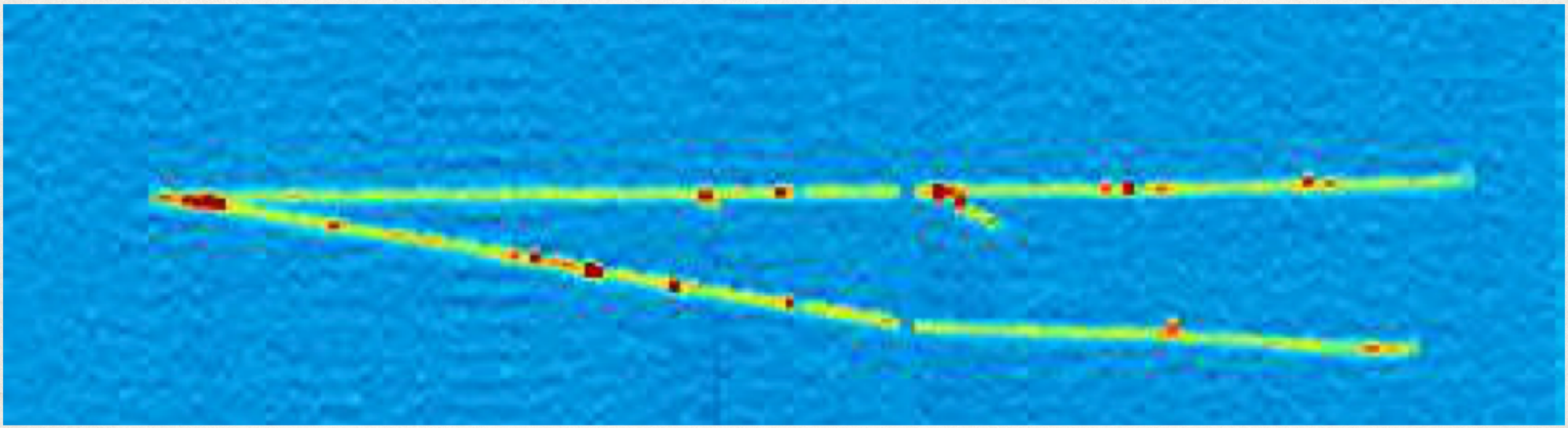


Coherent Charged Pion Production in ArgoNeuT

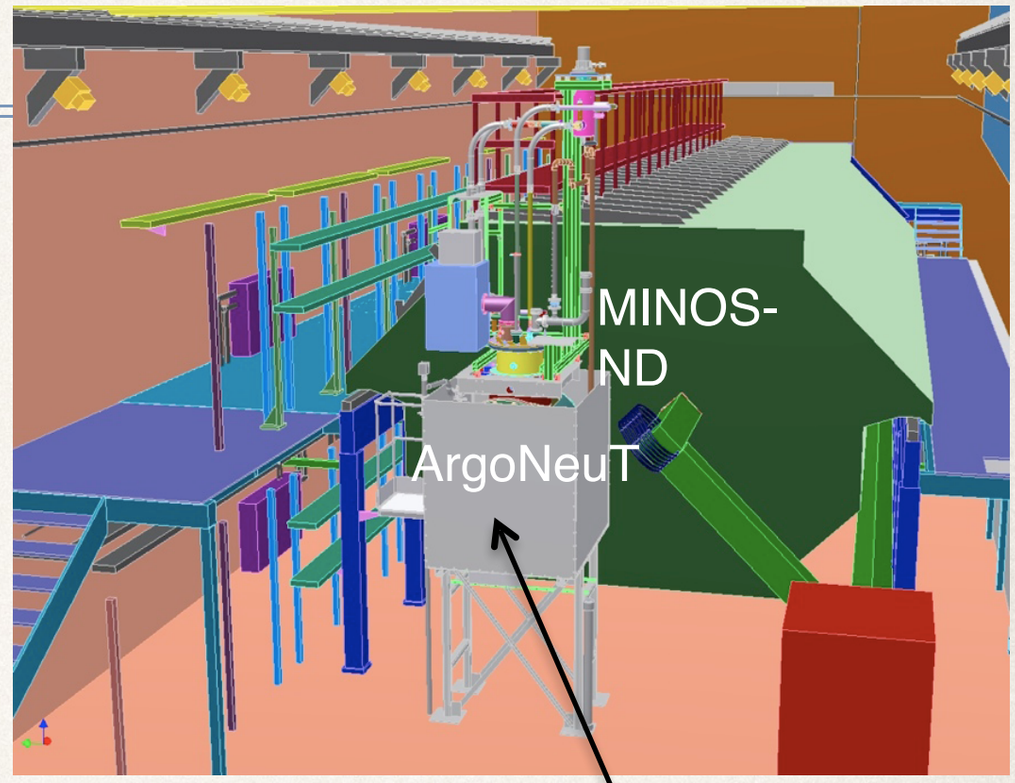
Tingjun Yang

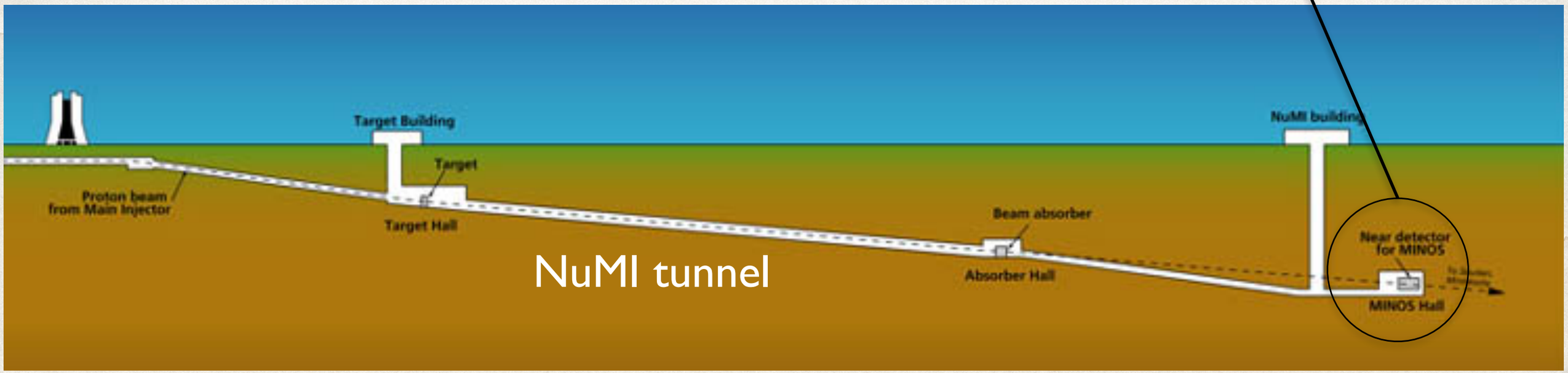
FNAL

Nu-tion premeeting, University of Toronto, June 23, 2017

ArgoNeuT - Argon Neutrino TesT

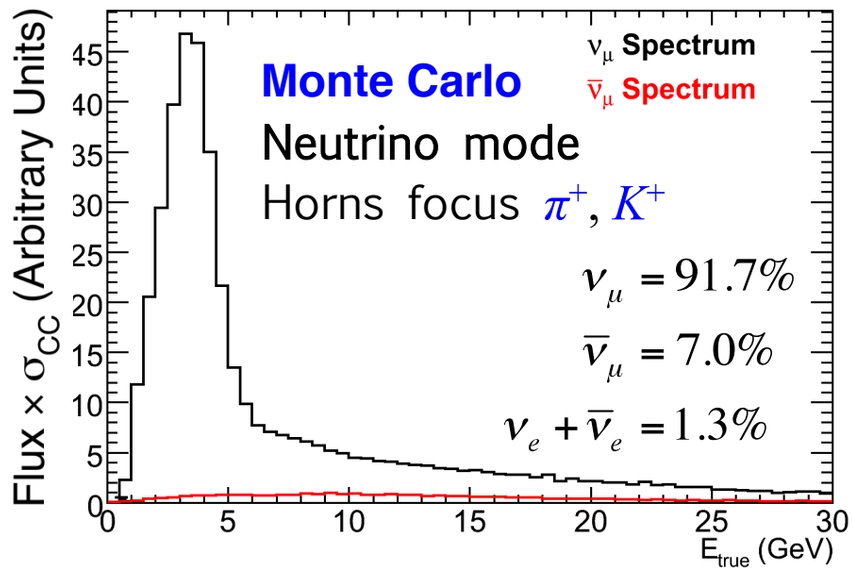
- First TPC in a neutrino beam in the US
- Sitting in NuMI beam
- Located in front of MINOS near detector
- 47×40×90 cm^3 (170 L), wire spacing 4 mm



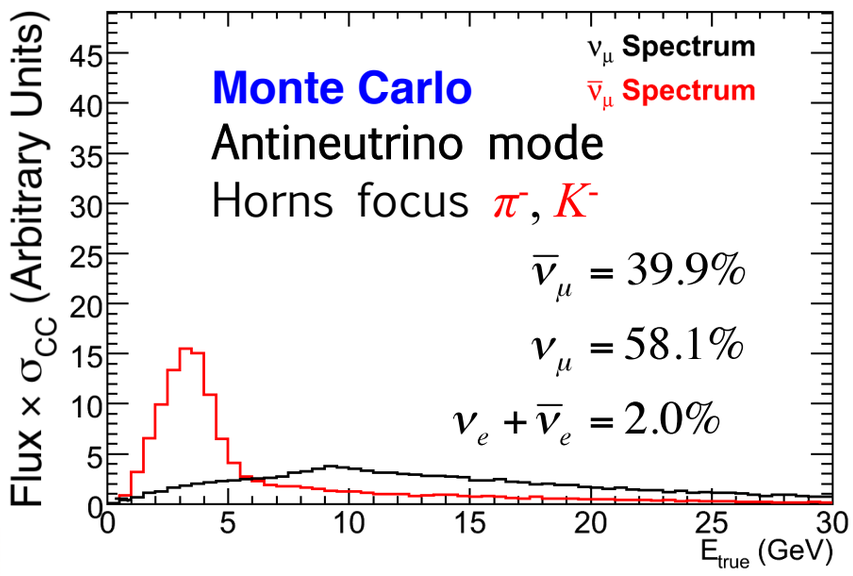


ArgoNeuT's Physics Run

v-mode (2 weeks): 0.085e20 POT



$\bar{\nu}$-mode (5 months): 1.2e20



- ArgoNeuT completed taking data. (9/14/2009-2/22/2010)
- Physics goals:
  - Measure ν-Ar CC cross sections
  - Develop automated reconstruction techniques
    - Track reco
    - Shower reco
    - Calorimetry / PID

Physics Results

- ArgoNeuT has published 9 papers so far.
- 5 papers are on cross section measurements.
  - "First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon." PRL 108 (2012), 161802.
  - "Measurements of Inclusive Muon Neutrino and Antineutrino Charged Current Differential Cross Sections on Argon in the NuMI Antineutrino Beam" PRD 89, 112003 (2014).
  - "The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line" PRD 90, 012008 (2014).
  - **"First Measurement of Neutrino and Antineutrino Coherent Charged Pion Production on Argon" PRL 113, 261801 (2014).**
  - "Measurement of ν_μ and $\bar{\nu}_\mu$ Neutral Current $\pi^0 \rightarrow \gamma\gamma$ Production in the ArgoNeuT Detector" accepted by PRD (2017).
- A small LArTPC that provides valuable information on neutrino-Ar interactions!

ArgoNeuT Cross Section Measurements

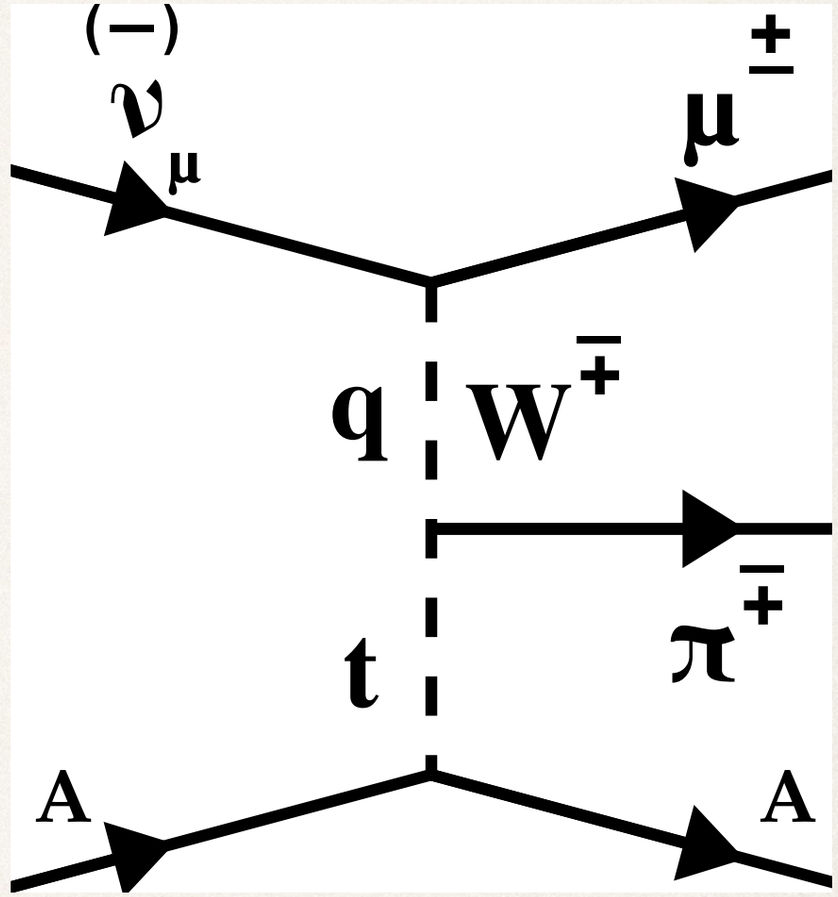
- This talk focuses on the ArgoNeuT cross section measurements, using charged current (CC) coherent pion production cross section measurement as an example.
- Questions we need to ask for any cross section measurements:
  - What am I trying to measure, what's my signal definition?
  - Why is my measurement useful?
  - How do I selection signal events?
  - How do I deal with backgrounds?
  - How do I correct for efficiency and smearing?
  - What are the potential sources of systematic uncertainties?

Overview of CC coherent pion measurement

- **Motivation**
  - Understand neutrino-Ar interaction and help understand anomalies in the previous experiments.
- **Selection**
  - Use MINOS information to select CC events.
  - Use LArTPC topology and calorimetric information to select CC coherent pion events.
- **Background estimation**
  - Boosted decision trees to reduce and estimate background.
- **Unfolding**
  - Correct for efficiency and smearing
- **Systematic uncertainties**
  - Detector, flux and cross section models

Coherent Pion Production

- Neutrino can scatter coherently on the entire nucleus if momentum transfer to nucleus |t| is small
  - Forward going lepton and pion in final state
  - No visible recoil
- NC coherent pi0 is background to electron neutrinos.



$q^2=(p_\nu-p_\mu)^2$

$t=(q-p_\pi)^2$

Theoretical Model (PCAC)

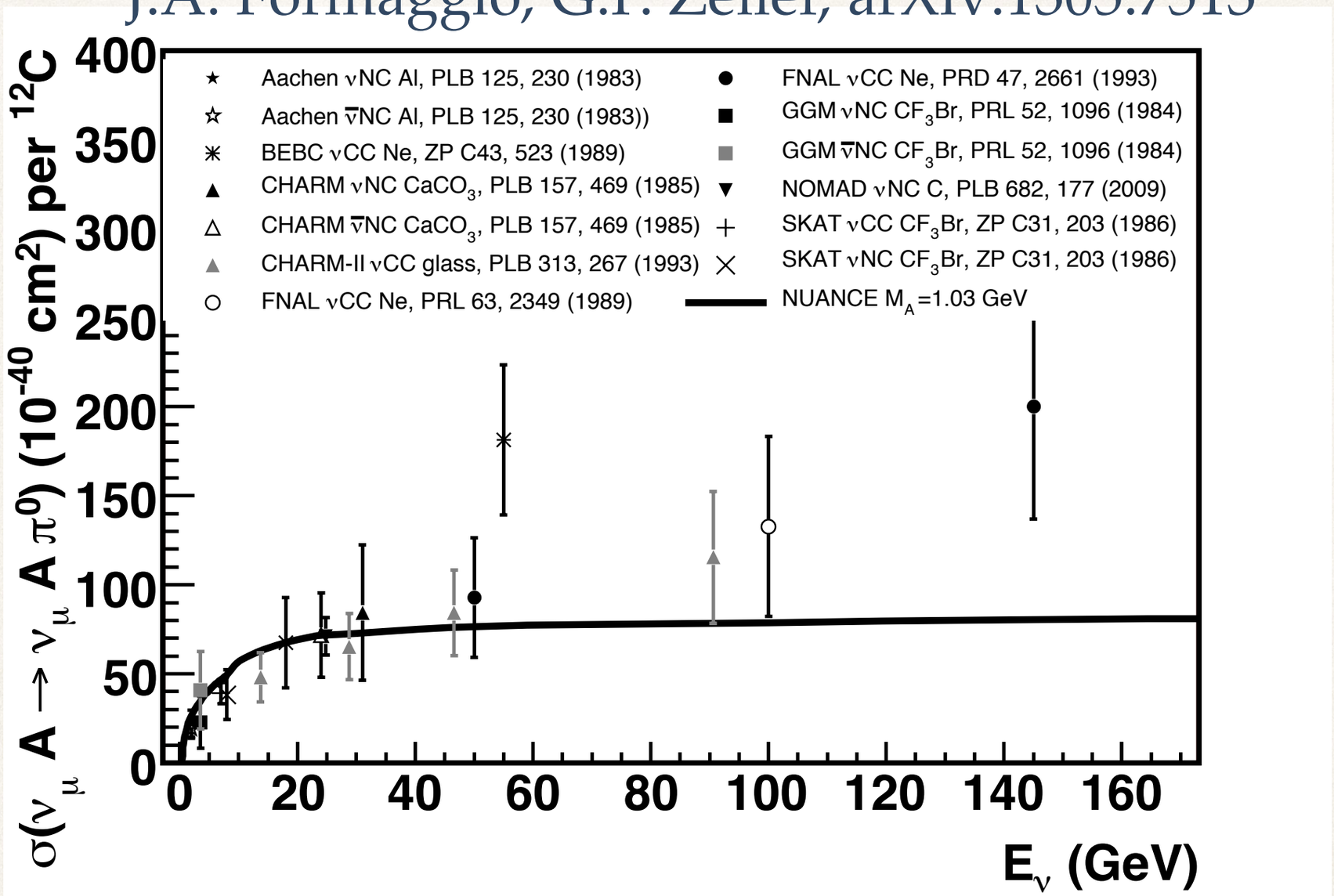
- Partially Conserved Axial Current (PCAC) relates neutrino-induced coherent pion production to pion-nucleus elastic scattering.

$$\left.\frac{d\sigma}{dq^2 dy dt}\right|_{q^2=0} = r\frac{G_F^2 f_\pi^2}{2\pi^2}\frac{1-y}{y}\left.\frac{d\sigma}{dt}(\pi A \to \pi A_{gs})\right|_{q^2=0, E_\pi = q^0}$$

- Form factor $(1-q^2/M^2_A)^{-2}$ applied to extend to $q^2 \neq 0$.
- Scale as $A^{1/3}$, $\sigma_{CC}=2\sigma_{NC}$, $\sigma_\nu=\sigma_{\bar{\nu}}$.
- Used in Rein-Seghal model and most of generators.

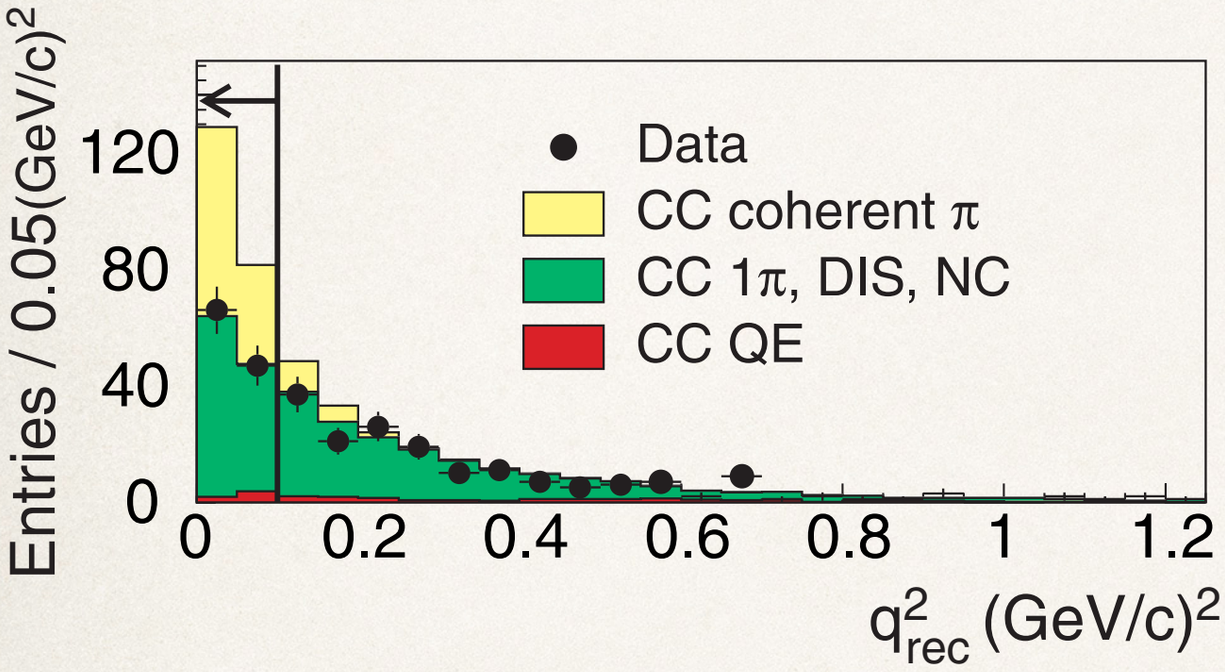
Experimental Results

J.A. Formaggio, G.P. Zeller, arXiv:1305.7513



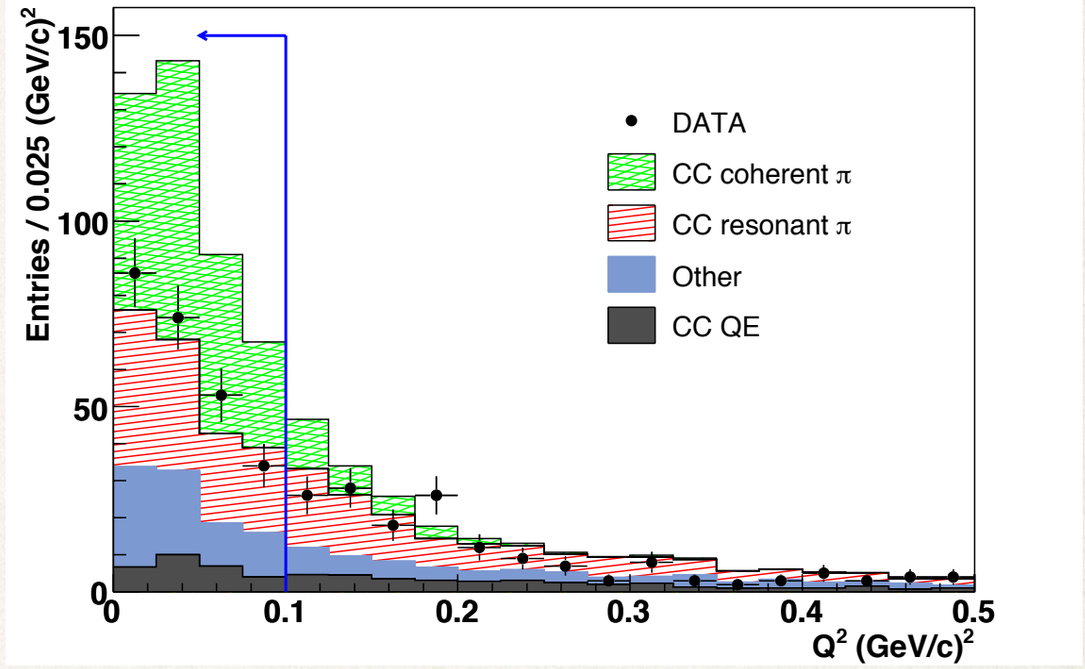
- Well established at high energy (E > 2 GeV).

Surprises



K2K, PRL 95, 252301 (2005)

C target, <E> = 1.3 GeV



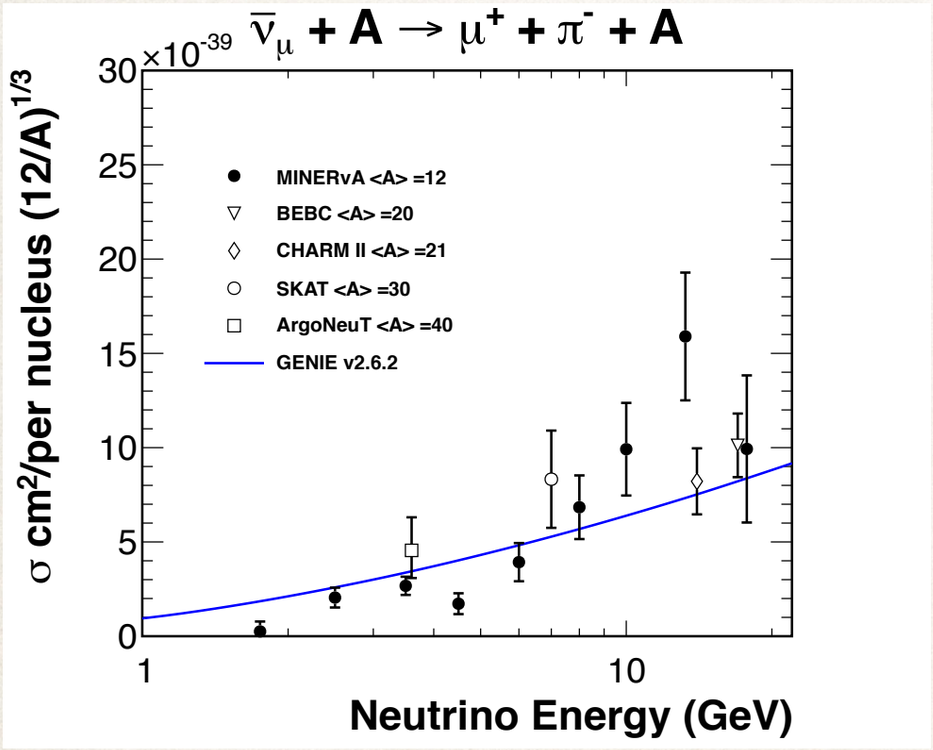
SciBooNE, PRD 78, 112004 (2008)

C target, <E> = 1.1 GeV, 2.2 GeV

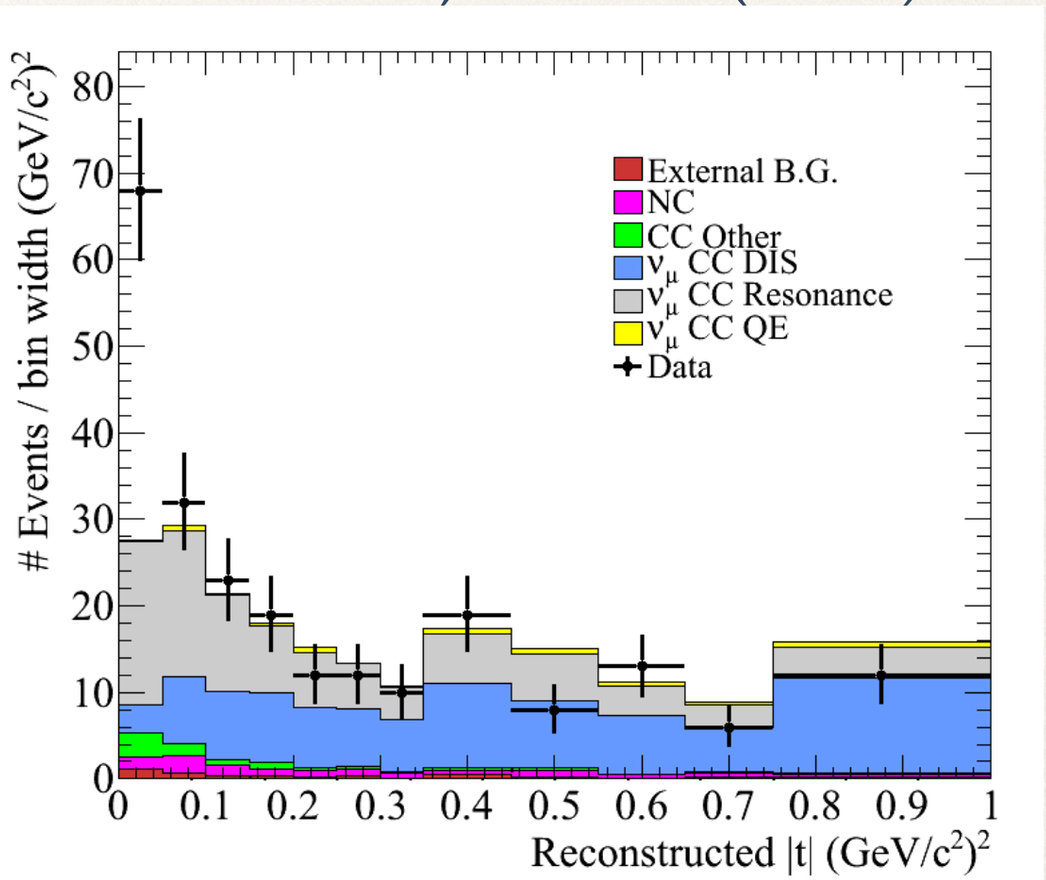
- No evidence of coherent pion production at low energy from K2K and SciBooNE.

More recent measurements

MINERvA: arXiv: 1409.3835
PRL 113, 261802 (2014)



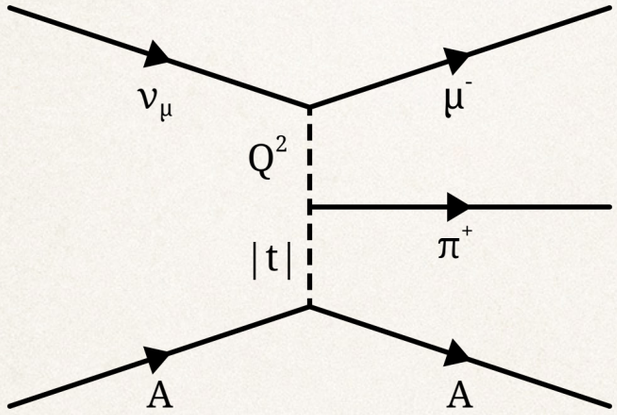
T2K: arXiv:1604.04406
PRL 117, 192501 (2016)

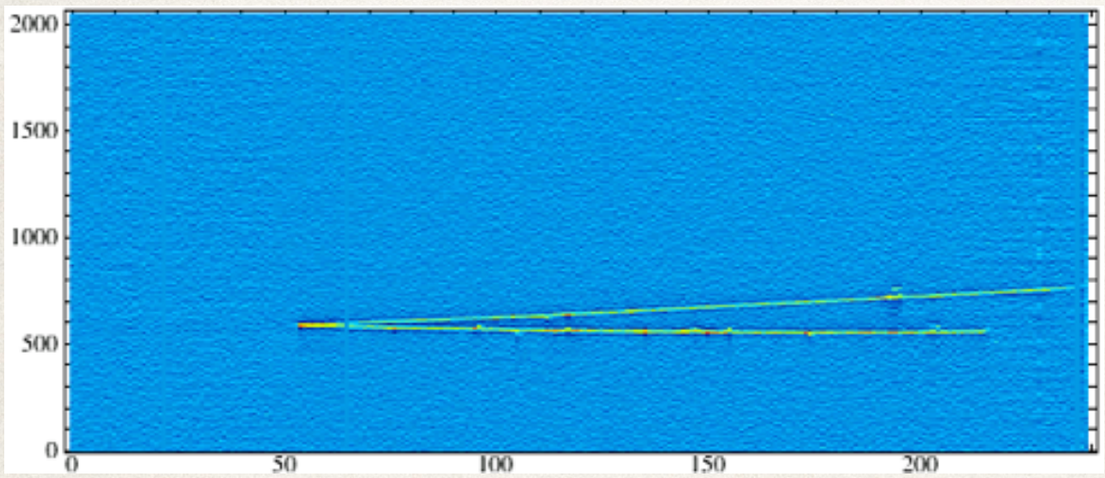


<E> < 1.5 GeV, 2.2σ excess

Look for CC Coherent Pion Production in ArgoNeuT

- Look for events with 2 tracks with small opening angle.





Event Selection

[Reconstruction Cuts]

Event Classification

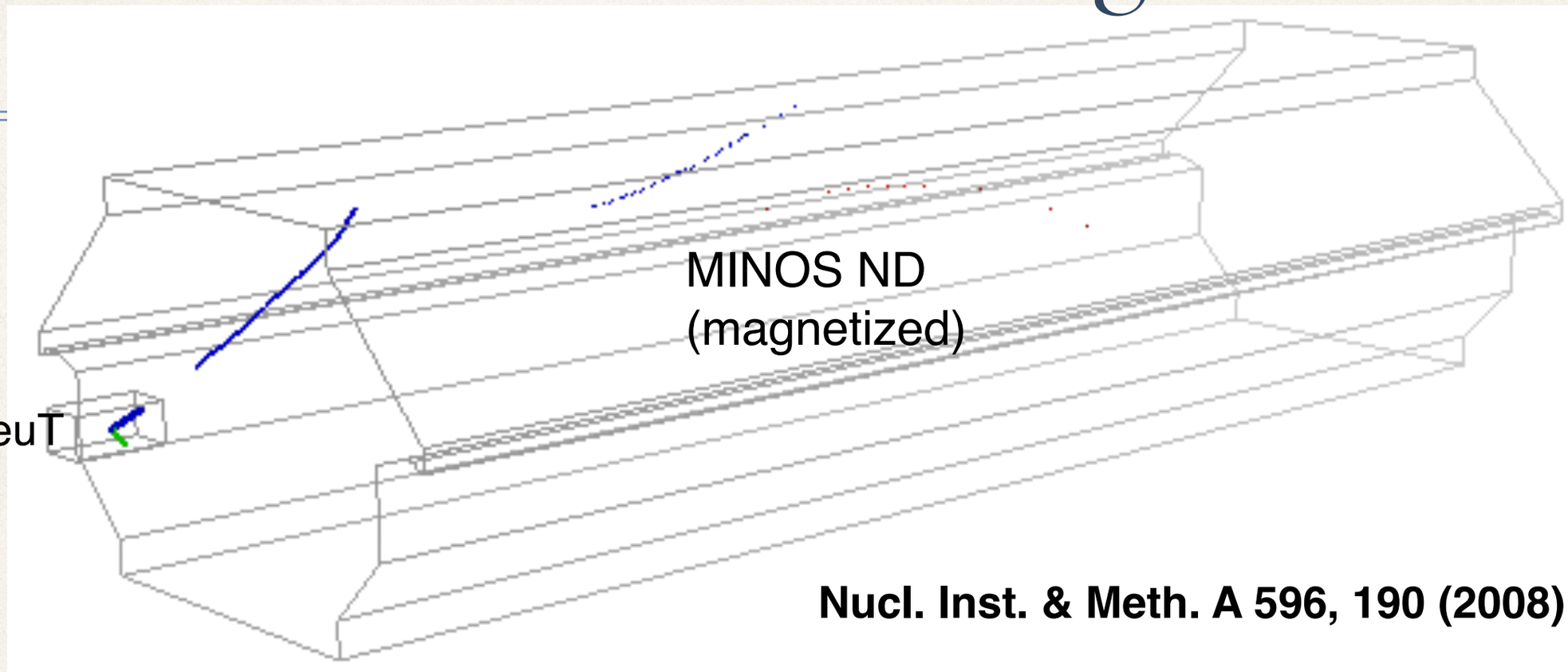
[Boosted Decision Trees]

Signal Extraction & Cross Section

Event Selection

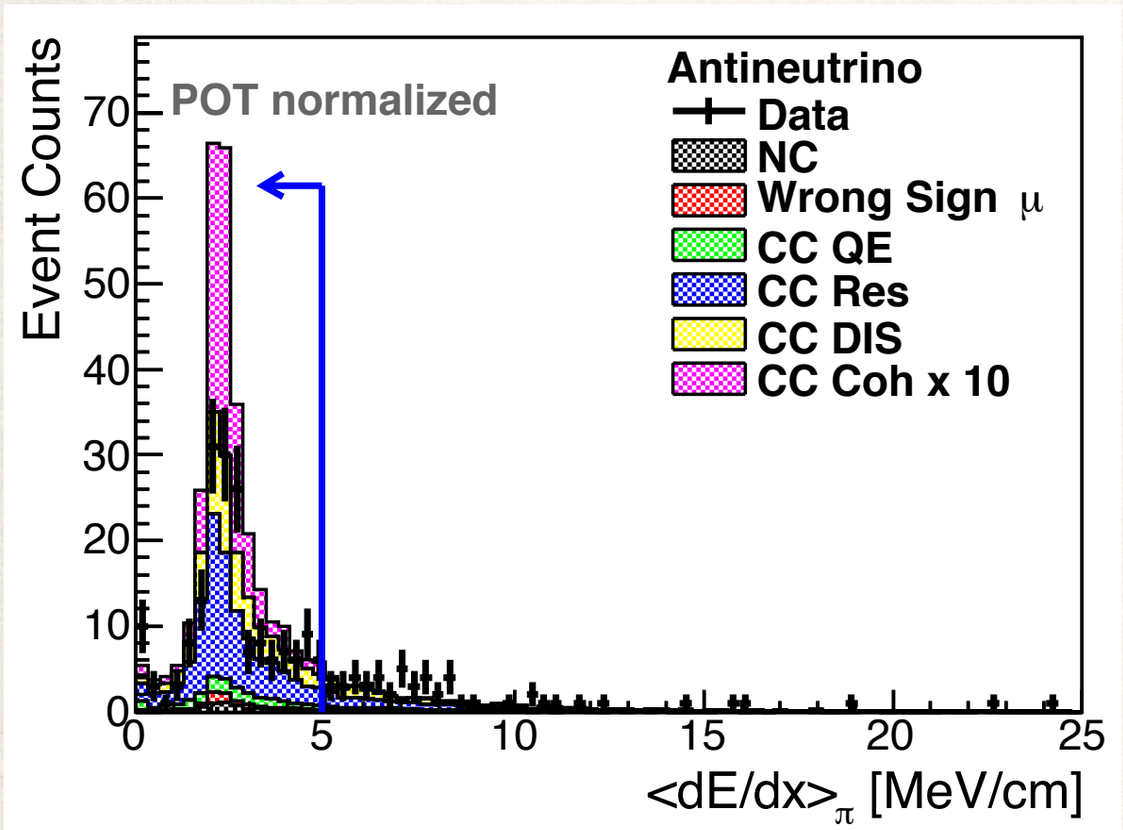
- Recall the event topology (forward going μ and π):
  - $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$
  - $\bar{\nu}_\mu + A \rightarrow \mu^+ + \pi^- + A$
- Two tracks.
- One track is matched to a MINOS track ($\mu^{+/-}$).
- dE/dx of the other track is consistent with MIP ($\pi^{+/-}$).
- No activity around the vertex.

MINOS Track Matching

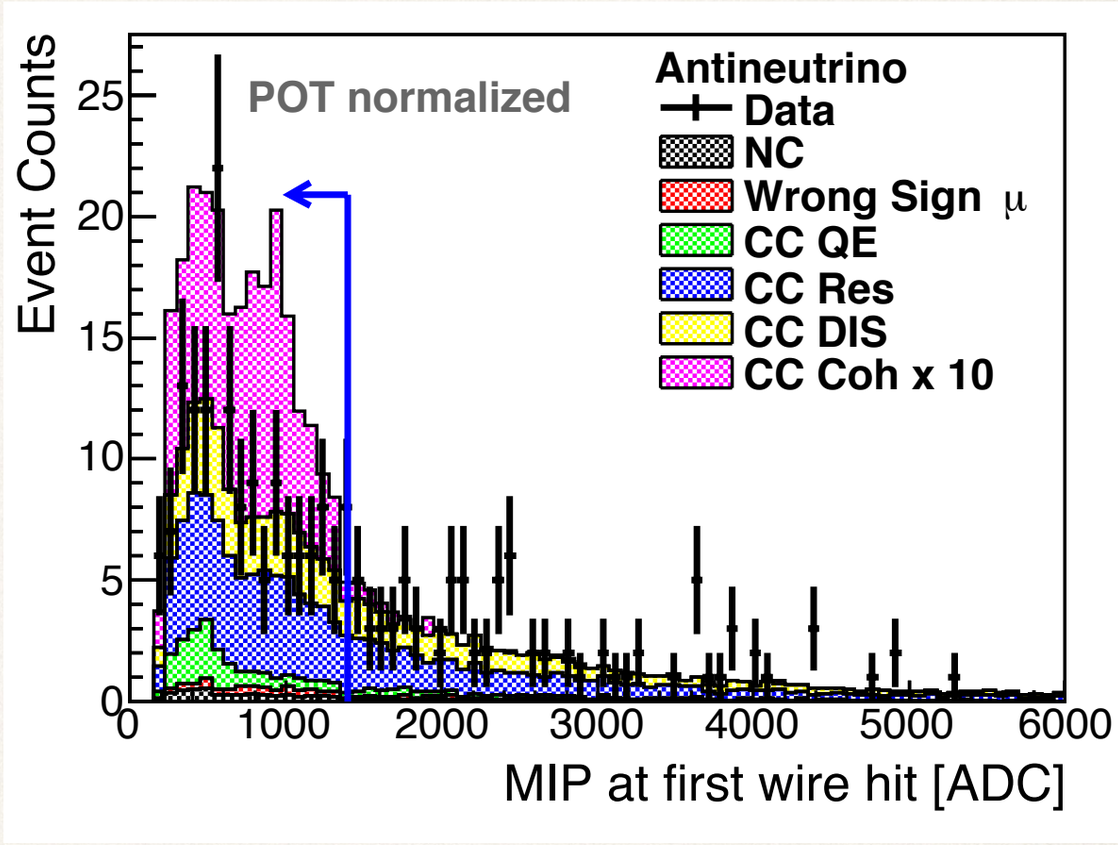


- The presence of the MINOS ND allows for energy reconstruction and charge identification of escaping muons.
- Majority of matched tracks are muons - selection of CC events.
- Because of the small size of ArgoNeuT detector and its proximity to the MINOS detector, we have good acceptance for muons up to 40 degrees.

Remove Protons

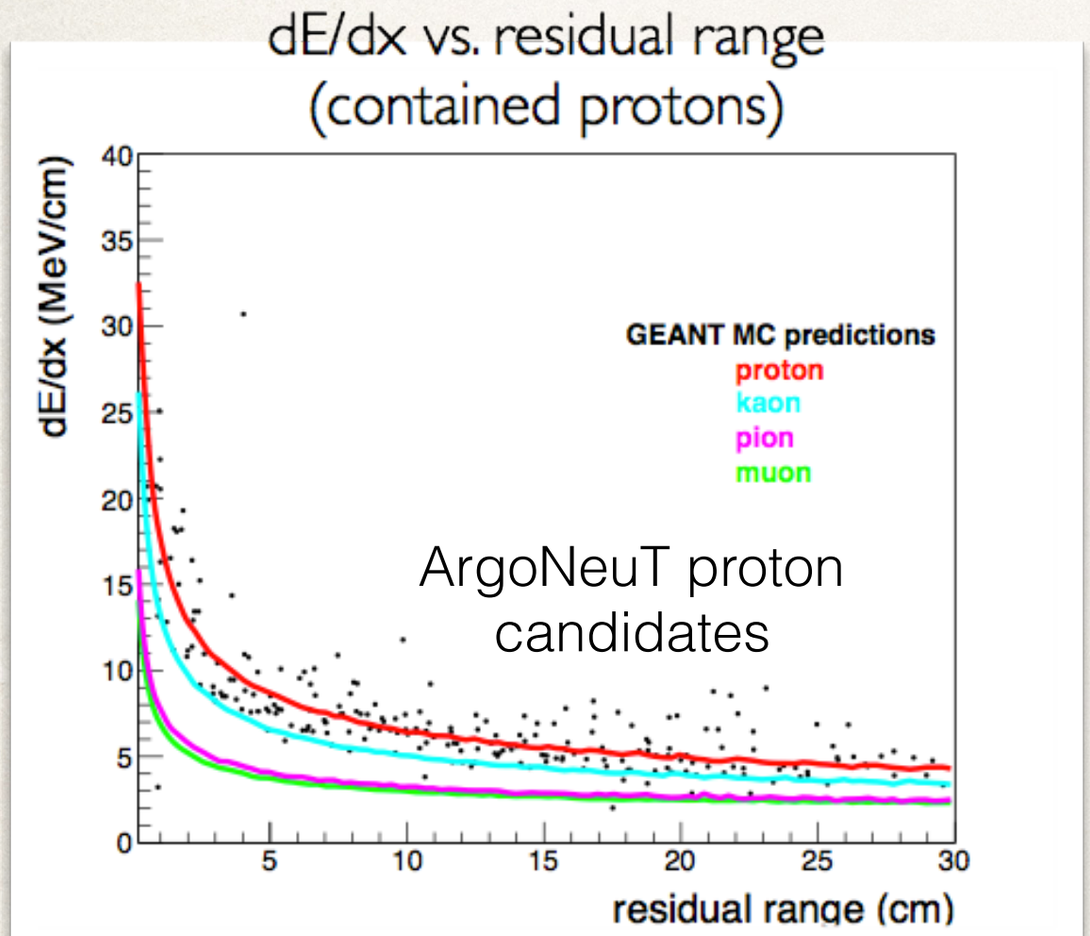


Require pion candidate mean dE/dx <5 MeV/cm
Removing highly ionizing particles



Remove events with high pulse height on the first wire: proton overlapping with muon or pion.

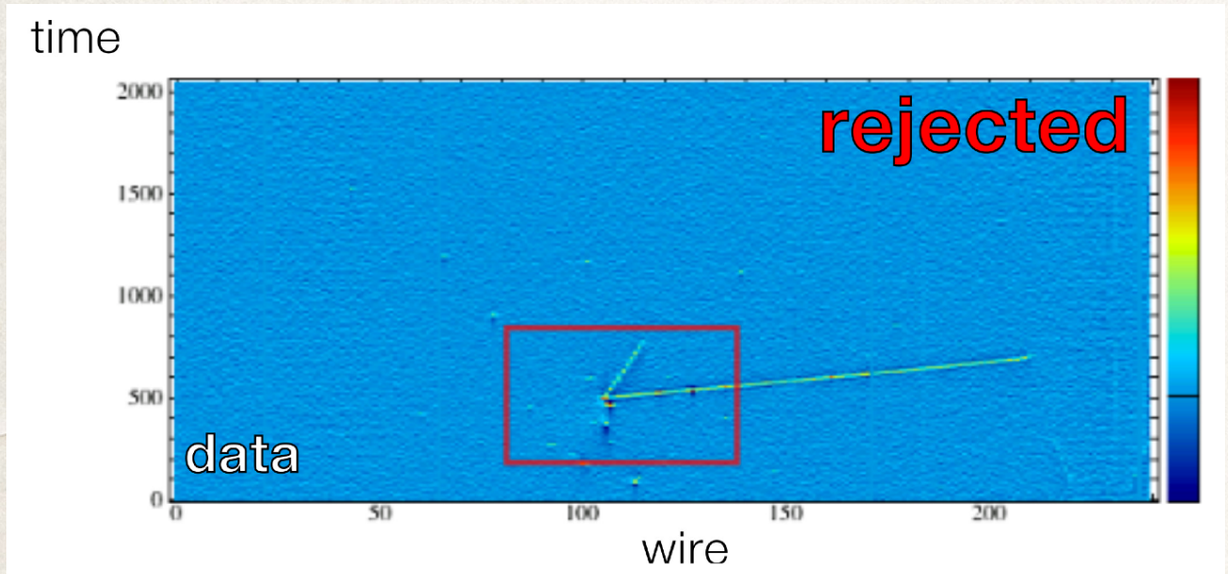
Calorimetry and PID for Stopped Particles

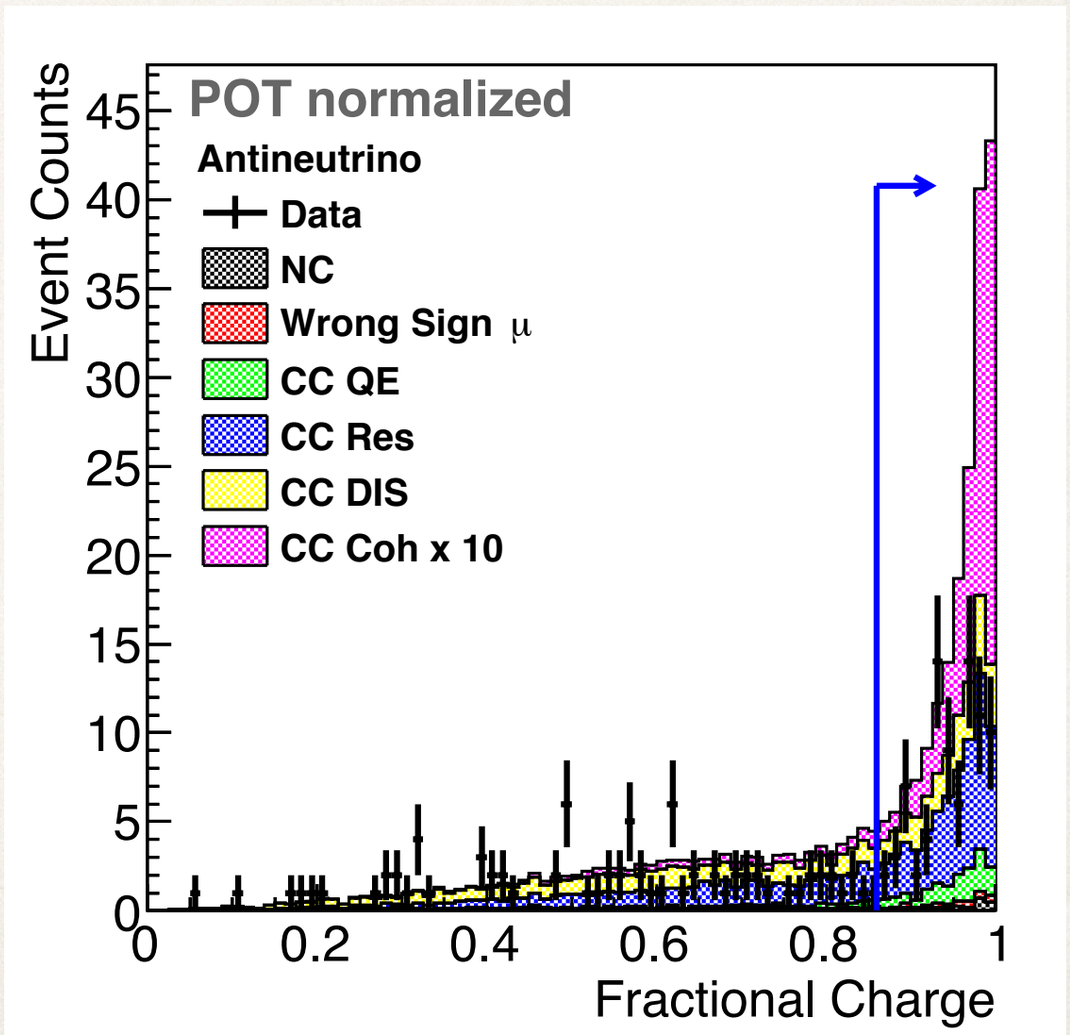


- dQ/dx -> dE/dx
  - Electronics calibration factor
  - Electron lifetime correction
  - Recombination correction (Birks model or Modified Box model)
- Calorimetry based particle ID
  - dE/dx vs residual range for contained tracks
- Remove proton tracks for this analysis.

Vertex Activity

- Define a box surrounding the vertex, require charge inside the box must be associated with the two tracks.

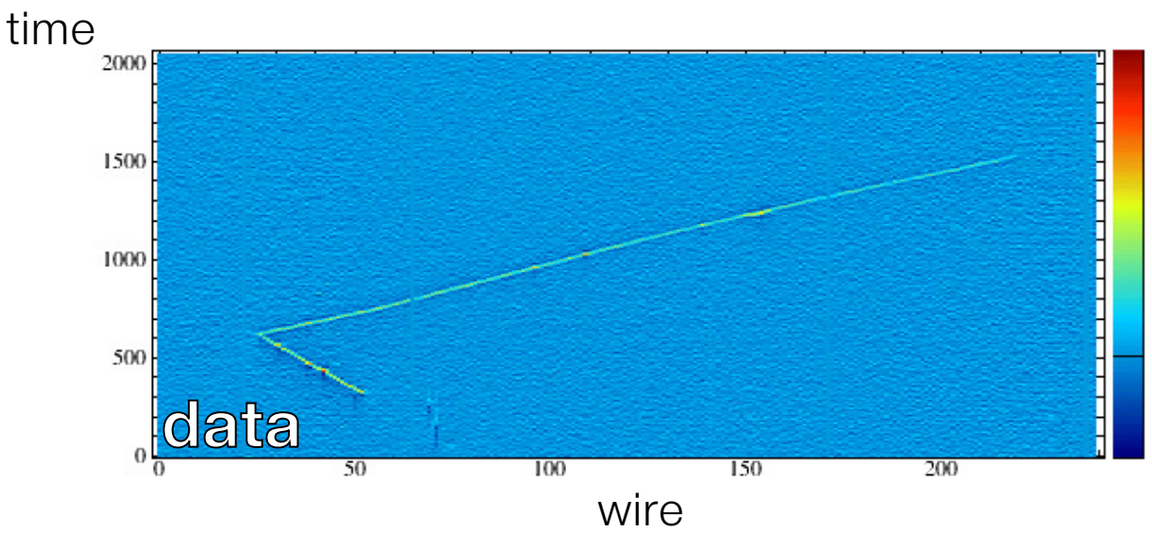


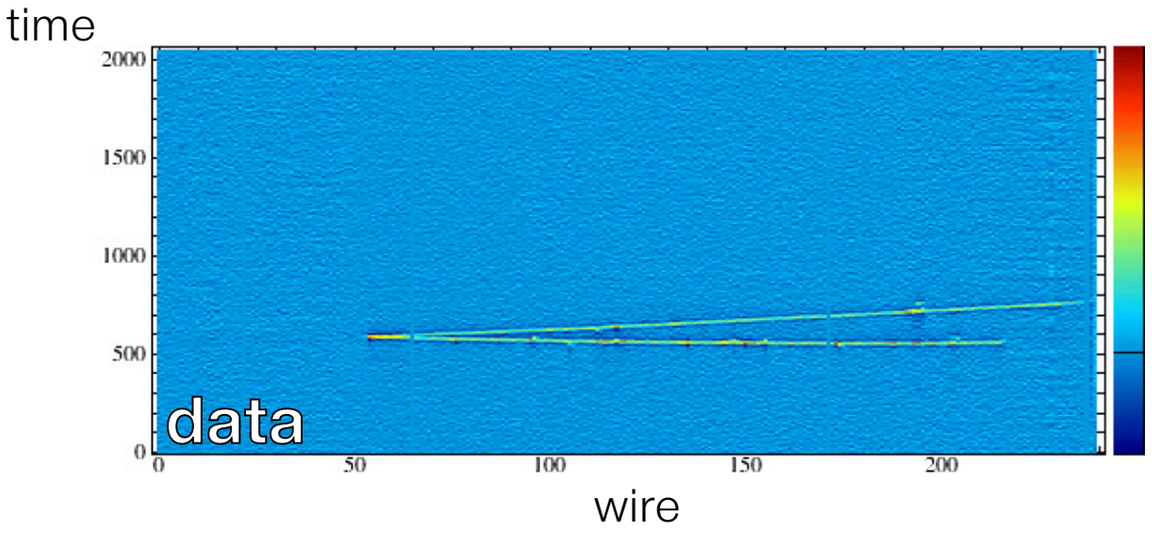


Remove stubs not reconstructed as tracks, deexitation gammas, etc.

Clean 2-track sample

- The Event Selection leaves us with a collection of neutrino/antineutrino events with clean 2 track topology.
- Signal efficiency ~ 20%.
- 30 antineutrino and 24 neutrino events in data.
- The next step is to classify these events into Signal (CCCohPion) or Background (mainly CCRES and CCDIS)



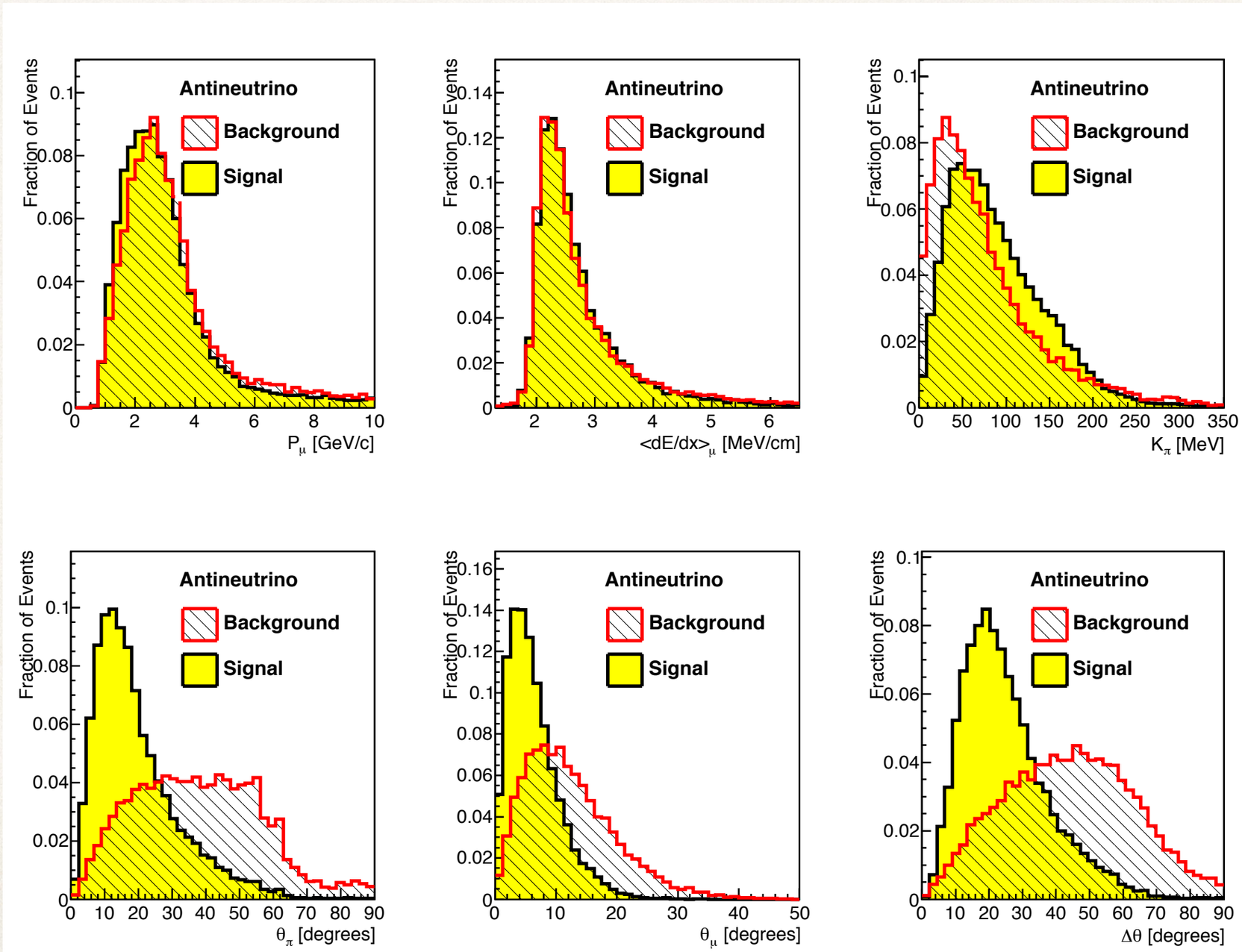


Multivariant Analysis

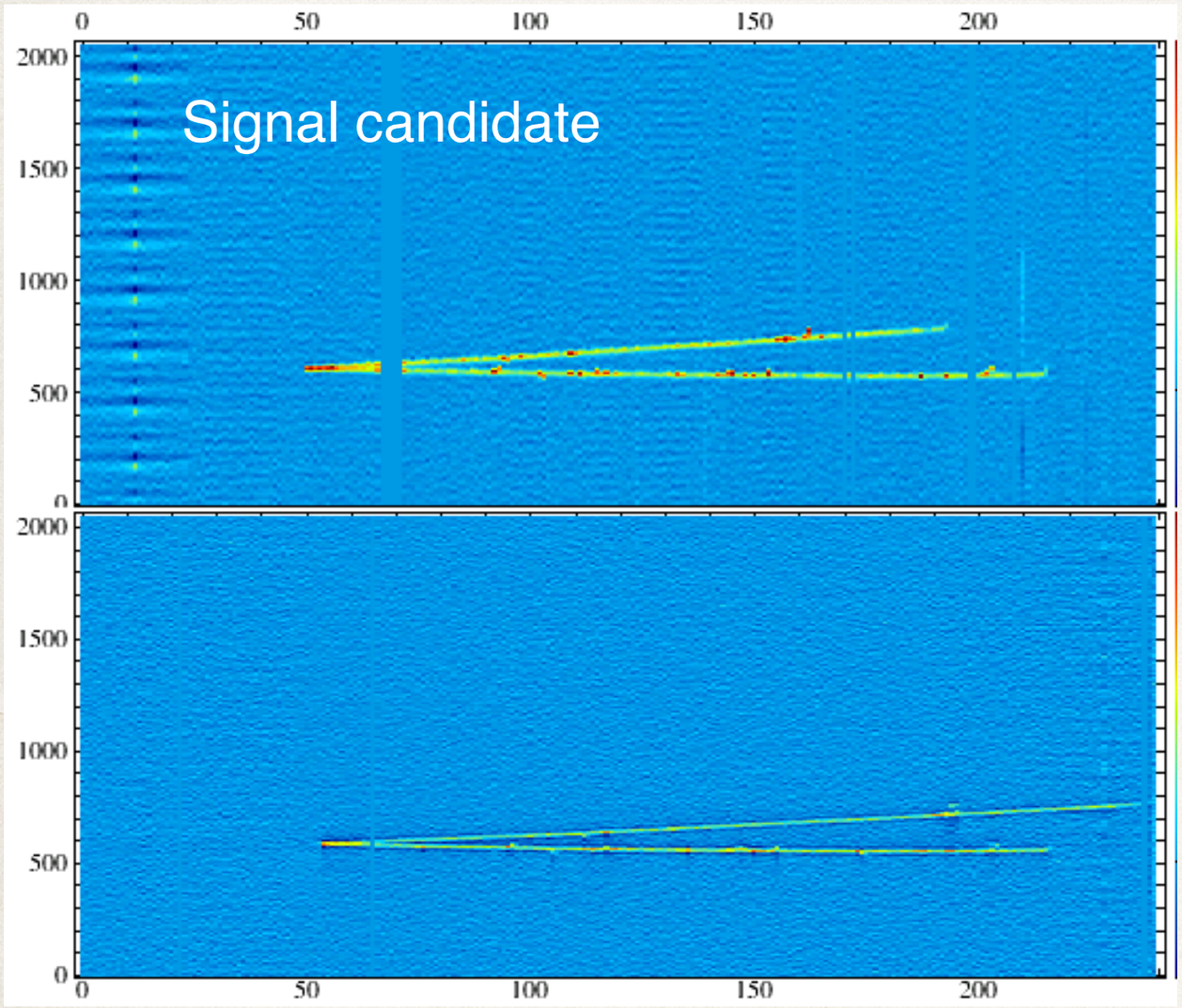
- Ideally we would cut on $|t| = |(q-p_{\pi})^2|$
- Most of the pions are not contained in ArgoNeuT, it's impossible to fully reconstruct event kinematics.
- We built a Boosted Decision Trees with all the available information:
  - Muon momentum measured by MINOS
  - Pion kinetic energy measured by ArgoNeuT
  - Muon <dE/dx>
  - Muon angle
  - Pion angle
  - Angle between muon and pion

Signal/Background Discrimination

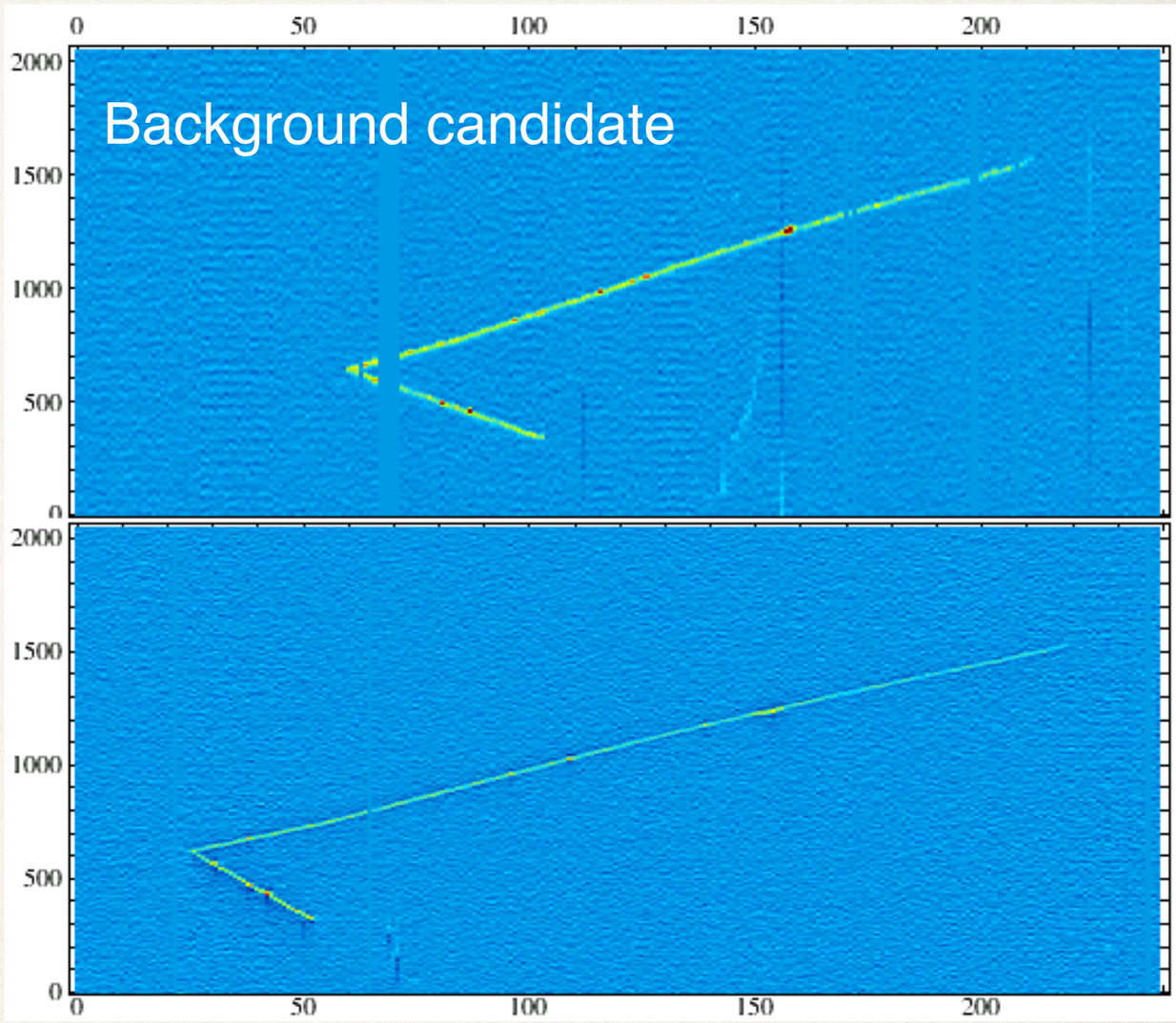
GENIE 2.8.2/LArSoft simulation&reconstruction



Signal and Background Candidates

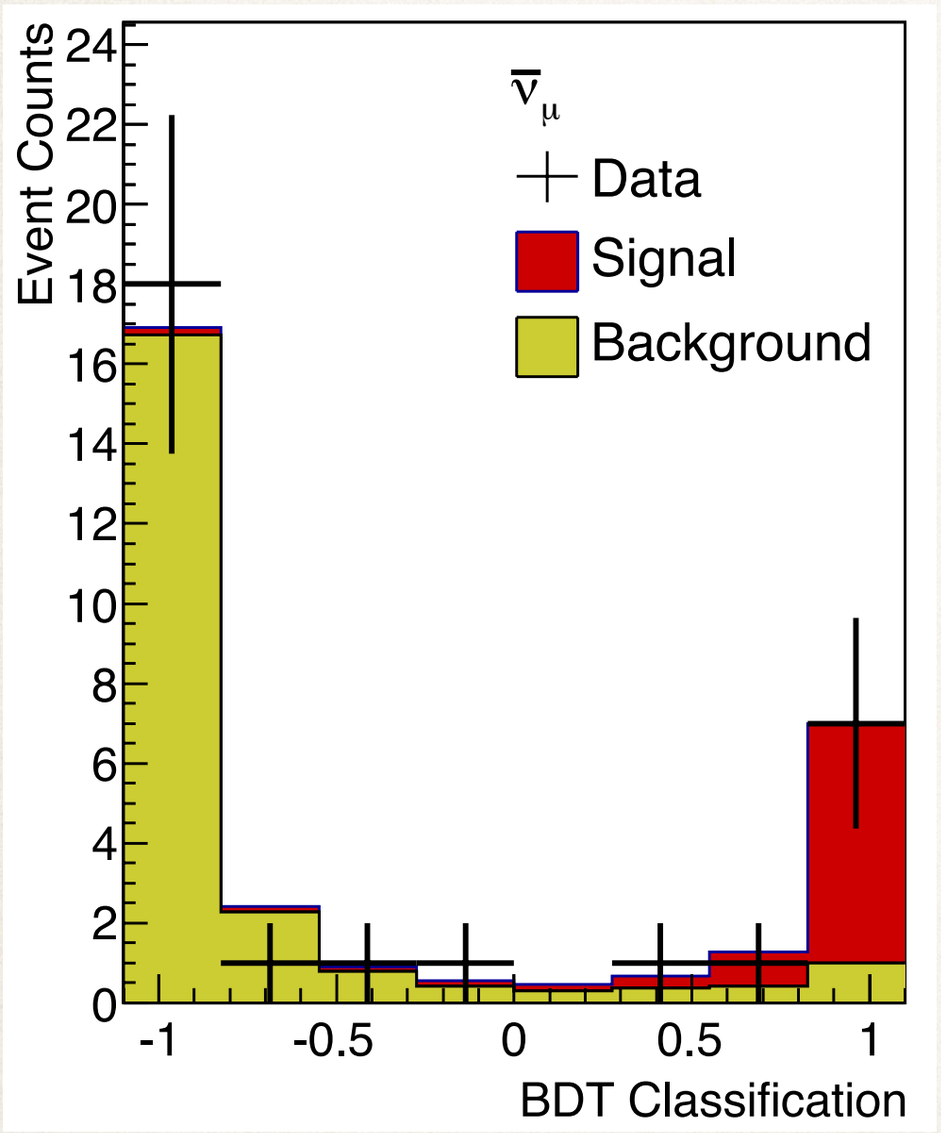


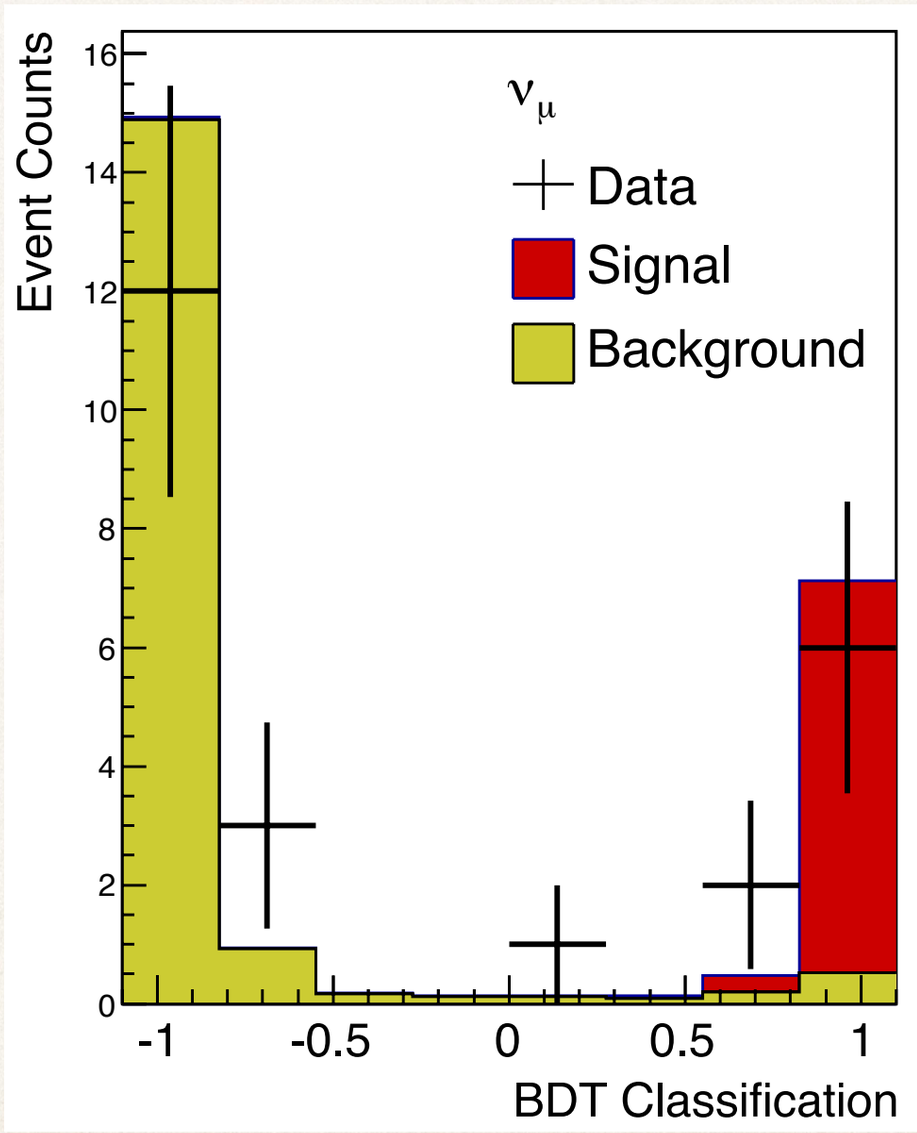
Run 800/Event 29745
BDT = 0.95



Run 767/Event 7307
BDT = -1.00

Data Fit with Signal and Background Shapes





Signal = $7.9^{+3.7}_{-3.0}$

Signal = $7.0^{+3.3}_{-2.6}$

Almost background free!

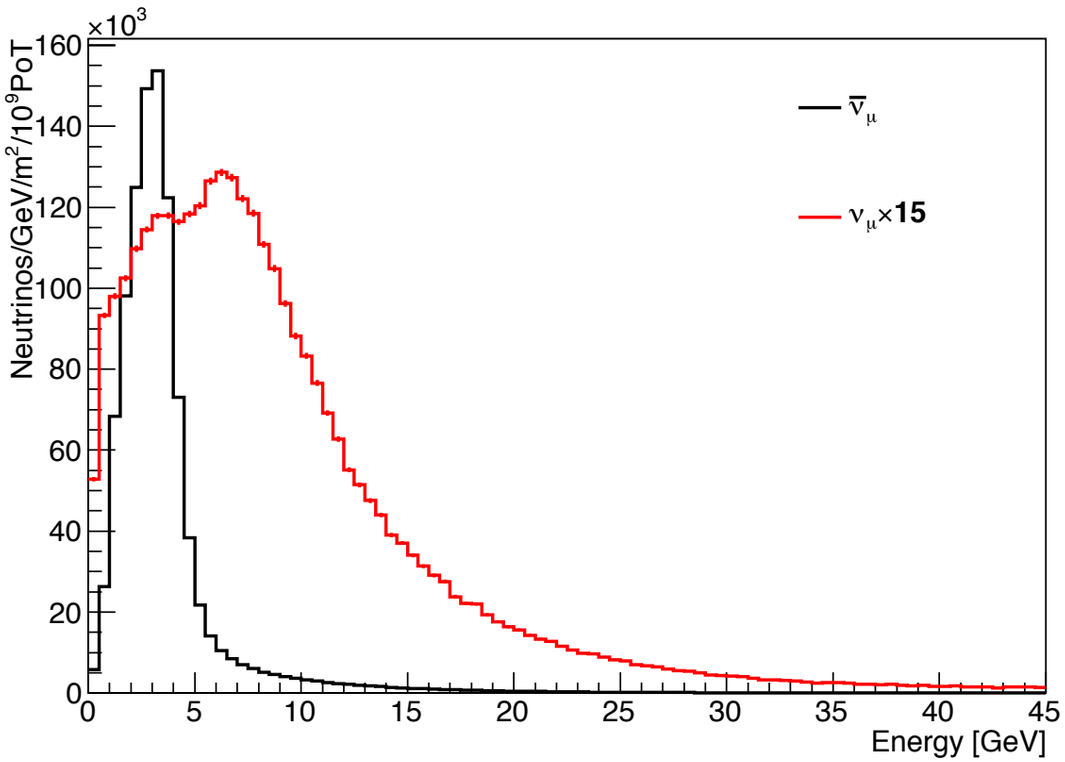
Efficiency/unfolding

- Since we only measure integrated cross sections in this analysis, we define efficiency as the ratio of true selected signal events over the generated signal events in the fiducial volume.
  - (18.4±1.8)% for neutrino and (21.8±0.8)% for anti- neutrino events.
- In the other analyses where we measure differential cross sections, we do unfolding to convert measured information to true information.
  - Unfolding factor defined as ratio of reconstructed quantity of selected signal events over true quantity of all true signal events.

Systematic uncertainties

- Flux normalization (11%) - dominant systematic error.
- Reconstruction
  - MINOS momentum res. ArgoNeuT angle res., energy scale
  - The reconstructed parameters are varied by 1σ
- Background Scale
  - We vary each background channel by ±20%
- Nuclear Effects
  - Background added by FSI. The model uncertainty is large, we vary this faction of events by ±20%
- Signal efficiency and model dependence
  - Use NuWro MC to evaluate signal-related systematics

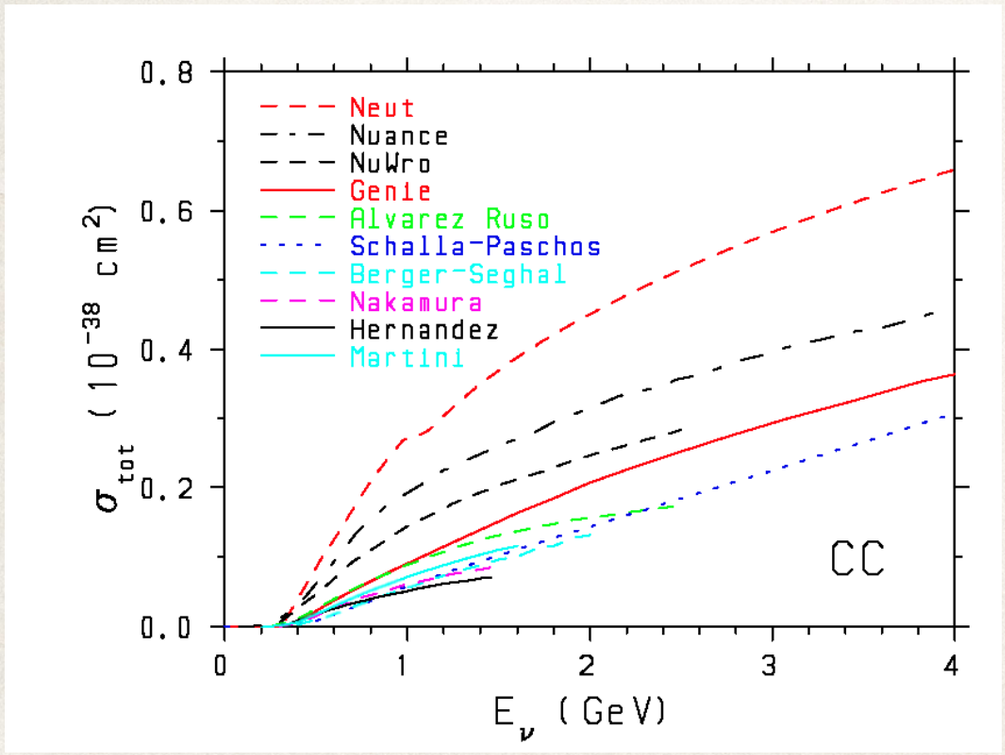
Neutrino Flux

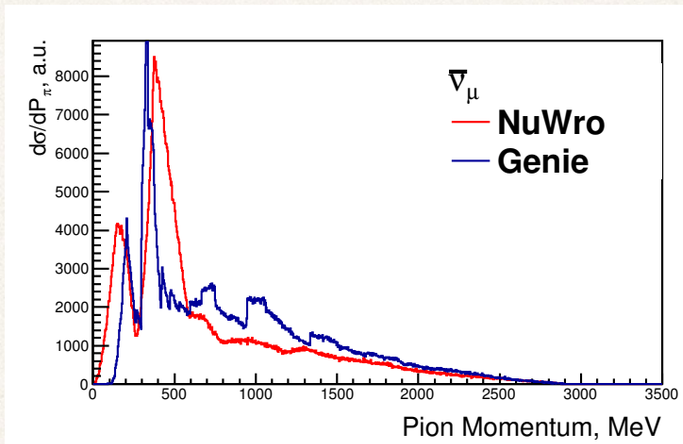


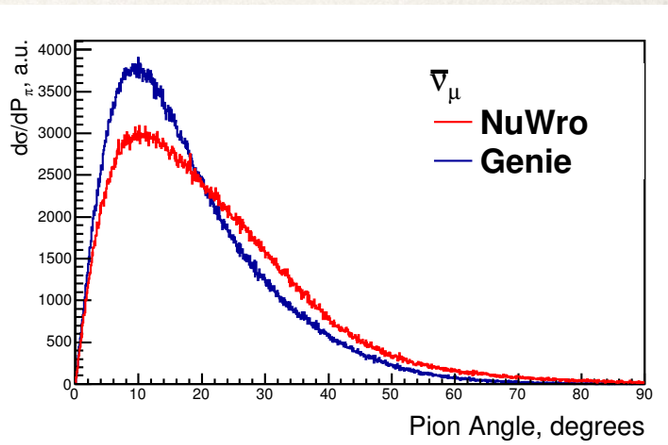
- We use hadron tuning provided by MINOS (SKZP).
  - Tuning was based on MINOS ND data and NA49 data.
- We assign a 11% flat error on flux.
  - Dominant systematic error on final cross section results.
- In our later analyses, we use the flux provided by MINERvA - arXiv: 1607.00704

Signal Modeling

- Different models give very different predictions.
- Use NuWro MC to evaluate systematics in signal efficiency and signal template shape.

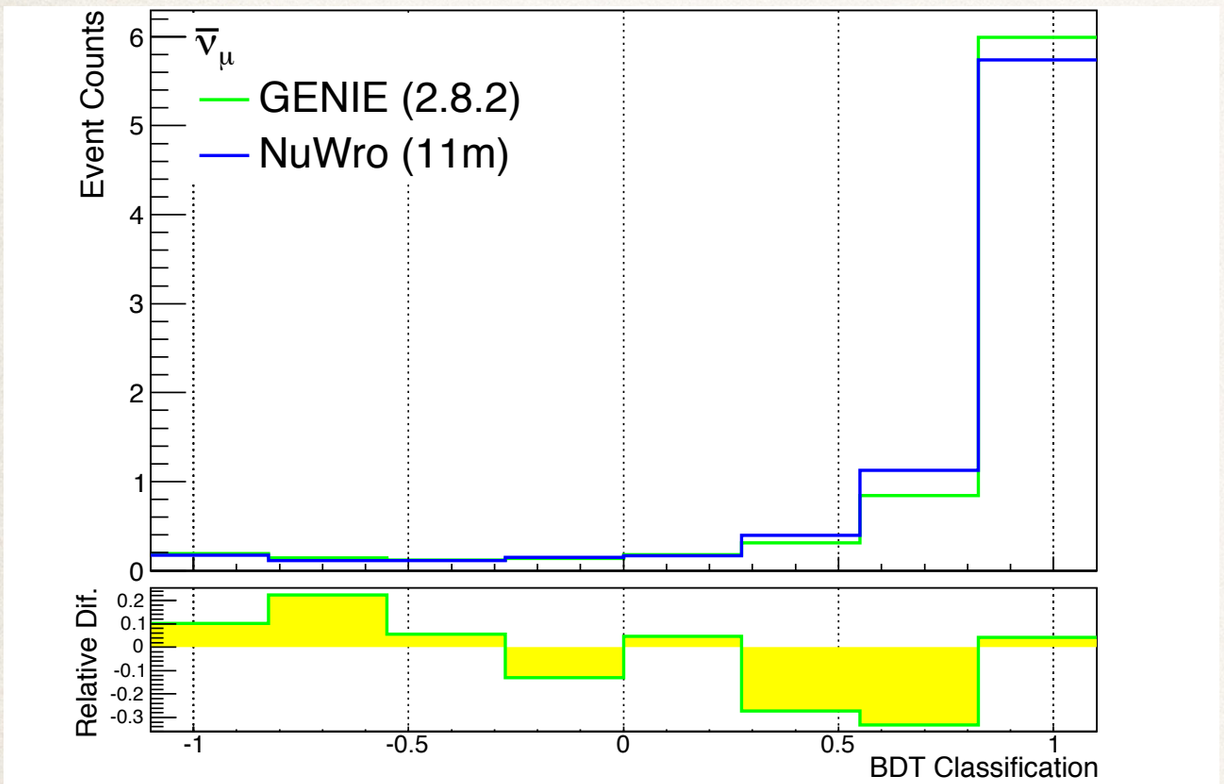


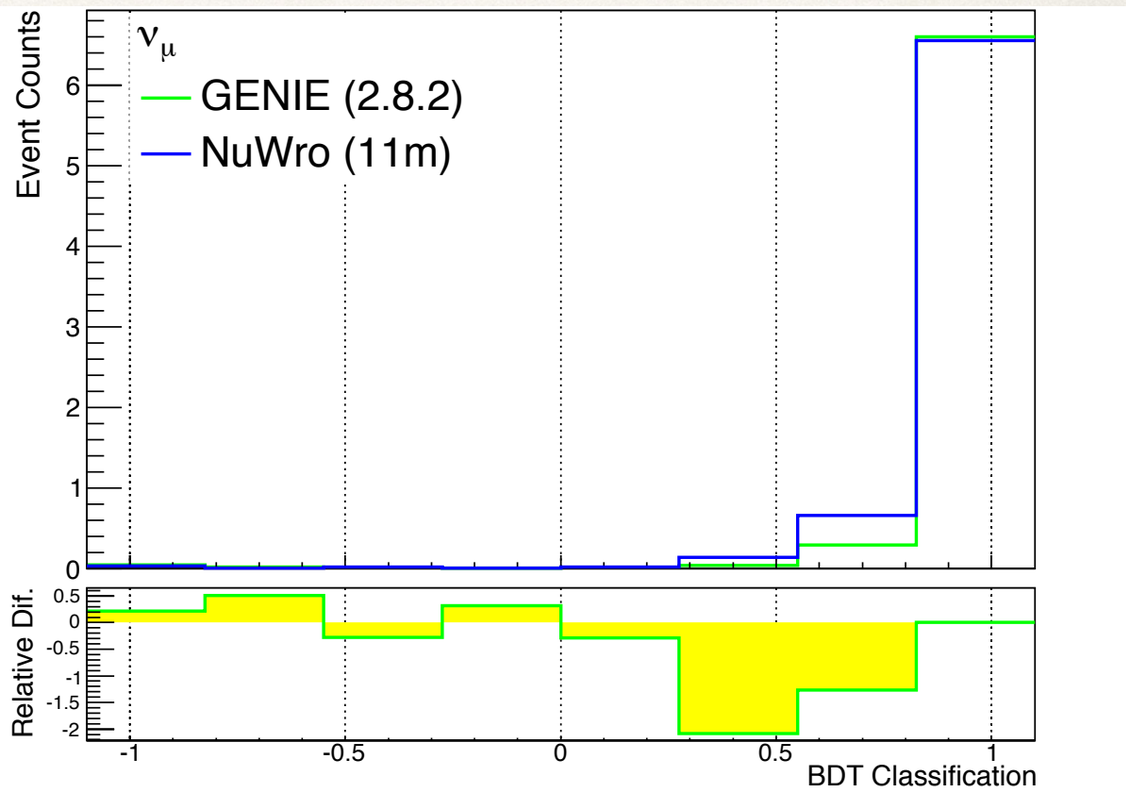




S. Boyd et. al., AIP Conf. Proc. 1189, 60-73 (2009).

Signal Template Shapes

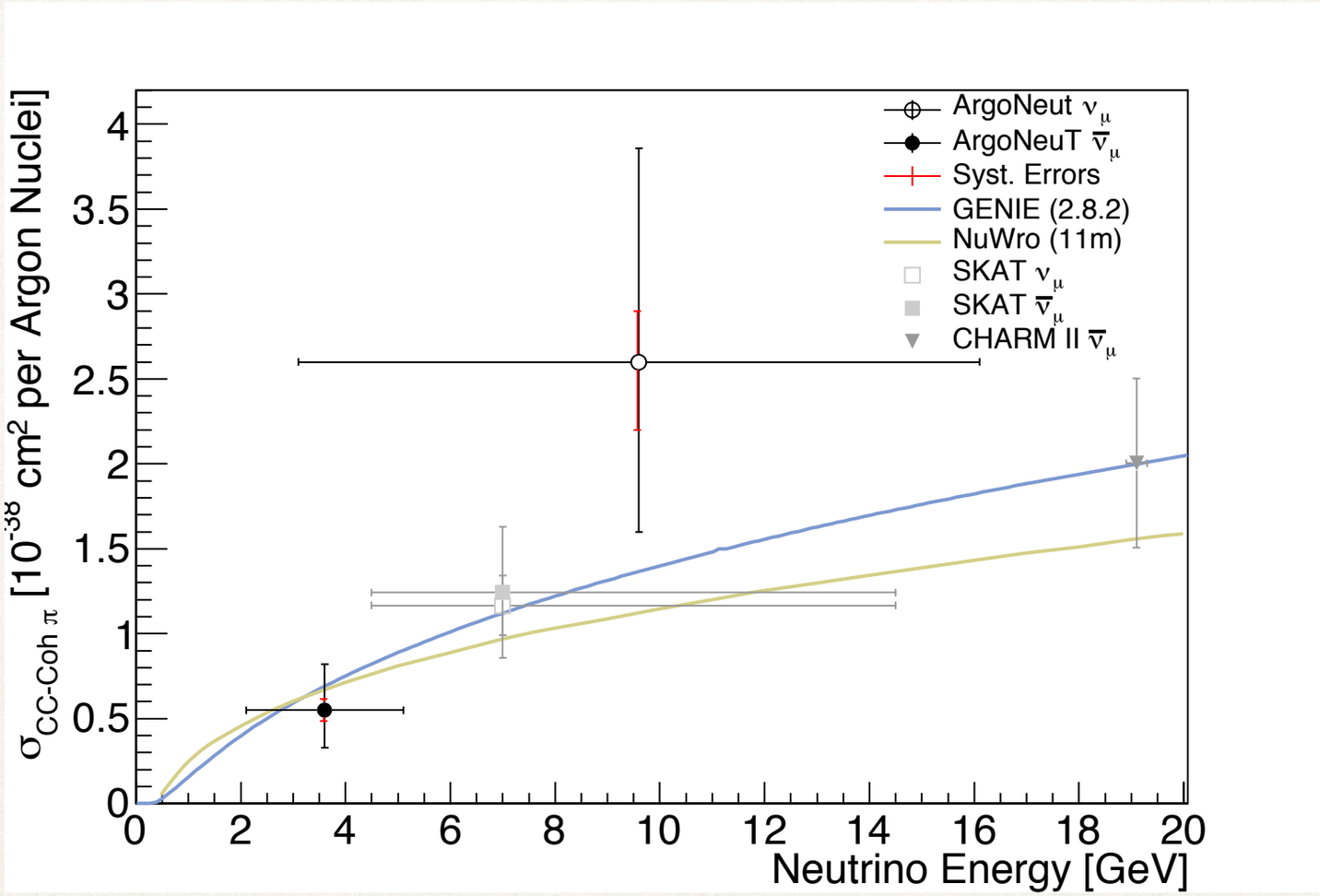




Similar Shapes Constructed with GENIE and NuWro.

		Cross section uncertainty [%]	
	Systematic Effect	$\bar{\nu}_\mu$	ν_μ
Background	CC QE	$^{+0.3}_{-0.4}$	$^{+1.2}_{-0.6}$
	CC RES	$^{+0.2}_{-0.5}$	$^{+0.4}_{-0.3}$
	CC DIS	± 0.1	± 0.3
	NC	± 0.1	± 0.1
	Wrong-sign μ	± 0.1	± 0.2
Nuclear Effects		± 0.3	± 0.7
Recon.	MINOS momentum res.	± 4.1	± 4.3
	ArgoNeuT angle res.	± 1.6	± 2.7
POT		± 1.0	± 1.0
Flux normalization		$^{+10.0}_{-12.0}$	$^{+10.0}_{-12.0}$
Number of Ar targets		± 2.2	± 2.2
Efficiency		± 0.8	± 1.8
Model dependancy		± 0.8	± 5.7
Total systematics		$^{+11.3}_{-13.1}$	$^{+12.9}_{-14.5}$

Cross Section Results



$$\langle \sigma_{\bar{\nu}_\mu} \rangle = \left(5.5^{+2.6}_{-2.1}(stat)^{+0.6}_{-0.7}(syst)\right) \times 10^{-39} cm^2$$

$$\langle \sigma_{\nu_\mu} \rangle = \left(2.6^{+1.2}_{-1.0}(stat)^{+0.3}_{-0.4}(syst)\right) \times 10^{-38} cm^2$$

Summary

- We present the measurement of CC Coherent π production on Argon, with an emphasis on the detailed steps that lead to the final results.
- The LAr technique shows great potential for this measurement:
  - Great resolution at the vertex
  - Precise calorimetry