NOvA Cross Section Results

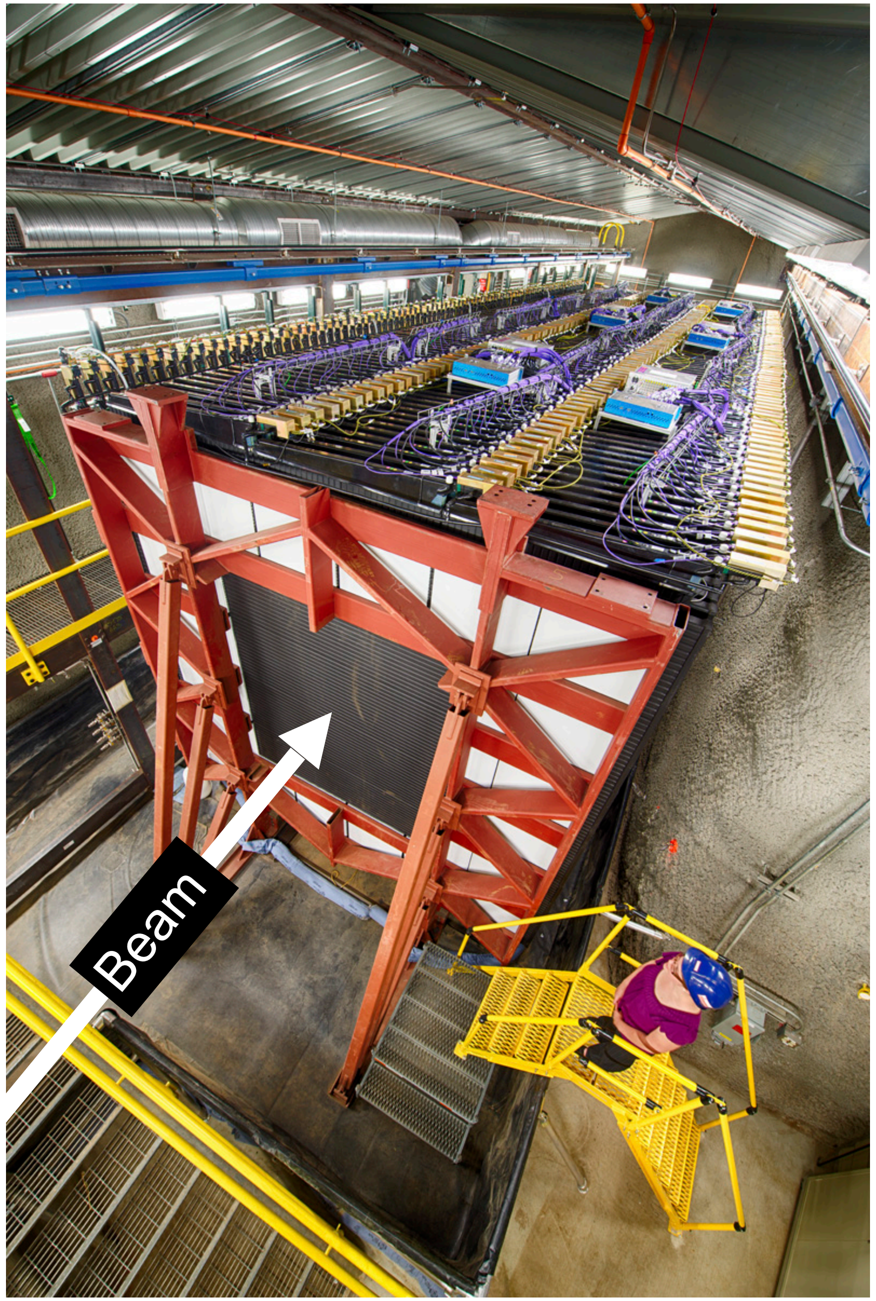
Matthew Judah for the NOvA Collaboration

NuFACT 2018, Virginia

August 13, 2018

NOvA - NuMI Off-Axis ν_e Appearance Experiment

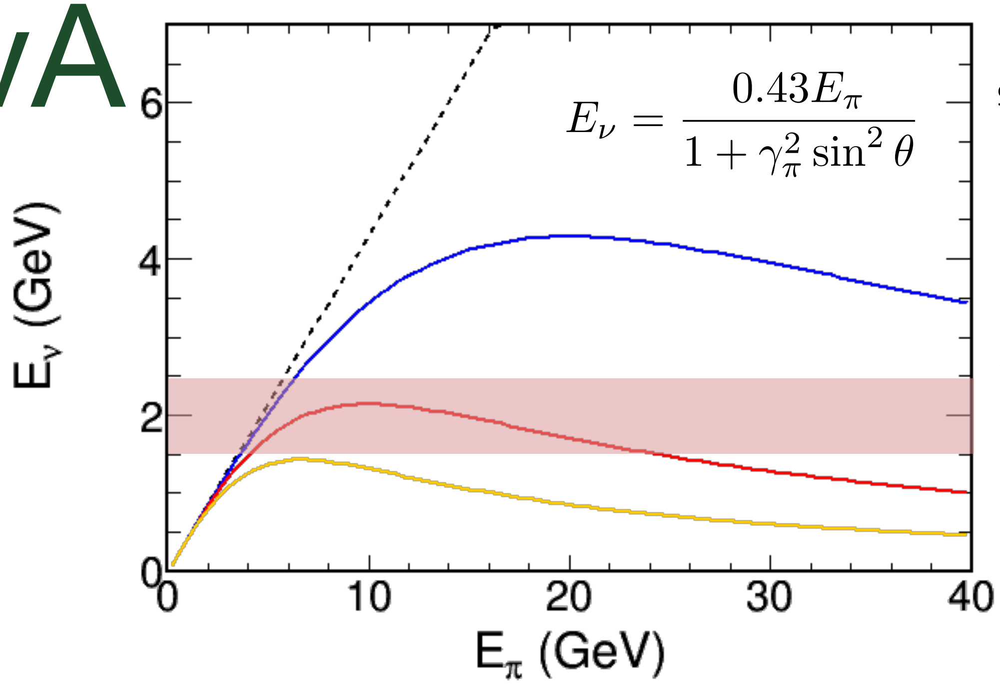
- NOvA is a long baseline oscillation experiment to:
  - Measure the mixing angle θ_{23}
  - Determine the CP-violating phase, δ_{CP}
  - Determine mass hierarchy
- Near Detector provides an excellent platform to measure neutrino interaction cross sections
- These measurements can:
  - Constrain our cross-section systematics
  - Contribute to the current efforts of the neutrino community on understanding neutrino interactions.
  - Collaborate with future experiments

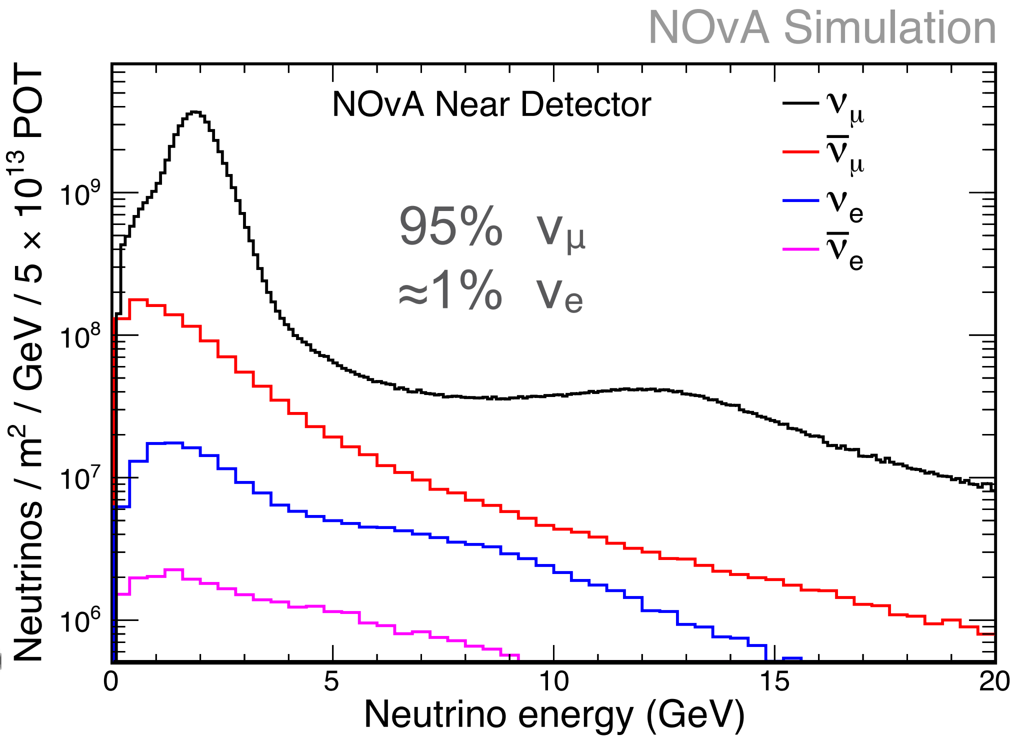


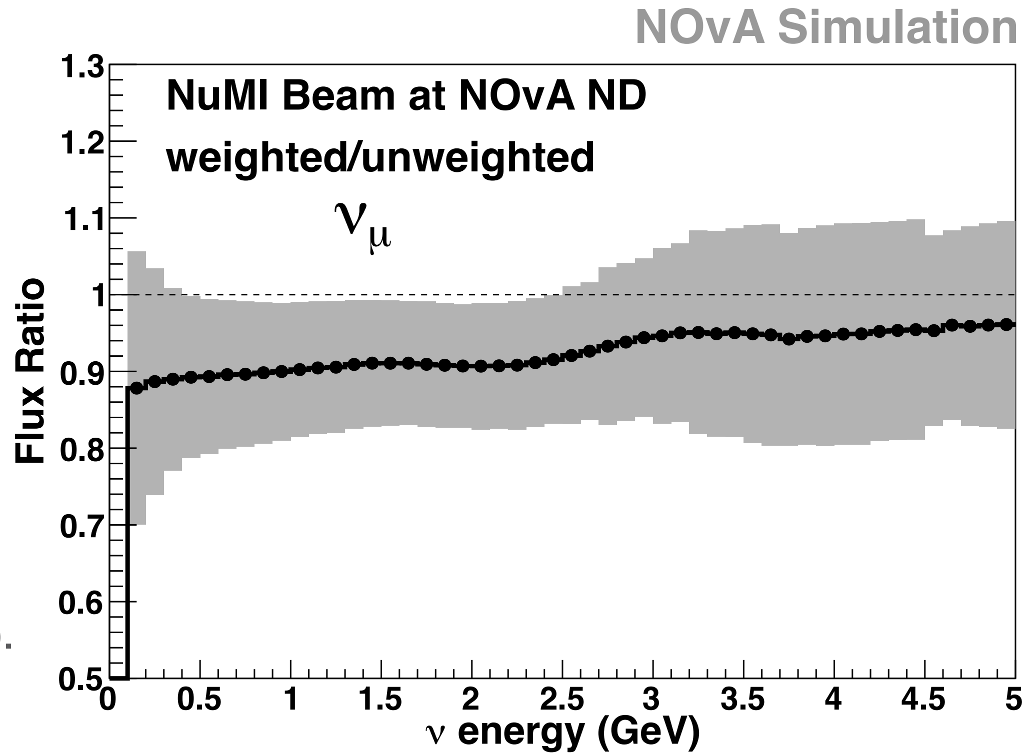
Flux at NOvA

Detectors are 14 mrad off-axis with respect to the NuMI beam axis:

- Narrow-band beam centered around 2 GeV
- Hadron production uncertainties are mostly a normalization effect
- Hadron production uncertainty constraint by external hadron production data



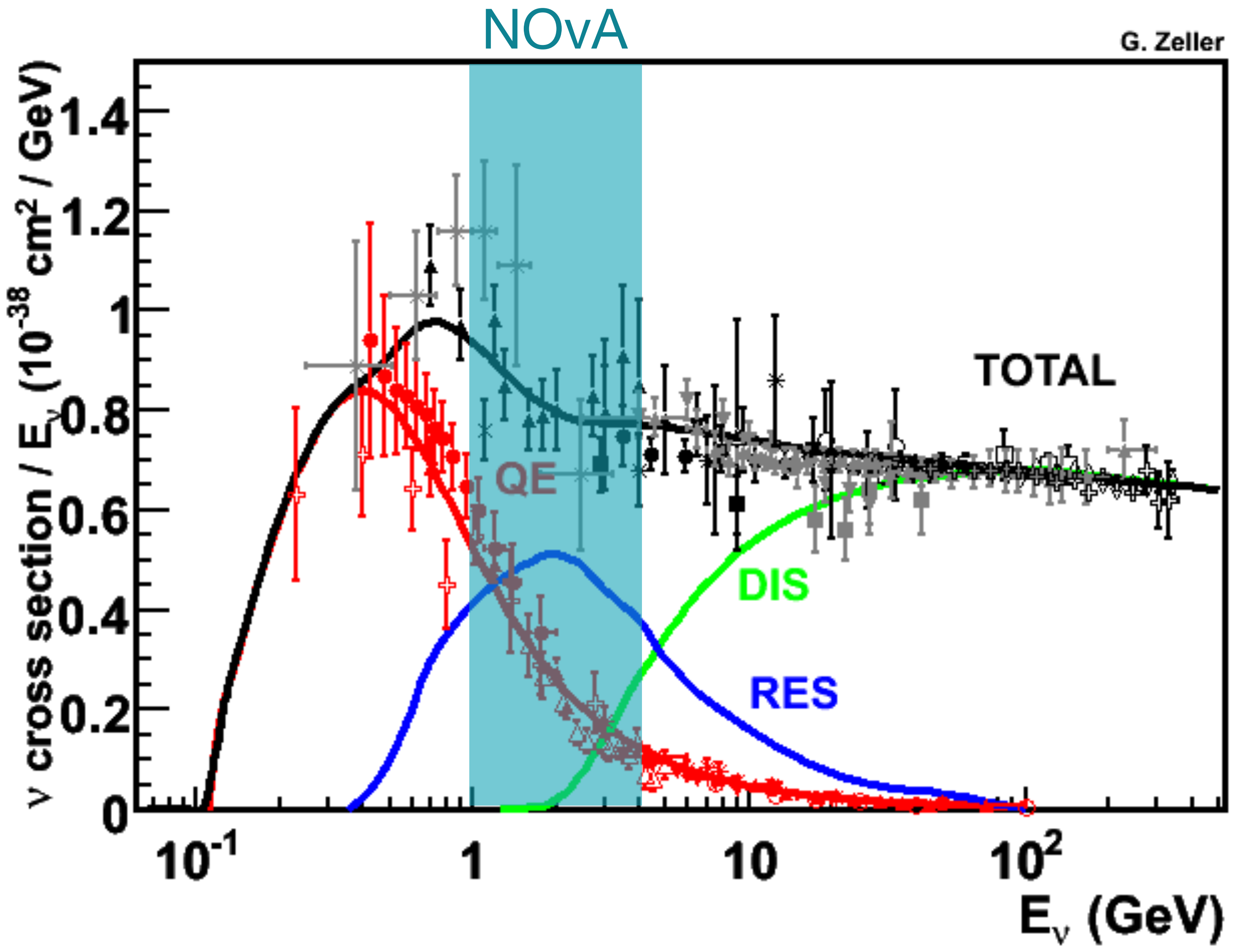




PPFX, Package to Predict the FluX, Phys. Rev. D 93, 112007 (2016).

Flux at NOvA

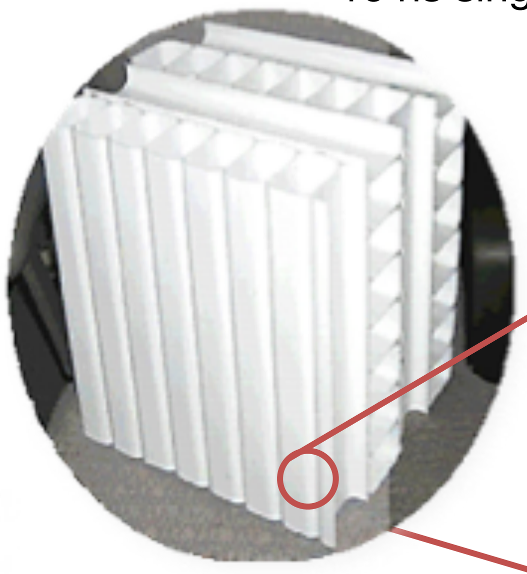
- Even with a narrow-band beam, NOvA has sensitivity to many different ν+A interaction channels
- Protons on target:
  - 8.09 x 10^{20} in neutrino mode
  - Currently 6.26 X 10^{20} in antineutrino mode



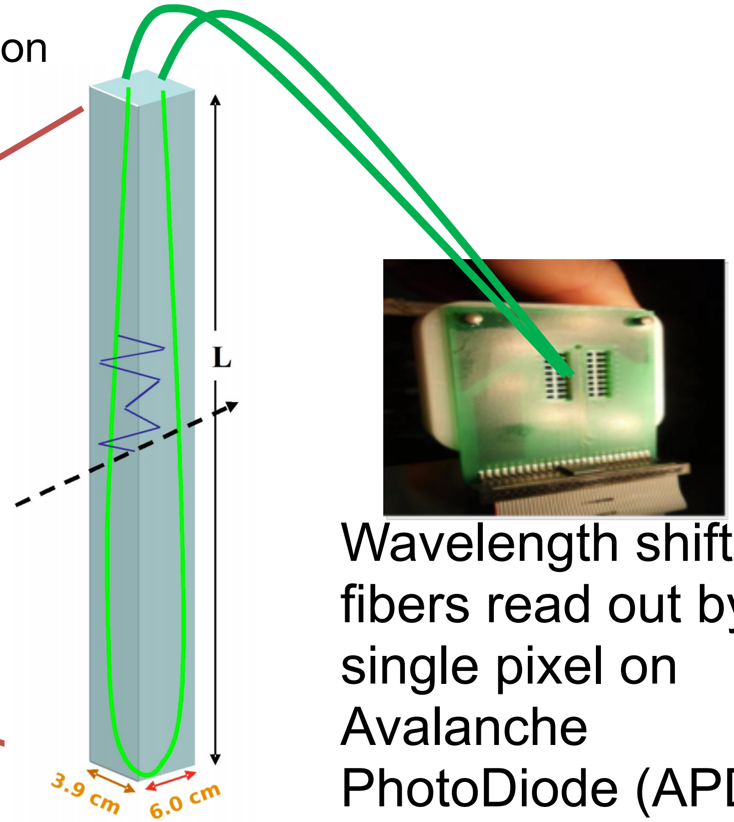
J.A. Formaggio, G.P. Zeller Rev. Mod. Phys. 84, 1307 (2012)

NOvA Near Detector

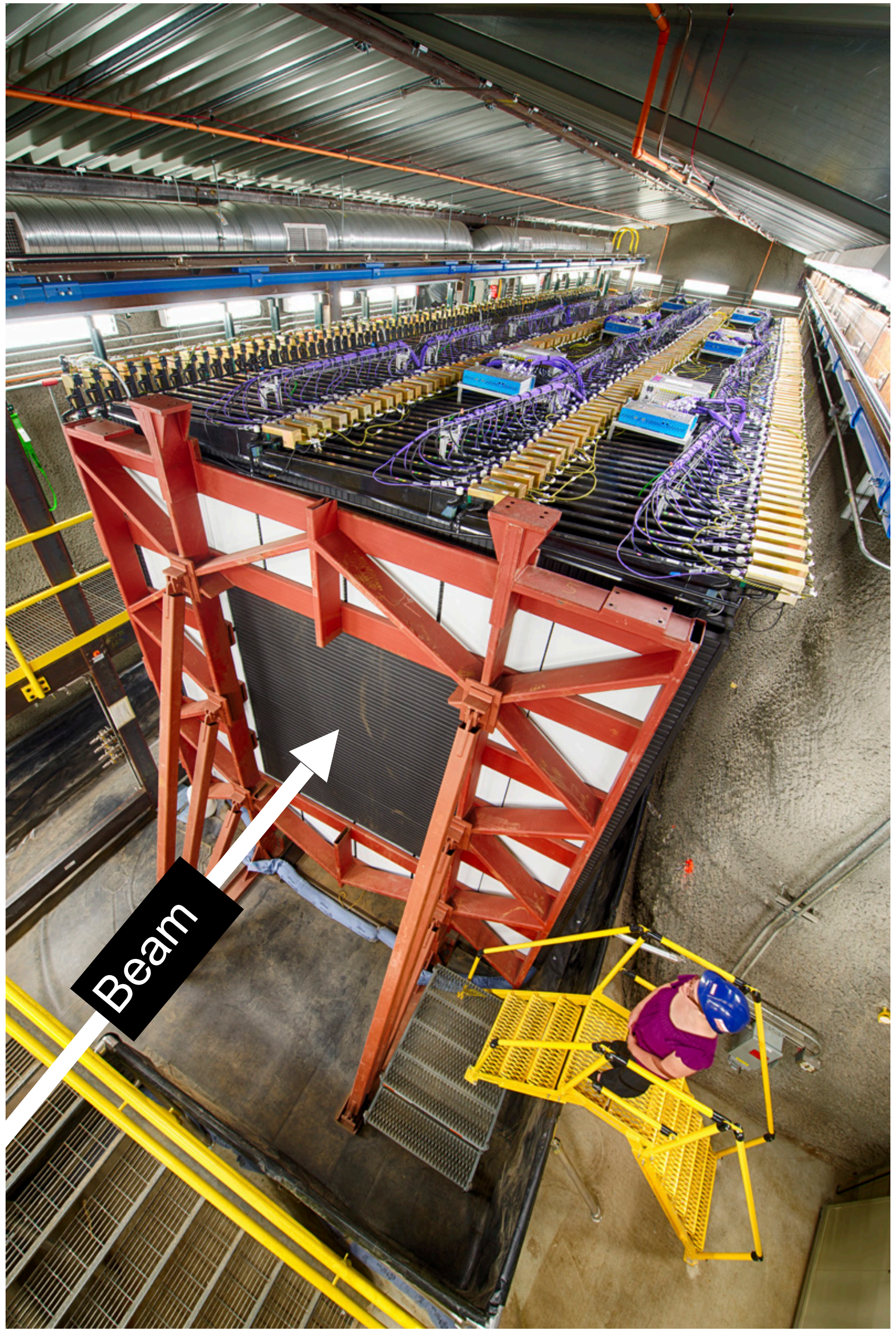
- Lies 1 km from the source, 100 m underground
- Tracking calorimeter:
    - Segmented (alternating horizontal/vertical)
    - Low Z, with 65% active volume
    - 290 tons, 77% hydrocarbon, 16% chlorine, 6% TiO_2 by mass
    - Muon catcher (steel + NOvA cells) ranges-out ~ 2 GeV muons at the downstream end
    - ~10 ns single hit timing resolution



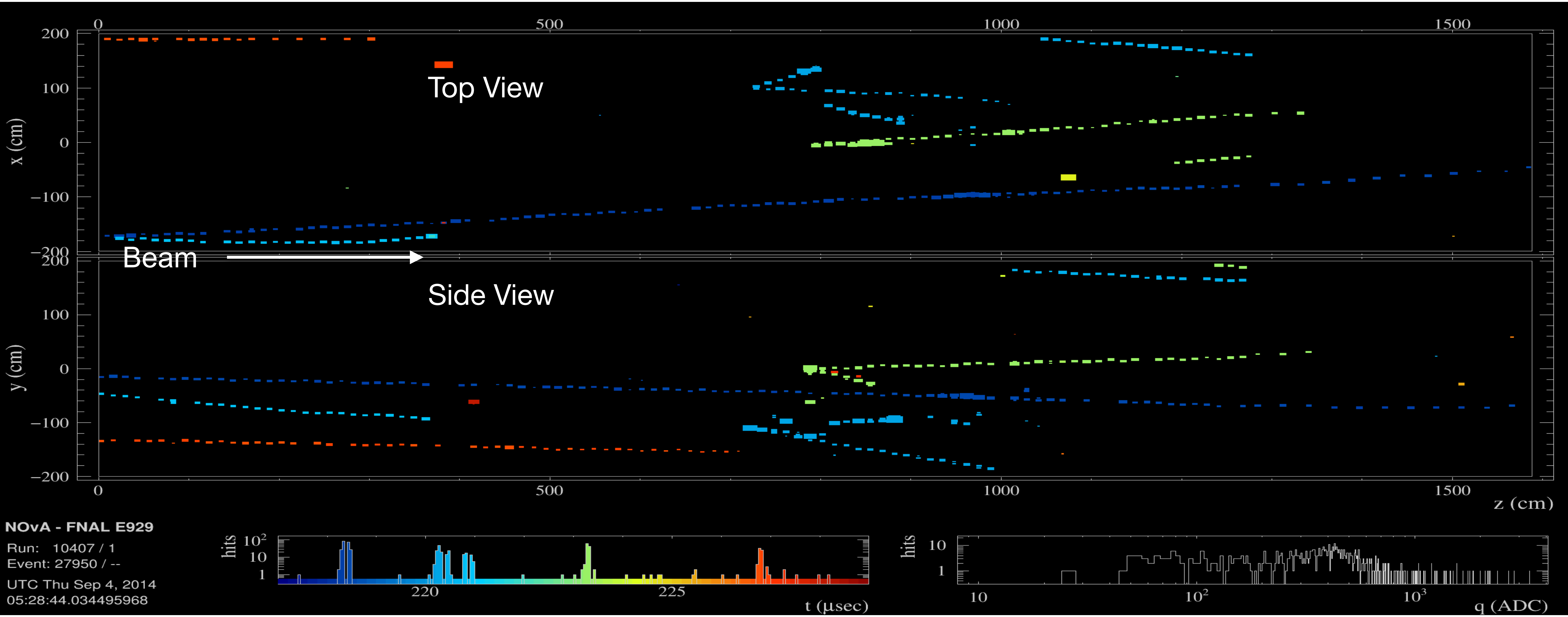
Alternating planes allow for 3D reconstruction



Wavelength shifting fibers read out by a single pixel on Avalanche PhotoDiode (APD)

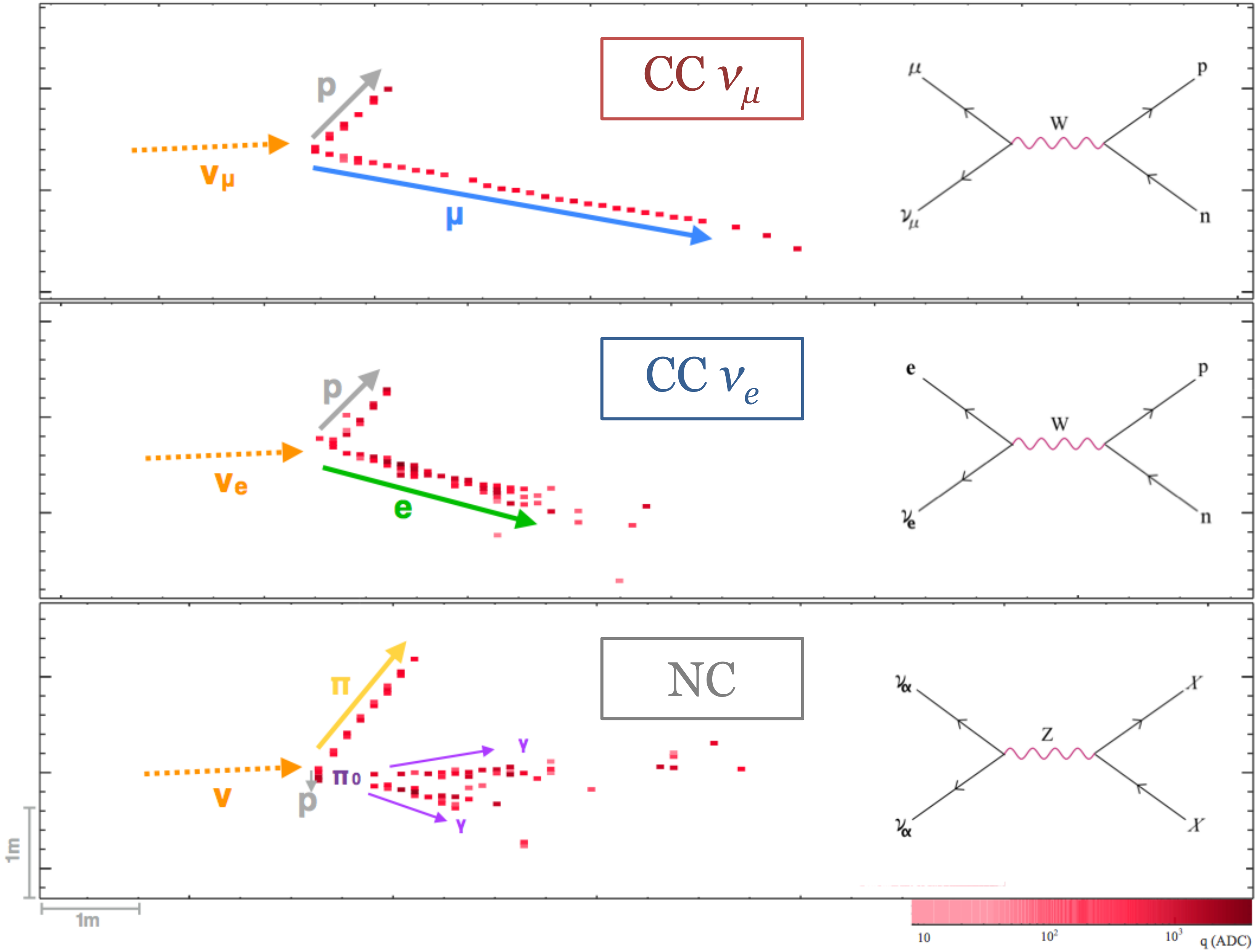


NOvA Near Detector



- Events are separated by slicing algorithm that accounts for correlations between hits in time and space.
- Tracks and showers are reconstructed from these hits.

Neutrino Candidates from NOvA Data



Current NOvA Cross Section Analyses

CC Inclusive
- Muon neutrino
- Electron neutrino

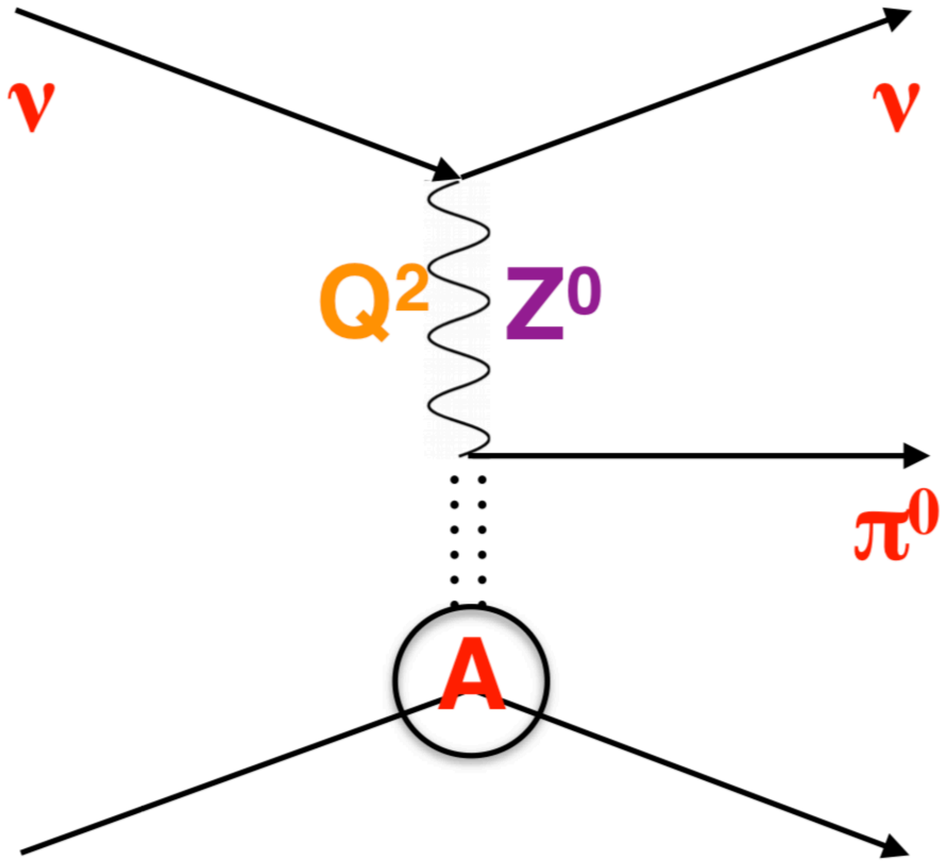
CC muon neutrino semi-[ex,in]clusive
- Charged Pion
- Zero Pion
- 2p2h
- Neutral Pion ← Results

NC
- Coherent Neutral Pion ← Results
- Inclusive Neutral Pion

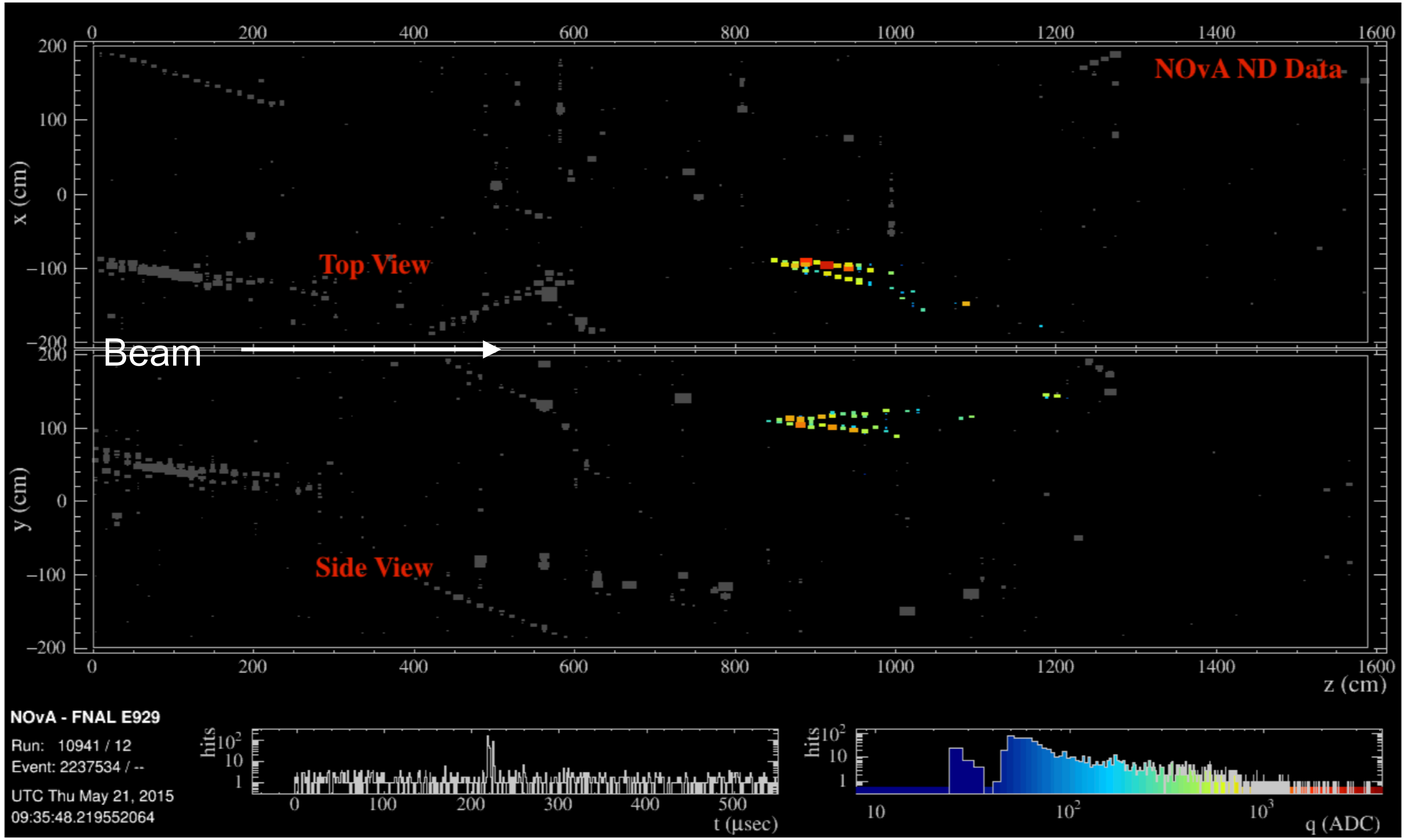
Others
- Neutrino-on-electron
- Booster neutrino at NOvA

Neutral Current Coherent Pion Production

- Neutrino coherently scatters off target nucleus via neutral current exchange producing a π^0
- Very small momentum transfer, no quantum number exchange (charge, spin, isospin)
- Target nucleus remains in ground state
    - No vertex activity
- Single forward-going pion in the final state, no other pions or nucleons



Analysis Strategy



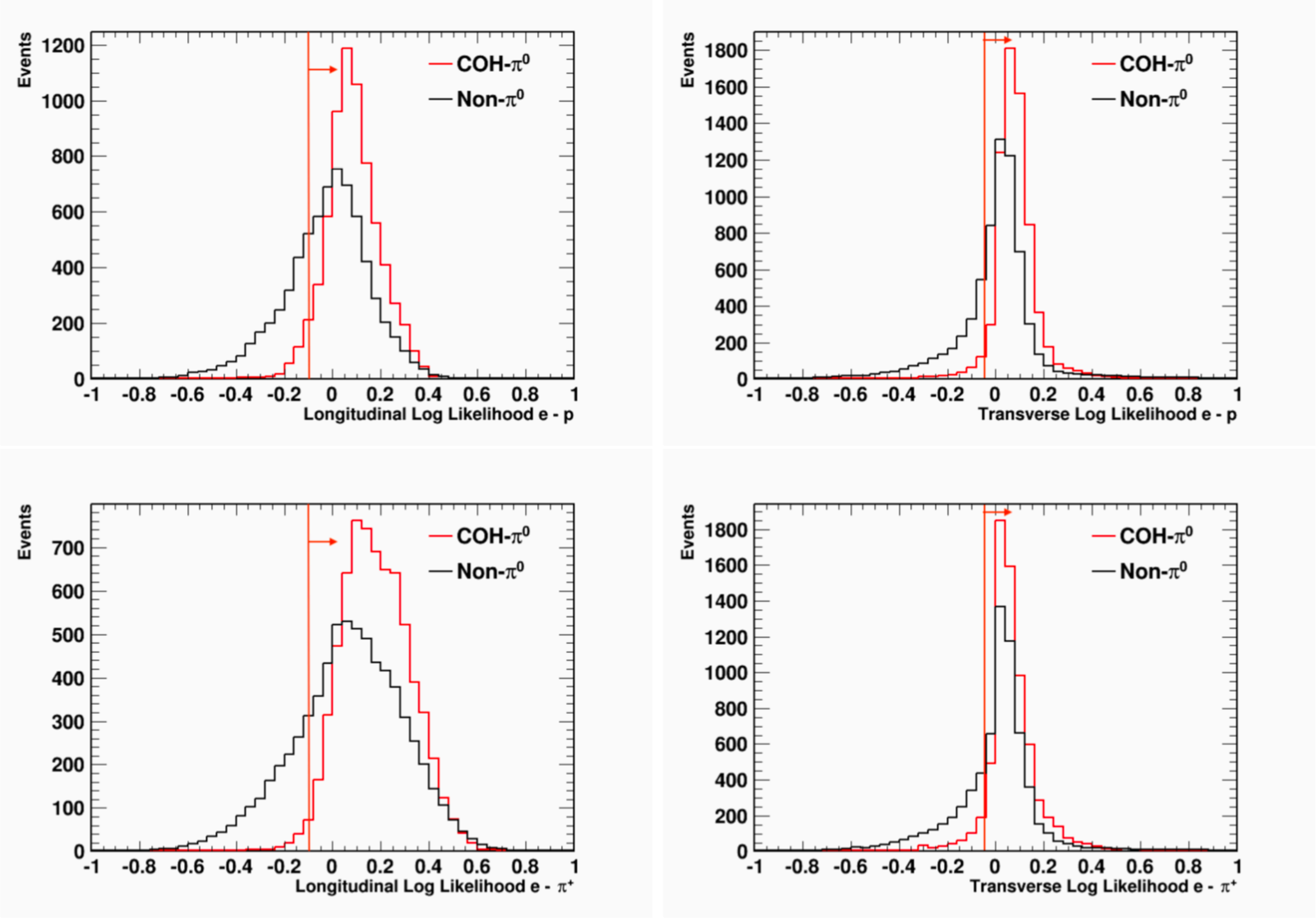
- Select events with no muon track candidate, two photon showers candidates, and no other reconstructed tracks or showers
- NC coherent candidate event from data is shown on the left

Identifying Photon Showers

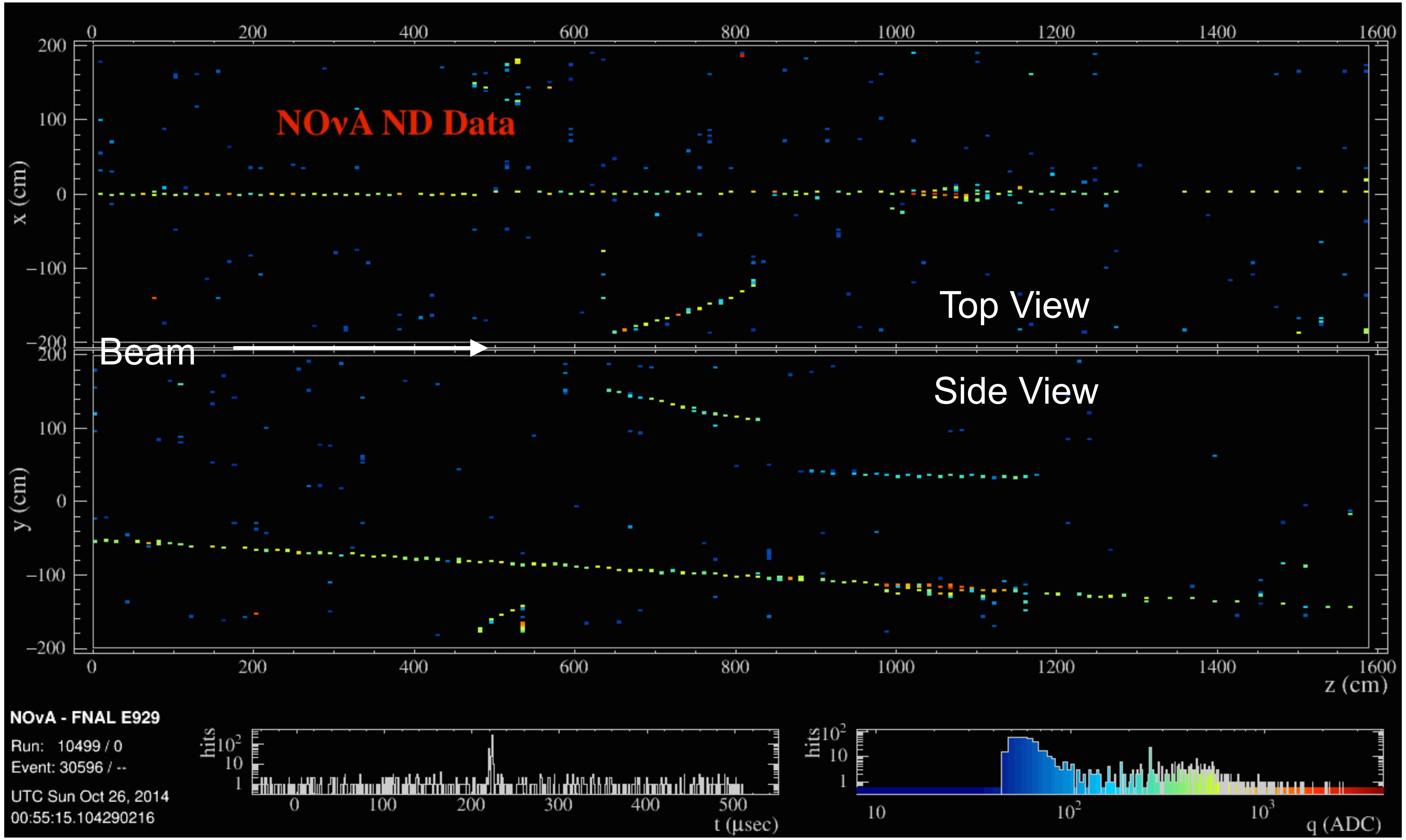
Both photon showers are identified using likelihoods based on longitudinal and transverse dE/dx information

- Red line depicts cut used to select highest energy photon shower candidate
- Second photon shower candidate is selected using slightly different cuts

- Use data-driven technique to constrain photon shower identification

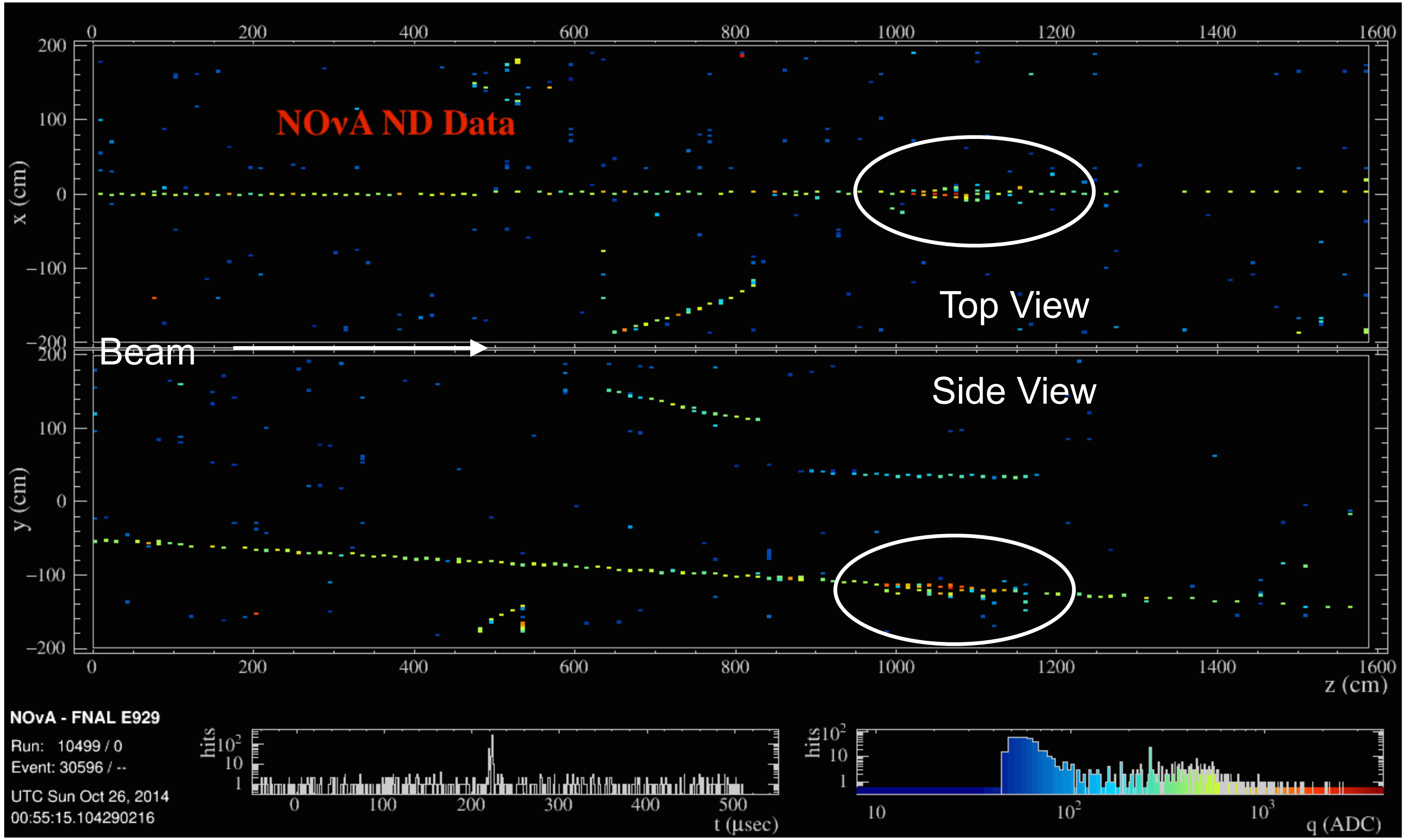


Constrainting Photon Simulation



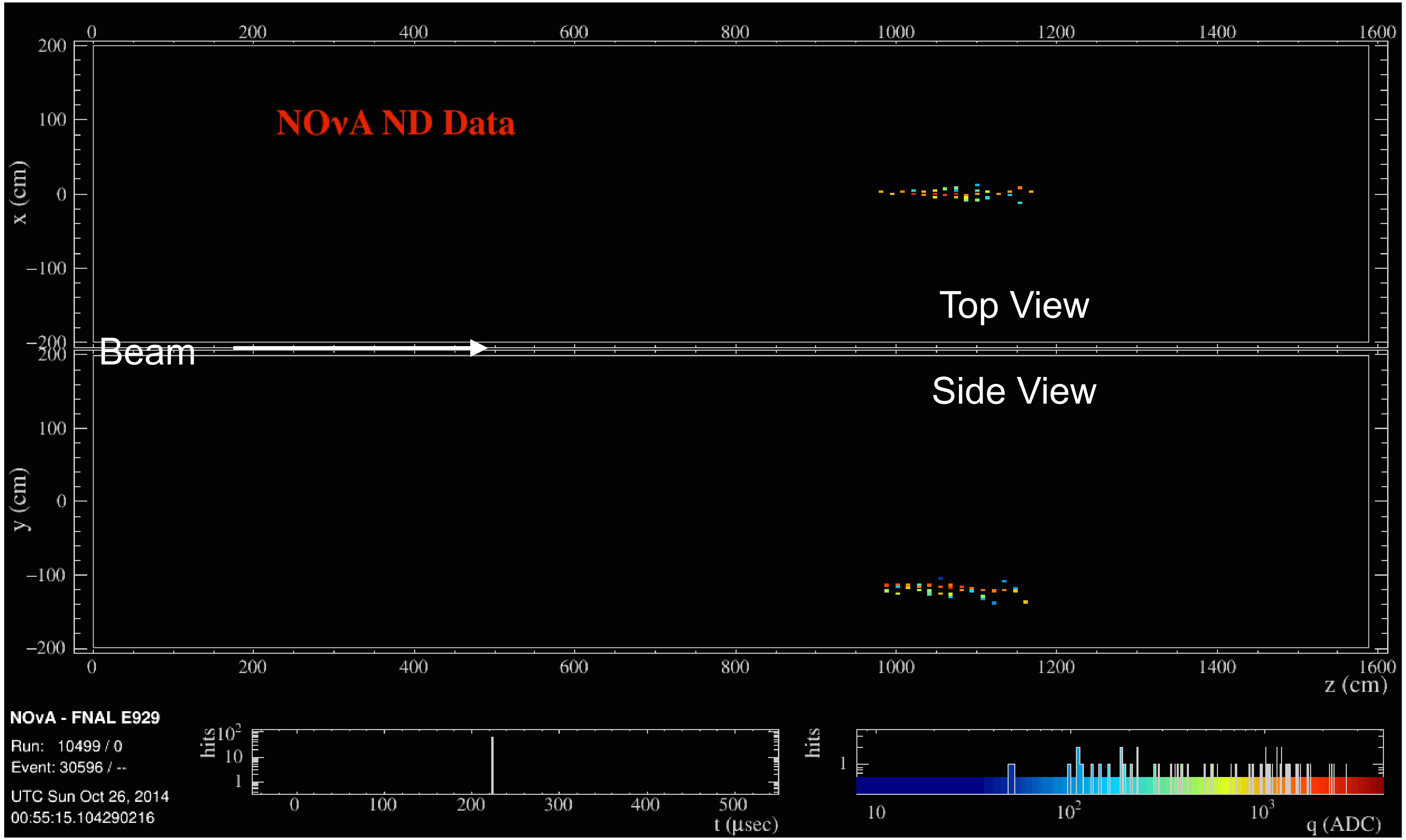
- Muons from interactions outside of the detector can induce EM showers in the detector via bremsstrahlung radiation

Constrainting Photon Simulation



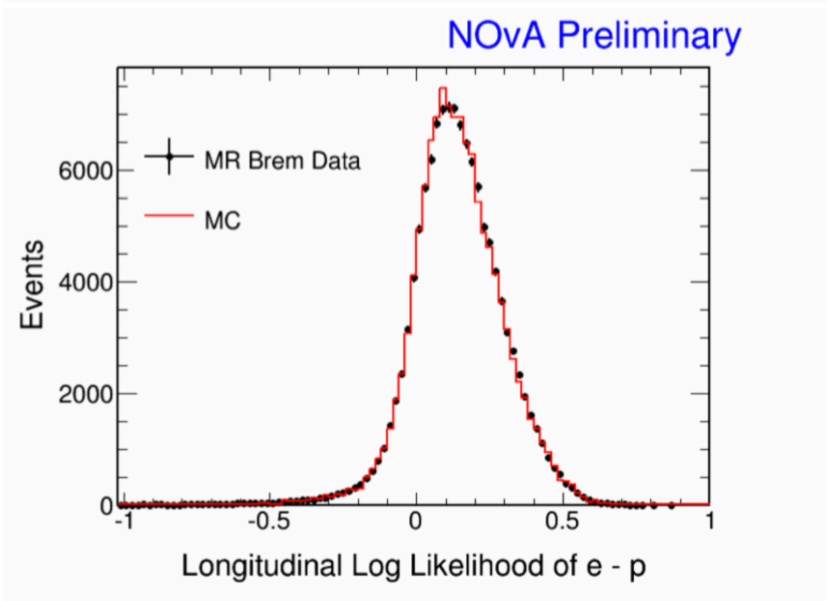
- Muons from interactions outside of the detector can induce EM showers in the detector via bremsstrahlung radiation
- The EM showers are identified around the muon track

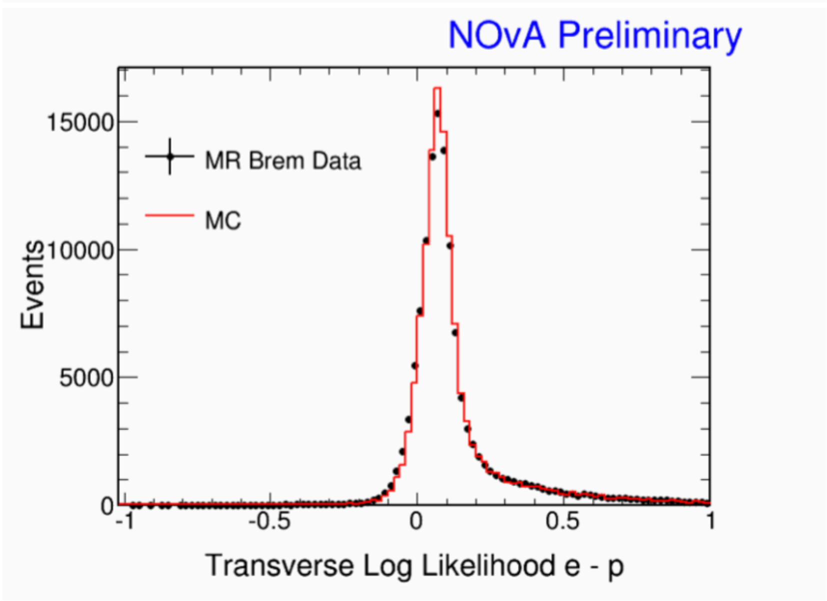
Constrainting Photon Simulation

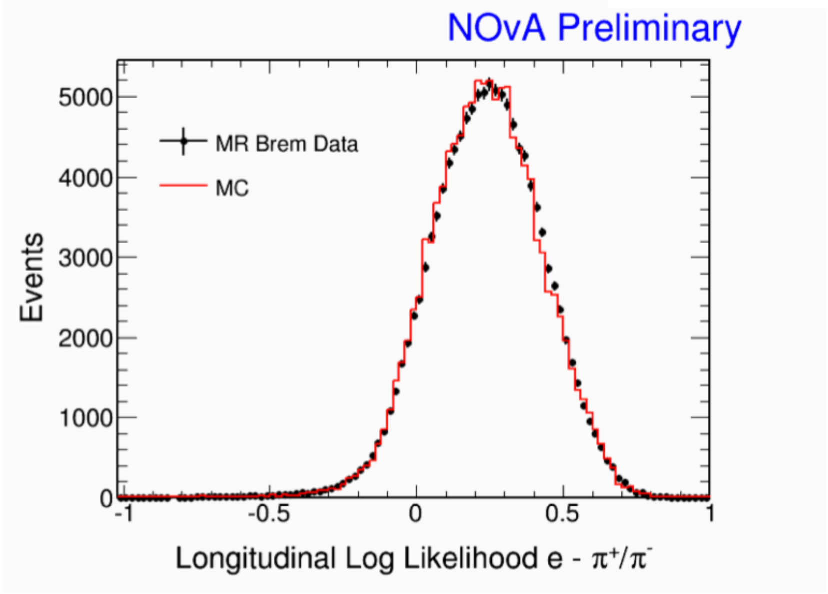


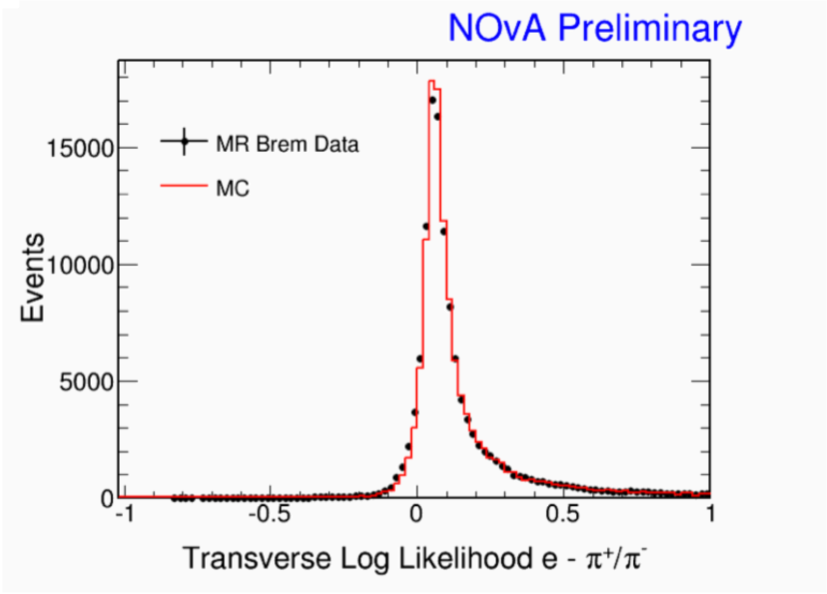
- Muon removal techniques isolate the EM showers
- Data-driven method to constrain photon simulation

Constrainting Photon Simulation



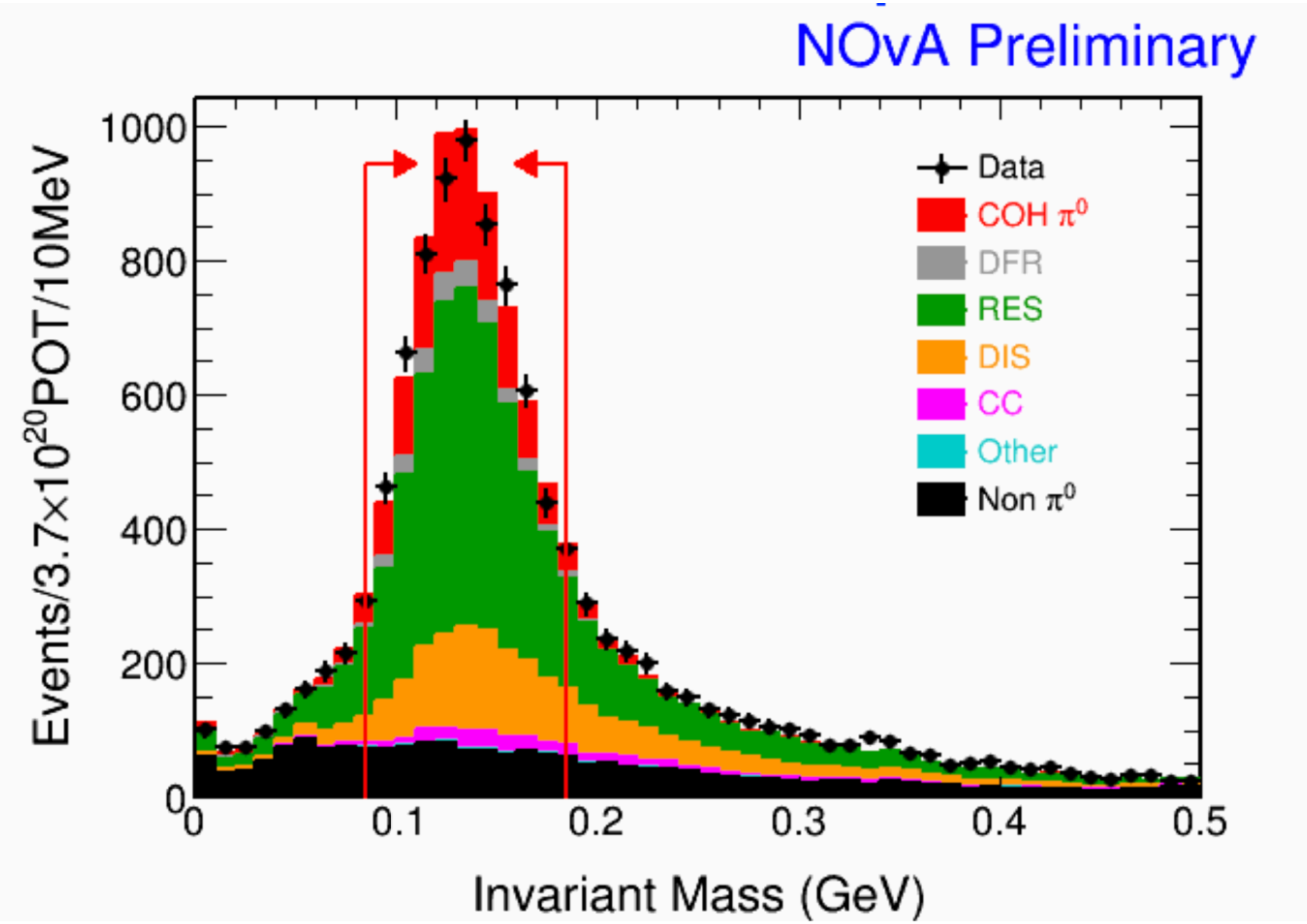






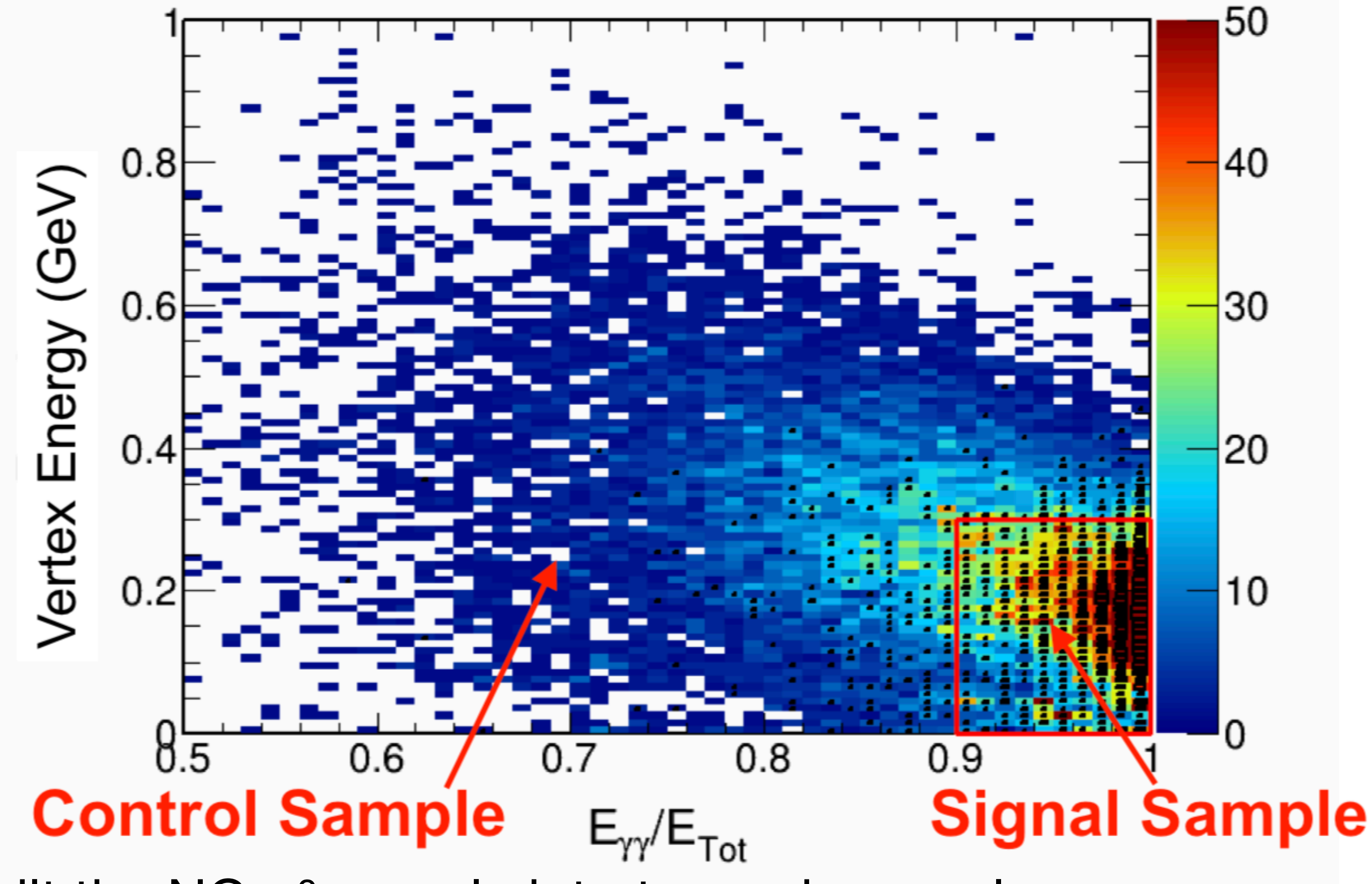
- Very good agreement between bremsstrahlung shower data and MC
- 1% difference in selection efficiency is taken as systematic uncertainties

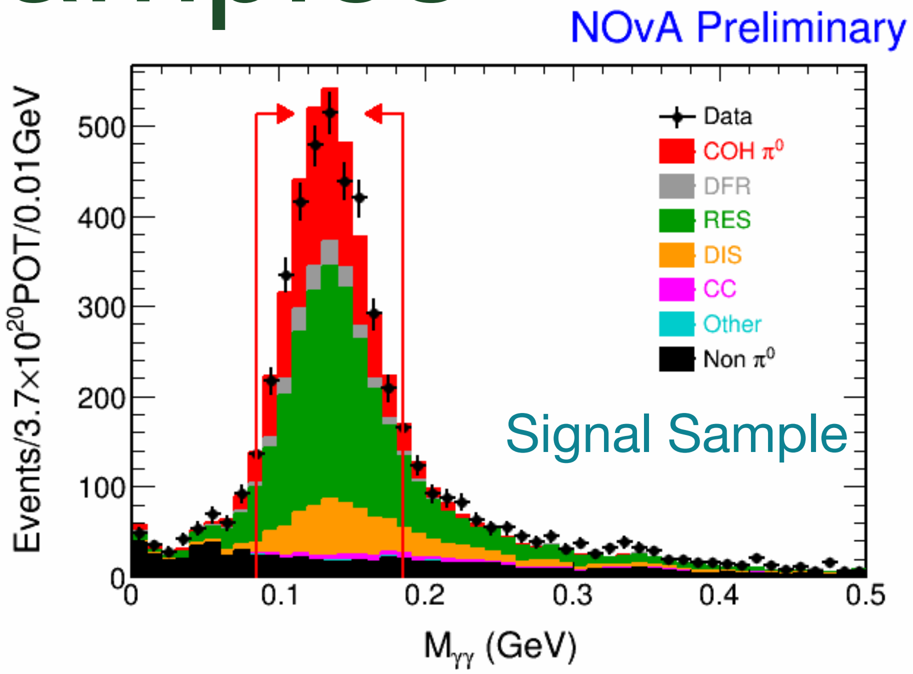
NC π^0 Sample

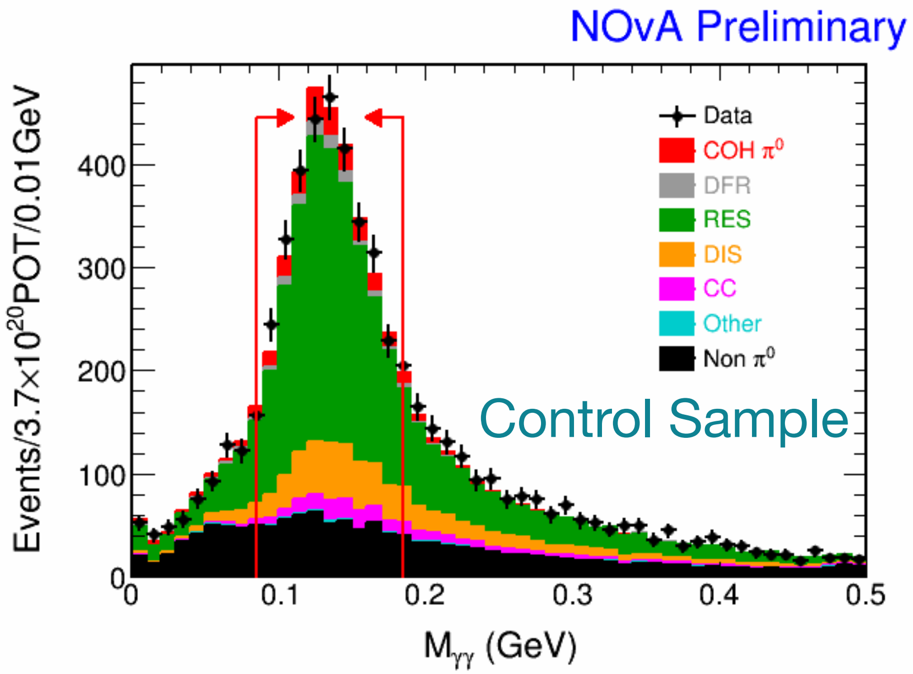


- The NC π^0 sample is defined by:
  - No muon candidate in the event
  - Two photon shower candidates
  - Vertex in the fiducial volume and showers contained
- Background is dominated by resonant and DIS π^0 events
- Cut on invariant mass further reduces these backgrounds

NC π^0 Control and Signal Samples





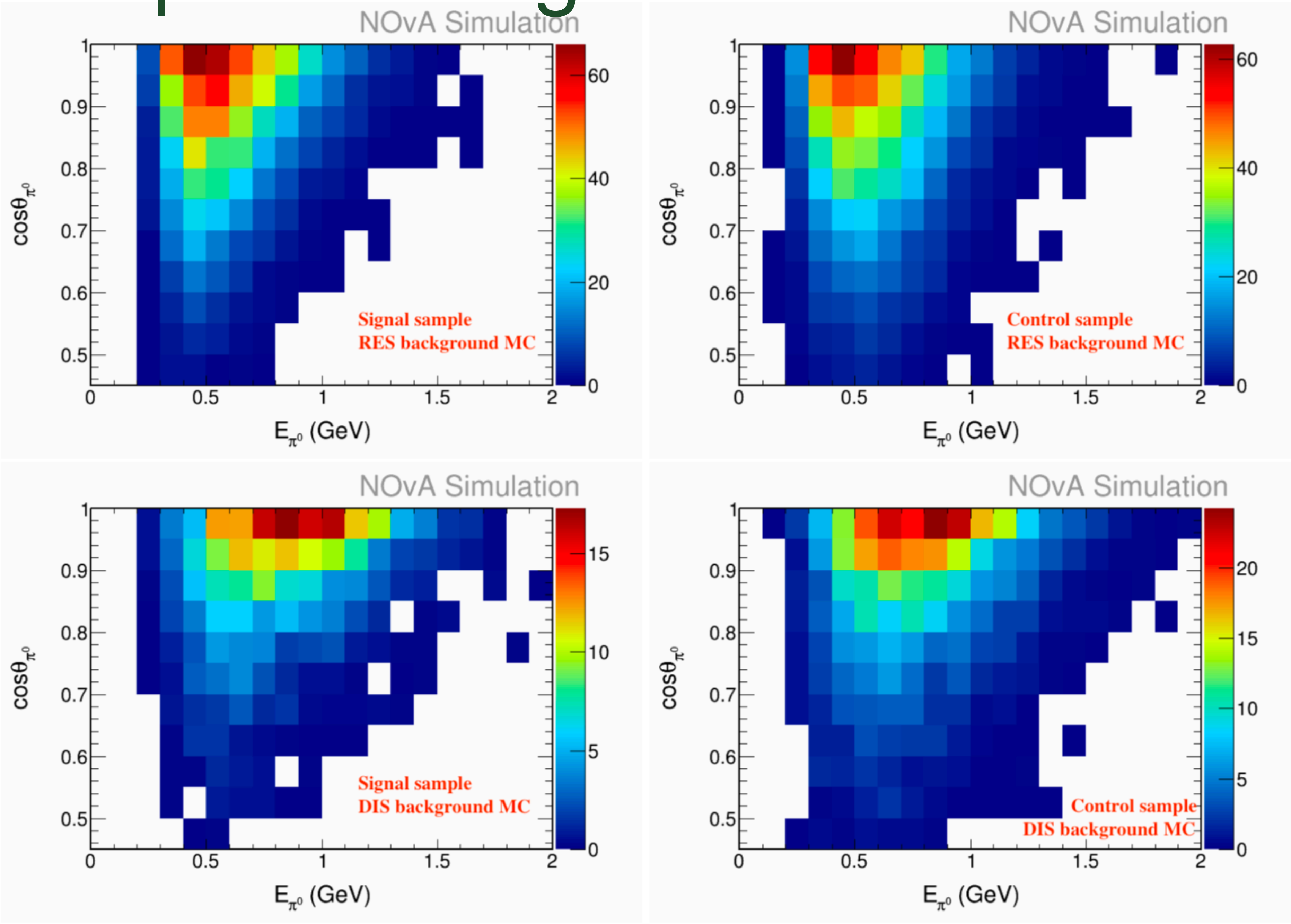


Spilt the NC π^0 sample into two sub-samples:

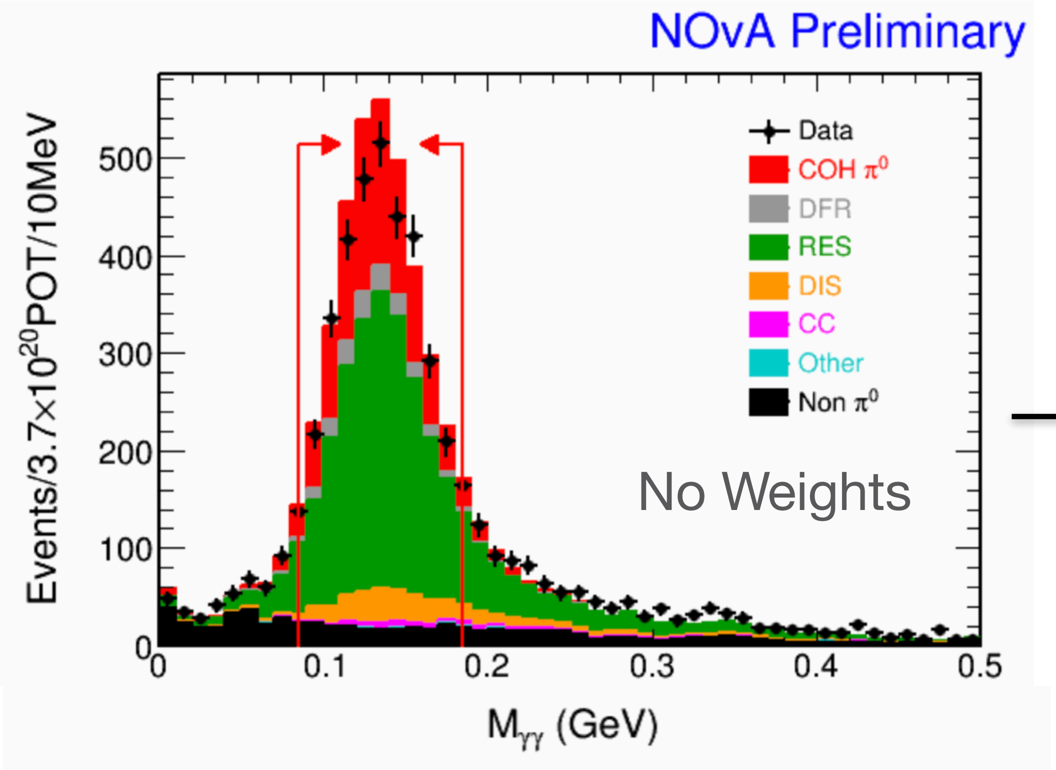
- Signal:events with most of their energy in the 2 photon- showers and low vertex energy: it has >90% of the signal.
- Control -> Consists primarily of backgrounds

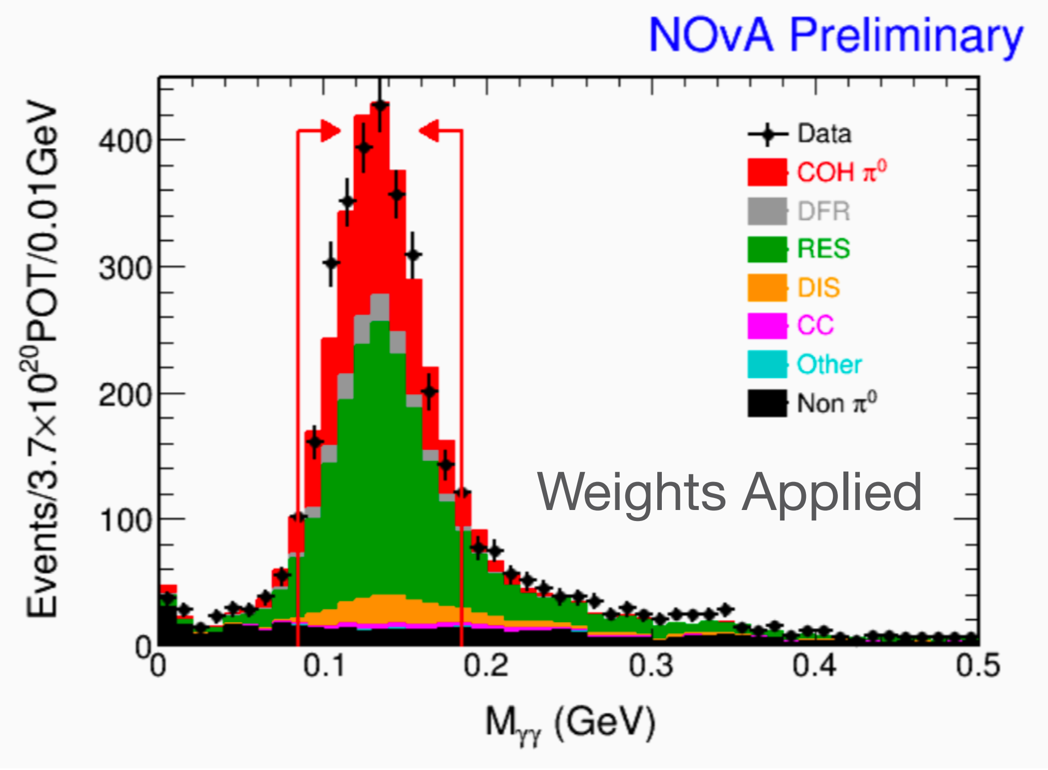
NC π^0 Control Sample - Background Constraint

- The control sample is used to fit background to data using templates in π^0 energy vs angle 2D space
- 2D templates show shape differences between resonant and DIS backgrounds
- Fitting procedure determines constant scale factors for resonant and DIS backgrounds



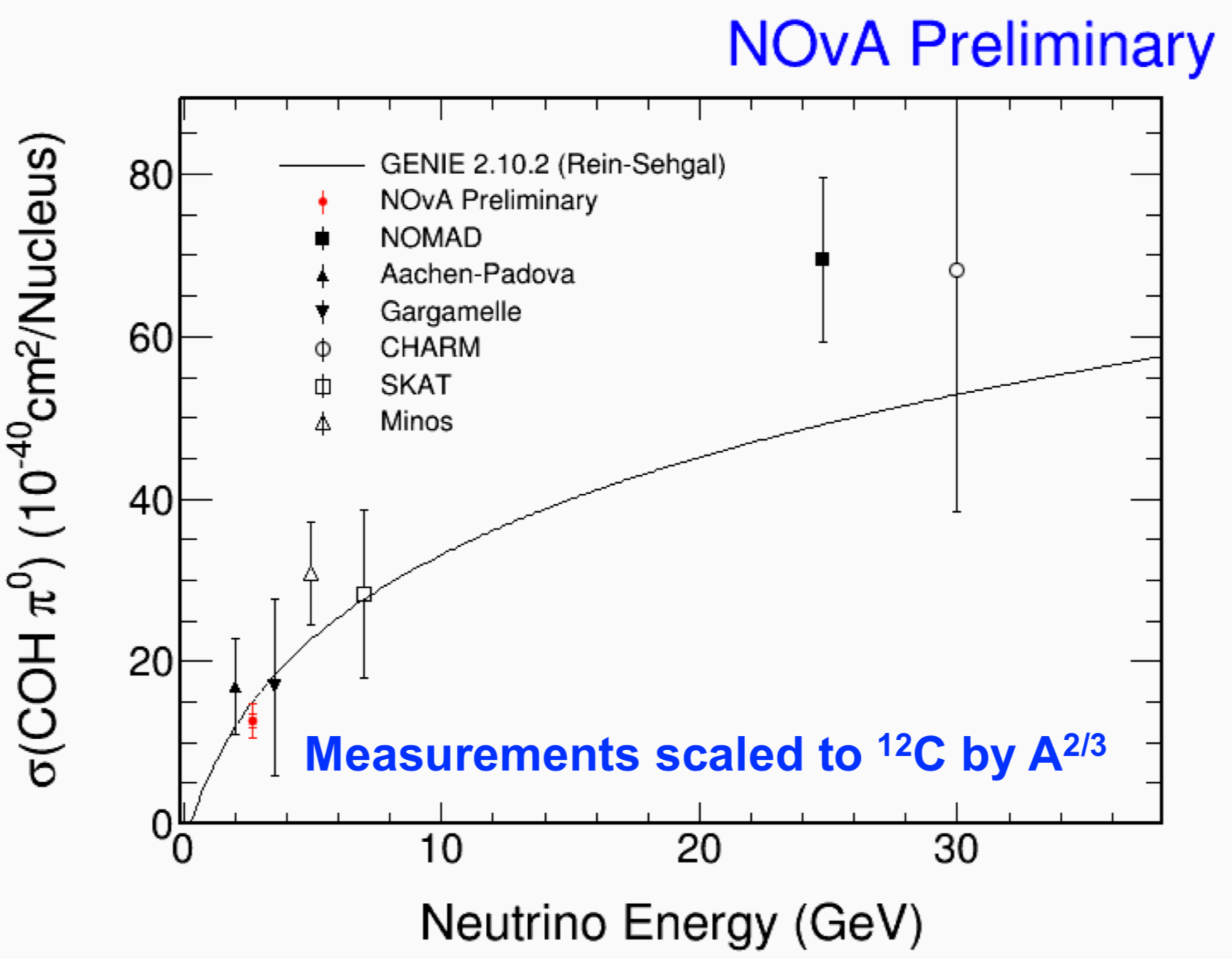
NC π^0 Signal Sample





- Background tuning is then applied to the Signal sample

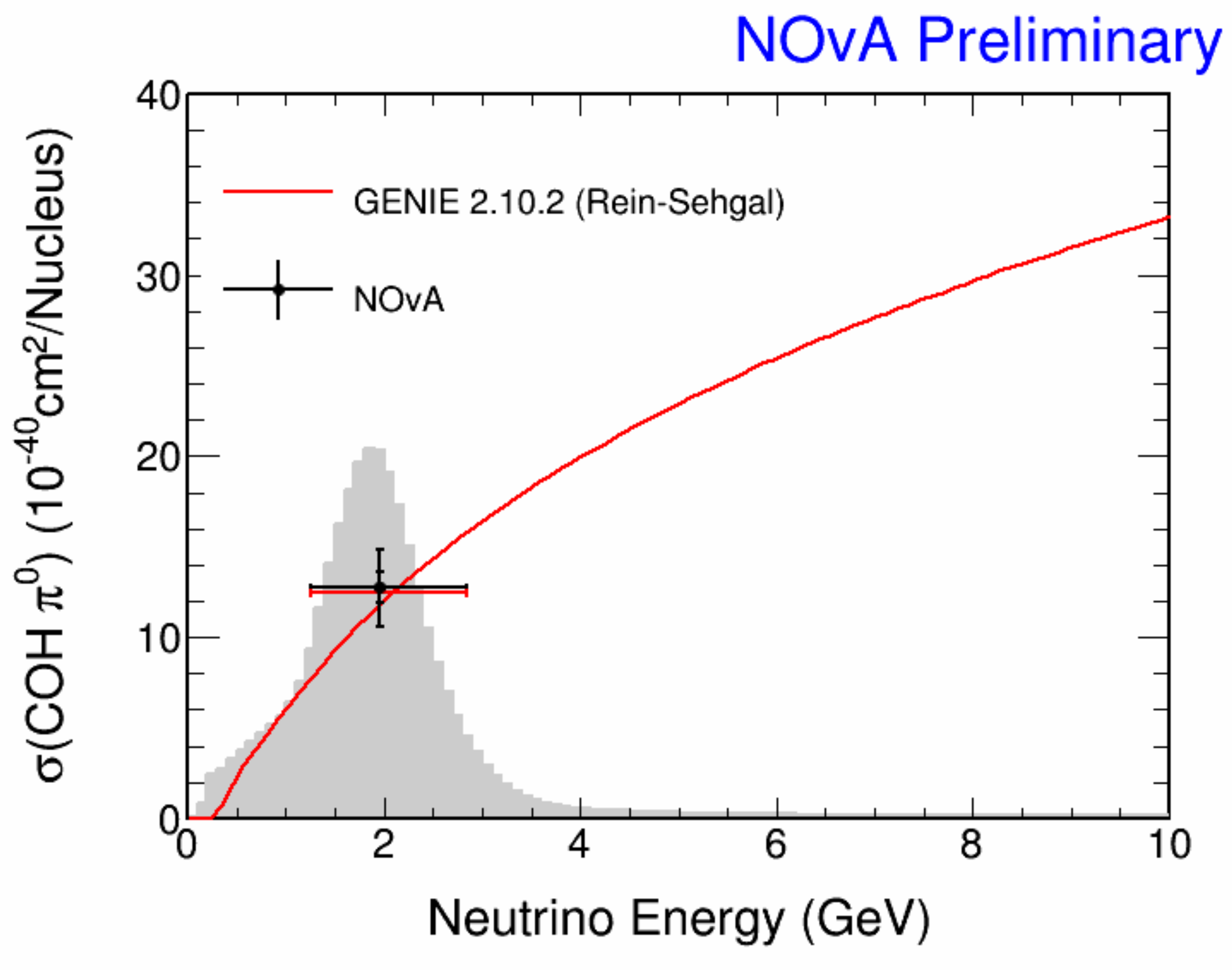
NC Coherent π^0 Results



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- Flux averaged cross section: $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40}\text{cm}^2/\text{nucleus}$

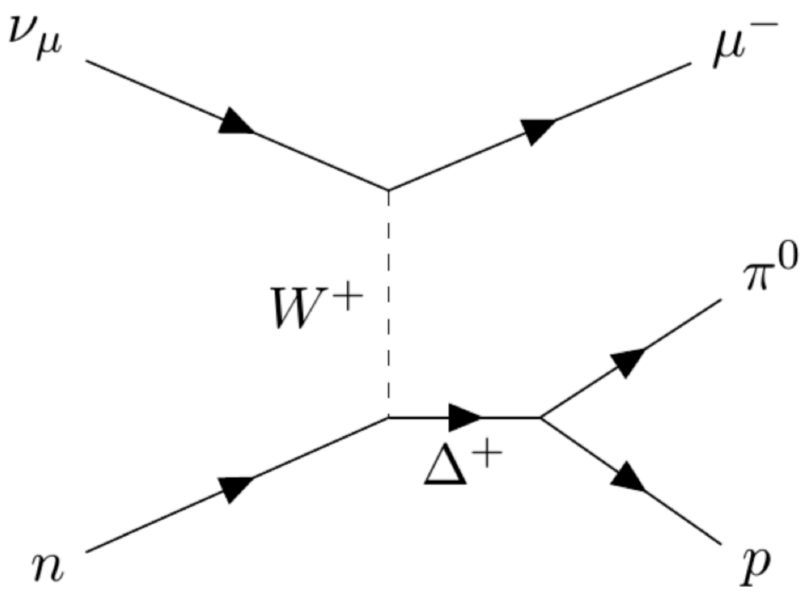
NC Coherent π^0 Results

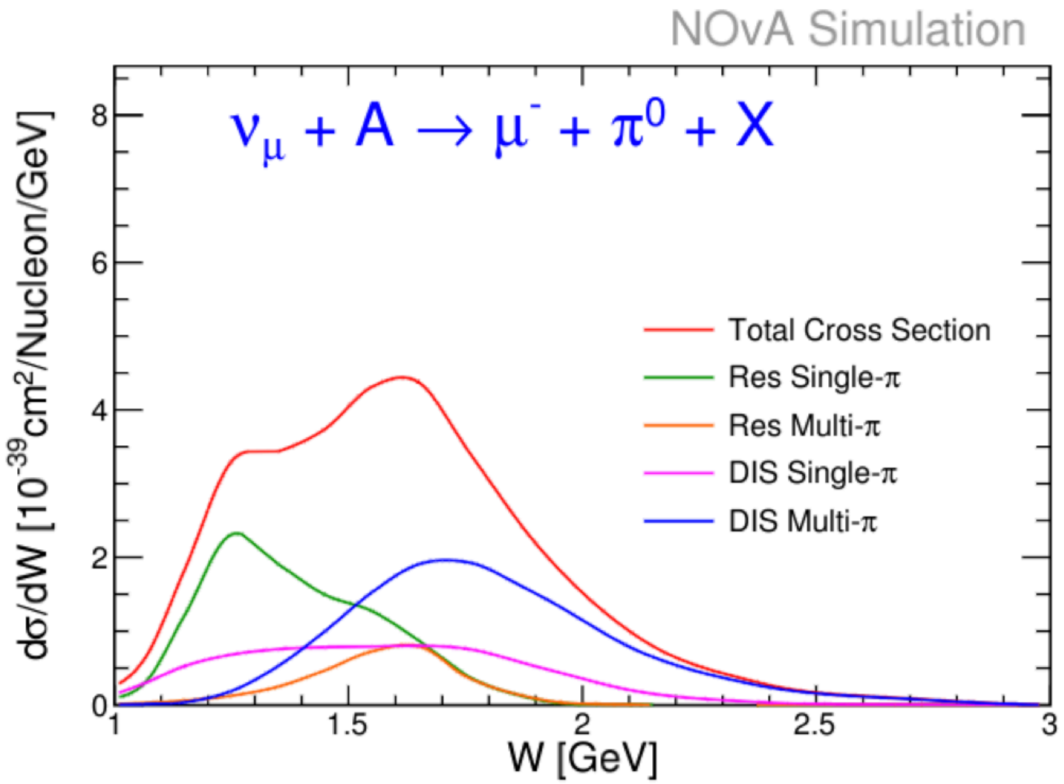


Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

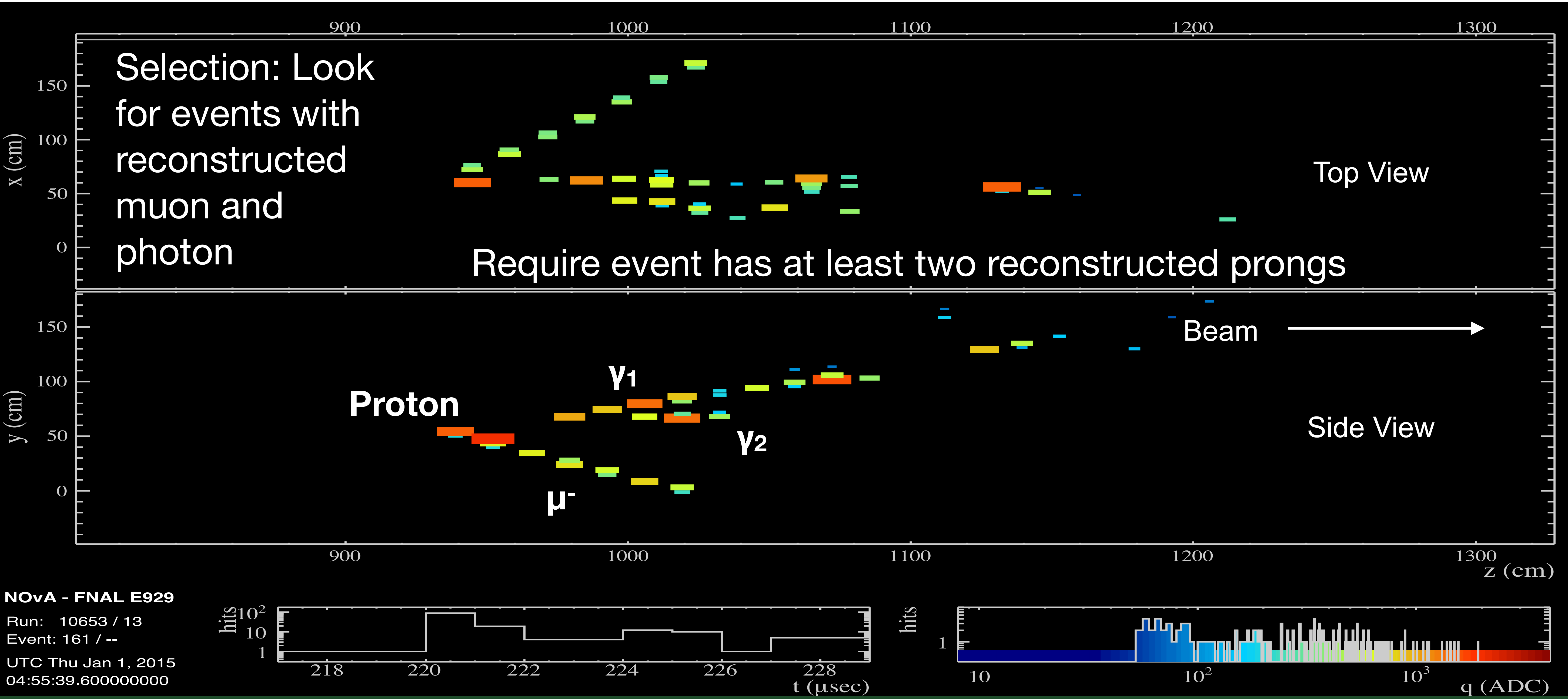
ν_μ CC π^0 Analysis

- Analysis signal has large contributions from both resonant and DIS interactions
- There is a large multi-π component in $\nu_\mu CC+\pi^0$ events which is included in the analysis signal
- Flux averaged differential cross sections measured in:
    - Direct observables: pion momentum and angle, muon momentum and angle
    - 4-momentum transfer to hadronic system (Q^2)
    - Invariant mass of the hadronic system (W)

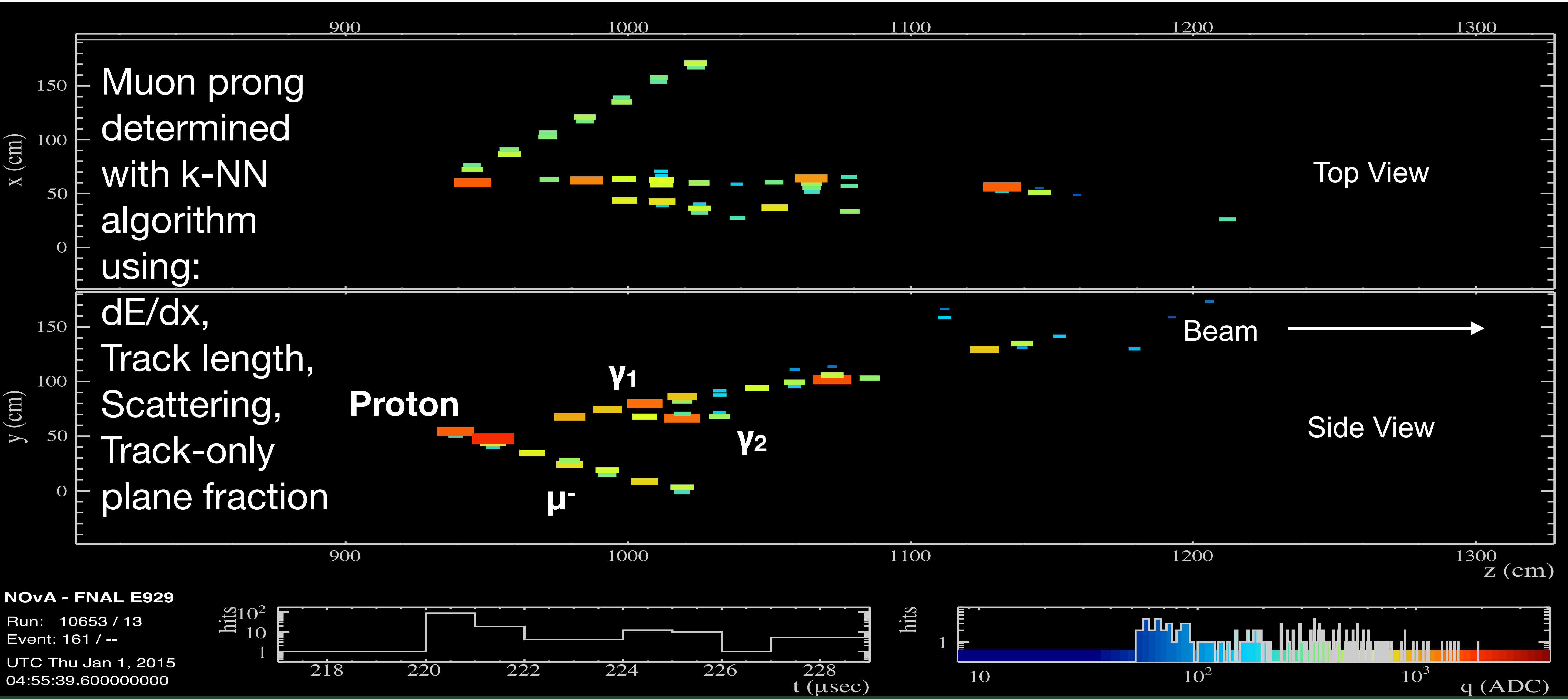




Simulated ν_μ CC π^0 Event

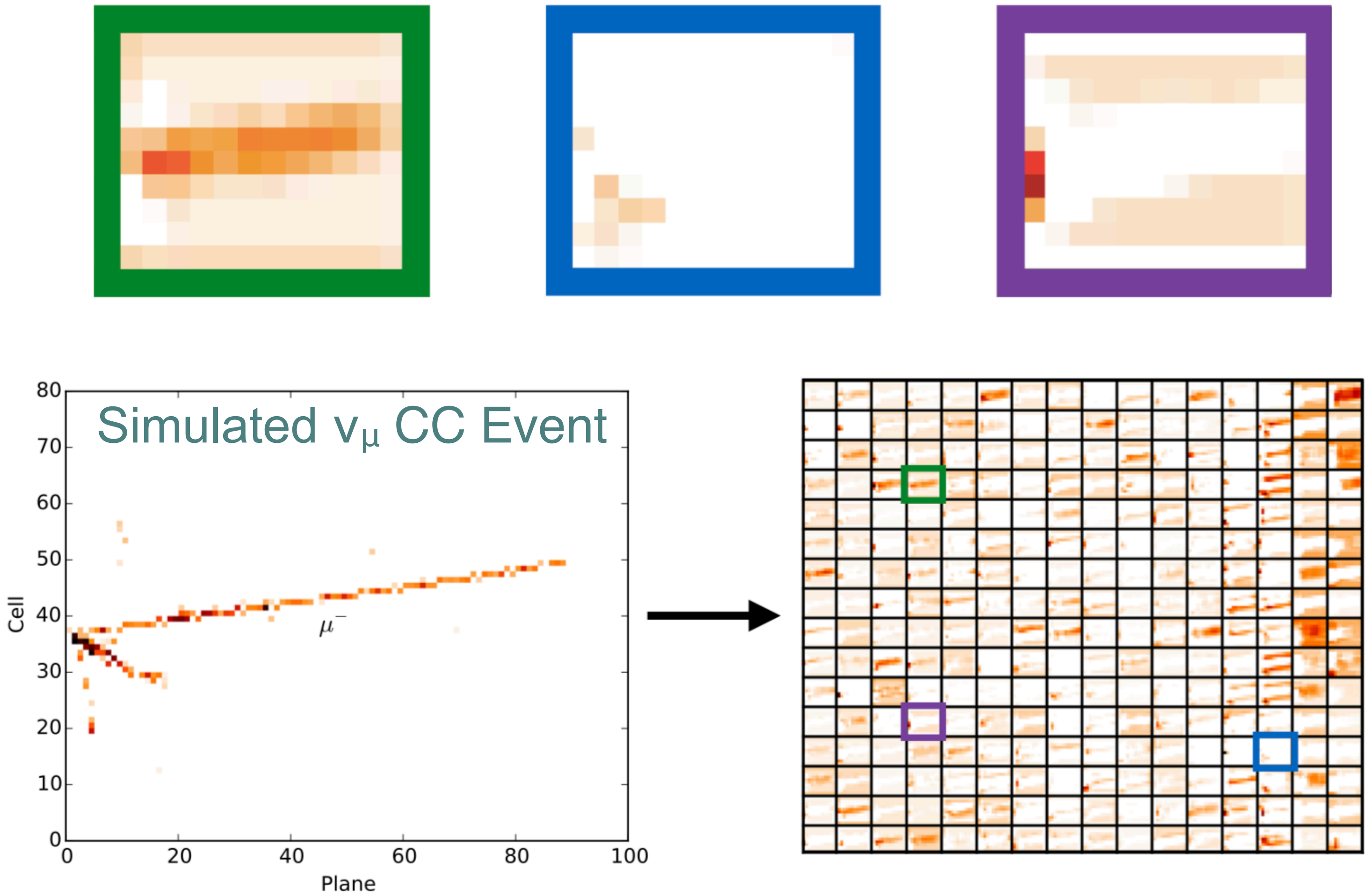


Simulated ν_μ CC π^0 Event



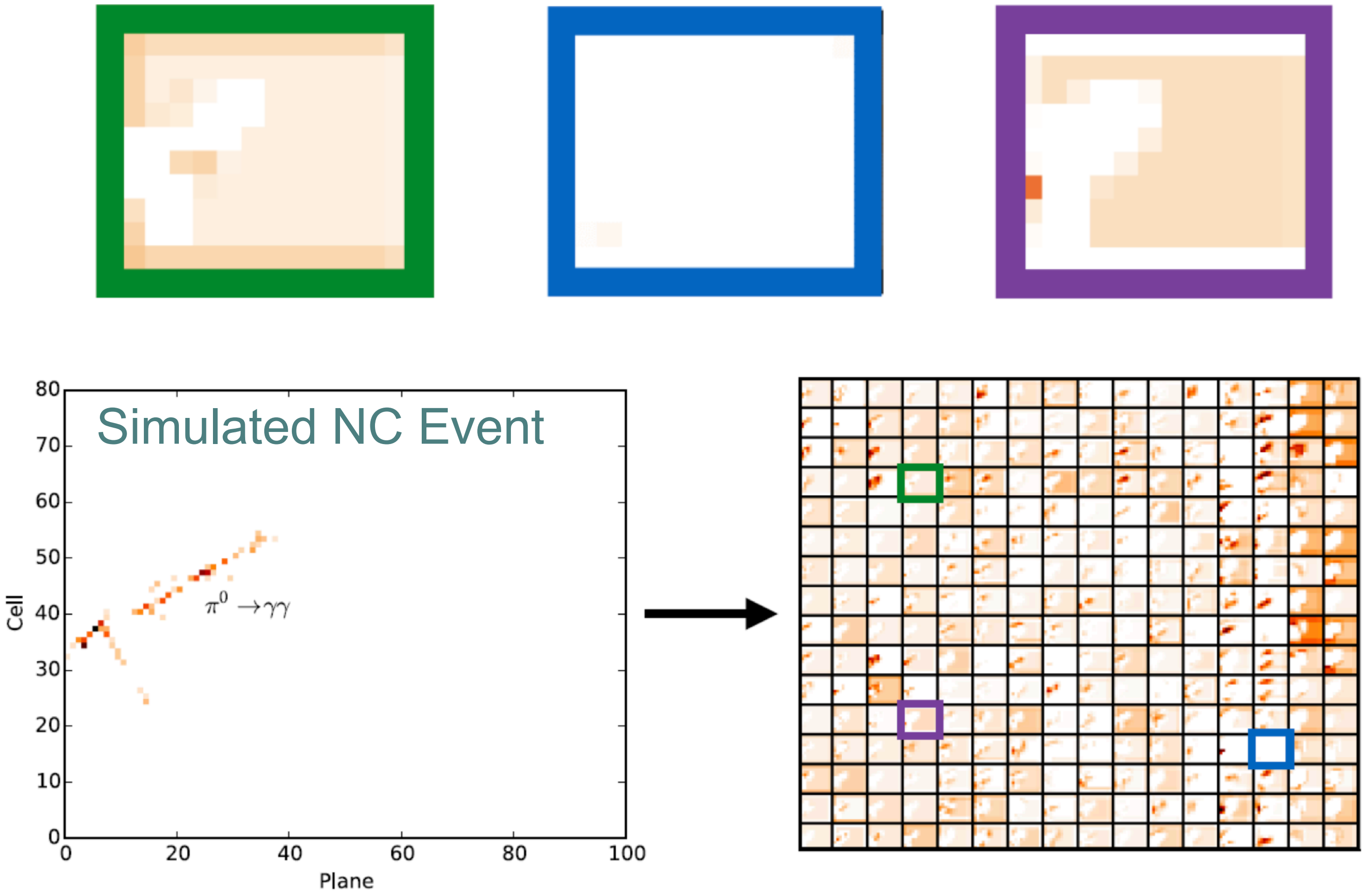
Machine Learning for Neutral Current Rejection

- Analysis has large neutral current background
- Use a convolutional neutral network PID to reject this background
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event



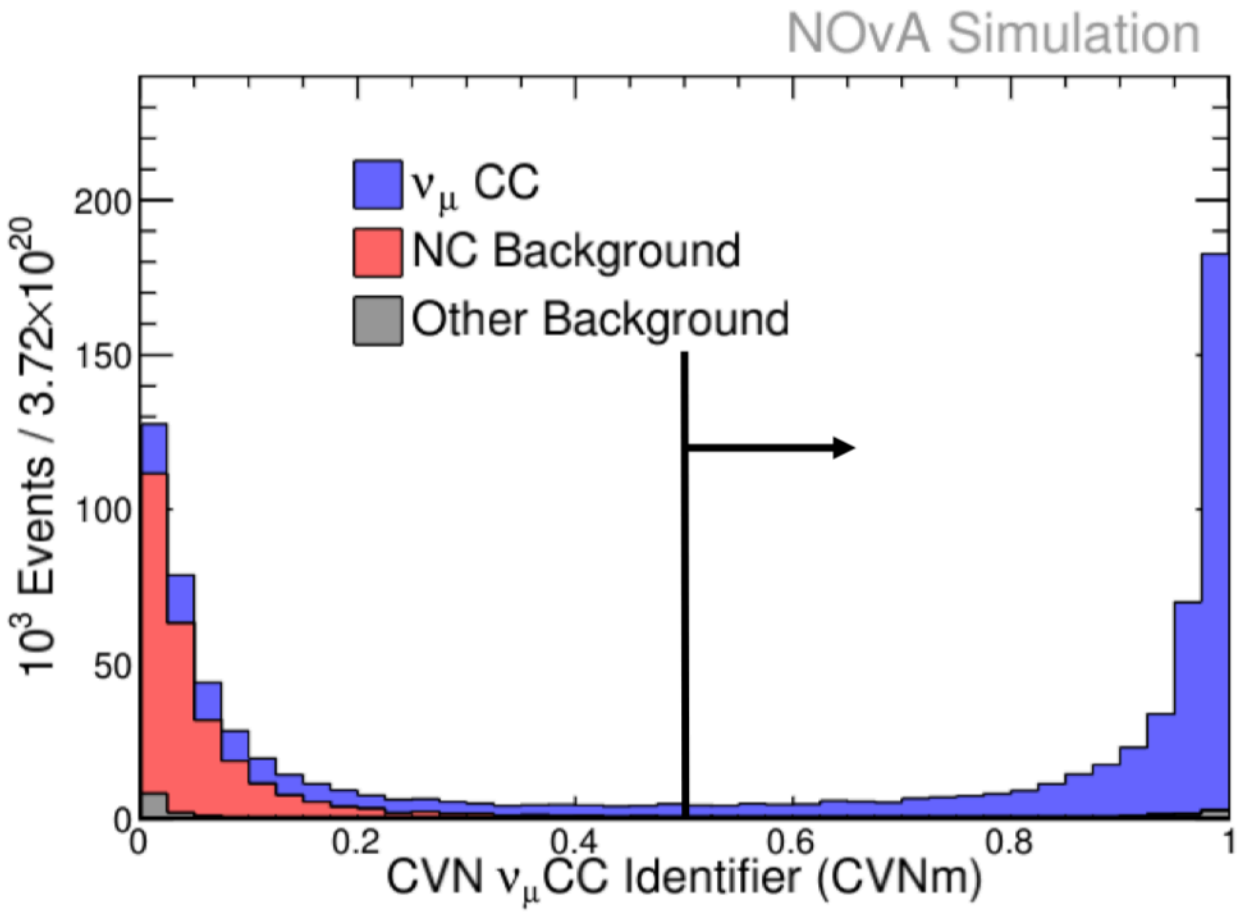
Machine Learning for Neutral Current Rejection

- Analysis has large neutral current background
- Use a convolutional neutral network PID to reject this background
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

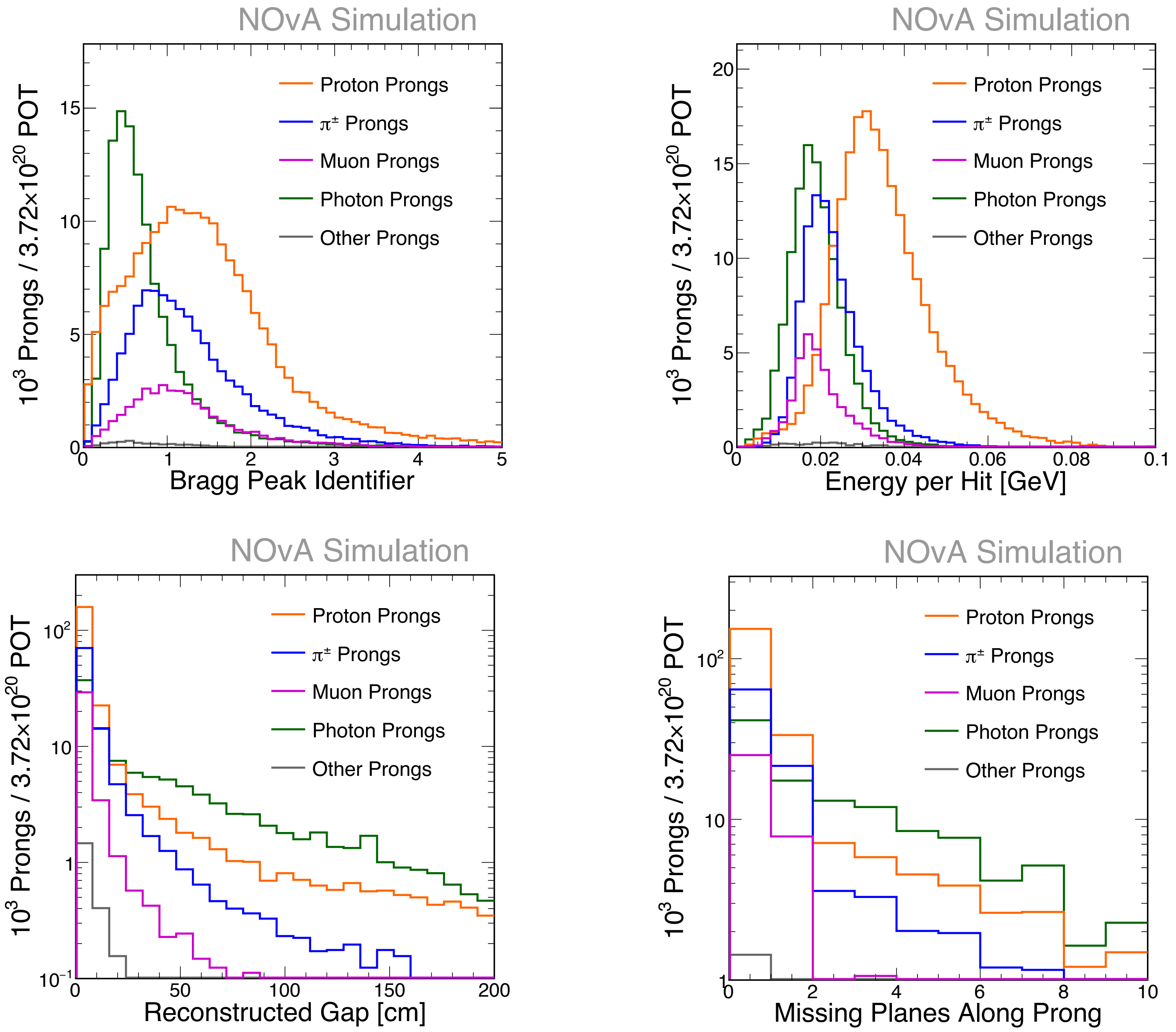


Machine Learning for Neutral Current Rejection

- Analysis has large neutral current background
- Use a convolutional neutral network PID to reject this background
- Extracted features used as inputs to a conventional neural network to classify the event
- CVN is able to reject neutral current background from sample
  - NC ~ 1.7% of sample after cut
- CVN has only identified ν_μ CC events, still need a way to find events with a π^0 in the final state



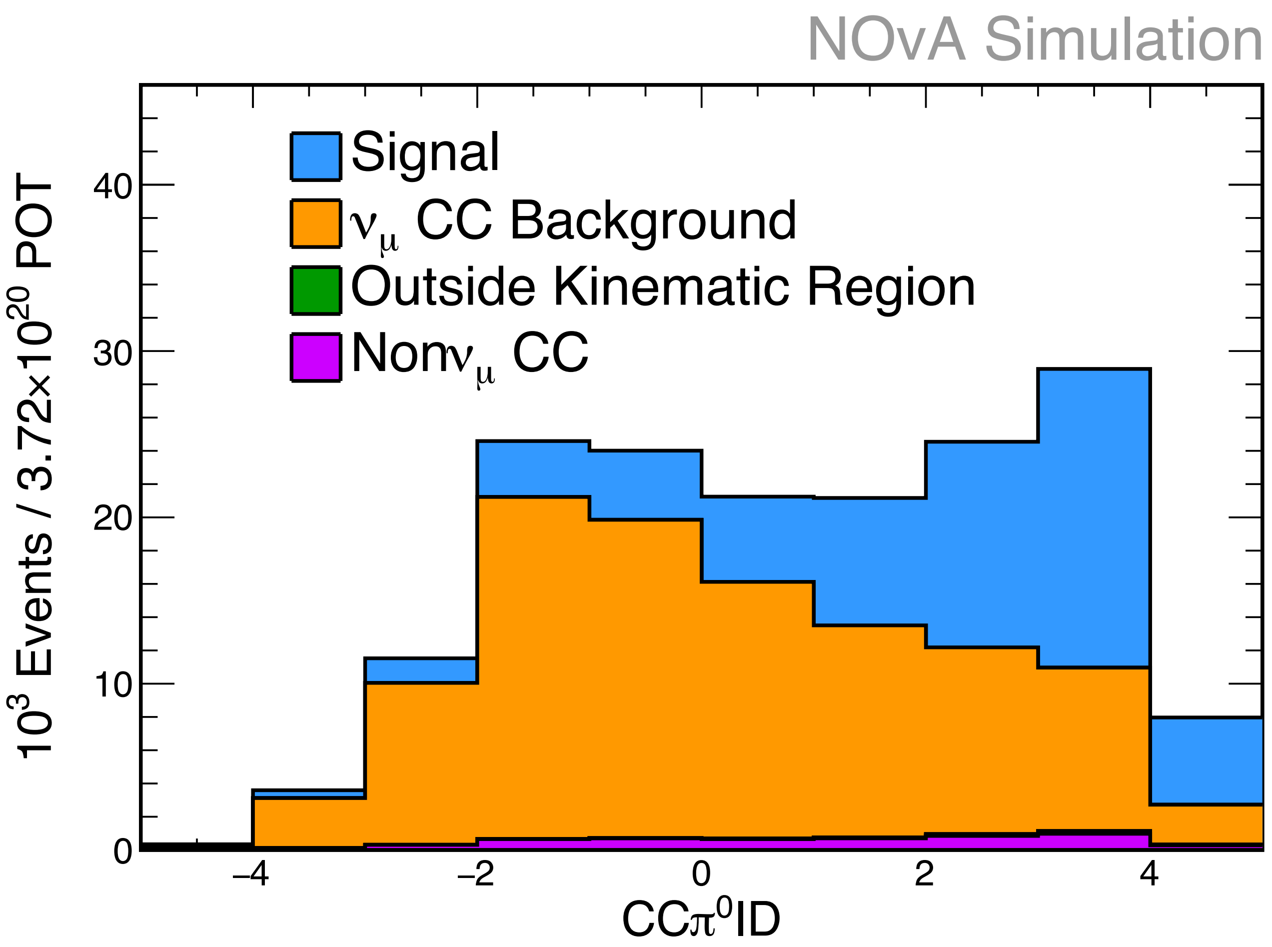
Photon Identification

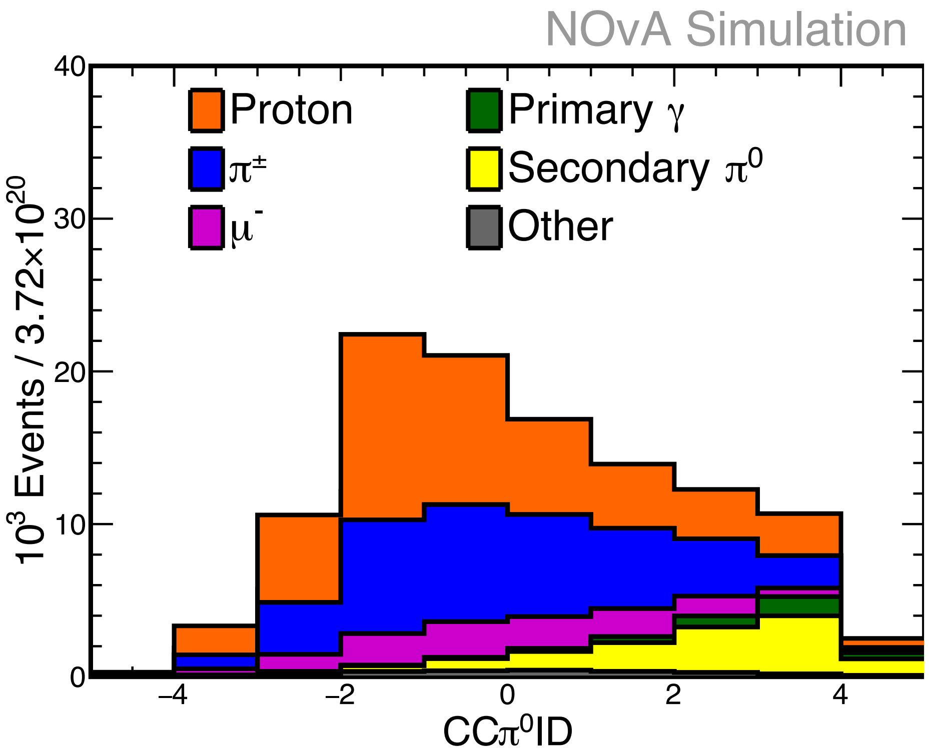


- Photon identification is done through a ΔLL selector
- Two variables to describe dE/dx
  - Bragg peak identifier:
    - dE/dx at end of prong compared to the bulk
  - Energy/Hit
- Two variables to characterize “gappiness”:
  - Distance from vertex
  - Skipped planes along prong

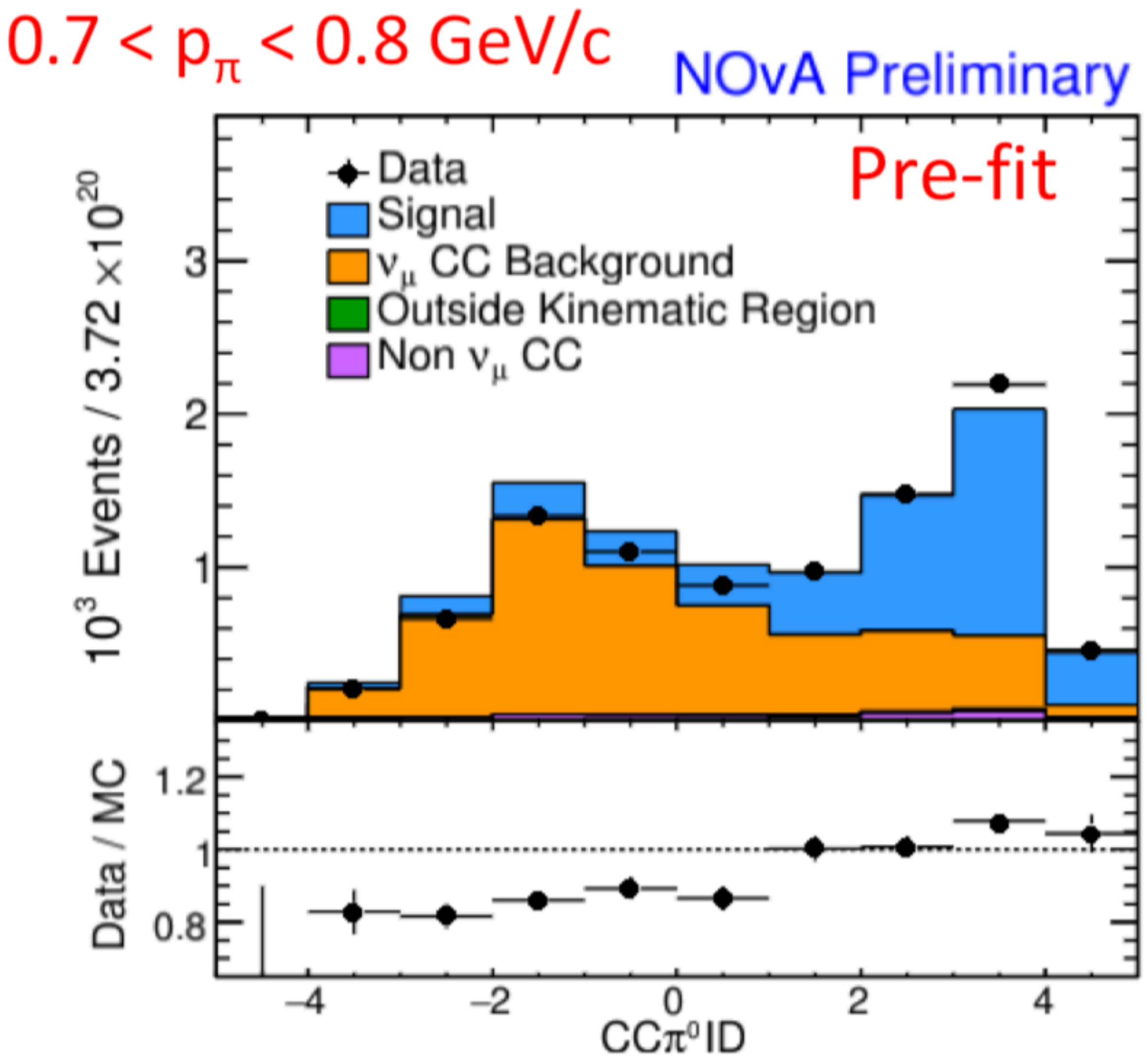
Photon Identification

- CCπ^0ID is defined as highest photon score in the event
- Used to ID prongs for π^0 reconstruction





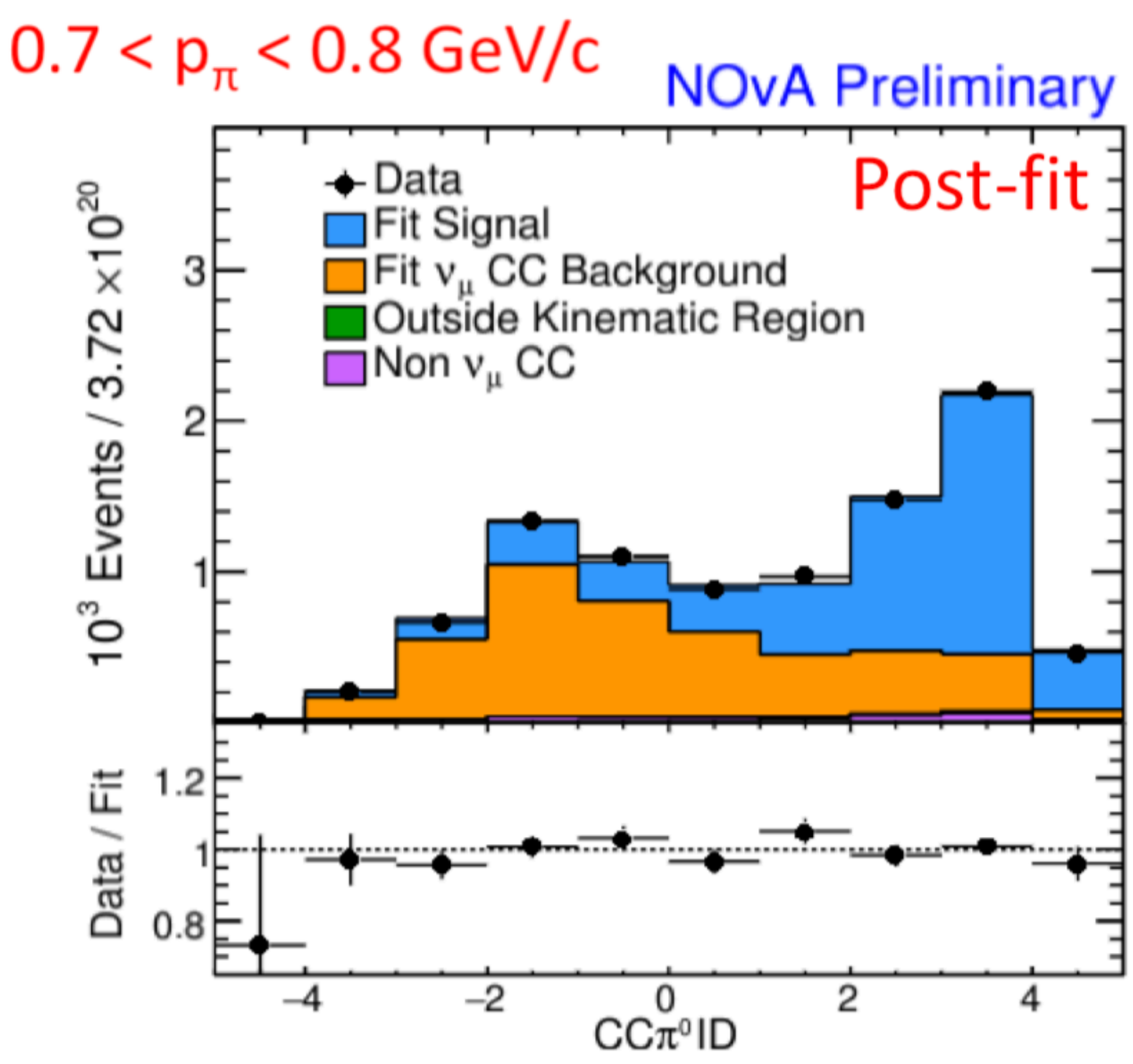
Template Fit



CCπ^{0}ID is also used to apply a data-driven constraint to simulation using a template fit

- Template fit determines normalization
- Measurement is differential, fit is performed in each analysis bin independently
- Systematic effects are not included in the fit

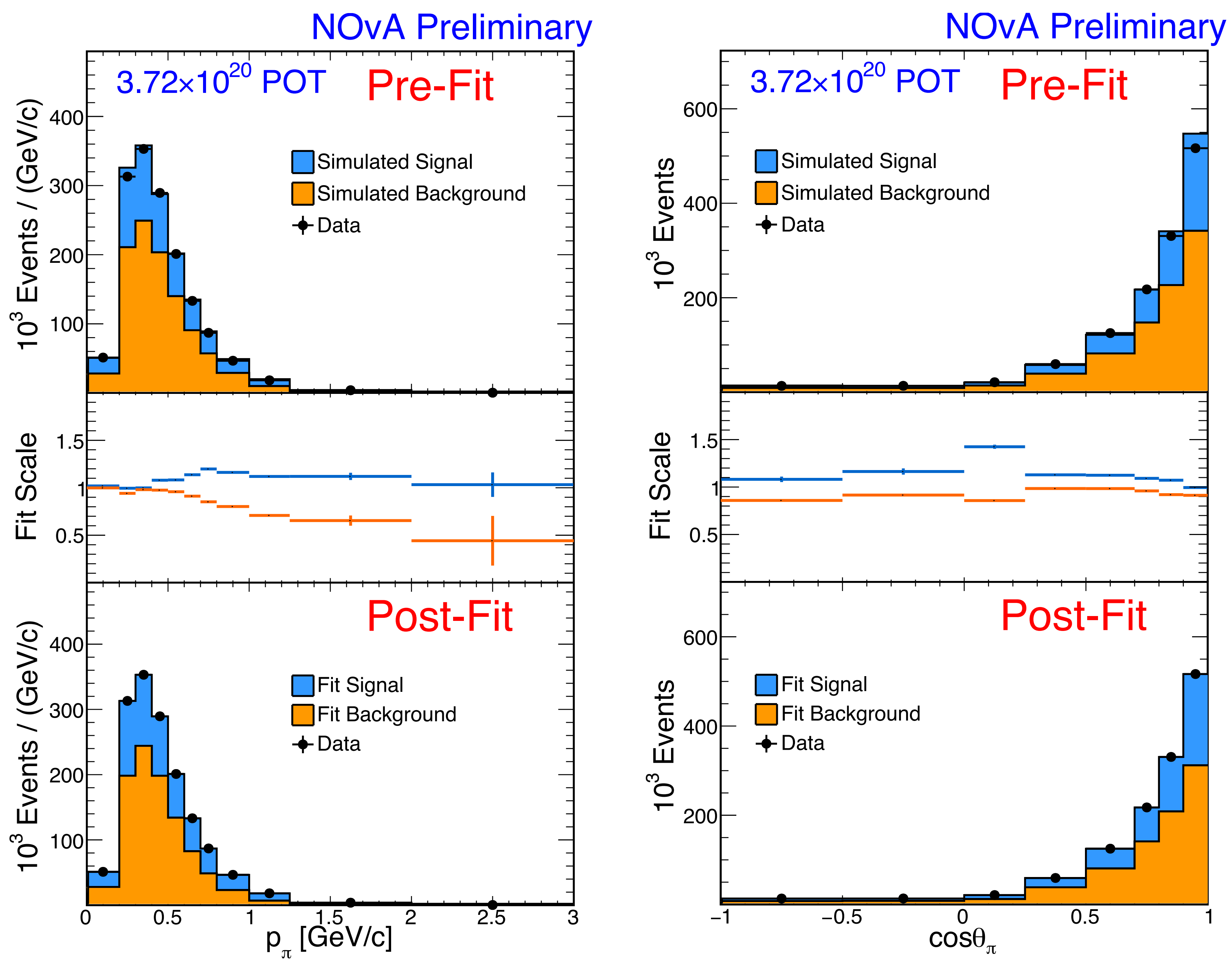
Template Fit



$CC\pi^0$ID is also used to apply a data-driven constraint to simulation using a template fit

- Template fit determines normalization
- Measurement is differential, fit is performed in each analysis bin independently
- Systematic effects are not included in the fit

Template Fit Results



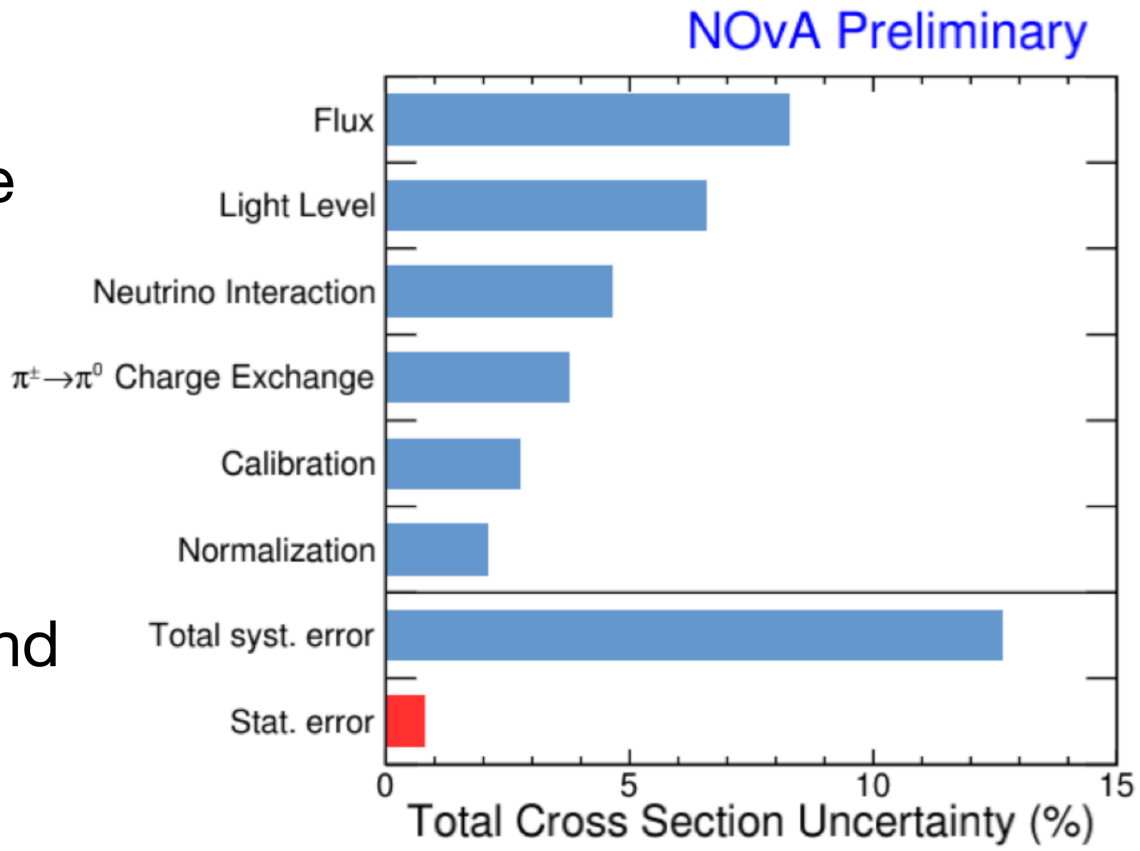
$CC\pi^0$ID is also used to apply a data-driven constraint to simulation using a template fit

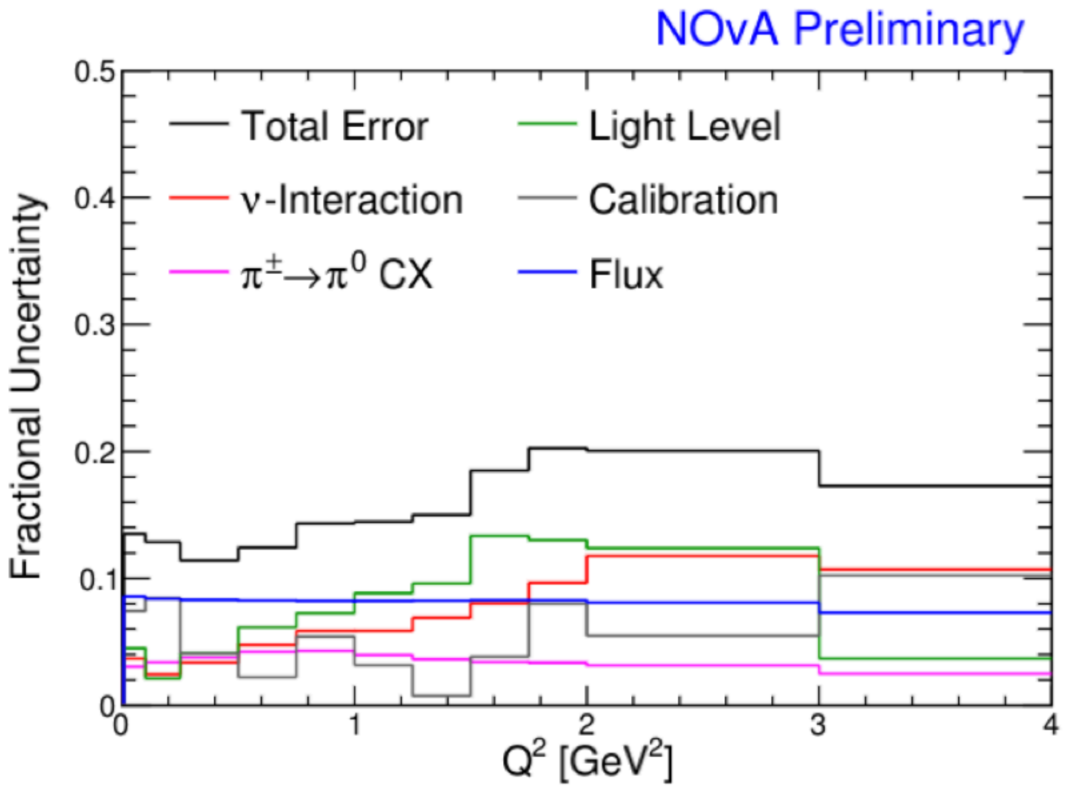
- Template fit determines normalization
- Measurement is differential, fit is performed in each analysis bin independently
- Systematic effects are not included in the fit

Systematic Uncertainties

- Each source of systematic uncertainty is evaluated by modifying the simulation and comparing the extracted cross section to the nominal simulated prediction.
- Largest sources of uncertainty for this analysis are flux and light-level modeling

We make use of the GENIE reweighting scheme to assess Neutrino Interaction and FSI systematics.

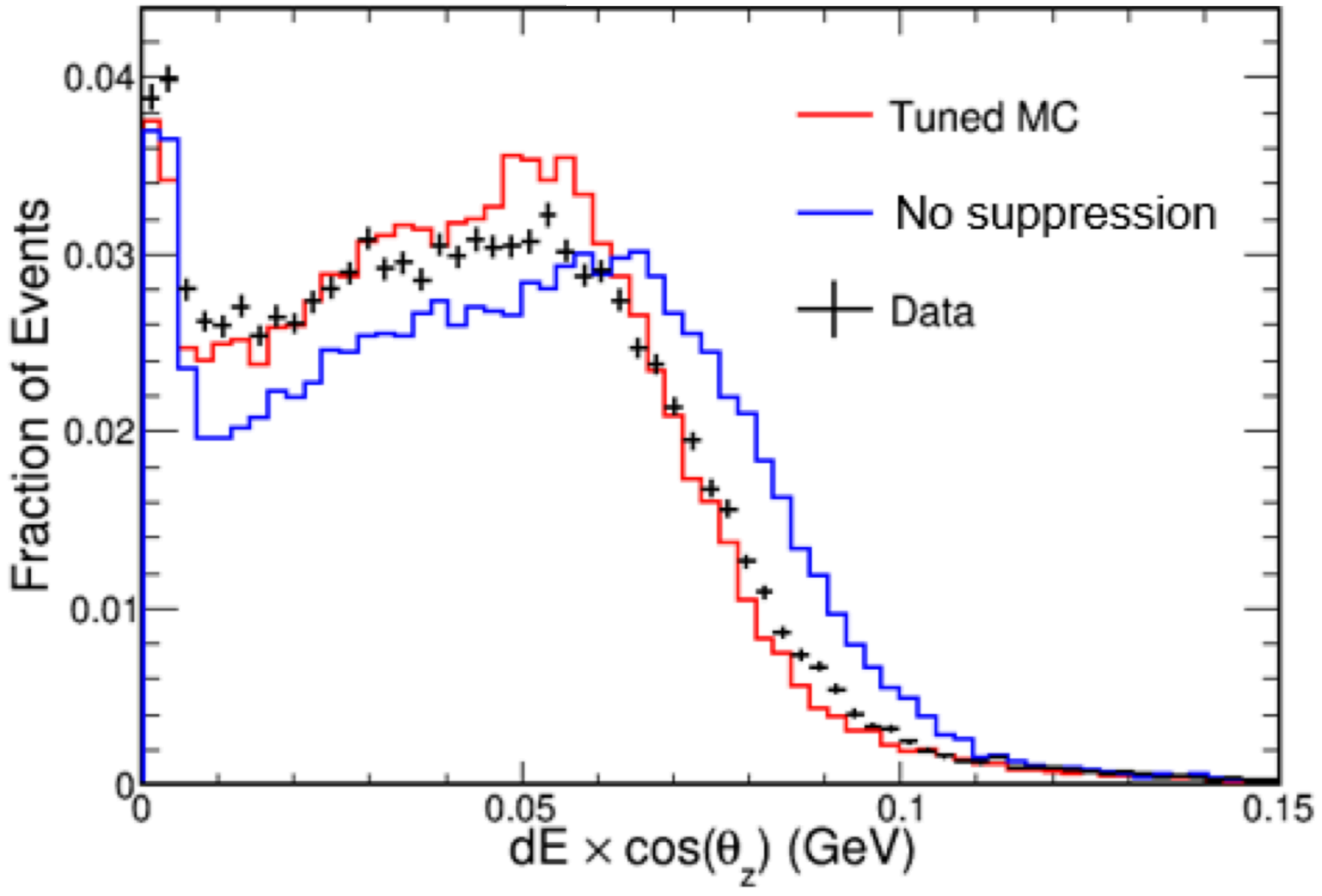




Light-Level Modeling Systematic

ND proton sample from data shows lower dE/dx than predicted by simulation

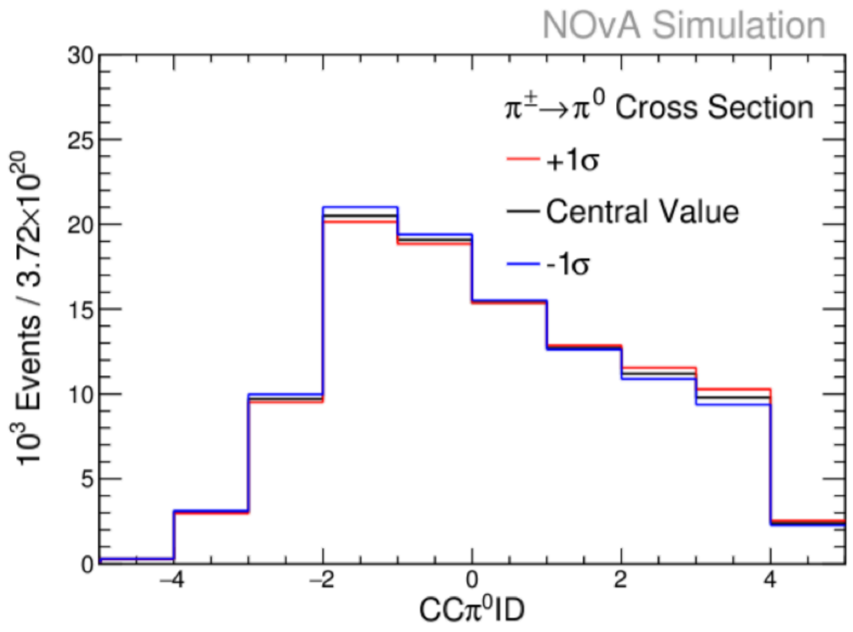
- Simulation incorporates Birks-Chou model for light yield: $LY = \frac{A}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2}$
- Using ND protons find:
  - k_B = 0.4 g/cm²/MeV
  - k_C = -0.0005 cm²/MeV²
- Direct measurements of k_B for organic scintillator is around 0.1-0.2 g/cm²/MeV
- Re-simulate using k_B = 0.1 g/cm²/MeV and k_C = 0 and take the difference in extracted cross sections as a systematic

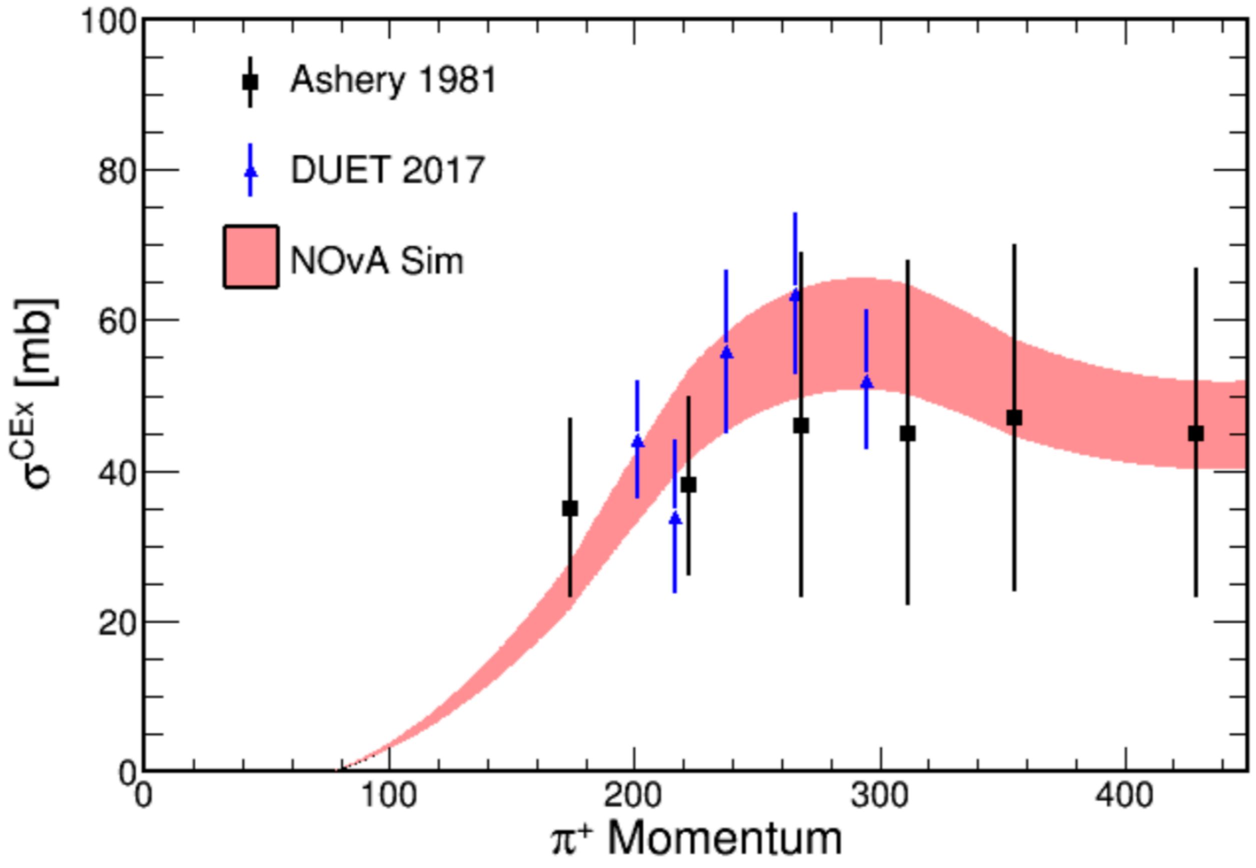


Charge Exchange Cross Section Systematic

Charge exchange (CEx) makes a non-primary π^0 in the detector through $\pi^\pm \rightarrow \pi^0 + X$

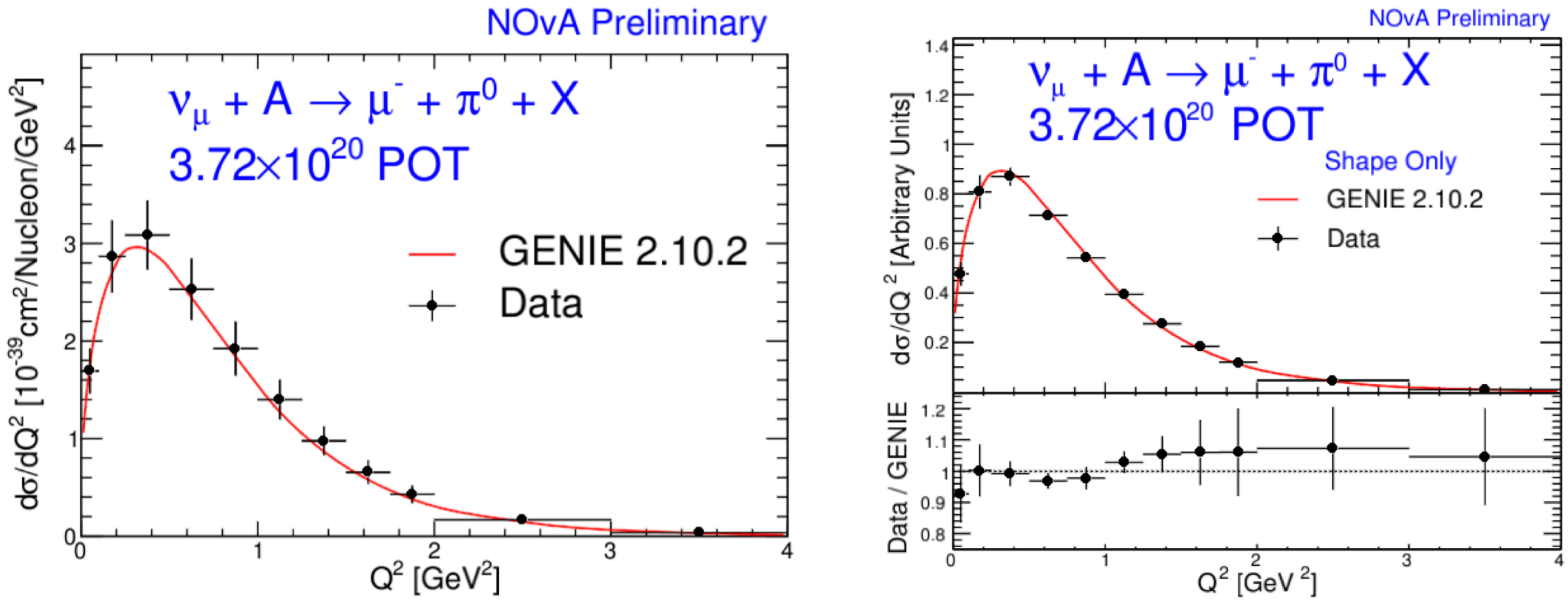
- This cross section is only known to the 20% level from the 1981 Ashery and 2017 DUET analysis
- The NOvA simulation for CEx was tuned according to DUET data
- Noticeable effect on CCπ^0ID





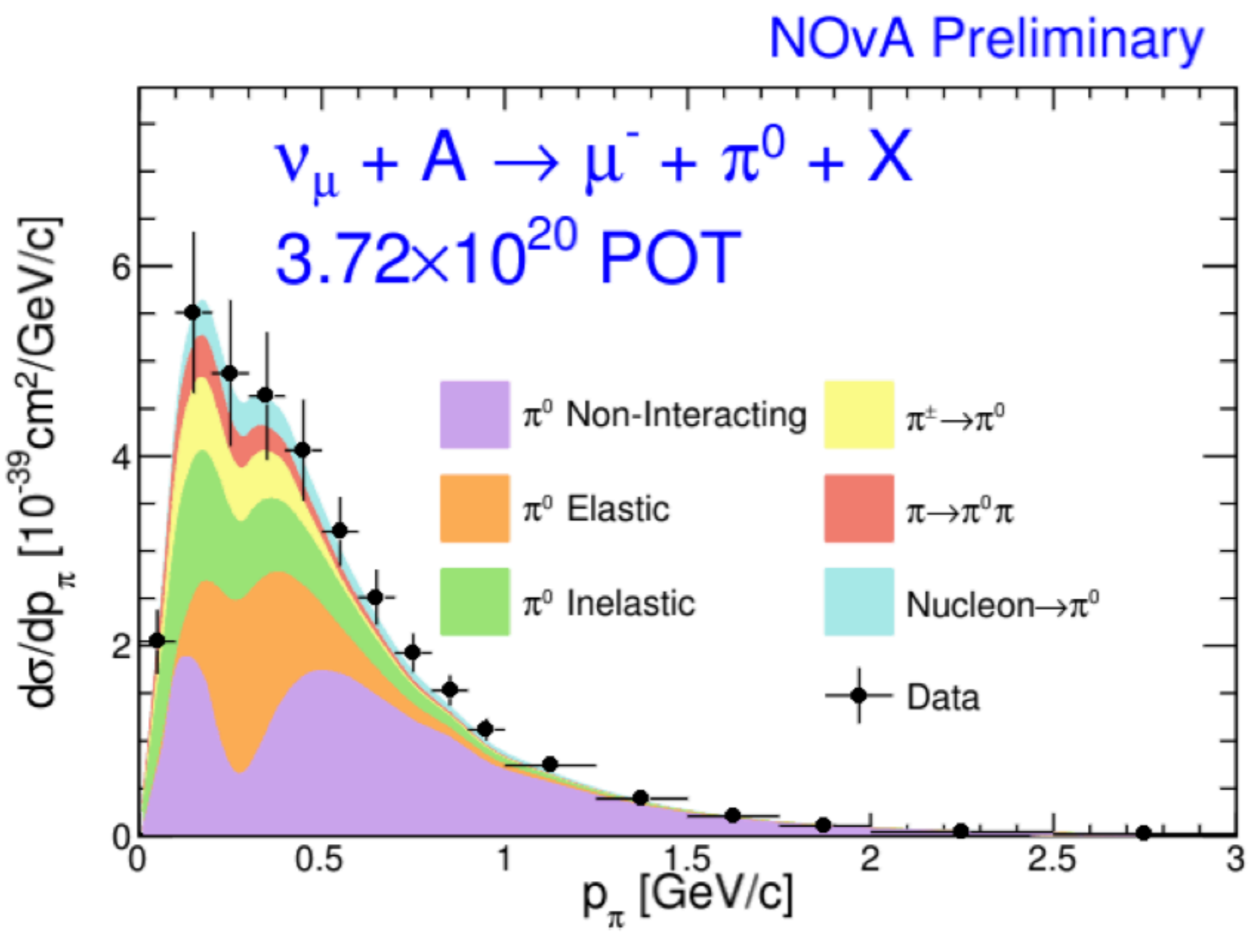
Phys Rev C 23, 2173 (1981), Phys Rev C 95, 045203 (2017)

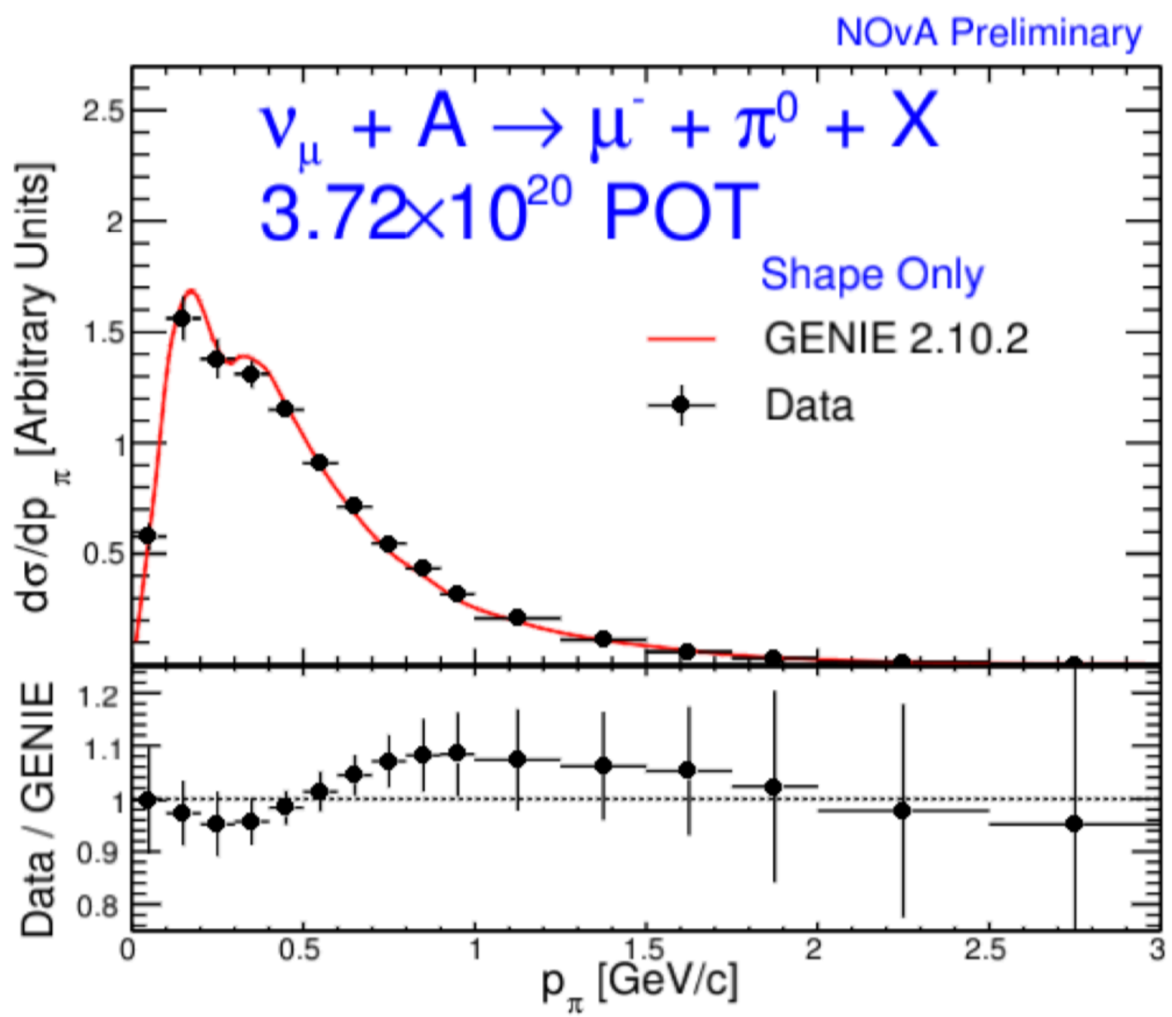
Differential Cross Section - Q^2



- Measured cross section is 7% higher than GENIE prediction
- Data suggests a slightly harder Q^2 shape than predicted by GENIE

Differential Cross Section - p_{π^0}





Summary

- Measurement of NC Coherent π^0 total flux averaged cross section is

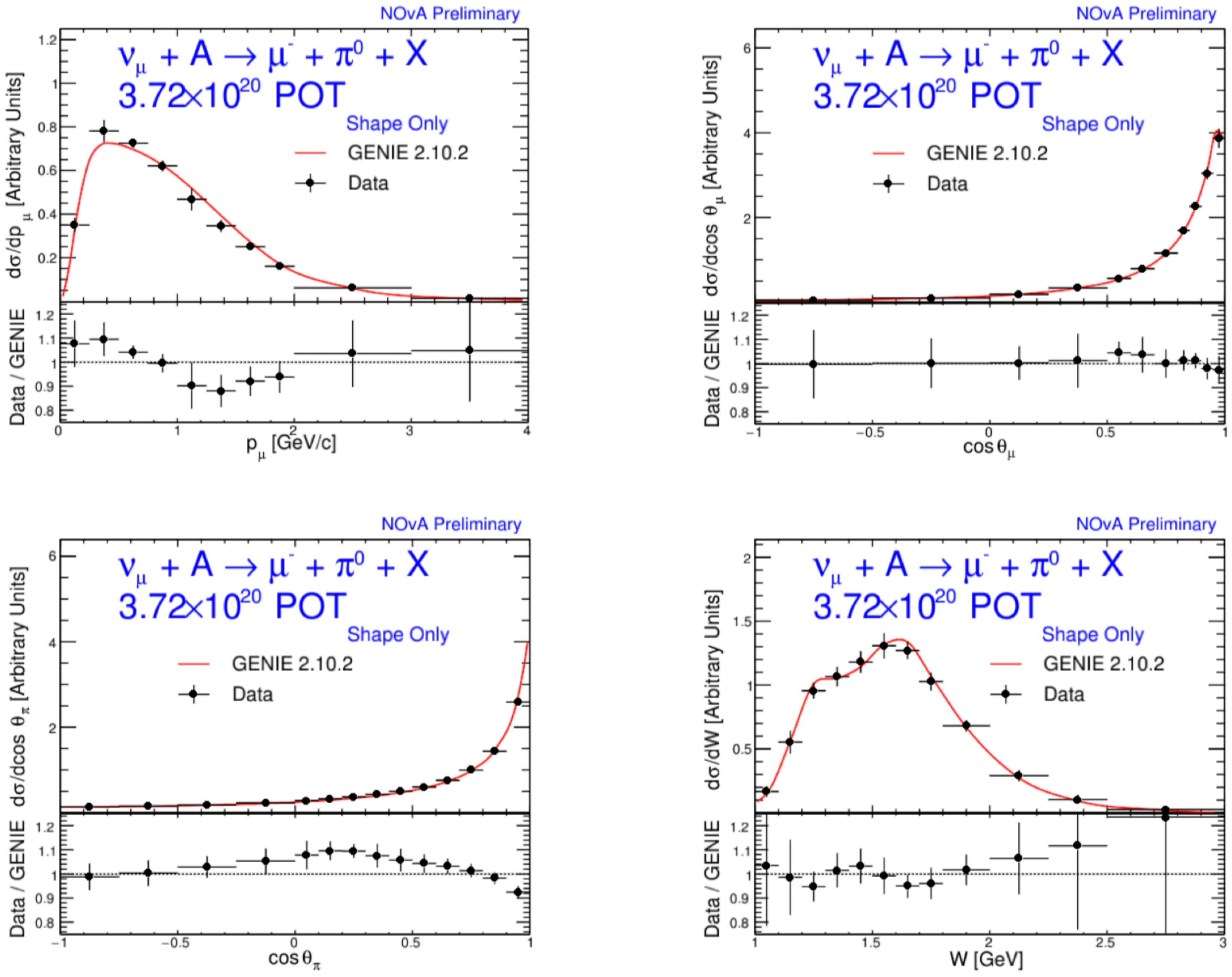
  $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.})\times10^{-40}\text{cm}^2/\text{nucleus}$

- Differential cross section for ν_μ CC π^0 semi-inclusive is generally consistent with GENIE interaction and FSI models.
- Both analyses are working towards publication.
- Be on the look out for additional results on the ν_μ and ν_e inclusive cross sections later this year!

Thank You!

Backups

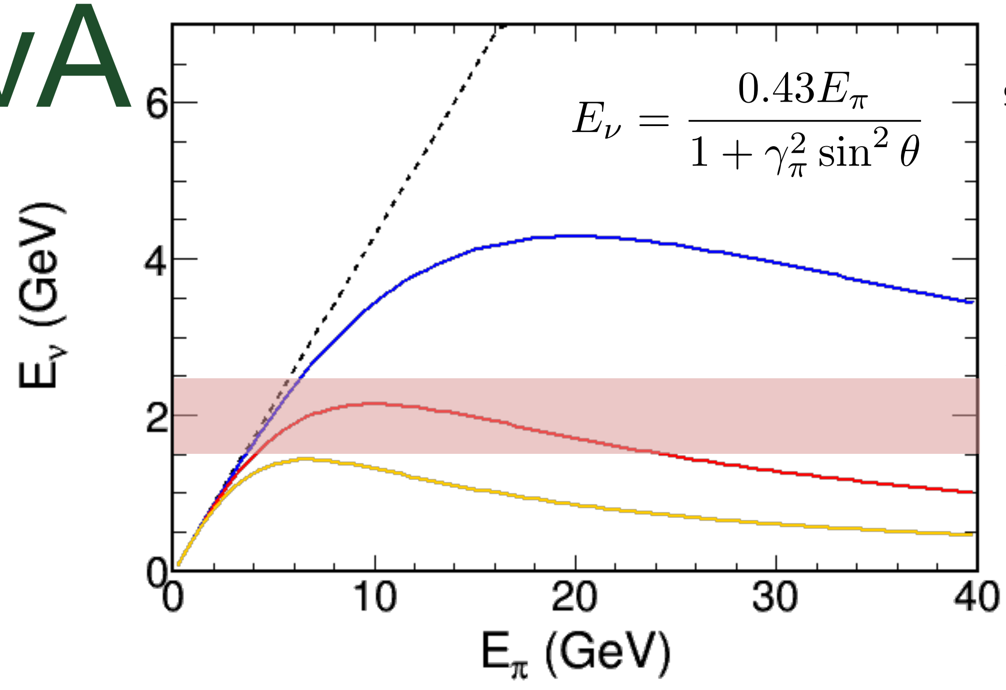
Differential Cross Sections

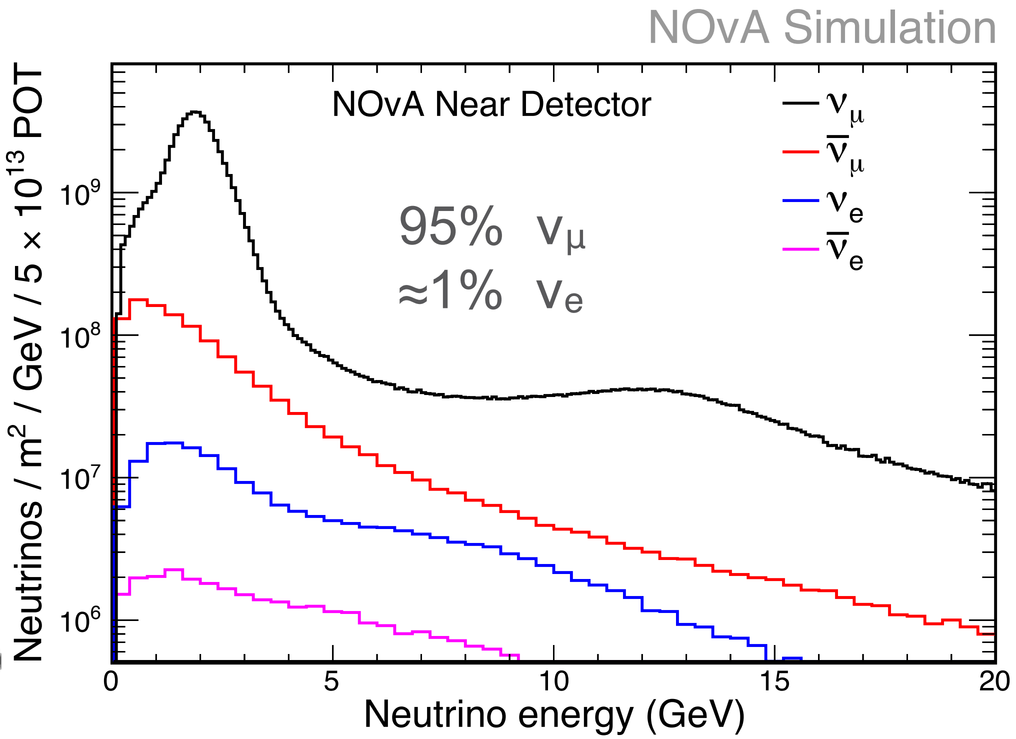


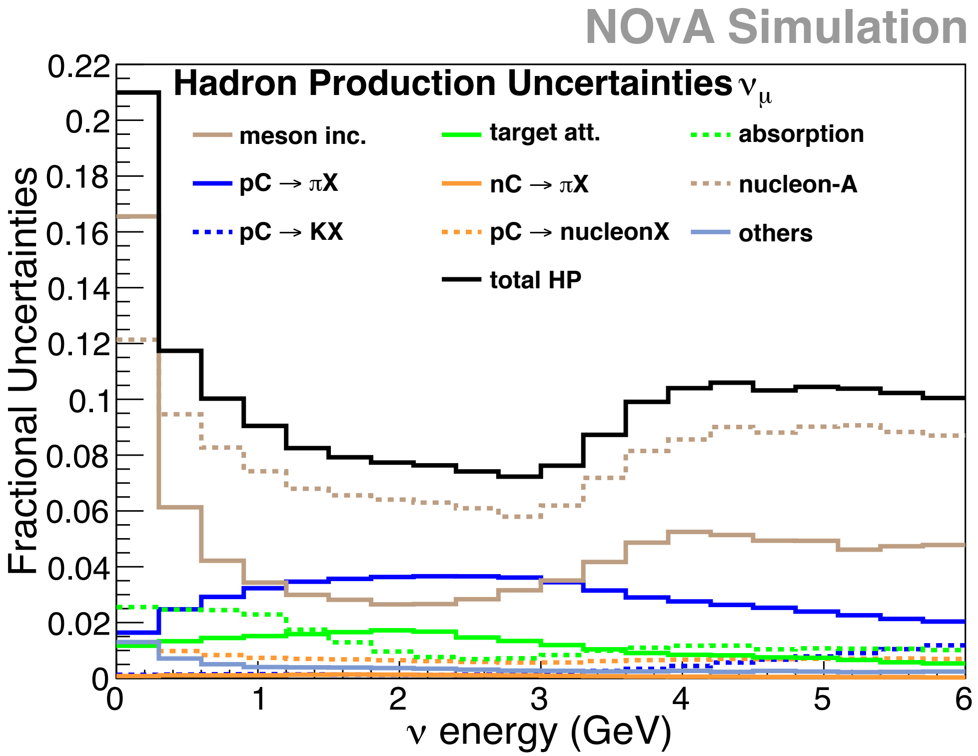
Flux at NOvA

Detectors are 14 mrad off-axis with respect to the NuMI beam axis:

- Narrow-band beam centered around 2 GeV
- Hadron production uncertainties are mostly a normalization effect



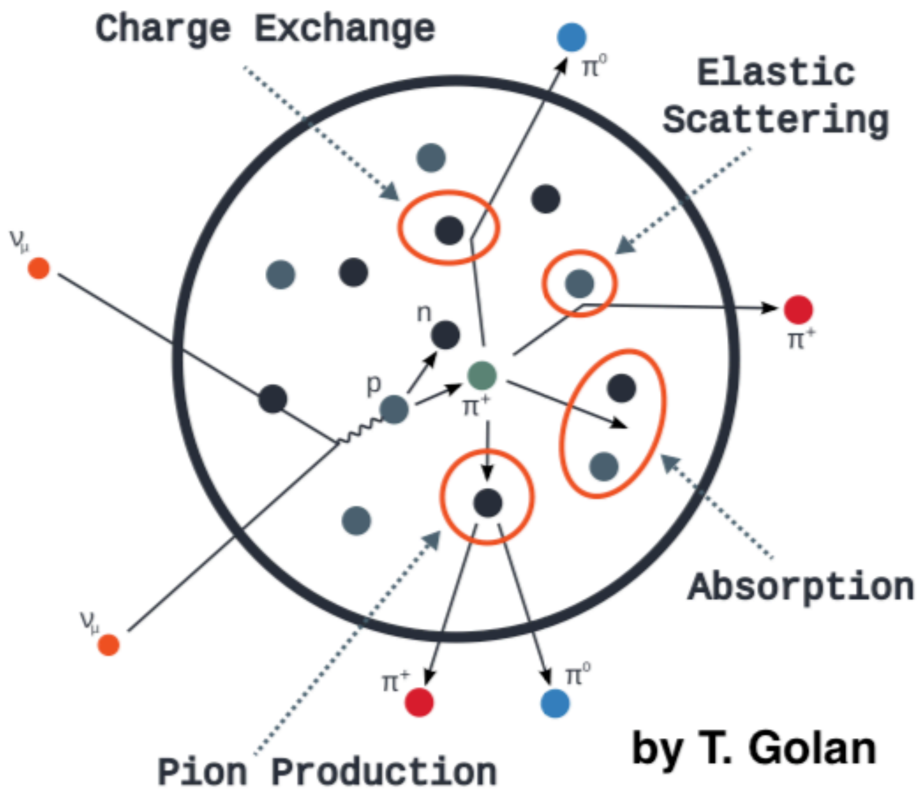




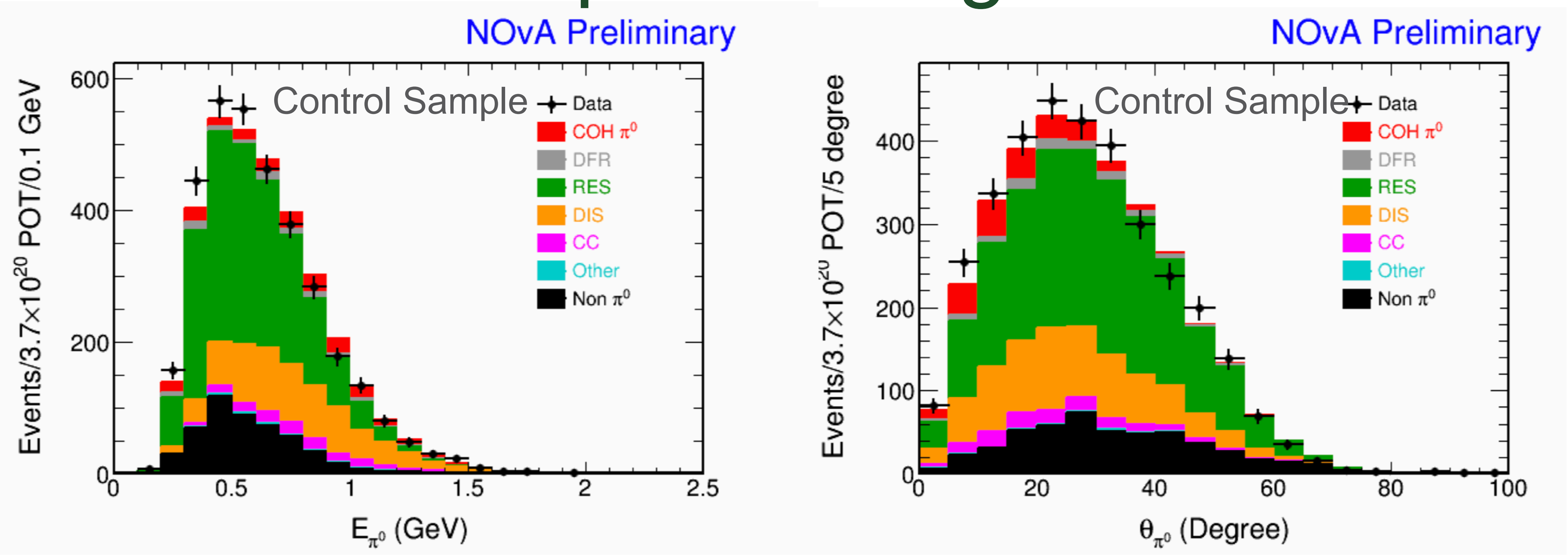
Motivation of measuring π^0

Oscillations are measured as a function of neutrino energy

- Need to reconstruct E_ν correctly
- Nuclear effects (fermi motion, nuclear correlation, final state interactions) are important
- Pion kinematics are sensitive to nuclear effects and can provide information to constrain models

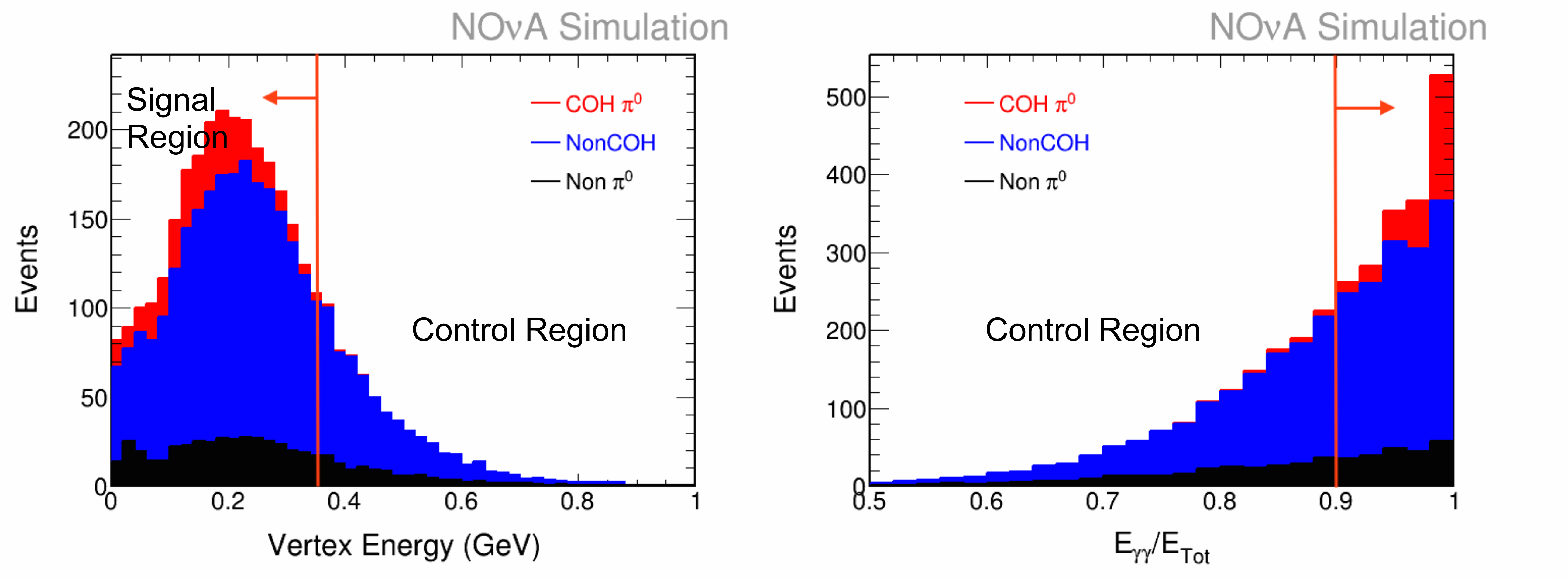


NC π⁰ Control Sample - Background Constraint



- The control sample is used to fit background to data using templates in π^0 energy vs angle 2D space

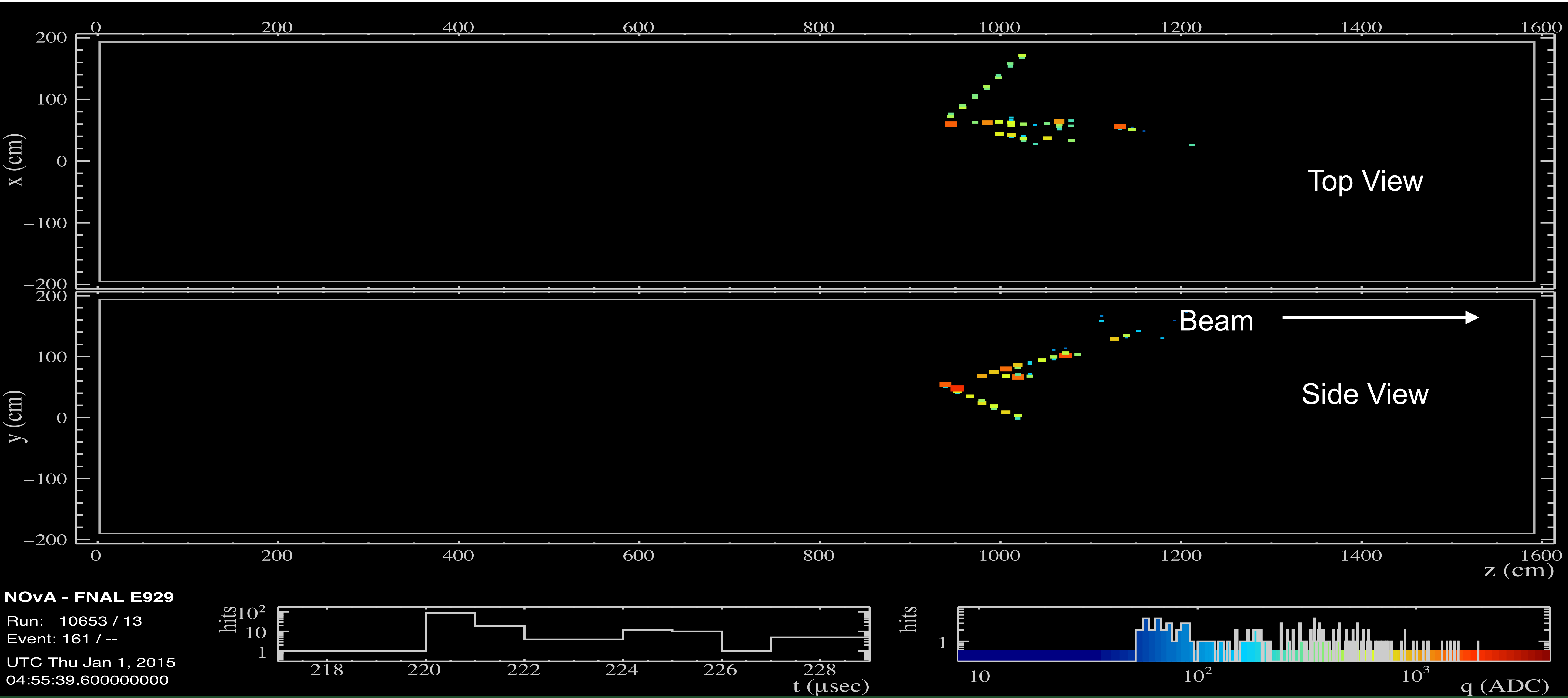
NC Pi0 Control and Signal Samples



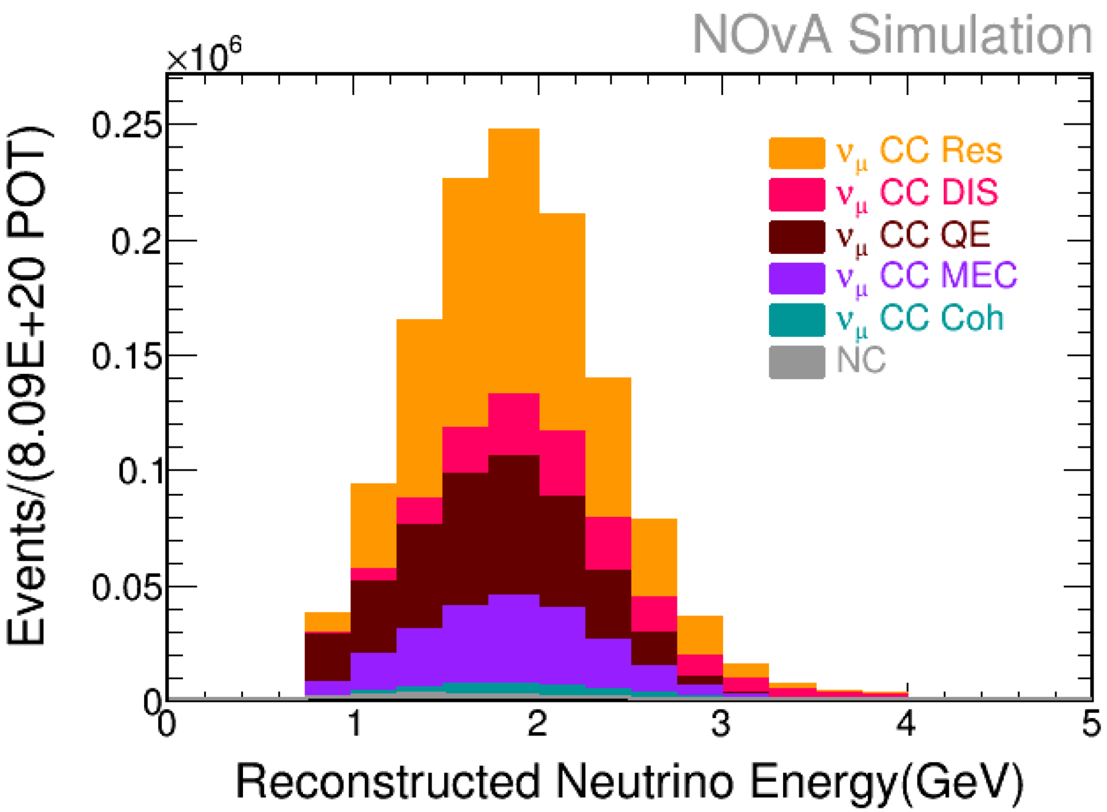
Spilt the NC Pi0 sample into two sub-samples:

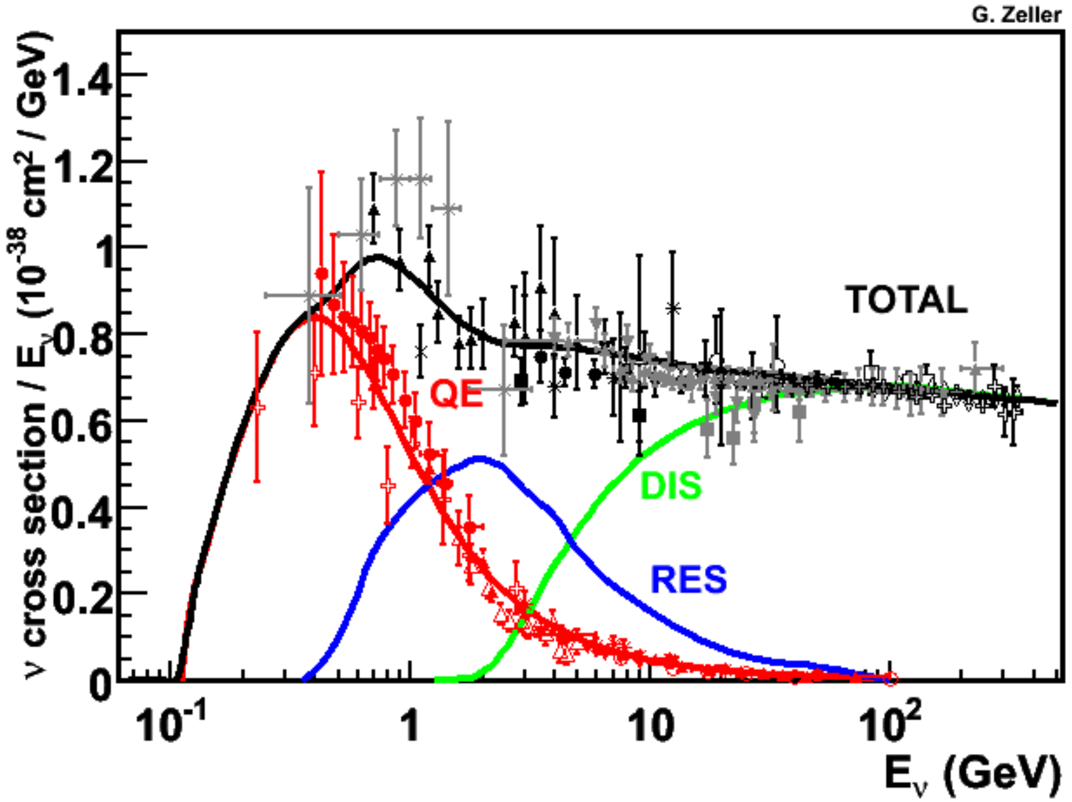
- Signal
- Control

Simulated Numu CC π^0 Event



Energy Spectrum and Interactions



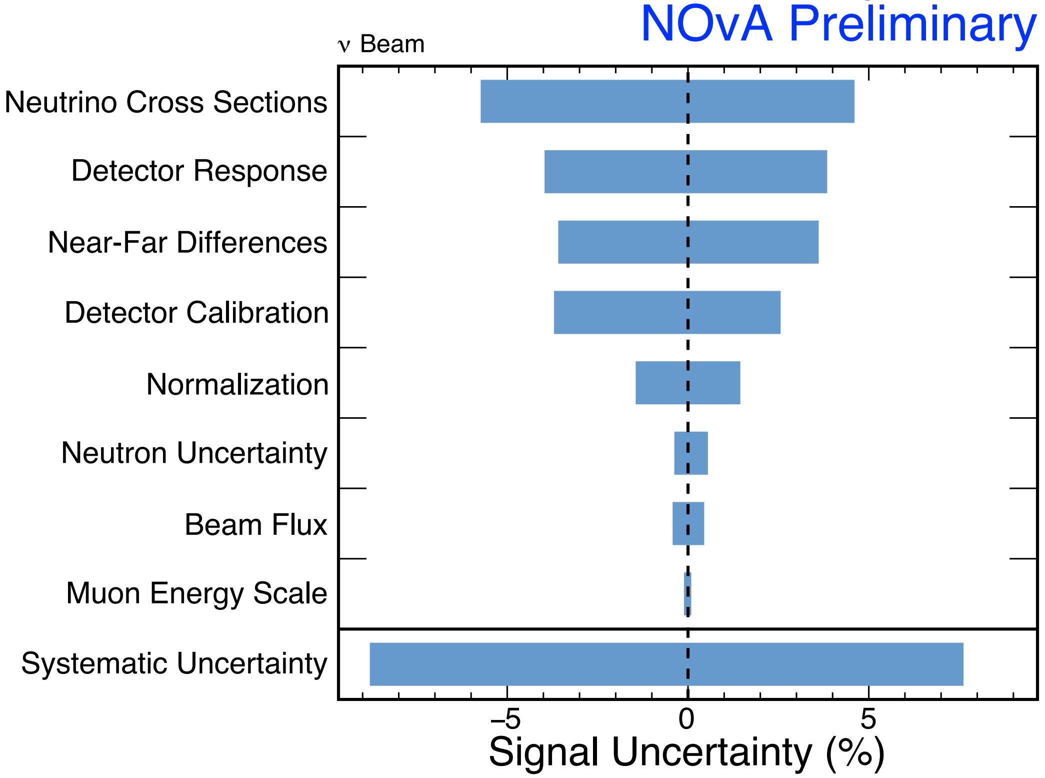


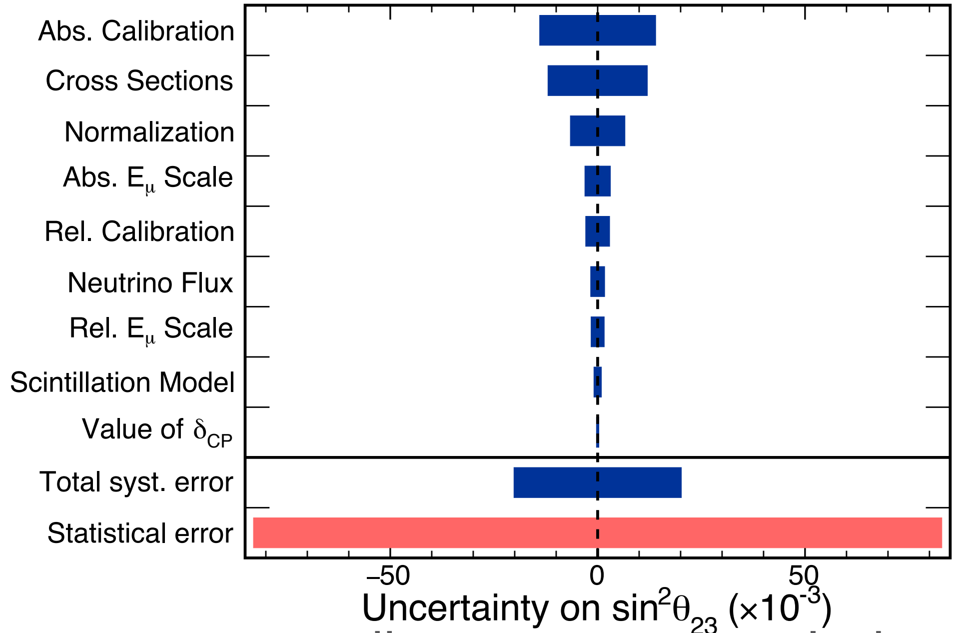
- Even with a narrow band beam, NOvA has sensitivity to many different v+A interaction channels
  - Quasi-elastic (nominally 26%), resonant (39%), pion-continuum/DIS (34%), and coherent (1%) channels.
- Cross sections in NOvA's energy range are not well measured

NOvA Cross Sections

- Focusing on measurements which will provide an internal XS constraint useful to the oscillation analyses
- Trying to pick well defined signals which can reduce model dependency.
- Looking to provided differential cross section as a function of useful kinematics where possible.
- Impactful measurements useful to the community in general.

ν_e appearance analysis



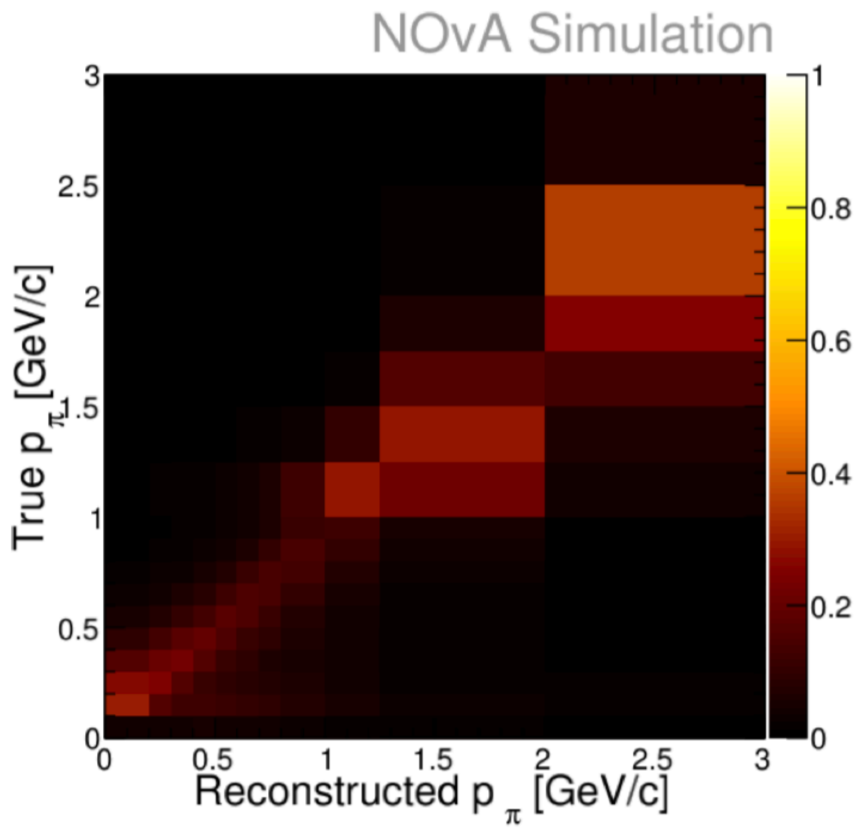


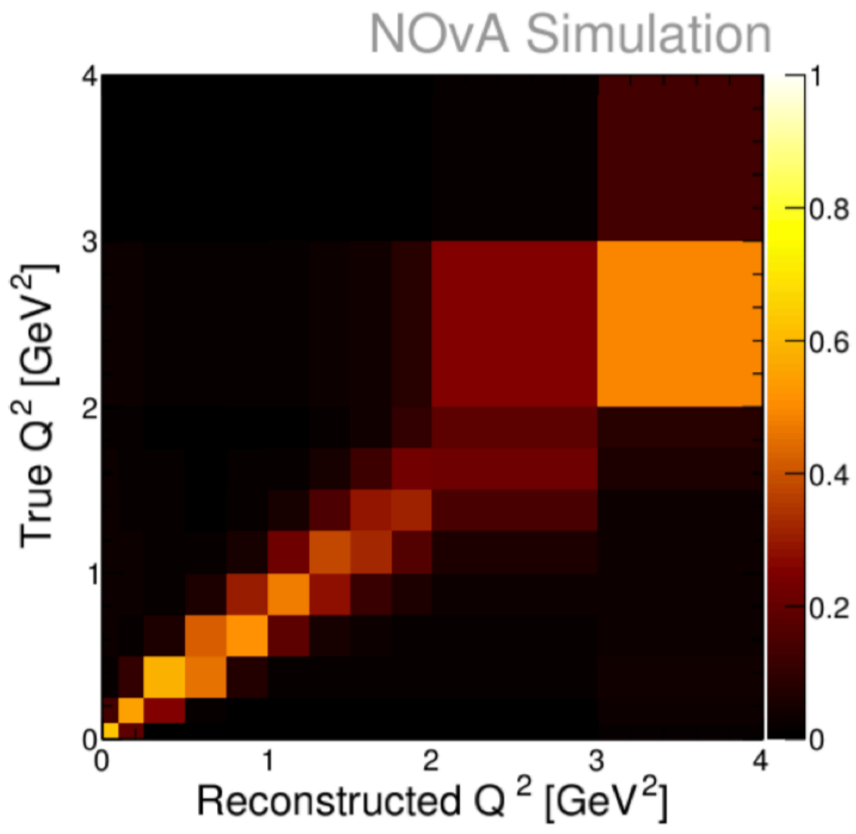
ν_μ disappearance analysis

Measuring a Differential Cross Section

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{1}{\Delta x}\frac{U(S,x)}{\epsilon_i N_{\text{nuc}} \int \Phi(E)dE}$$

- Signal estimate is obtained from data-driven constraint from the template fitting procedure
- Signal is unfolded using D'Agostini method with 2 iterations - migration matrix is determined from simulation

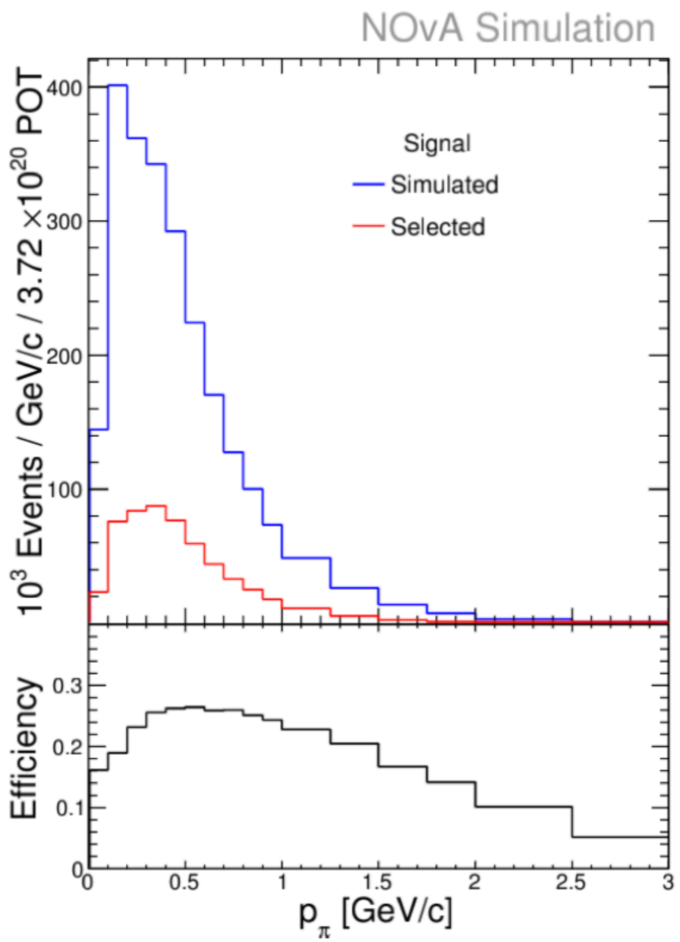




Measuring a Differential Cross Section

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{1}{\Delta x} \frac{U(S,x)}{\epsilon_i N_{\text{nuc}} \int \Phi(E) dE}$$

- Efficiency is calculated from simulation in each kinematic bin
- Number of target nucleons in determined using a 3D random pull algorithm



Element	Total Mass (kg)	N_{Nuc}
H	3815	2.28×10^{30}
C	23651	1.41×10^{31}
O	1053	6.30×10^{29}
Cl	5685	3.40×10^{30}
Ti	1139	6.81×10^{29}
Other	95.4	5.71×10^{28}
Total	35438	2.11×10^{31}

Measuring a Differential Cross Section

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{1}{\Delta x}\frac{U(S,x)}{\epsilon_i N_{\text{nuc}} \int \Phi(E)dE}$$

- Flux estimate from the PPFX framework developed by MINERvA
- Measurement is restricted to ν_μ flux from 1-5 GeV