Results from the ArgoNeuT Experiment

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Outline

- **Overview of the ArgoNeuT experiment**
- **ArgoNeuT's published results**
  - Large sample of neutrino induced muons
  - Inclusive ν_μ charged current differential cross-section
  - Study of electron recombination using highly ionizing particles
- **Analyses in progress**
  - Inclusive ν_μ charged current differential cross-section
  - Study of nuclear final state interactions (FSI)
  - Neutral current π^0 analysis
- **Outlook & Conclusions**

LArTPC's

Liquid Argon is an excellent choice for neutrino detectors:

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by my boss Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

→ **Dense**
40% more dense than water

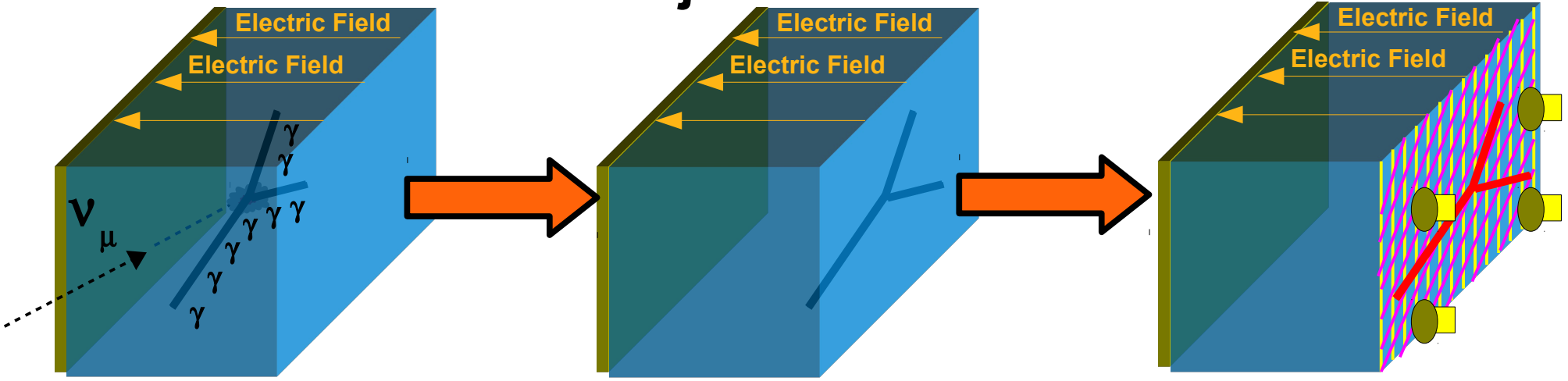
→ **Abundant**
1% of the atmosphere

→ **Ionizes easily**
55,000 electrons / cm

→ **High electron lifetime**
Greek name means "lazy"

→ **Produces copious scintillation light**
Transparent to light produced

Time Projection Chamber



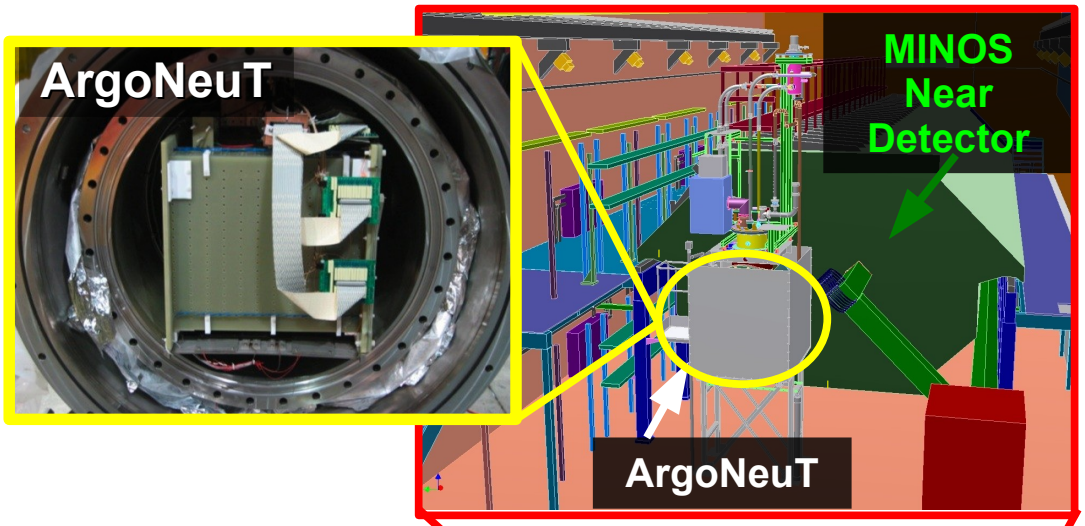
Neutrino interaction in LAr produces ionization and scintillation light

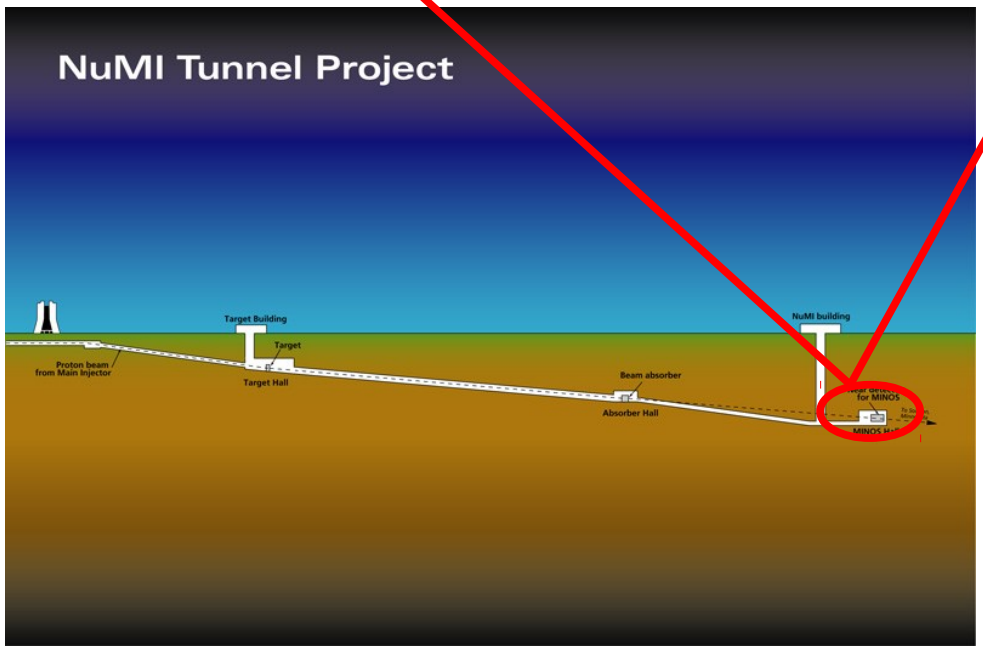
Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

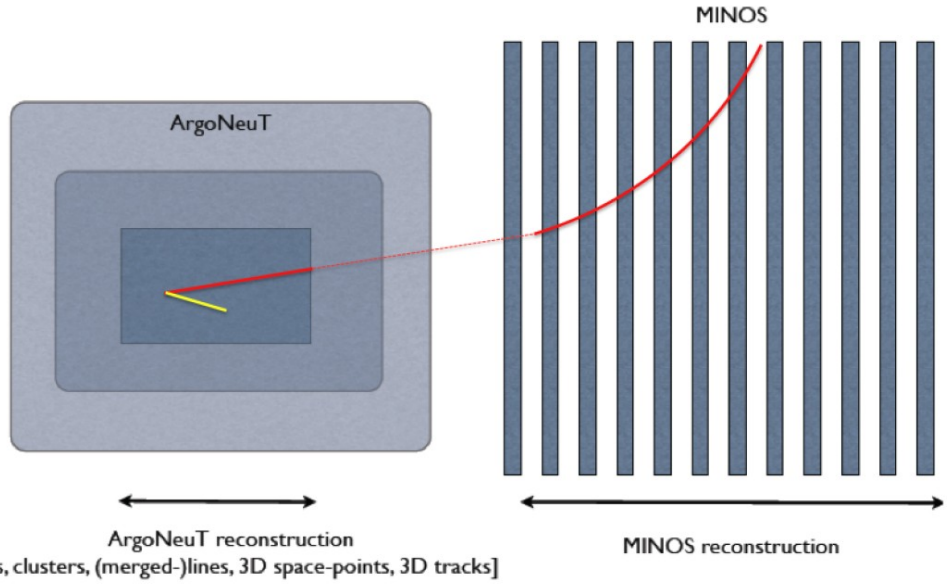
ArgoNeuT
(*Argon Neutrino Teststand*)

MINOS TDR: NUMI-L-337, FERMILAB-DESIGN-1998-02

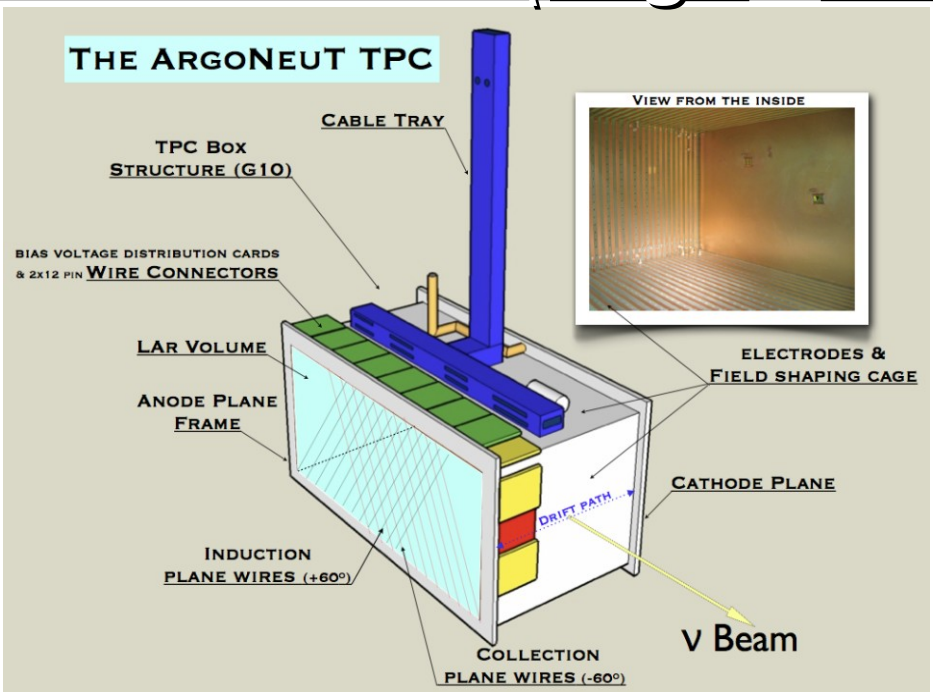


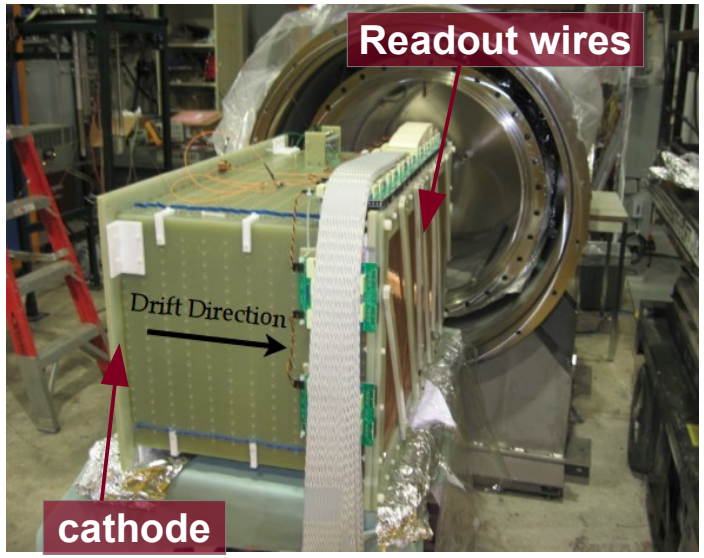


- **ArgoNeuT was the first Liquid Argon TPC in a neutrino beam in the U.S.**
  - Located in the NuMI beam at Fermilab
  - Utilized the MINOS near detector as a muon spectrometer (sign & momentum determination)



ArgoNeuT
(Argon Neutrino Teststand)





TPC dimensions	$40\ h \times 47\ w \times 90\ l\ \text{cm}^3$
TPC (active) volume	170 liters
Max. Drift Length (TPC width)	$\ell_d = 470$ mm
# of wire-planes	3 (2 instrumented - I, C)
Interplane gaps width	$\ell_g = 4$ mm
Wire pitch (normal to wire direction)	$\delta s = 4$ mm (all planes)
Wire Type	Be-Cu Alloy #25, diam. 152 μm
# of wires (total) Shield plane (S) Induction plane (I) Collection plane (C)	705 225 (non-instrumented) 240 (instrumented - w-index: n_w^I) 240 (instrumented - w-index: n_w^C)
Wire Orientation (w.r.t. horizontal)	90^o, $+60^o$, -60^o (S, I, C)
Non-destructive Configuration Drift volume S-I gap I-C gap	EF nominal (Transparency Ratio) $E_d = 500$ V/cm E_{g1}=700 V/cm ($r_T = 1.4$) E_{g2}=900 V/cm ($r_T = 1.3$)
Drift Velocity (at nominal field)	1.59 mm/μs
Max. Drift Time (at nominal field)	$t_d = 295\ \mu$s

Cliffnotes

0.26 Tons (active mass)

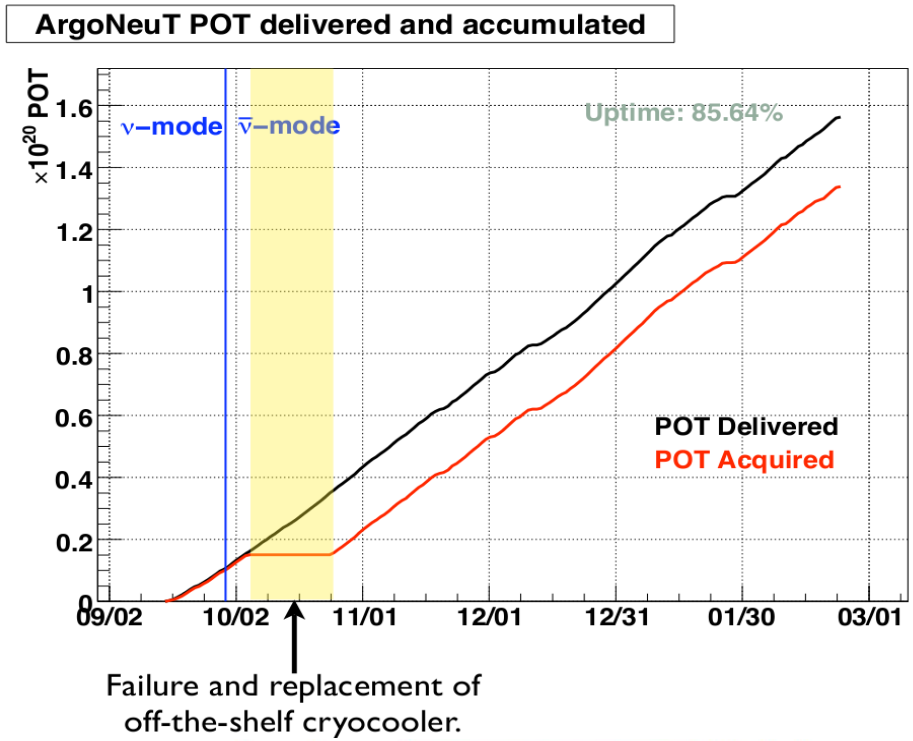
0.40 m tall x 0.47 m wide (drift length) x 0.90 m long

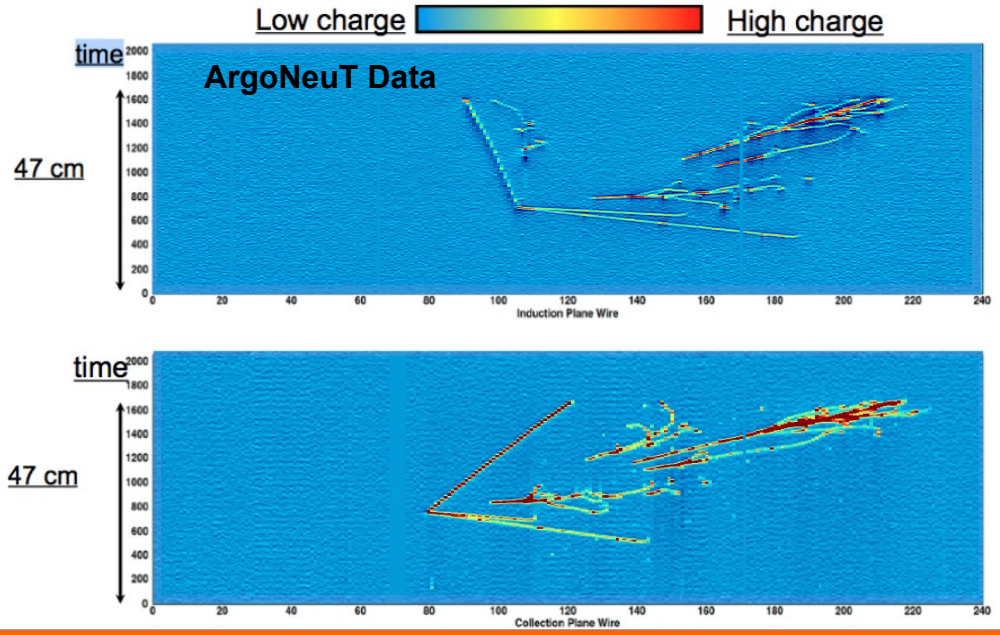
480 wires (4mm pitch) (*Oriented +/- 30° w.r.t vertical)*

No light detection system

ArgoNeuT TDR: JINST 7 P10019 (2012)

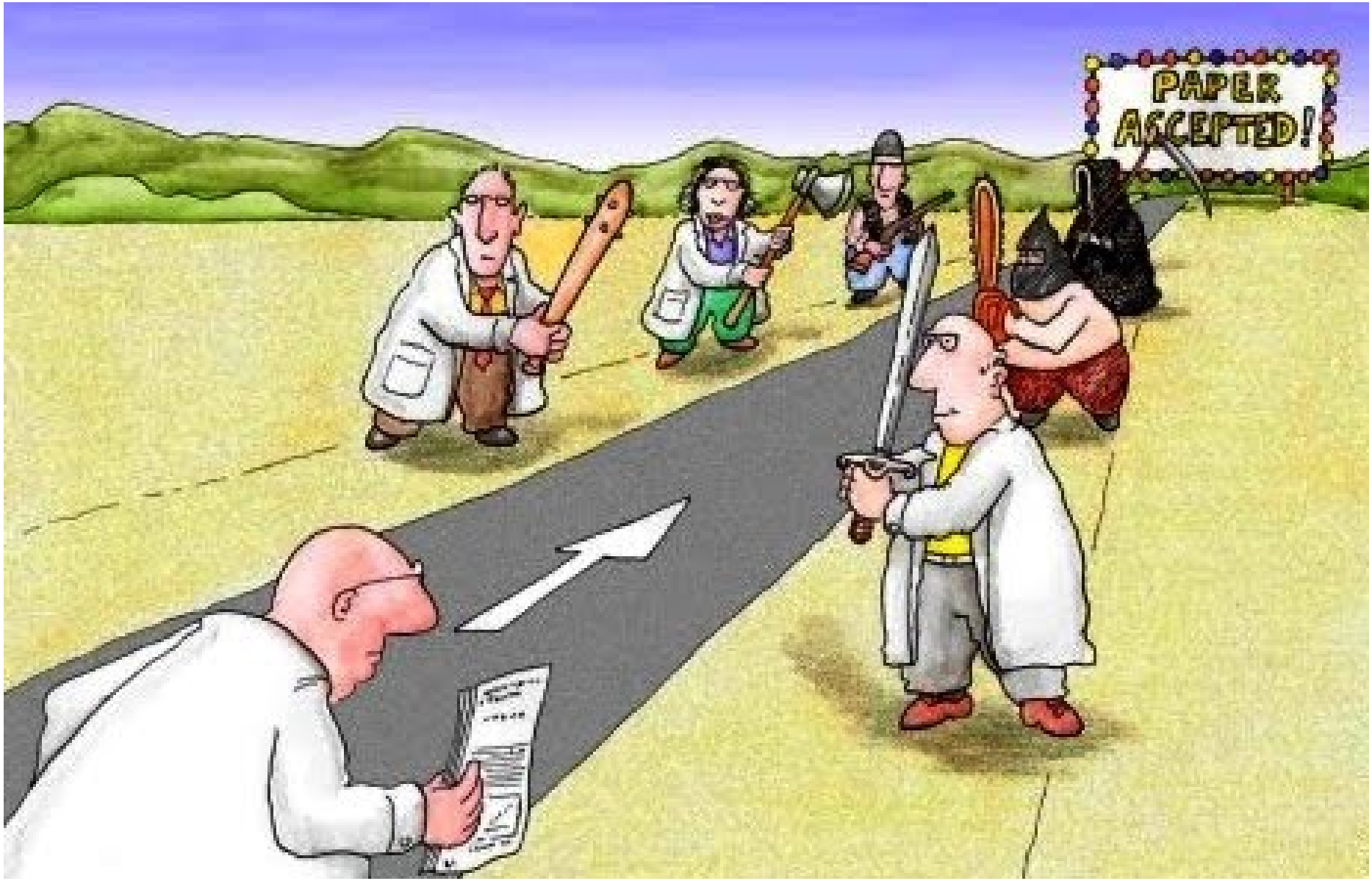
ArgoNeuT: Overview





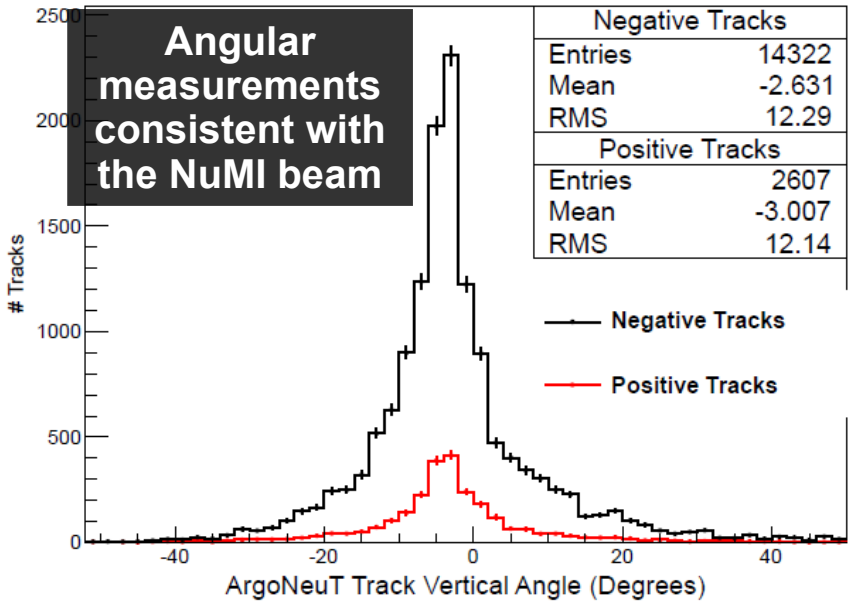
- **ArgoNeuT took data from 09/2009 – 02/2010**
  - 2 weeks in Neutrino mode (0.085 x10^{20} POT)
  - 4 months in Antineutrino mode (1.2 x 10^{20} POT)
- **Collected high quality neutrino data in the range of 0.1→20 GeV**
  - Measure ν-Ar cross-sections
  - Study calibration of LAr detectors
  - Study nuclear effects
    - Final state interactions (FSI)
    - Nucleon/Nucleon Correlation
  - Develop automated reconstruction techniques

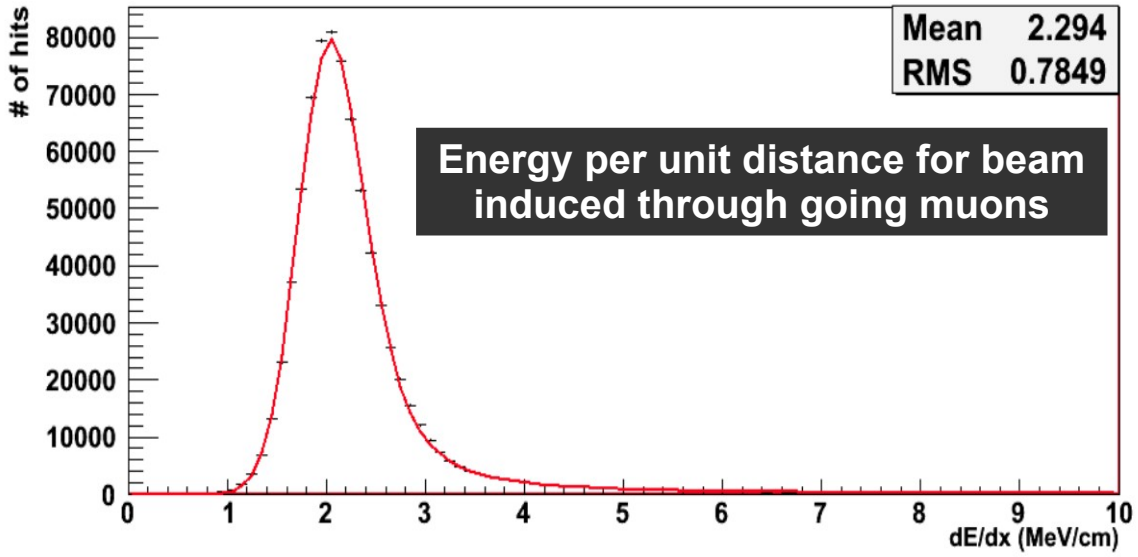
ArgoNeuT's Published Results



Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector

JINST 7 P10020 (2012)



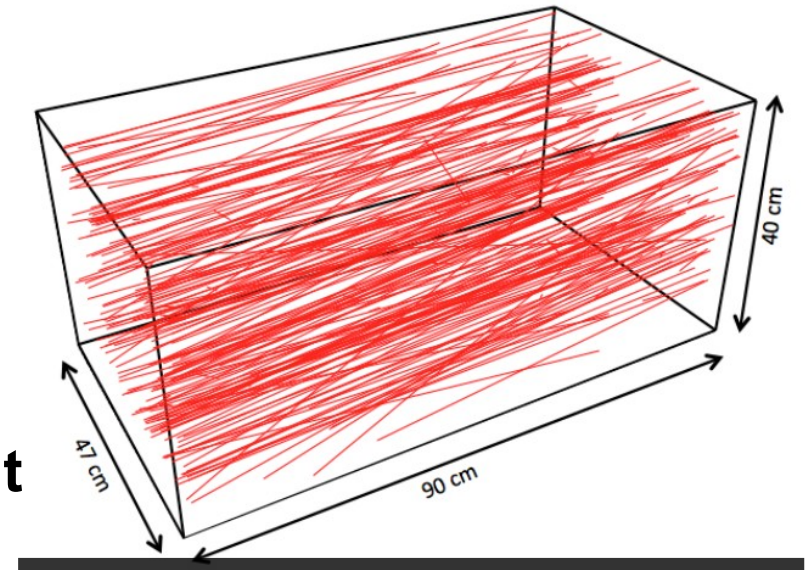


Paper released from ArgoNeuT

Analysis only used 2 weeks of neutrino data

Demonstrates geometric and calorimetric reconstruction capabilities

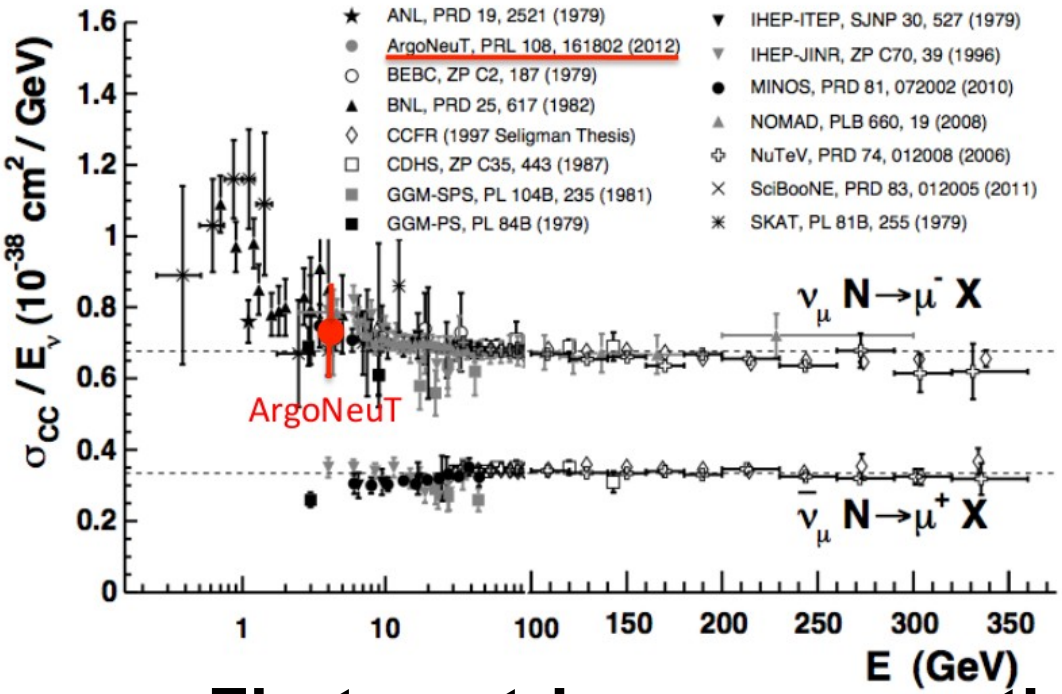
Provides calibration input into charge-current analyses

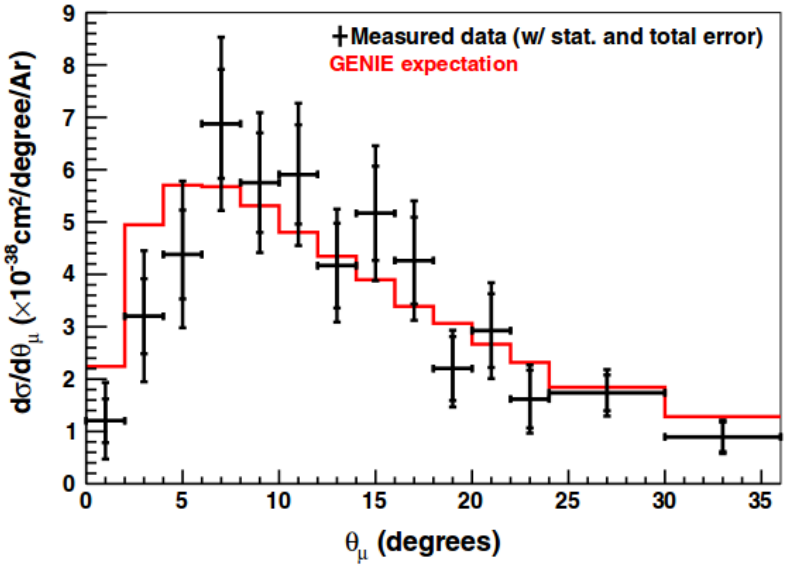


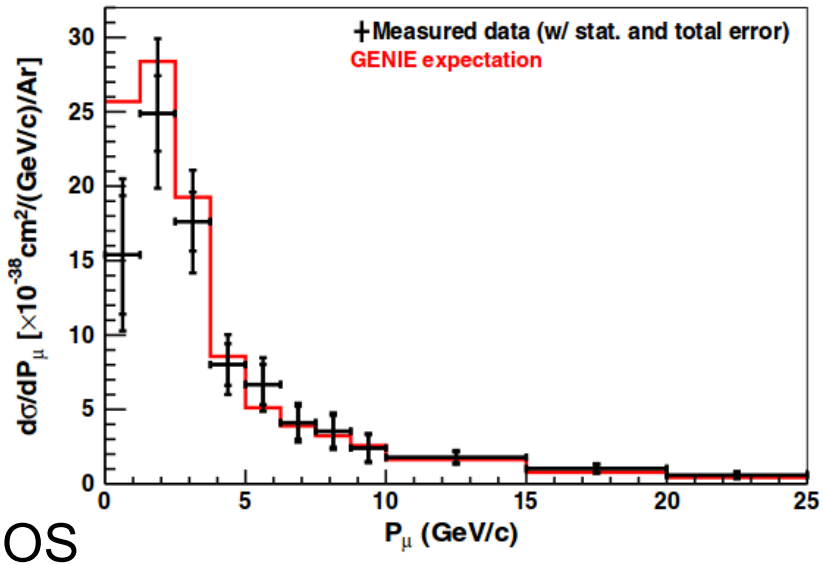
Reconstructed through-going muons

Inclusive ν_μ Charged Current Differential Cross-section

PRL 108, 161802 (2012)







First neutrino cross-section measurement done on Argon!

Analysis only used 2 weeks of neutrino data

Straightforward analysis

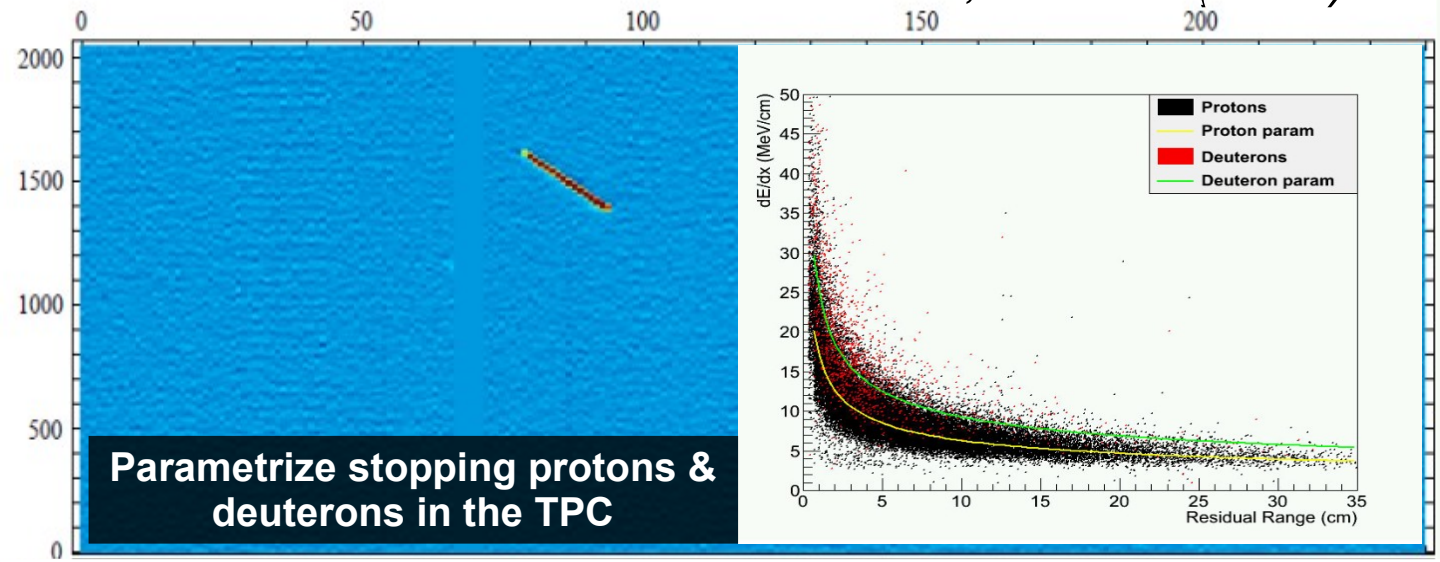
→ Interaction vertex in the fiducial volume

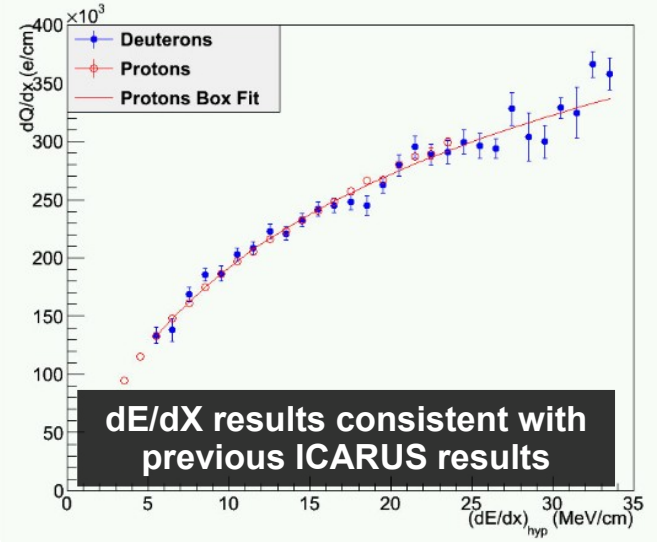
→ Reconstructed track which is matched to MINOS

→ Use MINOS for sign determination (choose μ^-) and momentum measurement

A study of electron recombination using highly ionizing particles in the ArgoNeuT Liquid Argon TPC

JINST 8, P08005 (2013)





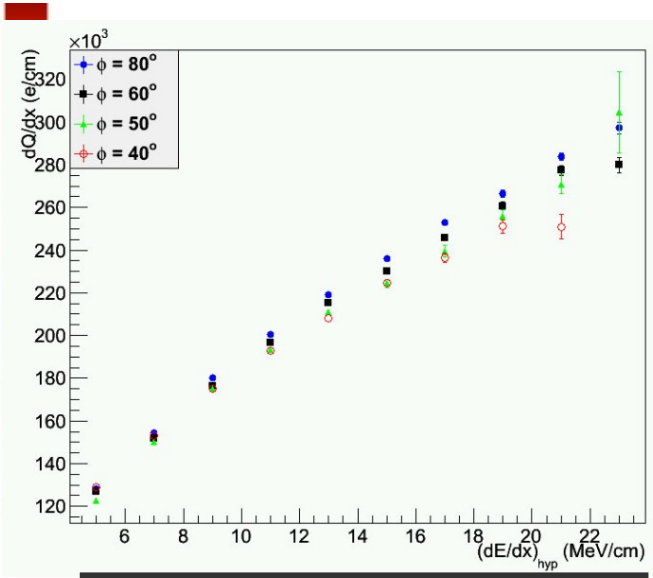
Study the electron-ion recombination effects using contained proton/deuteron tracks found in ArgoNeuT

Small angular dependence of recombination

→ Collected charge is reduced by 5%-10% at small angle (w.r.t. to Electric Field)

→ Less than the 25% loss predicted by the Jaffe Columnar theory and simulations.

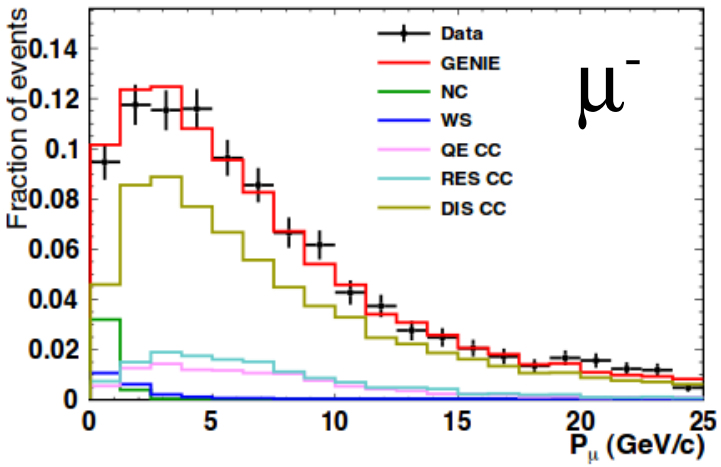
dE/dx results extended beyond the ICARUS result with smaller uncertainties

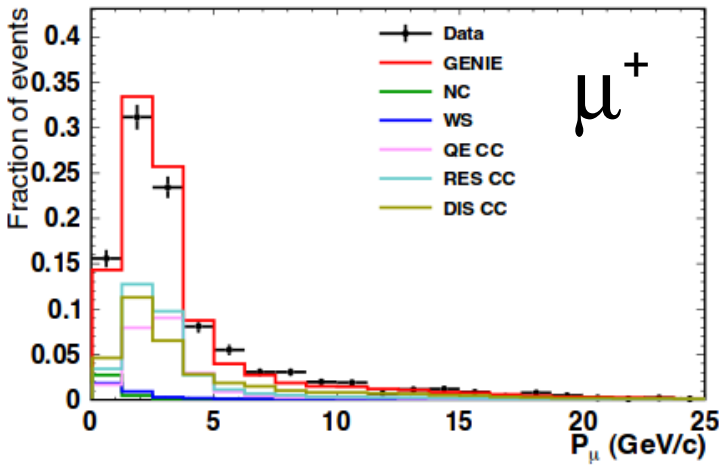


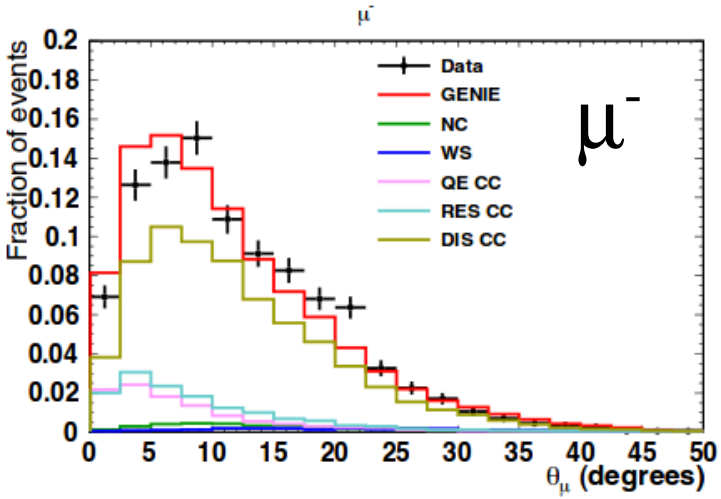
ArgoNeuT Analyses in Progress

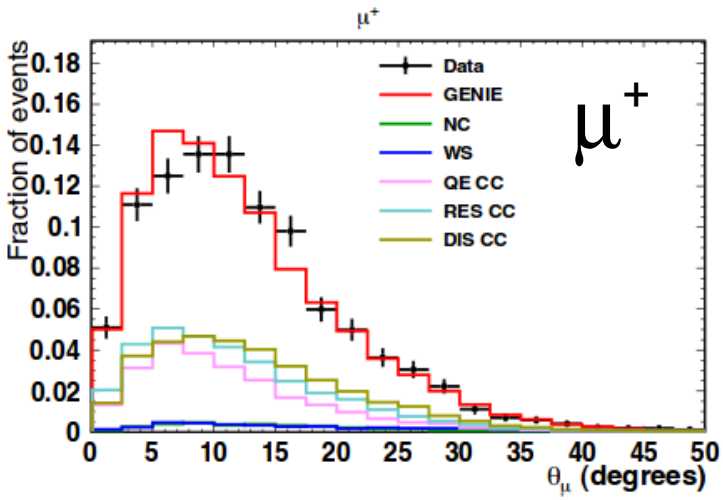
Inclusive $\bar{\nu}_\mu$ Charged Current Differential Cross-section

Paper in preparation









Similar analysis to what was done in neutrino mode

→ Interaction vertex

→ Track matched to MINOS

→ Use MINOS for sign determination (choose μ^+ or μ^-) and momentum measurement

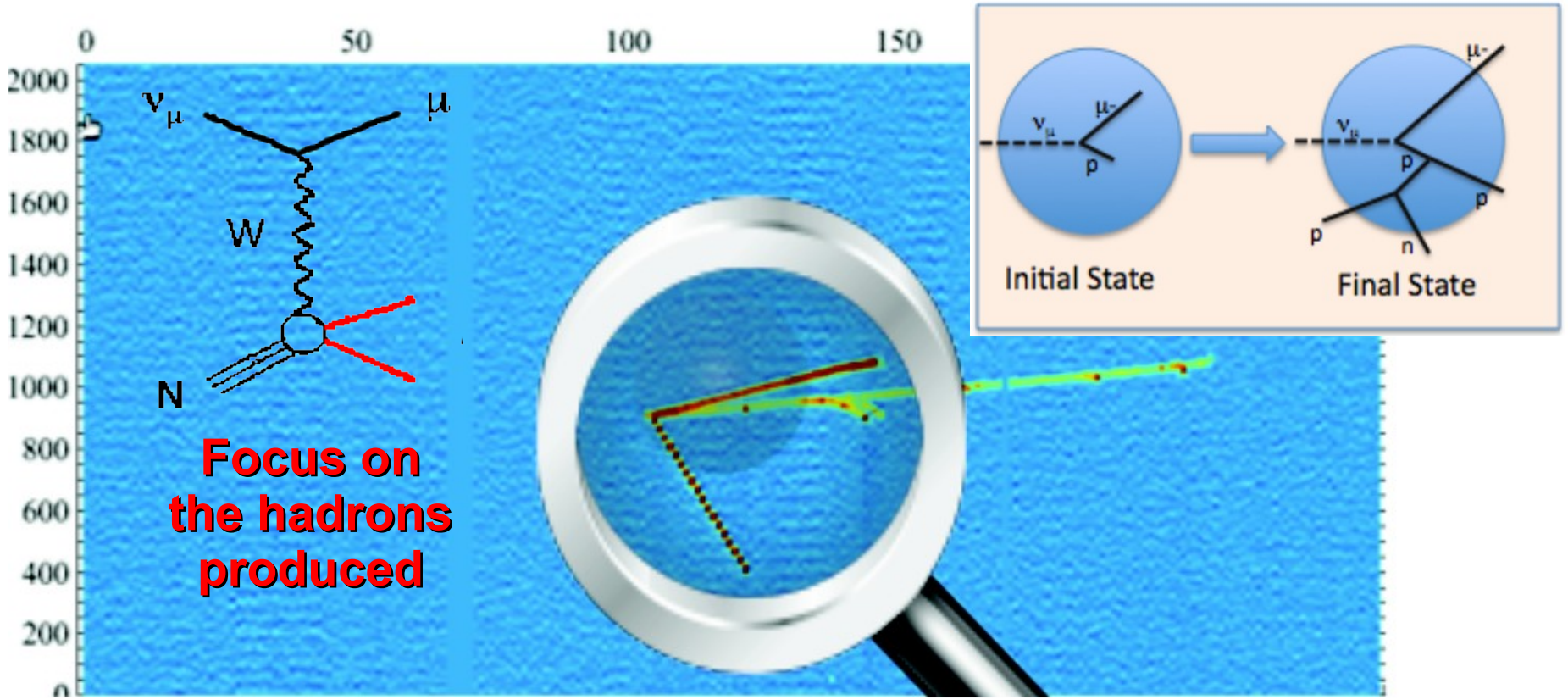
→ 8 times the data available in anti-neutrino mode

→ Beam composition allows you to select both neutrino (μ^-) and anti-neutrino (μ^+) interactions

→ Working on final flux normalizations and uncertainties

Study of Nuclear Final State Interactions (FSI)

Paper in preparation



Nuclear effects play an important role in neutrino-nucleus scattering

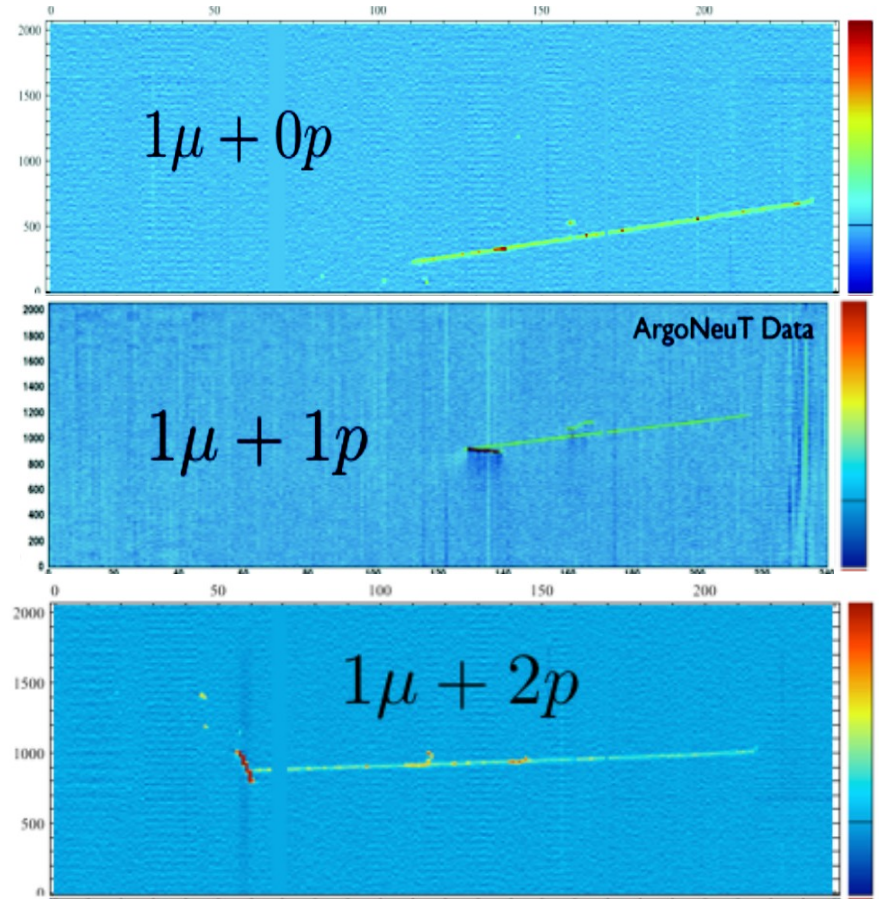
Intra-nuclear scattering and nucleon-nucleon correlations can cause quasi-elastic events to be accompanied by additional final state particles

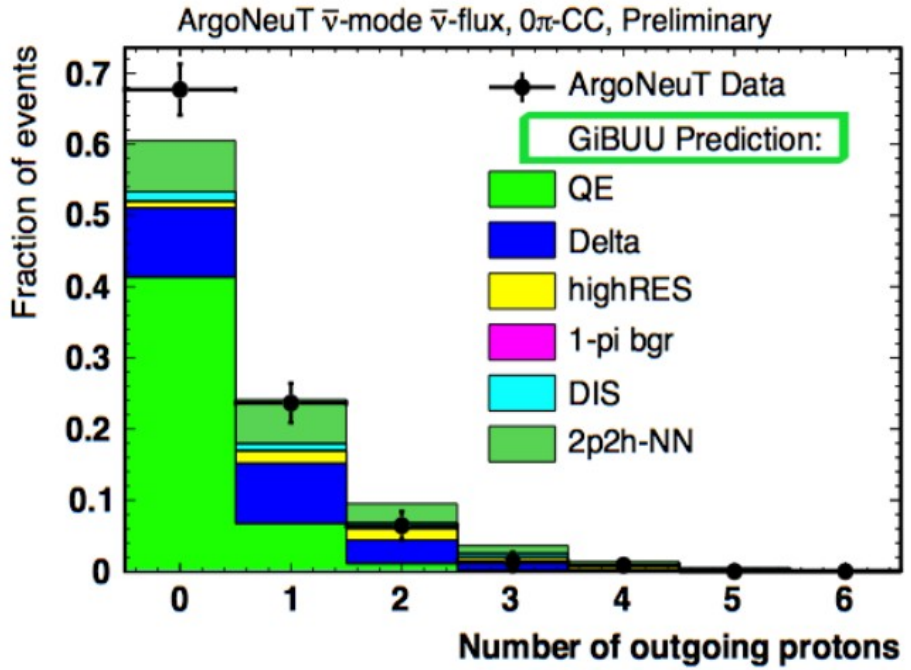
ArgoNeuT is able to **observe and reconstruct** these final state particles

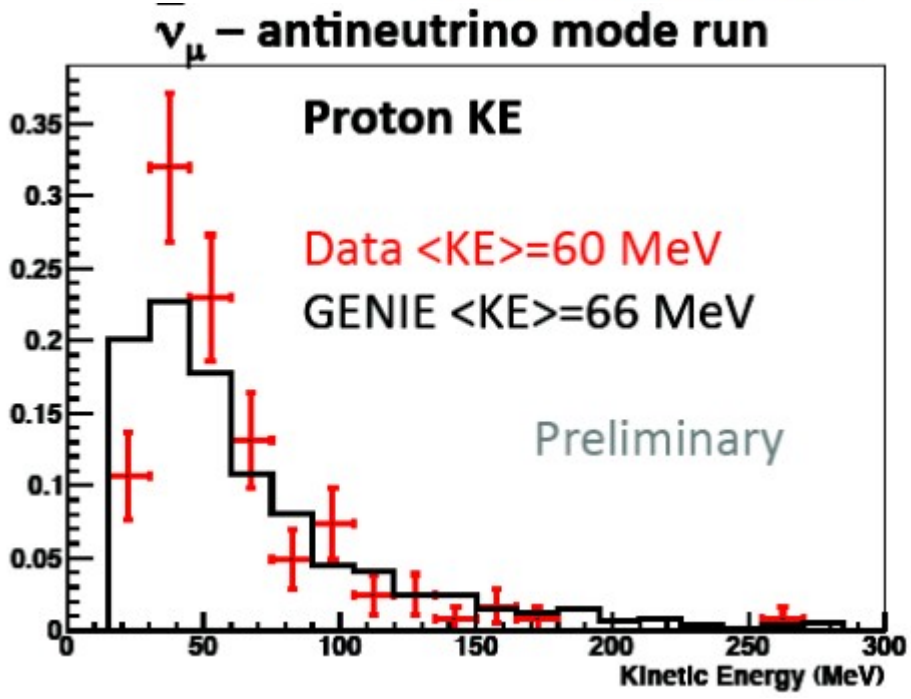
Allows classification of events based on **final state topology**

Study of Nuclear Final State Interactions (FSI)

Paper in preparation



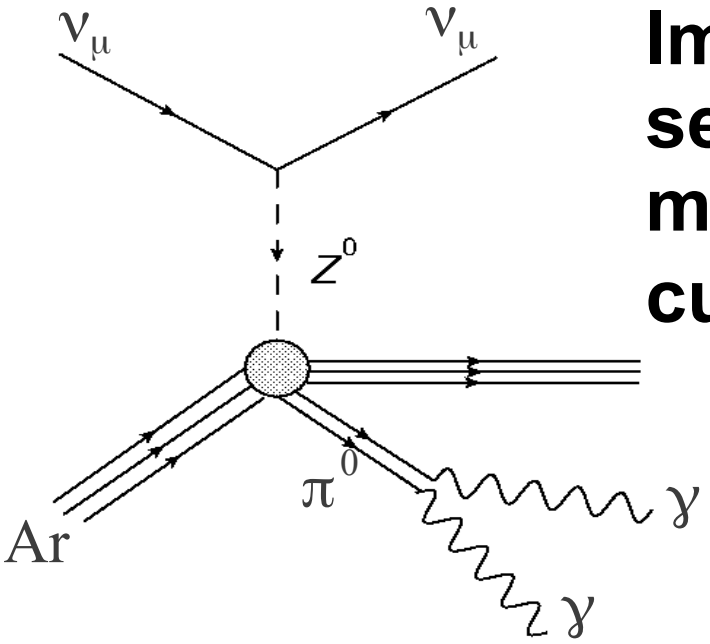




Measurements of **proton multiplicity** and **proton kinematics** in these multiple proton final states provides powerful insight into FSI

→ LAr experiments will be able to discriminate various FSI models based on data

Neutral Current π^0 analysis



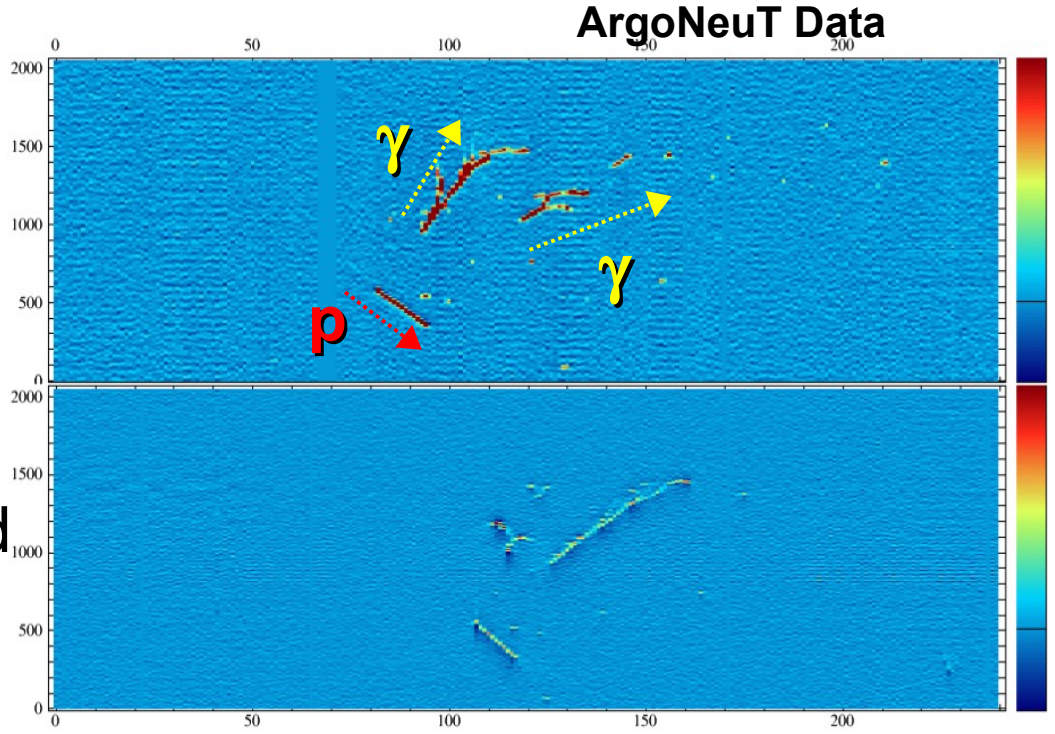
Important channel for both oscillation searches and cross-section measurements comes from neutral current π^0 production.

→ Particularly insidious background for ν_e appearance searches

→ Notoriously difficult topology to reconstruct

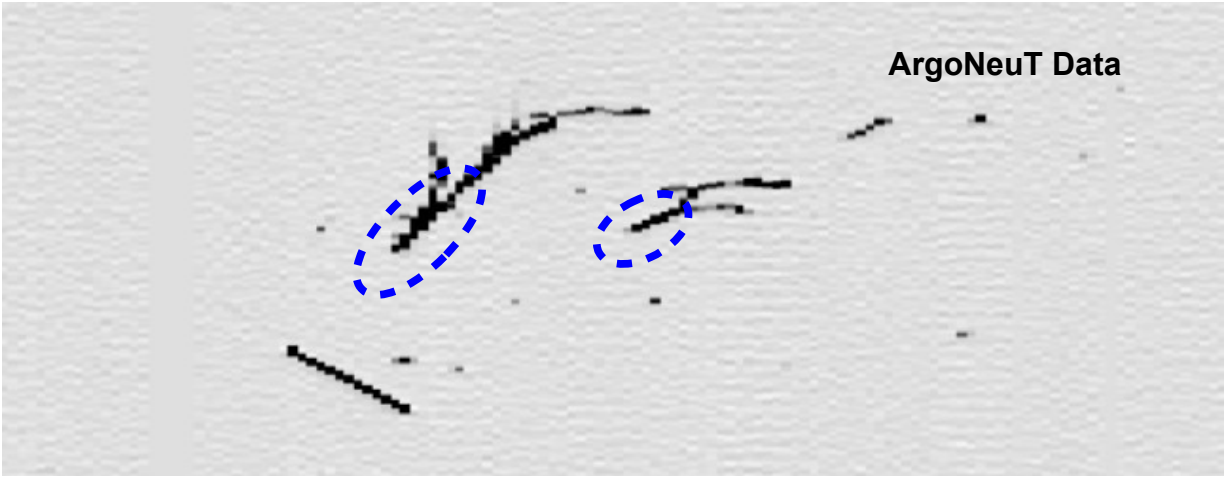
The ArgoNeuT detector is to small to contain the majority of photon showers produced from π^0's

→ However, it should still be possible to utilize this data and look for NC π^0 production



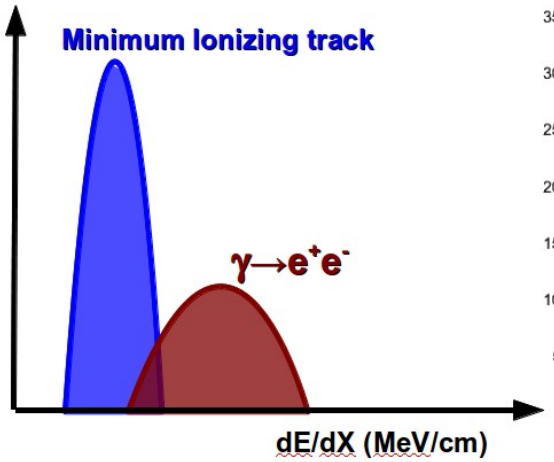
Neutral Current π^0 analysis

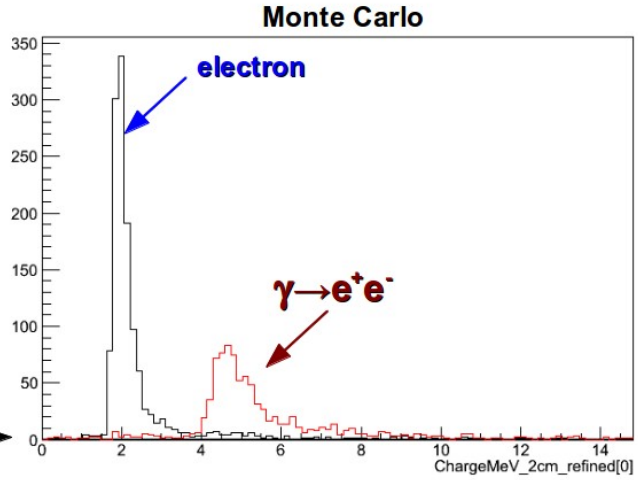
Break the clusters into smaller "track-like" segments and reconstruct the shower's "track-segments" and analyze the dE/dX profile of the track segments



Example of how we expect the dE/dX profiles to look like

→ Method utilized in e/γ separation studies



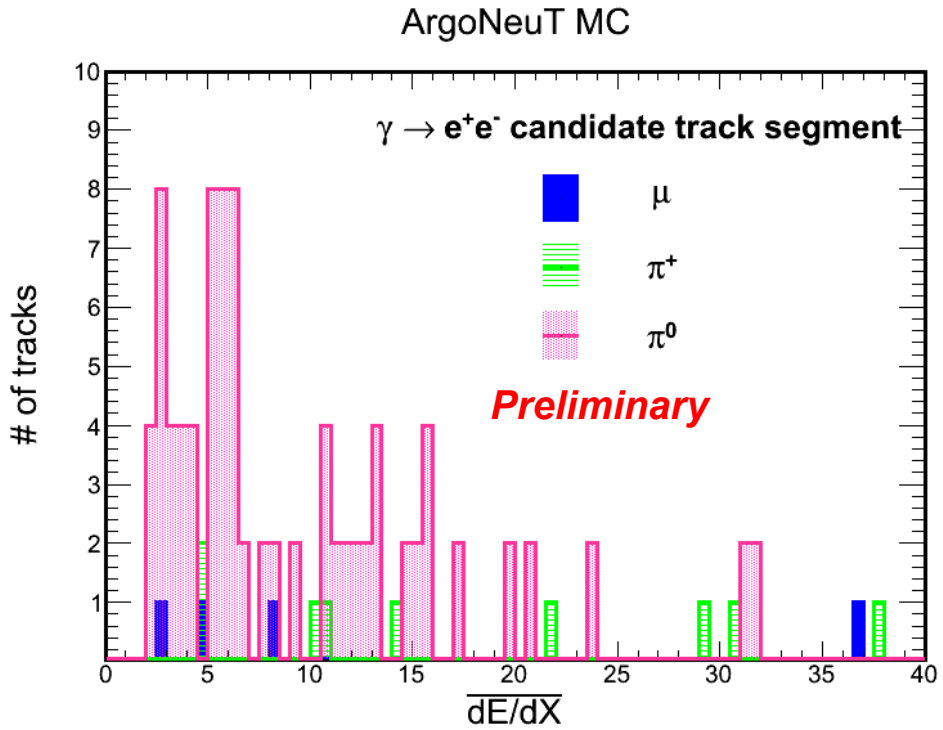


Begin by selecting a sample of events likely to be neutral current

→ Require no track matched to MINOS
→ Require at least to clusters of energy found in each wire plane
→ Require a reconstructed vertex in the detector

Neutral Current π^0 analysis

Candidate neutral current π^0 events should have **two highly ionizing "track-segments" consistent with dE/dX profile for a photon pointed back to a common point**



Looking at the dE/dX of these "track-segments" in MC and data show early promise of potential event discrimination

$\gamma \rightarrow e^+e^-$ candidate track segment requirement

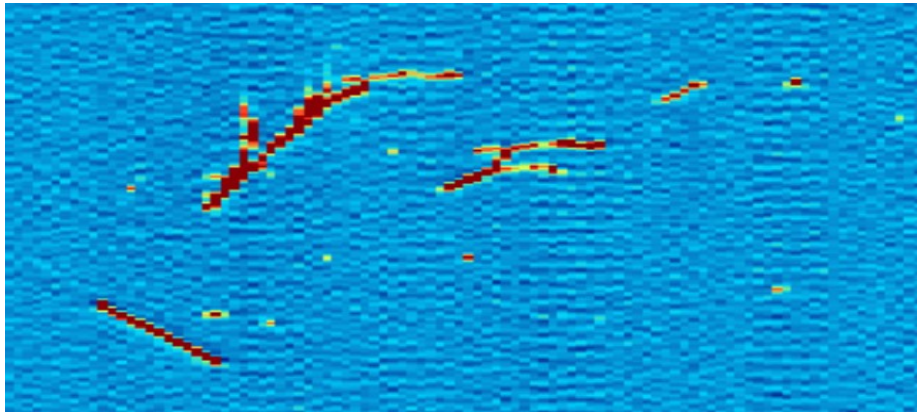
- Greater than 80% of the hits must have a dE/dX > 3 MeV/cm ***(not minimum ionizing)***
- Track segments residual range < 10 cm ***(trying get the start of the shower)***
- Track must start within 10 cm of a reconstructed vertex ***(trying get the start of the shower)***

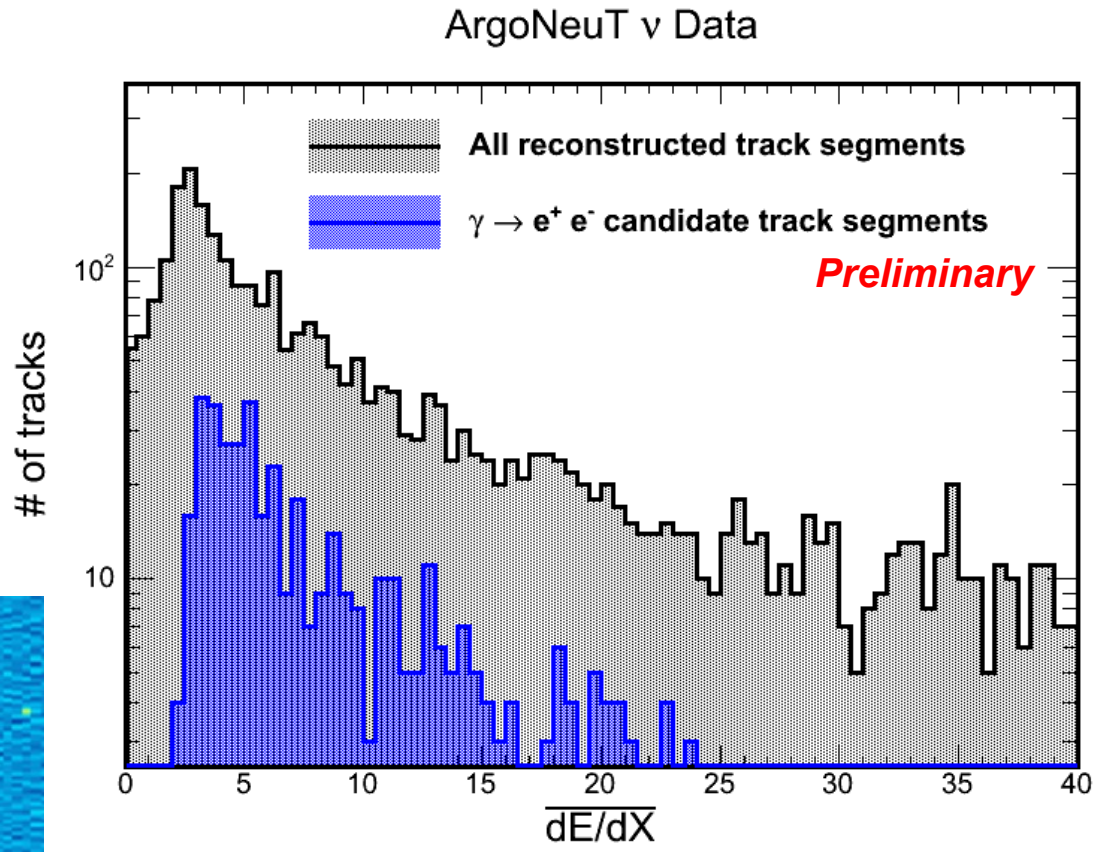
See back-up slides for more details about reco-cuts

Neutral Current π^0 analysis

Preliminary look at Neutrino mode data applying our selection looks promising

→ Events with two $\gamma \rightarrow e^+e^-$ track segments in the event are still under investigation

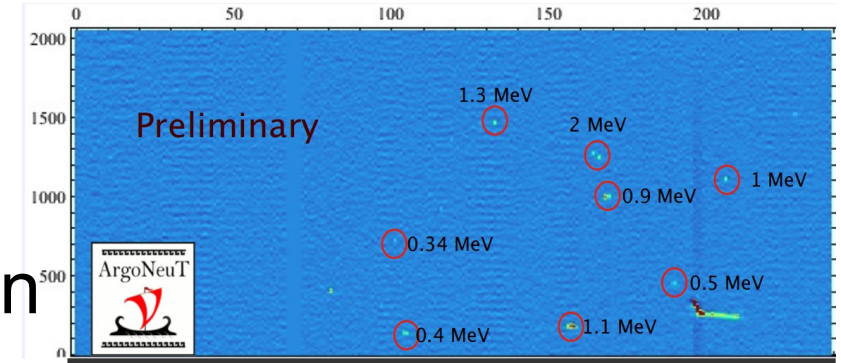




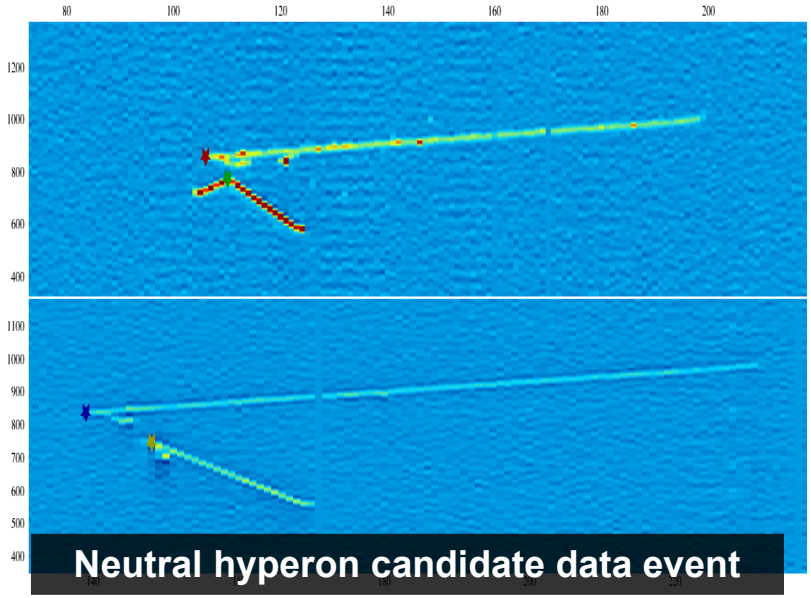
More detailed reconstruction studies of these events in progress as well as processing the Antineutrino mode data...updates coming soon!

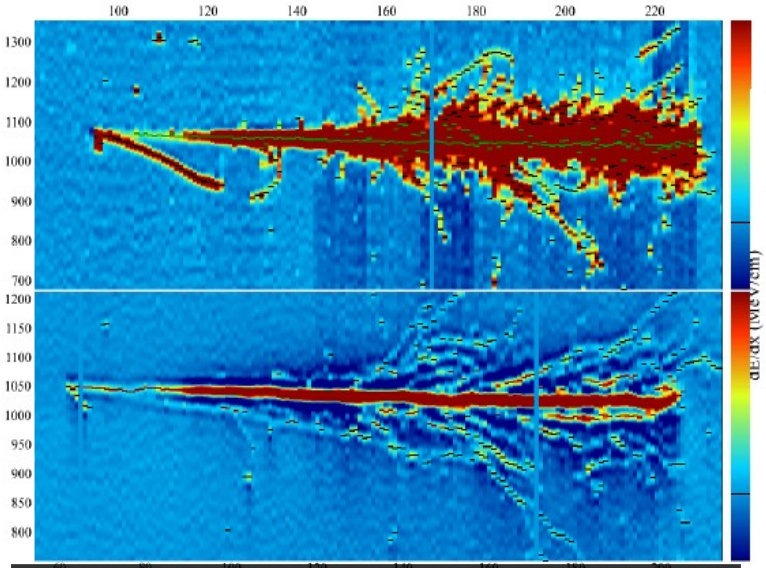
Other ongoing analyses....

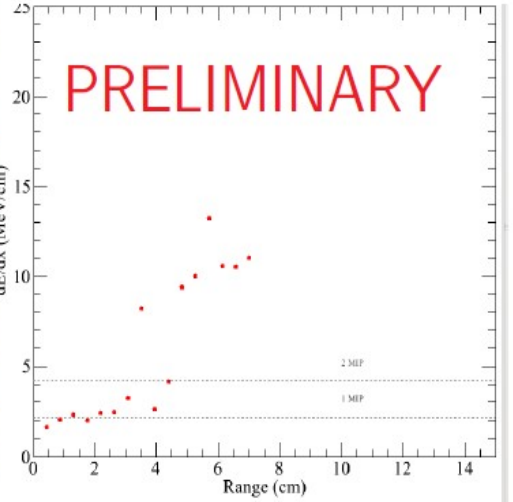
- Nuclear de-excitation photons
- Coherent pion production
- Electron neutrino event identification
- dE/dX electron / photon identification
- Search for neutral hyperon production



De-excitation gamma candidate event


Neutral hyperon candidate data event


Electron neutrino candidate event



Outlook & Conclusions

- **The ArgoNeuT experiment has already demonstrated the power of LAr technology in neutrino interactions**
  - 4 publications thus far (TDR + 3 physics results) based on ~4 months of data in the NuMI beam at Fermilab
- **Analysis of the data continues with interesting results forthcoming**
  - Inclusive anti-neutrino charged current cross-section
  - Study of nuclear final state interactions in LAr
  - Neutral Current π^0 analysis
- **Looking forward to a bright future with LArTPC's with the forthcoming startup of the MicroBooNE experiment**
  - See Andrzej's talk immediately following this one!


Thank you for your attention
Stay tuned for more exciting results from ArgoNeuT

Back-up Slides

ArgoNeuT Collaboration

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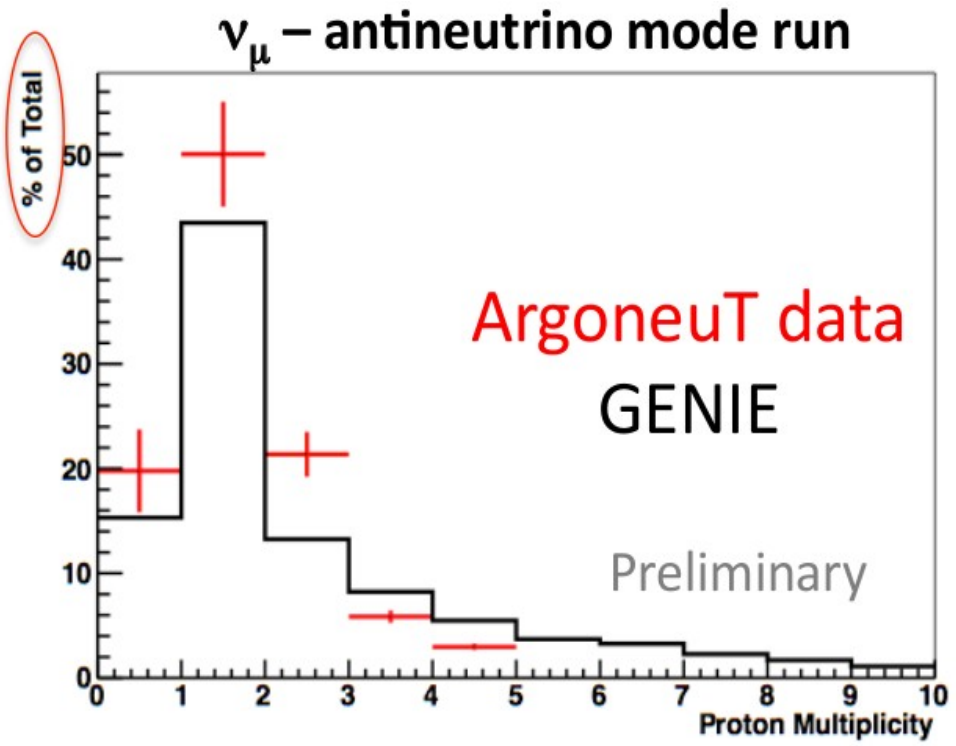
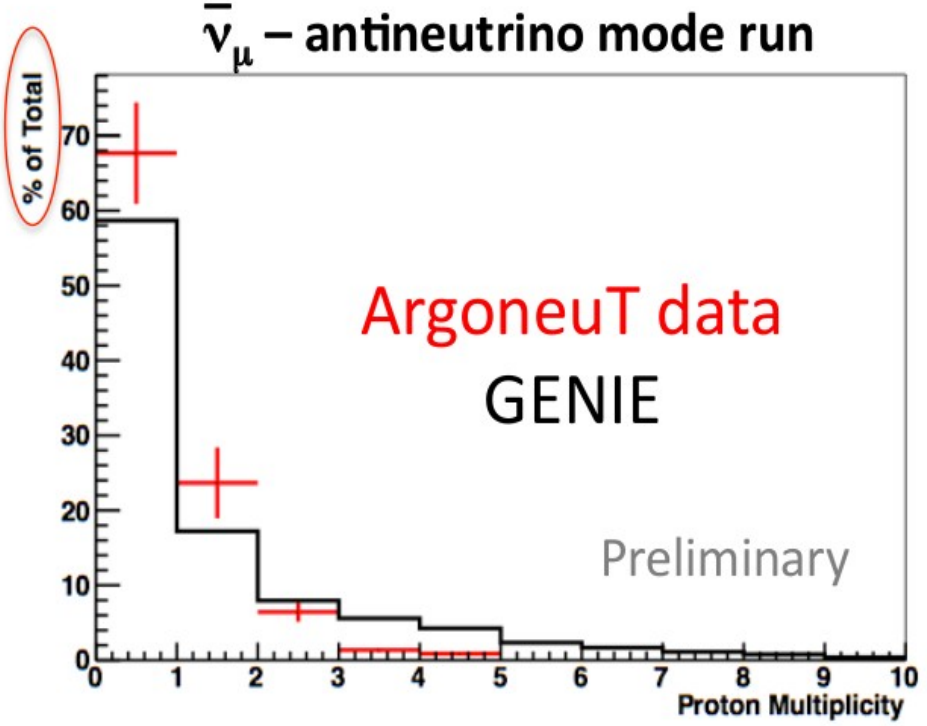
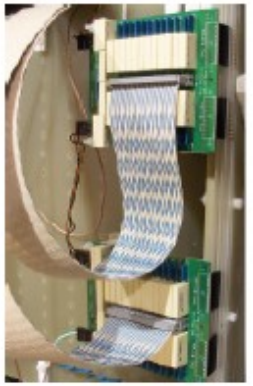
Study of Nuclear Final State Interactions (FSI)

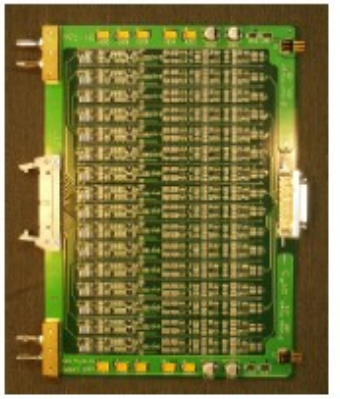




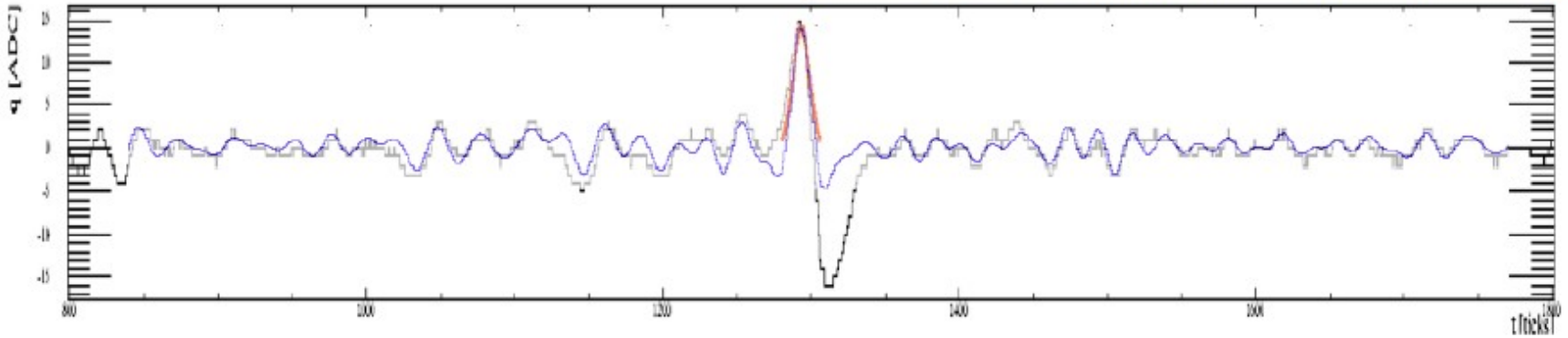
ArgoNeuT Electronics

- "Warm" JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Currrent trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)

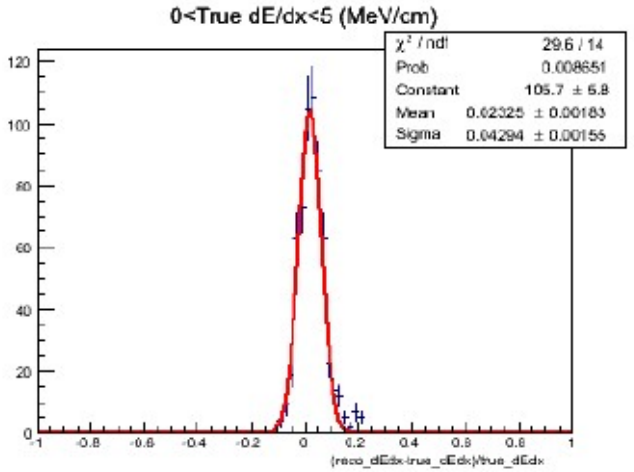


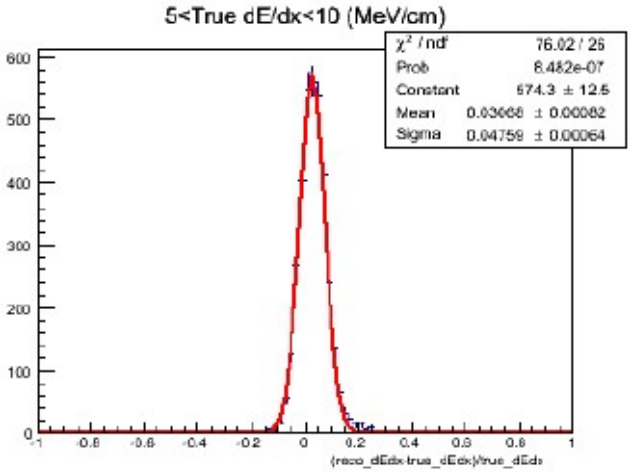


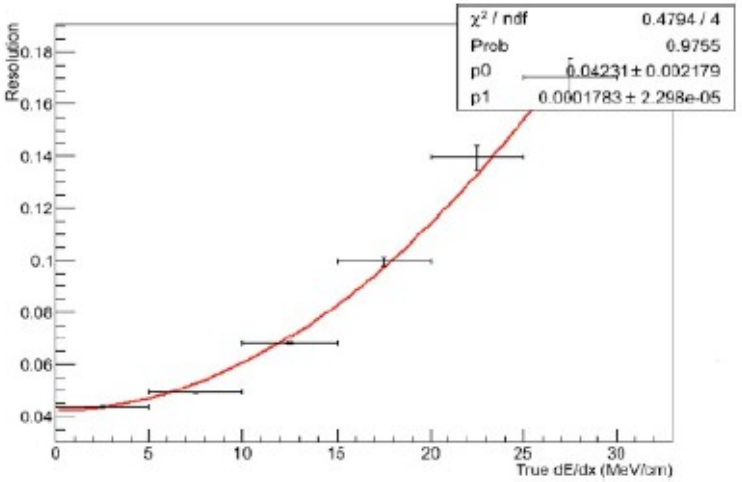
PreAmp stage - FET Voltage Gain	0.5 mV/fC
Digitizer Module (ADF-2)	
ADC range	10 bit
ADC Gain	0.1881 ADC/mV
Sampling Time (FPGA)	δt=198 ns (0.03cm)
Electronics Charge Sensitivity	7.49 ADC/fC
Tot. Capacitance (Det. and Cables)	230 pF
Response to mip (Coll. wires)	$S/N \geq 15$



Energy Resolution

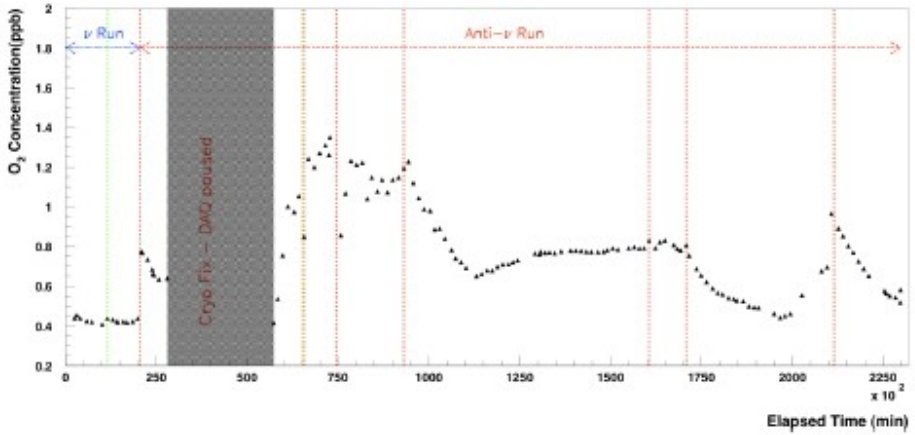


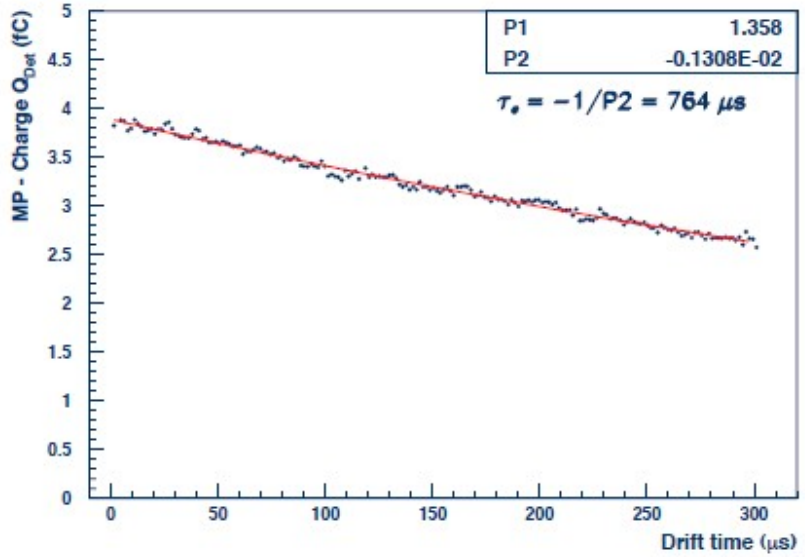




- Energy resolution $\simeq$5% for Minimum Ionizing Particles
- $\delta \frac{dE}{dx} = 0.042 + 1.78 \times 10^{-4} \frac{dE}{dx}^2$

Purity and Electron lifetime





- Electron lifetime calculated using passing muons.
- Converts to O_2 concentration
- Recirculation in gas.
- G10 in gas causes problems due to water outgassing
- Lots of lessons learned that are beneficial to new projects.

Nuclear Final State Interactions

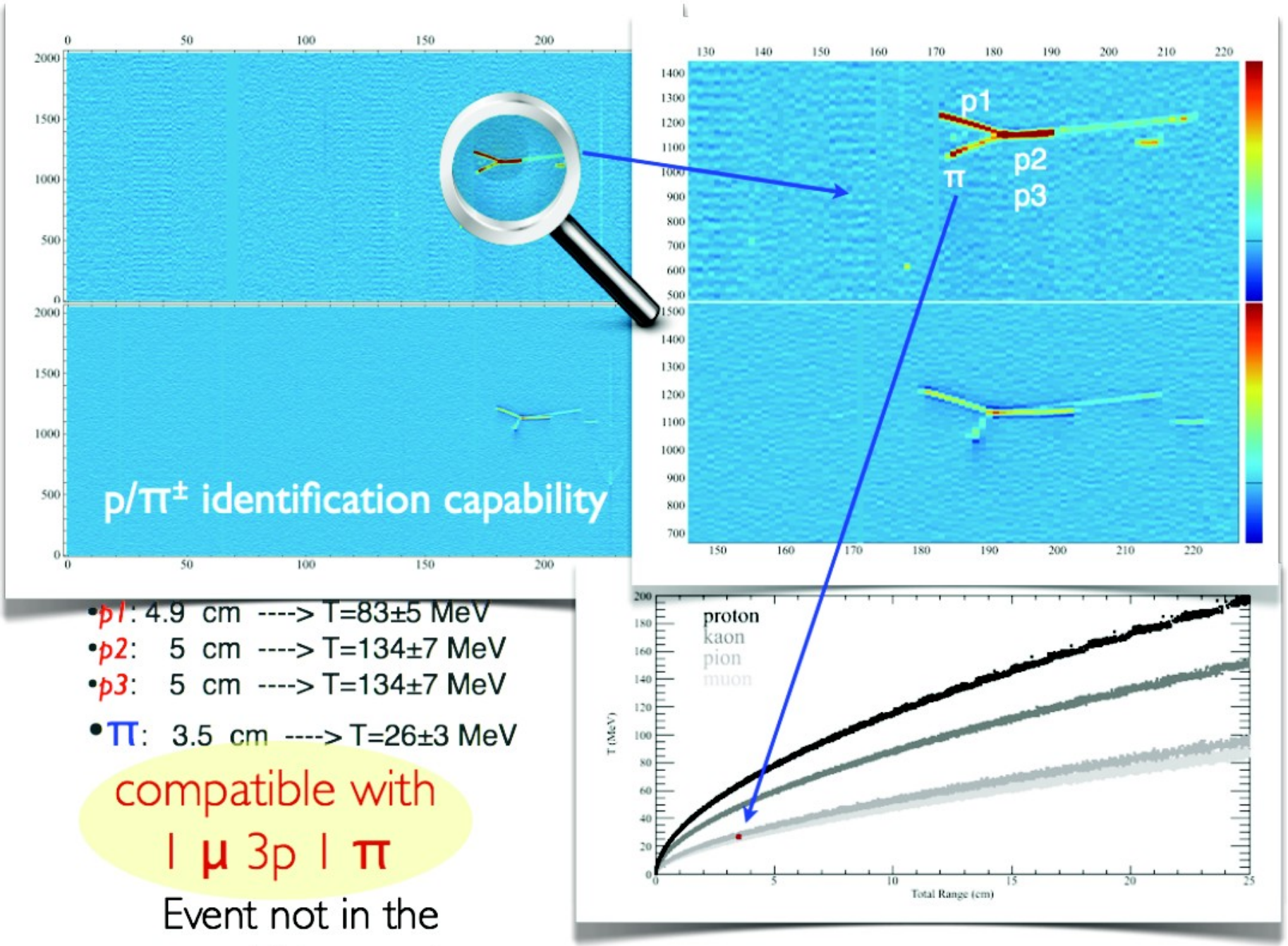
DATA-MC Comparison

- GENIE- Generates Events for Neutrino Interaction Experiments*
  - FSI: Intranuclear Cascade model (INC)
  - Preliminary meson exchange (MEC) model
- GIBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project**
  - FSI: Transport model
  - 2p2h-NN channel with 2 nucleons produced

*ArgoNeuT Coll. is grateful to GENIE authors, in particular S. Dytman and H. Gallagher, for many useful discussions

**ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

Muon + 3 Proton + Pion event



- p1: 4.9 cm ----> T=83±5 MeV
- p2: 5 cm ----> T=134±7 MeV
- p3: 5 cm ----> T=134±7 MeV
- π: 3.5 cm ----> T=26±3 MeV

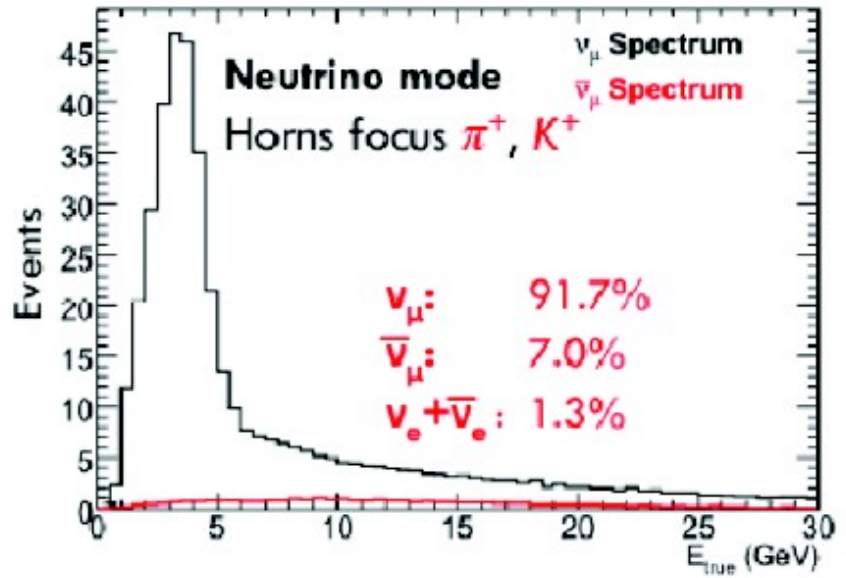
compatible with

1 μ 3p 1 π

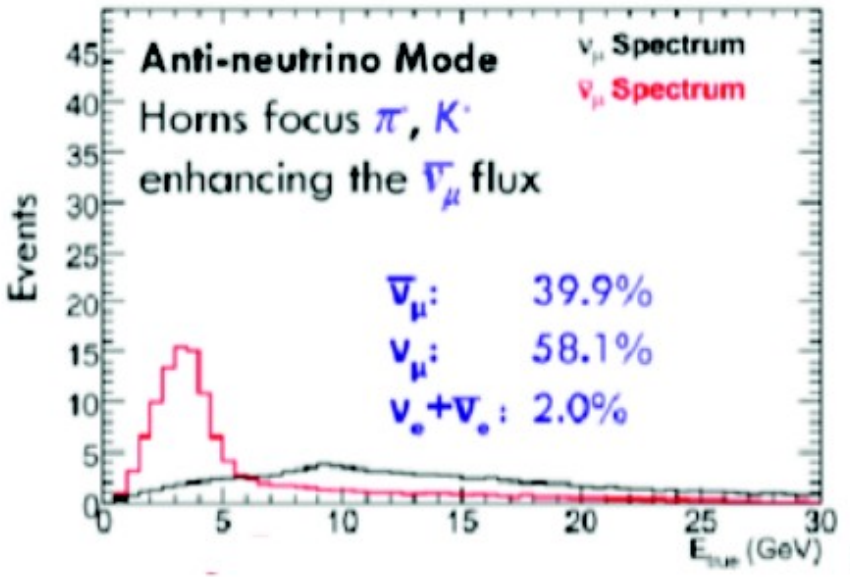
Event not in the muon+Np sample

NUMI spectrum in ArgoNeuT

ν-mode (2 weeks): 0.085e20 POT

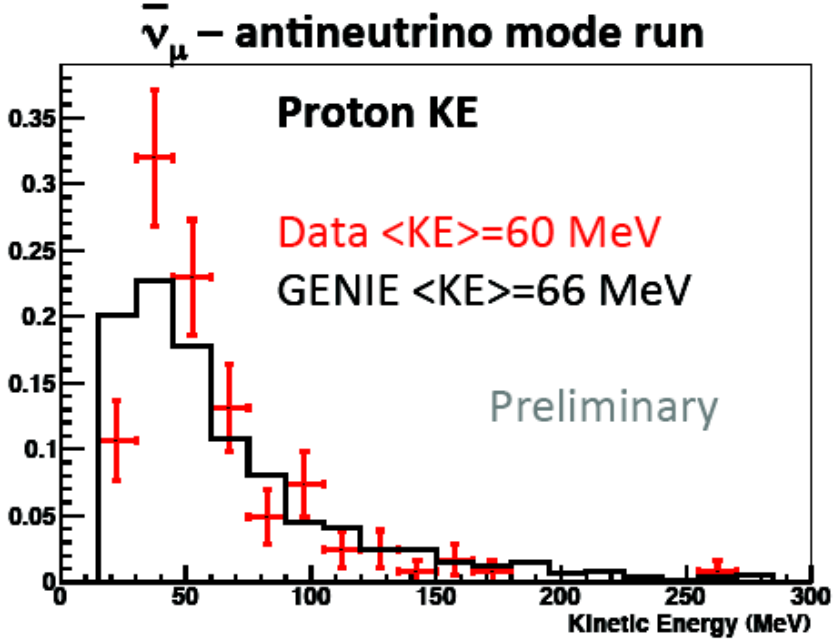


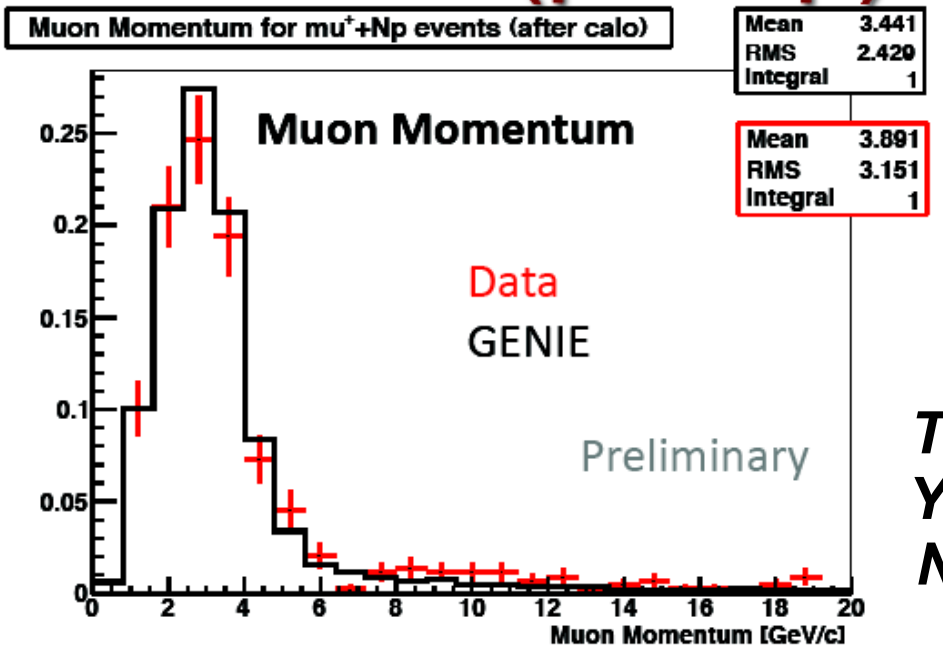
$\bar{\nu}$-mode (5 months): 1.2e20 POT



N

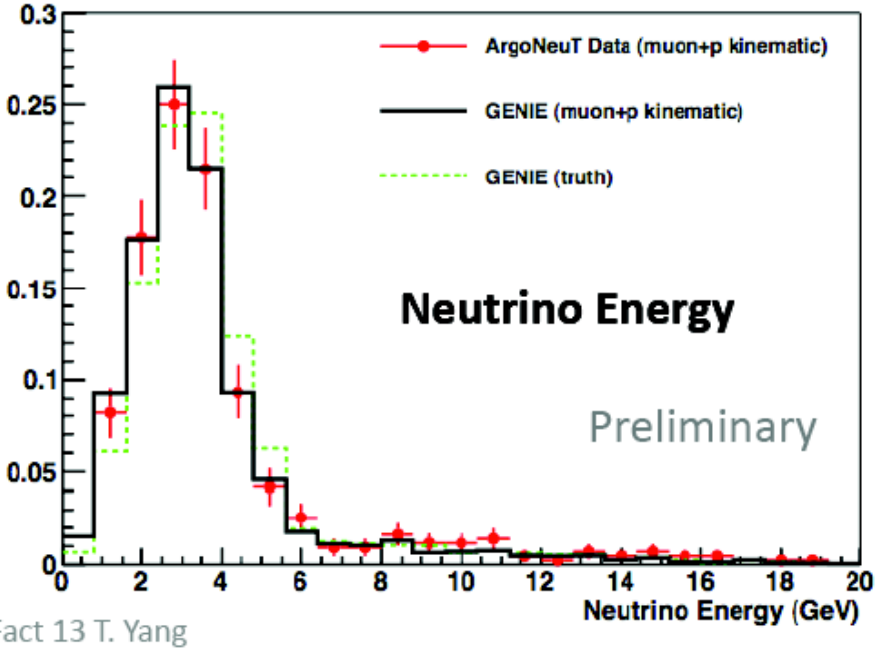
Kinematics Reconstruction (μ^++Np)



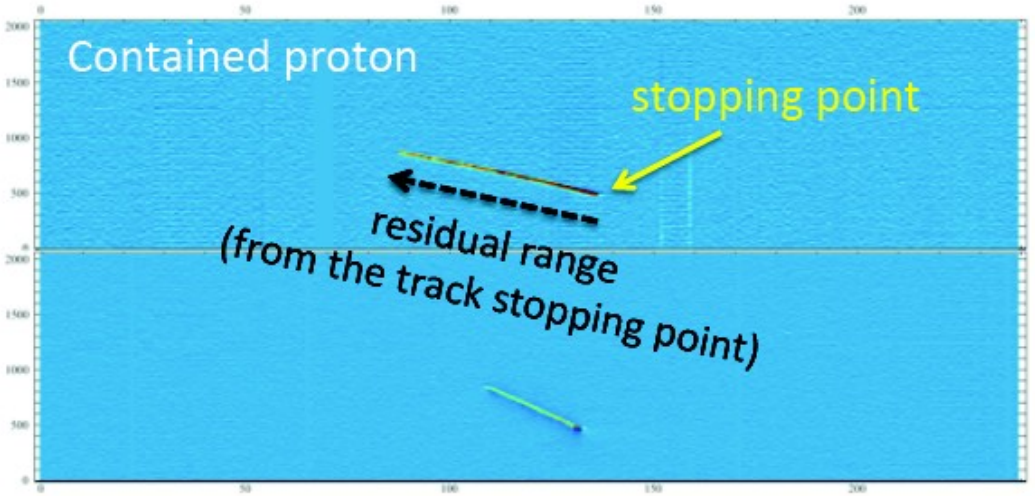


Slide from Tingjun Yang @ NuFact 2013

- Neutrino Energy $E_\nu = E_\mu + \Sigma T_p$
- No just muon information, model independent
- Other kinematic quantity reconstruction (Q^2 etc.) in progress



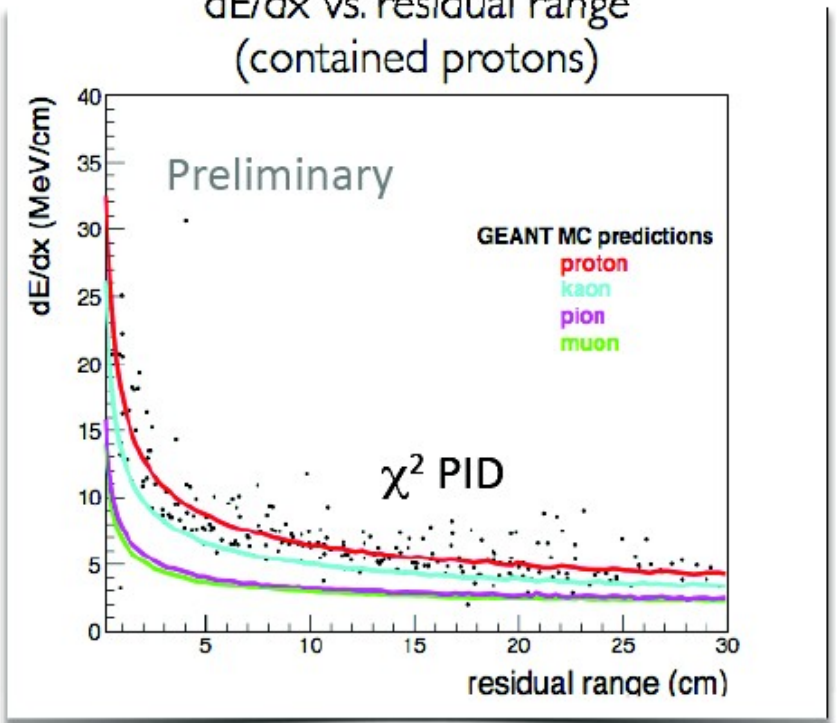
Calorimetric ParticleID



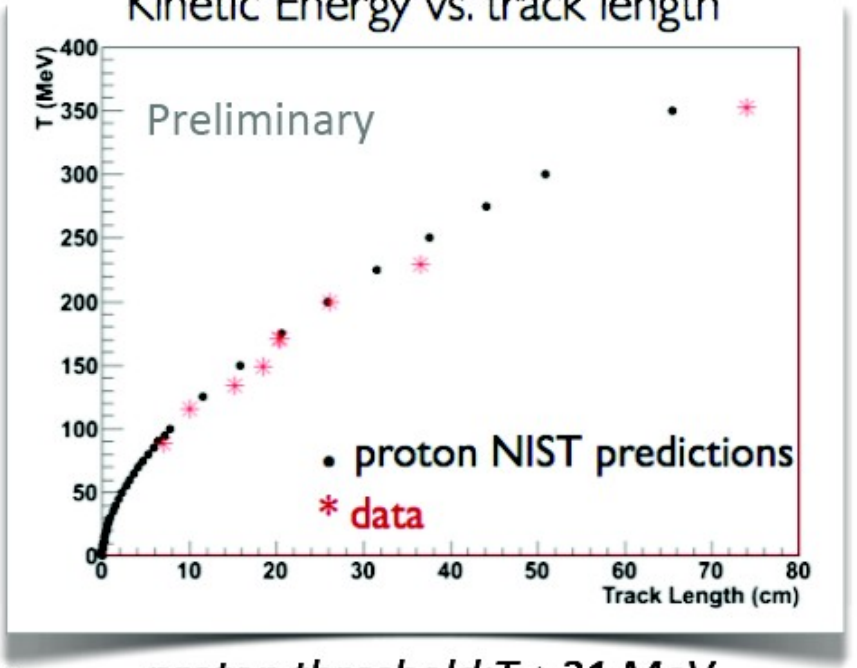
- Measurement of:
  - dE/dx vs. residual range along the track
  - kinetic energy vs. track length

Slide from Tingjun Yang @ NuFact 2013

dE/dx vs. residual range
(contained protons)



Kinetic Energy vs. track length



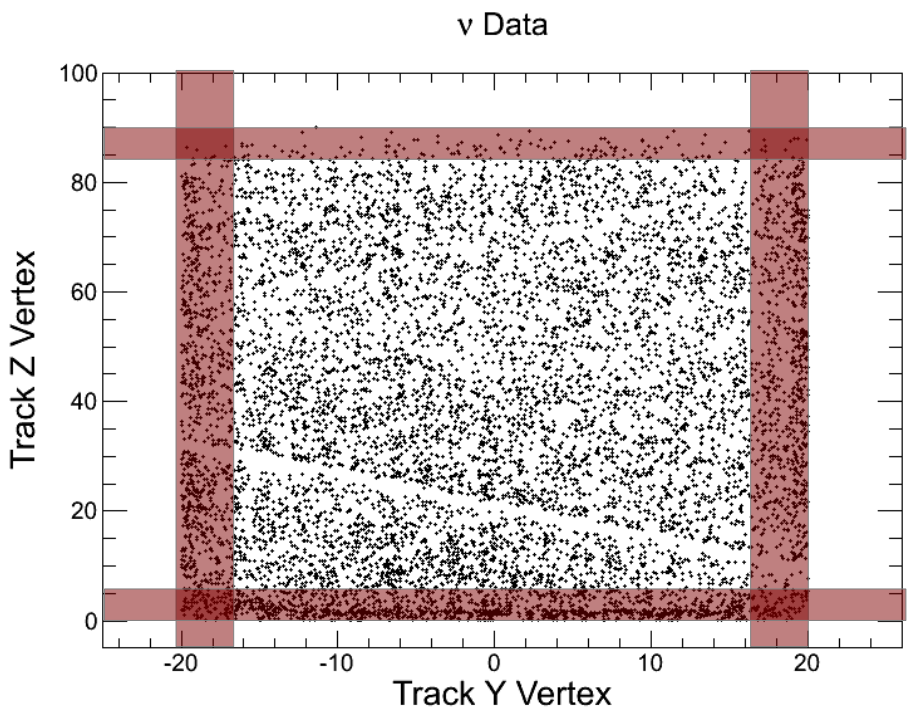
proton threshold:T_p>21 MeV

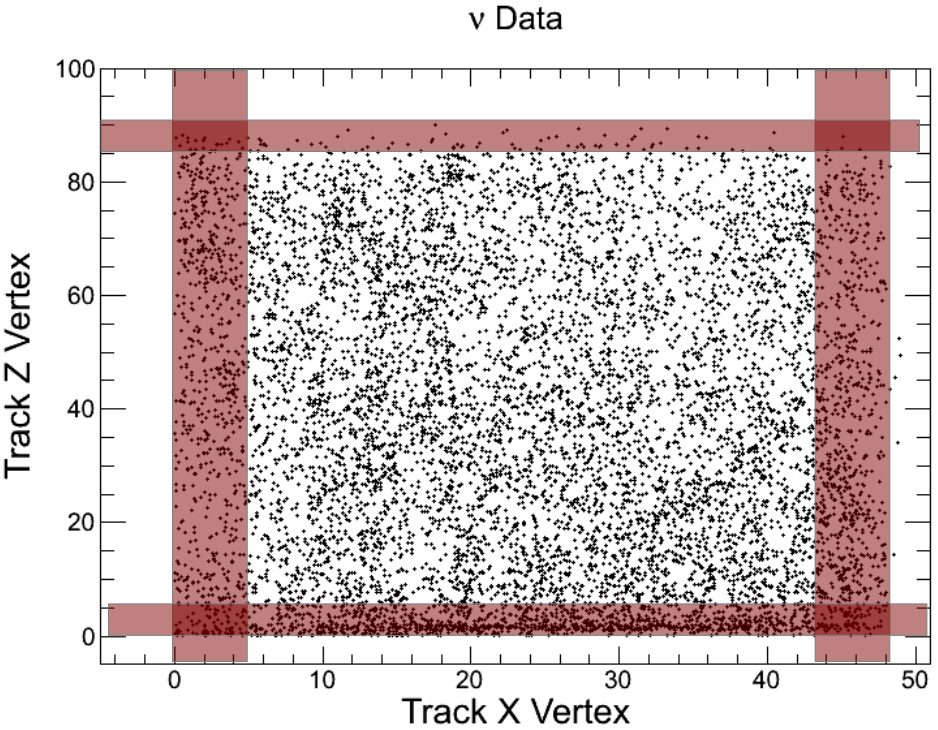
Neutral Current π^0 analysis

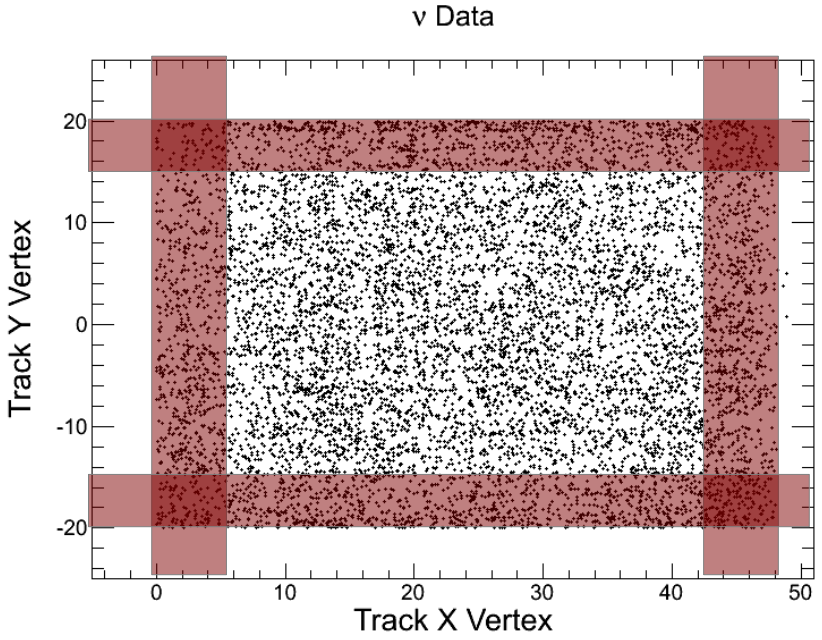
-
  - **Reconstructed information**
    - **Signal:** *(π^0 presample)*:
      - Reconstructed 2d/3d vertex in the active volume
      - Require Anti-Minos Matching **(no track in ArgoNeuT matched to Minos)**
      - Require 2 clusters in both views w/ 5 or more hits per cluster
      - Require no through going track reconstructed **(no track that starts and ends 1.0 cm from the edge of the active volume)**
    - **Background:**
      - Failing any one of the above reco-selections

Active Volume	Fiducial Volume
0 cm < X < 50 cm	5 cm < X < 45 cm
-20 cm < Y < 20 cm	-15 cm < Y < 15 cm
0 cm < Z < 90 cm	5 cm < Z < 85 cm

Neutral Current π^0 analysis







Note: We apply a 5cm fiducial volume cut on the start and end point of the reconstructed track segments