π^0 Results and Status of the ν_μ CC Inclusive Measurements

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For the NOvA Collaboration

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NuINT-2018 International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

Outline

- Overview of the NOvA ND cross-section program.
- π^0 measurements:
  - NC Coherent π^0
  - ν_μ CC π^0
- ν_μ CC inclusive analysis status.

Introduction

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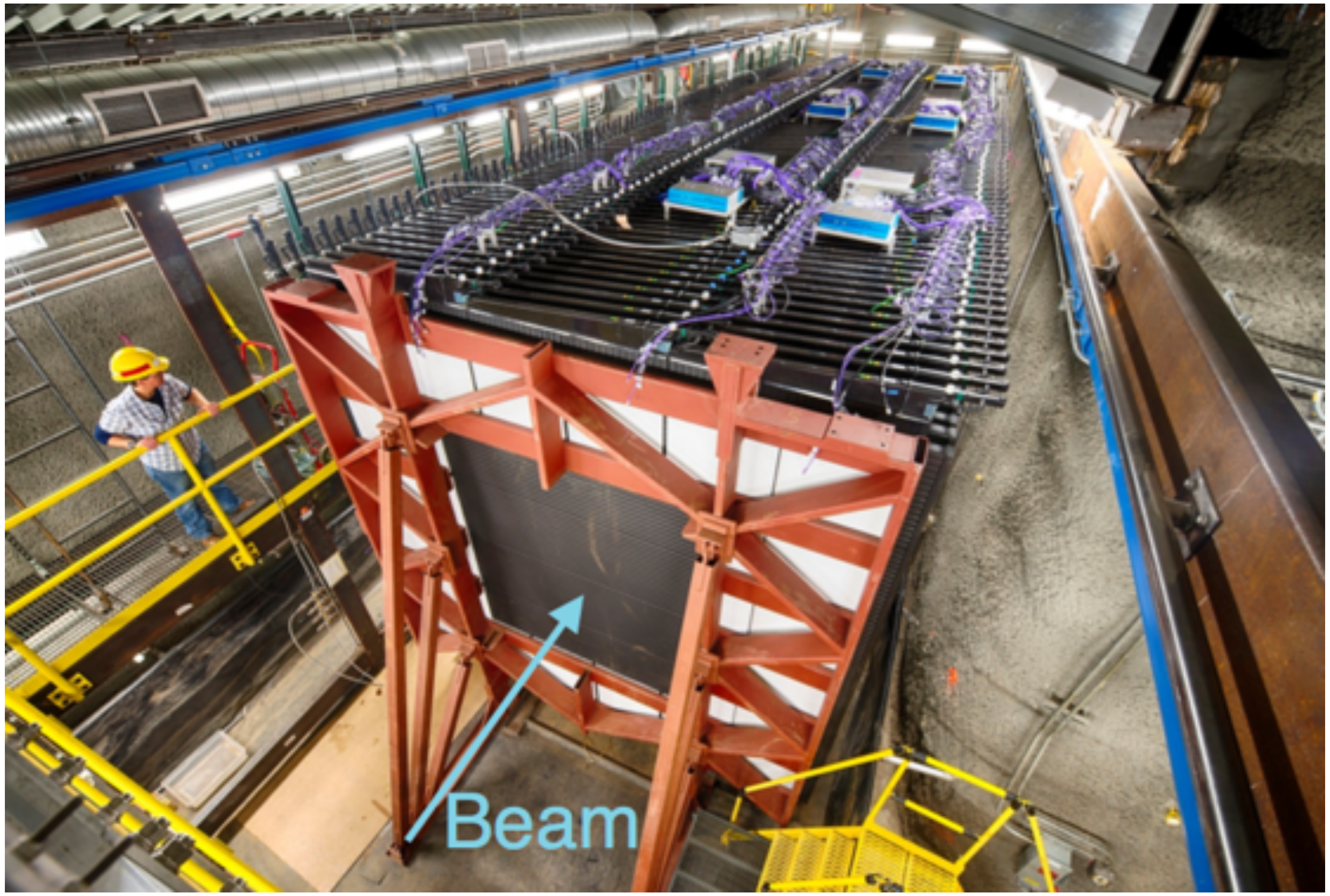
- NOvA is a long-baseline oscillation experiment to measure:
  - Mixing angle θ_{23}.
  - CP-violating phase.
  - Mass hierarchy determination.



- The ND provides an excellent opportunity to measure neutrino interaction cross sections with high statistics.

- With these measurements we can
  - Constrain our cross section systematics in the NOvA oscillation measurements.
  - Contribute to the current efforts of the neutrino community on understanding neutrino interactions.

Active NOvA Cross Section Analyses

- **Charged Current**
  - Inclusive ν_μ
  - Inclusive ν_e
  - $\nu_\mu \pi^0$ Inclusive
  - $\nu_\mu \pi^{+/-}$
  - ν_μ 0π
  - ν_μ 2p2h
  - ν-e flux constraint
- **Neutral Current**
  - Coherent π^0 Inclusive
  - π^0 Inclusive
- **+ Planned measurements using antineutrino beam**
  - Already active work on charged current analyses: inclusive $\bar{\nu}_\mu$, $\bar{\nu}_\mu \pi^0$,$\bar{\nu}_\mu$ 2p2h

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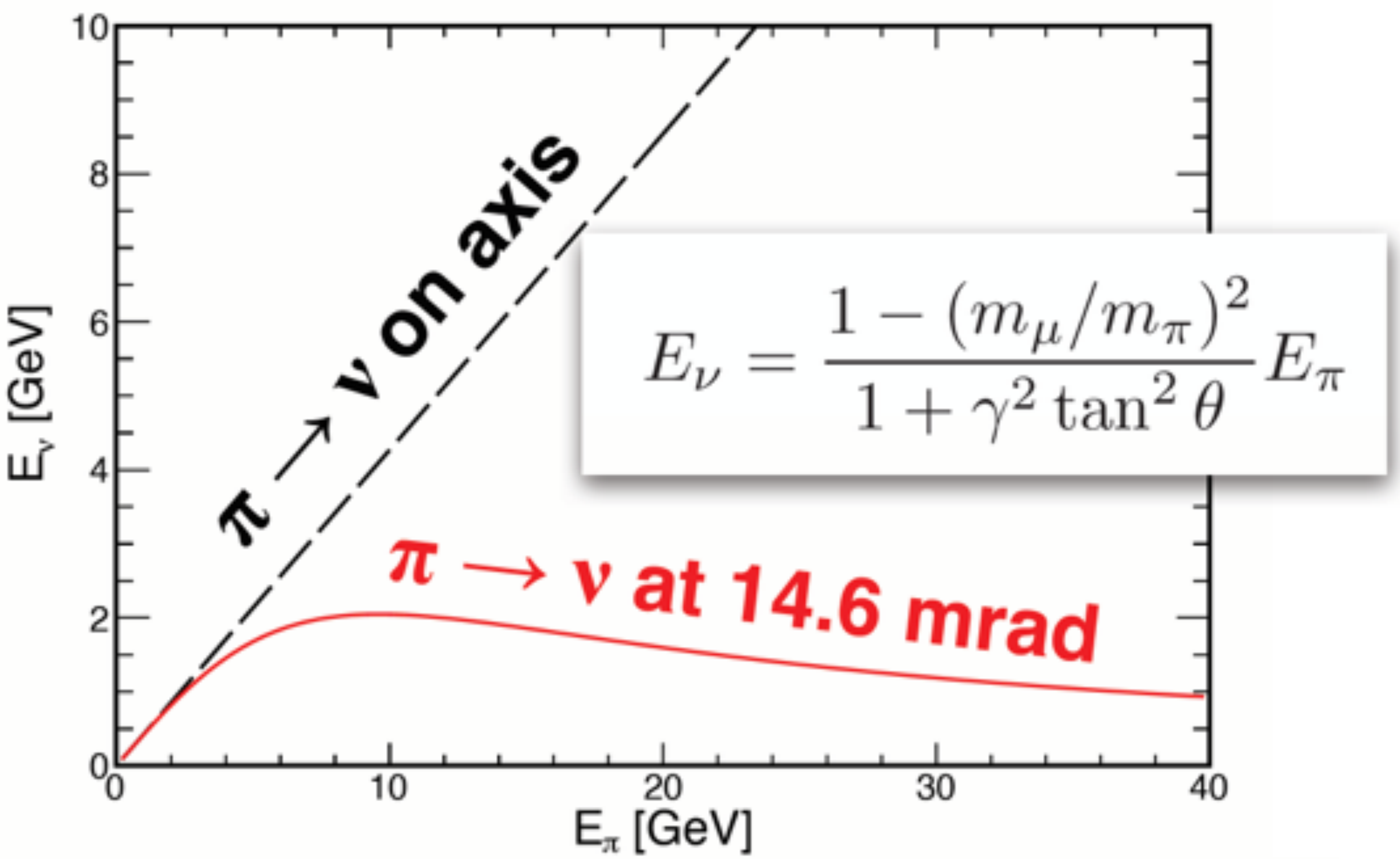
Focused on these analyses

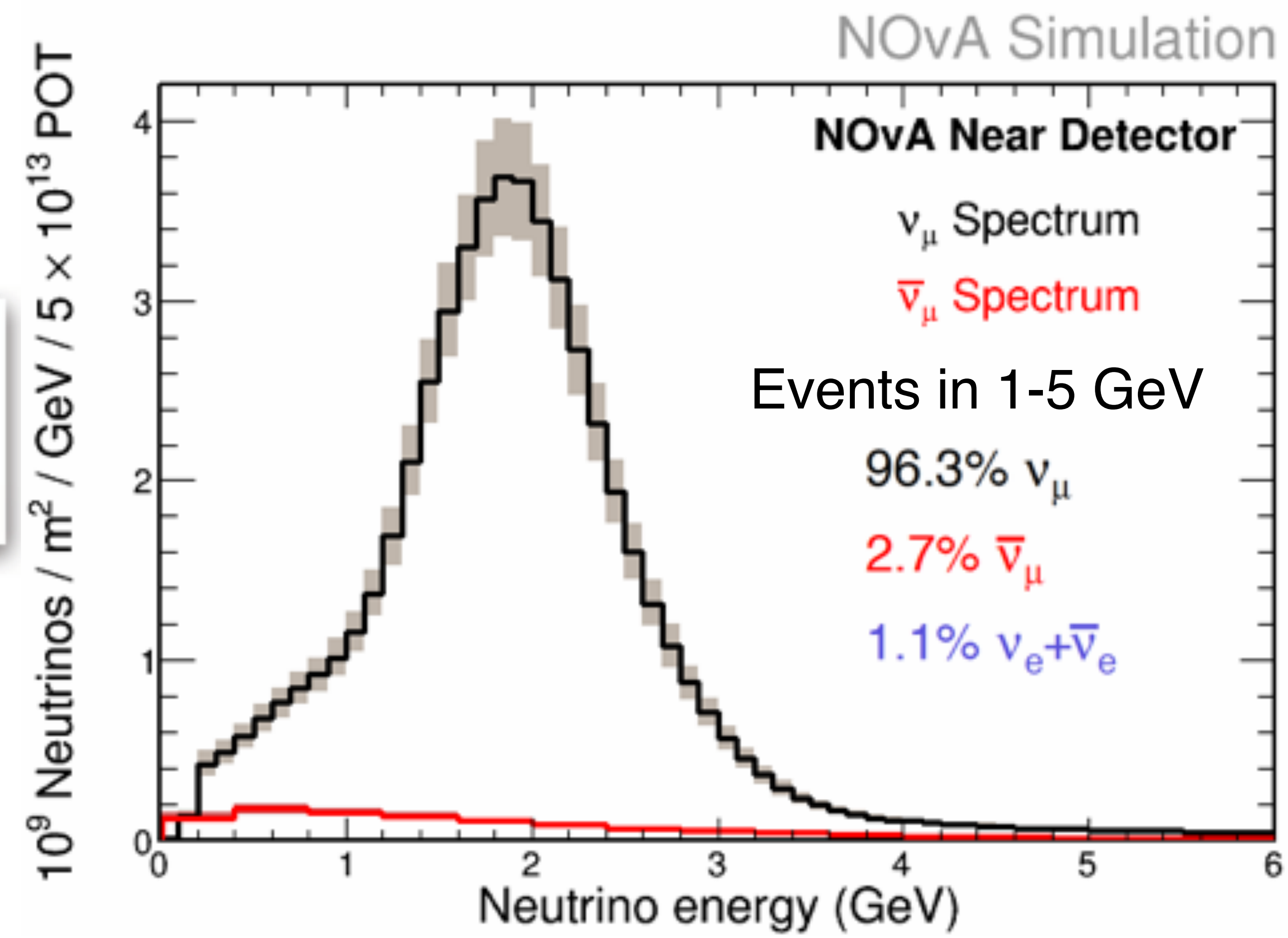
NuMI Beam at NOvA

- NOvA detectors are off-axis, 14 mrad w.r.t NuMI beam axis.
    - It is a narrow-band beam centered at 2 GeV.

- The NOvA ND is located ~ 1 km from the production point.

- NuMI runs in: **muon neutrino enhanced mode** (FHC) and **muon antineutrino enhanced mode** (RHC).

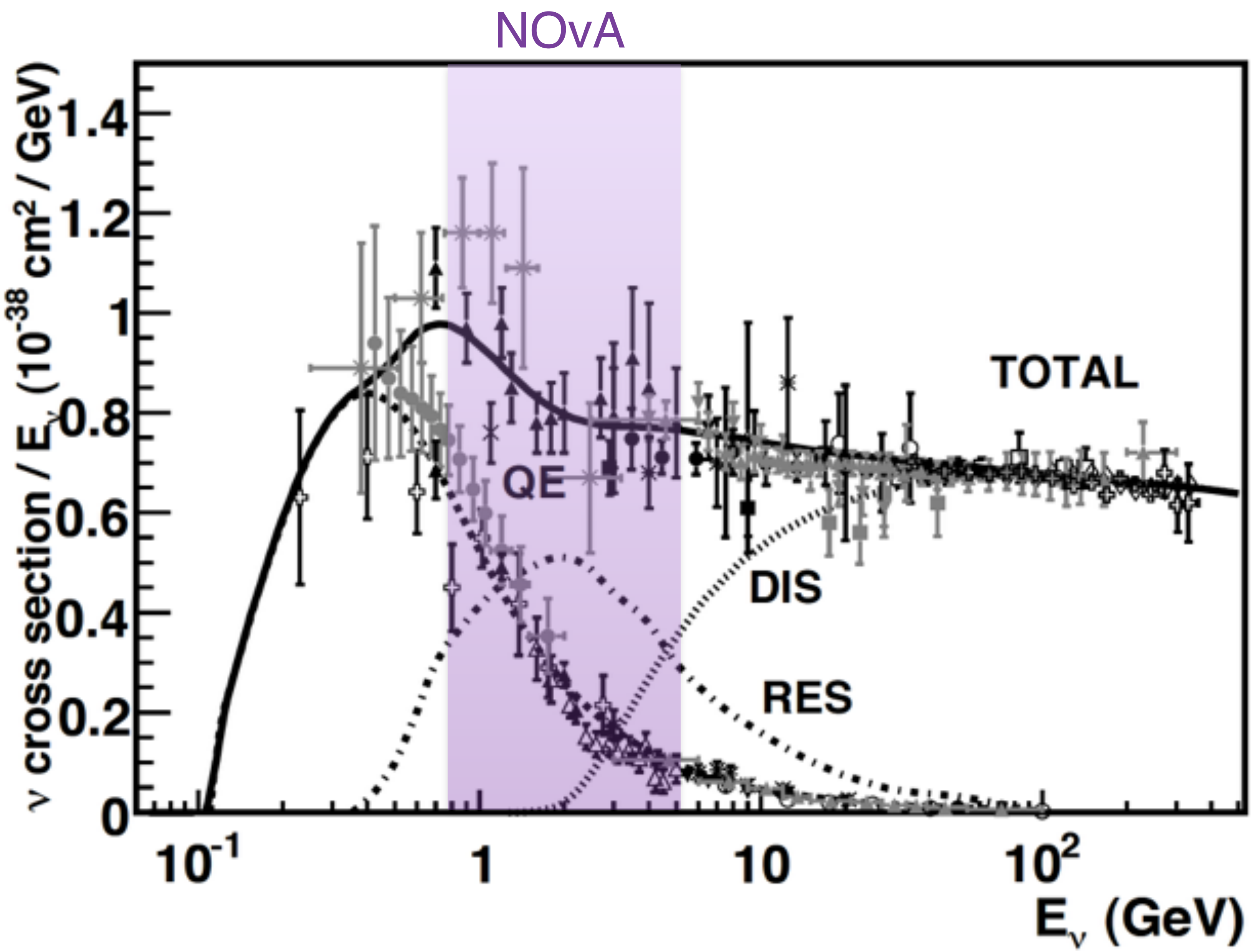




NuMI Beam at NOvA

- NOvA's narrow band beam gives use access to a very interesting region with sensitivity to multiple channels.
- High data rate at the ND.
- Protons on target:
  - 8.09×10^{20} in the FHC mode.
  - Currently 6.26×10^{20} in the RHC mode.

Muon Neutrino



J.A. Formaggio, G.P. Zeller
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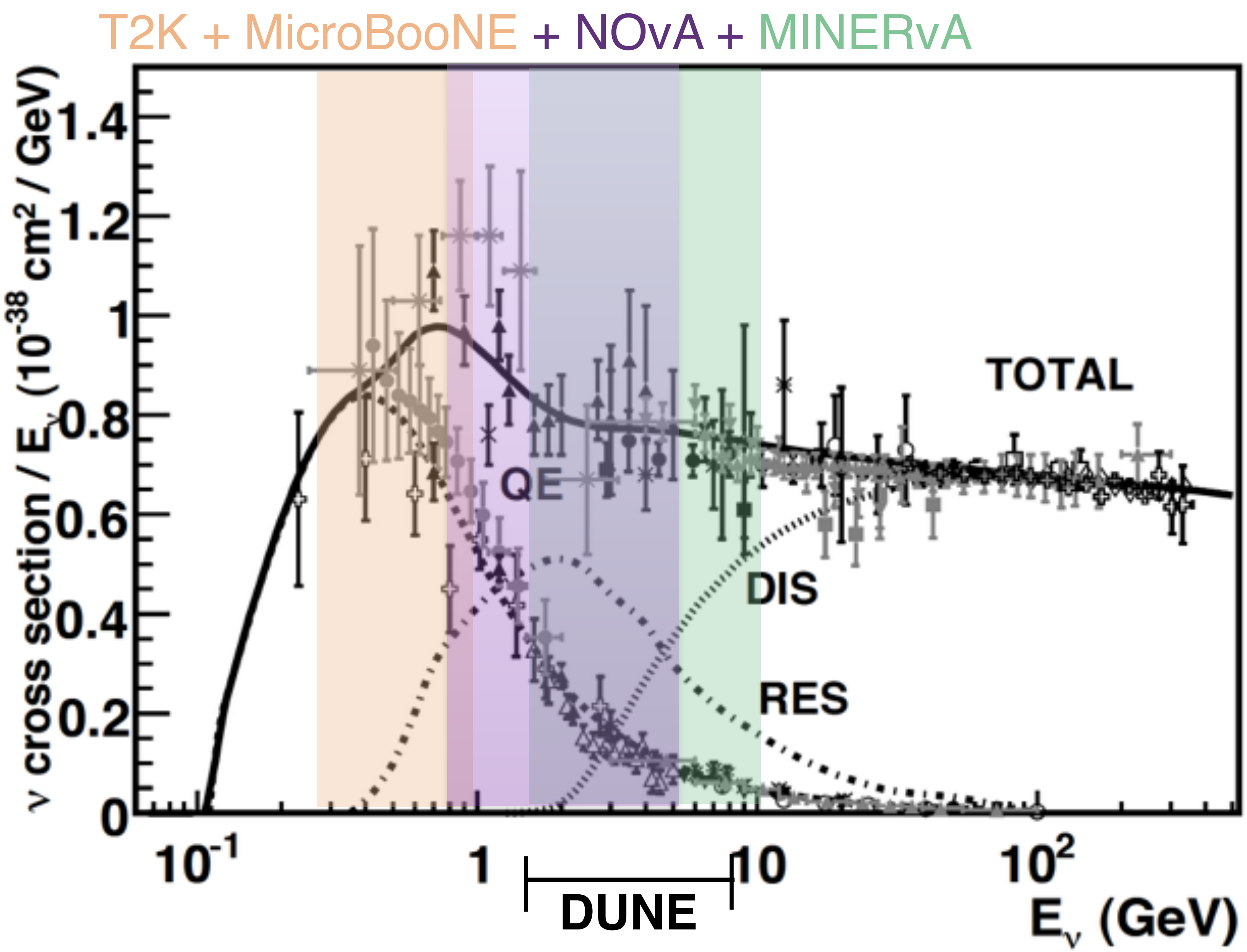

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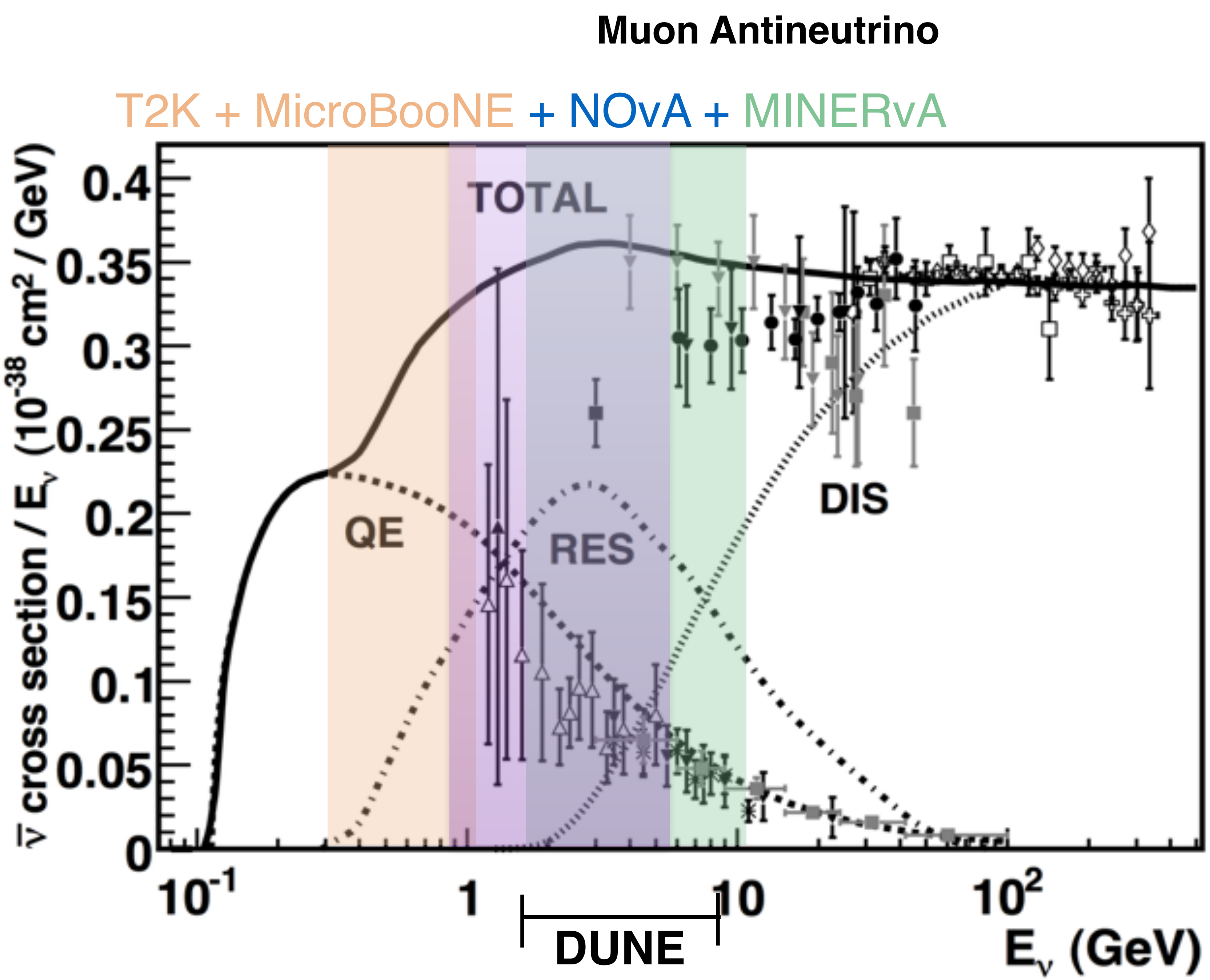

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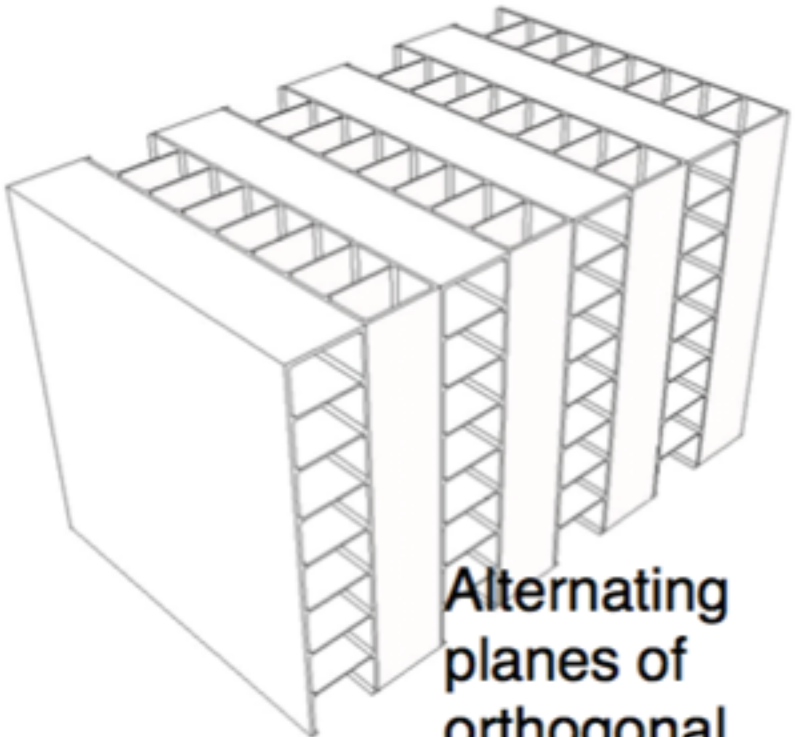
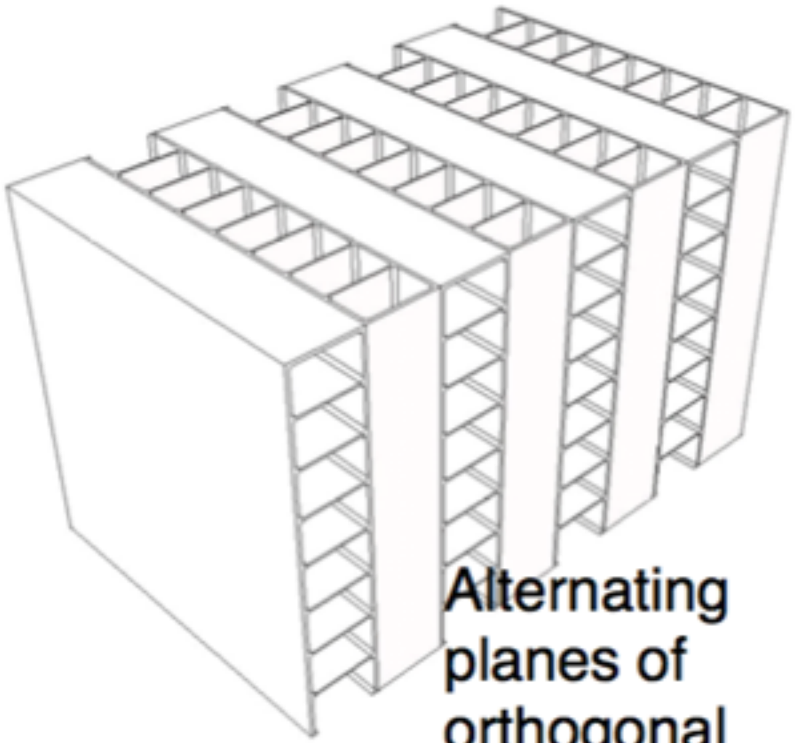
NOvA Near Detector



- Made of PVC with liquid scintillator, 3.9m x 3.9 m x 12.67 m. 193 ton, 192 planes and ~20k channels.
  - Fully active region: 77% hydrocarbon, 16% chlorine and 6% TiO_2.
  - Muon Catcher: steel + NOvA cell at downstream end to range-out muons.

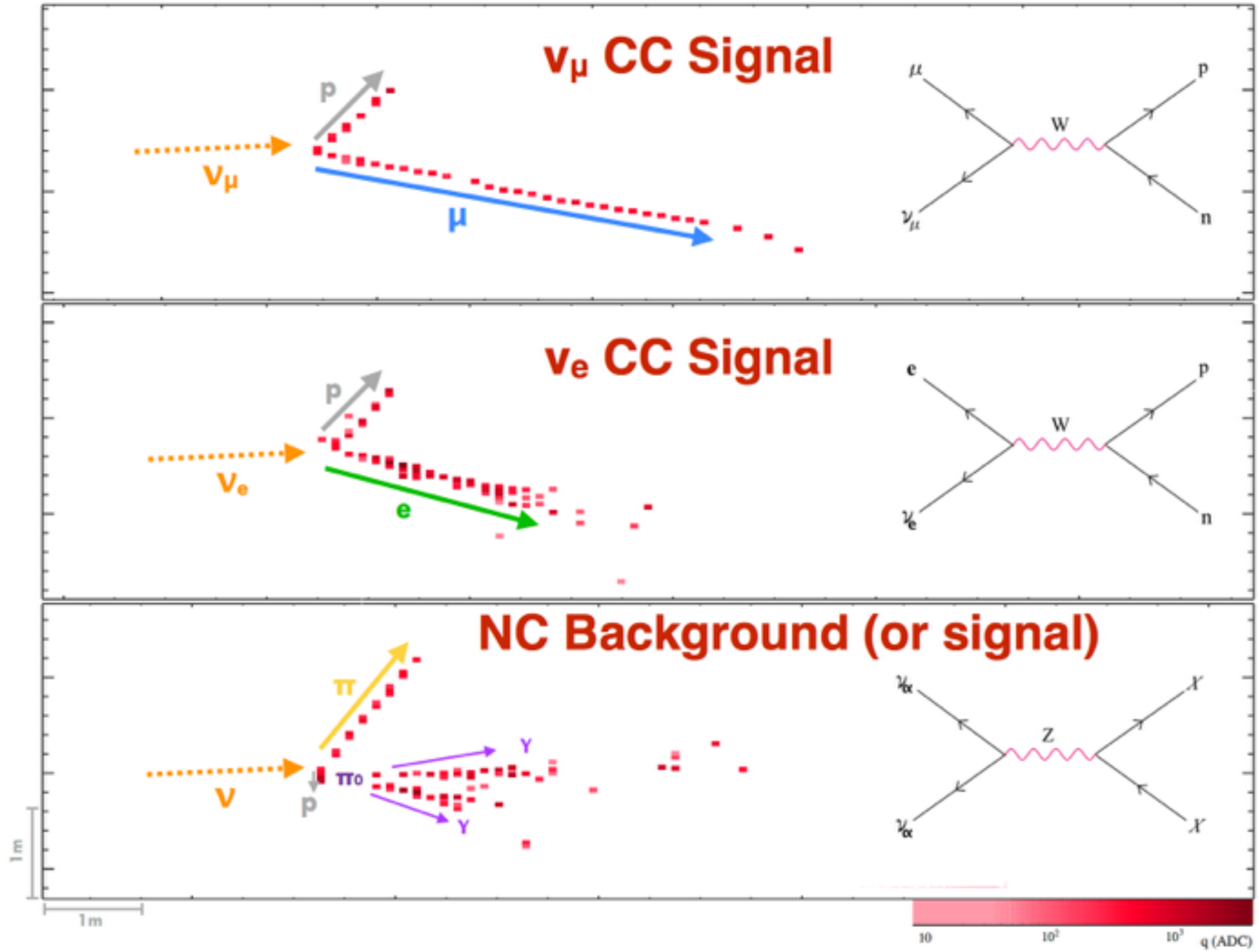
- Wavelength- shifting fibers routed to a single cell on an Avalanche Photodiode (APD).

NOvA Near Detector



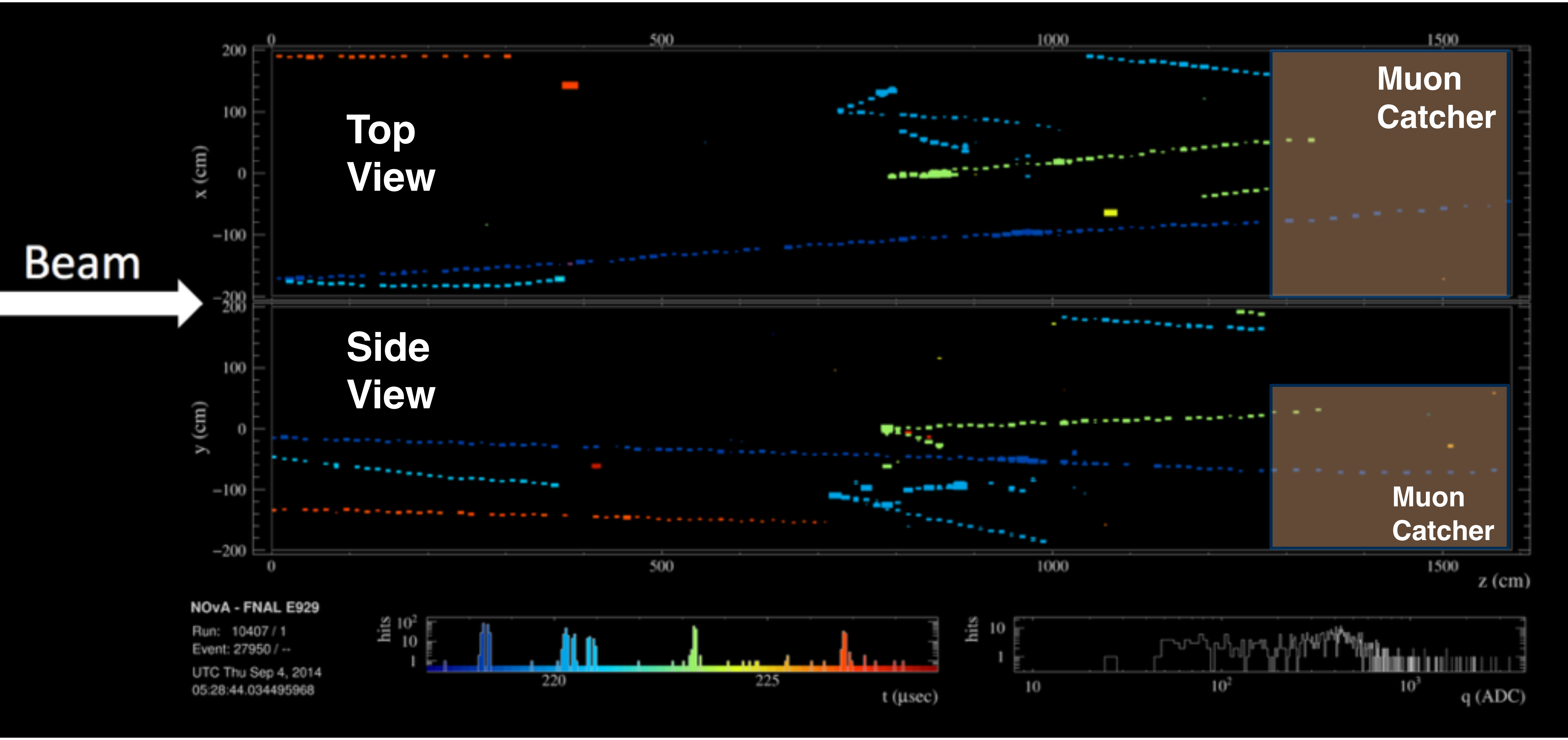
Alternating planes of orthogonal views.

Event topologies



NOvA Near Detector Events Display

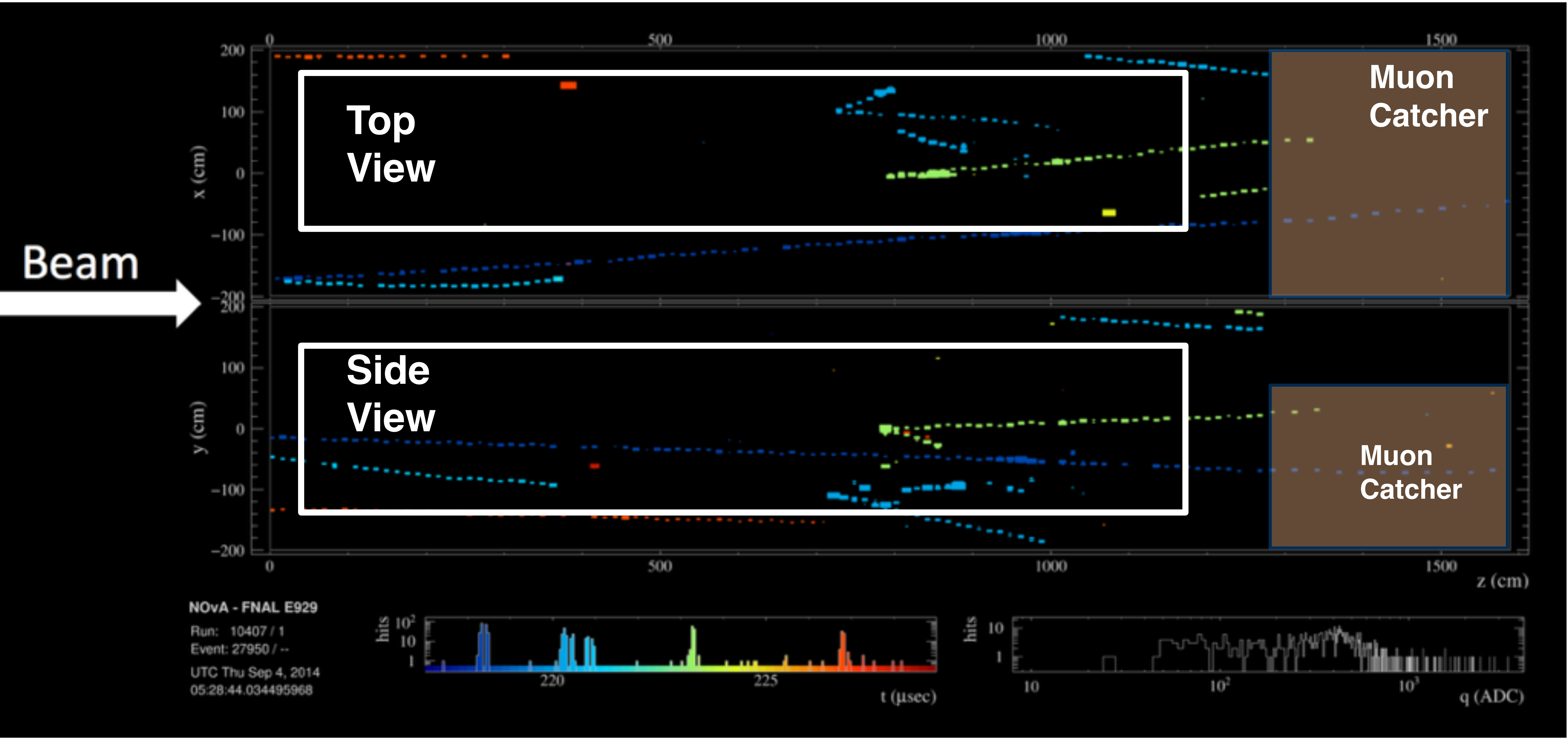
- Colors show time:



- Hits associated in time and space are used to form a candidate interaction. Tracks and showers are reconstructed from these hits.

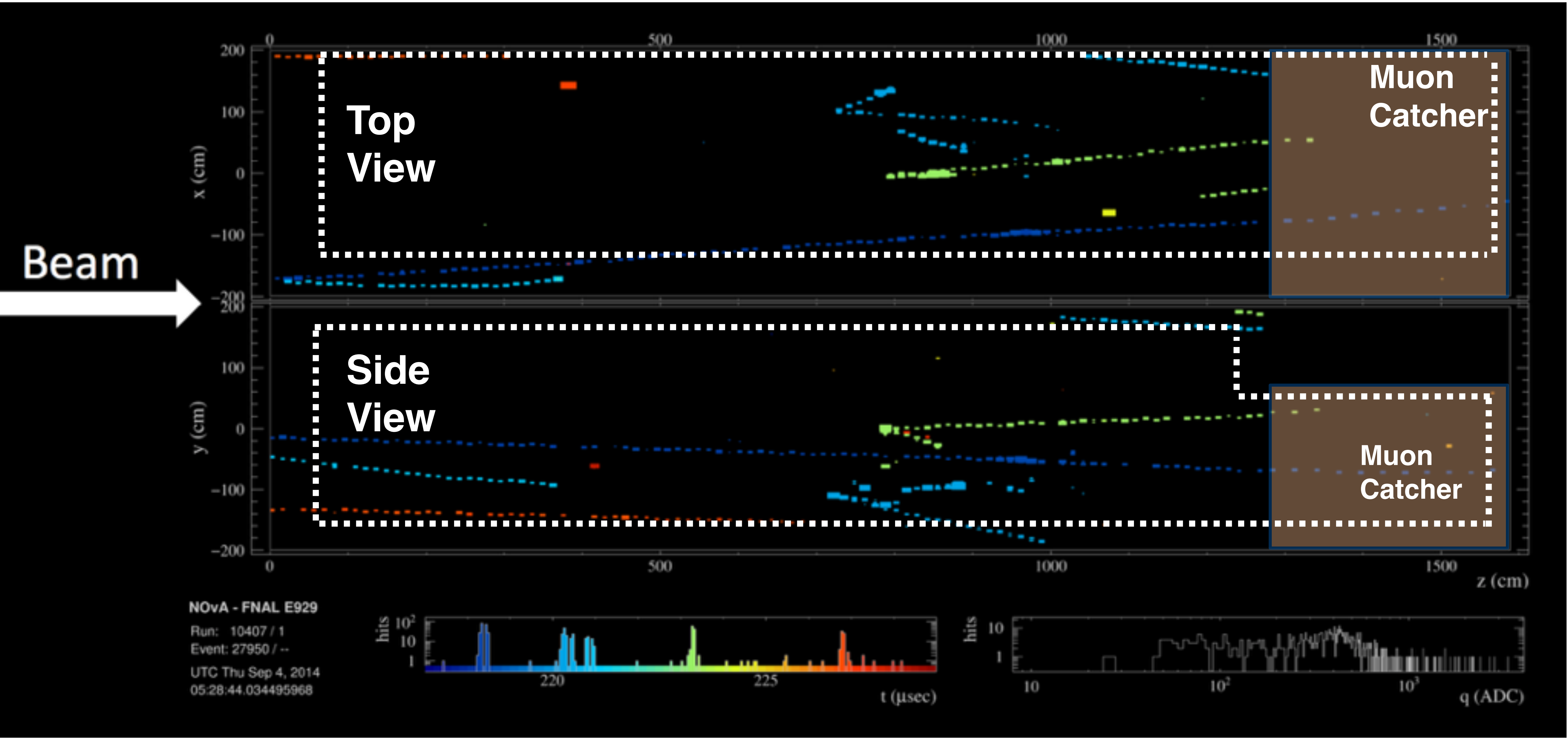
NOvA Near Detector Events Display

- Vertices should be inside a fully active (fiducial) region to cut rock muons.



NOvA Near Detector Events Display

- Tracks should be contained in the fiducial + Muon Catcher to avoid shower leaking.



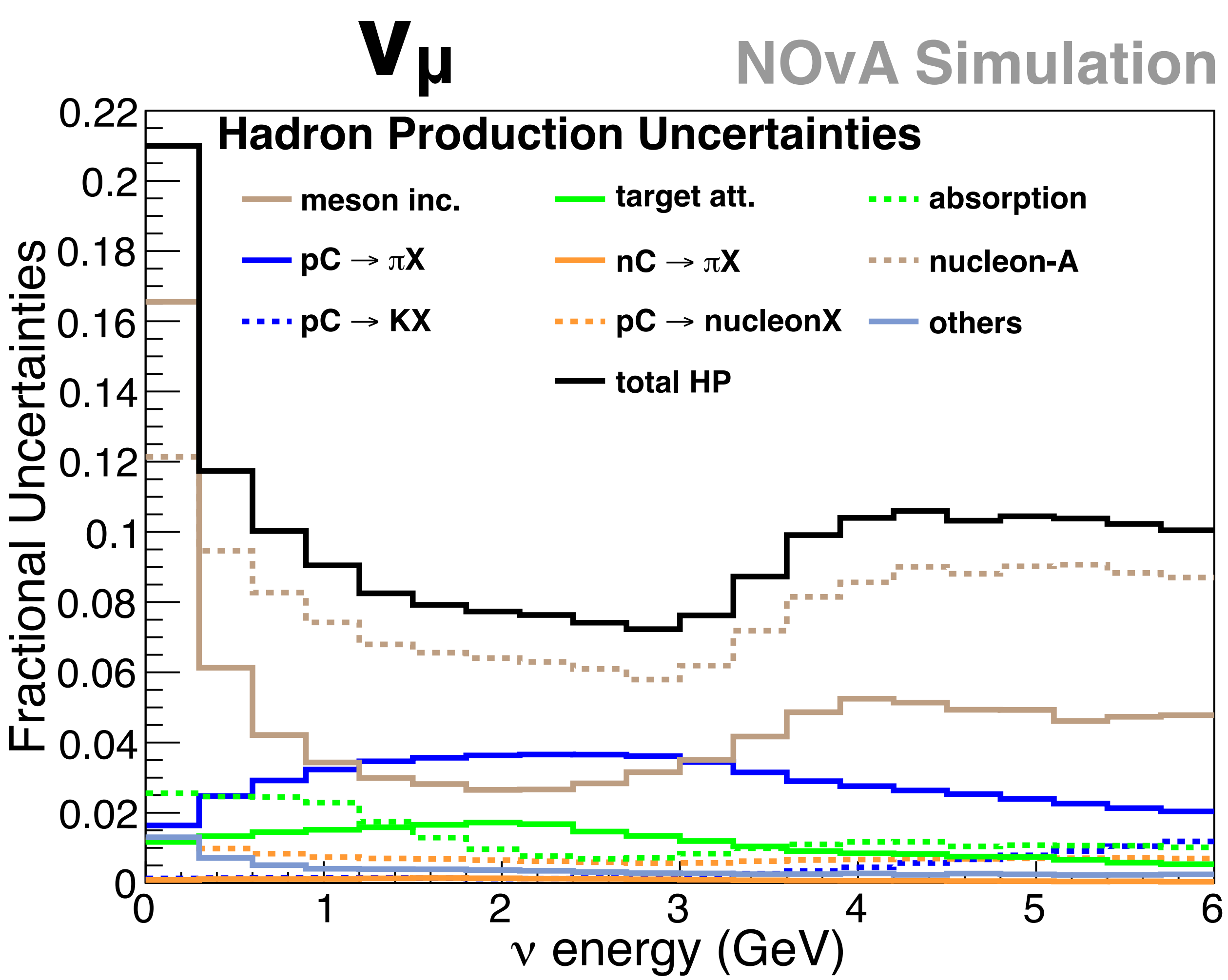
Simulation Strategy

- We use **G4NuMI** for the beam simulation, **GENIE** (2.12.2) for the neutrino interactions and **GEANT4** (4.10.1) for propagating the particles.
- **A correction to the central value** is made coming from:
  - The beam: **PPFX** for the hadrons production in the beamline.
  - The cross section: a tuning is applied to account for FSI current knowledge **(see previous talk by Jeremy' Wolcott)**.
- **The beam and cross section systematics** are determined by **PPFX** and the **GENIE** reweighing scheme, respectively.
- **The simulation of the intensity dependent of high rate of muons** originating in the surrounding rocks is integrated overlaying with the neutrino events .
- **The detector response** is also simulated and the uncertainties on the calibration parameters are dealt with systematic shifted MC.

Systematic Strategy

We use two approaches:

- **Multi-universe technique**: ensemble of 100 alternative predictions done by **weights (flux** and **GENIE)**.
- **Sample of Shifted MC**: generated shifting a parameter by 1 sigma (mostly detector systematics such us calibration values).



Flux uncertainty in the peak comes from HP: 8%, Focusing: 4%.

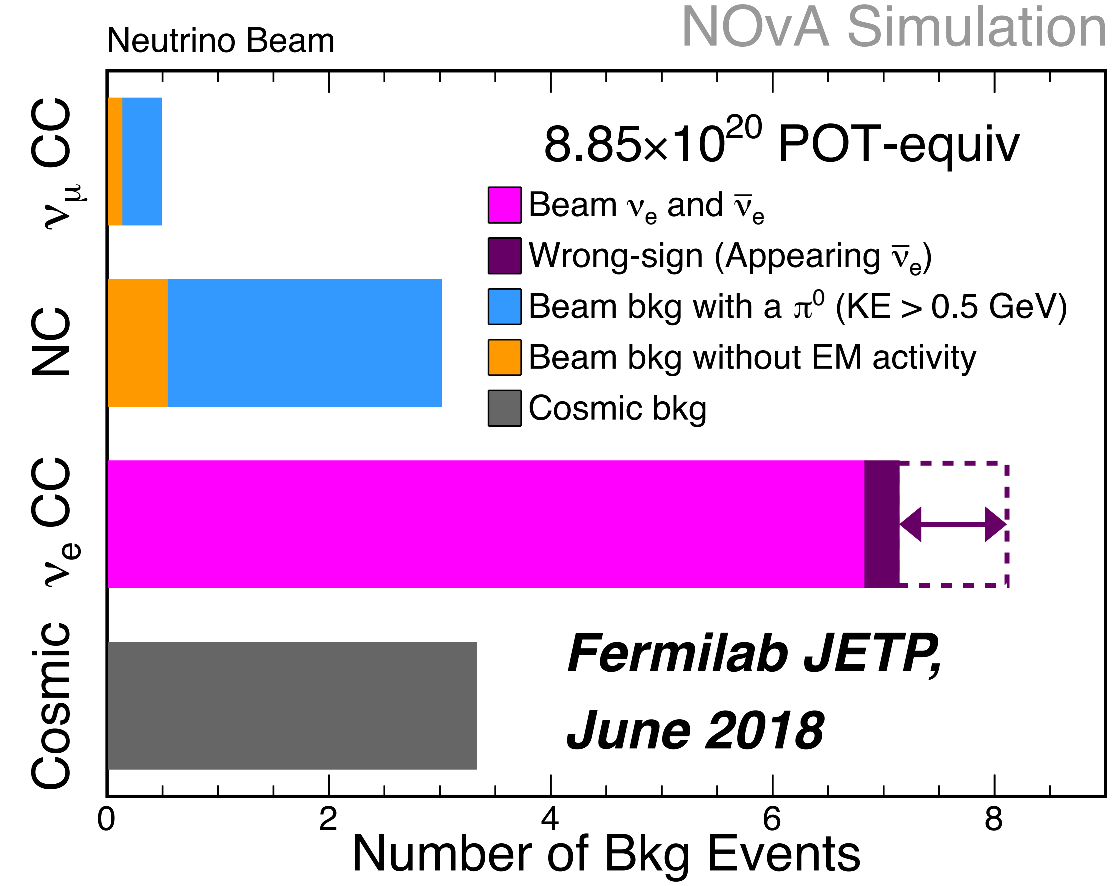
This uncertainty is mainly normalization and almost flat in 1-3 GeV

PPFX *(Phys. Rev. D 94, 092005 2016).*

Review of ν + A -> π^0 X cross section measurements

π^0 at the NOvA Near Detector

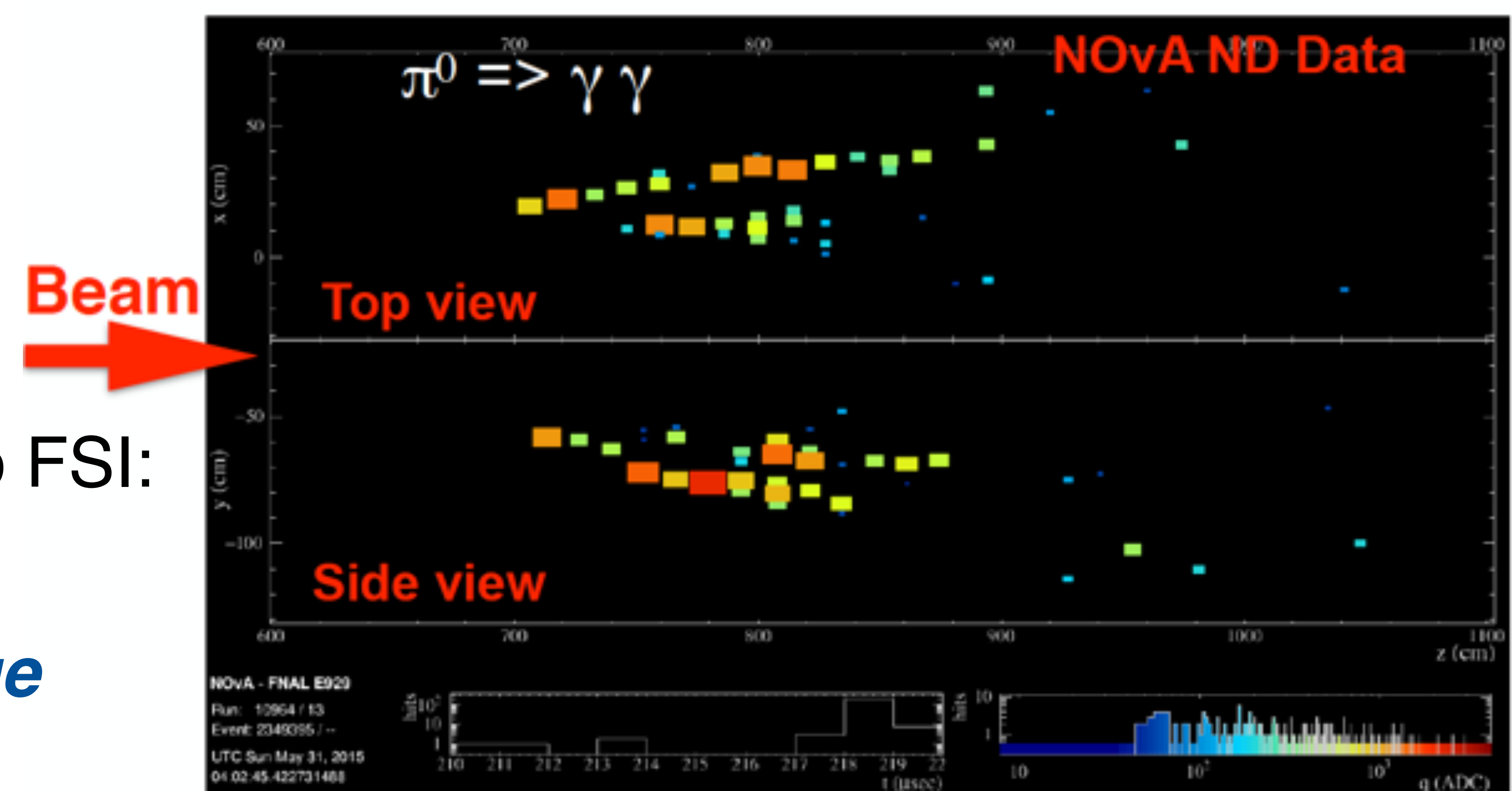
Background at the FD from 58 observed ν_e.



- π^0s are one of the most important background to ν_e appearance oscillation analysis:

  We want to measure them in our own detector!

- Photons from π^0 decay make EM shower.

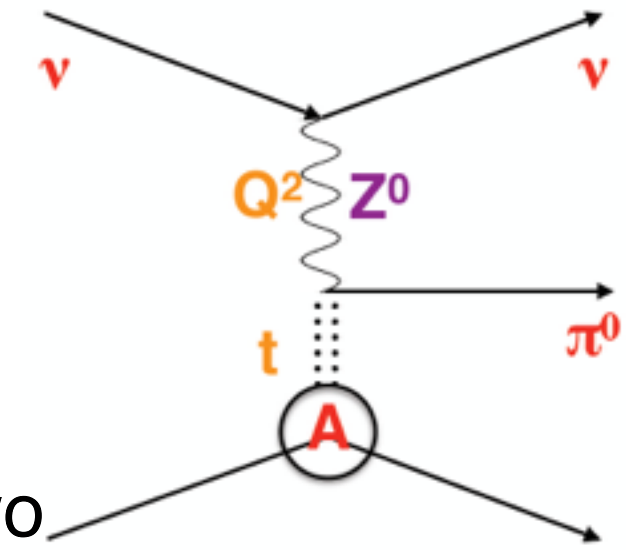


- Pion kinematics are sensitive to FSI:

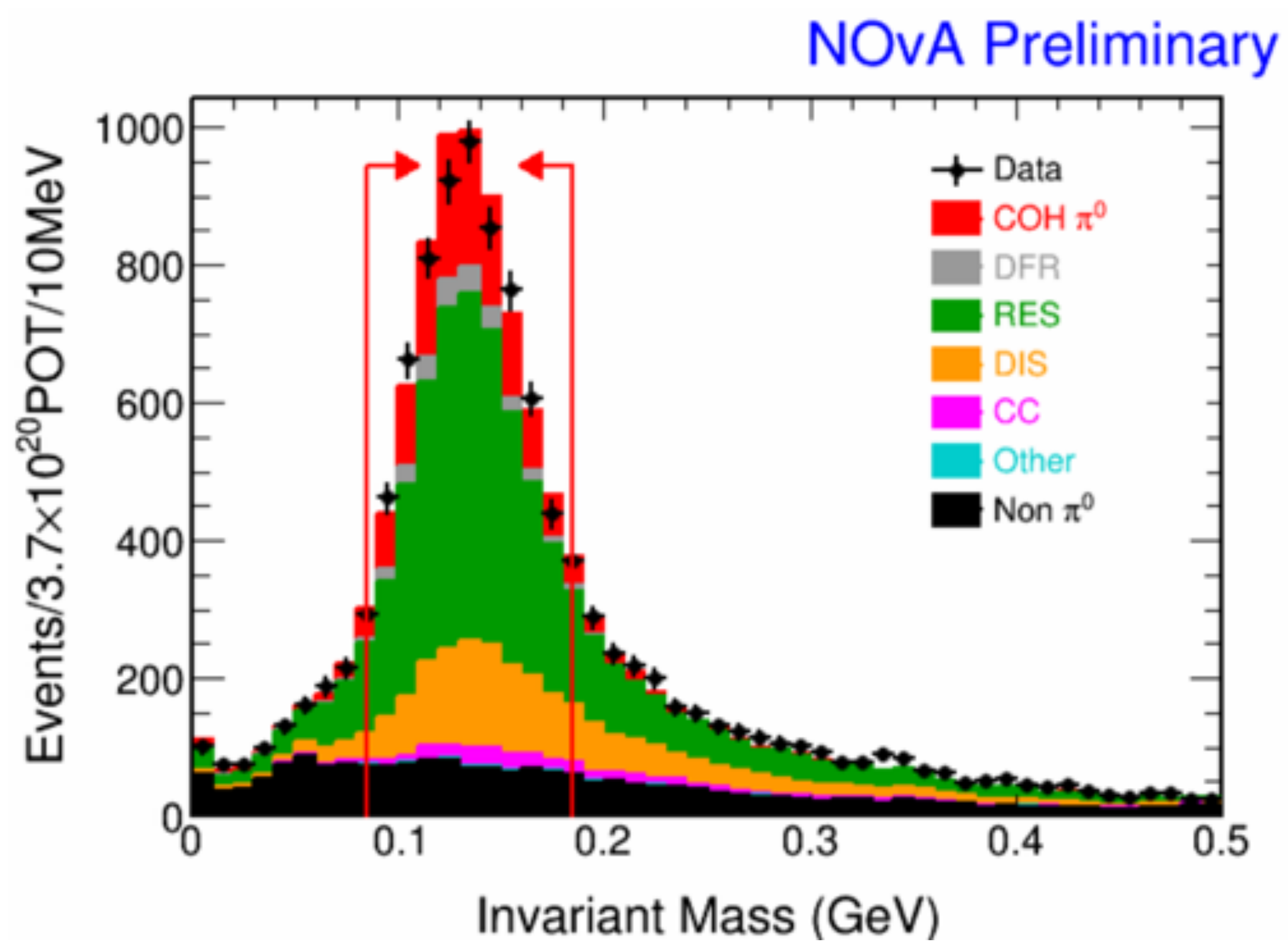
  (in)elastic scattering, absorption, charge-exchange

NC Coherent π^0

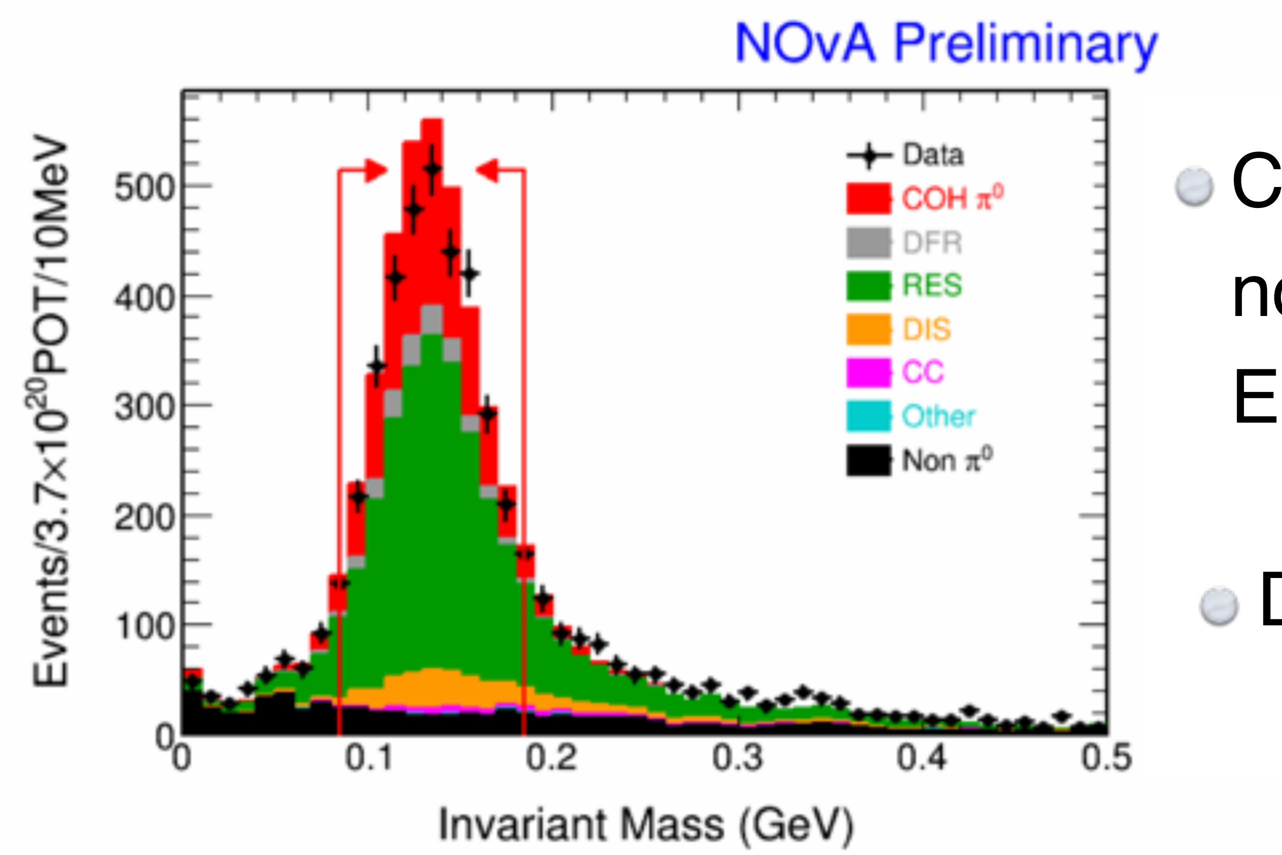
- **Challenge**: cross section is relatively small compared to other π^0 production modes.
- Construct a NC-π^0 identifier: exclude muons and identify two photons by dE/dx-based likelihood.



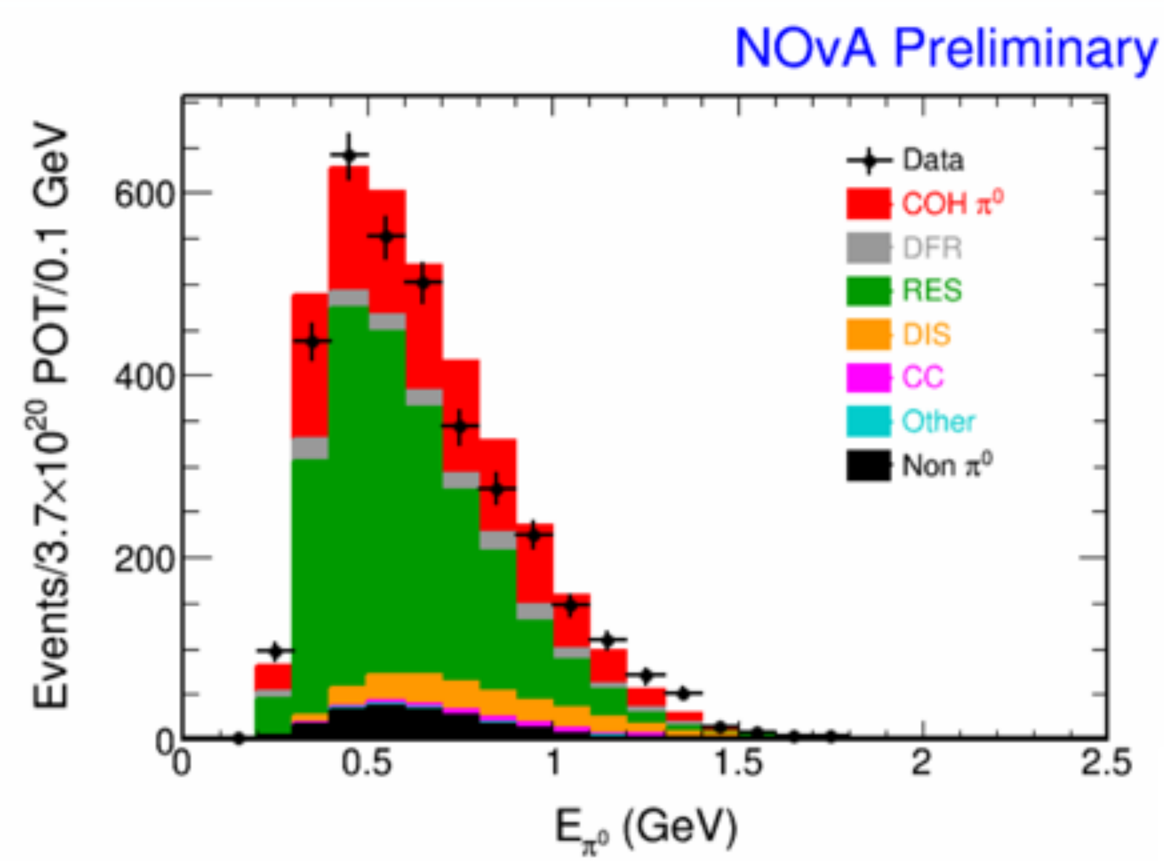
- Background dominated by **NC RES** and **NC DIS**
- Cut on invariant mass further reduces background.
- Signal and control samples based on the **activity around the vertex** and the **fraction of the total energy in the two photons**.

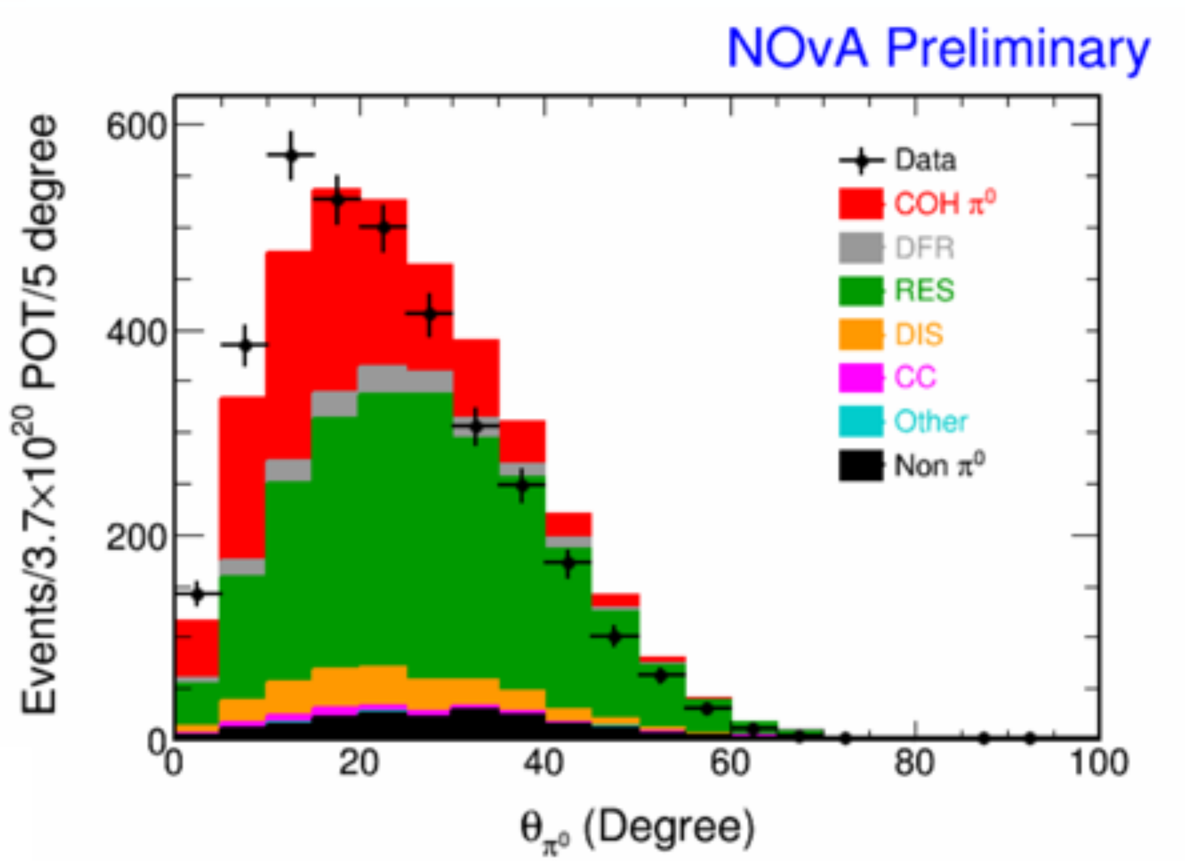


Signal Sample After Background Fit



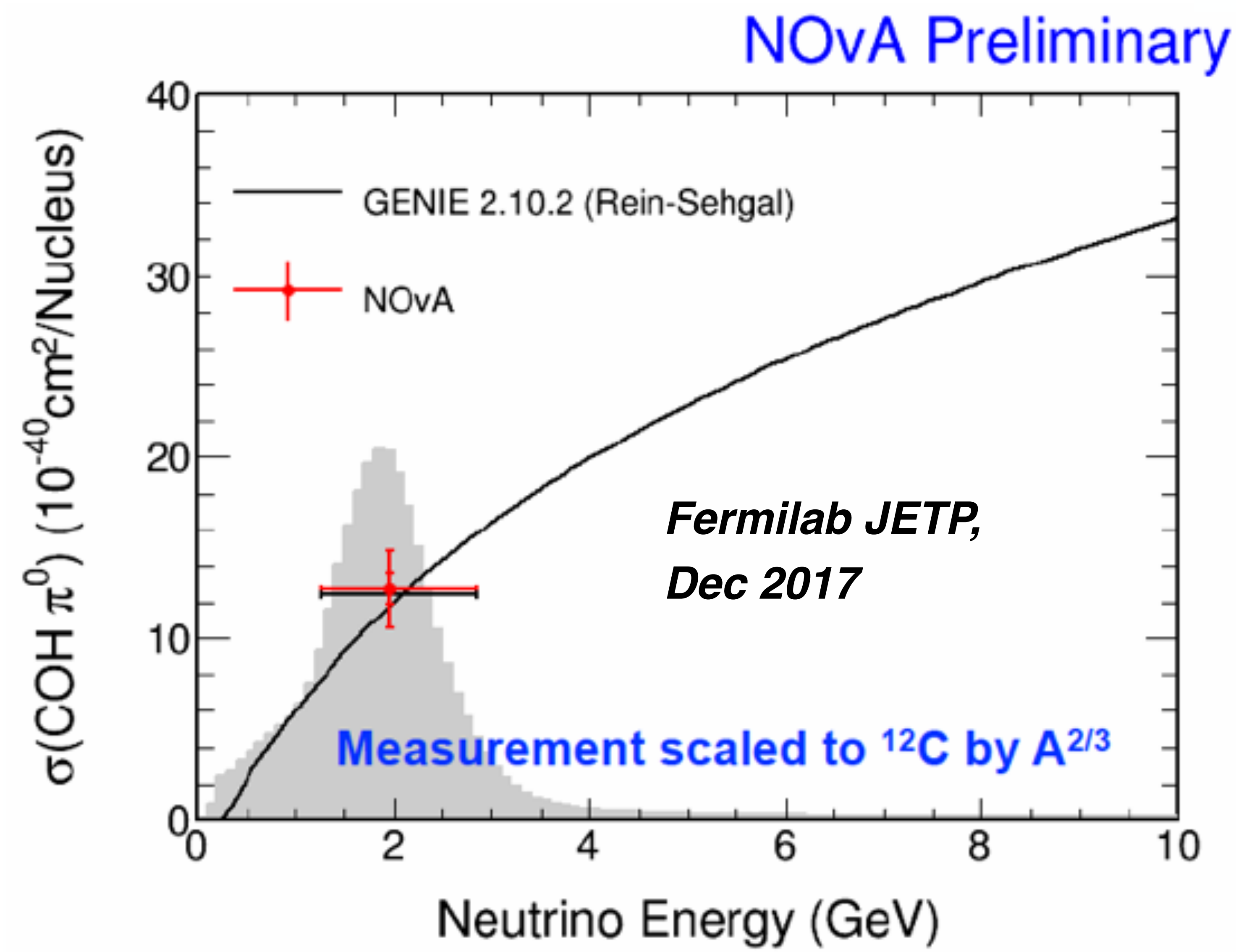
- Coherent signal results by subtracting normalized background from data in the Energy-angle π^0 space.
- Data favors smaller π^0 angle.





Results

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



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

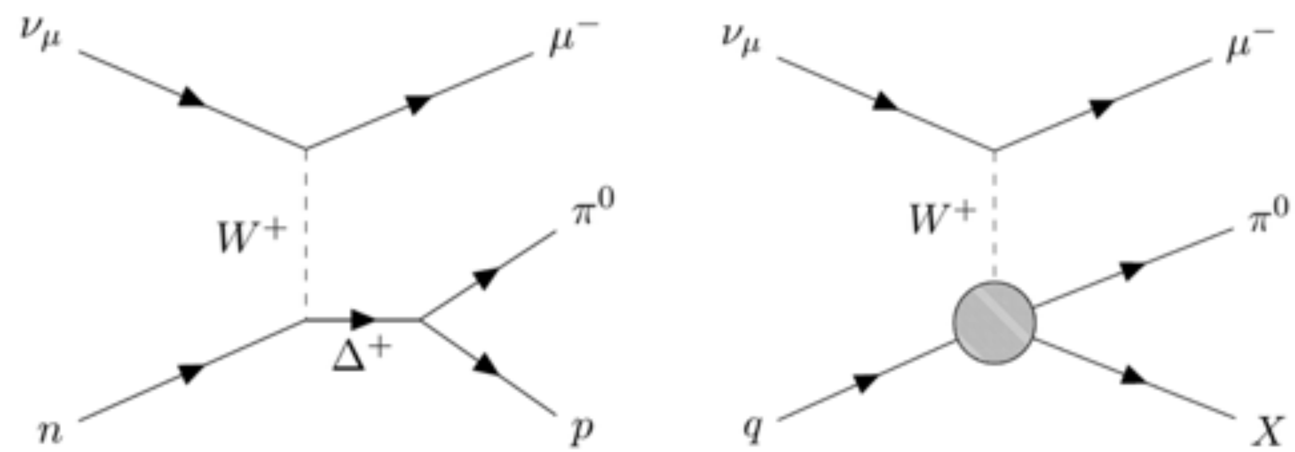
- Measured flux-averaged cross-section:

  $\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40}$ cm²/nucleus

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

Paper is in final Collaboration Review, publication very soon!

$\nu_\mu + A \to \mu^- + \pi^0 + X$



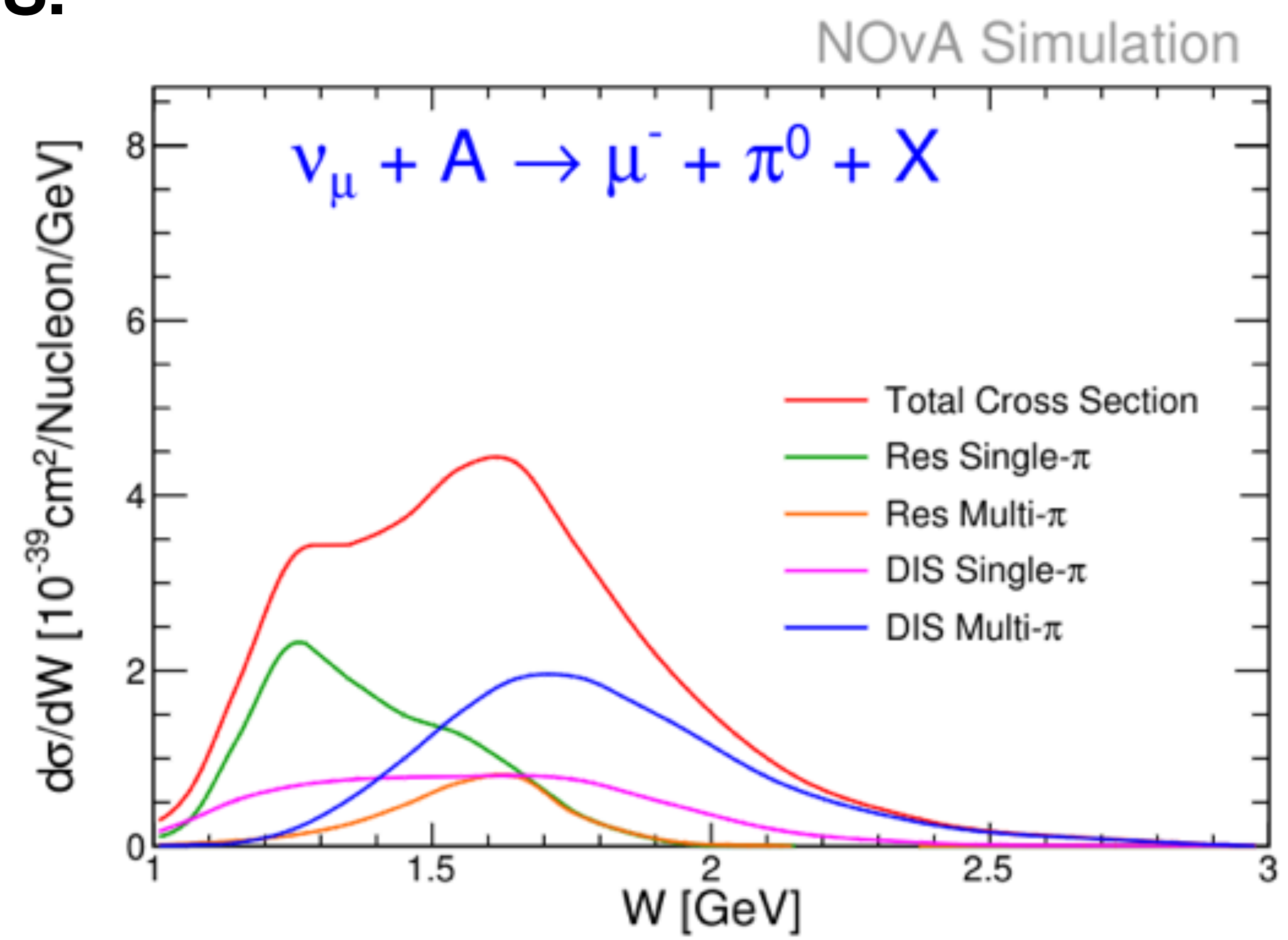
Signal has:

- large contributions from **RES** and **DIS.**
- large multi-π component.

Analysis has:

- large NC background: reject by deep learning techniques.

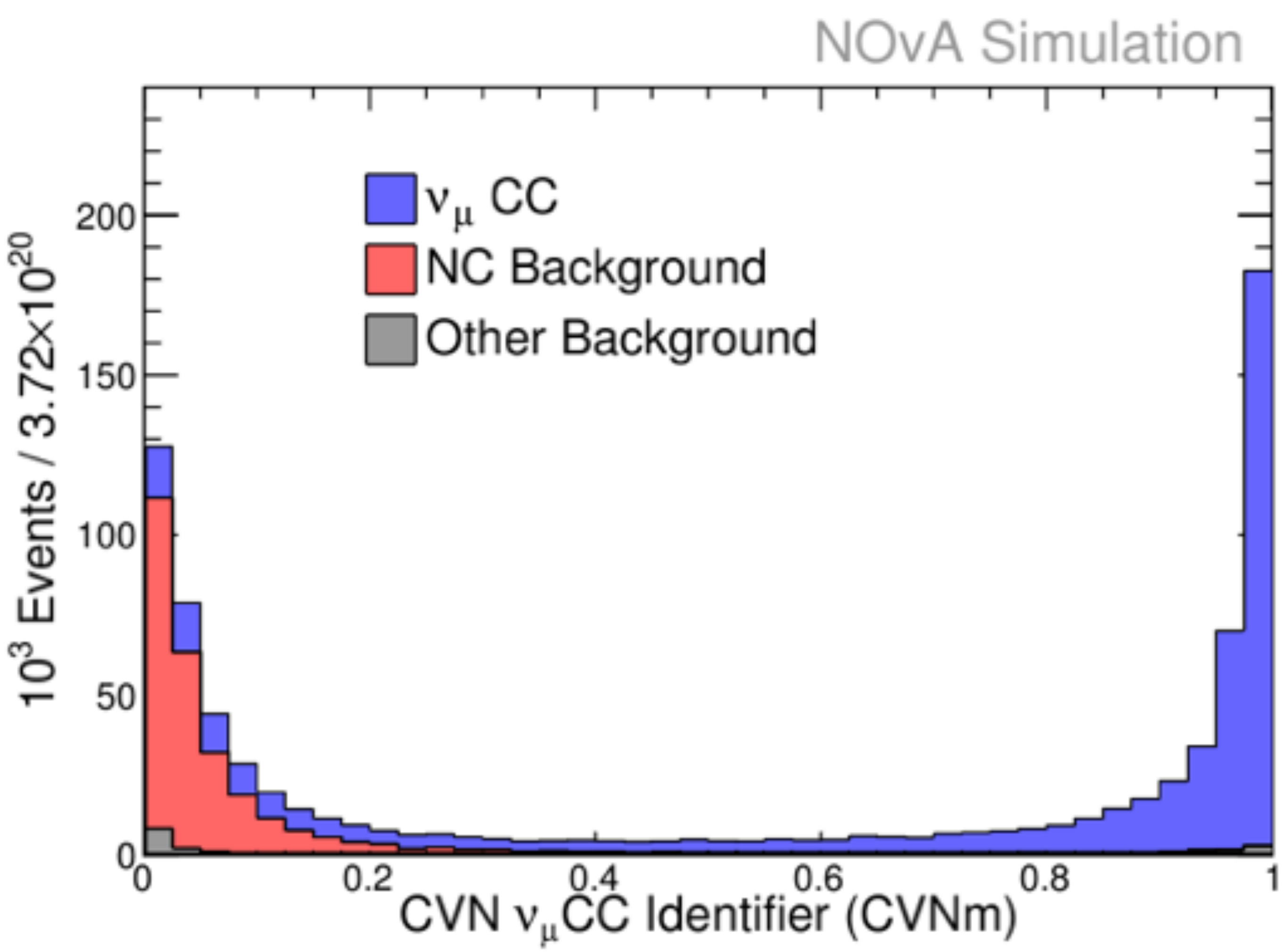
Photon identification based on photon kinematics.



Use a template fit of MC-predicted shapes of signal and backgrounds to the data.

NC Rejection and Signal Enrichment

- We use Convolutional Neural Network PID (CVN) to reject NC.

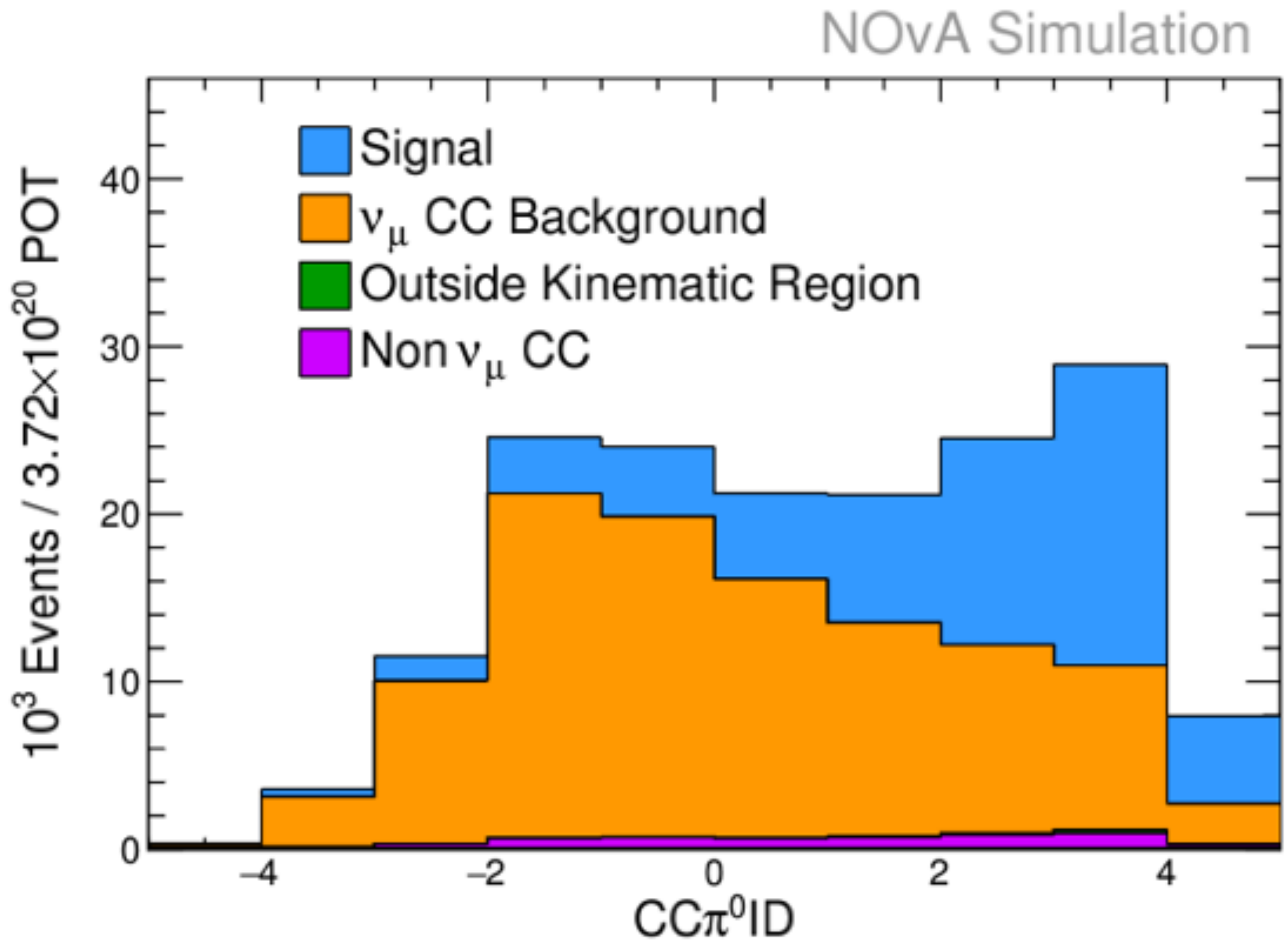


- CVN trained to select ν_μ CC events.
- 1.7% of sample after CVNm cut

- We use also CVN trained to classify events by GENIE interaction mode (efficiency=23%)
  - Select only events CVN classified as RES-like or DIS-like.
  - Reject background events classified as QE-like or Coh-like.

π^0 Identification

- Developed four-variable photon score based on:
  - Two variables describe dE/dx: Bragg peak and energy per hit.
  - Two variables describe “gappiness": gap distance and missing planes along the particle candidate.



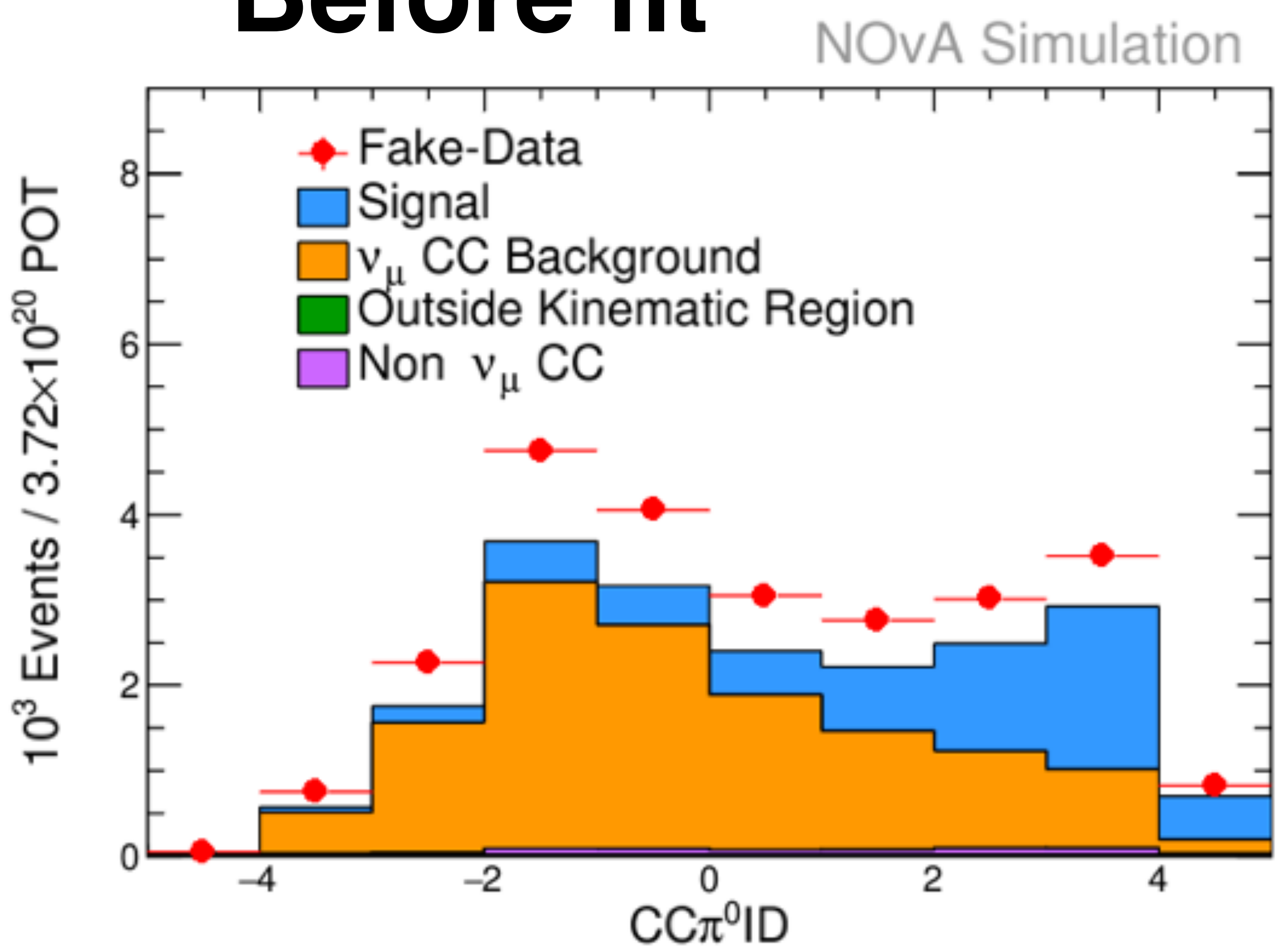
- CCπ^0ID: defined as highest photon score in event.

Constraining Simulation: Template Fitting

Example: 0.5 < p_μ < 0.6 GeV/c

- 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

Before fit



Measurement is differential: must perform template fit in every kinematic bin separately

Constraining Simulation: Template Fitting

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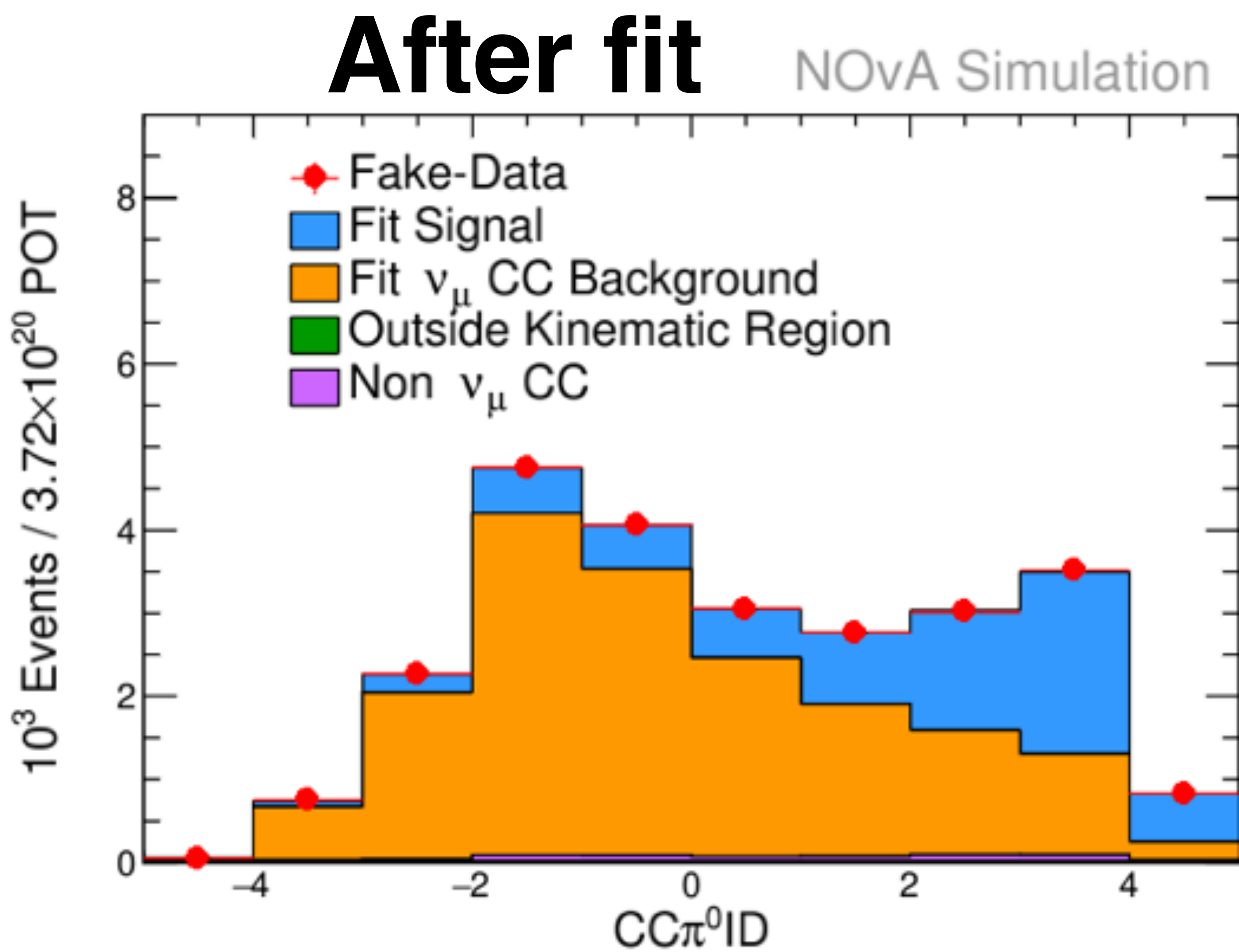
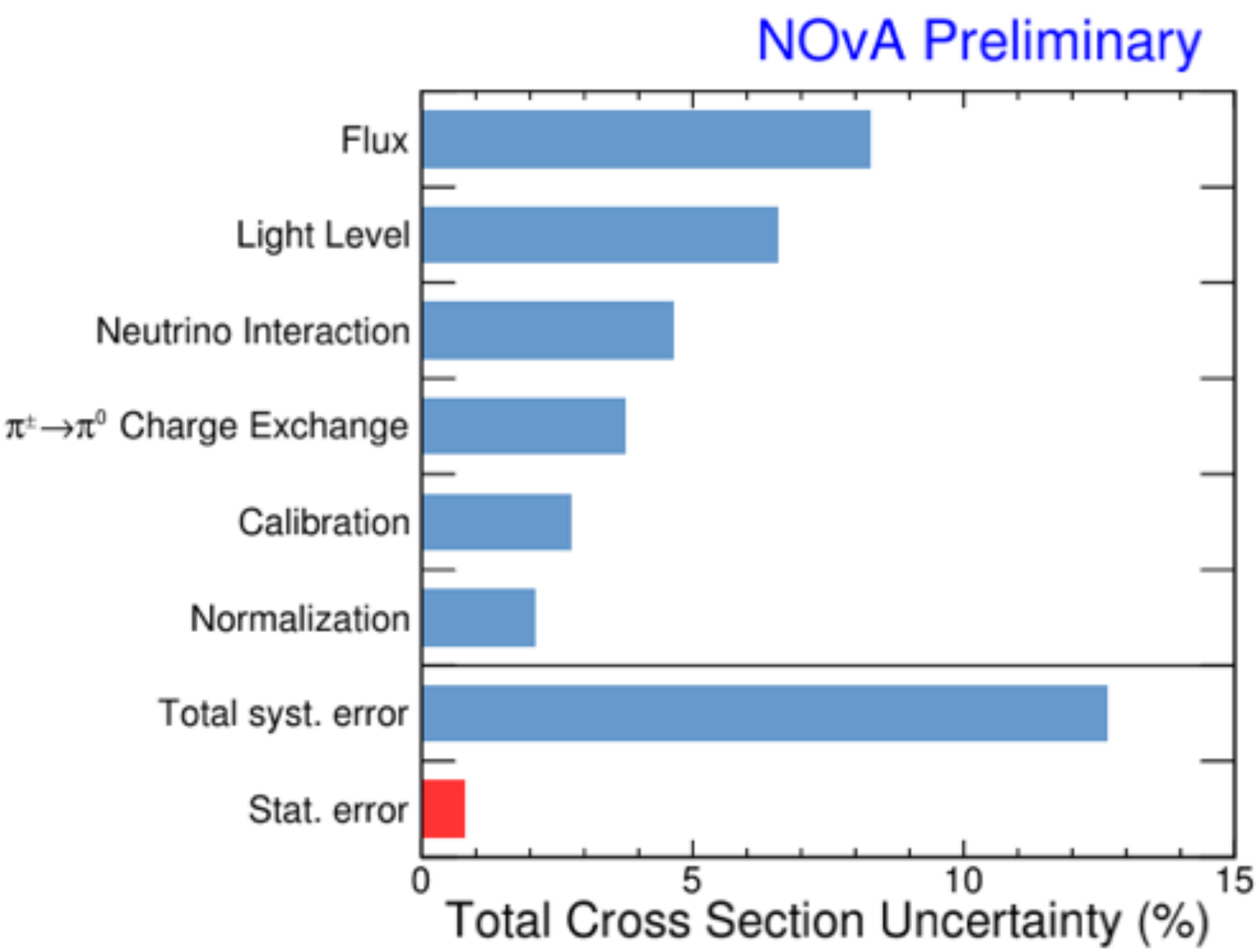
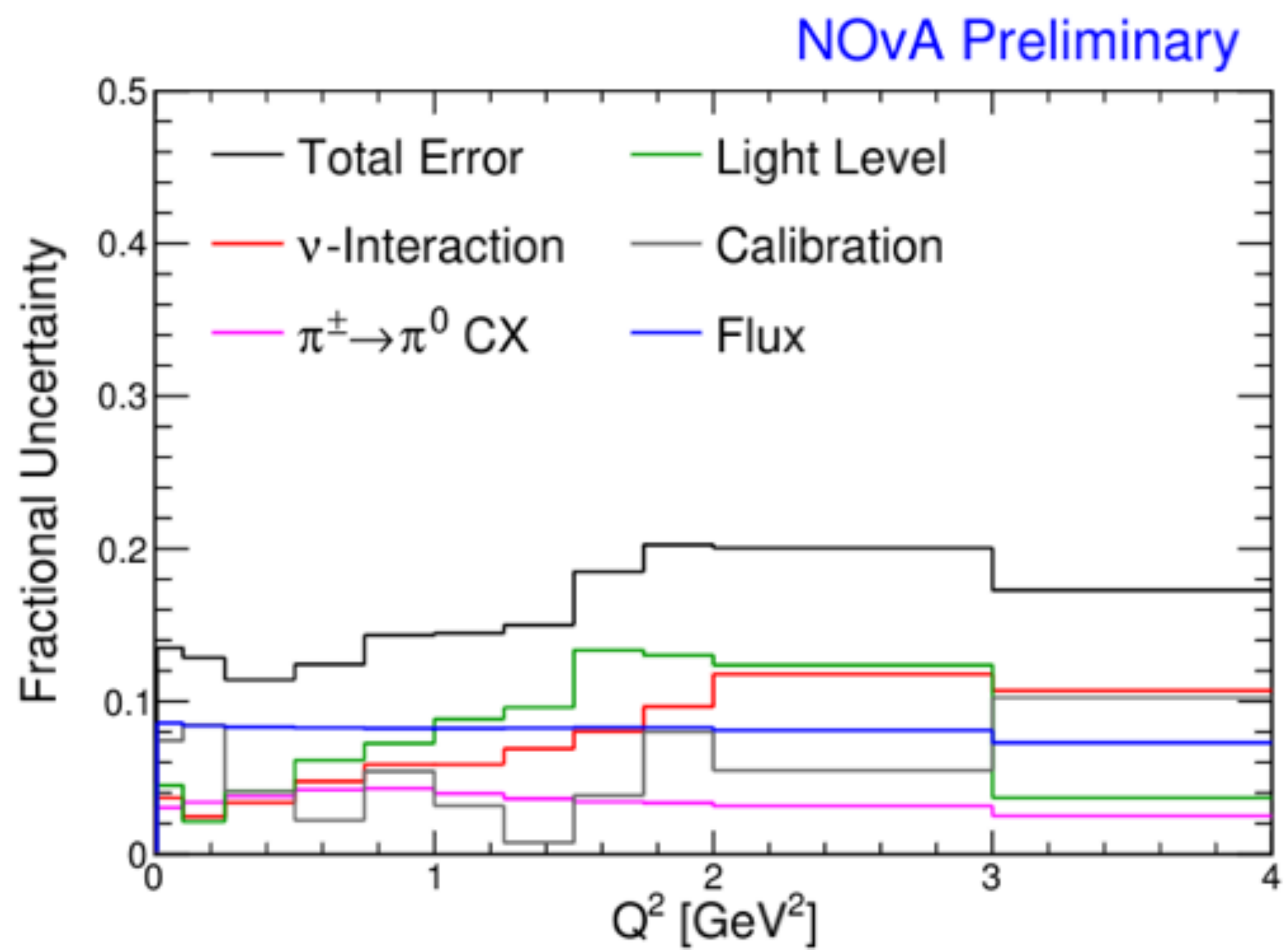


Measurement is differential: must perform template fit in every kinematic bin separately

Results: differential Cross Section

- **Flux-average cross section of muon and neutral pion kinematics (angle respect to the beam and momentum), Q^2 and W.**





Systematics on π^{+-} -> π^0 Charge Exchange

- Background with π^{+-} -> π^0 looks very signal-like.

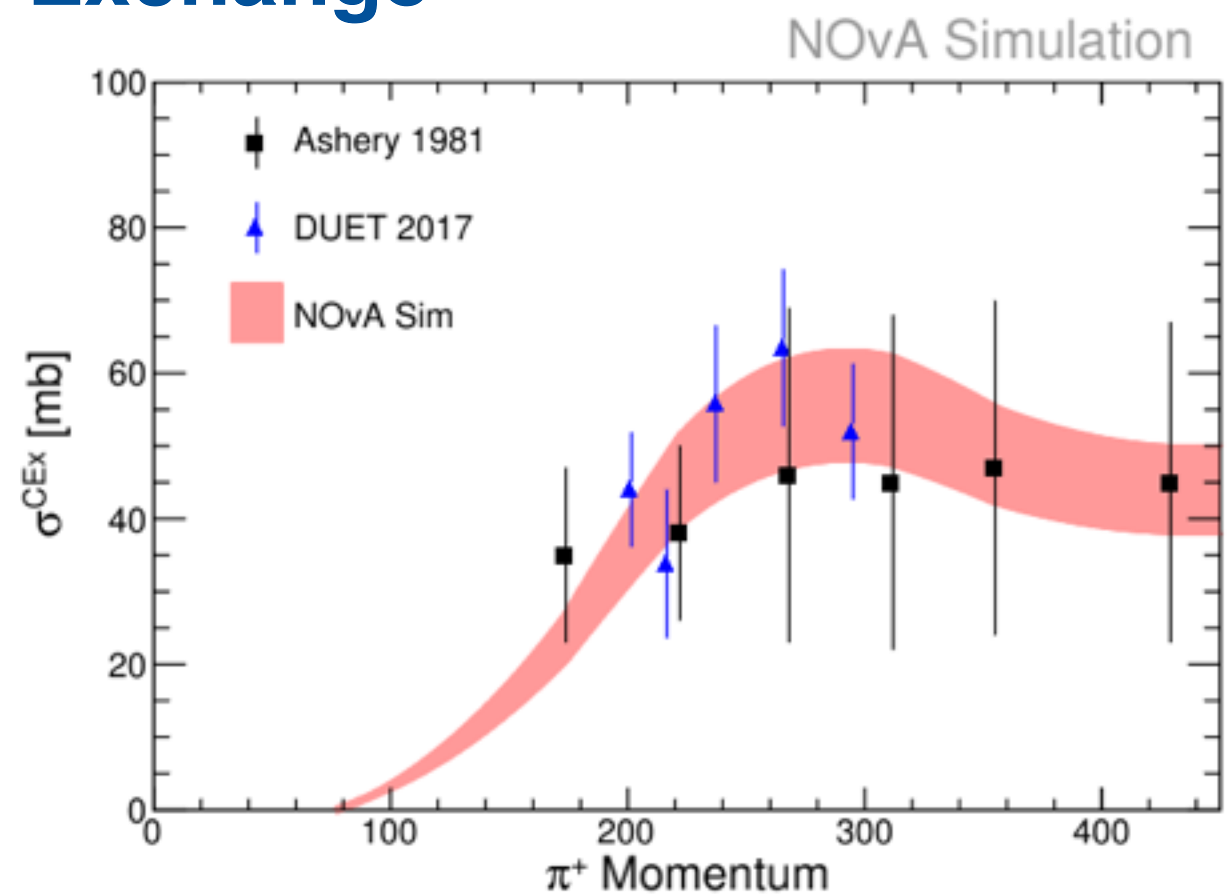
- Covariance fit of simulation to DUET 2017 results:

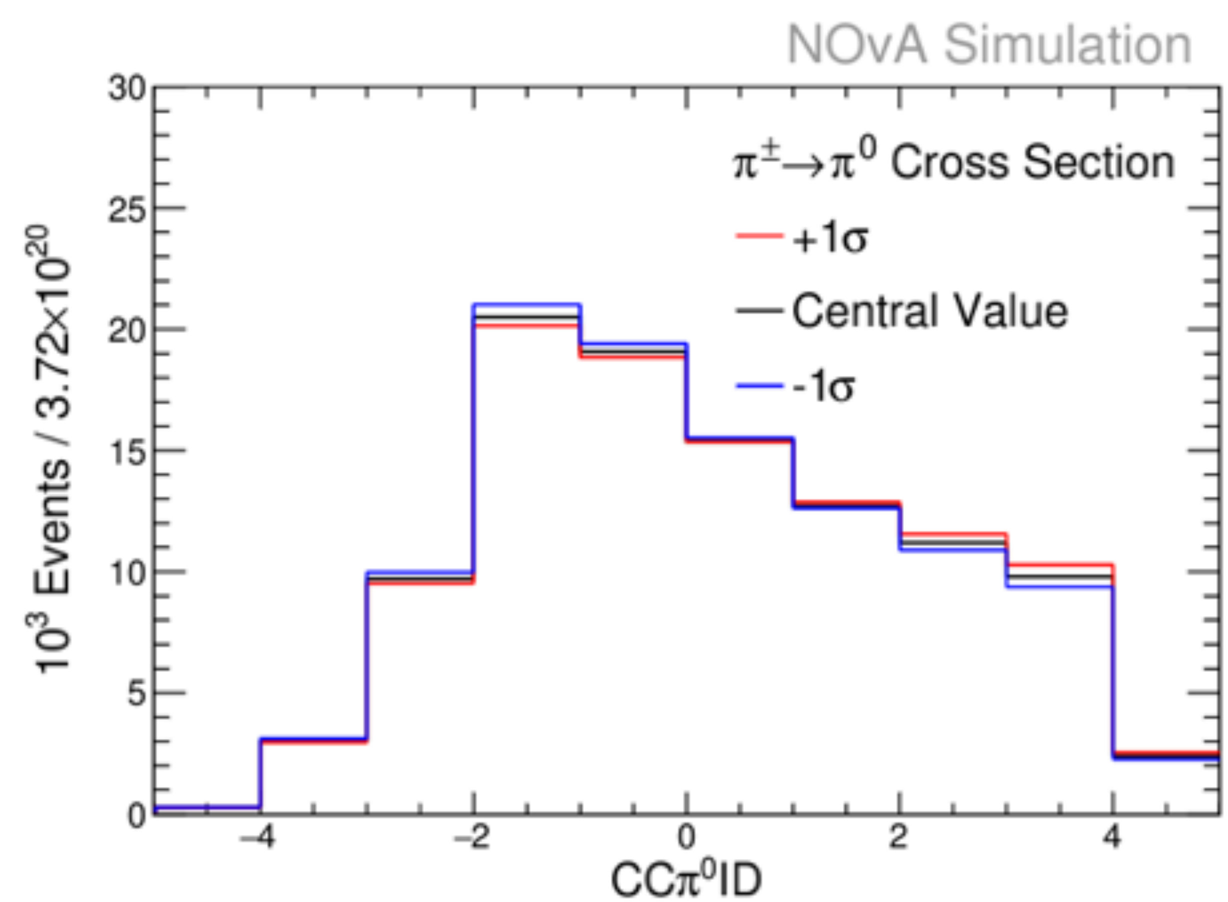
  Weight σ^{CX} to 1.061±0.146 of nominal value

  Phys. Rev. C 95, 045203 (2017)

- Noticeably skews CCπ0ID distribution for background

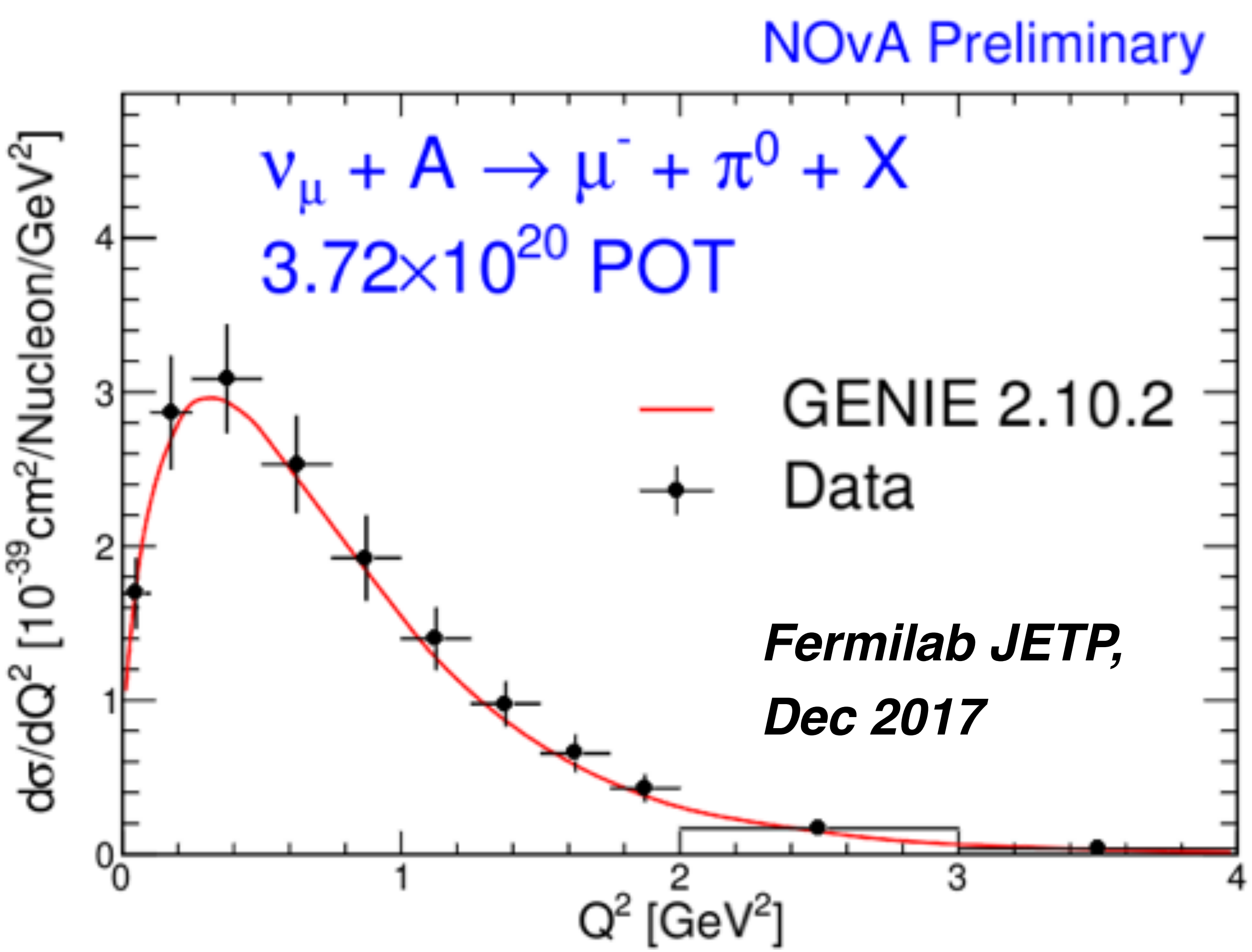
  4% impact on total cross section

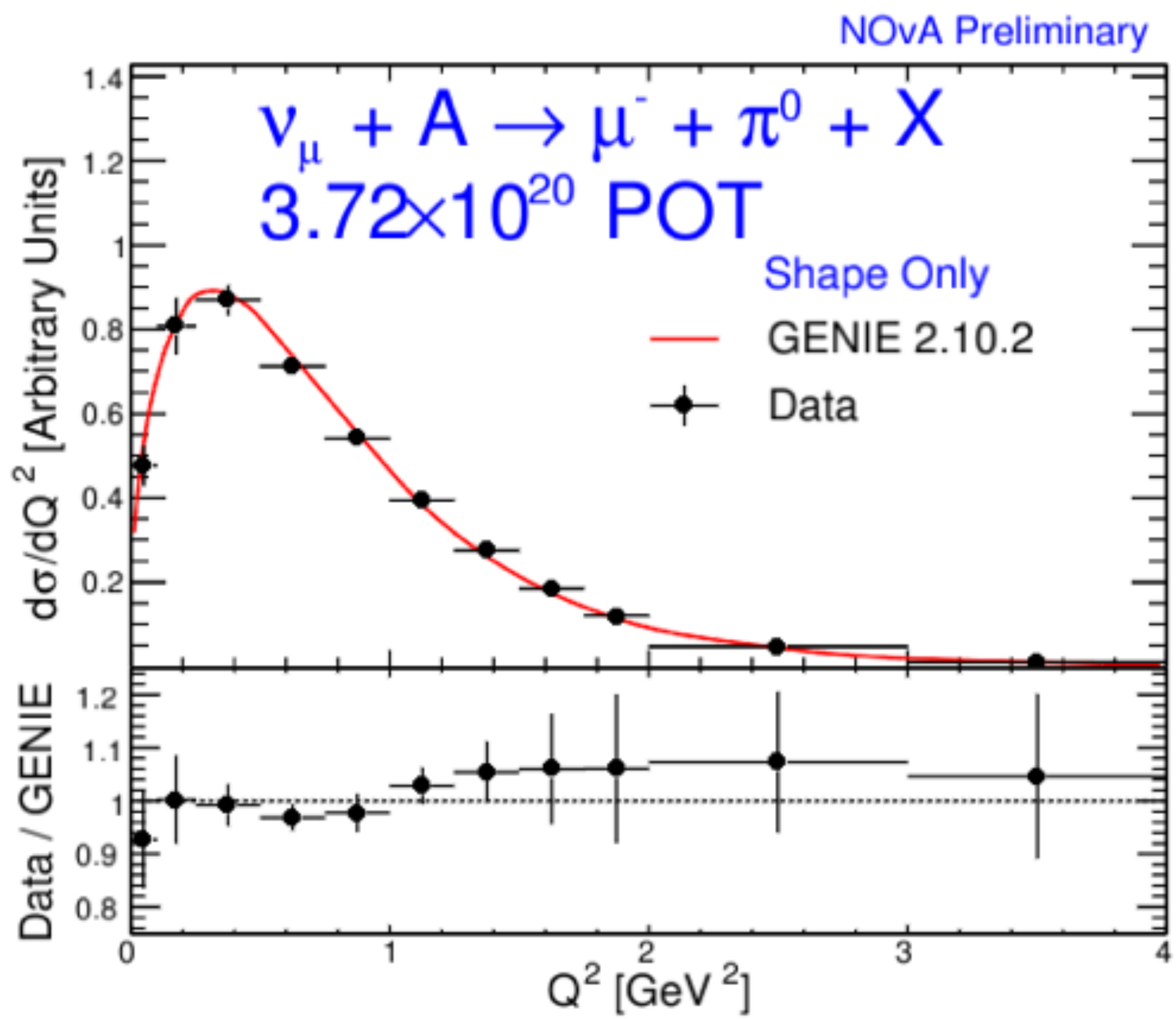




dσ/dQ² Cross Section

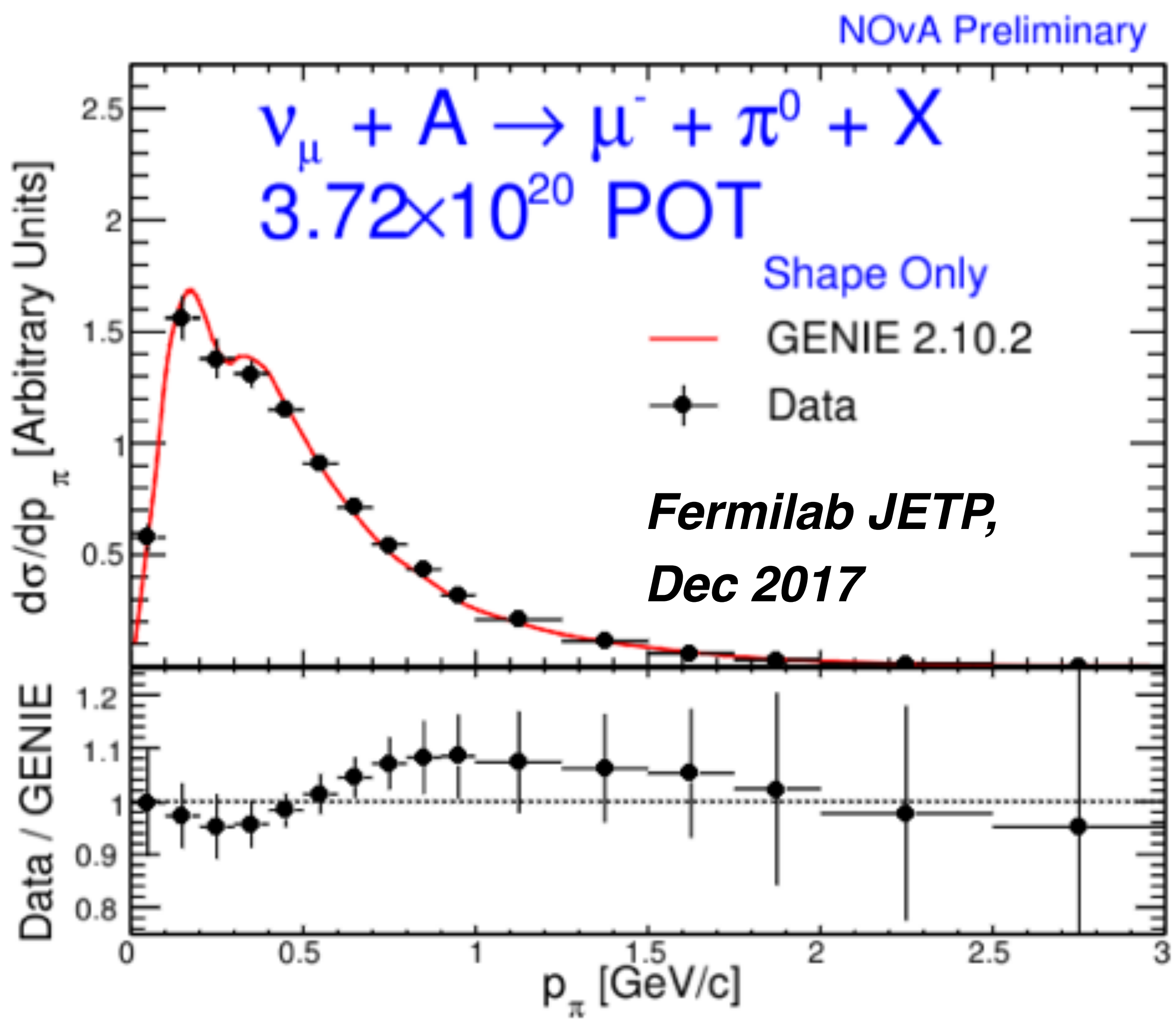
Good shape agreement.

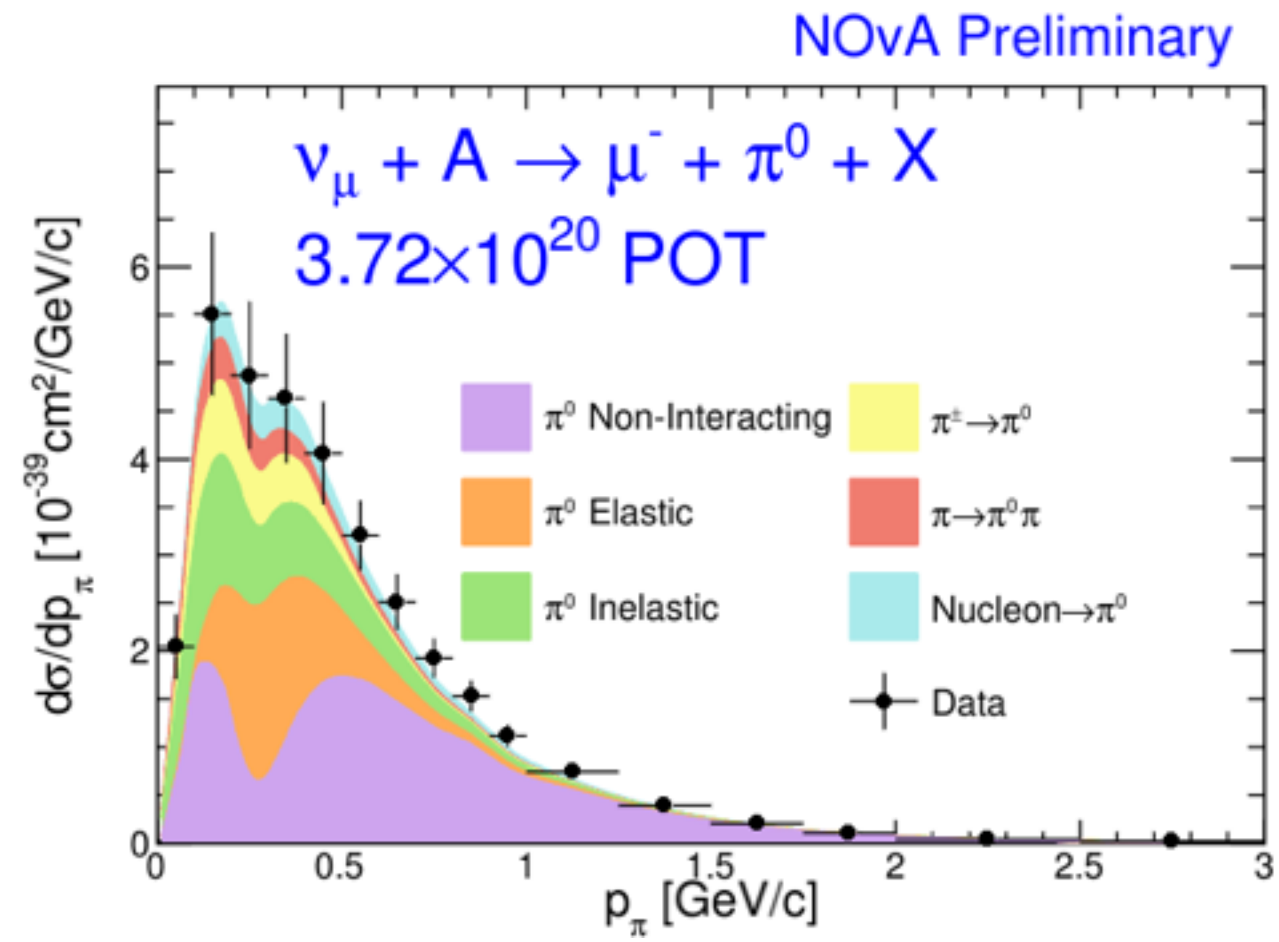




Fermilab

$d\sigma/dP_\pi$ Cross Section





- **We expect to deliver the flux-average cross section of muon and neutral pion kinematics (angle respect to the beam and momentum), Q^2 and W.**
  - Also, the corresponding covariance matrix
  - Detailed model comparisons.

Paper is in final Collaboration Review, publication very soon!

Status of the NuMu CC Inclusive

NuMu CC Inclusive

- The plan is to measure: **flux-averaged double differential cross section in the muon angle respect to the beam and the muon kinetic energy, as well the neutrino energy.**

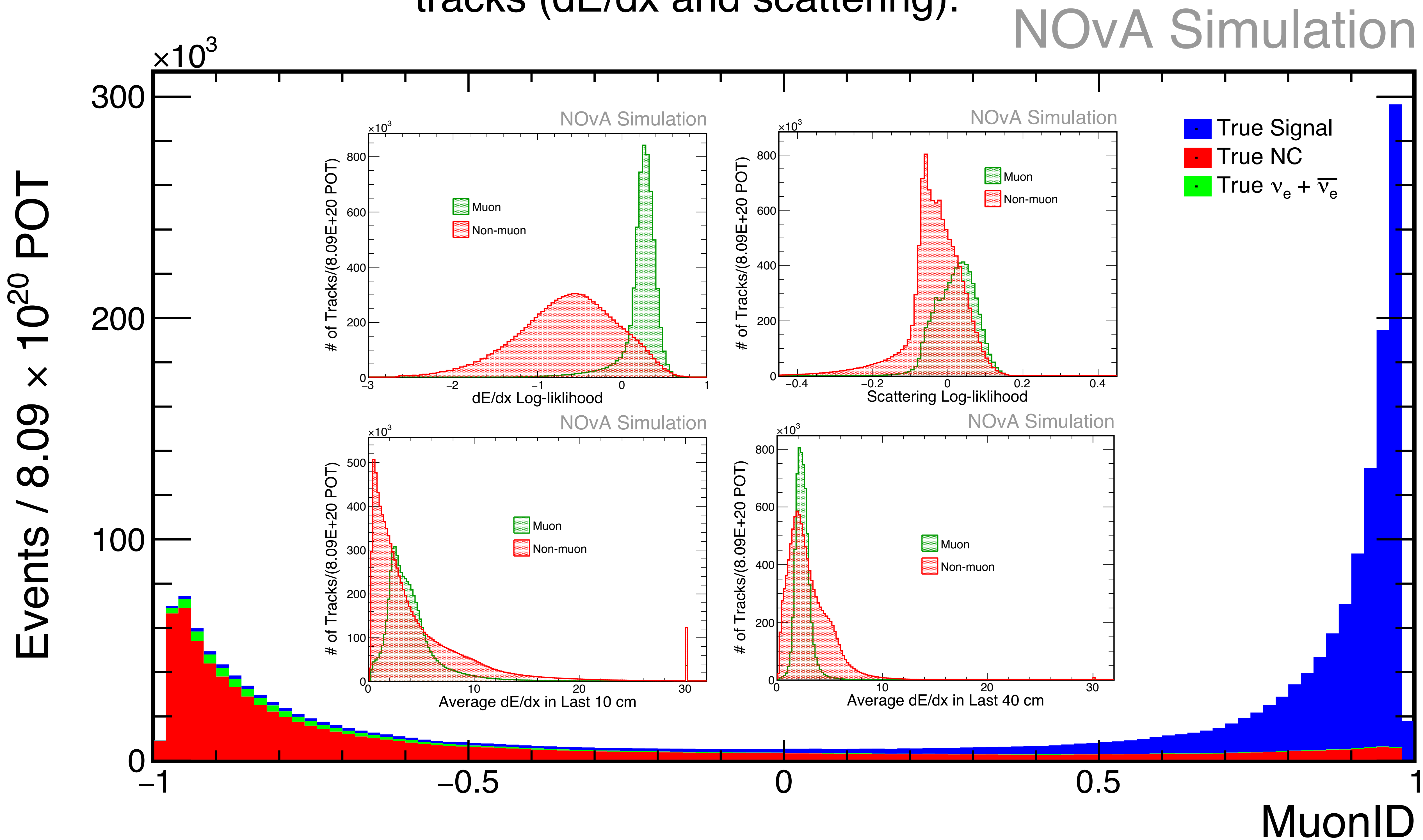
- Optimization of selection criteria are based on a new FOM that reduces the uncertainty on the measured total cross section.

- **Philosophy**: this measurement is systematics-limited, so relevant **GENIE** and **detector response** uncertainties are included in the FOM:

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{(\delta N_{\mathrm{sel}}^{\mathrm{stat}})^2 + (\delta N_{\mathrm{bkg}}^{\mathrm{stat}})^2 + (\delta N_{\mathrm{bkg}}^{\mathrm{syst}})^2}{(N_{\mathrm{sel}} - N_{\mathrm{bkg}})^2} + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

Event Selection

A muonID is developed, based on the kinematic of the tracks (dE/dx and scattering).



Event Selection Optimization

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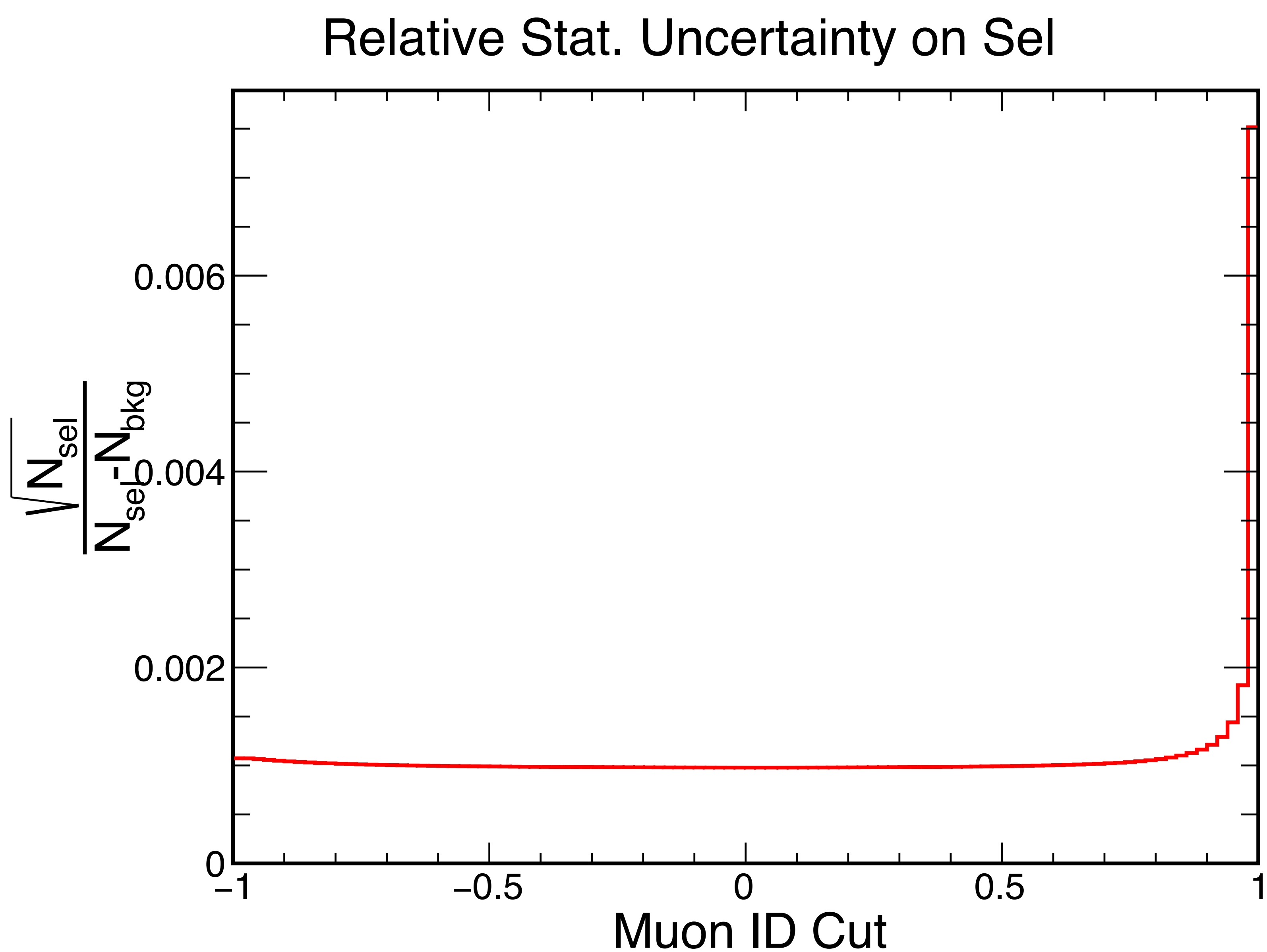

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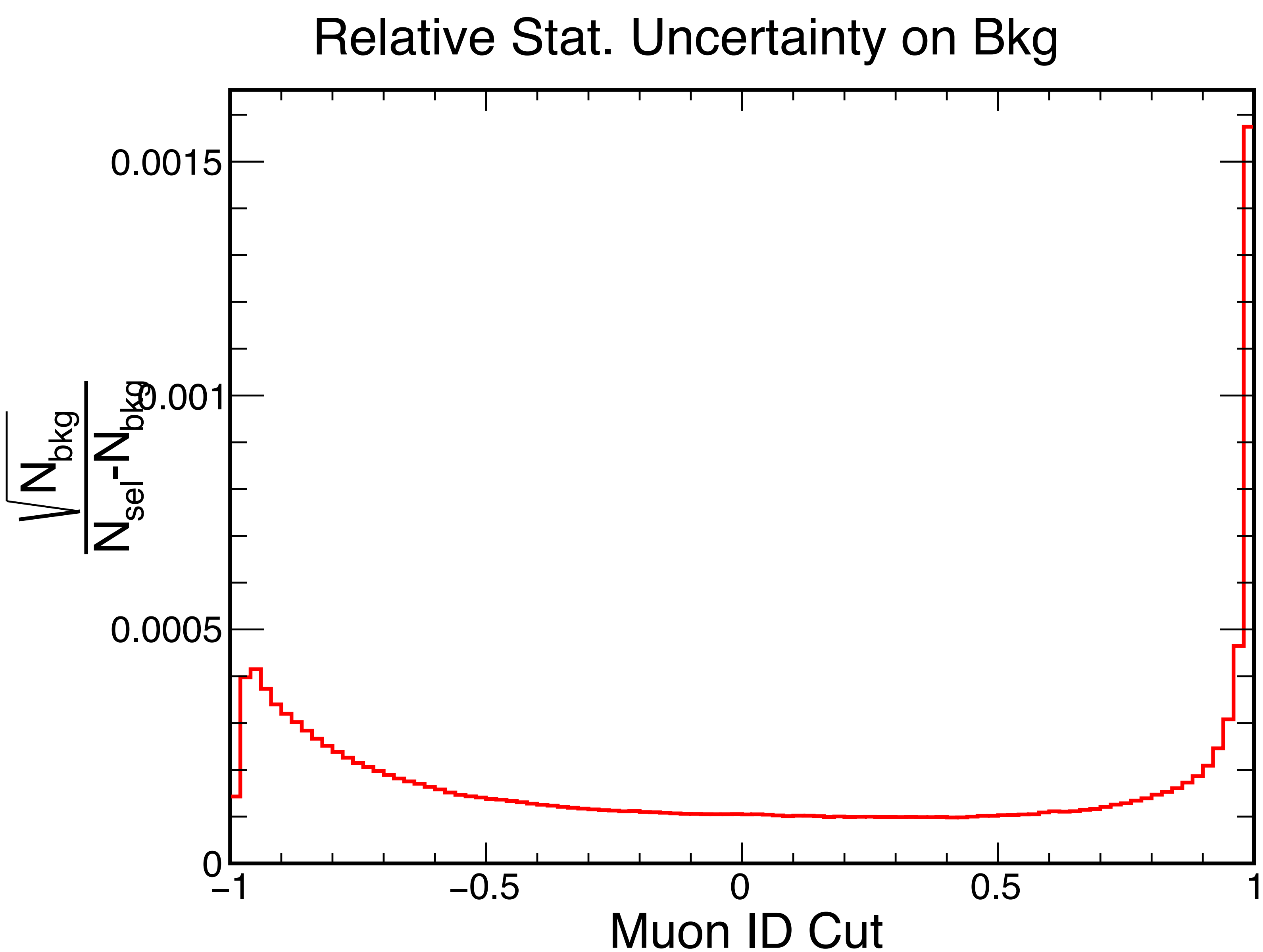

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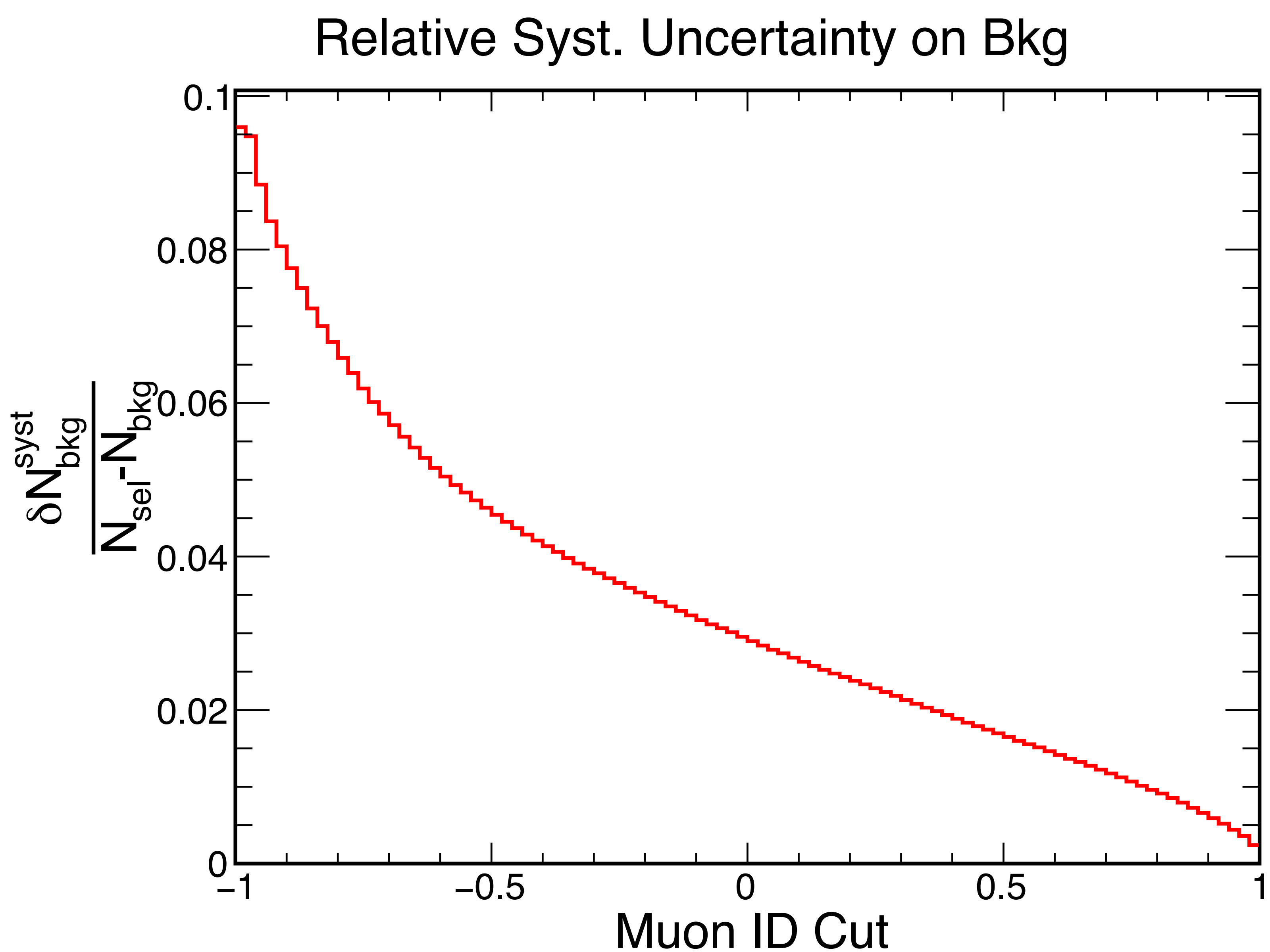

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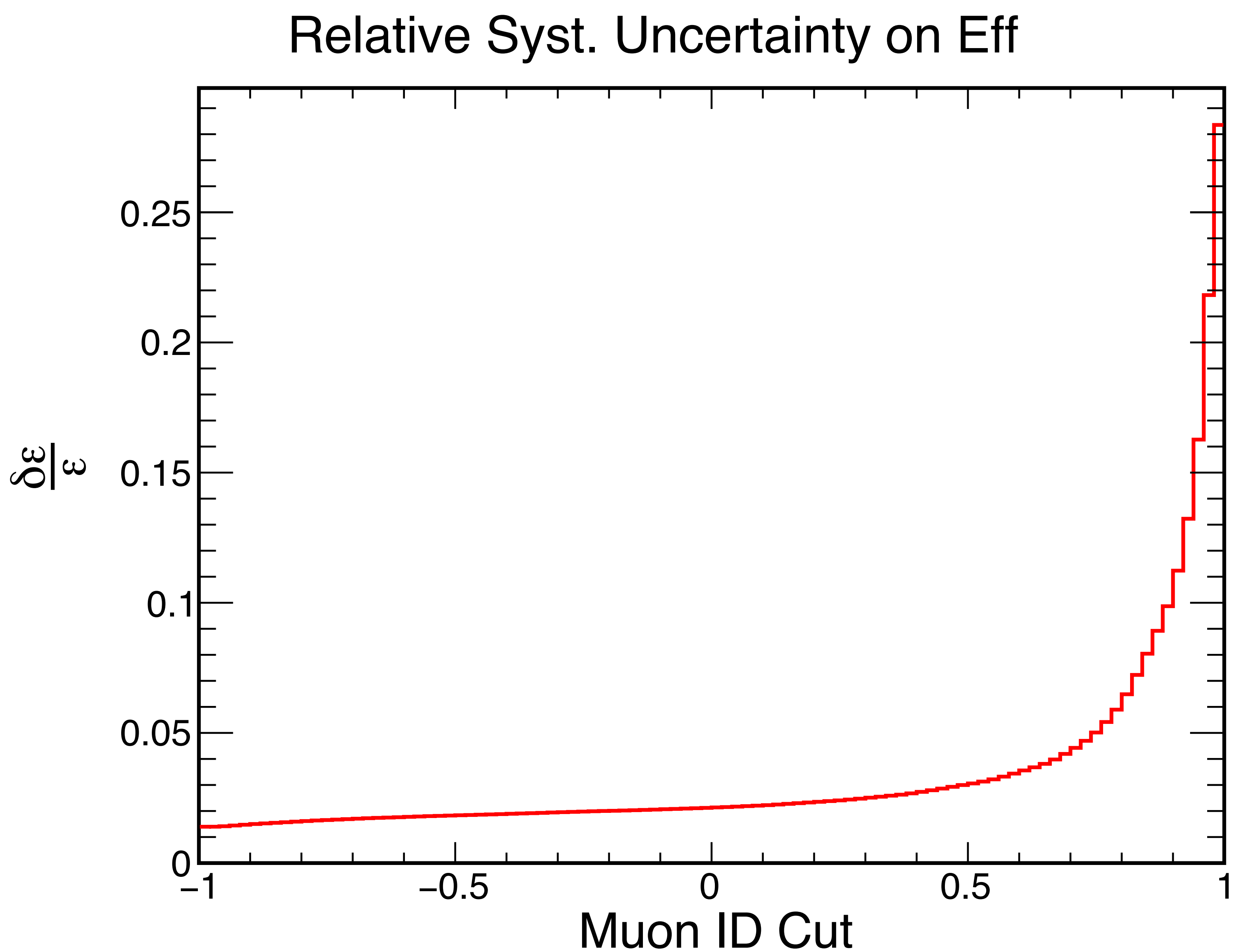

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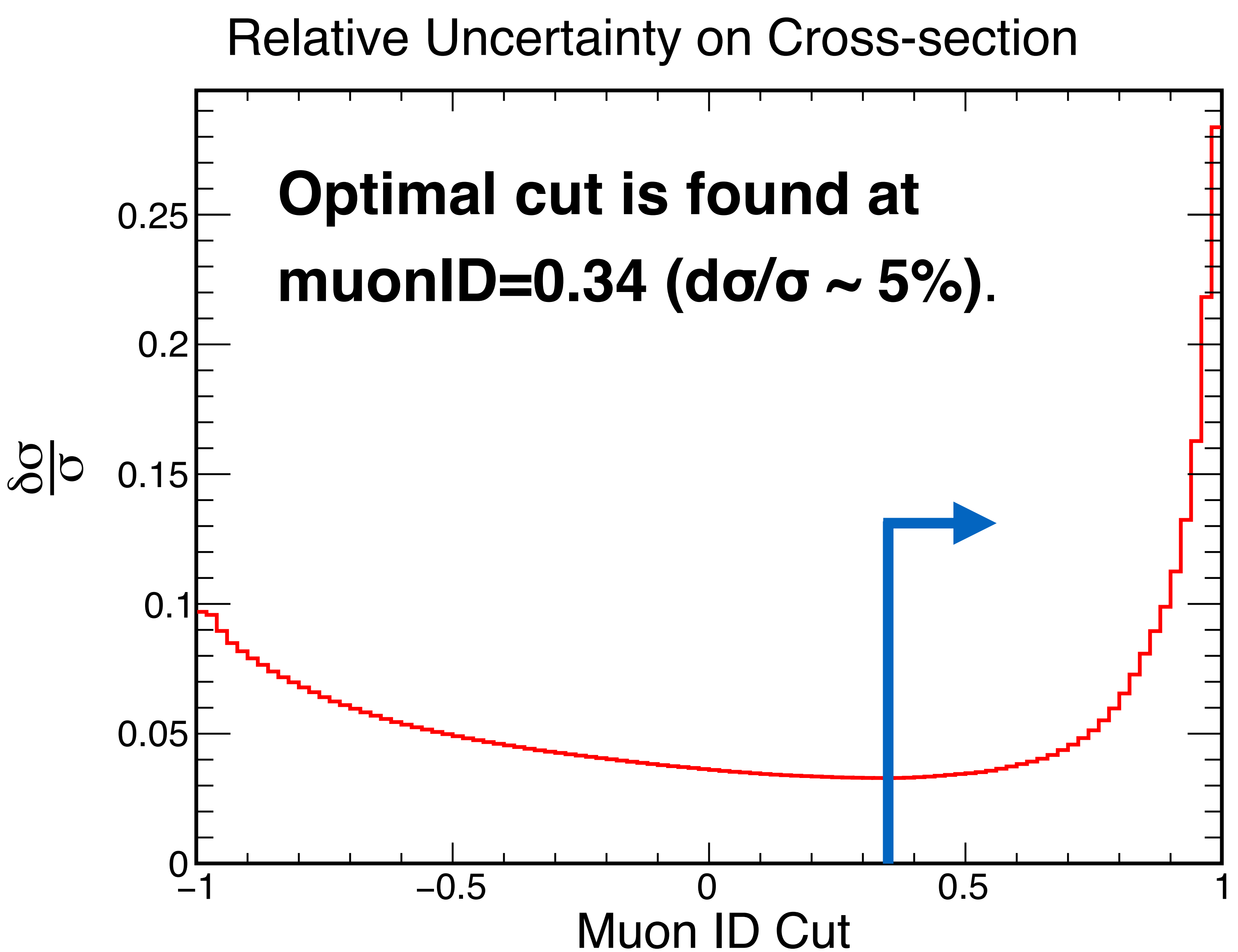


Event Selection

- The event selection cuts include: quality, fiducial, containment and the MuonID cut.

Signal CC Inc. ν_μ	CC Inc. $\bar{\nu}_\mu$	NC	CC Inc. $\nu_e + \bar{\nu}_e$	Non-fiducial
86.4 % (1.18×10^6)	2.57%	7.60%	0.44%	2.96%

- Fraction of signal events per interaction mode:

QE	Res	DIS	Coh	MEC
20.85%	38.68%	19.80%	1.79%	18.88%

Muon and Neutrino Energy Estimation

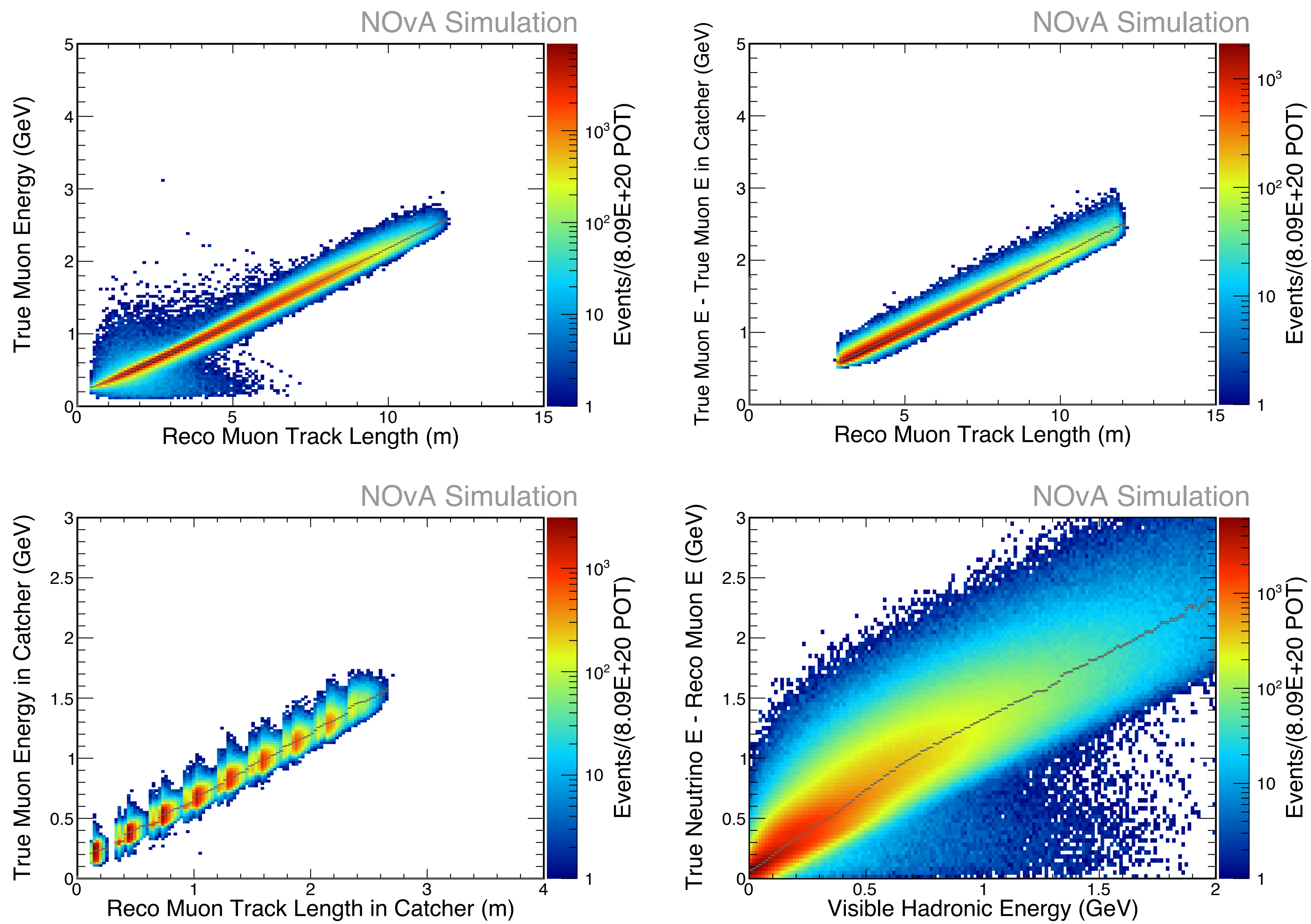
Simulated neutrino interactions are used to relate reconstructed tracks and visible hadronic energies to the neutrino energy.

1. E_μ is estimated from the track length. Two cases:
   - Contained in the active region or in the active + muon catcher region.

2. E_{had} is estimated from the difference between the true neutrino energy and the muon energy.

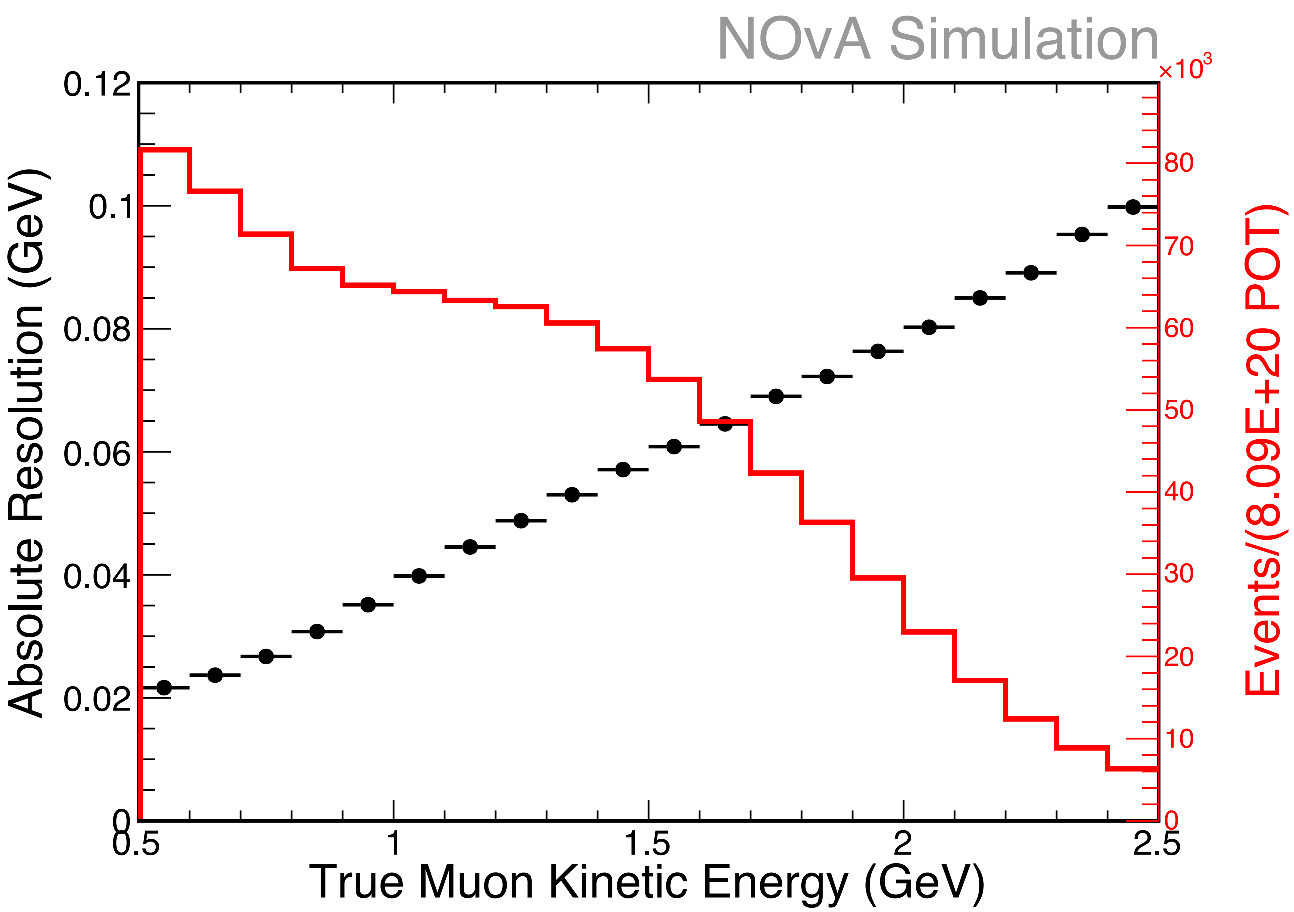
3. E_ν is sum of both:

$$E_\nu = E_\mu + E_{had}$$

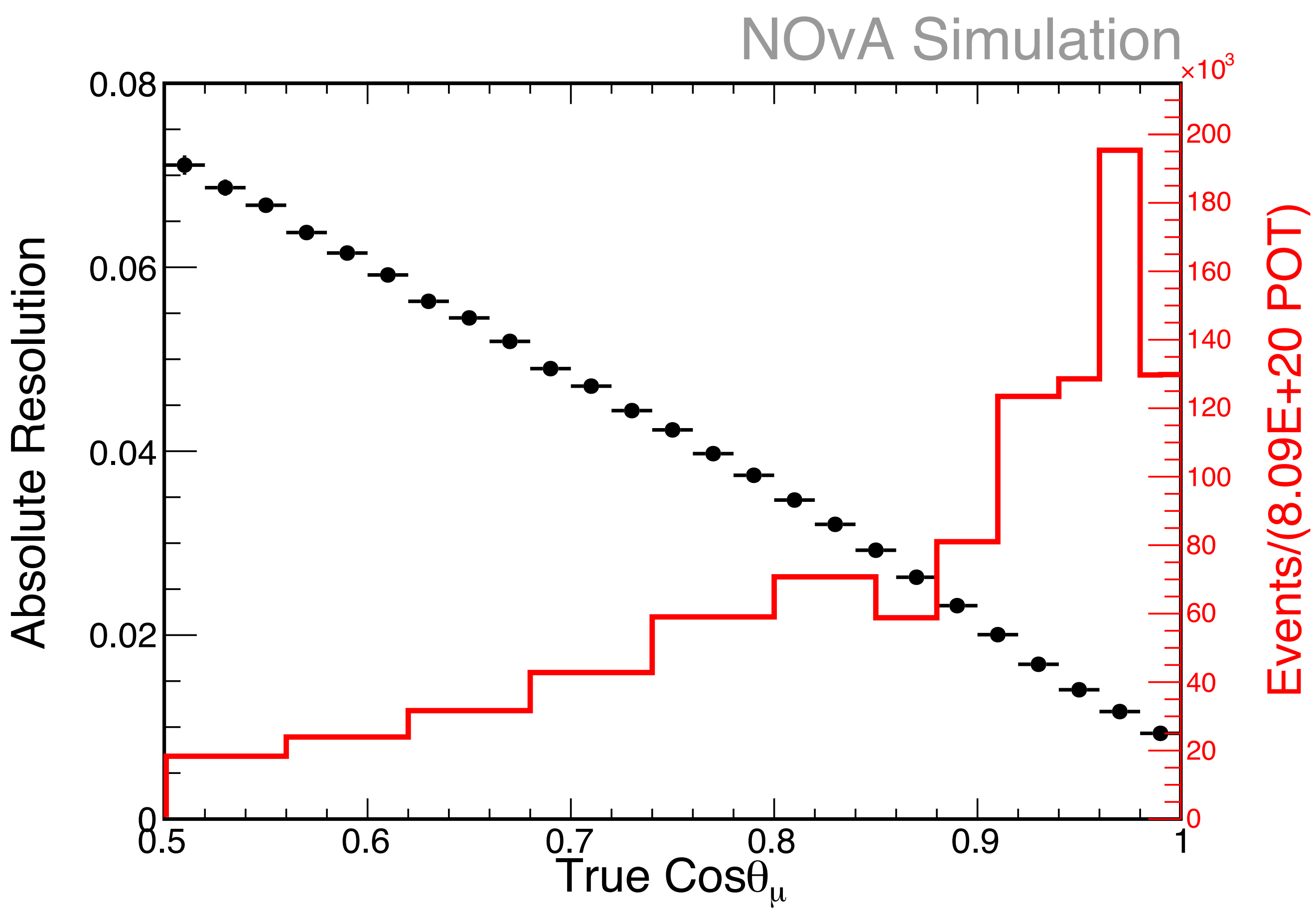


Resolution and Binning

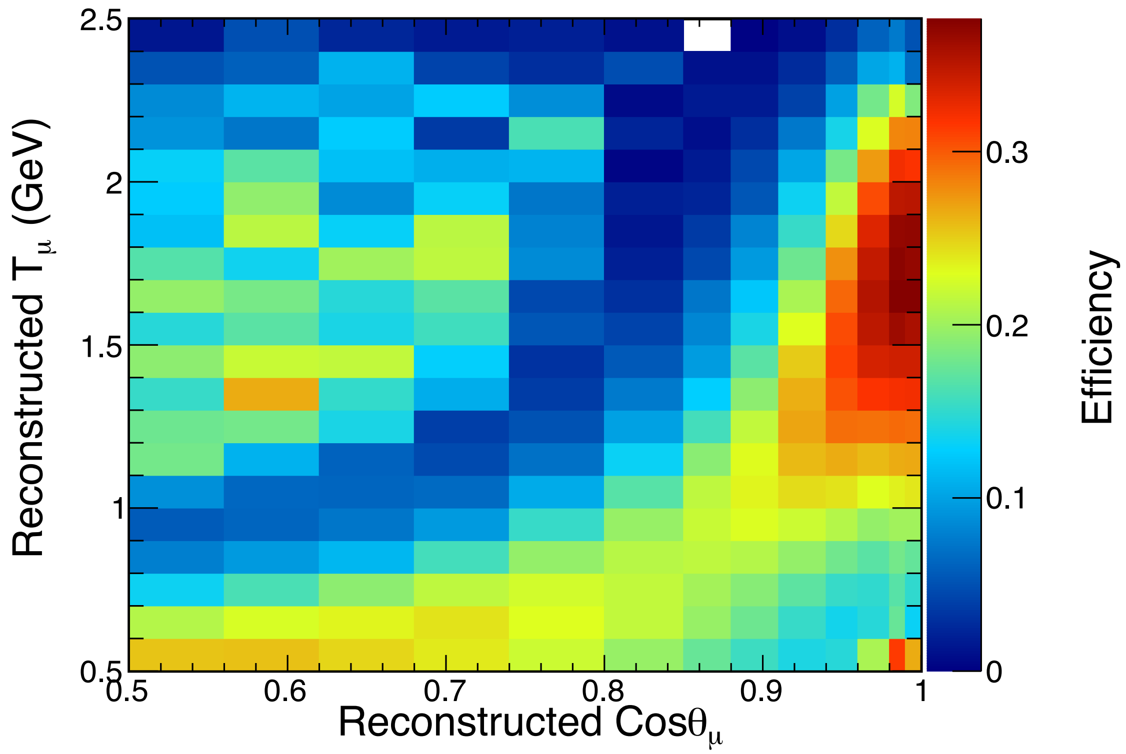
- Muon energy resolution is 20-110 MeV.

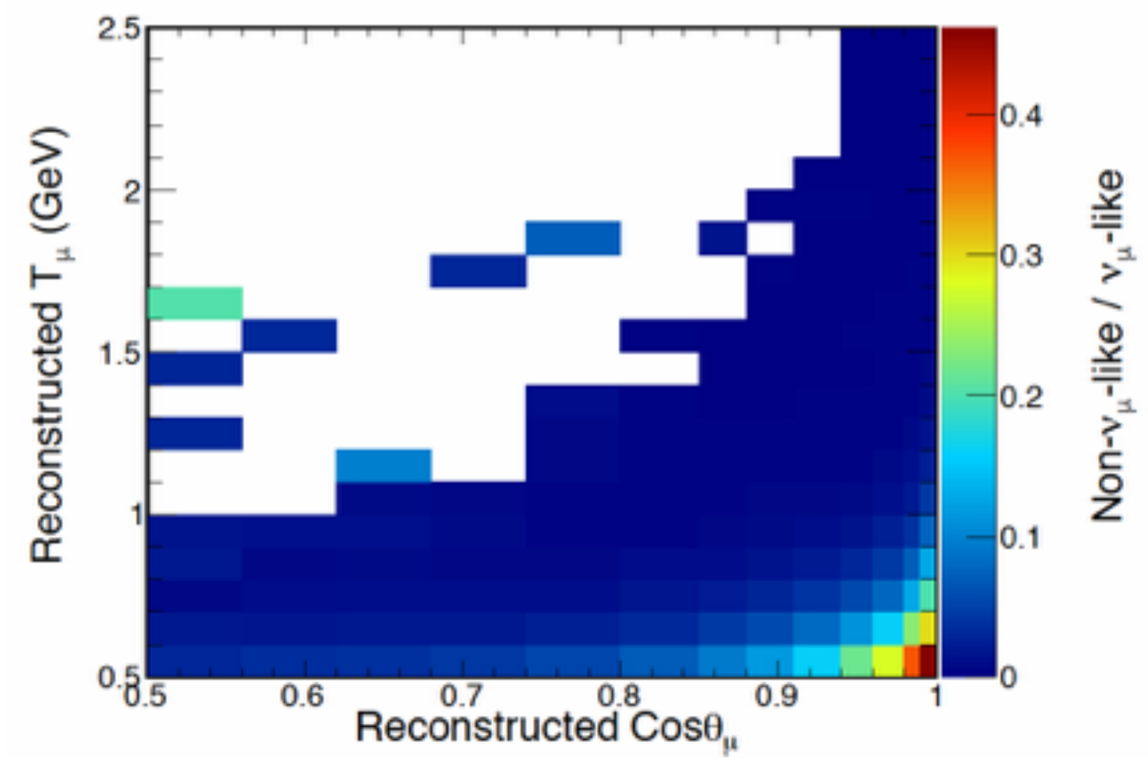


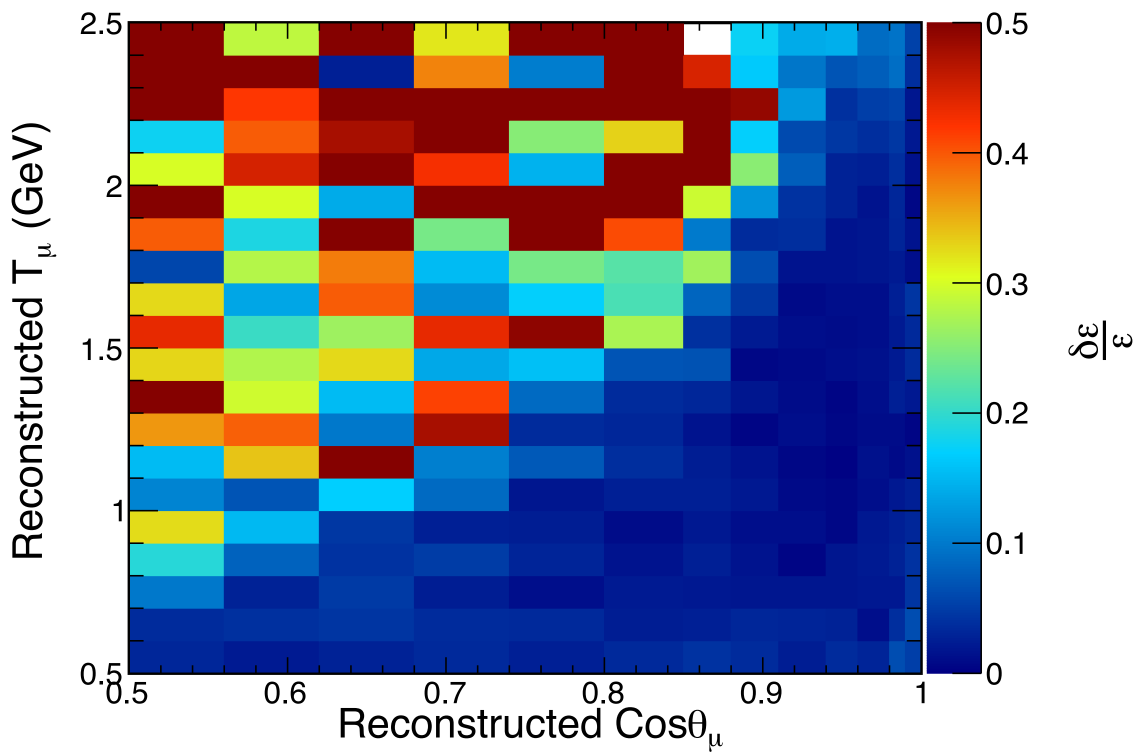
- Resolution in cosθ is 0.01-0.07

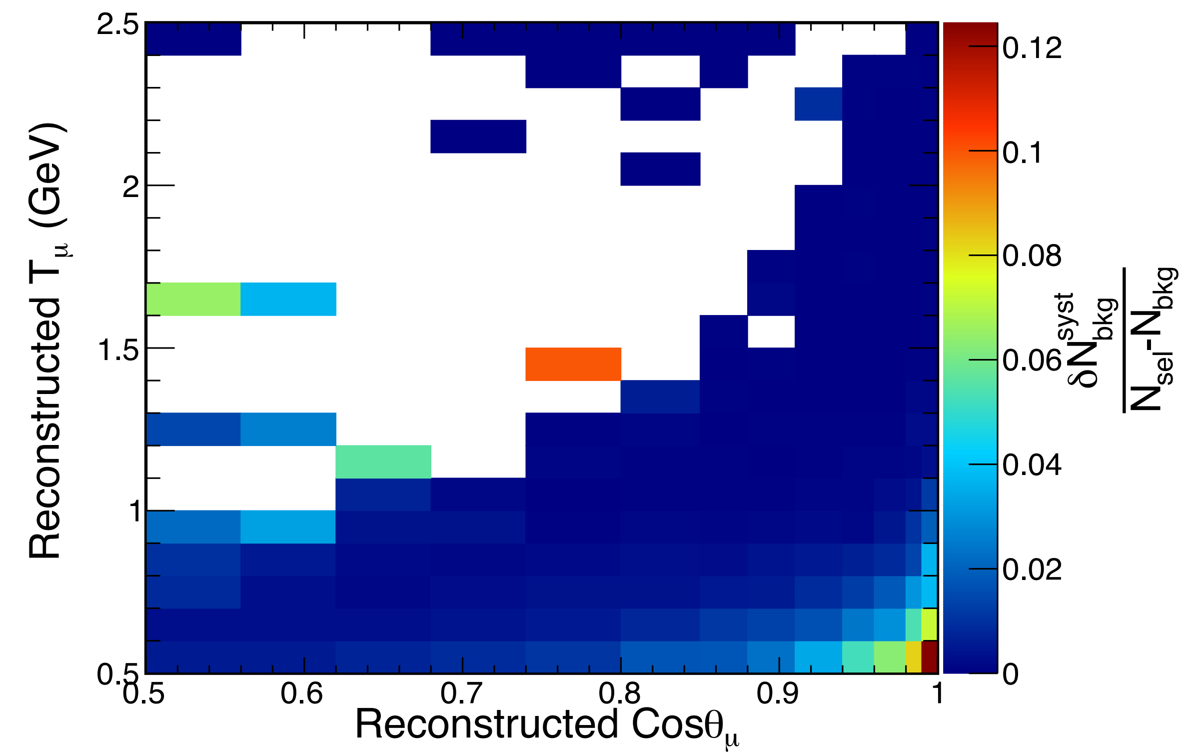


Event Selection Efficiency and Purity

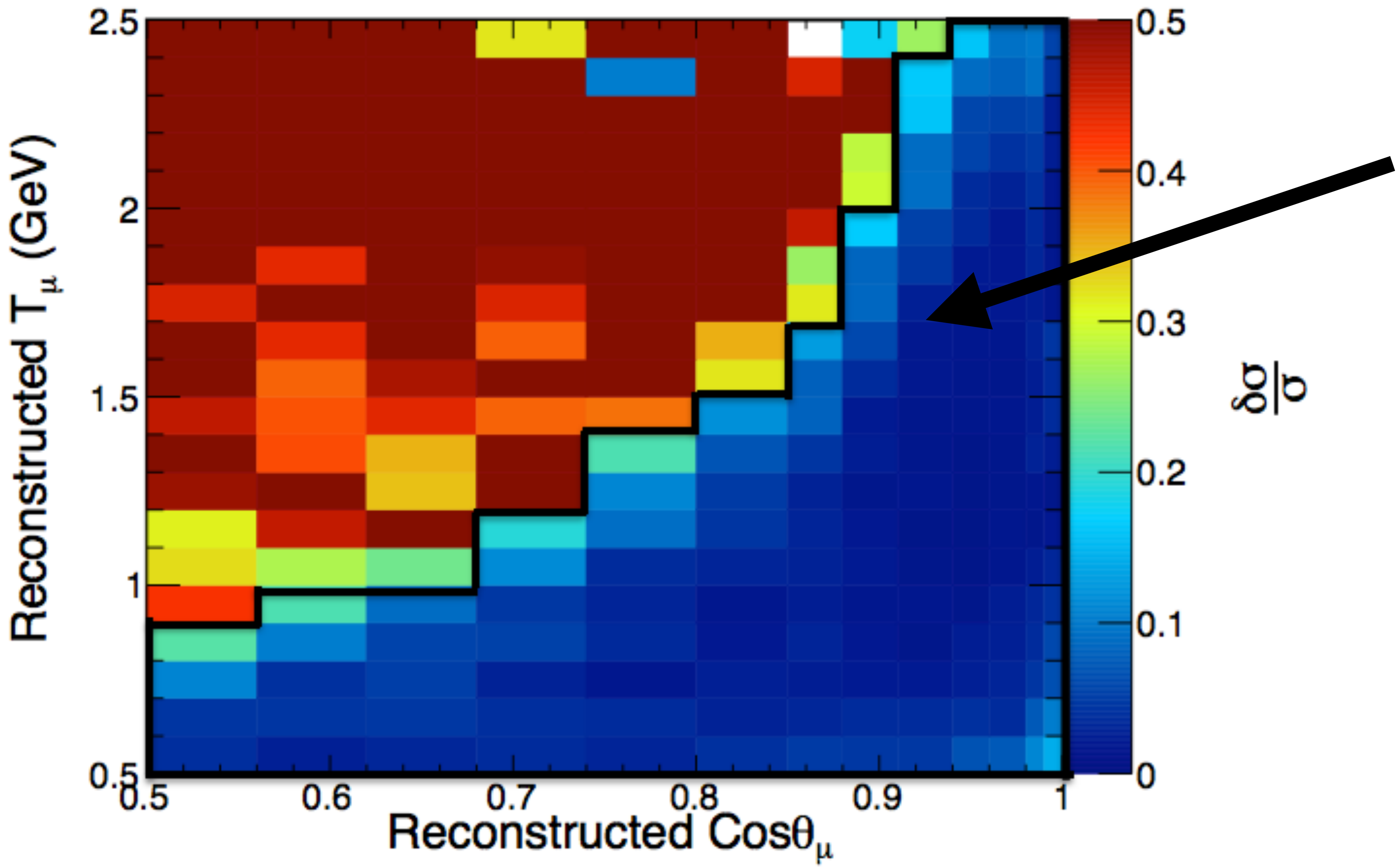








Muon Phase Space Cuts



We will report results for bins below the line

Good phase space coverage.

Analysis is its final stage evaluating systematics and it is expected results very soon.

Our Delivery

- Double differential cross section with respect to muon kinematics (**T_{μ}, $\cos\theta_{\mu}$**) and cross section vs **neutrino energy** (and possibly other derived quantities).
- Unfolded results with covariance matrices and results in reconstructed space with forward-folding matrices.
- Quantitative comparisons to generators.
- **Anything else?**

Conclusions

- The NOvA ND is a powerful detector with high statistics for [anti-]neutrino-nucleus cross section measurements.

- We have presented results for the CC semi-inclusive π^0 and the NC coherent π^0 cross sections that **will be submitted for publication soon**.

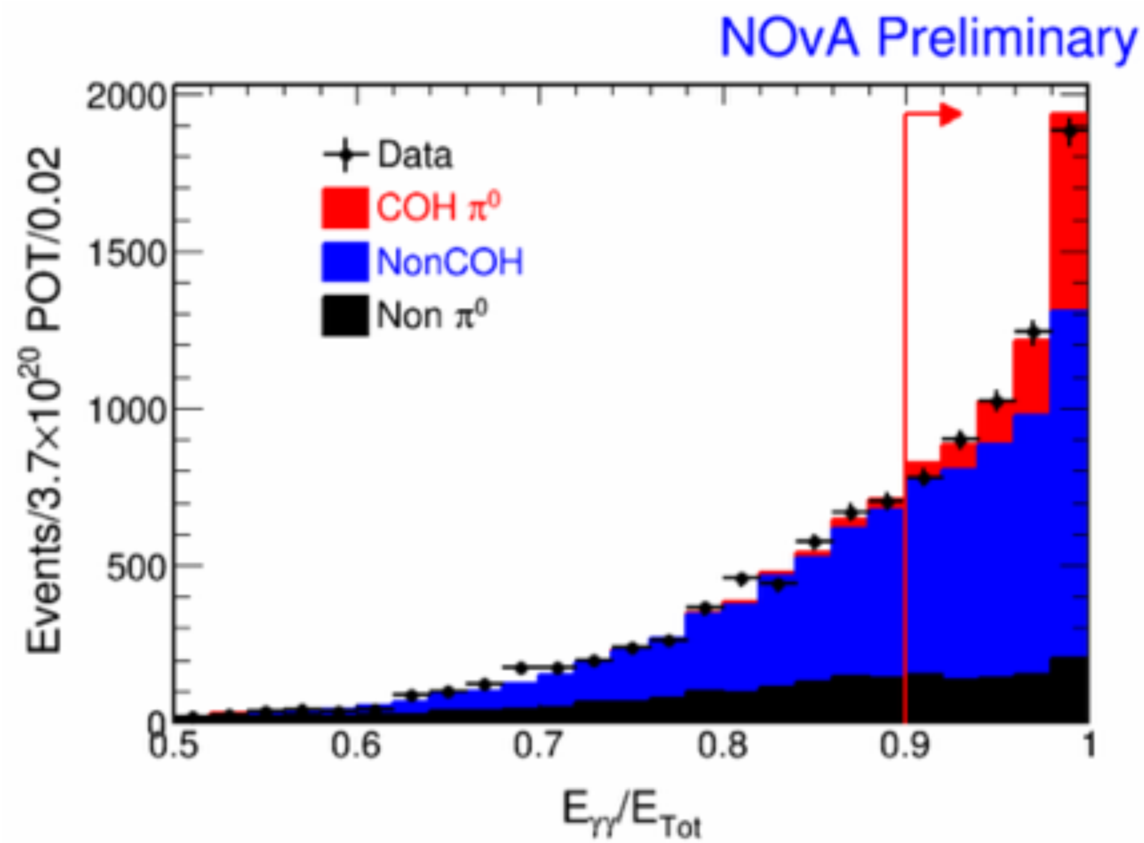
- **The CC inclusive channels have the highest priority and expects to present results in the Fermilab Joint Experimental-theoretical Physics Seminar soon.**

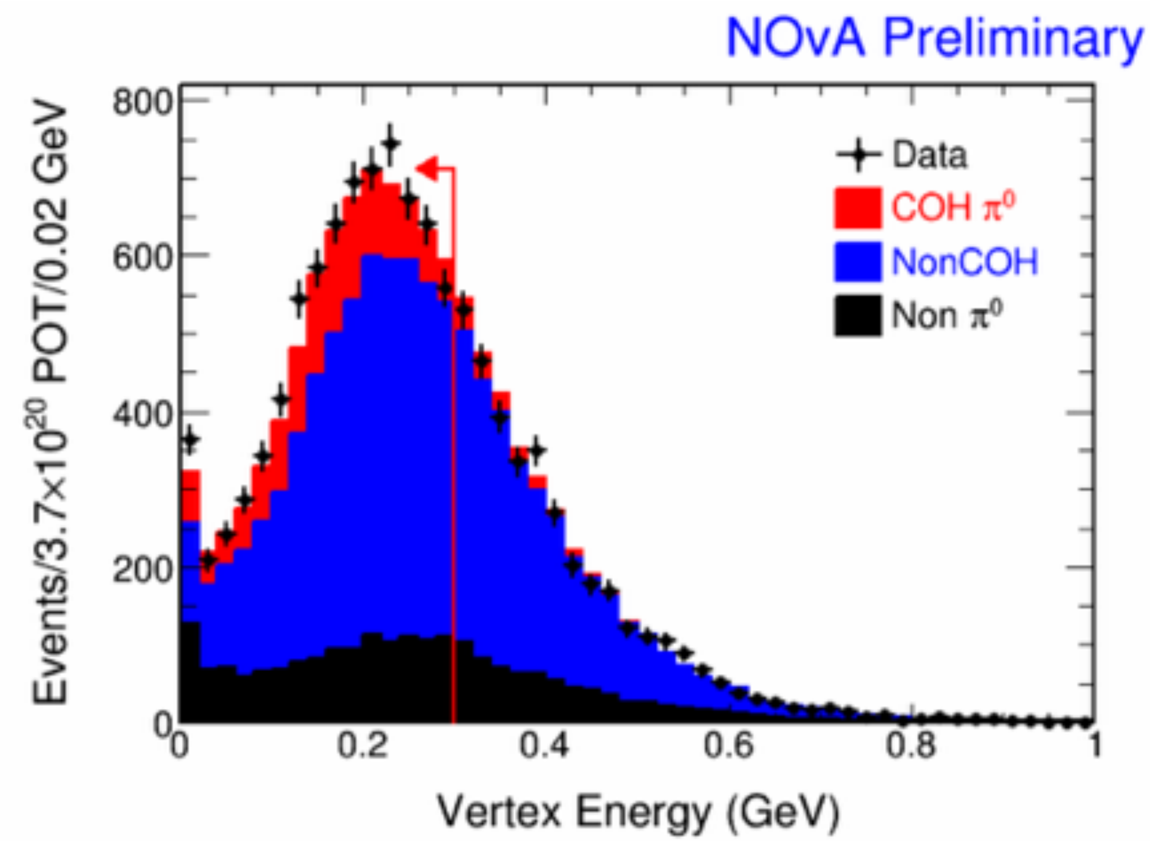
- Ratio measurements of semi-[in,ex]clusive channels respect to the inclusive cross section are being pushed forward **(see next talk by Matt Judah)**.

- Muon antineutrino analysis will follow soon.

Backup

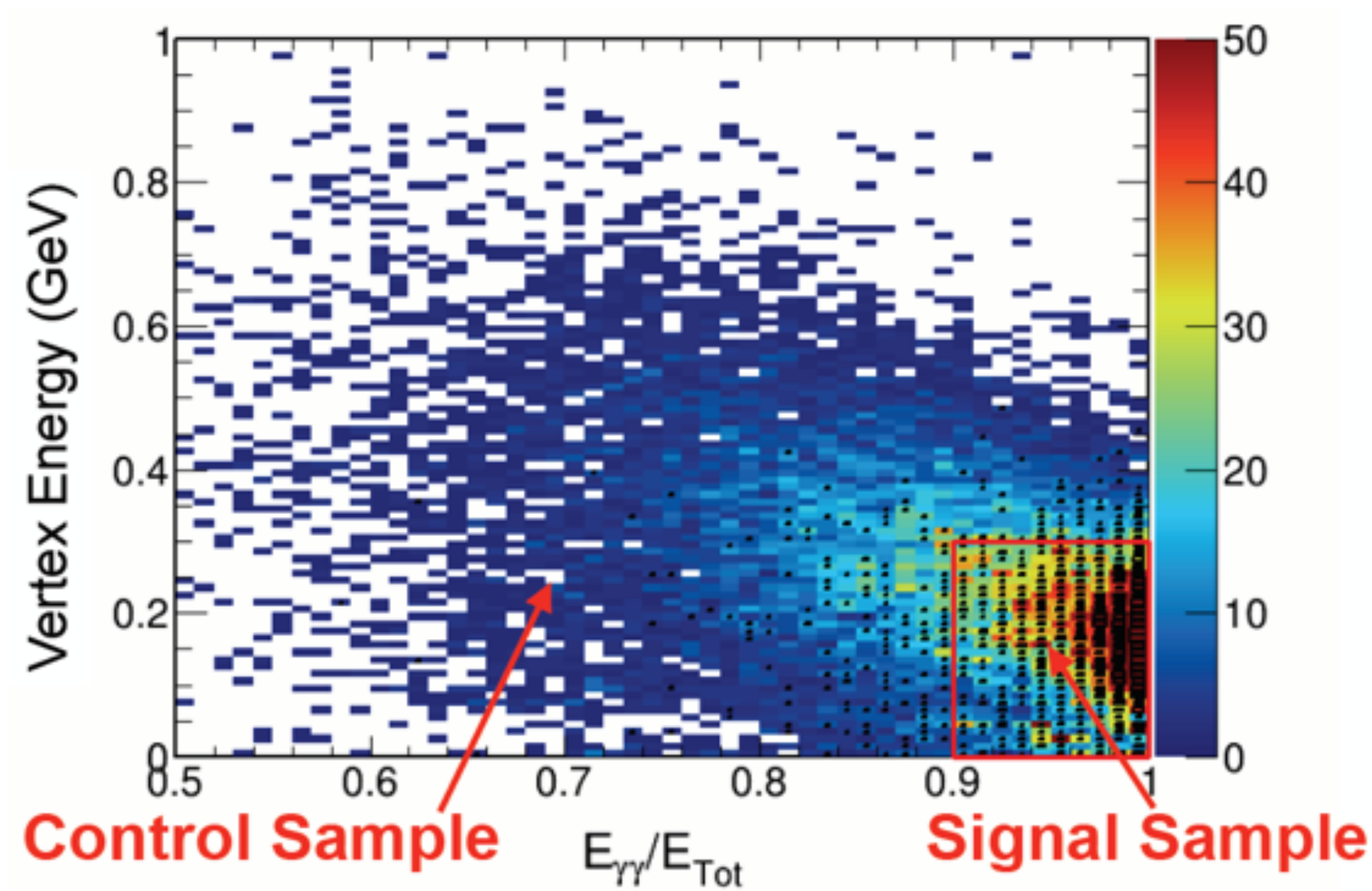
NC Coh: Signal and Control Samples



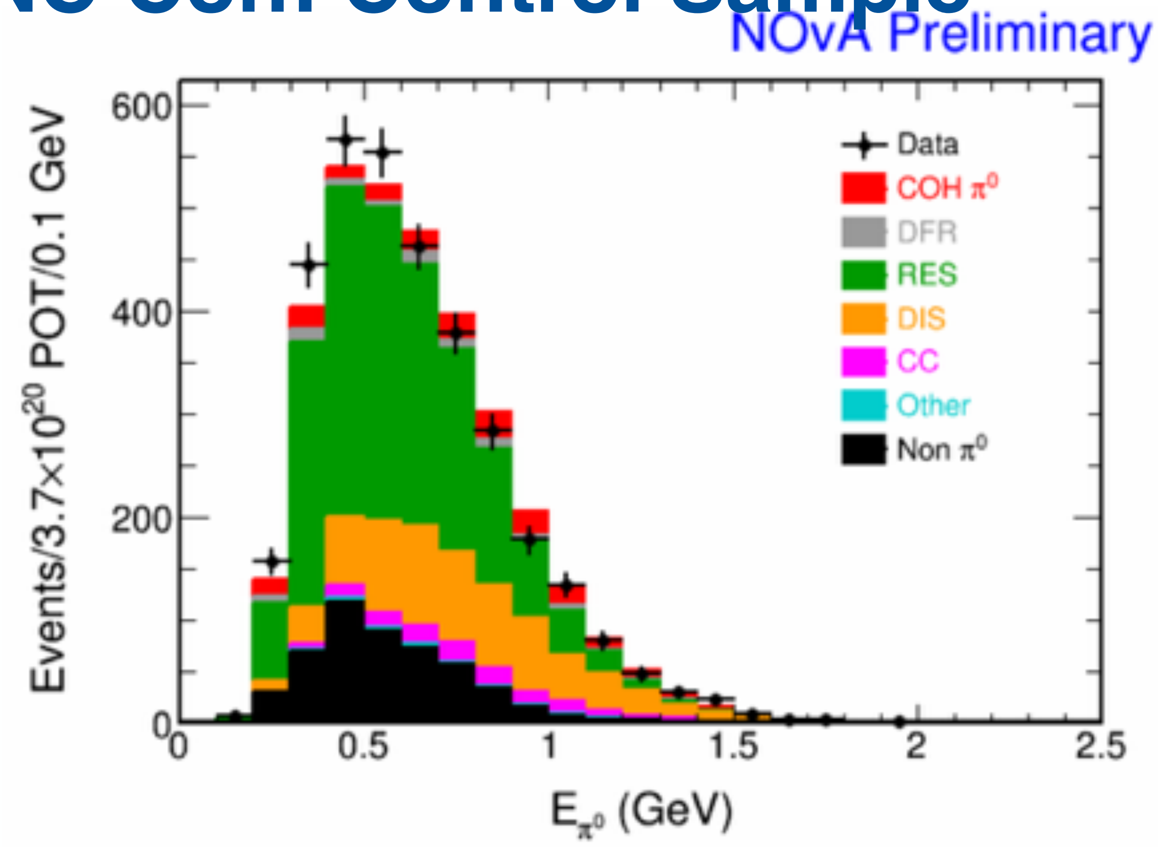


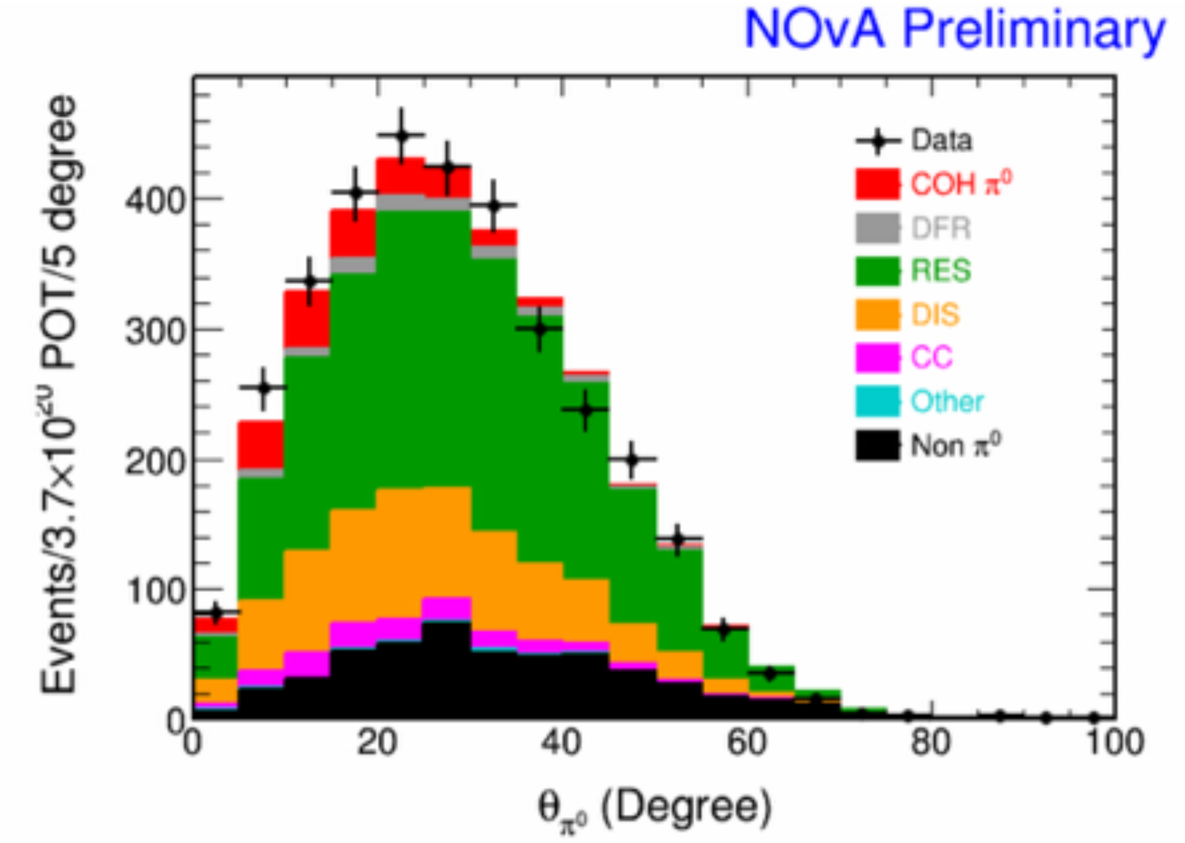
Signal sample: events with most of their energy in the 2 γ showers and with low vertex energy (>90% of signal).

Control sample: dominated by non-coherent π^0s (RES and DIS).



NC Coh: Control Sample





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

- Apply the background tuning to the signal sample.