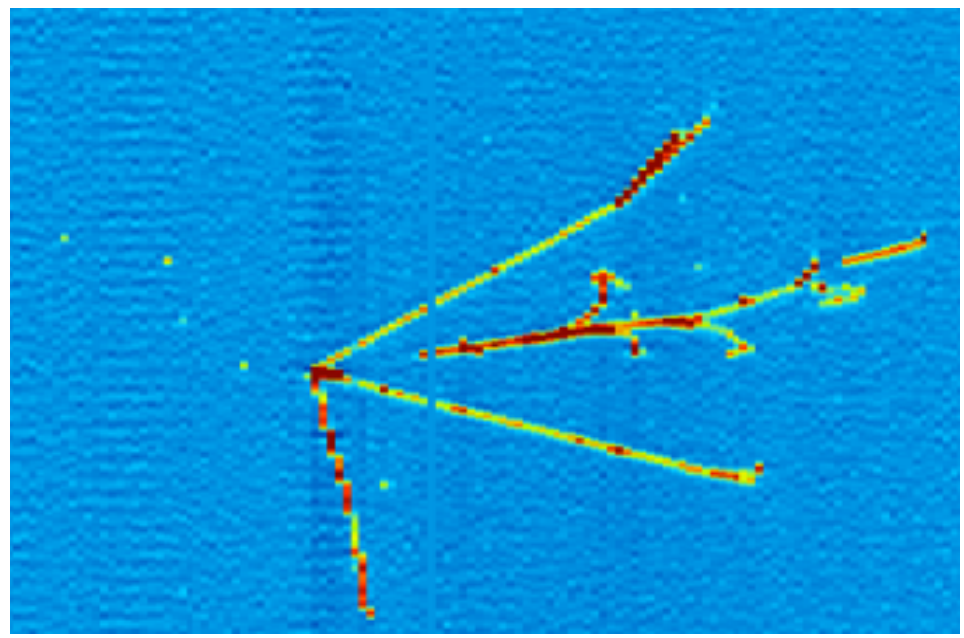
Probing Neutrino-Nucleus Interactions: New Results from ArgoNeuT

NUFACT 2013, Beijing, China

Tingjun Yang For the ArgoNeuT Collaboration
Fermilab

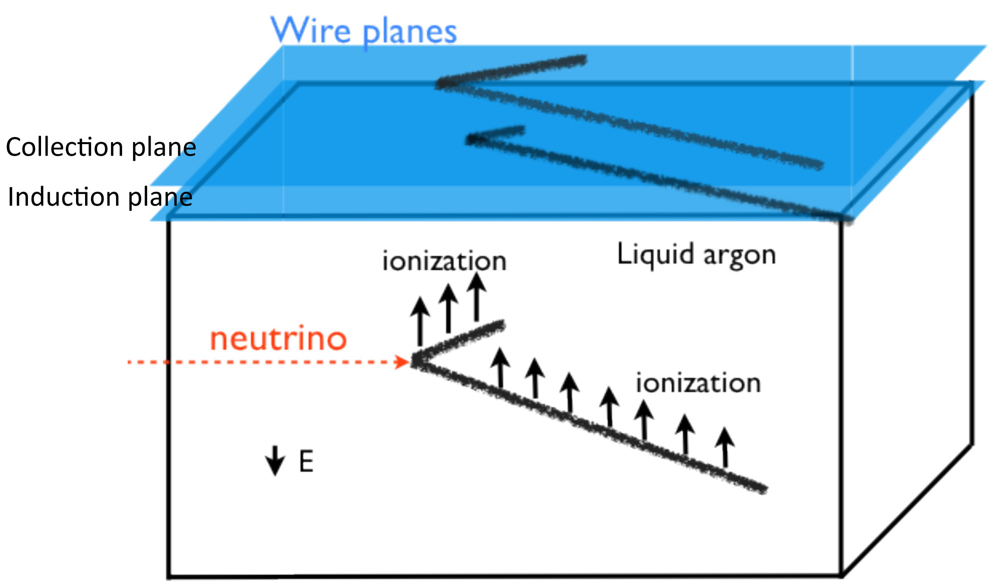


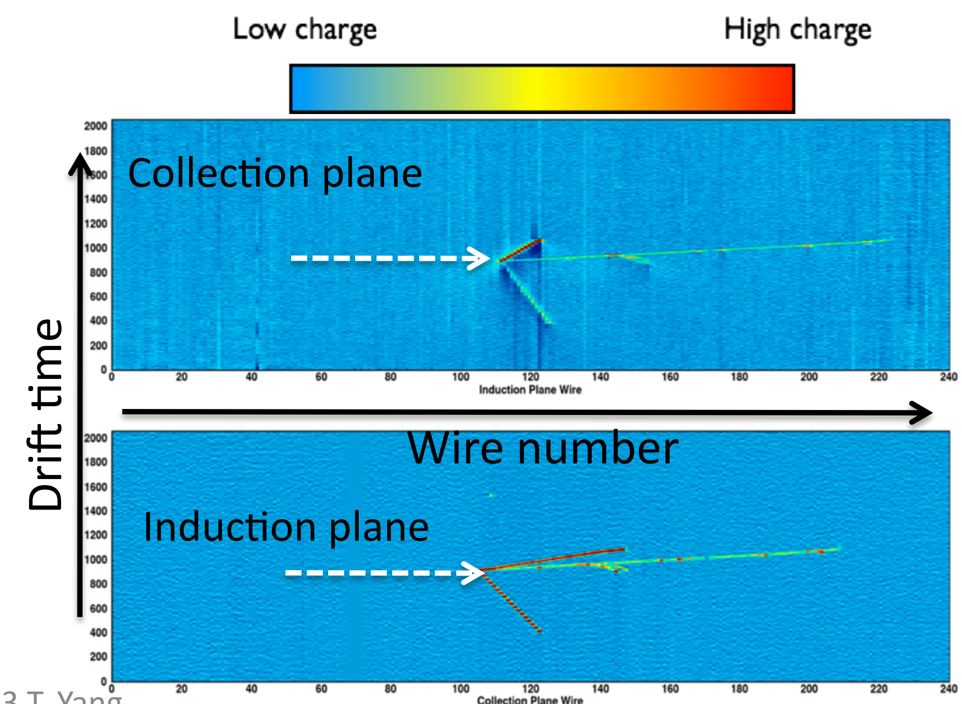
Liquid Argon TPC - LArTPC

- Liquid argon offers abundant ionization electrons and scintillation light for particle detection.
  - Suitable for studies of neutrino physics, search for proton decays, etc.
  - Relative cheap and scalable.

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

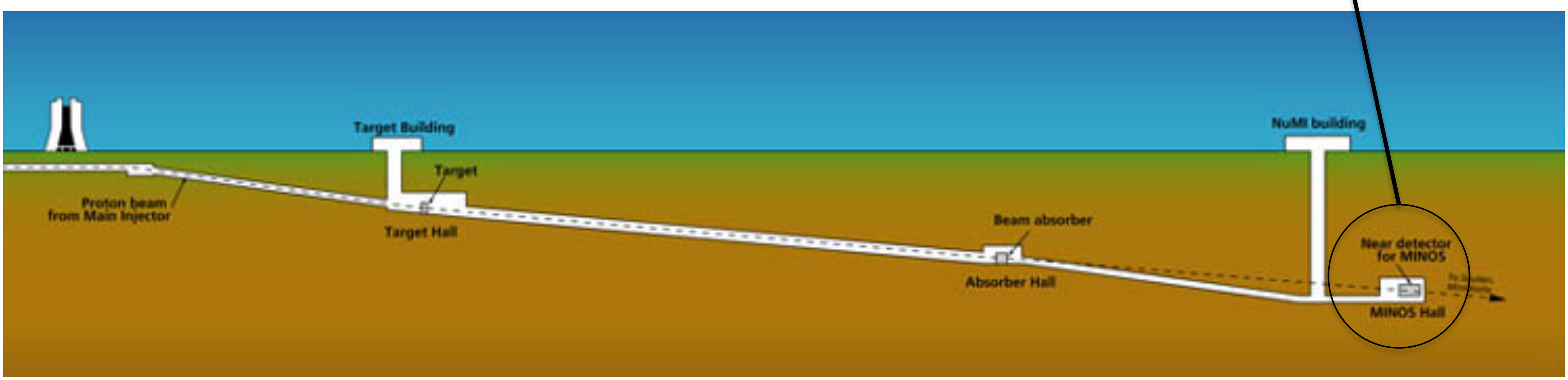
- Jim Strait: “LBNE”
- Paola Sala: “ICARUS status and results”
- Jason St. John: “MicroBooNE: prospects for making the first neutrino interaction measurements on argon at low energy”





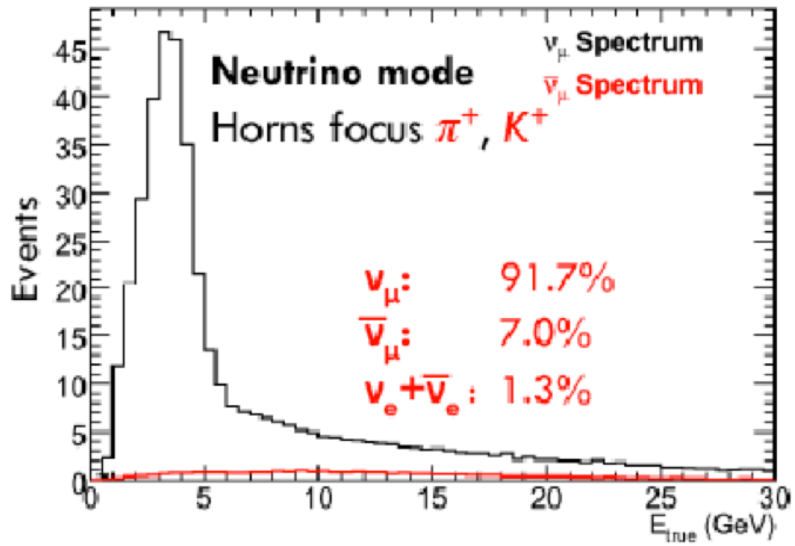
ArgoNeuT - Argon Neutrino Teststand

- First TPC in a neutrino beam in the US
- Sitting in NuMI beam - Neutrinos at the Main Injector
- Located in front of MINOS near detector
- Use MINOS ND as muon spectrometer
- $47 \times 40 \times 90$ cm^3 (170 L), wire spacing 4 mm

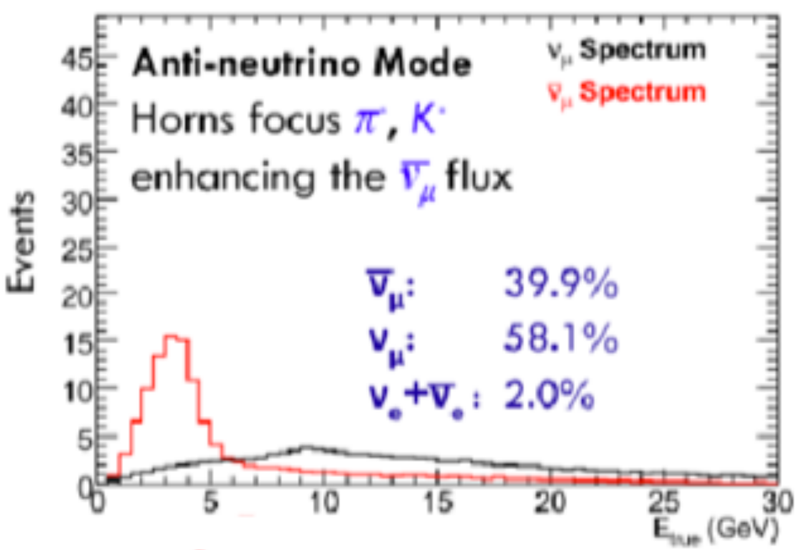


ArgoNeuT's Physics Run

ν-mode (2 weeks): 0.085e20 POT

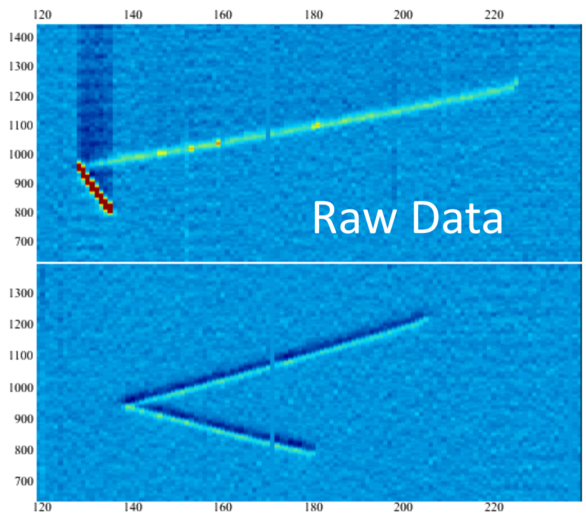


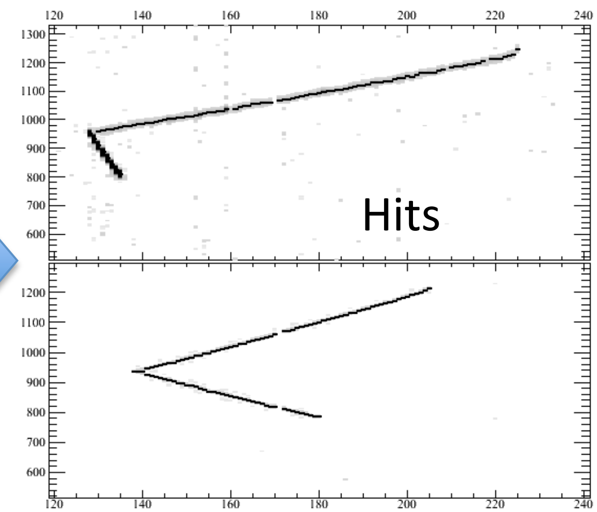
$\bar{\nu}$-mode (5 months): 1.2e20 POT

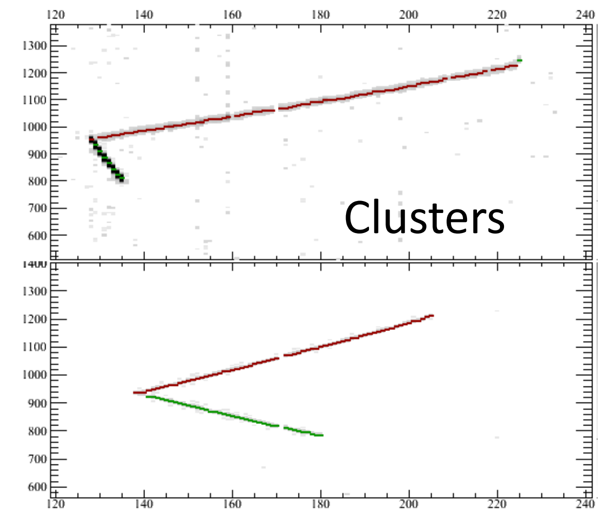


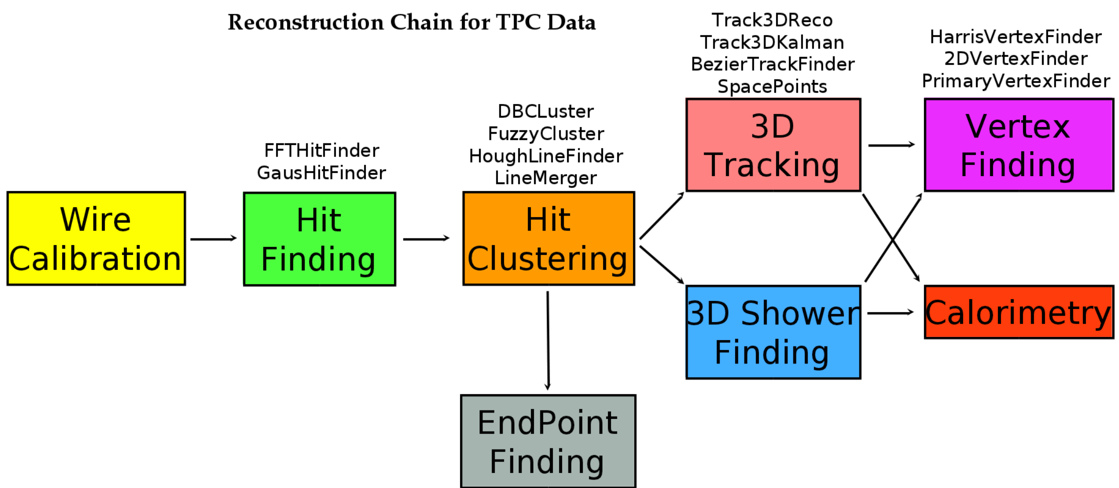
- ArgoNeuT completed taking data. (9/14/2009-2/22/2010)
- Collected events in the 0.1 to ~20 GeV range.
  - First low energy neutrino interactions in LArTPC
- Physics goals:
  - Measure ν-Ar CC cross sections
  - Study Nuclear effects (FSI, SRC, etc.)
  - Examine dE/dx particle ID, especially e/γ separation
  - Develop automated reconstruction techniques

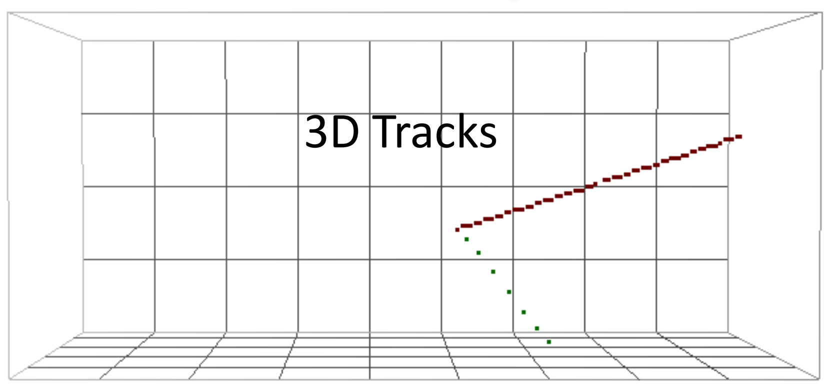
Track Reconstruction







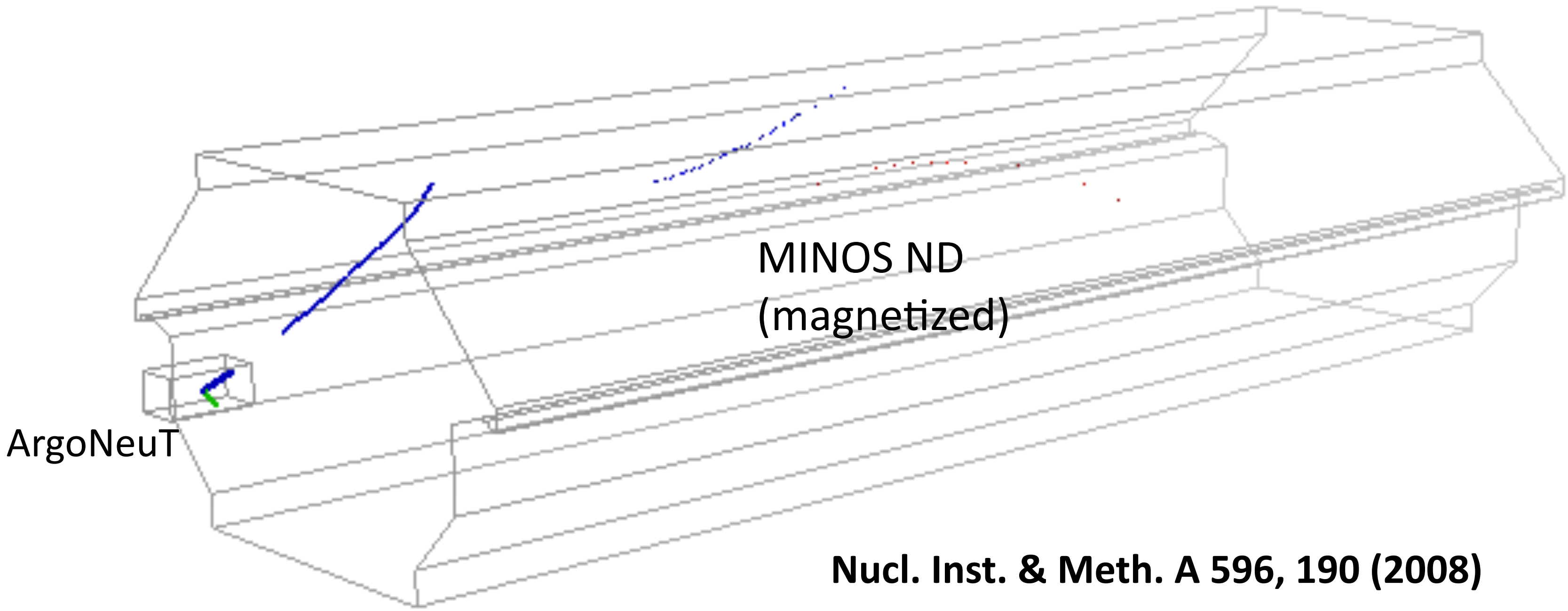




LArSoft

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

MINOS Track Matching

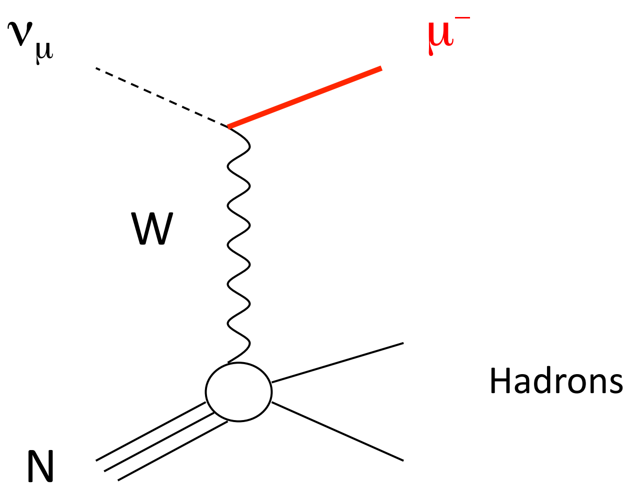


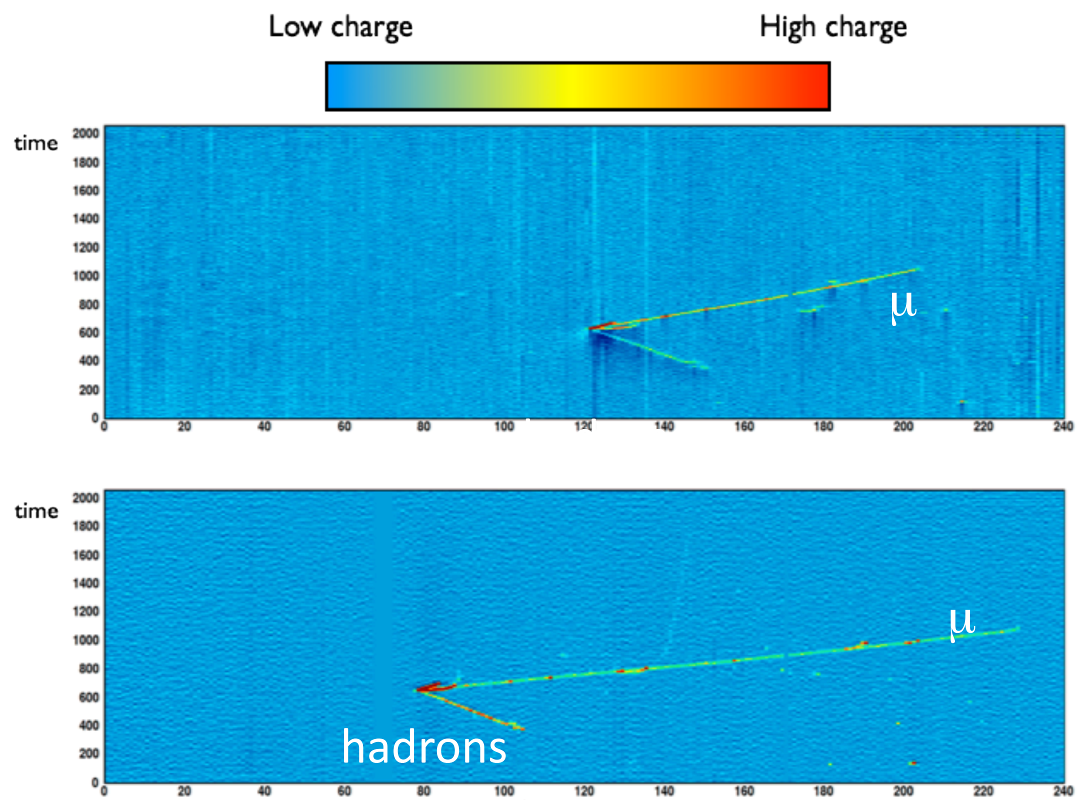
Nucl. Inst. & Meth. A 596, 190 (2008)

- 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.

Muon Neutrino Inclusive Charged Current Cross Sections

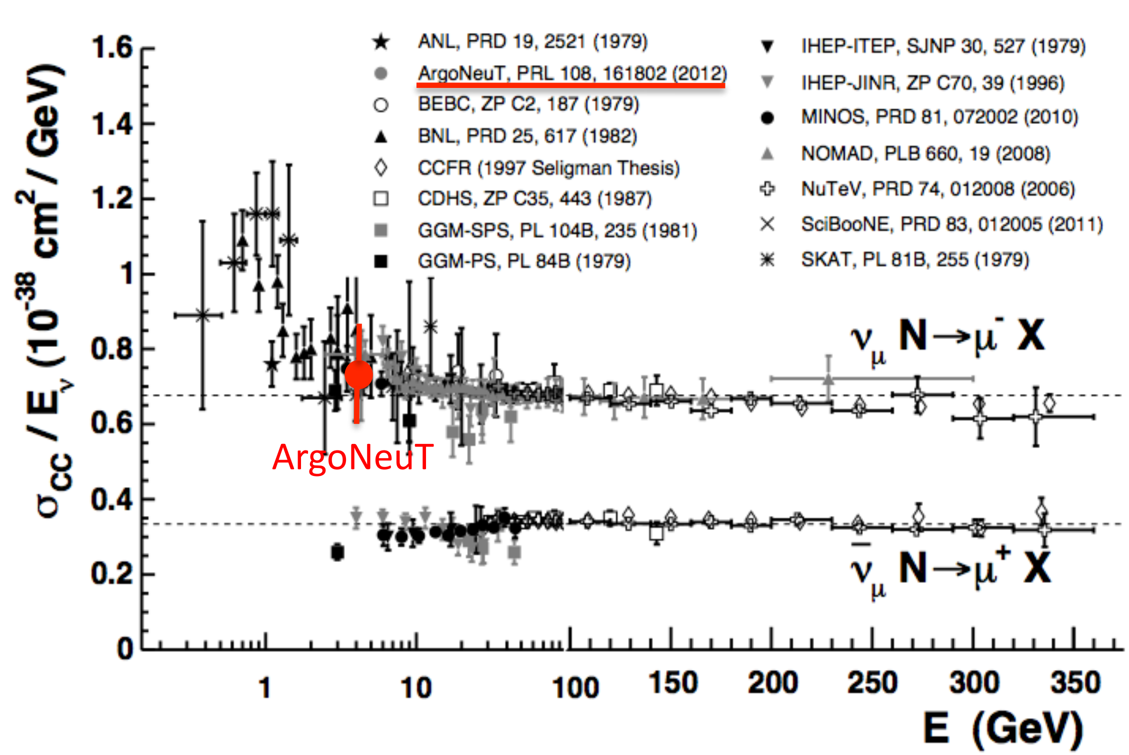
- First results based on 8.5e18 POT (2 weeks) neutrino data published in **PRL 108 (2012) 161802**.

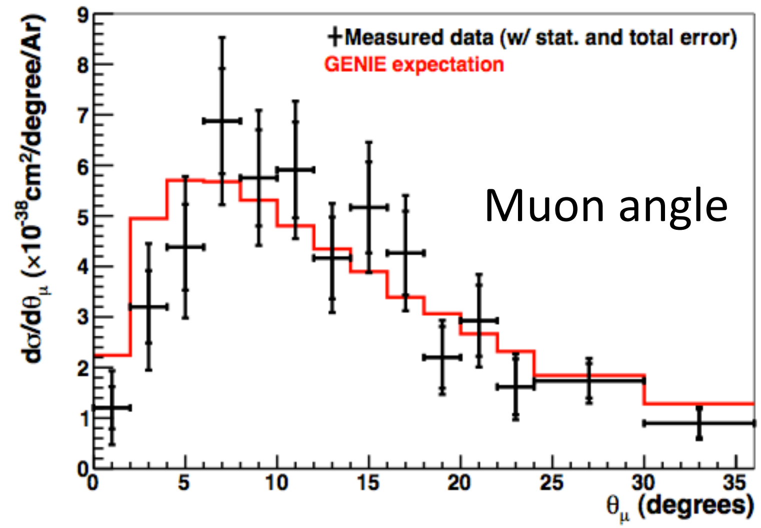


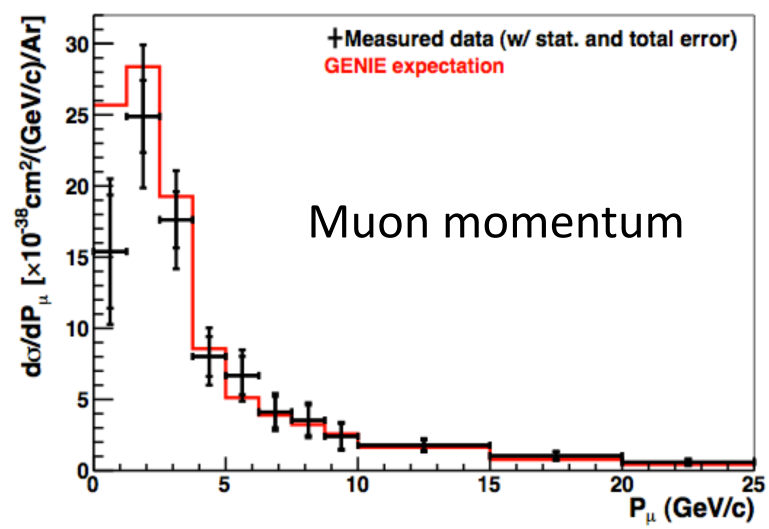


Previous Results in ν Mode (8.5e18 POT)

"First Measurements of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon " **PRL 108 (2012) 161802**

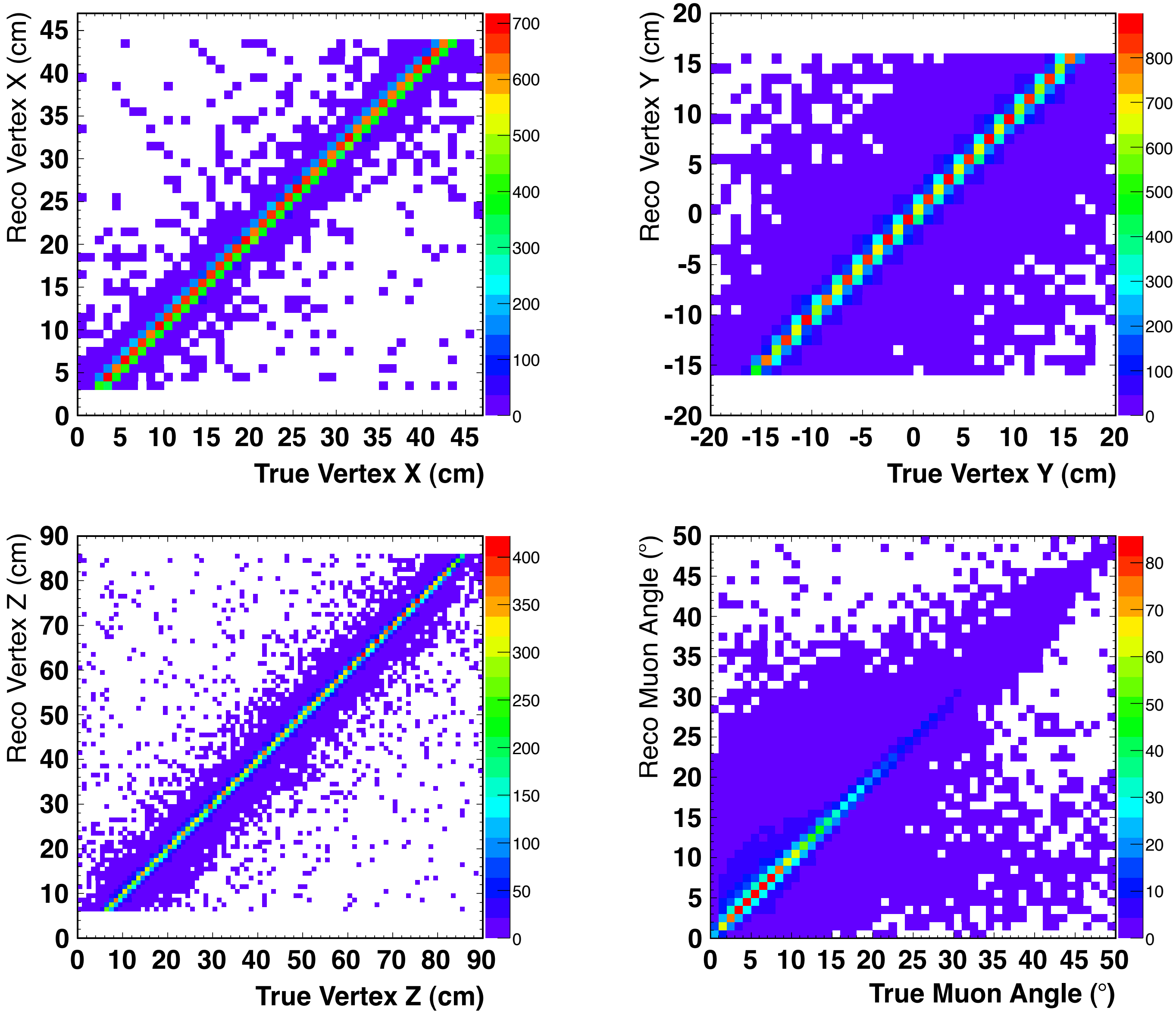






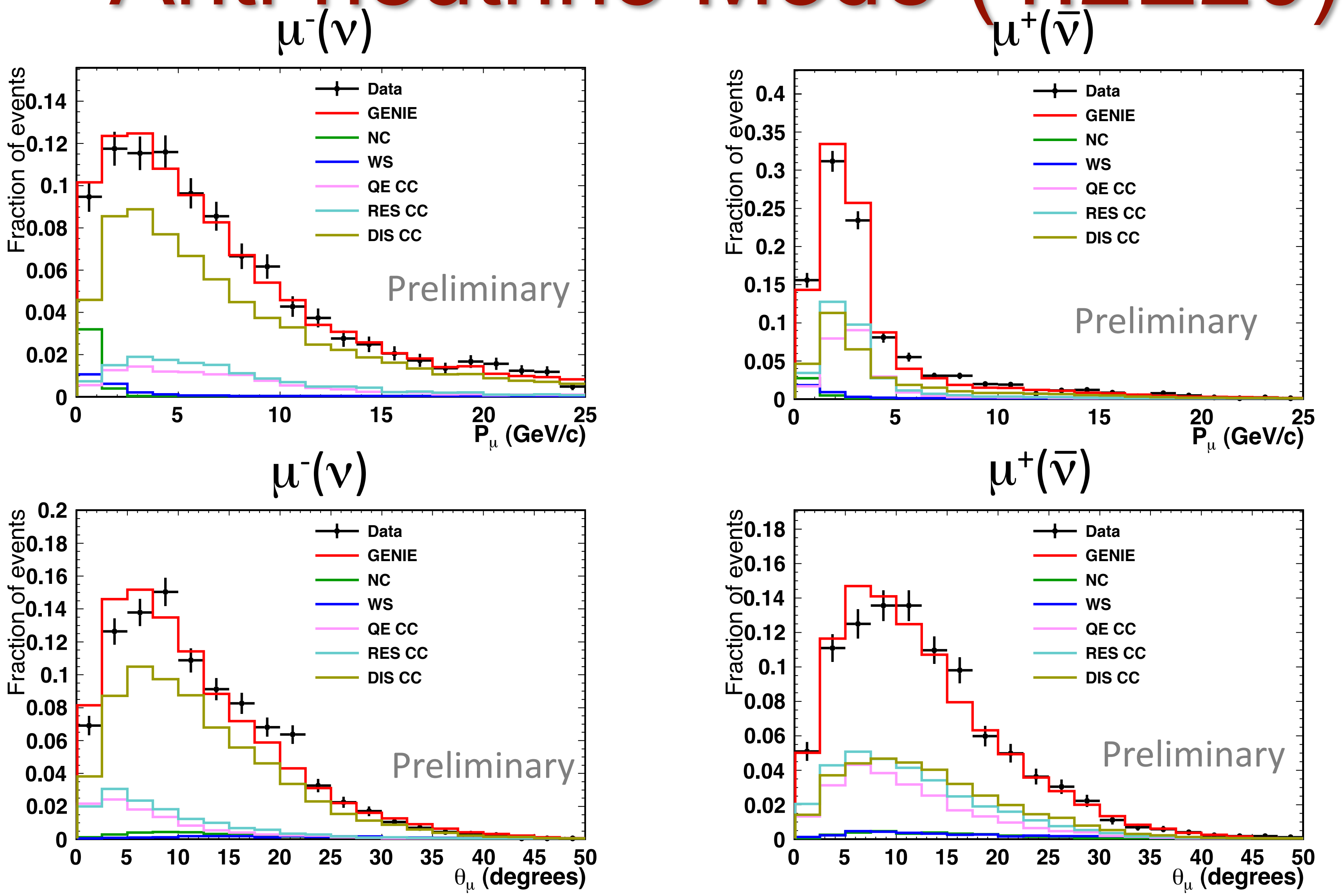
- Interaction vertex in fiducial volume
- Track matched to muon in MINOS ND
- Negatively charged muon in MINOS

Reconstruction Checks



Reconstructed quantities consistent with true quantities.

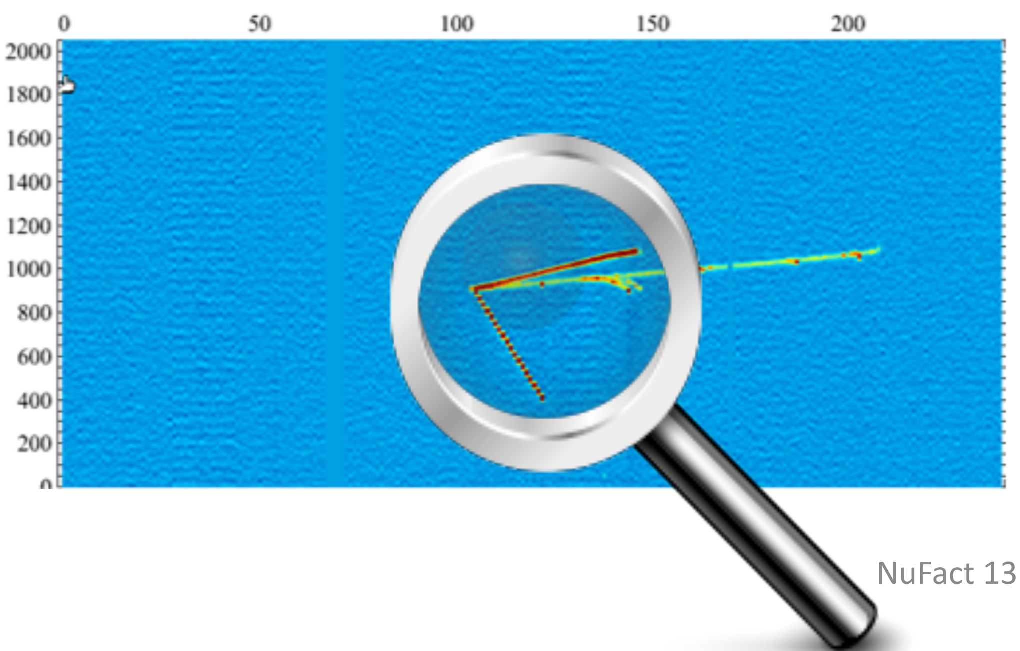
Anti-neutrino Mode (1.2E20)

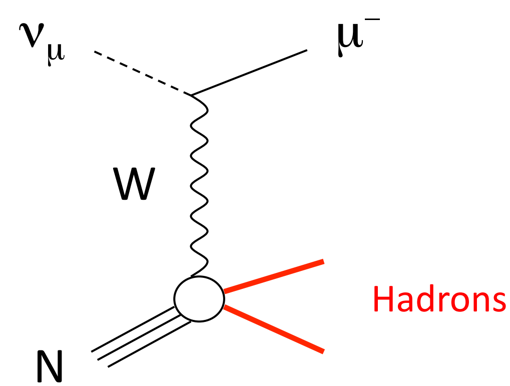


- Area normalized
- Need to improve flux prediction
- Paper in preparation

Examine the Hadronic System

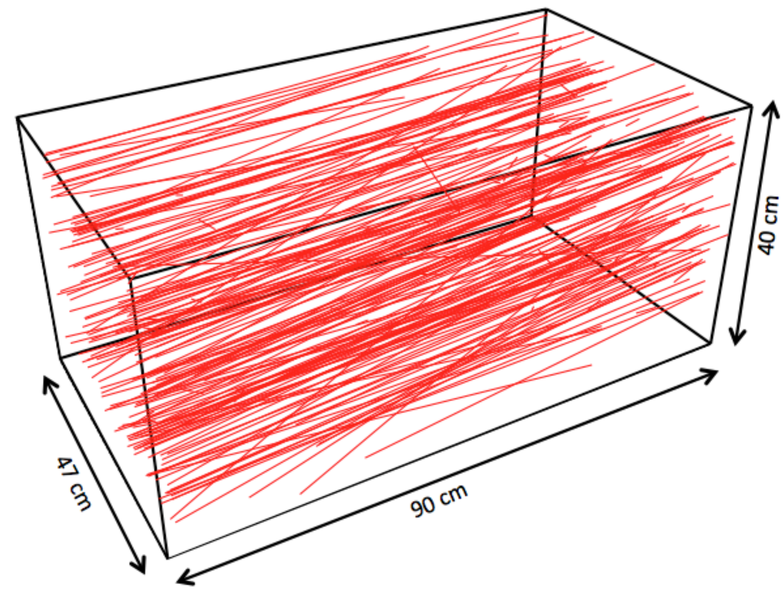
- LArTPC provides a 3D imaging of charged particle interacions with fine **spatial and energy resolution**.
- It is an excellent tool to study the **hadron production** in ν-Ar interactions.
  - Good for studies of nuclear effects.
- Proton/pion separation through the energy deposition vs range measurements.
  - Understanding the detector calorimetric response.

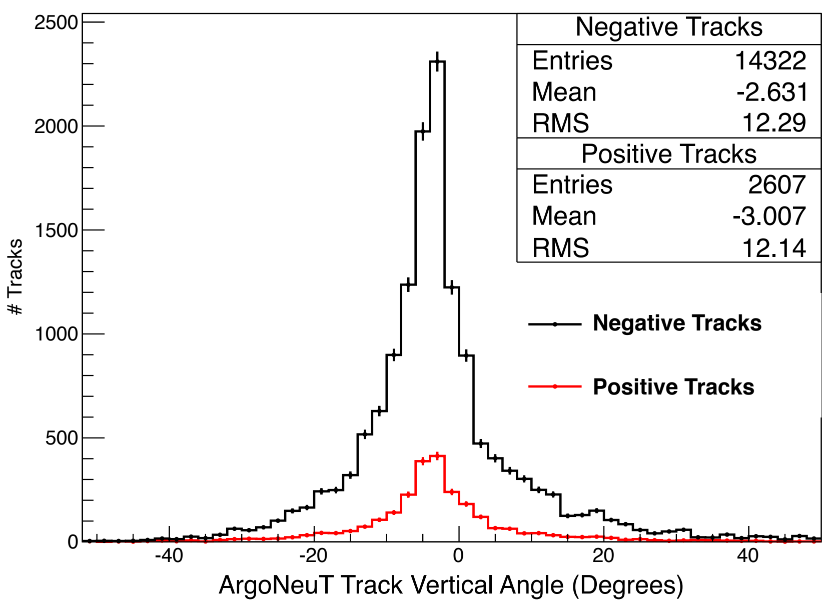


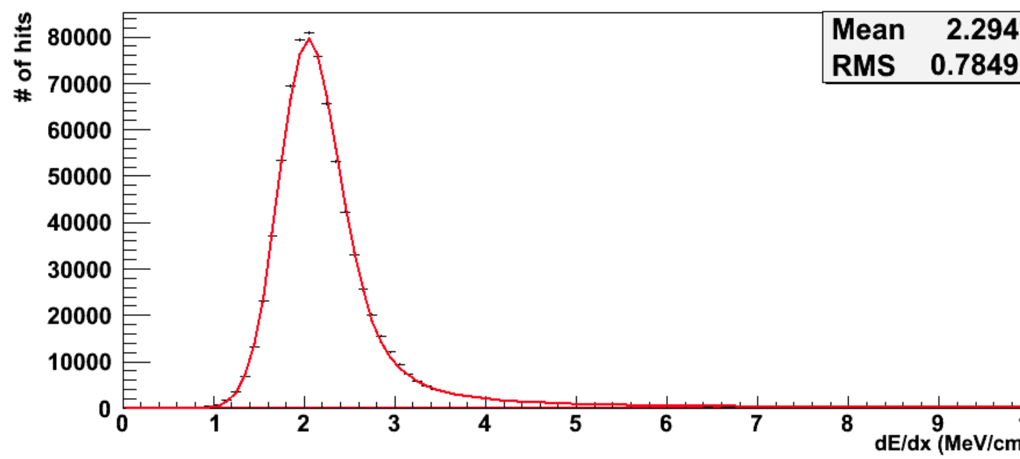


Detector Calibration with Through-going Muons

- A large sample of neutrino induced through-going muons are useful for detector calibration
- Test geometric and calorimetric reconstruction in the ArgoNeuT detector
- JINST 7 (2012) P10020; arXiv: 1205.6702







$\langle dE/dx \rangle = 2.3 \pm 0.2$ MeV/cm, in good agreement with theoretical expectations for $\langle E_\mu \rangle = 7.0$ GeV

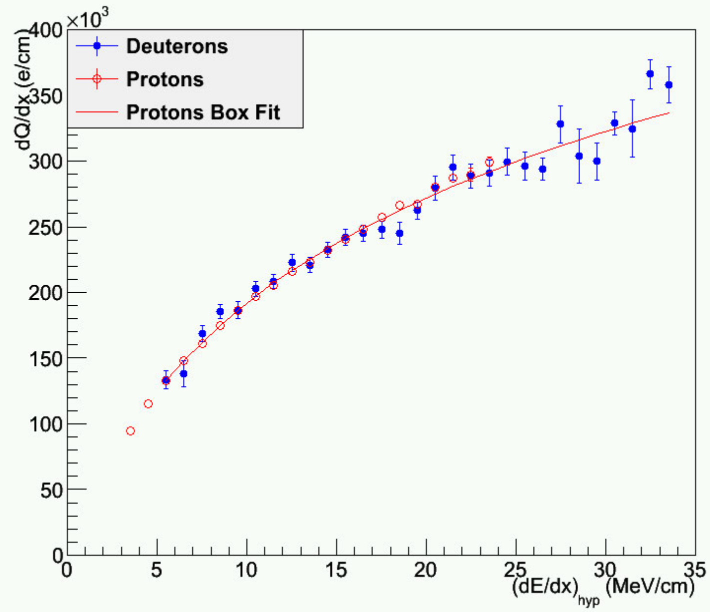
Recombination Studies

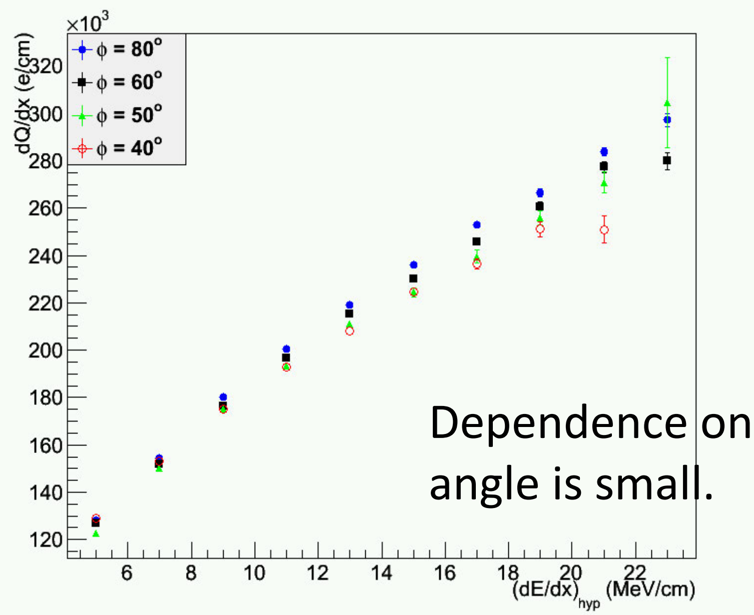
- Study the recombination of electron-ion pairs produced by ionizing tracks using stopping protons and deuterons

- Results in agreement with ICARUS with extended dE/dx range and smaller uncertainties

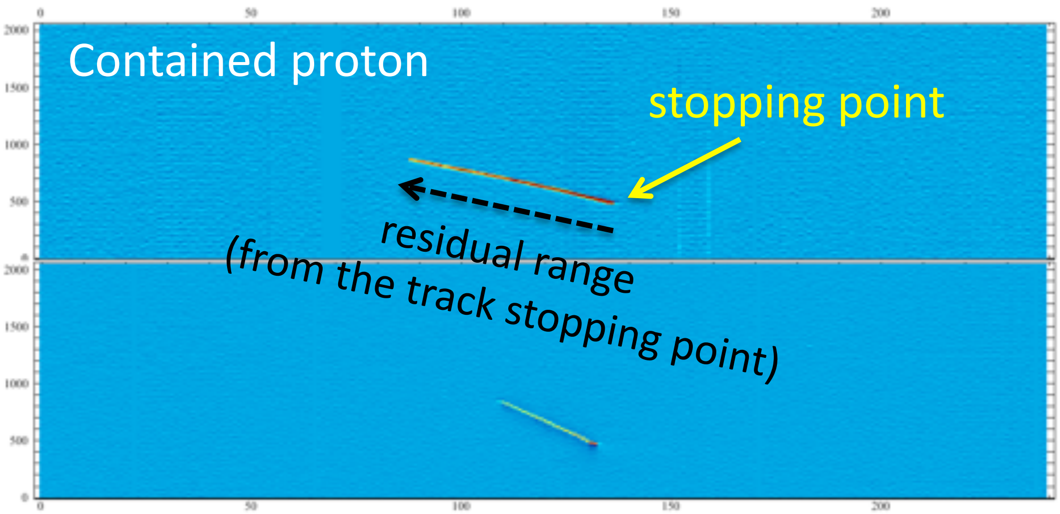
- Also study the dependence of recombination on the track angle

- arXiv: 1306.1712, accepted by JINST

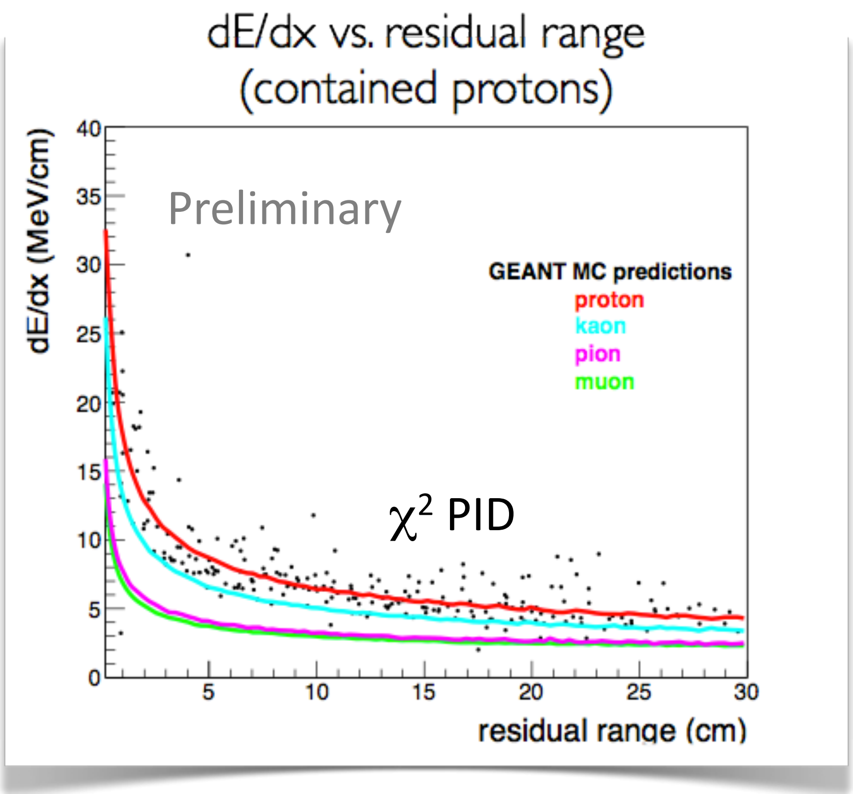


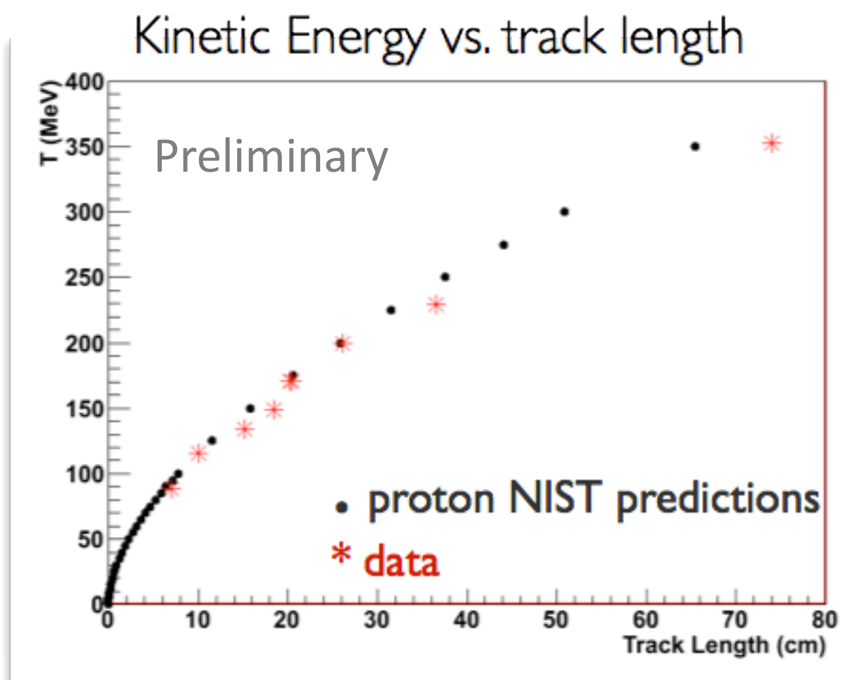


Calorimetric ParticleID



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

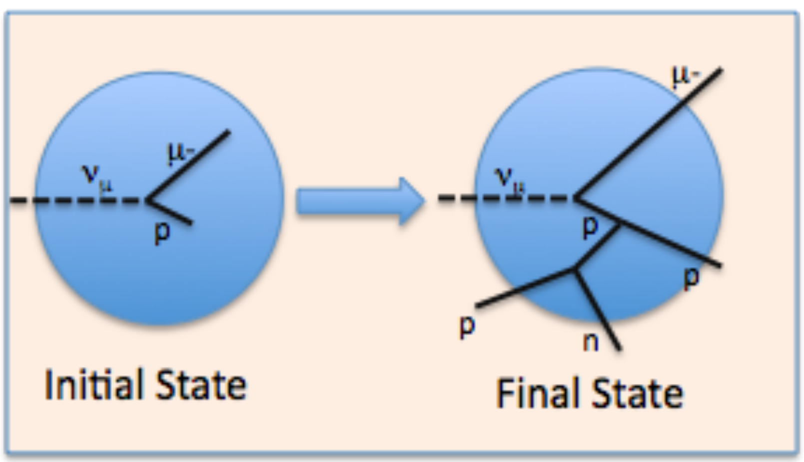


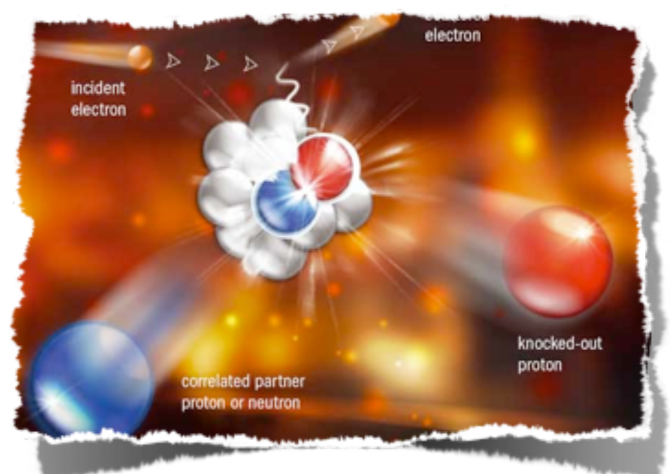


proton threshold: $T_p > 21$ *MeV*

ν-Ar Interactions: Nuclear Effects

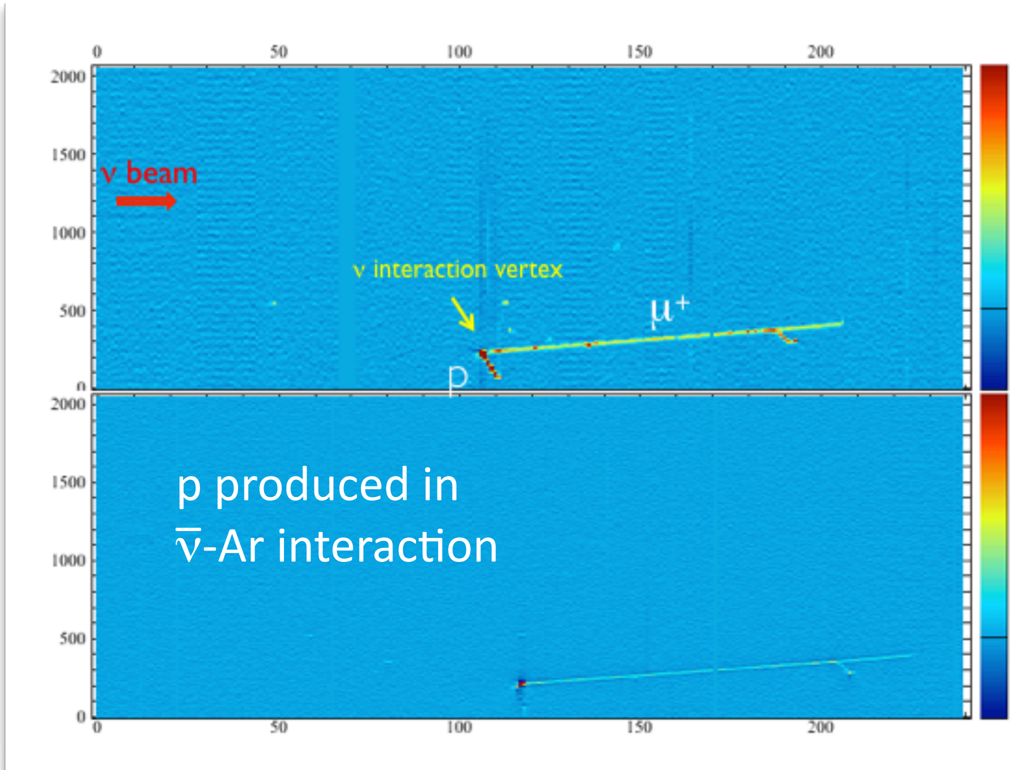
- Conventional measurement of exclusive channels: quasi-elastic (QE), resonance pion production (RES) etc.
- **Nuclear effects** play a key role in neutrino-nucleus interactions in nuclear targets.
- Due to ***intra-nuclear re-scattering (FSI)*** and possible effects of ***correlation between target nucleons***, a genuine QE interaction can often be accompanied by additional particles (nucleons, de-excitation γ's and soft pions) in the Final State.

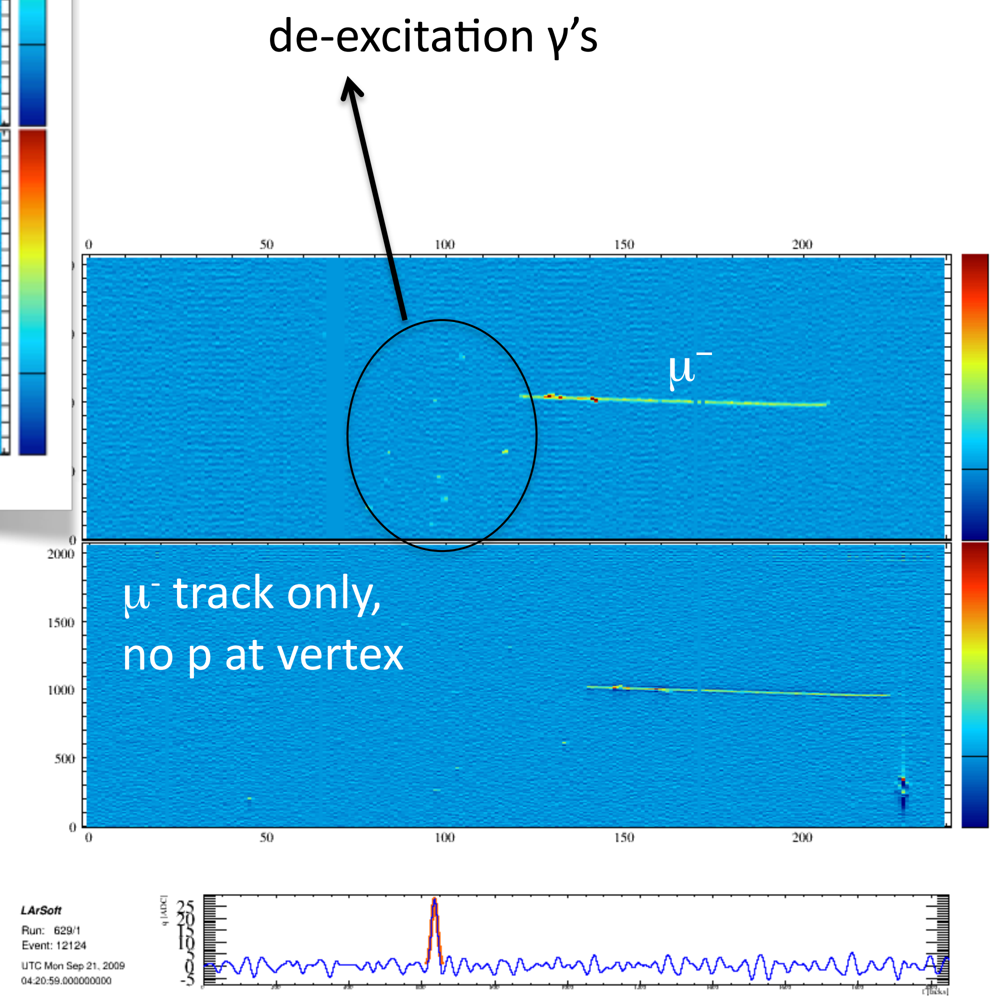




Multi-nucleon correlations

Hints for Nuclear Effects





Topological Analysis 1μ+Np

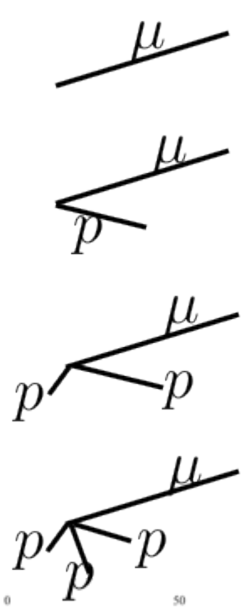
- A first Topological analysis is currently developed by the ArgoNeuT experiment: 1μ+Np (0π)
  - Sensitive to nuclear effects

- Analysis steps
  - automated reconstruction (muon angle and momentum)
  - visual scanning
  - calorimetric reconstruction
    - Background (pion) removed

  } Proton angle and momentum

- GENIE MC:
  - Estimate efficiency of the automated reconstruction, detector acceptance and proton containment (for Pid)
  - estimate backgrounds
    - NC background
    - Wrong-sign (WS) background
    - π^0 with both γ not converting

Event Topology

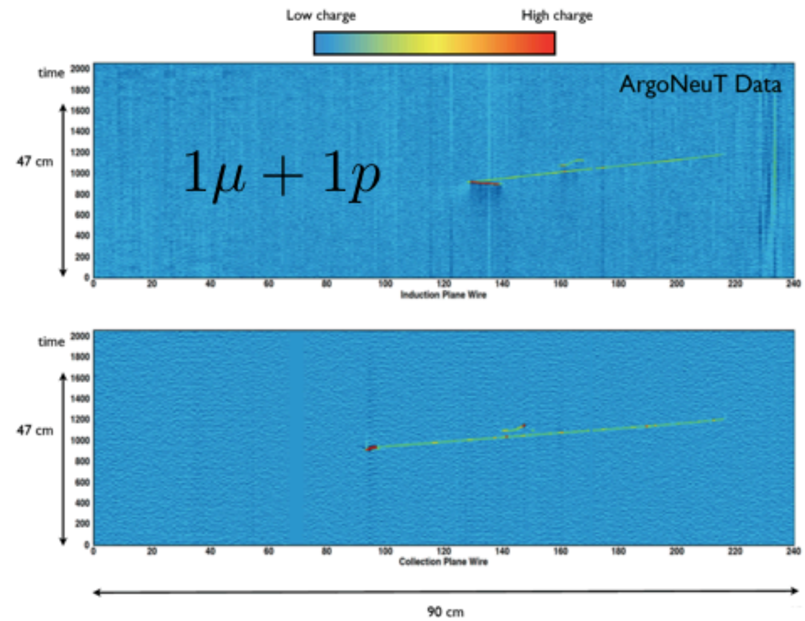


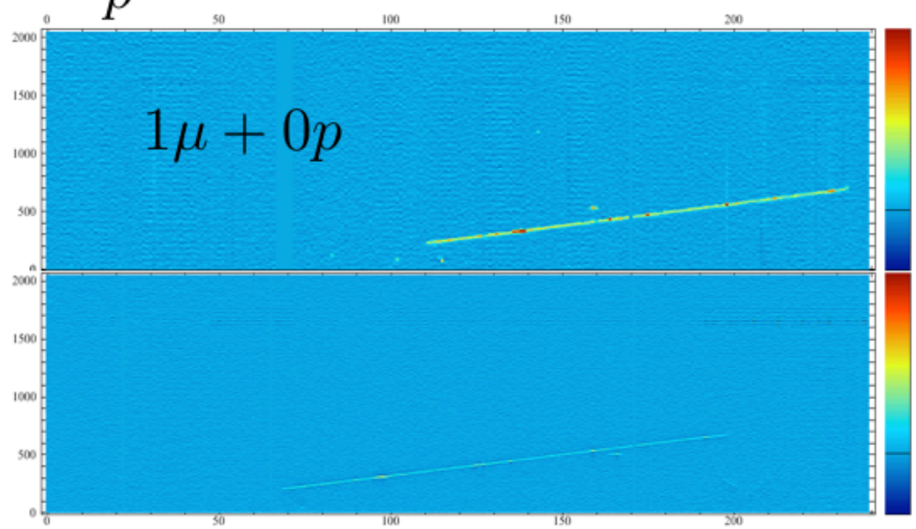
$$1\mu + 0p$$

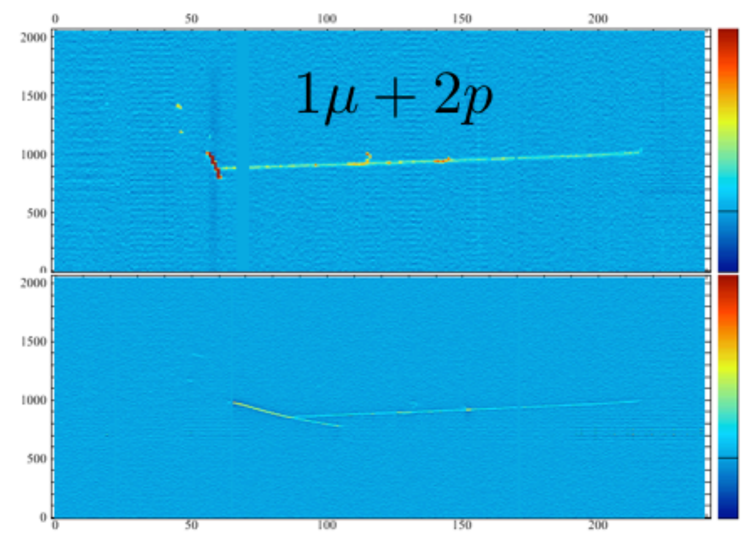
$$1\mu + 1p$$

$$1\mu + 2p$$

$$1\mu + 3p$$







DATA-MC Comparison

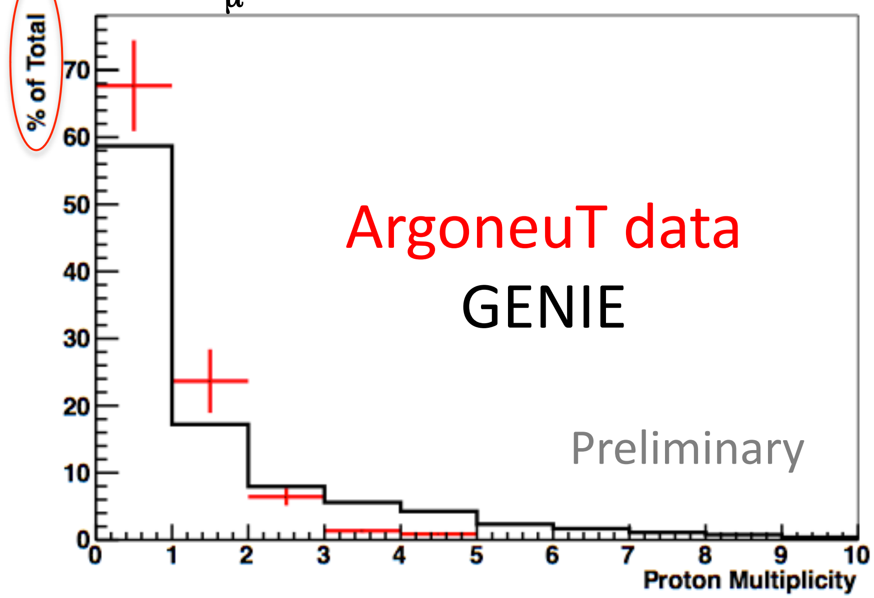
- GENIE- Generates Events for Neutrino Interaction Experiments*
  - FSI: Intranuclear Cascade model (INC)
  - Preliminary meson exchange (MEC) model
- GIBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project**
  - FSI: Transport model
  - 2p2h-NN channel with 2 nucleons produced

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

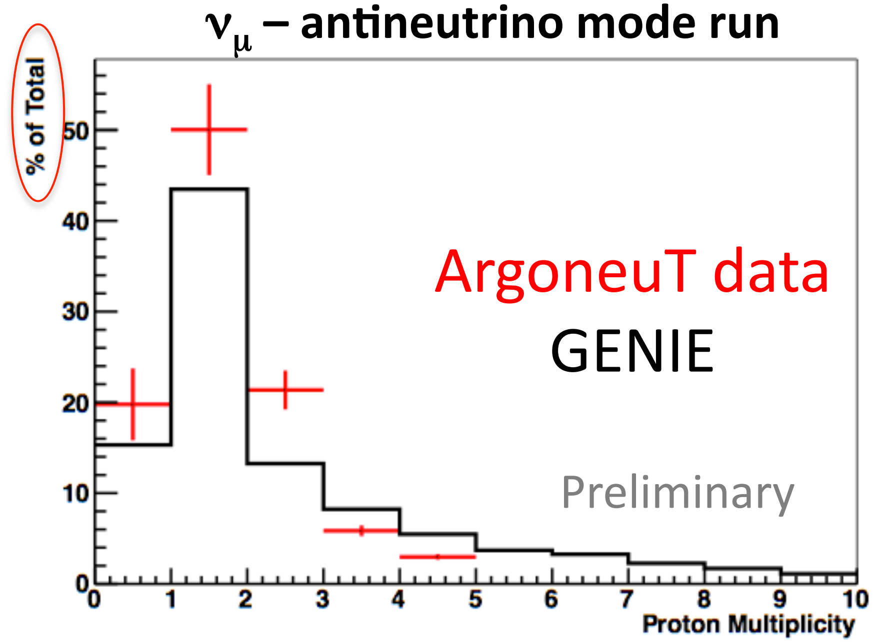
**ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

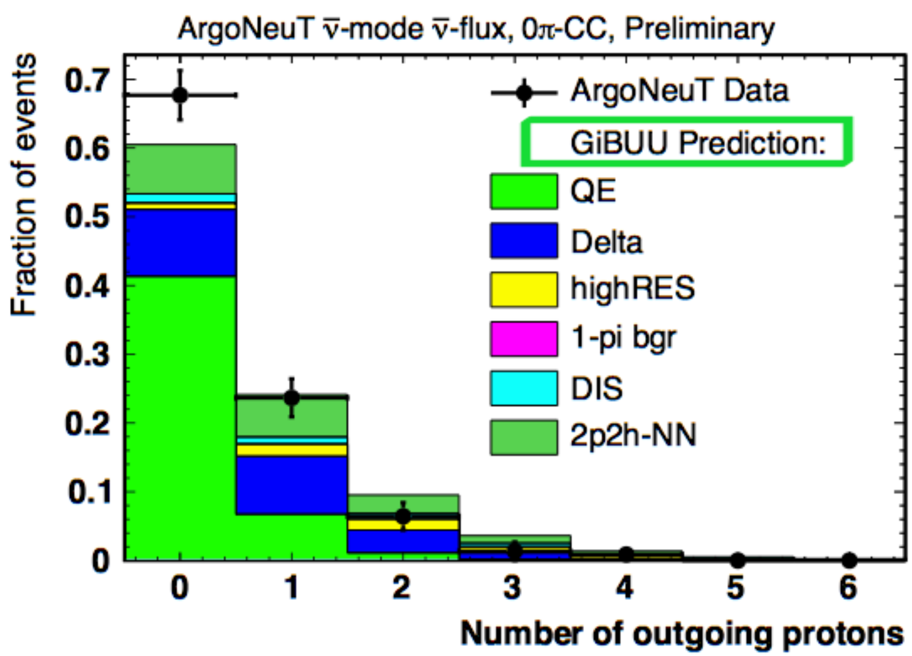
Proton Multiplicity

$\bar{\nu}_\mu$ – antineutrino mode run



ν_μ – antineutrino mode run



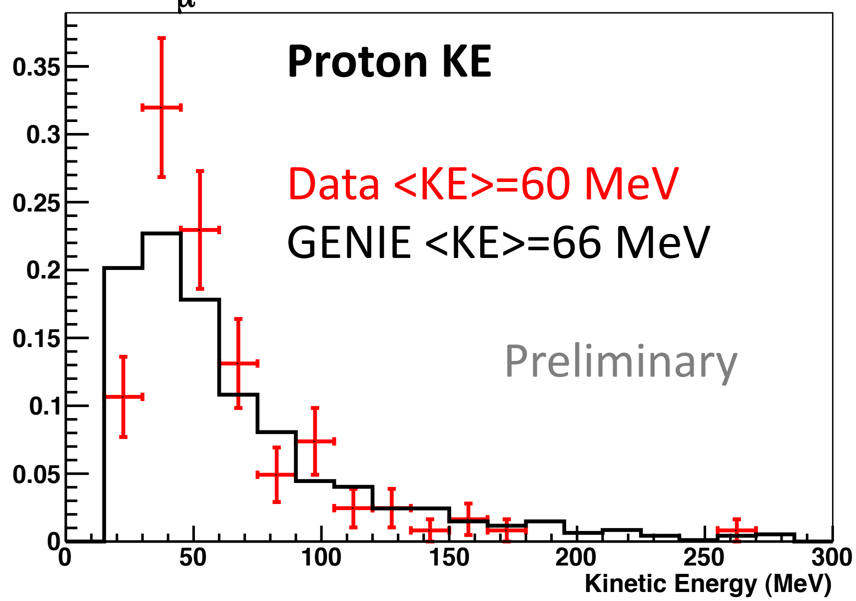


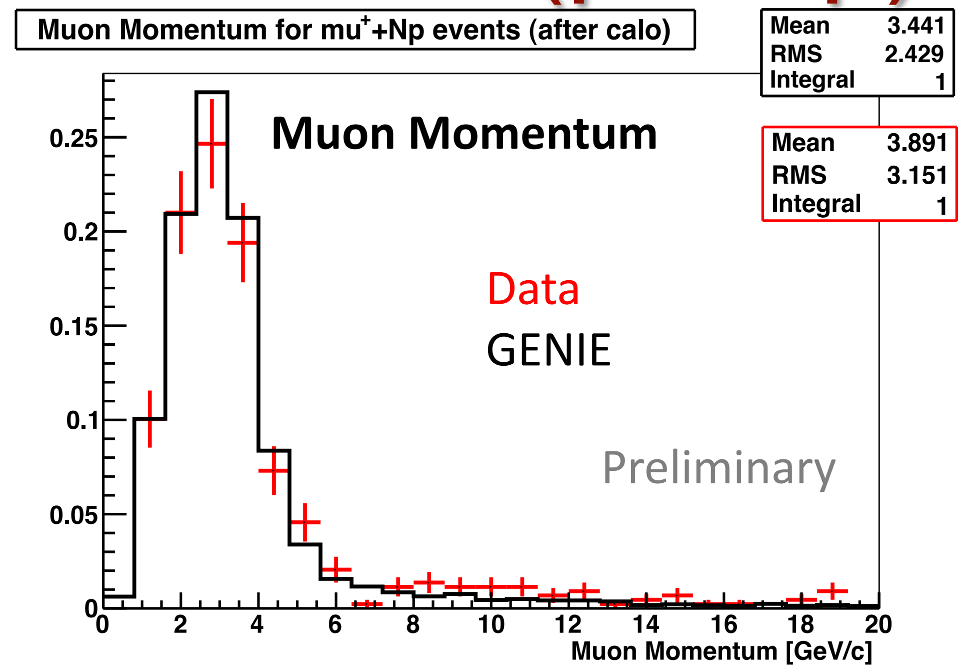
proton threshold:T_p>21 MeV

- LAr data can provide an important discriminator among models

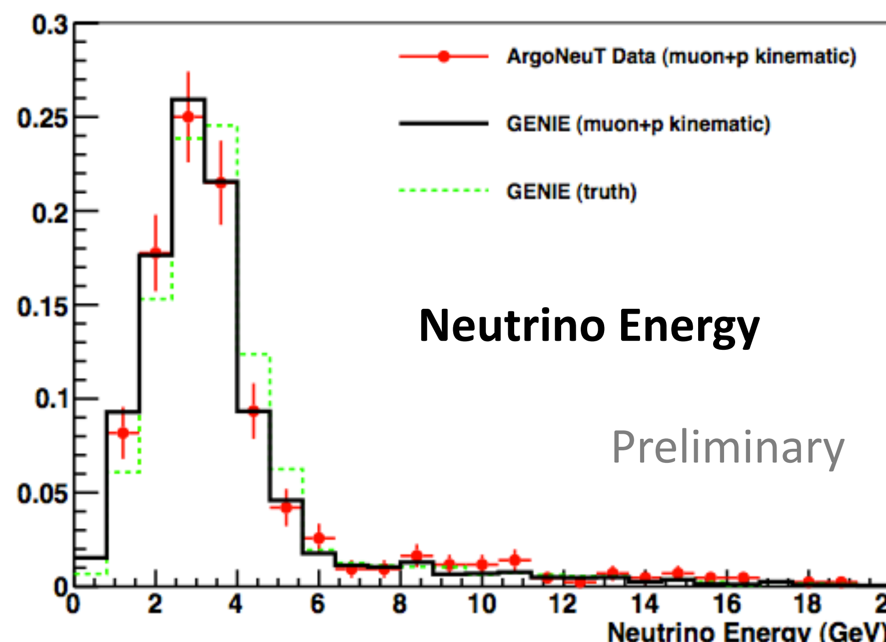
Kinematics Reconstruction (μ^++Np)

$\bar{\nu}_\mu$ – antineutrino mode run



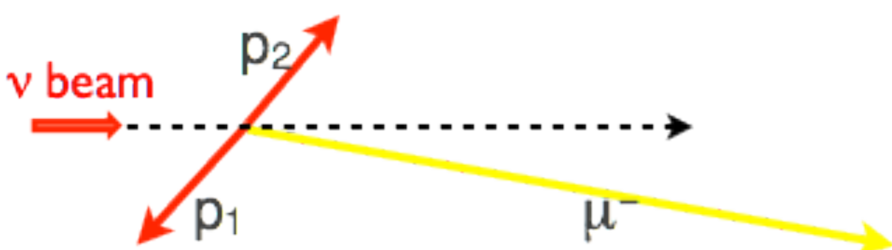


- Neutrino Energy $E_\nu = E_\mu + \Sigma T_p$
- No just muon information, model independent
- Other kinematic quantity reconstruction (Q^2 etc.) in progress

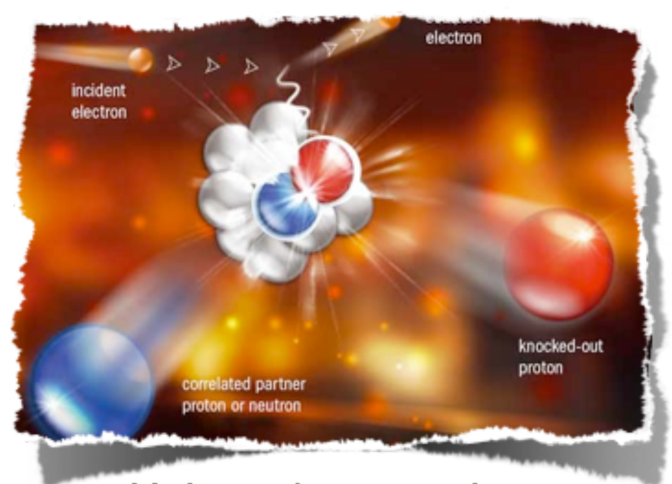


Proton Kinematics & Nuclear Effects

- If nucleon in a correlated pair is knocked out of a nucleus, the "paired" nucleon is also emitted.
- Based on e-scattering data, correlated nucleon pairs are emitted preferentially back-to-back.
- Search of back-back protons in the ArgoNeuT muon+2p event samples
  - indication for nucleon-nucleon correlation in neutrino scattering.

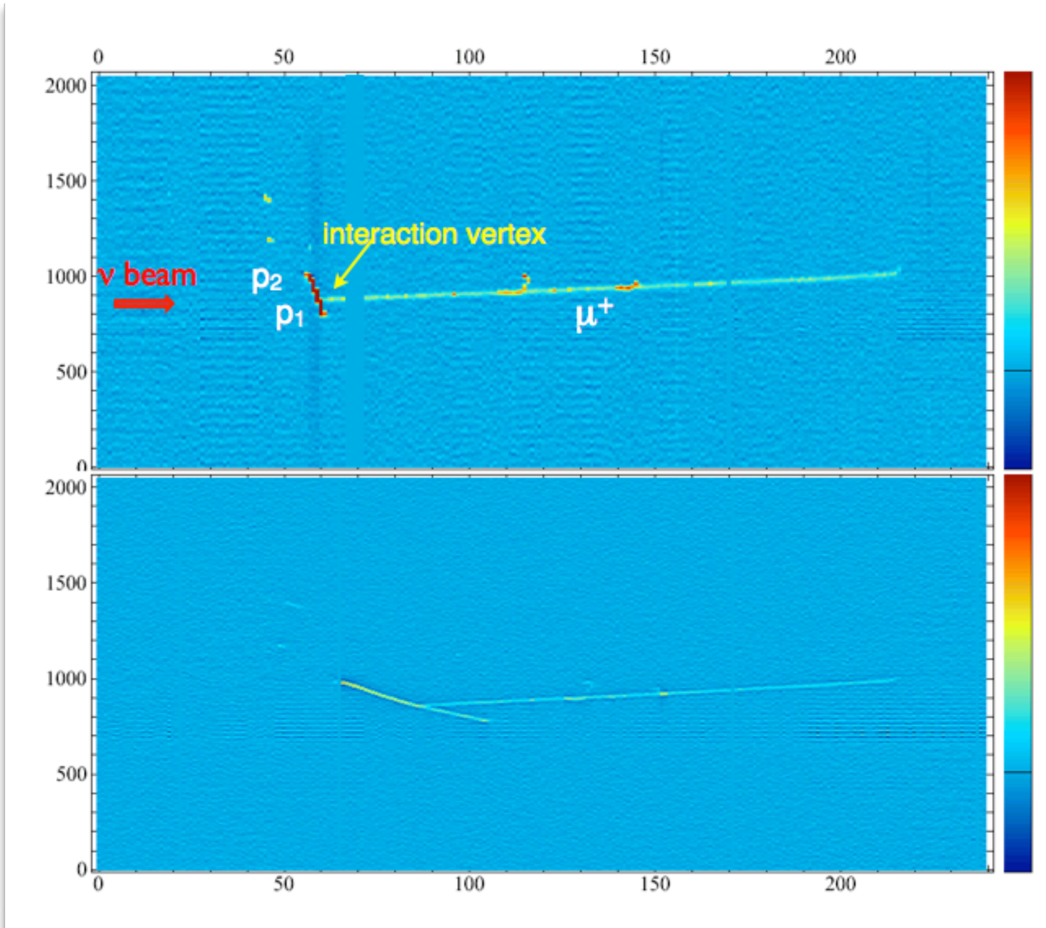


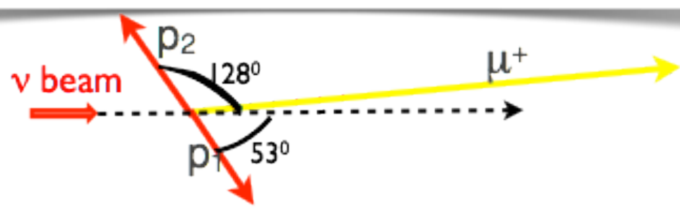
back-to-back protons
(angle between 2 p ~ 180^0)



Multi-nucleon correlations

Back-to-back Proton Pair

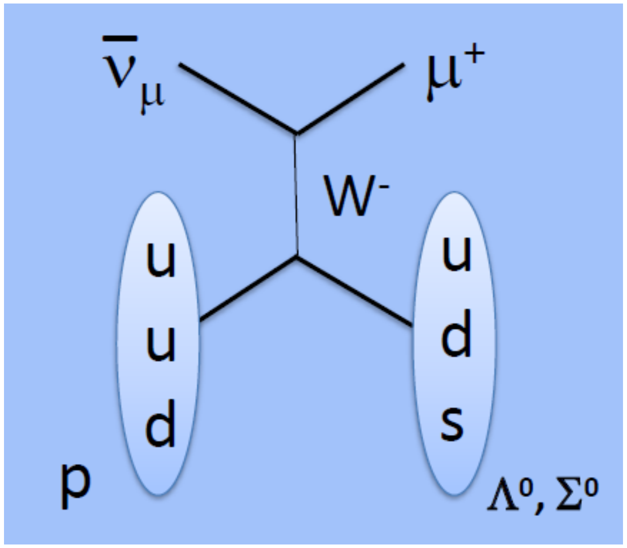




back-to-back protons

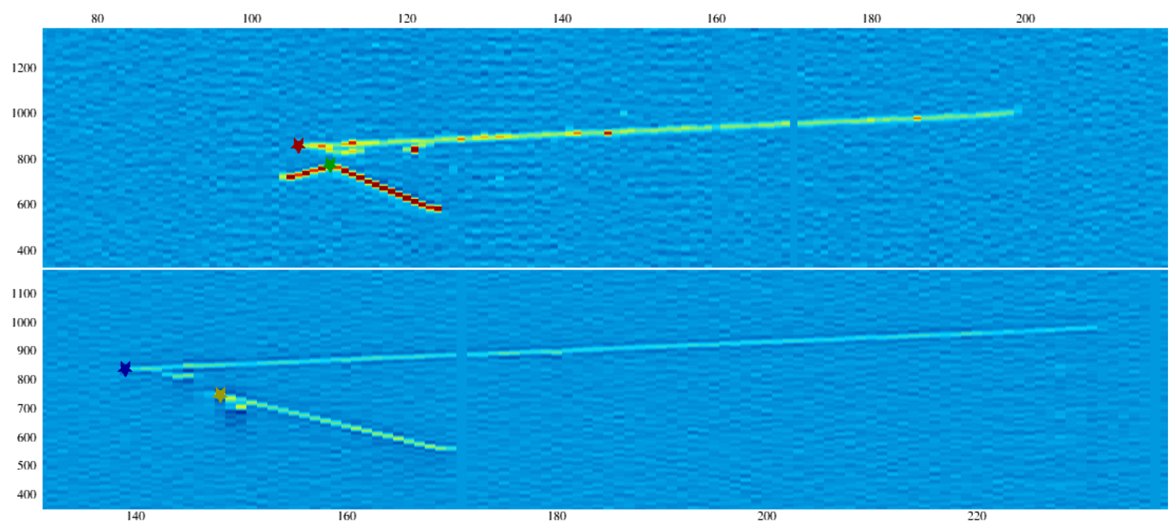
- *p_1: θ_1=53° L_1=7.5 cm, p_1=443±26 MeV/c*
- *p_2: θ_2=128° L_2=8.9 cm, p_2=466±28 MeV/c*
- *Angle between two protons γ=181°*
- Find 5 such events in antineutrino sample
- Need to estimate FSI background and signal expectation

Search for Neutral Hyperon Production



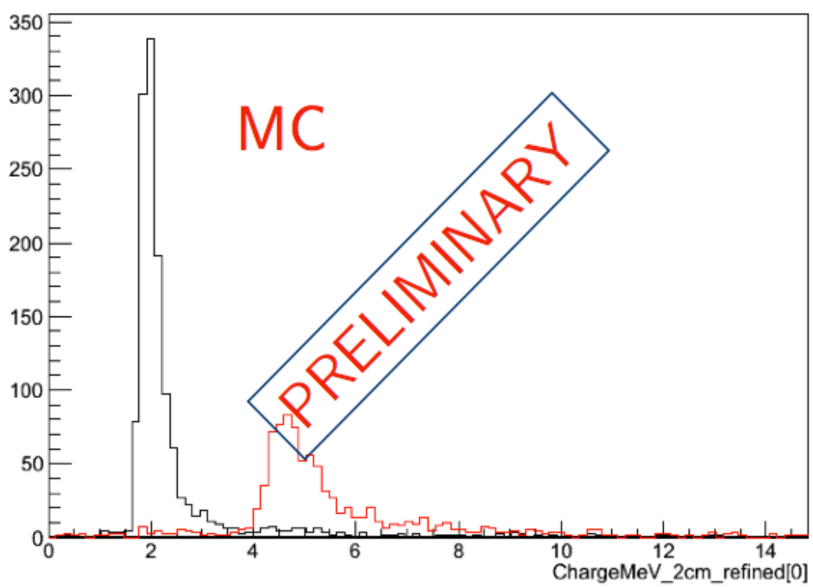
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + \Lambda^0$$
$$\downarrow$$
$$\Lambda^0 \rightarrow p\pi^- \quad 64\%$$
$$\rightarrow n\pi^0 \quad 36\%$$

- Antineutrino only. (u→s transition), E_ν>325 MeV threshold.
- In $SU(3)_F$ symmetric quark model, this process is very closely related to QE neutron production.
- Relatively long lifetime
  - For Λ^0, $c\tau$ = 7.89 cm
- Looking for displaced vertex

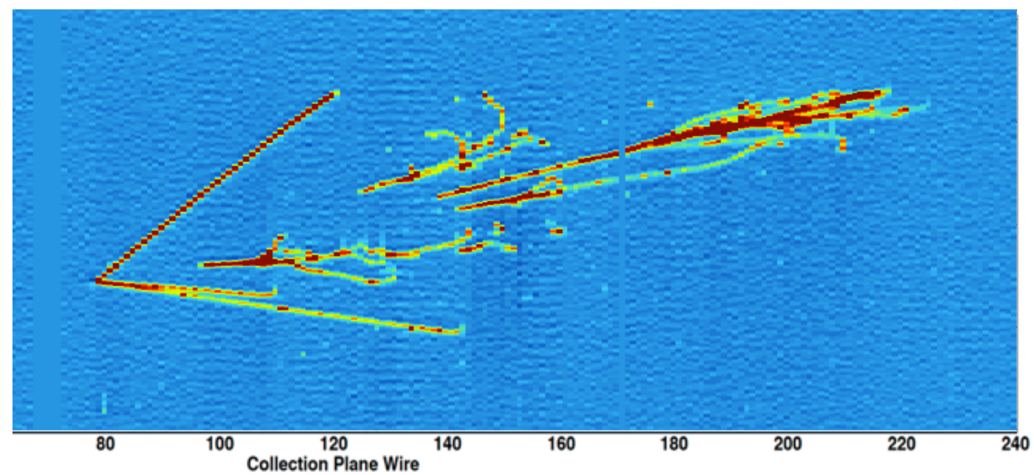


dE/dx e/γ ID

- Separating electrons from γs is important in precision measurements
- e.g. understanding whether the MiniBooNE anomaly is an effect of oscillation or background
- LongBaseline measurements e.g. CP violation etc.
- The dE/dx of a shower can be a powerful discrimination tool



Neutrino interaction with 4 photon conversions



On Going Analyses

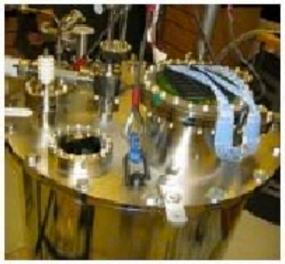
- NC π^0 cross sections
- Nuclear de-excitation γs
- Coherent pion production
- μ + nprotons + npions
- Electron neutrino event id
- Electron neutrino and antineutrino beam fractions.

Conclusions

- Data from LAr are extremely helpful and can provide important hints to tune MC generators and discriminate among models.
- Progressing with the development of more and more accurate reconstruction tools for data analysis, in combination with larger mass LAr-TPC detectors (MicroBooNE and future LAr detectors) is an important step for accurate topological analysis of neutrino events, on the line pioneered by ArgoNeuT.

Development in the US

Yale TPC



Location: Yale University
Active volume: 0.002 ton
operational: 2007

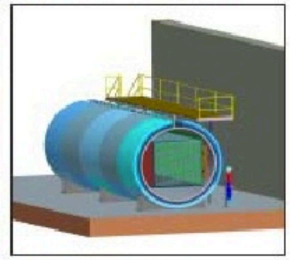
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

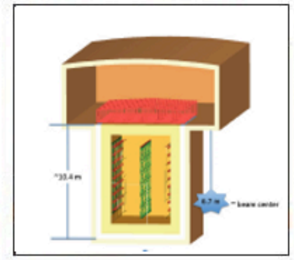
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



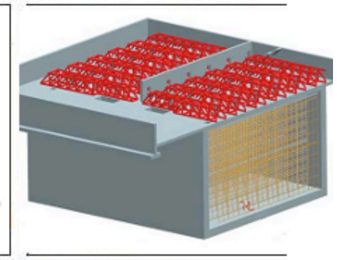
Location Fermilab
Active volume: 0.1 kton
Construction start: 2011

LAr1



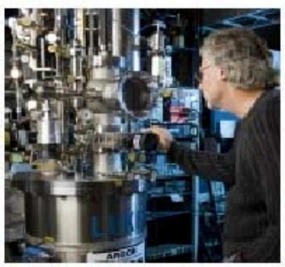
Location: Fermilab
Active volume: 1 kton
Construction start: 2016?

LBNE



Location: Homestake
Active volume: 10 kton
Construction start 2020

Luke

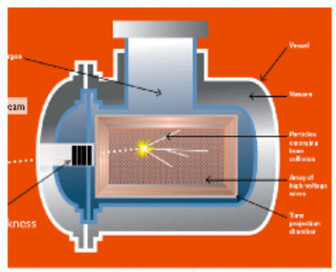


Location: Fermilab
Purpose: materials test st
Operational: since 2008

LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LAriAT

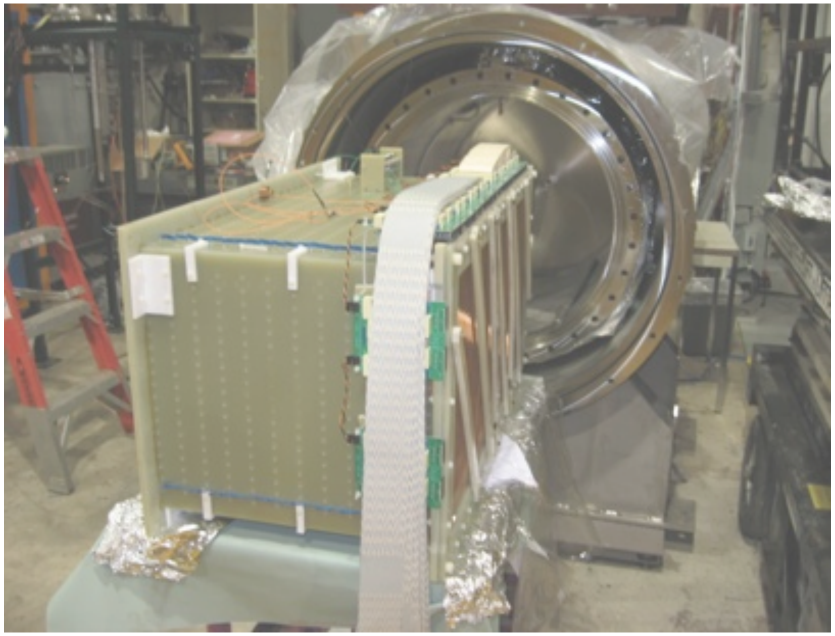


Location: Fermilab
Purpose: LArTPC calibration
Operational: 2013 (phase 1)

- Challenges
  - Good LAr purity in large vessels
  - Stable electric field over long drift distance.

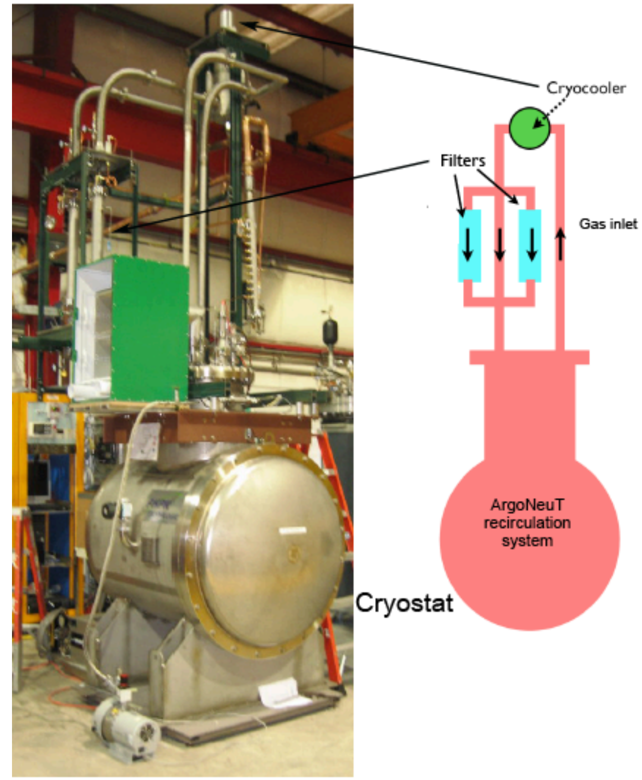
ArgoNeuT TPC and Cryostat

"The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab" **JINST 7 (2012) P10019**



The TPC, about to enter the inner cryostat

Cryostat Volume	500 Liters
TPC Volume	170 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length	47 cm
Light Collection	None



- Self contained system
- Recirculate argon through a copper-based filter
- Cryocooler used to recondense boil-off gas

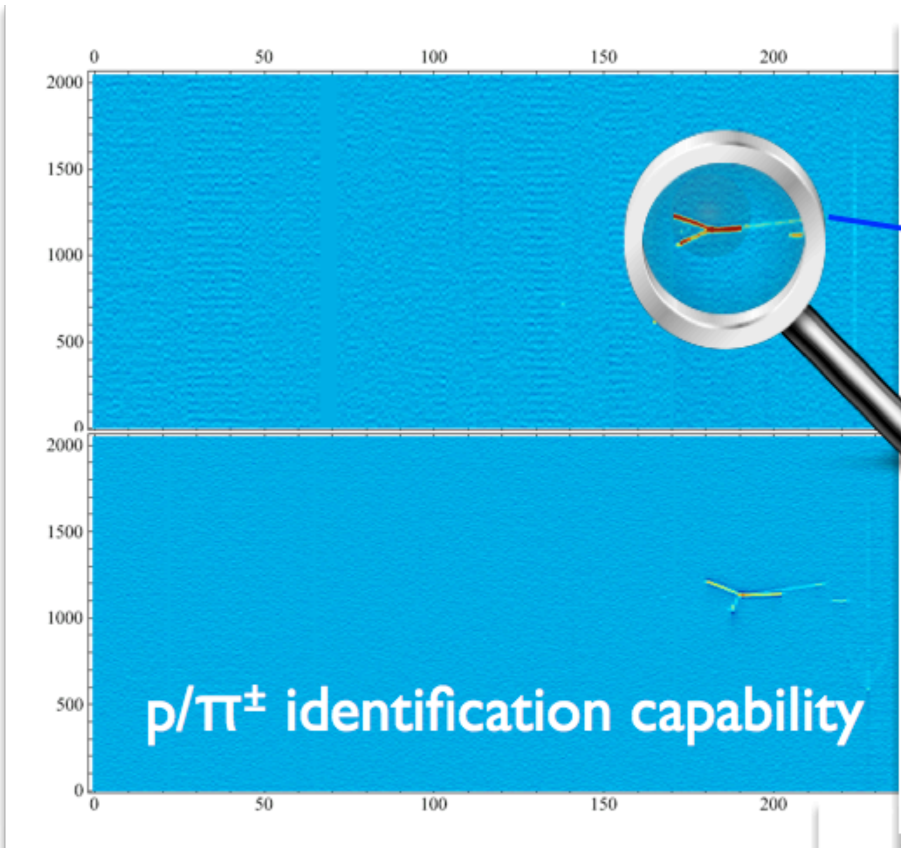
PID Efficiencies

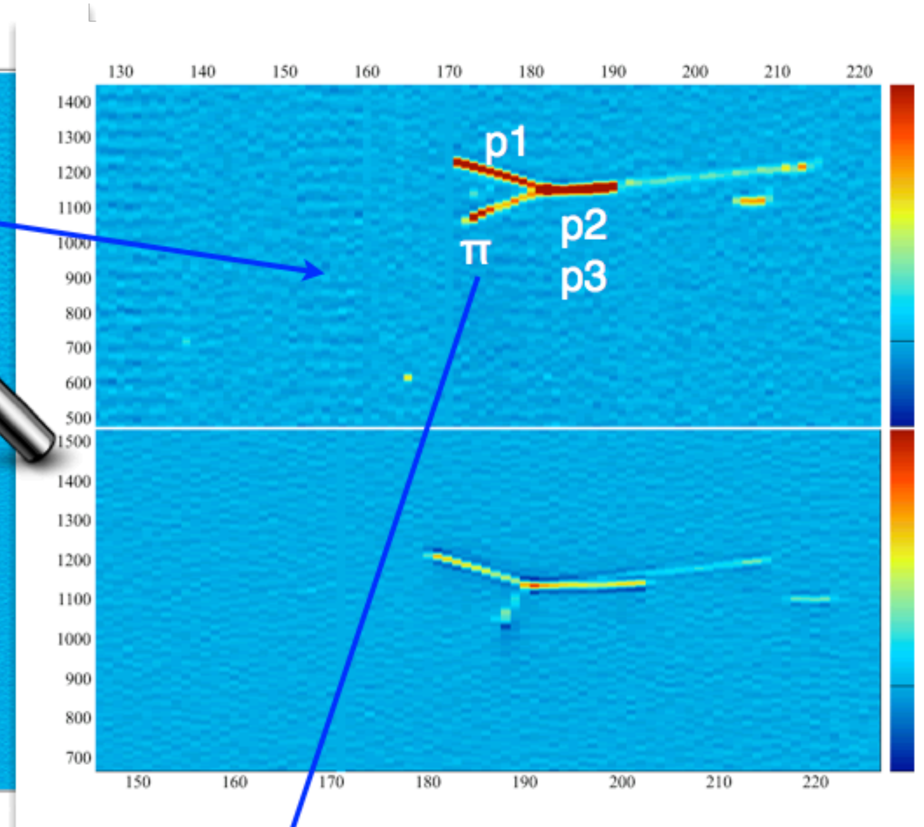
Generated

Identified as

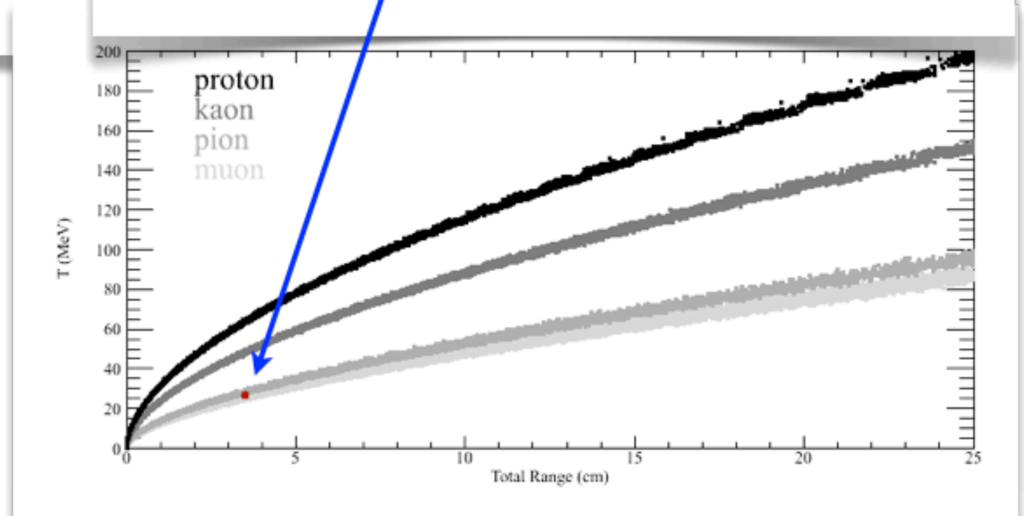
	Proton	Kaon	Pion	Muon
Proton	0.97	0.15	0.05	0
Kaon	0.03	0.60	0.09	0.01
Pion	0	0.06	0.25	0.28
Muon	0	0.20	0.61	0.71

- Good efficiency to identify protons.
- No separation between pions and muons.





- *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