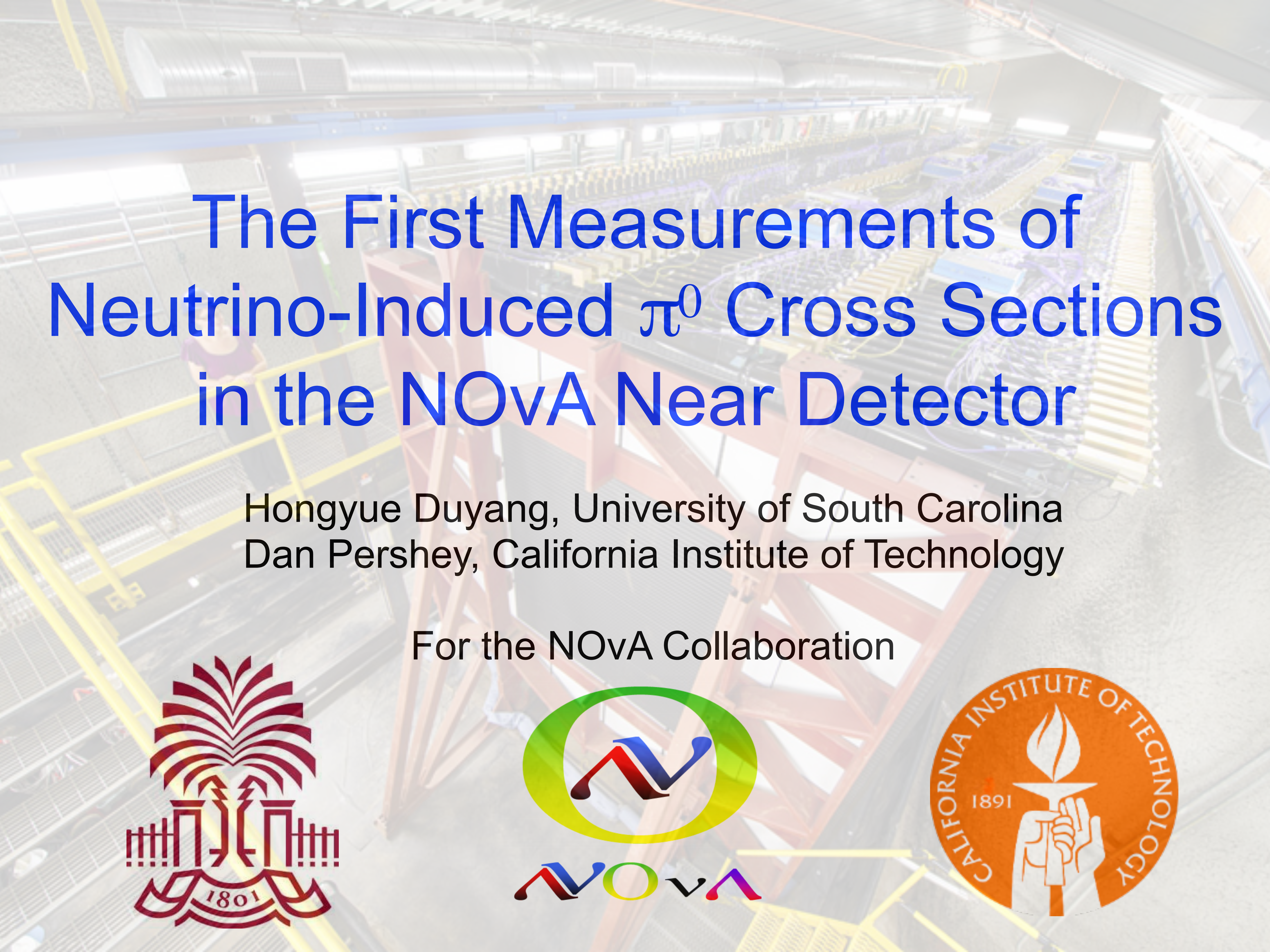


The First Measurements of Neutrino-Induced π^0 Cross Sections in the NOvA Near Detector

Hongyue Duyang, University of South Carolina
Dan Pershey, California Institute of Technology

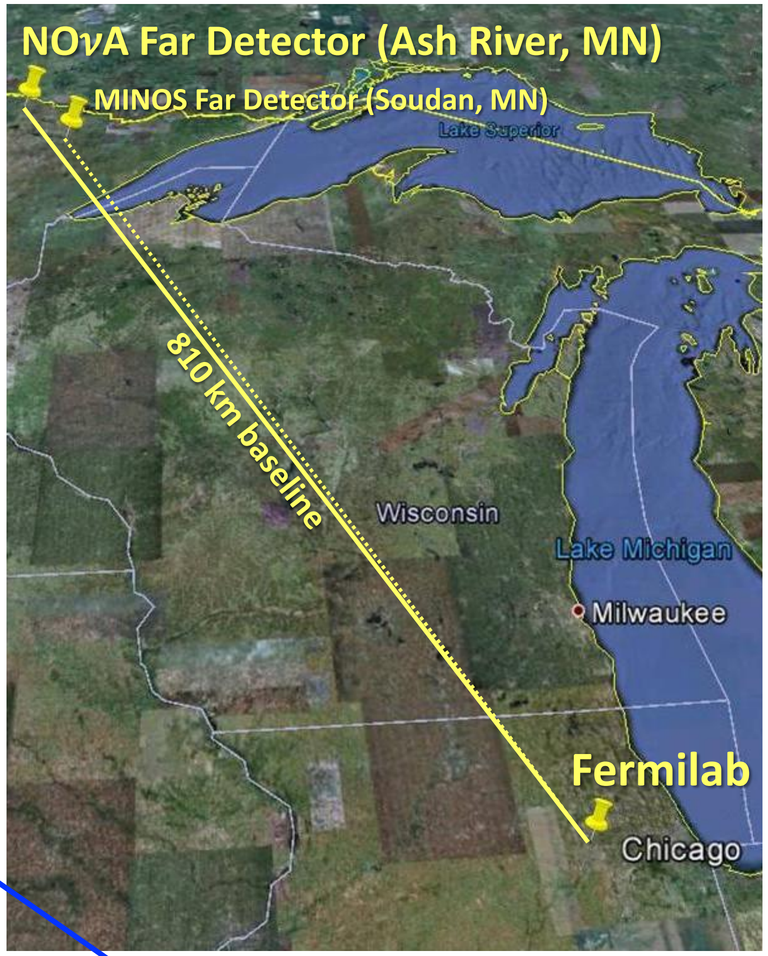
For the NOvA Collaboration

Outline

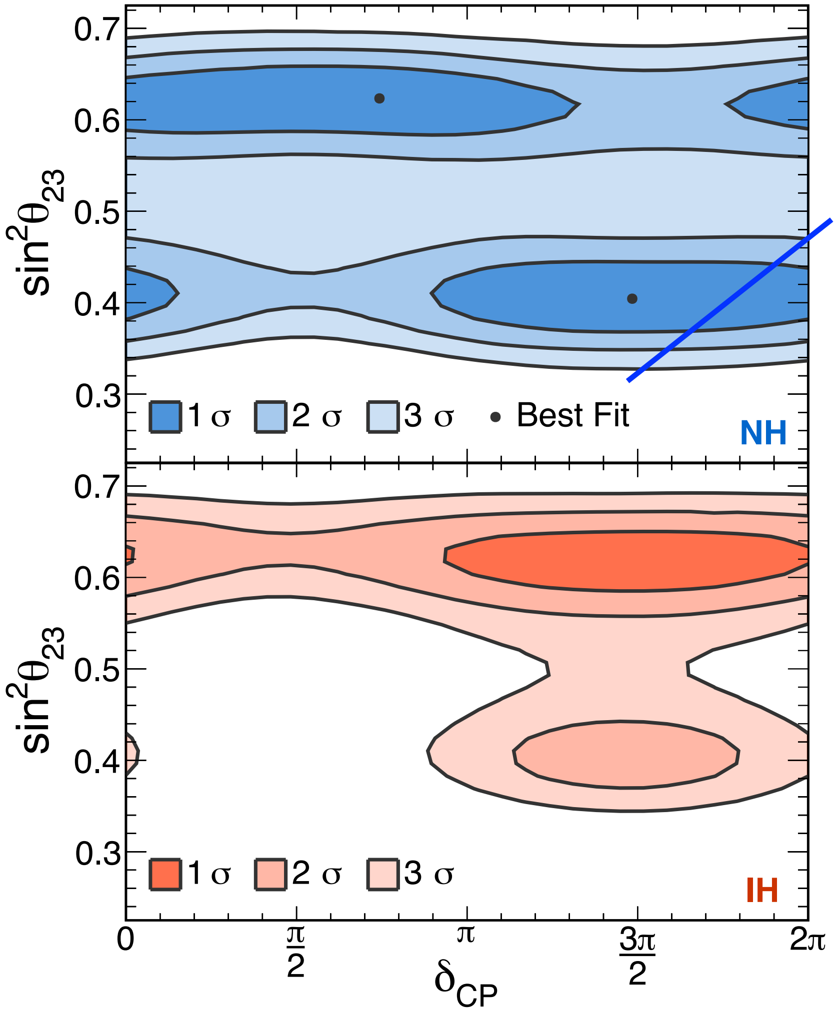
- Introduction
  - Motivation
  - NOvA Near Detector and Flux
- **Neutral current coherent π^0** (H. Duyang)
- **Charged current semi-inclusive π^0** (D. Pershey)
- Summary

NOvA Neutrino Oscillation Experiment

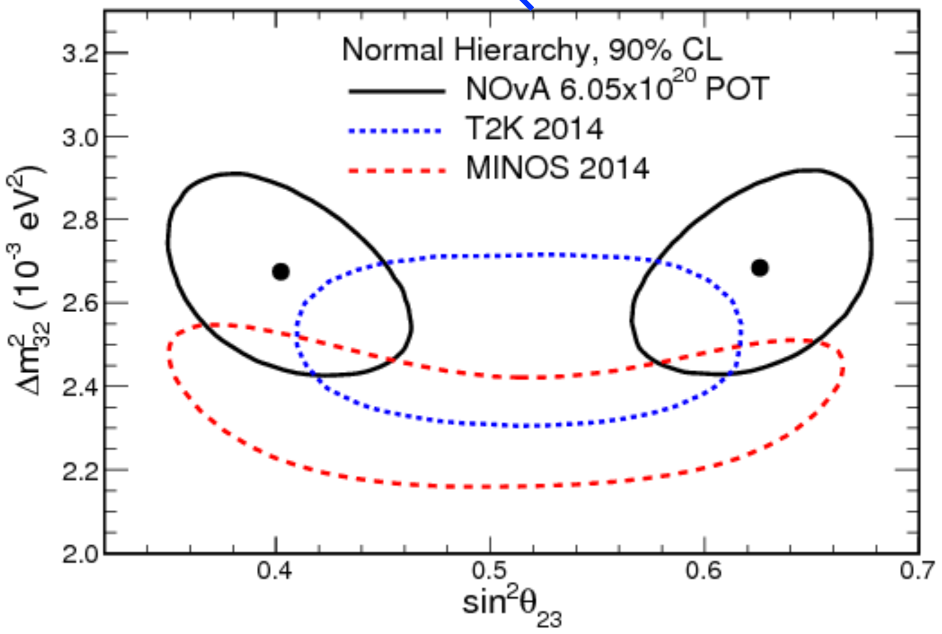
- Long-baseline neutrino oscillation measurements:
  - ν_μ to ν_e appearance & ν_μ disappearance
    - Mass hierarchy, θ_{23} octant, δ_{cp}
  - NC disappearance sterile neutrino search

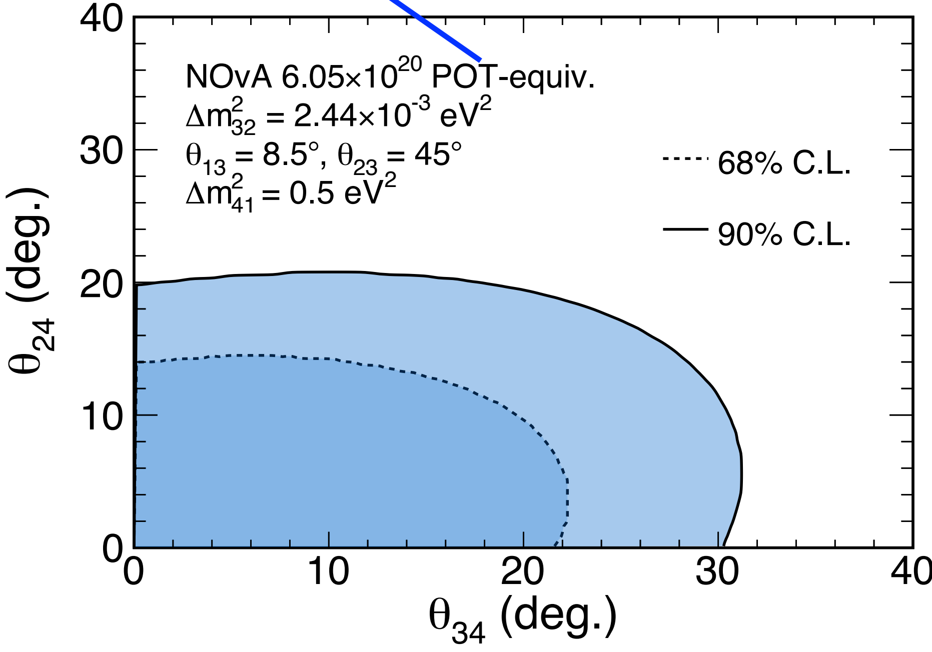


Recent Publications:
Phys.Rev. D96 (2017) no.7, 072006
Phys.Rev.Lett. 118 (2017) no.23, 231801
Phys.Rev.Lett. 118 (2017) no.15, 151802



NOvA π^0 Measurements

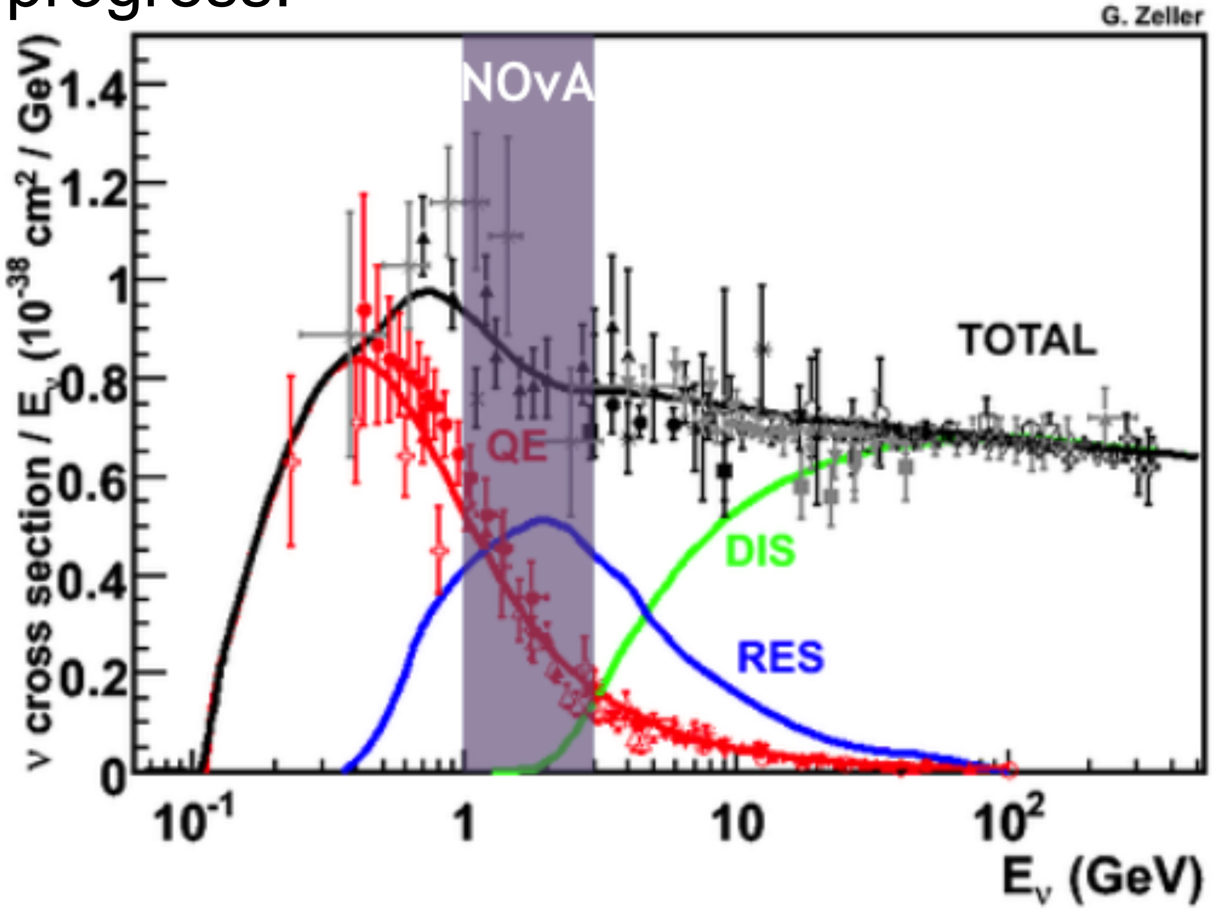




H. Duyang & D. Pershey

NOvA Cross-Section Measurements Overview

- NOvA is in 1-3 GeV energy region:
  - Covers the DUNE 1st oscillation maximum.
  - Overlaps with MiniBooNE, MINERvA, T2K.
  - Both neutrino and anti-neutrino modes.
- A very active neutrino cross-section program:
  - **Neutral current coherent π^0** (H. Duyang)
  - **Charged current semi-inclusive π^0** (D. Pershey)
  - A lot of other measurements in progress:
    - ν_μ-CC inclusive
    - ν_e-CC inclusive
    - NC π^0
    - CC π^+&π^-



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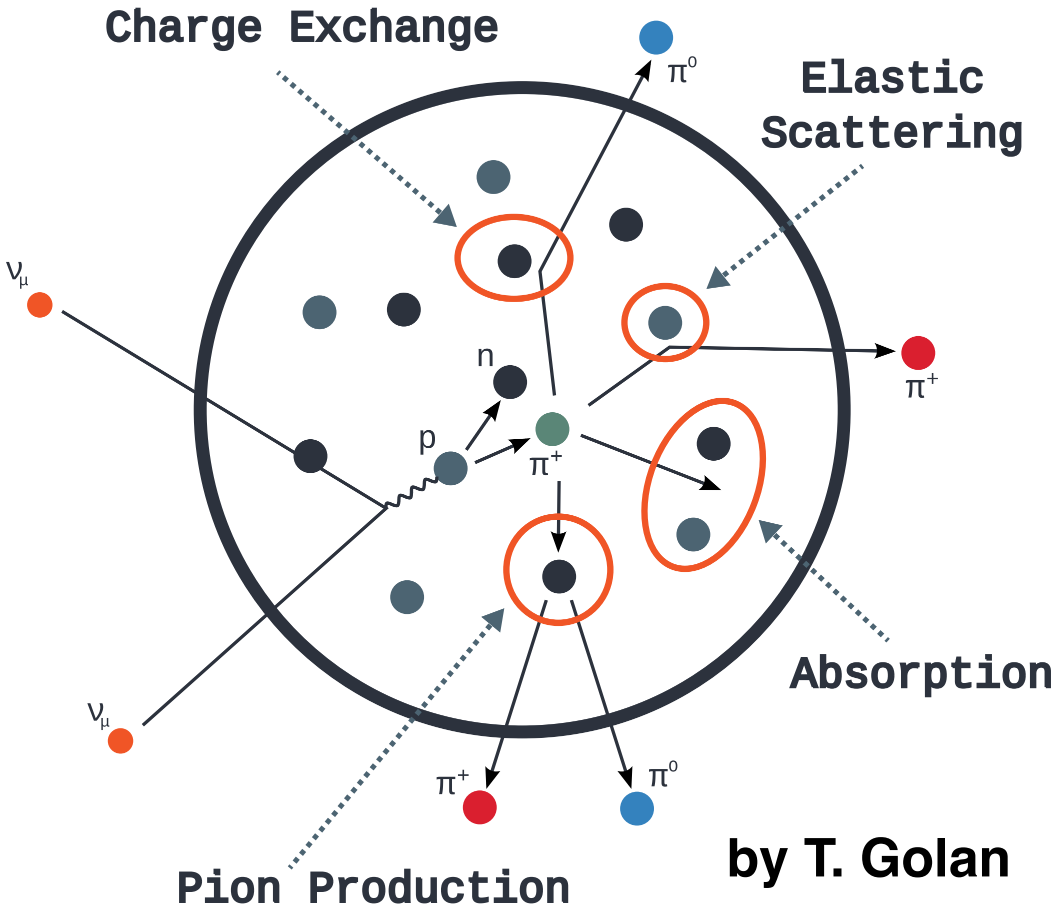

by T. Golan

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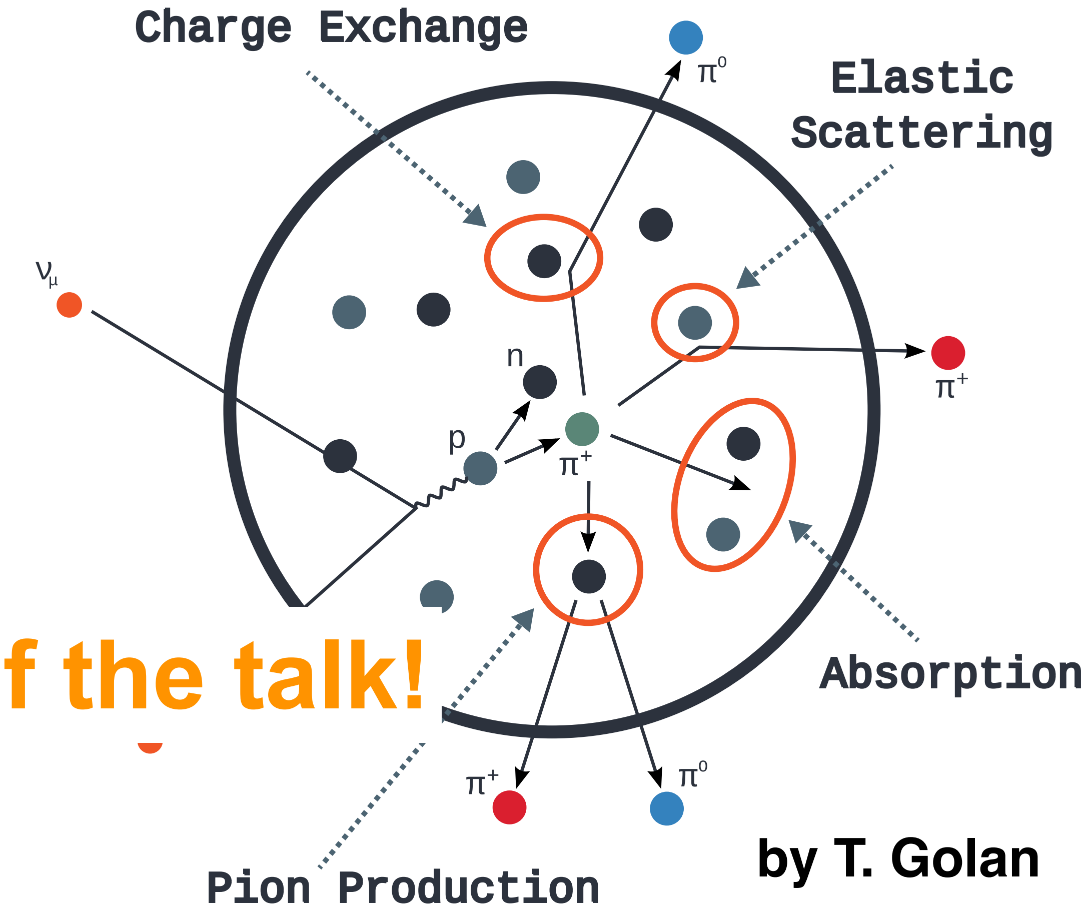
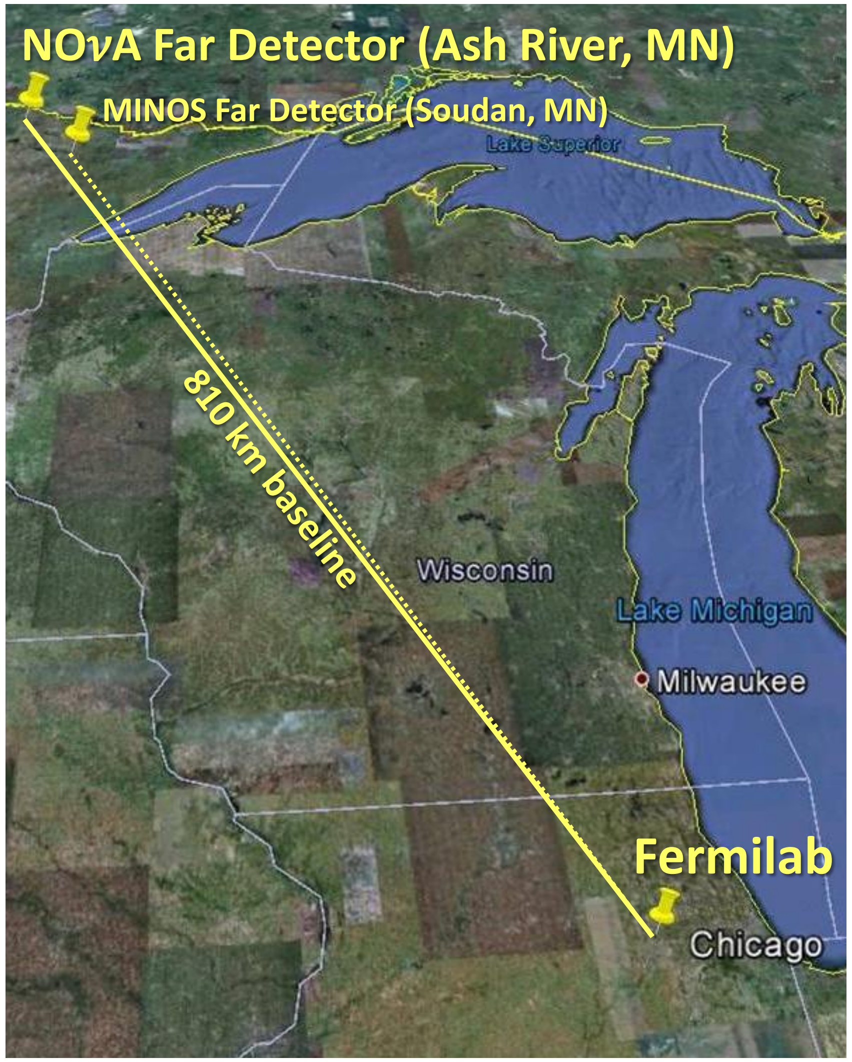


More in the 2nd part (CC π^0) of the talk!

by T. Golan

The NOvA Near Detector



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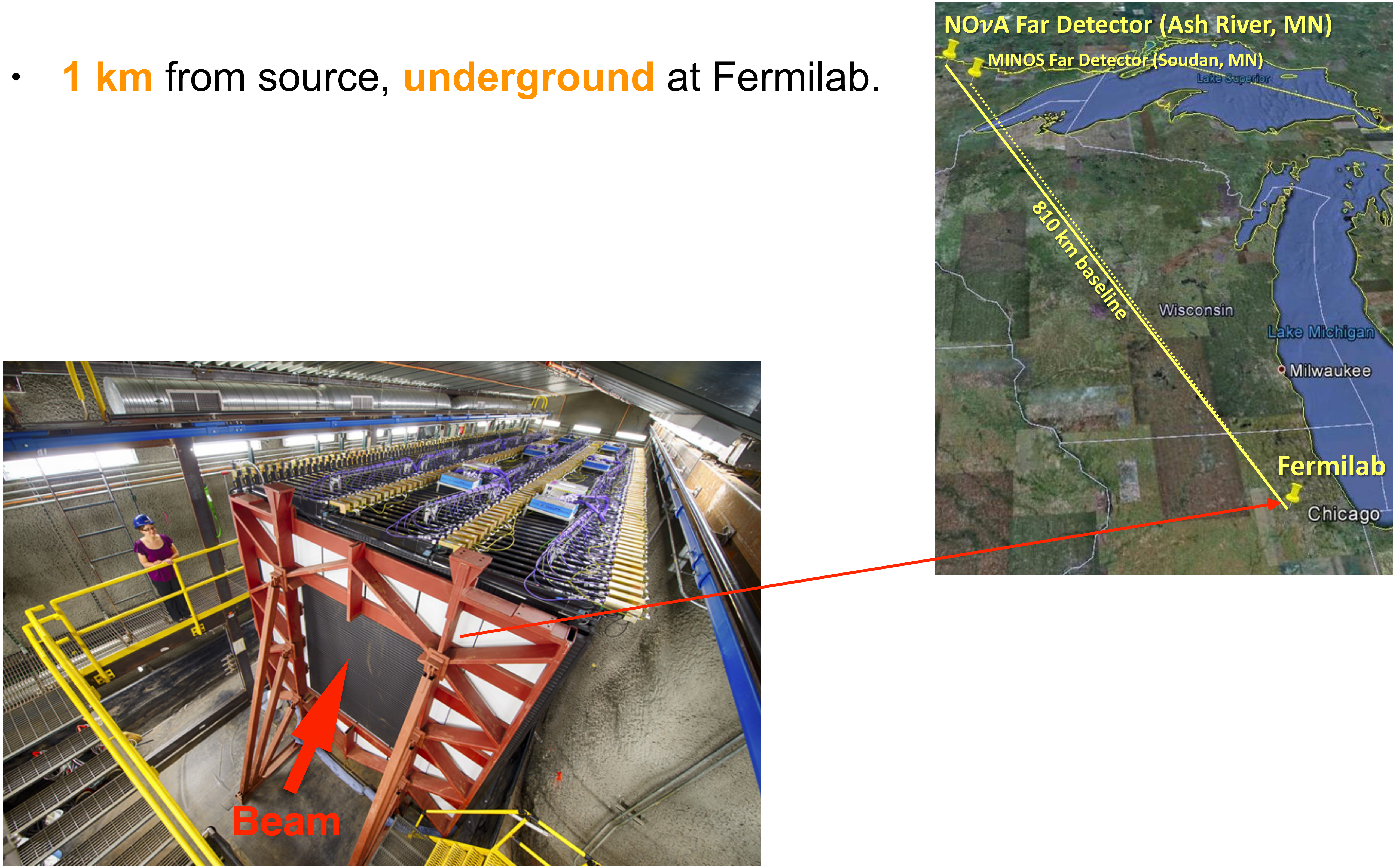

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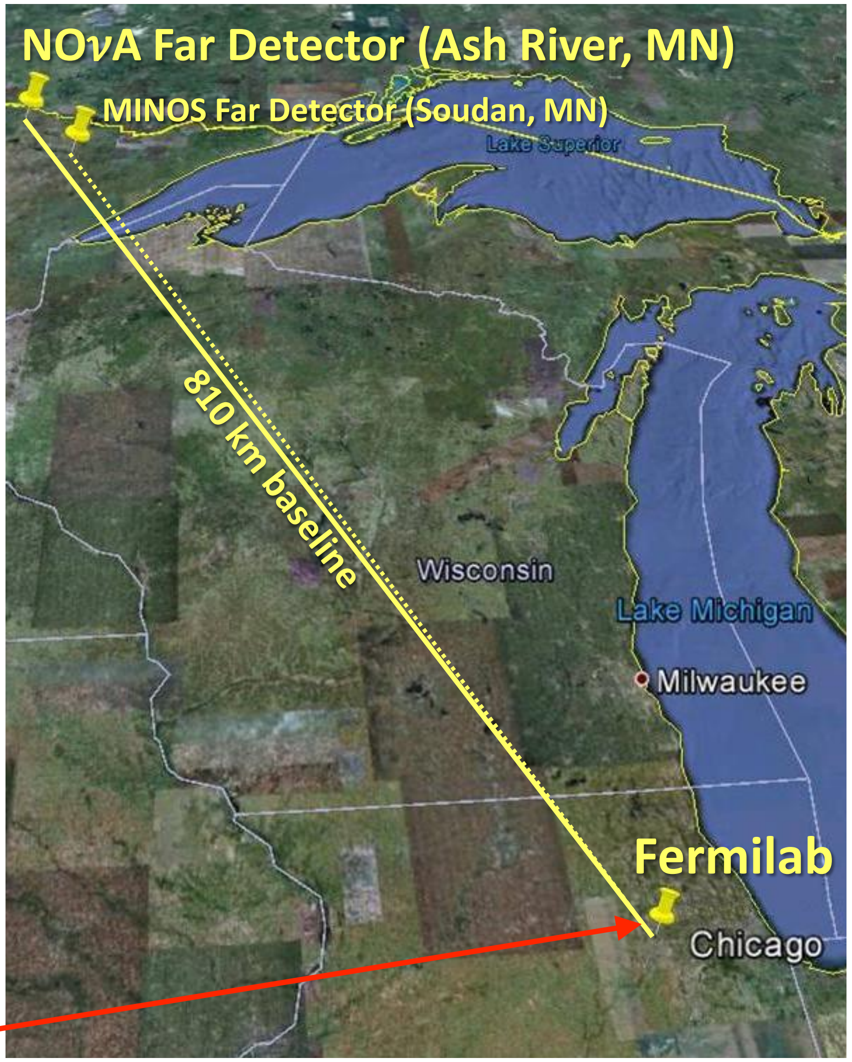

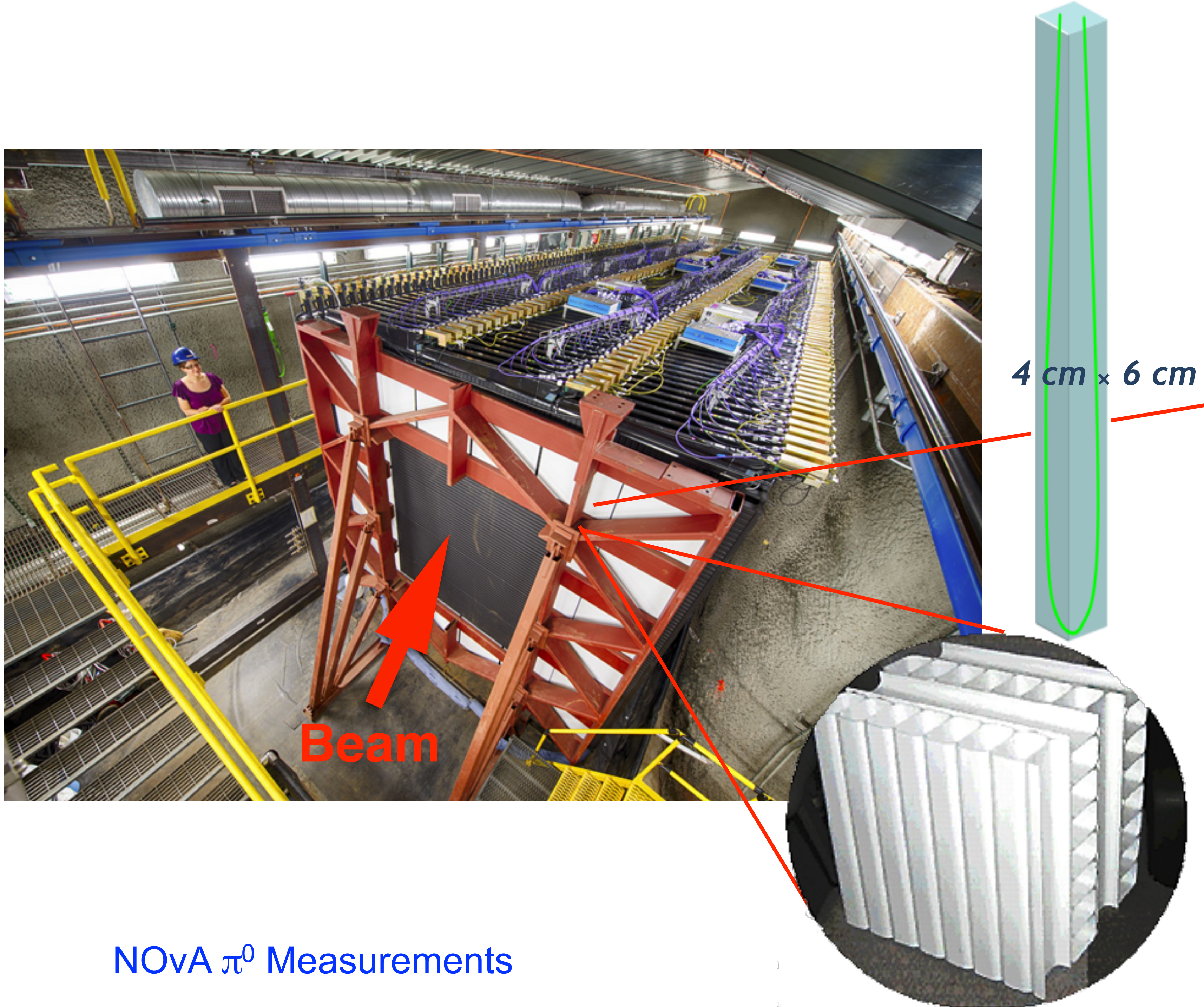

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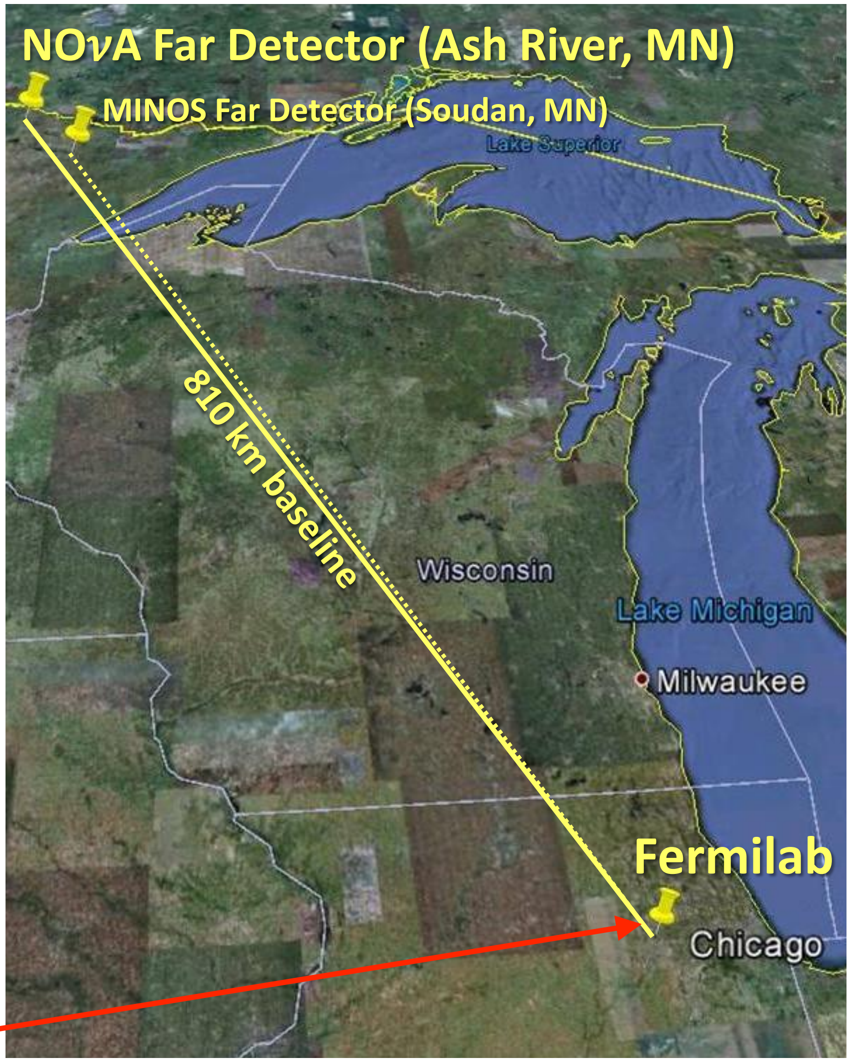

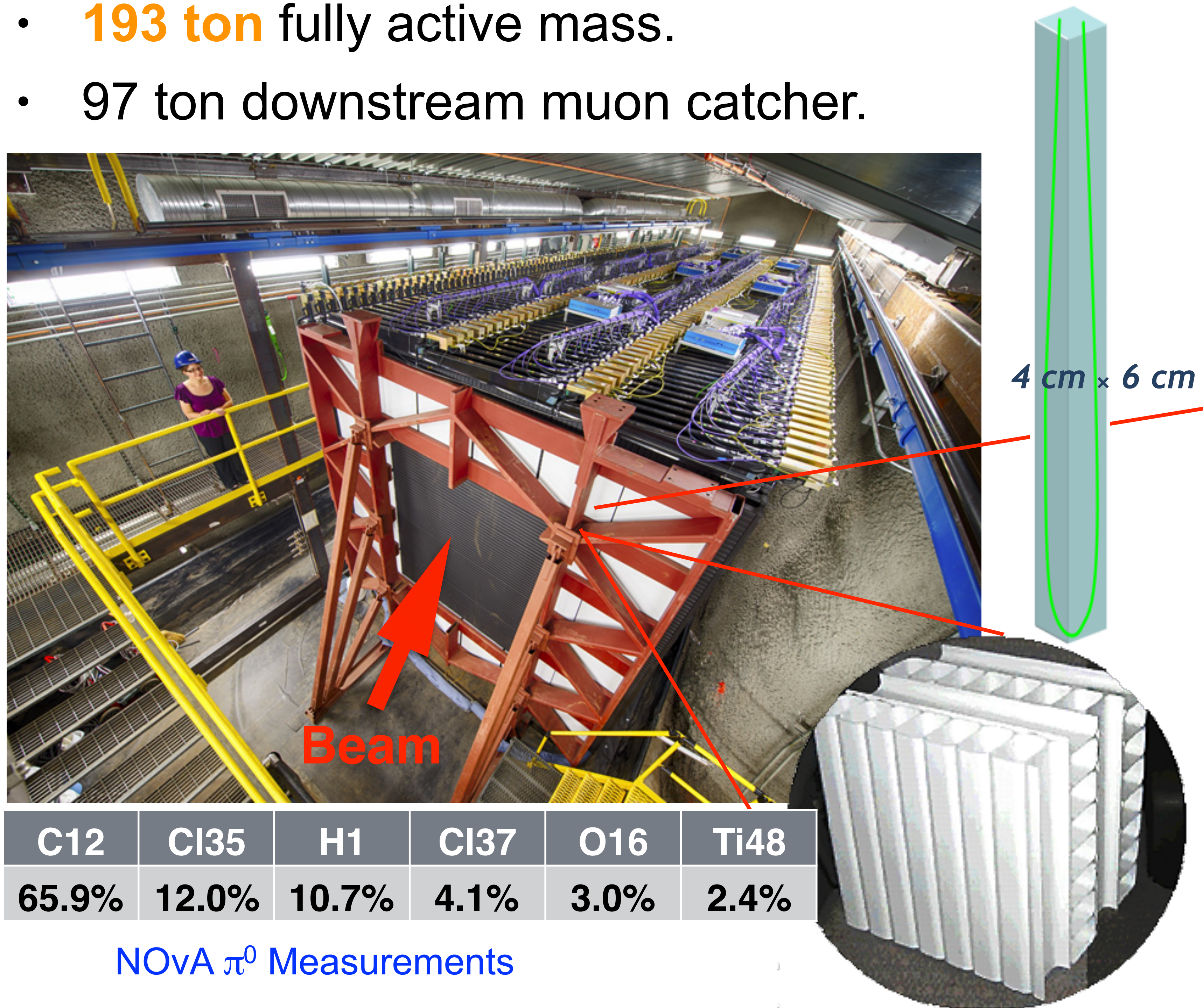

C12	Cl35	H1	Cl37	O16	Ti48
65.9%	12.0%	10.7%	4.1%	3.0%	2.4%

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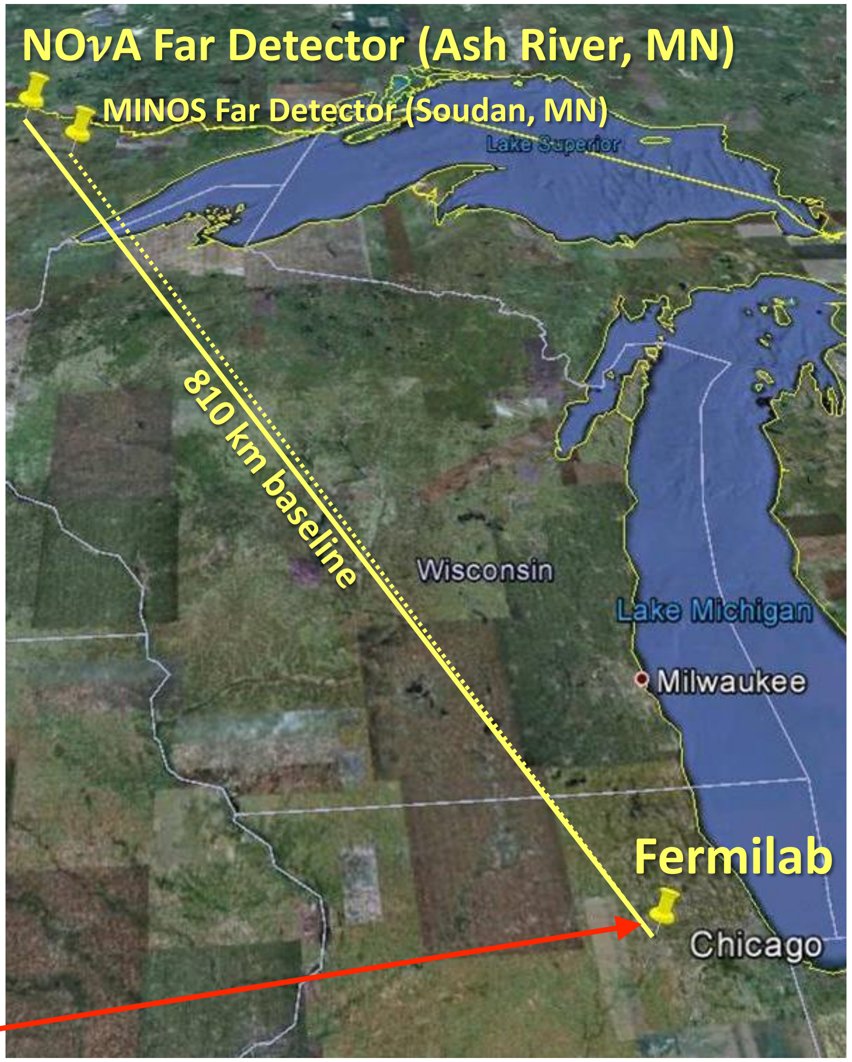

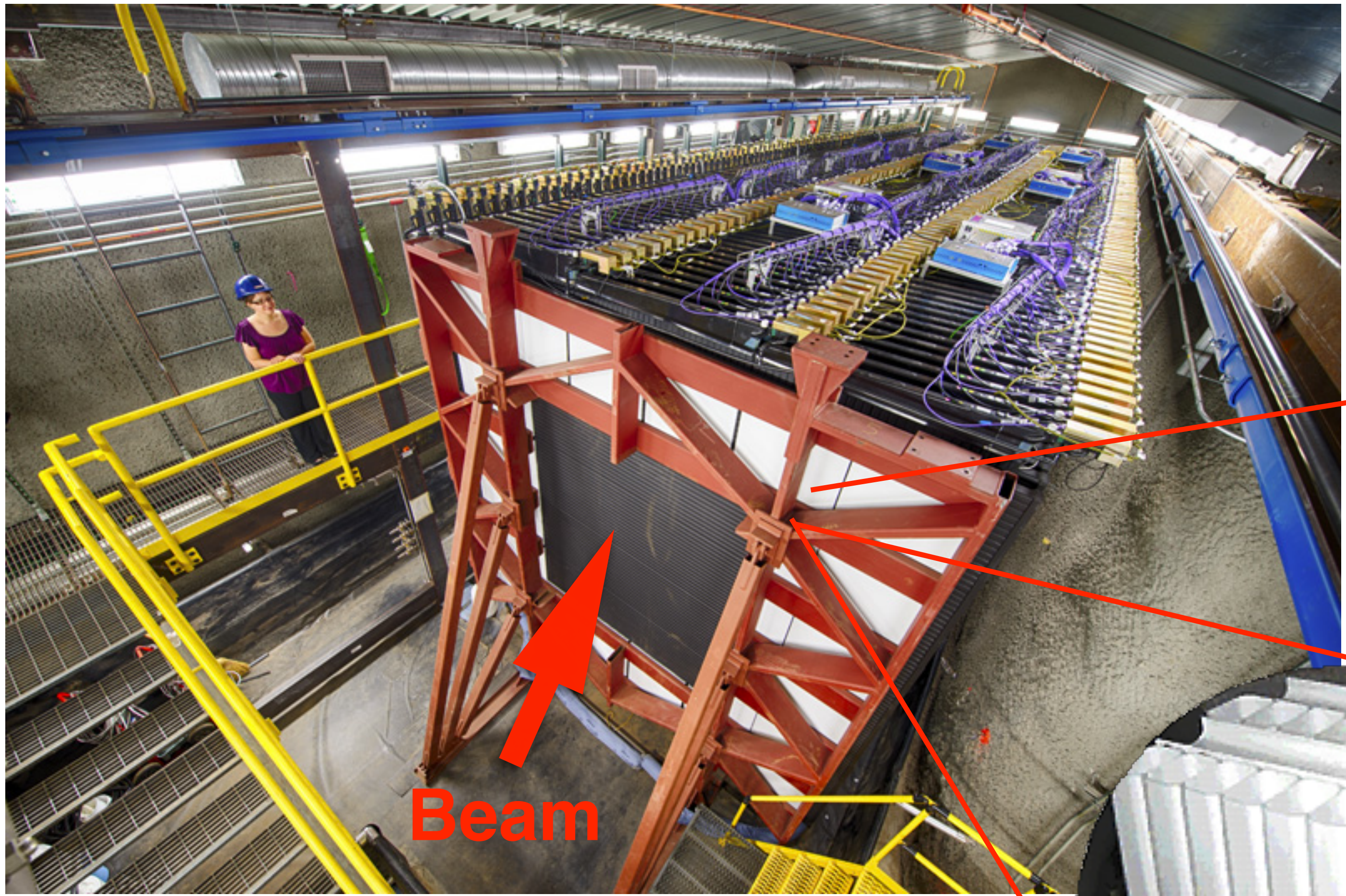

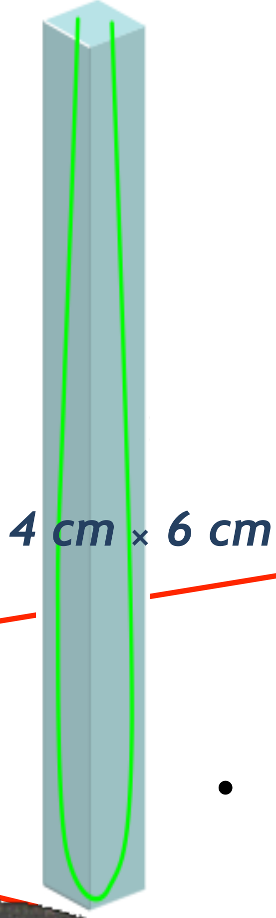

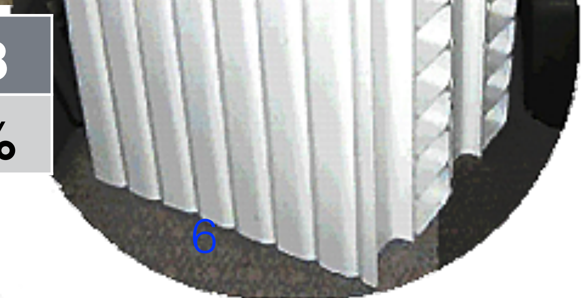

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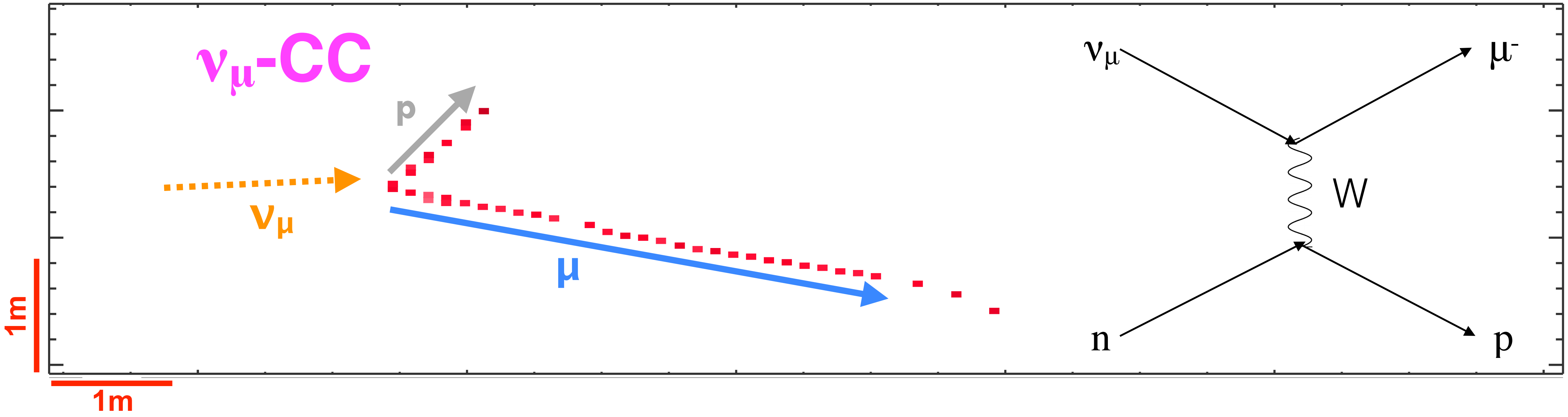
- **Low-Z, fine-grained**
  1 plane ~$0.15X_0$ (38 cm).
- Optimized for EM shower measurement, including π^0s.

ν Interactions in The NOvA ND



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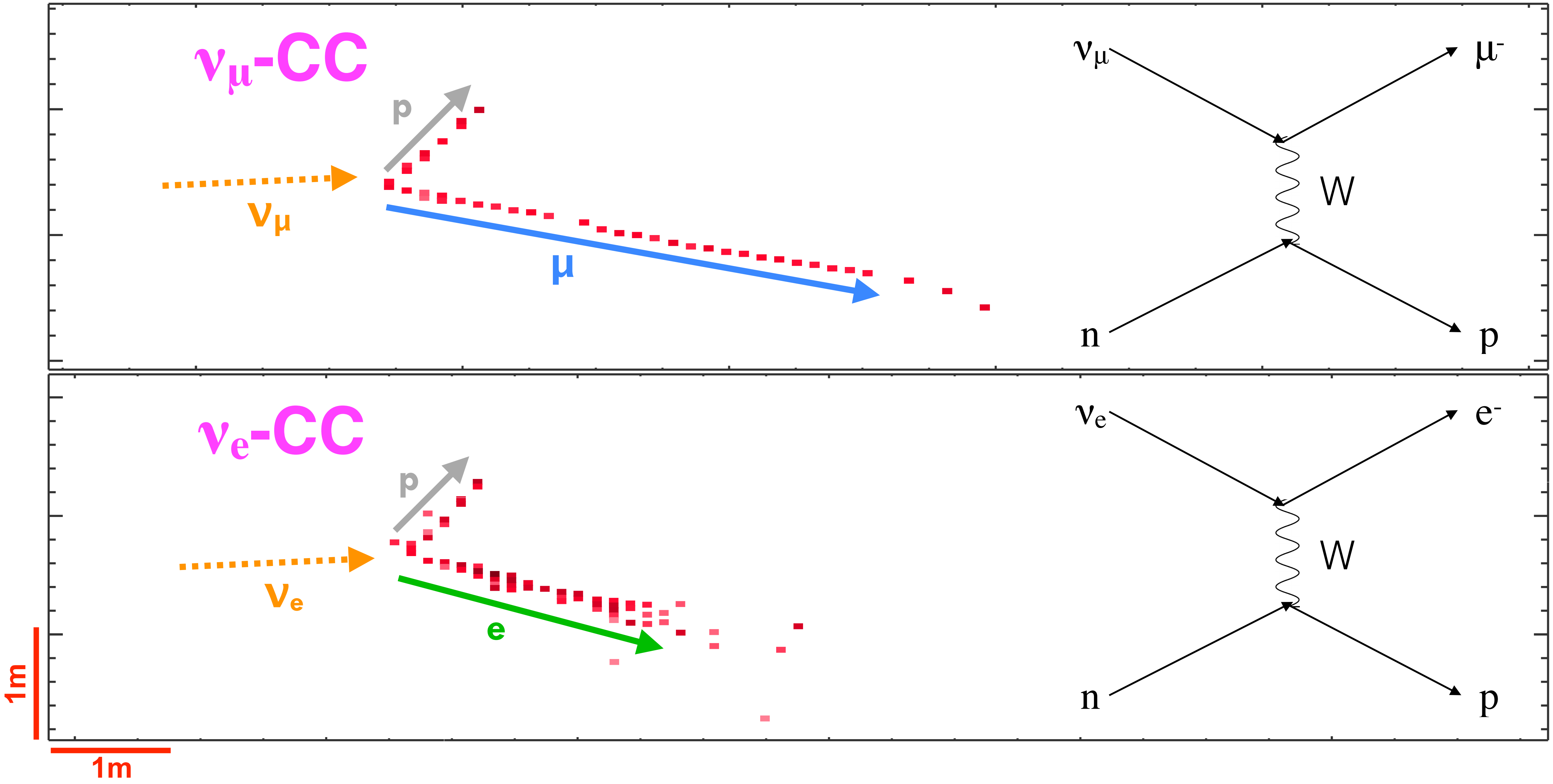

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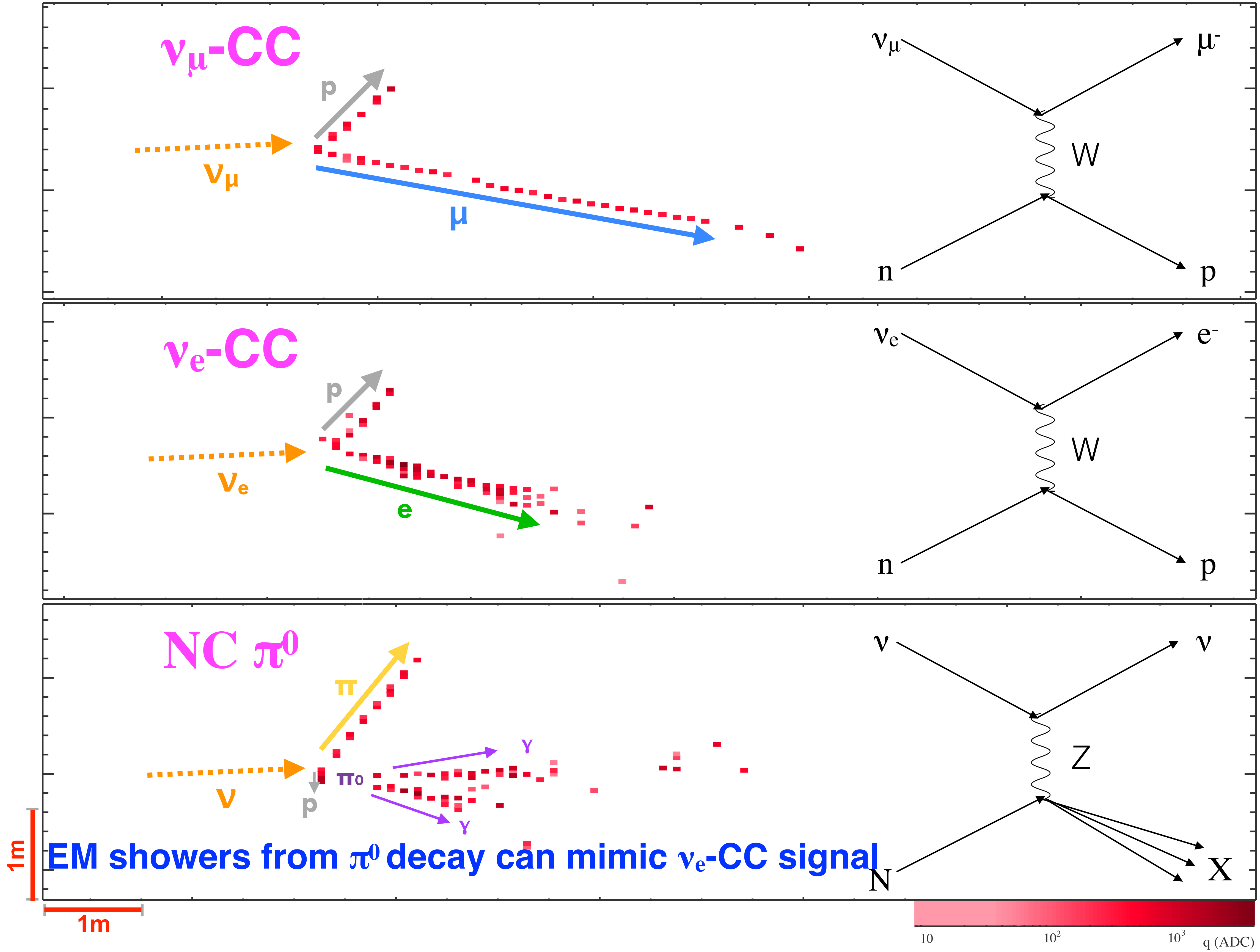
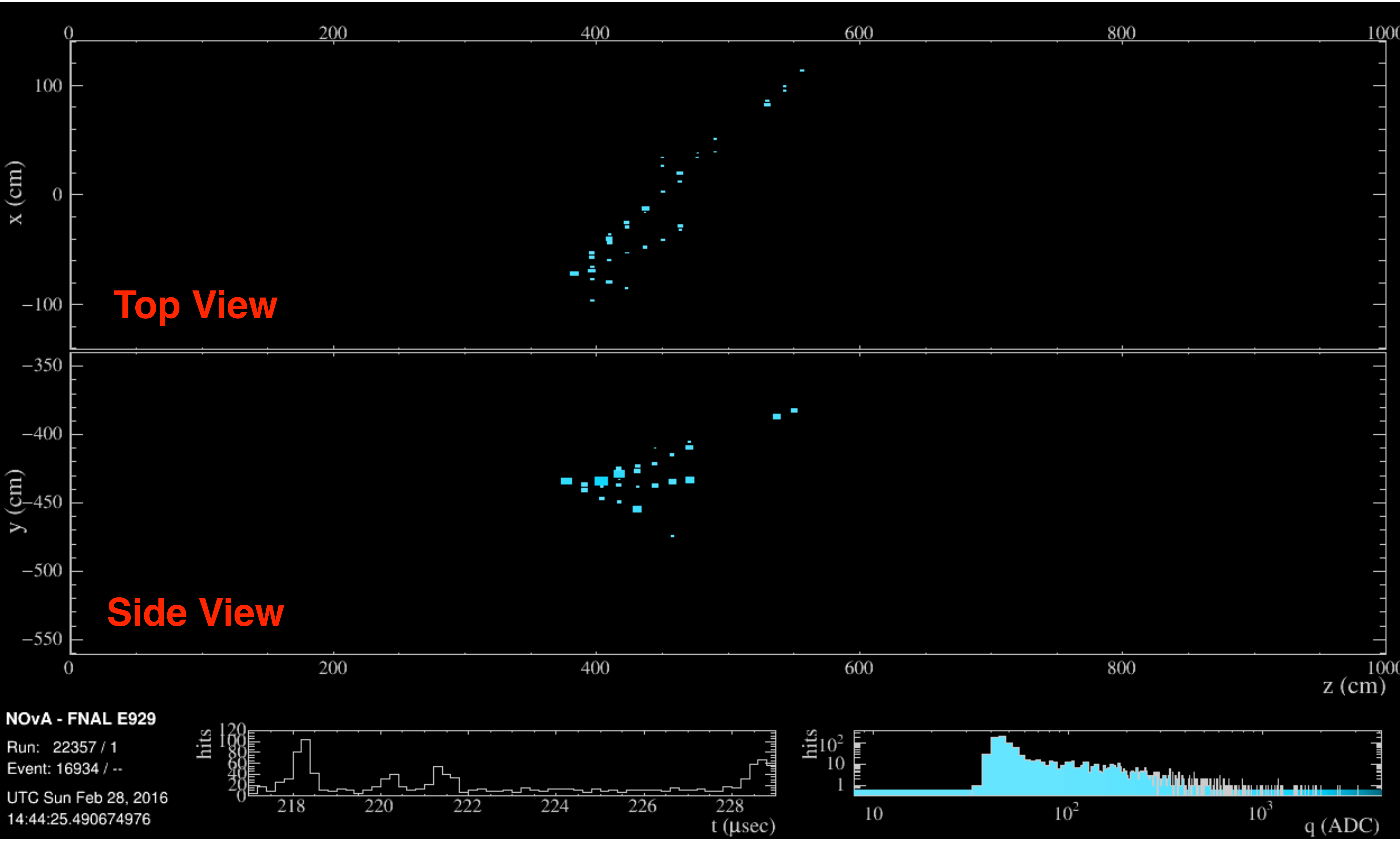


EM showers from π^0 decay can mimic ν_e-CC signal

Reconstruction



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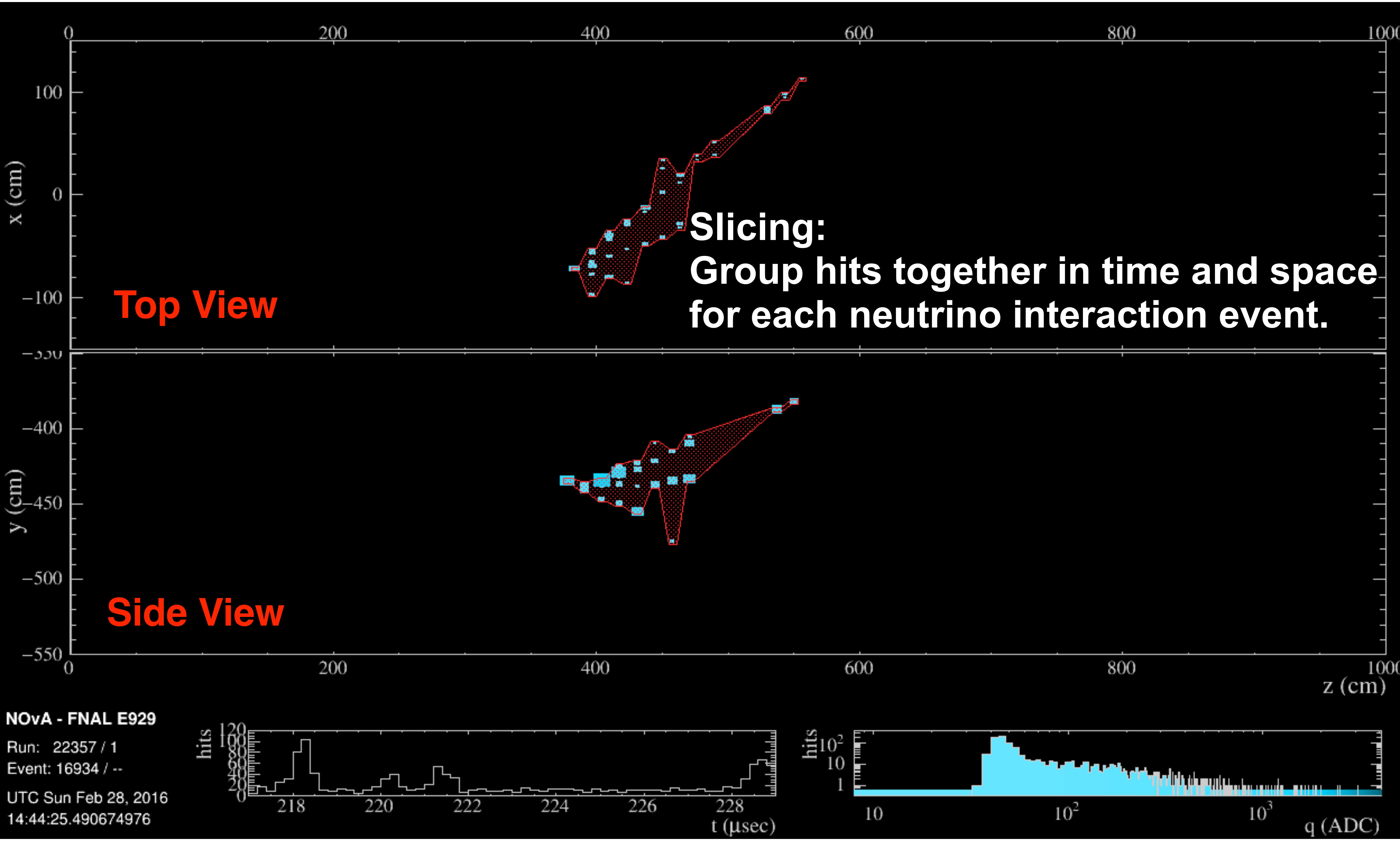
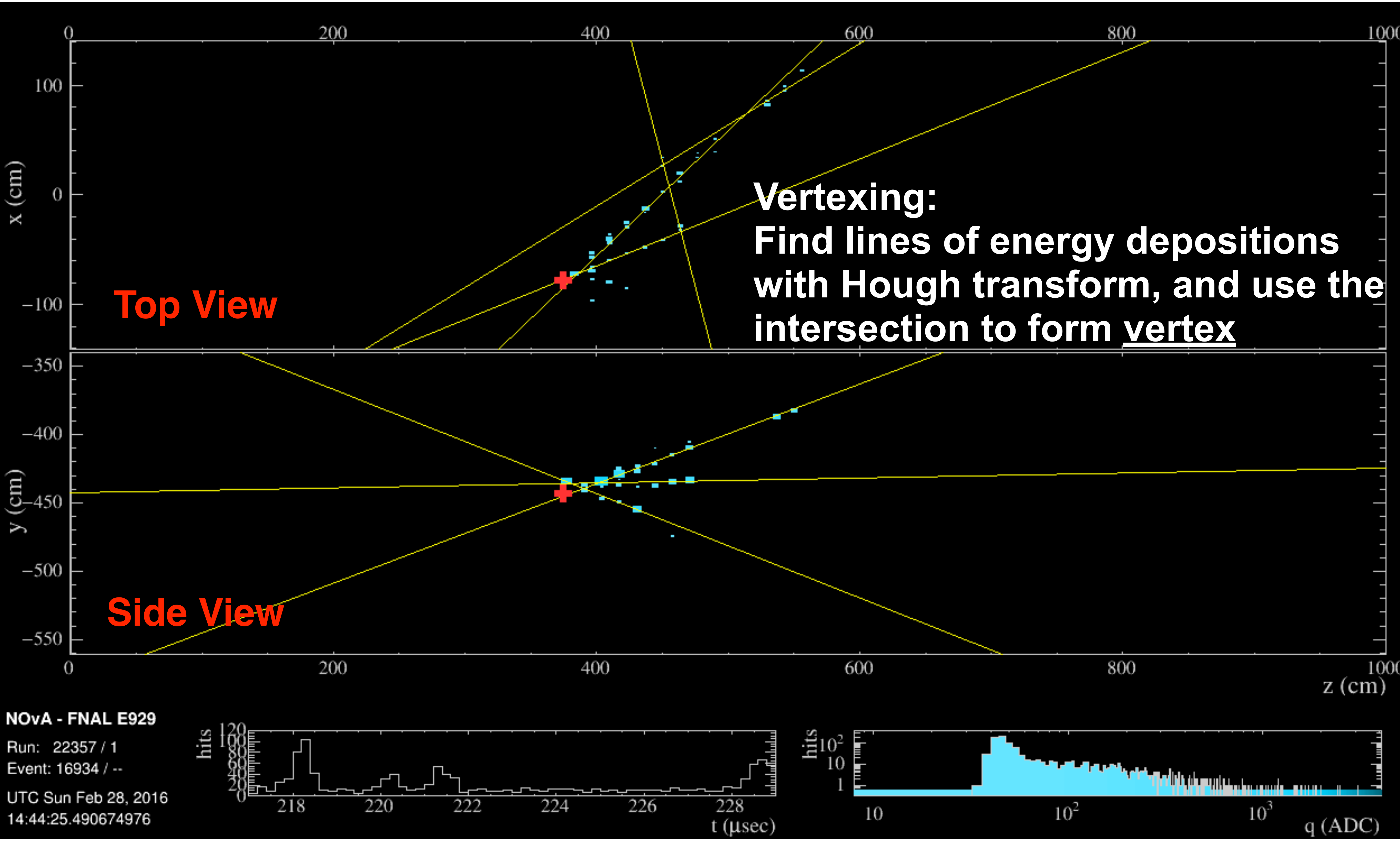


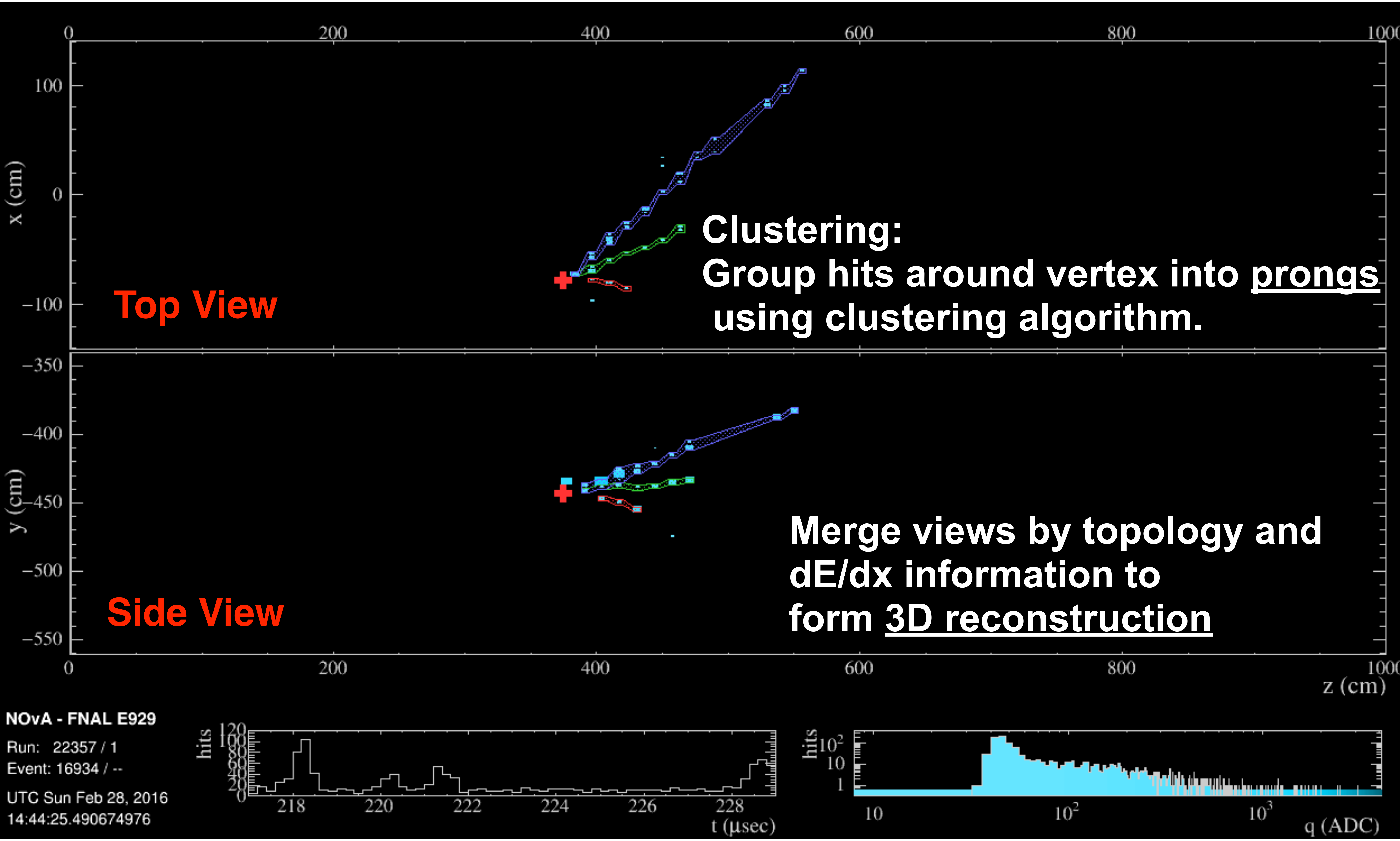
Slicing:
Group hits together in time and space for each neutrino interaction event.

Reconstruction



Vertexing:
Find lines of energy depositions with Hough transform, and use the intersection to form <u>vertex</u>

Reconstruction



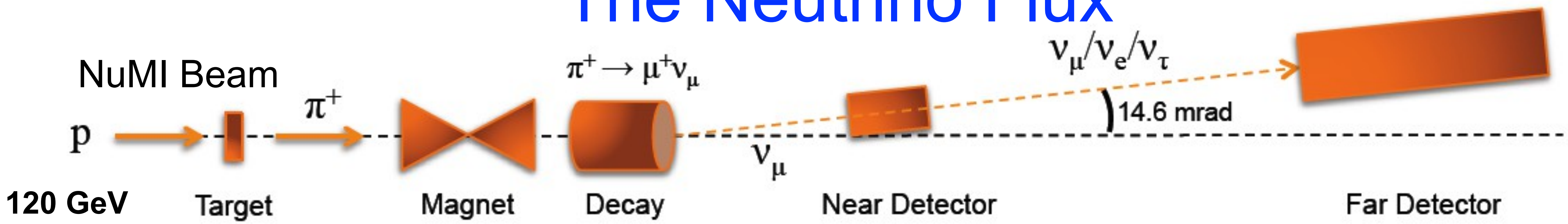
Top View

Clustering:
Group hits around vertex into <u>prongs</u> using clustering algorithm.

Side View

Merge views by topology and dE/dx information to form <u>3D reconstruction</u>

The Neutrino Flux



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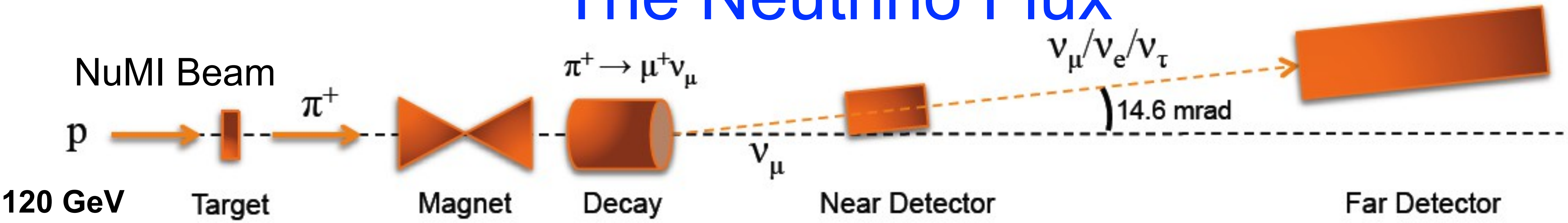

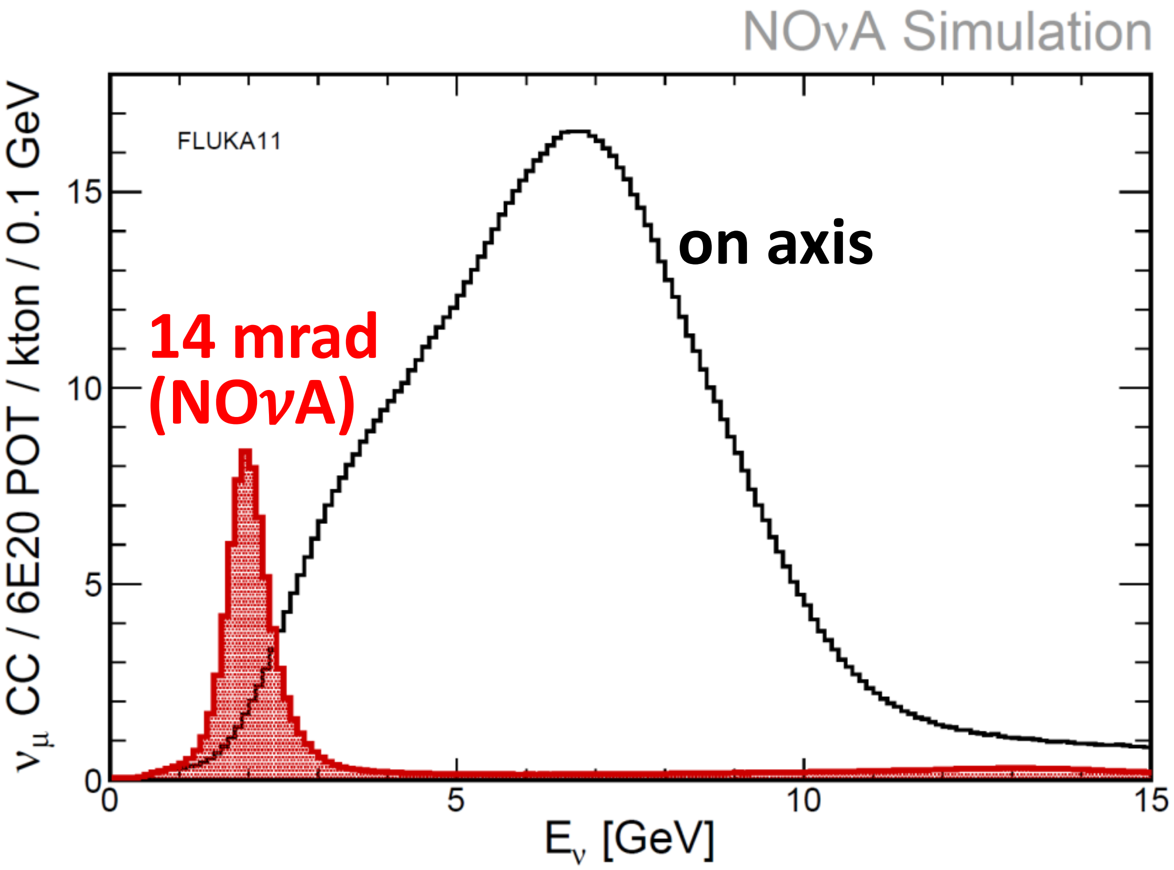

- Narrow band neutrino beam **1-3GeV** peak at **~2GeV**, dominated by **ν_μ (94%)**, with ν_e (1%).

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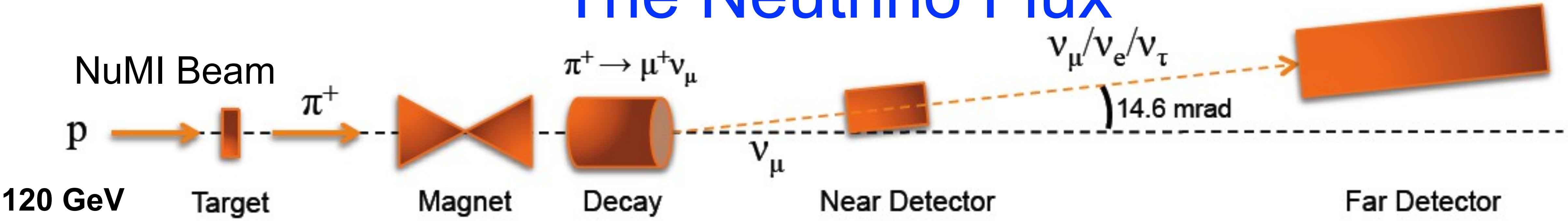

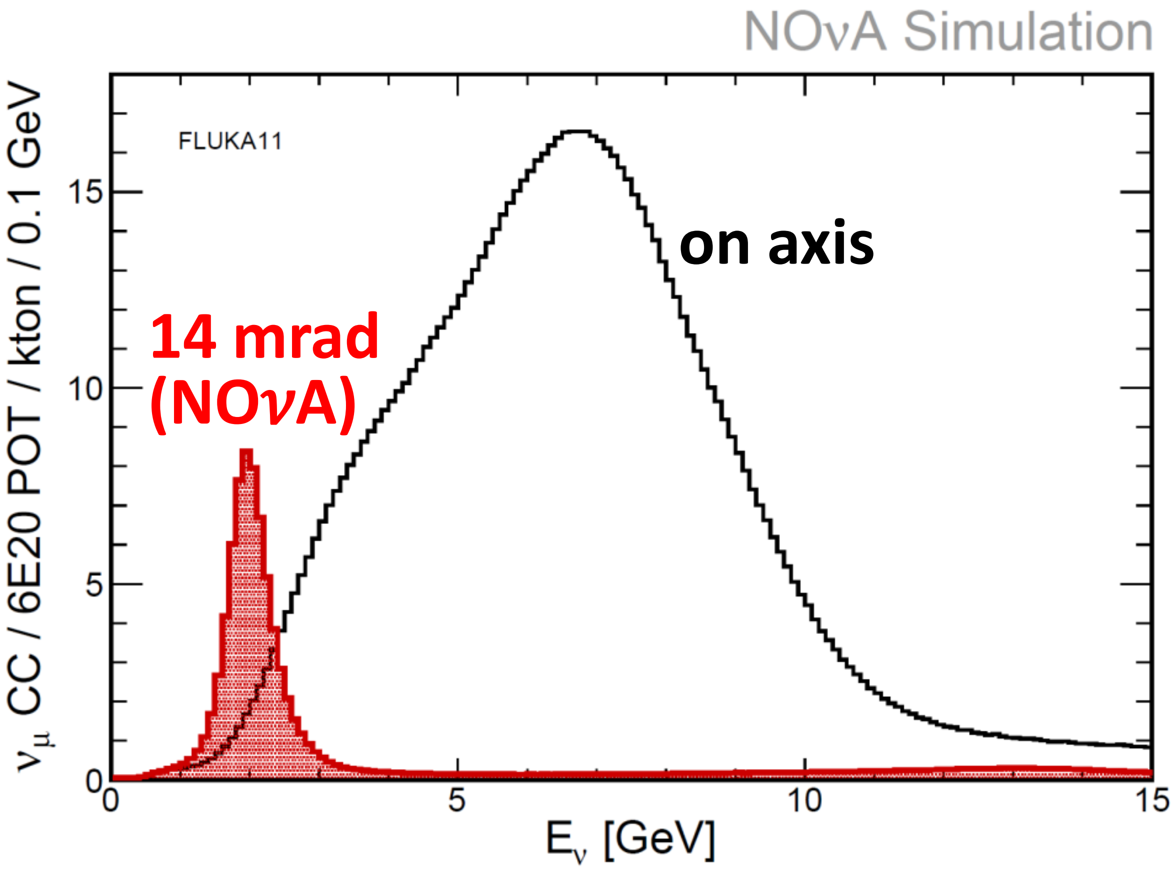

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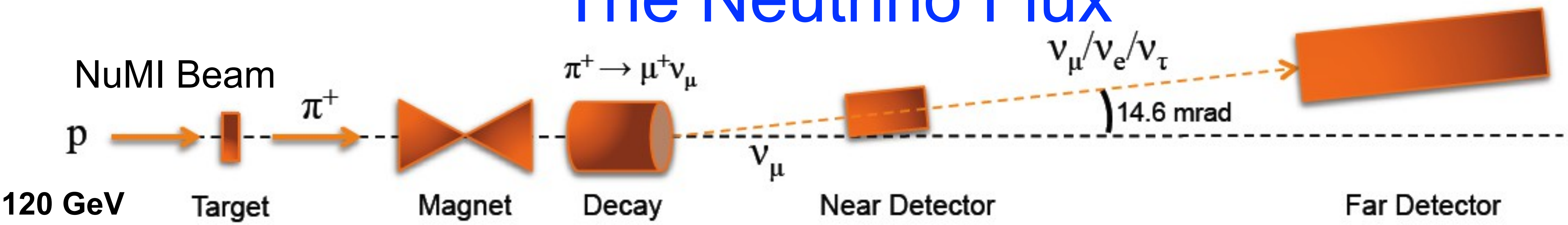

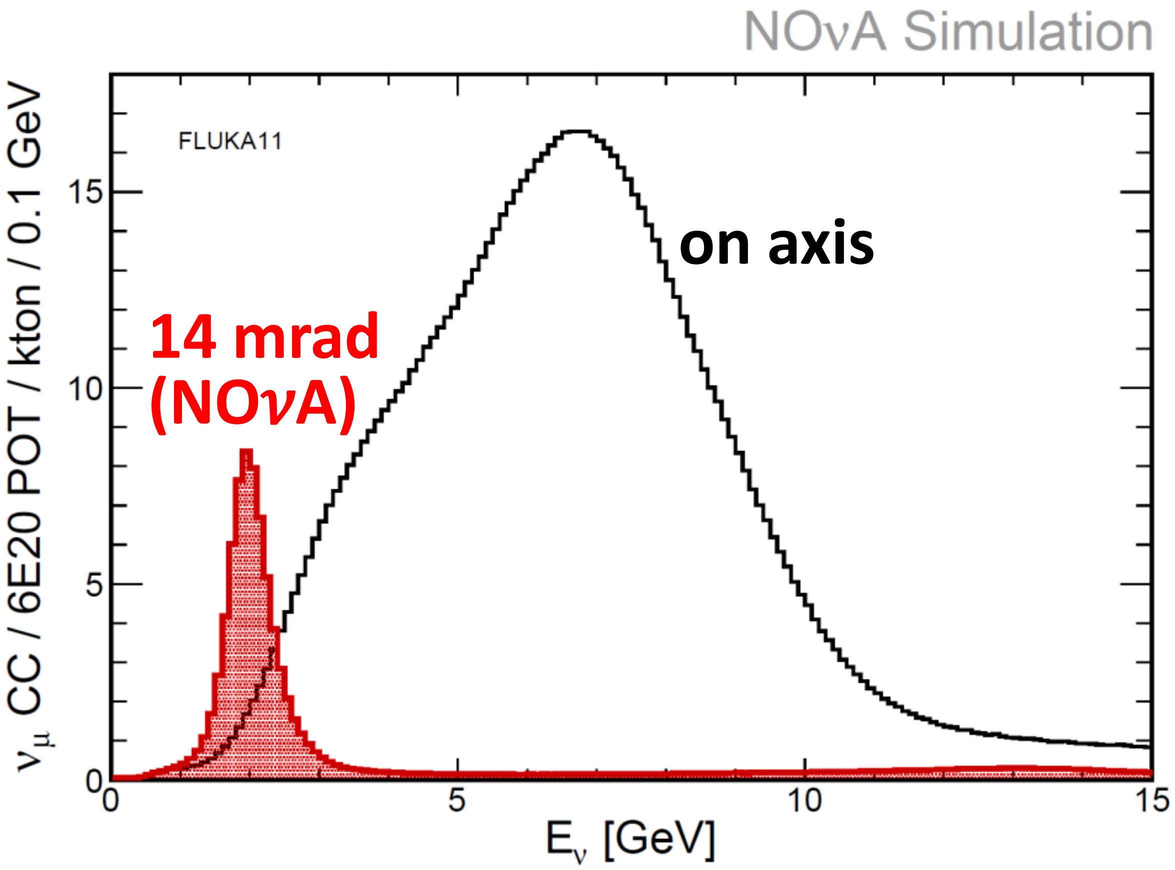

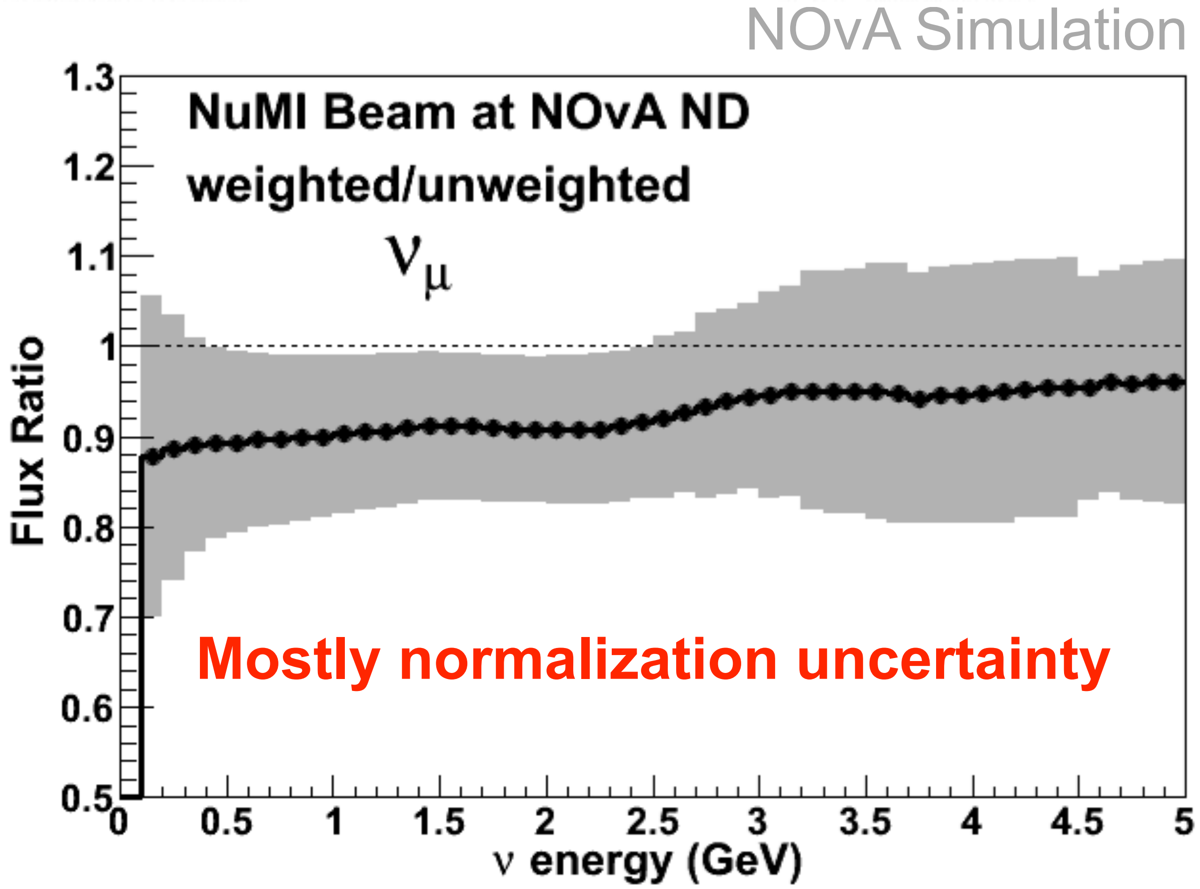

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  PPFX, **P**ackage to **P**redict the **F**lu**X**, *Phys. Rev. D 93, 112007 (2016)*.

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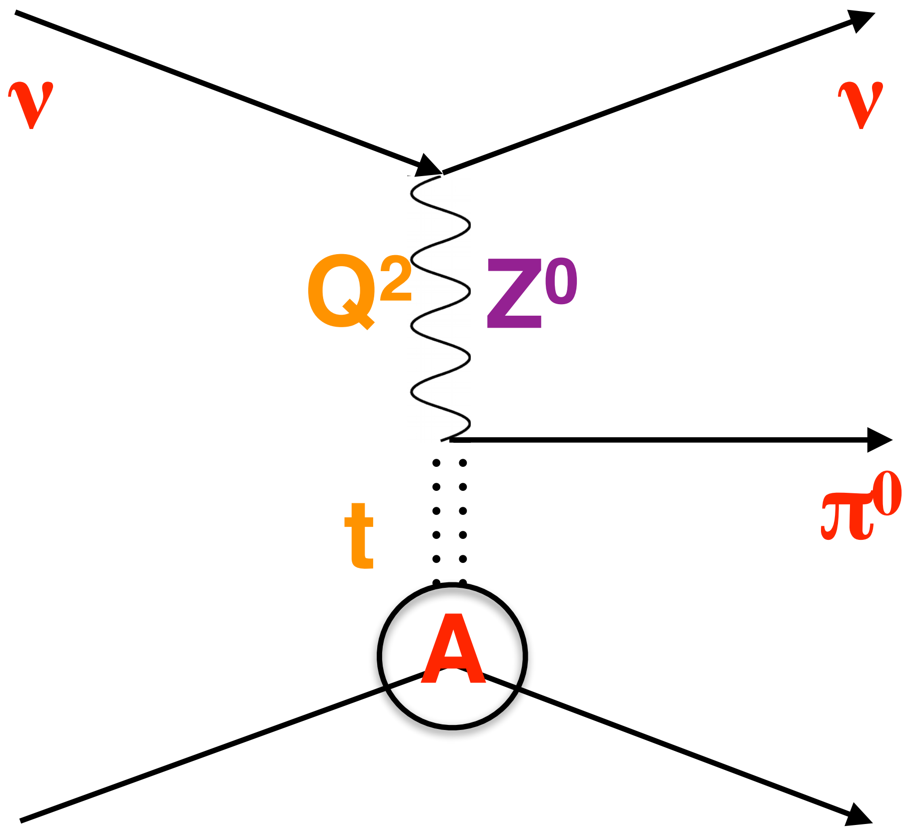

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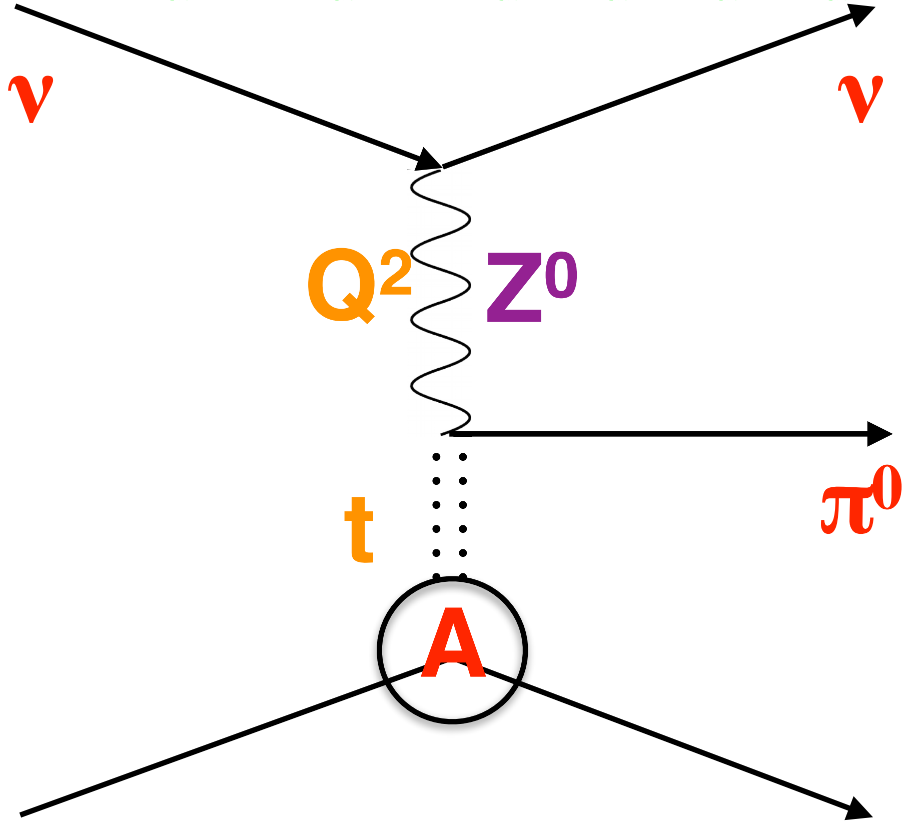

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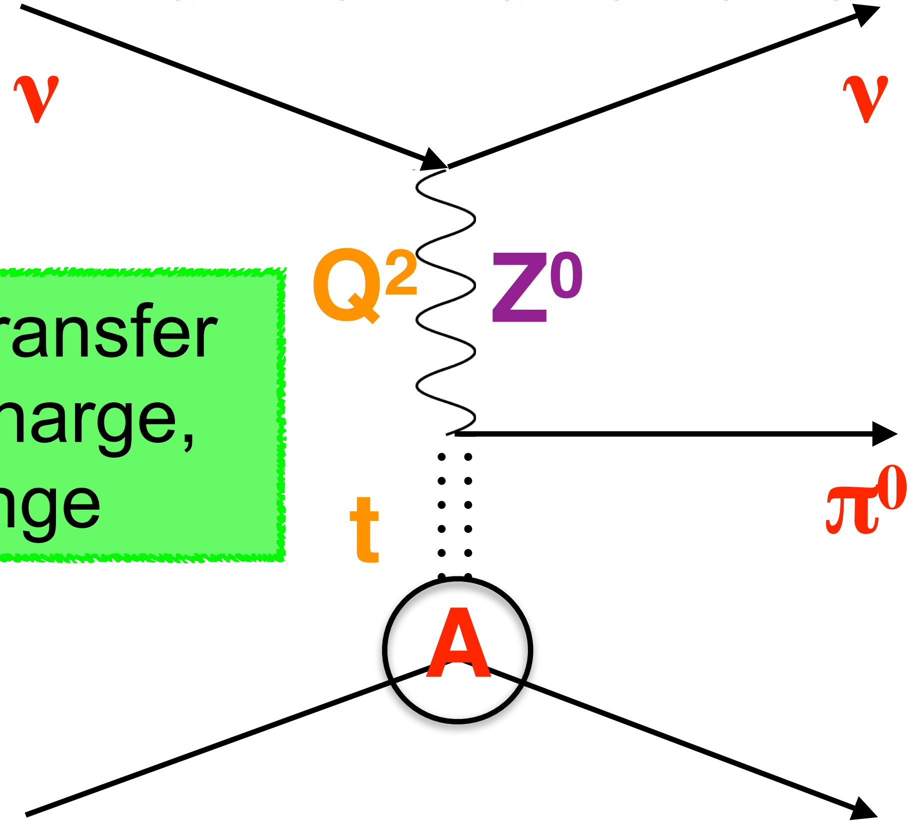

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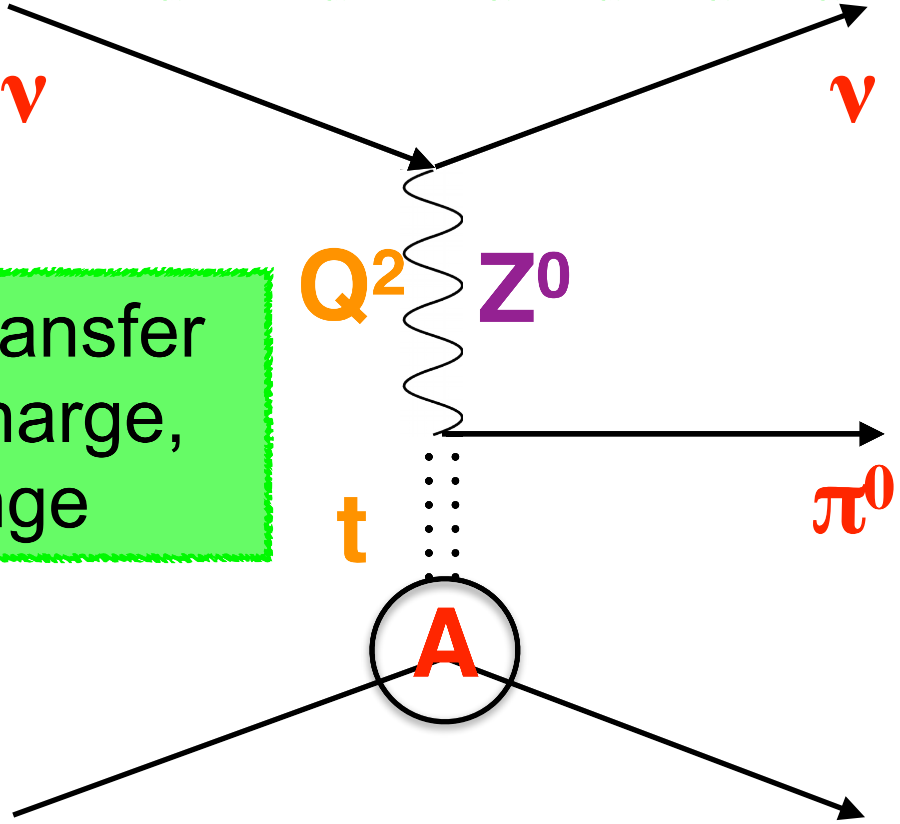

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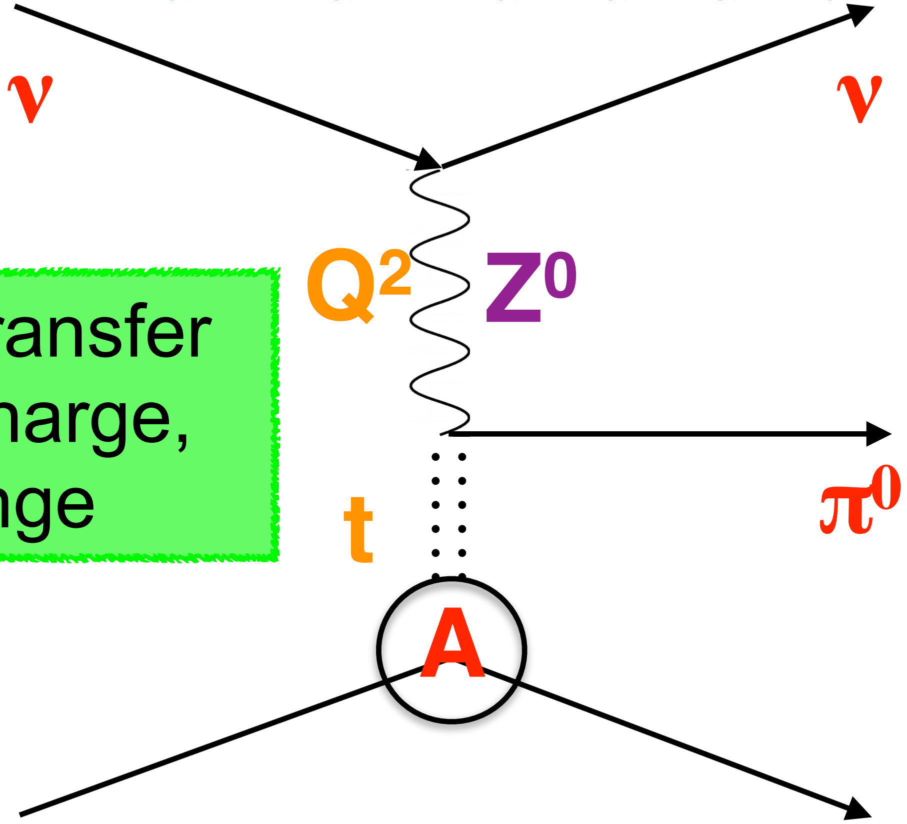

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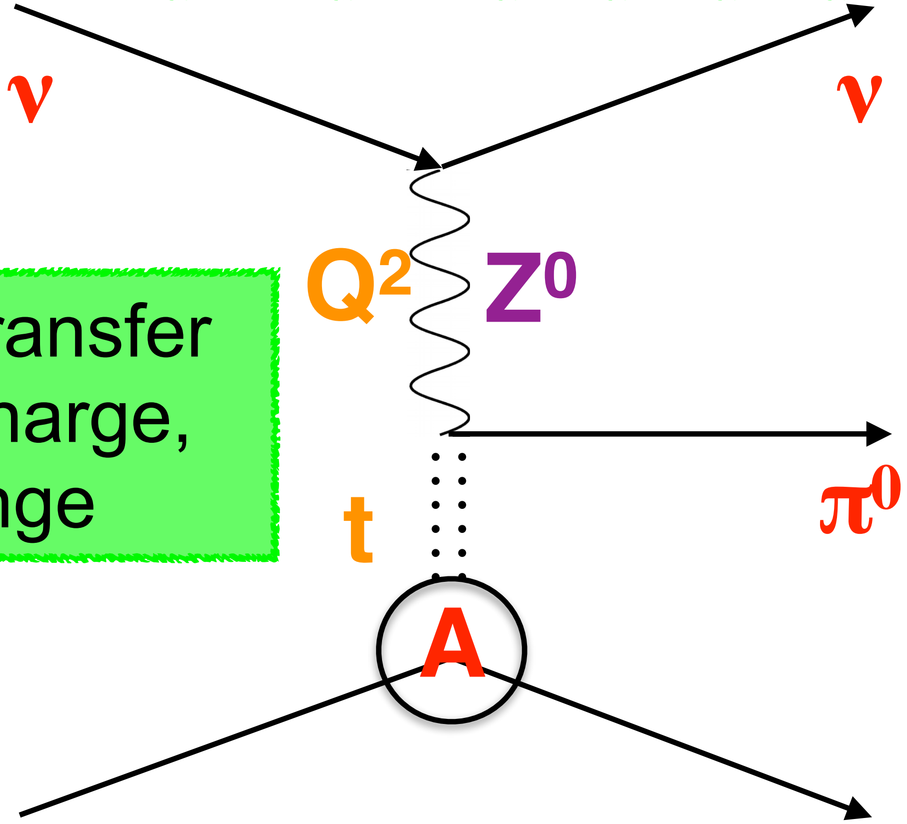

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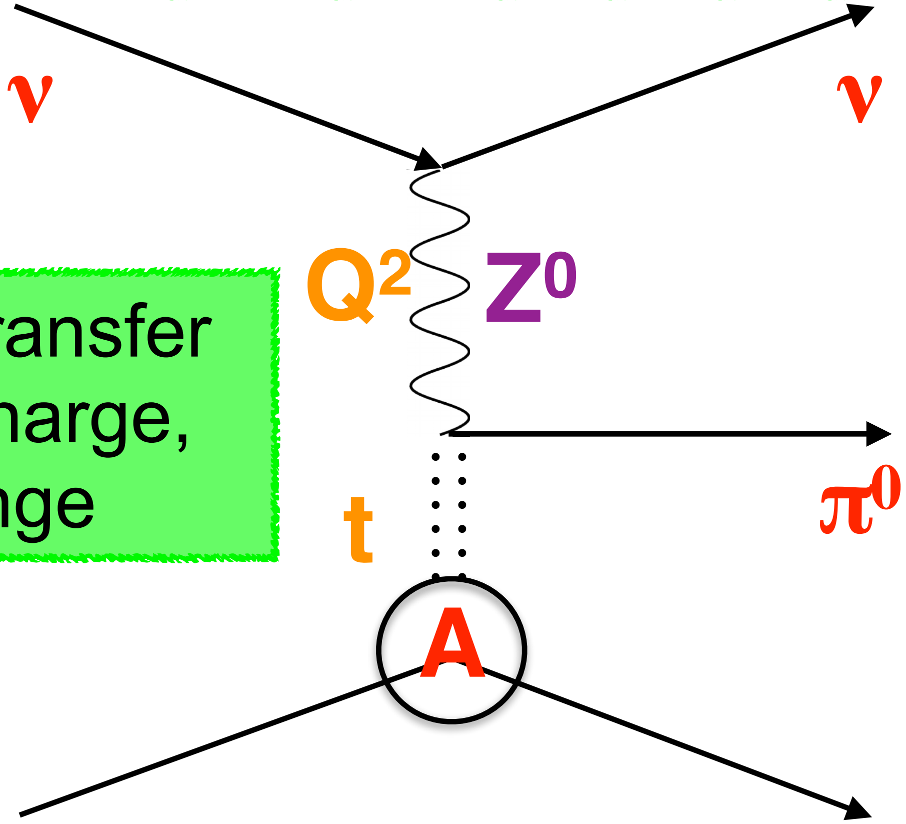

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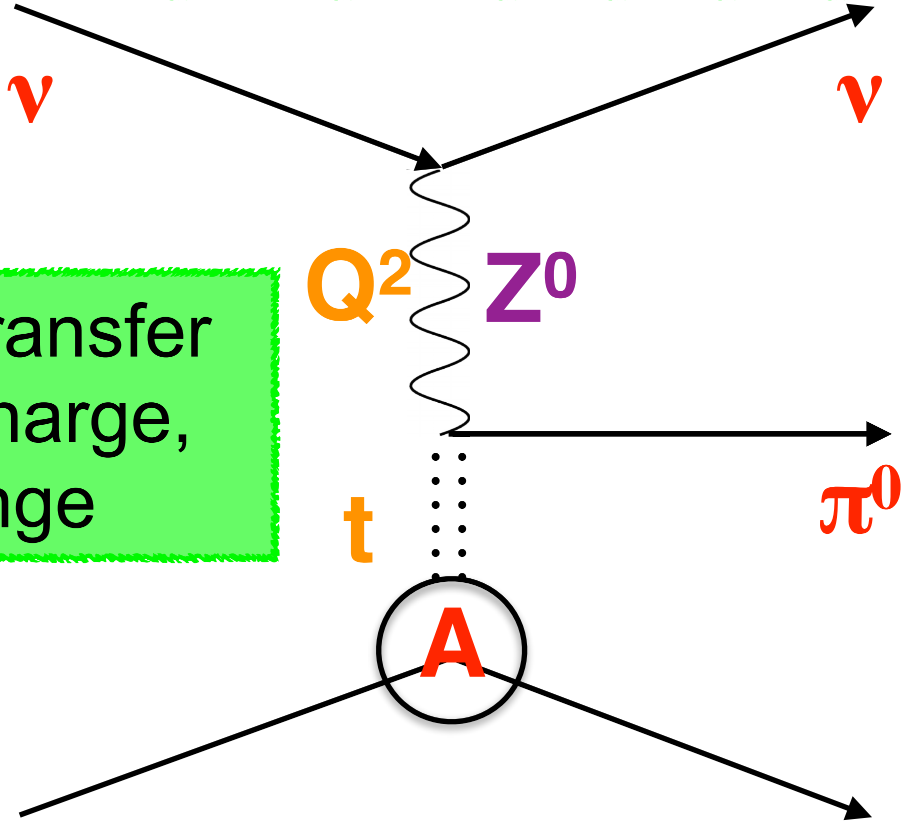

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- **Microscopic models:** start from particle production models on nucleons and perform a coherent sum over all nucleonic currents.

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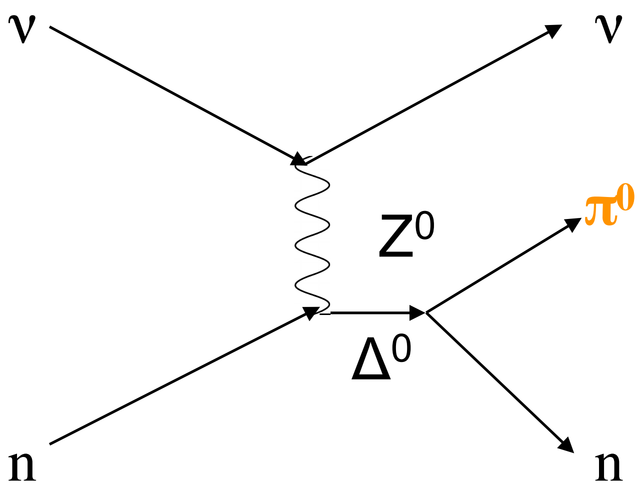

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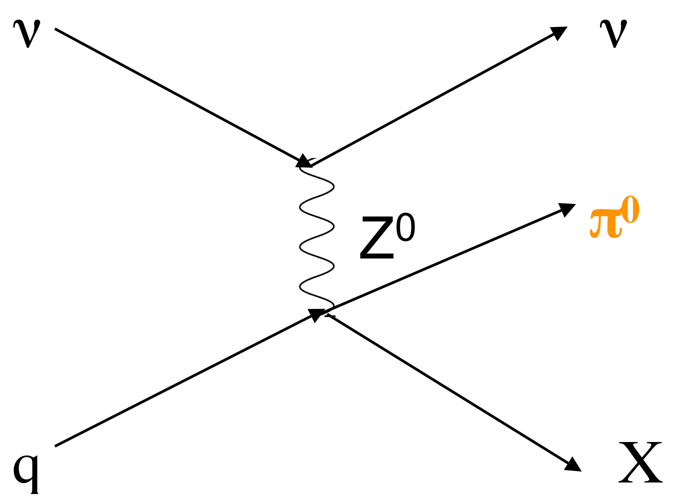

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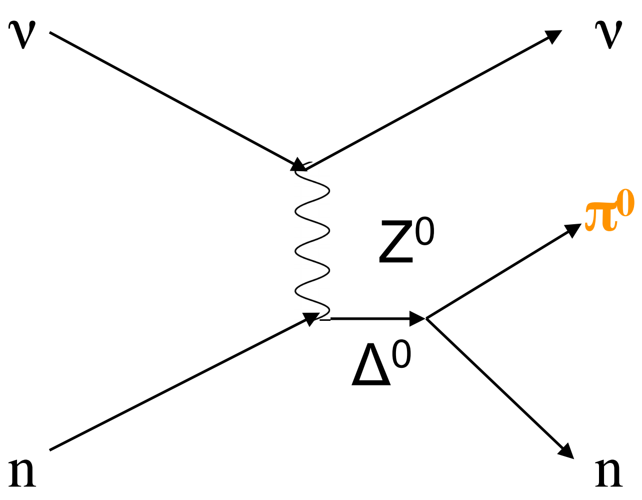

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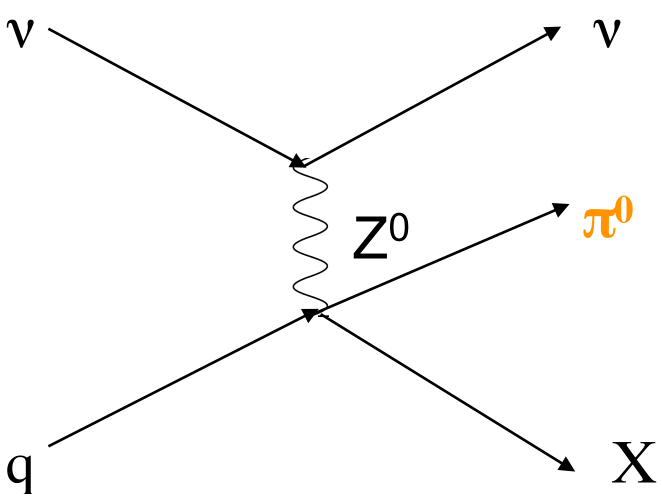

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- Important to constrain the background uncertainty using a data-driven method.

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no muon track, two photon showers, no other particles

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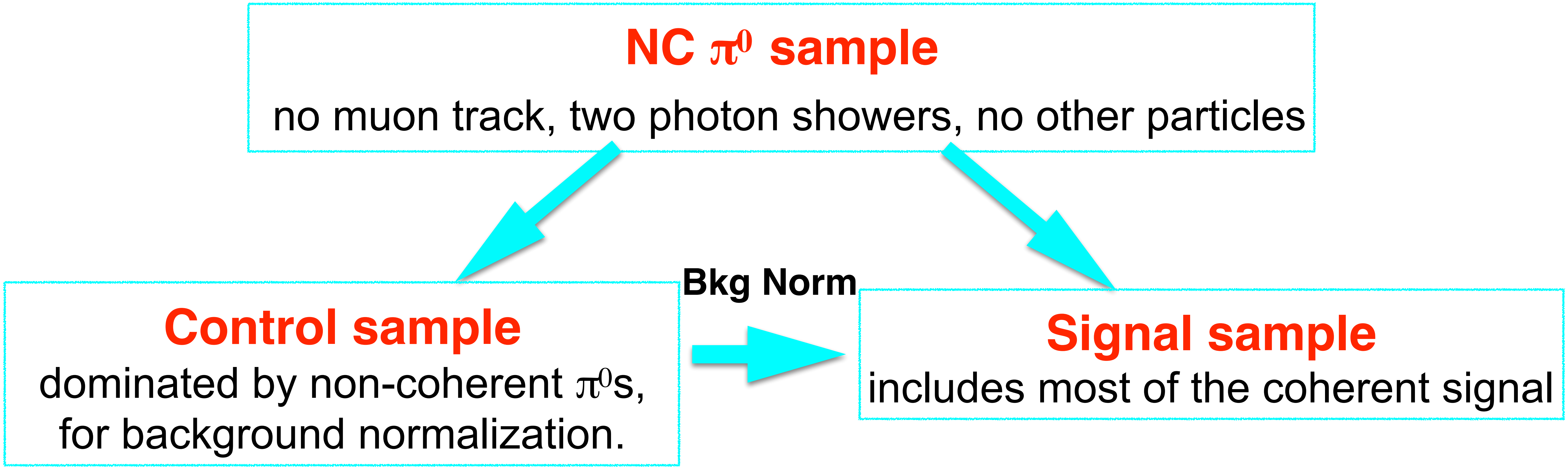

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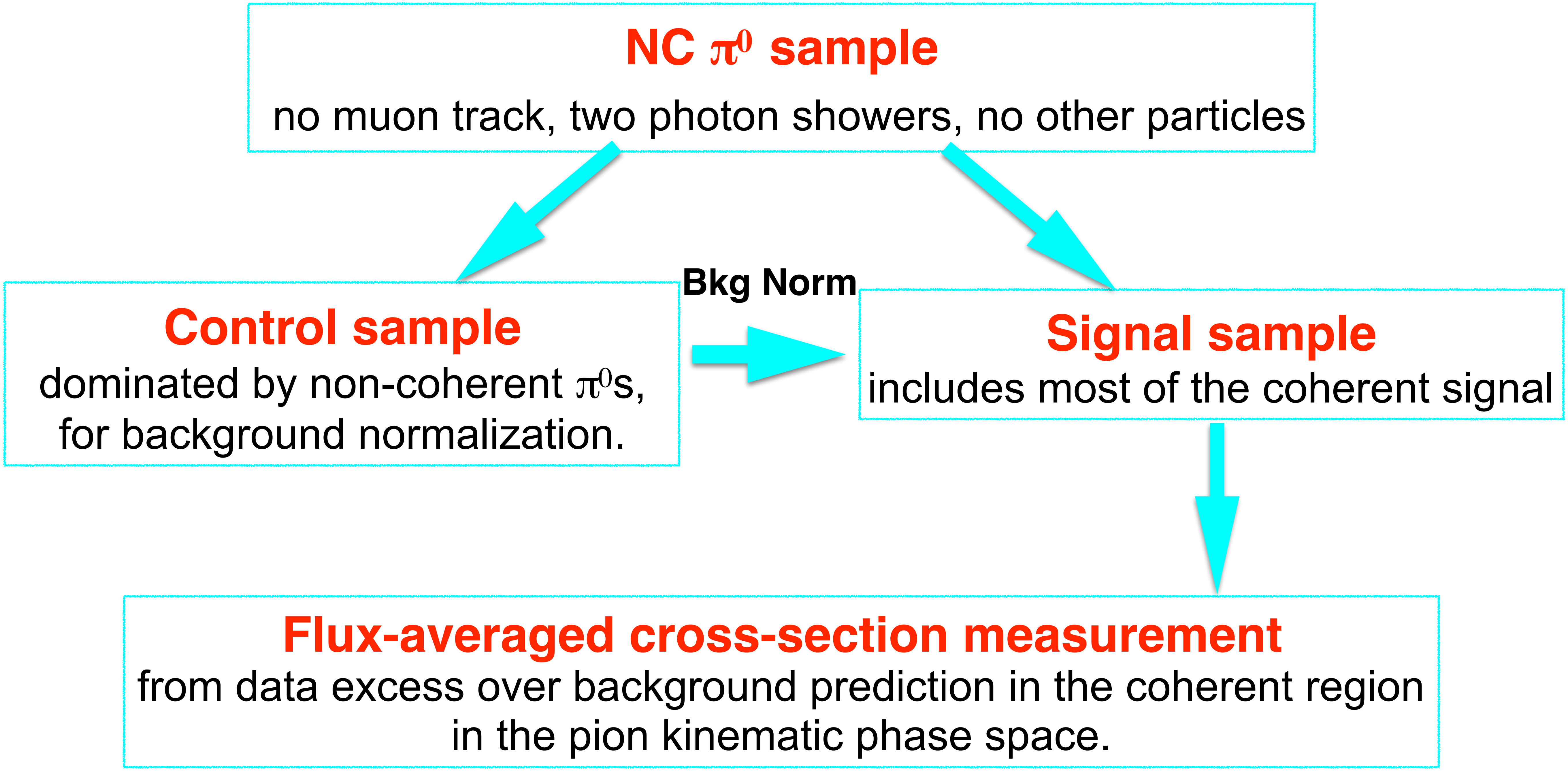

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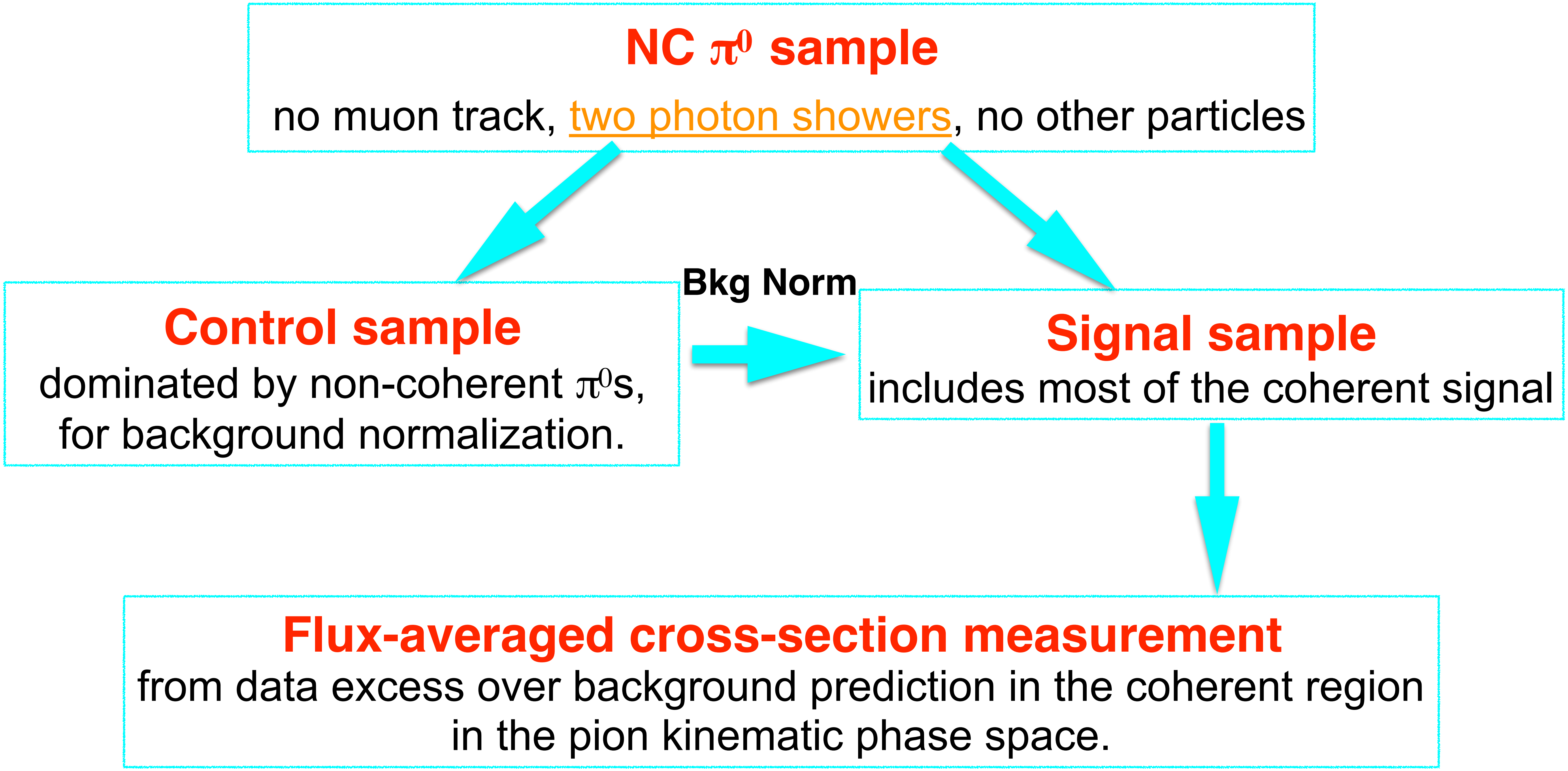

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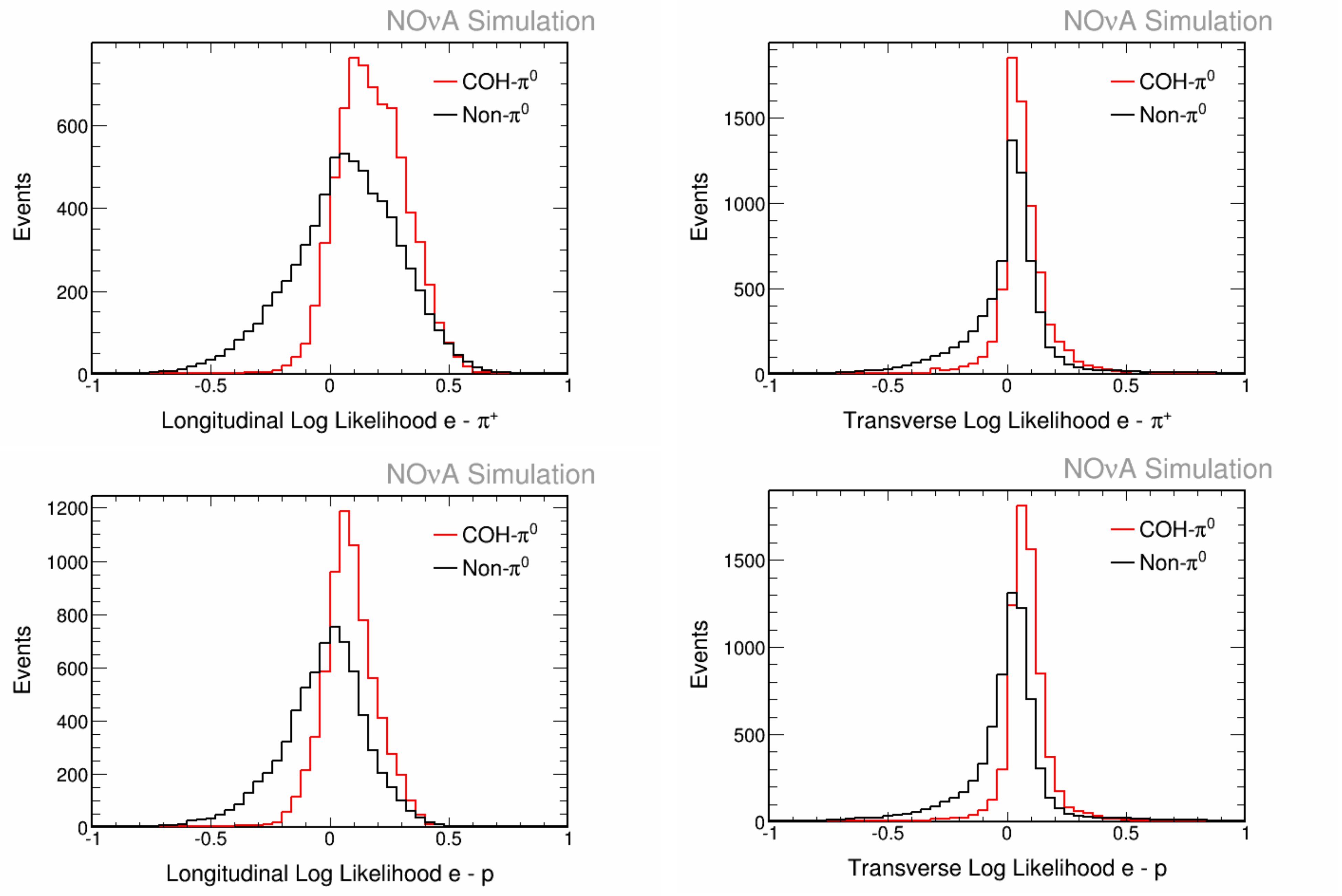
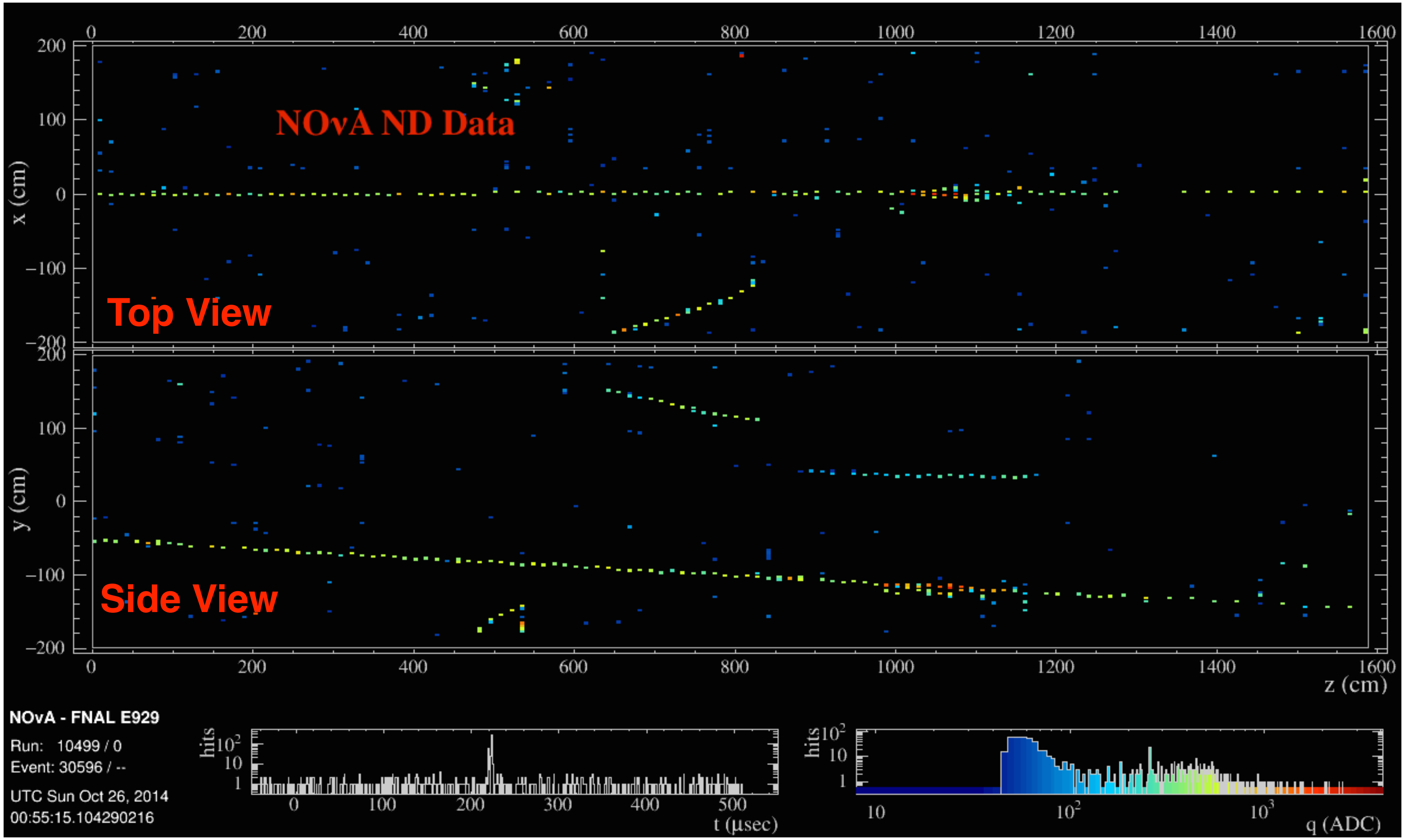
from data excess over background prediction in the coherent region in the pion kinematic phase space.

Photon Shower Identification



- Identify photons by likelihoods build upon shower longitudinal and transverse **dE/dx** information.

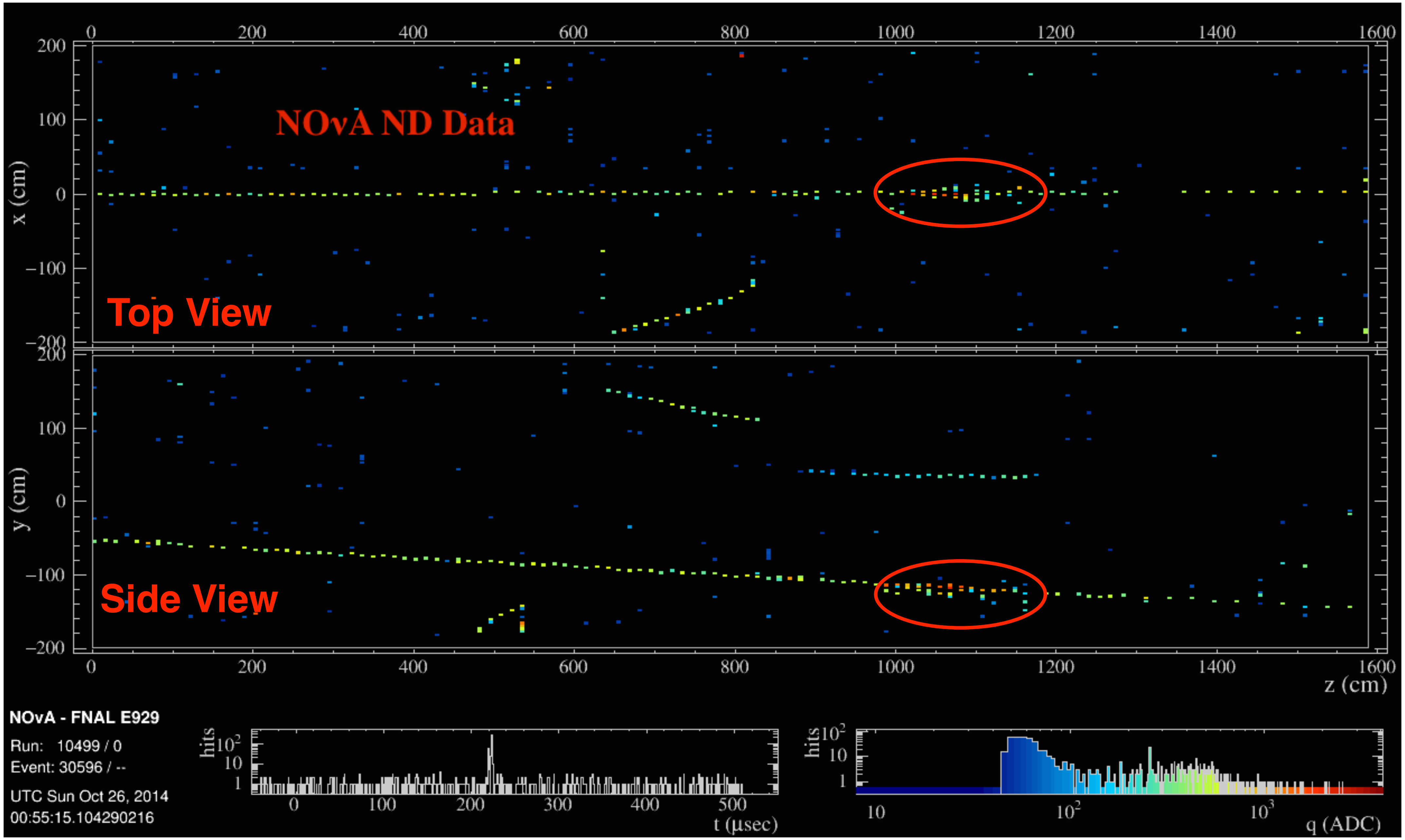
Constraining Photon Simulation



NOvA - FNAL E929
Run: 10499 / 0
Event: 30596 / --
UTC Sun Oct 26, 2014
00:55:15.104290216

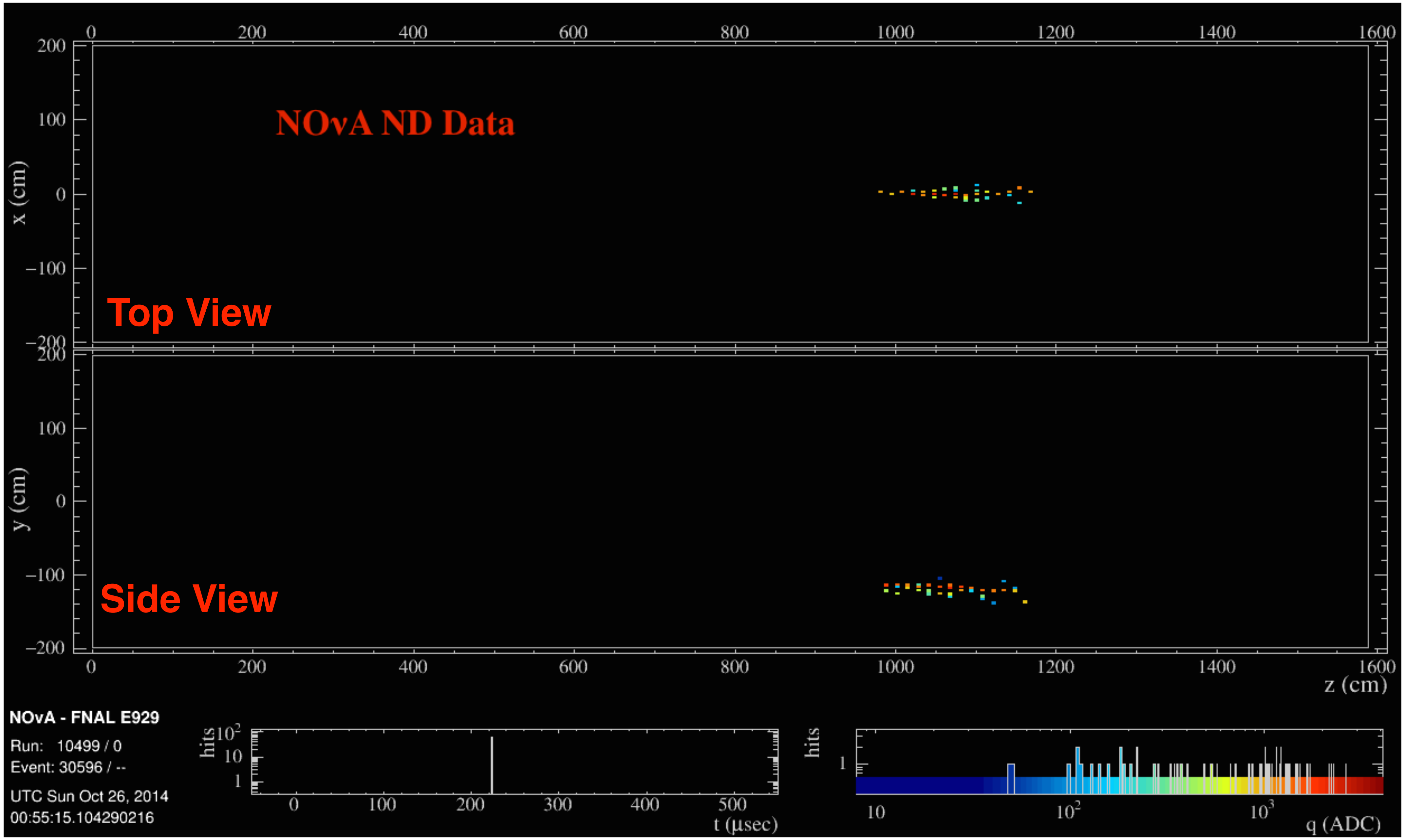
- Muons from interactions outside the detector can induce EM showers in the detector via **bremsstrahlung radiation**.

Constraining Photon Simulation



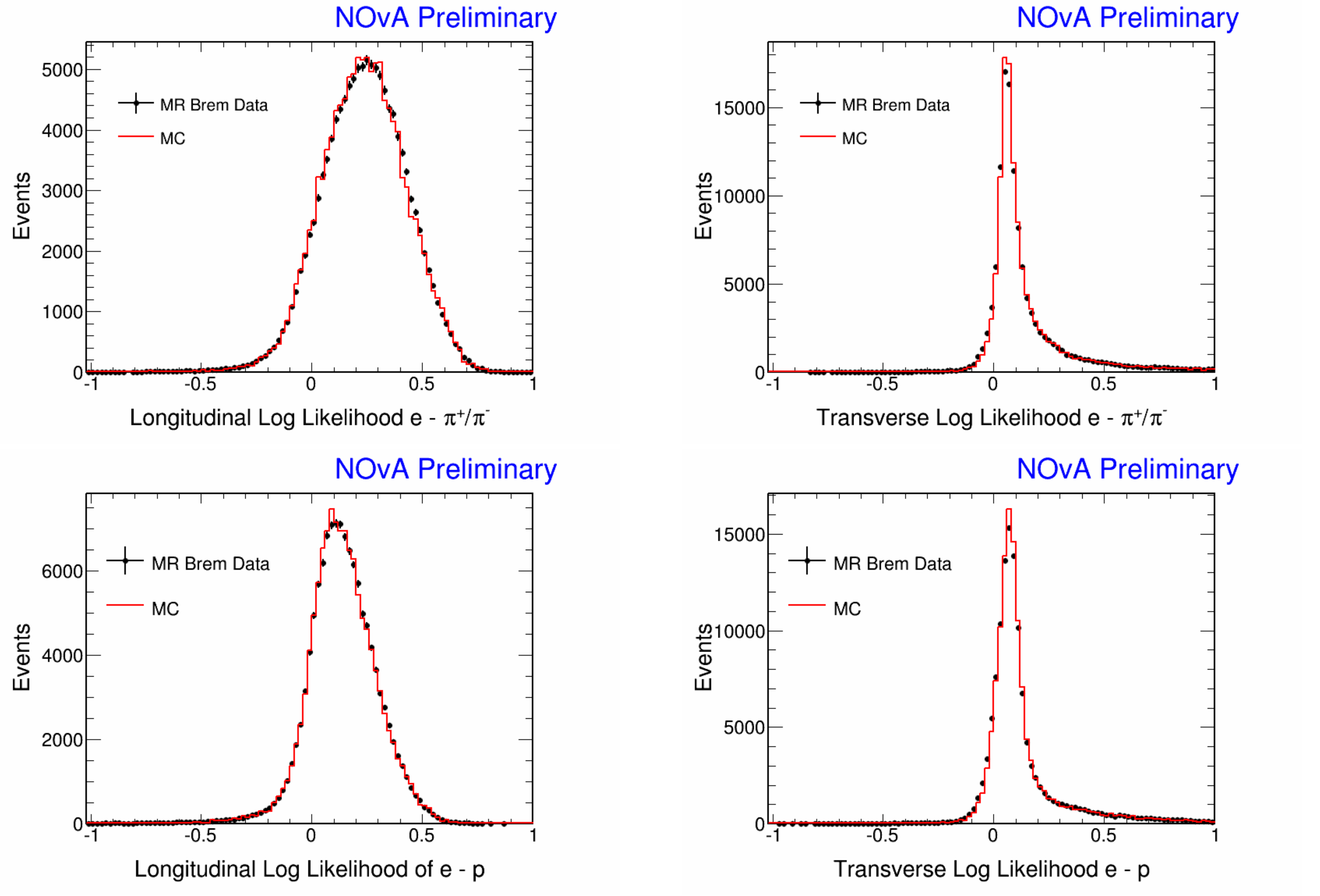
- Muons from interactions outside the detector can induce EM showers in the detector via **bremsstrahlung radiation**.

Constraining Photon Simulation



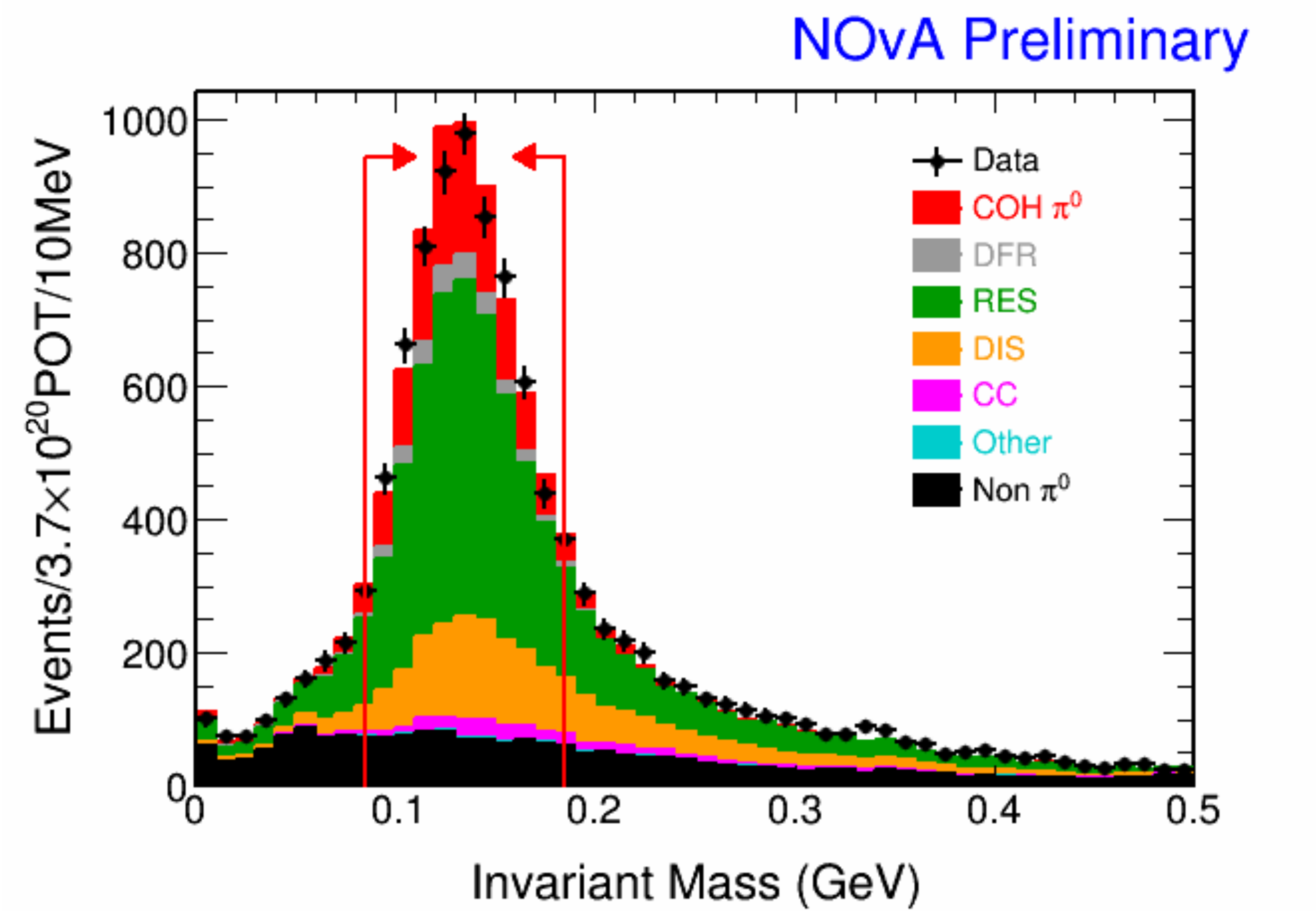
- Muons from interactions outside the detector can induce EM showers in the detector via **bremsstrahlung radiation**.
- A **muon-removal (MR)** technique is developed to isolate those EM showers .
- Provide a data-driven method to constrain photon simulation.

Constraining Photon Simulation



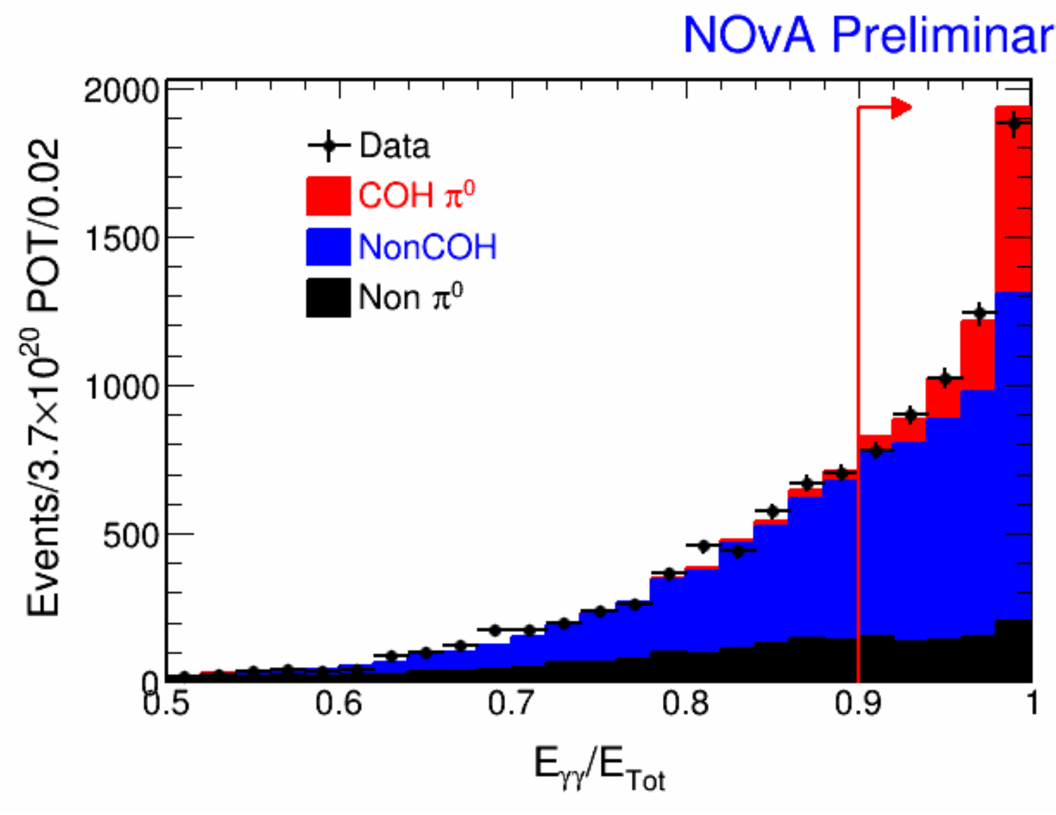
- Very good agreement between data and MC.
- **1%** difference in selection efficiency taken into systematic uncertainty.

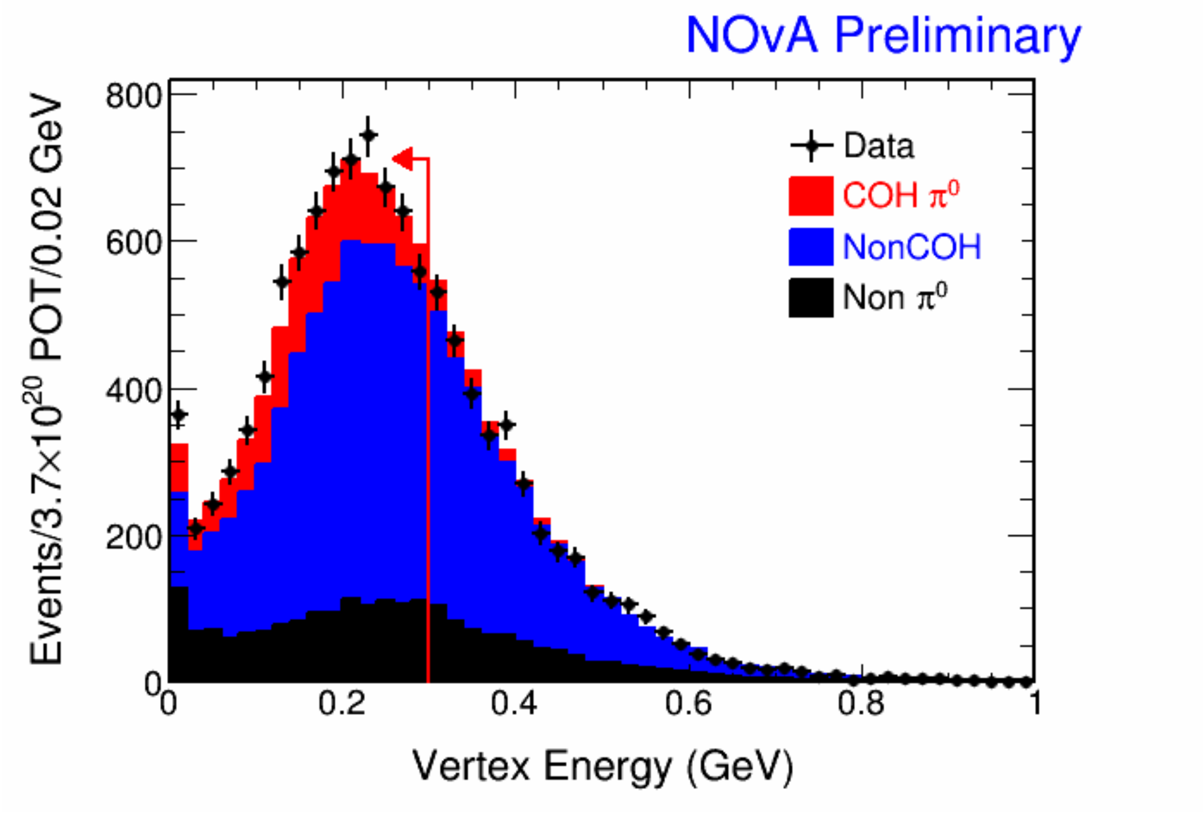
NC π^0 Sample



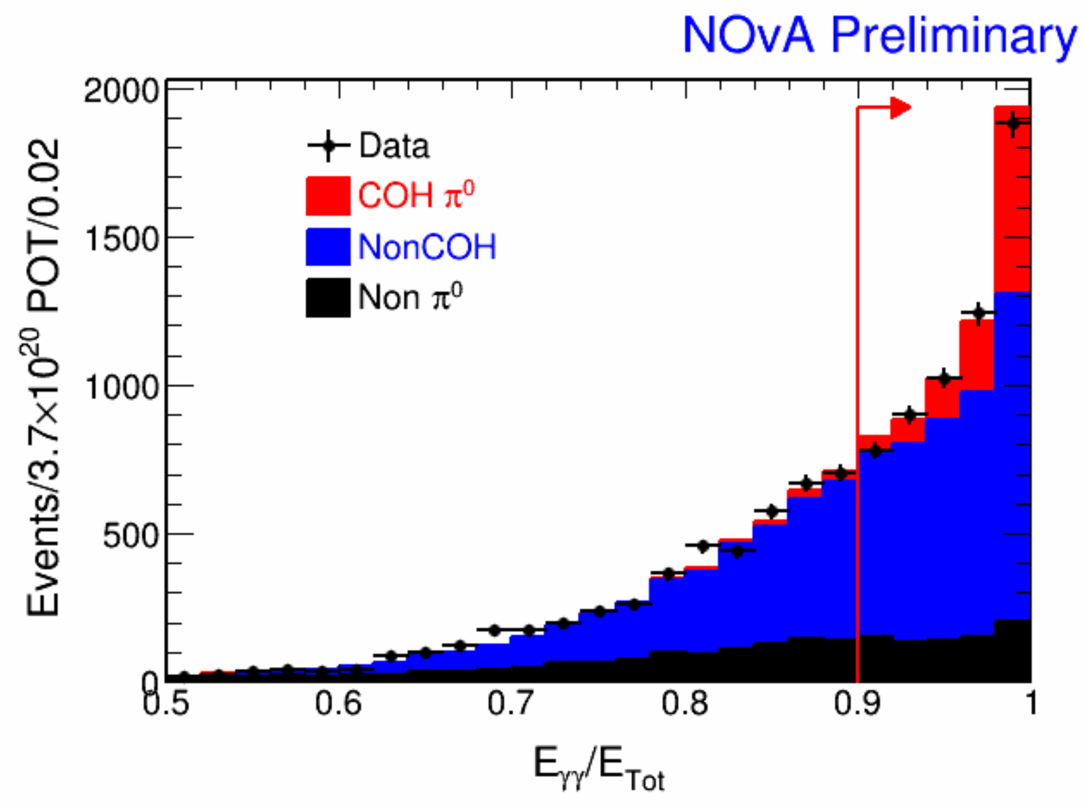
- The identified **NC π^0 sample:**
  - No muon.
  - Two showers identified as photons by dE/dx-based likelihoods.
  - Vertex in fiducial volume and showers contained.
- Background dominated by **RES** and **DIS** π^0s.
- Cut on invariant mass further reduces background.
- Also serve as a check of photon reconstruction and energy scale.

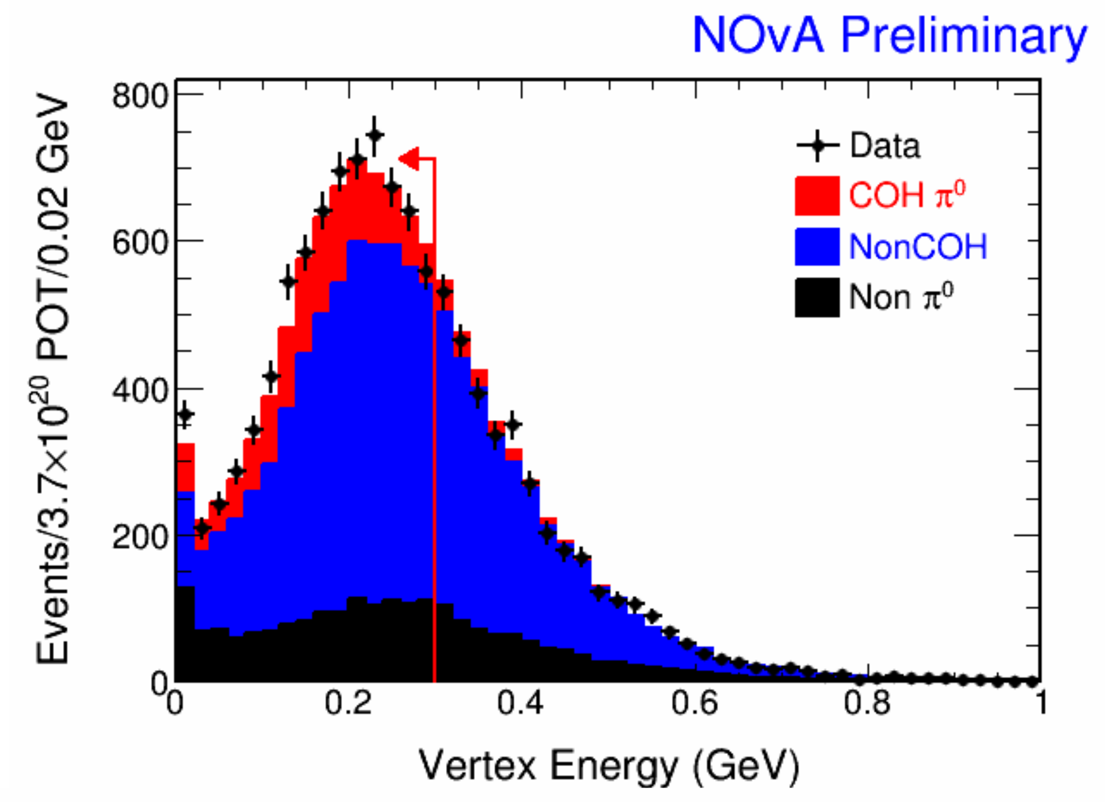
Signal Sample and Control Sample



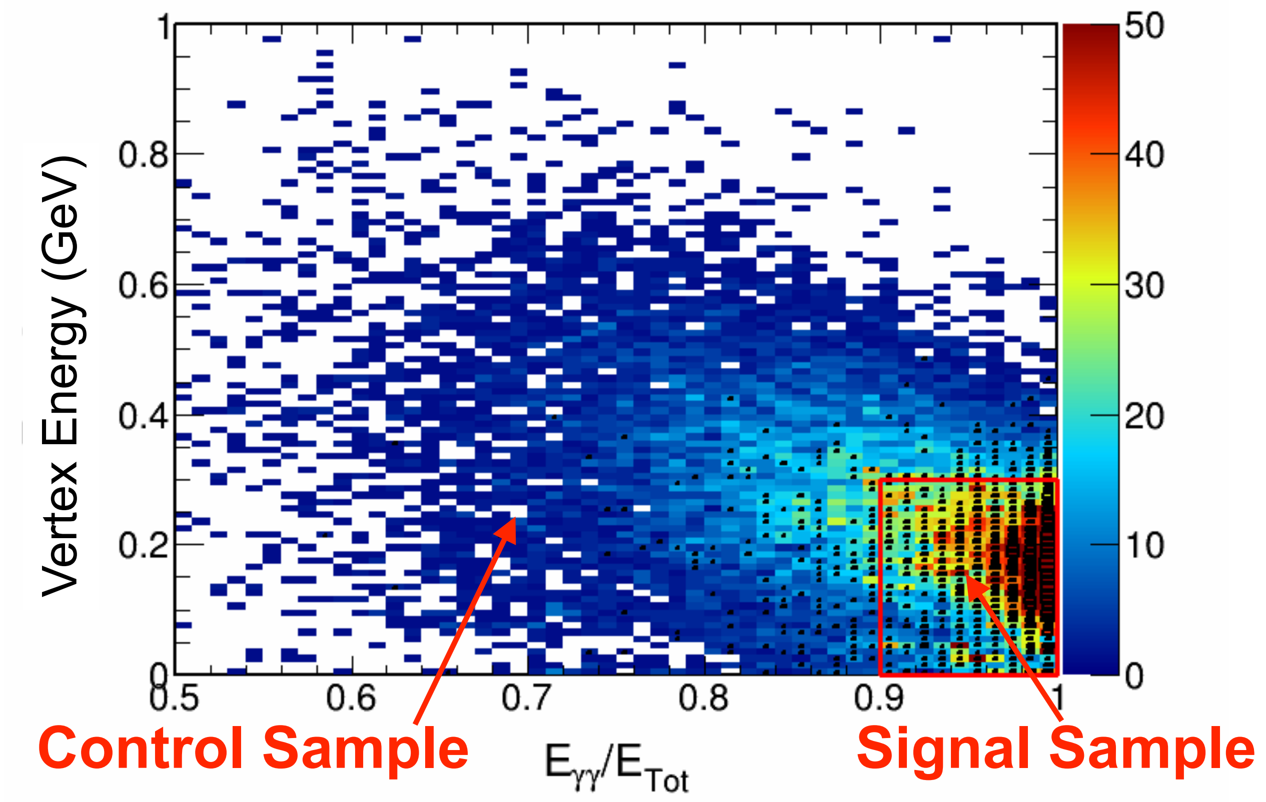


Signal Sample and Control Sample





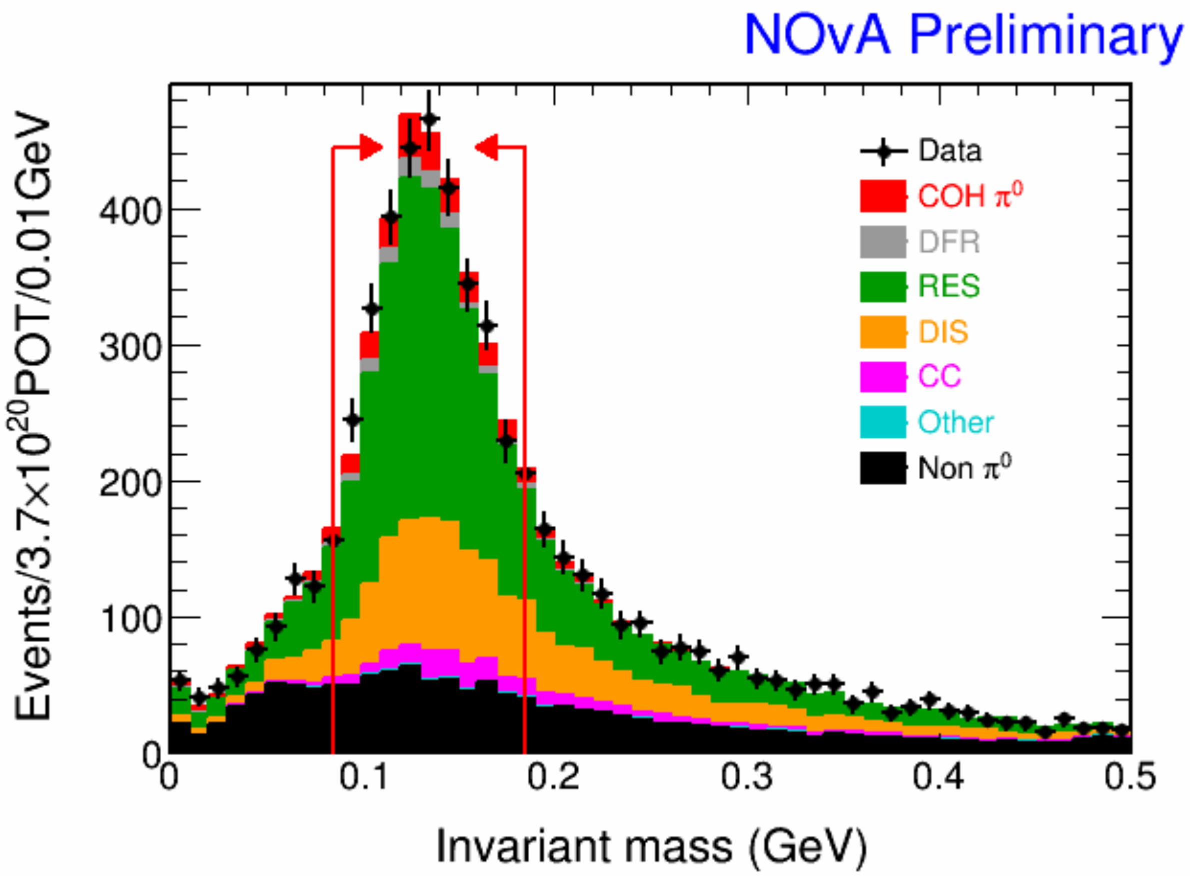
- Divide the NC π^0 into two sub-samples:
  - **Signal sample:** events with most of their energy in the 2 photon-showers and low vertex energy: it has >90% of the signal.
  - **Control sample:** the events with extra energy other than the photons or in the vertex region, dominated by non-coherent π^0 s (RES and DIS).



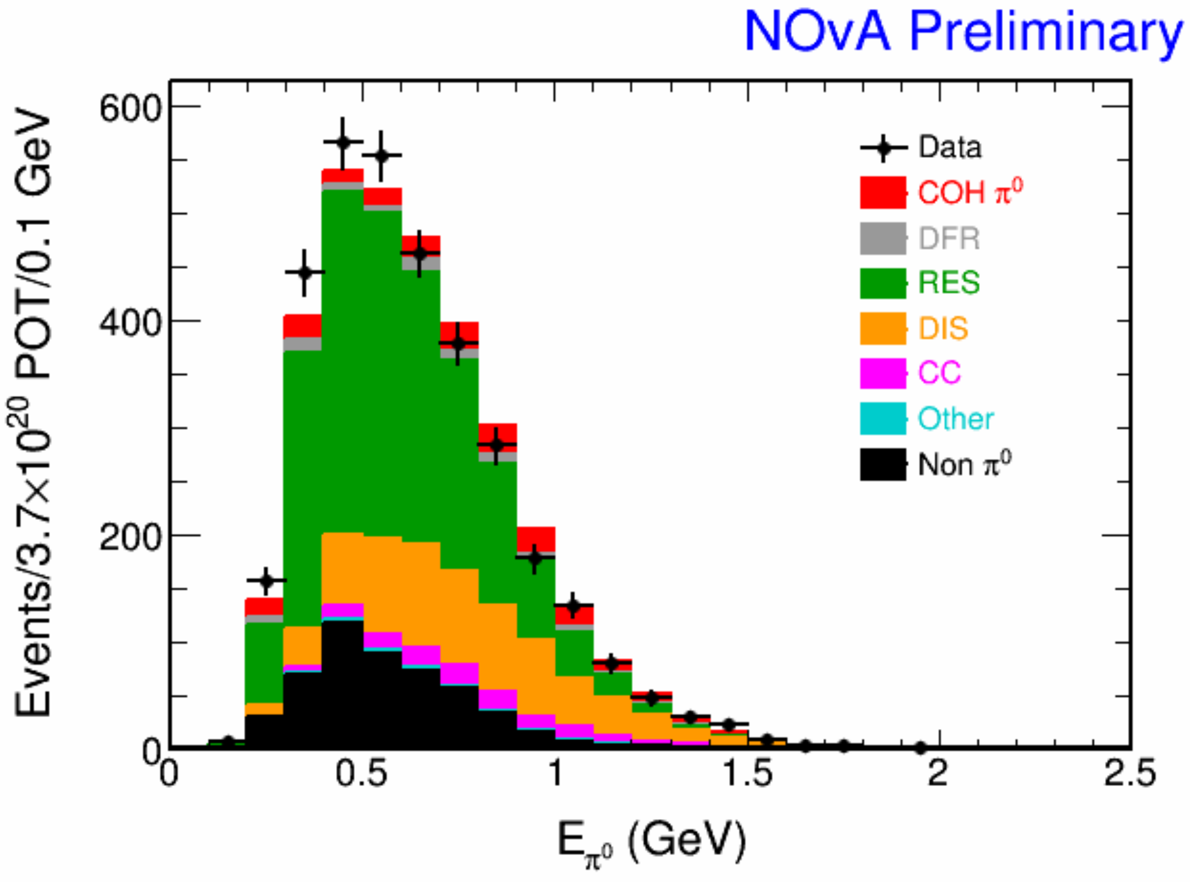
Control Sample

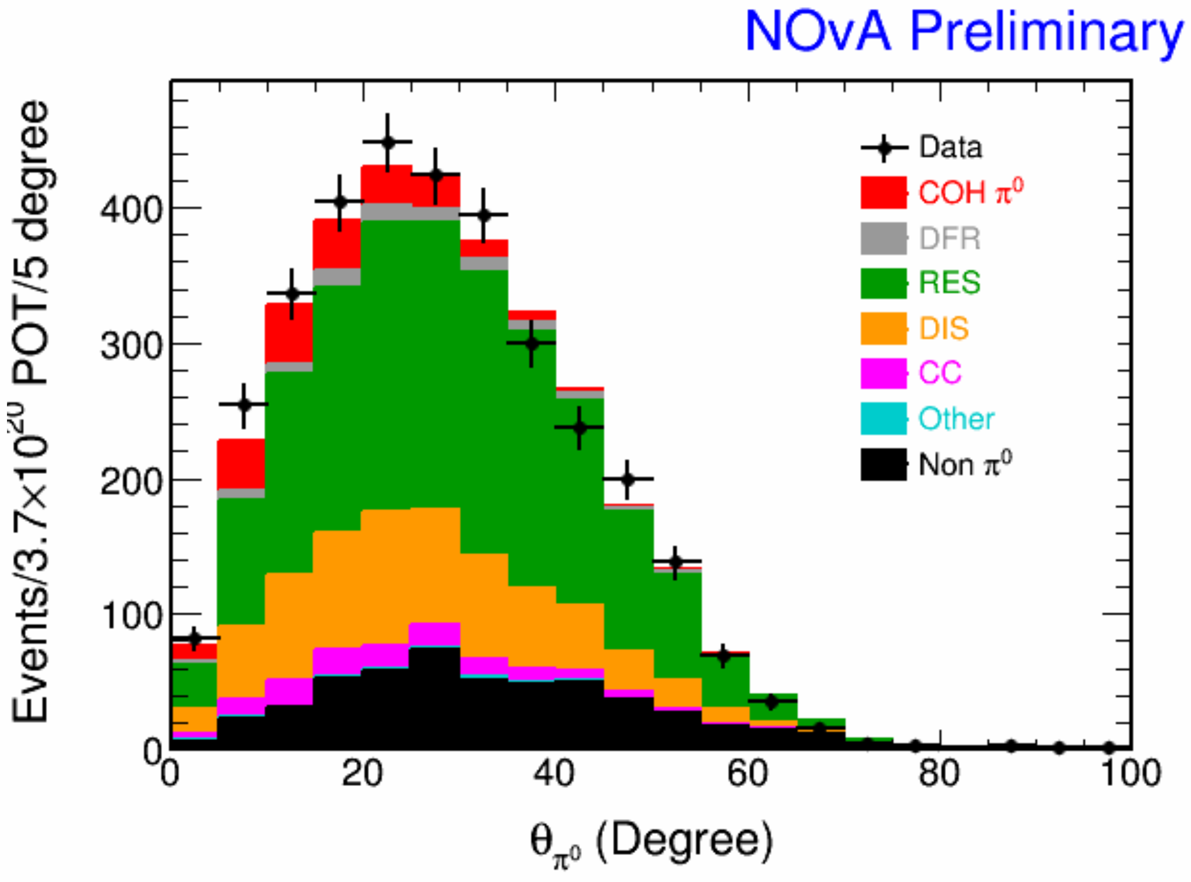
Signal Sample

Control Sample



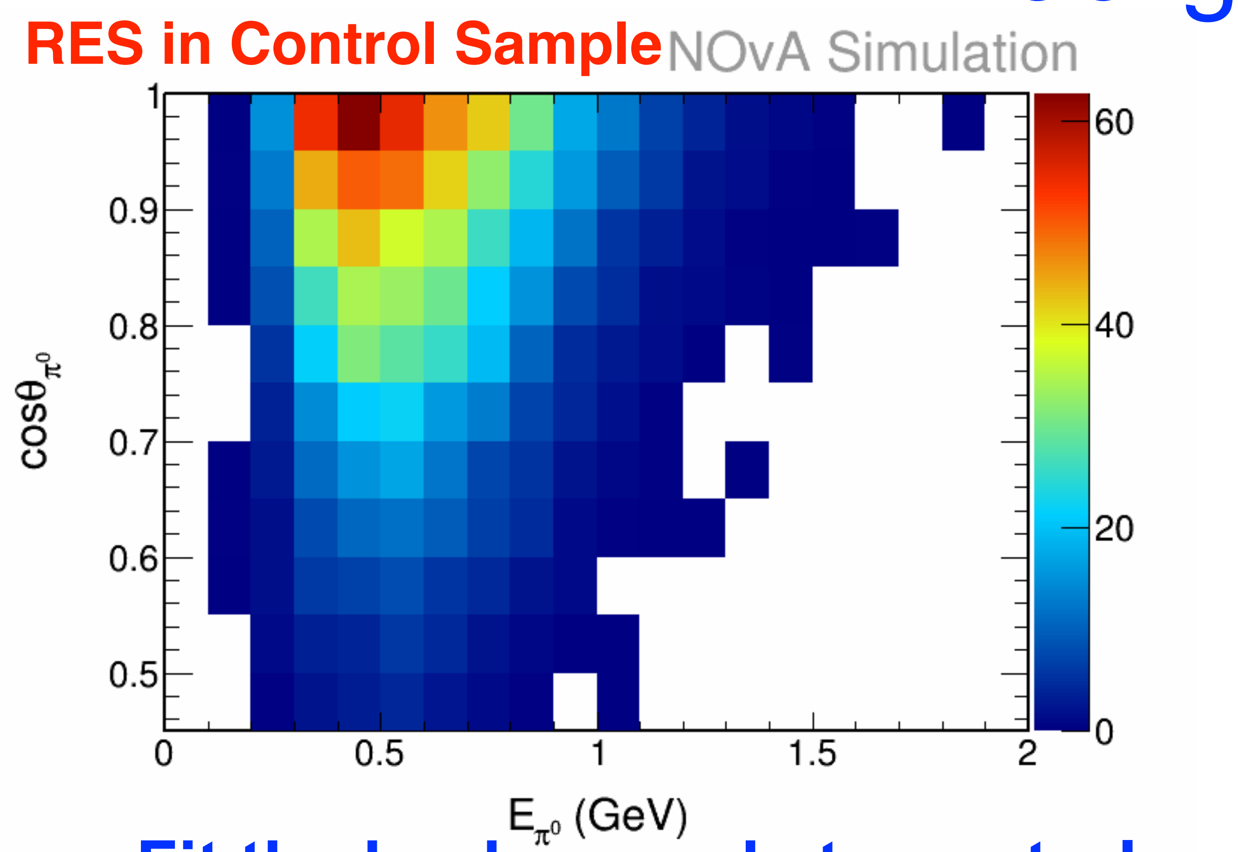
The control sample is used to fit background to data in π^0 energy vs angle 2D space.



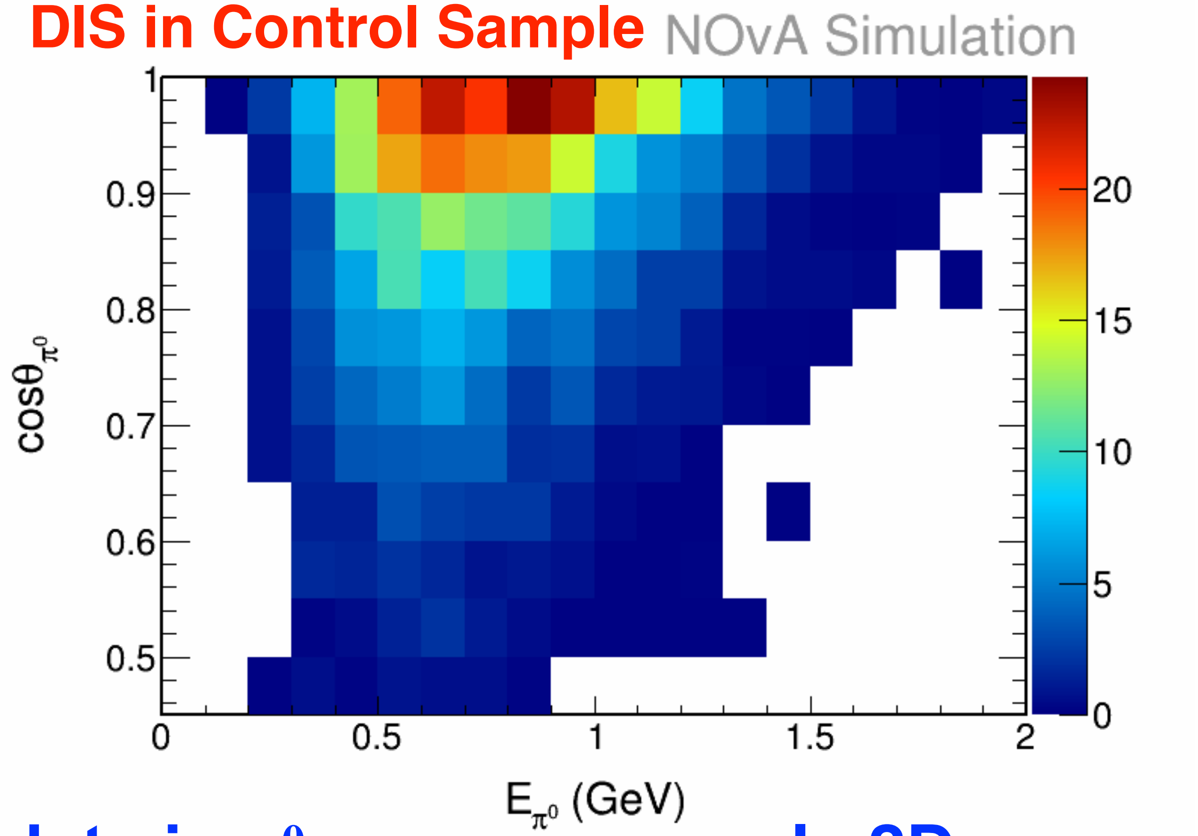


Background Fit

RES in Control Sample



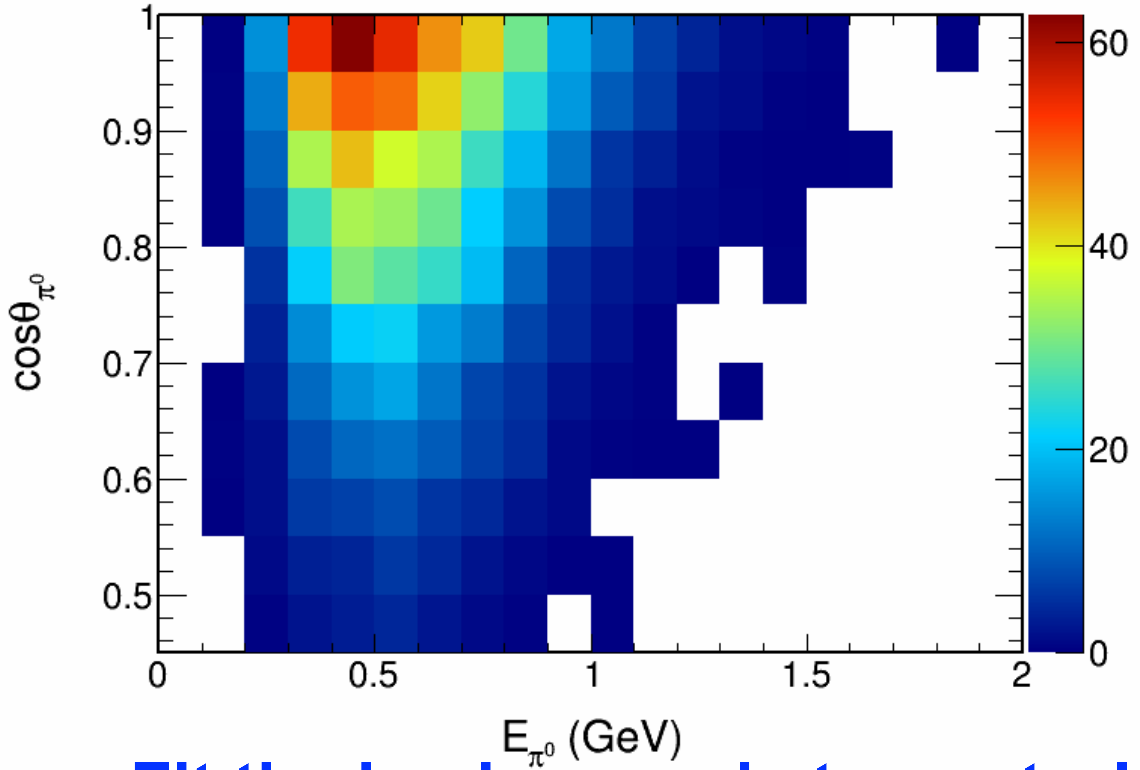
DIS in Control Sample



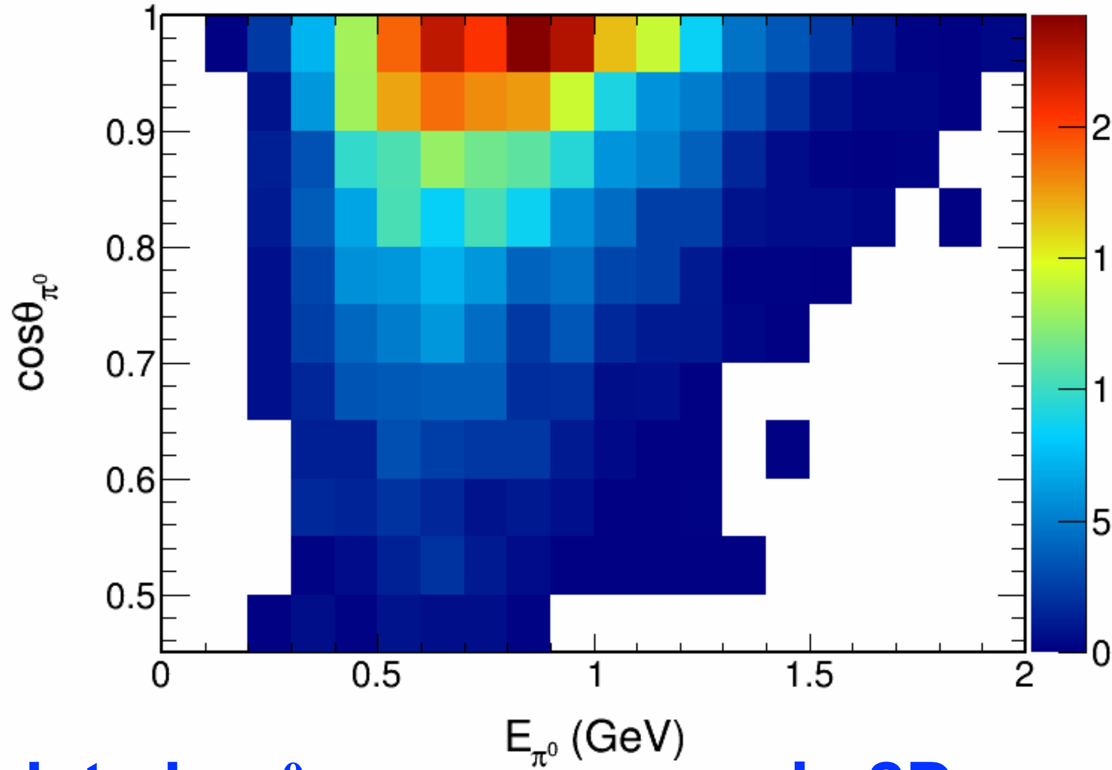
- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

Background Fit

RES in Control Sample

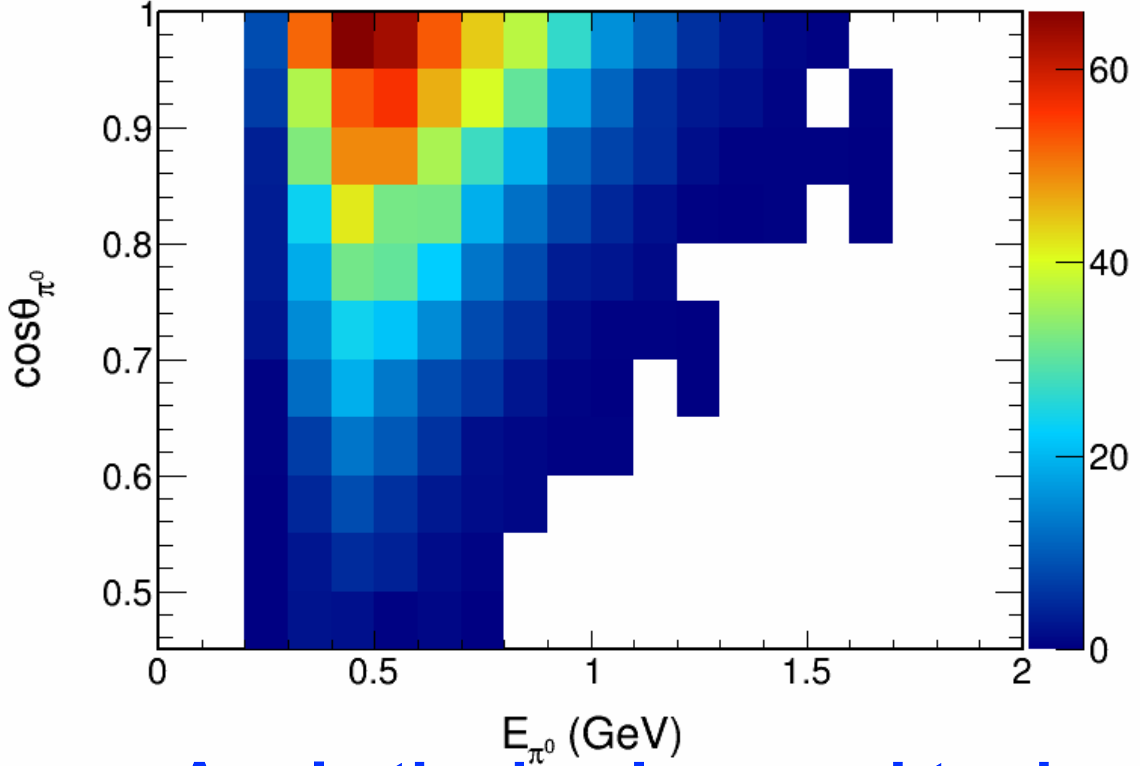


DIS in Control Sample

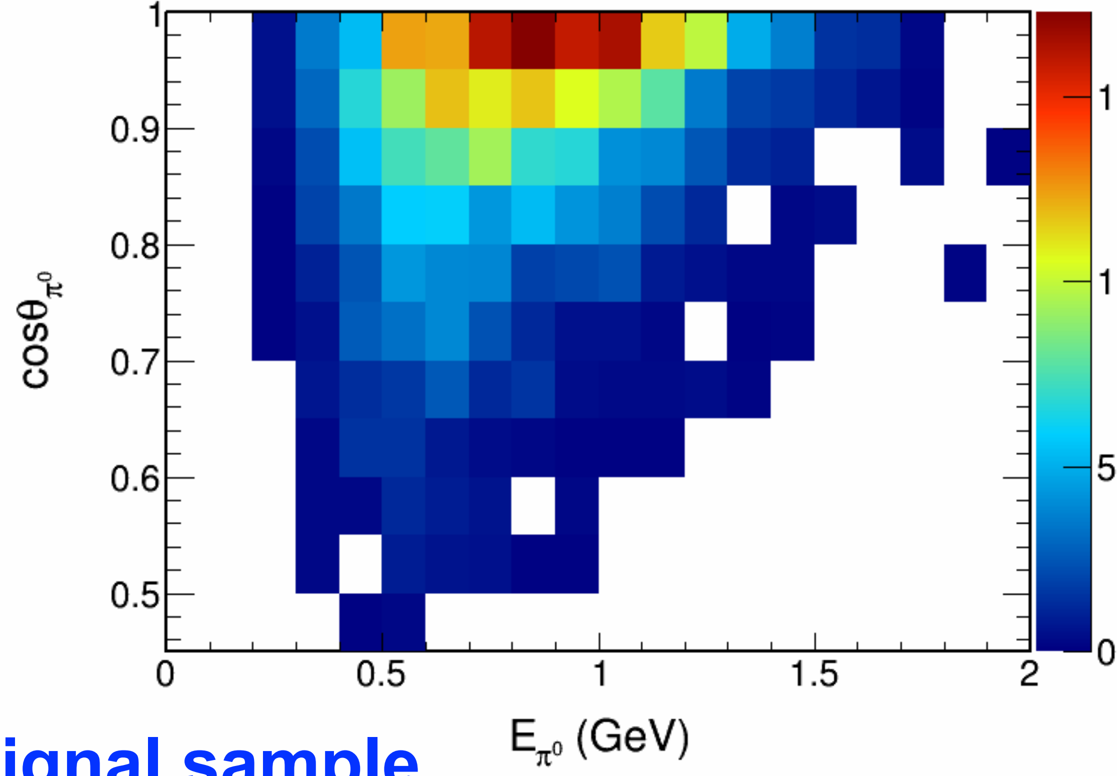


- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

RES in Signal Sample

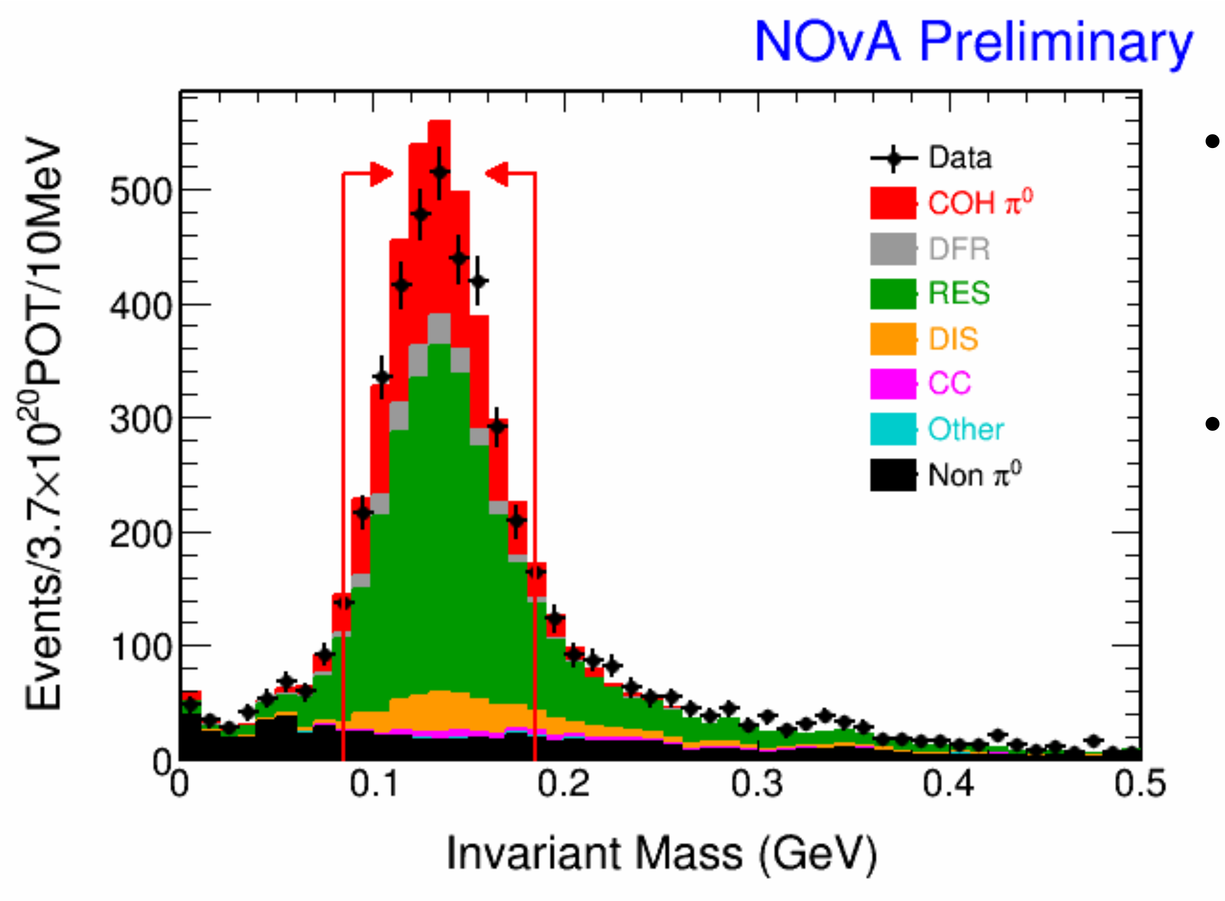


DIS in Signal Sample

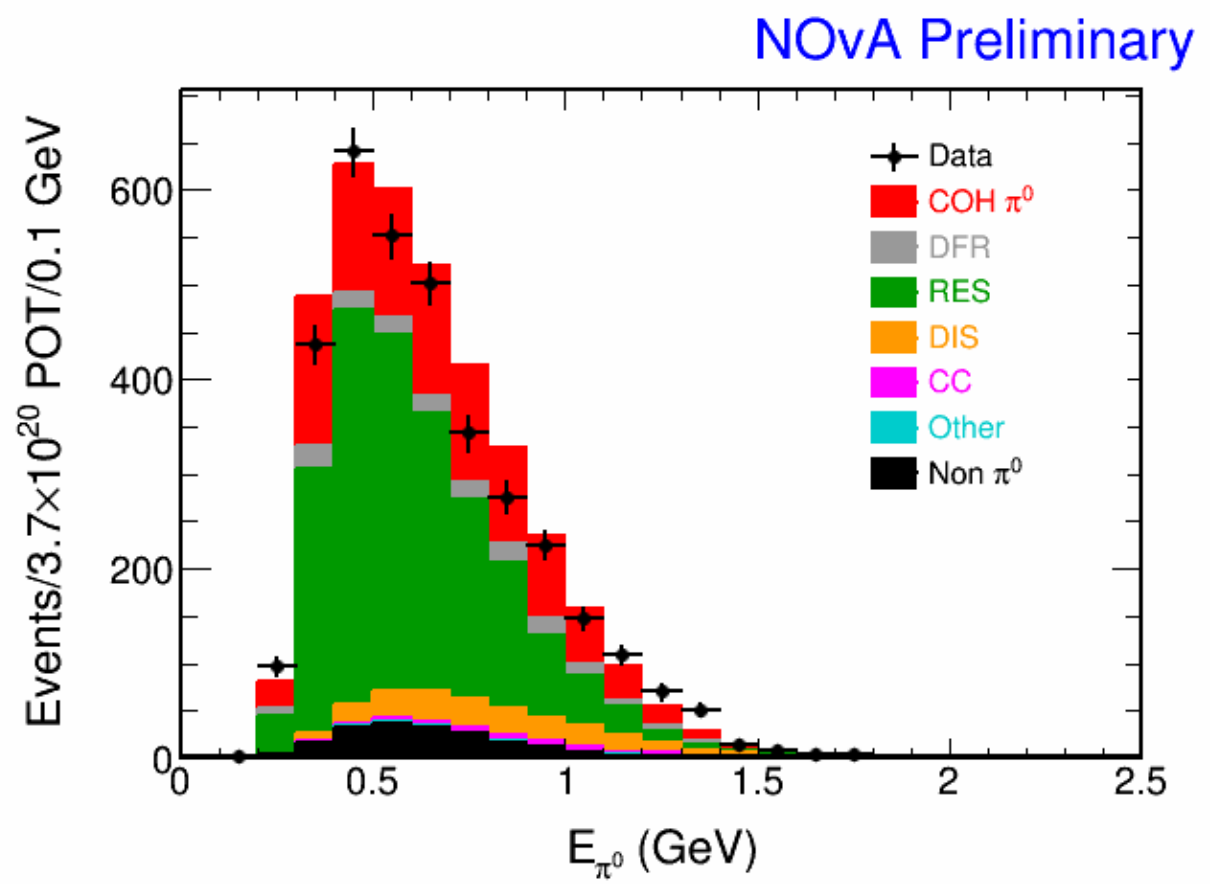


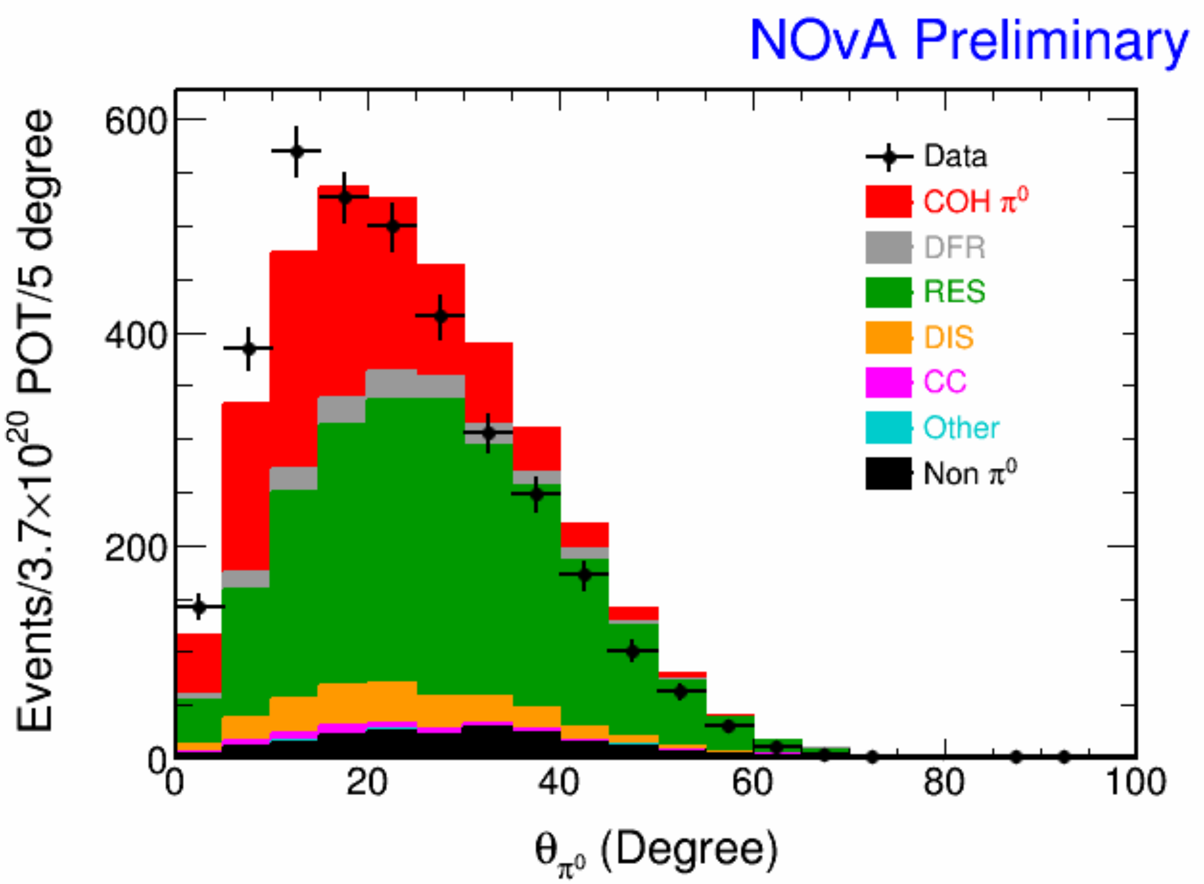
- **Apply the background tuning to the signal sample.**

Signal Sample

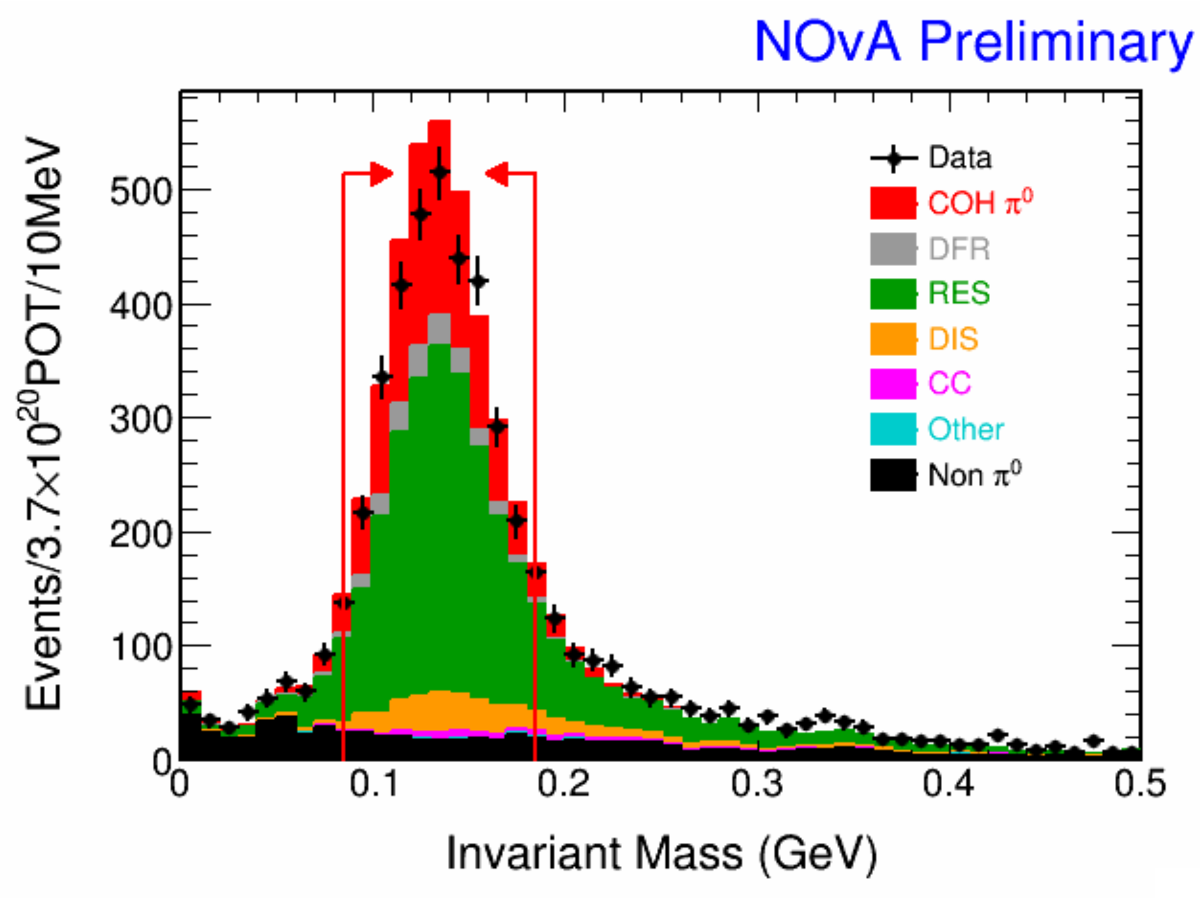


- Background fit result are applied to the backgrounds in the signal sample.
- Coherent signal measurement by subtracting normalized background from data in the coherent region of the energy and angle 2D space.





Signal Sample



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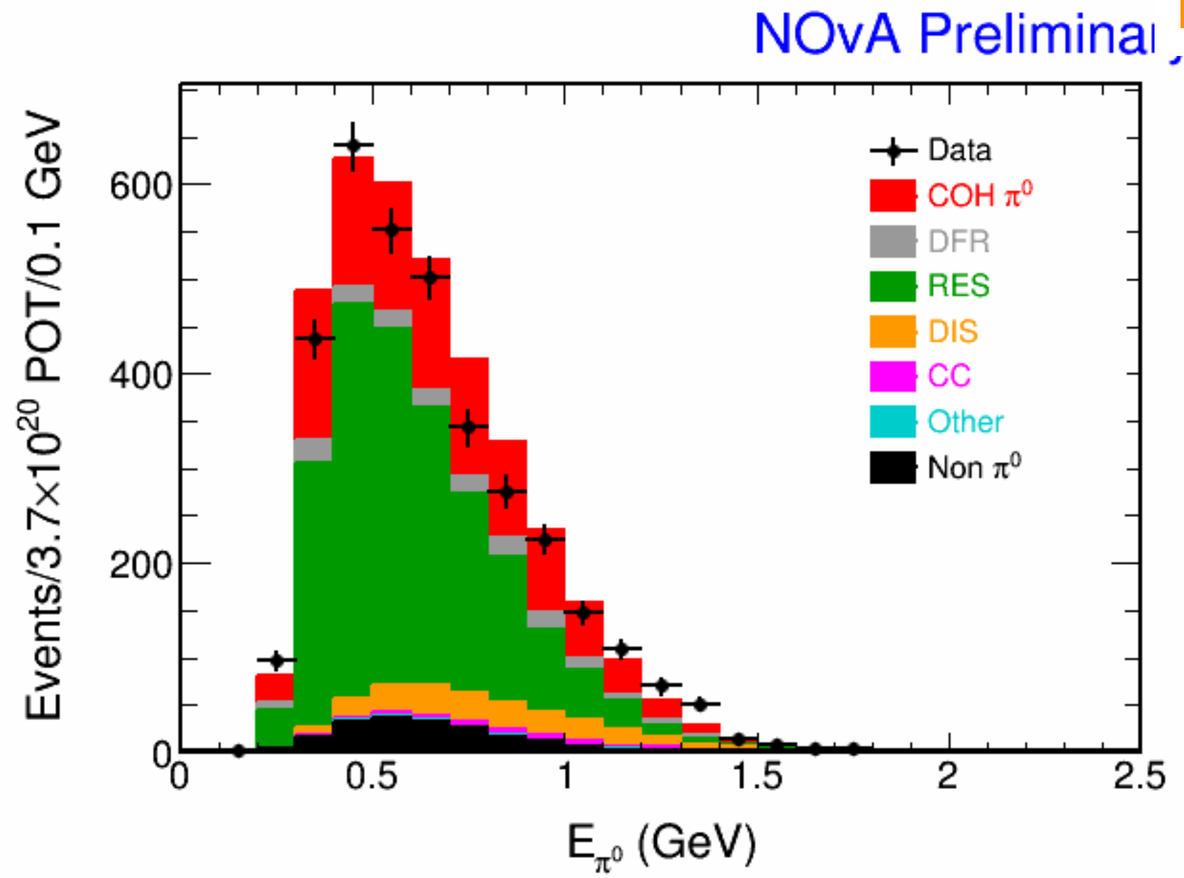

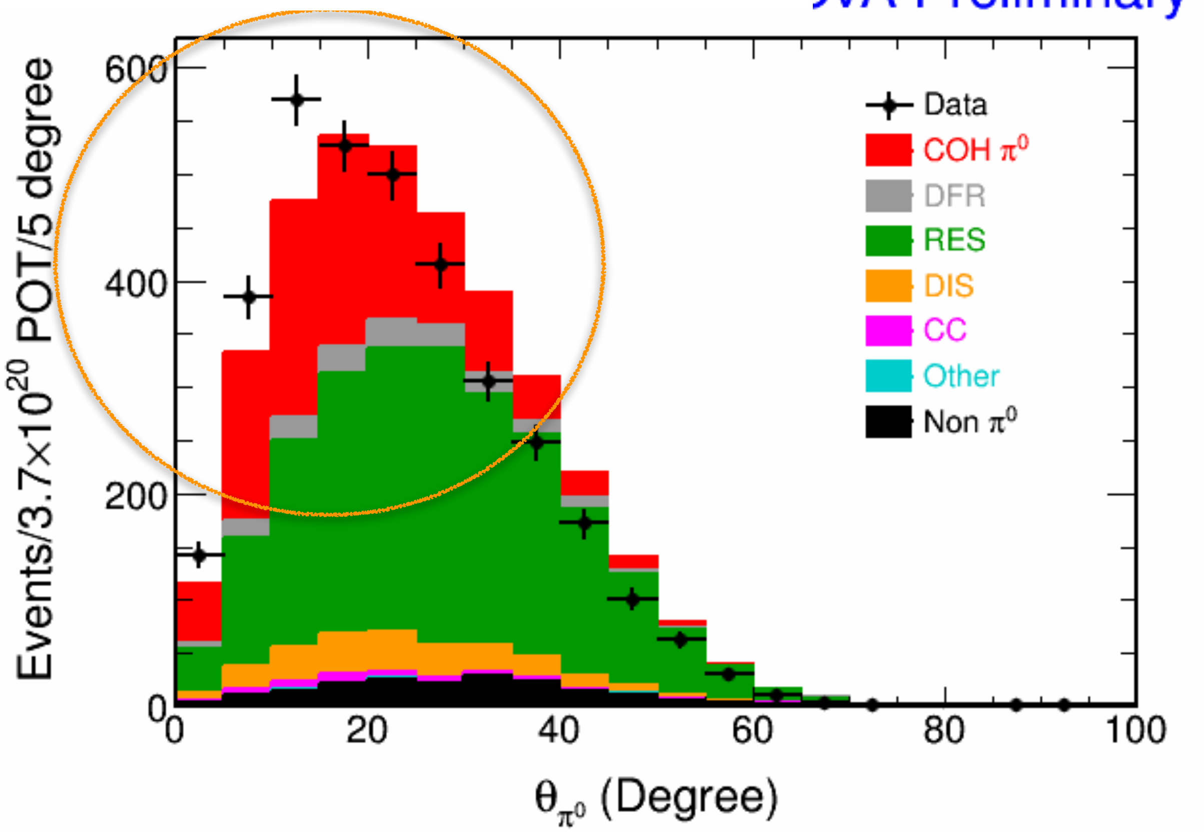
Data favors smaller π^0 angle

Cross-Section Measurement and Uncertainties

Selected data

Normalized Background

$$\sigma = \frac{N_{Data,selected} - N_{Bkg,norm}}{\epsilon \times N_{Target} \times \phi}$$

Signal efficiency

Flux

Number of target nucleus

Cross-Section Measurement and Uncertainties

6.7% statistical uncertainty with 3.7E20POT data

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10.4% systematic uncertainty
from background modeling,
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3.7% Uncertainty from signal modeling and **1%** from EM shower modeling

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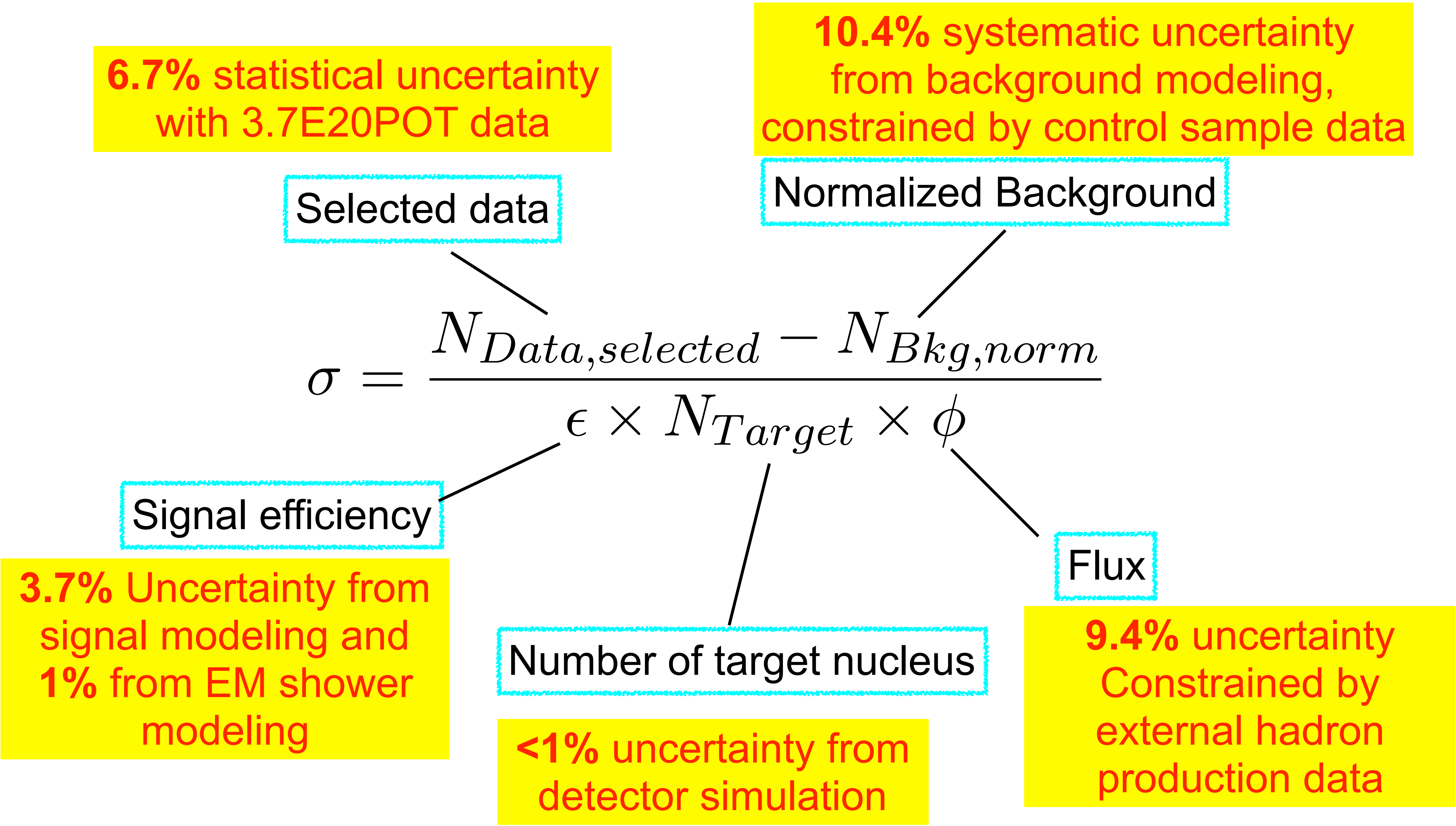
Number of target nucleus

<1% uncertainty from detector simulation

Cross-Section Measurement and Uncertainties



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9.4% uncertainty Constrained by external hadron production data

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Signal efficiency

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Flux

3.7% Uncertainty from signal modeling and **1%** from EM shower modeling

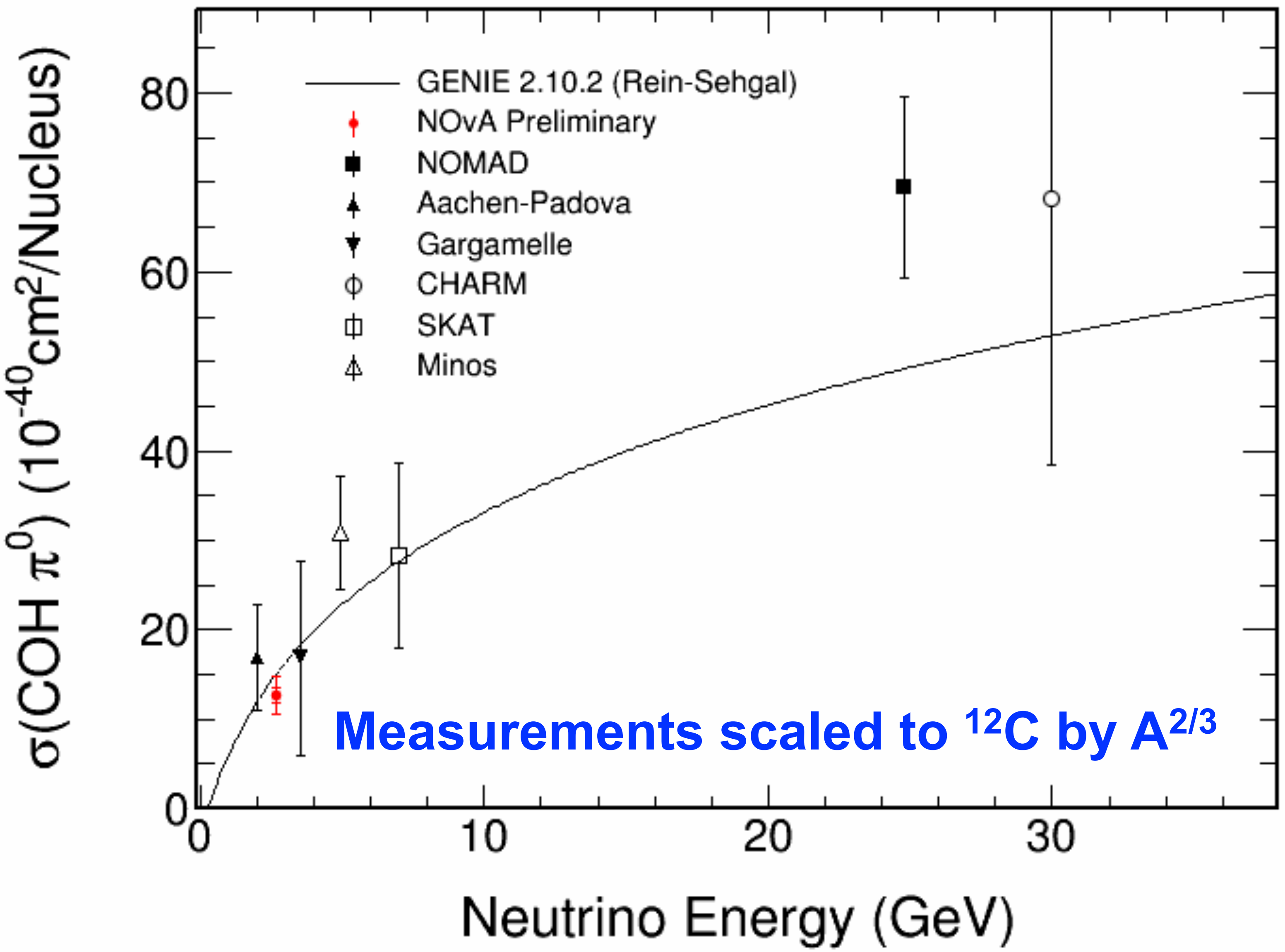
<1% uncertainty from detector simulation

9.4% uncertainty Constrained by external hadron production data

- **16.7% total uncertainty (stat + syst): systematic uncertainty dominates.**

Cross Section Result

NOvA Preliminary



Measurements scaled to ^{12}C by $A^{2/3}$

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

- Measured flux-averaged cross-section:
  σ = 14.0 ± 0.9(stat.) ± 2.1(syst.)×10^{-40}cm^2/nucleus
- One of the best measurements in the few-GeV region.

Cross Section Result

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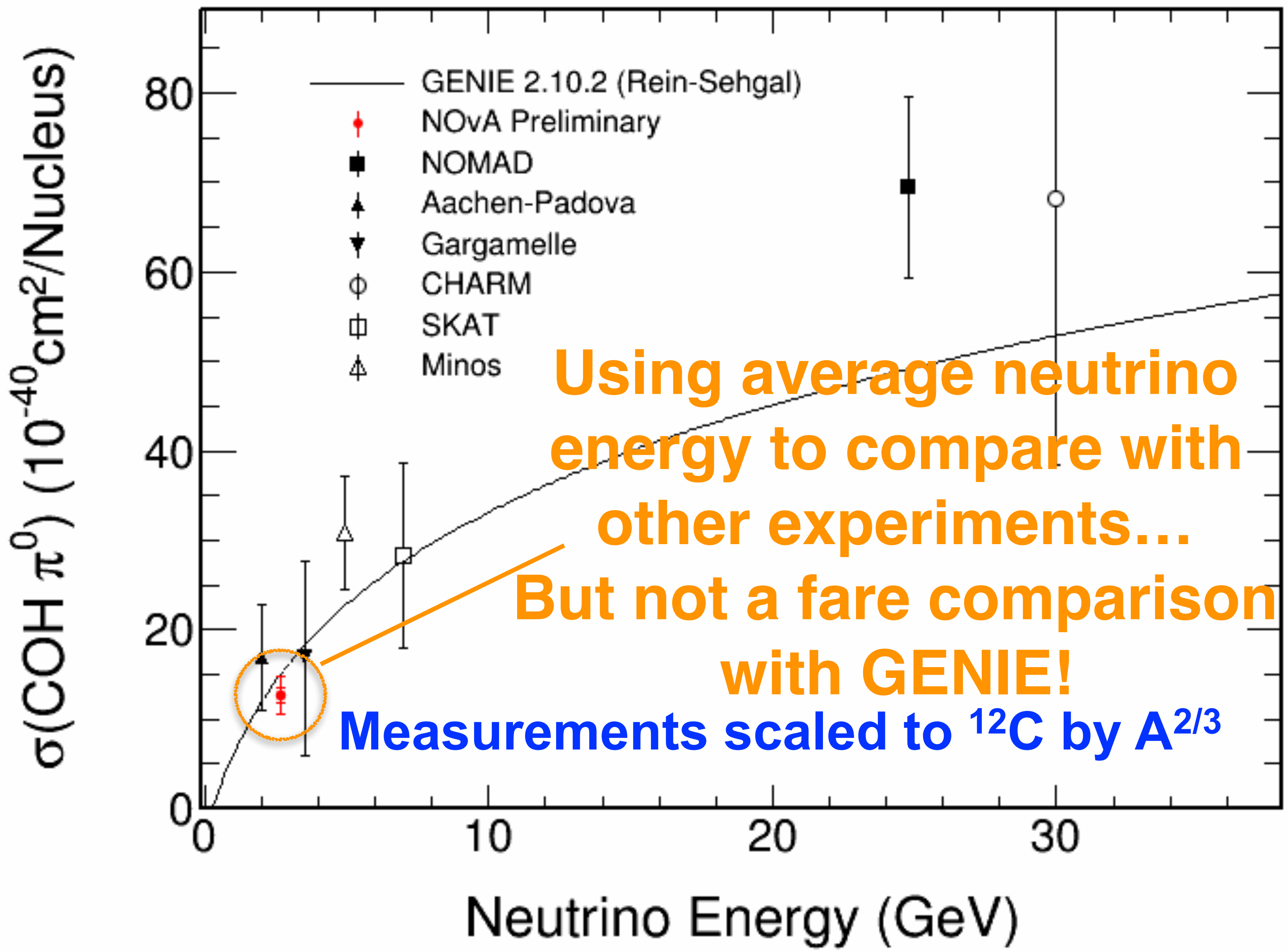

Using average neutrino energy to compare with other experiments… But not a fare comparison with GENIE!

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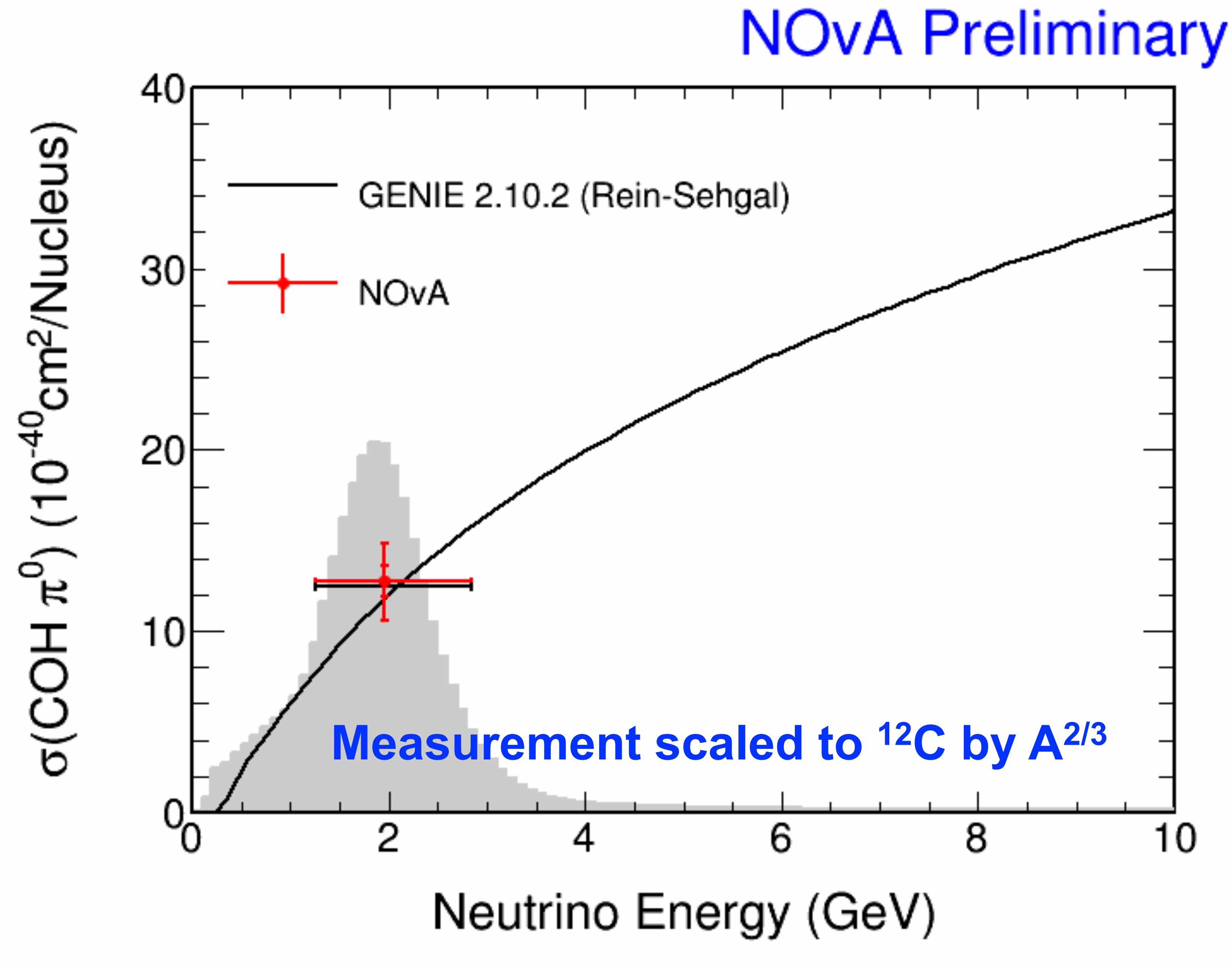

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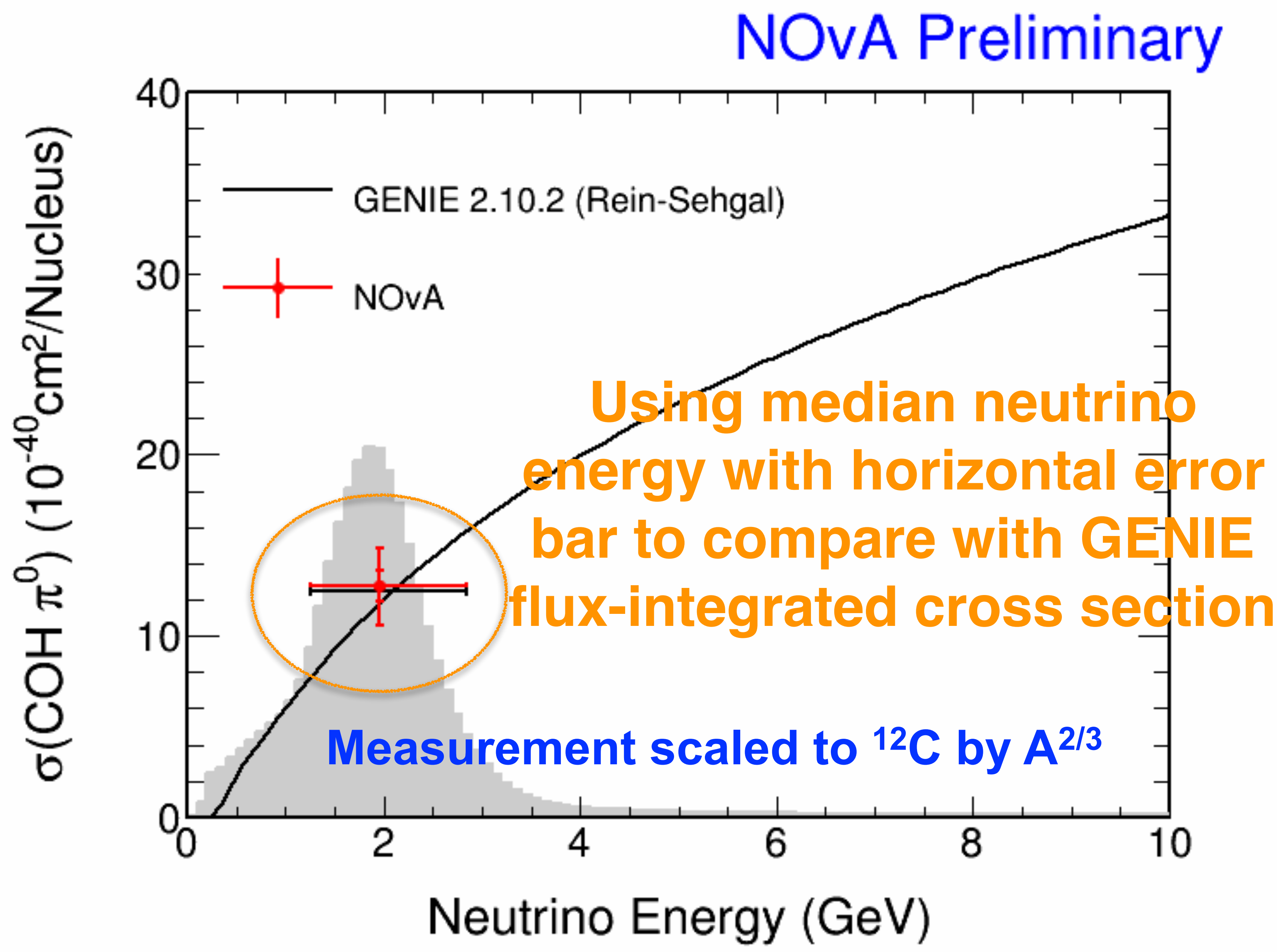
- Quite good agreement with GENIE's Rein-Sehgal model prediction.

Cross Section Result



Using median neutrino energy with horizontal error bar to compare with GENIE flux-integrated cross section

Measurement scaled to ^{12}C by $A^{2/3}$

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Outline

- Introduction
  - Motivation
  - NOvA Near Detector and Flux
- **Neutral current coherent π^0** (H. Duyang)
- **Charged current semi-inclusive π^0** (D. Pershey)
- Summary

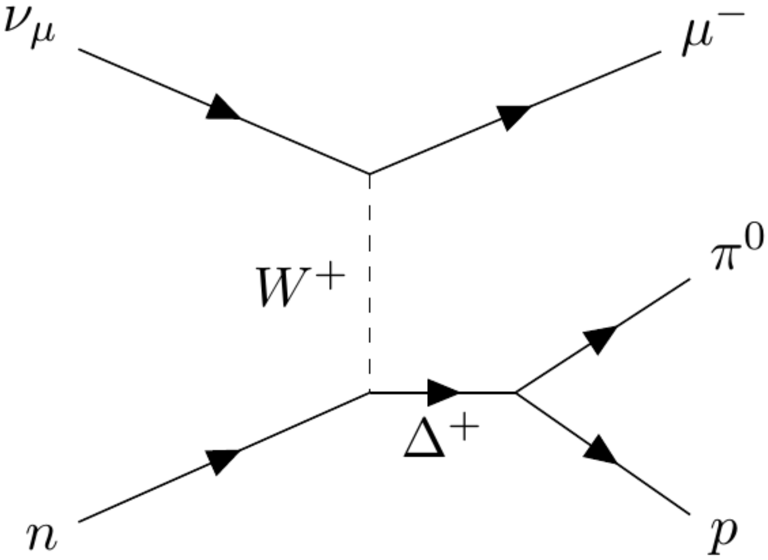
ν_μCC+π^0 Semi-Inclusive Analysis

- π^0 natural byproduct of neutrino scattering
- ν_μCC+π^0 semi-inclusive (CCPi0)

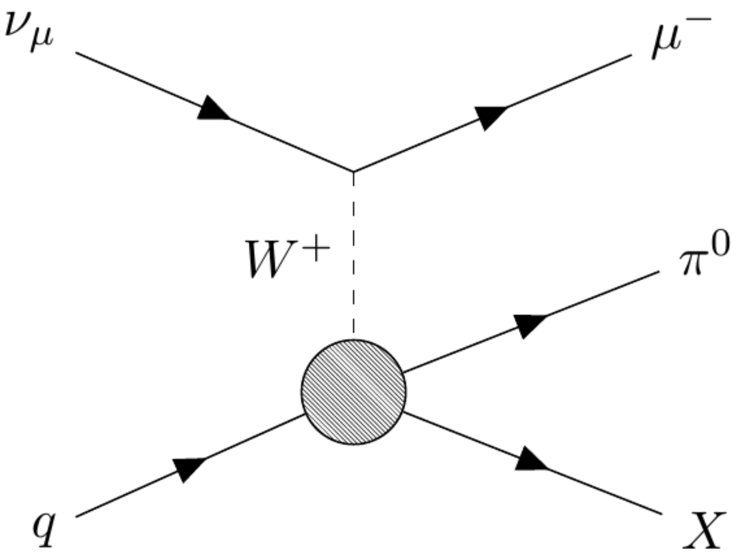
  Determined after intra-nuclear scattering

  Mimics $\nu_\mu \rightarrow \nu_e$ background for few GeV experiments

Resonant interactions



DIS interactions



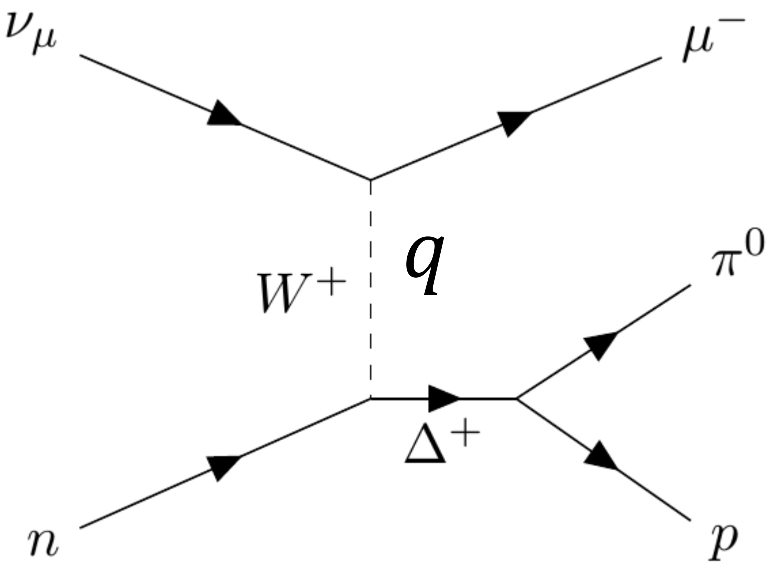
ν_μCC+π^0 Semi-Inclusive Analysis

- Deliver flux-averaged cross sections differential in:

p_π / $\cos\theta_\pi$ / p_μ / $\cos\theta_\mu$: direct observables

$Q^2 = -q^2$: four-momentum transfer to hadronic system

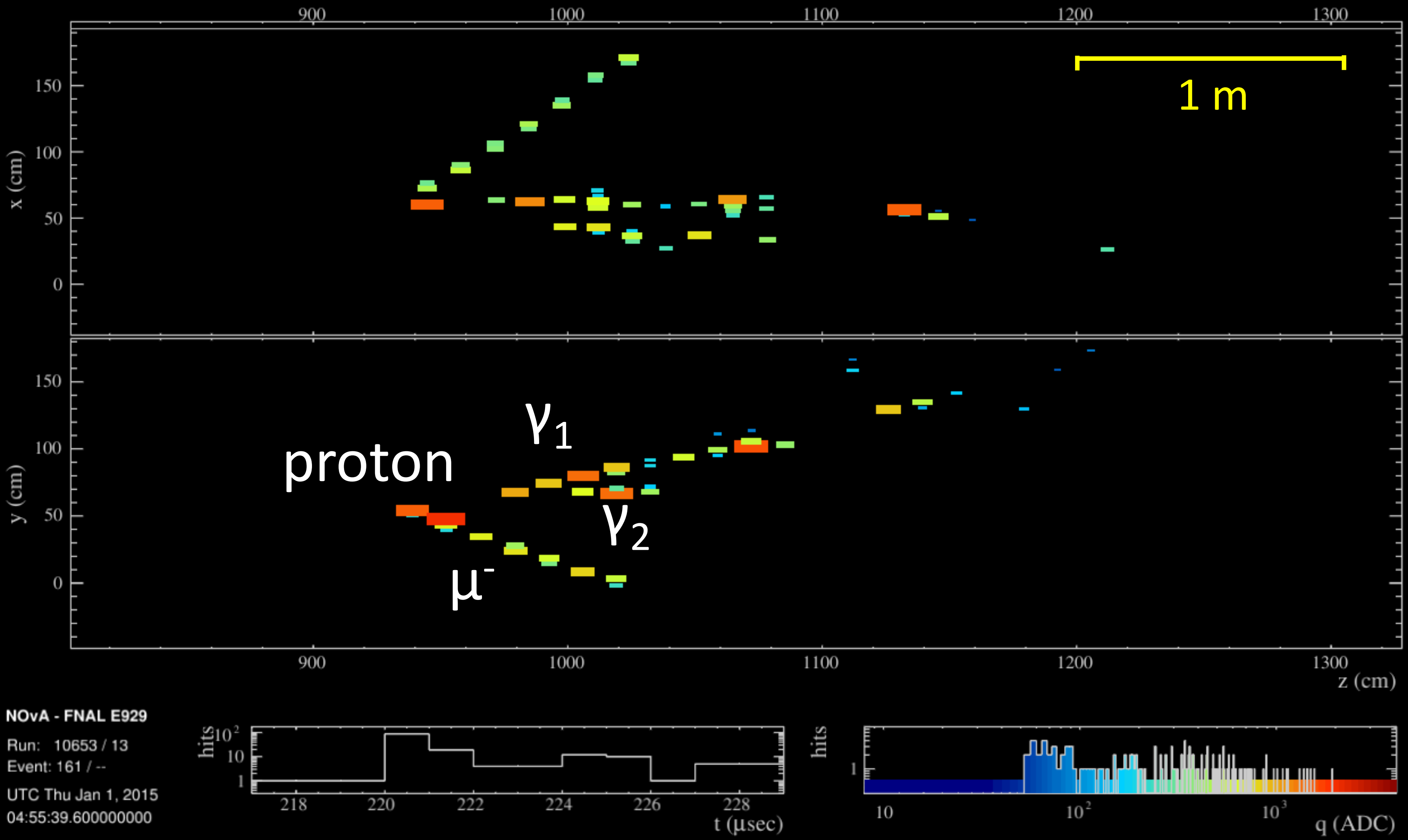
$W = \sqrt{(n+q)^2}$: invariant mass of the hadronic system, useful for separating DIS and Res events



$$Q^2 = -q^2 = -(\mu - \nu_\mu)^2$$
$$= 2E_\nu\left(E_\mu - p_\mu\cos\theta_\mu\right) - m_n^2$$

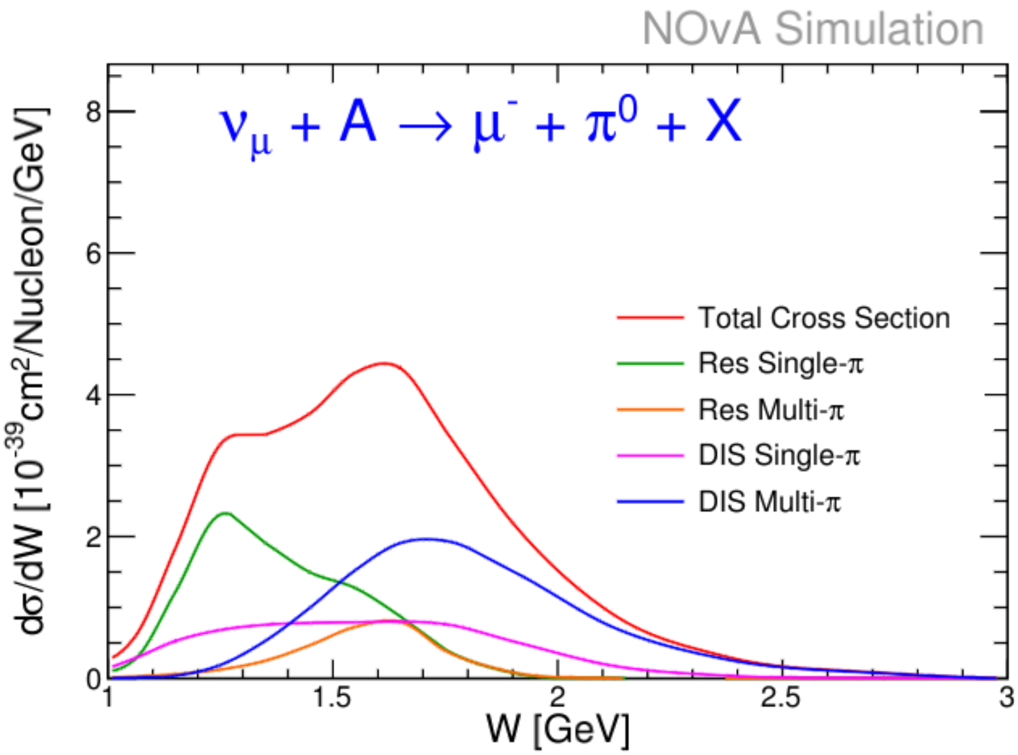
$$W = \sqrt{(n+q)^2}$$
$$= \sqrt{m_n^2 + 2m_n E_{had} - Q^2}$$

Simulated ν_μCC+π^0 Event

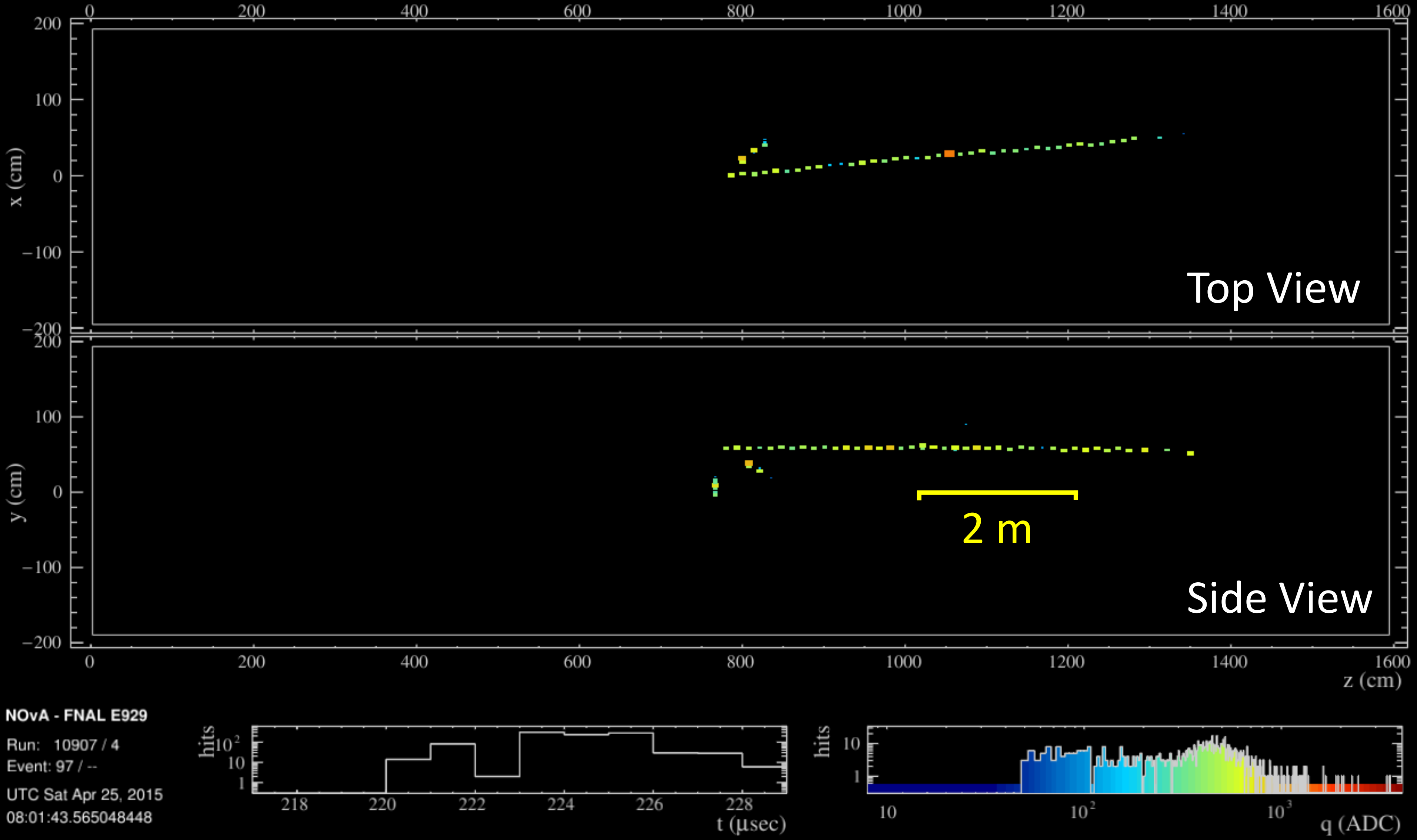


Signal Composition

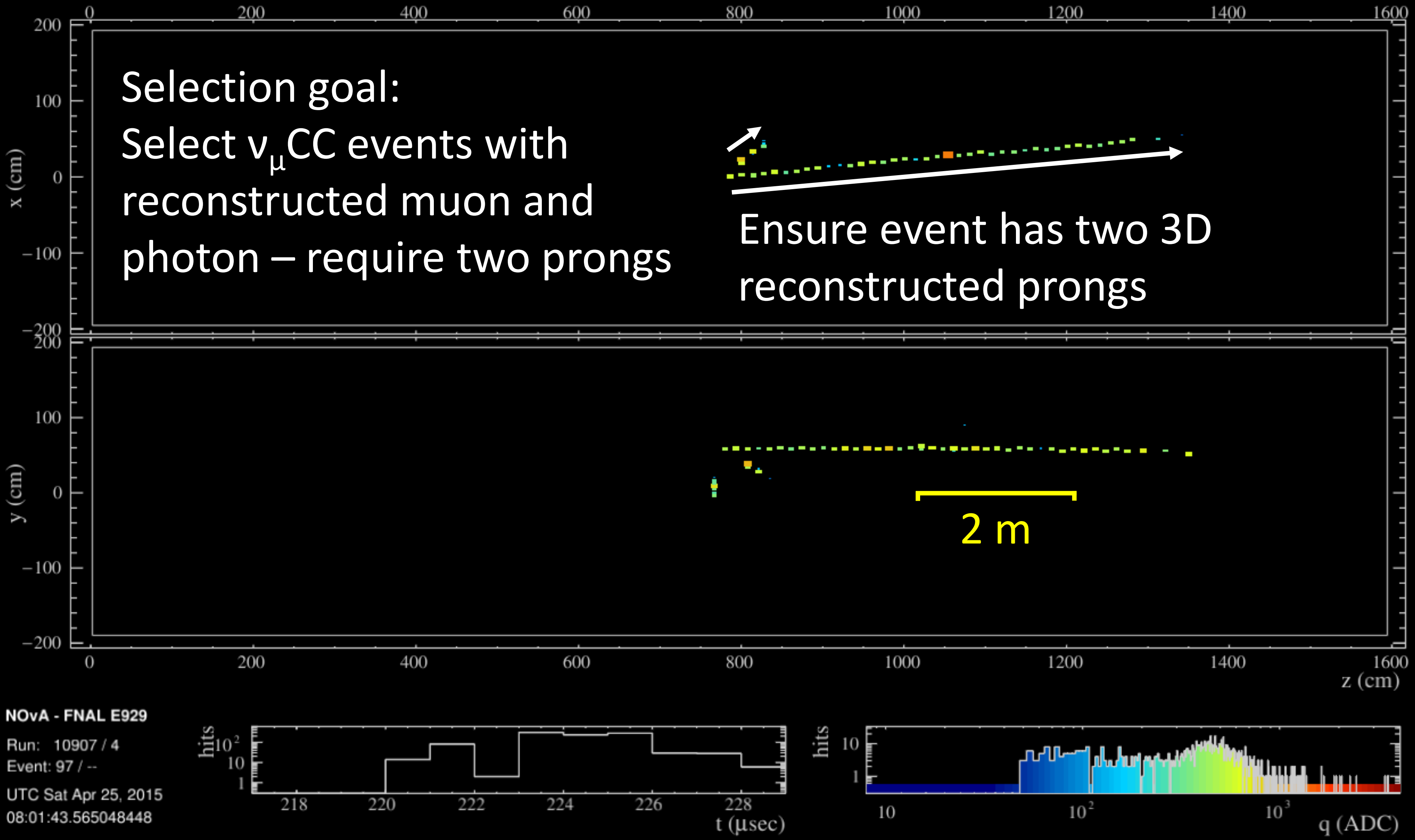
- Analysis signal has large contribution from both Res and DIS interactions
- There is a large multi-π component in ν_μCC+π^0 events which is included in the analysis signal



Example Simulated Event



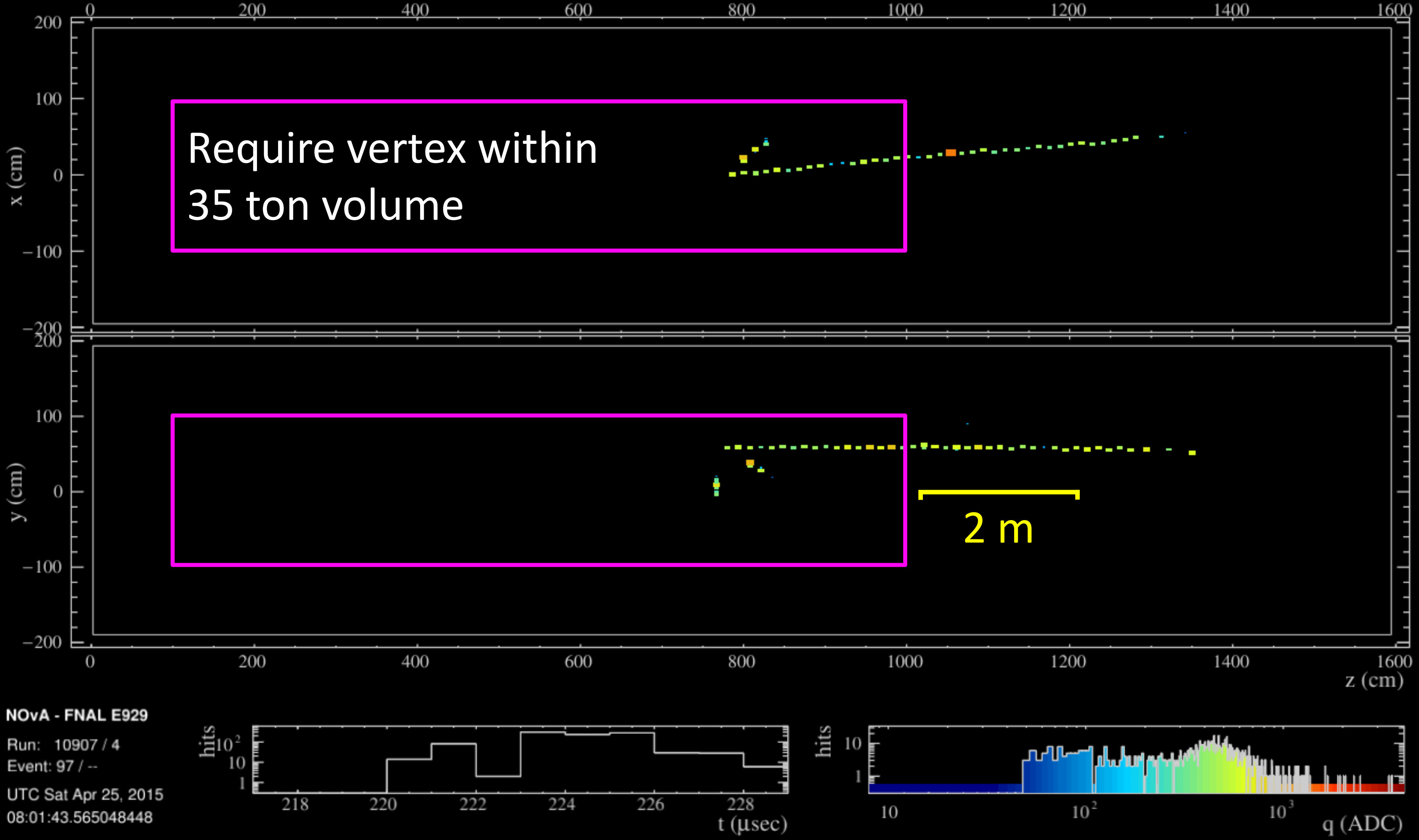
Basic Reconstruction



Selection goal:
Select ν_μCC events with reconstructed muon and photon – require two prongs

Ensure event has two 3D reconstructed prongs

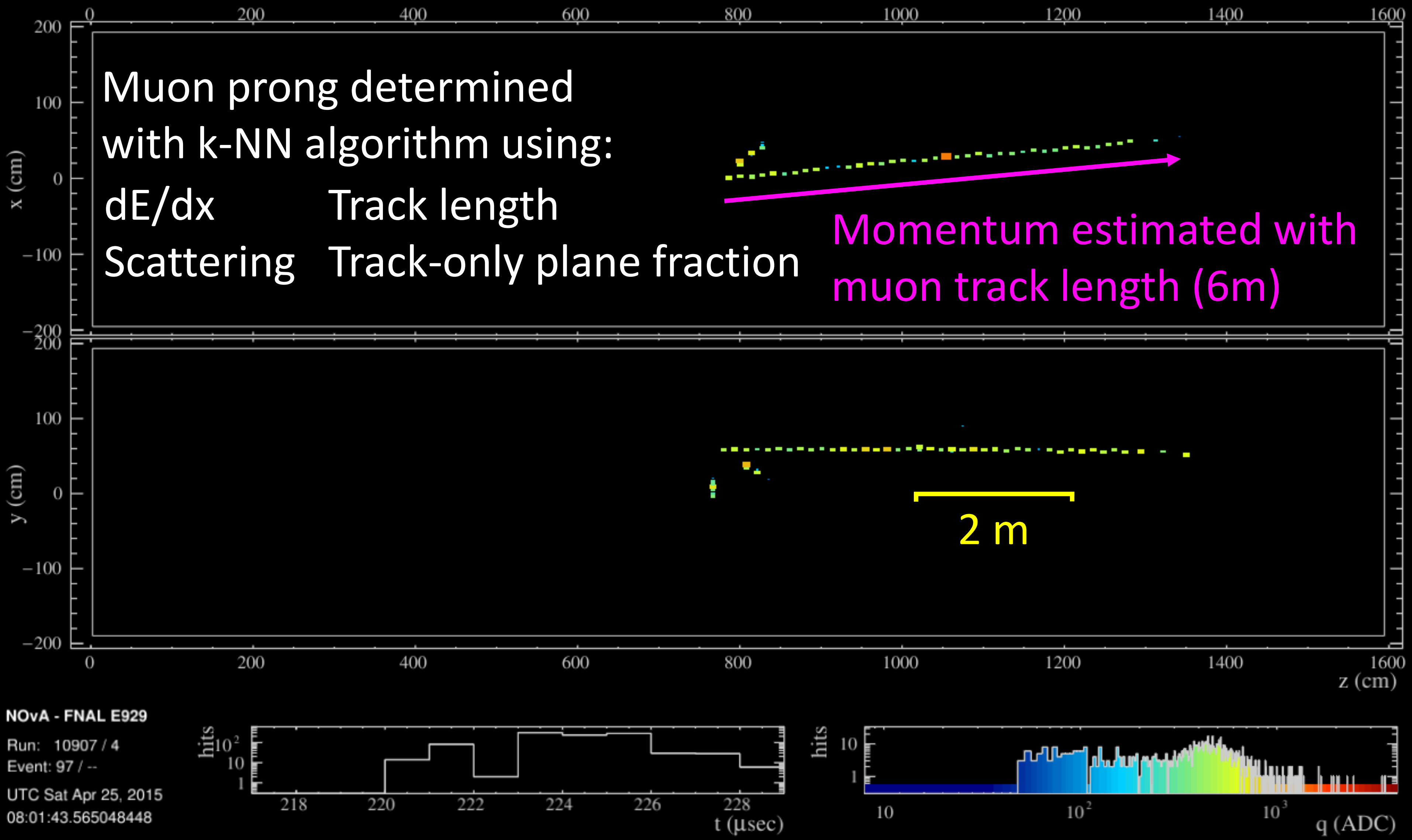
Selection: Fiducial Volume



Require vertex within 35 ton volume

2 m

Muon Identification

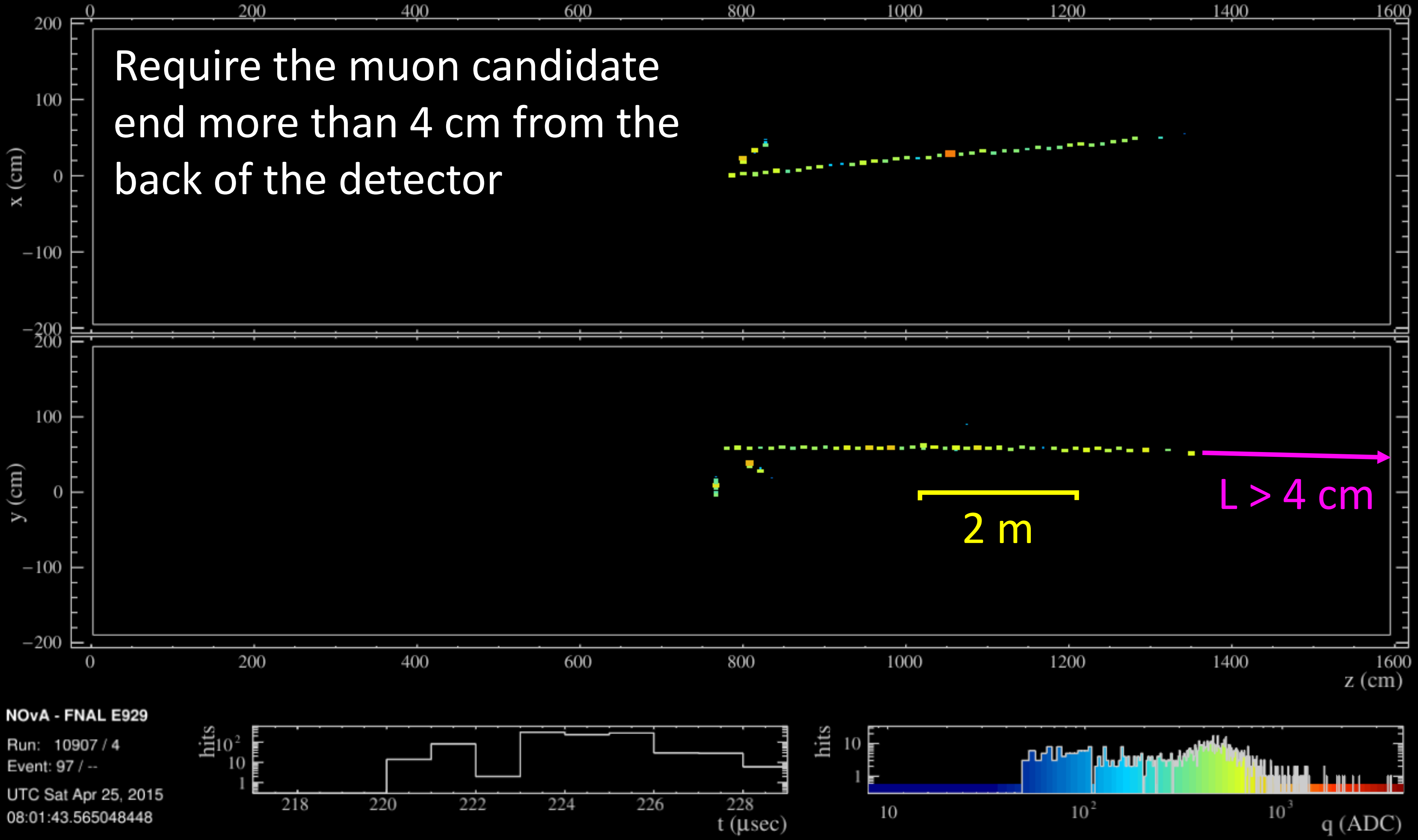


Muon prong determined with k-NN algorithm using:

dE/dx	Track length
Scattering	Track-only plane fraction

Momentum estimated with muon track length (6m)

Selection: Muon Containment

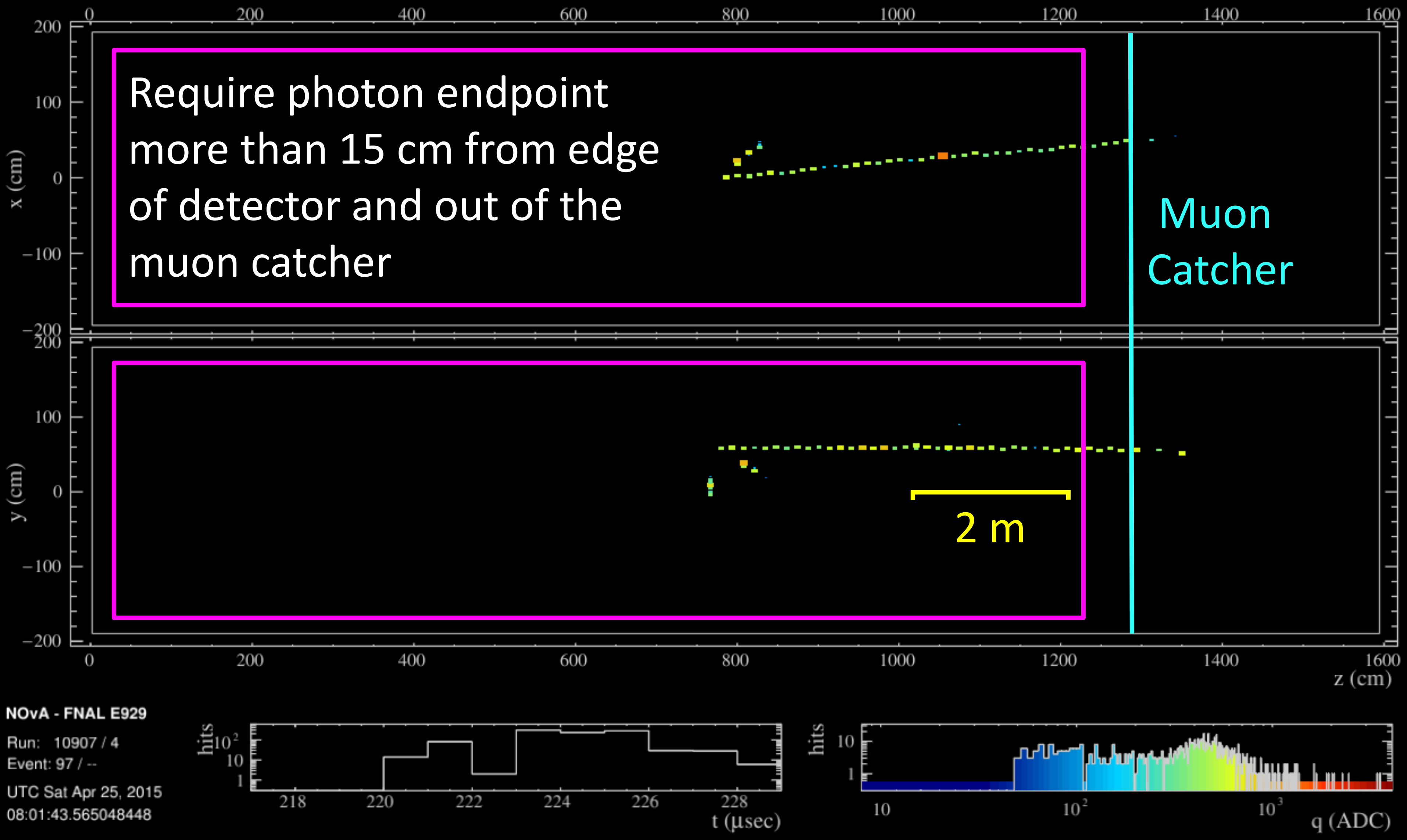


Require the muon candidate end more than 4 cm from the back of the detector

2 m

L > 4 cm

Selection: Prong Containment



Require photon endpoint more than 15 cm from edge of detector and out of the muon catcher

Signal Kinematic Range

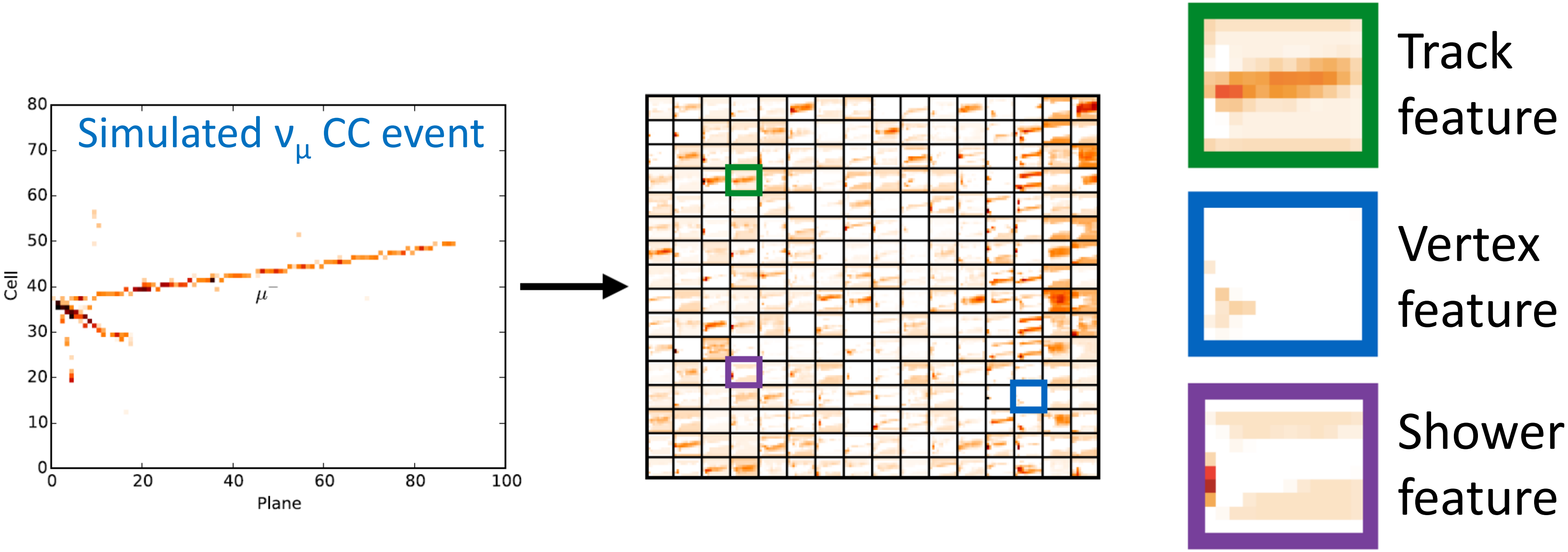
- Preselection has been defined, but now need to focus on selecting analysis signal
- Detector and beam energy limit the kinematic range where a measurement is reliable
- Add further selection criteria on kinematics to restrict analysis to this phase space

Rationale	Reco Selection	Analogous Truth Restriction
Reduce flux and acceptance modeling dependence	$1 < \text{Reco } E_\nu < 5$ GeV	$1 < \text{True } E_\nu < 5$ GeV
Maximum muon track length given detector size	Reco $p_\mu < 4$ GeV/c	True $p_\mu < 4$ GeV/c
Upper bound predicted by simulation	Reco $p_\pi < 3$ GeV/c	True $p_\pi < 3$ GeV/c

Passes cut but fails truth restriction: treat as background

Neutral Current Rejection

- Analysis has a large neutral current (NC) background
- Reject NC’s with a Convolutional Neural Network PID (CVN)



- Make a pixel map using event topology
- Produces a feature map using image detection algorithms
- Feed extracted features into a neural net

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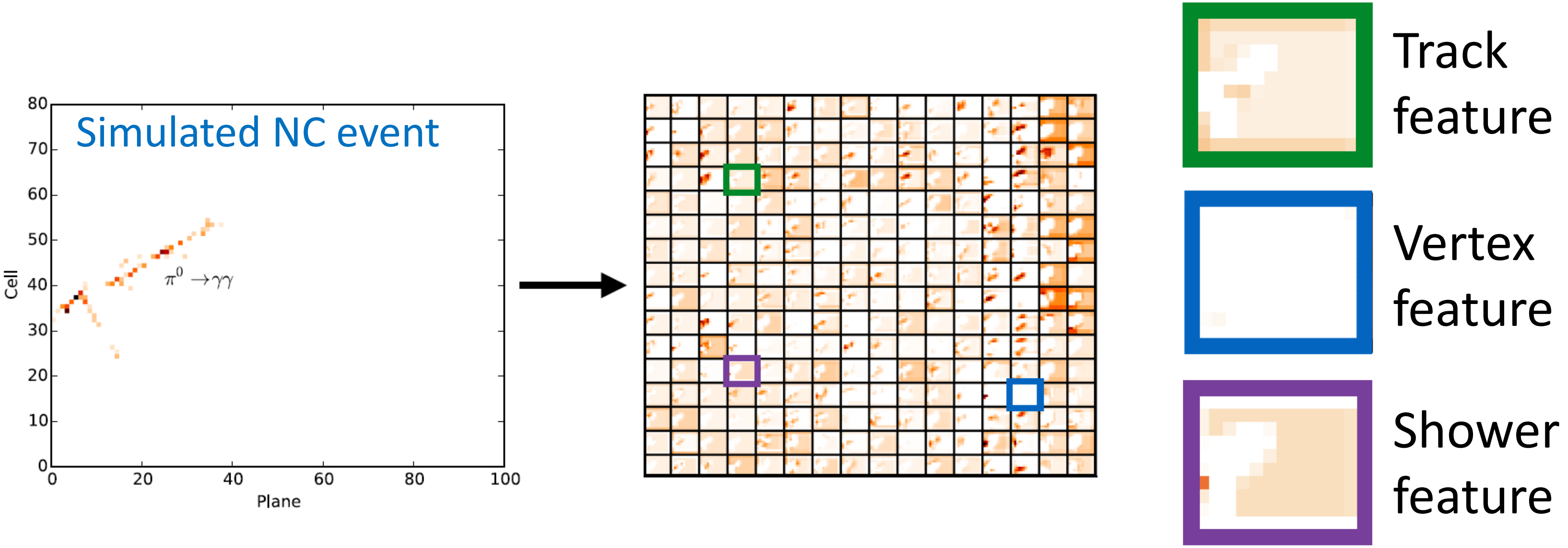

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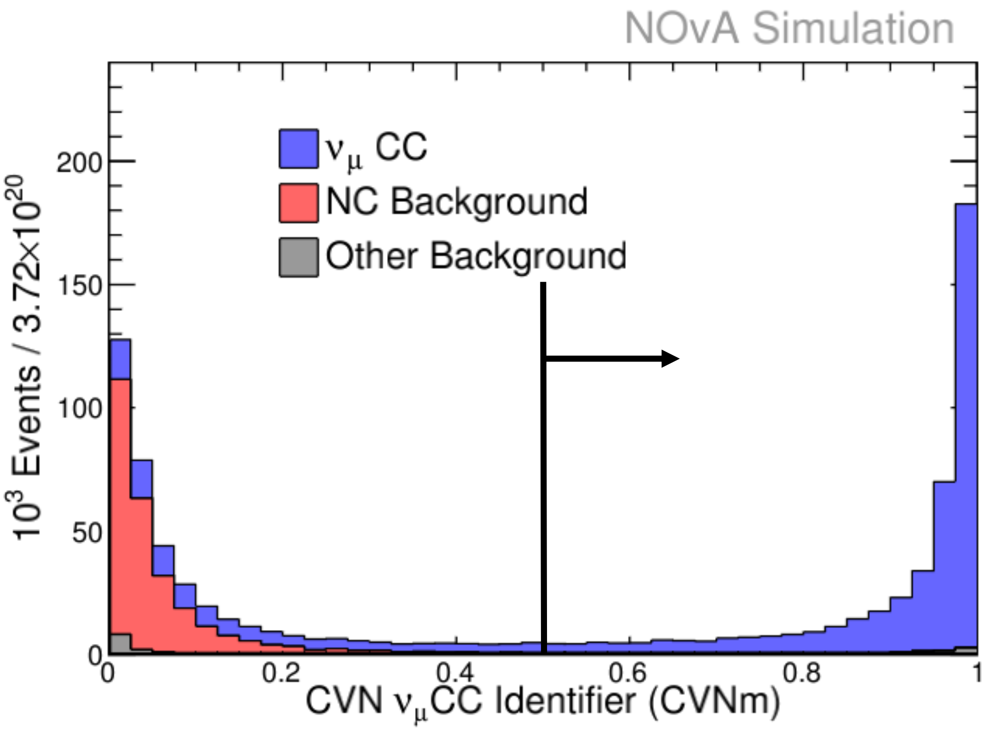
Neutral Current Rejection

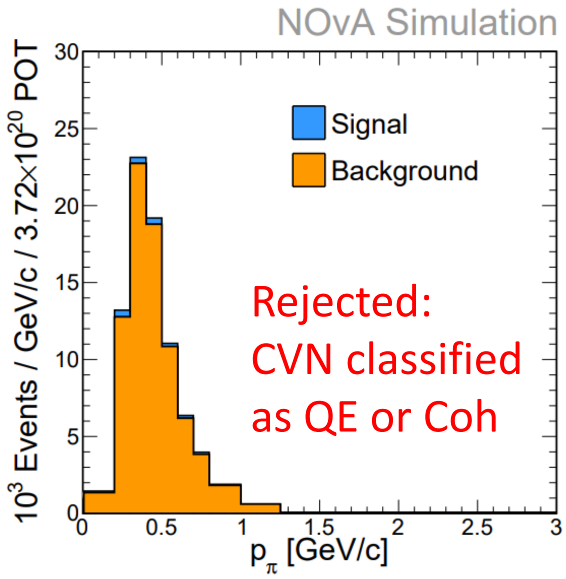
- CVN effectively rejects neutral current background from sample

  1.7% of sample after CVNm cut

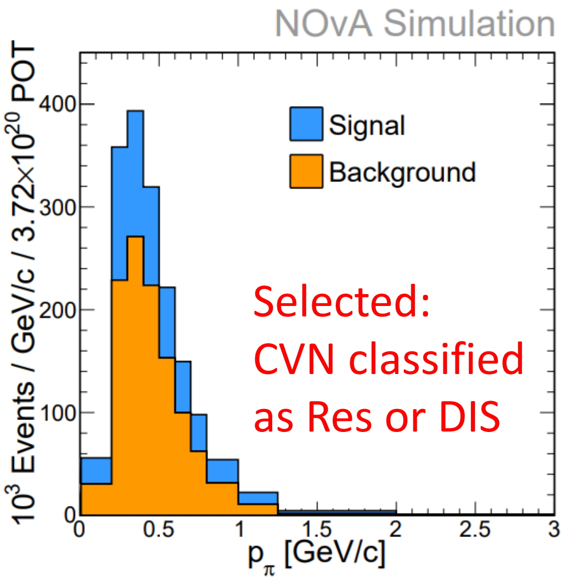


CVN trained to select ν_μCC events but this analysis needs events with a final state π^0

Signal Enhancement



Rejected:
CVN classified
as QE or Coh



Selected:
CVN classified
as Res or DIS

CVN also trained to classify events by GENIE interaction mode

- QE: $\nu_\mu n \rightarrow \mu p$ scatters of nucleon, no pion production
- Coh: $\nu_\mu A \rightarrow \mu \pi^+ A$ scatters off entire nucleus, no π^0 production
- Res:
- DIS:

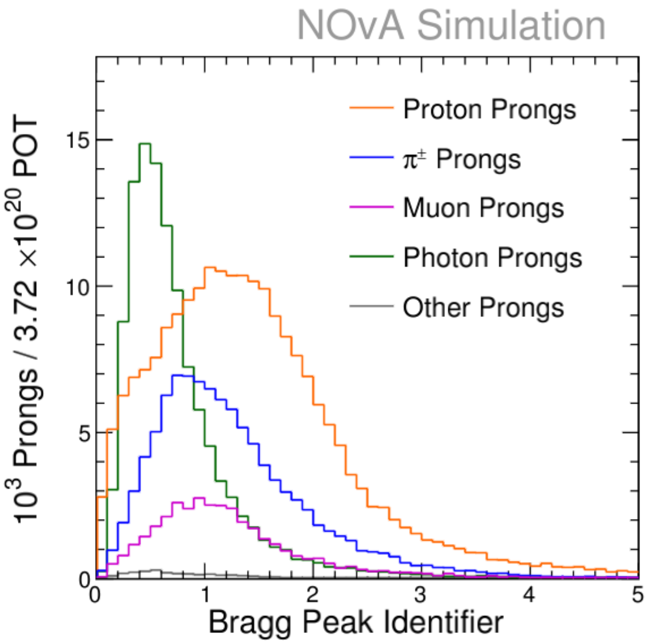
} Contribute to signal

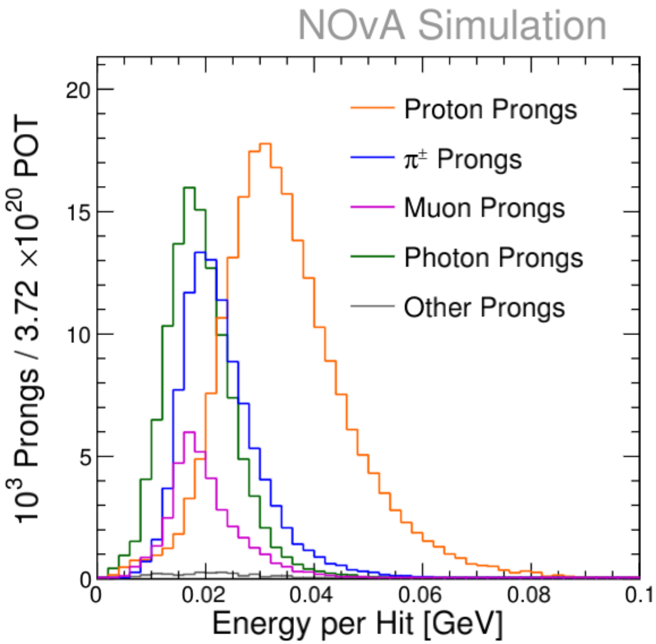
Total Efficiency:
23.0%

Select only events CVN classifies as RES or DIS

Reject background events classified as QE or Coh

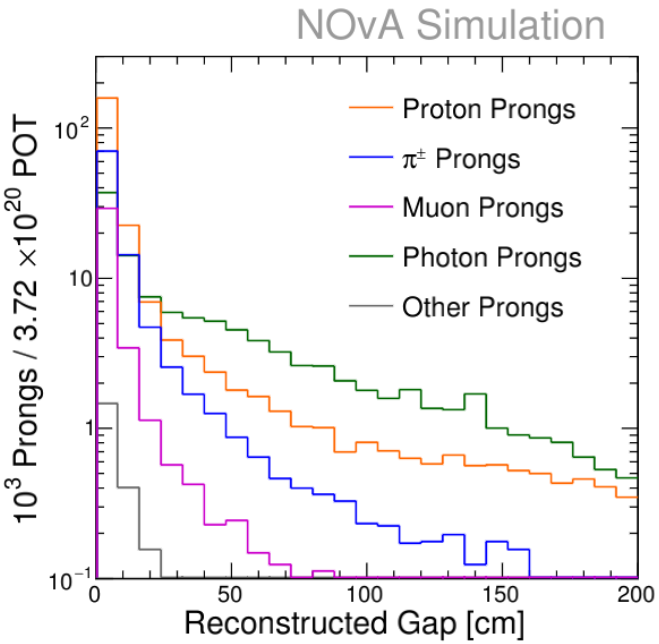
Photon Identification

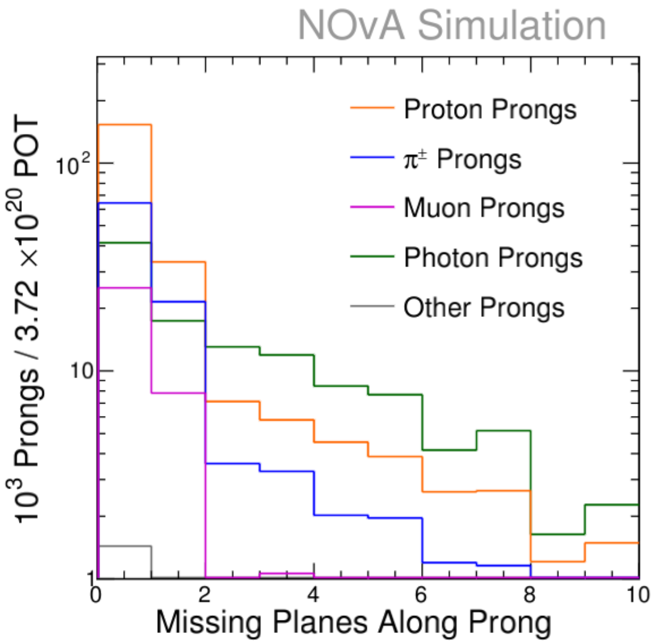




- Developed four-variable photon score
  A simple ΔLL selector
- **Two variables describe dE/dx**
  Bragg Peak Identifier: dE/dx at end of prong relative to bulk
  Energy per Hit: direct measure of average dE/dx
- Two variables describe “gappiness”

Photon Identification





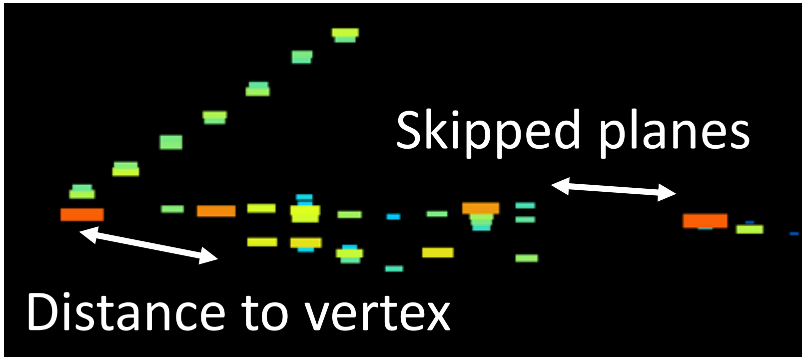
- Developed four-variable photon score

  A simple ΔLL selector

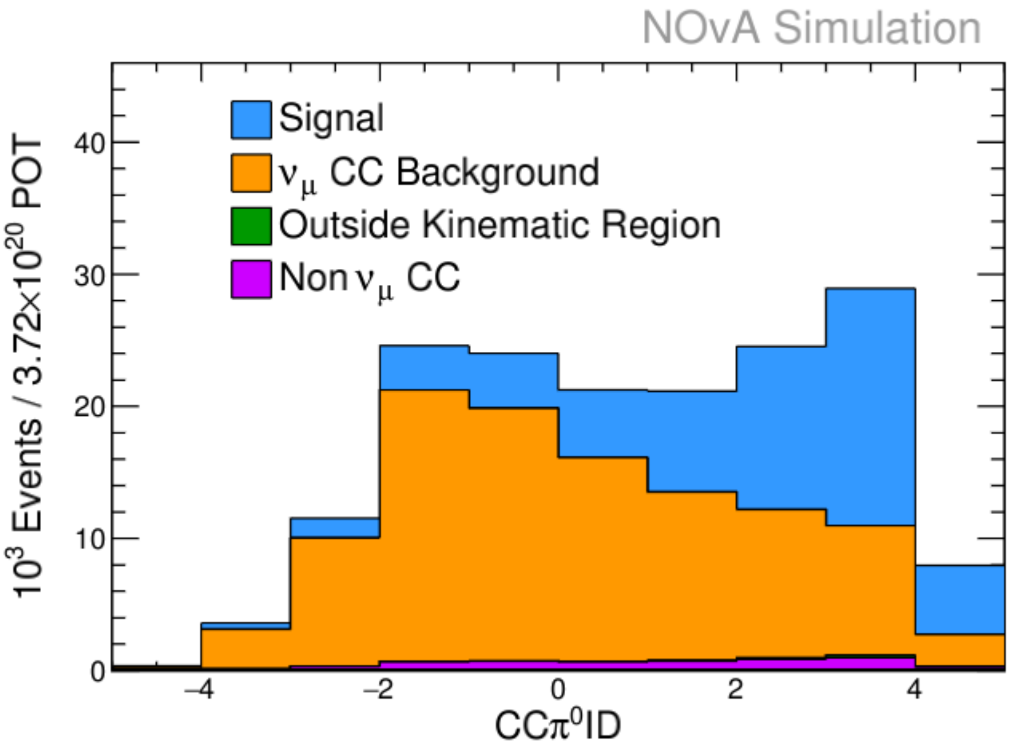
- Two variables describe dE/dx
- **Two variables describe "gappiness"**

  Distance from vertex $\sim X_0$

  Skipped planes along prong



π^0 Identification

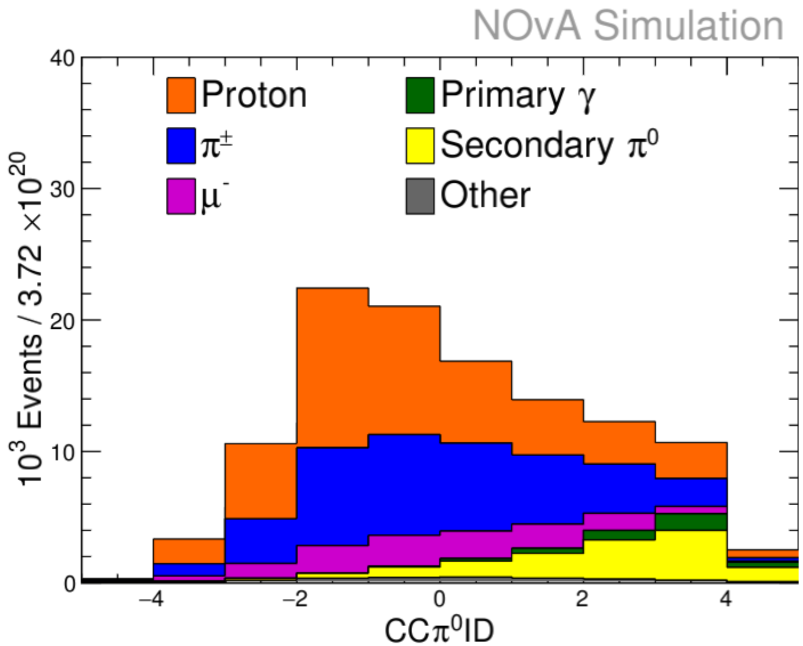


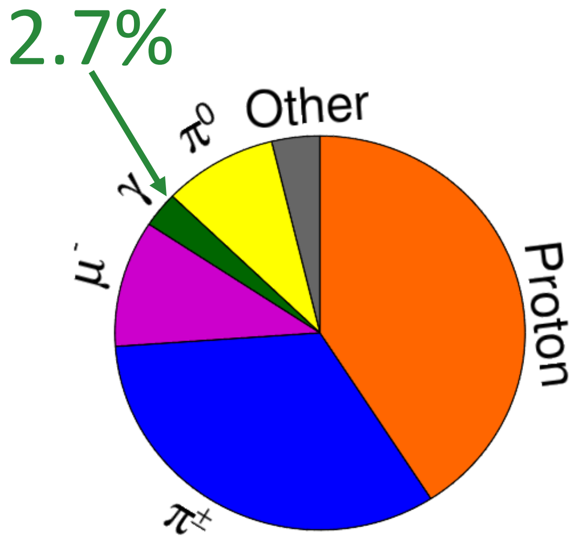
- $CC\pi^0$ID: defined as highest photon score in event
- Rely on photon candidate prong for π^0 reconstruction

  Momentum estimate: function of prong calorimetric energy

  Direction estimate: reconstructed prong direction

Background Composition





- Qualify our ν_μCC background – only large analysis background

Non-Electromagnetic Background:

Protons

$\pi^\pm$

μ^-

Peaks at low CCπ^0ID: data driven procedure to constrain

Electromagnetic Background:

Secondary π^0 (e.g. $\pi^\pm \rightarrow \pi^0$)

Photons (small, 2.7%)

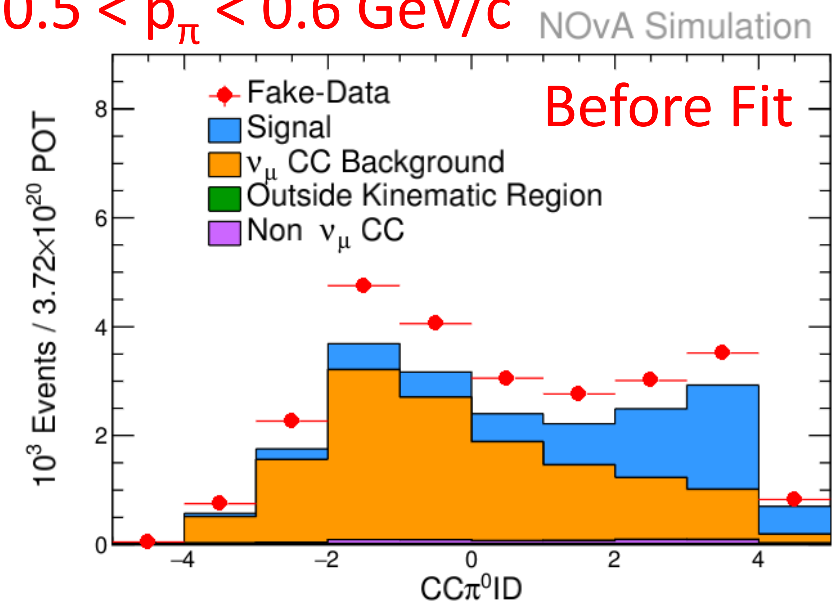
Lies under signal – understand modeling's effect on analysis

Constraining Simulation: Template Fitting

- Apply a data-driven constraint to simulation: a template fit
- Procedure assumes the simulated CCπ^0ID shape but allows signal and background normalization to float
- Measurement is differential: must perform template fit in every kinematic bin separately

Example kinematic bin:

$0.5 < p_\pi < 0.6$ GeV/c



- Test the accuracy of this procedure with systematic fake-data study
- Use nominal simulation to fit systematically shifted fake-data

   Artificially increase number of resonant events 40%

Constraining Simulation: Template Fitting

- Apply a data-driven constraint to simulation: a template fit
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Example kinematic bin:
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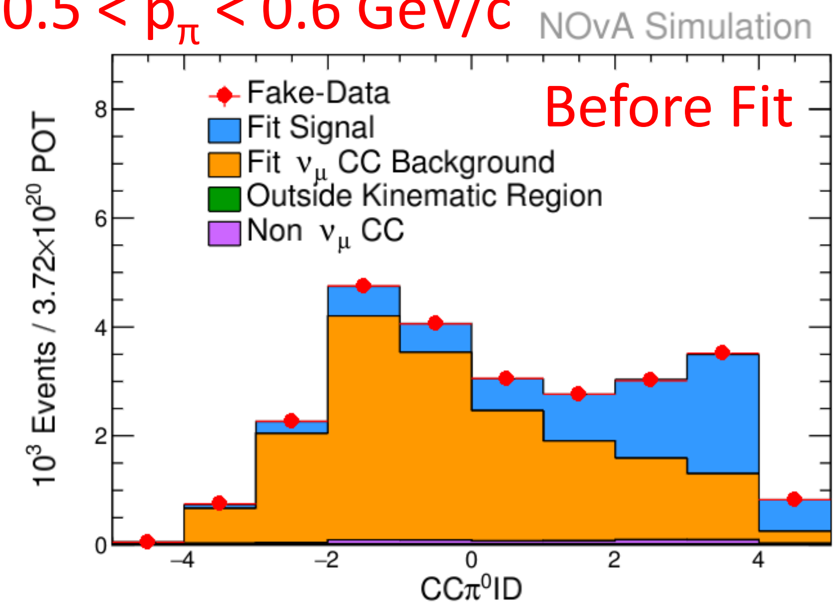


- Test the accuracy of this procedure with systematic fake-data study
- Use nominal simulation to fit systematically shifted fake-data

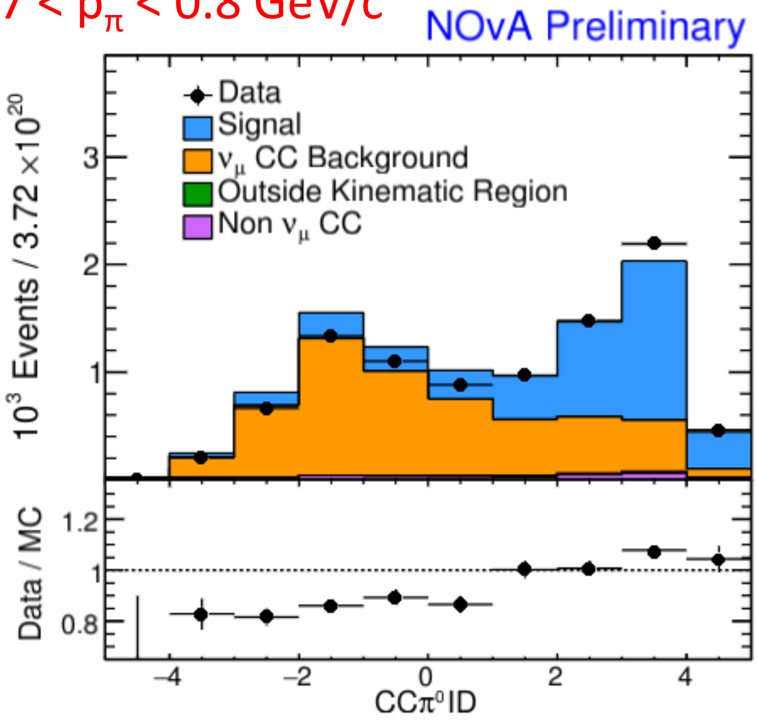
  Artificially increase number of resonant events 40%
- After the fit, total adjusted simulation agrees with fake-data

Measuring a Differential Cross Section

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

- Must apply a data-driven constraint to estimate signal
- Begins with observing data compared to simulated prediction

$0.7 < p_\pi < 0.8$ GeV/c

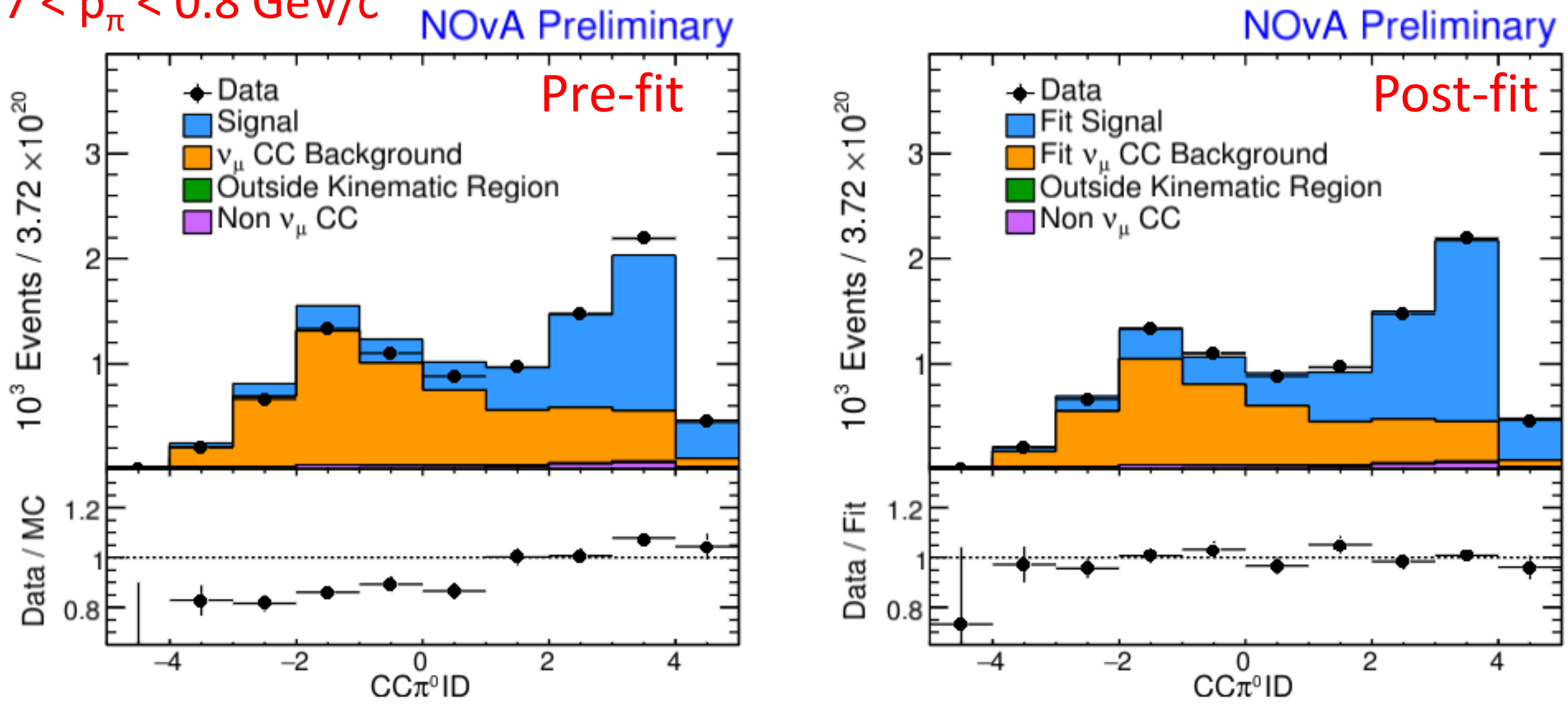


Measuring a Differential Cross Section

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

- Fit MC templates to observed data
- Adjusted MC determines signal estimate in analysis

$0.7 < p_\pi < 0.8$ GeV/c

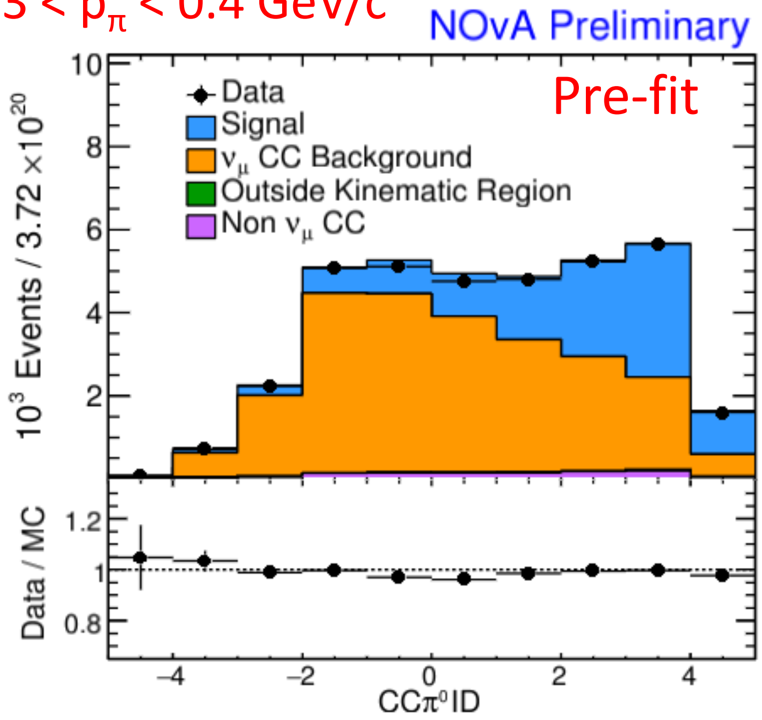


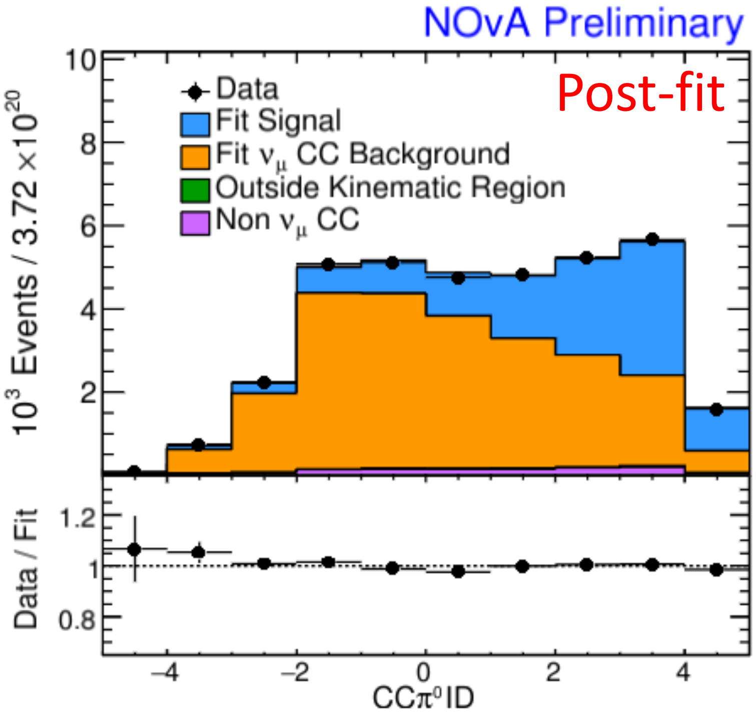
Measuring a Differential Cross Section

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

- Estimated signal shape critical for differential analysis
- Perform template fit in every bin of reconstructed x

$0.3 < p_\pi < 0.4$ GeV/c



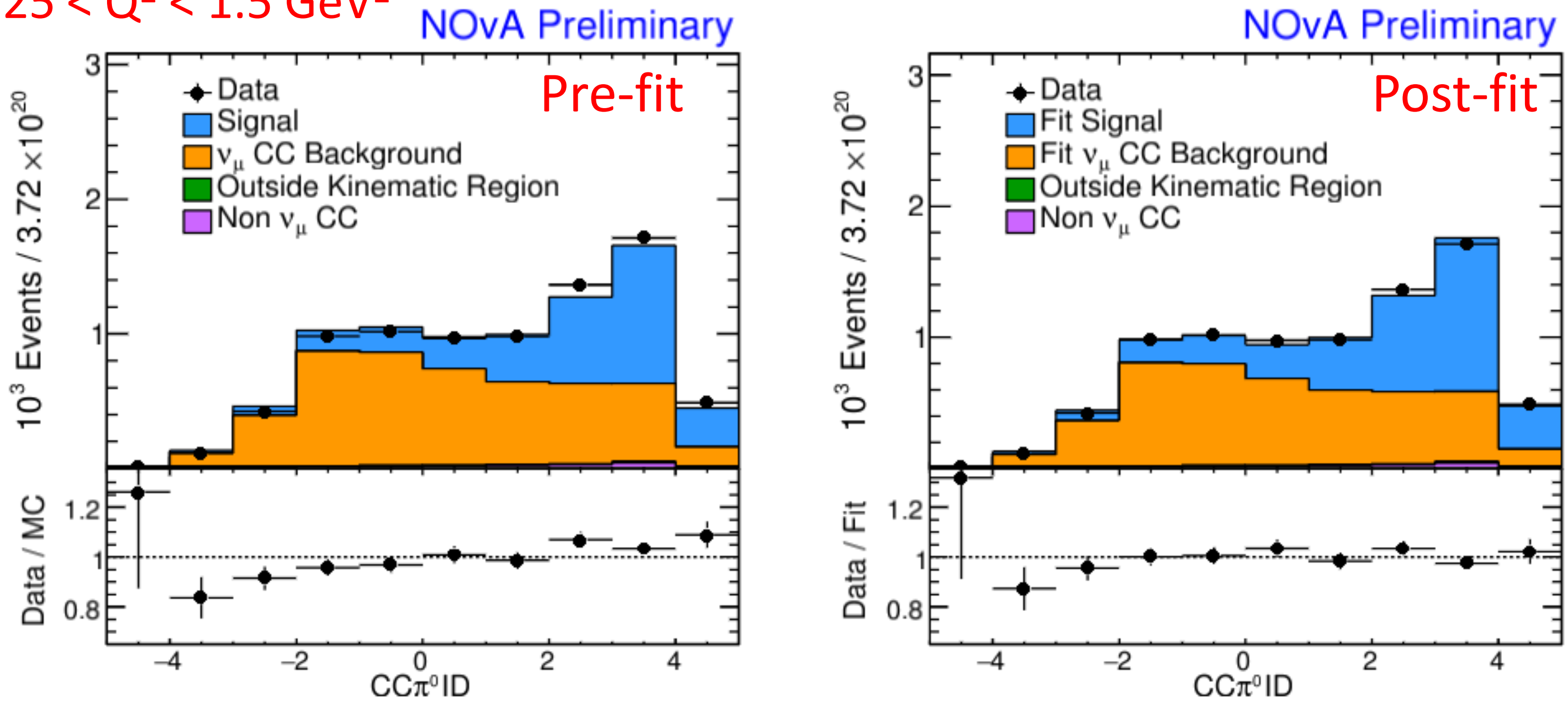


Measuring a Differential Cross Section

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

- Split same sample into bins for every measured variable
- Perform same procedure for each bin

1.25 < Q^2 < 1.5 GeV^2

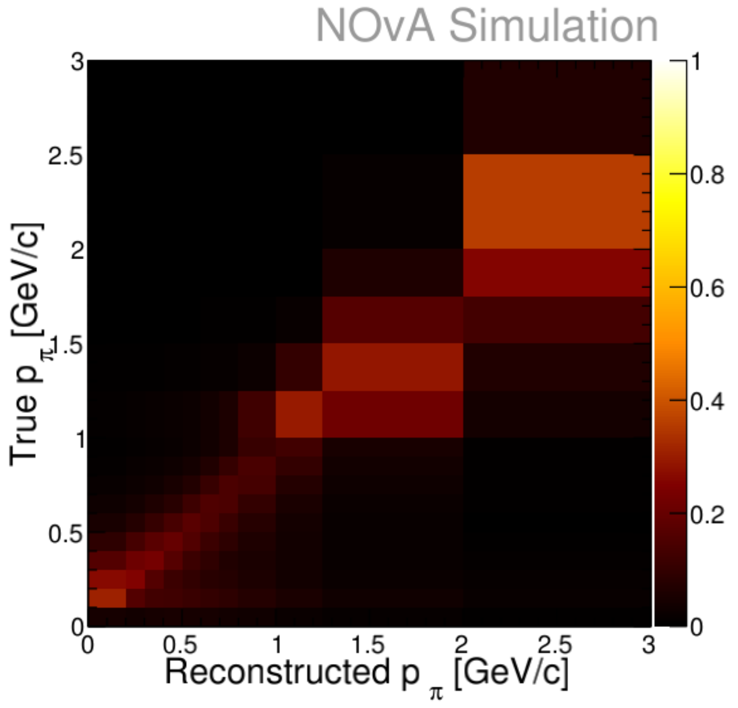


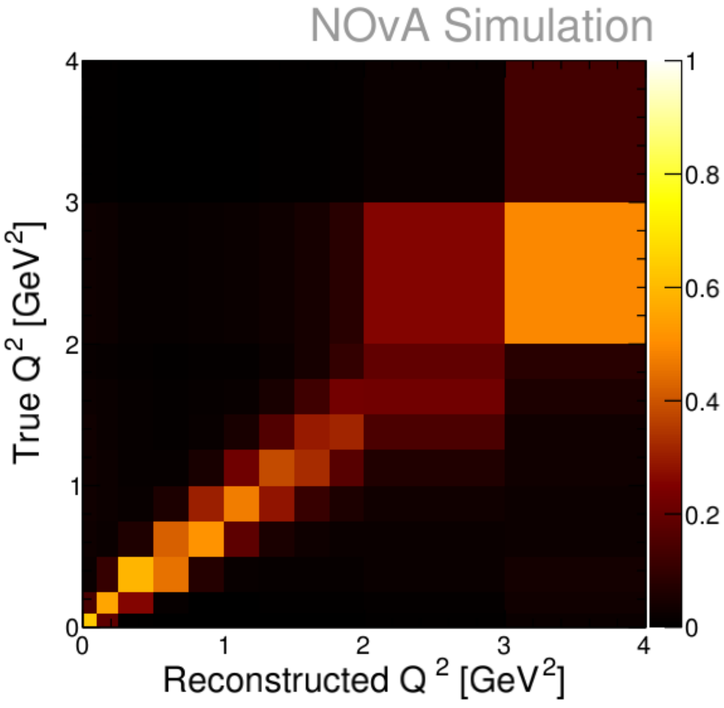
Measuring a Differential Cross Section

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

- Unfold: D’Agostini method with two iterations

  Nucl. Instrum. Methd. A362 487-498 (1995)
- Calculate migration matrices using simulation

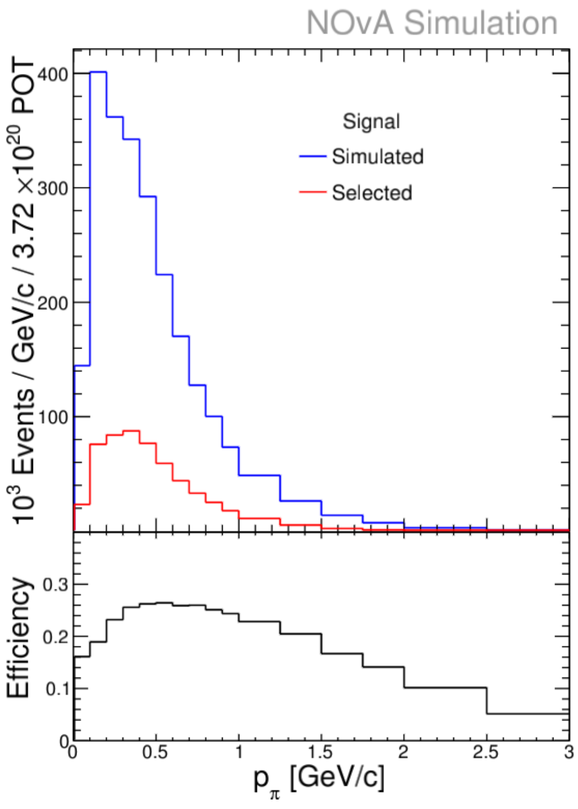


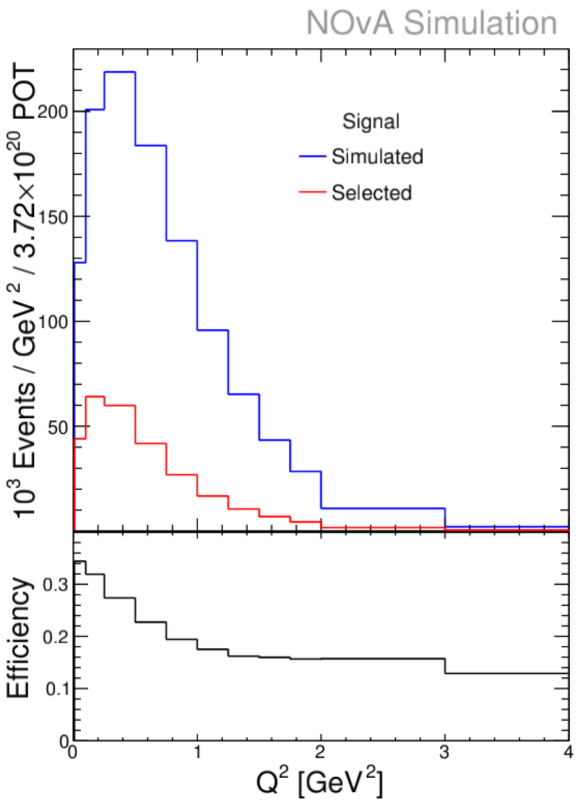


Measuring a Differential Cross Section

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

- Calculate efficiency in each kinematic bin

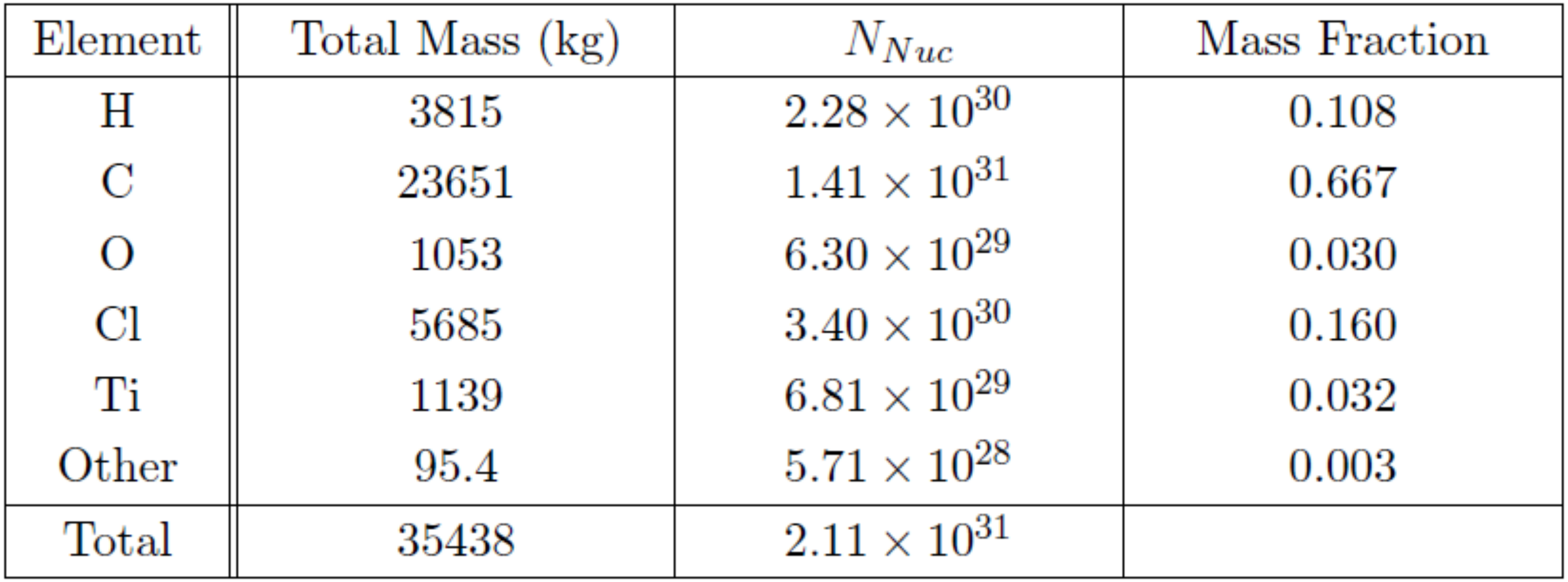




Measuring a Differential Cross Section

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

- Detector is composite material
- Count number of nucleons within fiducial region



Element	Total Mass (kg)	N_{Nuc}	Mass Fraction
H	3815	2.28×10^{30}	0.108
C	23651	1.41×10^{31}	0.667
O	1053	6.30×10^{29}	0.030
Cl	5685	3.40×10^{30}	0.160
Ti	1139	6.81×10^{29}	0.032
Other	95.4	5.71×10^{28}	0.003
Total	35438	2.11×10^{31}	

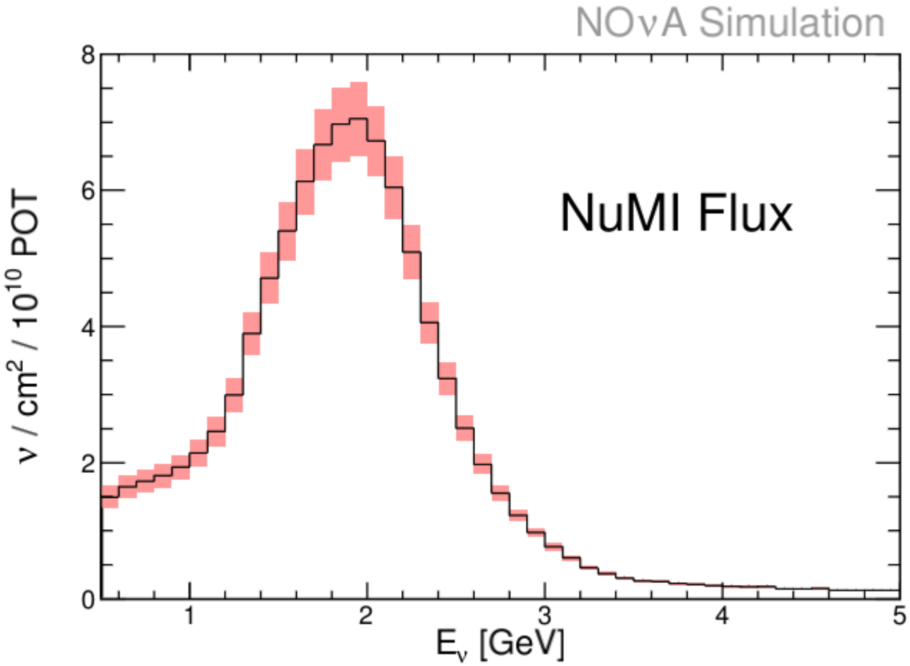
Measuring a Differential Cross Section

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

- Flux estimate from PPFX framework developed by MINERvA

  Phys Rev. D **95**, 039903 (2017)

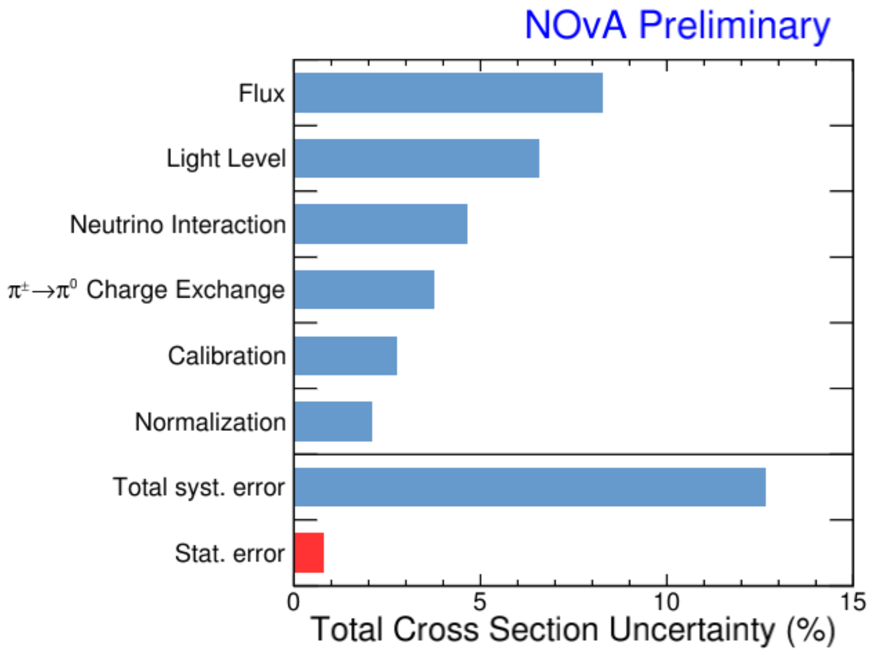
- Restrict to ν_μ flux from 1-5 GeV

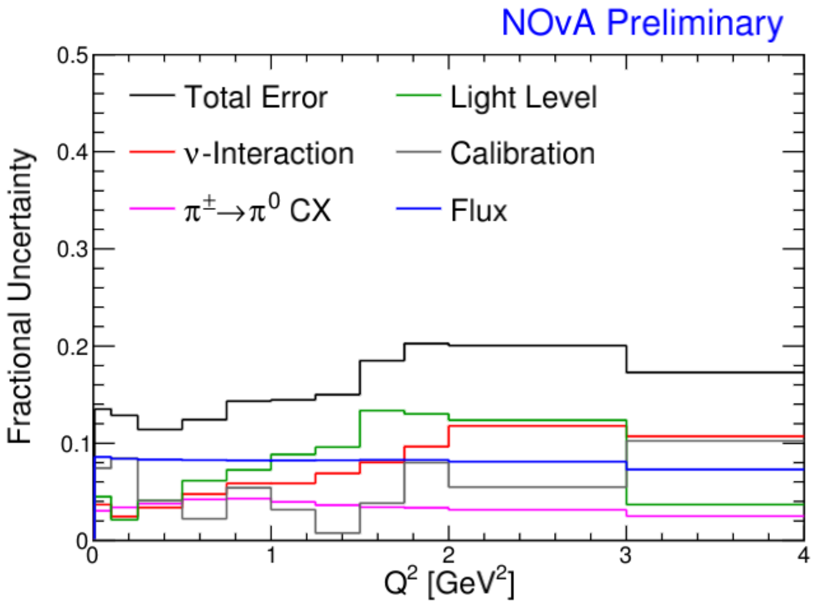


Systematic Uncertainties

- Evaluate each systematic source by modifying simulation and comparing the extracted cross section to the central value
- Systematic effects not included in fit, but the shape of the total error is quoted with measurement
- Largest sources are flux and light level

Will go into more detail on Light Level and $\pi^{\pm} \rightarrow \pi^0$ CX

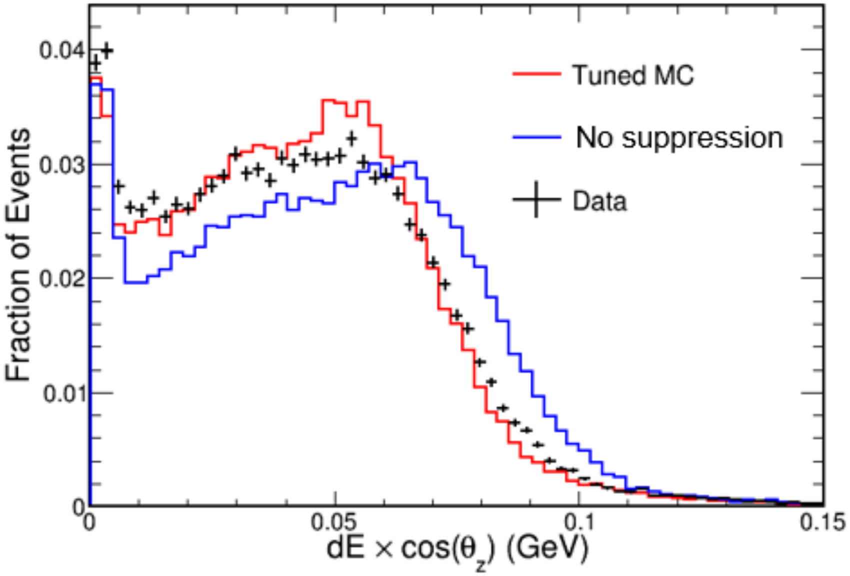




Systematic: Light Level Modeling

- ND proton sample shows dE/dx in data lower than simulation predicts
- Incorporate Birks-Chou model for light yield:

$$LY = \frac{A}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2}$$



- Direct measurements of k_B for organic scintillator cluster around 0.1-0.2 g/cm^2/MeV
- Tuned Birks-Chou parameters using ND protons:

  k_B = 0.4 g/cm^2/MeV
  k_C = -0.0005 cm^2/MeV^2
- Re-simulate using k_B = 0.1 g/cm^2/MeV and k_C = 0 and take the difference in extracted cross sections as a systematic

Systematic: $\pi^{\pm} \to \pi^0$ Charge Exchange

- Background with a $\pi^{\pm} \to \pi^0$ look very signal-like: test effect of cross section uncertainty on analysis

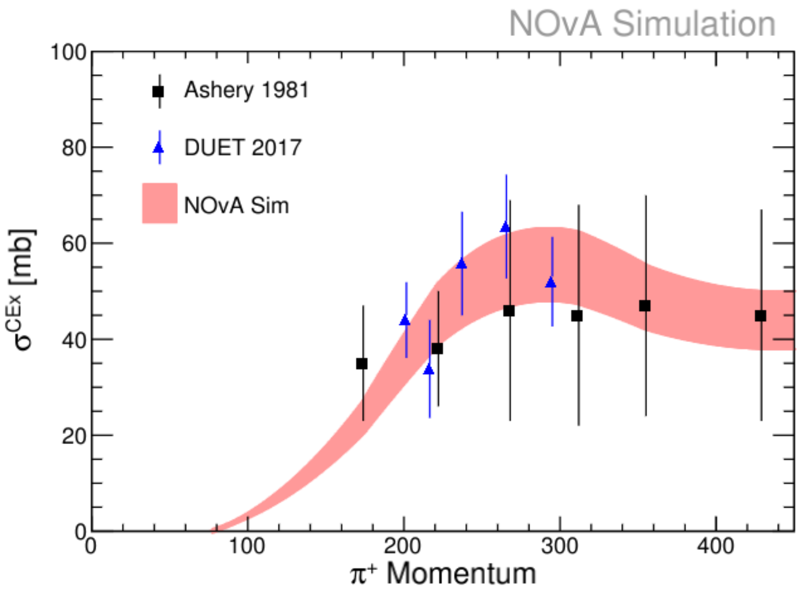
- Covariance fit of simulation to DUET 2017 results

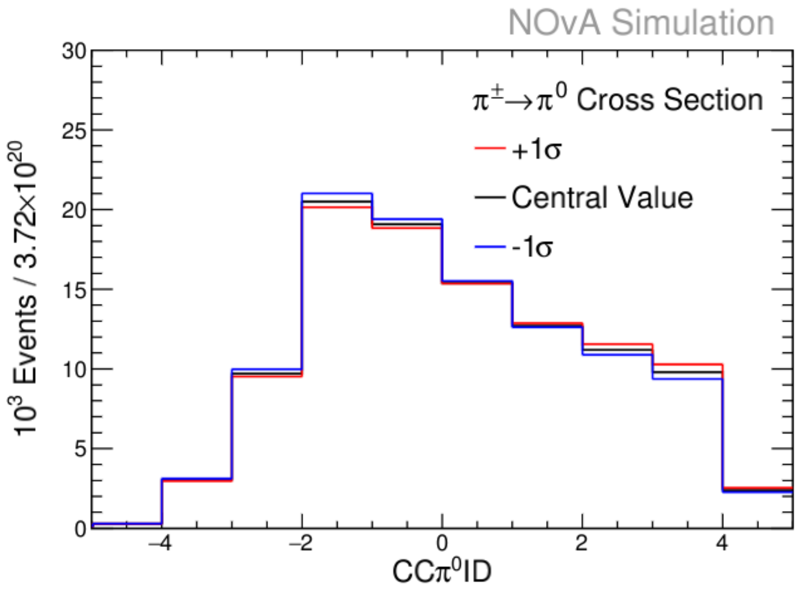
  Weight σ^{CX} to 1.061±0.146 of nominal value

  Phys. Rev. C **95**, 045203 (2017)

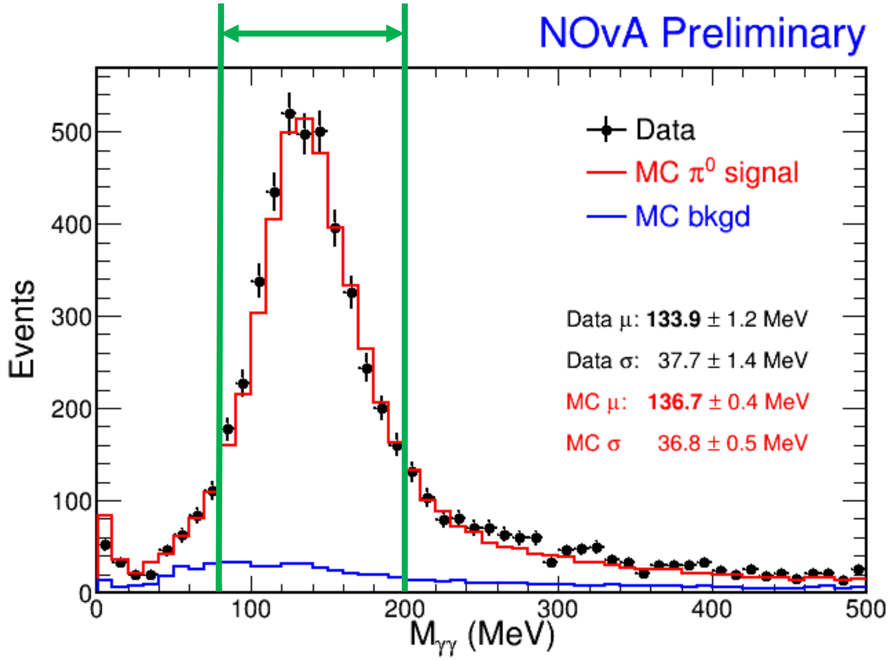
- Noticeably skews $CC\pi^0ID$ distribution for background

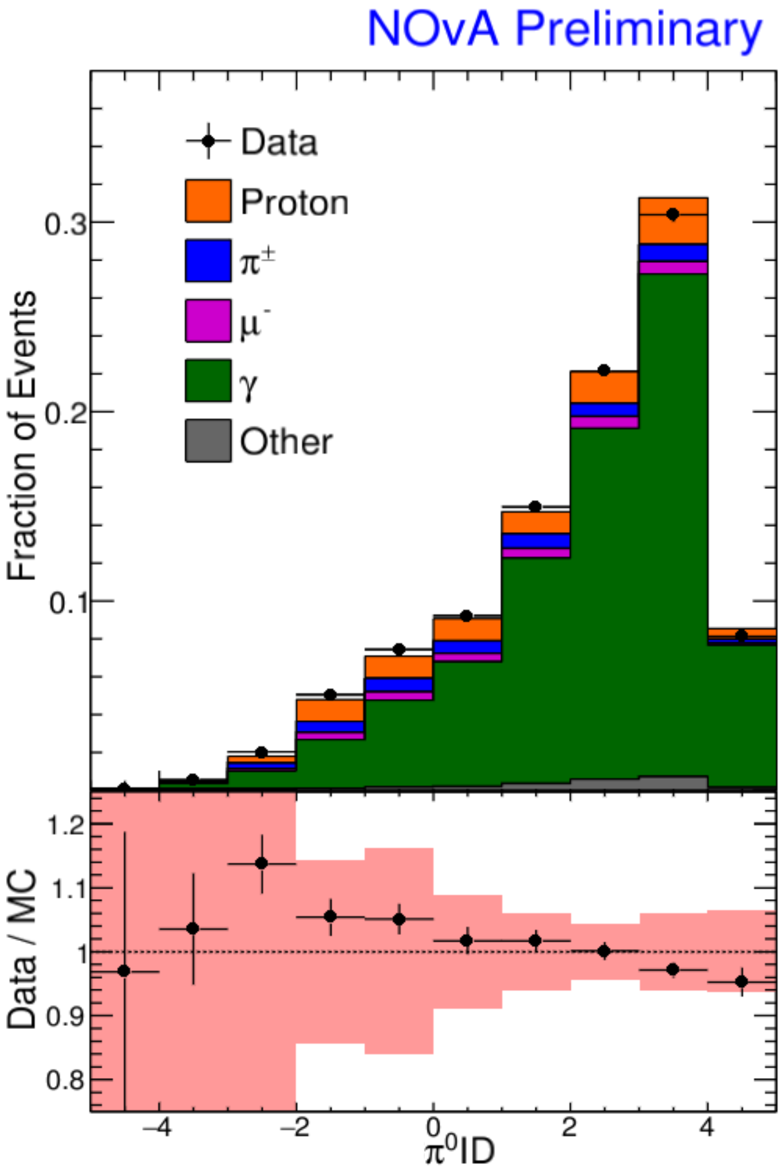
- 4% impact on total cross section





Systematic Error Cross-Check





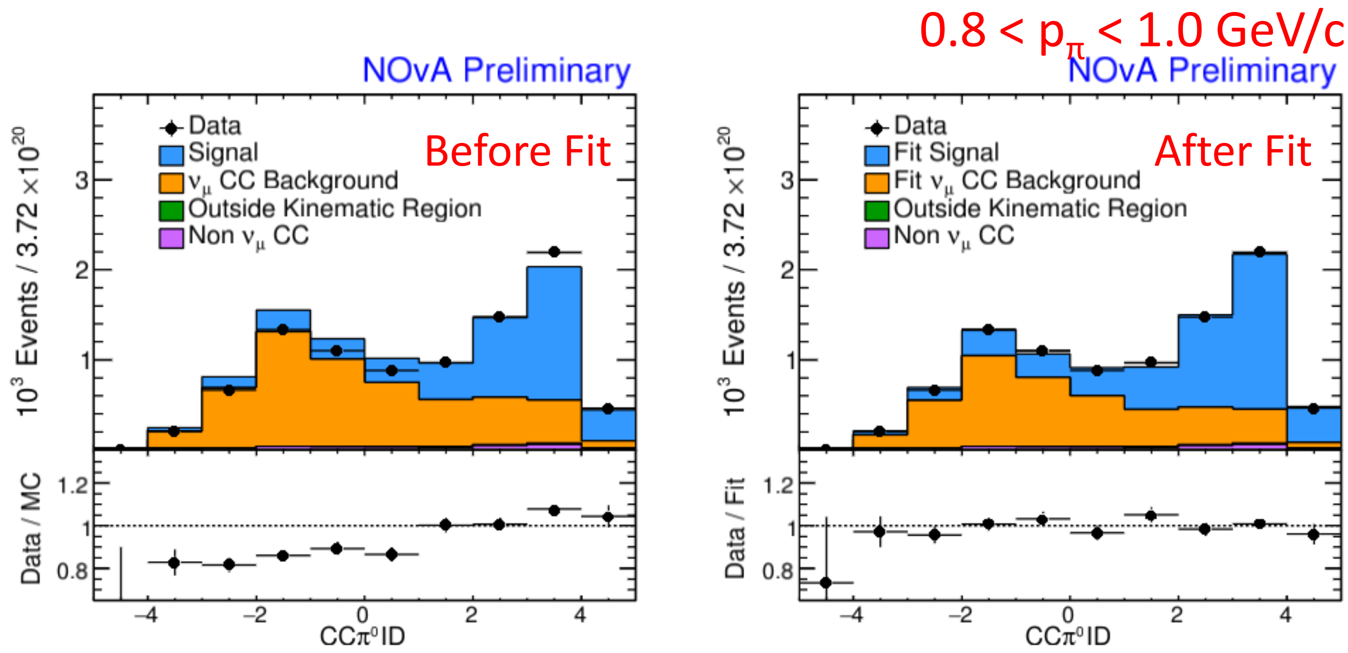
- $NC\pi^0$ sample gives high purity photon sample
- Disjoint from analysis sample

  Test of photon $CC\pi^0$ID shape
- Data lies within detector response error band

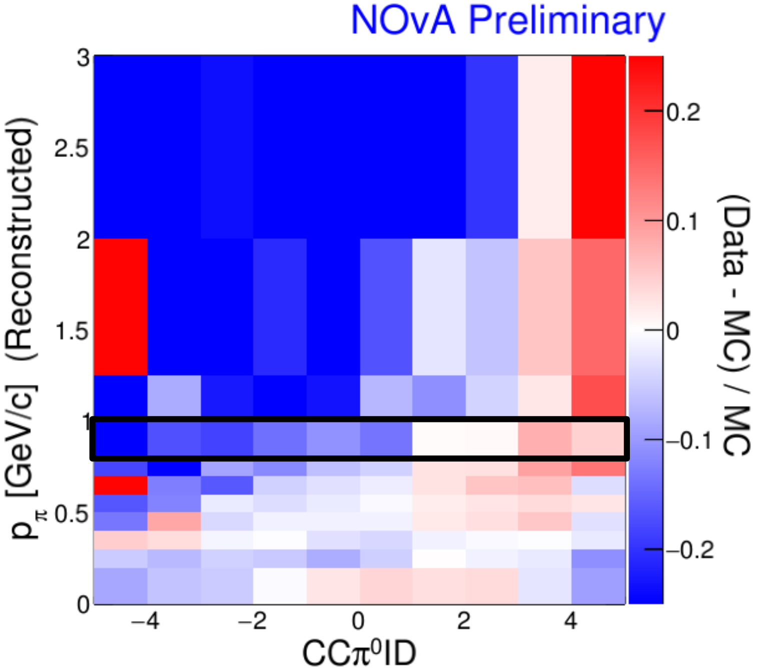
Fitting Data in Kinematic Bins

- Again rely on template fit to constrain signal estimate
- Compare data and simulated prediction for $CC\pi^0$ID in every kinematic bin

- Use observed data to adjust the simulated prediction
- Repeat process for each kinematic slice

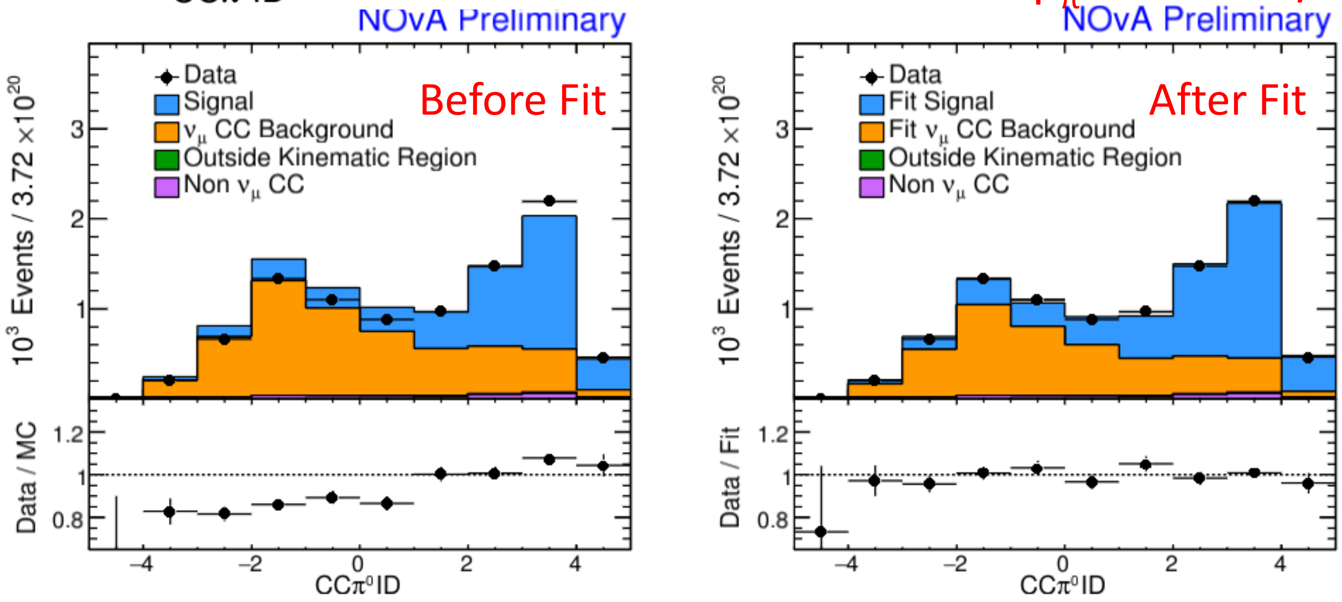


Estimating Signal

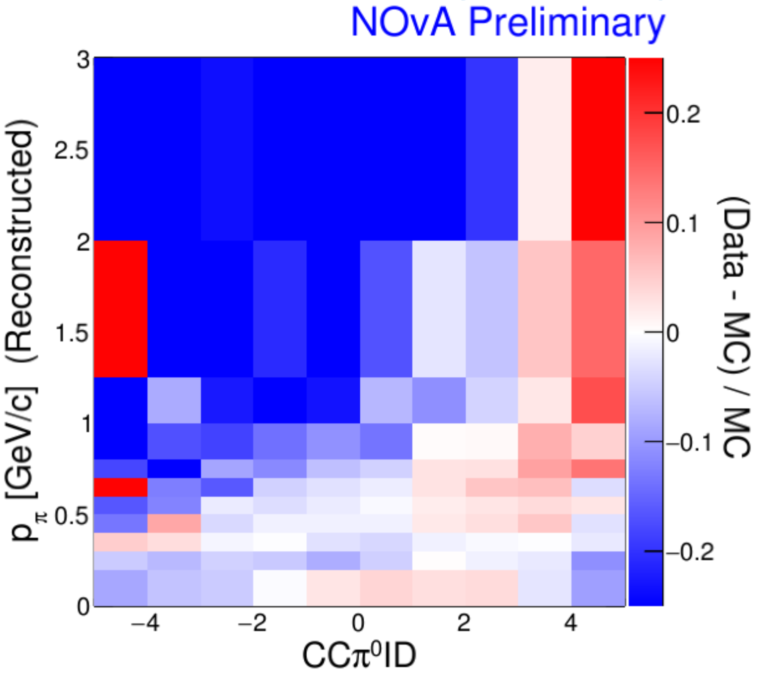


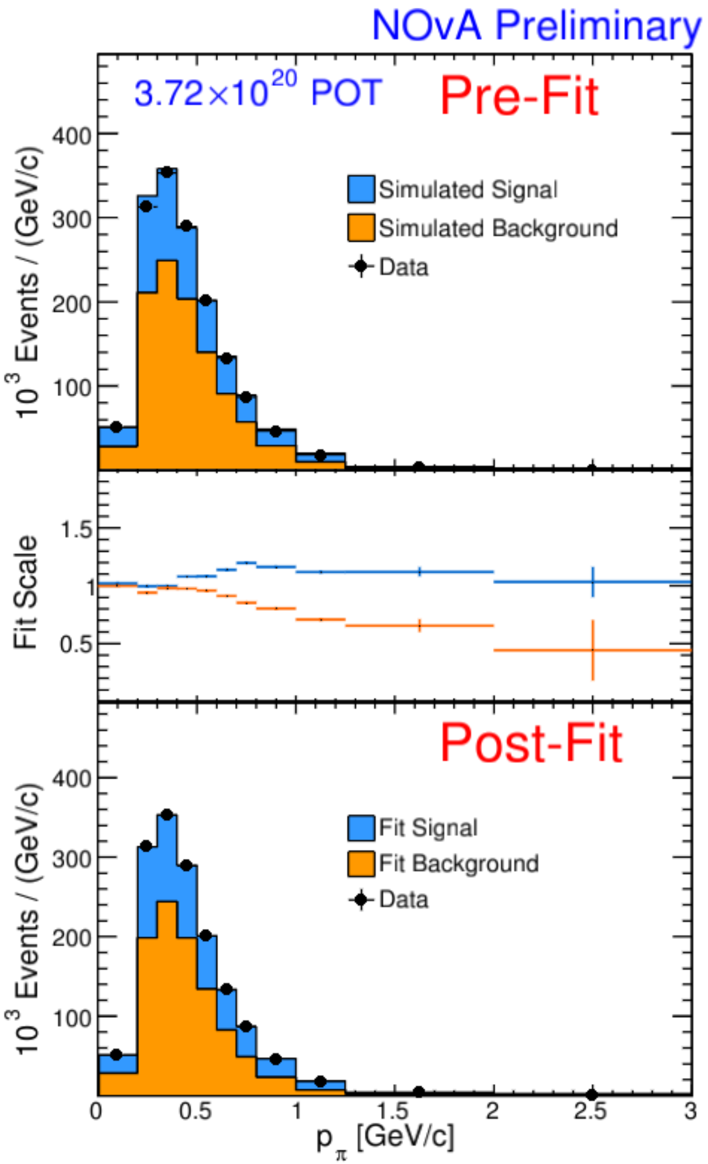
- Each $CC\pi^0ID$ template fit represents a slice in kinematic space
- Evident deficit at low PID and high p_π

$0.8 < p_\pi < 1.0$ GeV/c



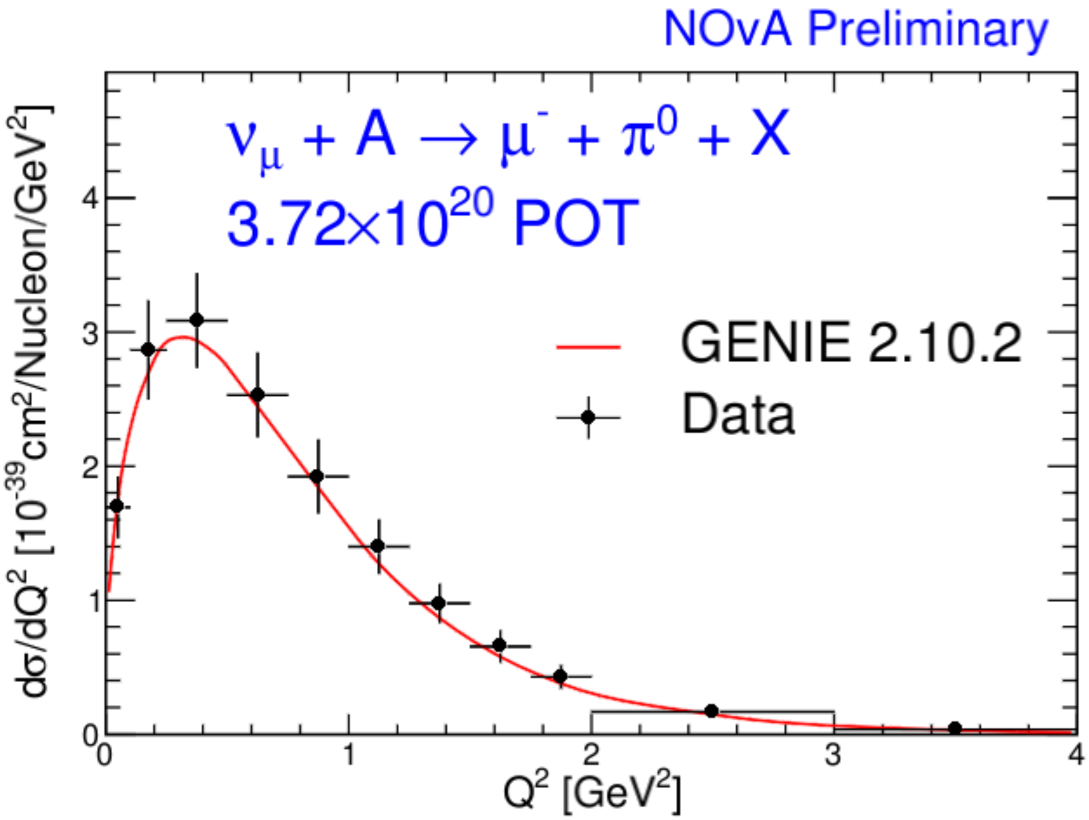
Estimating Signal





- Collect results of template fit in each kinematic bin
- Applying normalization constraints from these fits gives the fitted simulation

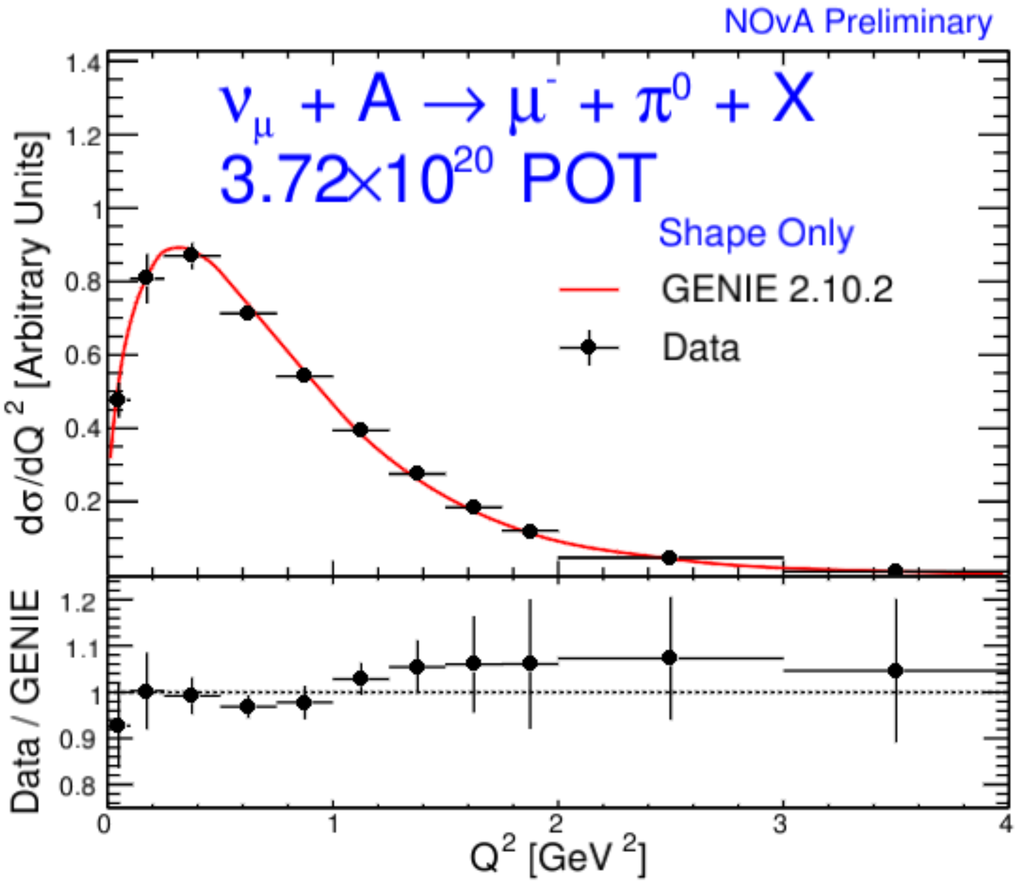
$d\sigma/dQ^2$



- Measured cross section 7% higher than GENIE prediction

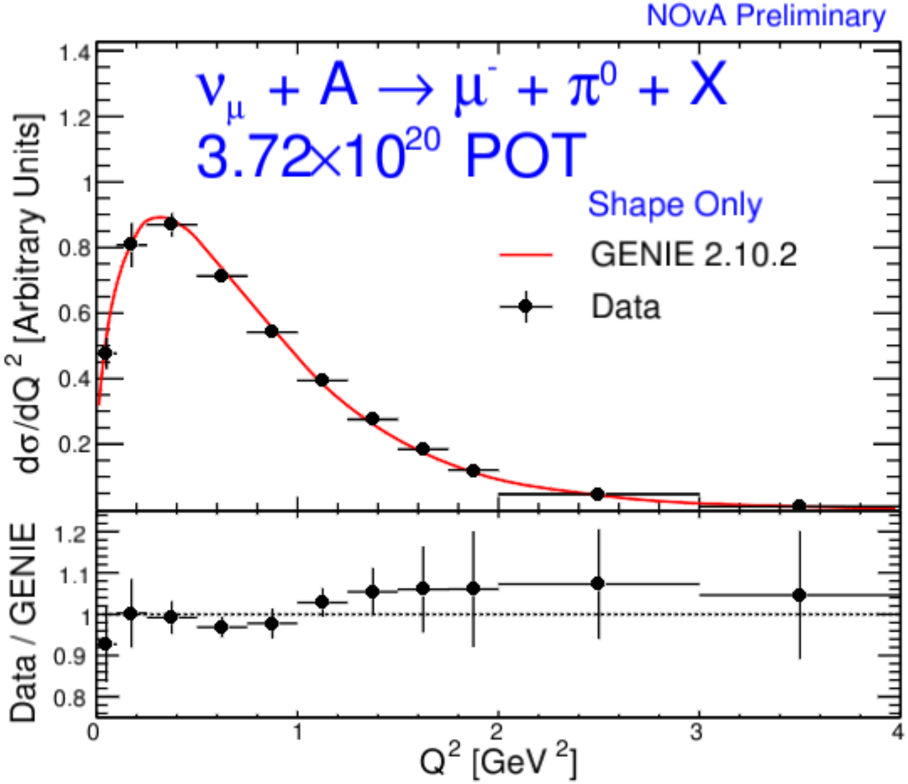
Reminder: $Q^2 = -q^2 = 2E_\nu\left(E_\mu - p_\mu\cos\theta_\mu\right) - m_n^2$

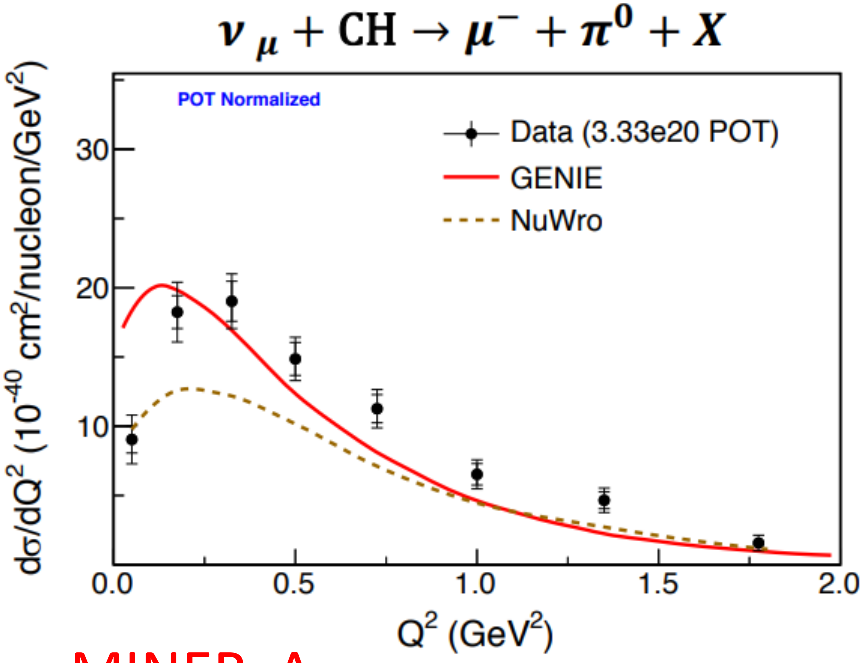
$d\sigma/dQ^2$



- Data suggests a slightly harder Q^2 shape than predicted by GENIE

$d\sigma/dQ^2$

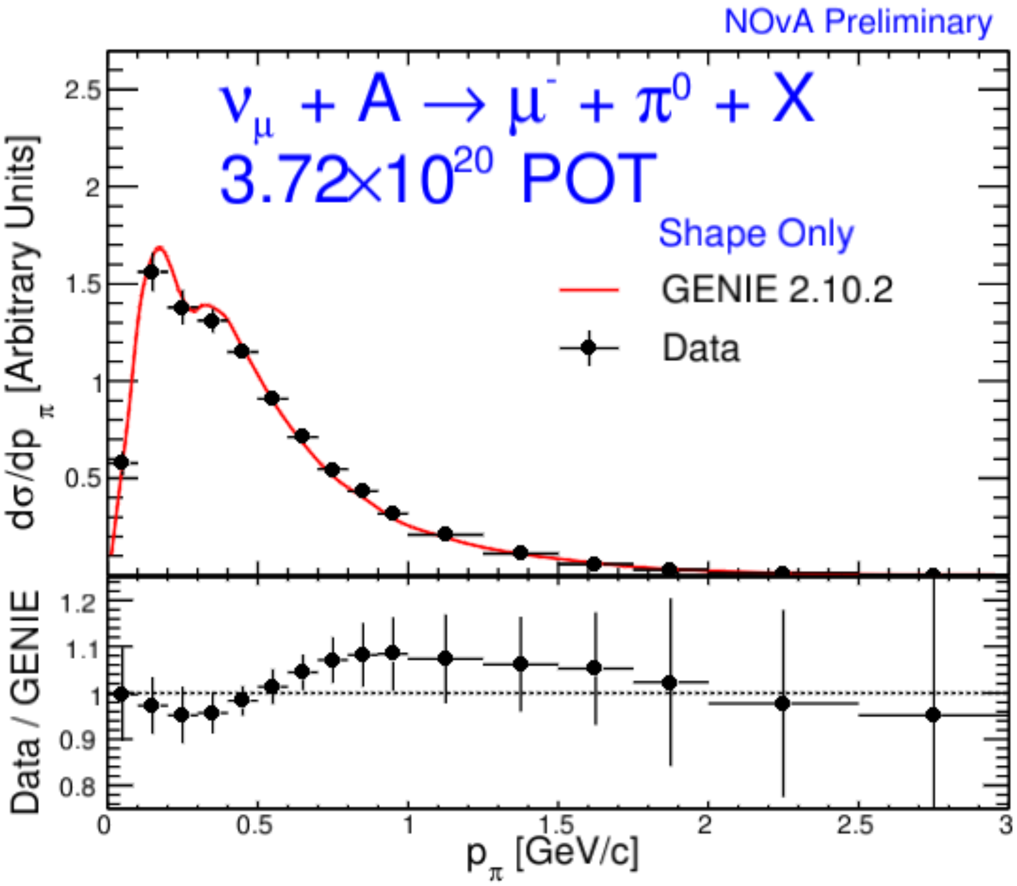




MINERvA,
Phys. Rev. D 96, 072003 (2017)

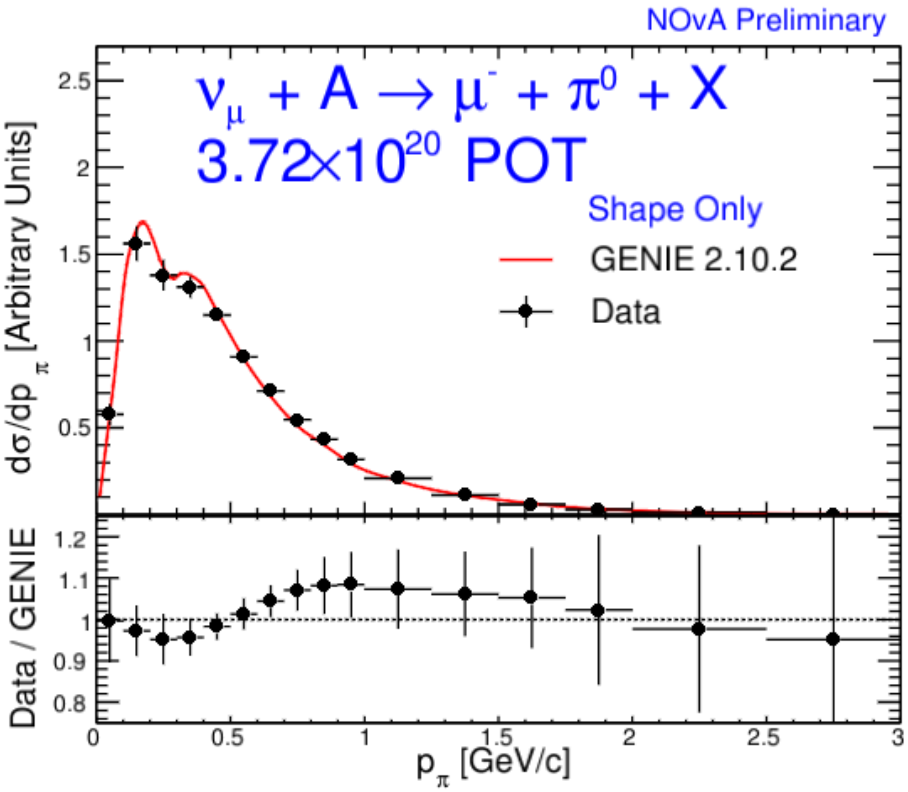
- Recent MINERvA data also tends to harder Q^2 than GENIE
- Significant differences between two analyses
  MINERvA beam peaks at roughly twice the NOvA beam peak
  MINERvA specifically targeted single-meson final states

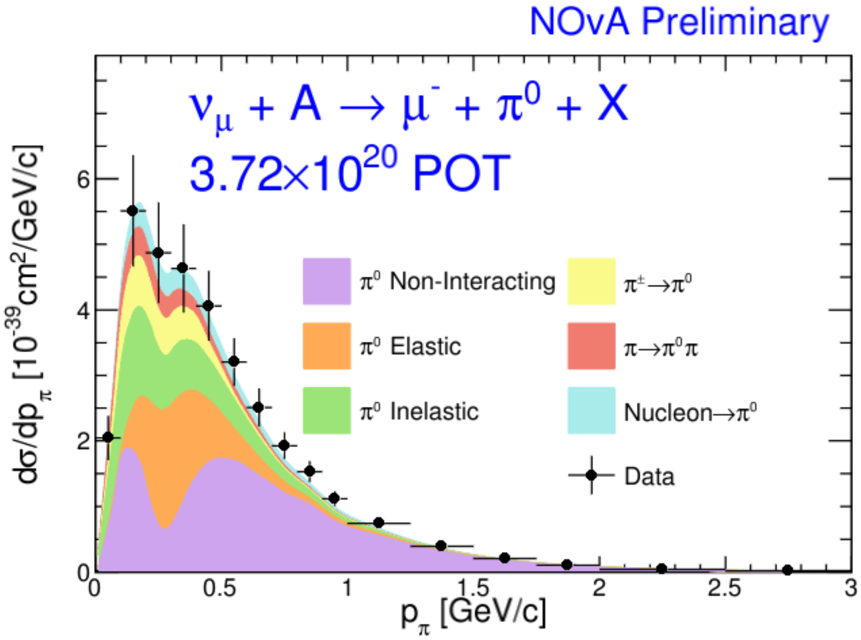
$d\sigma/dp_\pi$



- GENIE shape prediction lightly overpredicts around 0.3 GeV/c
- A general move towards to slightly harder p_π spectrum

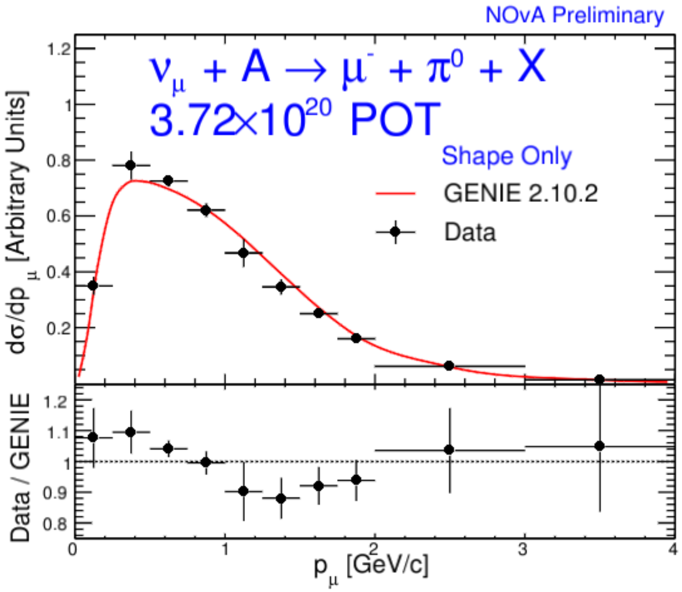
$d\sigma/dp_\pi$

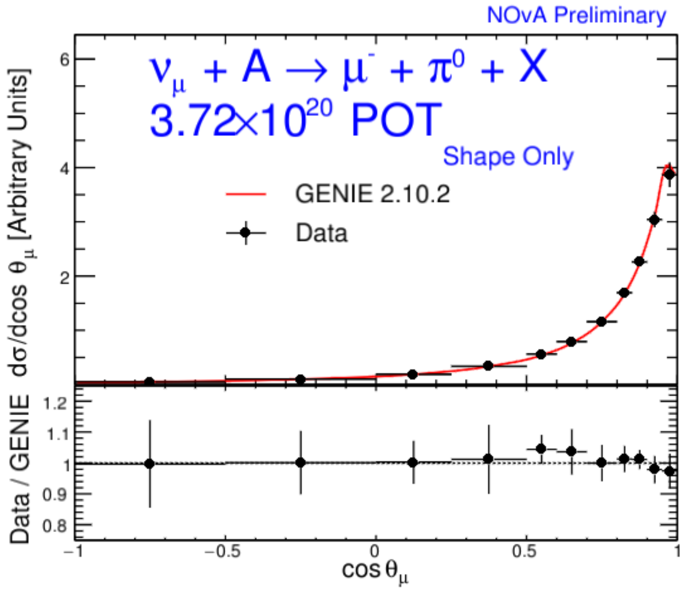


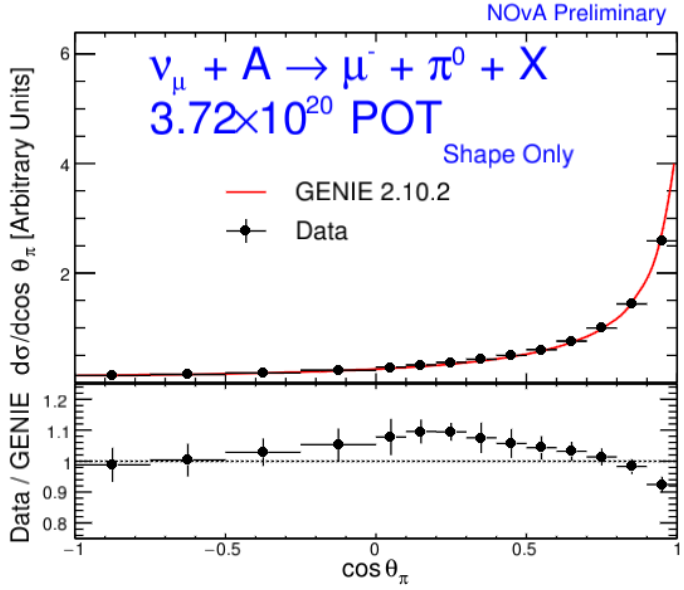


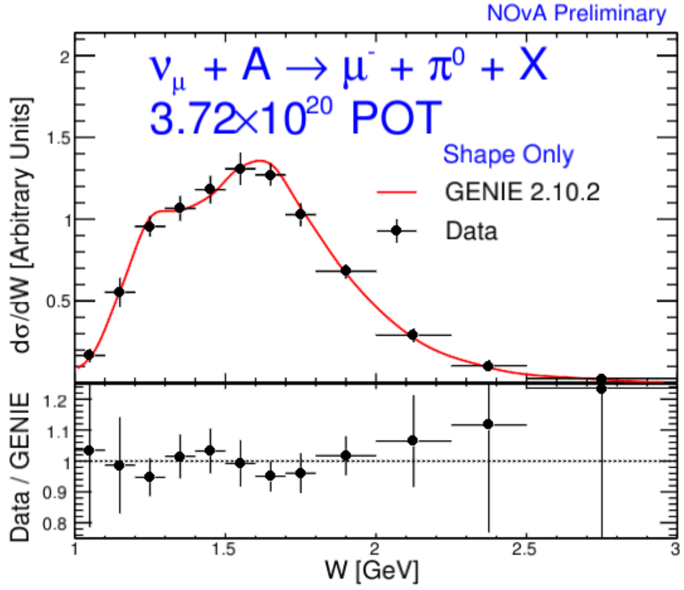
- Result consistent with GENIE FSI modeling
- Data confirms dip at πp→Δ resonance

Other Results



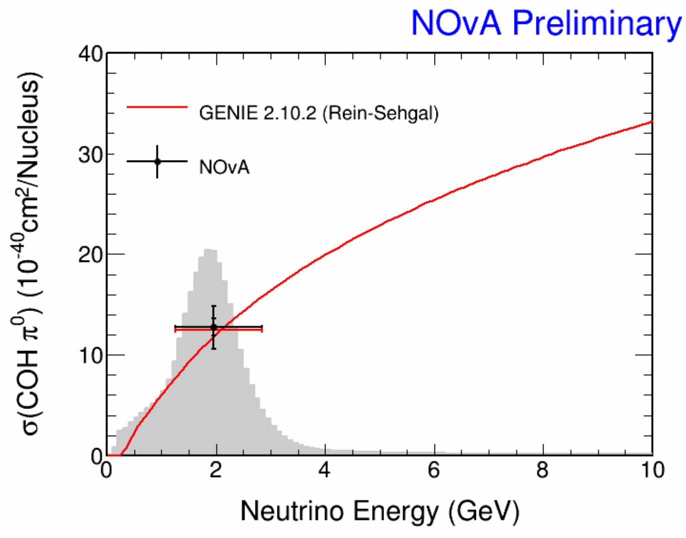


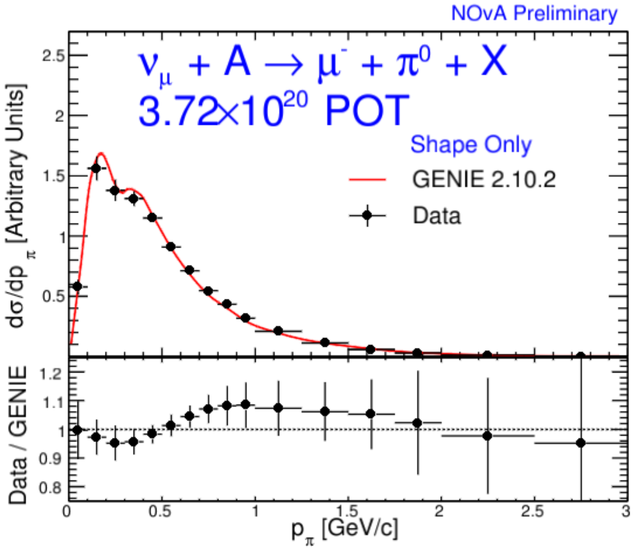




Summary

- Measurement of NCπ^0 coherent total cross section
  14.0± 0.9±2.1×10^{-40}cm^2/Nucleus, consistent with GENIE
- Differential cross sections for ν_μ CC+π^0 semi-inclusive
  See a 7% increase in total cross section relative to GENIE
  Generally consistent with GENIE interaction and FSI models
  Evidence for slightly harder Q^2 and p_π distributions
- Both analyses working towards publication





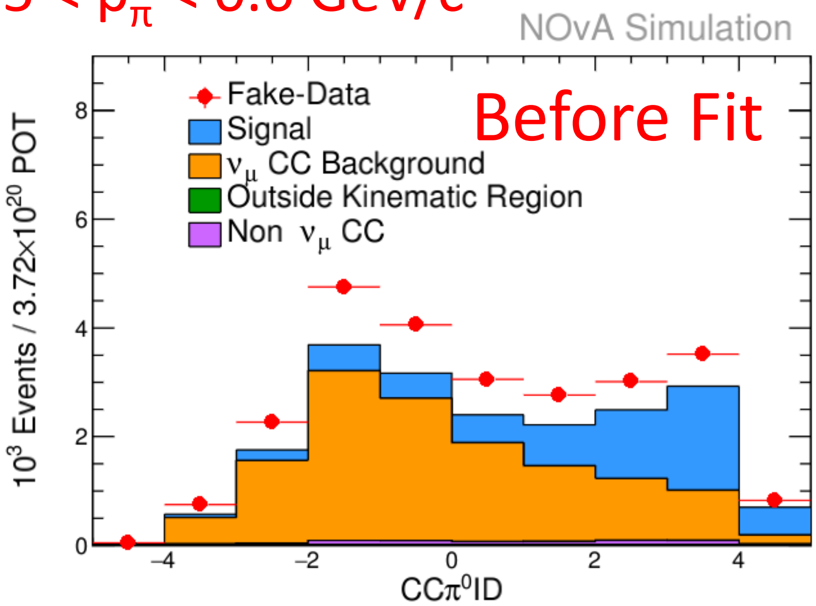
Fermilab
Fermilab
Fermilab
Fermilab
AISLE 1
AISLE 2
NORMAN F. RAMSEY
AUDITORIUM

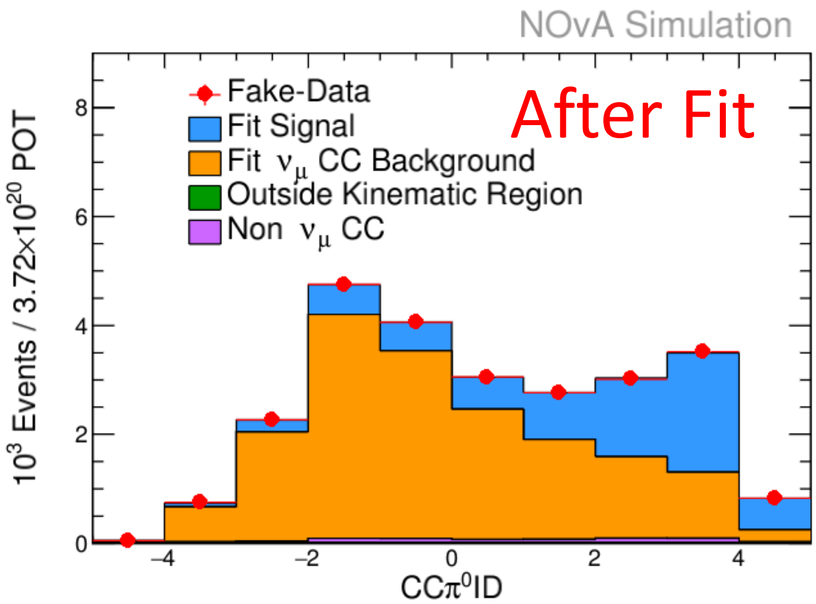
Thank You!

Backup

Validating Simulation Constraint:

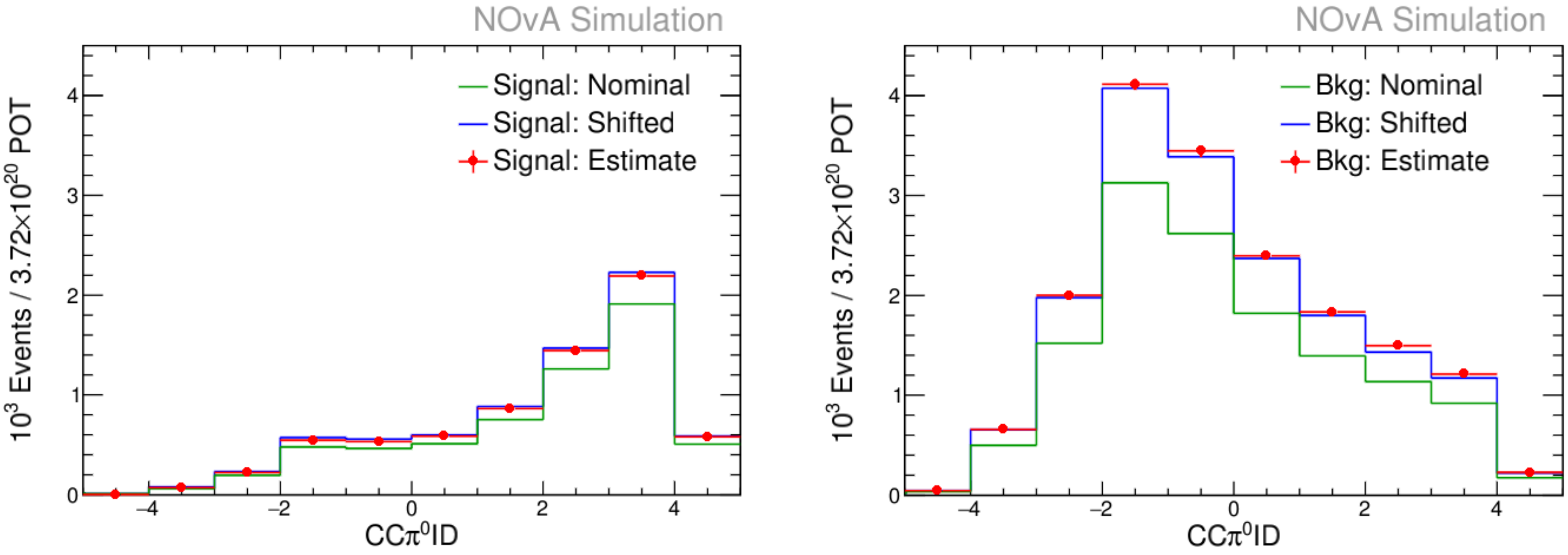
Example kinematic bin:
$0.5 < p_\pi < 0.6$ GeV/c





- Template fit adjusts simulation in response to the fake-data
- After the fit, total adjusted simulation agrees with fake-data

Validating Simulation Constraint:



- Use fake-data to adjust the simulation according to a template fit, yielding an estimate for signal background close to true fake-data simulation
- This fake-data study confirms the template method faithfully determines the correct signal (right) and background (left) normalizations

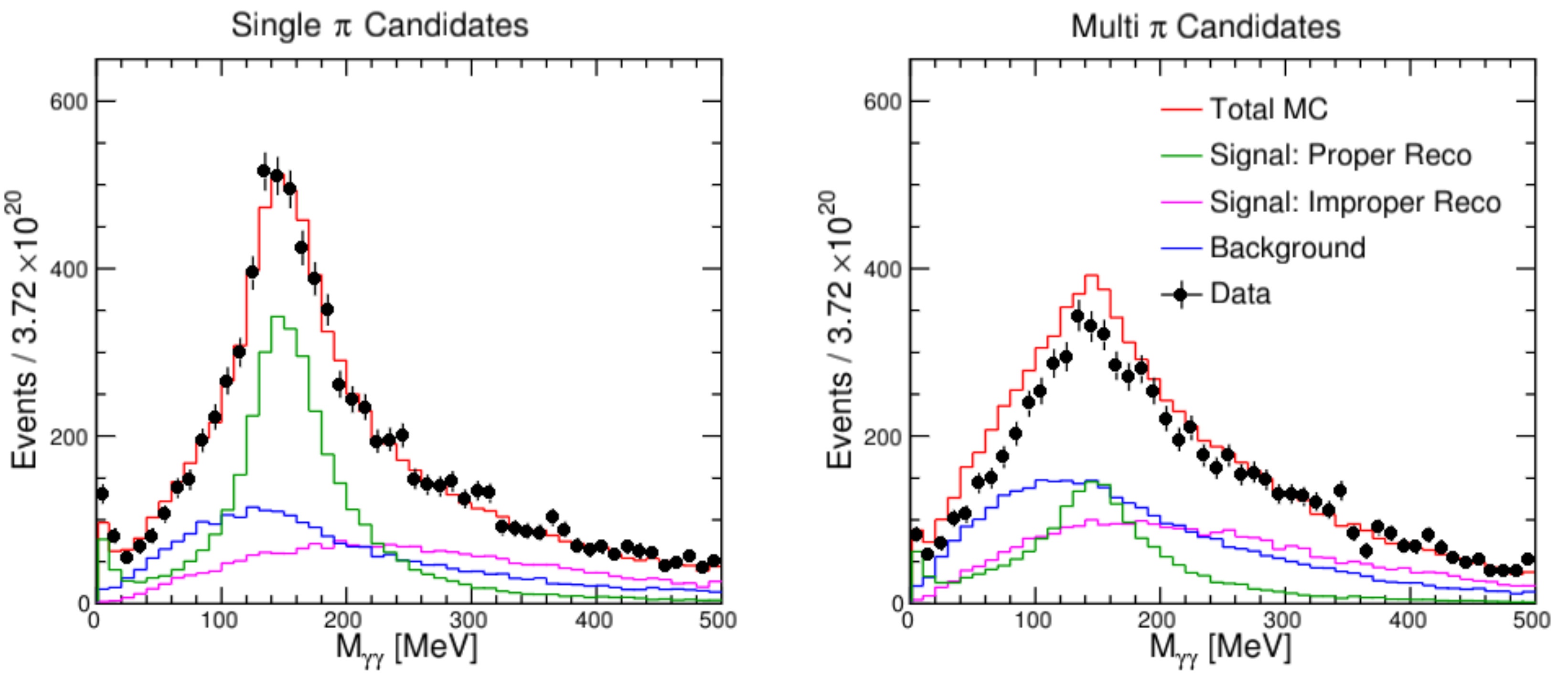
Reconstructing π^0's in Multi-π Events

- Combinatorics of non-photon prongs degrade multi-π reco

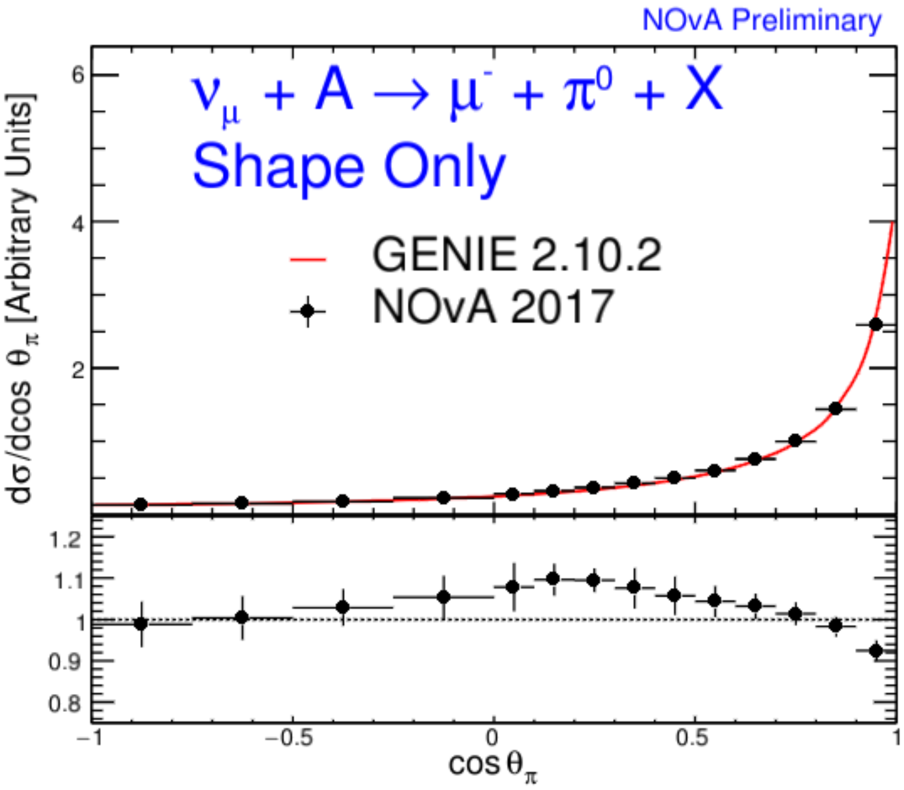
  Makes reconstructed π^0 mass less meaningful

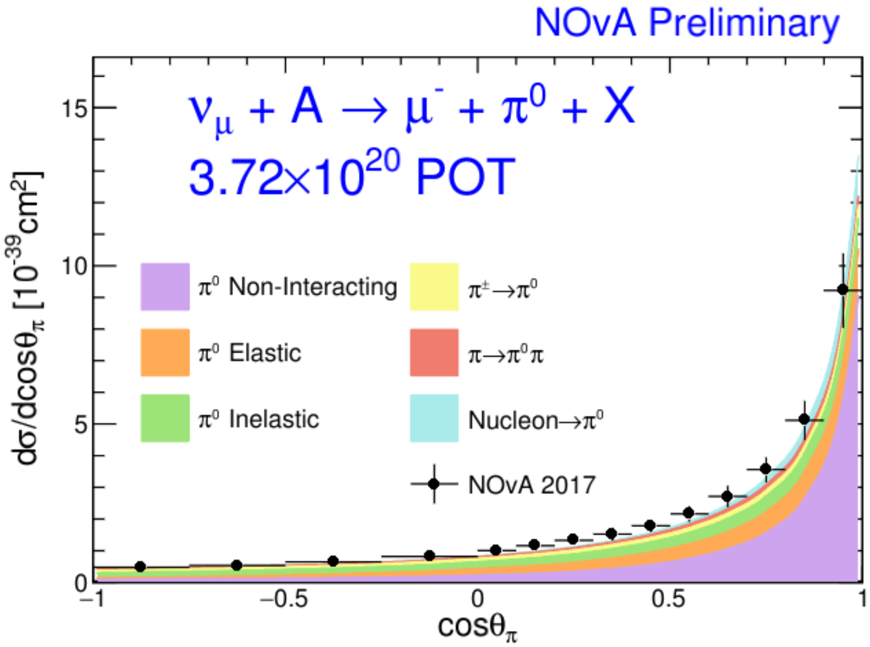
  Biases sample to single-π events

- Can still select a single photon from these events

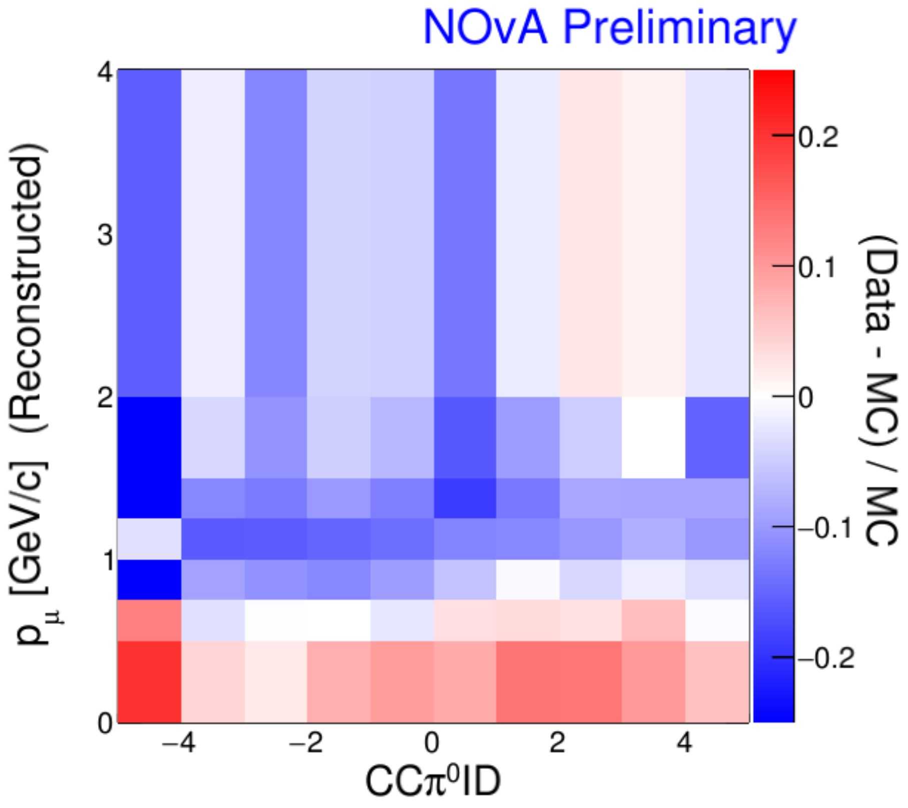


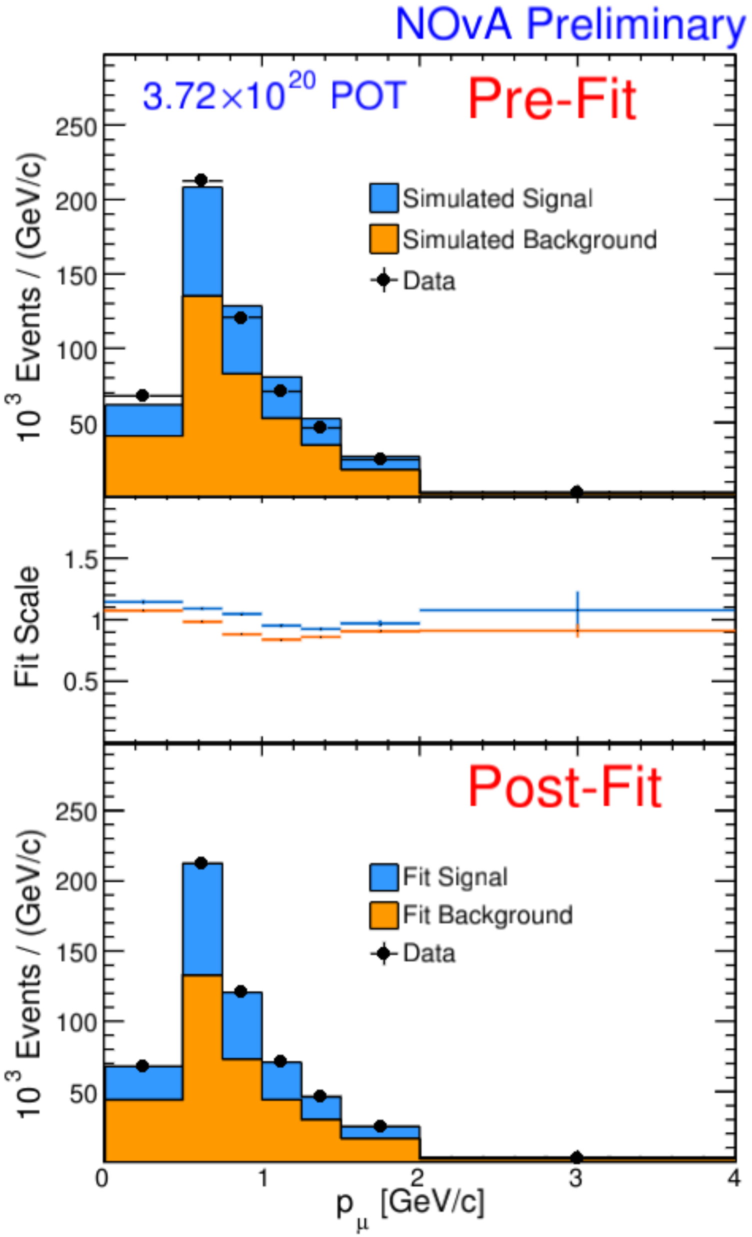
FSI Comparison: $d\sigma/d\cos\theta_\pi$



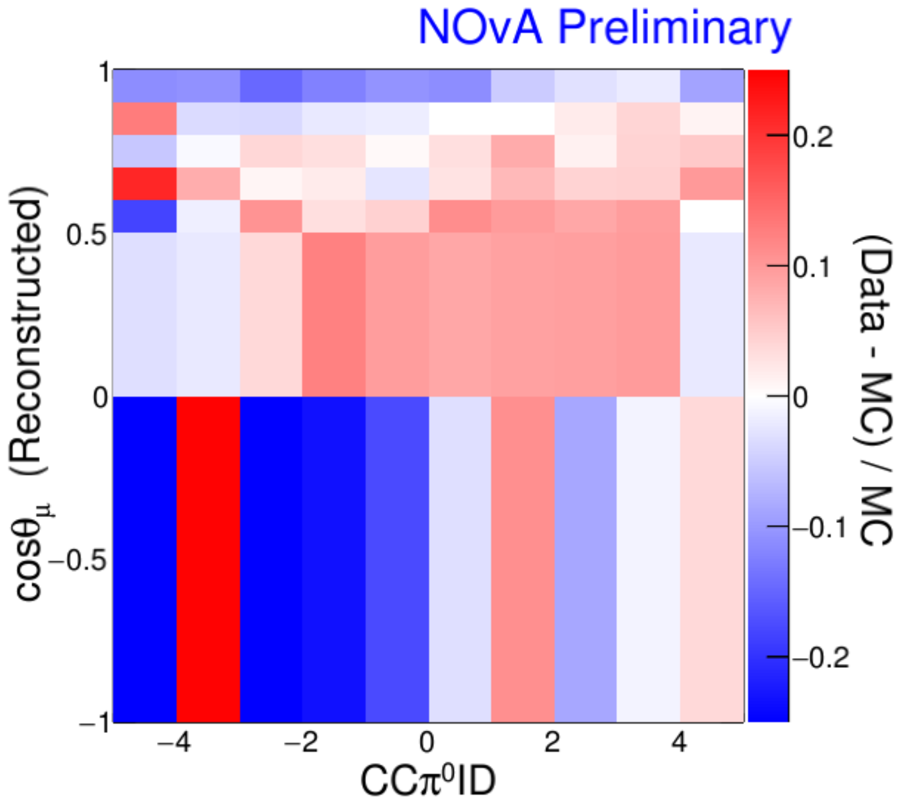


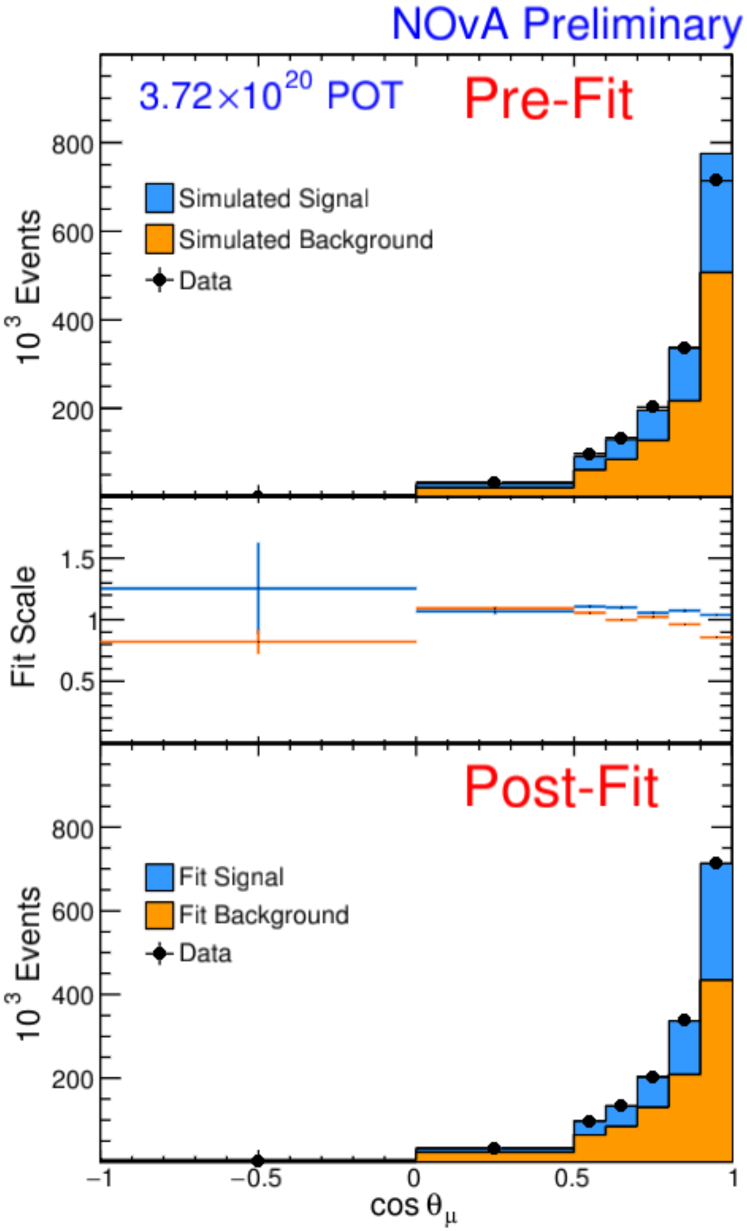
Estimating Signal



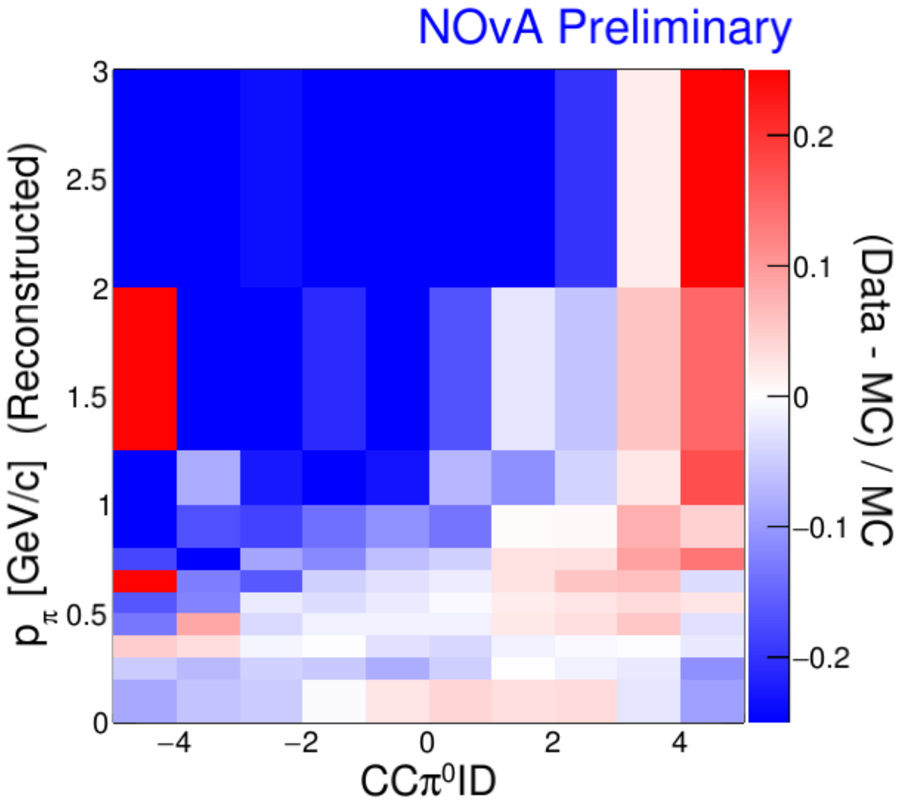


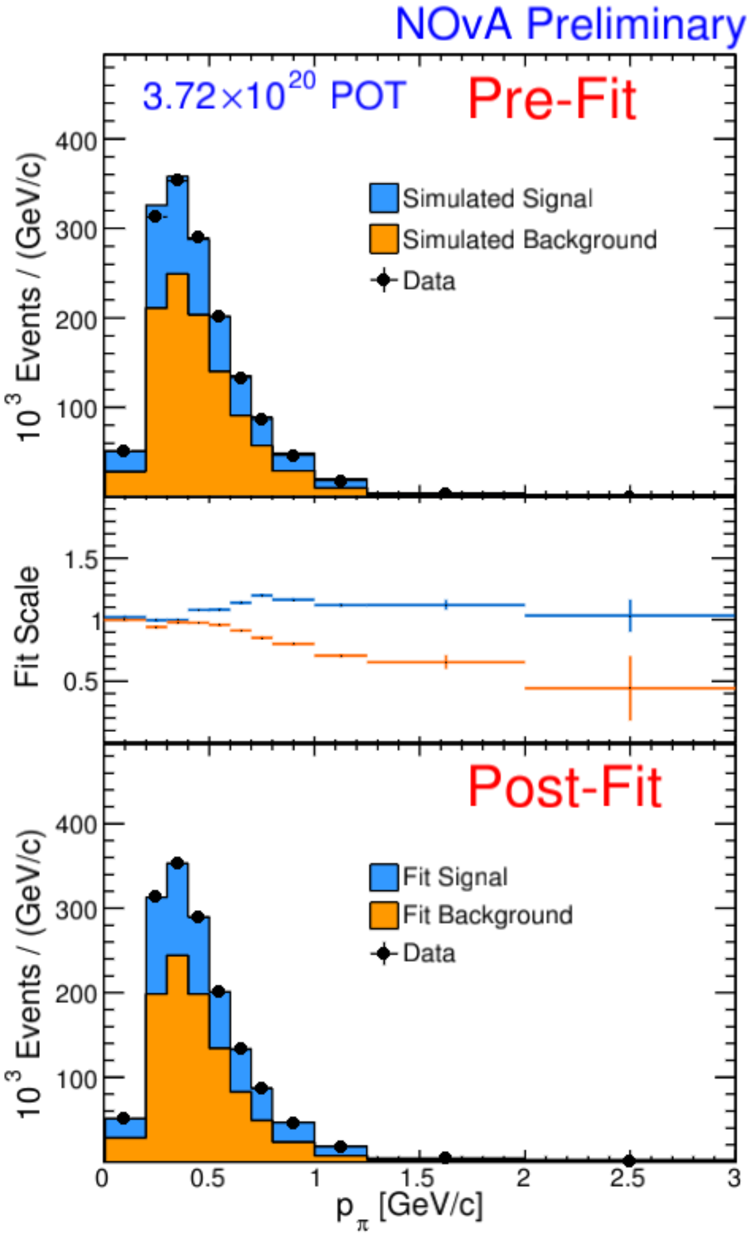
Estimating Signal



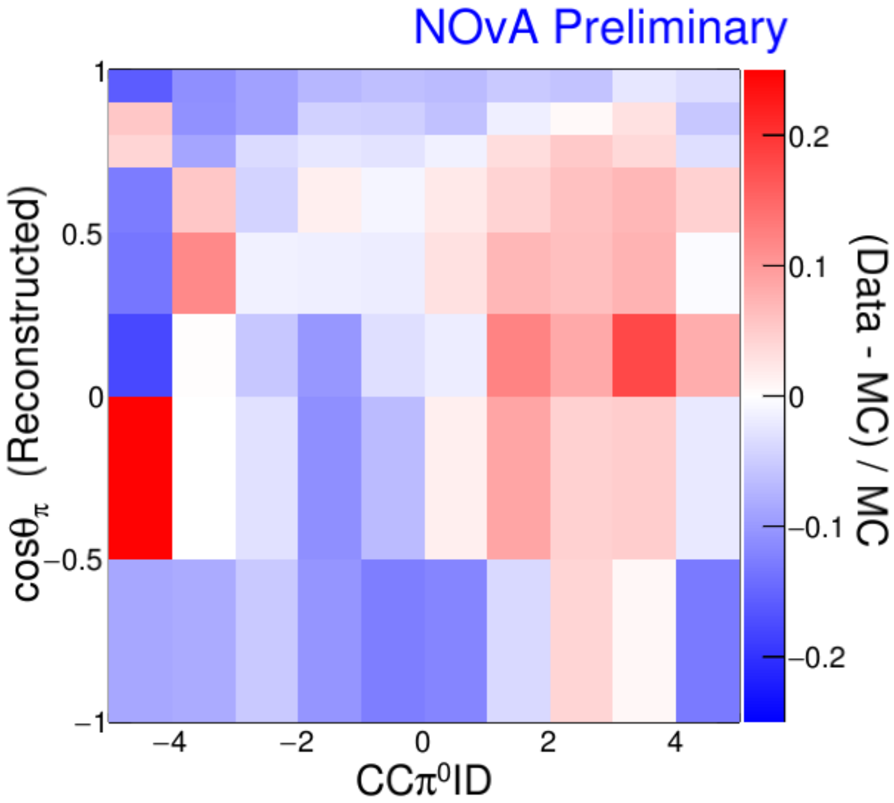


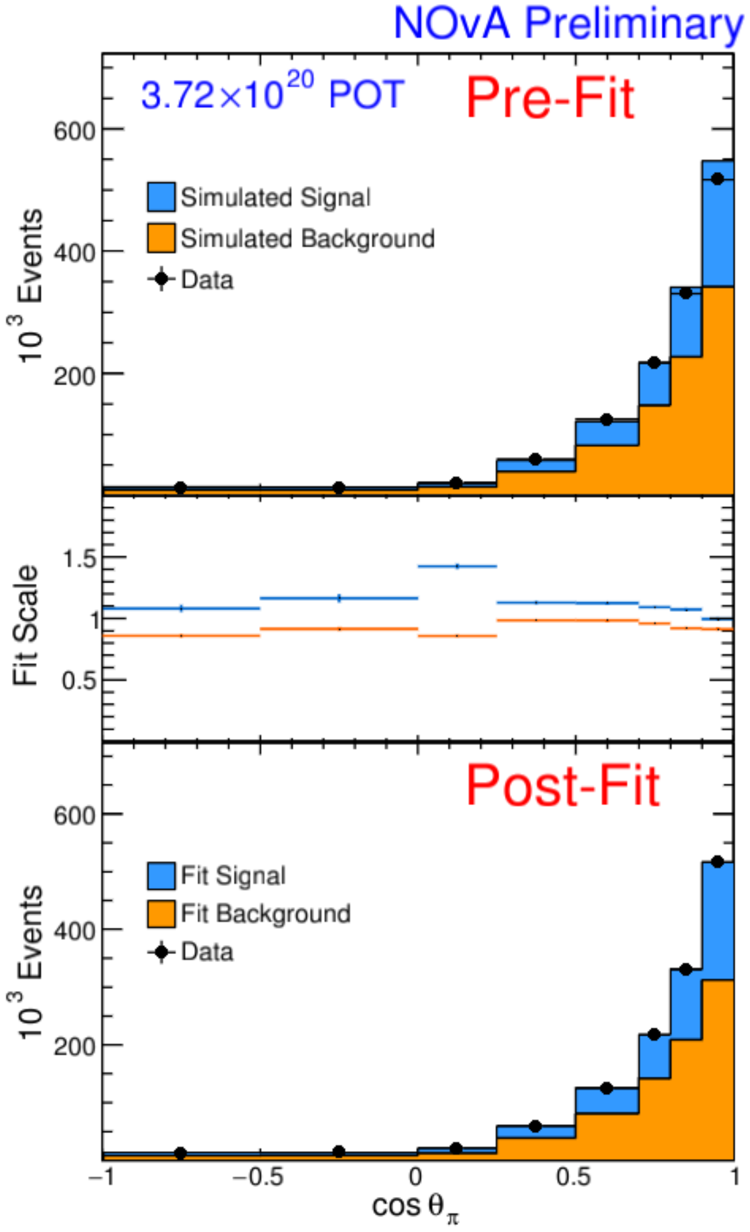
Estimating Signal



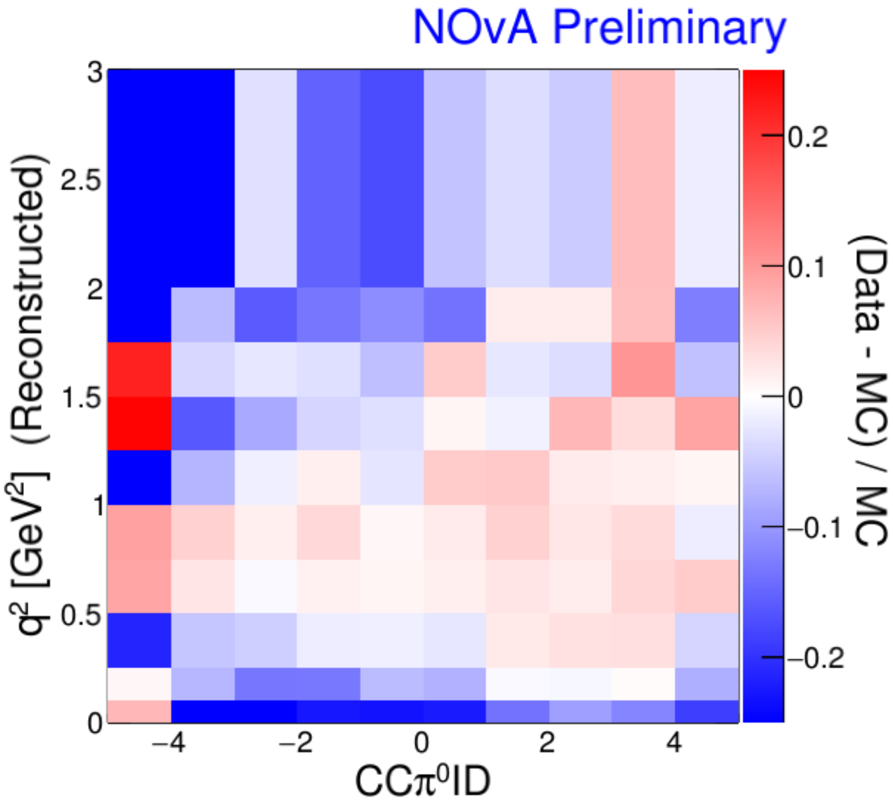


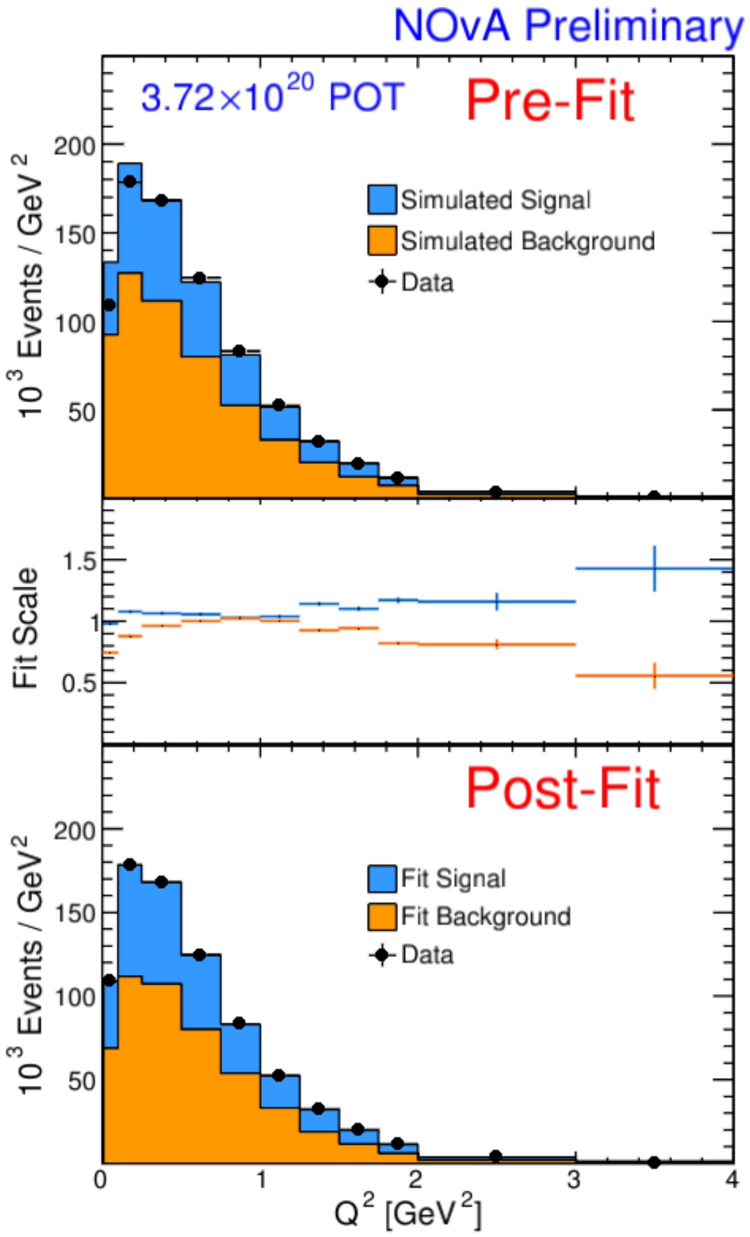
Estimating Signal



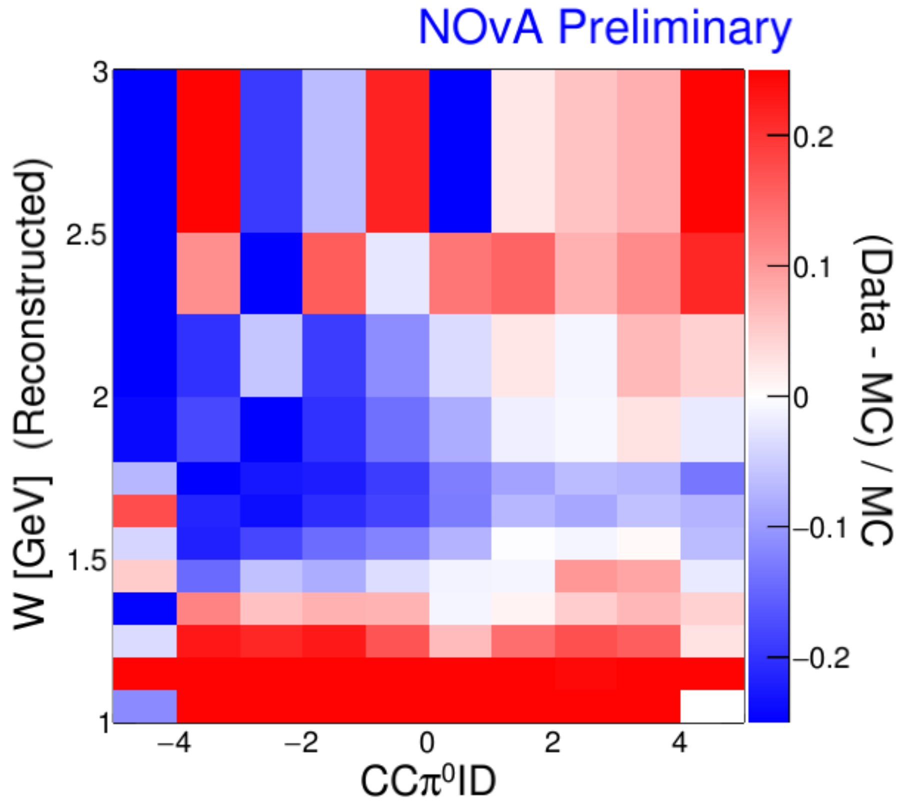


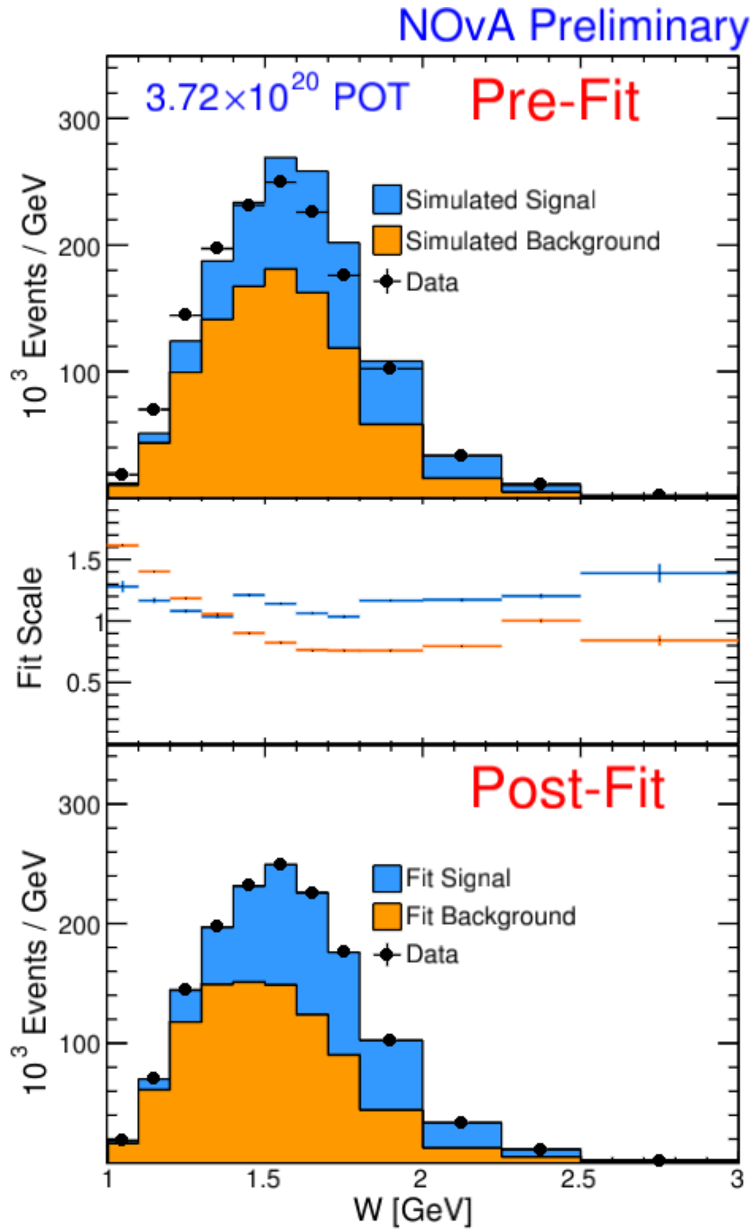
Estimating Signal





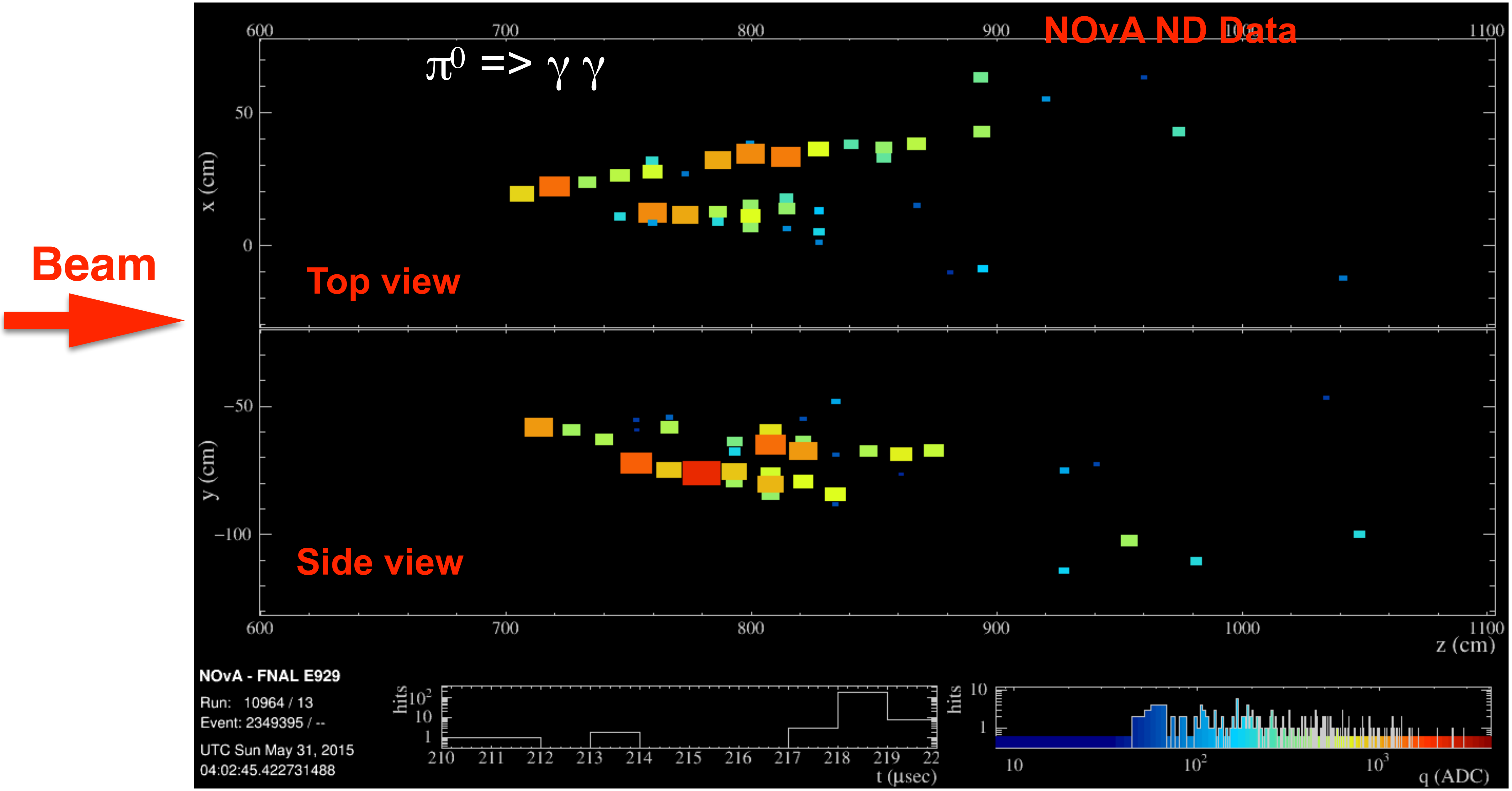
Estimating Signal





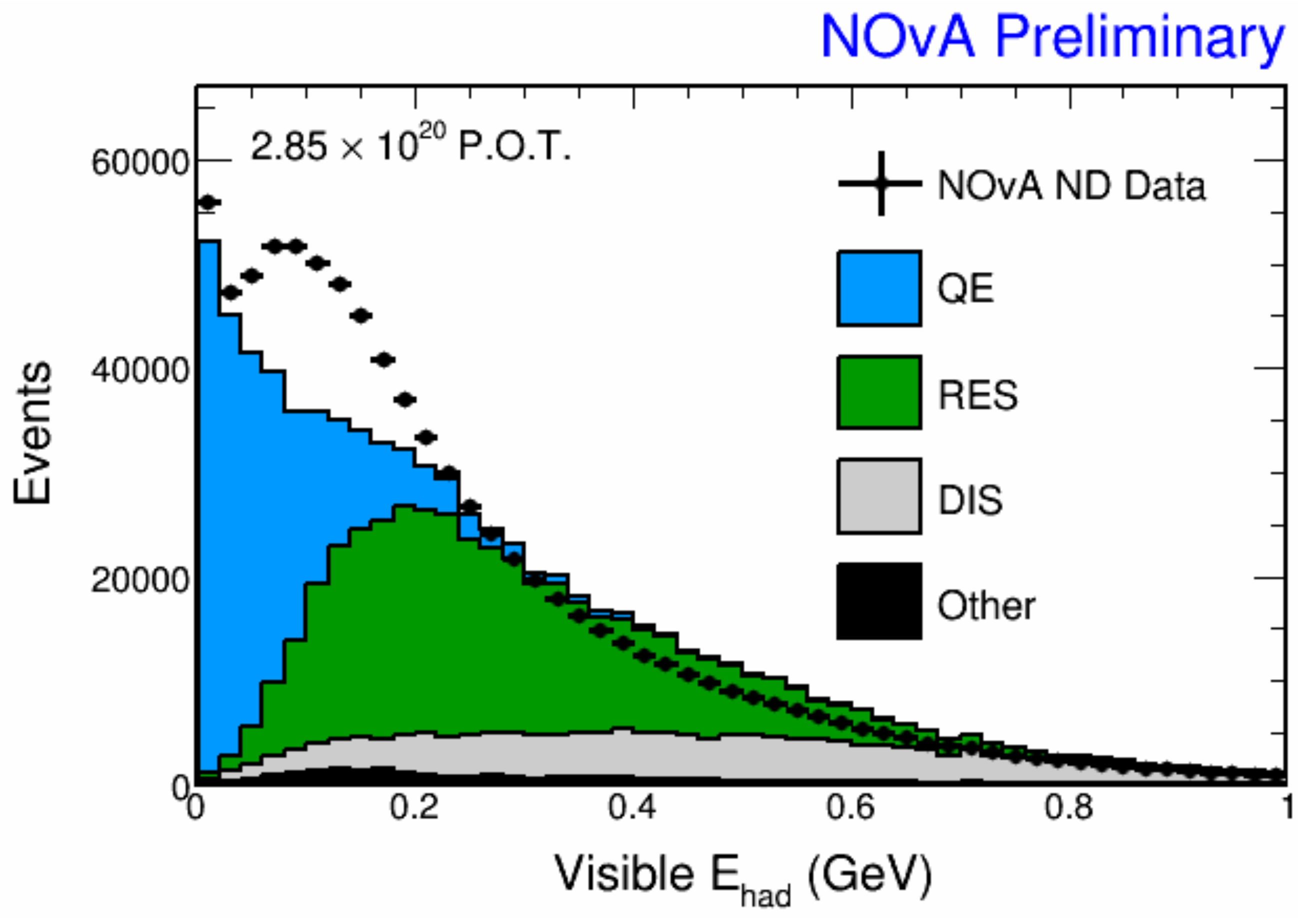
Back up slides

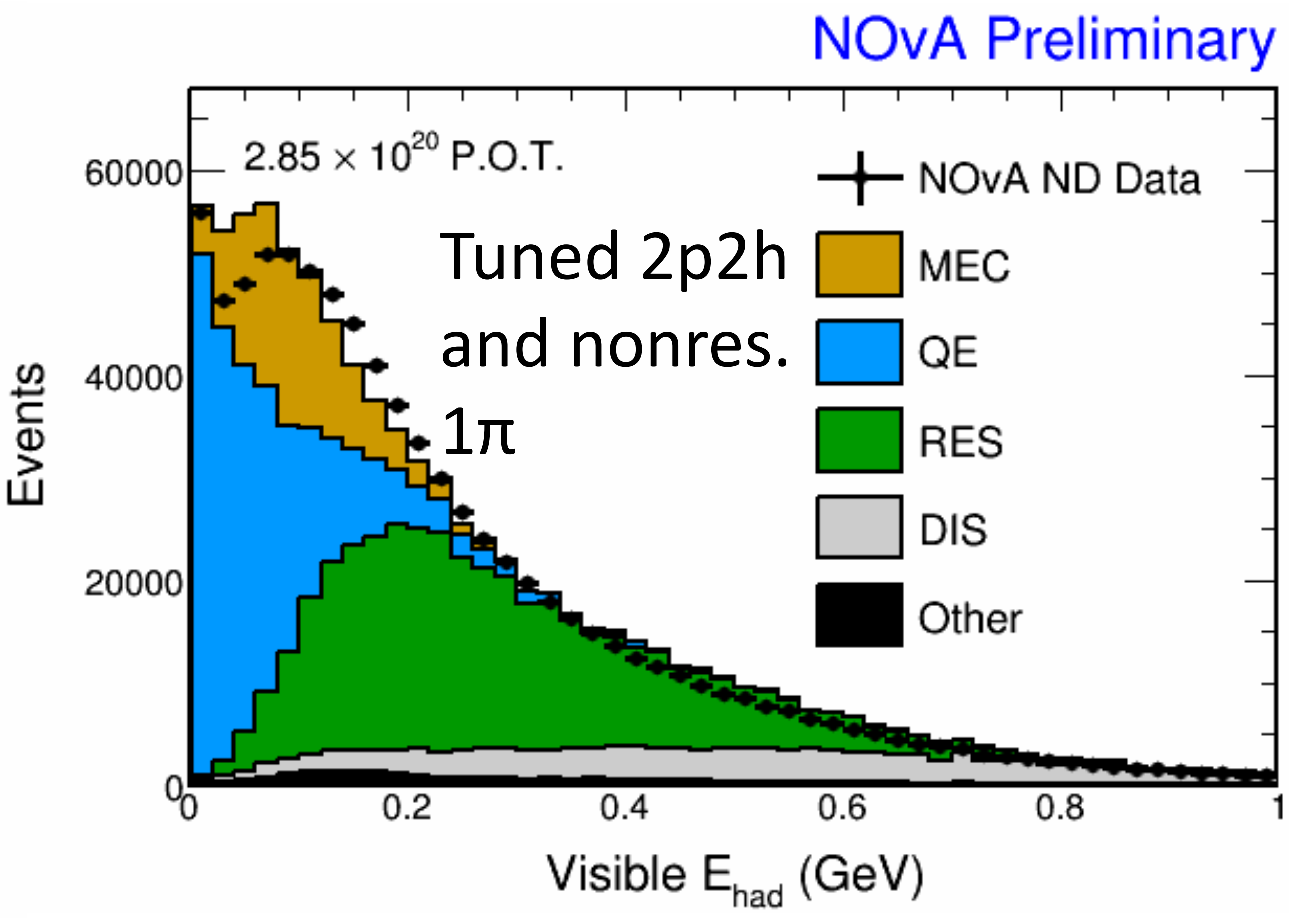
Coherent π^0 in The NOvA ND



- Single forward going pi0 decay into 2 photons.
- π^0s can be measured by reconstructing one or both photons from π^0 decay.

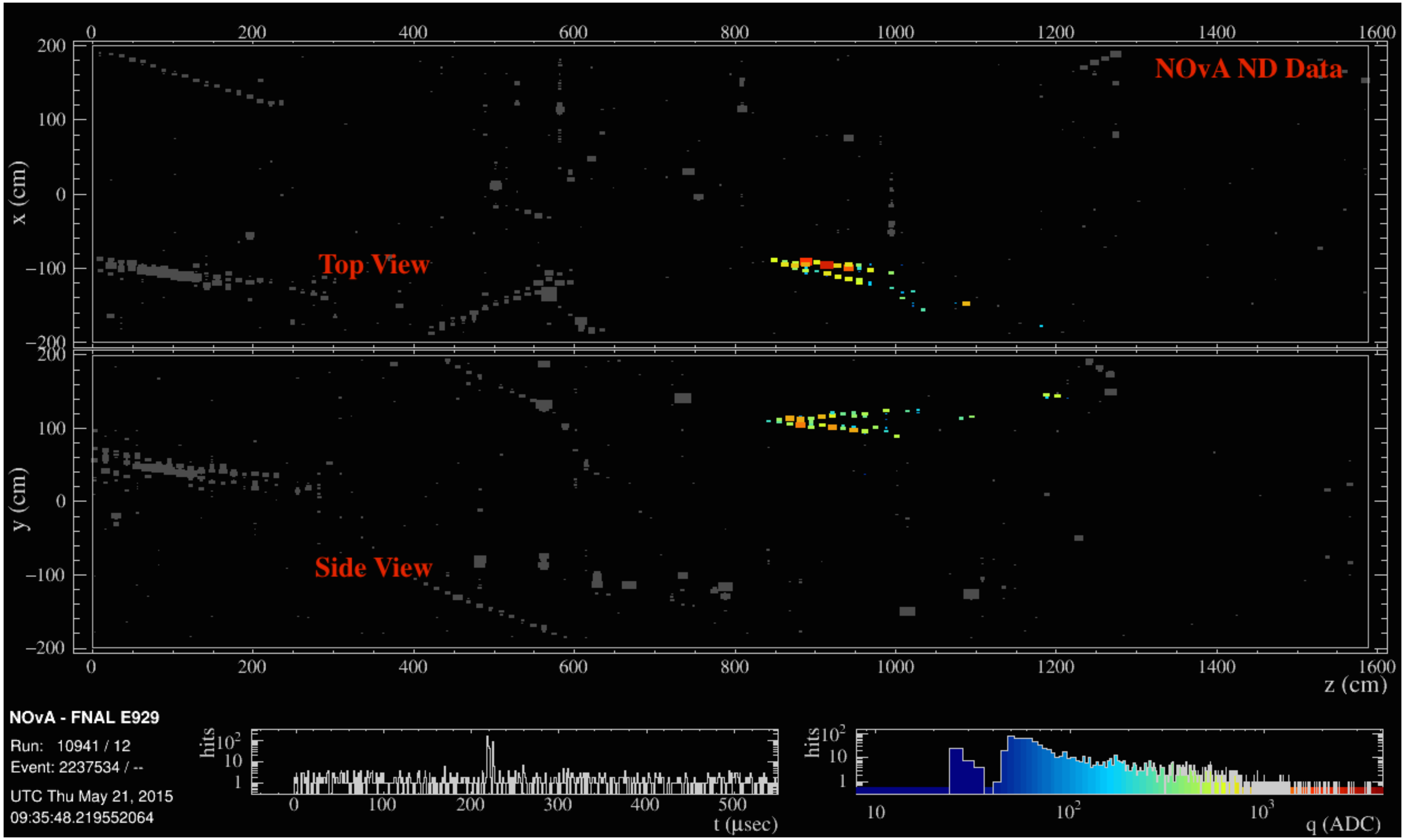
MC Tuning




Tuned 2p2h and nonres. 1π

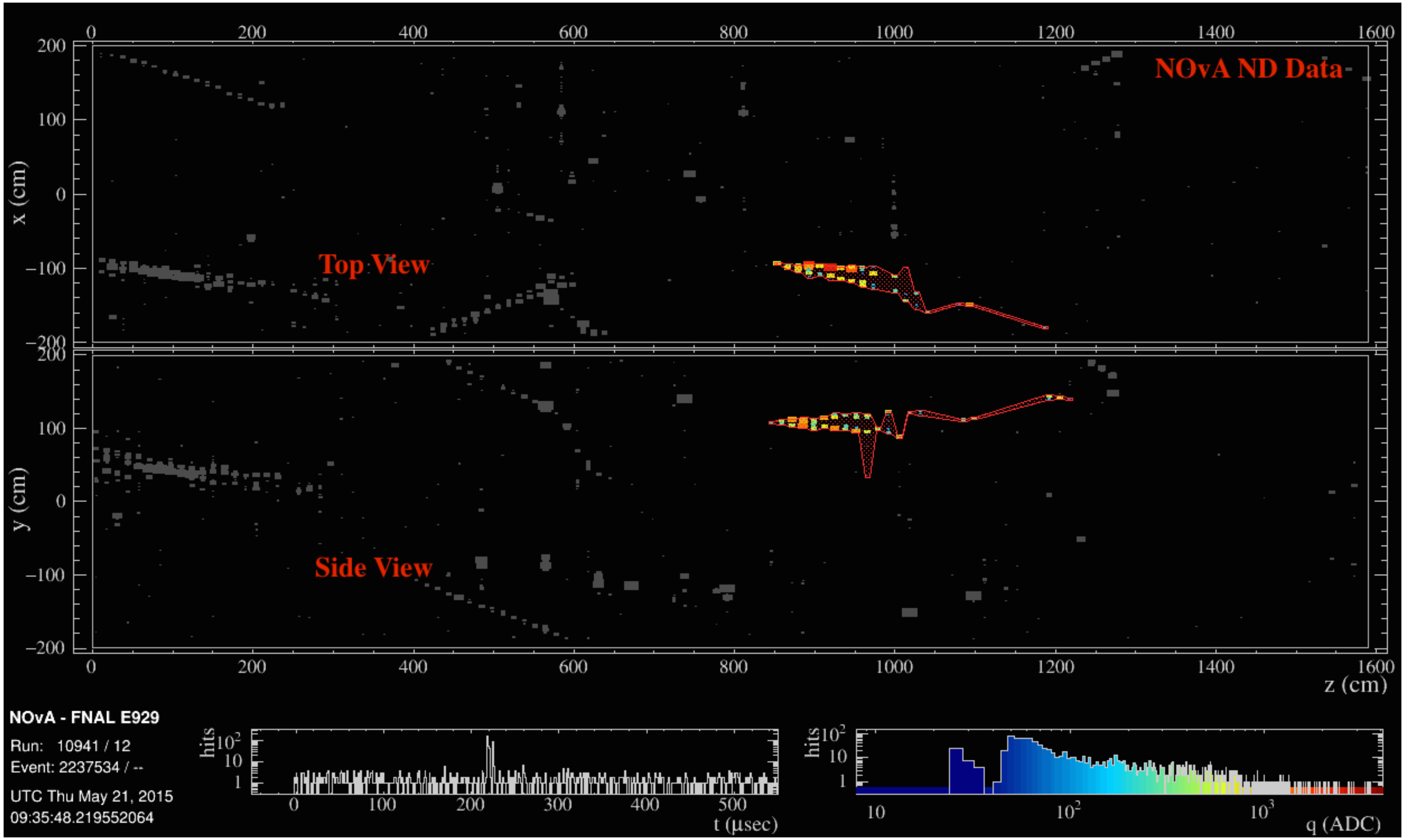
- Re-weight GENIE’s empirical Meson Exchange Current (MEC) model to match the observed event excess.
- Reduce non-resonance pion production by 50%.

Coherent π^0 Candidate in the NOvA ND



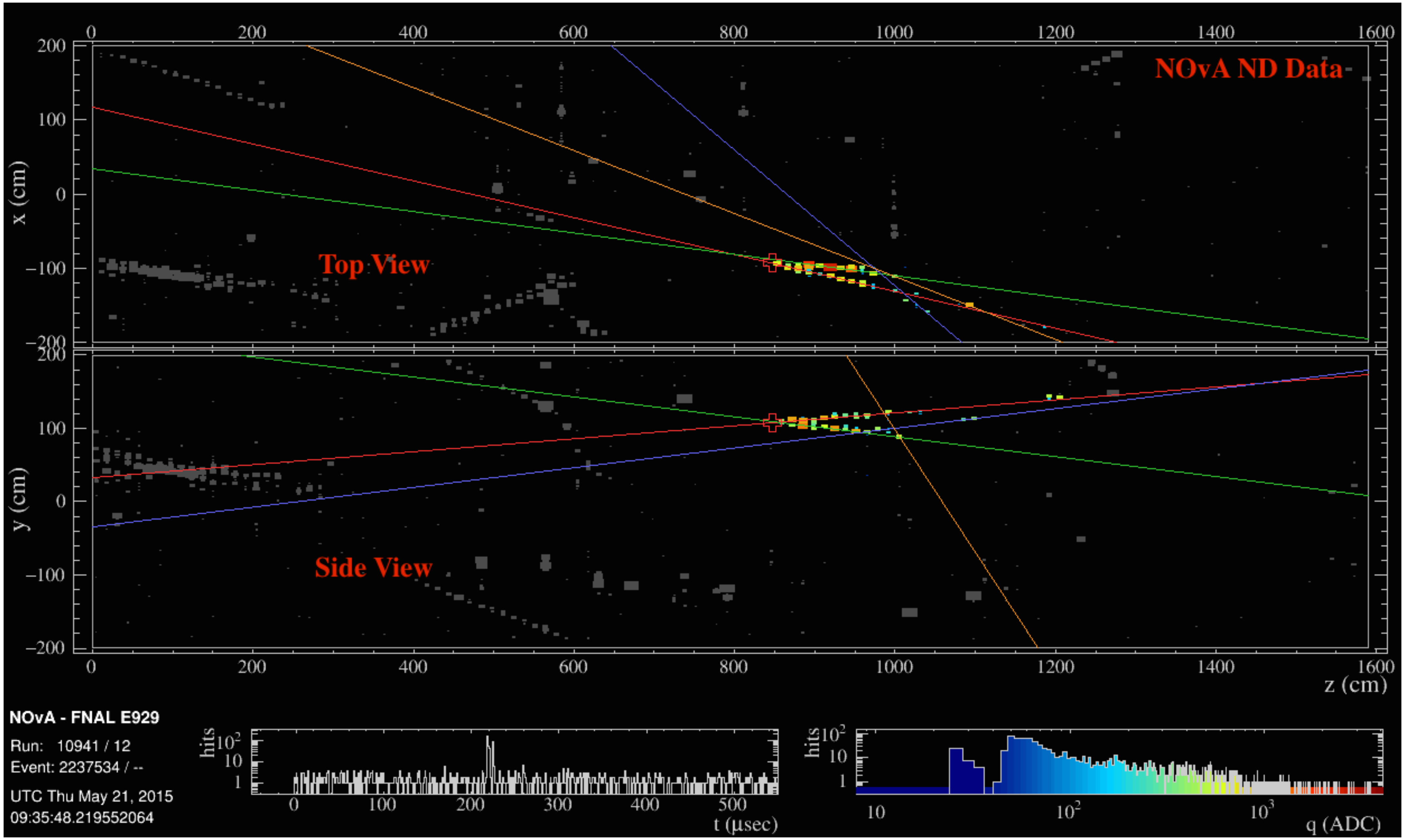
A coherent π^0 candidate events with 2 photons from π^0 decay.

Reconstruction: Slicing



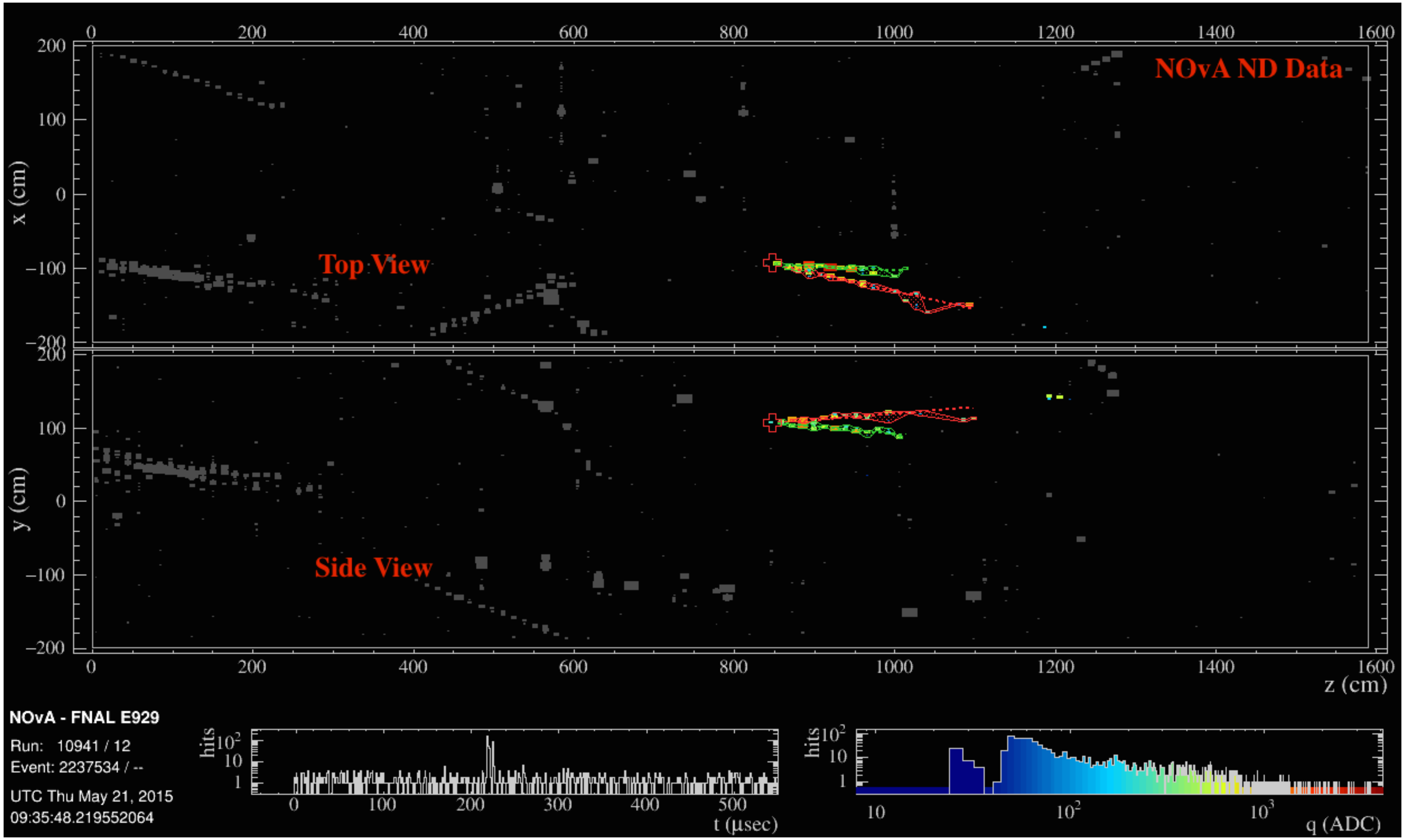
Group hits together in time and space for each neutrino interaction event.

Reconstruction: Vertexing



Find lines of energy depositions with Hough transform, and use the intersection to form vertex

Reconstruction: Clustering

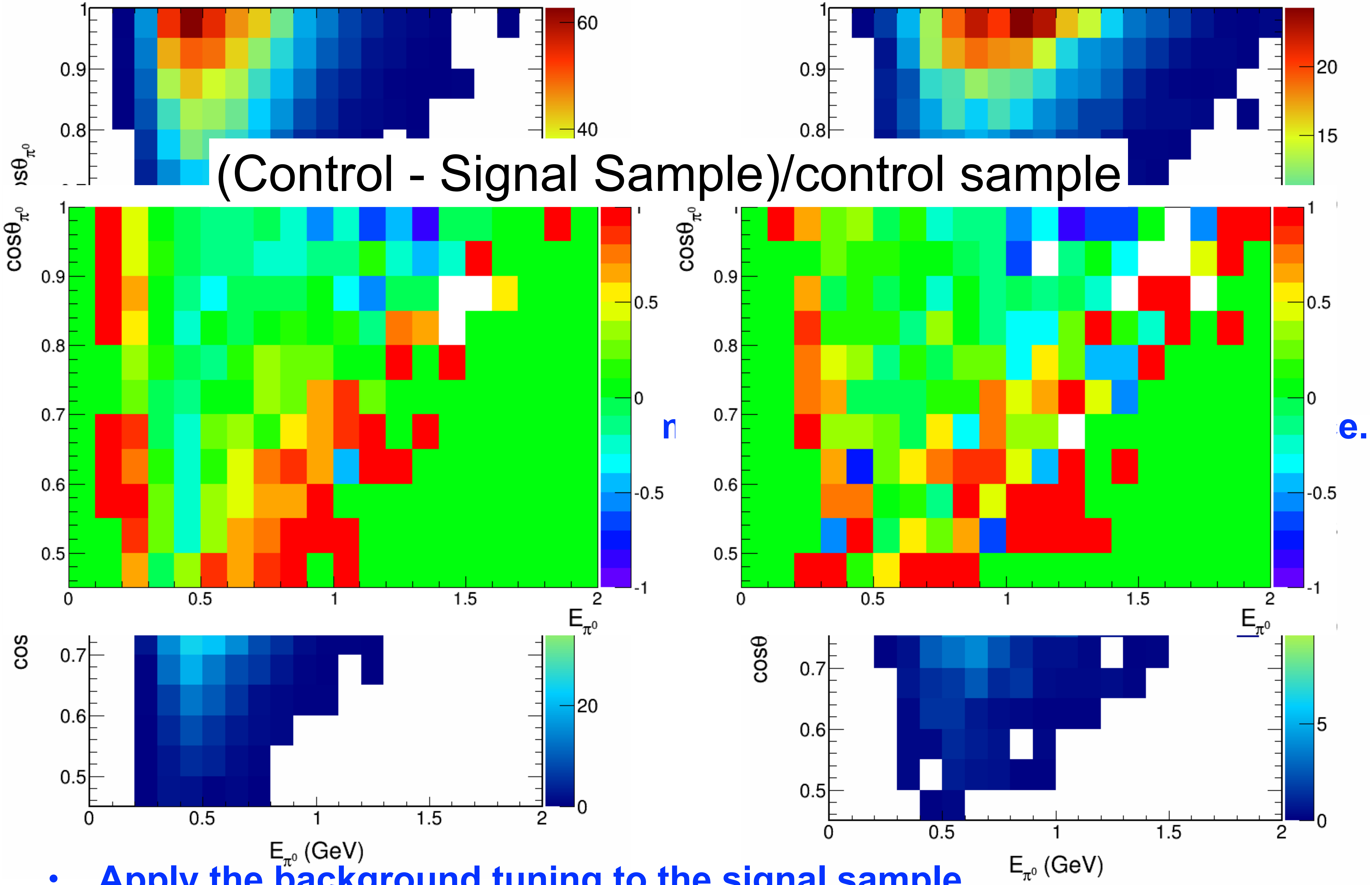


Group hits from each shower together using clustering algorithm.

Background Fit (Ratio Plot)

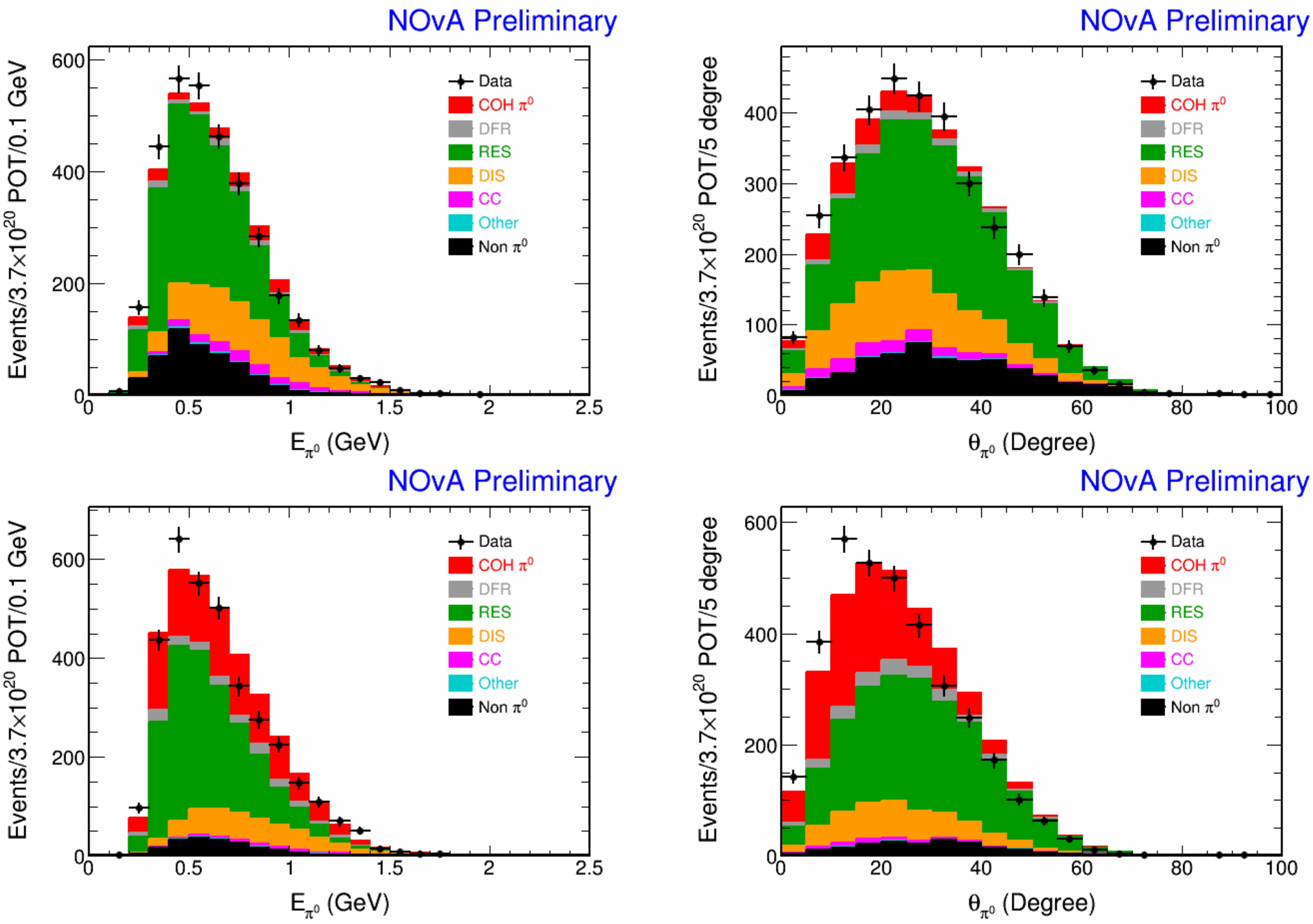
RES in Control Sample NOvA Simulation

DIS in Control Sample NOvA Simulation

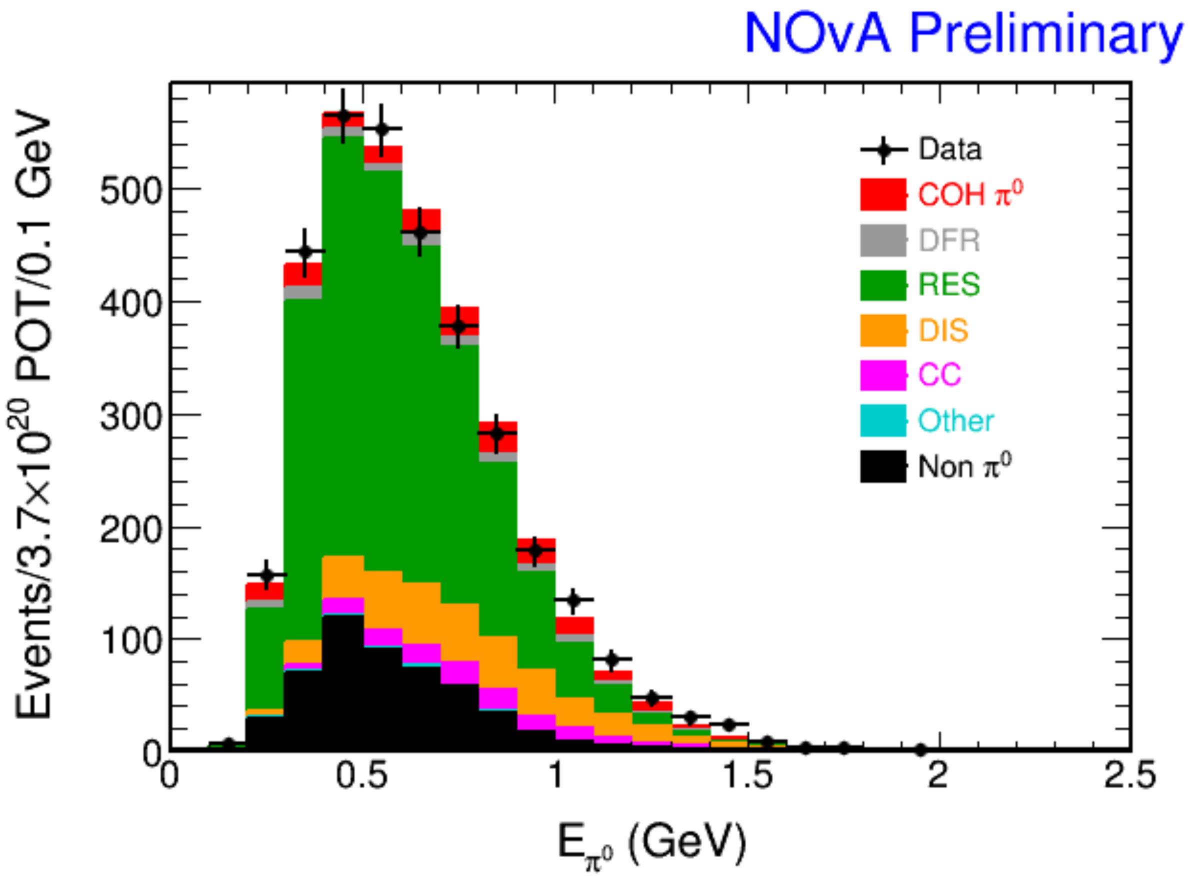


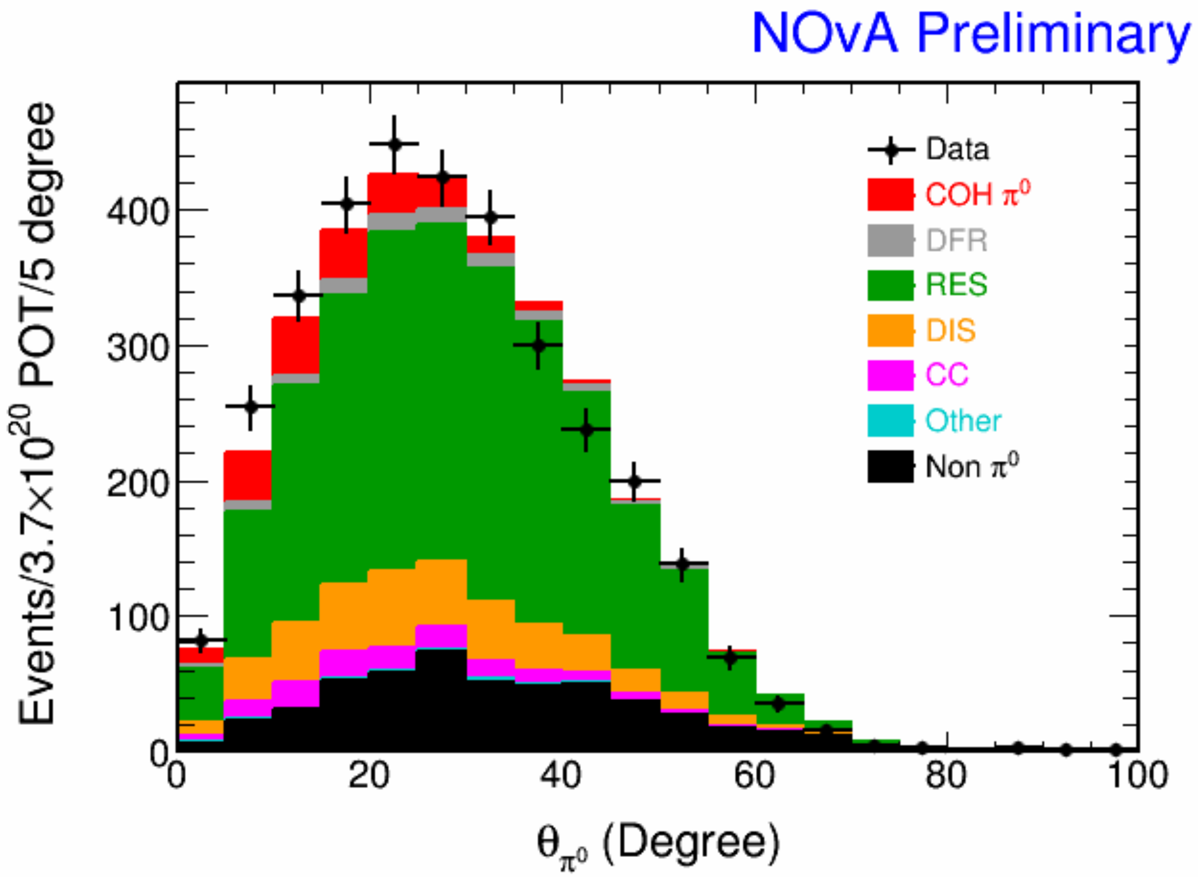
- **Apply the background tuning to the signal sample.**

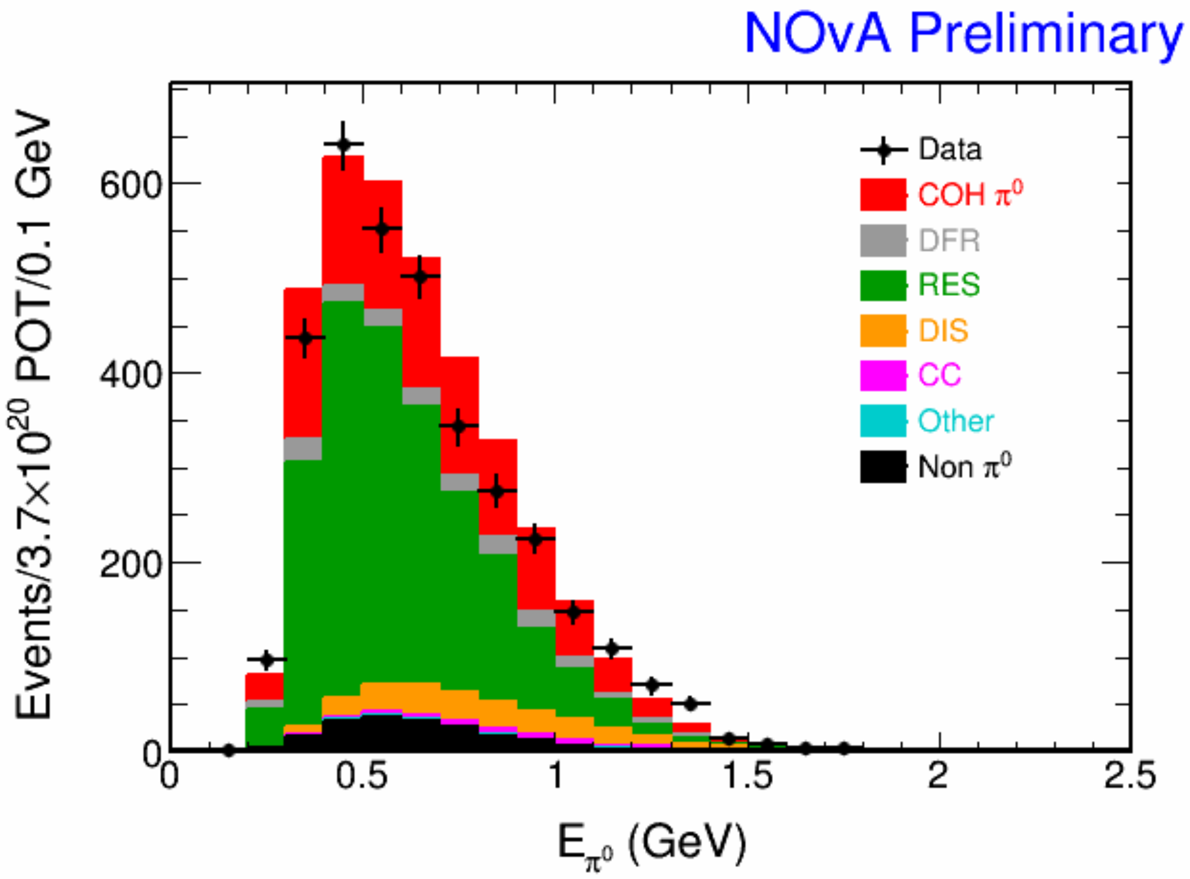
Background Fit (Before)

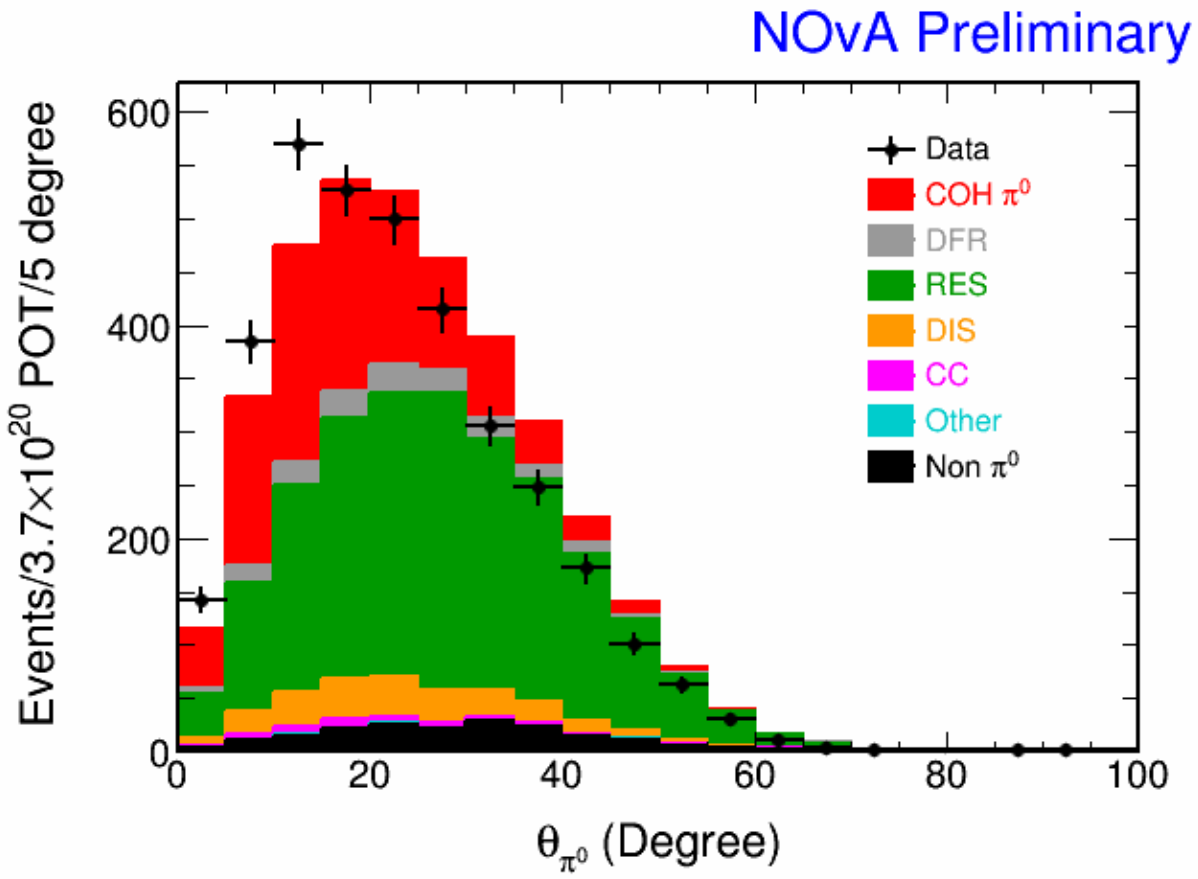


Background Fit (After)

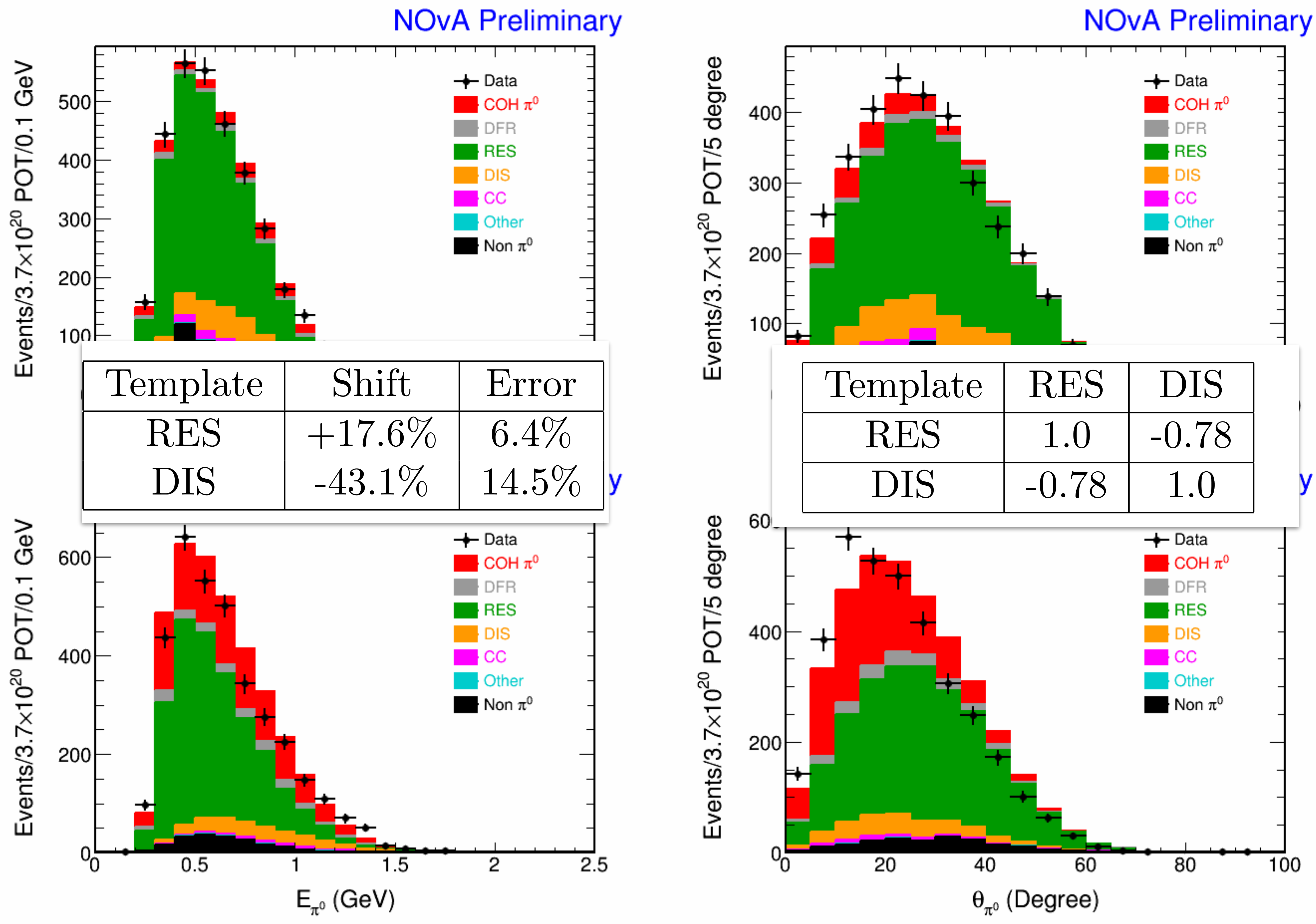








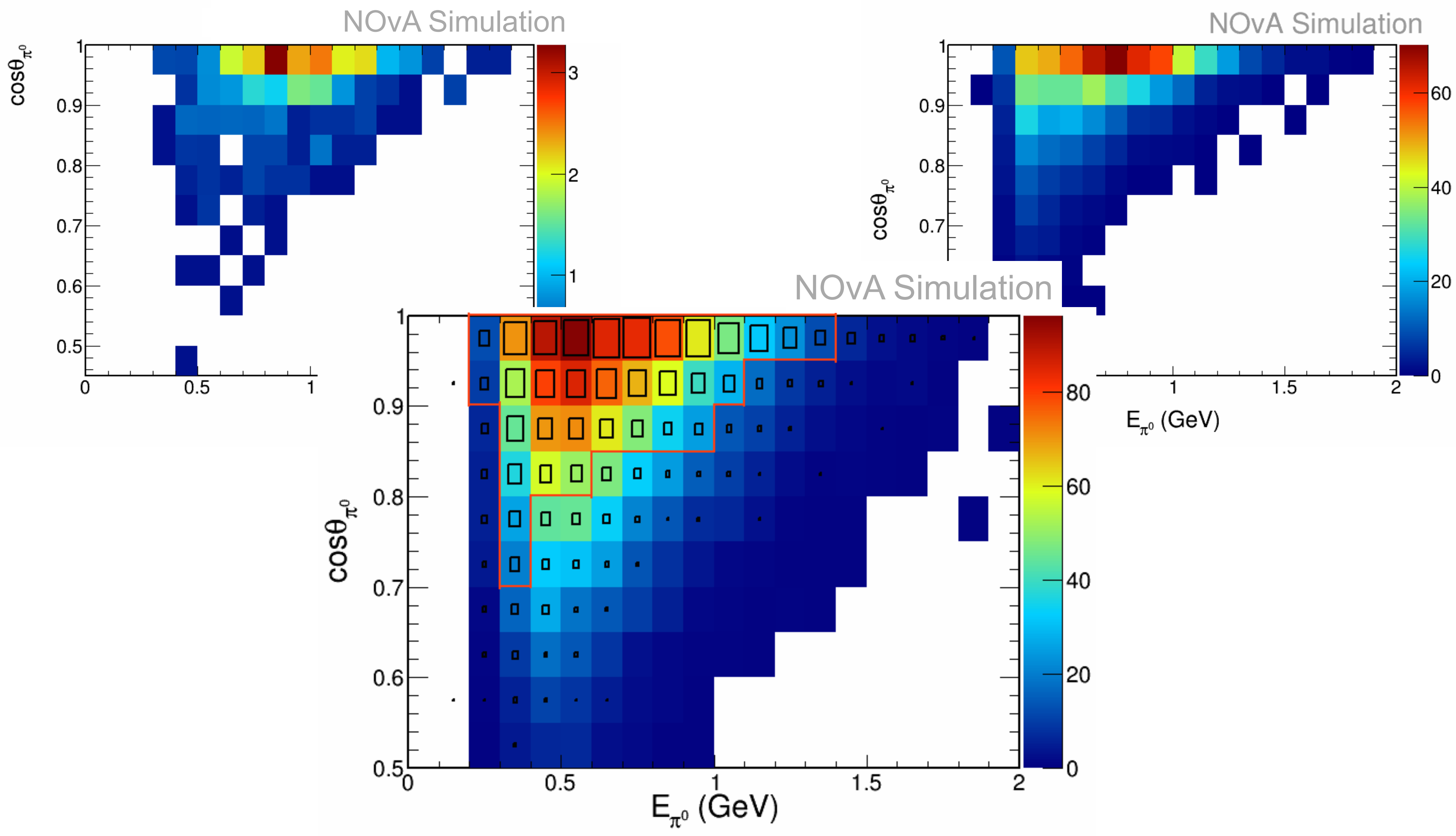
Background Fit (After)



Template	Shift	Error
RES	+17.6%	6.4%
DIS	-43.1%	14.5%

Template	RES	DIS
RES	1.0	-0.78
DIS	-0.78	1.0

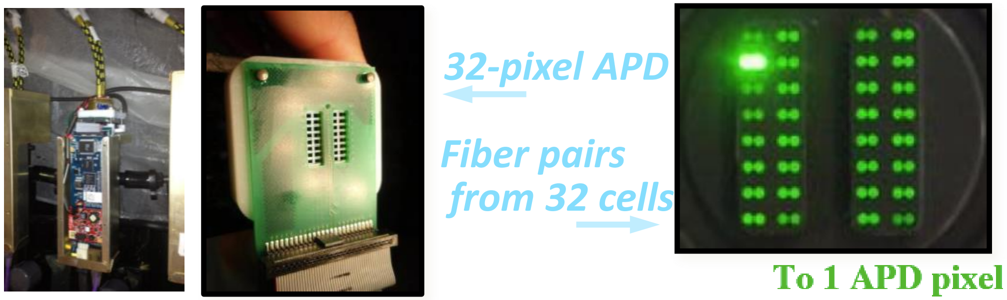
Background Substraction in 2D

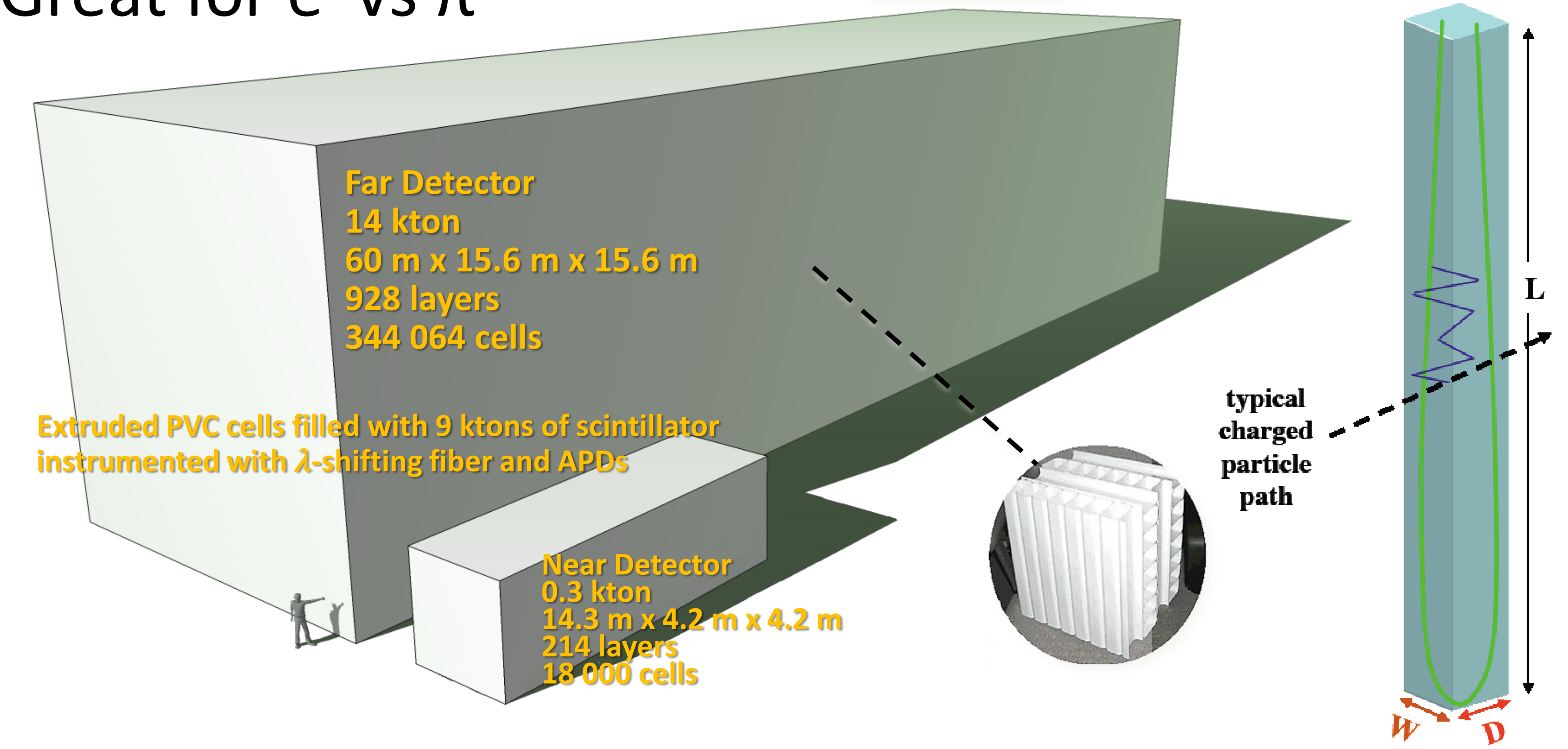


- Substract normalized background from data in the coherent-rich region in the pion kinematic space (E, cosθ)

The NOvA detectors

- 64% active detector
- Each plane just 0.15 X_0
  Great for e^- vs π^0





Far Detector
14 kton
60 m x 15.6 m x 15.6 m
928 layers
344 064 cells

Extruded PVC cells filled with 9 ktons of scintillator
instrumented with λ-shifting fiber and APDs

Near Detector
0.3 kton
14.3 m x 4.2 m x 4.2 m
214 layers
18 000 cells