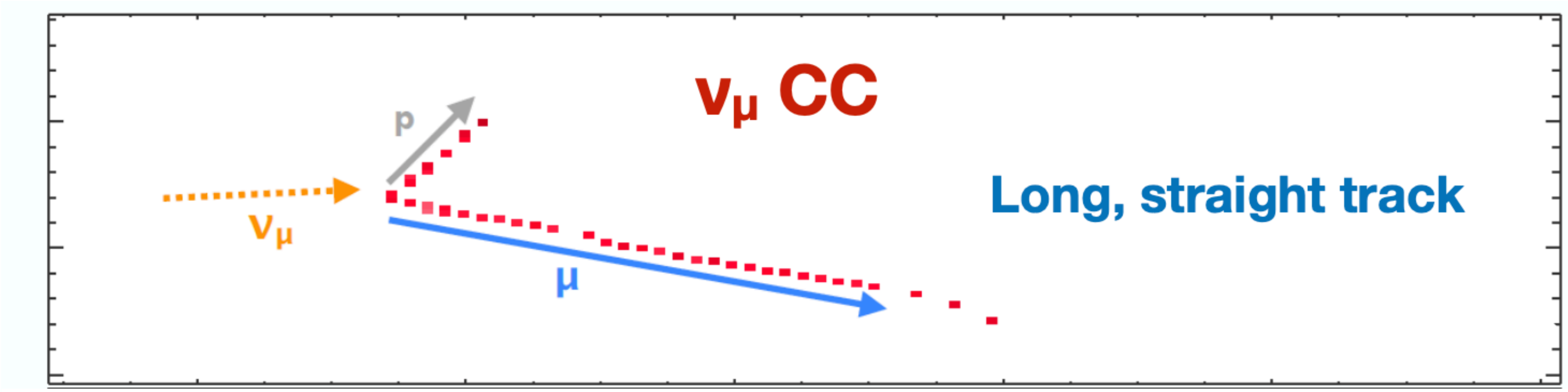
The NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment
- Both detectors filled with liquid scintillator and composed of 77% CH_2, 16% chlorine, 6% TiO_2 by mass
- 14.6 mrad off-axis detectors
- Neutrino beam peaks at 2GeV
- High neutrino flux at the near detector is used for neutrino cross-section measurements





Event Topologies



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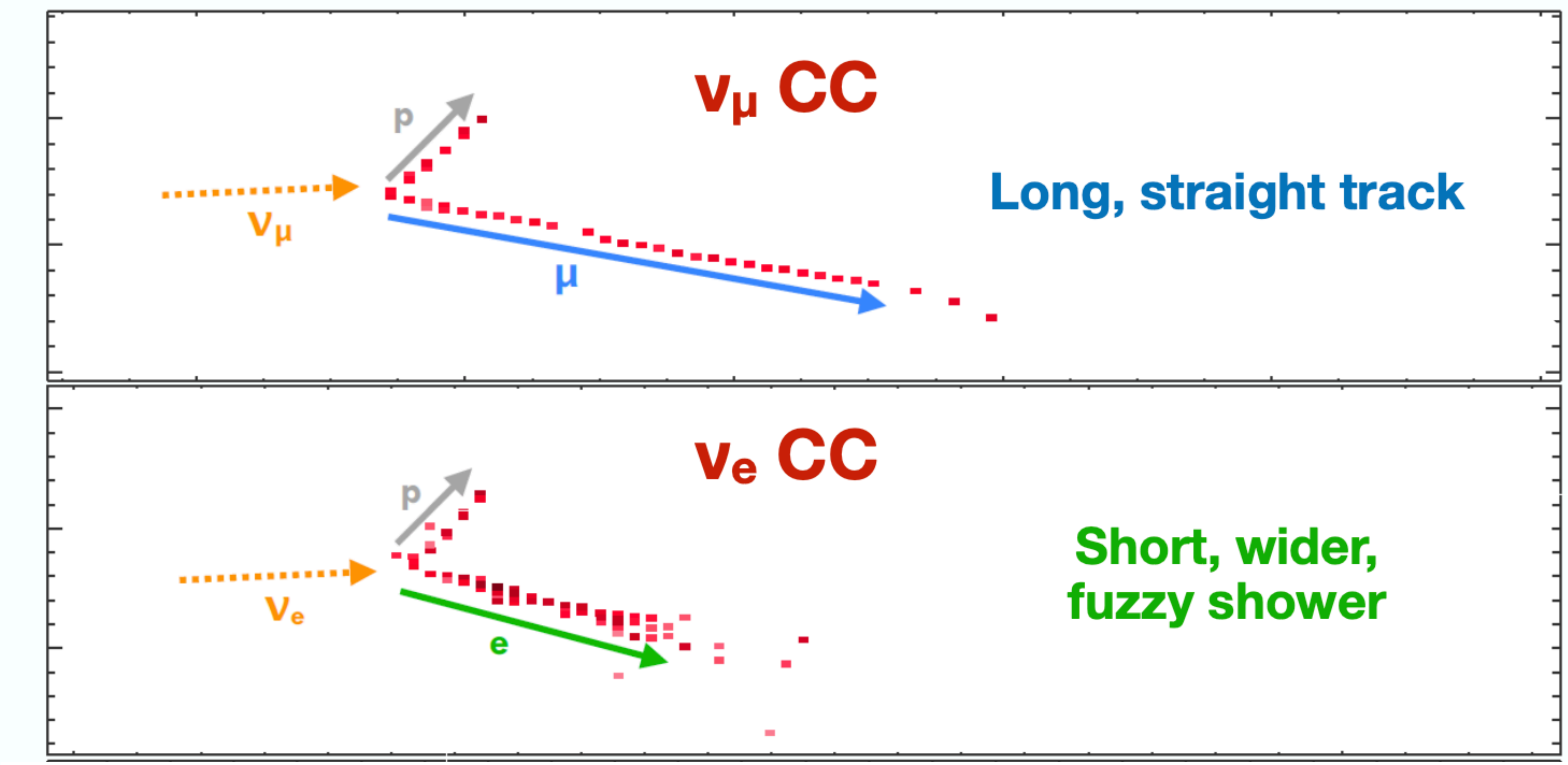

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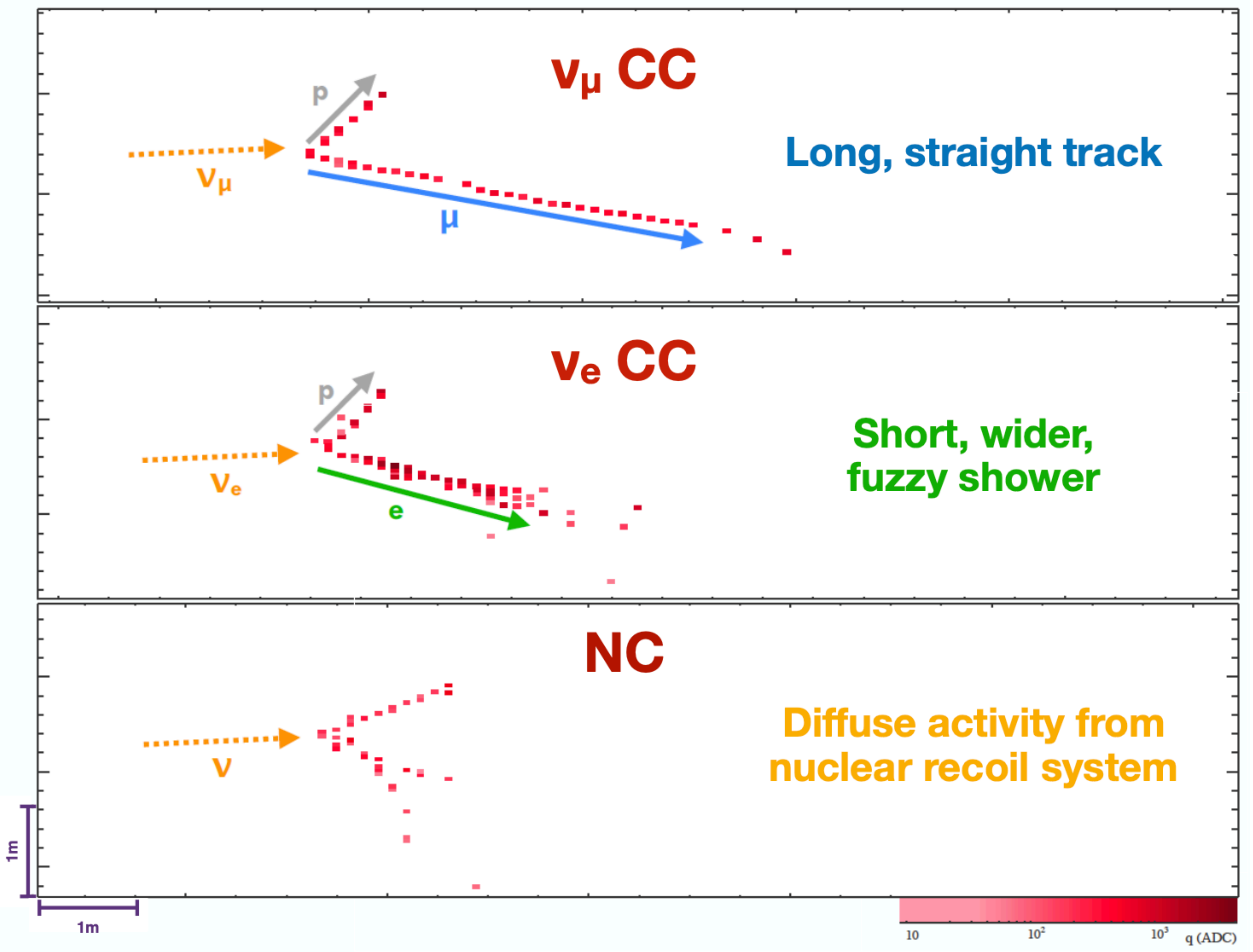
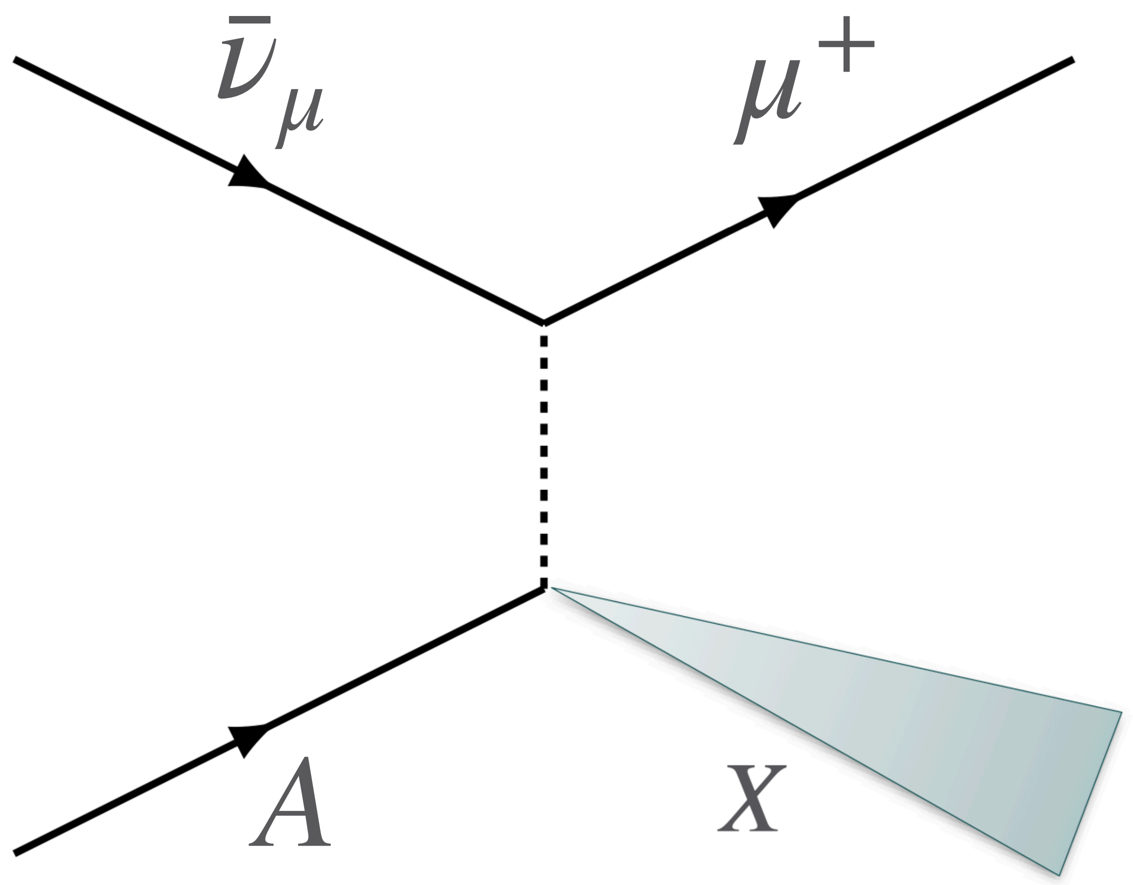


$\bar{\nu}_\mu$ CC Inclusive Cross Section

- Signal: $\bar{\nu}_\mu + A \rightarrow \mu^+ + X$

- We expect more than 1 million signal events giving us a good handle on statistics



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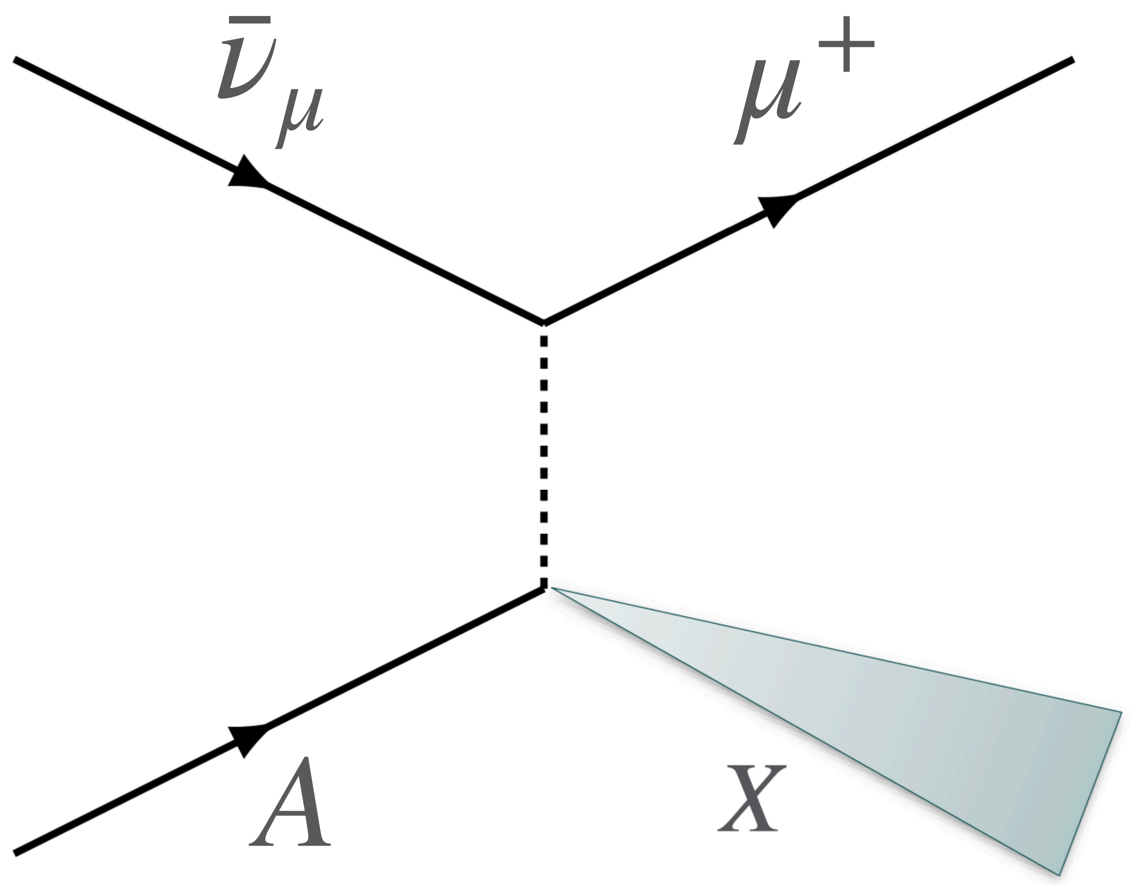
- The deliverables are triple differential cross sections in anti-muon kinematics (T_μ, $\cos\theta_\mu$), and E_{avail}

- E_{avail} is a measure of the hadronic energy deposited in the detector



Cross sections

$$\left(\frac{d^3\sigma}{d\cos\theta_\mu dT_\mu dE_{Avail}}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{Avail})_j P(\cos\theta_\mu, T_\mu, E_{Avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{Avail})_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i(\Delta E_{Avail})_i N_{\text{target}}\phi}$$

- For differential cross section measurements, we need
  - To select candidate signal events

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  - Selection efficiencies

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  - Selection efficiencies
  - Integrated beam flux, and number of target nucleons

Cross sections

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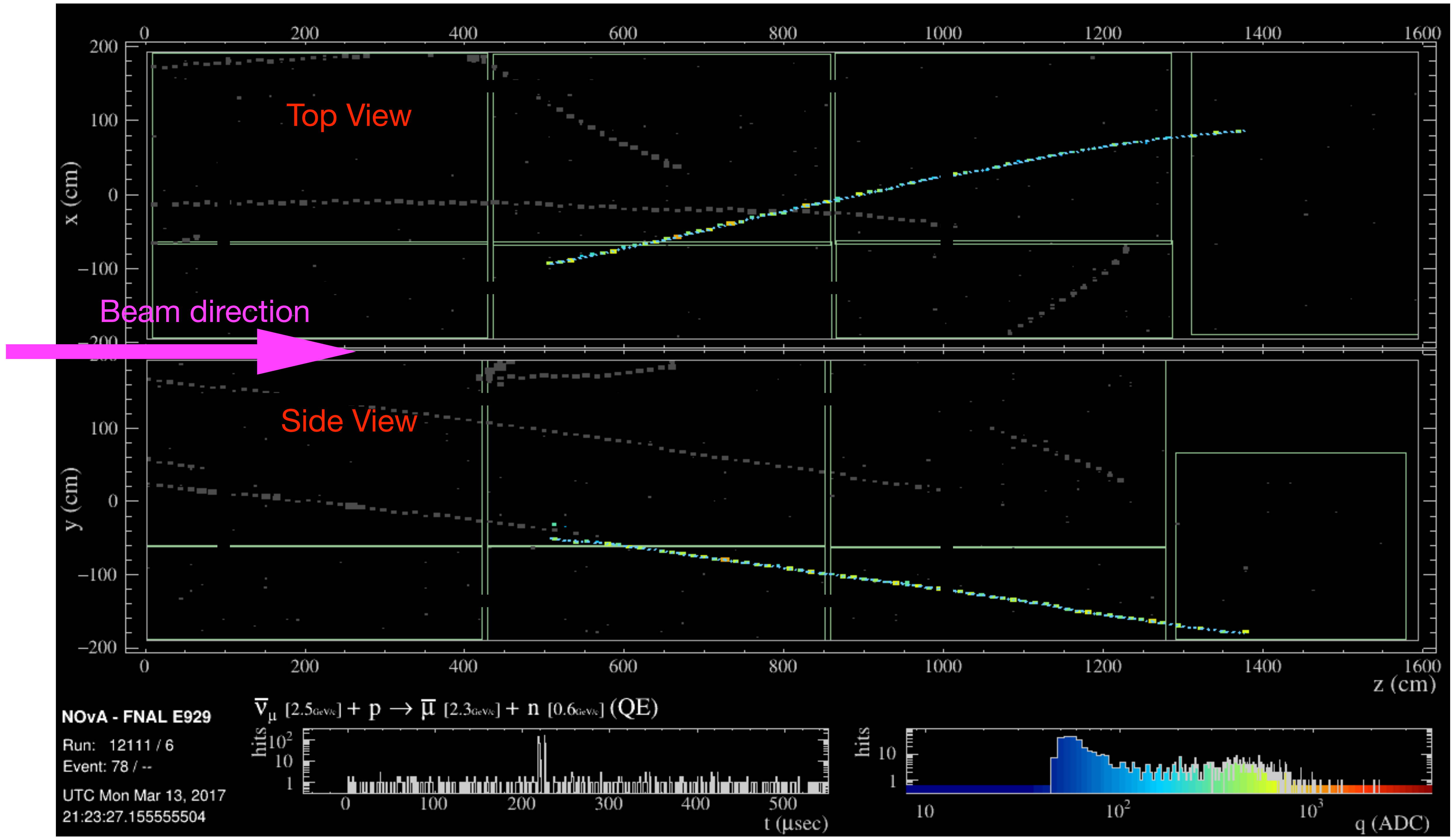
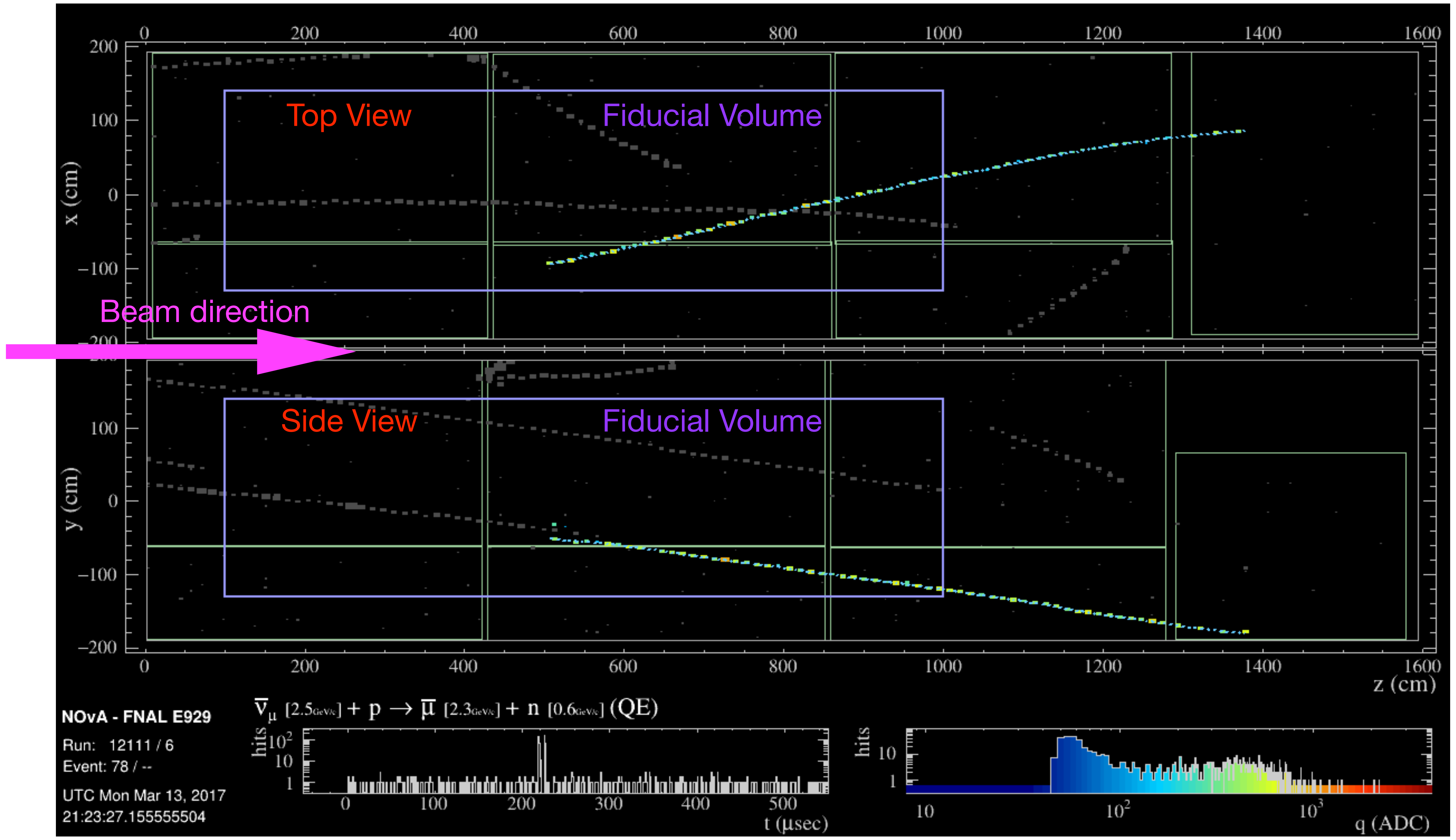
- For differential cross section measurements, we need
  - To select candidate signal events, sample purity
  - The unfolding matrix (reco to true migration)
  - Selection efficiencies
  - Integrated beam flux, and number of target nucleons
  - Normalization by bin widths

Selections



- Hits associated in time and space are used to reconstruct tracks and showers

Selections



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- Interaction vertex of events should be in the fiducial volume

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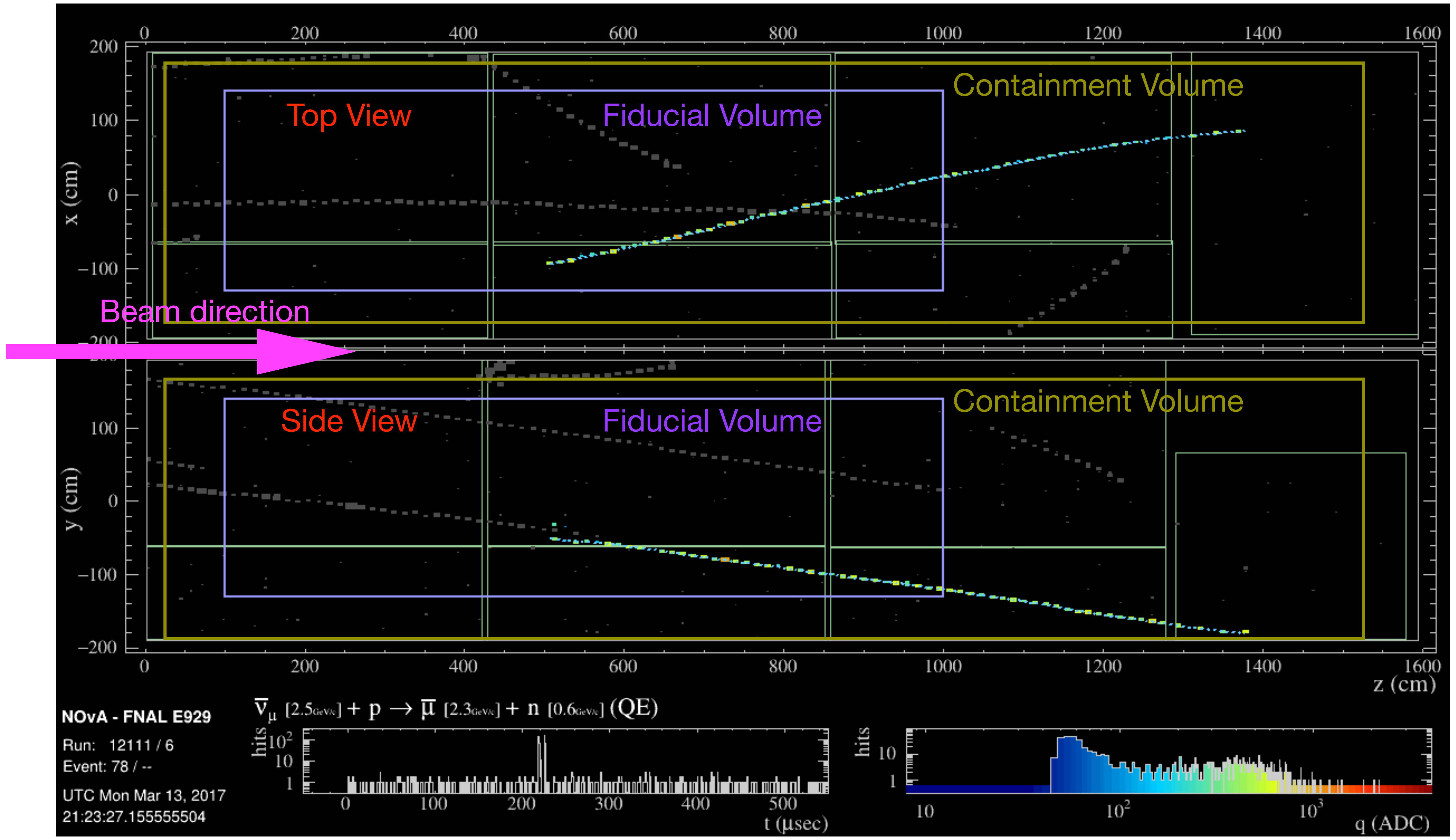
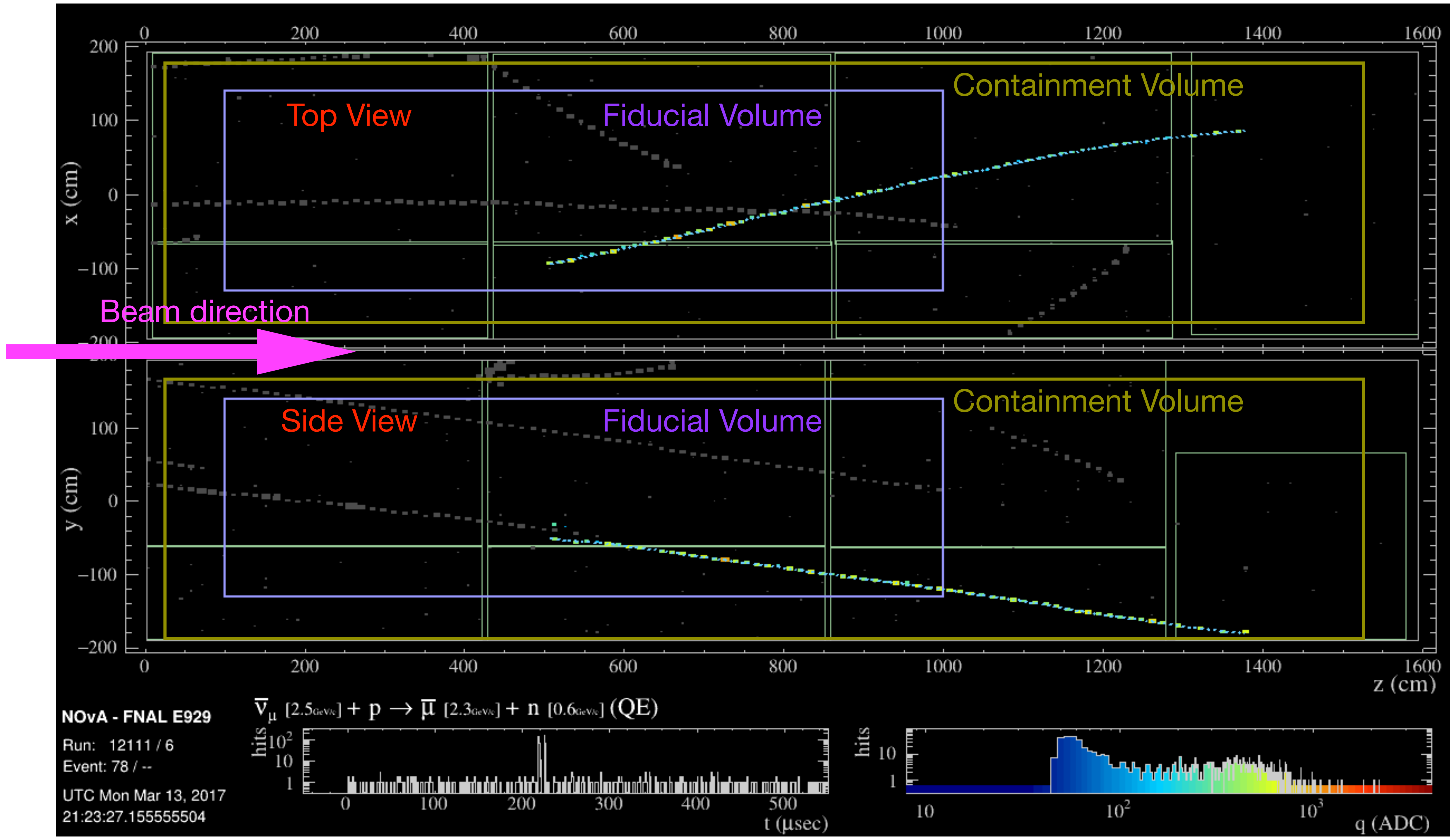
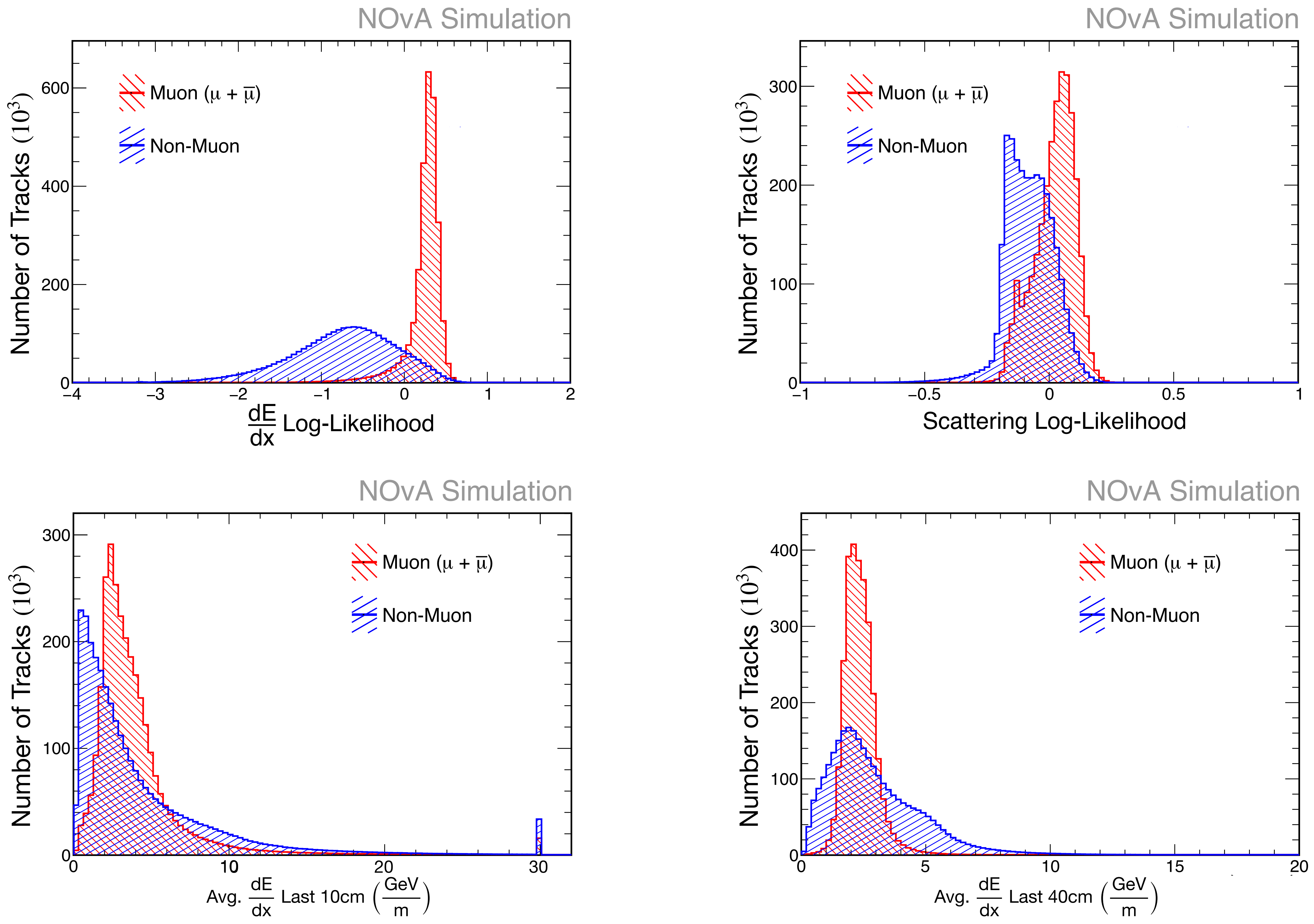


- Hits associated in time and space are used to reconstruct tracks and showers
- Interaction vertex of events should be in the fiducial volume
- Fully contained tracks and showers are selected for the analysis

Selections

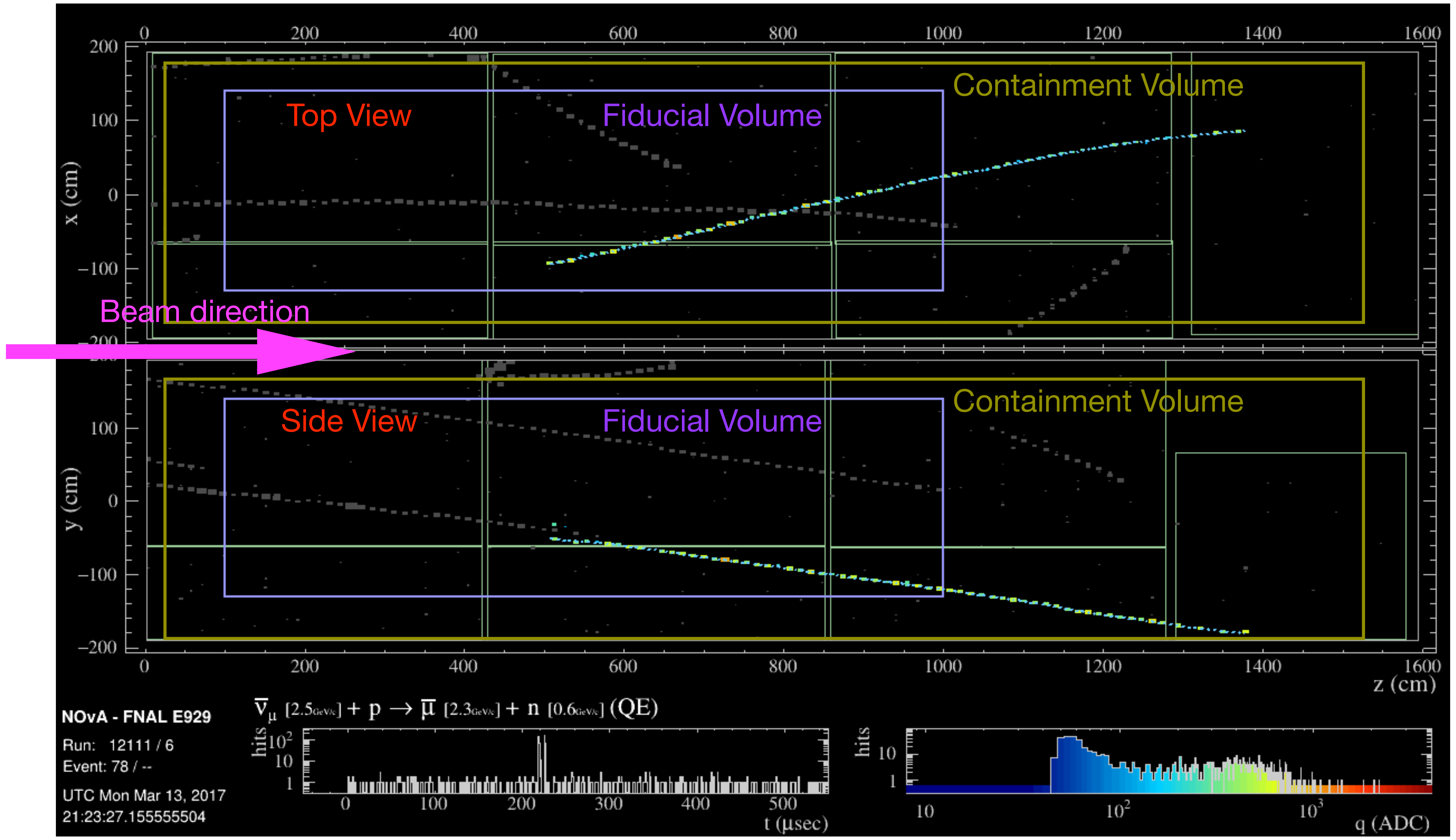
Plots by Connor Johnson

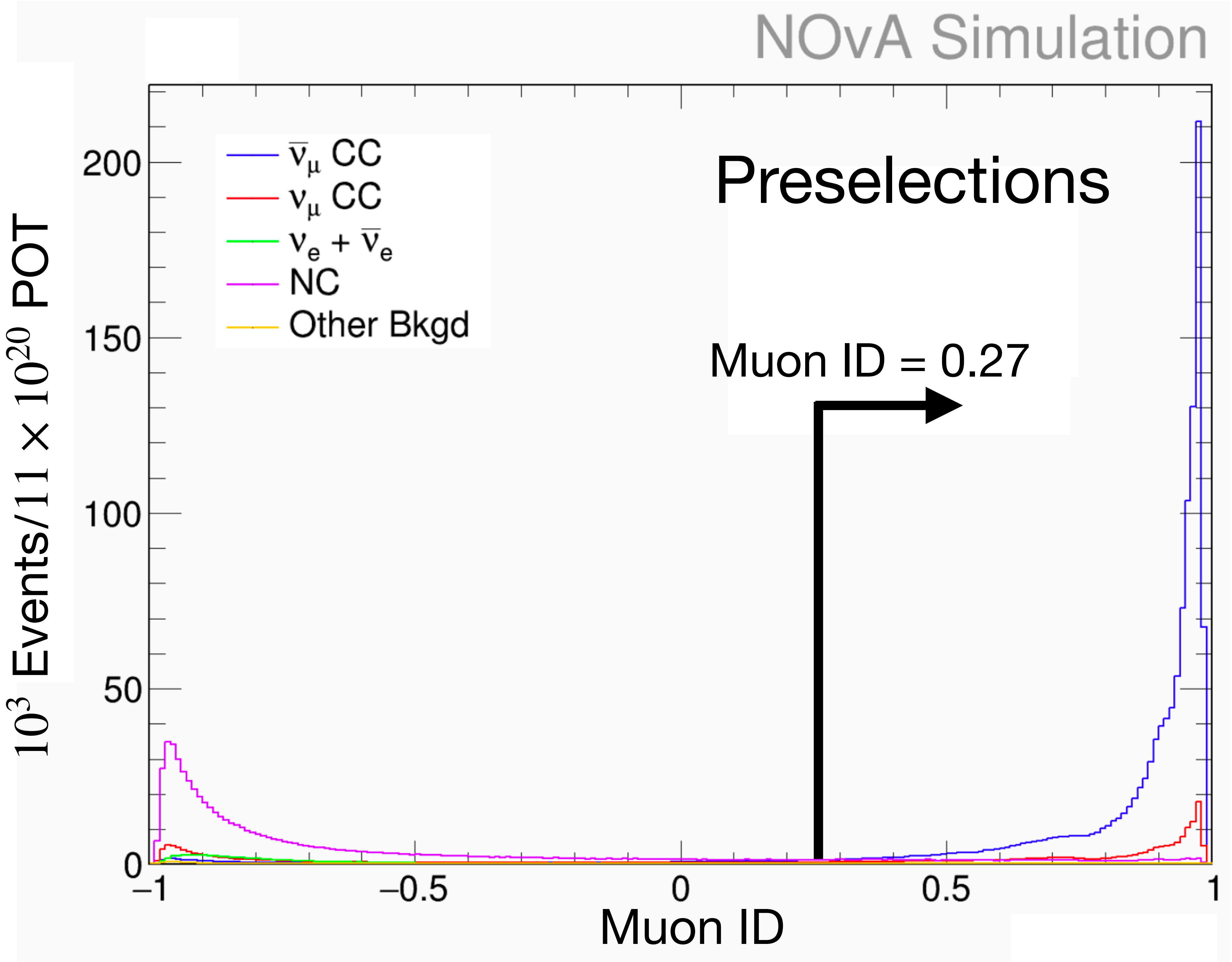




- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons

Selections

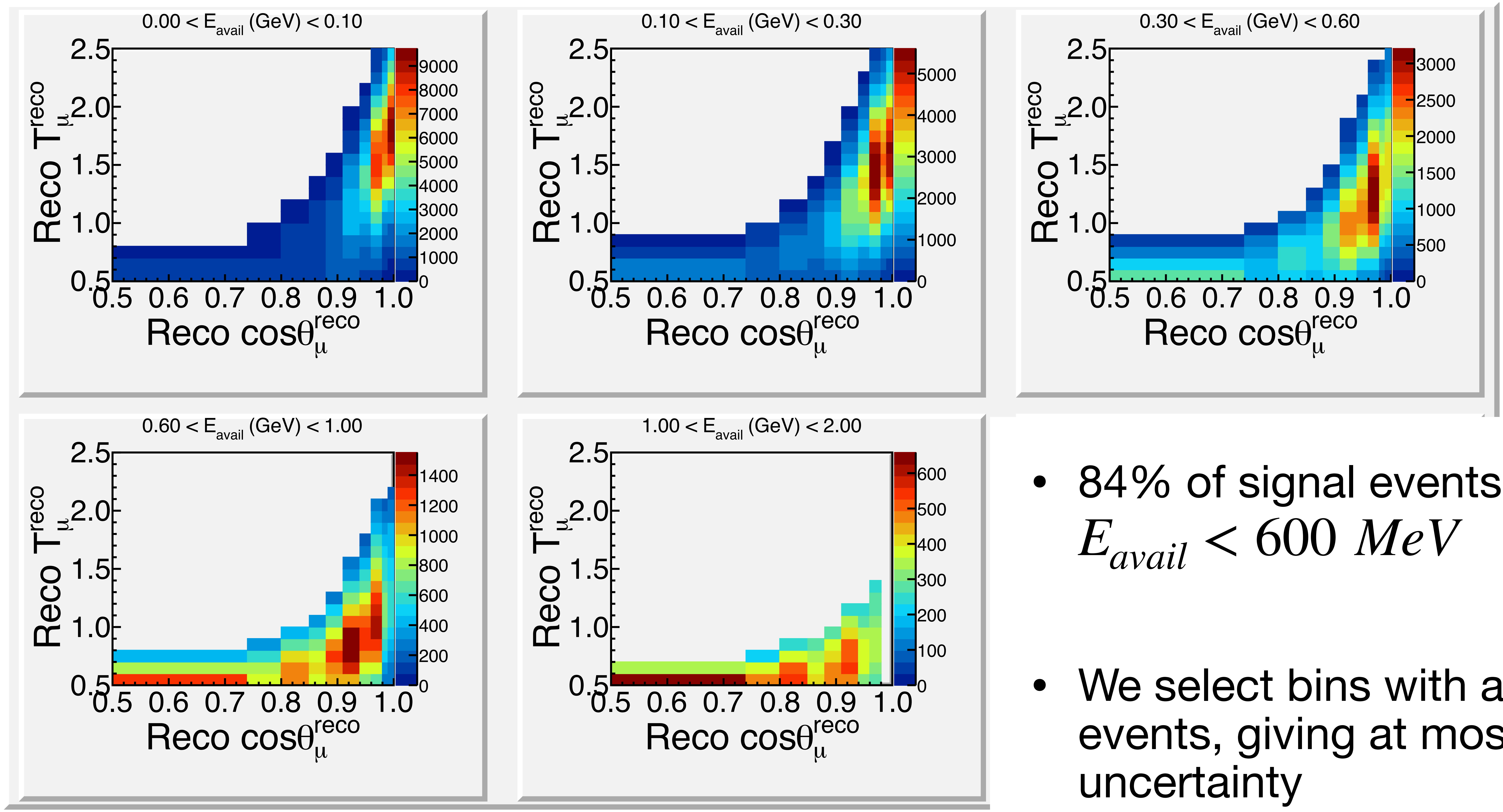




- Boosted decision tree with muon dE/dx and scattering input variables is used to select candidate muons
- BDT provides excellent separation of signal from backgrounds

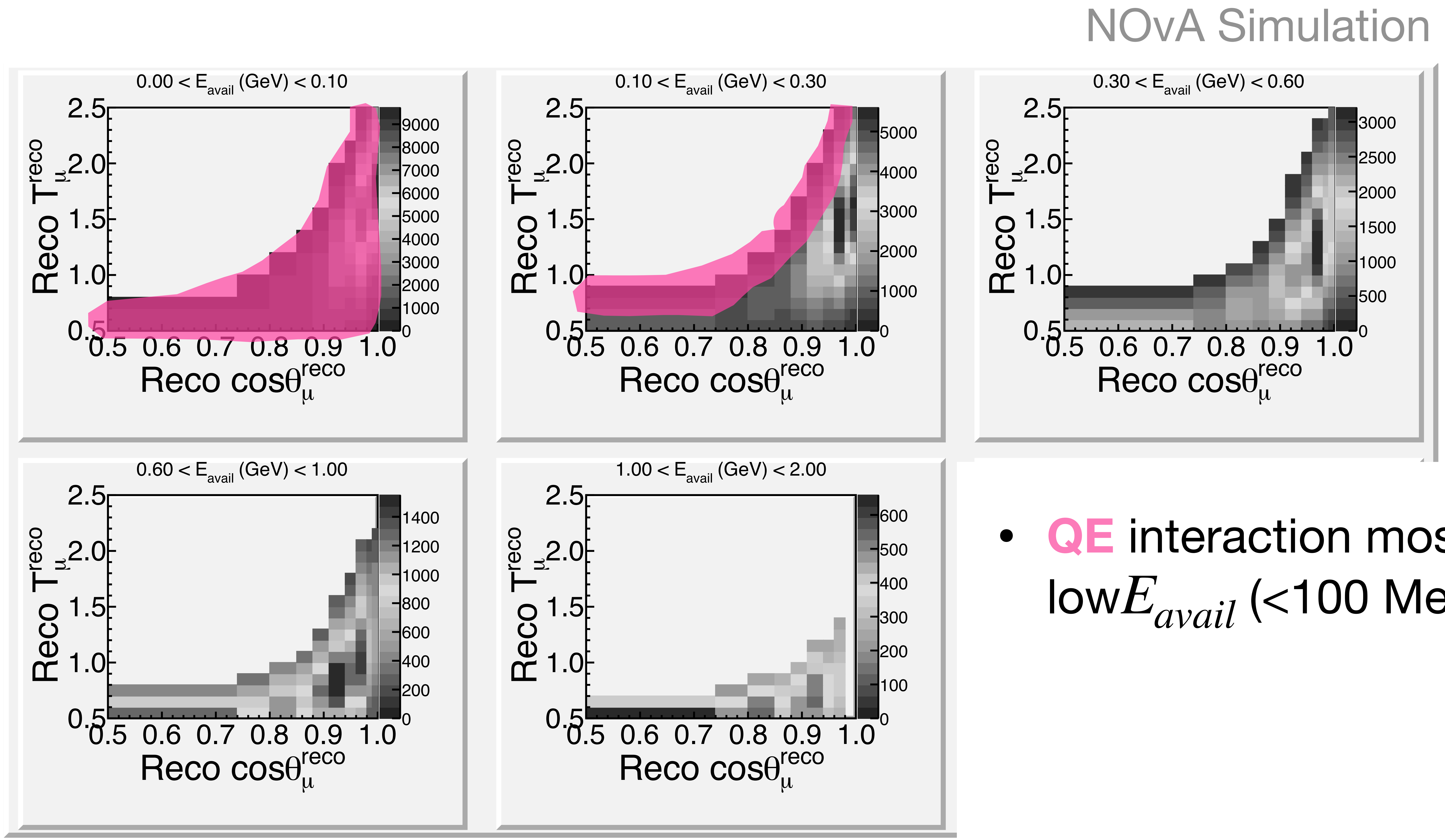
Analysis Bins

NOvA Simulation



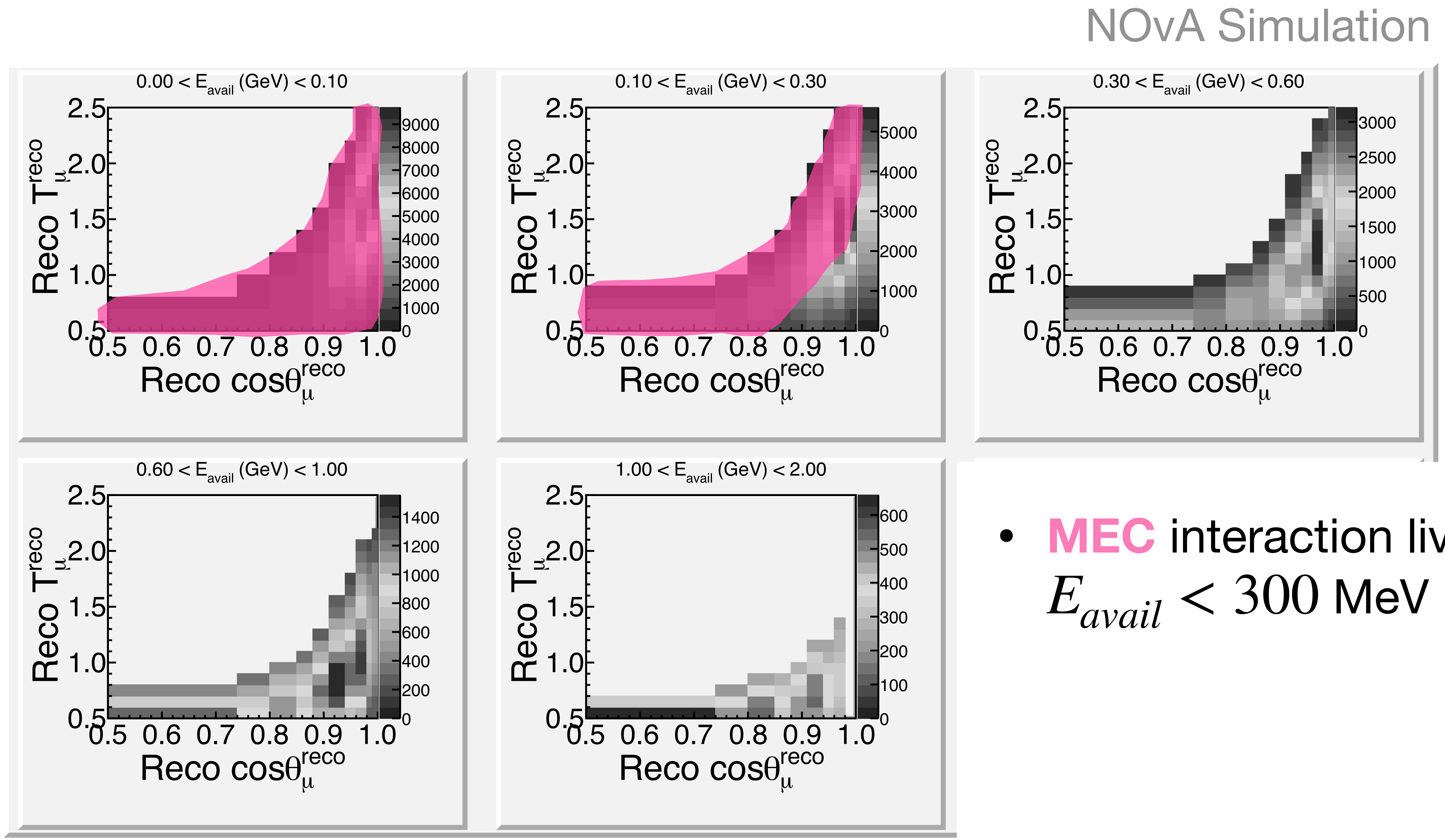
- 84% of signal events are in $E_{avail} < 600\ MeV$
- We select bins with at least 200 signal events, giving at most 7% statistical uncertainty

QE Interactions



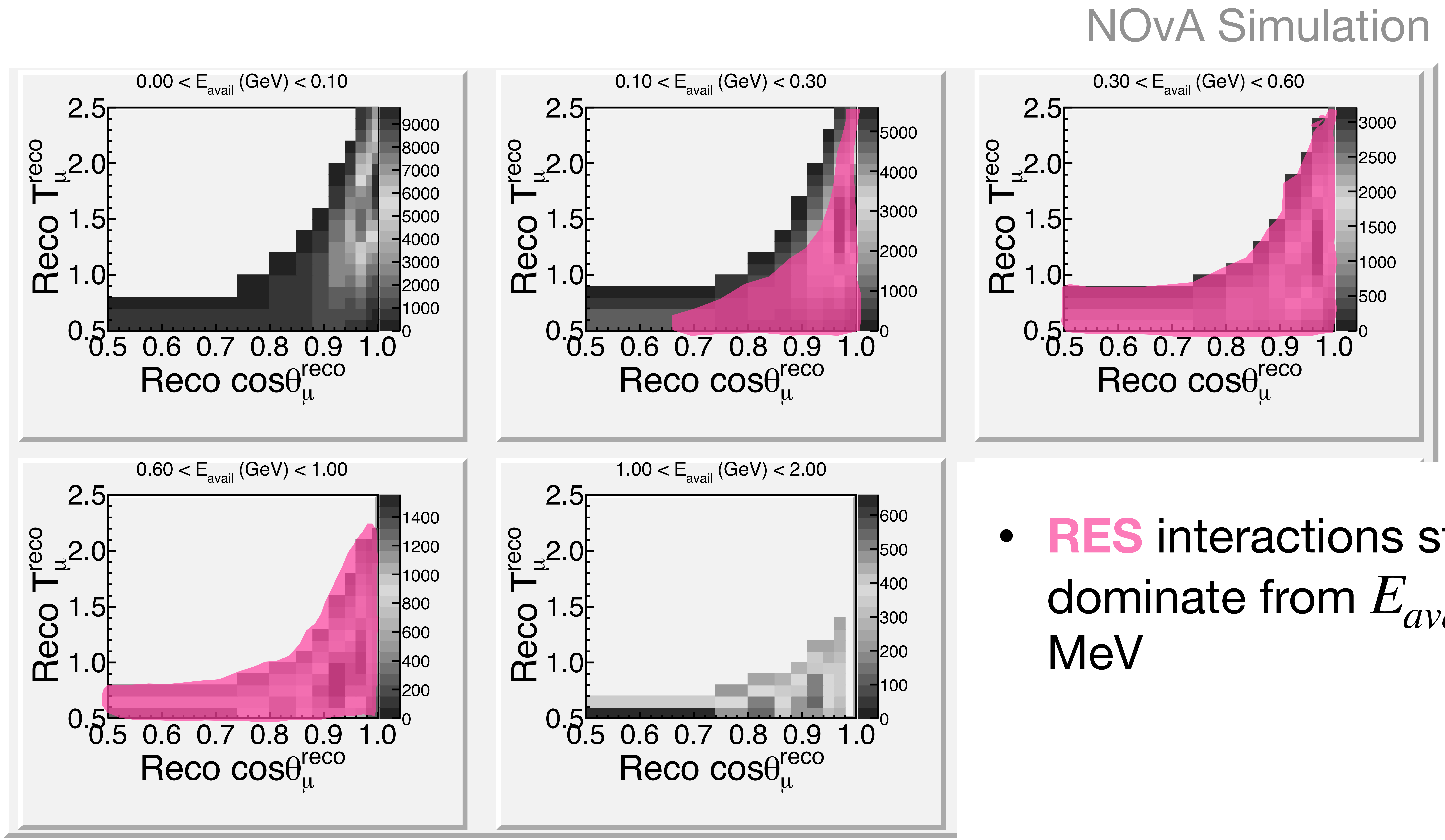
- **QE** interaction mostly live in lowE_{avail} (<100 MeV) regions

MEC Interactions



- **MEC** interaction live in low $E_{avail} < 300$ MeV regions

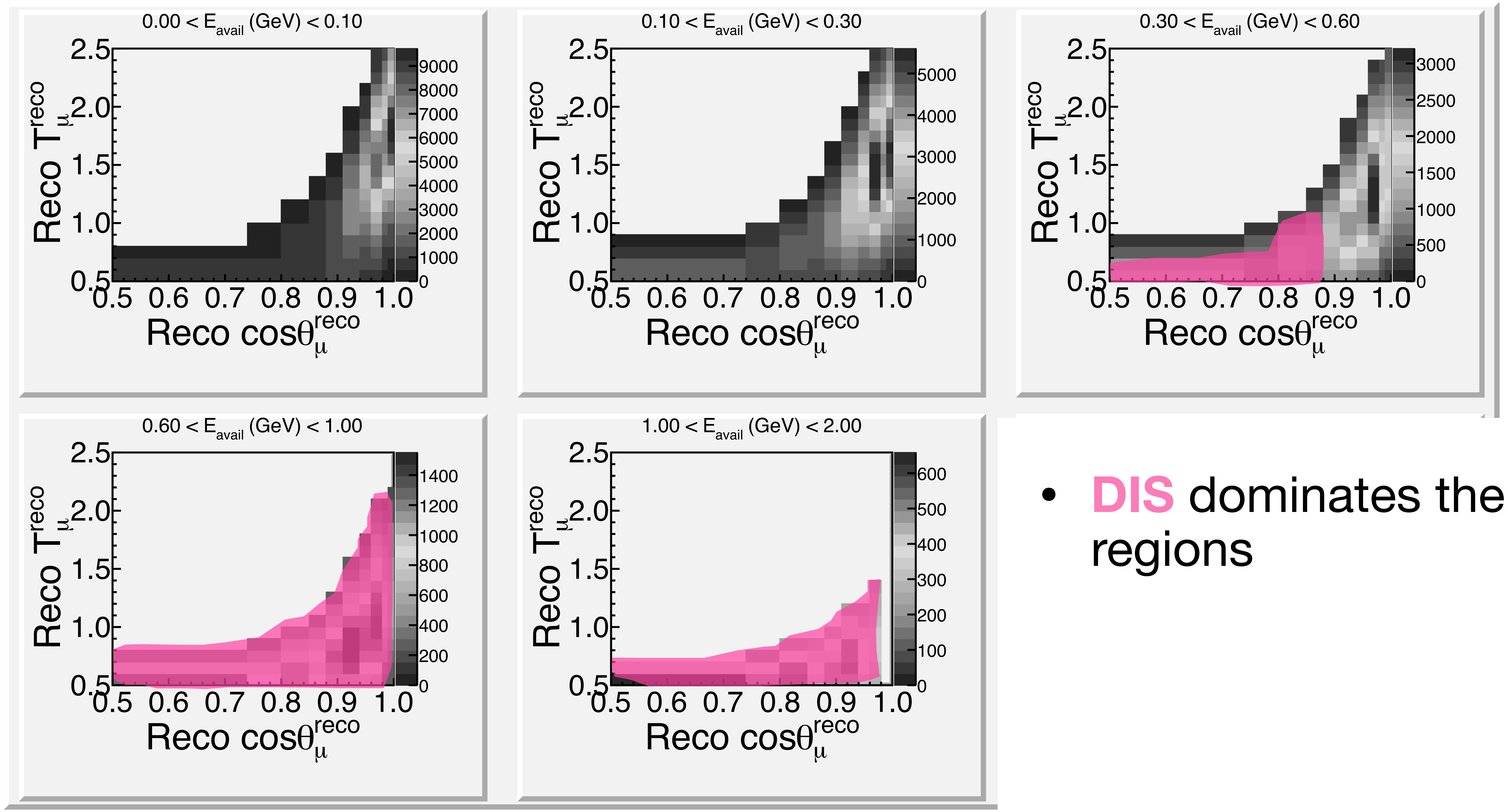
RES Interactions



- **RES** interactions start to dominate from $E_{avail} > 300$ MeV

DIS Interactions

NOvA Simulation

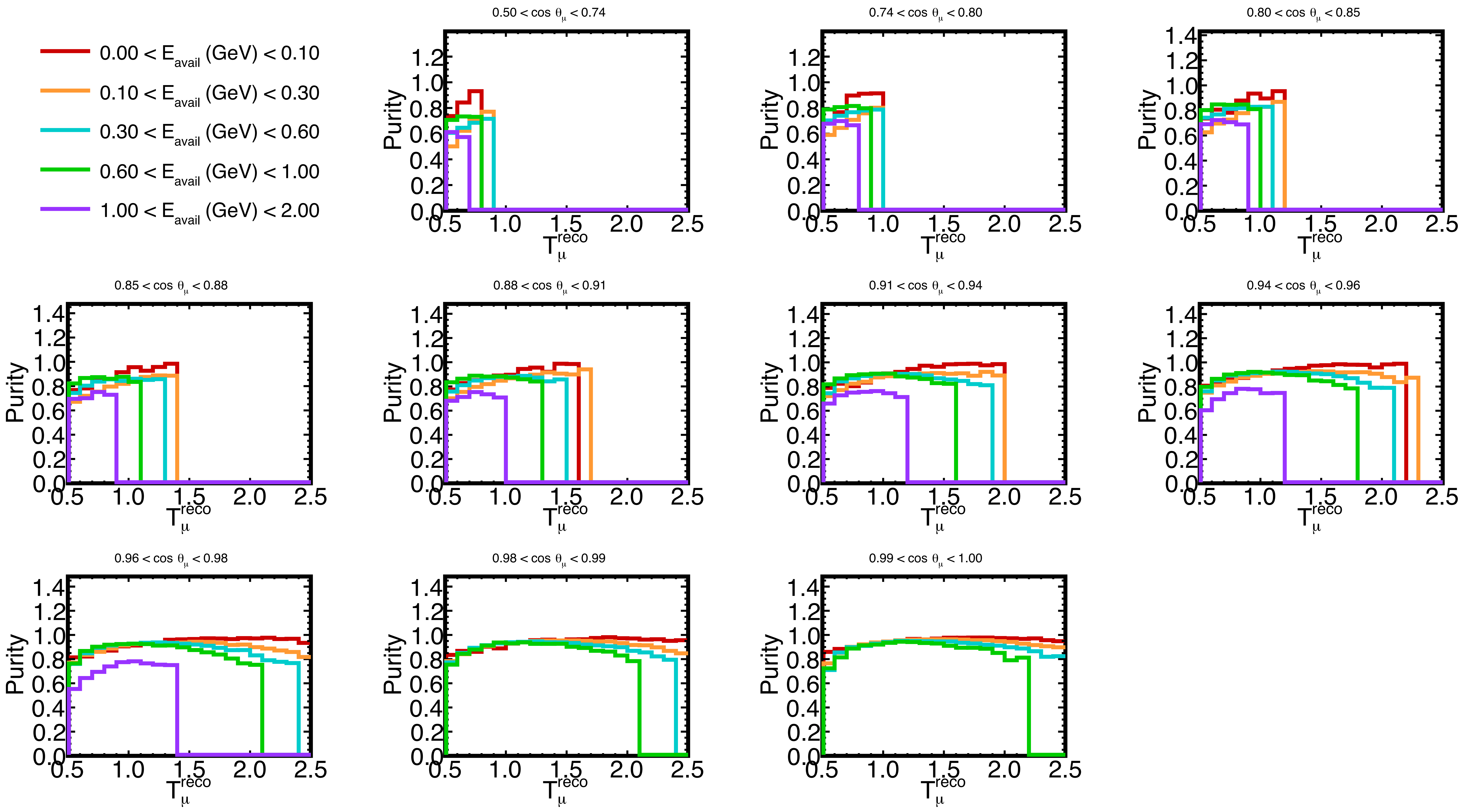


- **DIS** dominates the high energy regions

Purity

NOvA Simulation

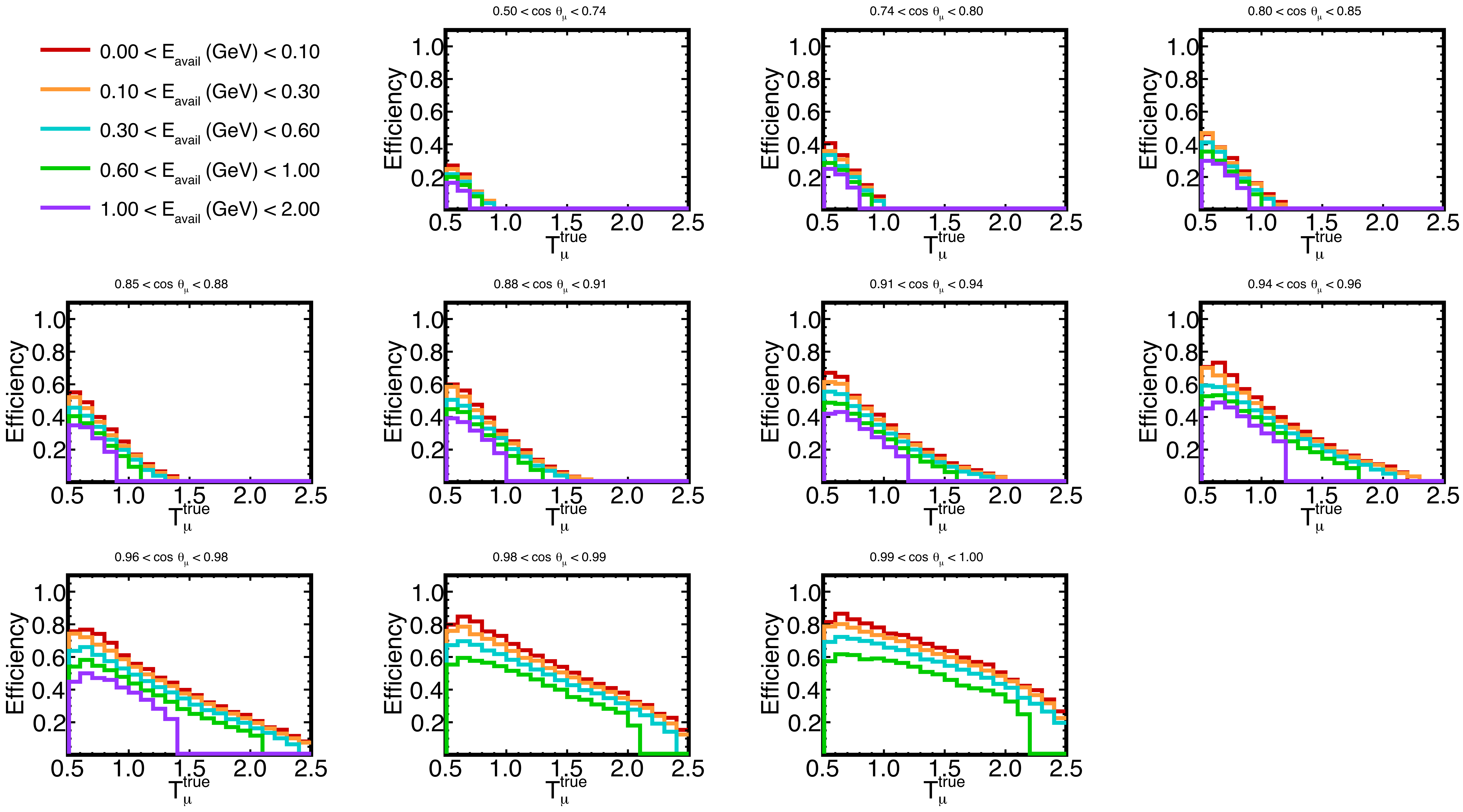
- Purity is also calculated in 3D bins of T_{μ}, $\cos\theta_{\mu}$, and E_{avail}
- 90.6% pure sample
- Purity reduces with E_{avail} since at higher E_{avail} NC backgrounds rise



Efficiency

NOvA Simulation

- 32.8% efficiency
- Efficiency reduces with T_μ due to longitudinal containment
- Efficiency reduces with θ_μ due to transverse containment



Conclusions

- Work is in progress to measure triple differential $\bar{\nu}_\mu$ CC inclusive cross section using 12e20 proton on target exposure collected by the NOvA experiment
- Our plan is to measure the cross section in 3D bins of muon kinematics and final state hadron energies
- First-ever triple differential measurement of $\bar{\nu}_\mu$ CC inclusive cross section
- Currently working to implement systematic uncertainties. We expect flux and calibration to be one of the biggest systematics of the order of 10% based on our neutrino cross section analysis
- Stay tuned for more updates on this analysis in future

Backup

Why Neutrino-Nucleus Interactions

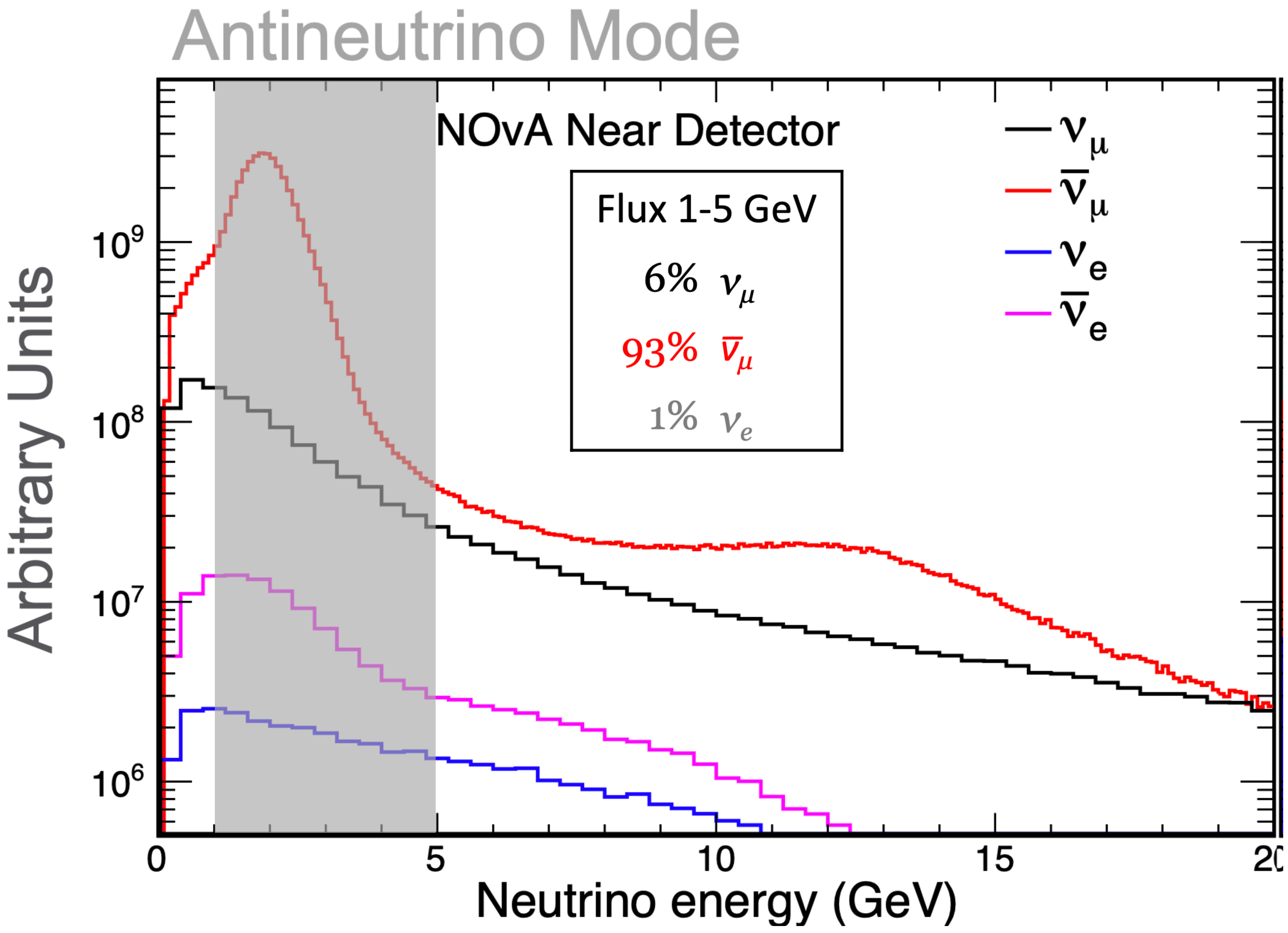
- Neutrino cross-sections are one of the important systematic uncertainties for neutrino experiments

NOvA: *Phys.Rev.D* 98 (2018) 032012

Source of uncertainty	ν_e signal (%)	Total beam background (%)
Cross sections and FSI	7.7	8.6
Normalization	3.5	3.4
Calibration	3.2	4.3
Detector response	0.67	2.8
Neutrino flux	0.63	0.43
ν_e extrapolation	0.36	1.2
Total systematic uncertainty	9.2	11
Statistical uncertainty	15	22
Total uncertainty	18	25

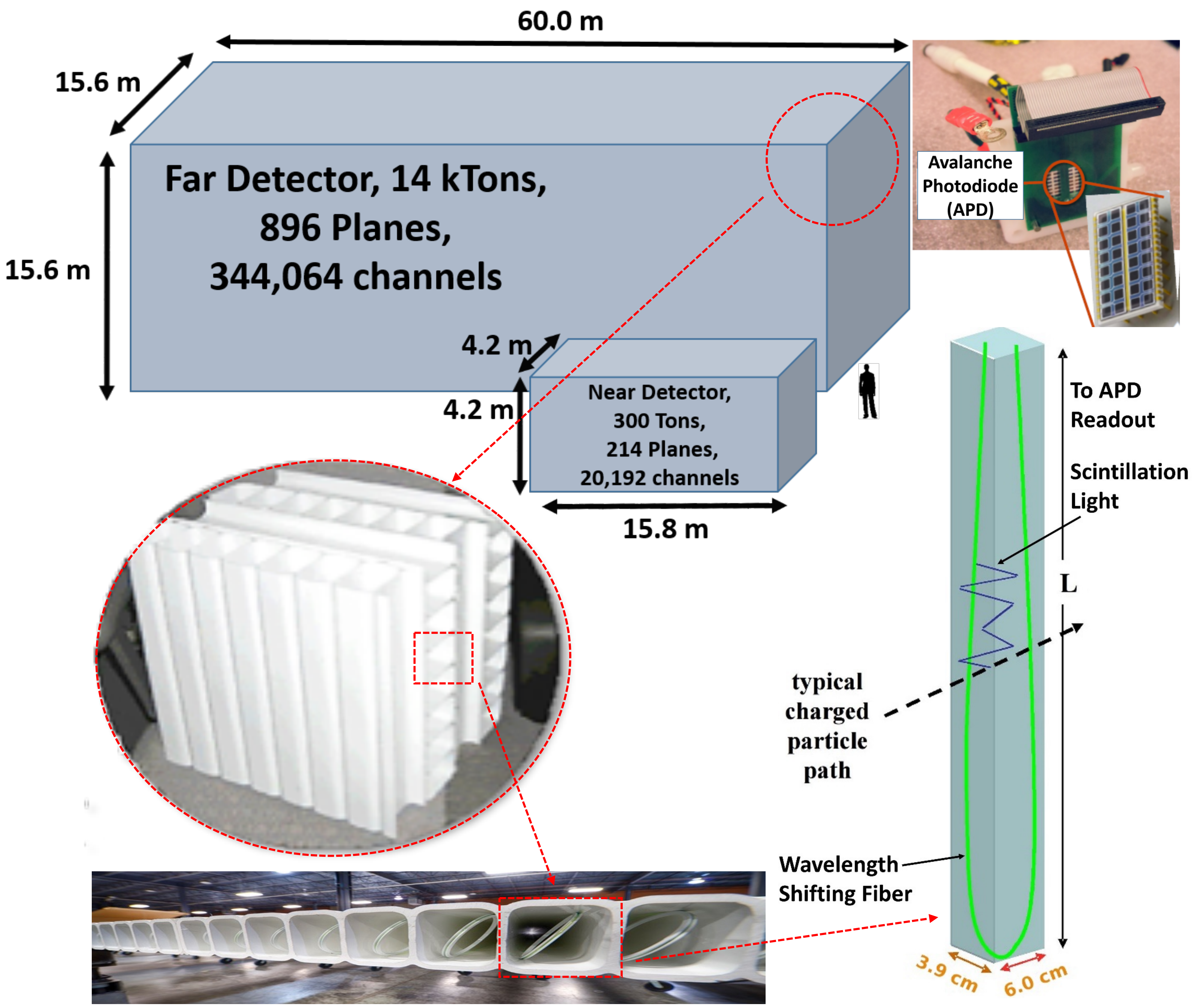
The NOvA Experiment

- NOvA is a long-baseline two-detector neutrino oscillation experiment
- To precisely measure neutrino oscillation parameters, neutrino cross sections and other exotic neutrino searches
- Detectors are 14.6 mrad off-axis resulting in neutrino spectrum peaking around 2 GeV
- High neutrino flux at the ND is used for neutrino cross section measurements



Detectors

- Liquid scintillator filled PVC near and far detectors
- 77% CH_2, 16% chlorine, 6% TiO_2 by mass
- Both detectors are functionally identical which helps in reducing systematic uncertainties
- 3D reconstruction of tracks using orthogonal planes
- Scintillation light is captured by WLS fibers and sent to APD for readouts



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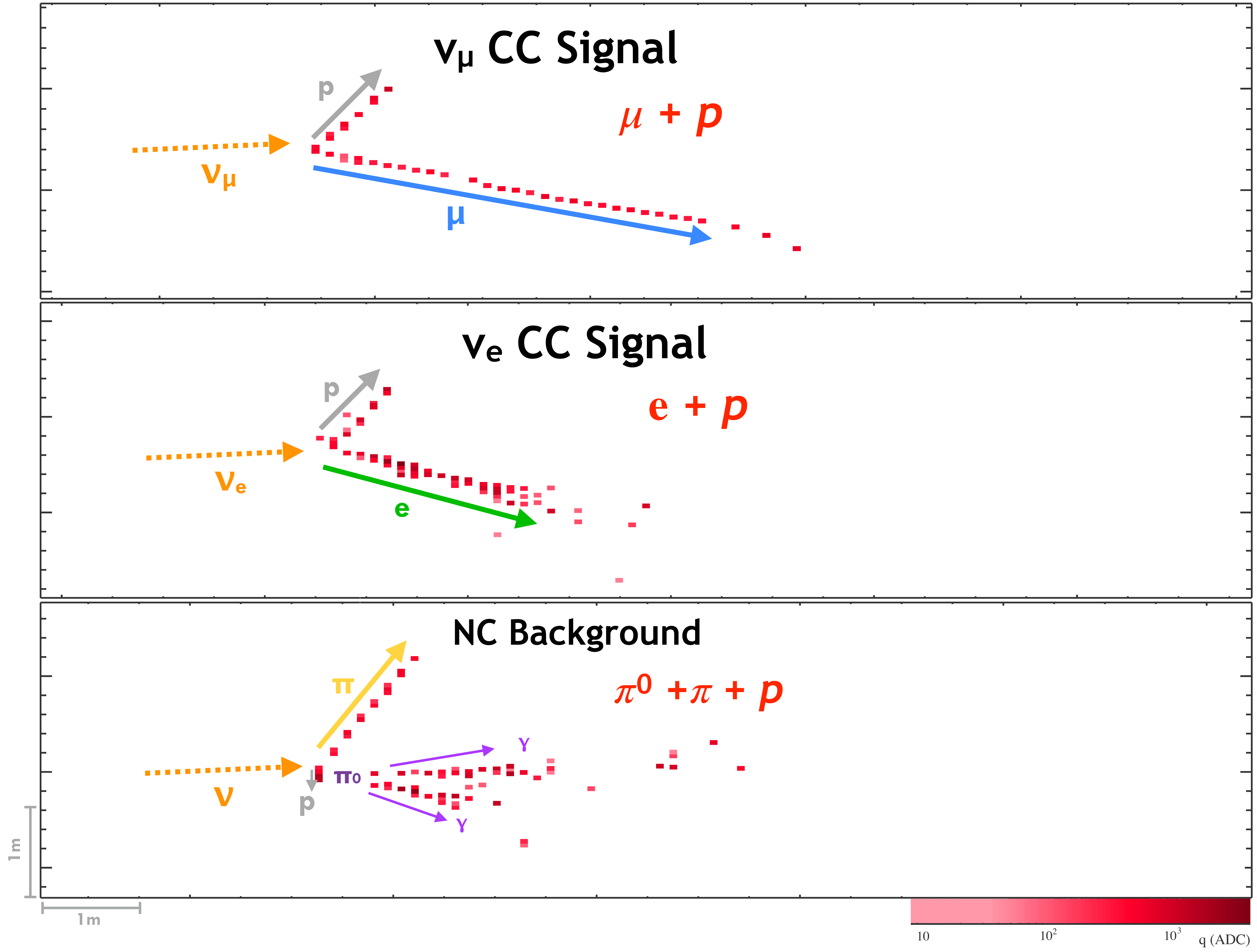
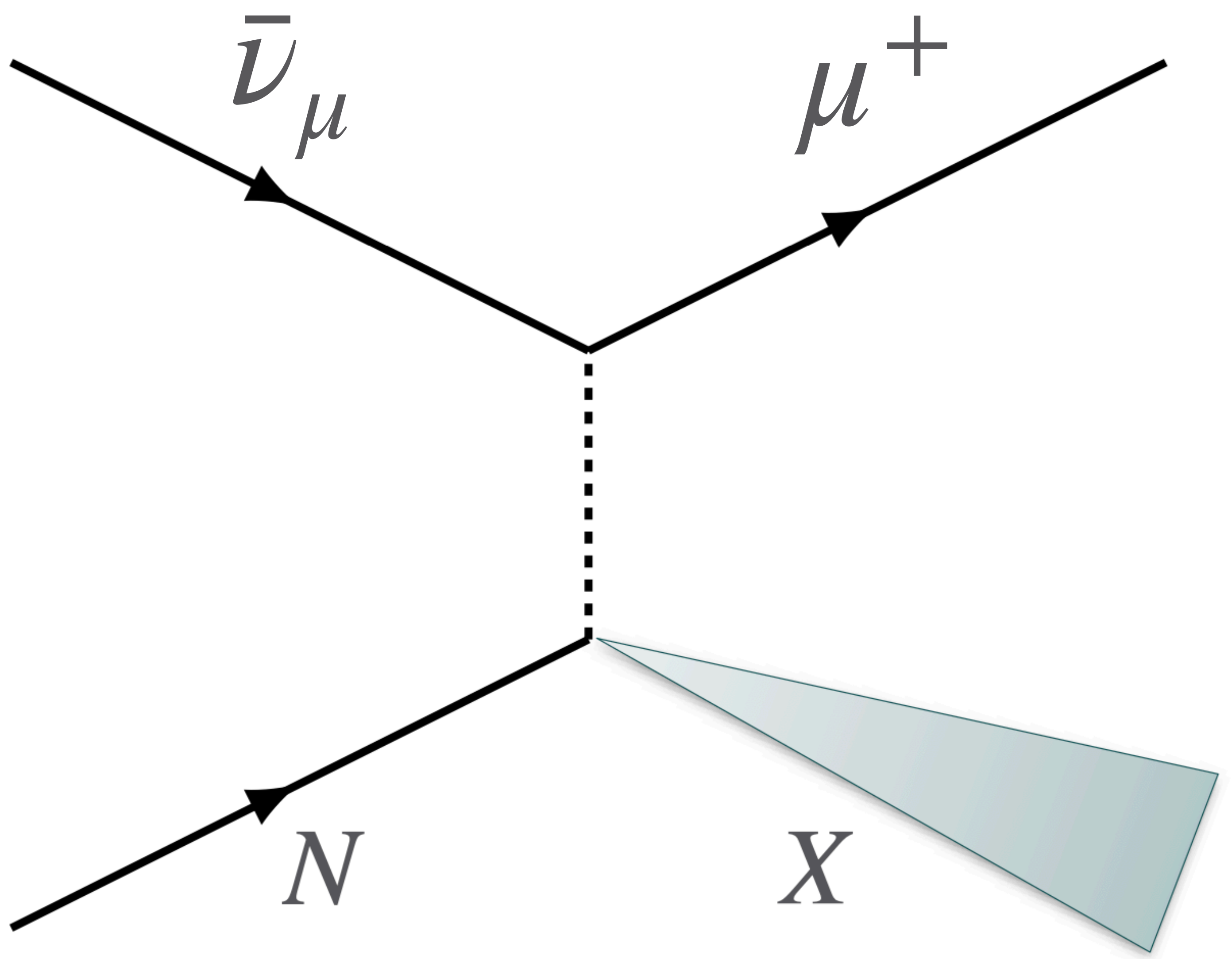


$\bar{\nu}_\mu$ CC Inclusive Cross Section

- NOvA plans to measure $\bar{\nu}_\mu$ CC inclusive cross section using 12e20 proton on target (POT) exposure
- The process is $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$, N is the target nucleus and X represents all other final state particles
- The deliverables are triple differential cross-section in
  - T_μ (GeV): kinetic energy of outgoing anti-muon
  - $\cos\theta_\mu$: scattering angle of the outgoing anti-muon with respect to beam
  - E_{avail} (GeV): energy of all observable final-state hadrons
- This reduces the model dependence of the analysis



Cross sections

$$\frac{d\sigma}{dx_i} = \frac{\sum_j U_{ij}^{-1} (N_j^{\text{sel}} P_j)}{\epsilon_i N_T \Phi \Delta x_i}$$

- For differential cross section measurements, we need
  - To select candidate signal events
  - The unfolding matrix (reco to true migration), purity, and efficiency
  - Integrated beam flux, and number of target nucleons

Triple differential Cross-sections

$$\left(\frac{d^3\sigma}{d\cos\theta_\mu dT_\mu dE_{Avail}}\right)_i = \frac{\sum_j U_{ij}(N^{\text{sel}}(\cos\theta_\mu, T_\mu, E_{Avail})_j P(\cos\theta_\mu, T_\mu, E_{Avail})_j)}{\epsilon(\cos\theta_\mu, T_\mu, E_{Avail})_i(\Delta\cos\theta_\mu)_i(\Delta T_\mu)_i(\Delta E_{Avail})_i N_{\text{target}}\phi}$$

- We plan to measure cross section in 518 3D bins of T_μ, $\cos\theta_\mu$ and E_{avail} analysis variables
- Corrections from unfolding, purity, and efficiency are applied to the selected candidate signal events
- Splitting cross sections into bins of E_{avail} gives us better handling to understand cross sections of different interaction modes