NOvA Pion Measurements

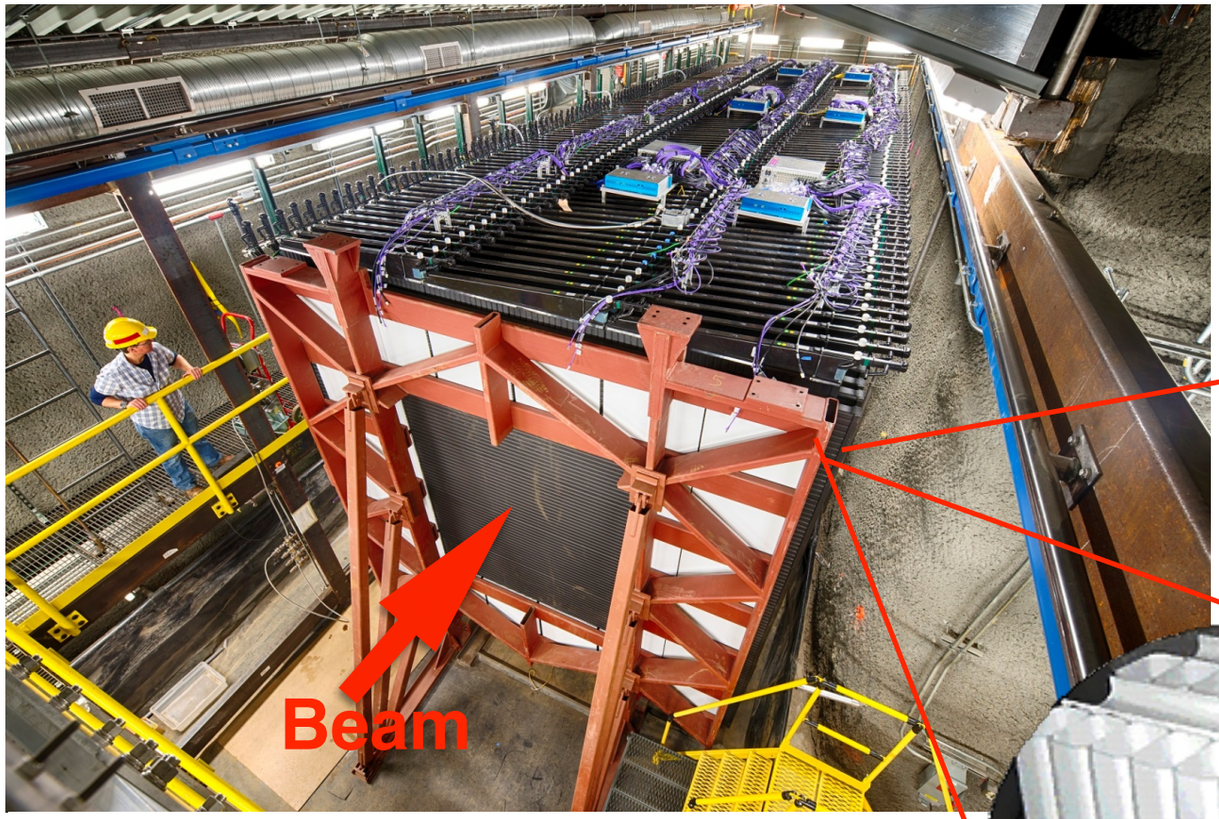
Hongyue Duyang

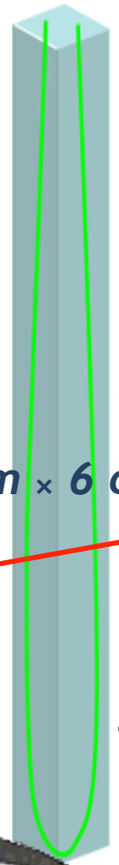
University of South Carolina

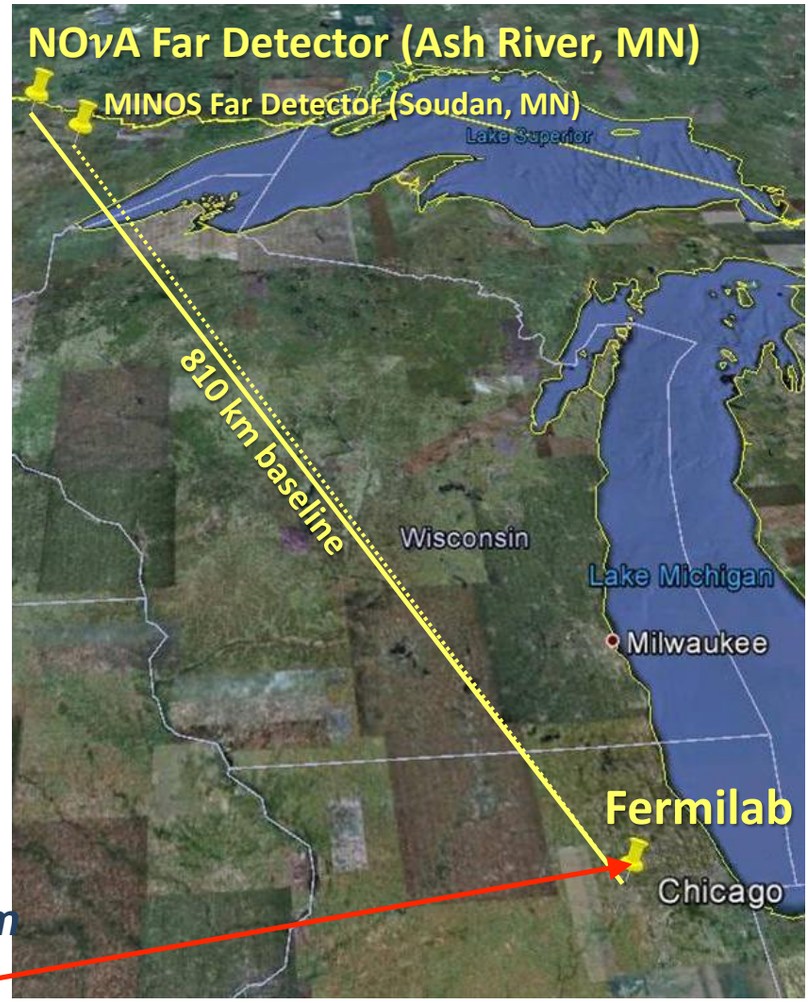
For the NOvA Collaboration

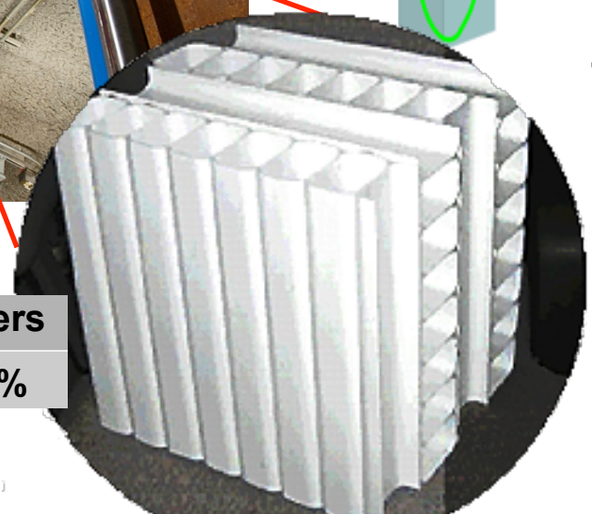
The NOvA Near Detector

- 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.





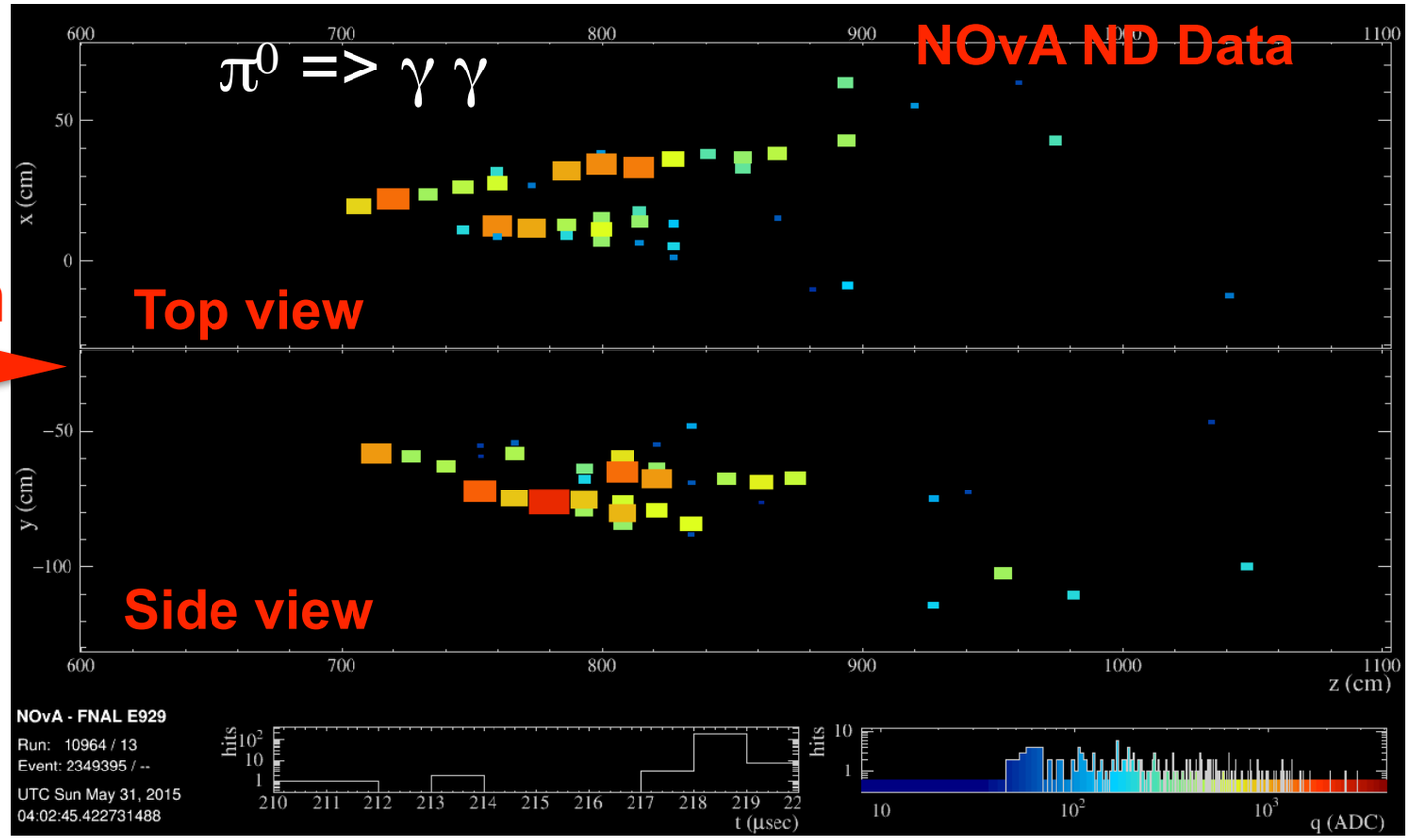




- Low-Z, fine-grained (1 plane ~ $0.15X_0$), highly-active tracking calorimeter.

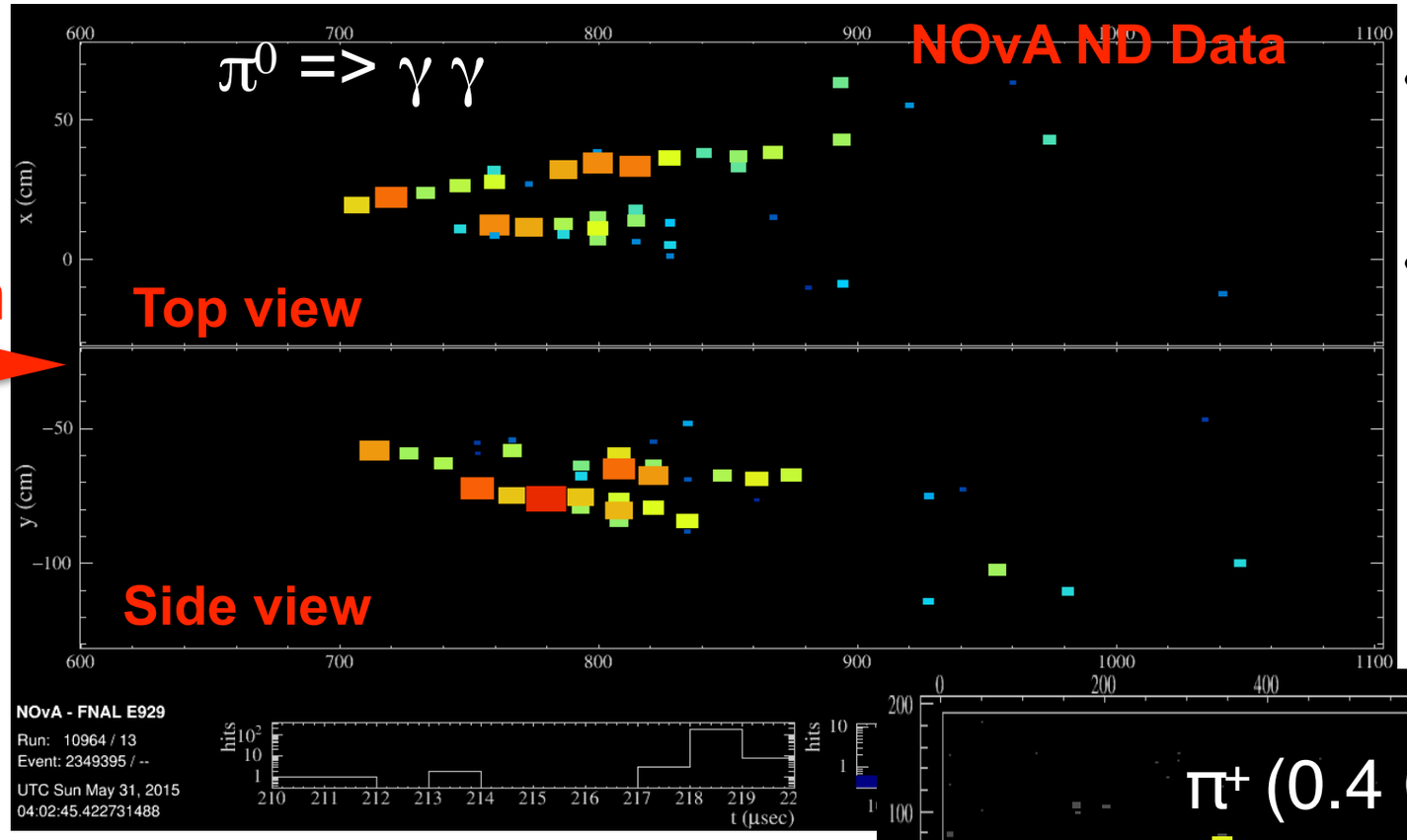
C12	Cl35	H1	Ti48	O16	Others
66.8%	16.4%	10.5%	3.3%	2.6%	0.4%

Pions in The NOvA ND



- Photons from neutral pion decay make EM showers.
- Reconstructing both photons provide constraint on background and energy scale.

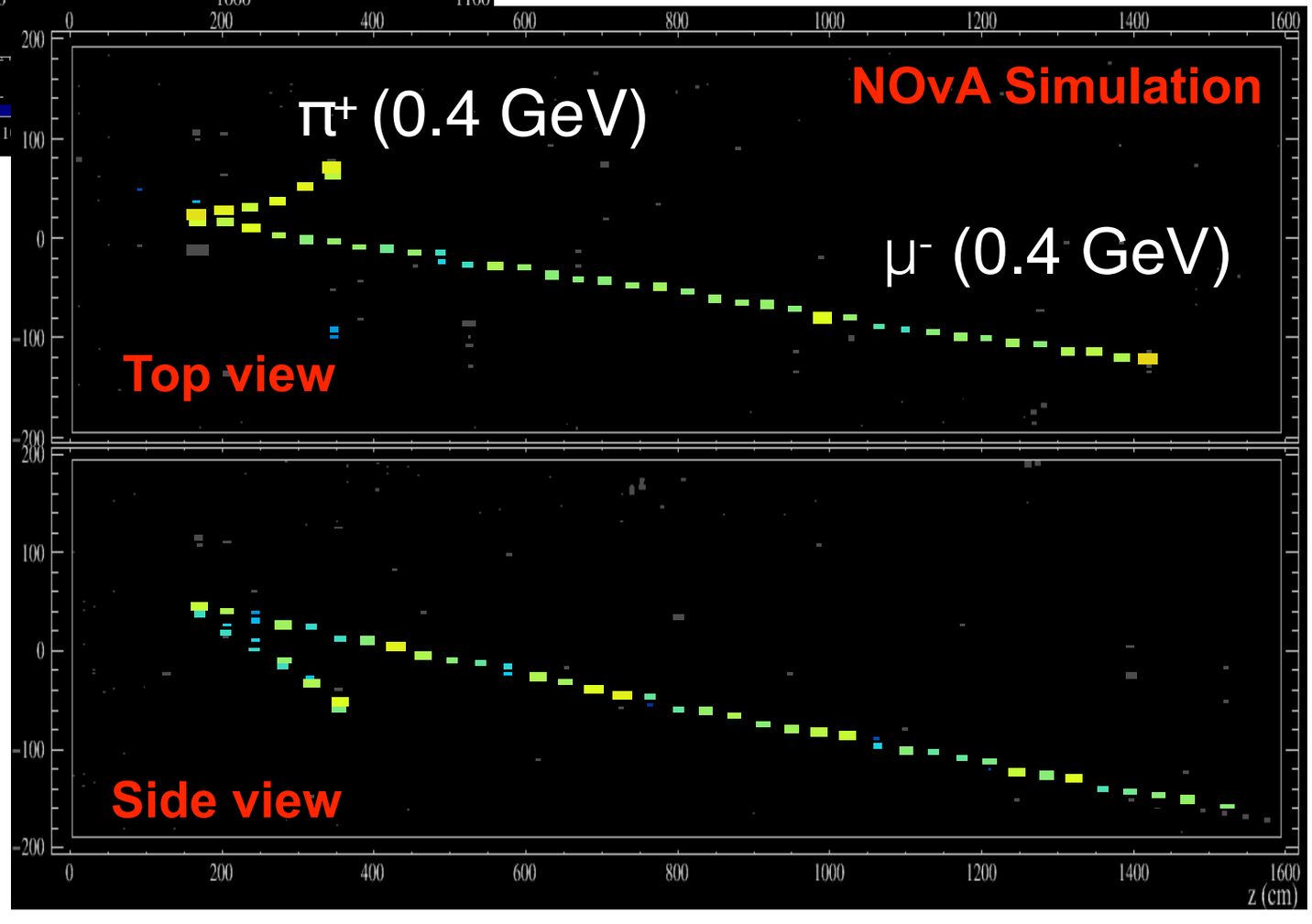
Pions in The NOvA ND



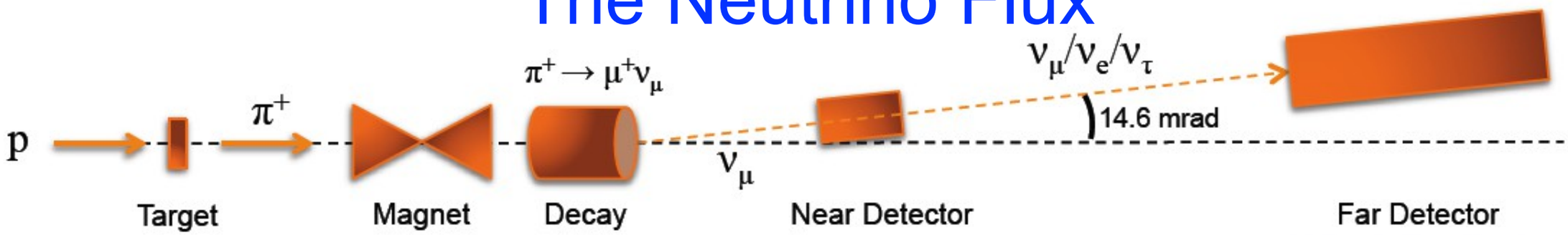
Beam

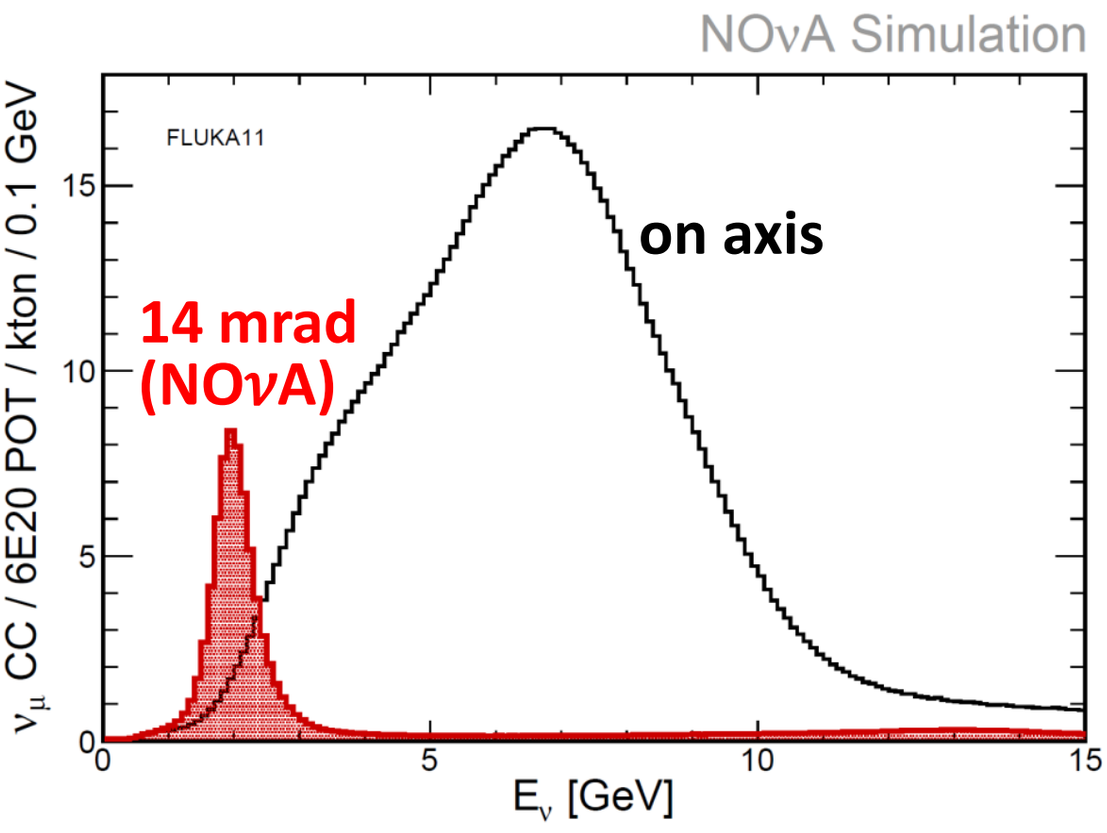
- Photons from neutral pion decay make EM showers.
- Reconstructing both photons provide constraint on background and energy scale.

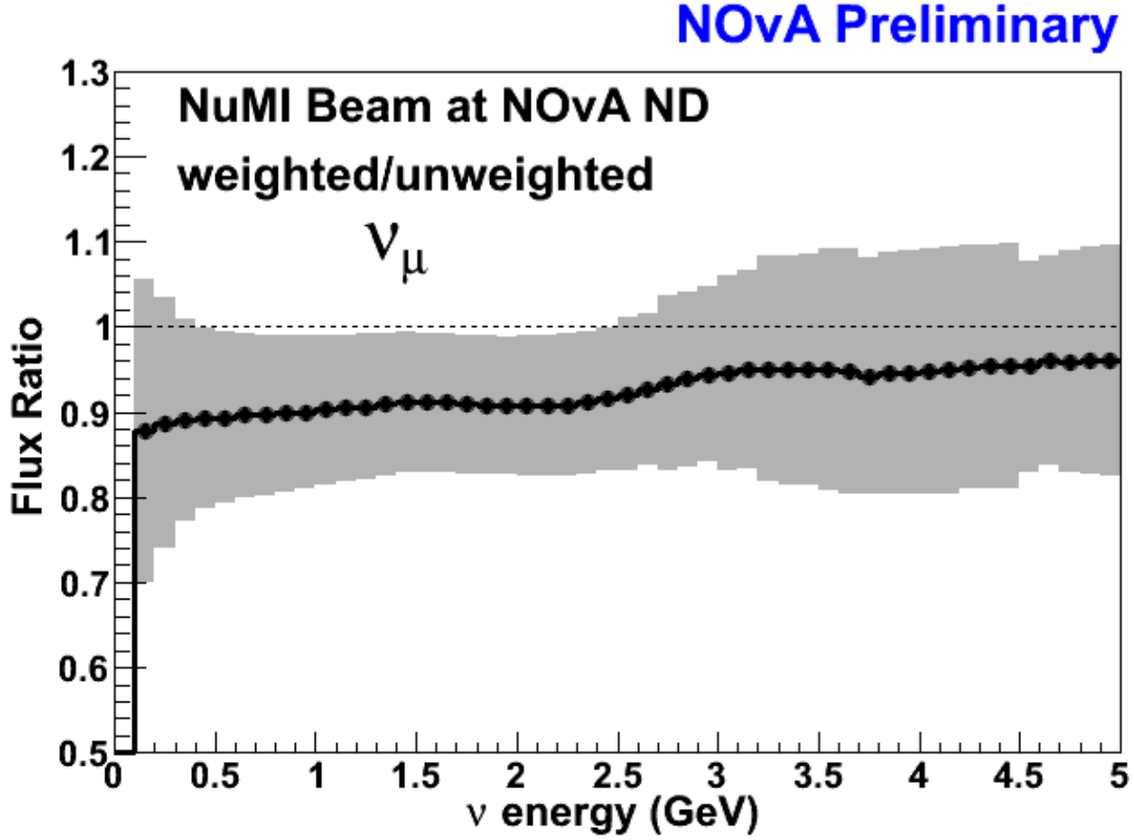
- Charged pions are tracks in NOvA ND.
- Developing charged pion tracking algorithm.



The Neutrino Flux



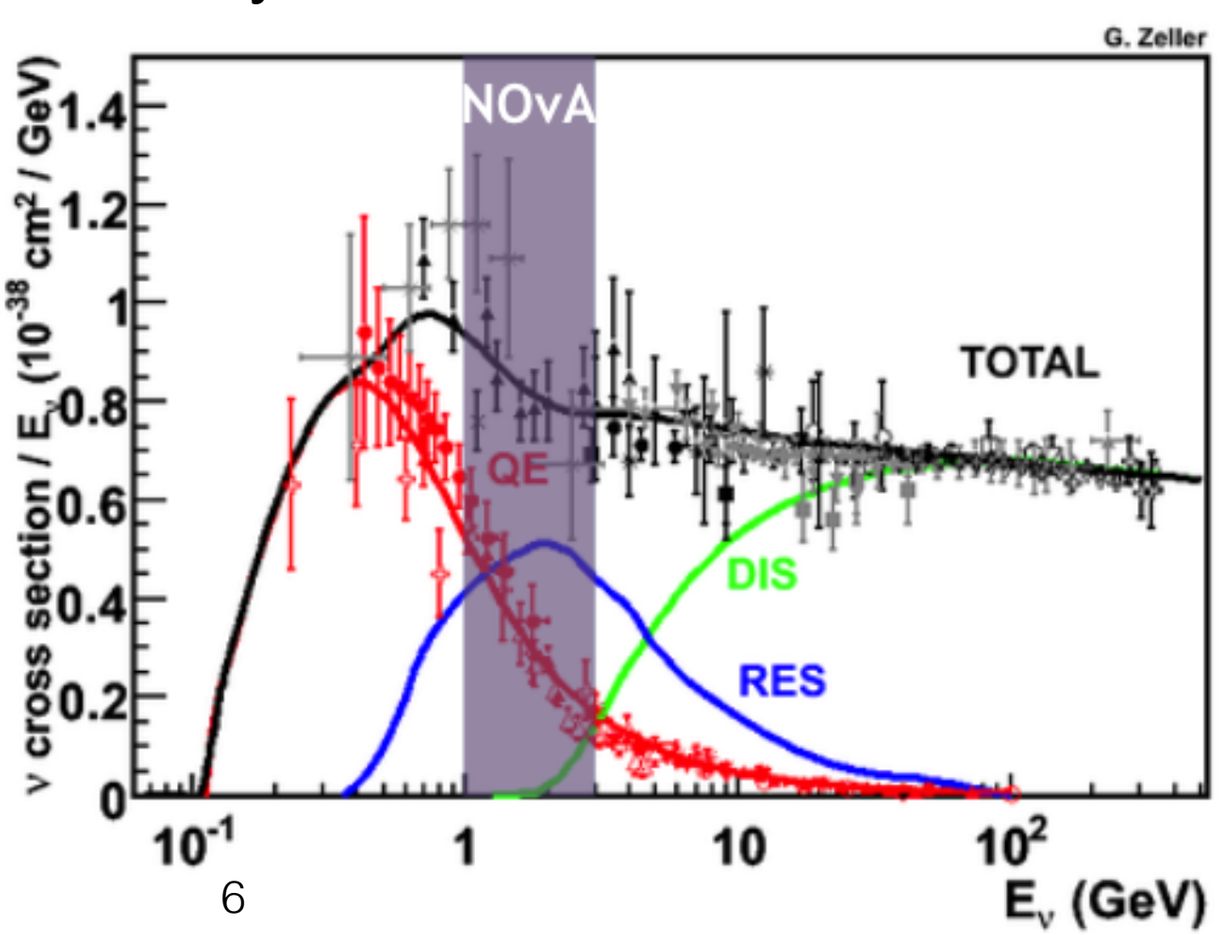




- Narrow band neutrino beam 1~3GeV peak at ~2GeV, Dominated by ν_μ (94%)
- Hadron production uncertainty constraint by external hadron production data. (See Leo Aliaga's talk on Monday)

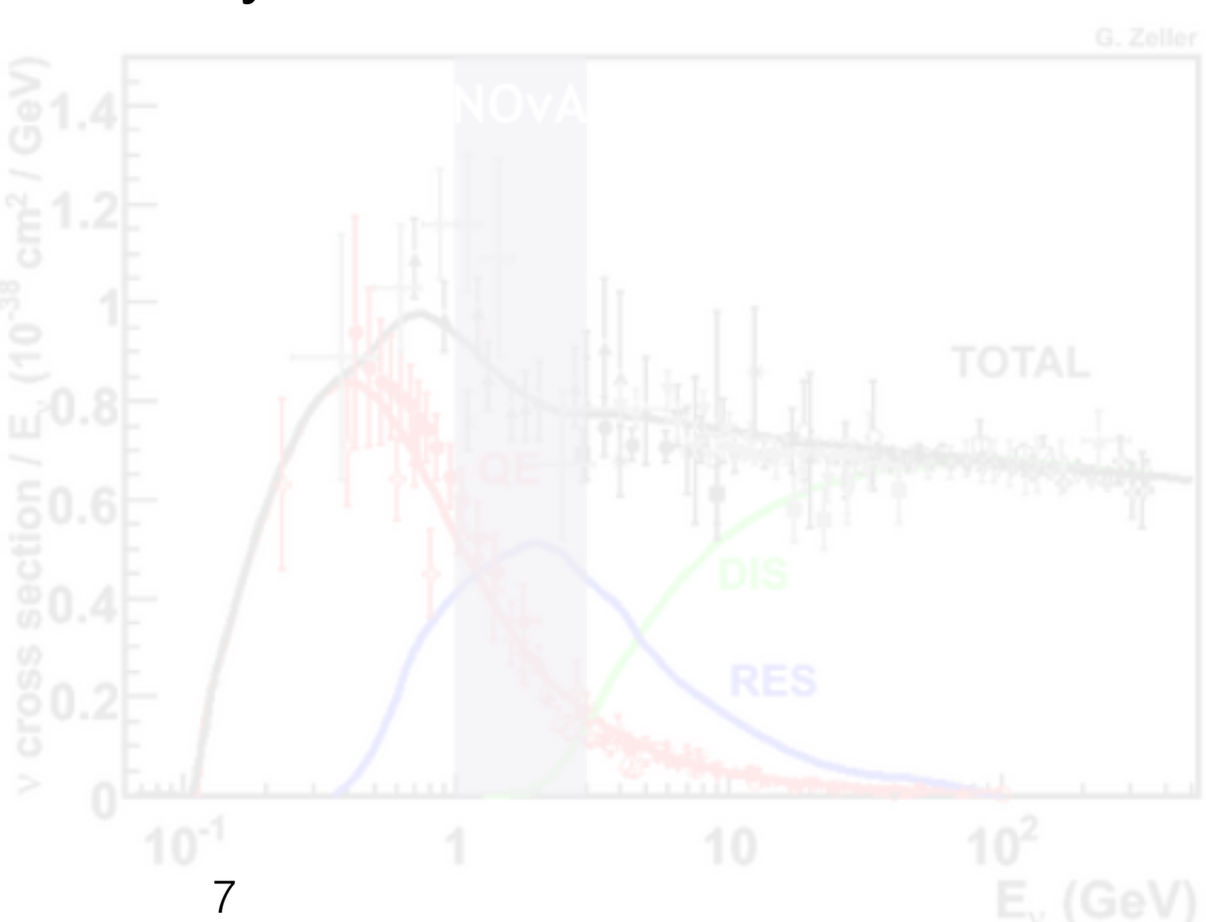
NOvA Pion Measurements Overview

- Pion production makes background to oscillation analysis.
  - We want to measure them in our own detector!
- Pion kinematics are sensitive to final-state interaction (elastic/inelastic scattering, absorption, charge-exchange).
- We are in 1~3 GeV region: cross-check with MINERvA, MiniBooNE, T2K.
- Working on several pion analysis:
  - NC COH π^0 : reporting preliminary result first time!
- Work in progress:
  - CC π^0
  - NC π^0
  - CC π^+/π^-

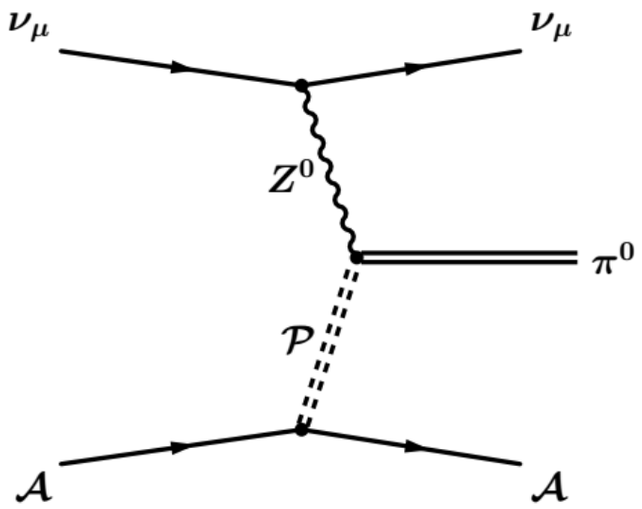


NOvA Pion Measurements Overview

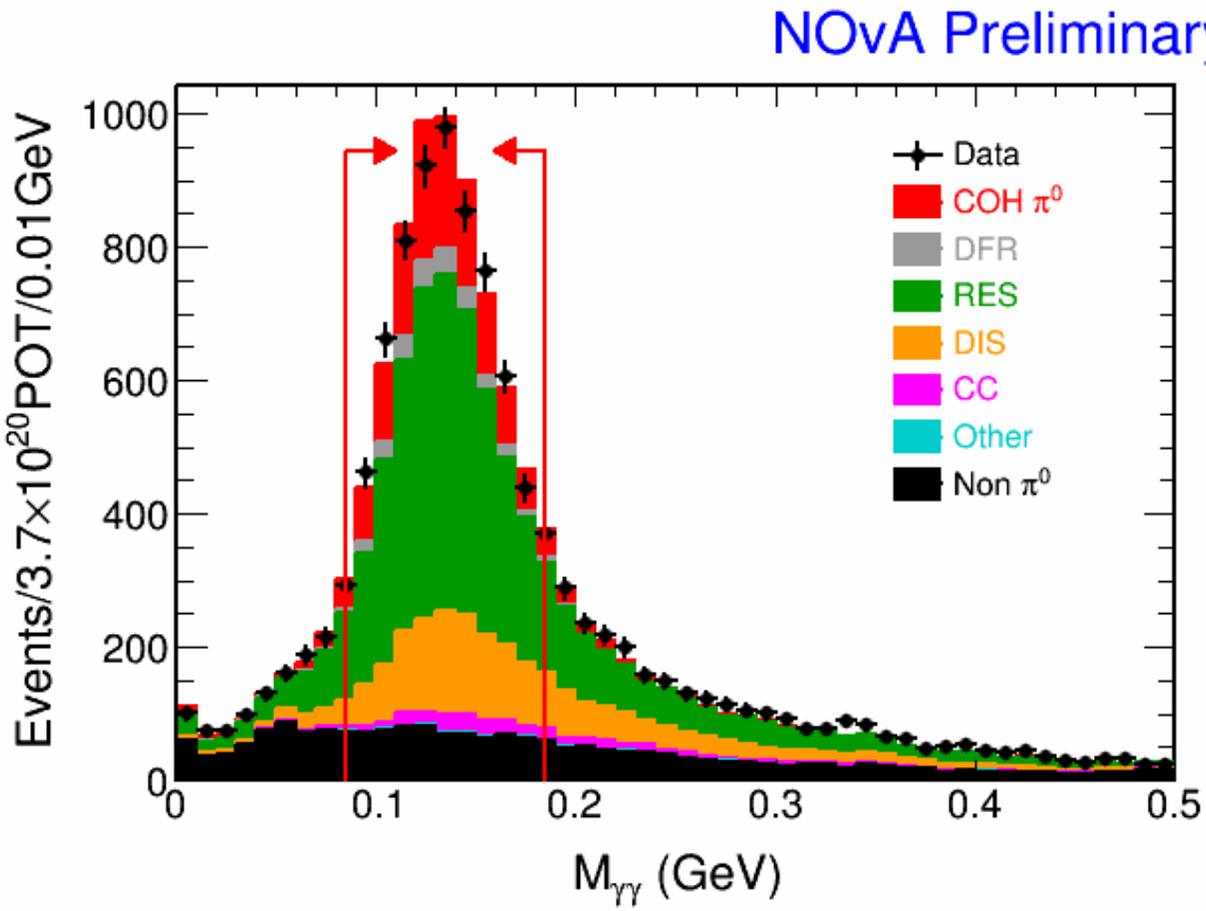
- Pion production makes background to oscillation analysis.
  - We want to measure them in our own detector!
- Pion kinematics are sensitive to final-state interaction (elastic/inelastic scattering, absorption, charge-exchange).
- We are in 1~3 GeV region: cross-check with MINERvA, MiniBooNE, T2K.
- Working on several pion analysis:
  - NC COH π^0 : reporting preliminary result first time!
  - Work in progress:
    - CC π^0
    - NC π^0
    - CC π^+/π^-



NC Coherent π^0

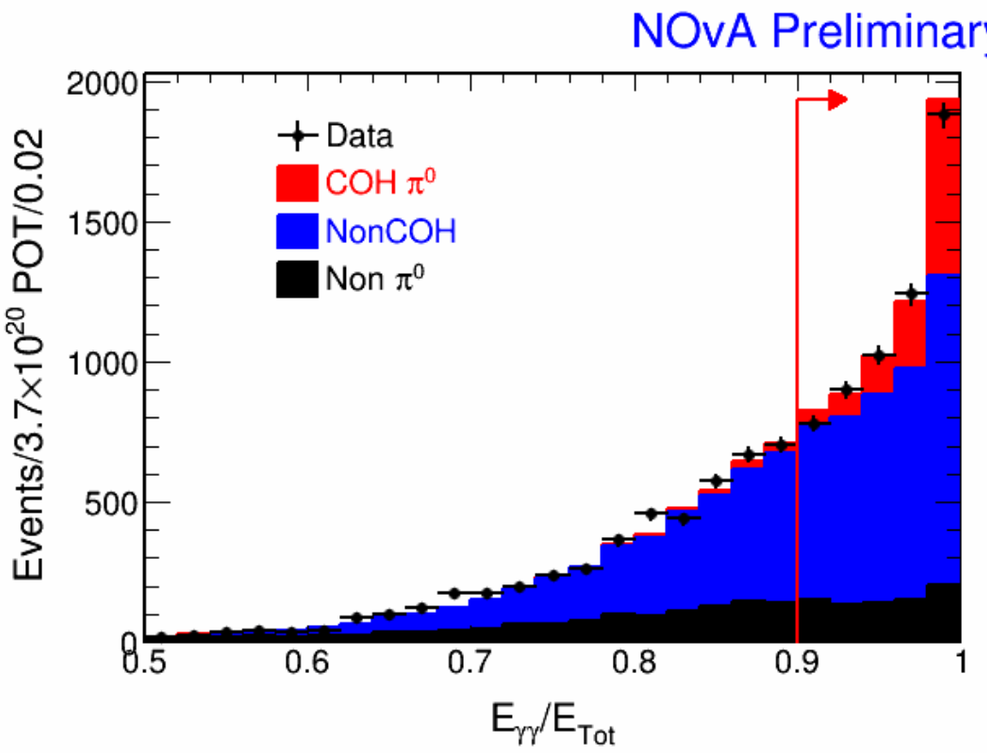


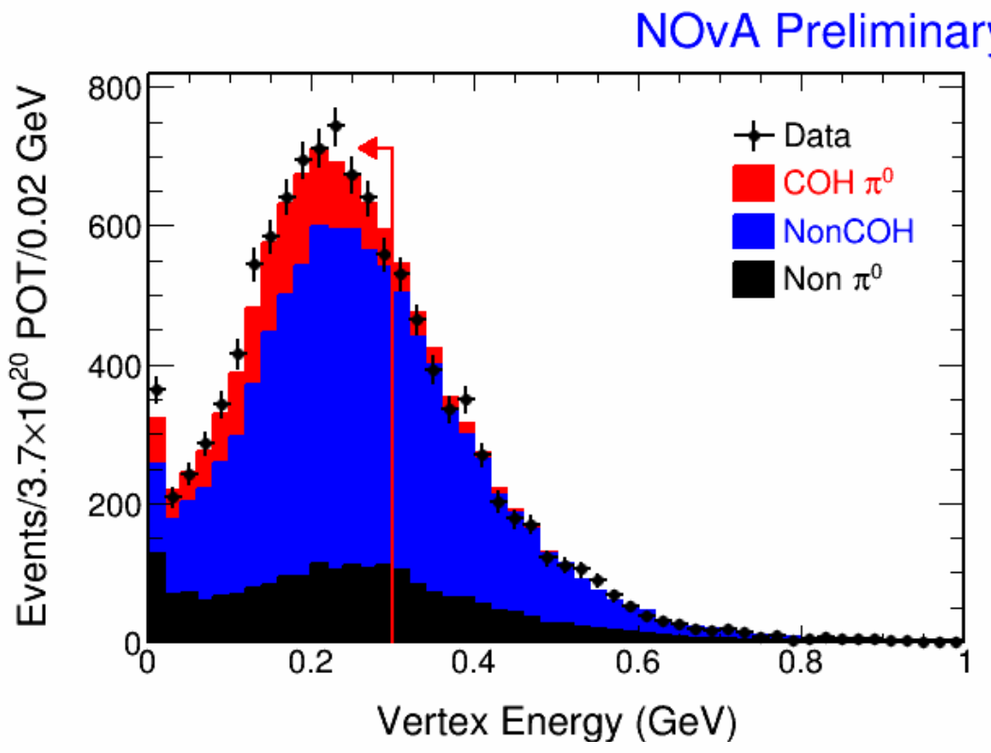
- Neutrinos scatter coherently off entire target nucleus with small momentum transfer.
- Single forward-going pion, without other pions or nucleons.



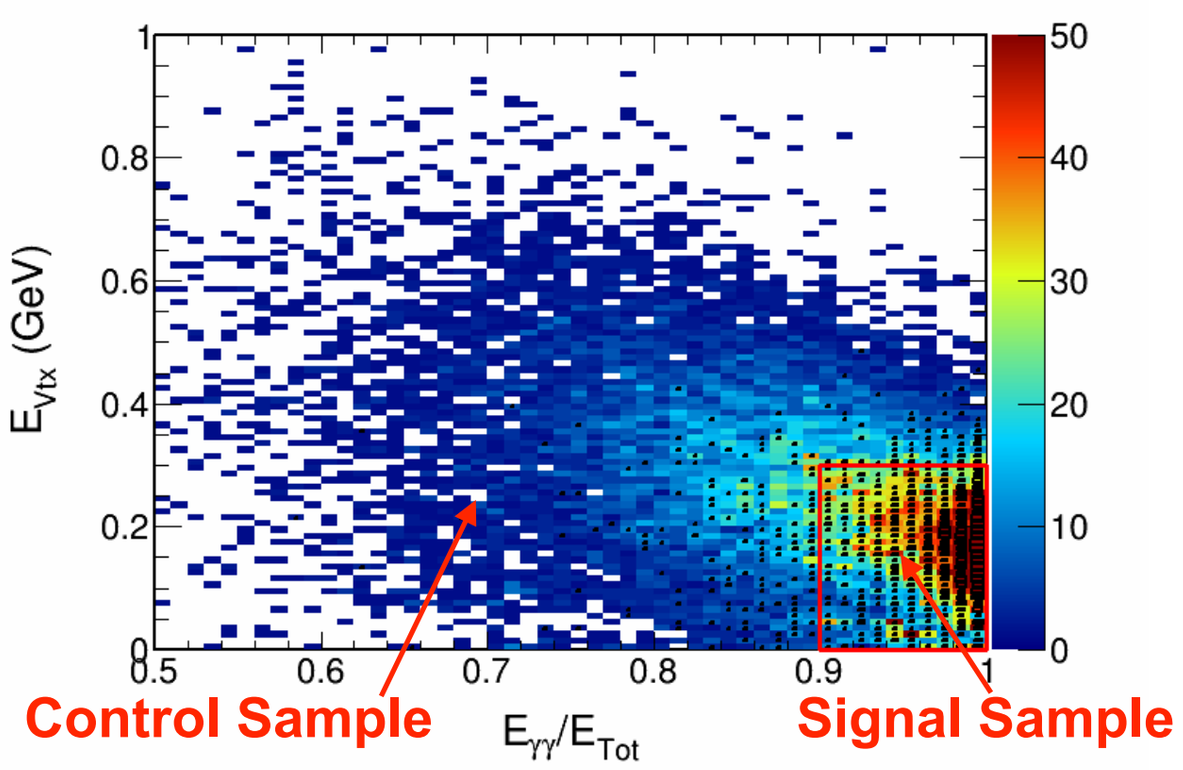
- Identify the NC π^0 sample
  - Absence of muon.
  - Two showers identified as photons by dE/dx-based likelihoods.
- Reconstruct invariant mass.
- Background dominated by RES and DIS π^0s.
- Cut on invariant mass further reduces background.
- Also serve as a check of photon reconstruction and energy scale.

NC Coherent π^0



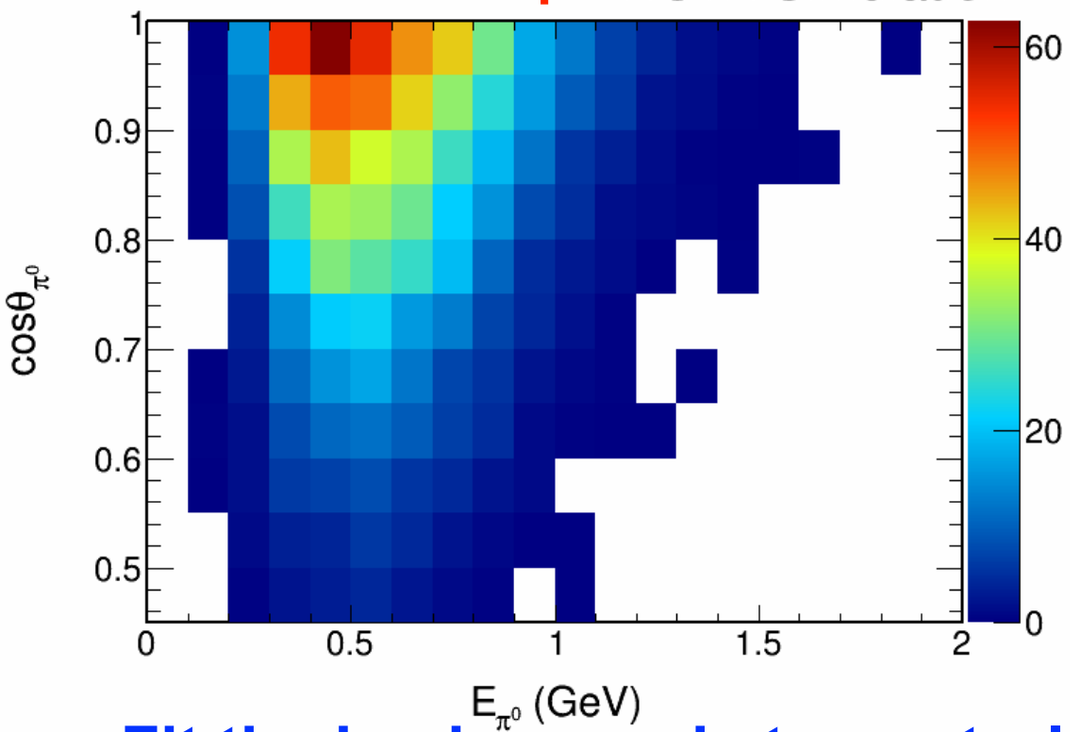


- Divide the NC π^0 into two sub-samples:
  - **Signal sample:** events with most of their energy in the 2 photon-showers and low vertex energy: it has >90% of the signal.
  - **Control sample:** the events with extra energy other than the photons or in the vertex region, dominated by non-coherent π^0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

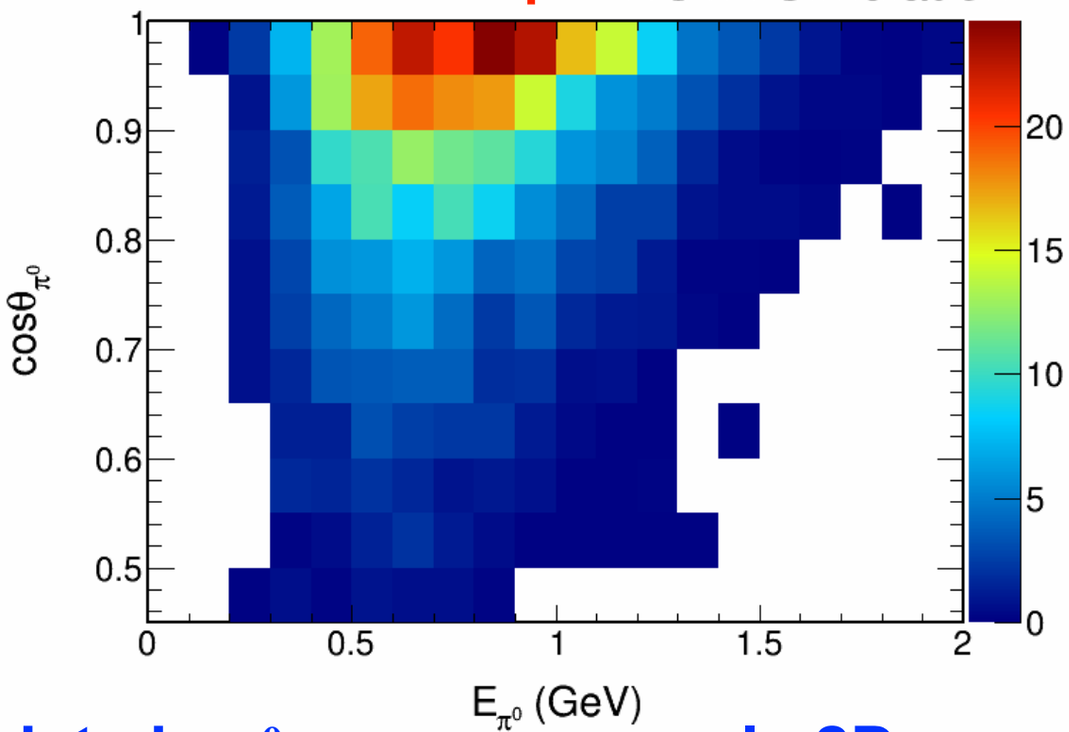


NC Coherent π^0

RES in Control Sample NOvA Simulation



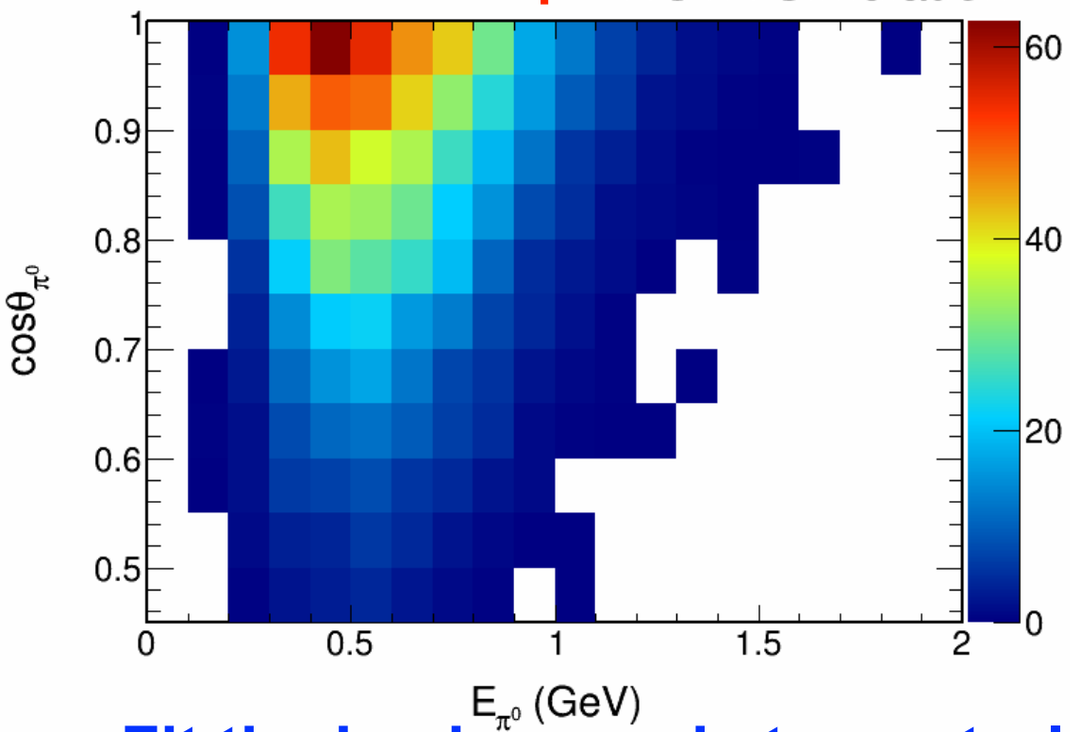
DIS in Control Sample NOvA Simulation



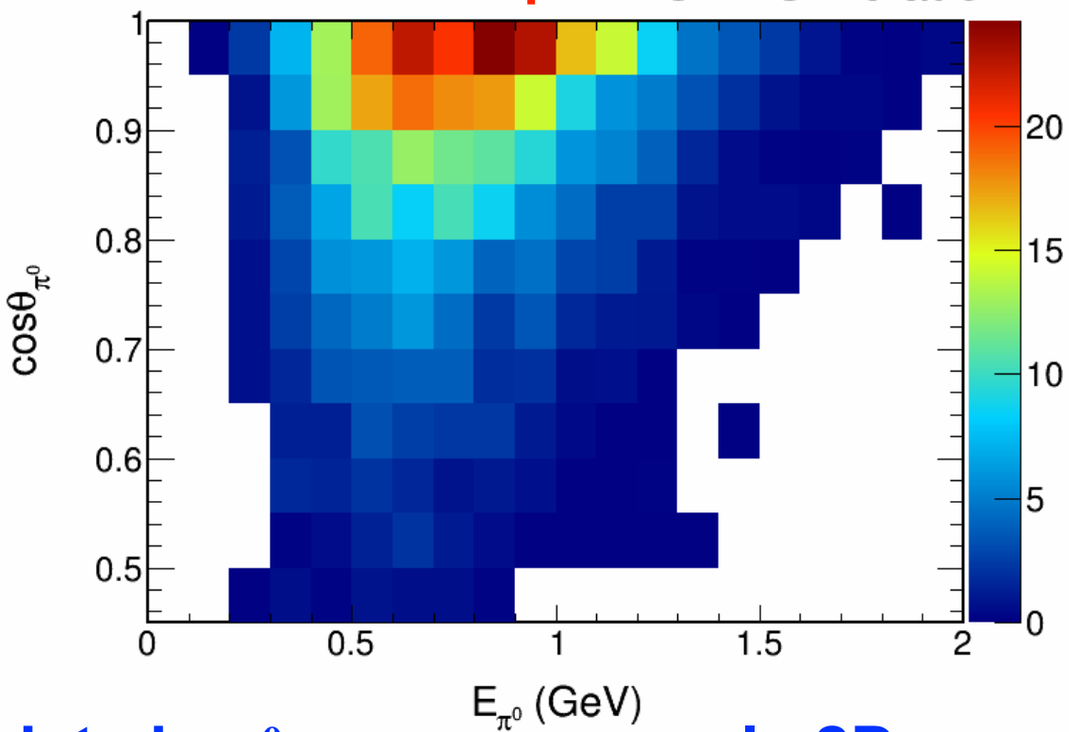
- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

NC Coherent π^0

RES in Control Sample NOvA Simulation

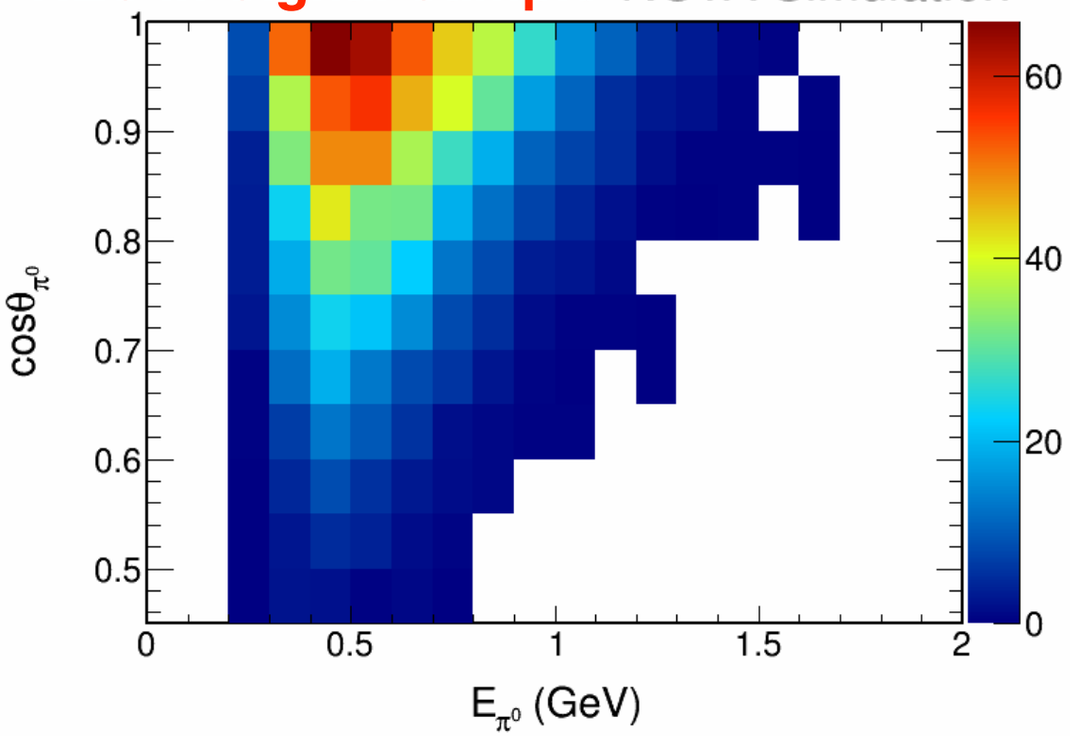


DIS in Control Sample NOvA Simulation

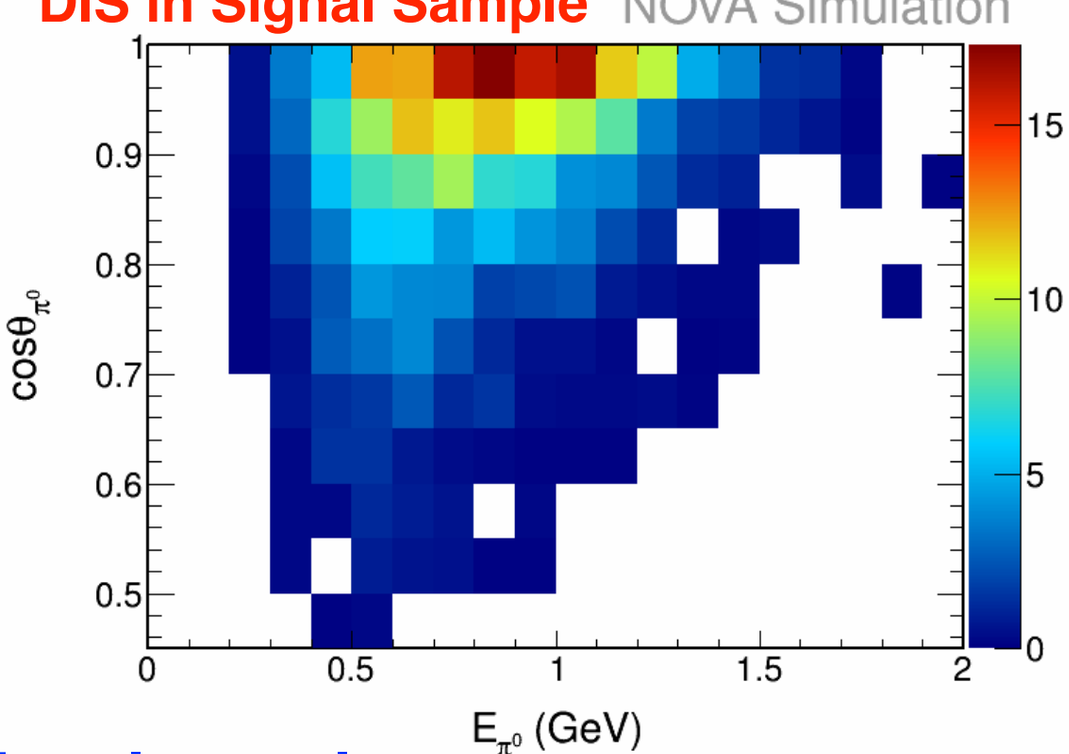


- **Fit the backgrounds to control sample data in π^0 energy vs angle 2D space.**

RES in Signal Sample NOvA Simulation

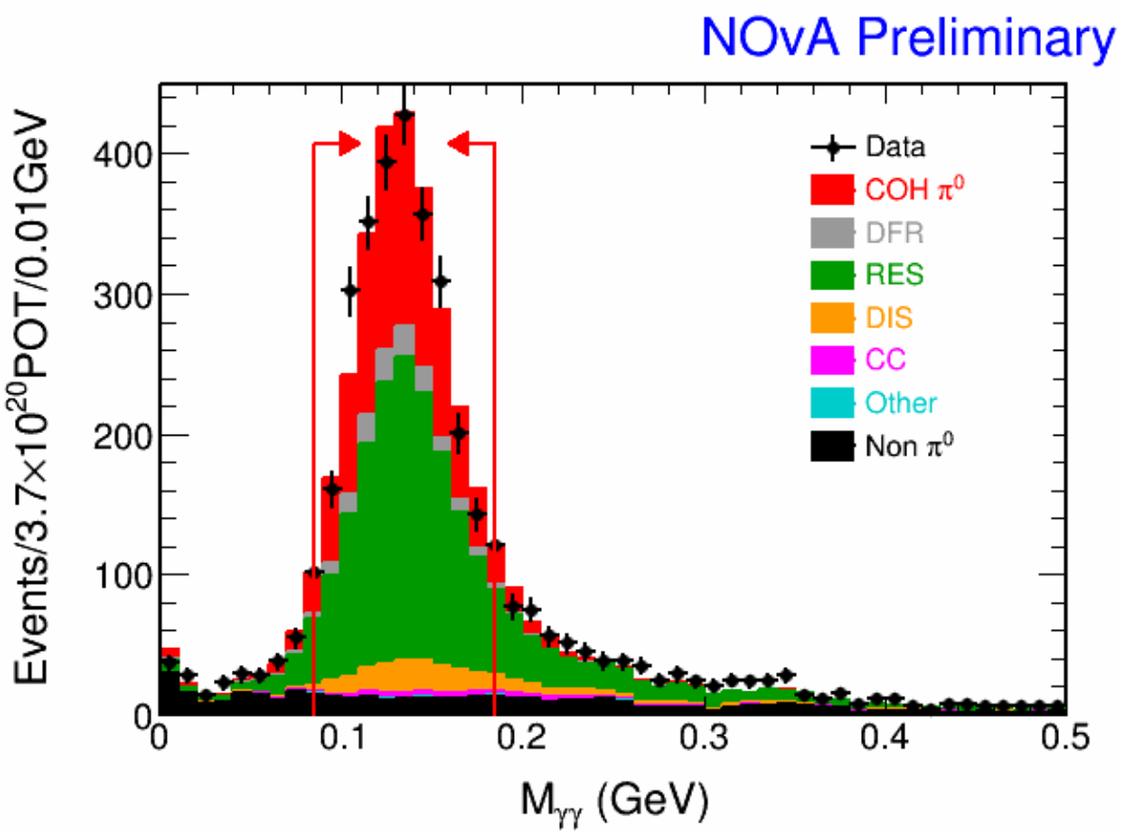


DIS in Signal Sample NOvA Simulation

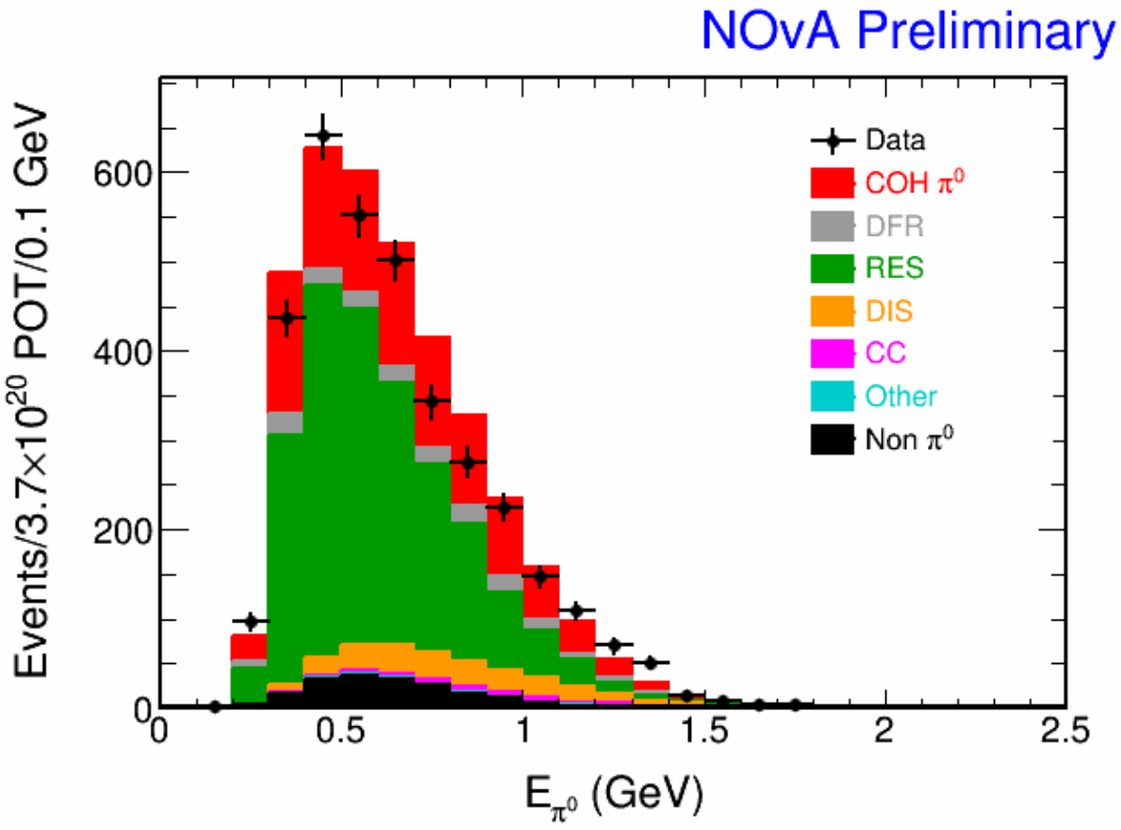


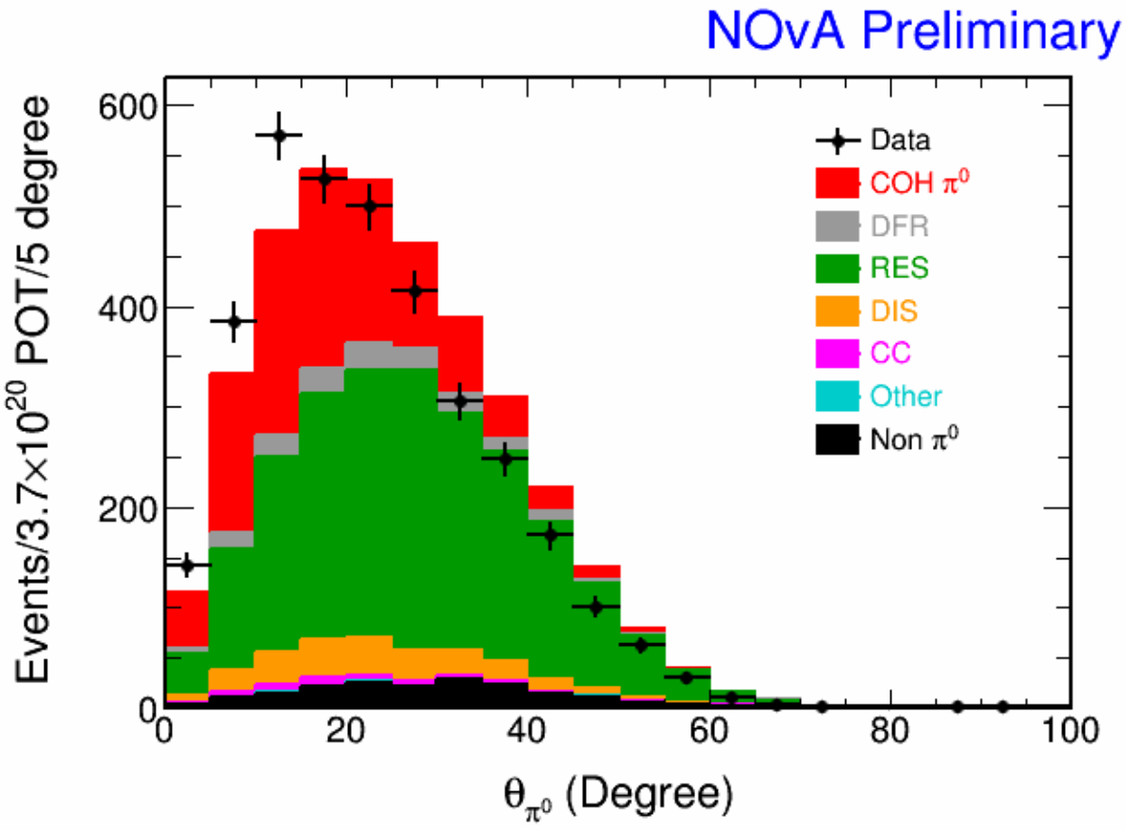
- **Apply the background tuning to the signal sample.**

NC Coherent π^0



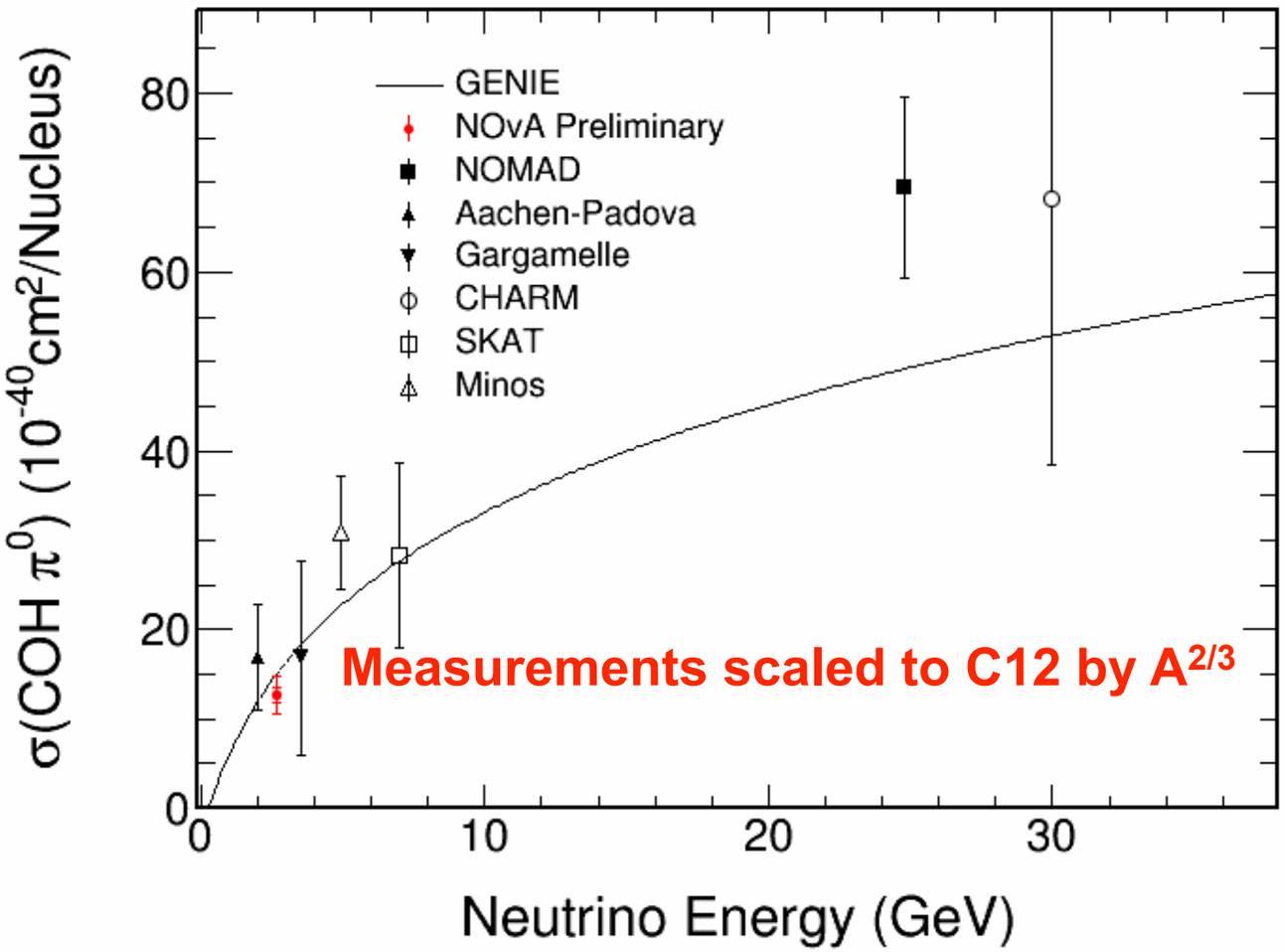
- Background fit result are applied to the backgrounds in the signal sample.
- Coherent signal measurement by subtracting normalized background from data in the coherent region of the energy and angle 2D space.





NC Coherent π^0

NOvA Preliminary

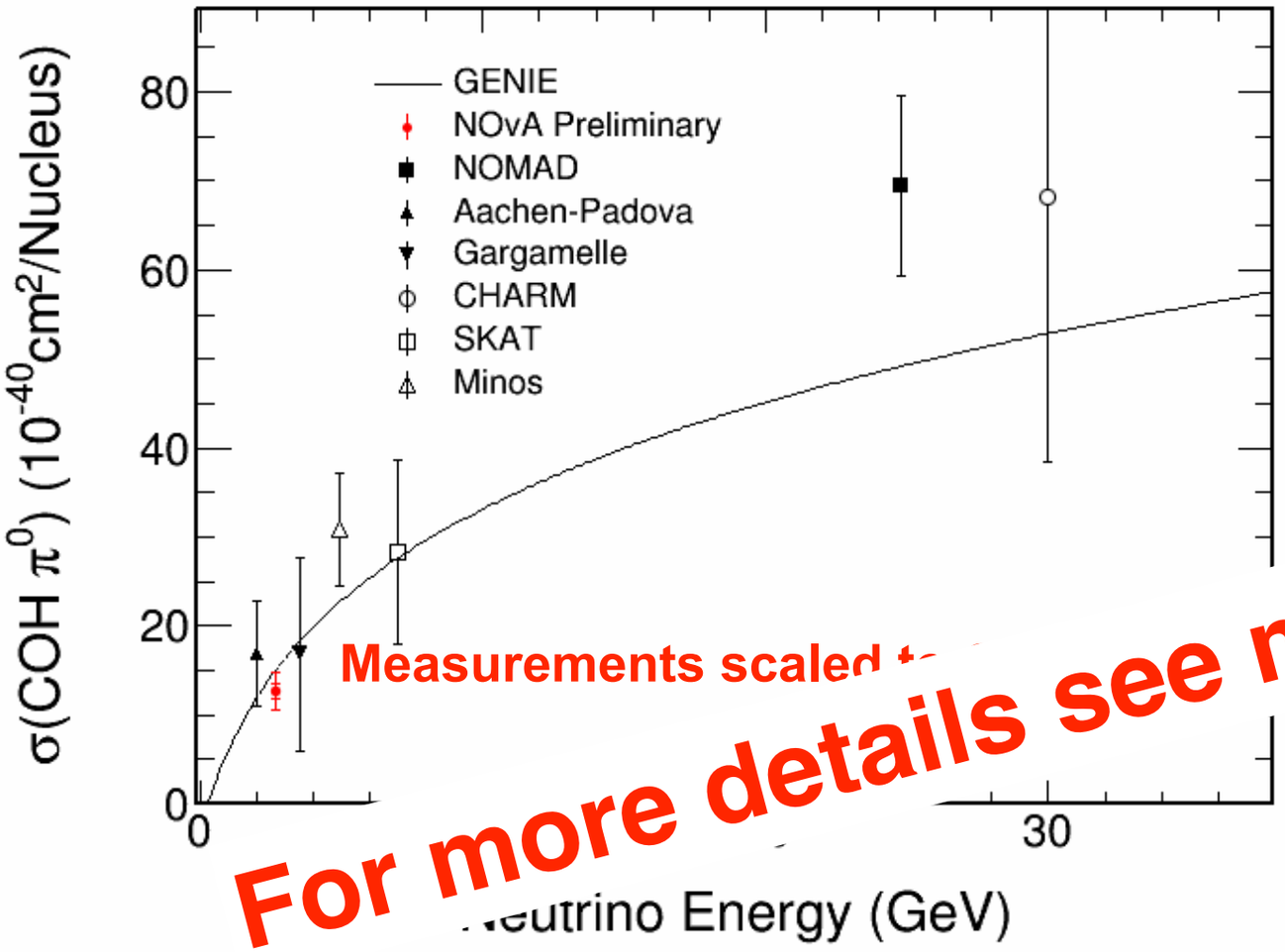


Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- 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 16.7%, systematic dominant.

NC Coherent π^0

NOvA Preliminary



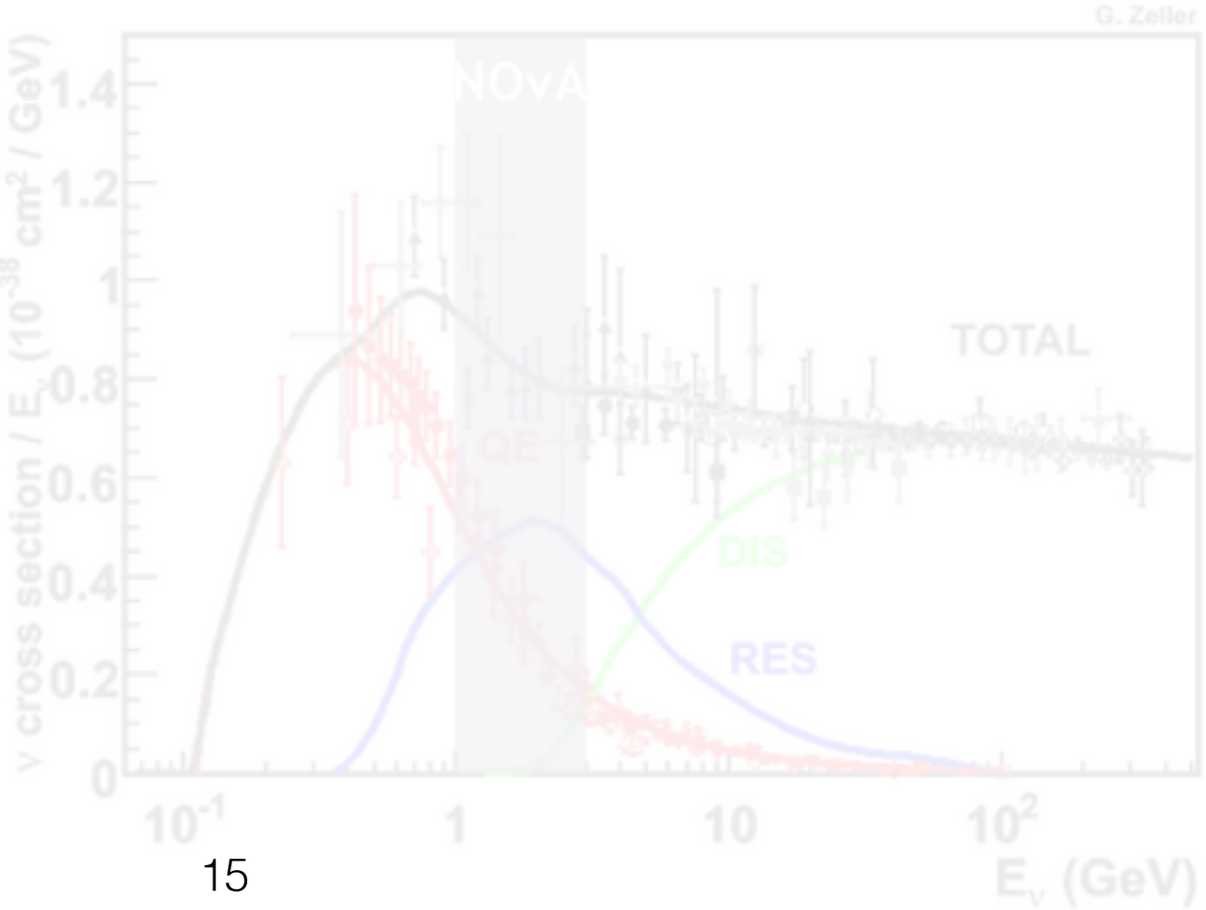
Source	δ(%)
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Even[illegible]	2.4
[illegible]	2.0
[illegible]	9.4
[illegible] Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

For more details see my poster tonight!

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

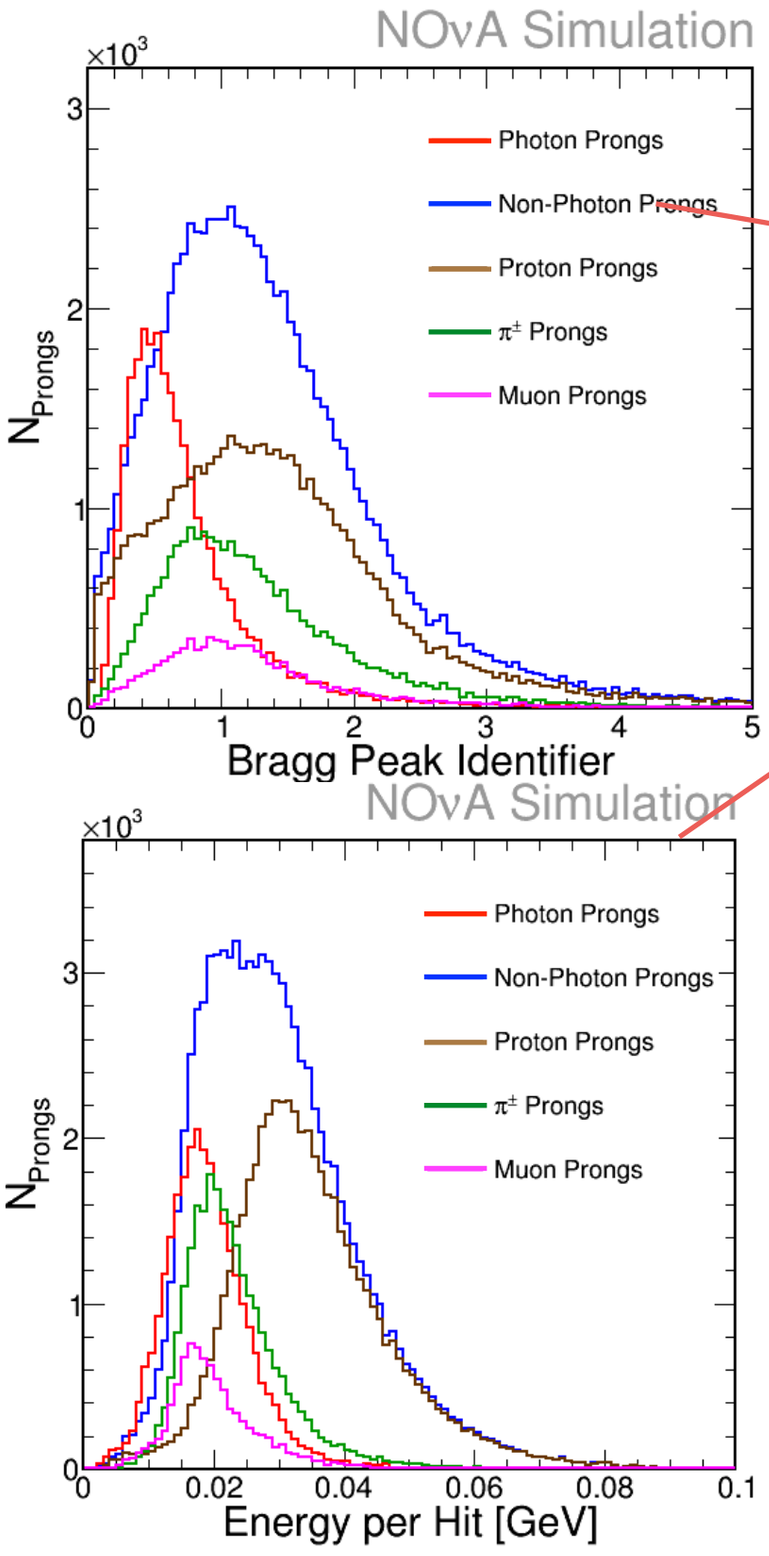
NOvA Pion Measurements Overview

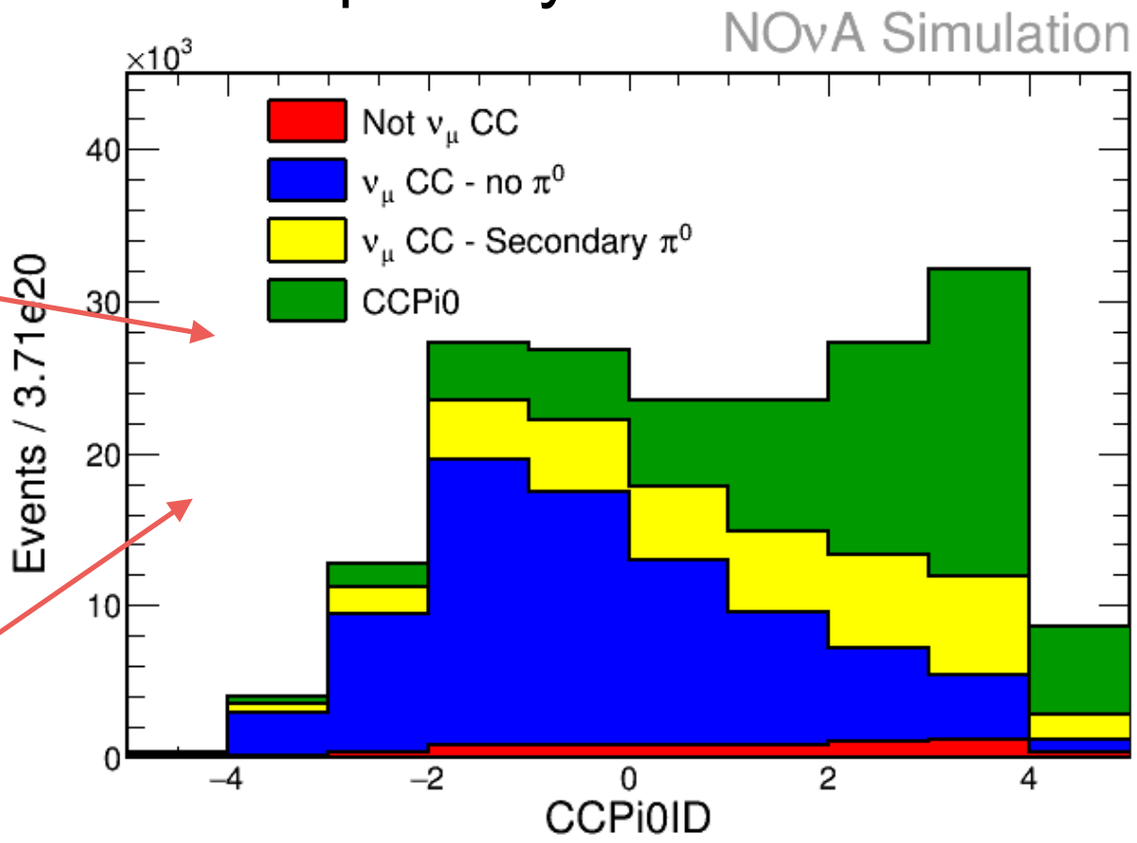
- Pion production makes background to oscillation analysis.
  - We want to measure them in our own detector!
- Pion kinematics are sensitive to final-state interaction (elastic/inelastic scattering, absorption, charge-exchange).
- We are in 1~3 GeV region: cross-check with MINERvA, MiniBooNE, T2K.
- Working on several pion analysis:
  - NC COH π^0 : reporting preliminary result first time!
- Work in progress:
  - CC π^0
  - NC π^0
  - CC π^+/π^-



ν_μ-CC π^0

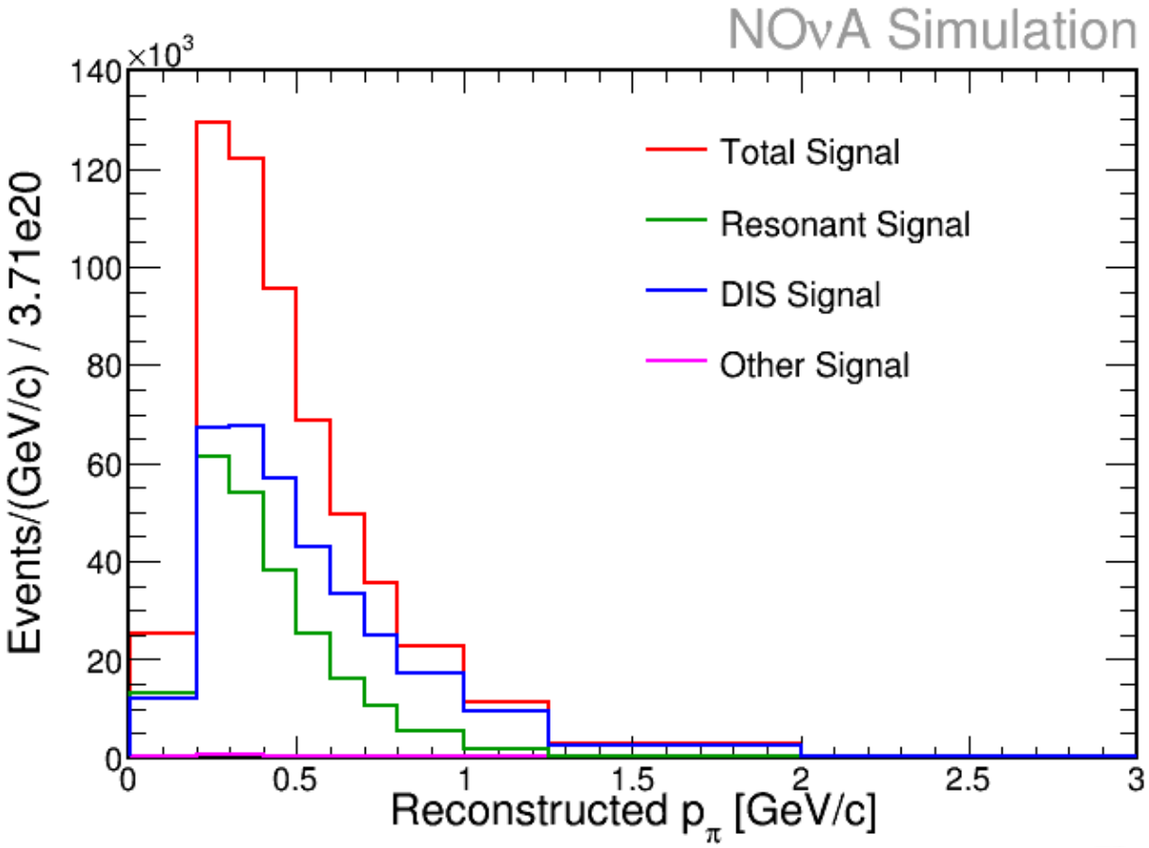
Signal: ν_μ-CC events with at least one primary π^0 in the final state.



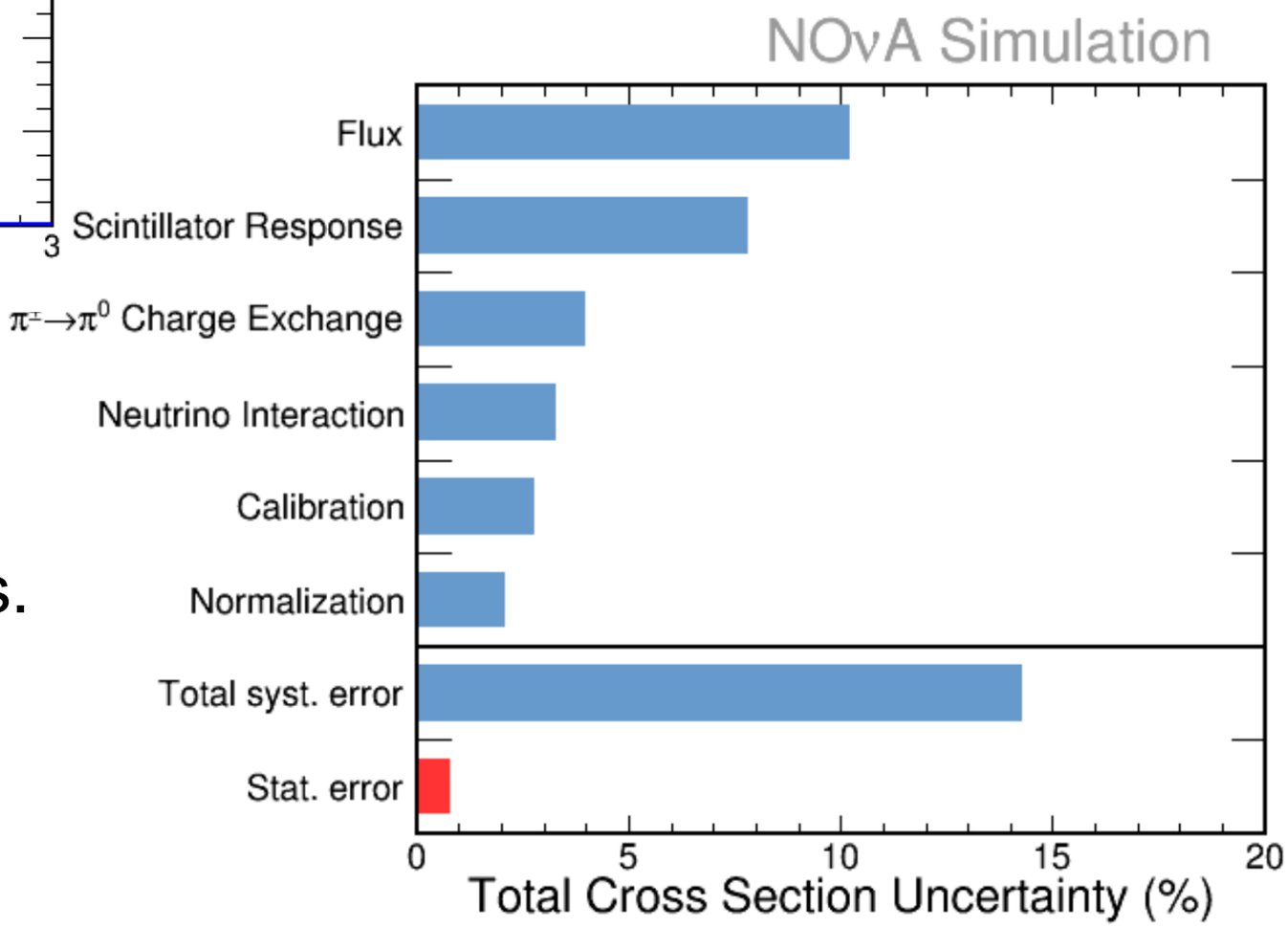


- Use non-muon shower variables to form a π^0 identifier:
  - Bragg peak identifier.
  - Energy per hit.
  - Photon gap from vertex.
  - Number of missing planes.
- Fit signal and background MC to data in each kinematic bin.

ν_μ-CC π^0



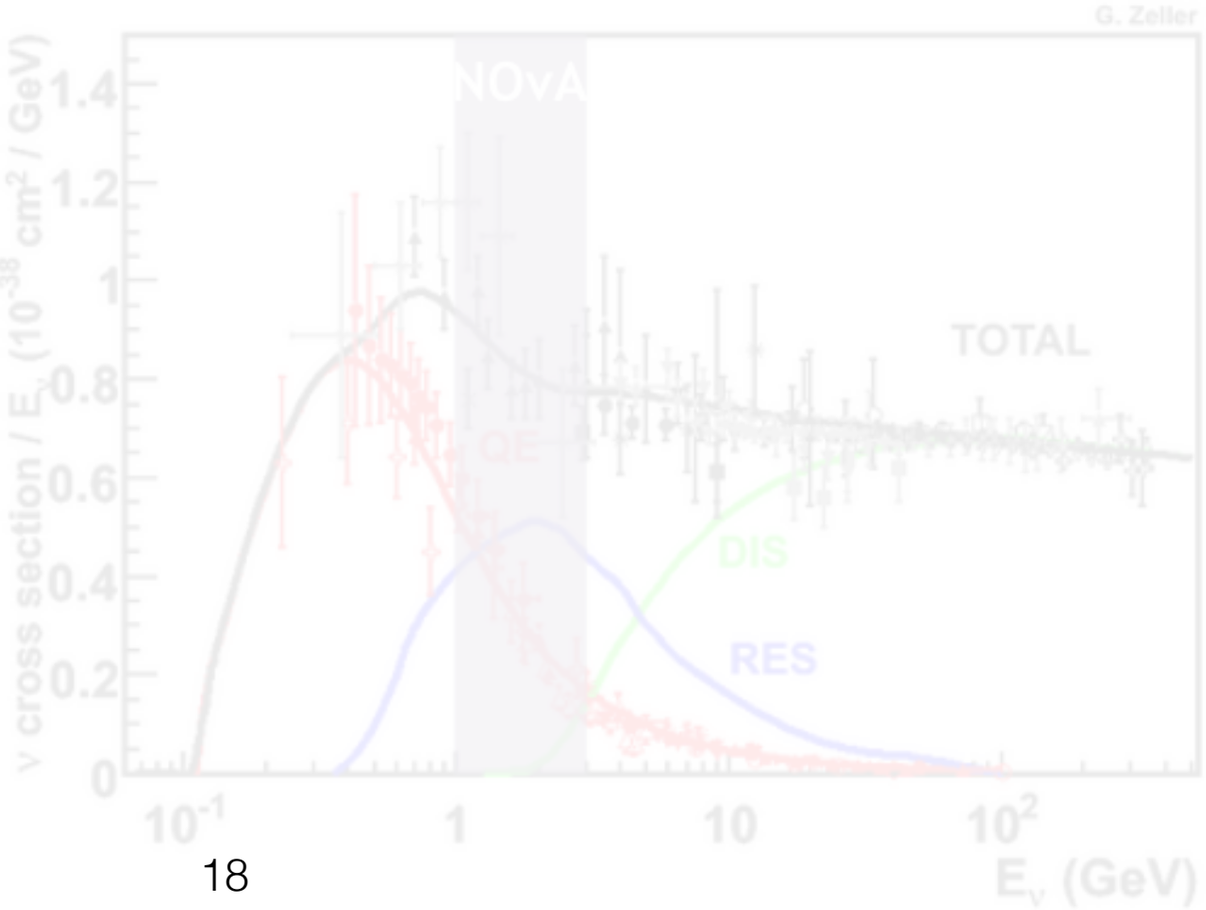
- Signal is dominantly RES (38.3%) and DIS (61.3%).
- Uncertainty (~15%) is systematic dominant.



- Plan to report flux-averaged differential cross section in final state muon and pion kinematics.
- At final stage of internal review. Preliminary result very soon!

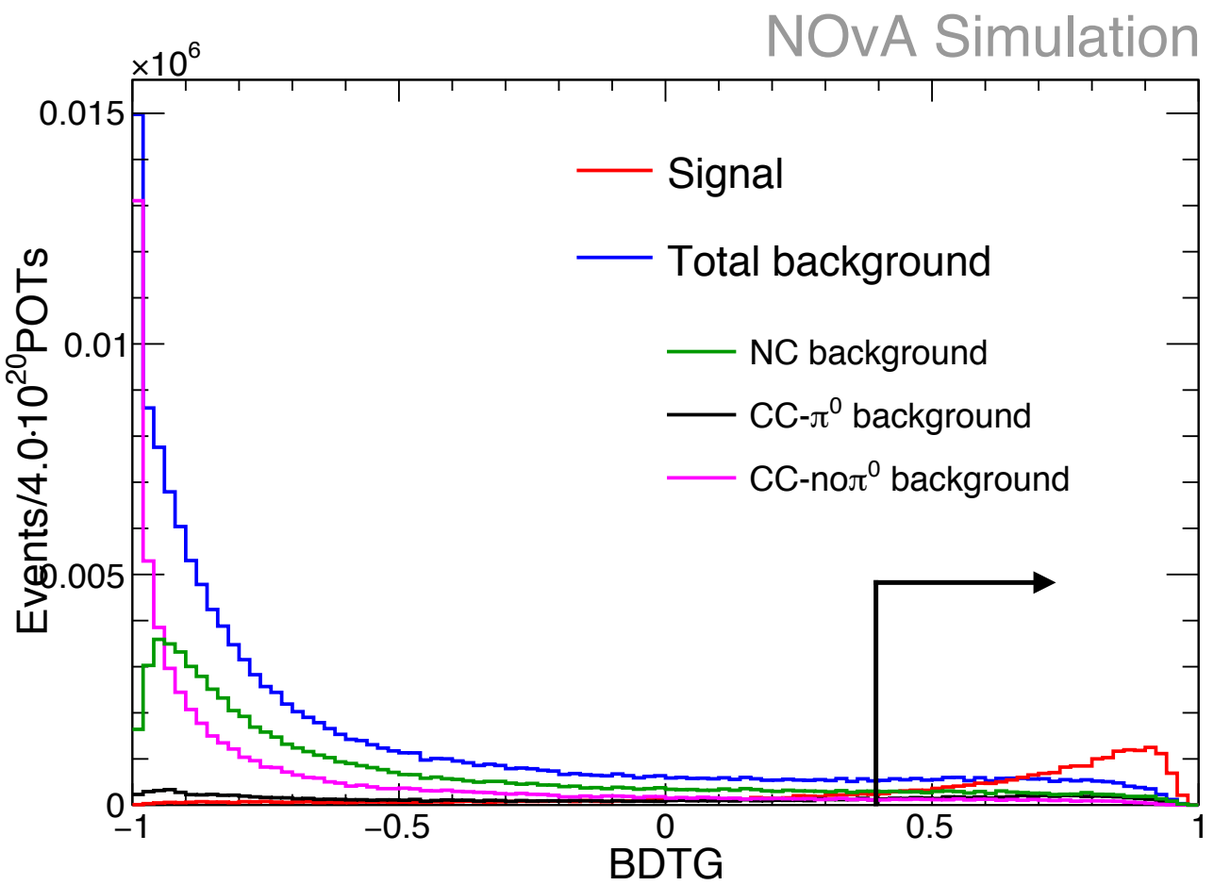
NOvA Pion Analysis Overview

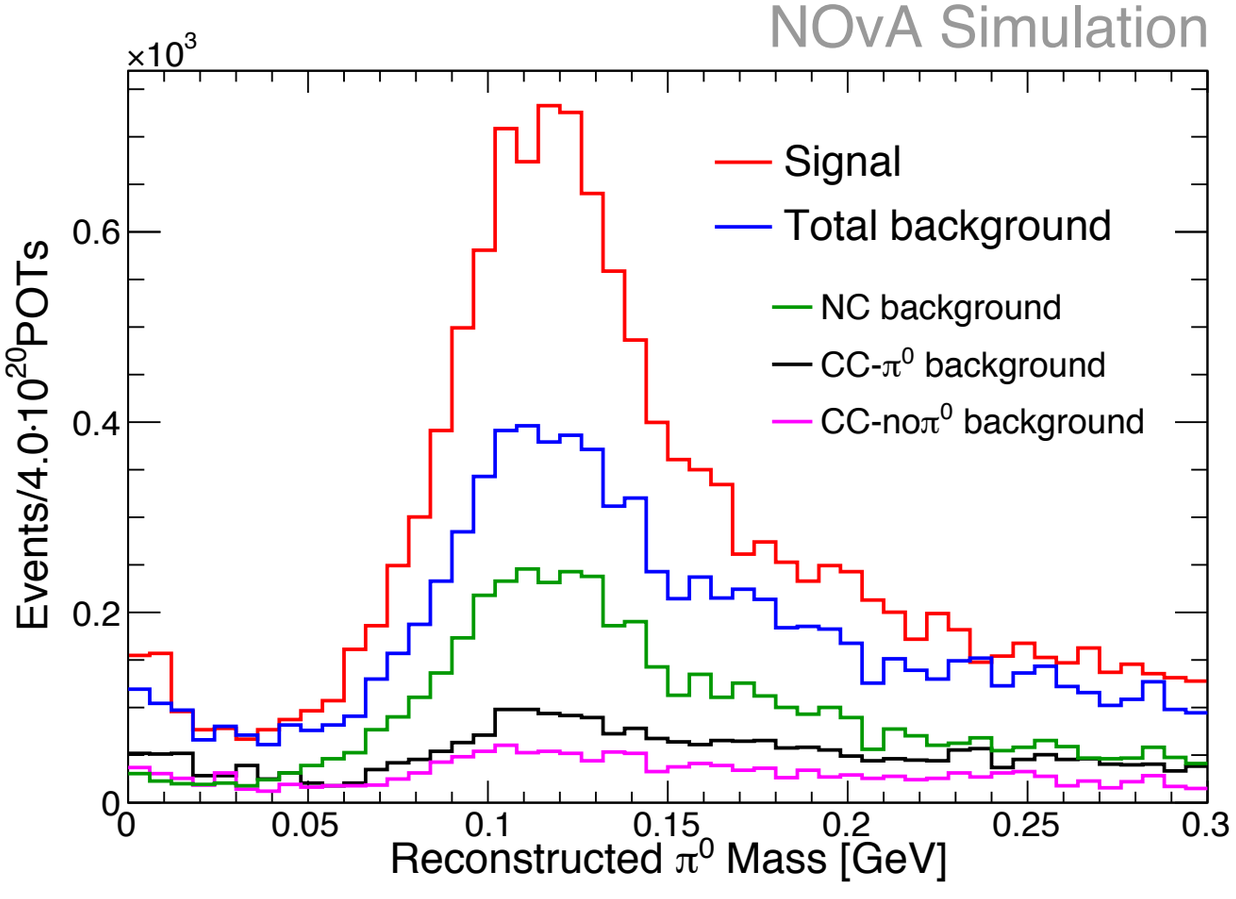
- Pion production makes background to oscillation analysis.
  - We want to measure them in our own detector!
- Pion kinematics are sensitive to final-state interaction (elastic/inelastic scattering, absorption, charge-exchange).
- We are in 1~3 GeV region: cross-check with MINERvA, MiniBooNE, T2K.
- Working on several pion analysis:
  - NC COH π^0 : reporting preliminary result first time!
- Work in progress:
  - CC π^0
  - NC π^0
  - CC π^+/π^-



Neutral Current π^0

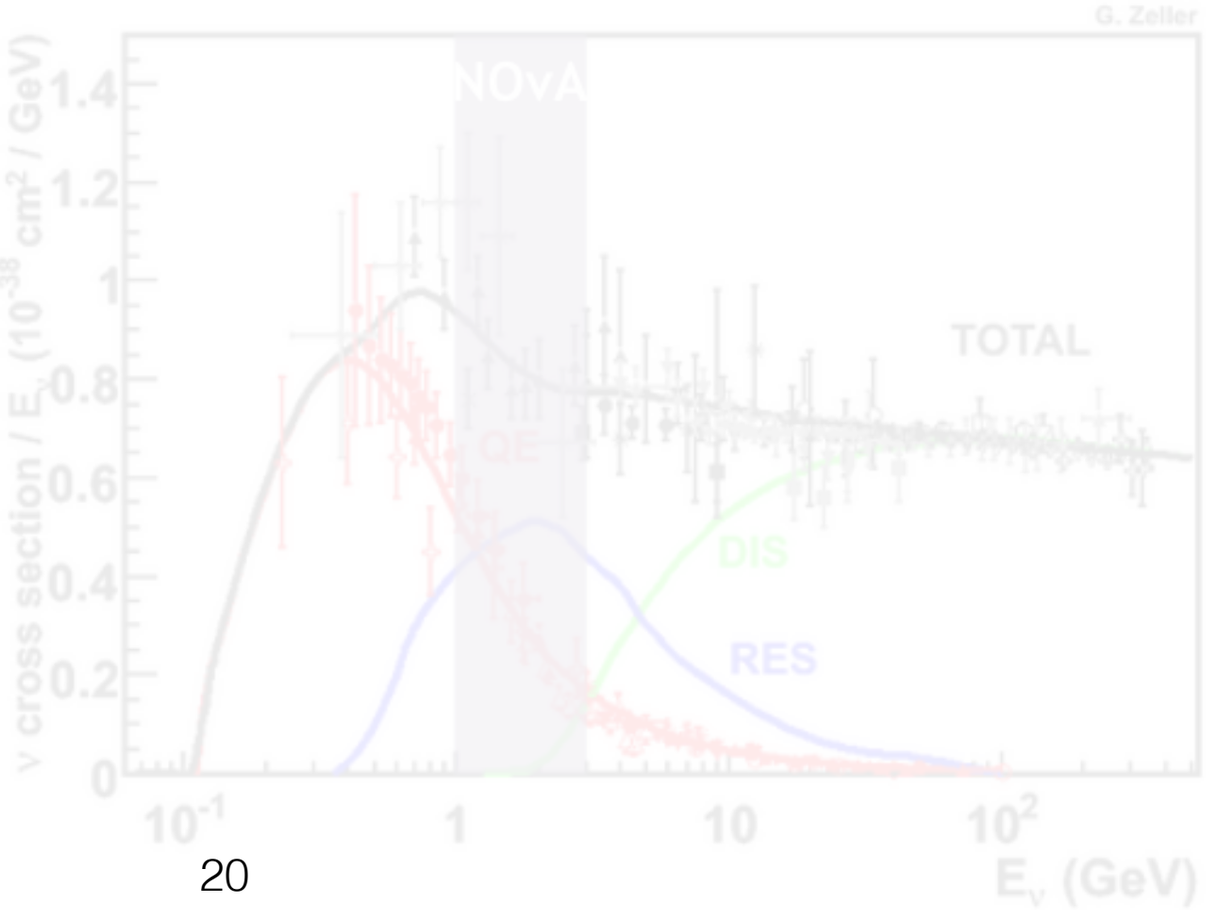
- Signal: NC with at least one π^0.
- Important background to ν_e appearance.
- A event-level Boost Decision Tree (BDT) developed using shower variables as inputs.
- Work in progress.
- Aiming to report differential cross-section in π^0 kinematics.





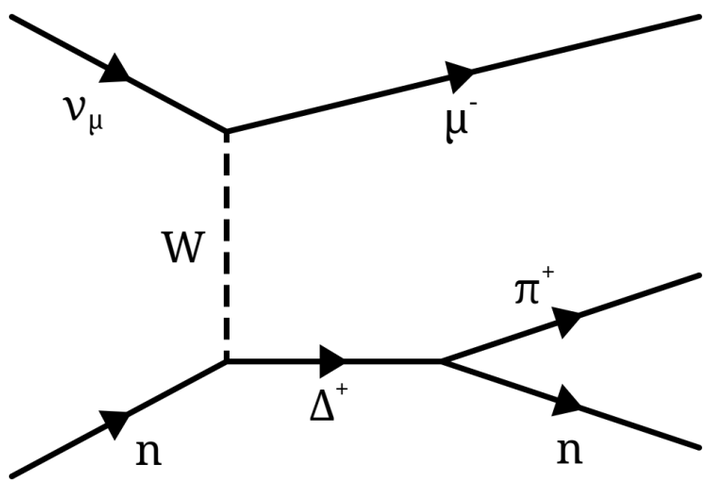
NOvA Pion Measurements Overview

- Pion production makes background to oscillation analysis.
  - We want to measure them in our own detector!
- Pion kinematics are sensitive to final-state interaction (elastic/inelastic scattering, absorption, charge-exchange).
- We are in 1~3 GeV region: cross-check with MINERvA, MiniBooNE, T2K.
- Working on several pion analysis:
  - NC COH π^0 : reporting preliminary result first time!
- Work in progress:
  - CC π^0
  - NC π^0
  - CC π^+/π^-



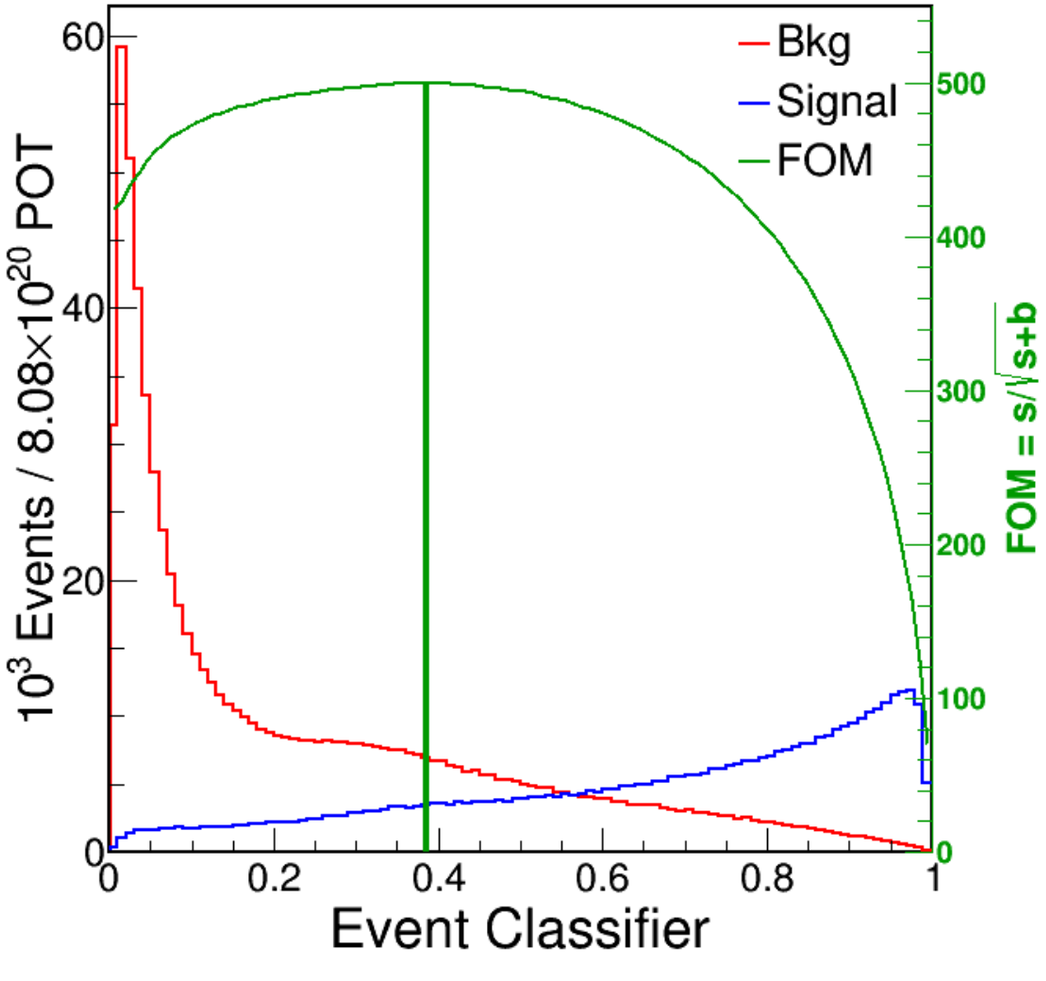
Charge Current π^+/π^-

Signal: CC events with at least one charged pion (π^+/π^-) in the final state.



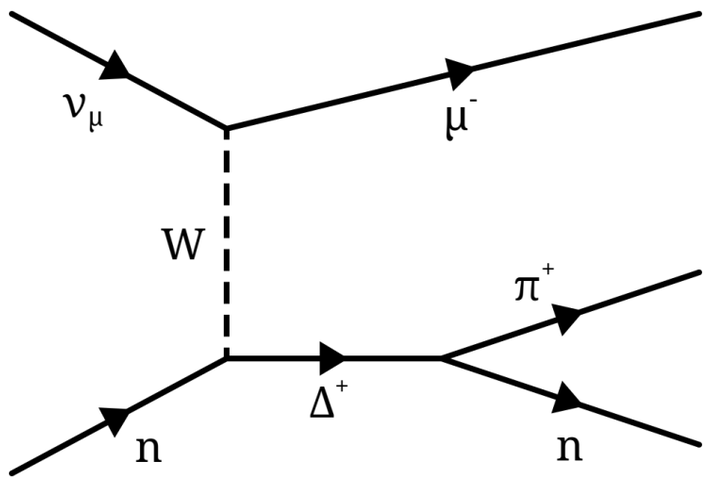
- Working on improving π^+/π^- reconstruction.
- Using deep-learning technique: A event-level Convolutional Visual Network (CVN) classifier.
  - Uses full near detector raw data/MC image as an input.

- Work in progress:
  - Efficiency of pre-selection and CVN selection.
  - Systematics on CVN.
  - Sideband background-fitting study.
- The first goal is to report differential cross-section in muon kinematics.



Charge Current π^+/π^-

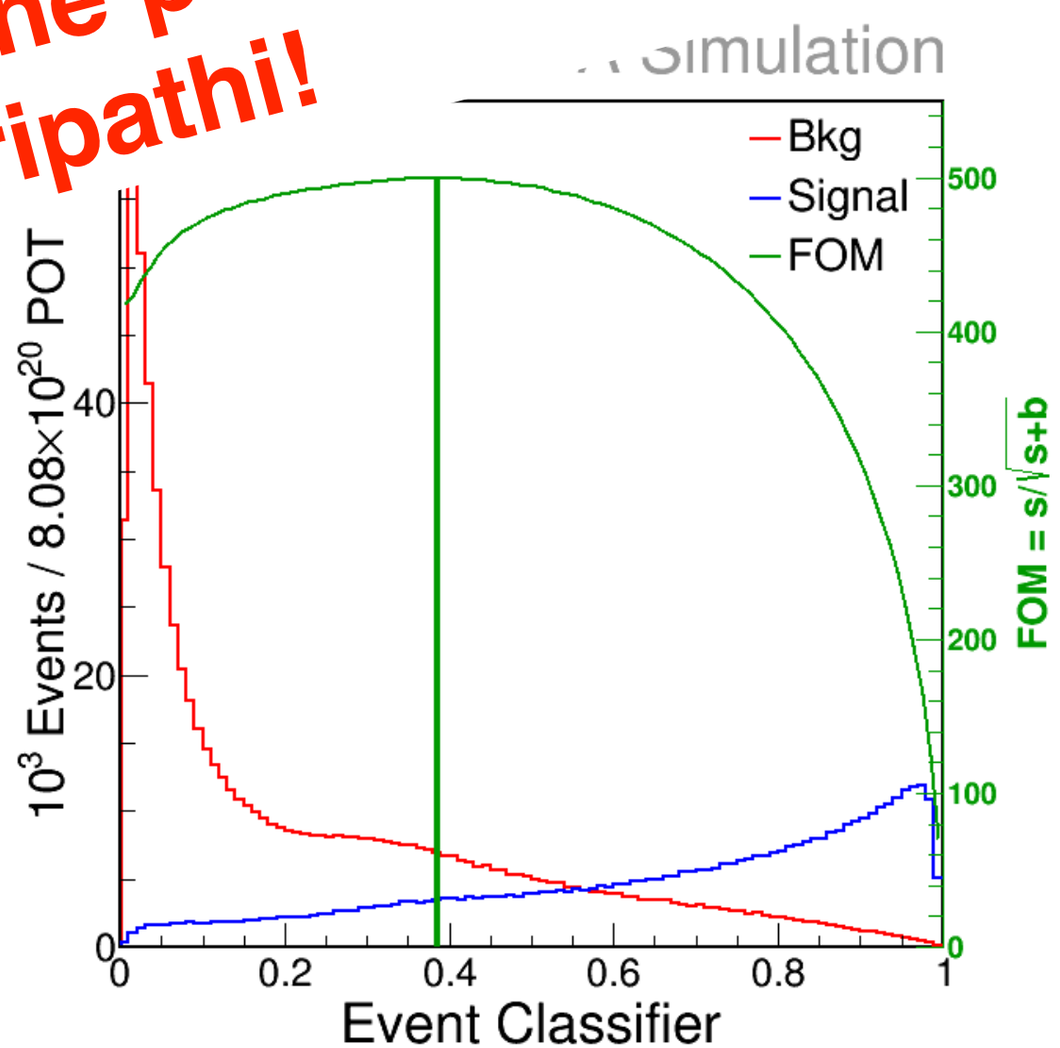
Signal: CC events with at least one charged pion (π^+/π^-) in the final state.



- Working on improving π^+/π^- reconstruction.
- Using deep-learning technique: A event-level Convolutional Visual Network (CVN) classifier.
  - Uses full near d
    imag

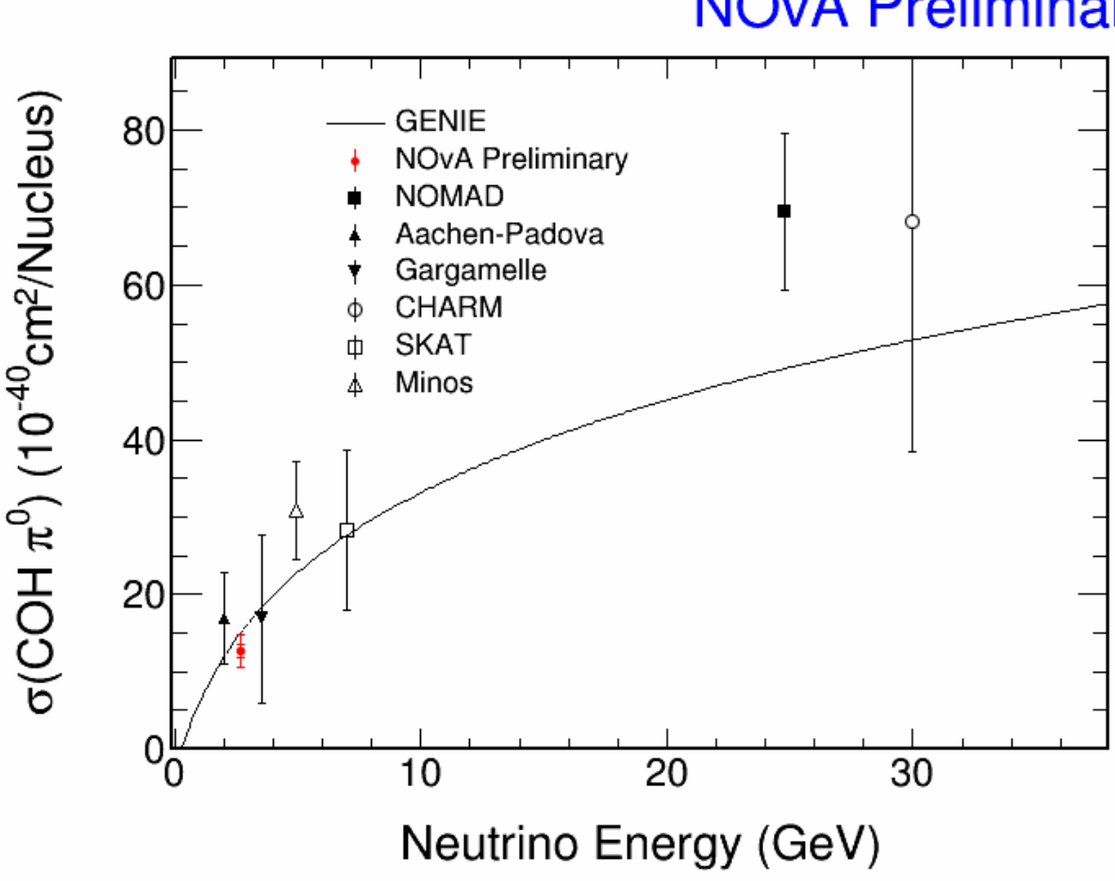
For more details see the poster tonight by Jyoti Tripathi!

- Work
  - and
  - Systematics on CVN.
  - Sideband background-fitting study.
- The first goal is to report differential cross-section in muon kinematics.



Summary

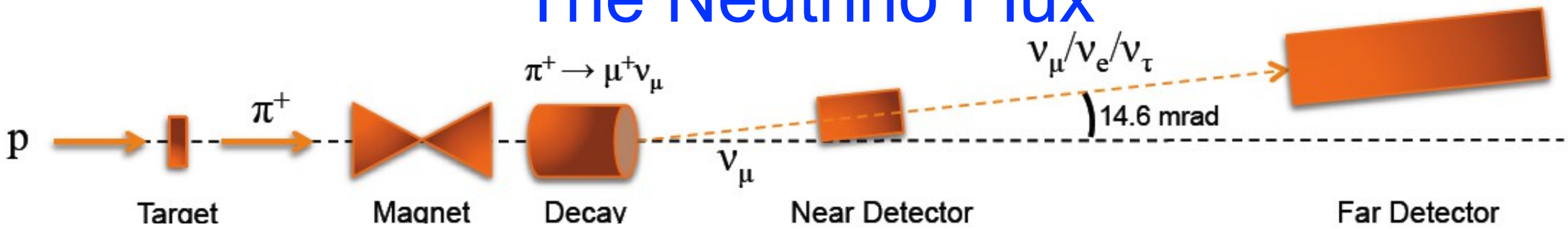
- NOvA is entering the game of neutrino pion production measurement.
  - Fine-grained liquid scintillator detector.
  - Narrow band neutrino flux at 1~3 GeV.
  - High statistics neutrino data. Taking anti-neutrino data too.
- NC-Coherent π^0: preliminary result reported for the first time
- CC π^0, NC π^0,and CC π^+/π^- in progress.
- Stay tuned!

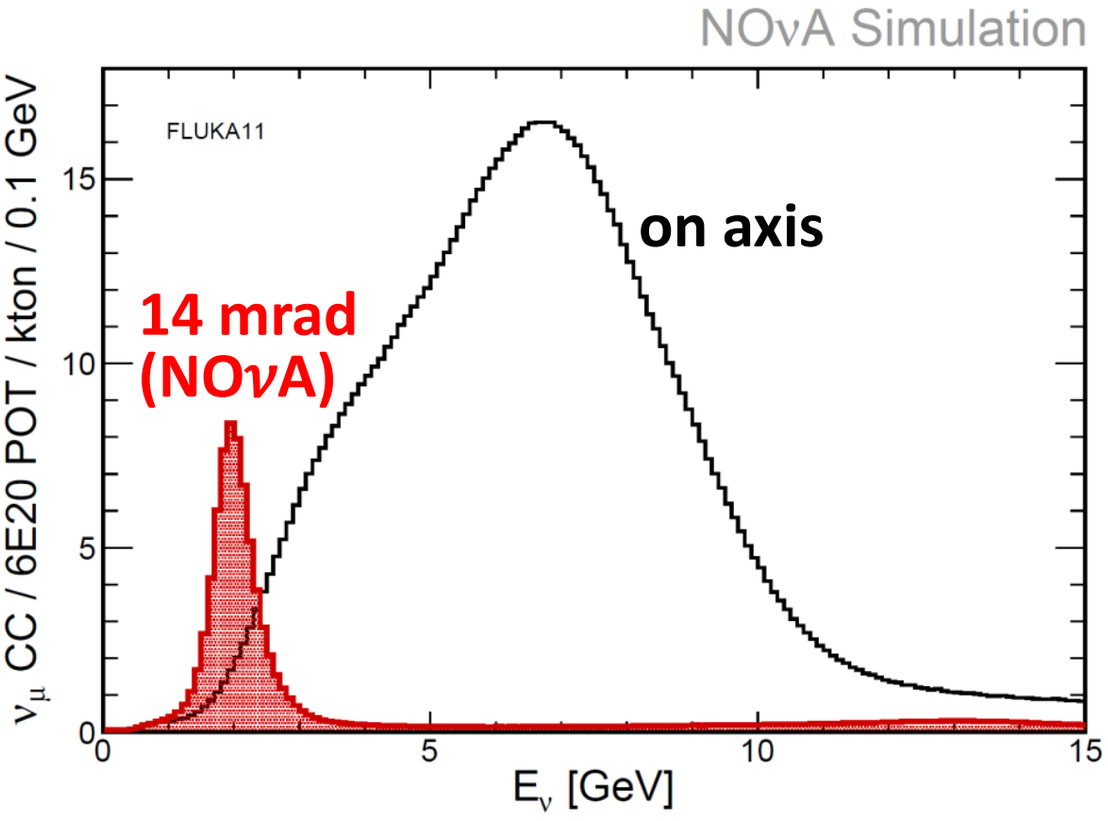


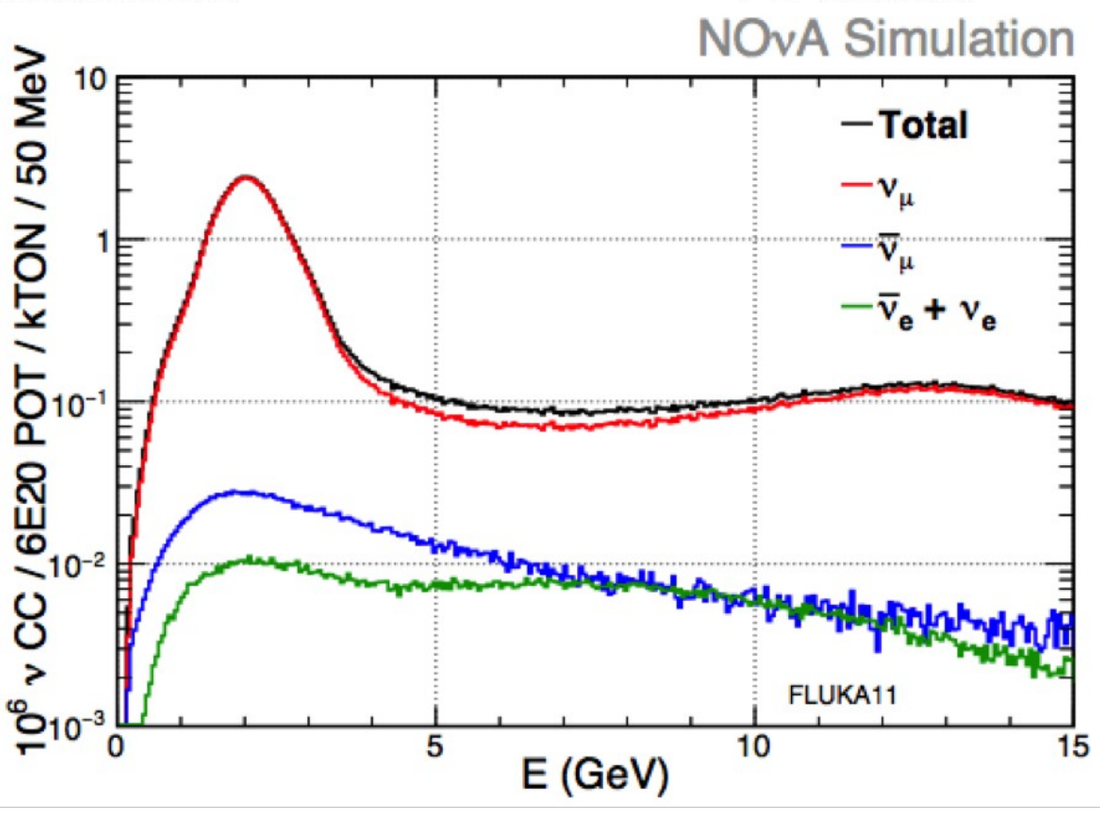
Thank you!

Back up slides

The Neutrino Flux

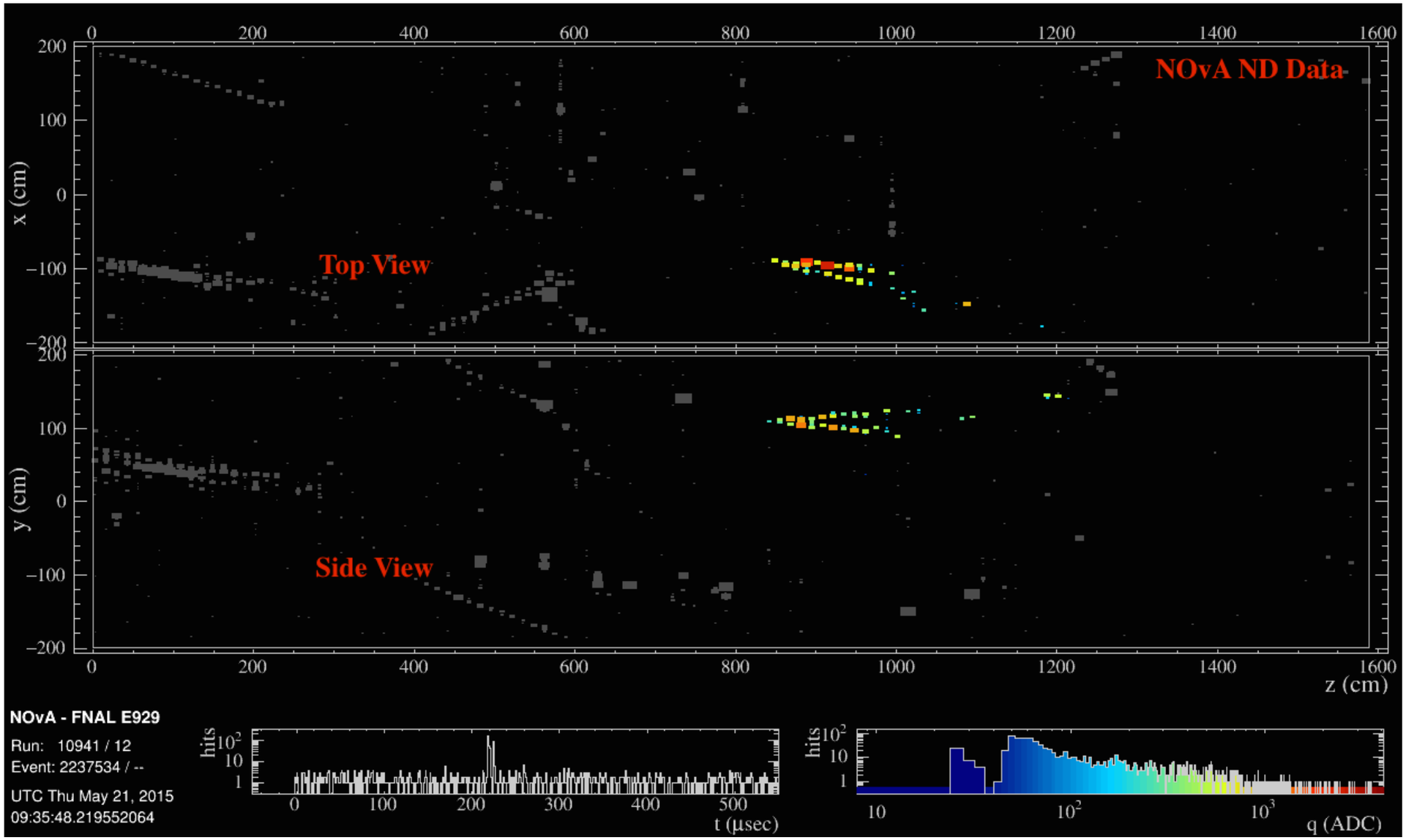






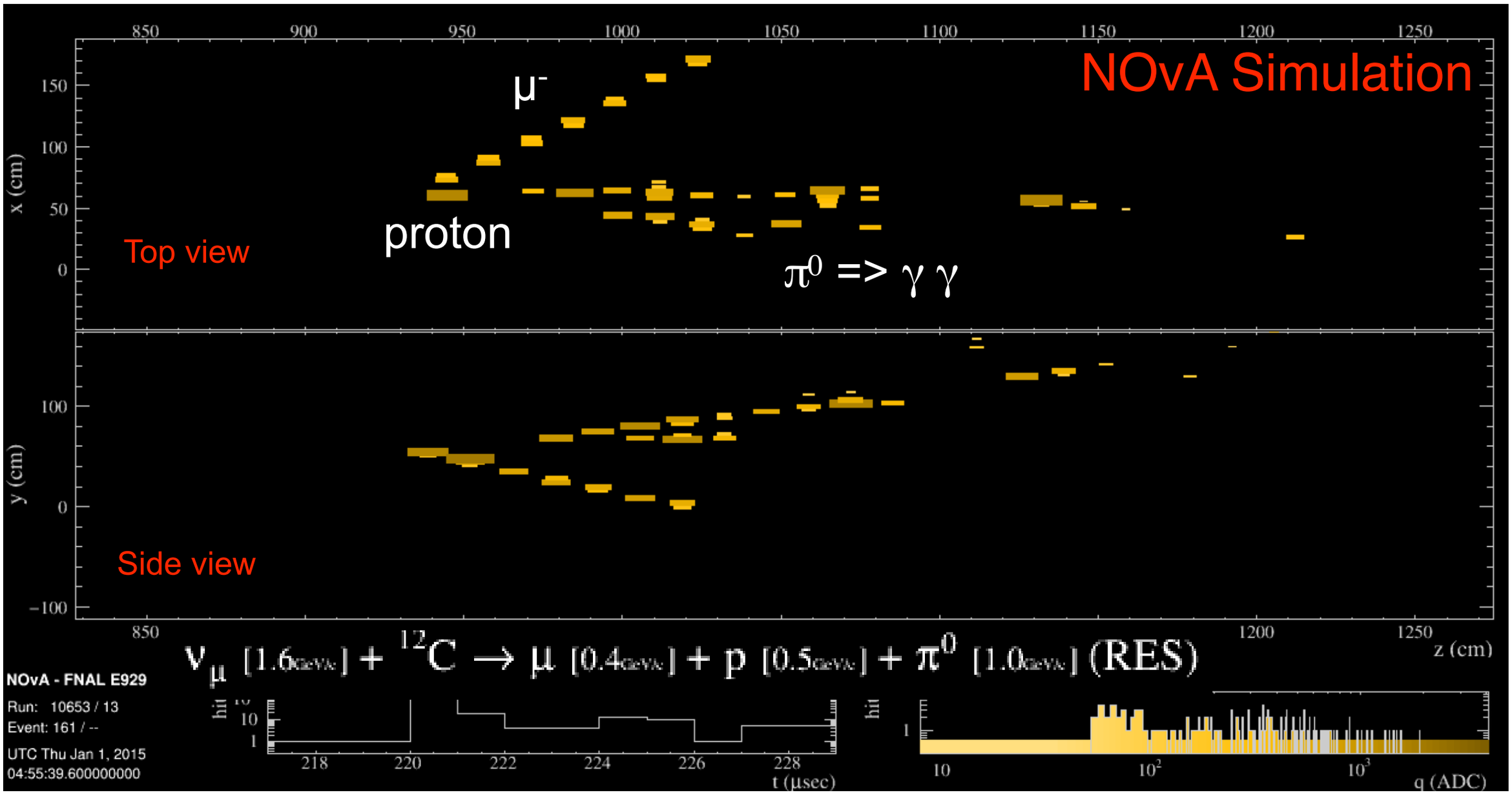
- Narrow band neutrino beam 1~3GeV peak at ~2GeV.
- Dominated by ν_μ (94%), with small contribution from ν_e (1%).
- Hadron production uncertainty constraint by external hadron production data. (See Leo Aliaga's talk on Monday)
- Also working on *in situ* flux measurement by neutrino-electron scattering.

NC Coherent π^0



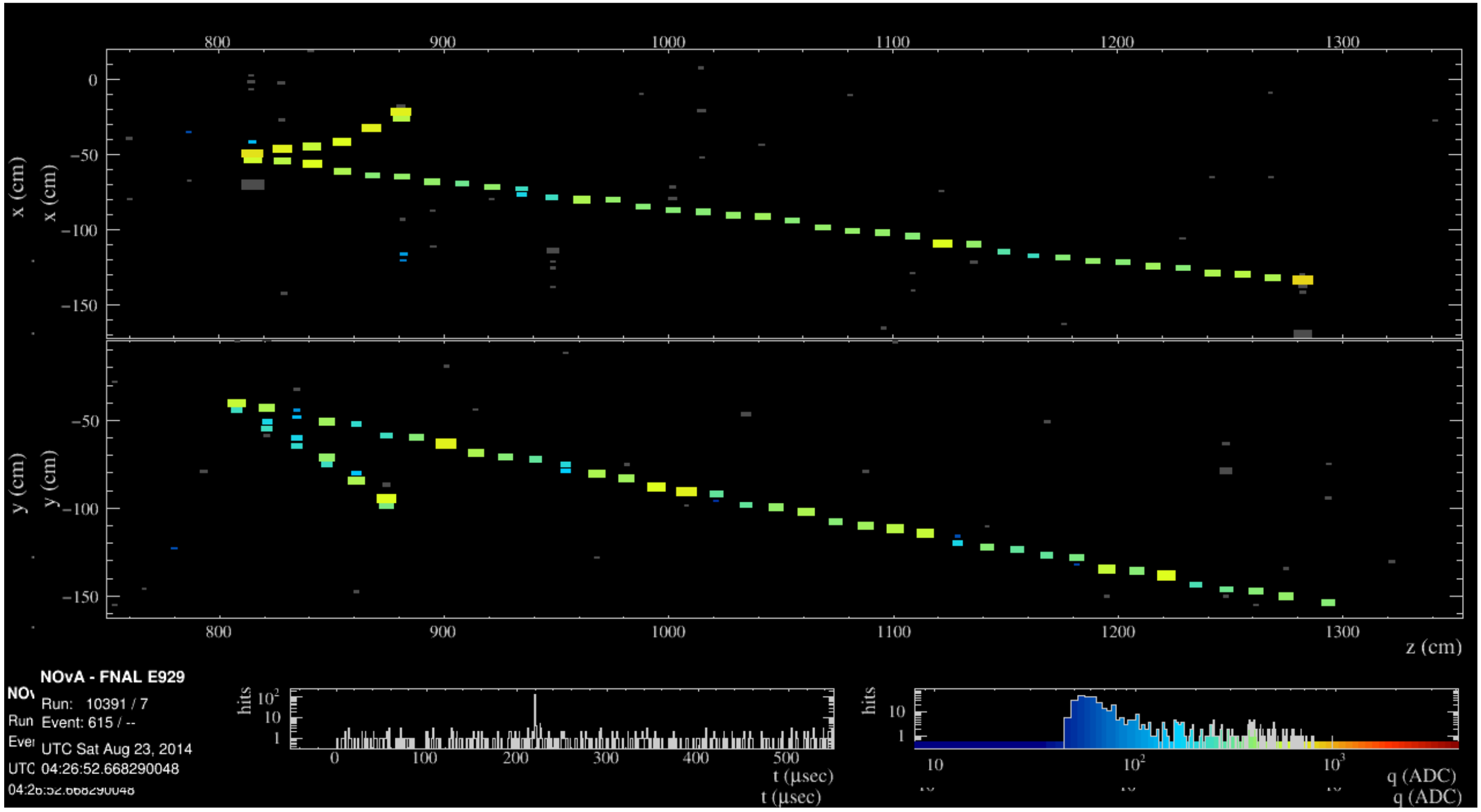
- Signal Sample: one pi0 decaying into two photons, both reconstructed in NOvA ND. No other nucleons or pions.

ν_μ-CC π^0



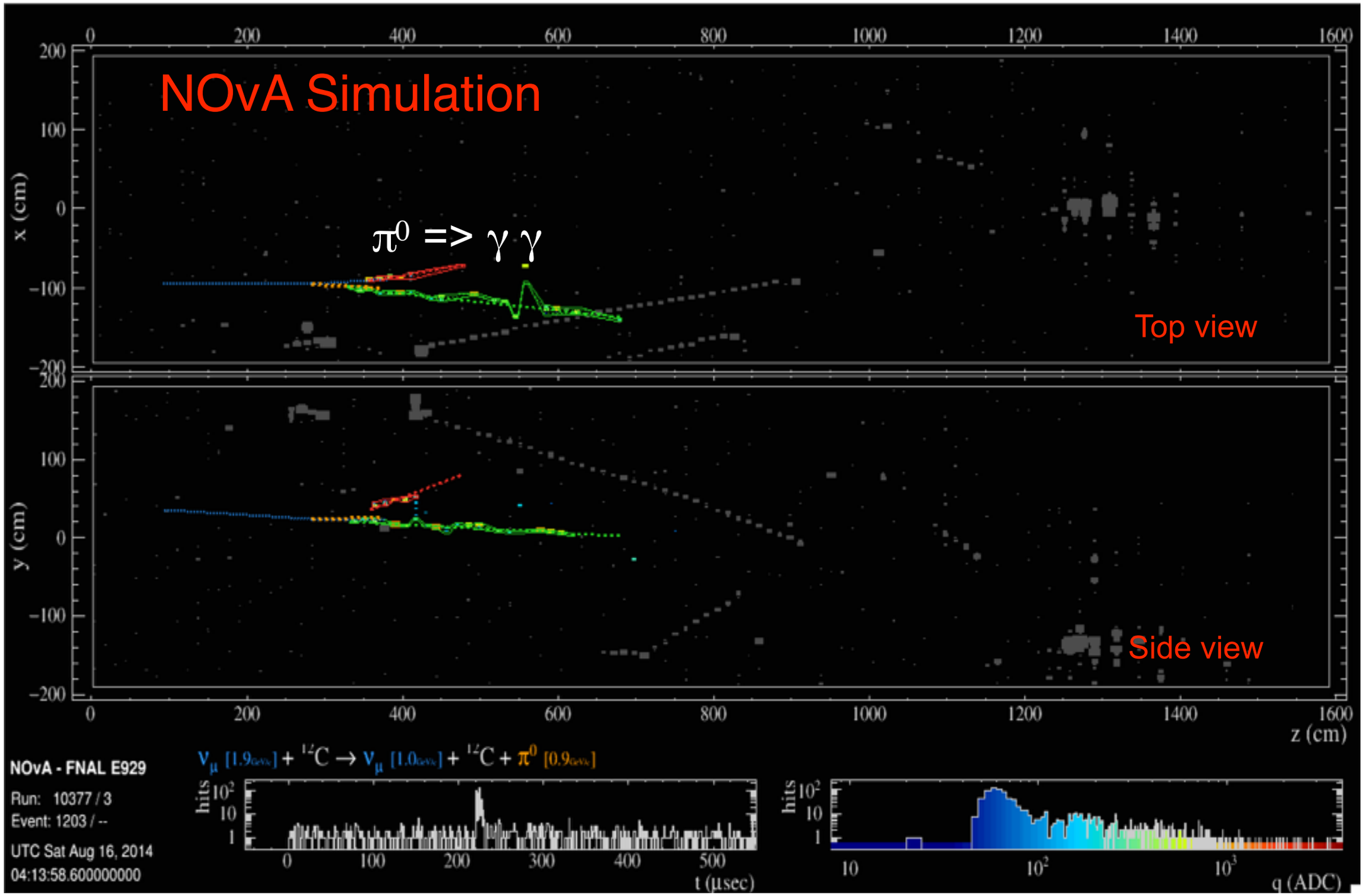
Signal: ν_μ-CC events with at least one primary π^0 in the final state

Charge Current π^+/π^-



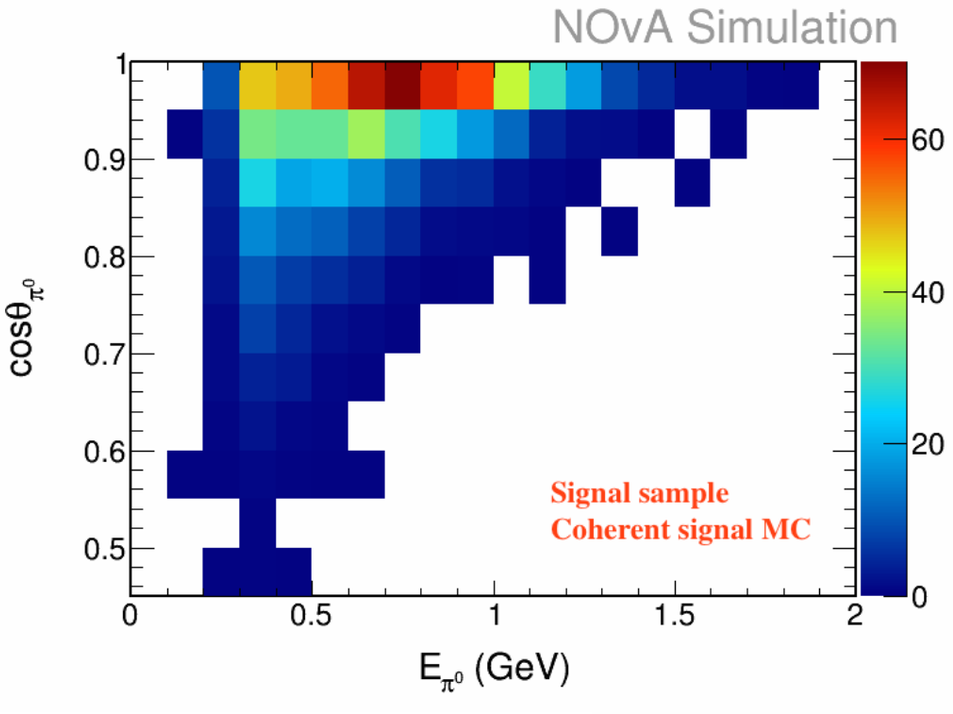
Signal: CC events with at least one charged pion (π^+/π^-) in the final state

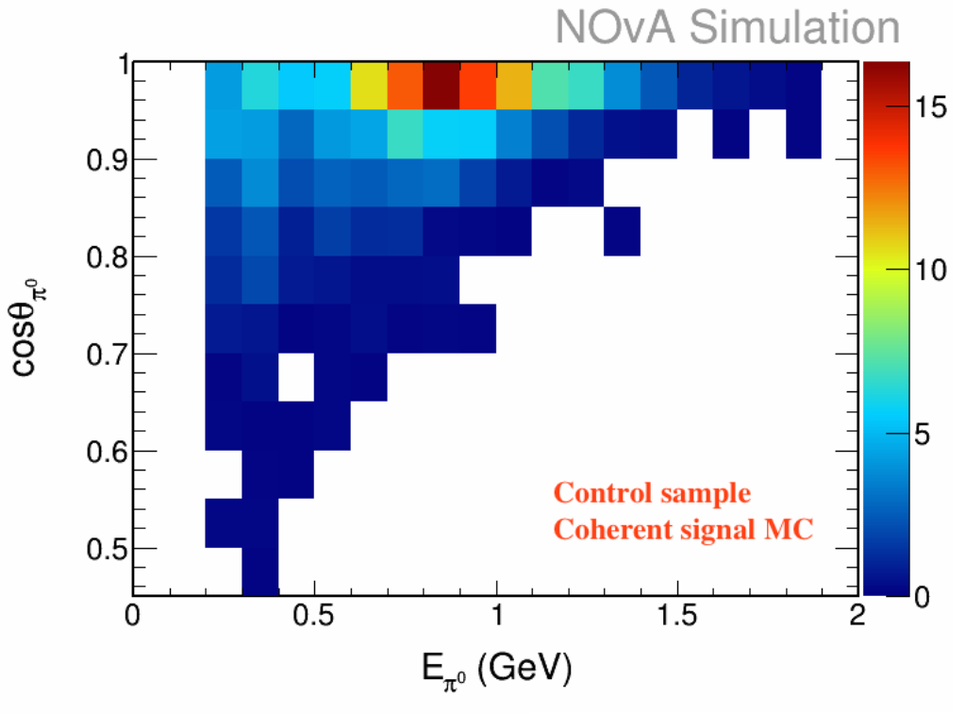
Neutral Current π^0

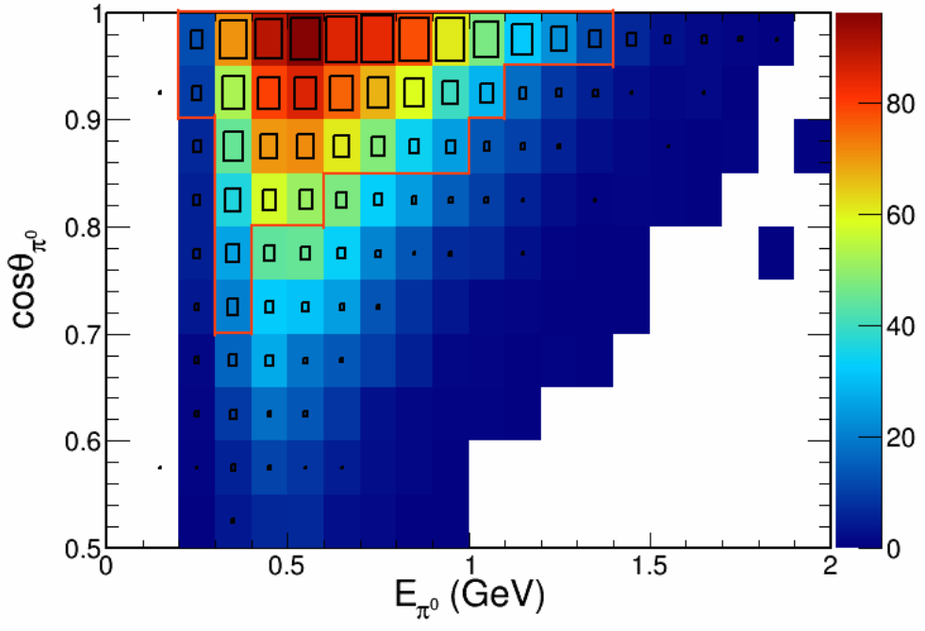


Signal: NC events with at least one π^0 in the final state

NC Coherent π^0

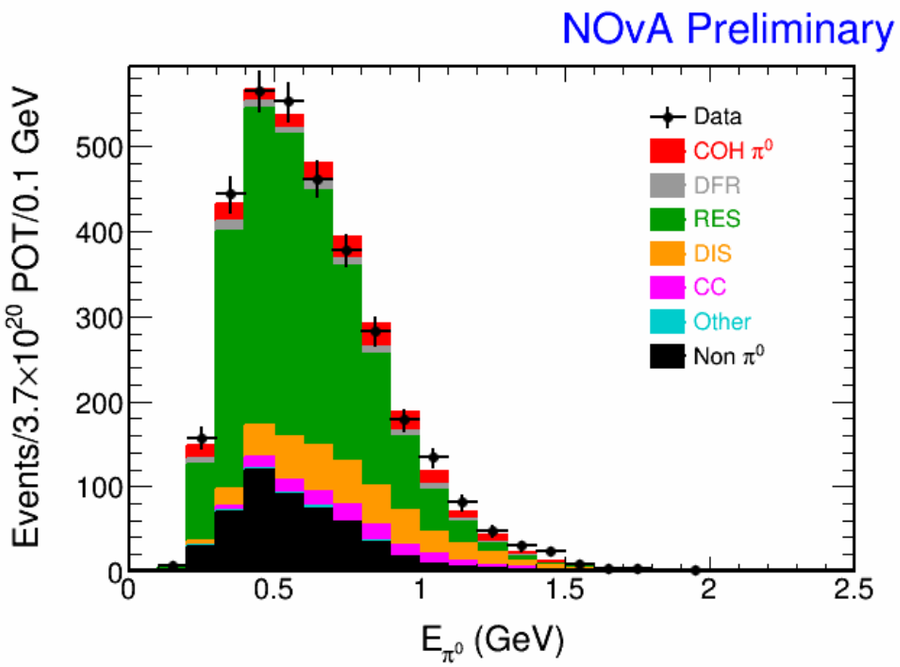


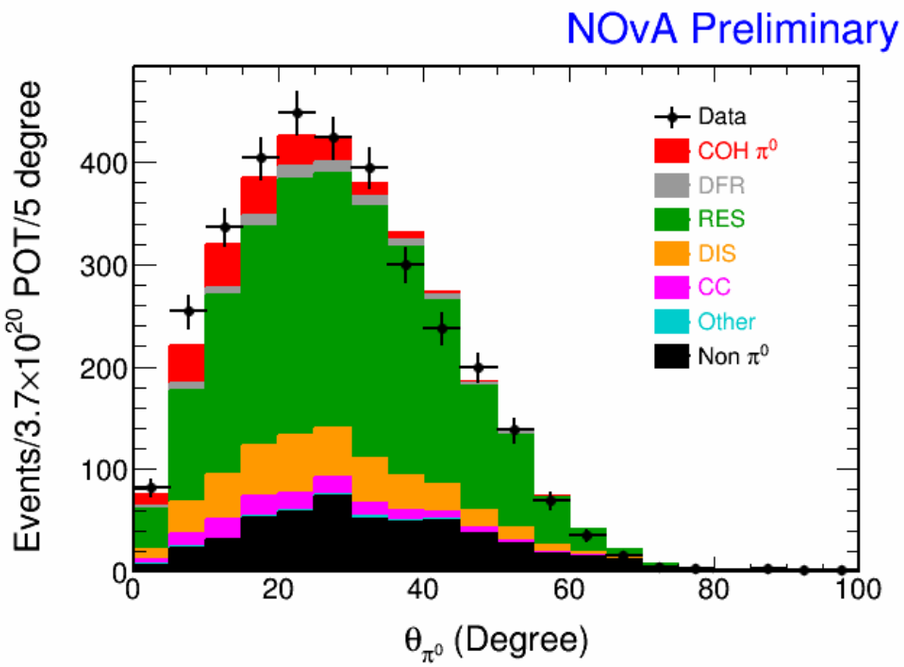




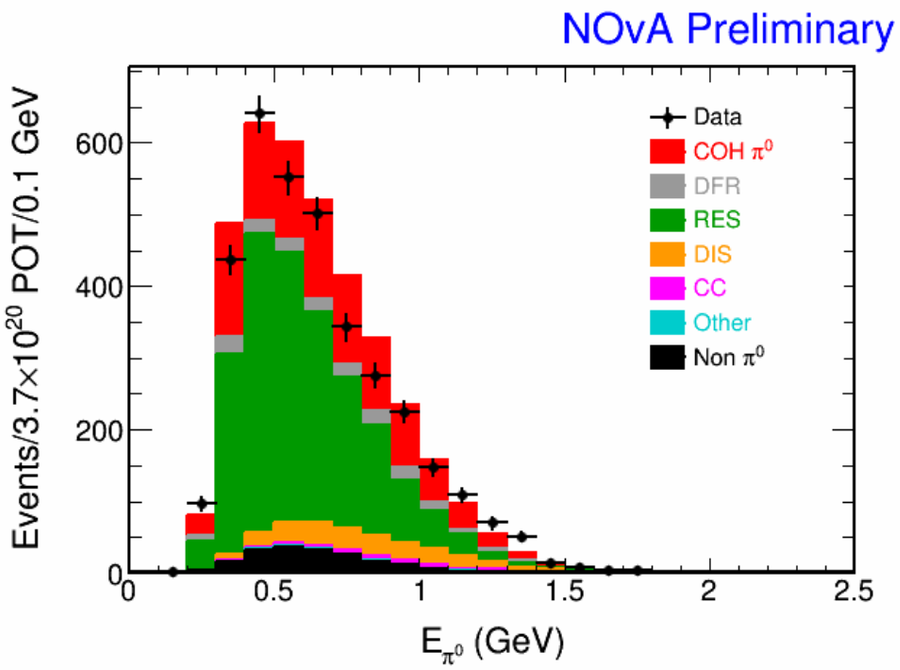
- Fit background to control sample data in π^0 energy vs angle 2D space.

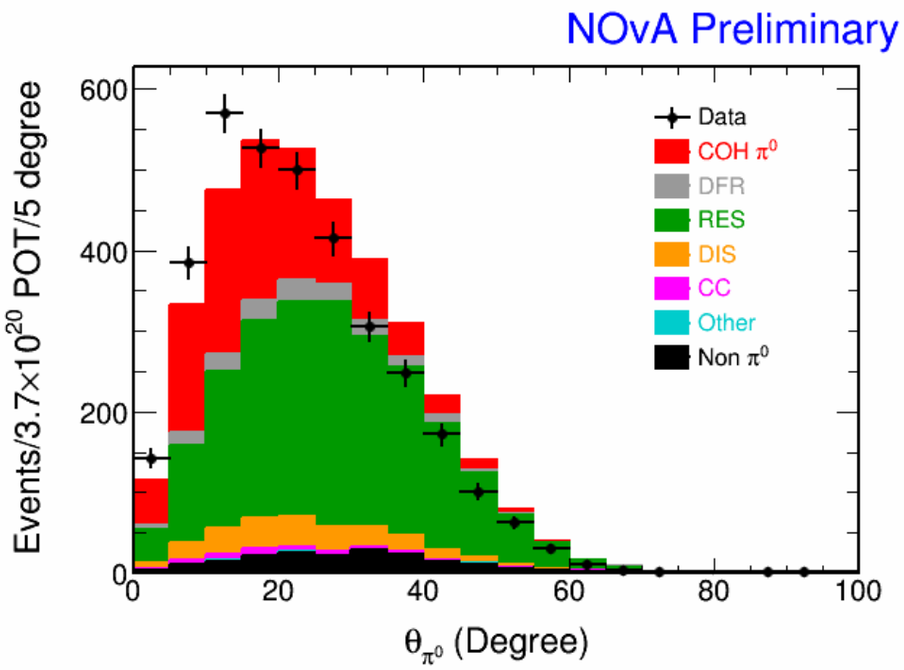
NC Coherent π^0





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

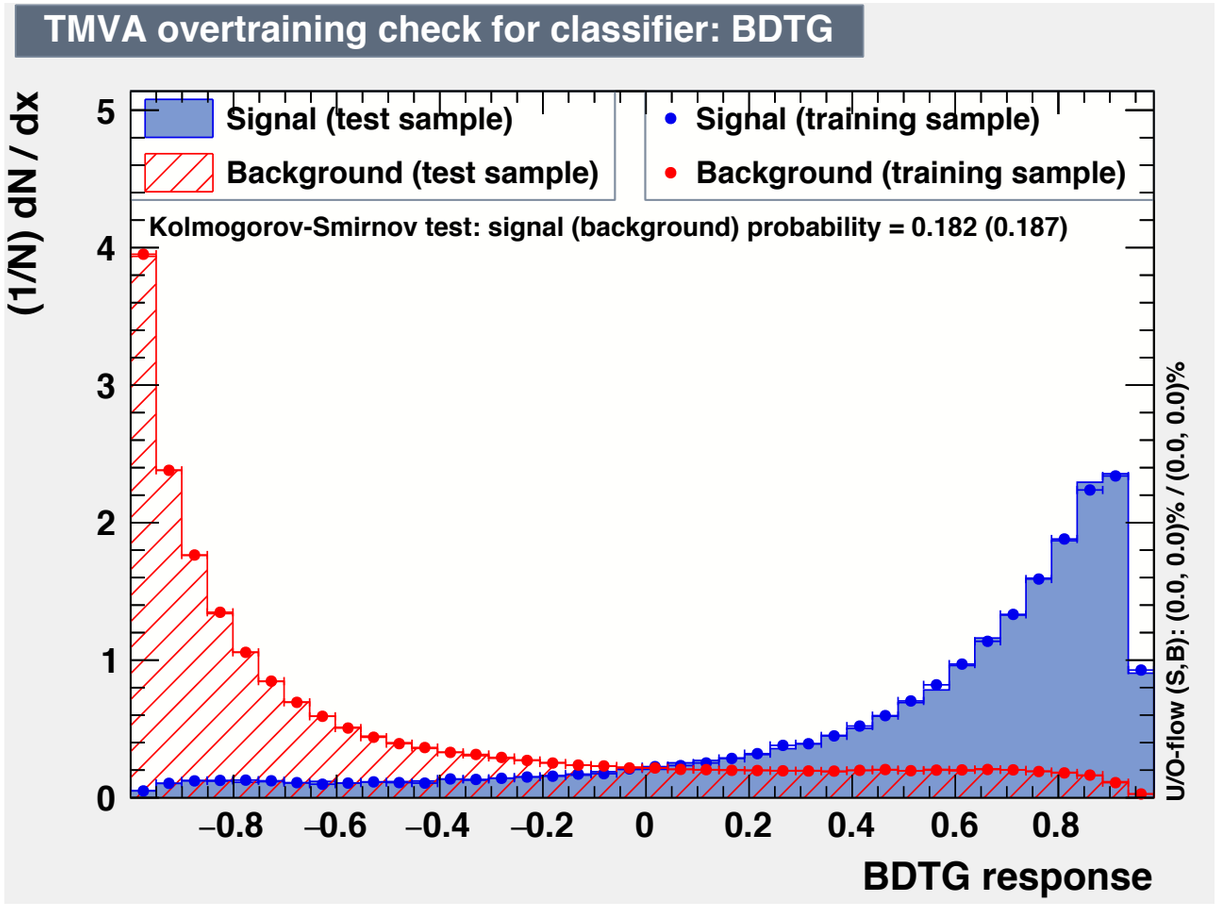




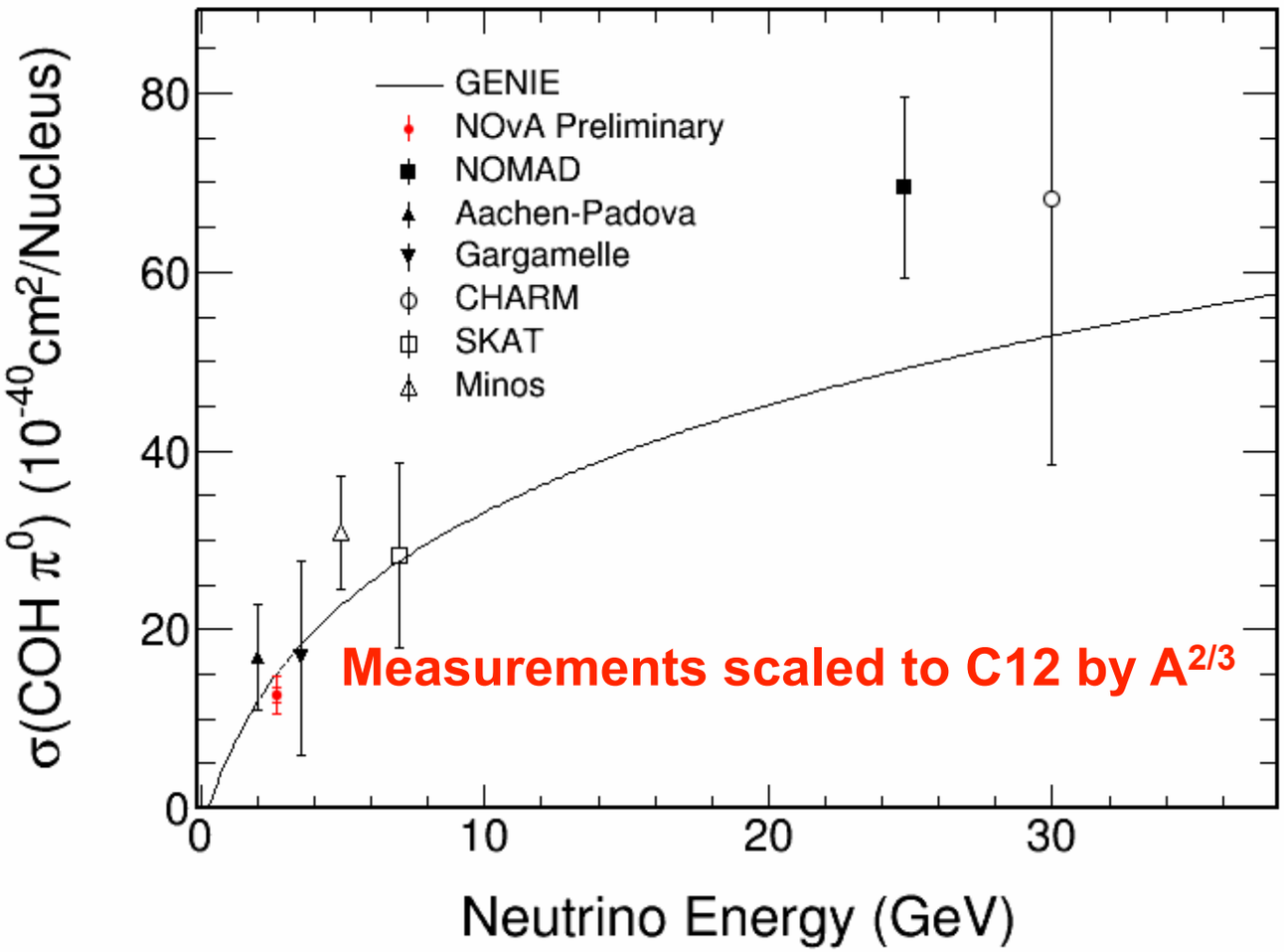
Neutral Current π^0

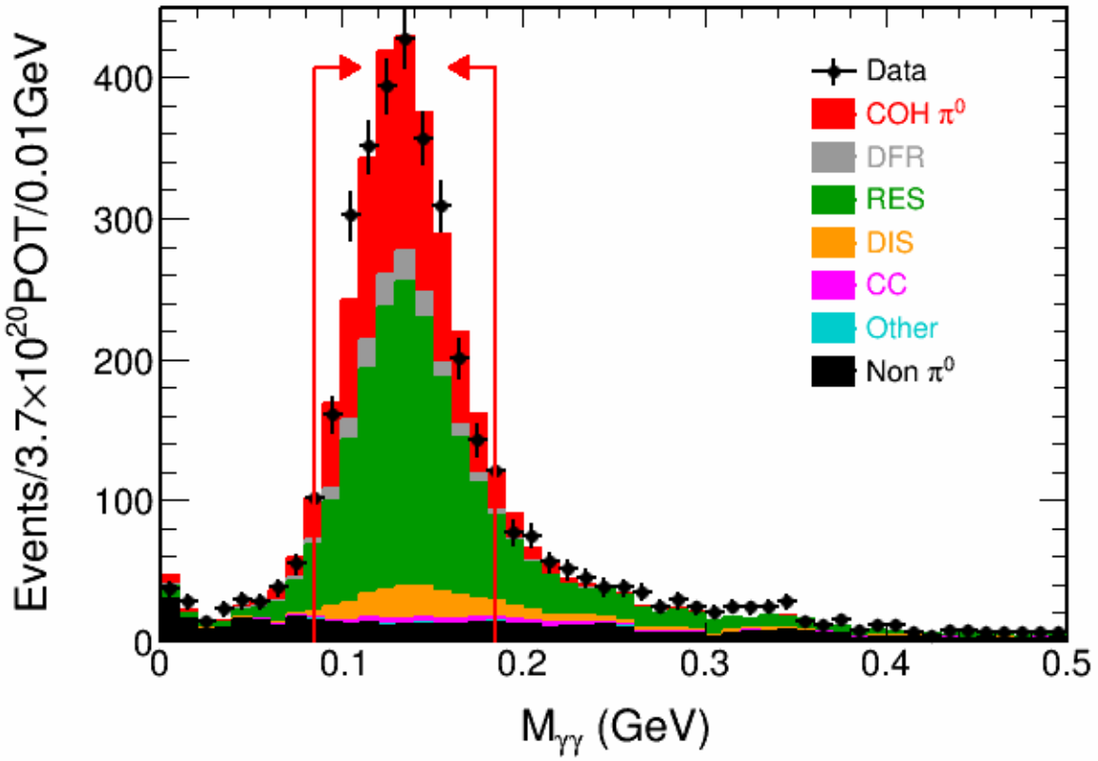
- Signal: ν_μ-NC with at least one π^0. Start with 2-prong events.
- A event-level Boost Decision Tree (BDT) developed using shower variables as inputs.

```
------------------------------------------
Rank : Variable            : Separation
------------------------------------------
   1 : CVN_numu            : 1.524e-01
   2 : Prong1 epi0LLL      : 8.832e-02
   3 : Prong1 epiLLL       : 8.293e-02
   4 : Prong1 Cont planes  : 8.248e-02
   5 : Prong1 epLLT        : 6.322e-02
   6 : Prong1 Width        : 5.794e-02
   7 : CVN_nc              : 3.129e-02
   8 : Prong1 dedx         : 2.090e-02
   9 : distPngStartPos     : 1.186e-02
  10 : Prong1 epi0LLT      : 1.158e-02
  11 : Prong2 dedx         : 1.150e-02
------------------------------------------
```



NC Coherent π^0





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

Source	δ(%)
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

Charge Exchange