Neutral Current Coherent π^0 Measurement in the NOvA ND

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For the NOvA Collaboration

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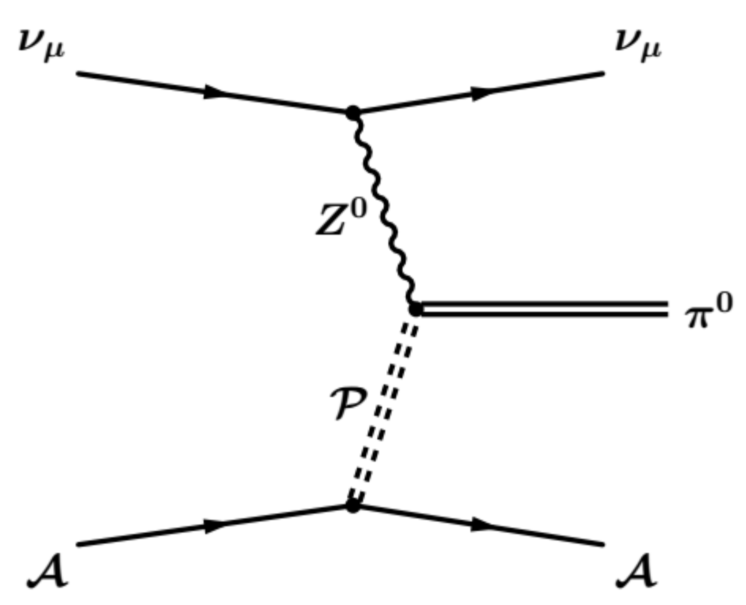
Introduction to Coherent Pion Production

- Neutrinos can coherently scatter off target nucleus via charge/neutral current interaction and produce pions:

$$\nu\mathcal{A} \rightarrow \nu\mathcal{A}\pi^0$$

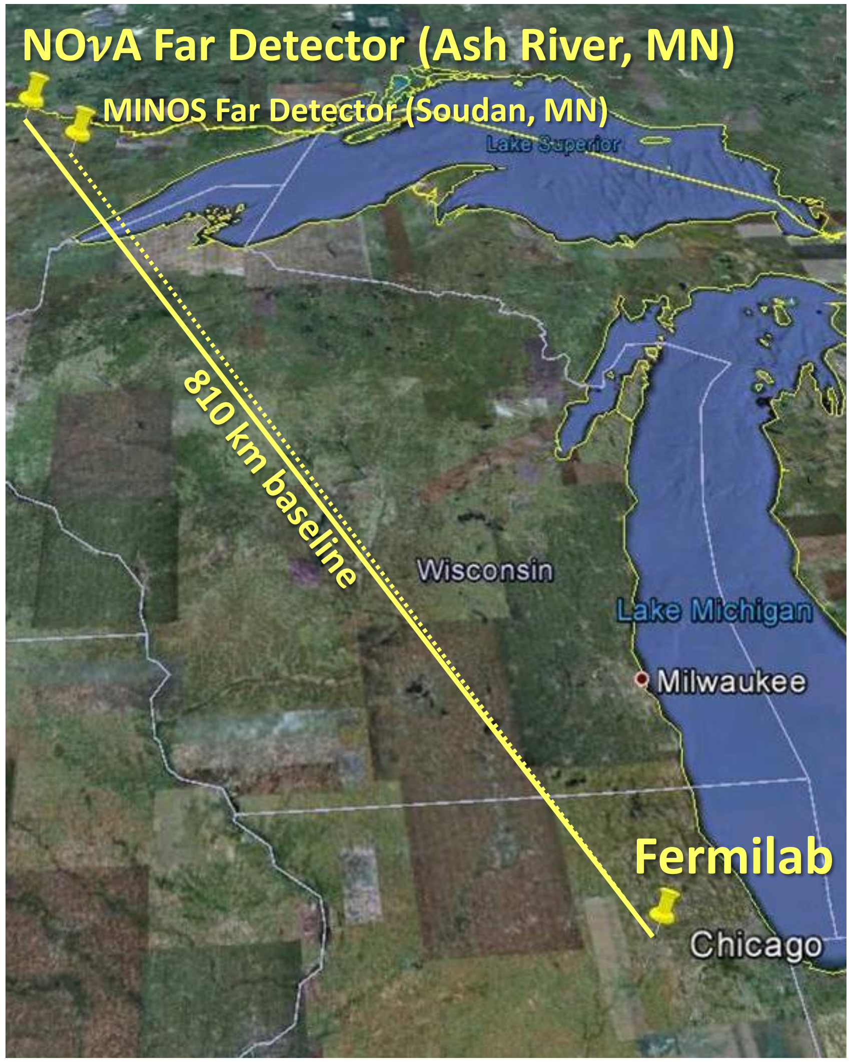
- The target nucleus stays in ground state.
- Small momentum transfer. No quantum number (charge, spin, isospin) exchange.
- Single forward-going pion in the final state, no other pions or nucleons or vertex activity.



- Coherent π^0 is an important background to ν_e appearance measurement..
- Physics in its own right: Partially Conserved Axial Current (PCAC) hypothesis, used in Rein-Seghal model and in most neutrino event generators such as GENIE.

The NOvA Near Detector

- 0.3 kton, 4.2mX4.2mX15.8m,
- 1 km from source, underground at Fermilab.
- PVC cells filled with liquid scintillator.
- Alternating planes of orthogonal view.



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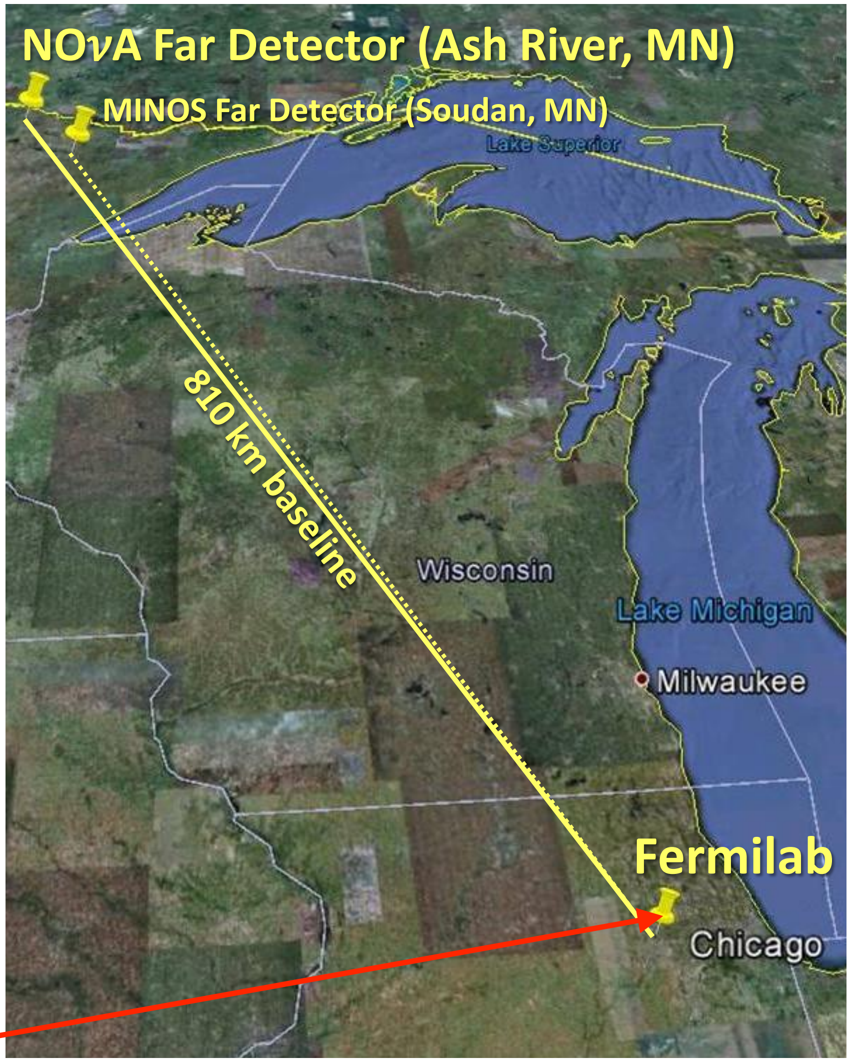

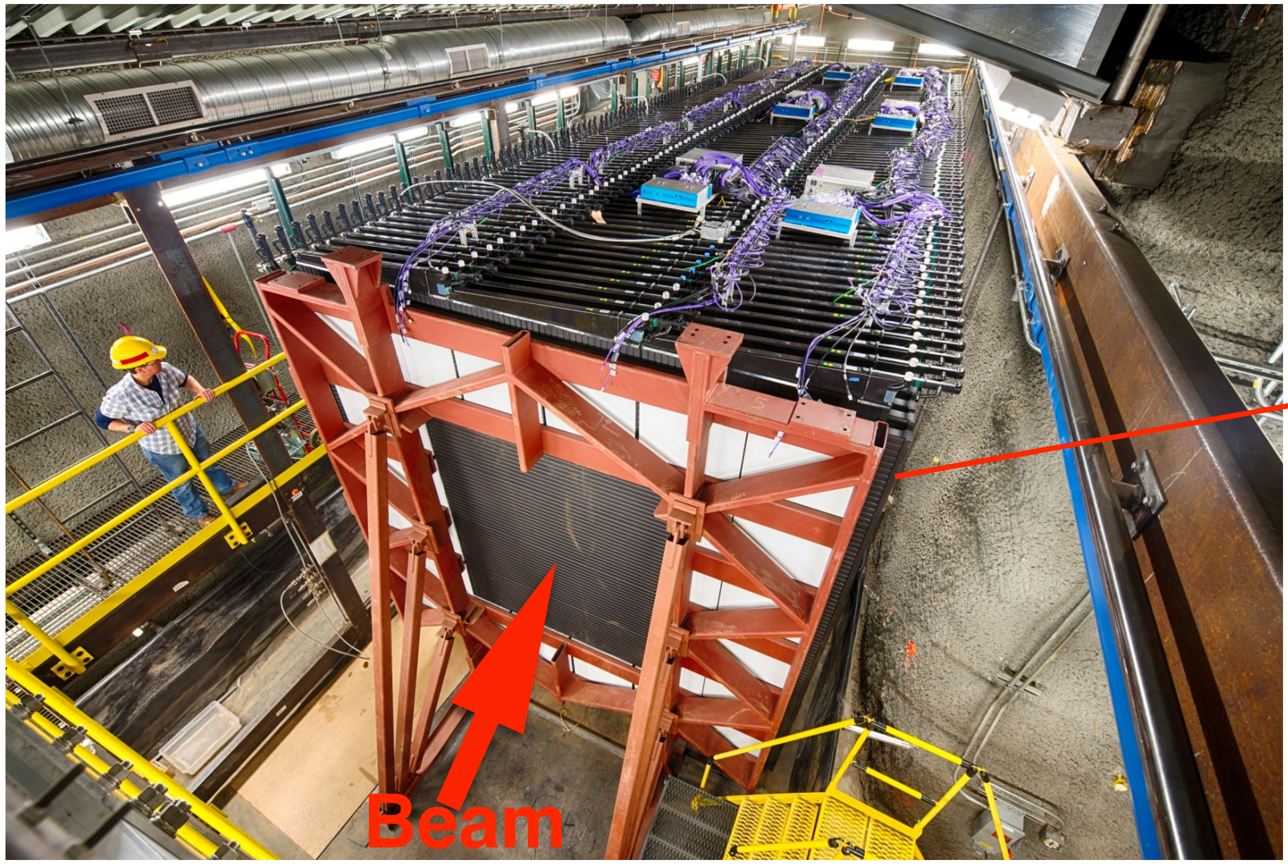

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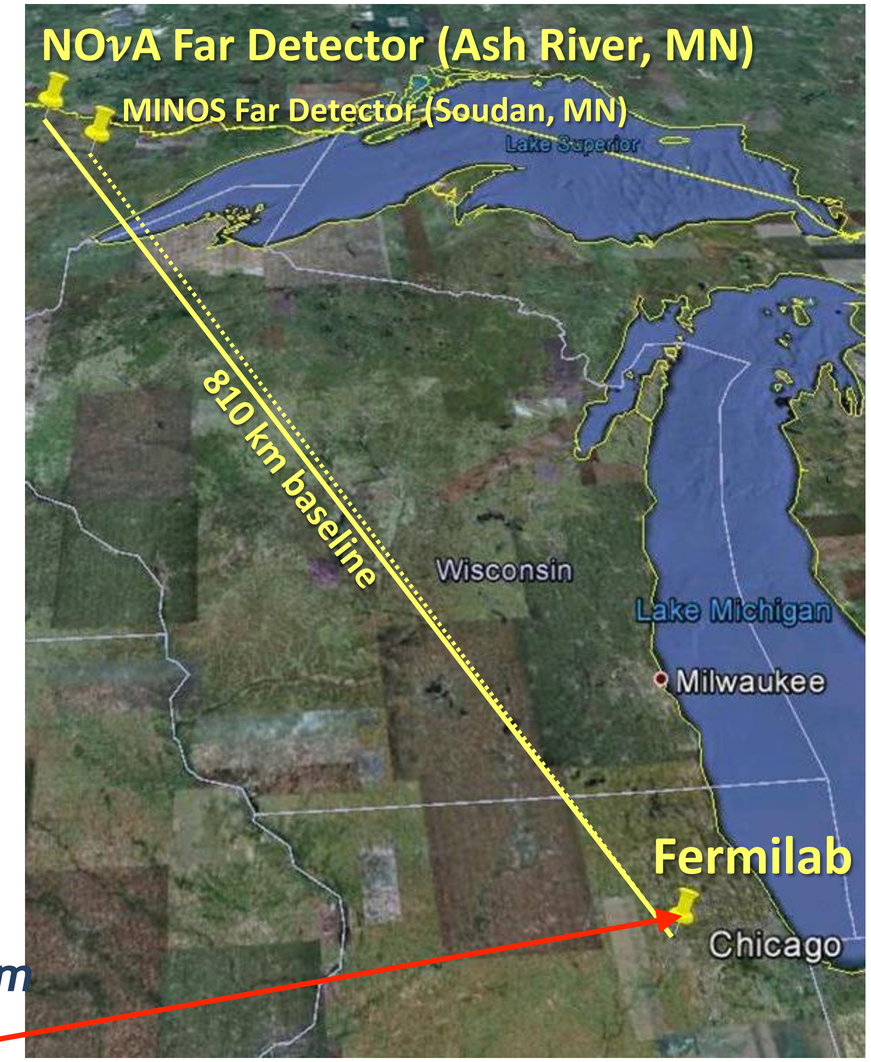

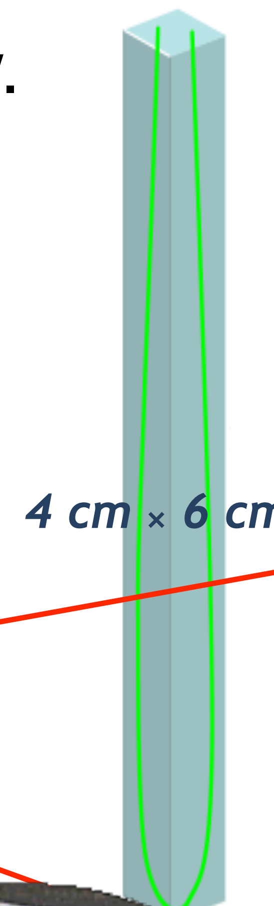

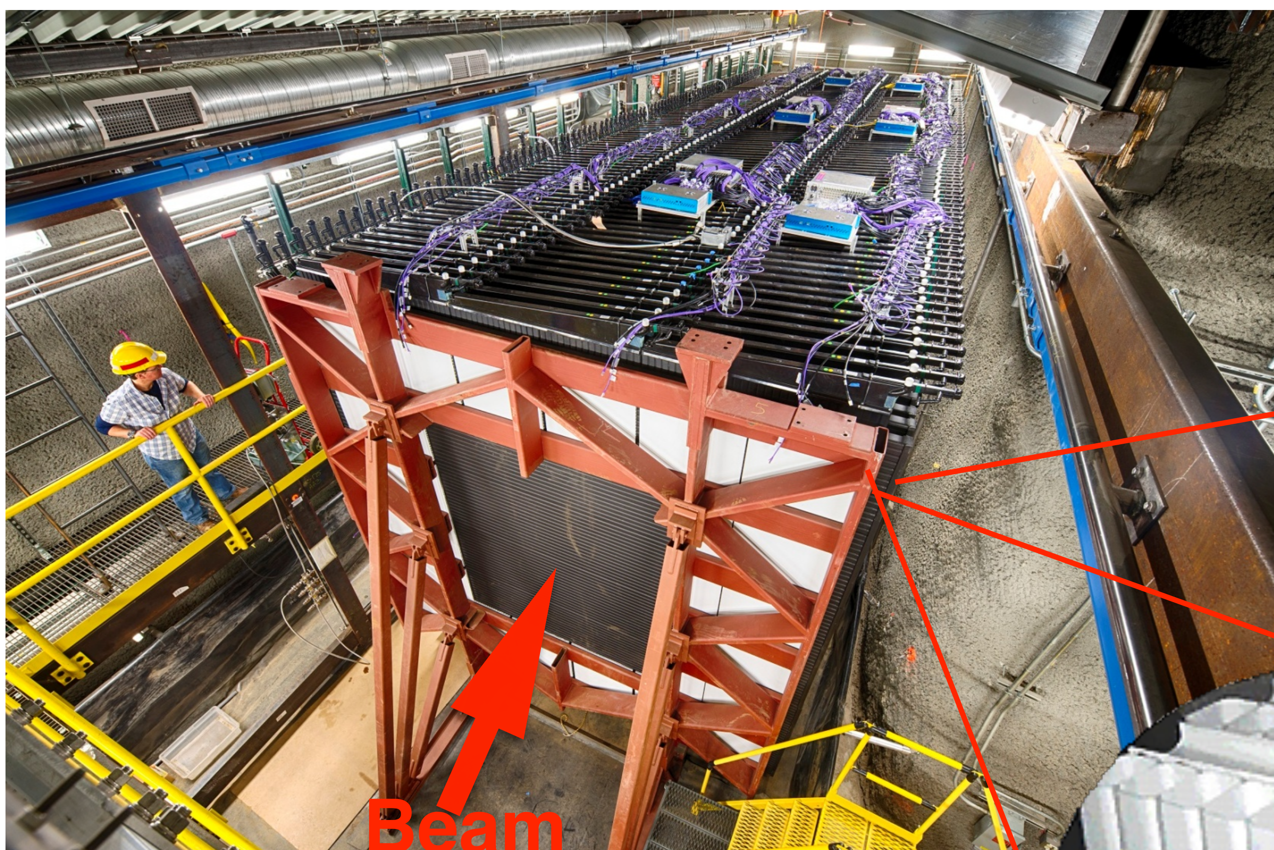

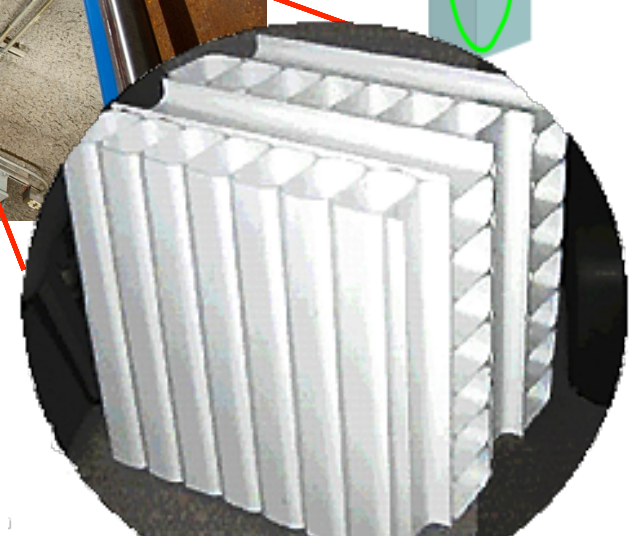

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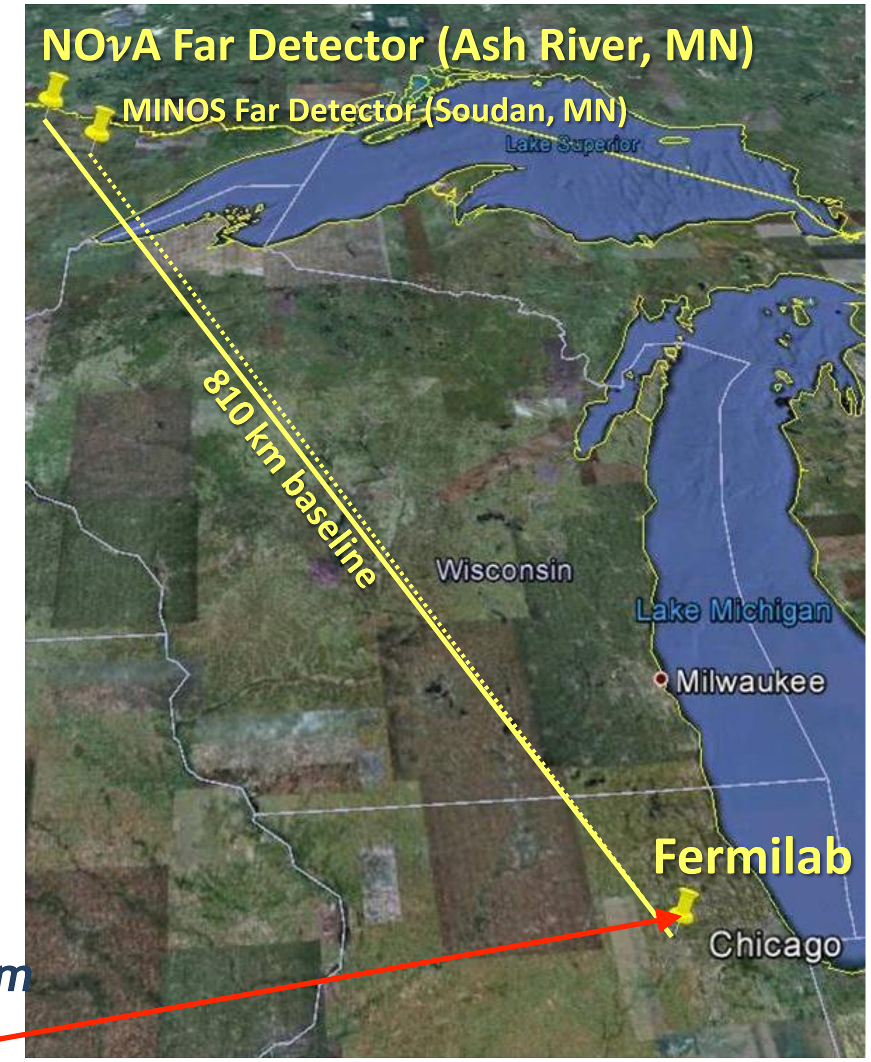

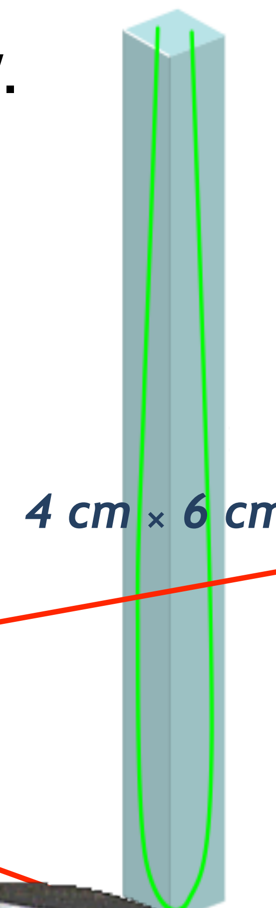

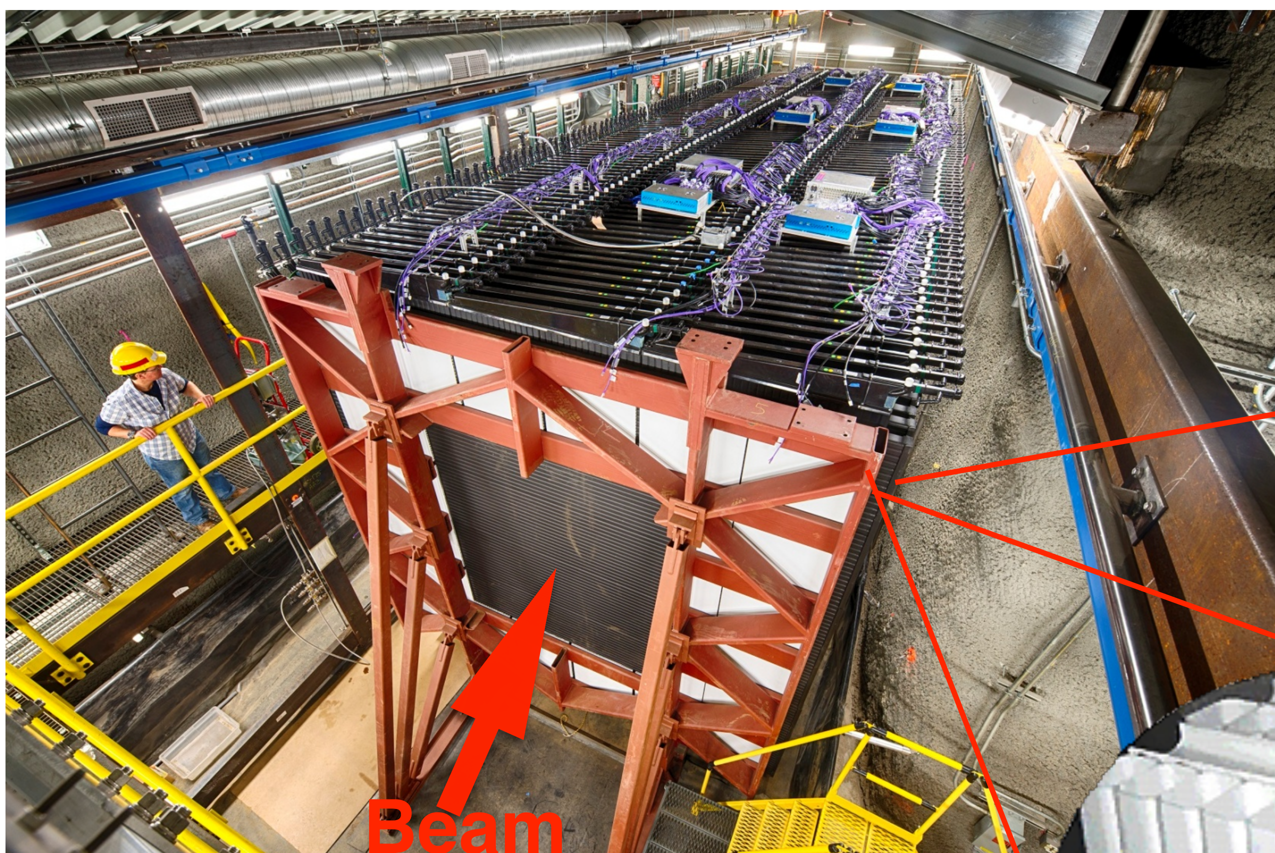

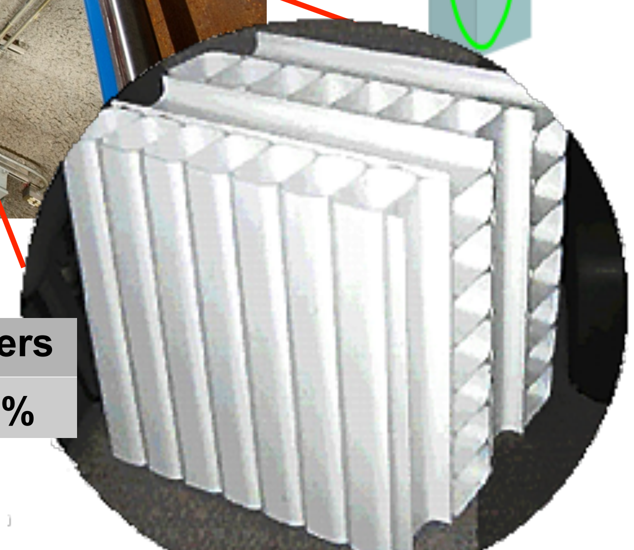

C12	Cl35	H1	Ti48	O16	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

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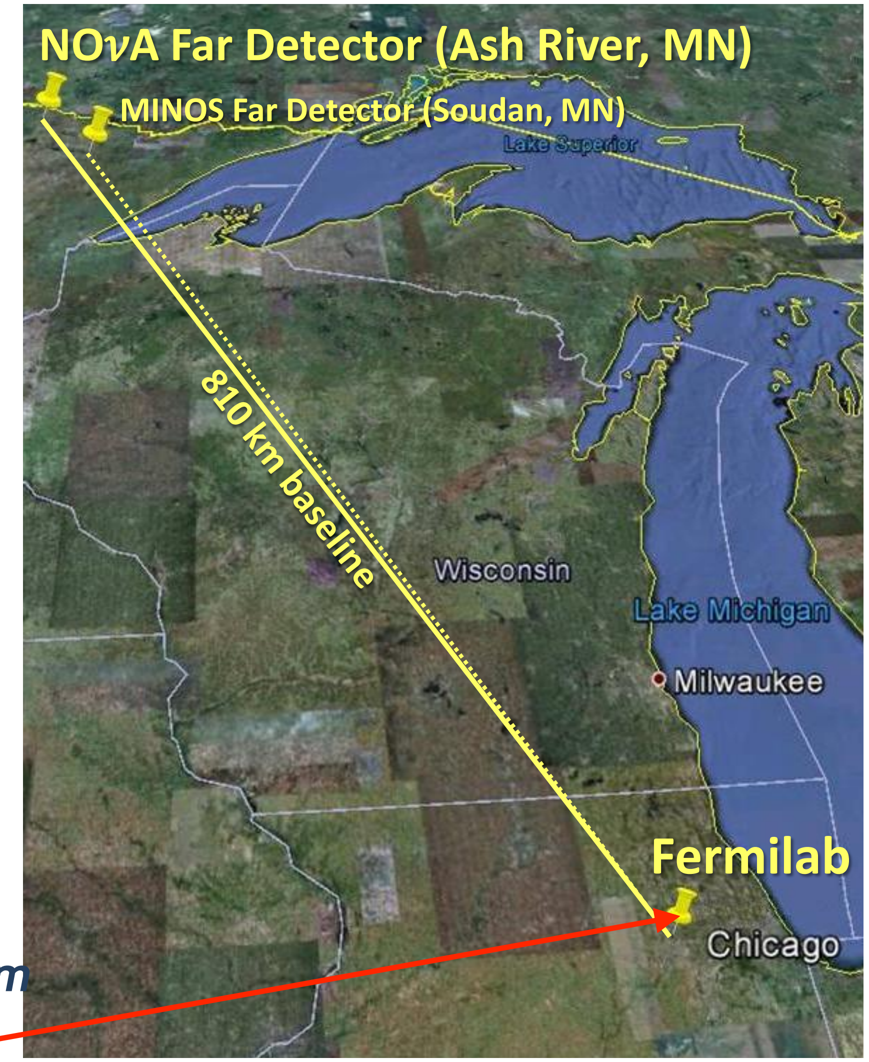
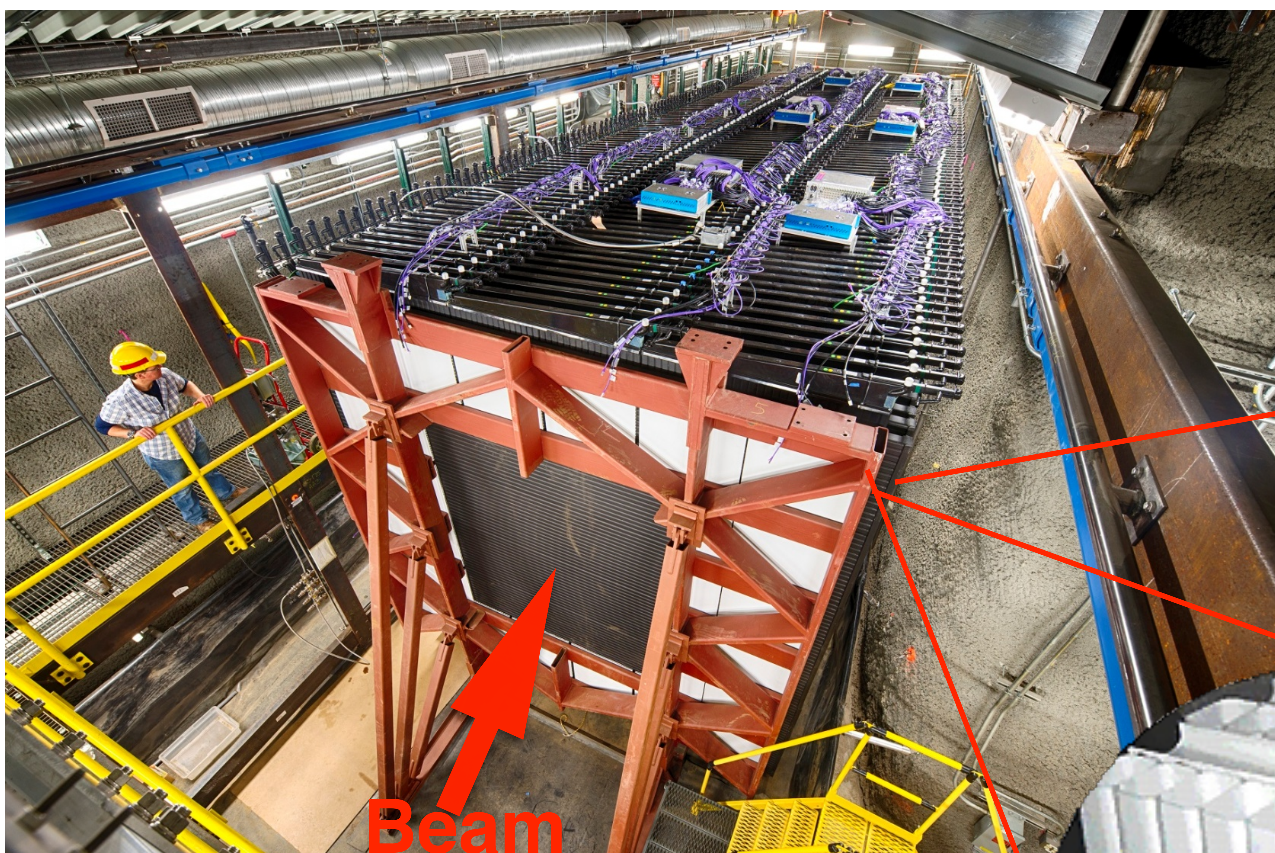
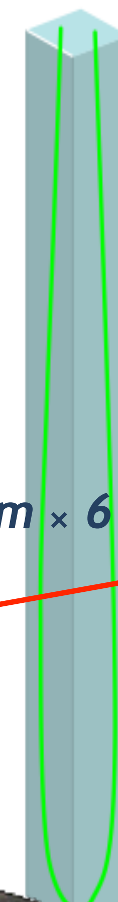
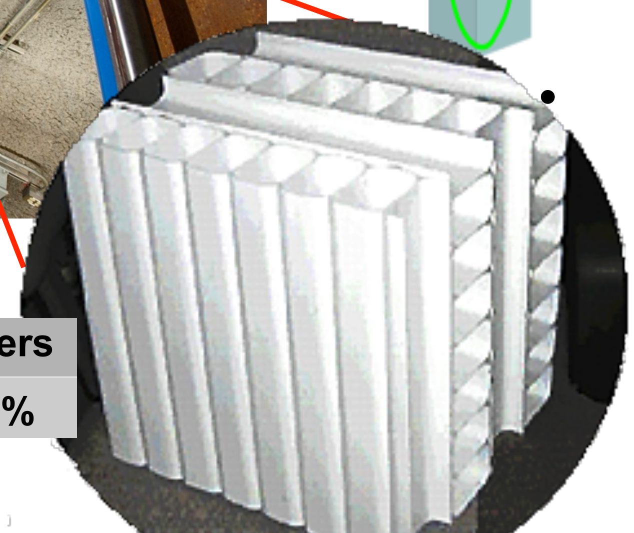




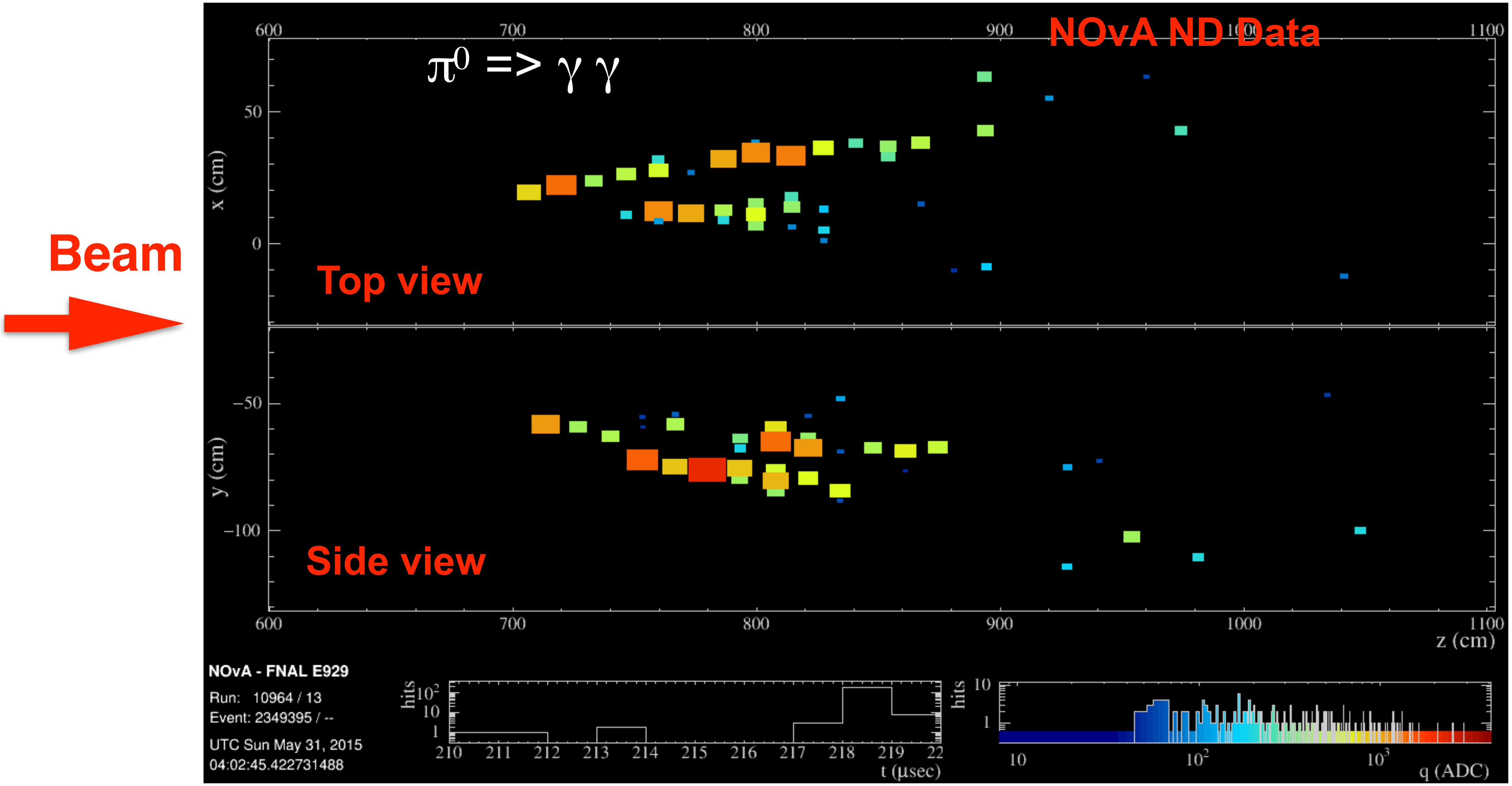




- Low-Z, fine-grained (1 plane ~ $0.15X_0$), highly-active tracking calorimeter
- Optimized for EM shower measurement, including the π^0s

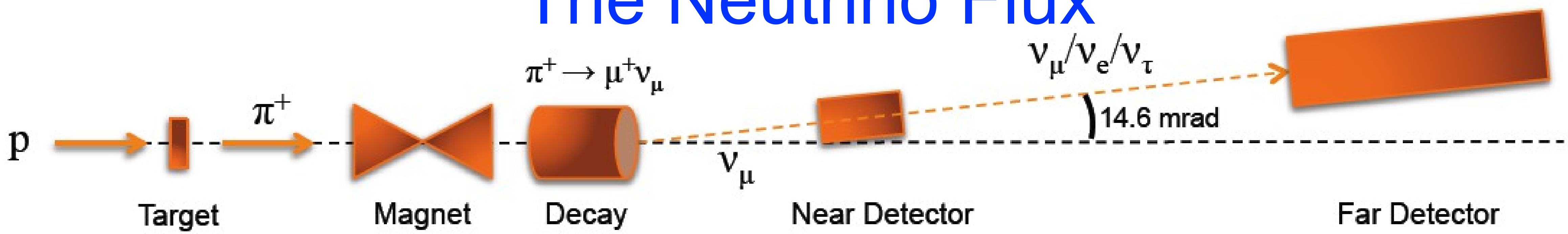
C12	Cl35	H1	Ti48	O16	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

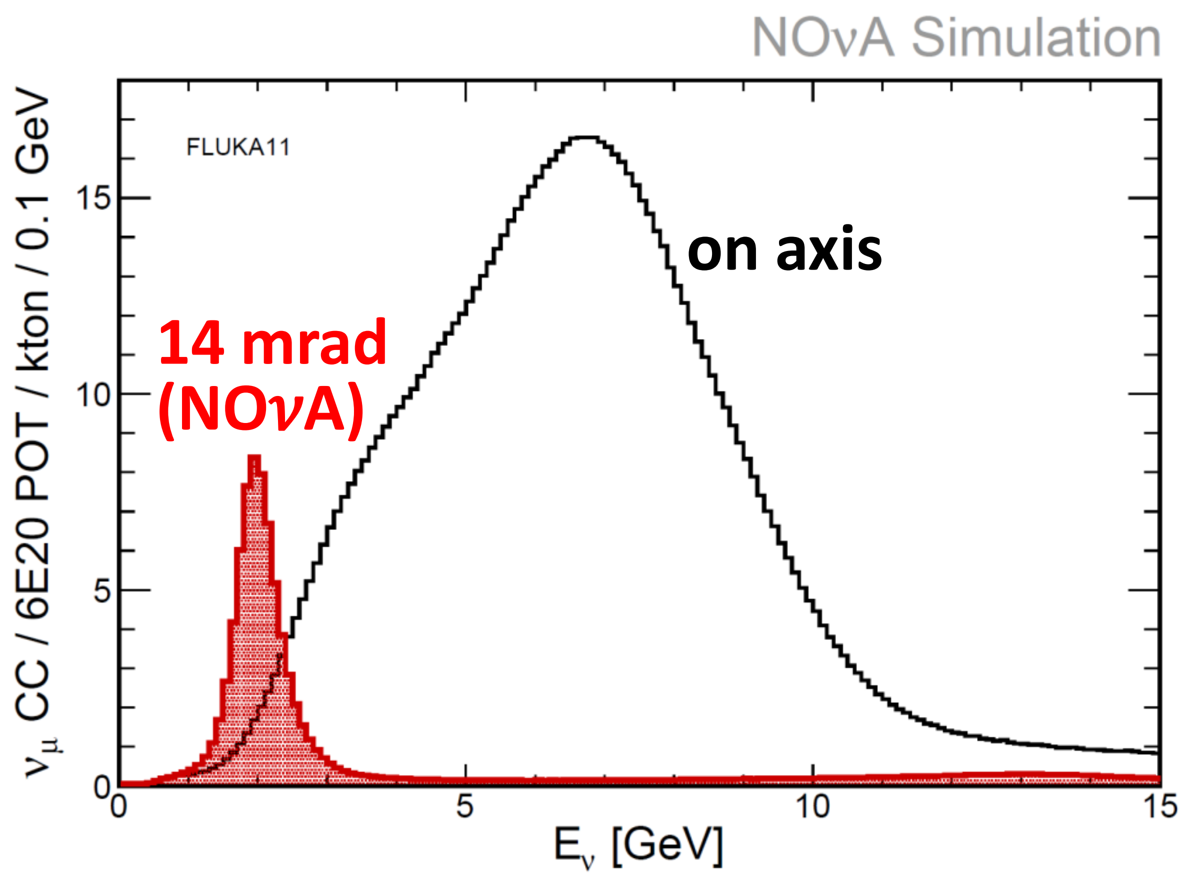
Coherent π^0 in The NOvA ND

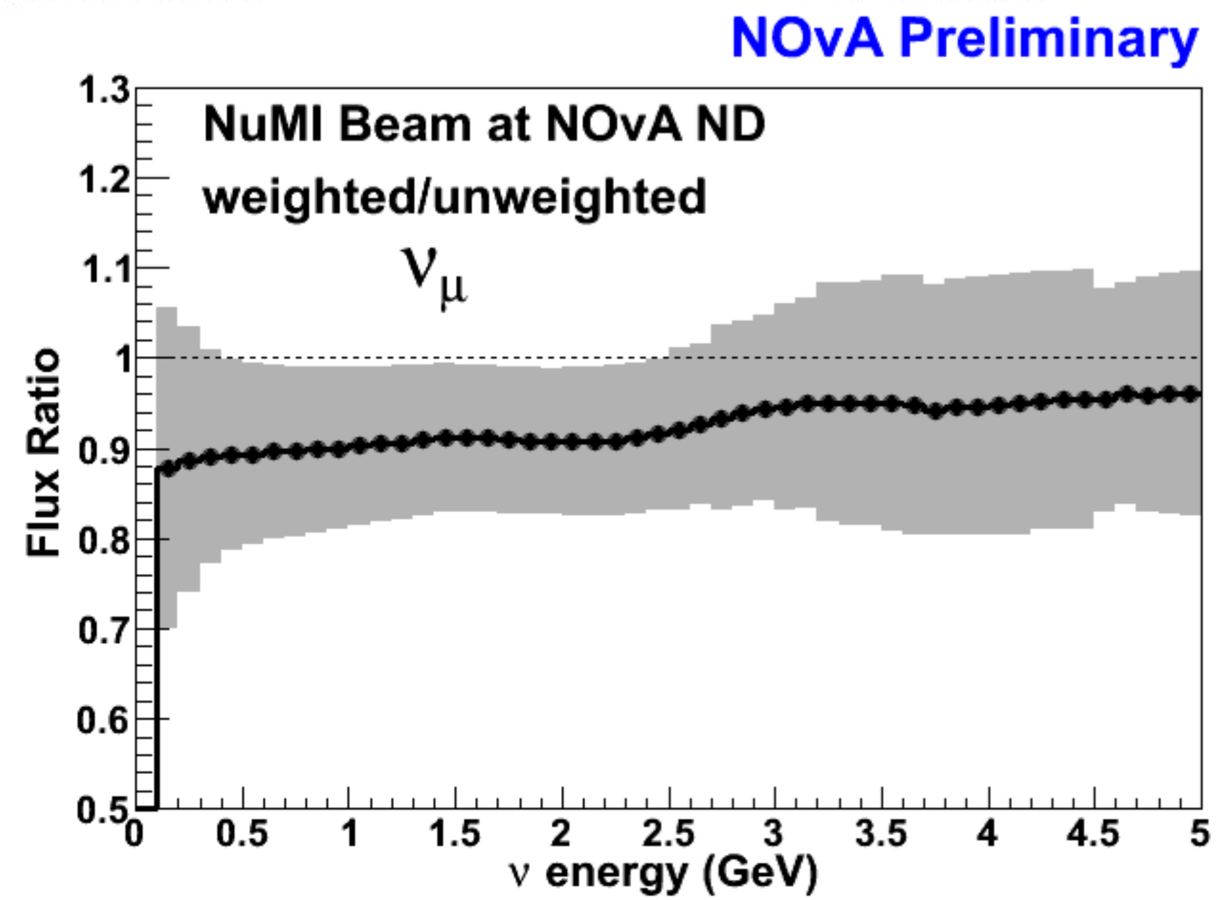


- Signature of COH π^0 in the NOvA ND is one single forward-going π^0.
- Photons from neutral pion decay make EM showers.
- Reconstructing both photons provide additional constraint on background and energy scale.

The Neutrino Flux





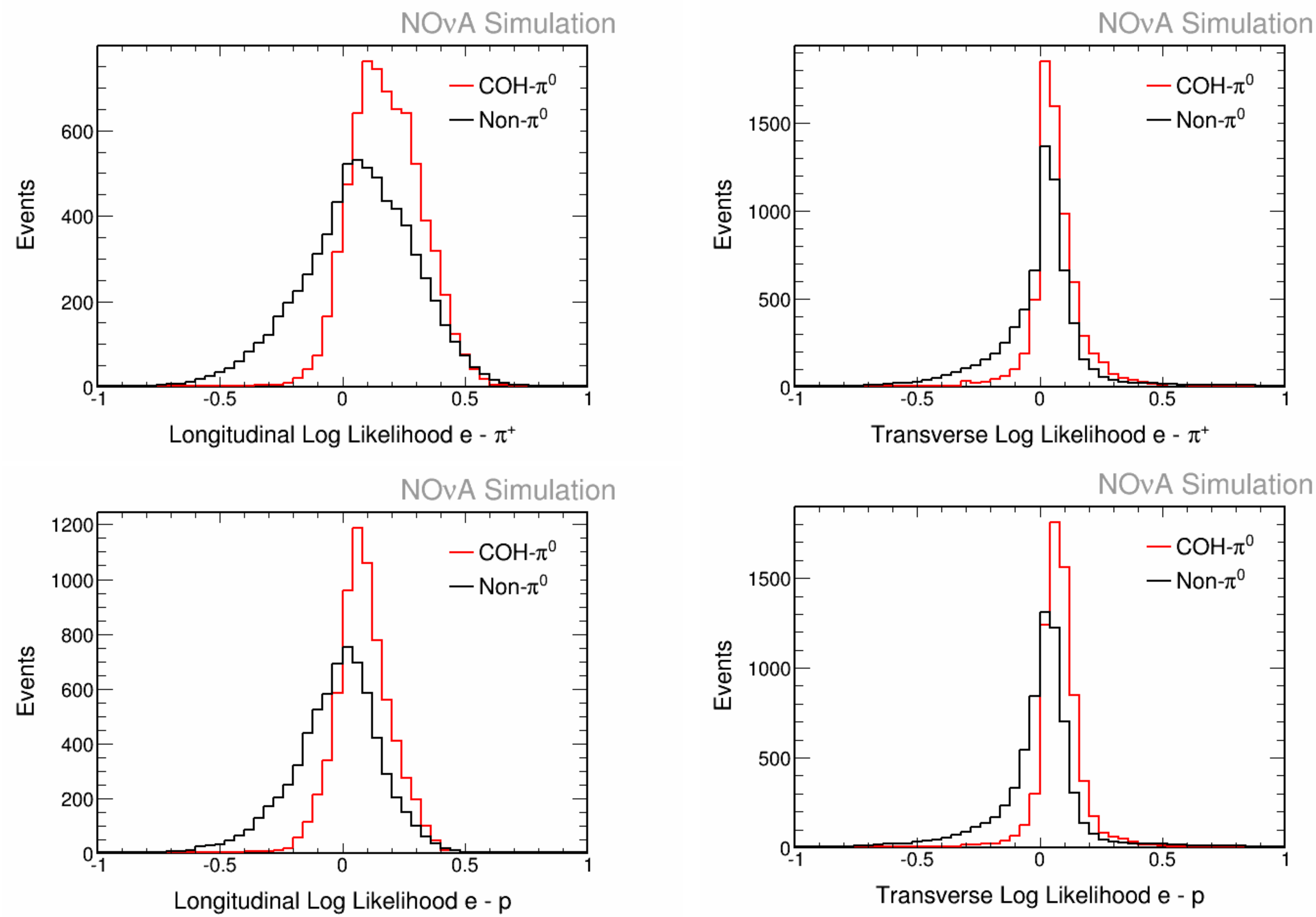


- Narrow band neutrino beam 1~3GeV peak at ~2GeV, Dominated by ν_μ (94%)
- Neutrino flux uncertainty comes form hadron production and beam focusing.
- Hadron production uncertainty constraint by external hadron production data (PPFX).

Analysis Strategy

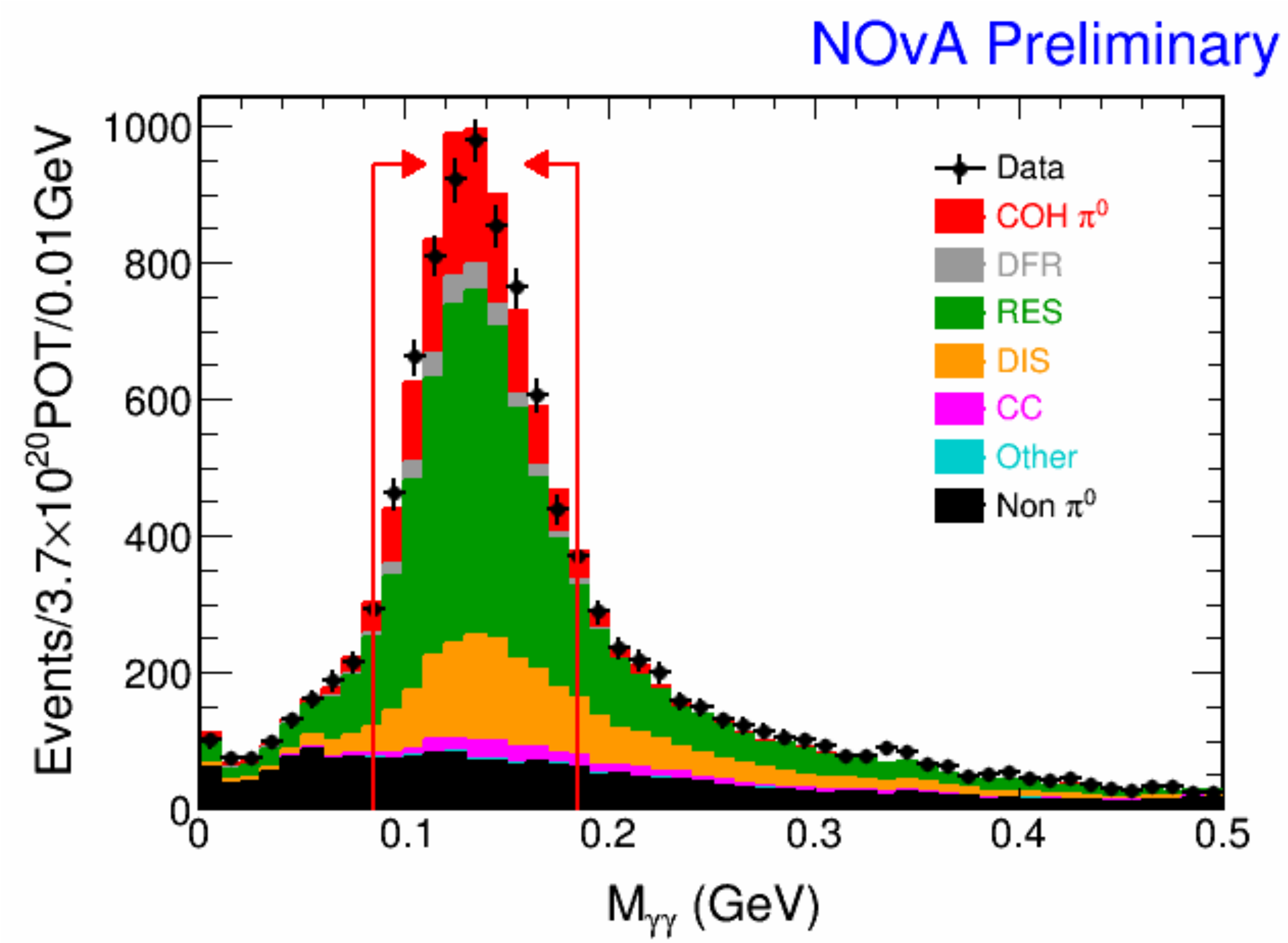
- Select **NC π^0 sample**: no muon track, two photon showers, no other particles. Reconstruct the invariant mass.
- Using kinematics, further select a **signal sample** with most of the coherent signal.
- Define a **control sample (sideband)**, dominated by non-coherent π^0s, to constrain background modeling.
- Apply the background fit result to the signal sample.
- Get a flux-averaged cross-section measurement from the signal sample as the data event excess over background prediction in the coherent region.

Photon Shower Identification



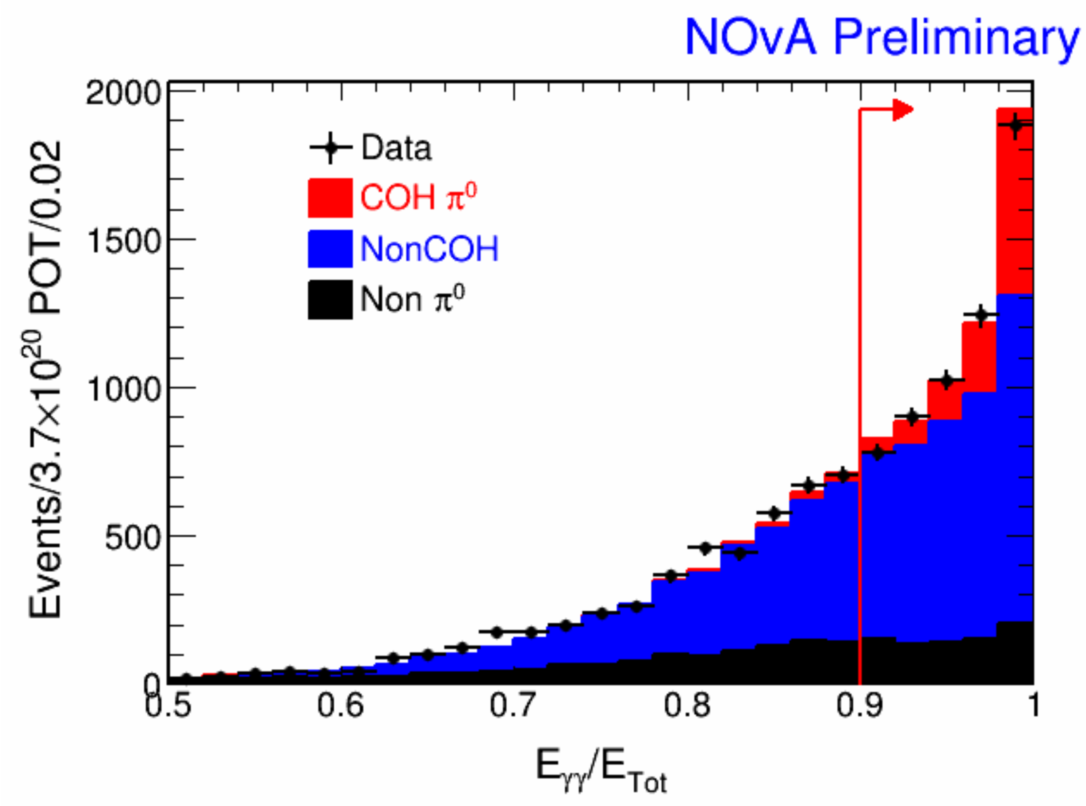
- Look for $\pi^0 \Rightarrow \gamma\,\gamma$ and both photons are reconstructed.
- Identify EM showers by likelihoods build upon shower longitudinal and transverse dE/dx information.

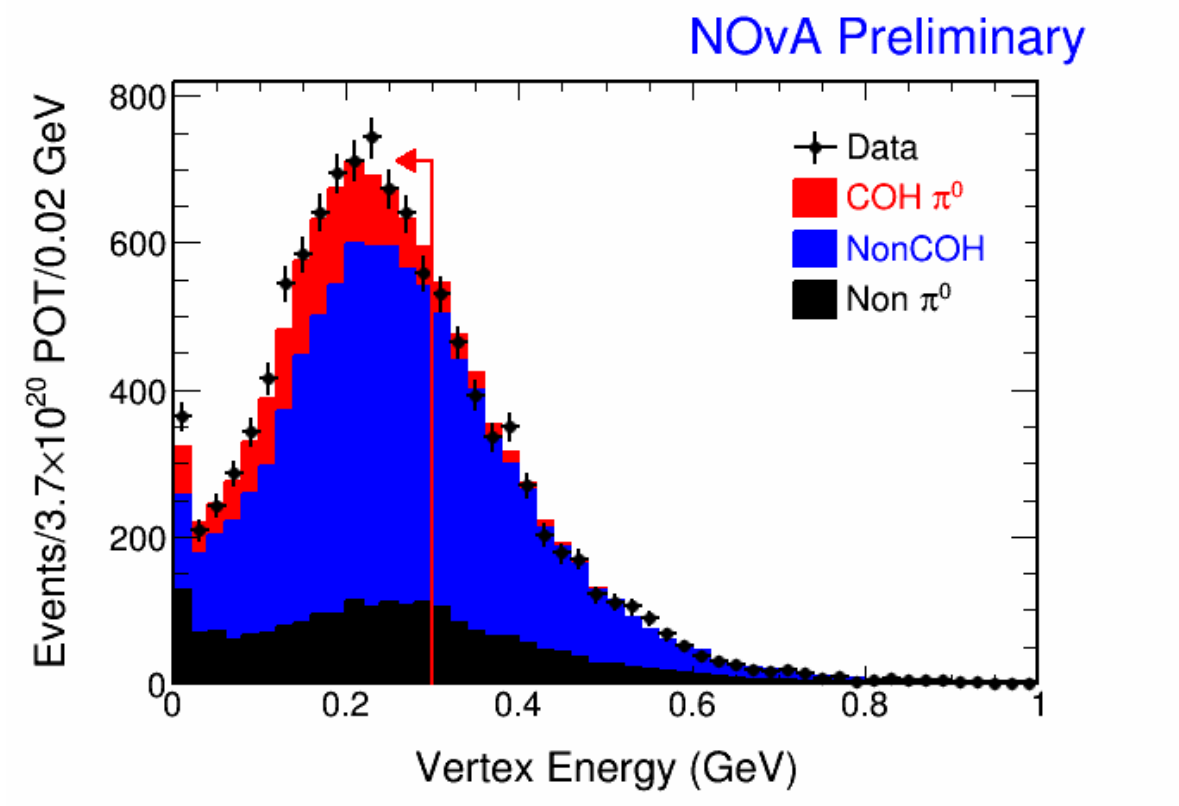
NC π^0 Sample



- Identify the NC π^0 sample
  - Absence of muon.
  - Two showers identified as photons by dE/dx-based likelihoods.
- Reconstruct invariant mass.
- 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





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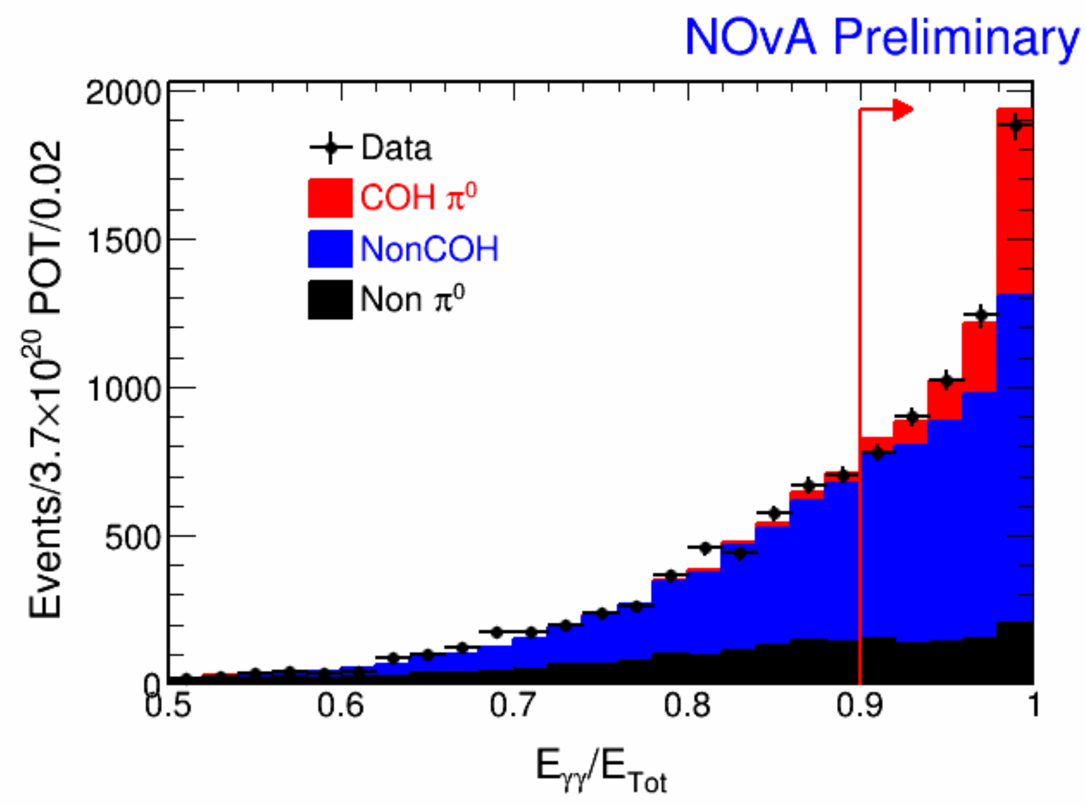
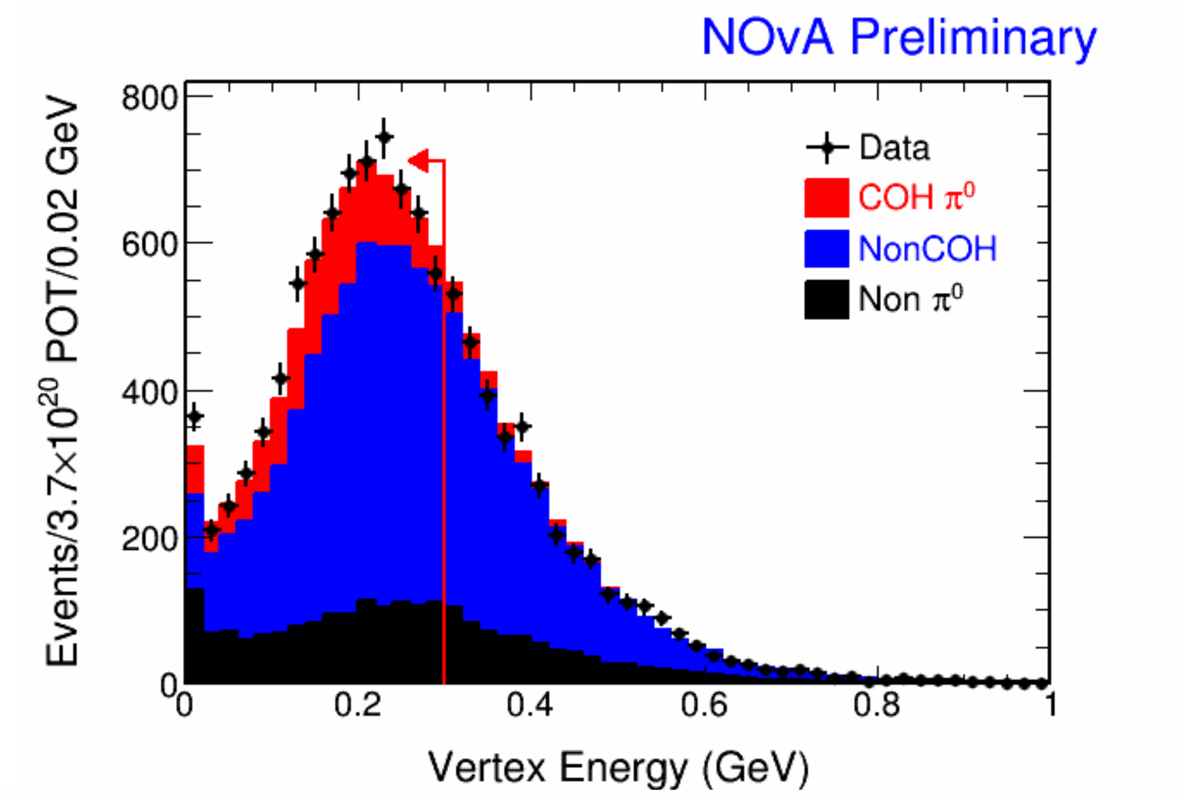
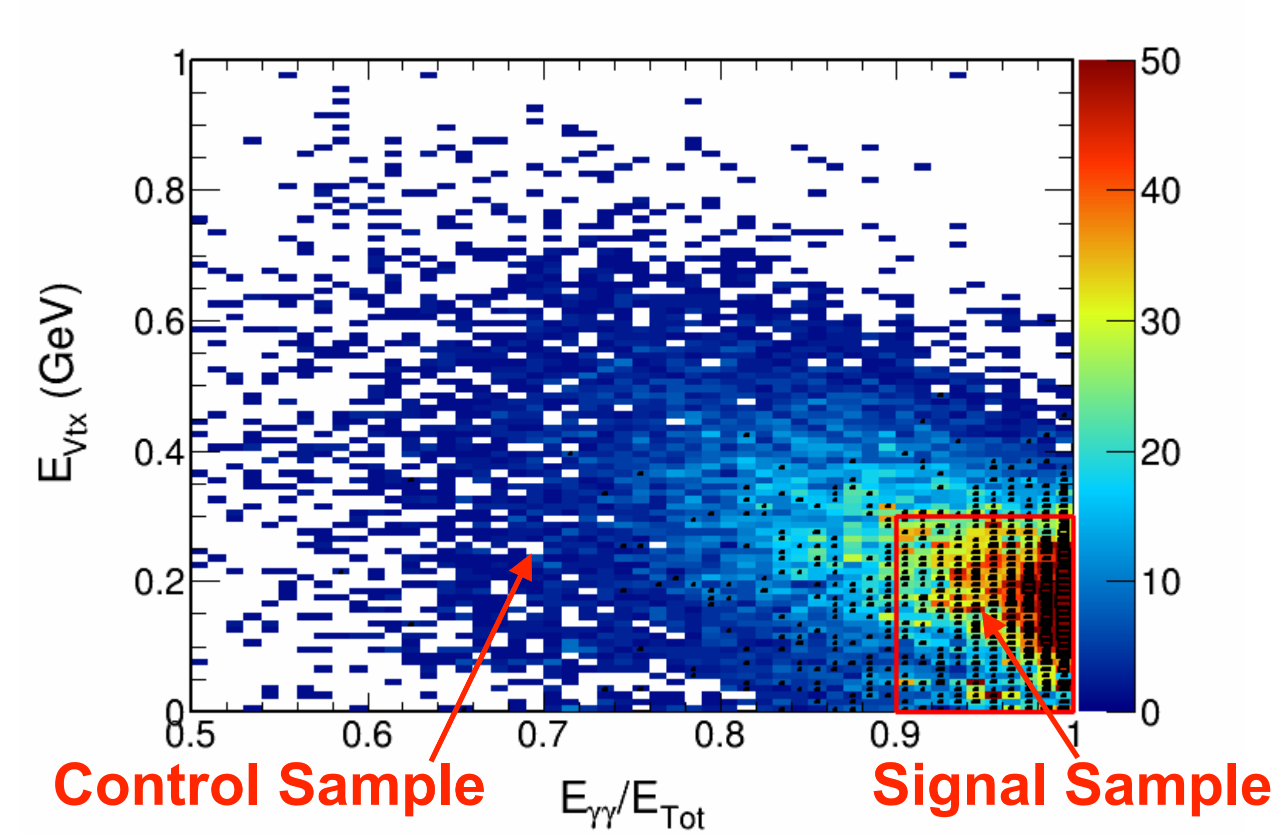
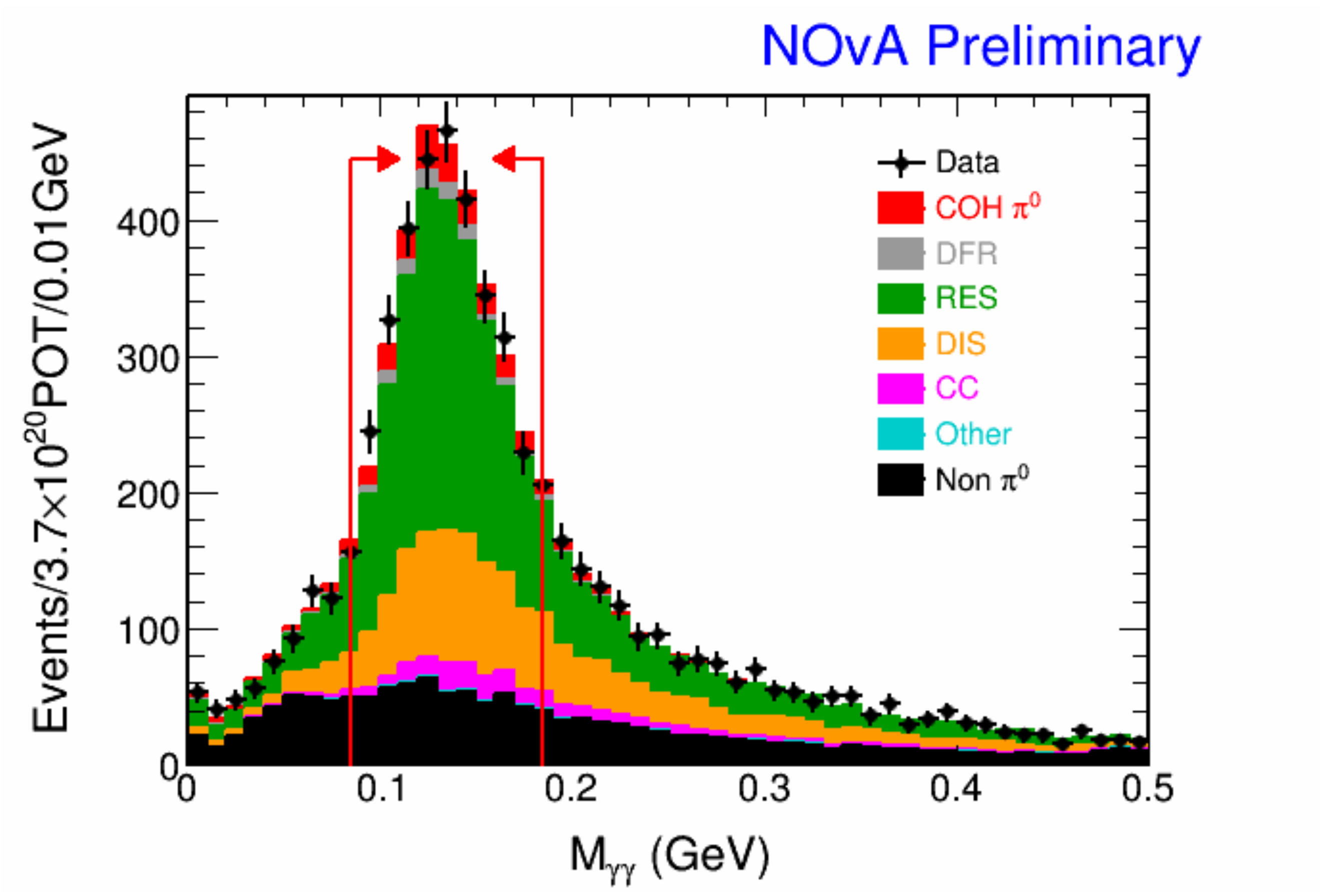




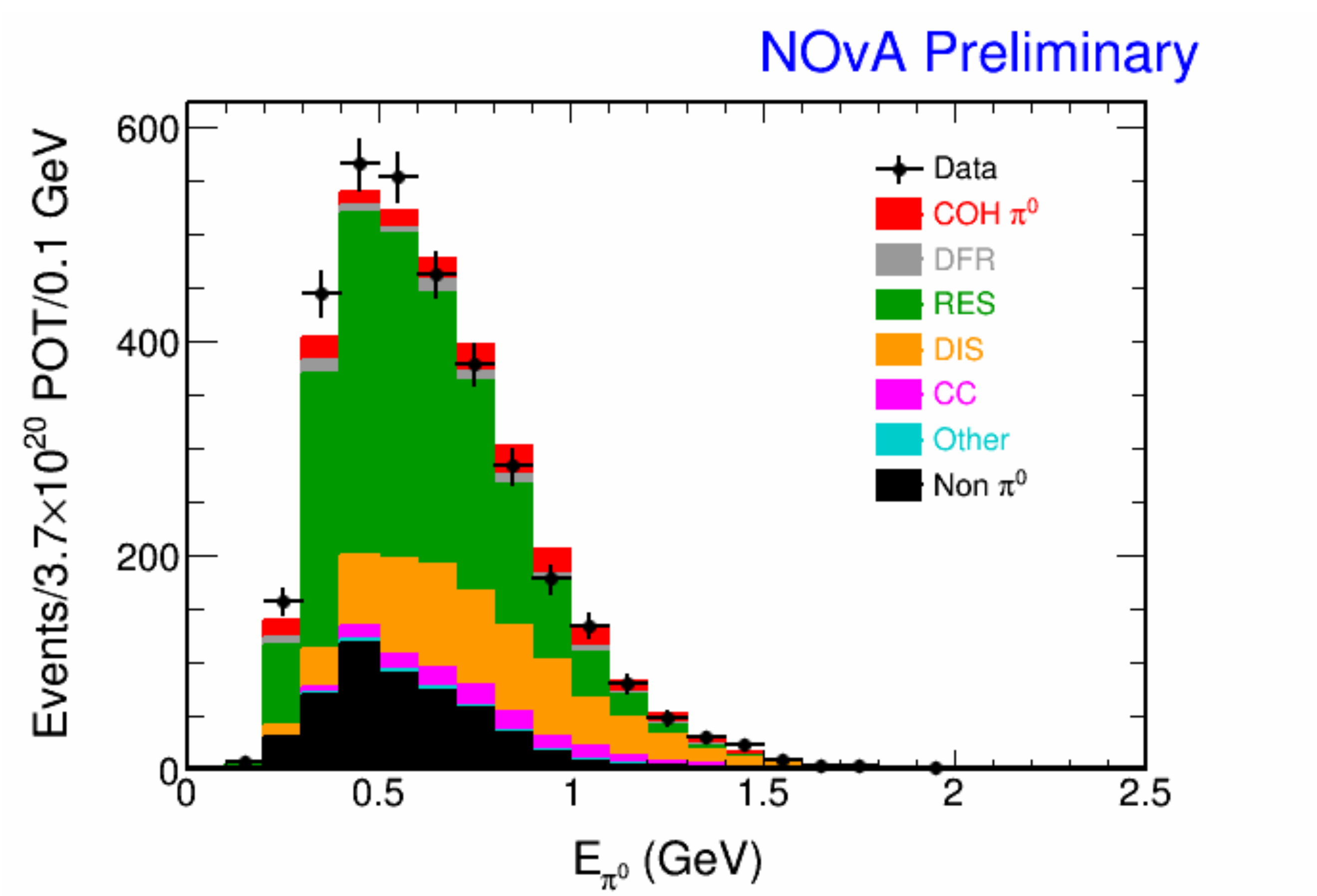
- Divide the NC π^0 into two sub-samples:
  - **Signal sample:** events with most of their energy in the 2 photon-showers and low vertex energy: it has >90% of the signal.
  - **Control sample:** the events with extra energy other than the photons or in the vertex region, dominated by non-coherent π^0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

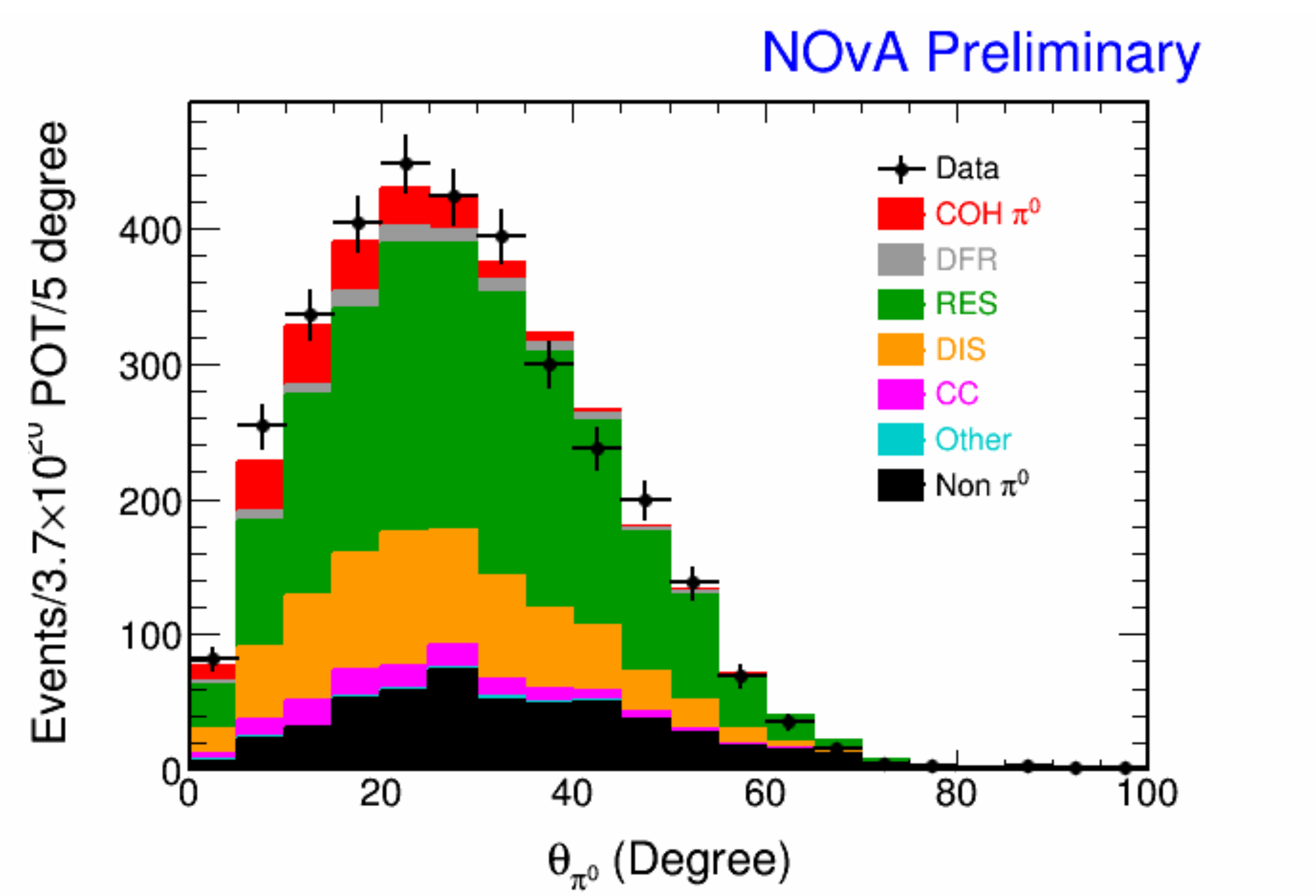


Control Sample

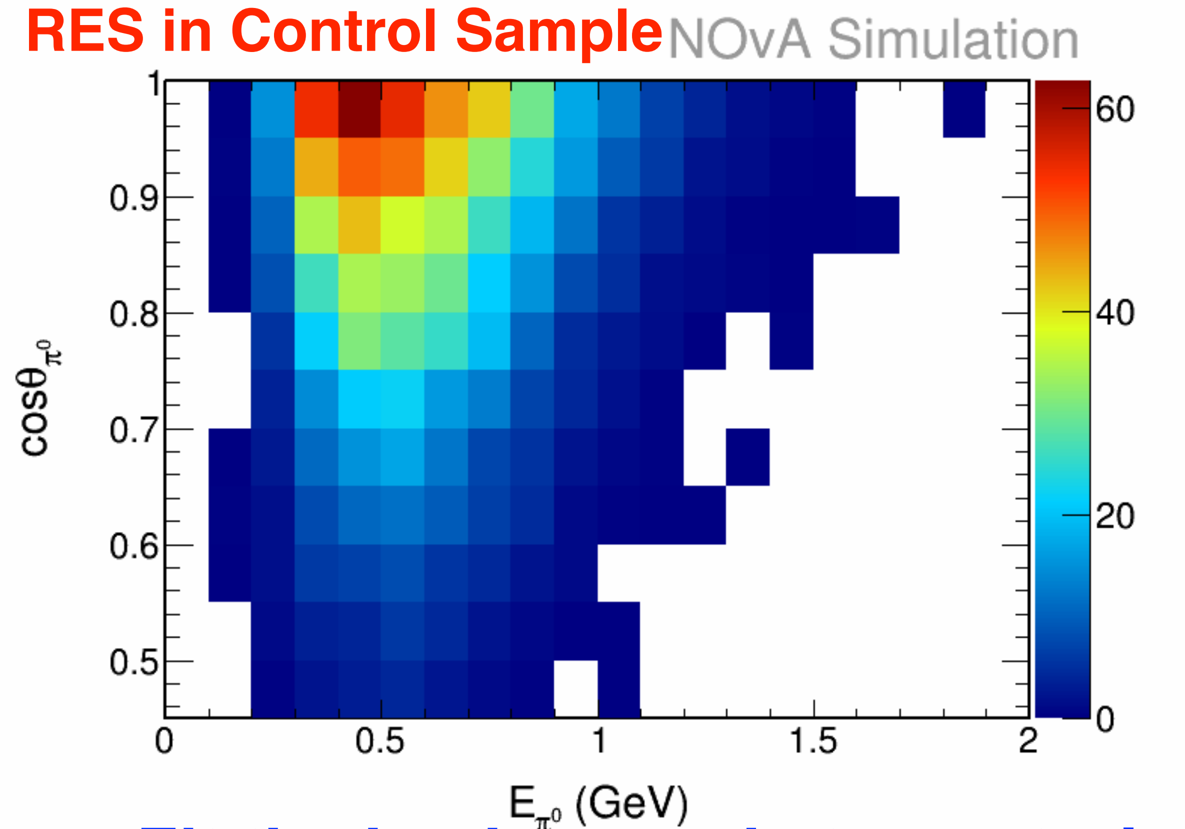


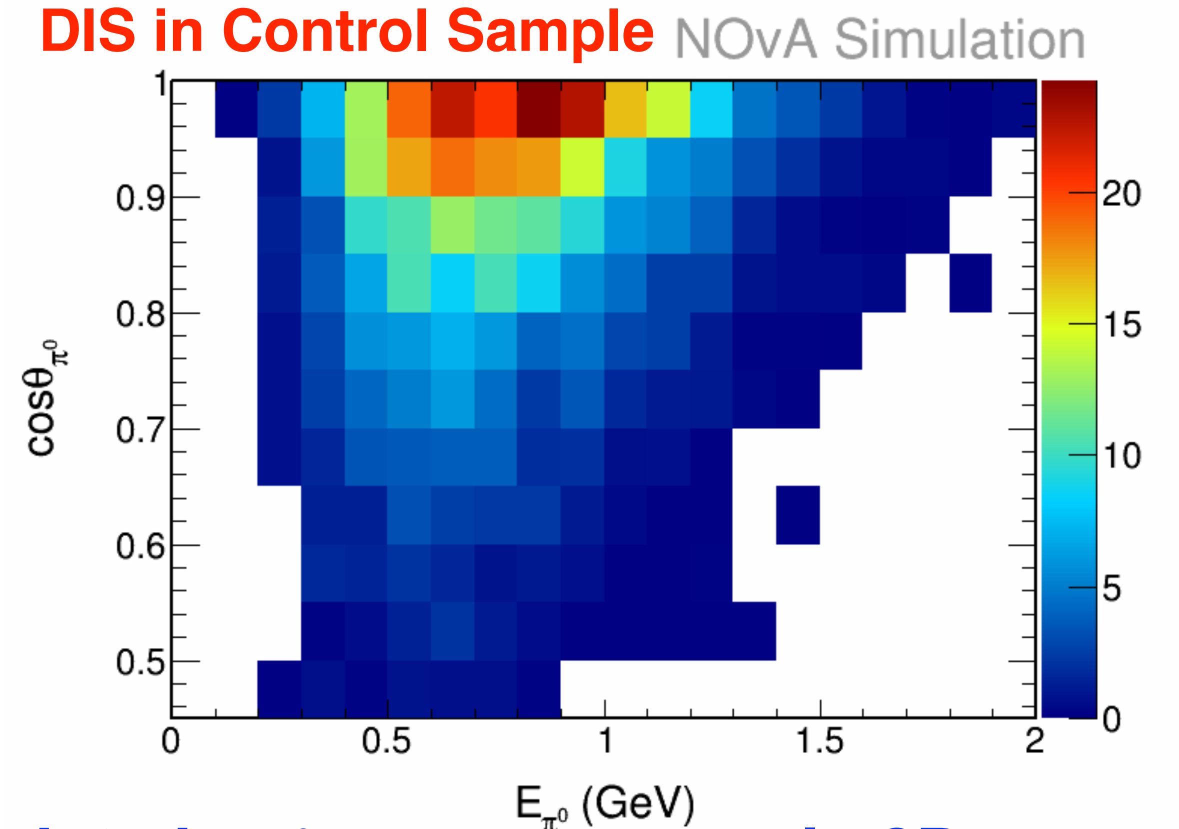
The control sample is used to fit background to data in π^0 energy vs angle 2D space.





Background Fit

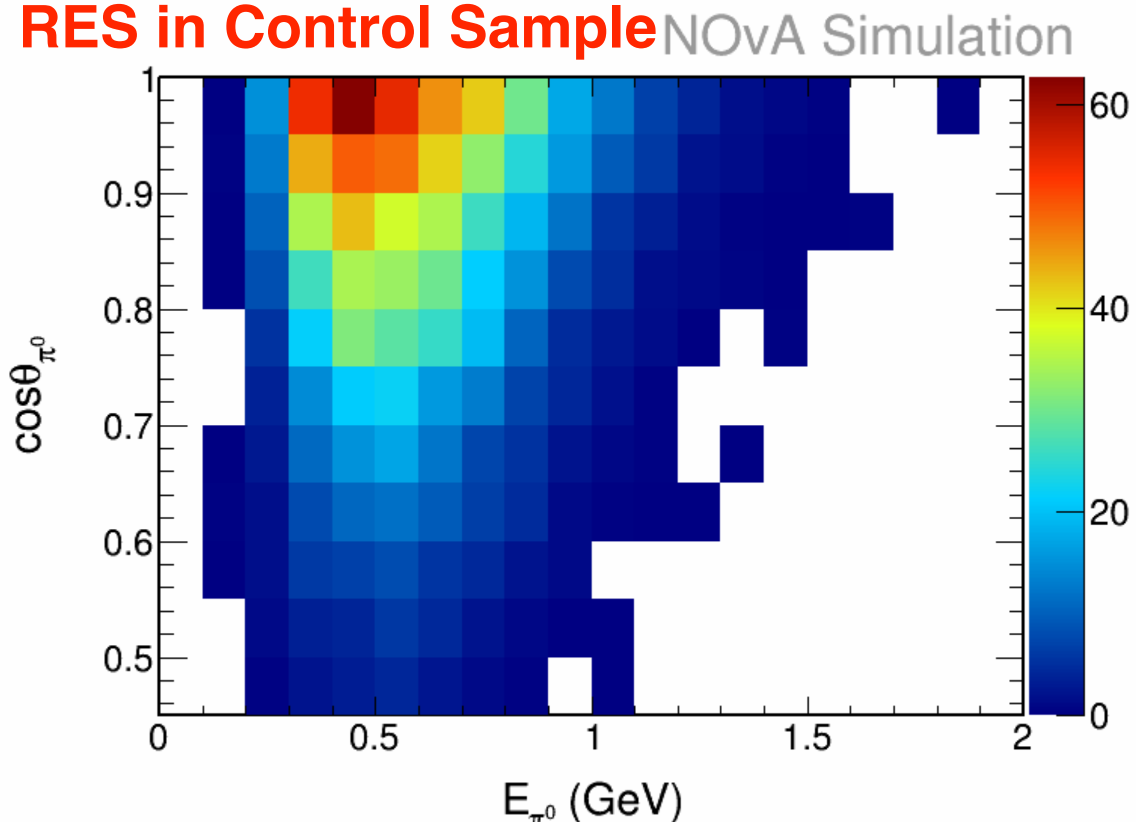




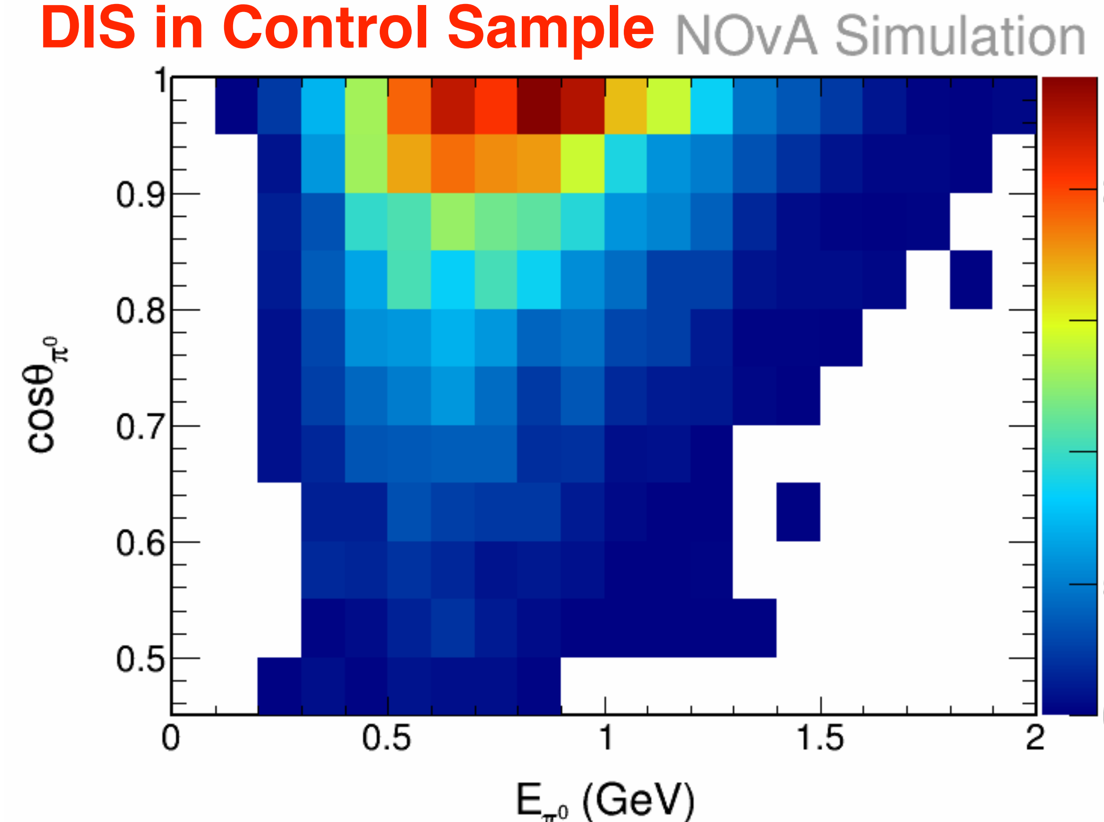
- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

Background Fit

RES in Control Sample

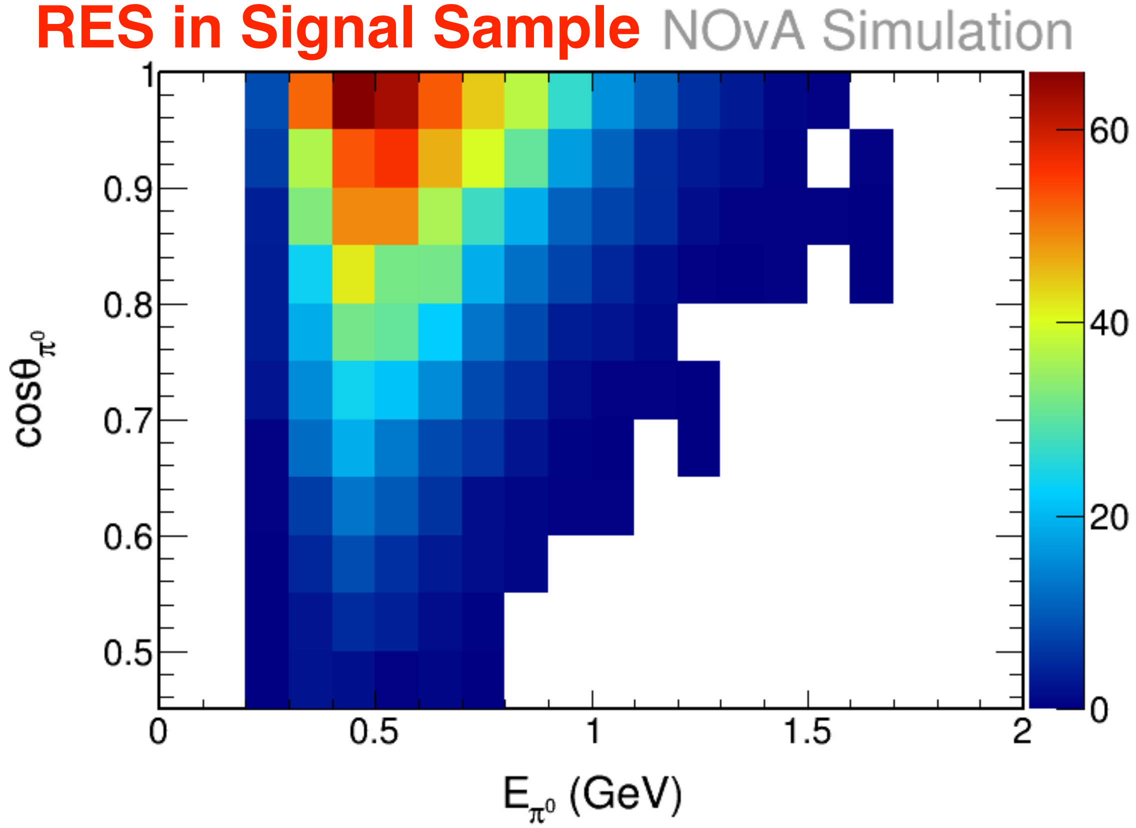


DIS in Control Sample

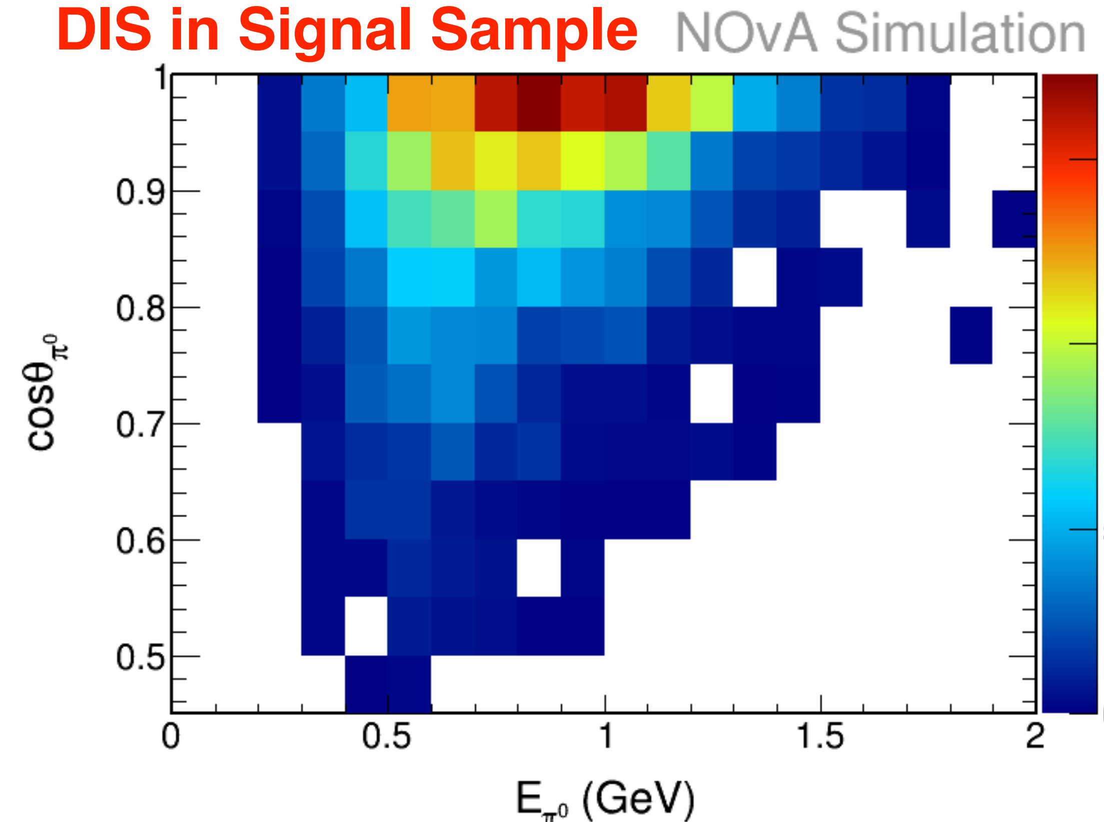


- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

RES in Signal Sample

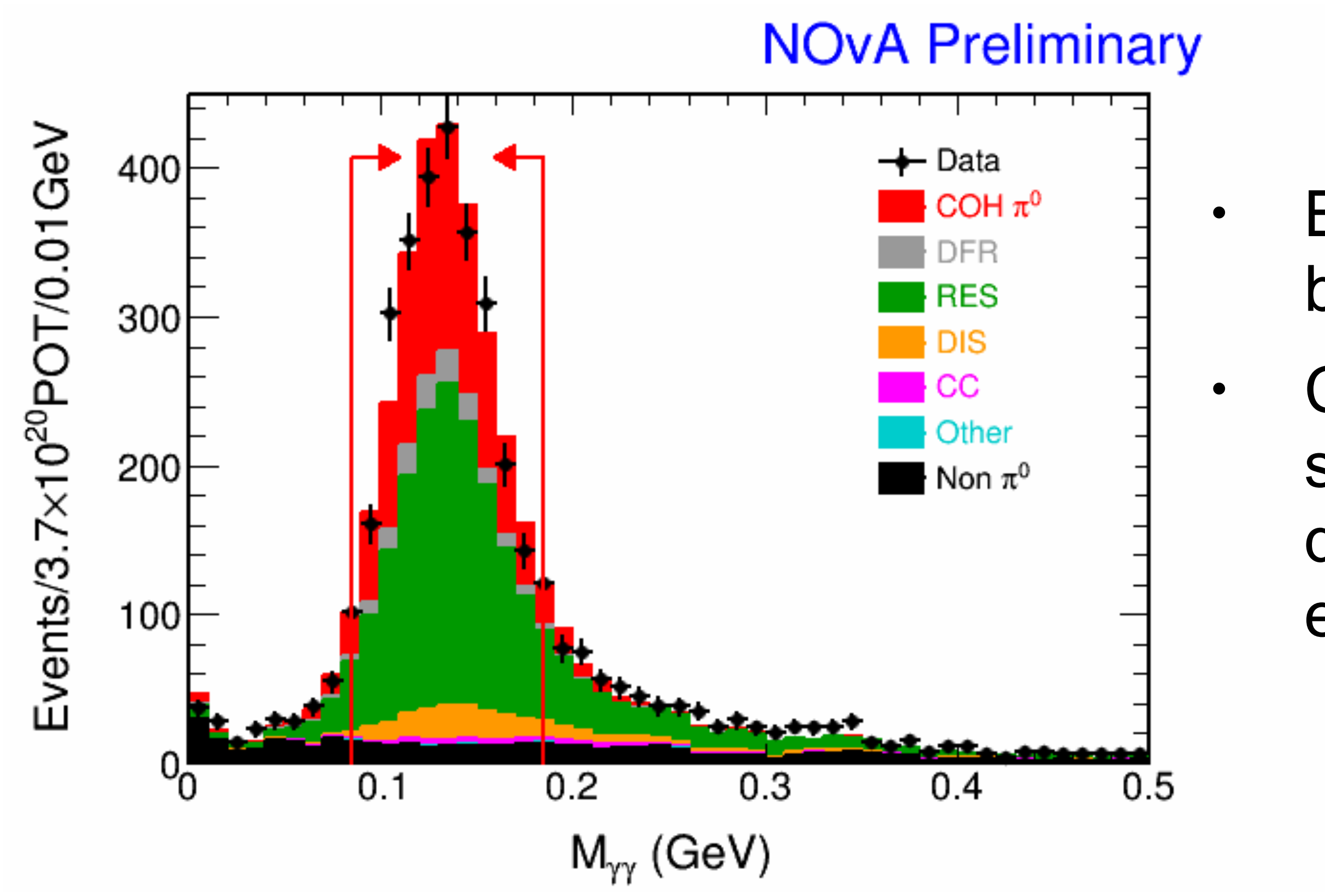


DIS in Signal Sample

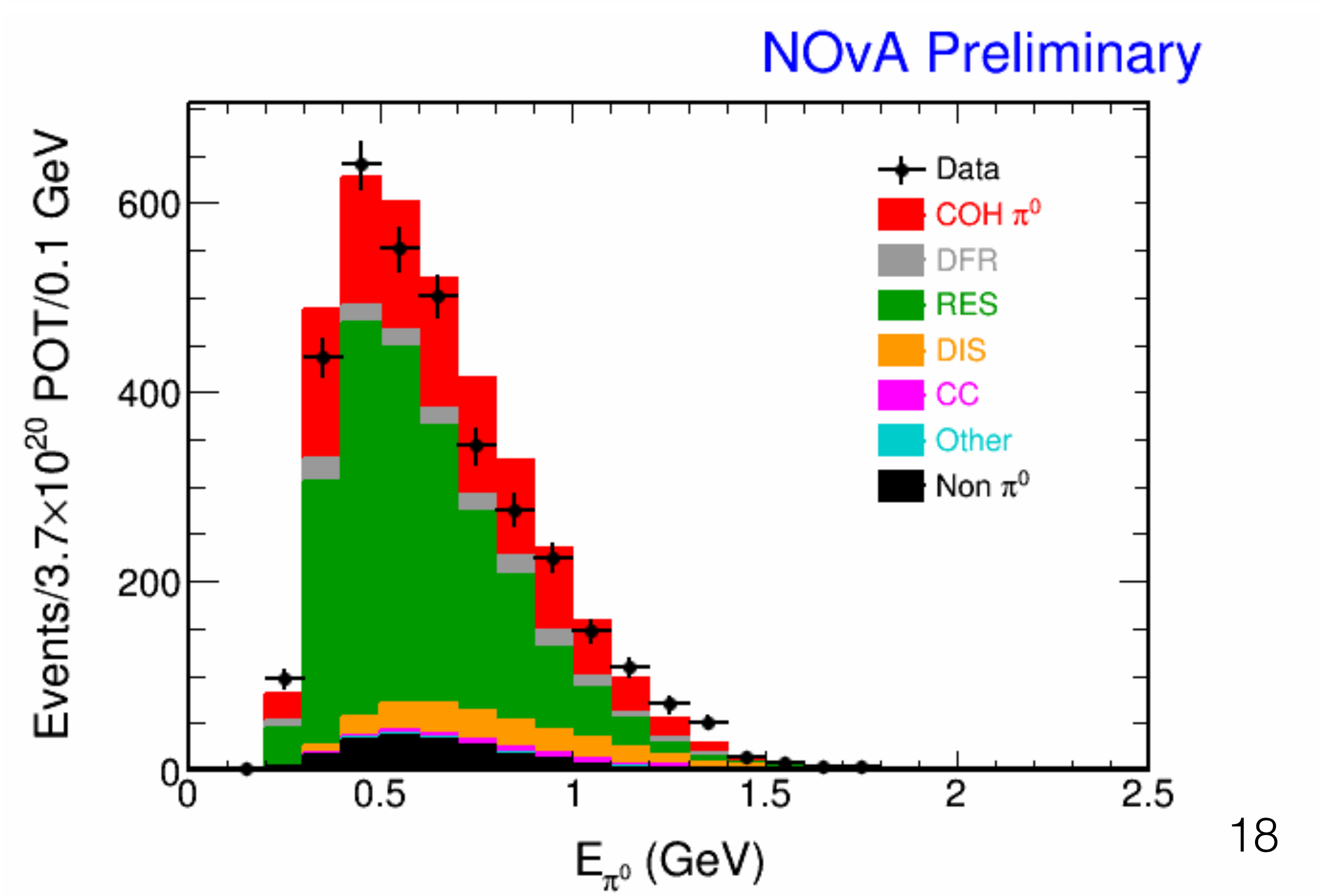


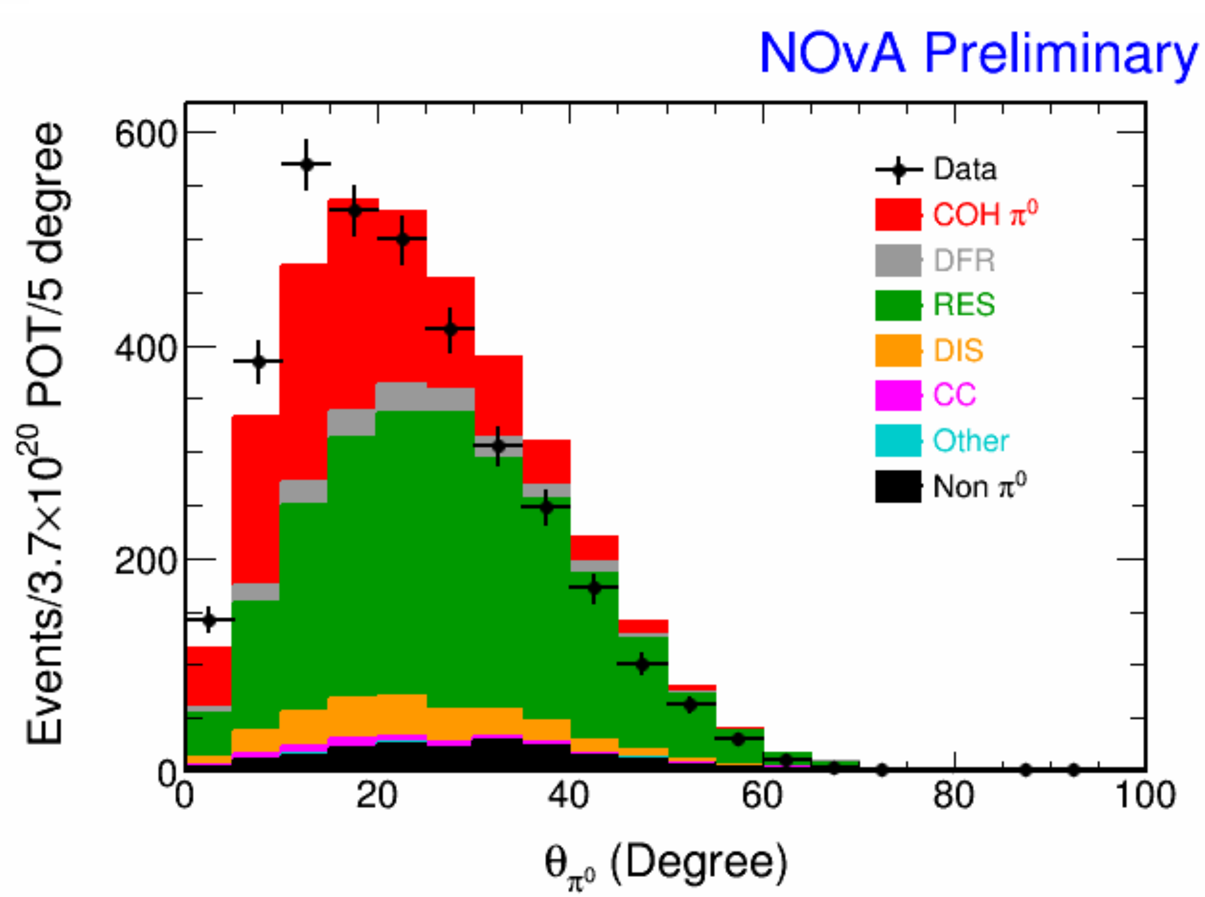
- **Apply the background tuning to the signal sample.**

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.





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, constrained by control sample data

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10.4% systematic uncertainty
from background modeling,
constrained by control sample data

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

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

Cross-Section Measurement And Uncertainties

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3.7% Uncertainty from
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Number of target nucleus

<1% uncertainty from
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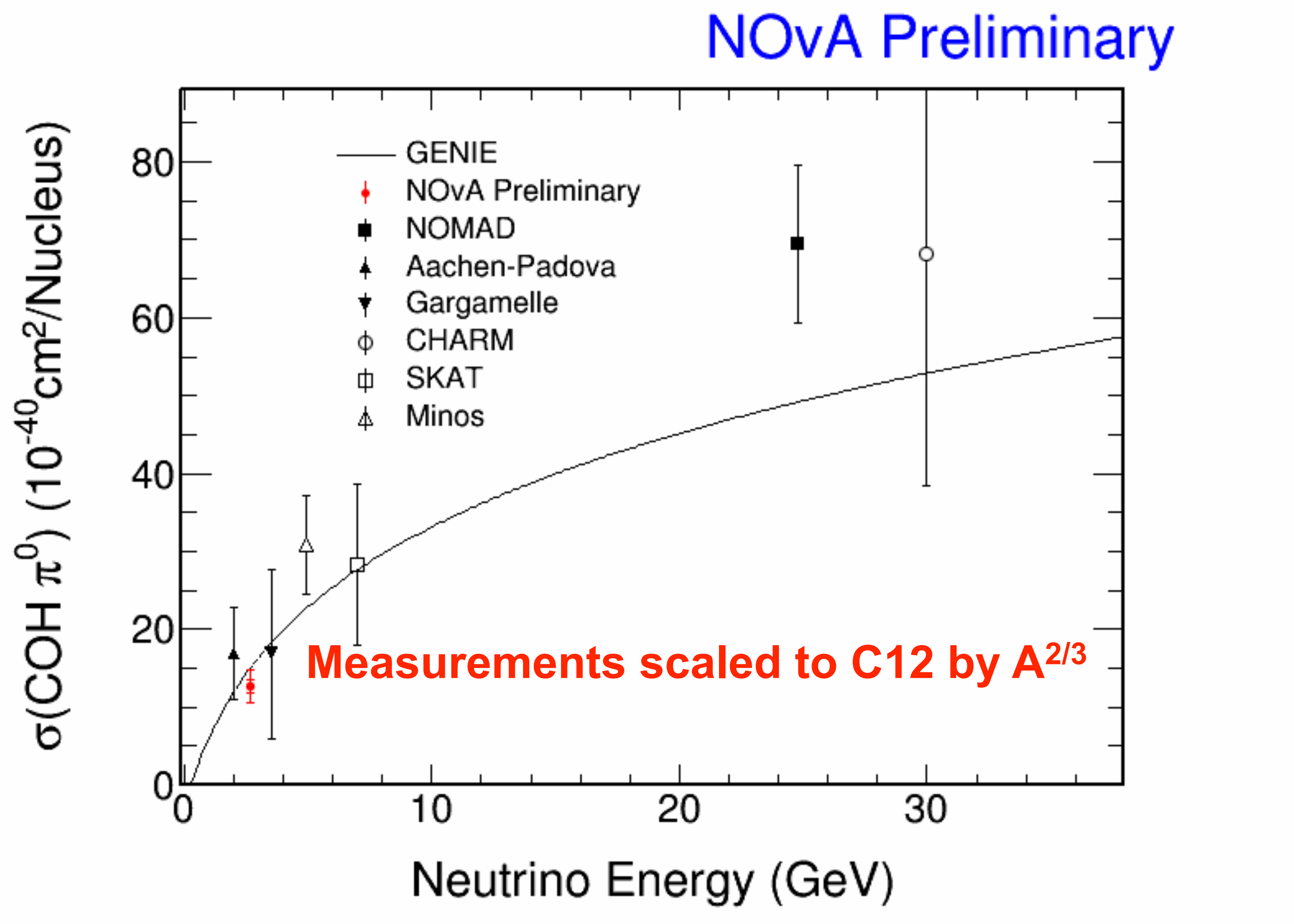
- **16.7% total uncertainty (stat + syst): a very competitive result.**

Cross Section Result



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

- Coherent signal measurement by subtracting normalized background from data in energy and angle 2D space.
- Measured flux-averaged cross-section:
  $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40}\text{cm}^2/\text{nucleus}$
- Total uncertainty is 16.7%, systematic dominant.

Summary

- Coherent is an important interaction mode for neutrino oscillation measurement, and also has its own physics interest.
- NOvA near detector is good for π^0 measurements.
- Large dataset leads to a small statistic uncertainty.
- Data-driven methods to constrain most of the systematic uncertainty.
- We measured the cross-section of NC coherent π^0:

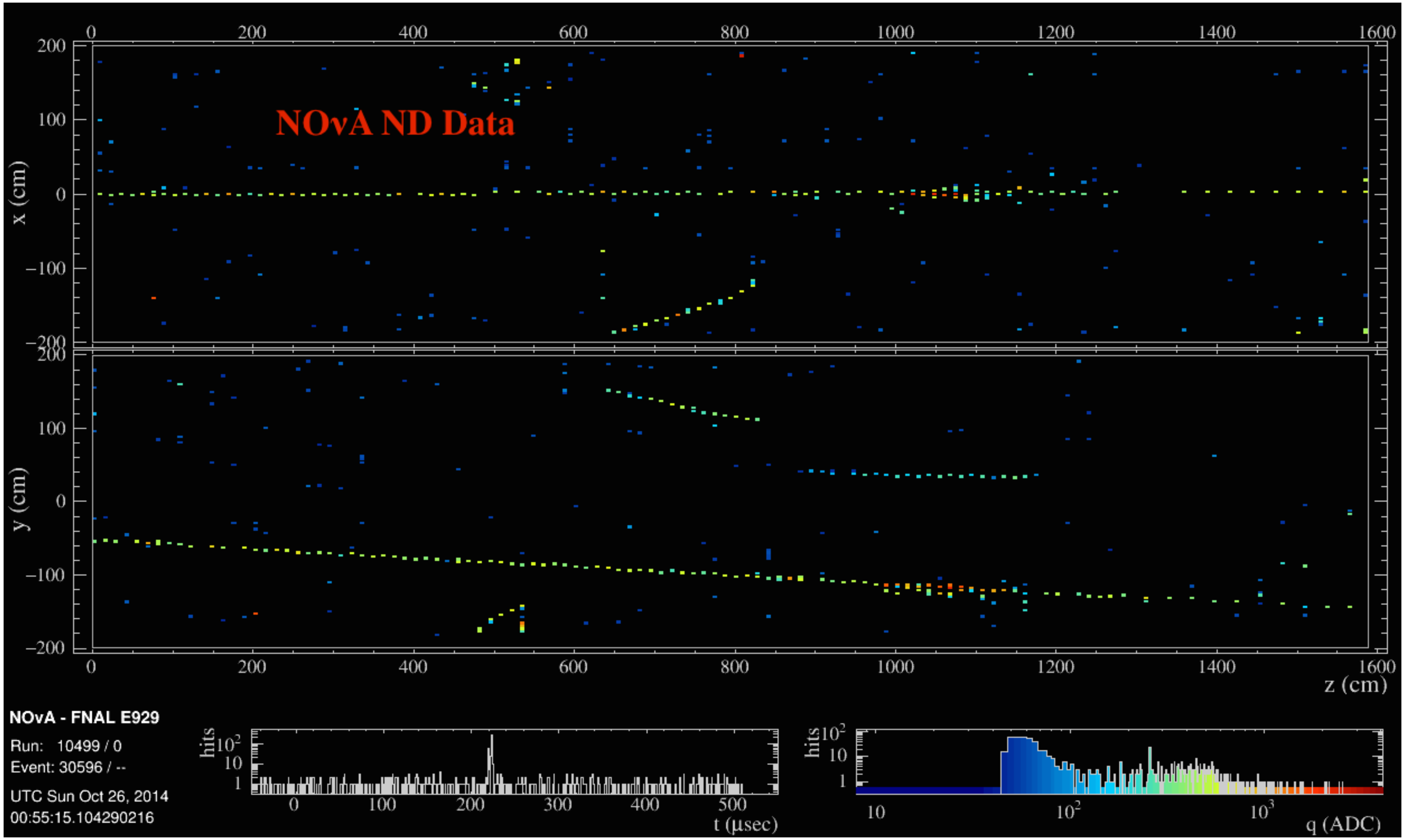
  $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40} \text{cm}^2/\text{nucleus}$

  Total uncertainty is 16.7%.
- A very precise measurement in the few-GeV region.

Thank you!

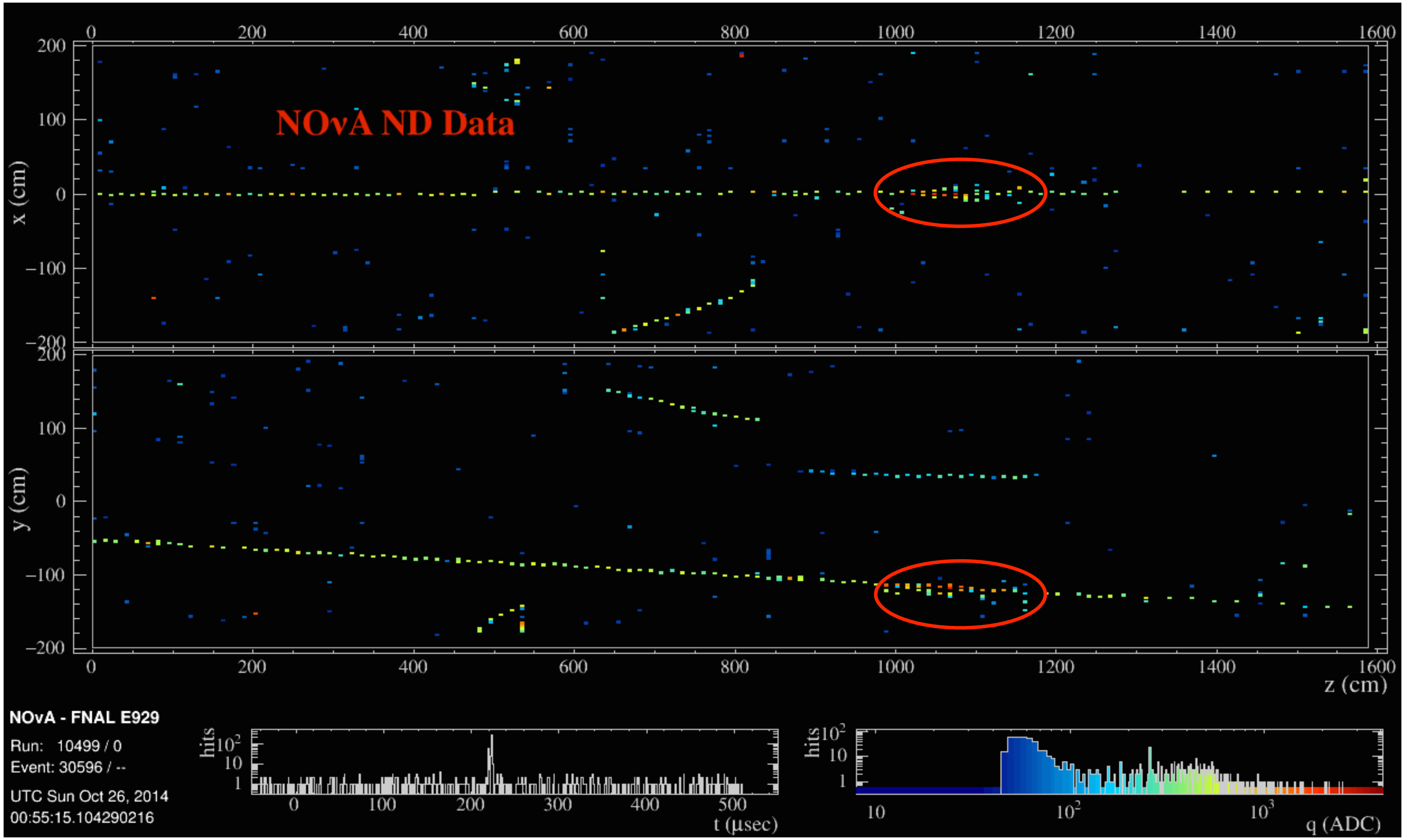
Back up slides

Muon-Removed Brem Showers



- Rock muons 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 check detector performance and benchmark EM shower modeling and likelihoods.

Muon-Removed Brem Showers



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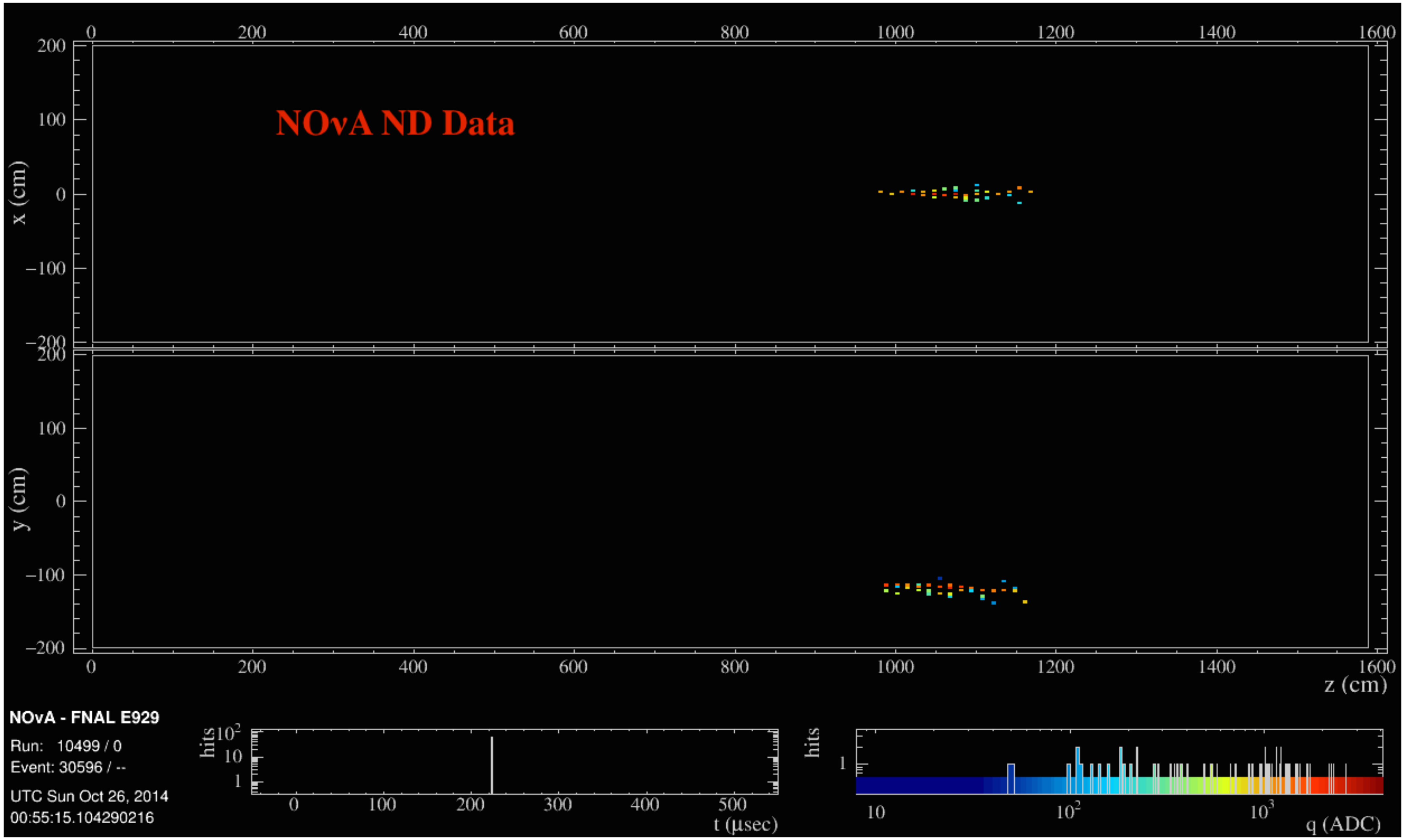

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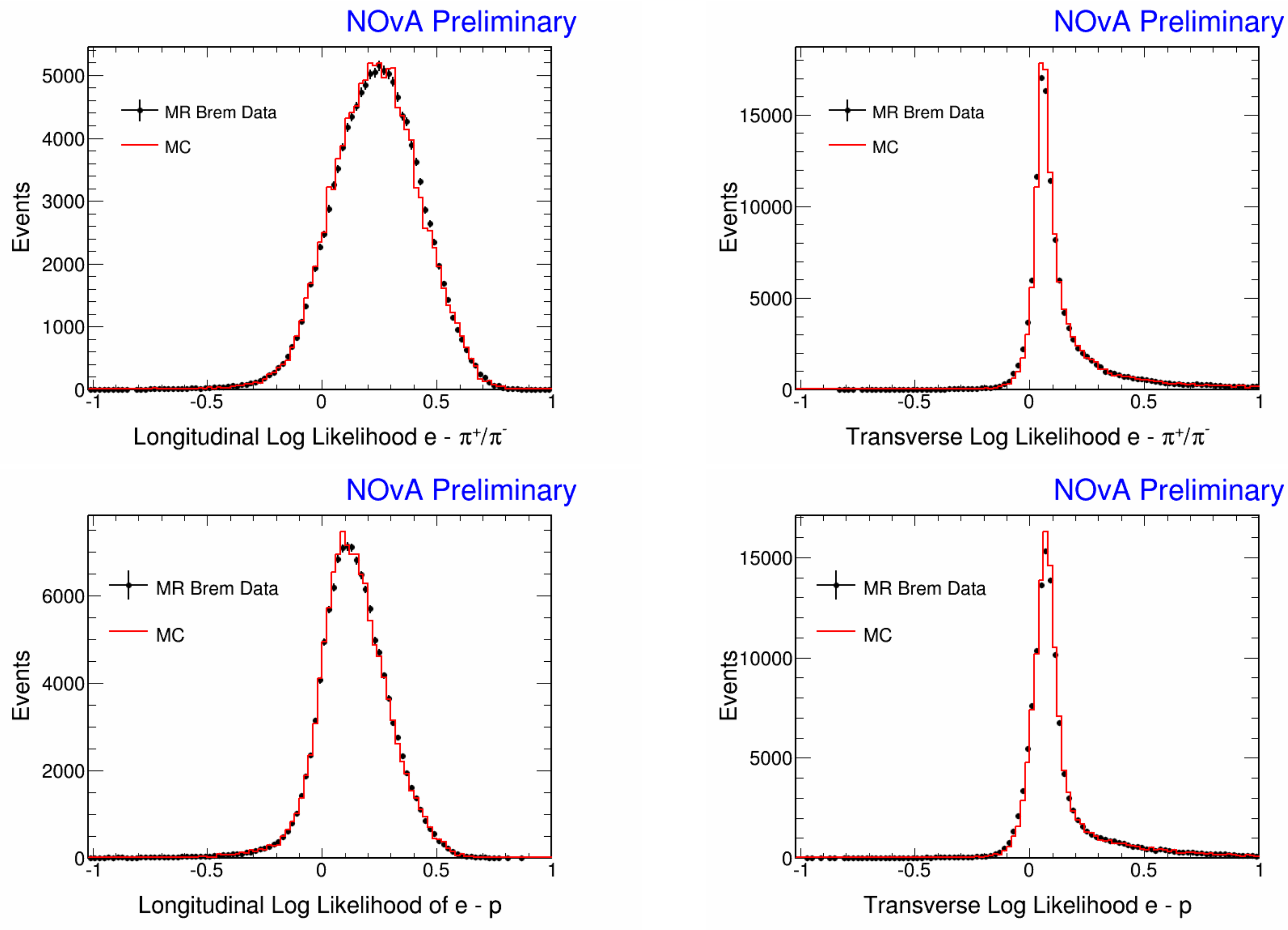
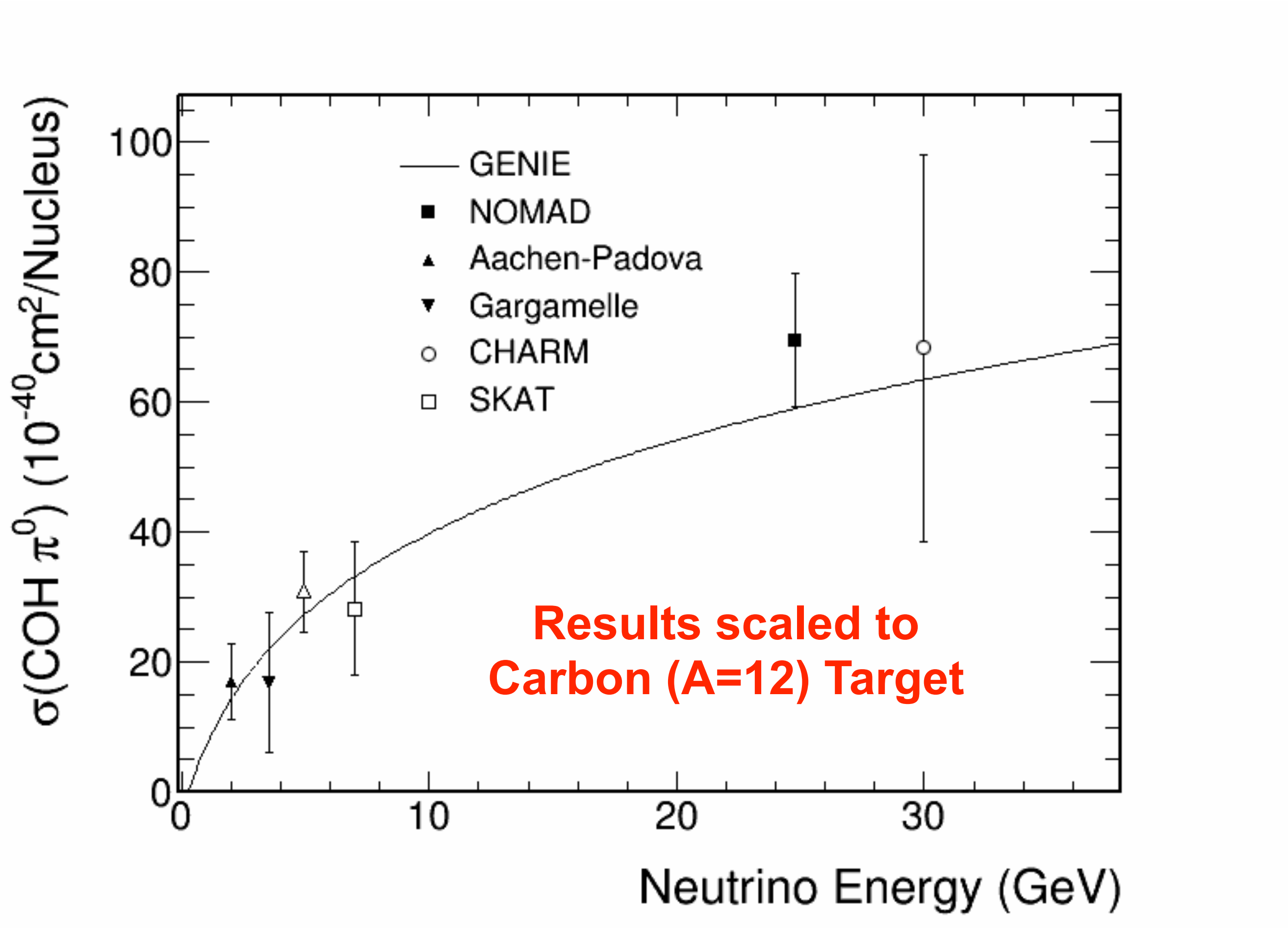


- Muon-Removed Brem showers provide a photon control sample to benchmark the modeling and selection efficiency of EM showers.
- Very good agreement between data and MC.
- **1%** difference in selection efficiency taken into systematic uncertainty.

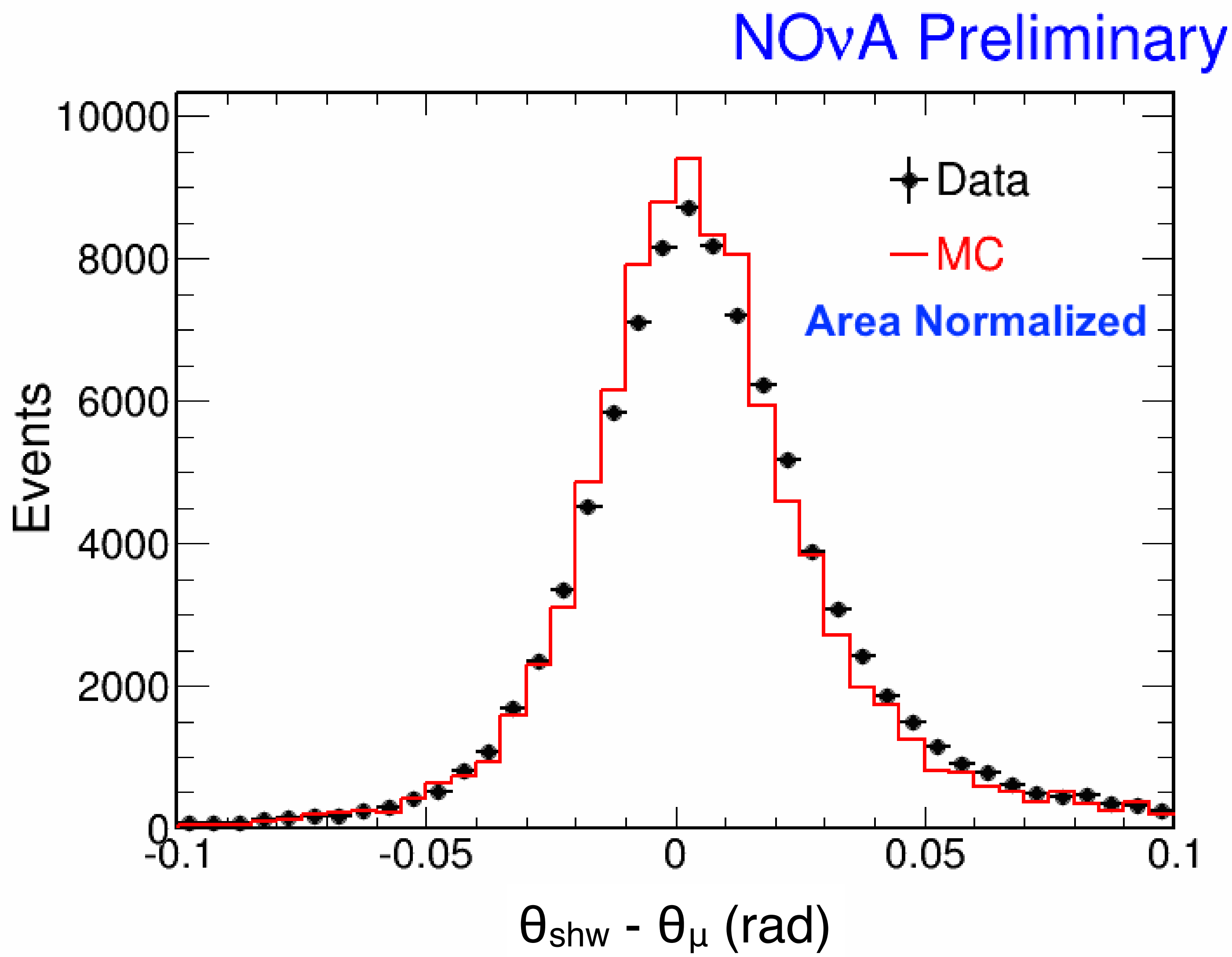
Coherent π^0: World Measurement



There are relatively few coherent π^0 measurement, most suffer from large uncertainty.

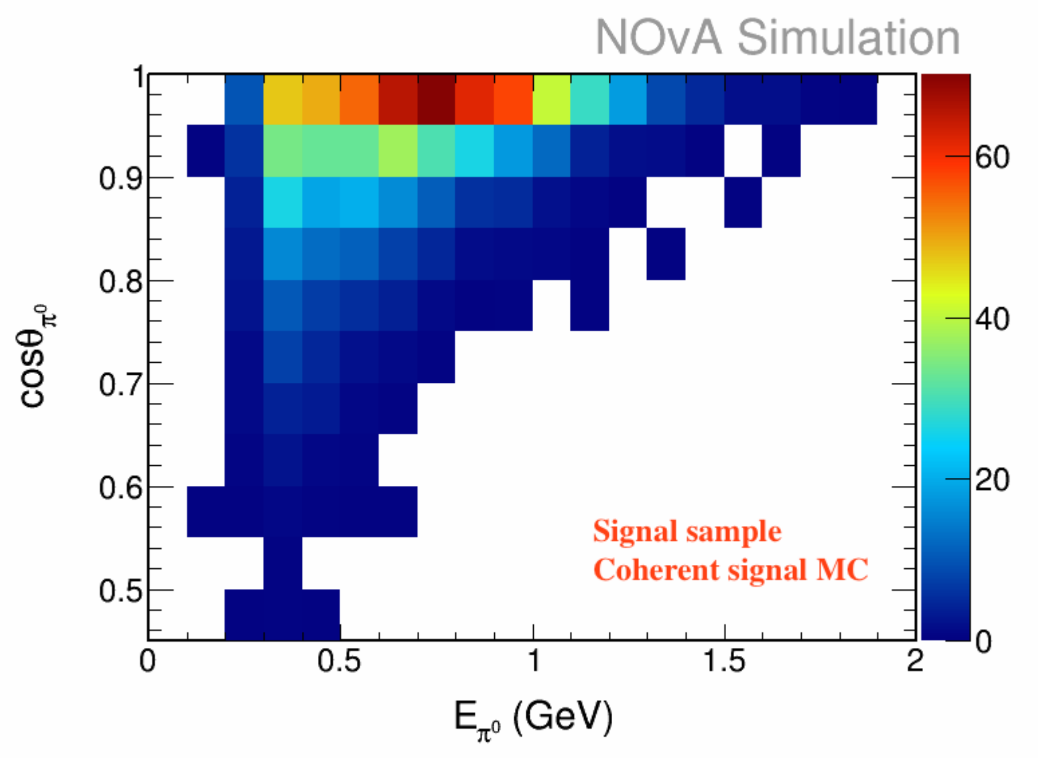
Experiments	A	$< E_\nu >$ (GeV)	σ $(10^{-40} cm^2/N)$	$\sigma/\sigma(\nu_\mu$-CC)	σ/σ(RS)
Aachen-Padova	27	2	29±10		
Gargamelle	31	3.5	31±20		
CHARM	20	30	96±42		
SKAT	30	7	79±28	4.3±1.5	
15' BC	20	20		0.20±0.04	
NOMAD	12.8	24.8	72.6±10.6	3.21±0.46	
MiniBooNE	12	0.8			0.65±0.14
SciBooNE	12	0.8			0.9±0.20
MINOS	48	4.9	$77.6^{+15.8}_{-17.5}$		

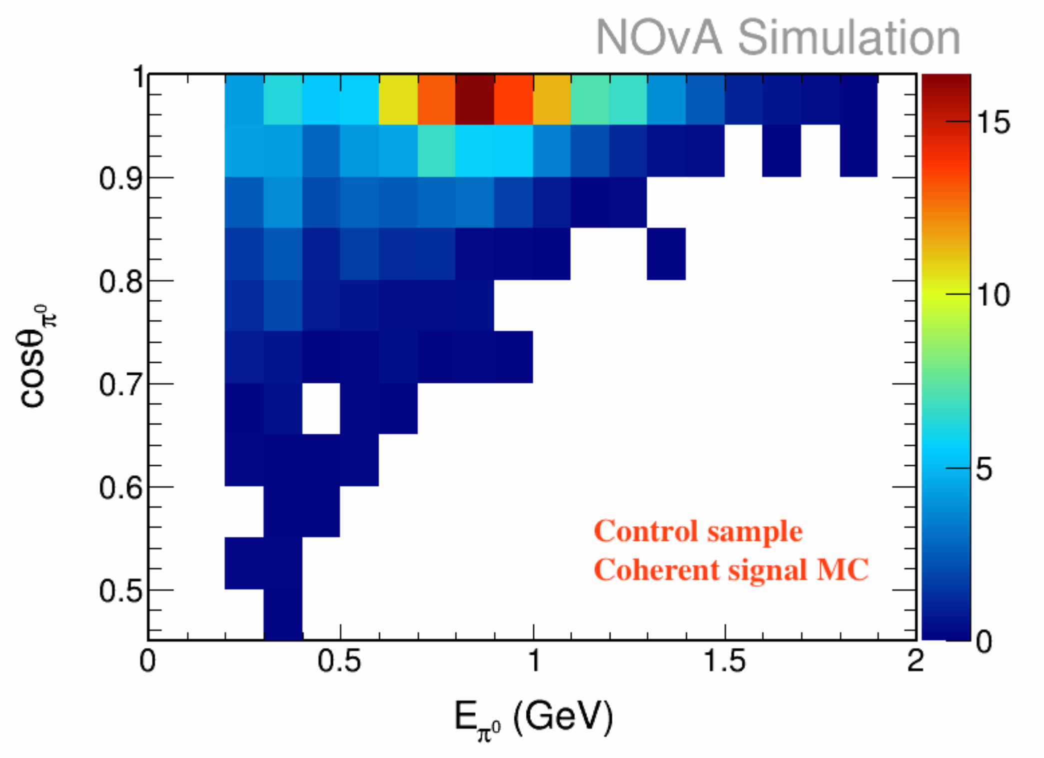
EM Shower Angular Resolution

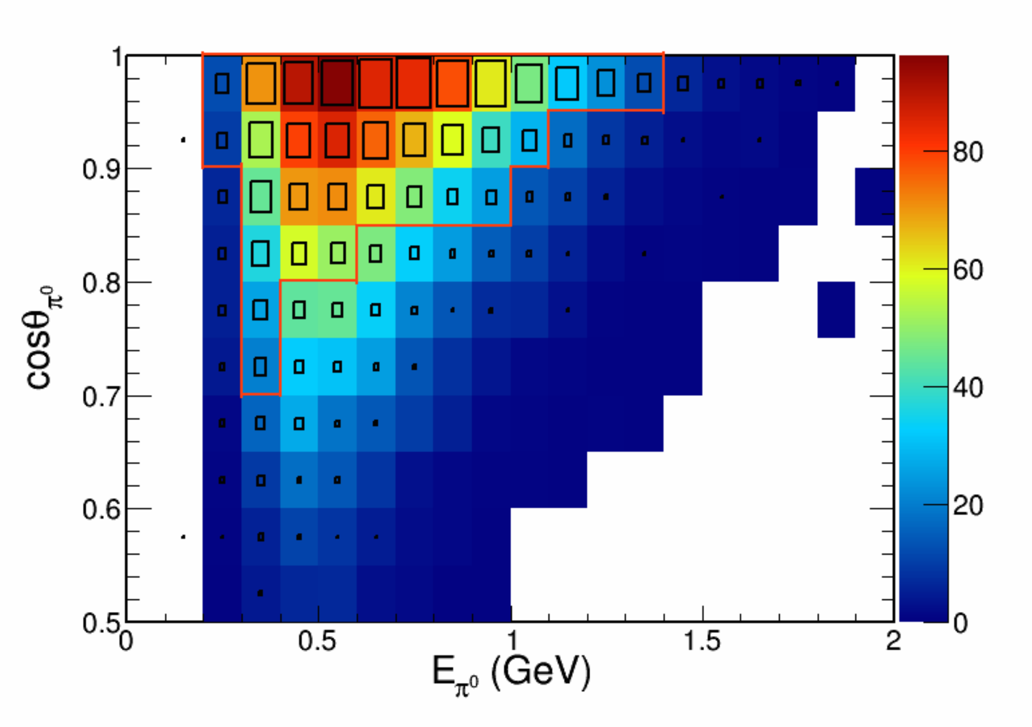


- A "measured" angular resolution in data by comparing the reconstructed EM shower direction to the muon direction.
- **The NOvA ND has good angular resolution (~0.02rad) for EM shower measurement.**
- Important to the coherent π^0 cross-section measurement.

NC Coherent π^0

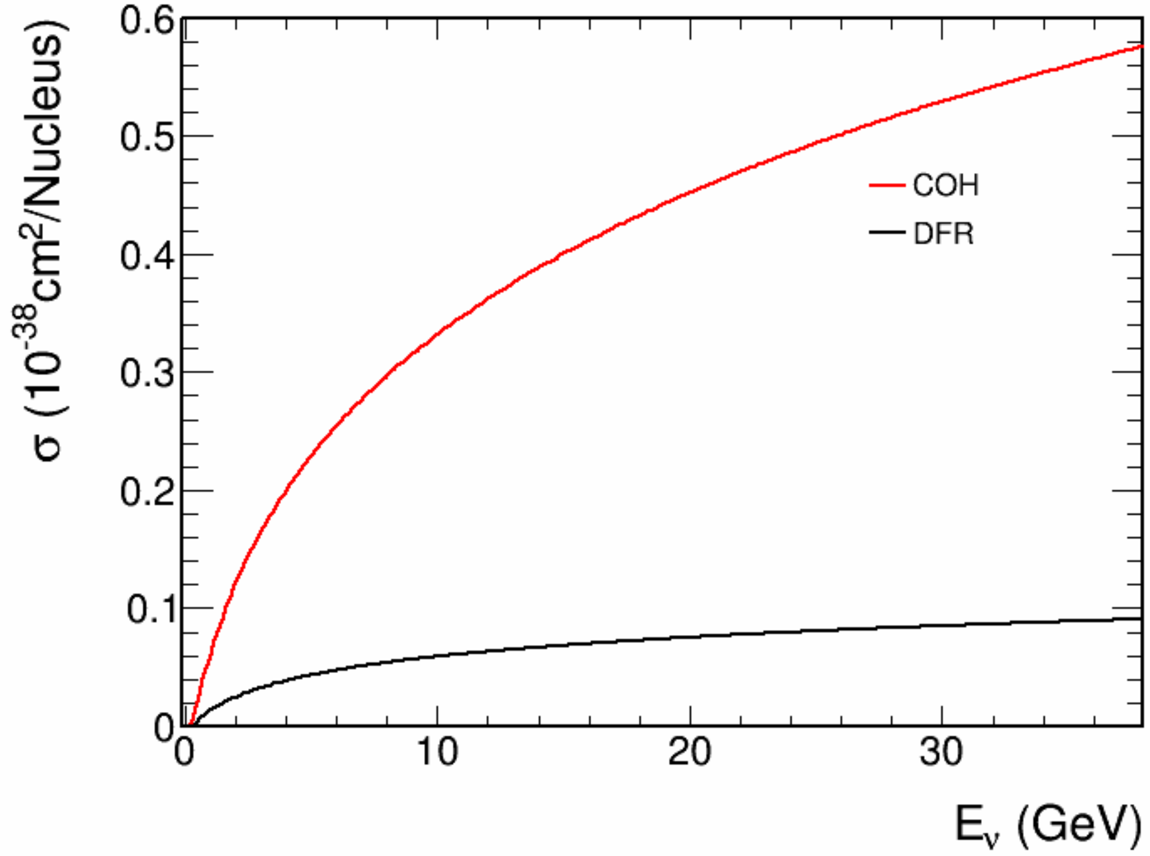




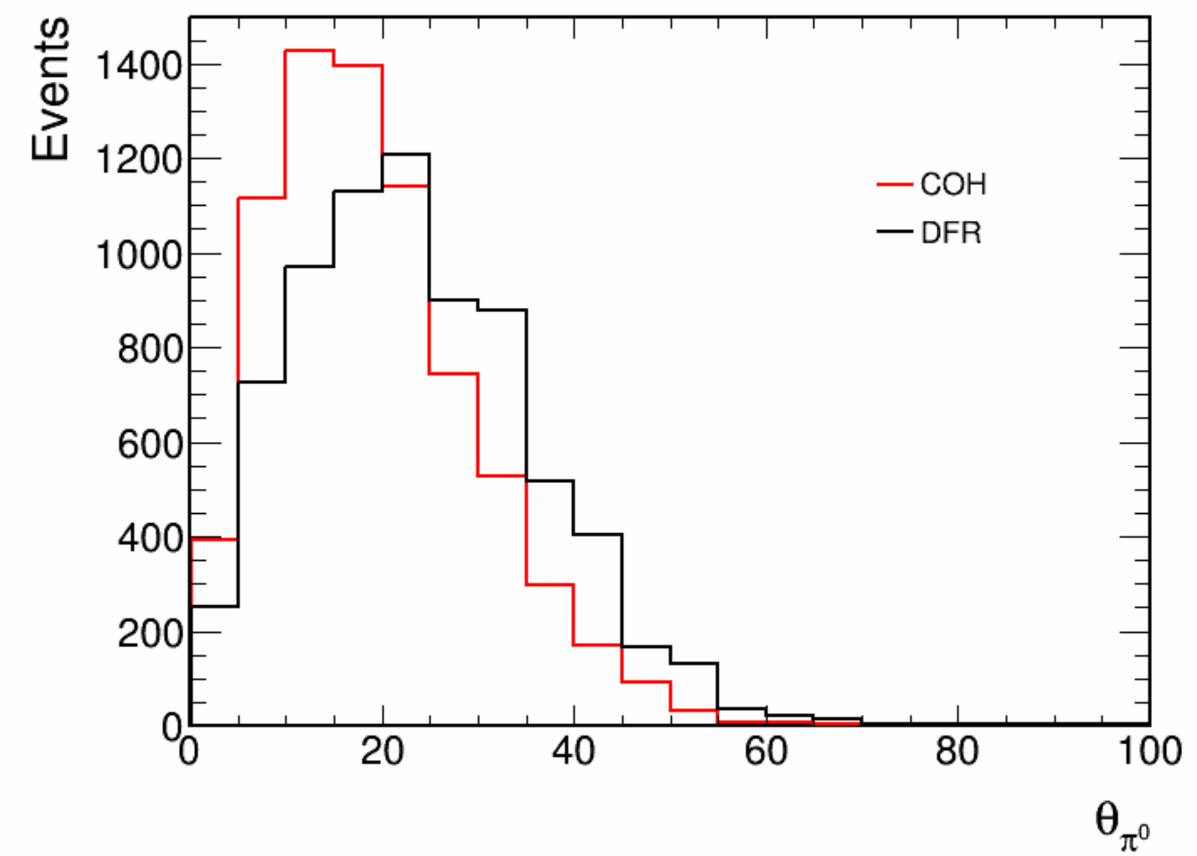


- Select the coherent region in energy vs angle 2D space

DFR π^0

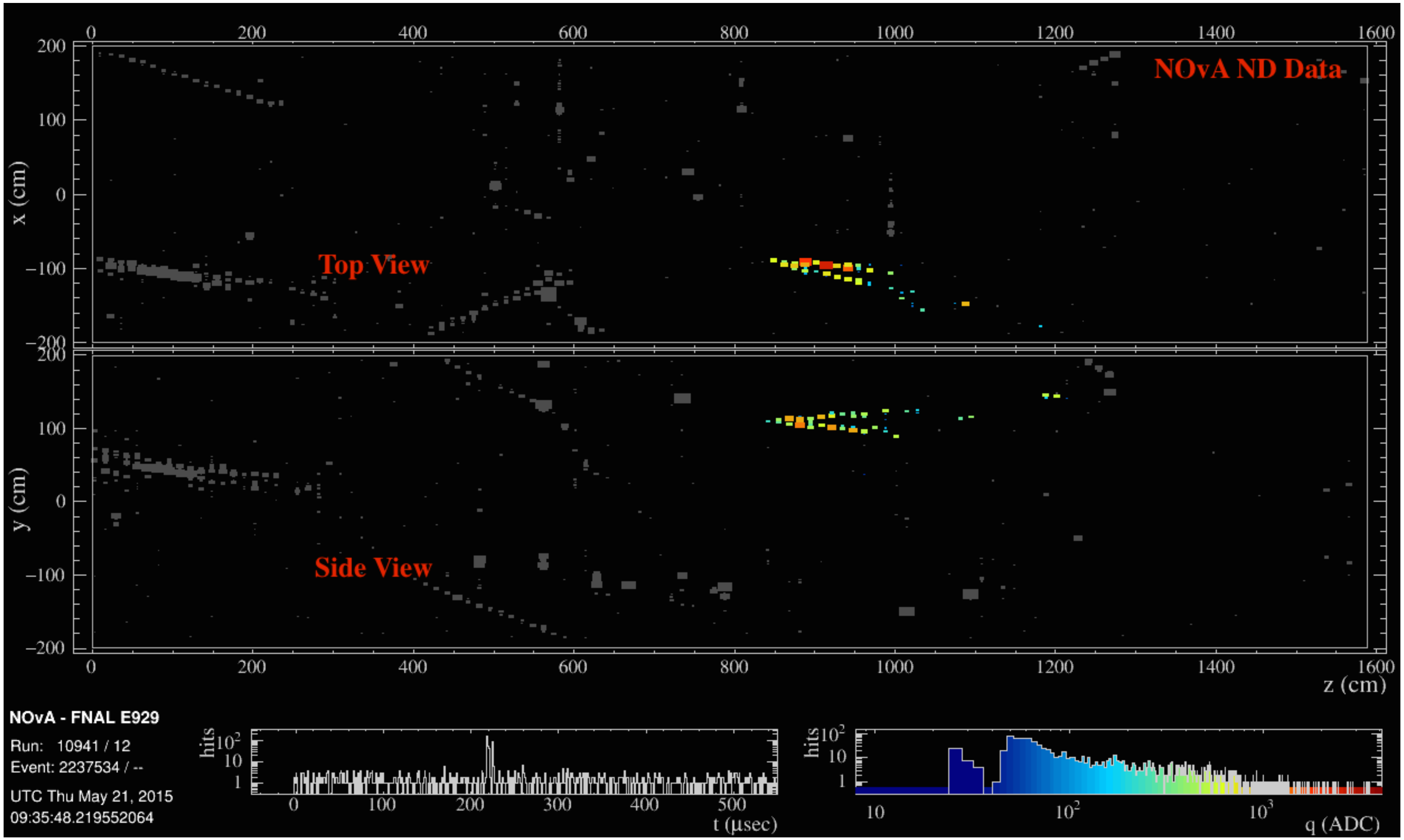


σ (10^-38 cm^2/Nucleus)
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
E_ν (GeV)
COH
DFR



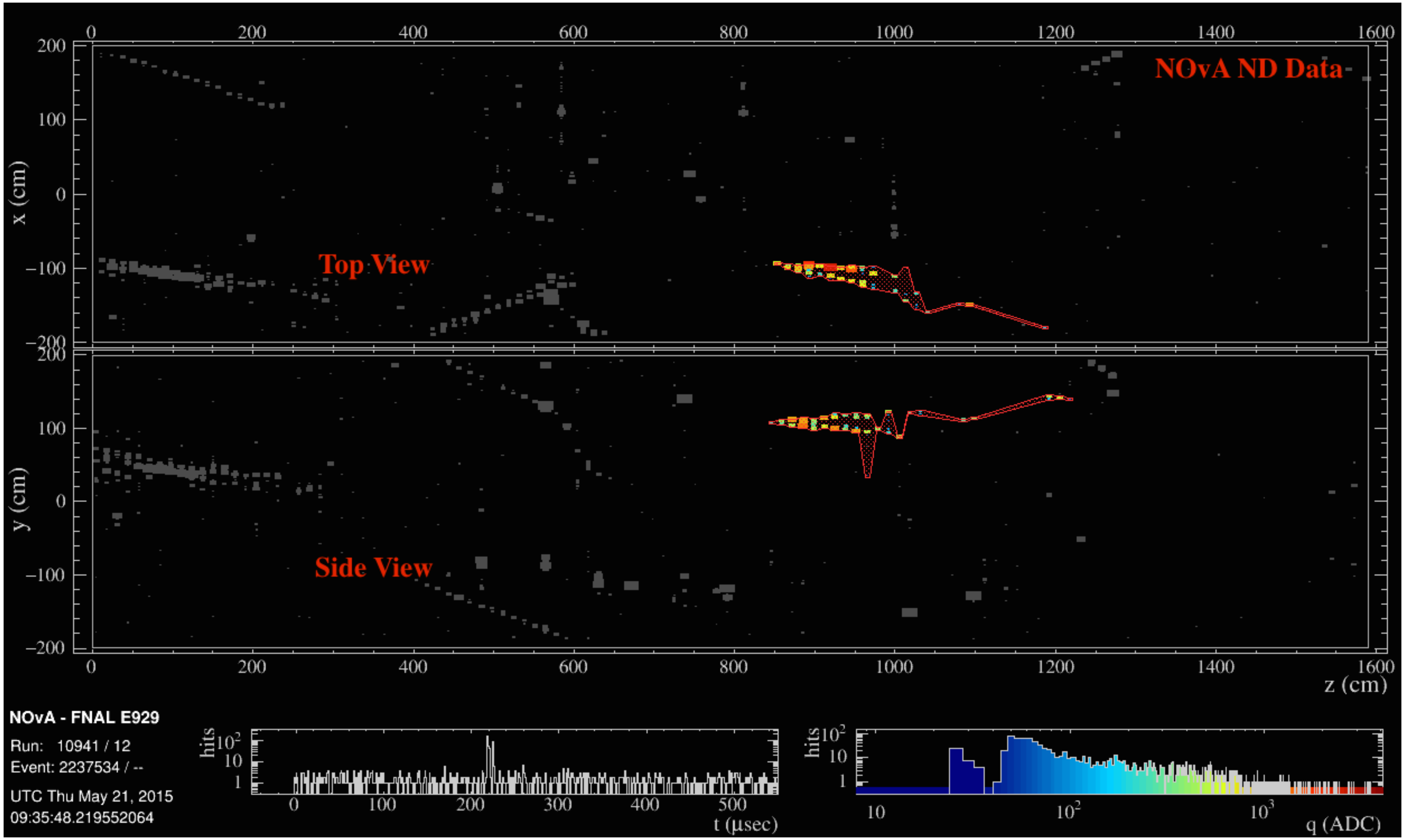
Events
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
θ_π0
COH
DFR

Coherent π^0 Candidate in the NOvA ND



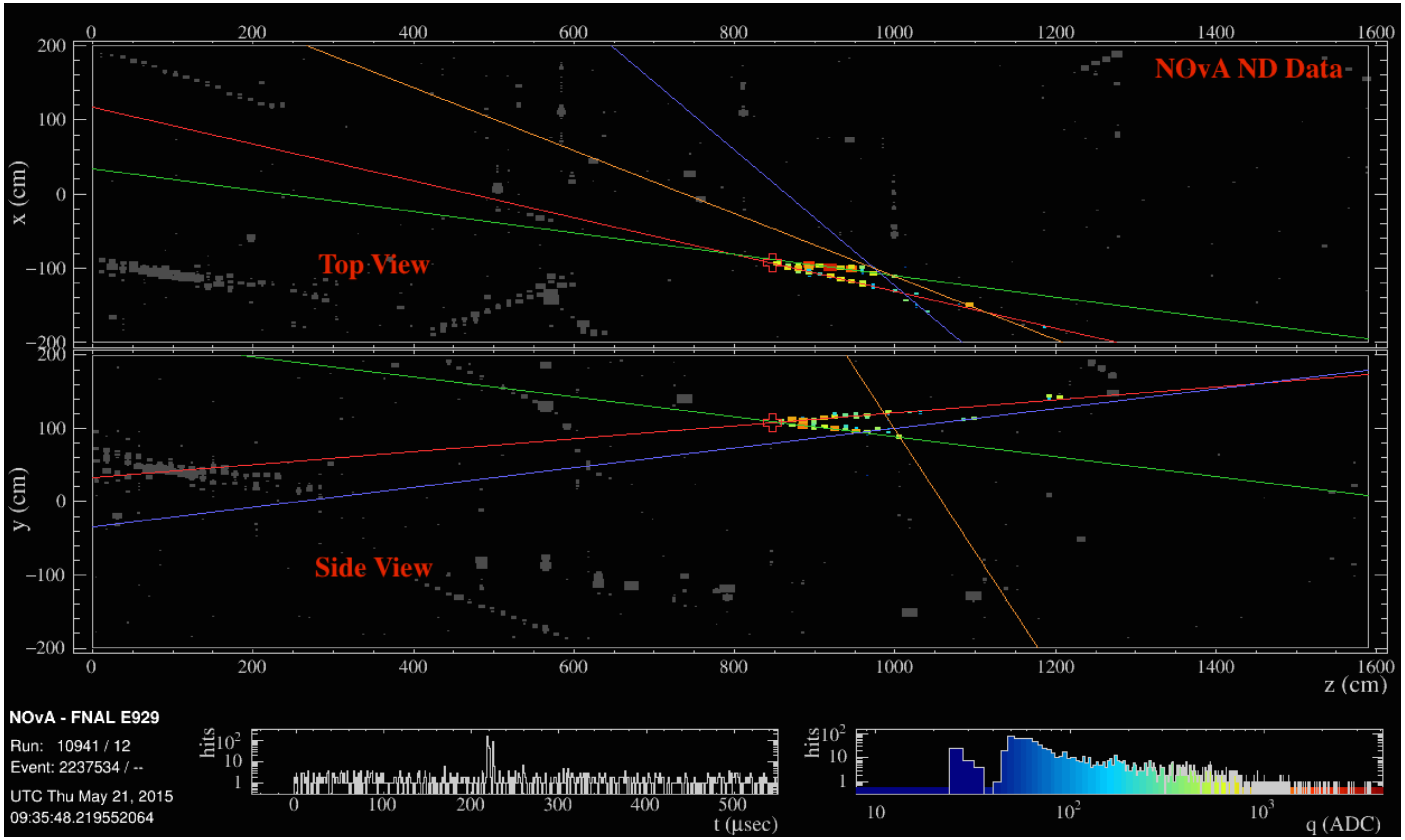
A coherent π^0 candidate events with 2 photons from π^0 decay.

Reconstruction: Slicing



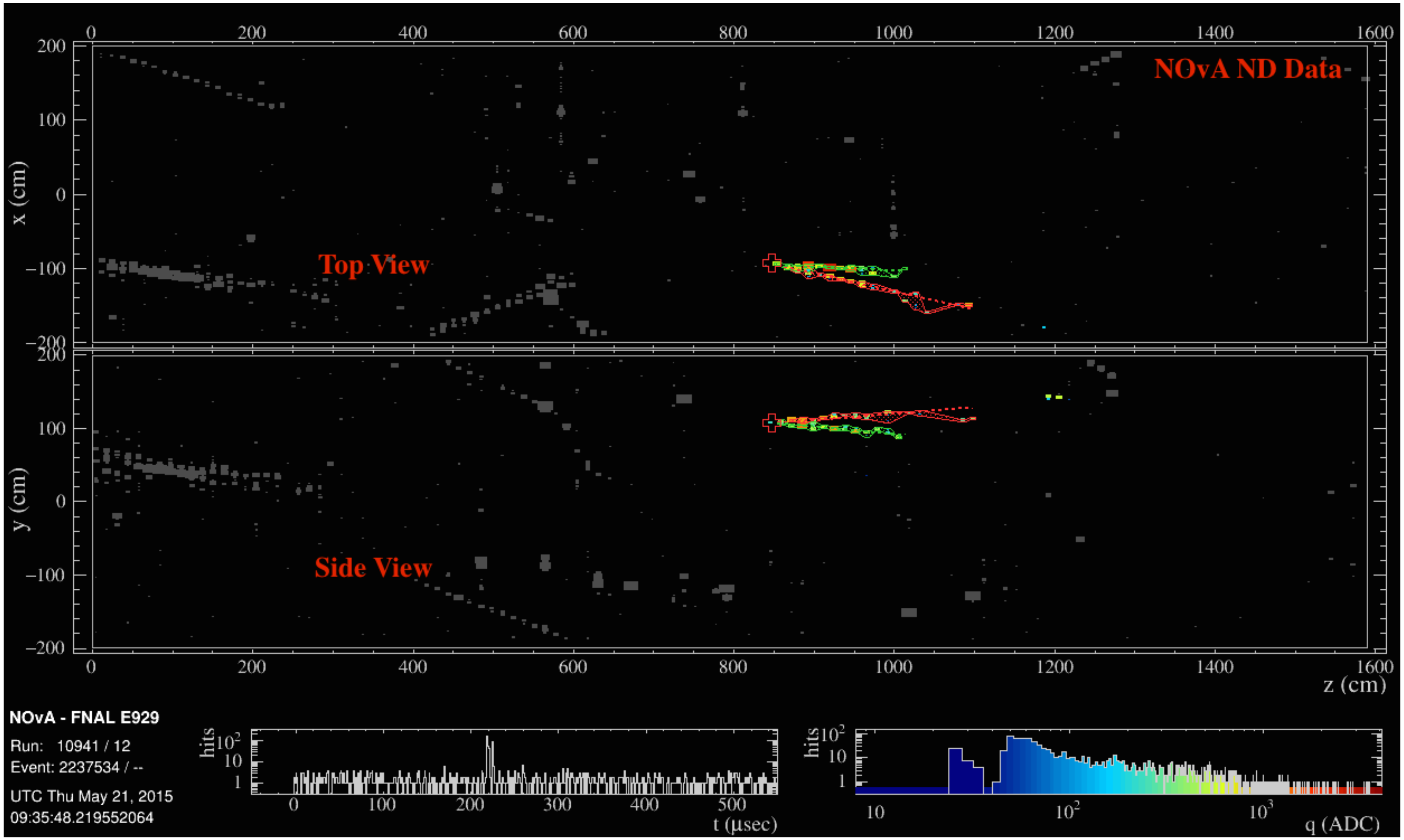
Group hits together in time and space for each neutrino interaction.

Reconstruction: Vertexing



Find particle paths, and use the intersection to form vertex

Reconstruction: Clustering



Group hits from each shower together using clustering algorithm.