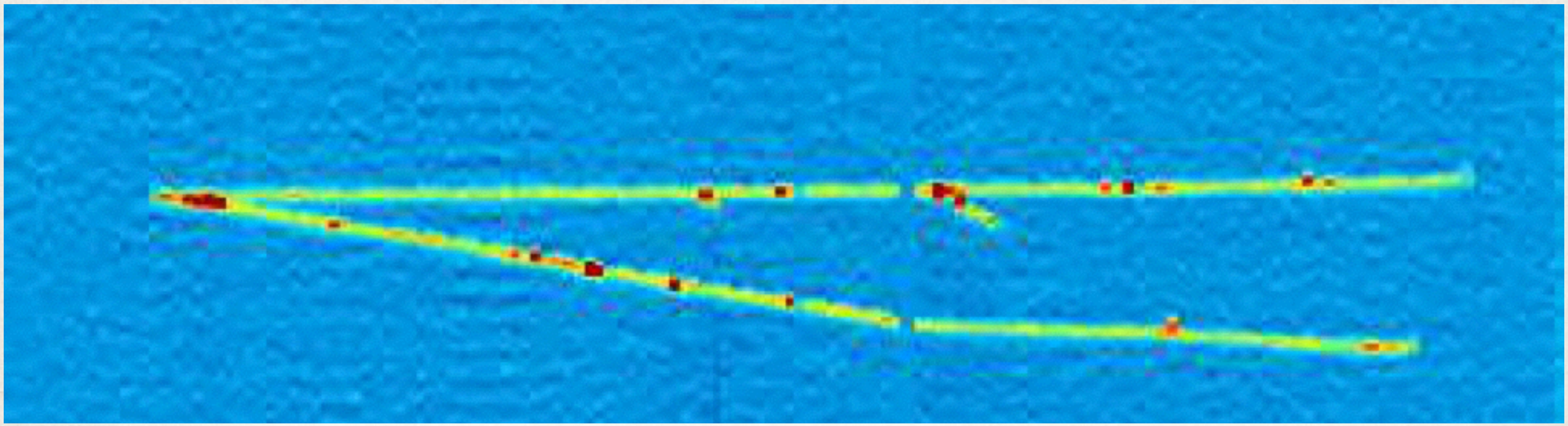


Coherent Charged Pion Production in ArgoNeuT

Tingjun Yang

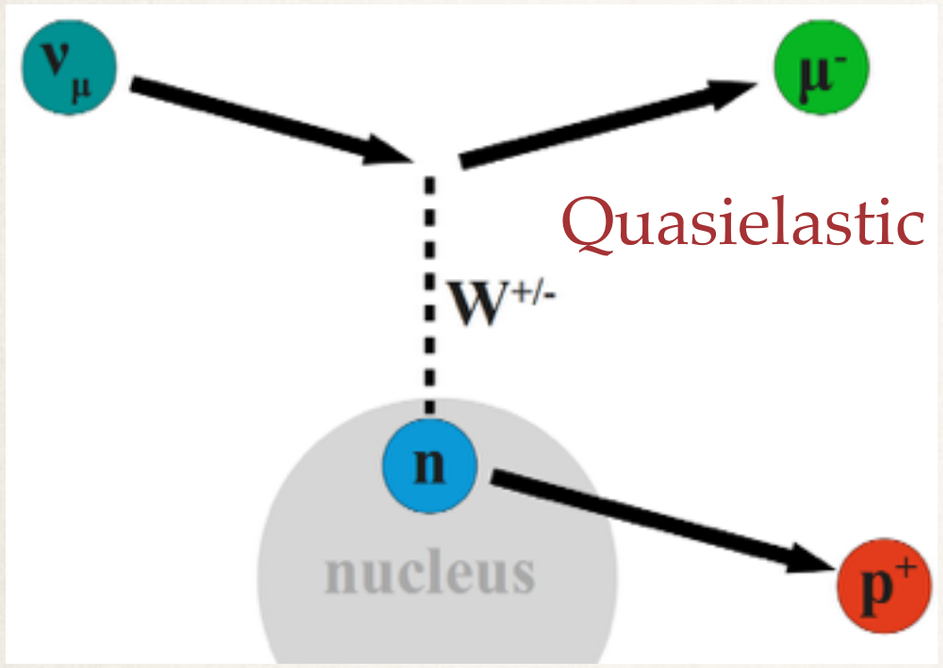
FNAL

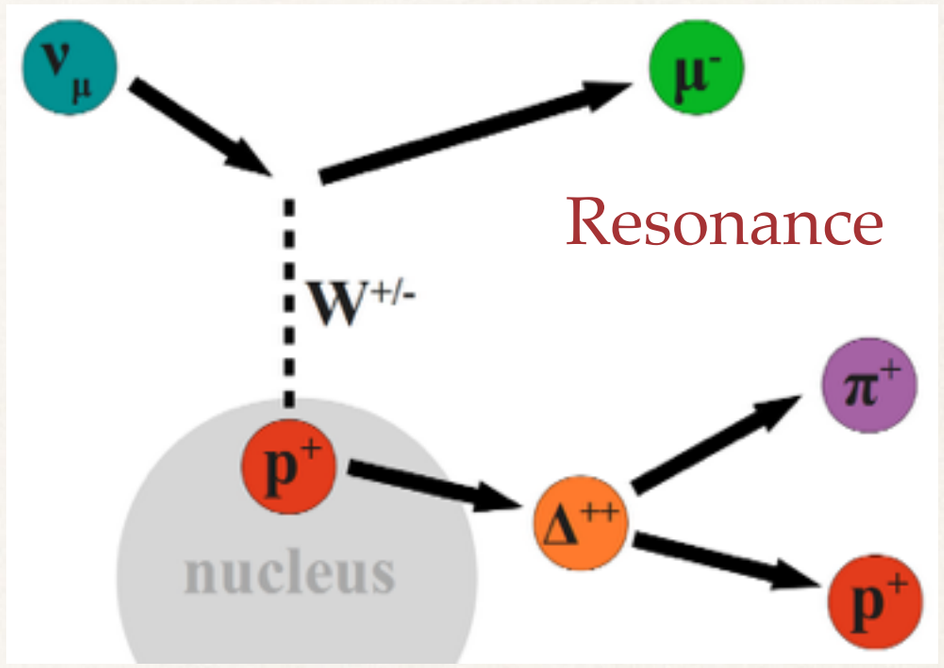
Sep 18, 2014

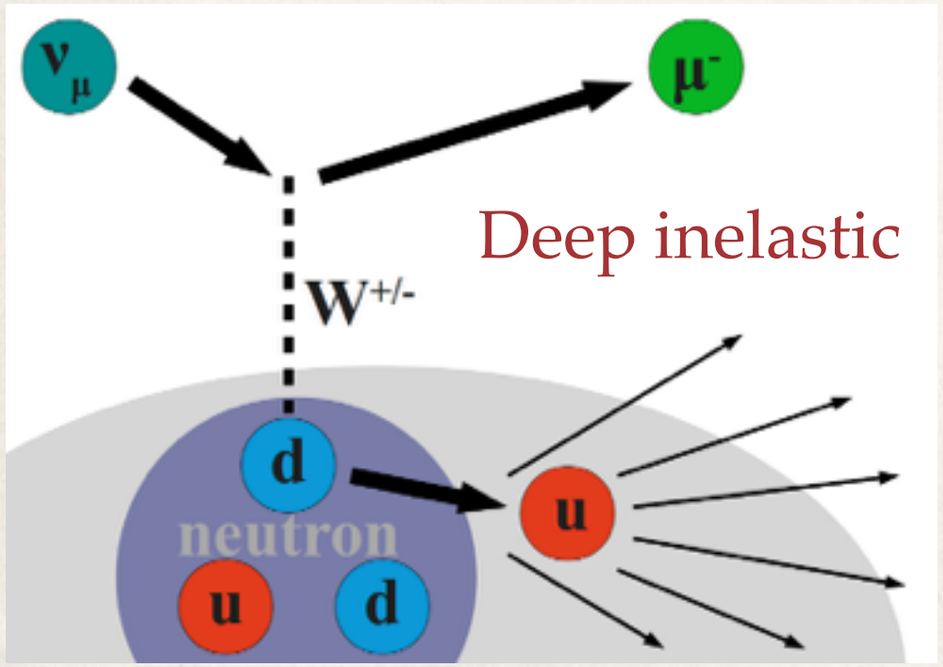
Outline

- Coherent pion production in neutrino interaction.
- Looking for charged current coherent pion production in ArgoNeuT.
- Results and outlook.

Neutrino Scattering





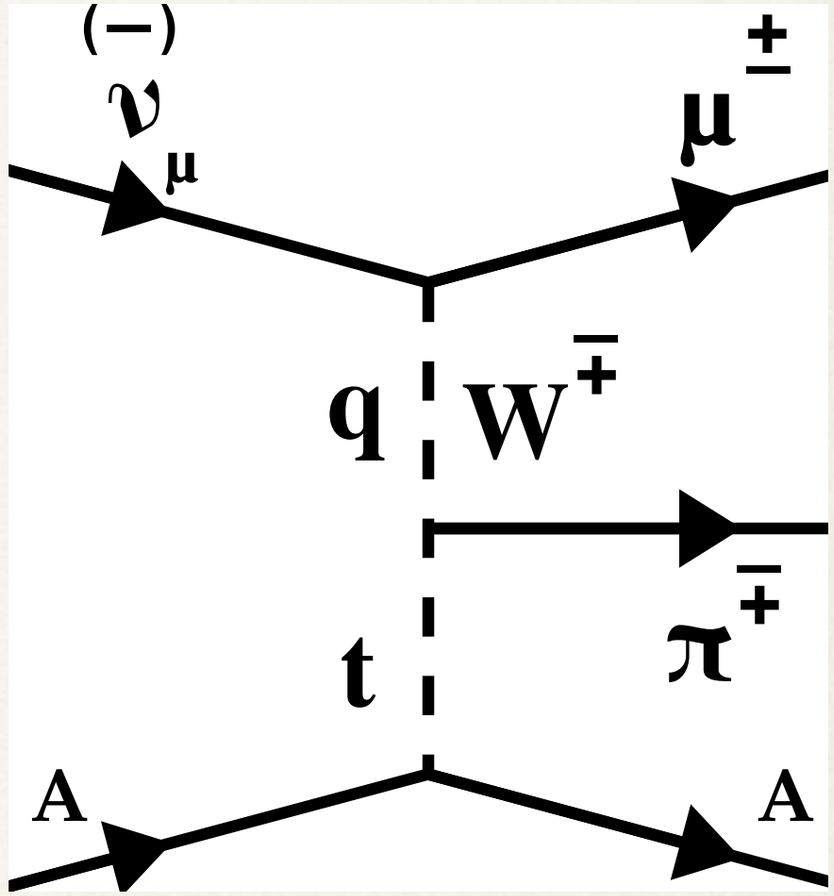


- Neutrinos can interact with matter in a variety of ways depending on the momentum transfer.

http://homepages.warwick.ac.uk/~phrfba/index.php

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)

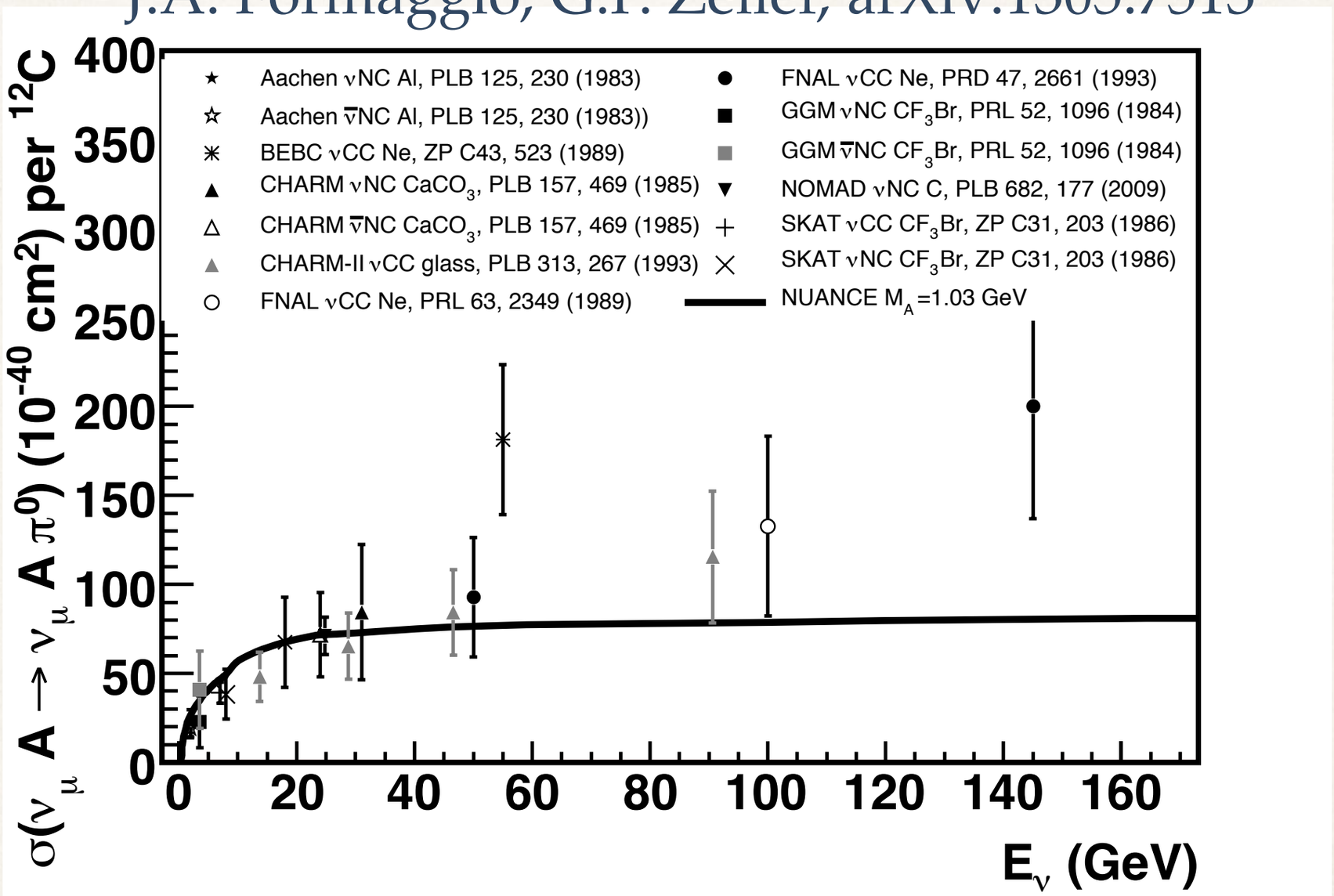
- Partially Conserved Axial Current (PCAC) relates neutrino-induced coherent pion production to pion-nucleus elastic scattering.

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

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

Experimental Results

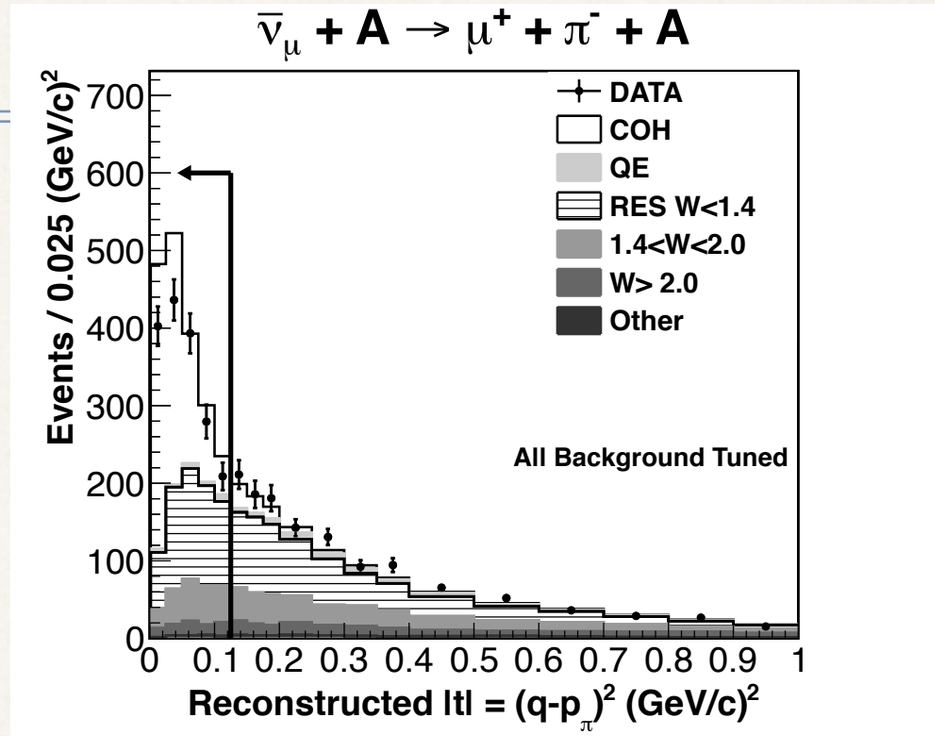
J.A. Formaggio, G.P. Zeller, arXiv:1305.7513



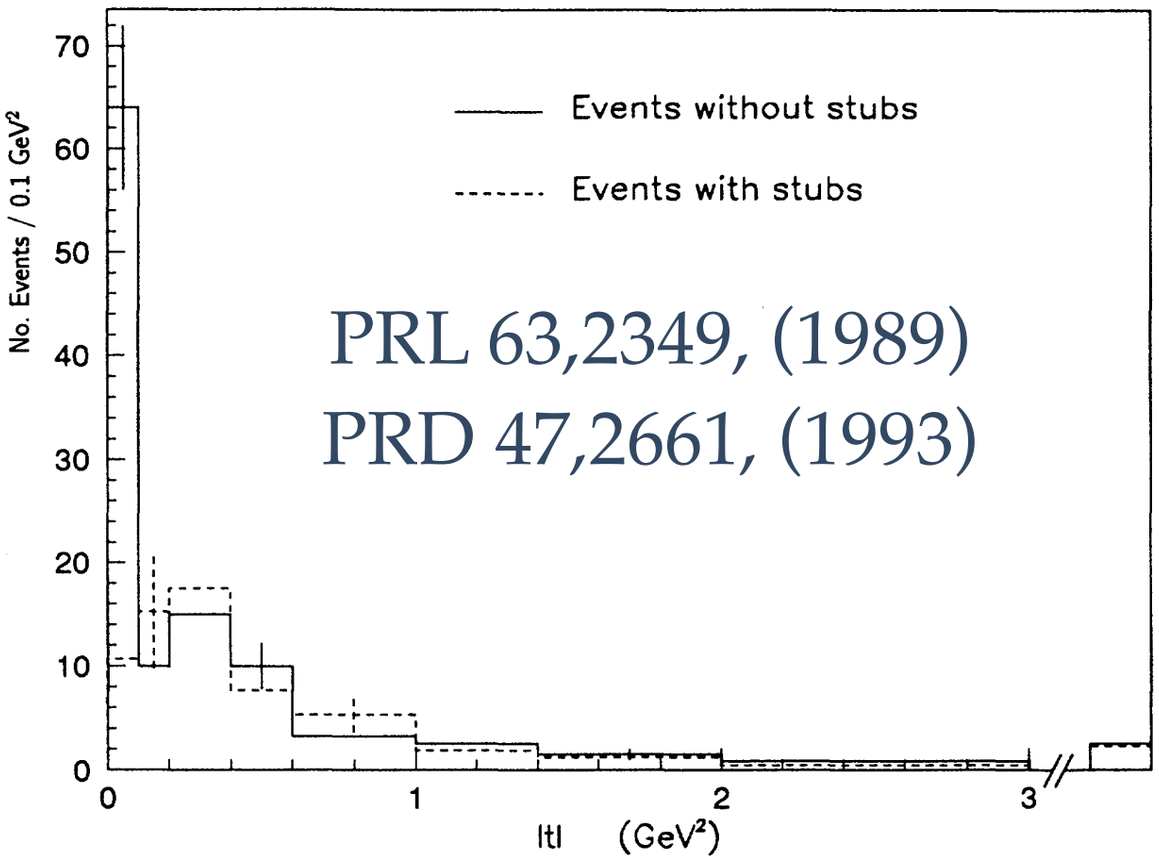
- Well established at high energy (E > 2 GeV).

Results from Fermilab

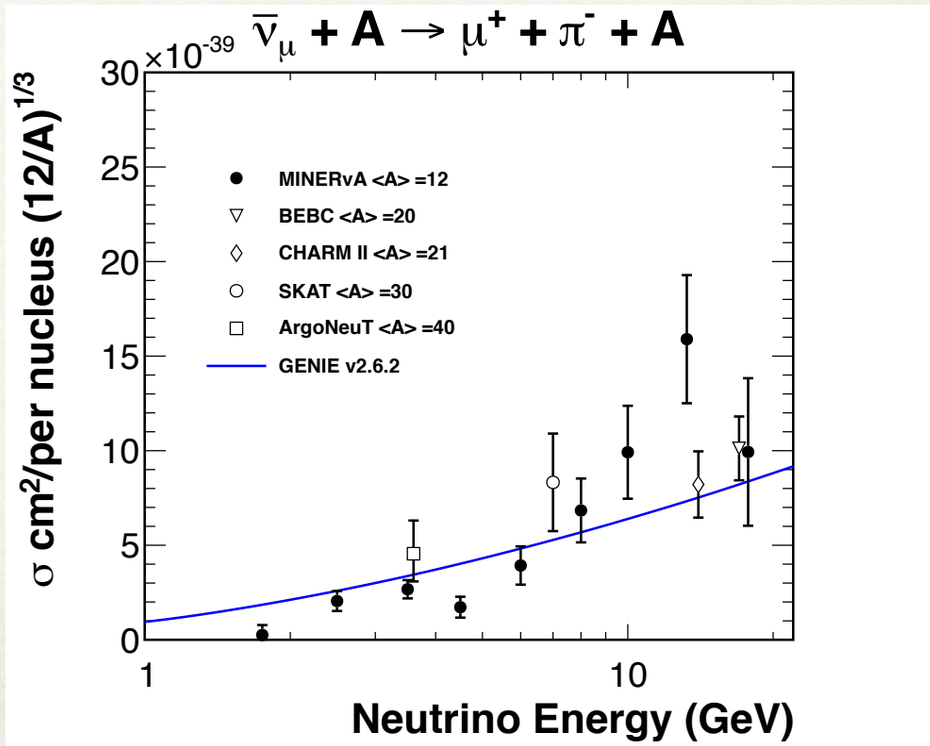
MINERvA: arXiv: 1409.3835



15′ Bubble Chamber Ne (E-632)

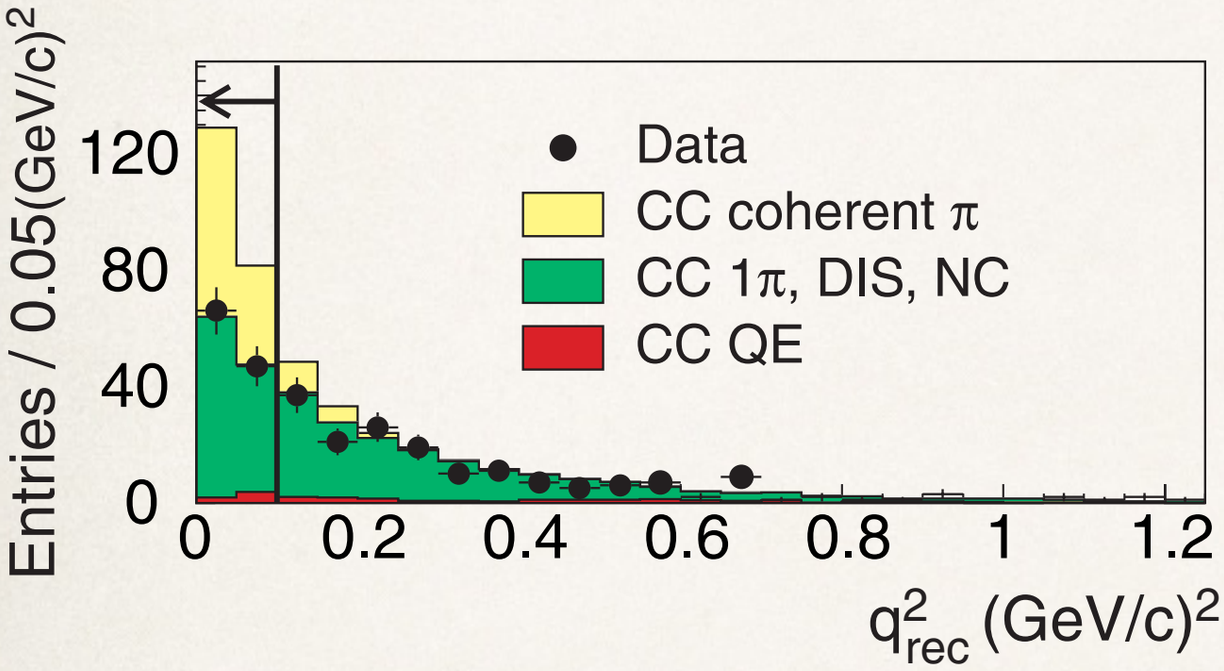


PRL 63,2349, (1989)
PRD 47,2661, (1993)

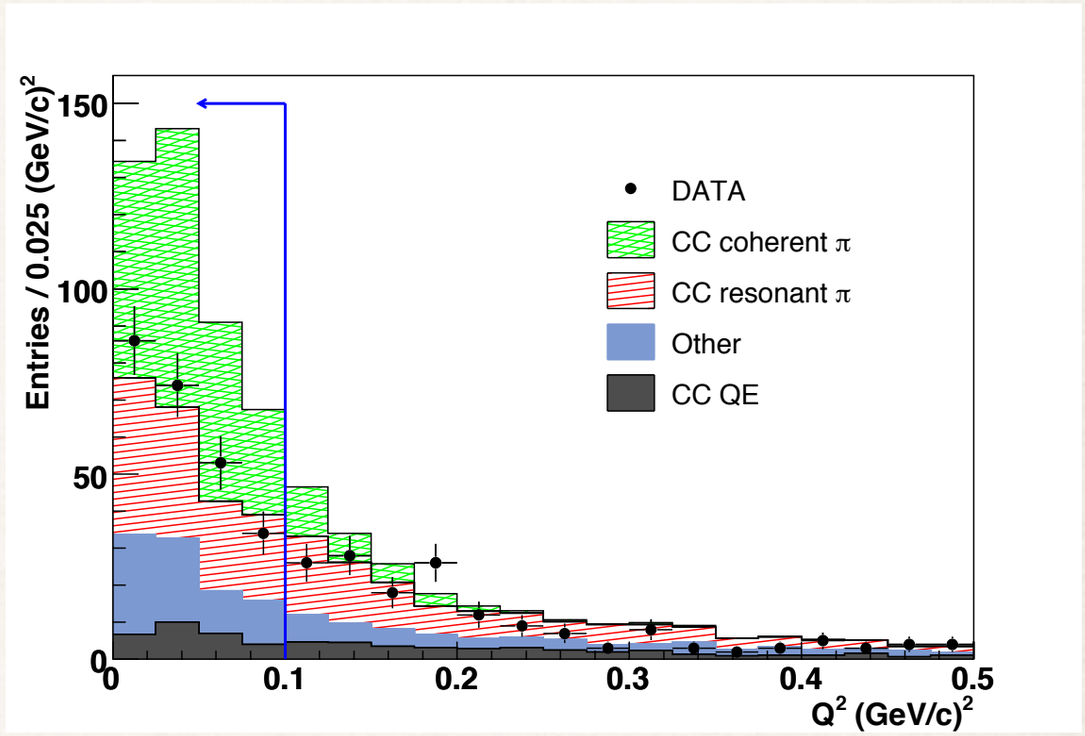


http://vmsstreamer1.fnal.gov/Lectures/WC/presentations/140801Higuera.pdf

Surprises



K2K, PRL 95, 252301 (2005)
C target, <E> = 1.3 GeV



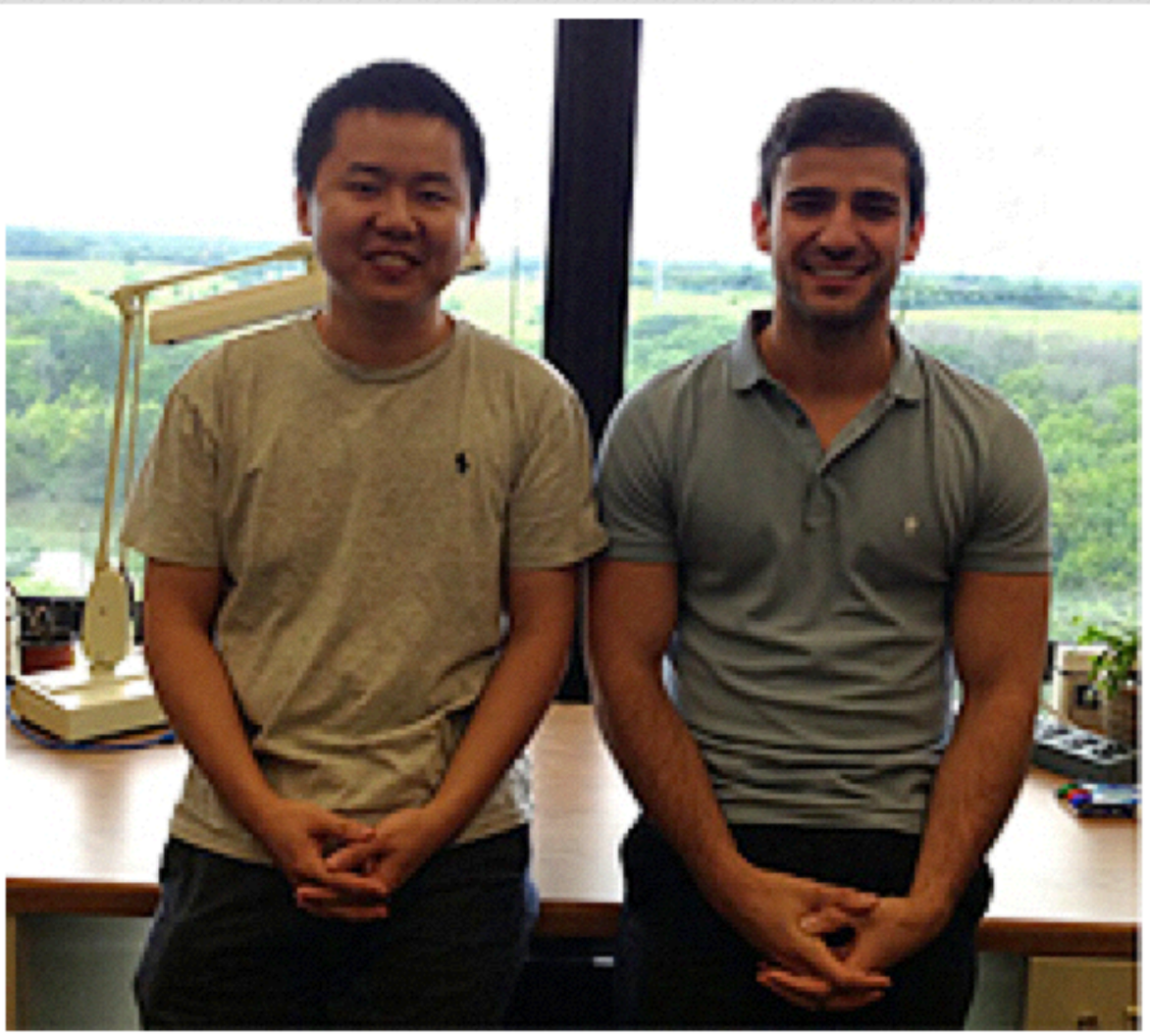
SciBooNE, PRD.78.112004 (2008)
C target, <E> = 1.1 GeV, 2.2 GeV

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

Limitation of PCAC model

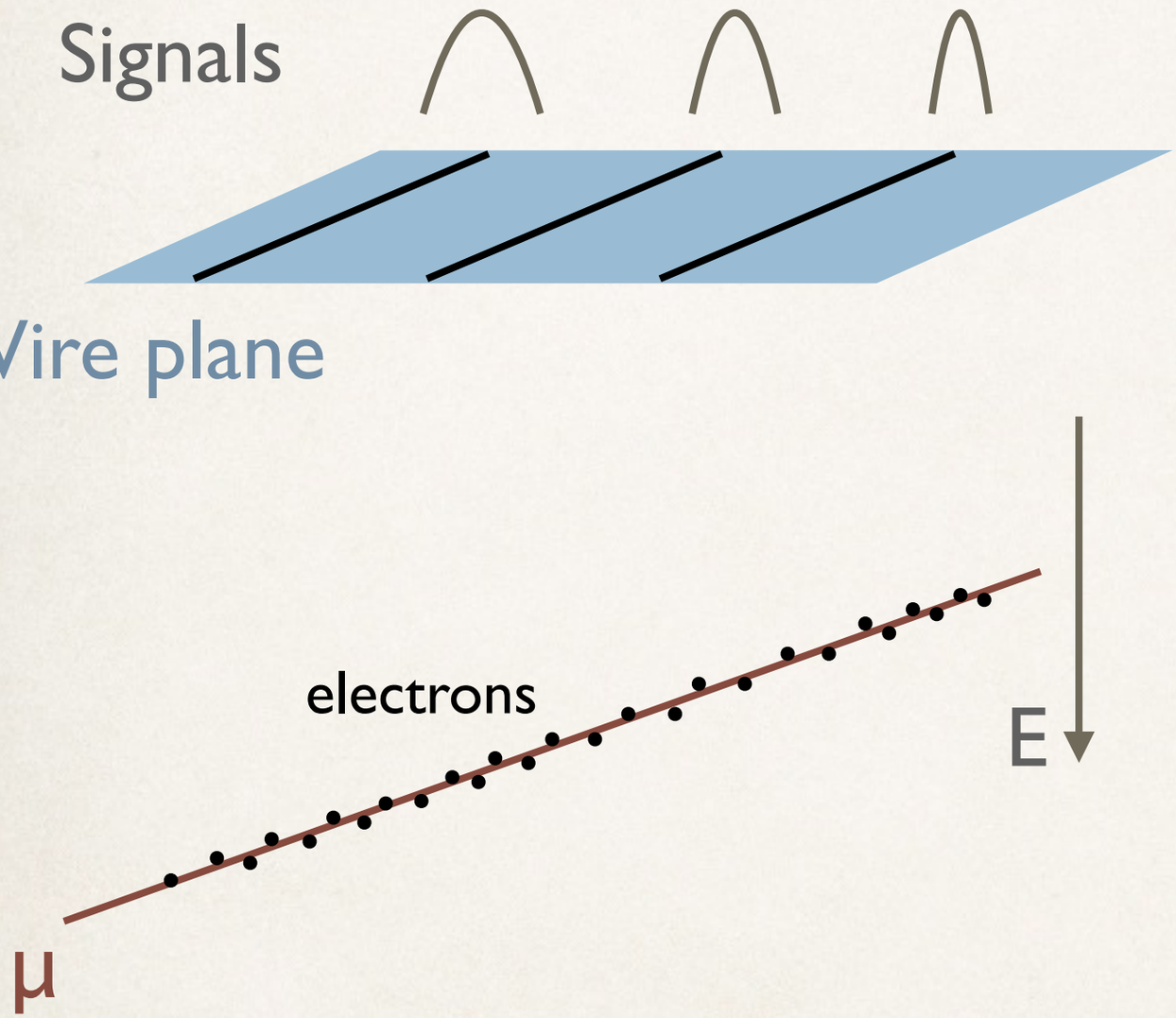
- PCAC model does not work well at low energy (E<2 GeV) and for lighter targets (^{12}C, ^{16}O).
  - Approximation of $q^2 \rightarrow 0$: pion angle too wide.
  - Uncertainty in pi-nucleus cross section treatment.
- Alternative approach: Microscopic Models.
  - Excitation of the Δ resonance, better motivated at low energy (E<1.5 GeV).

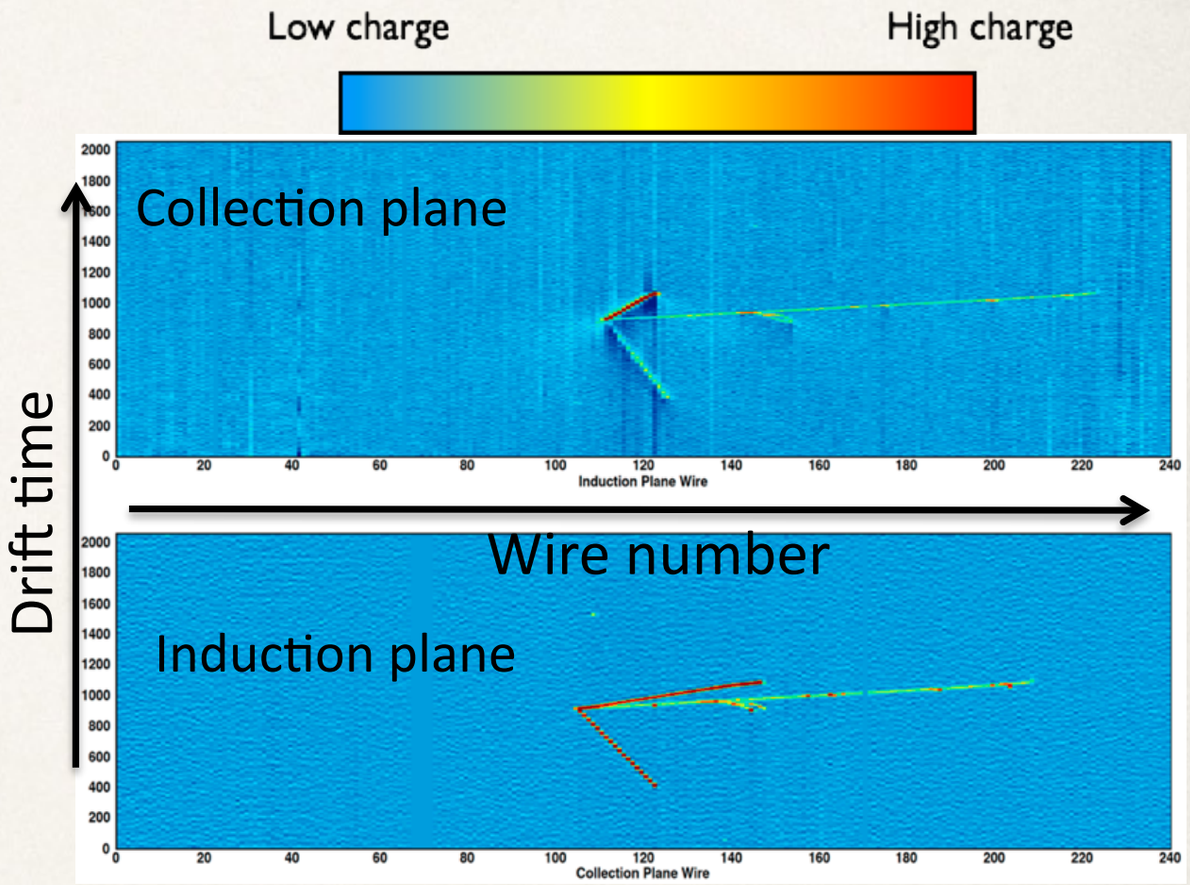
Coherent Pion Production in ArgoNeuT



The primary authors of this result are Tingjun Yang of Fermilab, left, and Edward Santos of Imperial College London.

Liquid Argon TPC

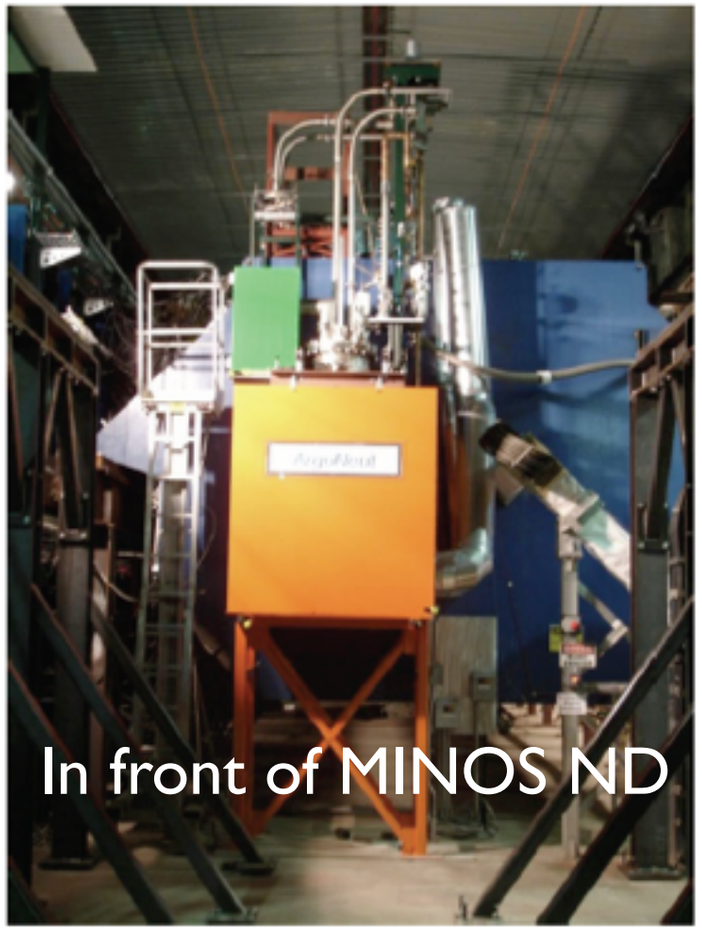




- mm-scale position resolution, three dimensional imaging, and calorimetry

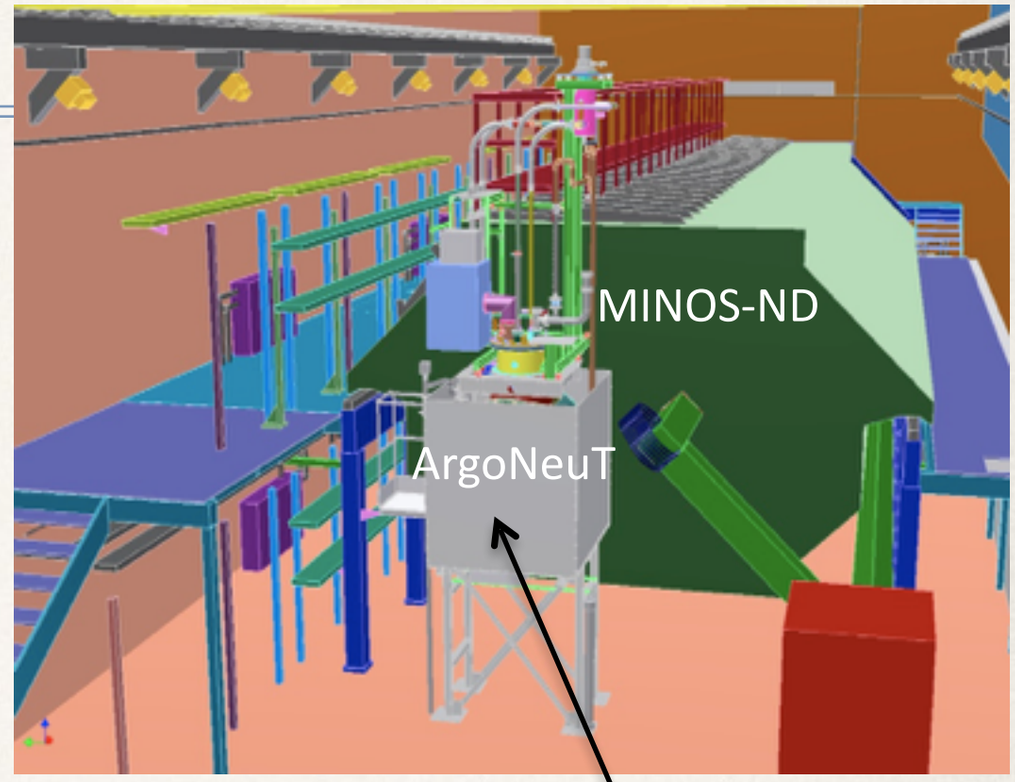
ArgoNeuT

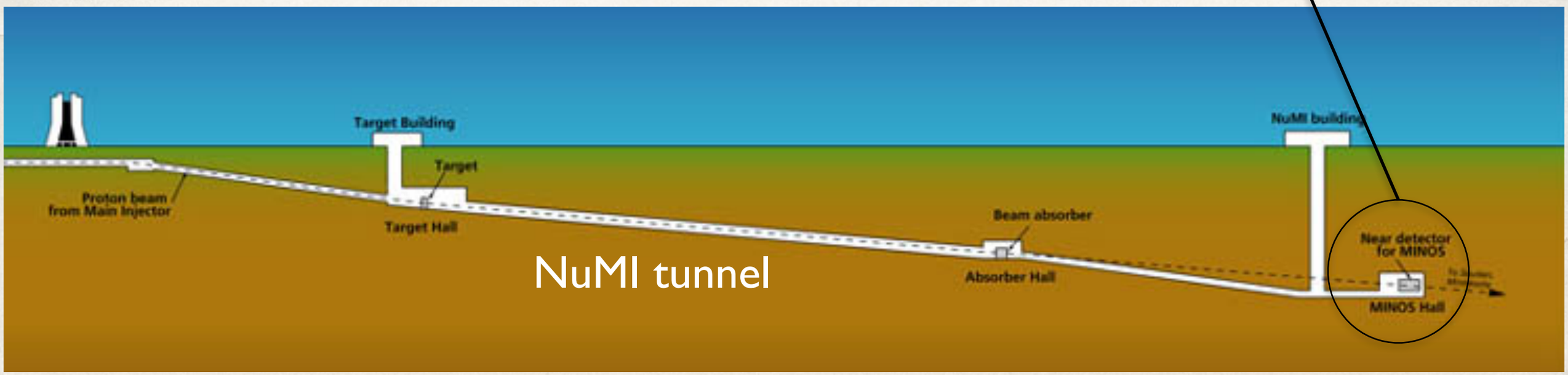
Moving from PAB to MINOS ND Hall
1/12/2009



ArgoNeuT - Argon Neutrino TesT

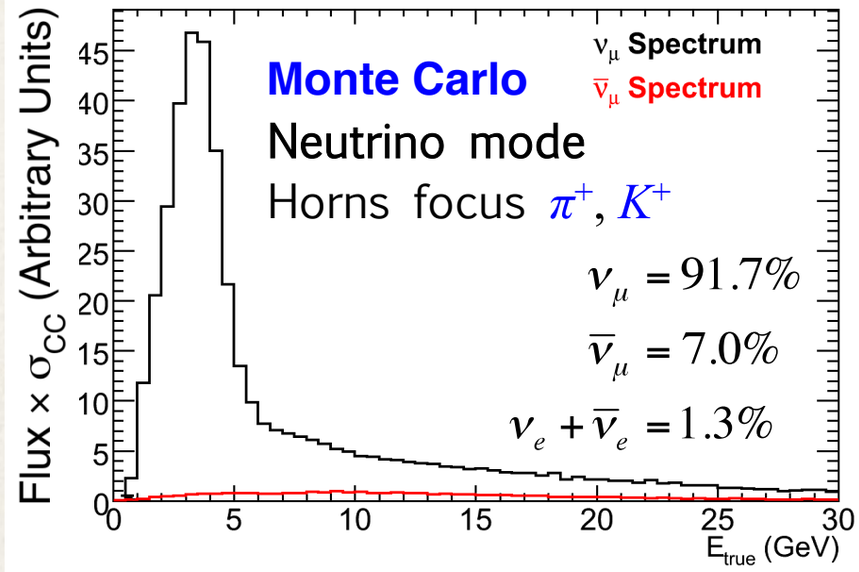
- First TPC in a neutrino beam in the US
- Sitting in NuMI beam
- Located in front of MINOS near detector
- 47×40×90 cm^3 (170 L), wire spacing 4 mm



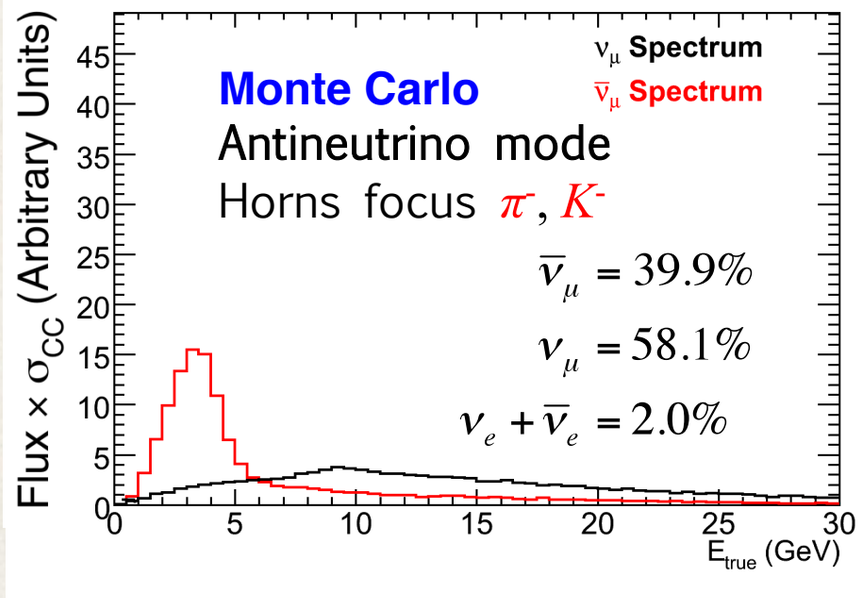


ArgoNeuT's Physics Run

ν-mode (2 weeks): 0.085e20 POT

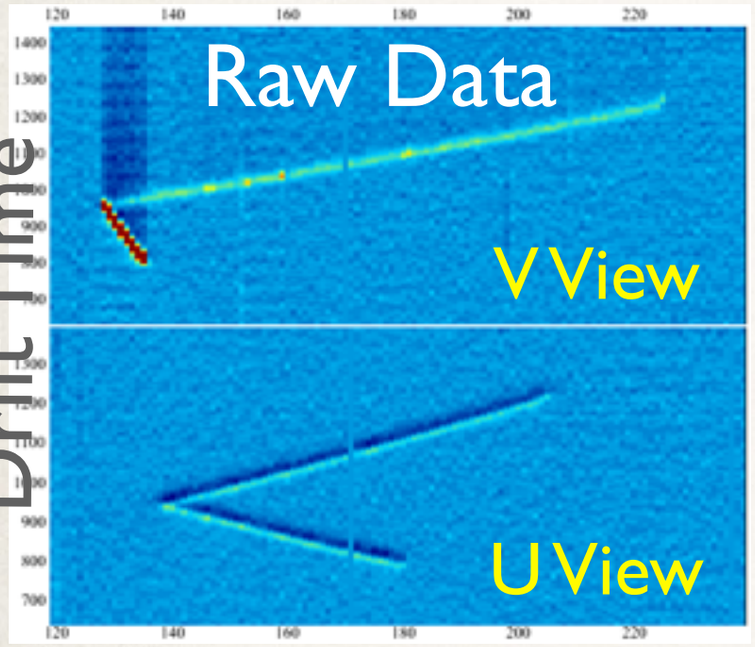


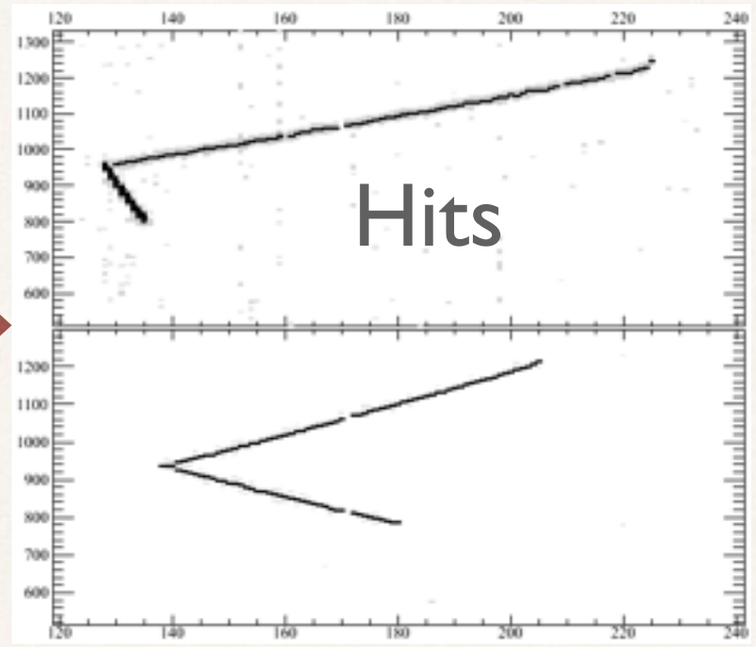
$\bar{\nu}$-mode (5 months): 1.2e20 POT

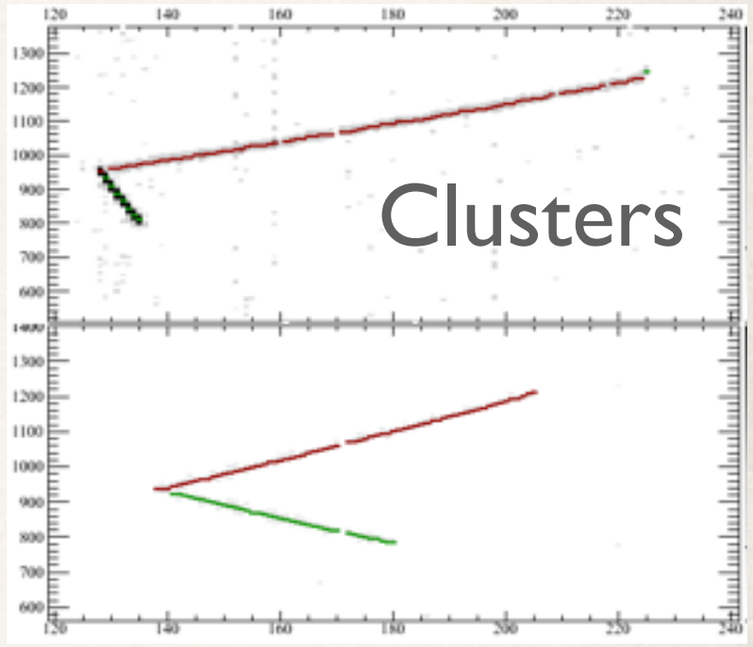


- ArgoNeuT completed taking data. (9/14/2009-2/22/2010)
- Physics goals:
  - Measure ν-Ar CC cross sections
  - Develop automated reconstruction techniques
    - Track reco
    - Shower reco
    - Calorimetry / PID

Automatic Track Reconstruction

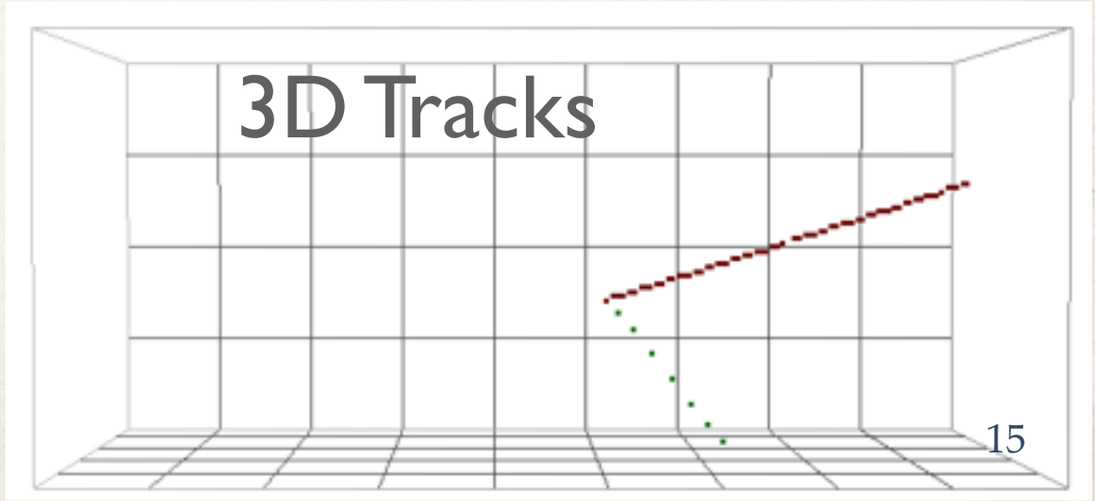




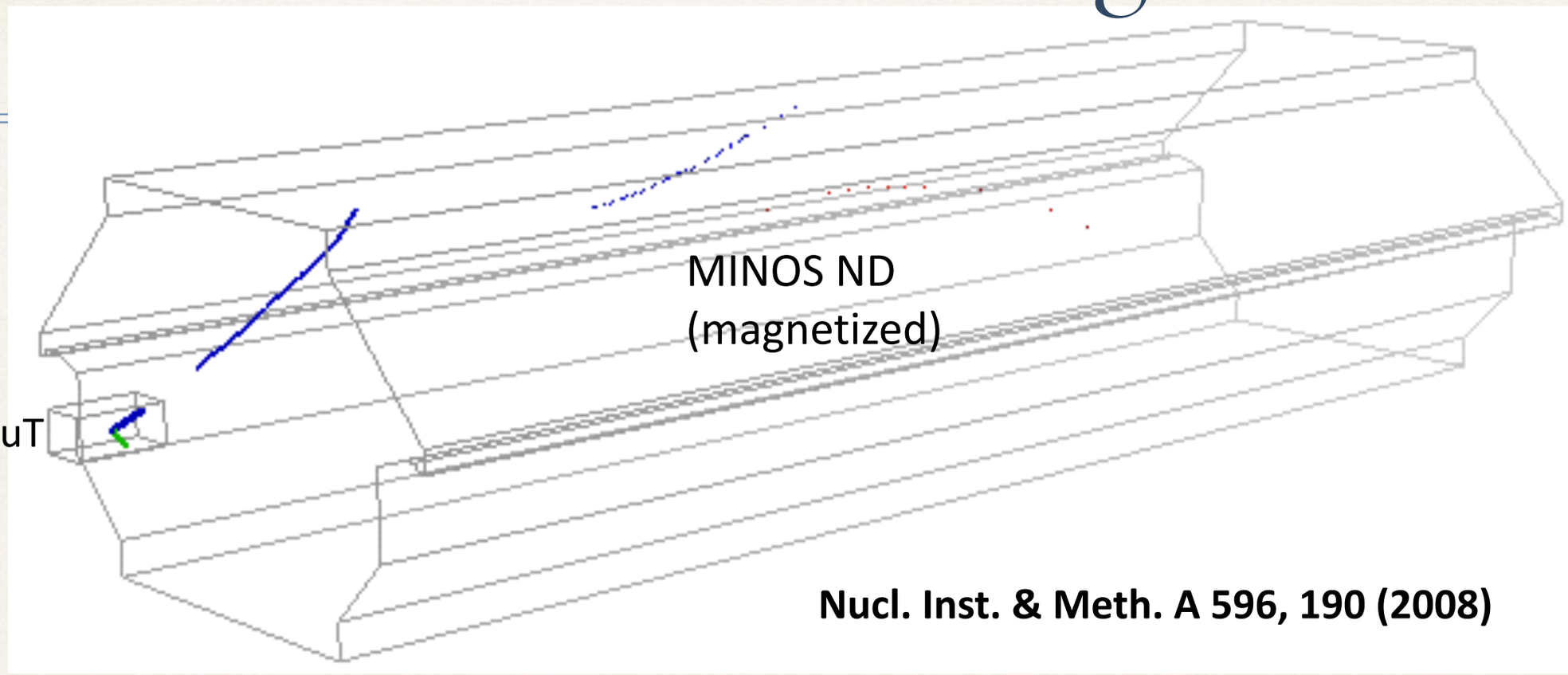


LArSoft

https://cdcvs.fnal.gov/redmine/projects/larsoft



MINOS Track Matching



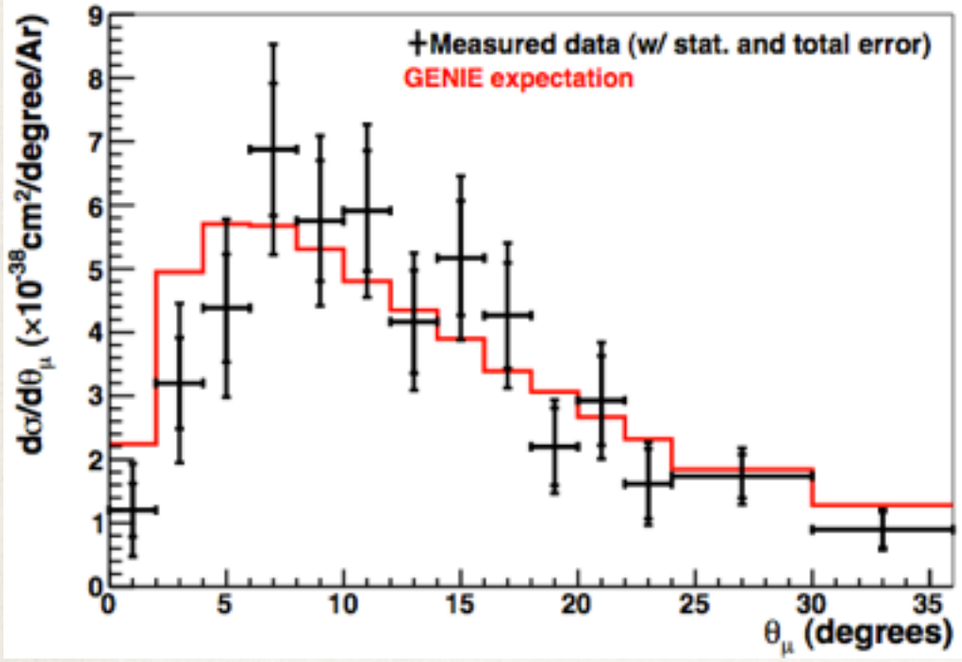
- The presence of the MINOS ND allows for energy reconstruction and charge identification of escaping muons.

- We gratefully acknowledge the help of the MINOS collaboration for providing simulated NuMI flux, ND data, simulation and reconstruction code.

Charged Current (CC) Inclusive Cross Sections

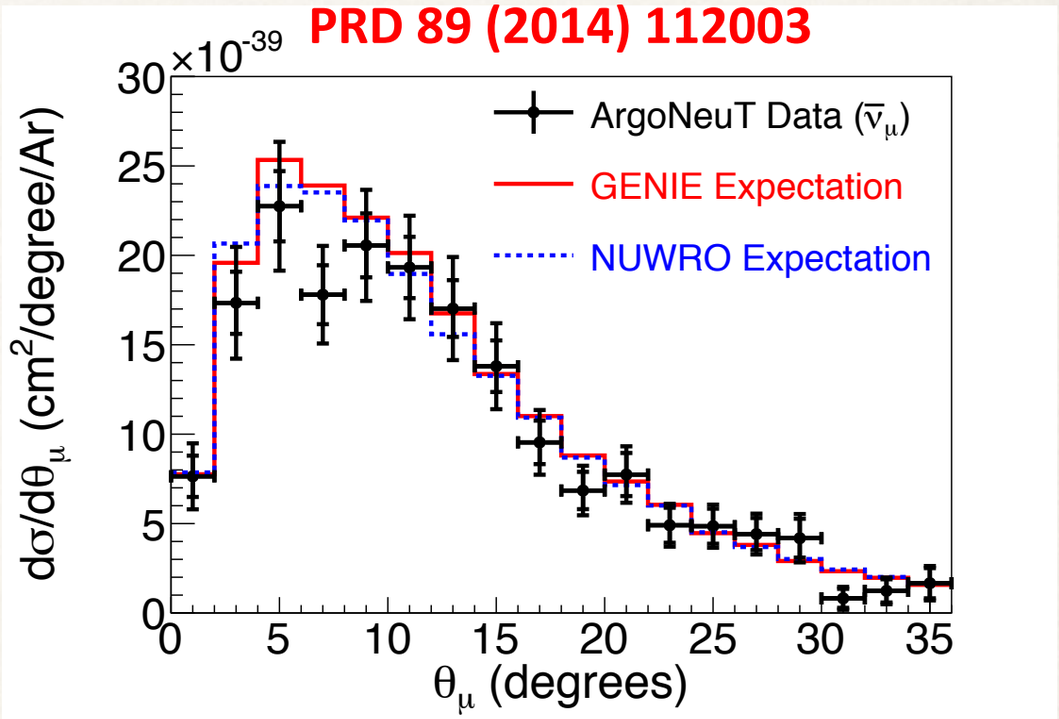
Neutrino mode, 8.5E18 POT

PRL 108 (2012) 161802



Antineutrino mode, 1.2E20 POT

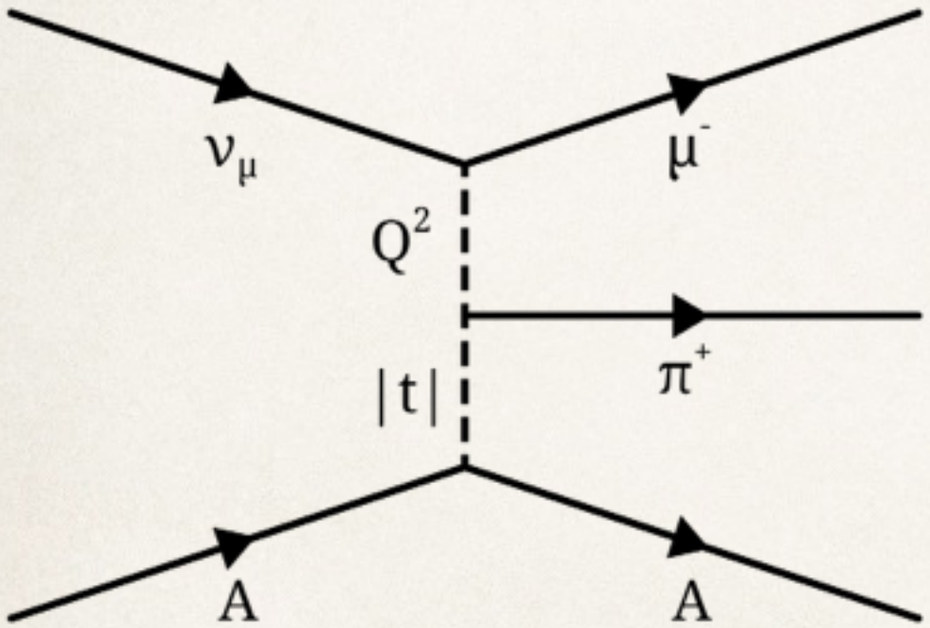
PRD 89 (2014) 112003



- Match track in TPC with track in MINOS - muon track.
  - NC background is negligible.
- TPC measures muon angle, MINOS measures muon charge and momentum.

Look for CC Coherent Pion Production

- Use antineutrino mode data (1.2E20 POT).



Event Selection

[Reconstruction Cuts]

Event Classification

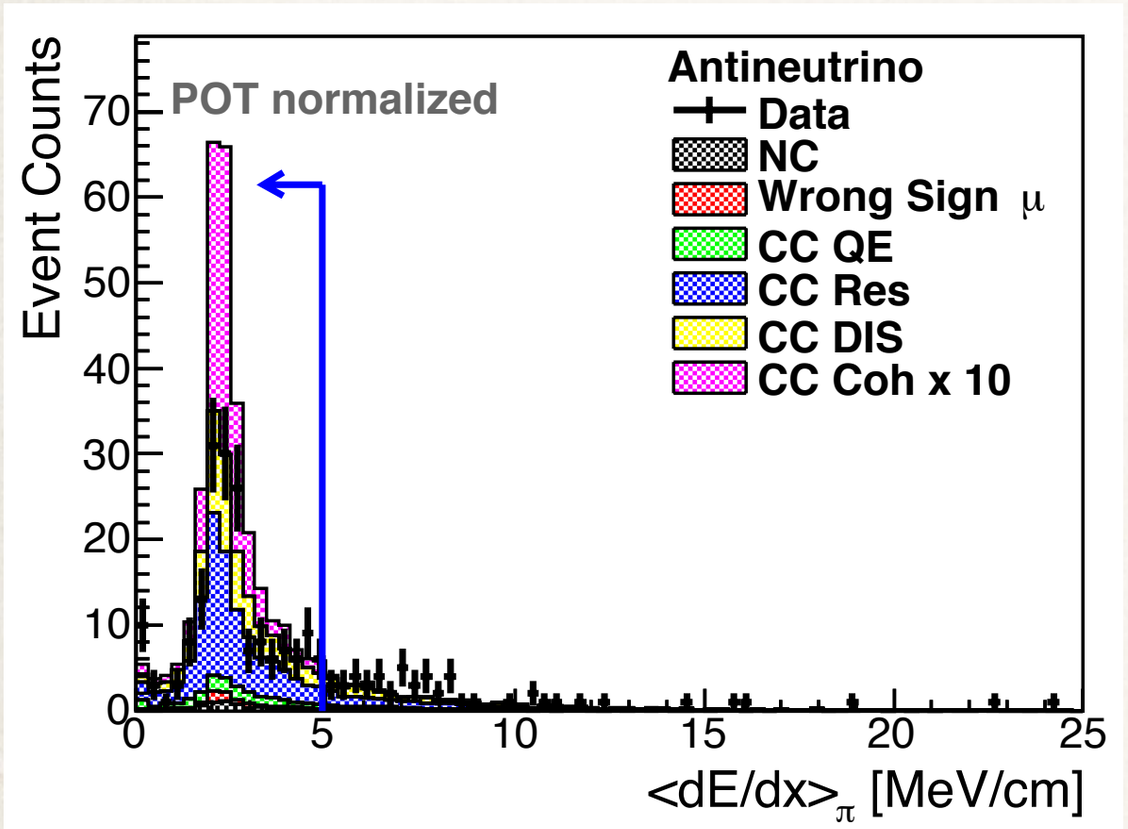
[Boosted Decision Trees]

Signal Extraction & Cross Section

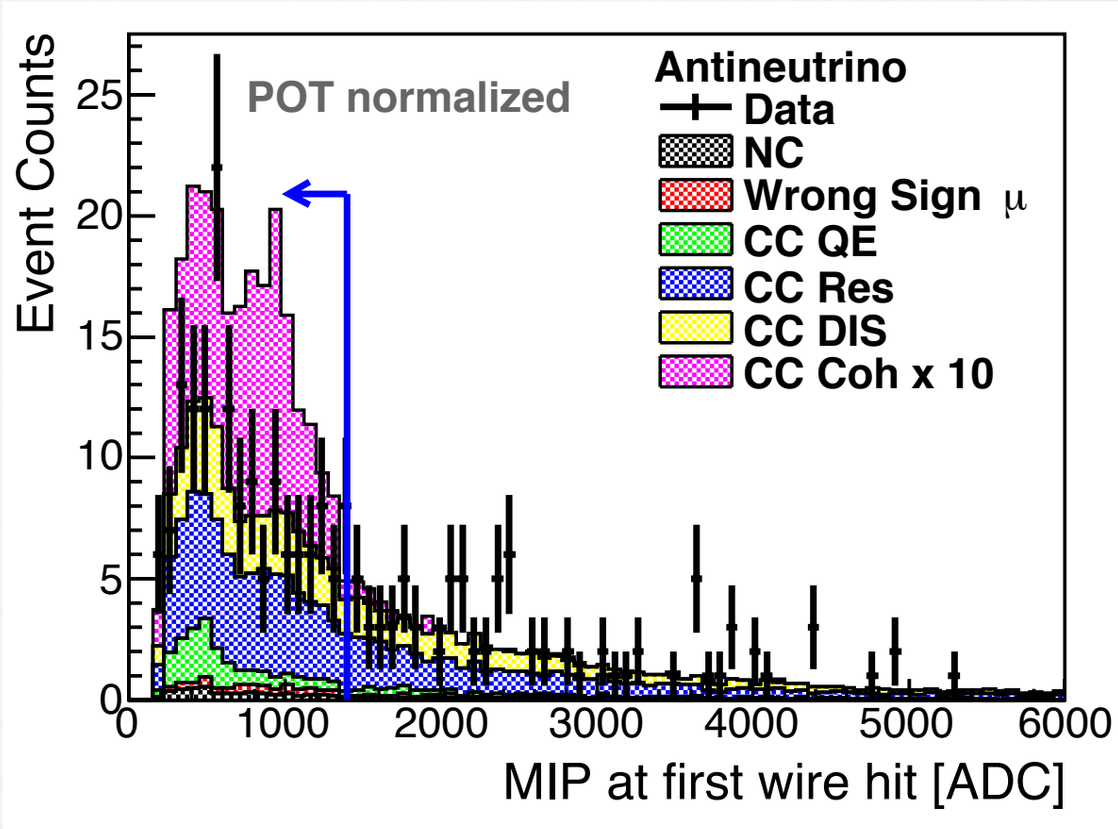
Event Selection

- 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.
- Selection determined by optimizing S/sqrt(S+B).

Remove Protons

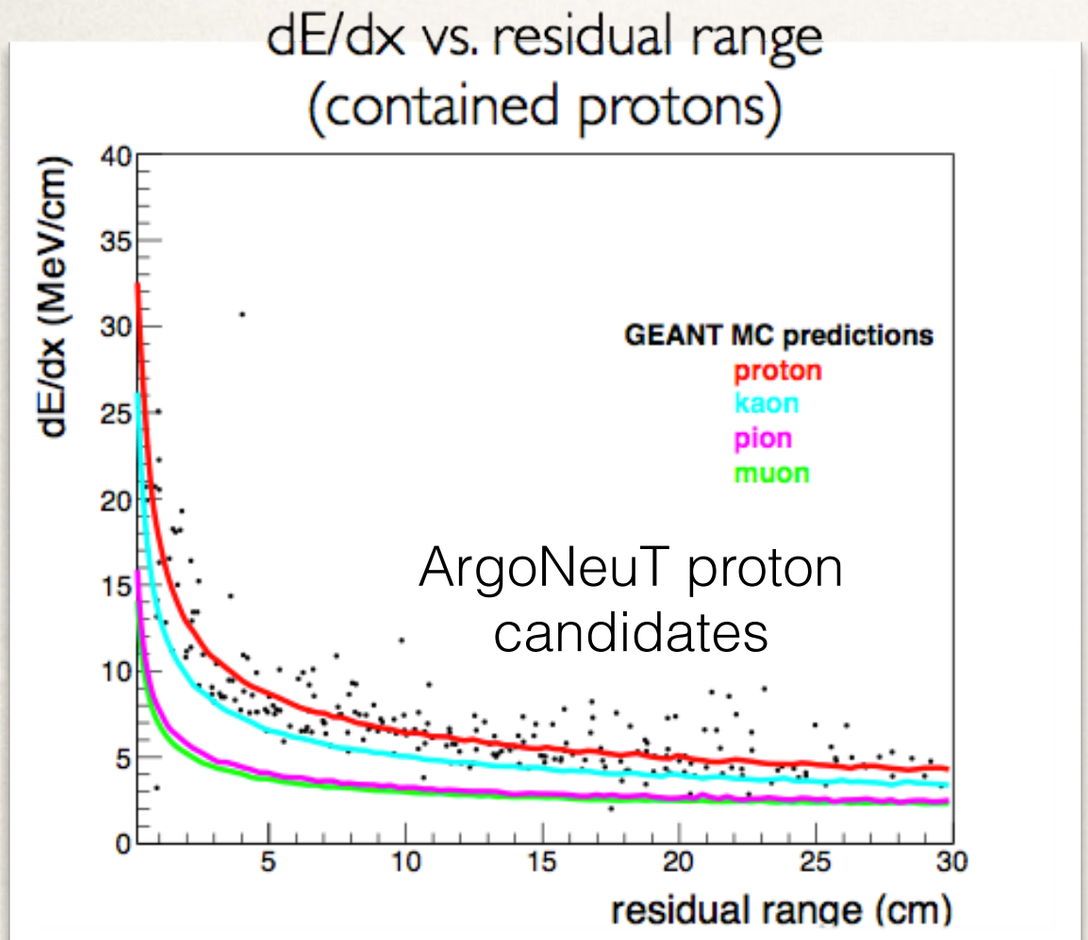


Require pion candidate
mean dE/dx <5 MeV/cm
Removing highly ionizing particles



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

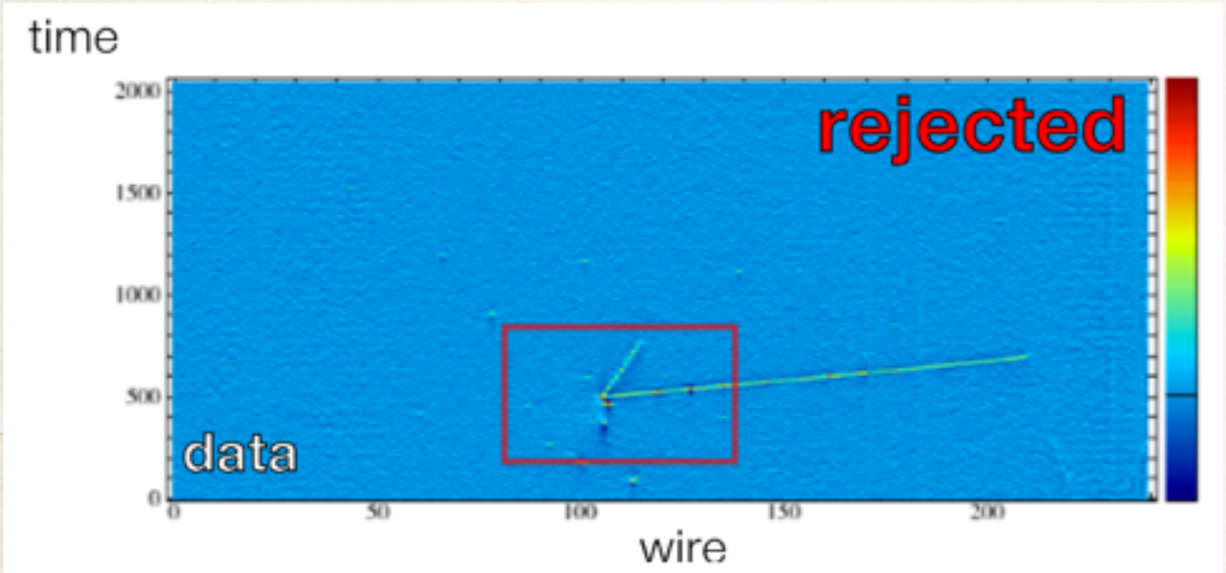
Calorimetry and PID for Stopped Particles

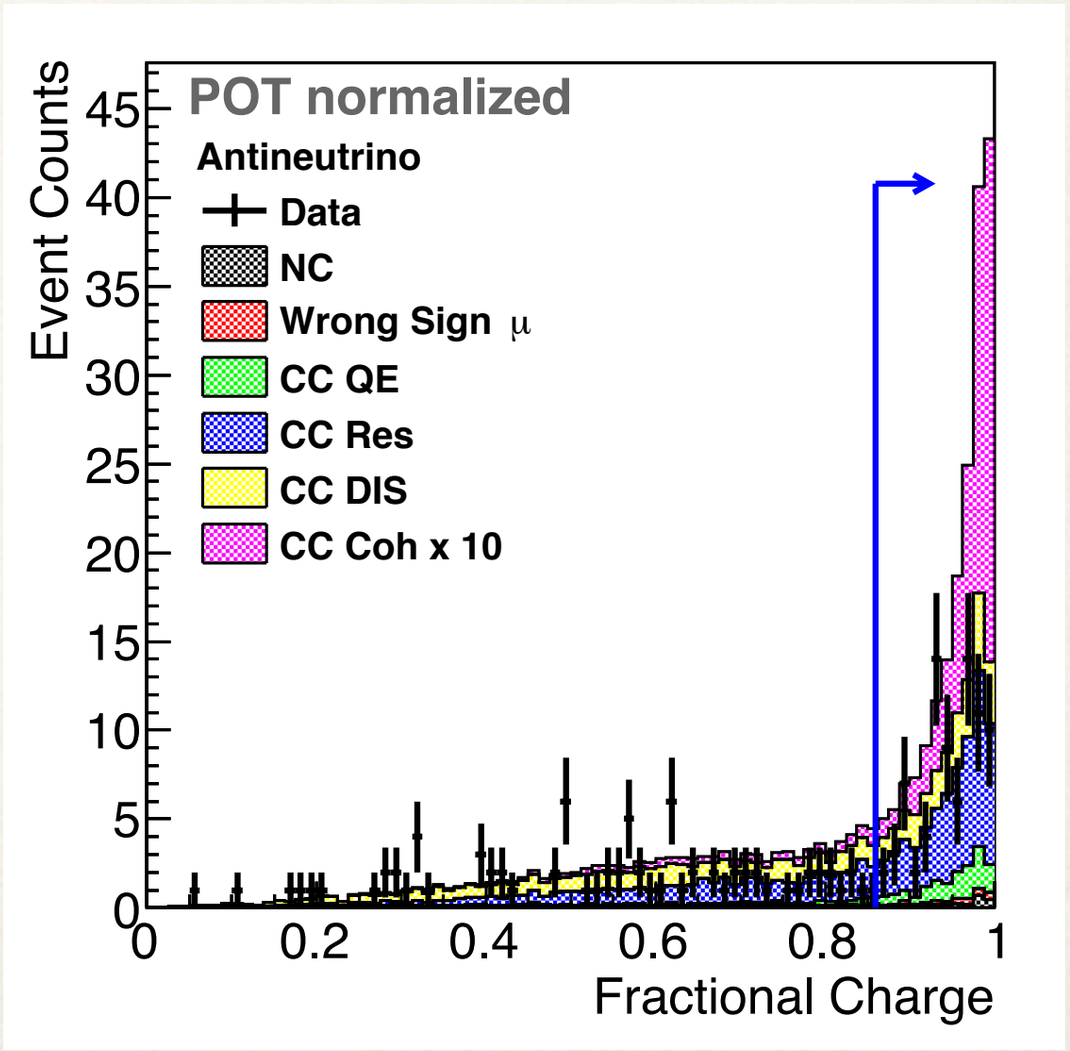


- dQ/dx -> dE/dx
  - Electronics calibration factor
  - Electron lifetime correction
  - Recombination correction (Birks model or Modified Box model)
- Calorimetry based particle ID
  - dE/dx vs residual range for contained tracks
- Remove proton tracks for this analysis.

Vertex Activity

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

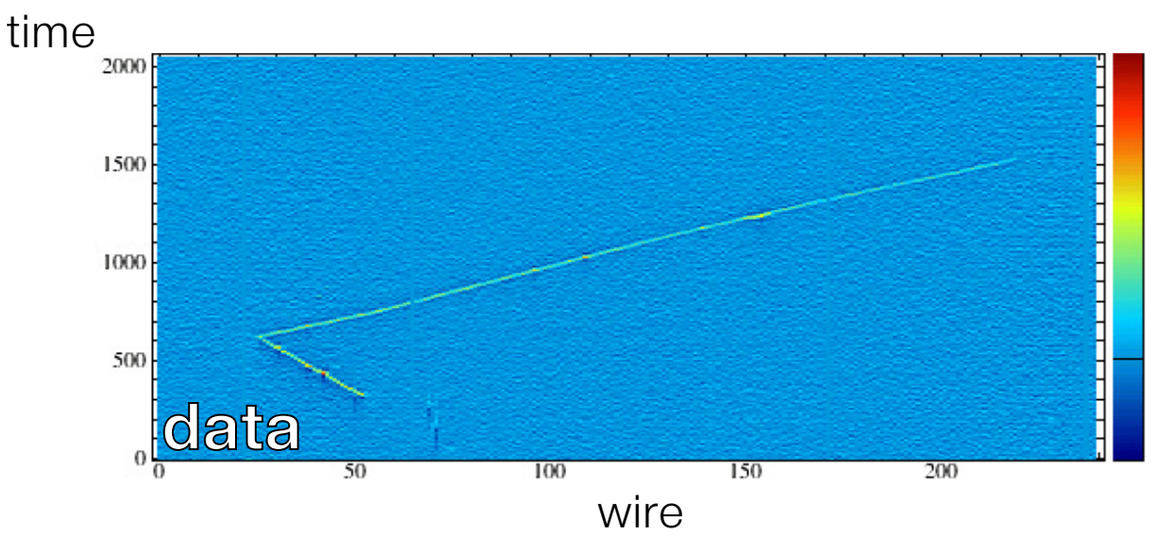


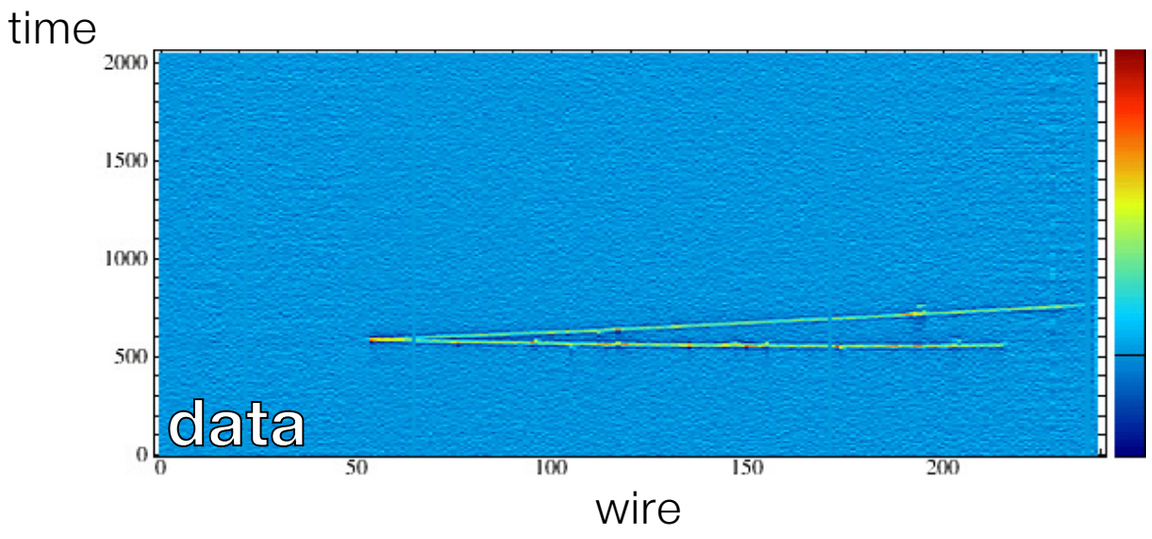


Remove stubs not reconstructed as tracks, deexitation gammas, etc.

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)



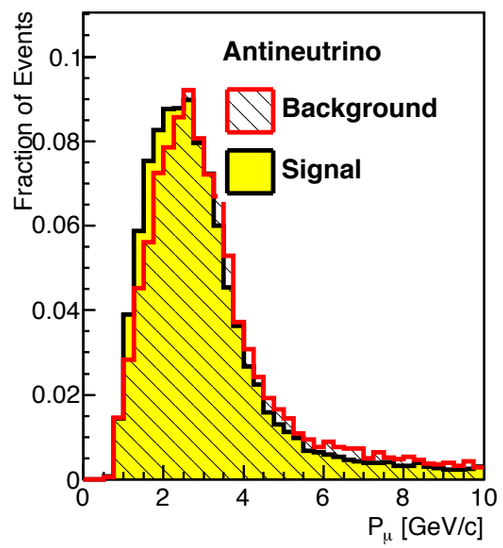


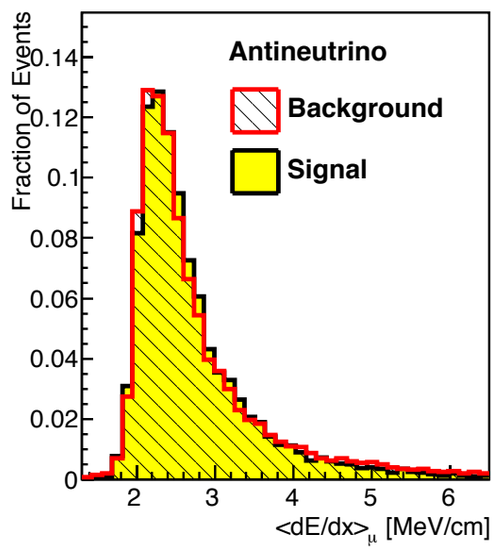
Multivariant Analysis

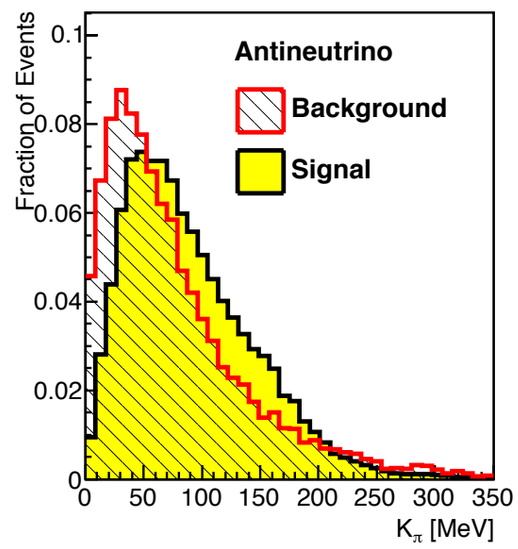
- Ideally we would cut on $|t| = |(q-p_{\pi})^2|$
- Most of the pions are not contained in ArgoNeuT, it's impossible to fully reconstruct event kinematics.
- We built a Boosted Decision Trees with all the available information:
  - Muon momentum measured by MINOS
  - Pion kinetic energy measured by ArgoNeuT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

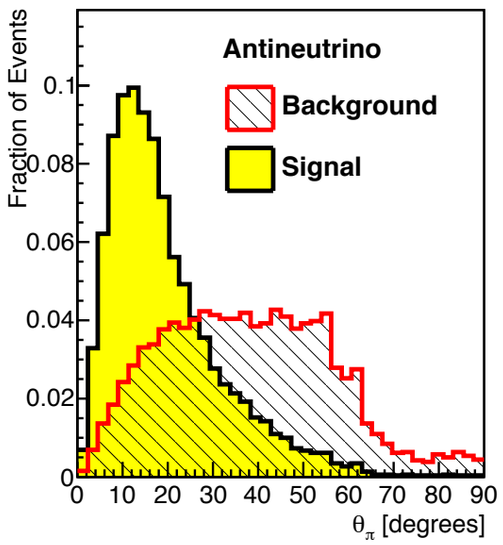
Signal/Background Discrimination

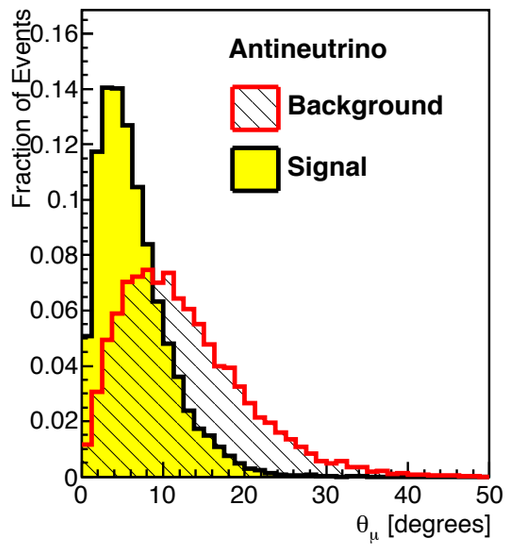
GENIE 2.8.2/LArSoft simulation&reconstruction

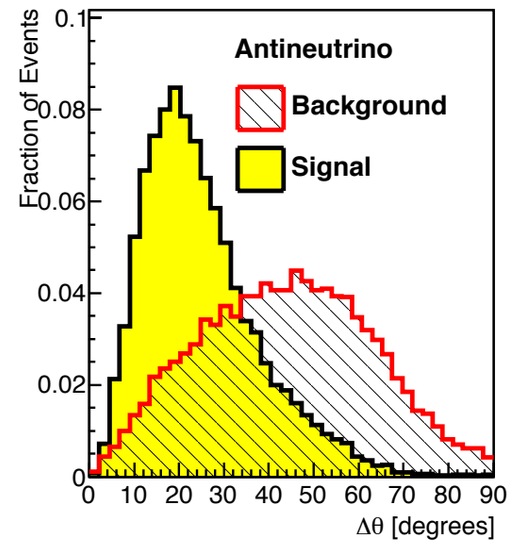




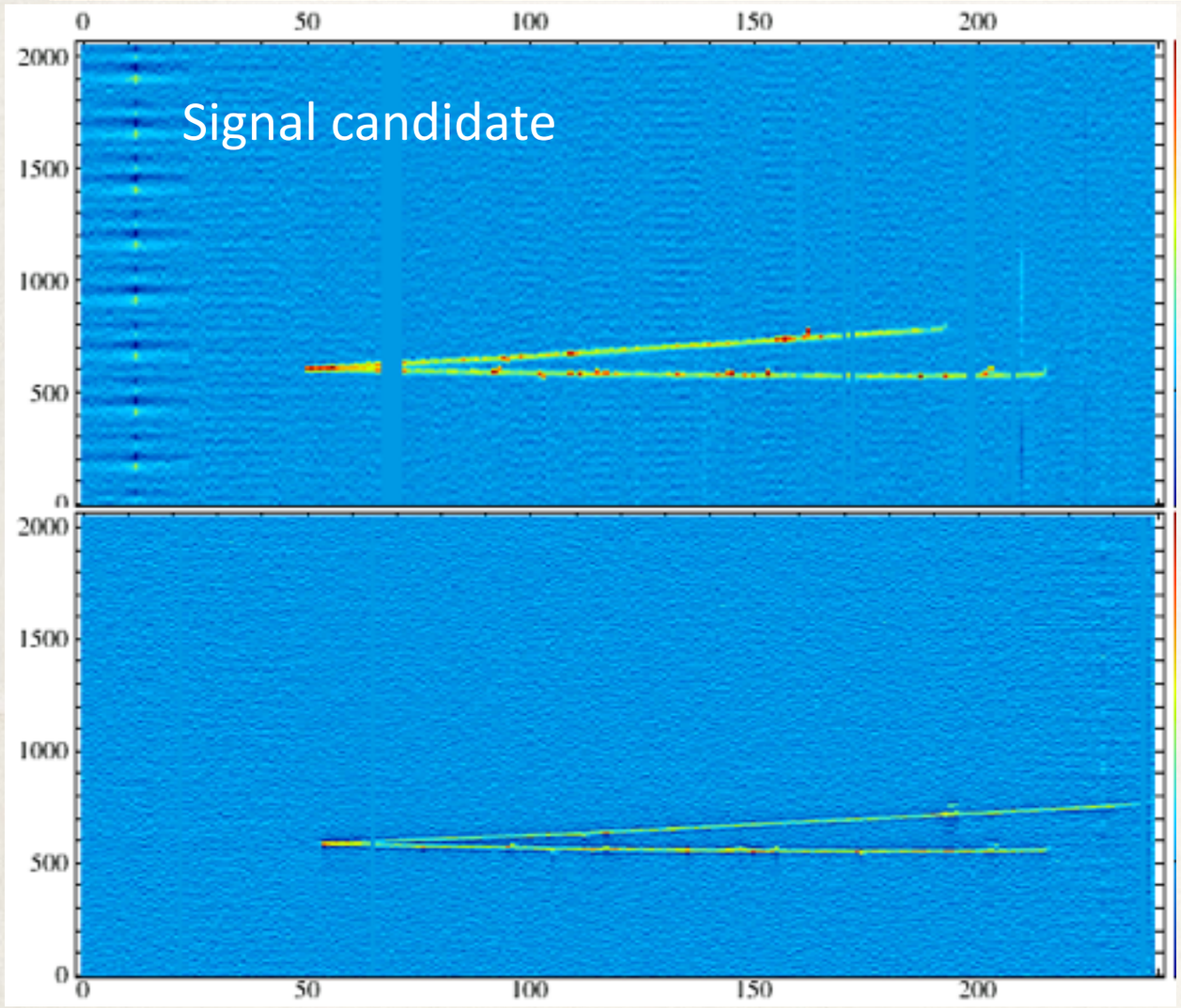




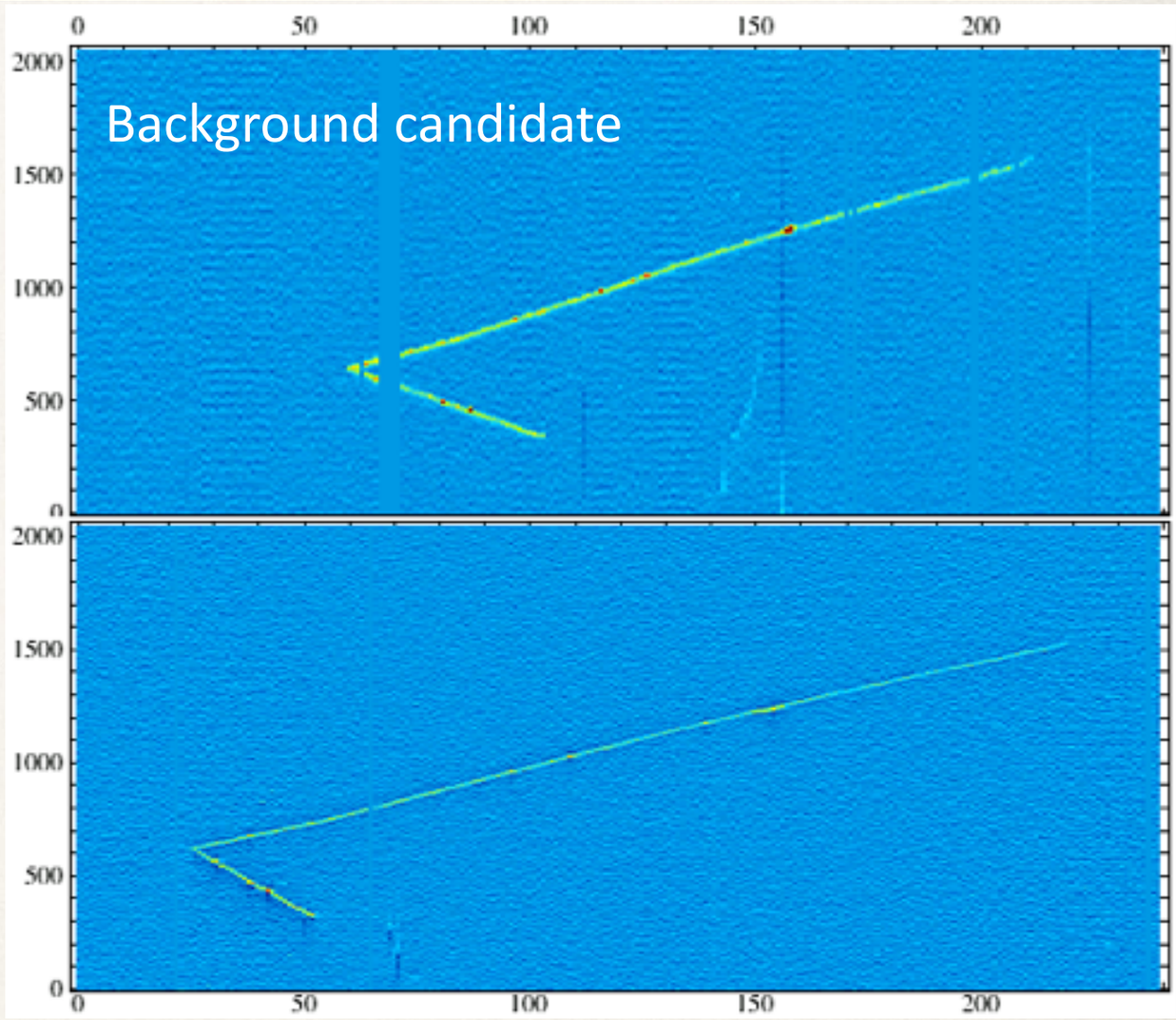




Signal and Background Candidates

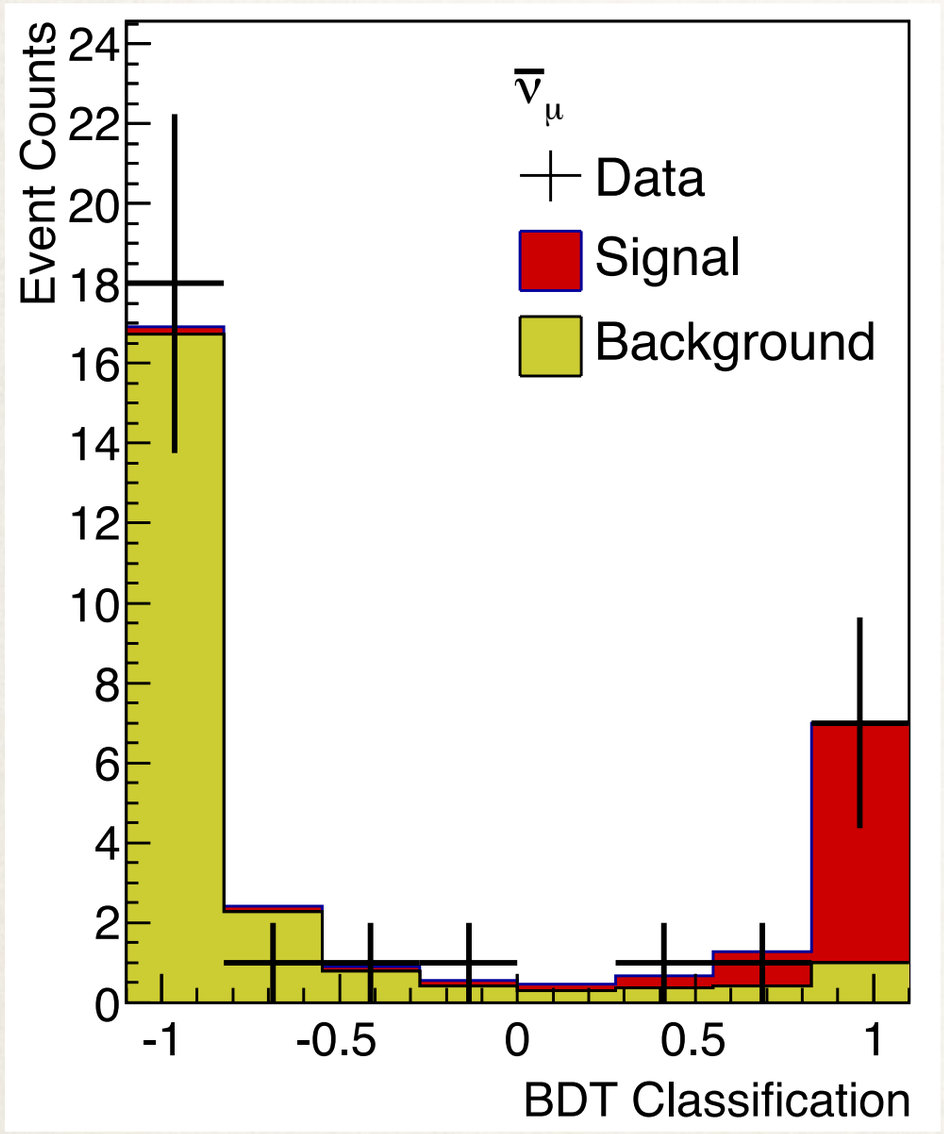


Run 800/Event 29745
BDT = 0.95

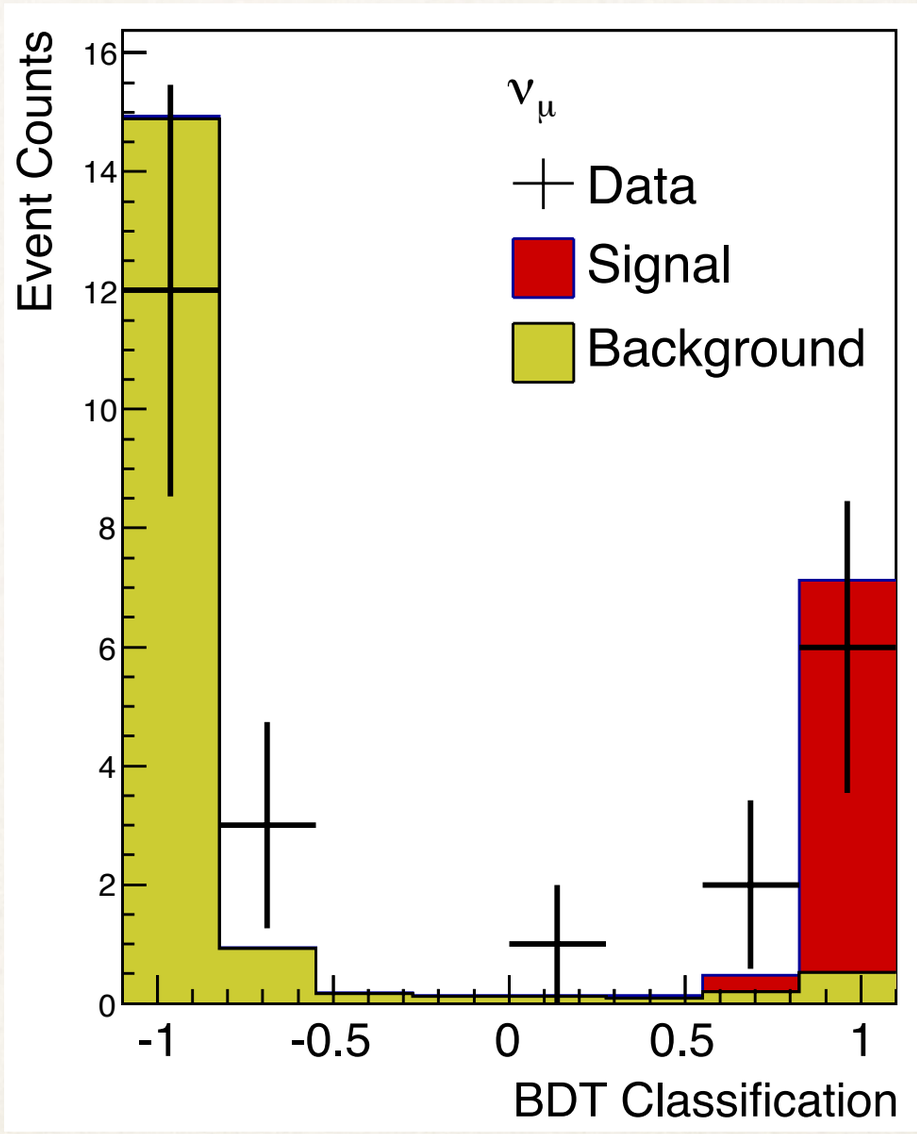


Run 767/Event 7307
BDT = -1.00

Data Fit with Signal and Background Shapes



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



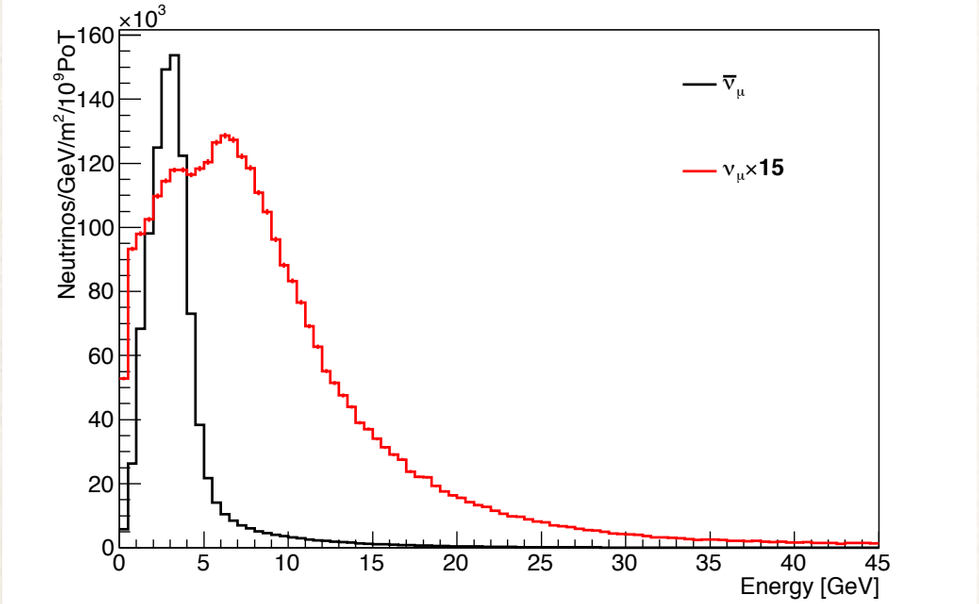
$\text{Signal} = 7.0^{+3.3}_{-2.6}$

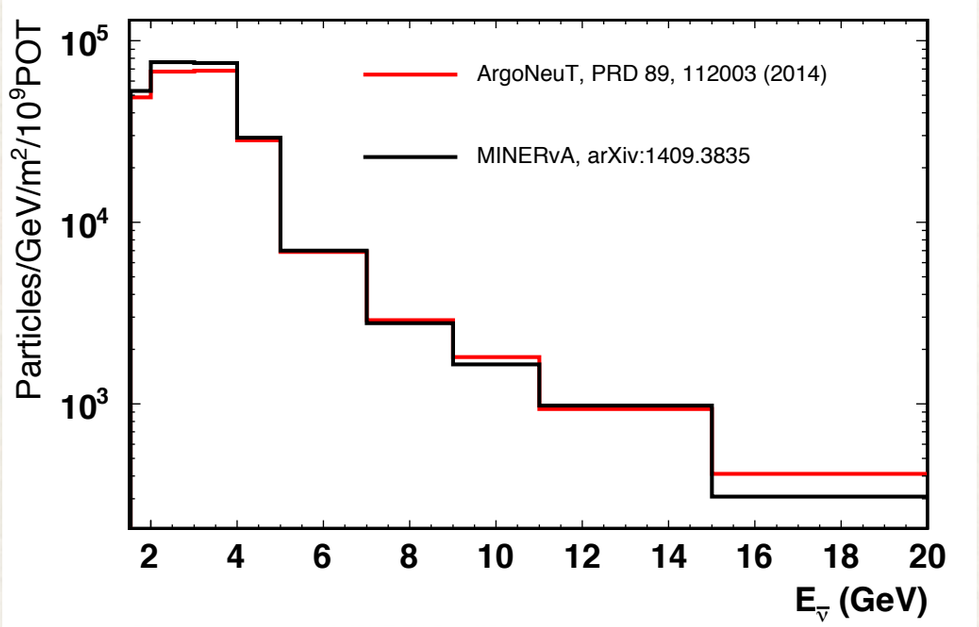
Well separated signal and background!

Systematics

- 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 process 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

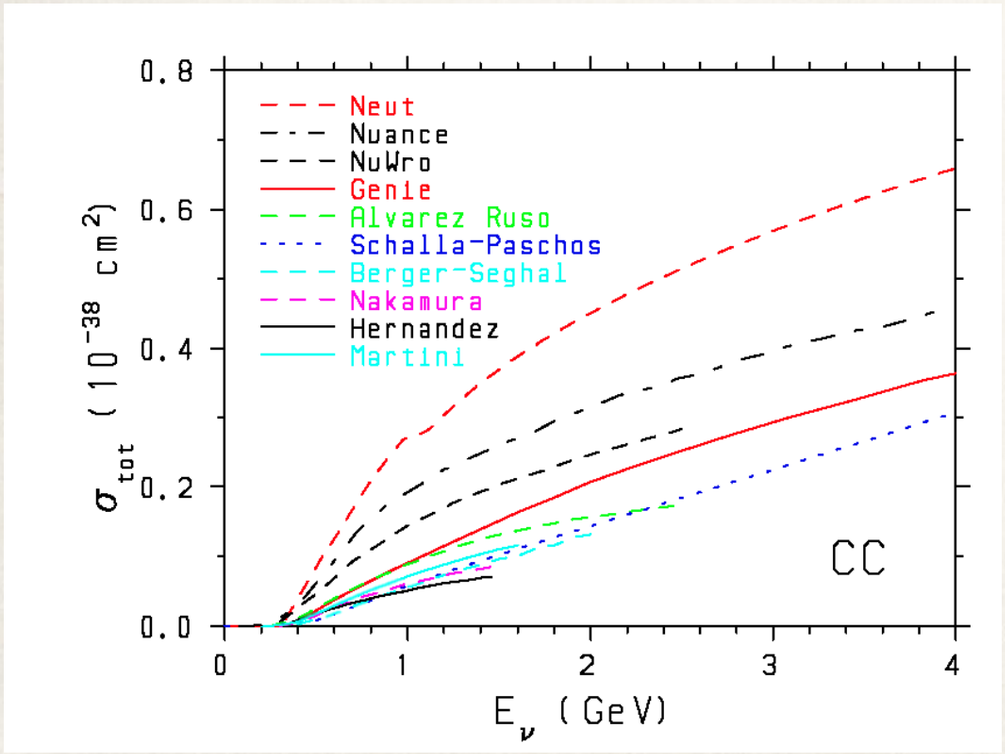


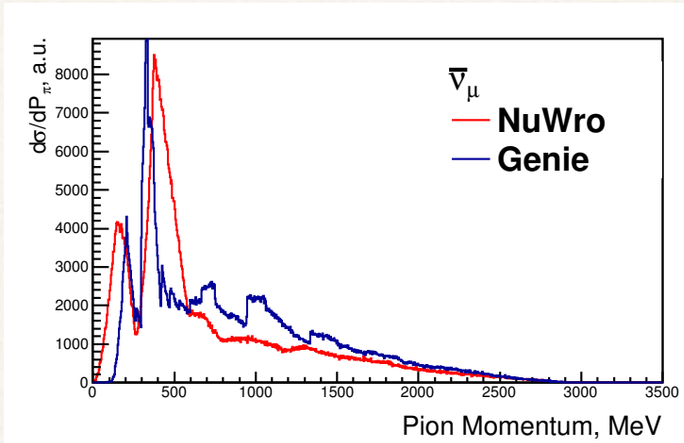


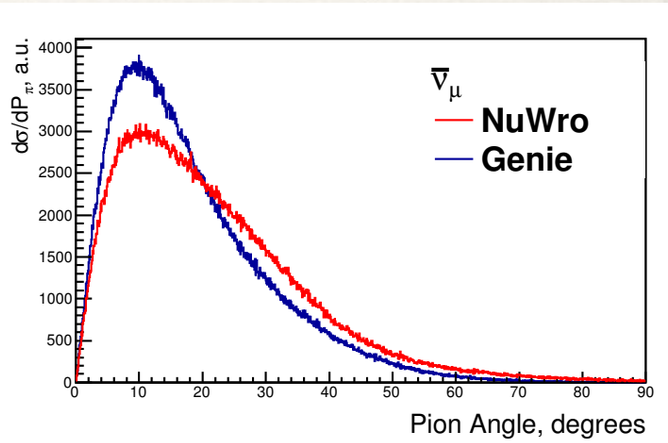
- We use hadron tuning provided by MINOS (SKZP).
  - Tuning was based on MINOS ND data and NA49 data.
- We validated the hadron tuning using low-nu flux in neutrino mode, which has a minimal dependence on cross sections.
- We assign a 11% flat error on flux.
  - Dominant systematic error on final cross section results.

Signal Modeling

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

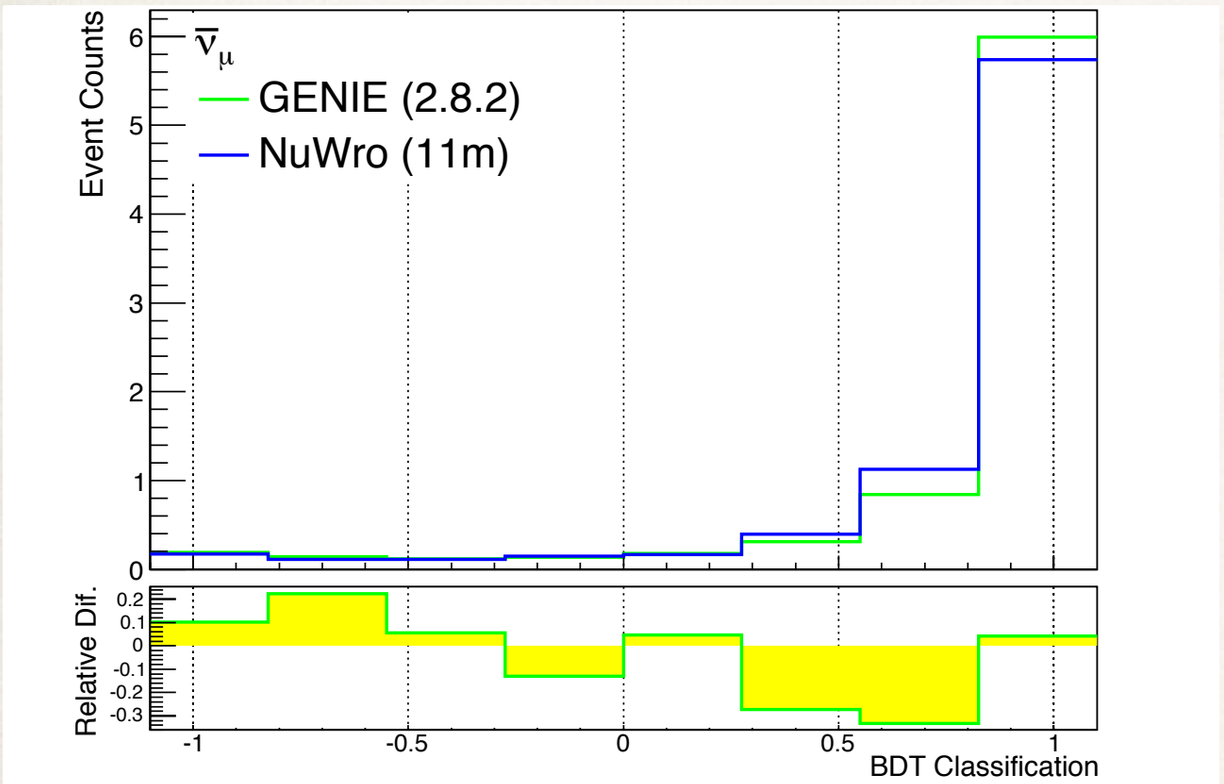


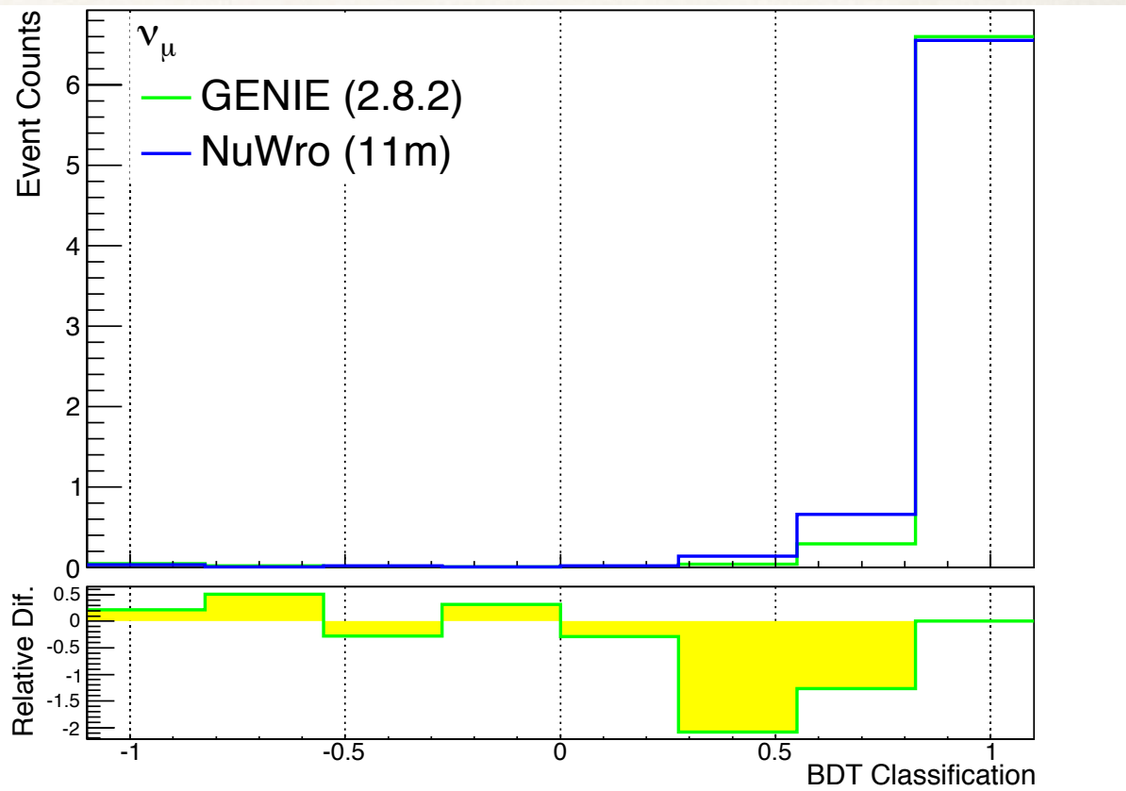




S. Boyd et. al., AIP Conf. Proc. 1189, 60-73 (2009).

Signal Template Shapes

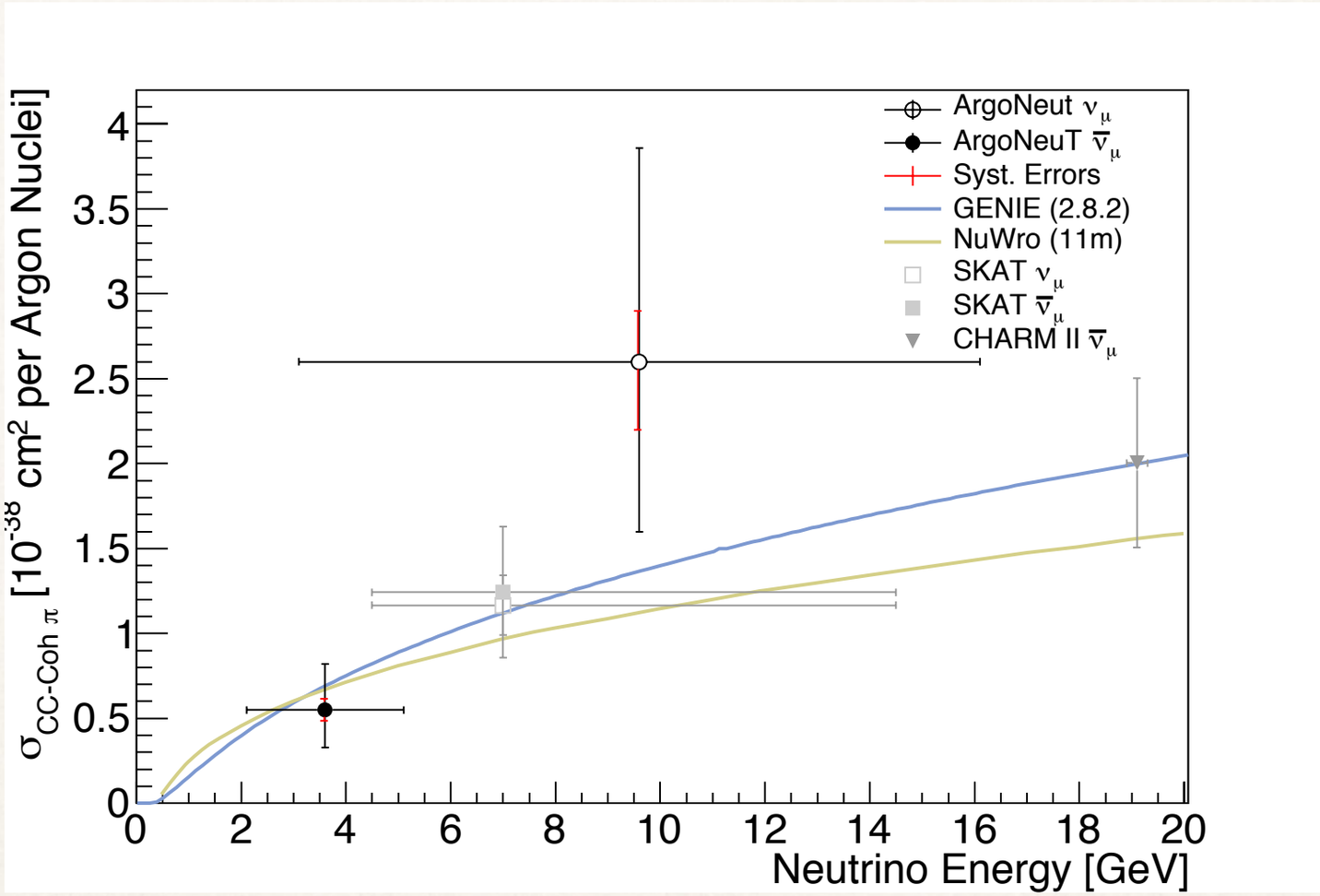




Similar Shapes Constructed with GENIE and NuWro.

		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 first measurement of CC Coherent π production on Argon.
- The LAr technique shows great potential for this measurement:
  - Great resolution at the vertex
  - Precise calorimetry
- Looking forward to measurements in future LArTPCs - MicroBooNE, LAr1ND, etc.

ArgoNeuT Collaboration

F. Cavanna

University of L'Aquila

A. Ereditato, M. Weber

University of Bern

R. Acciarri, B. Baller, H. Greenlee, C. James, G. Rameika, B. Rebel, A. Schukraft, T. Yang, G. Zeller

Fermi National Accelerator Laboratory

E. Santos

Imperial College London

O. Palamara

Gran Sasso National Laboratory

T. Bolton, S. Farooq, G. Horton-Smith

Kansas State University

C. Bromberg, D. Edmunds, P. Laurens, B. Page

Michigan State University

J. Asaadi, M. Soderberg

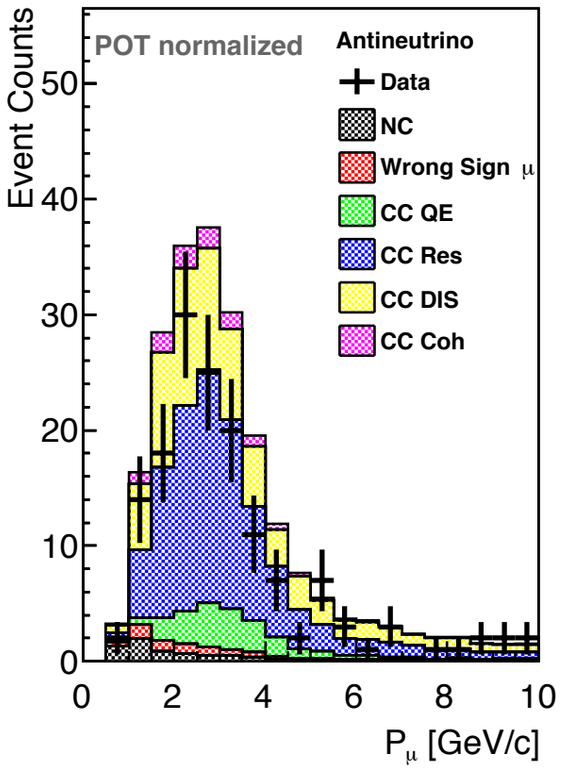
Syracuse University

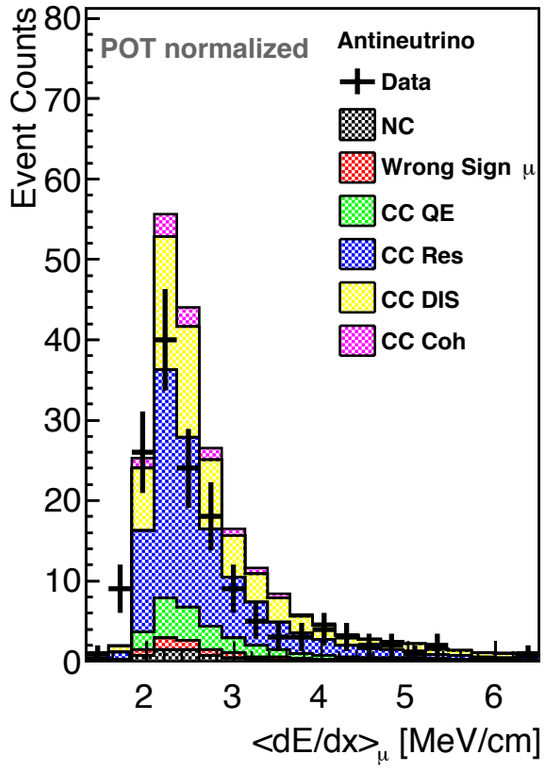
K. Lang, R. Mehdiyev

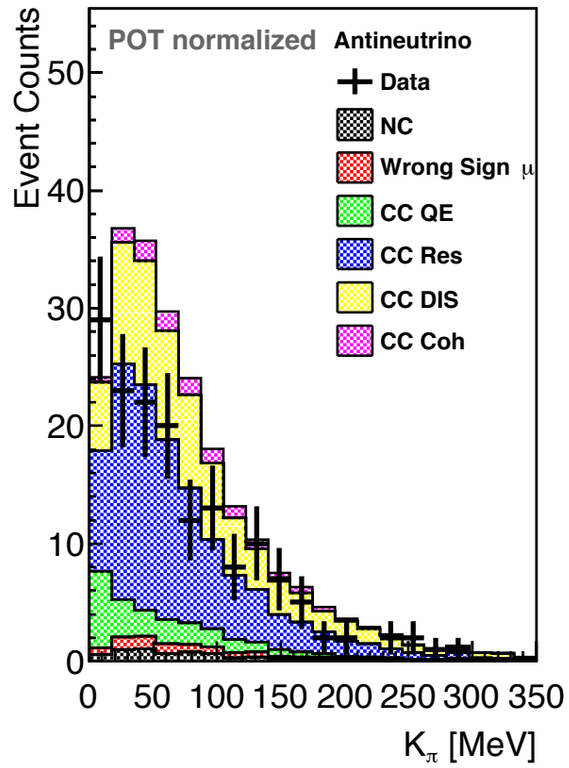
The University of Texas at Austin

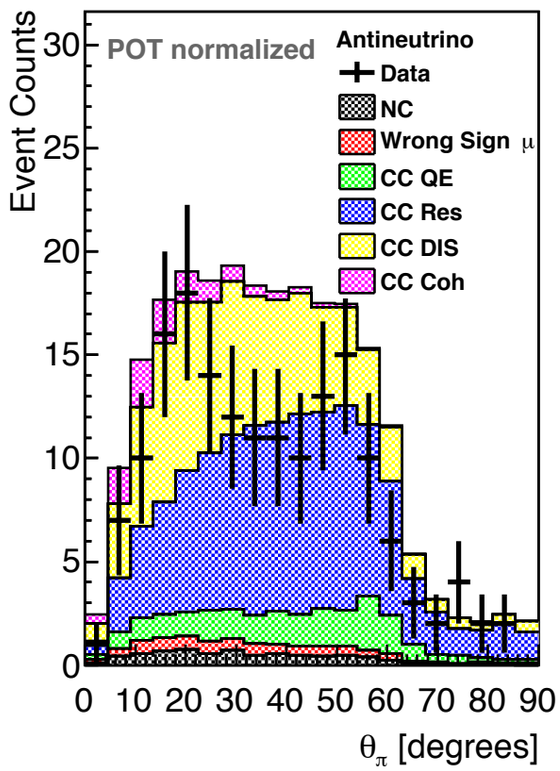
C. Adams, E. Church, B. Fleming, E. Klein, K. Partyka, J.Spitz, A. Szelc

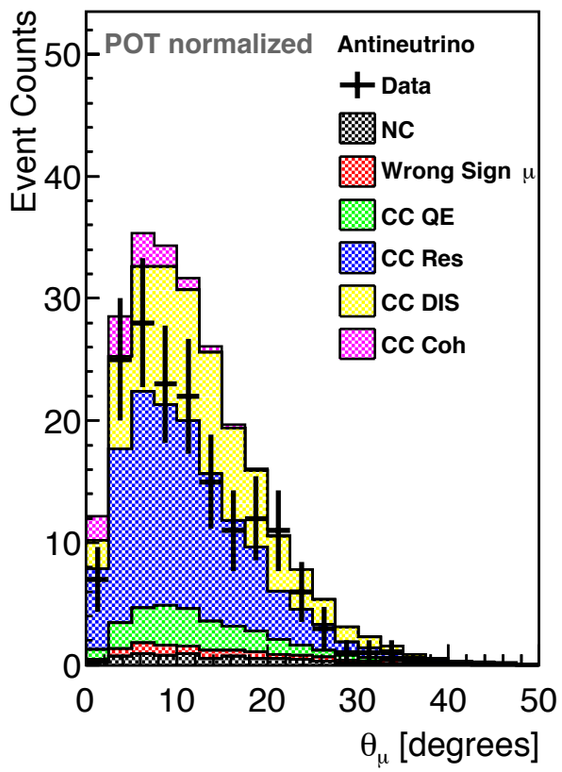
Yale University

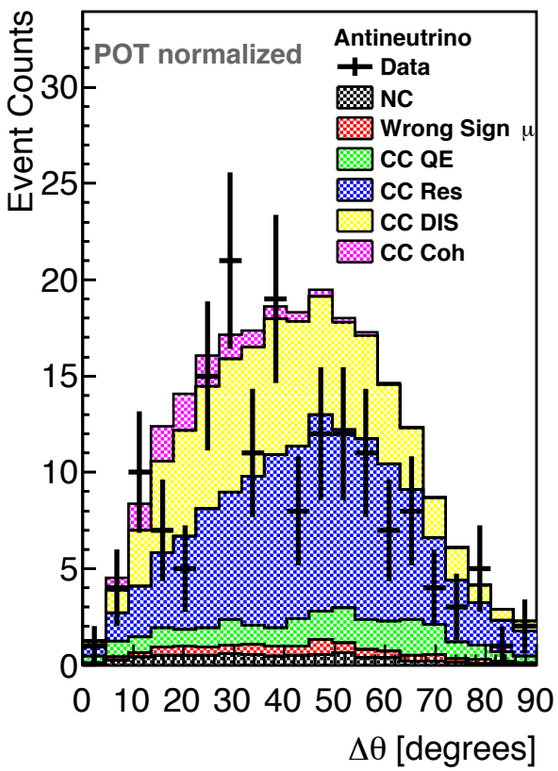

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
P_μ [GeV/c]

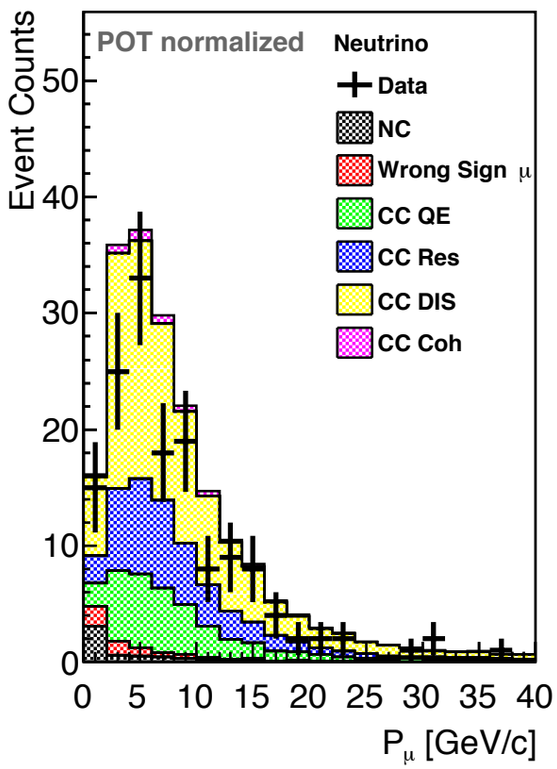

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
<dE/dx>$_\mu$ [MeV/cm]

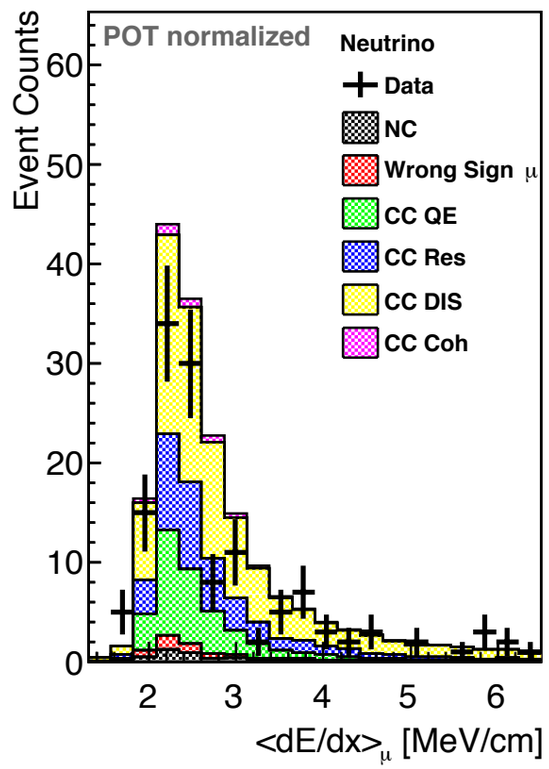

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
K_π [MeV]

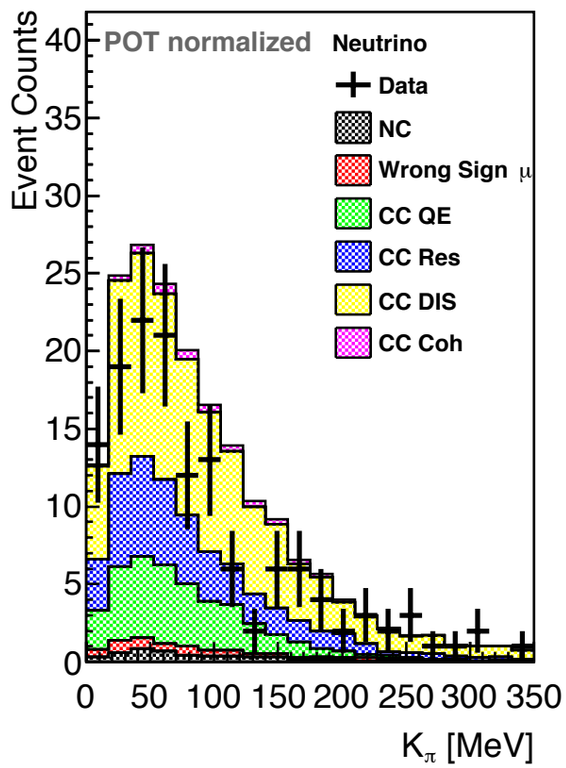

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
θ_π [degrees]

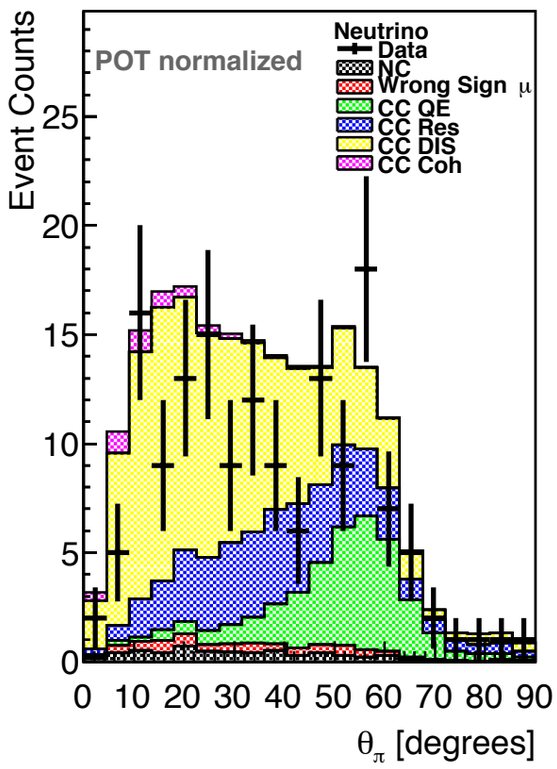

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
θ_μ [degrees]

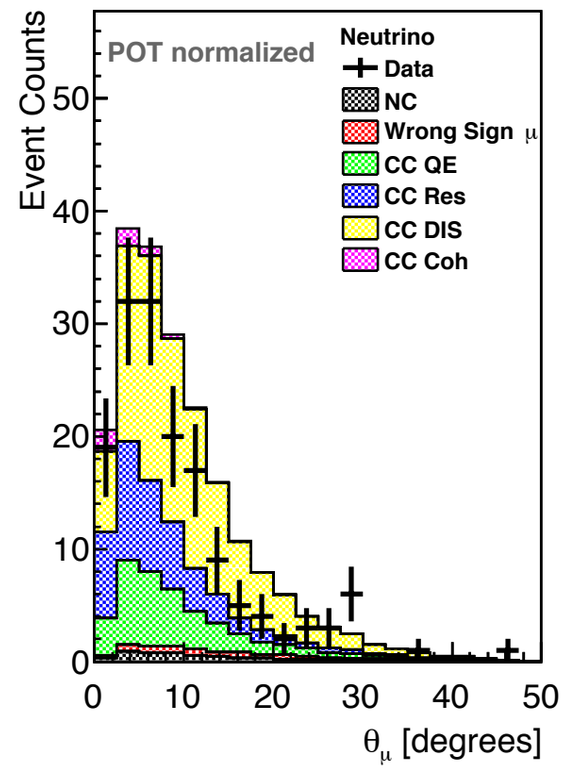

POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
Δθ [degrees]

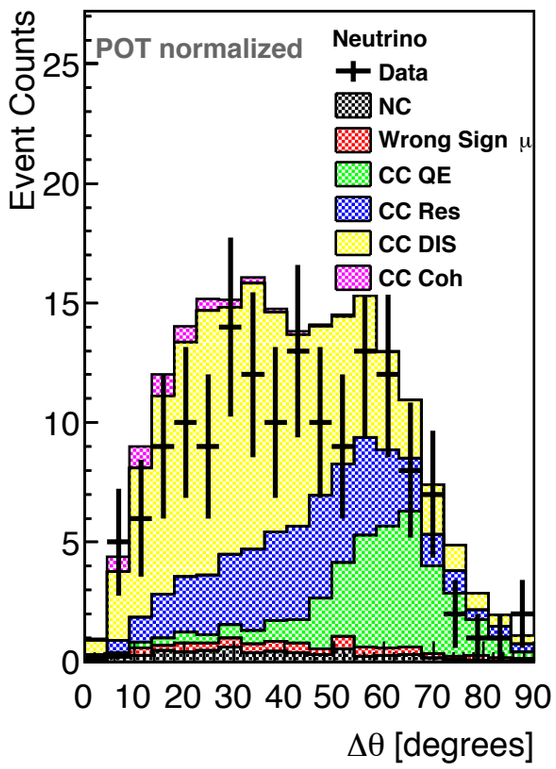

POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
P_μ [GeV/c]

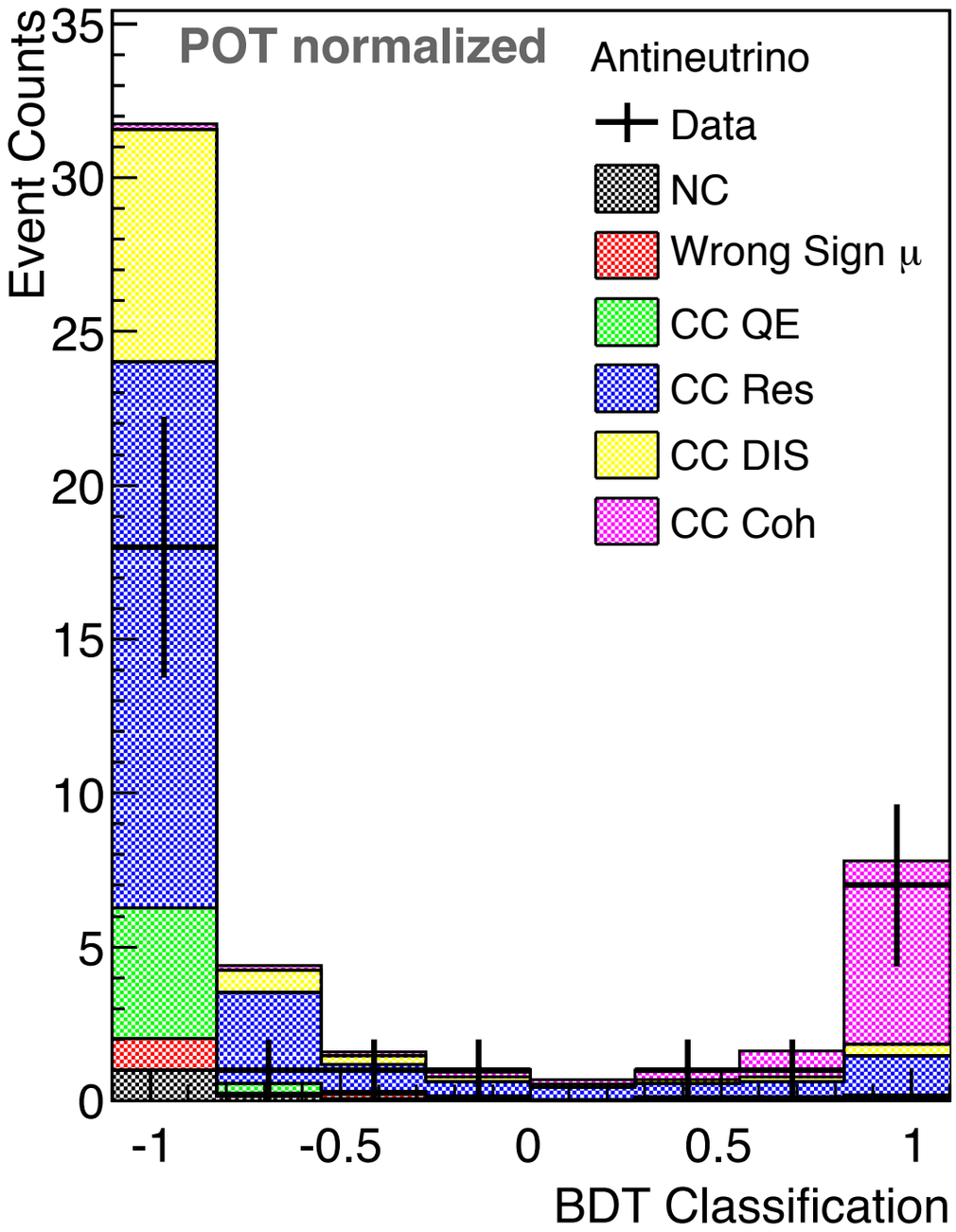

POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
<dE/dx>$_\mu$ [MeV/cm]

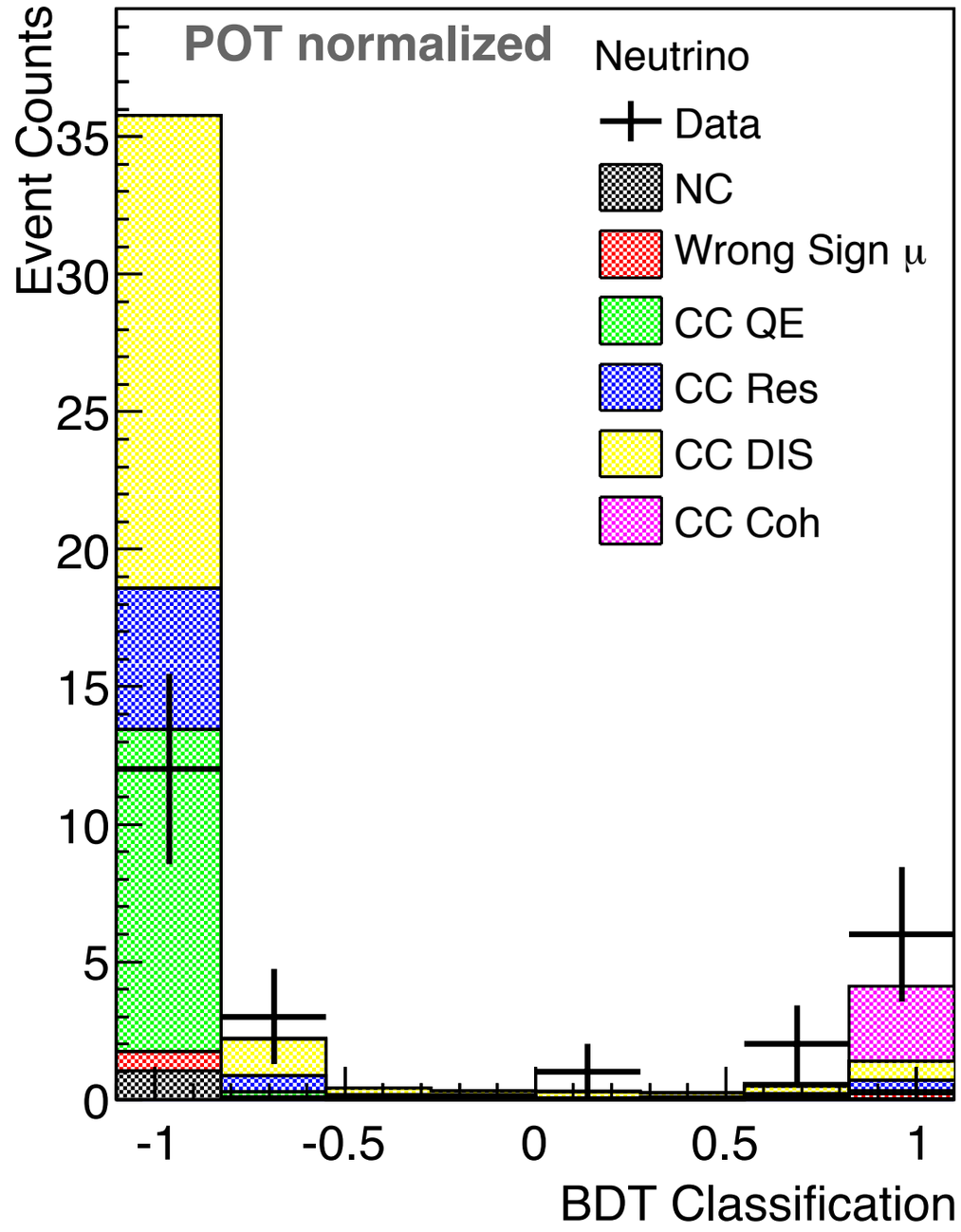

POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
K_π [MeV]


POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
θ_π [degrees]


POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
θ_μ [degrees]


POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
Δθ [degrees]


POT normalized
Antineutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
0
5
10
15
20
25
30
35
-1
-0.5
0
0.5
1
BDT Classification


POT normalized
Neutrino
Data
NC
Wrong Sign μ
CC QE
CC Res
CC DIS
CC Coh
Event Counts
0
5
10
15
20
25
30
35
-1
-0.5
0
0.5
1
BDT Classification