Neutrino Interactions on Liquid Argon – New Results from ArgoNeuT

Aspen Winter Workshop – New Directions in Neutrino Physics

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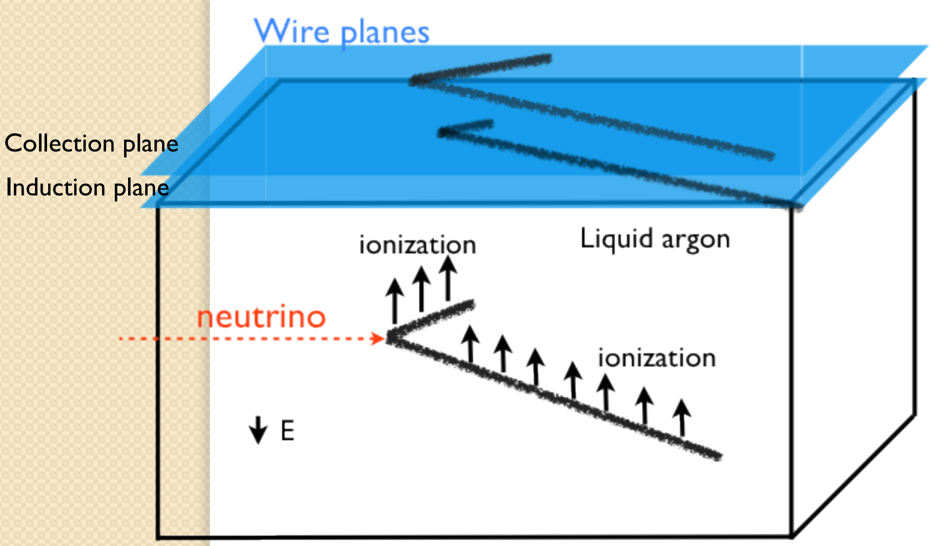
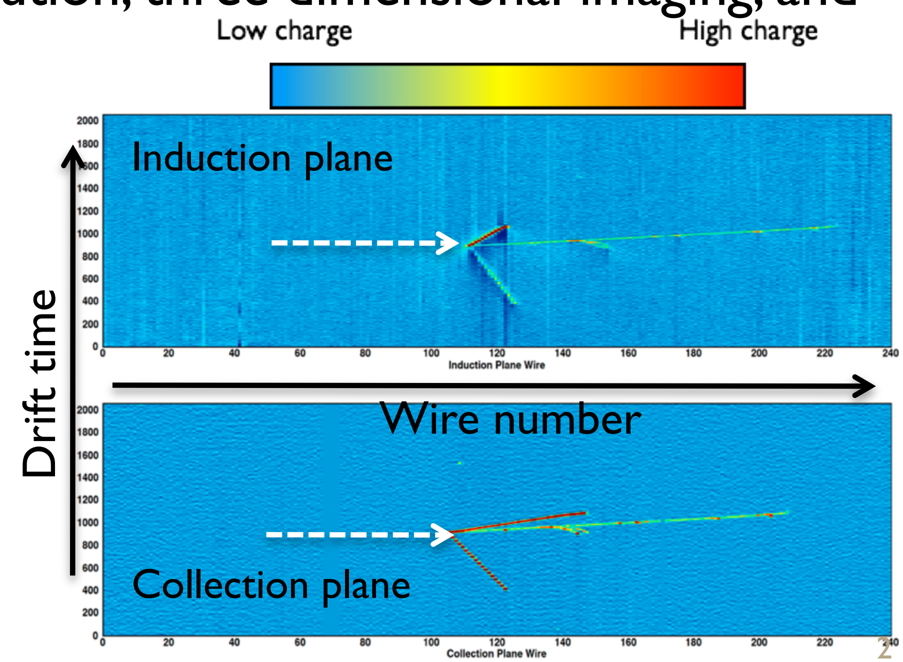
FNAL
2/8/13

Liquid Argon TPC - LArTPC

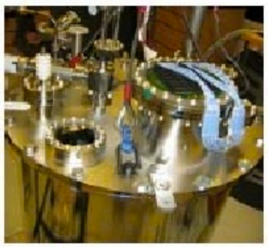
- Pioneered by the ICARUS collaboration.
- Liquid argon offers abundant ionization electrons and scintillation light for particle detection.
  - Suitable for studies of neutrino physics, search for proton decays, etc.
  - Relative cheap and scalable.
- mm-scale position resolution, three dimensional imaging, and calorimetry.





Development in the US

Yale TPC



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

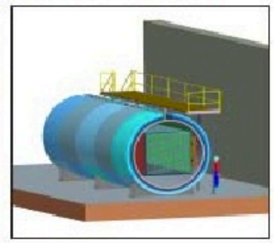
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

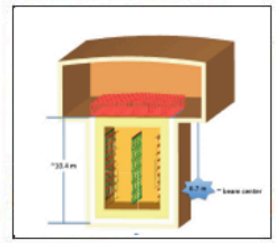
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



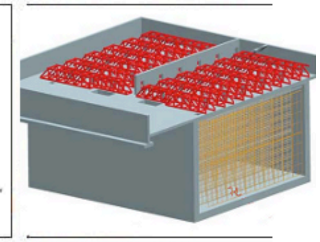
Location Fermilab
Active volume: 0.1 kton
Construction start: 2011

LAr1



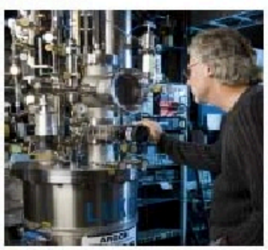
Location: Fermilab
Active volume: 1 kton
Construction start: 2016?

LBNE



Location: Homestake
Active volume: 10 kton
Construction start 2020

Luke

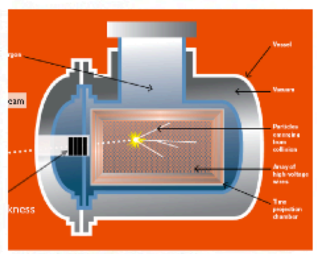


Location: Fermilab
Purpose: materials test st
Operational: since 2008

LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LAriAT



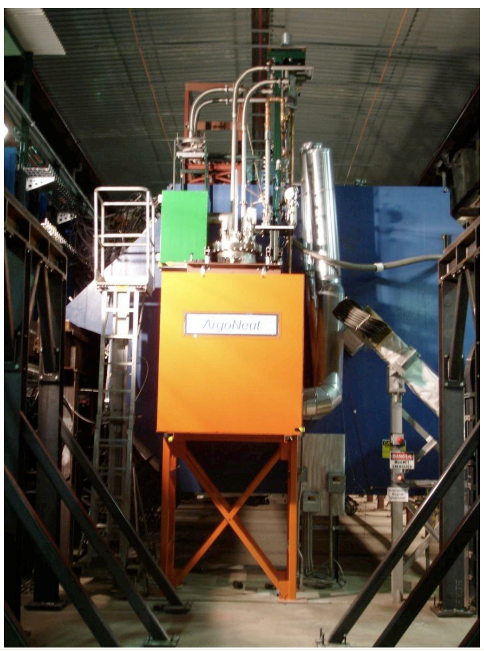
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2013 (phase 1)

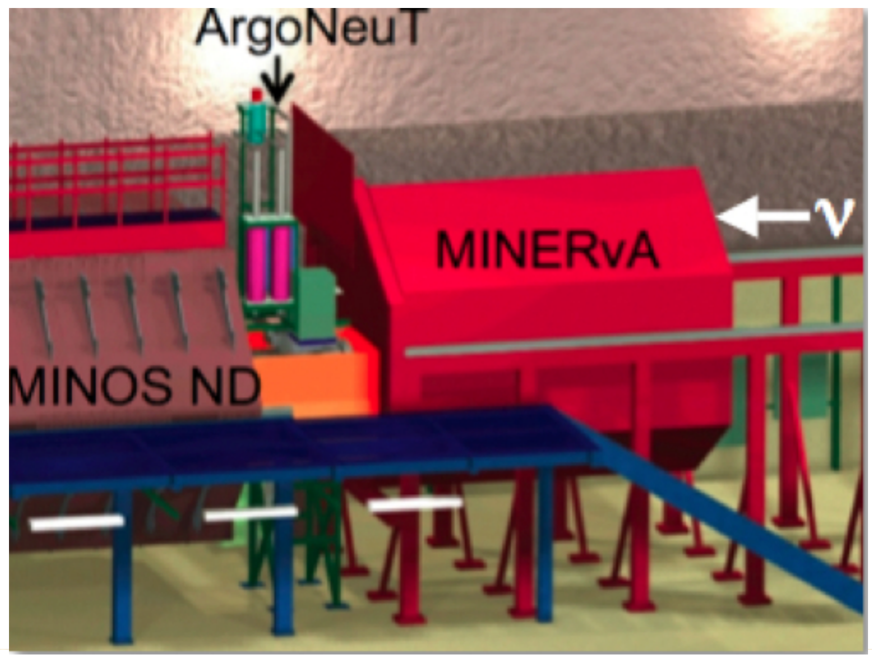
- Challenges
  - Good LAr purity in large vessels
  - Stable electric field over long drift distance.

- David Kaleko: "MicroBooNE and Liquid Argon Time Projection Chambers" (poster)
- Robert Svoboda: "LBNE Underground: Thinking Outside the Box"

ArgoNeuT - Argon Neutrino Teststand

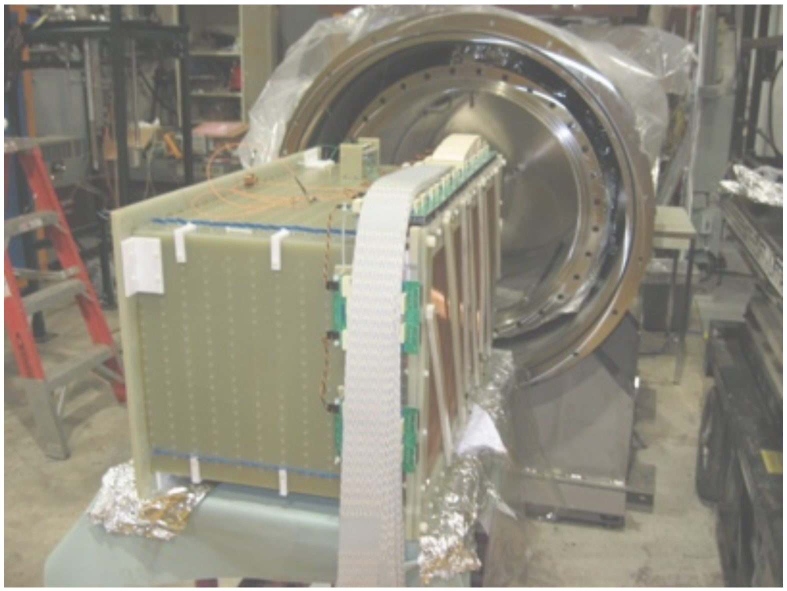
- First TPC in a neutrino beam in the US.
- Located between MINOS near detector (ND) and MINERvA.
- Sitting in NuMI beam - Neutrinos at the Main Injector
- Use MINOS ND as muon spectrometer





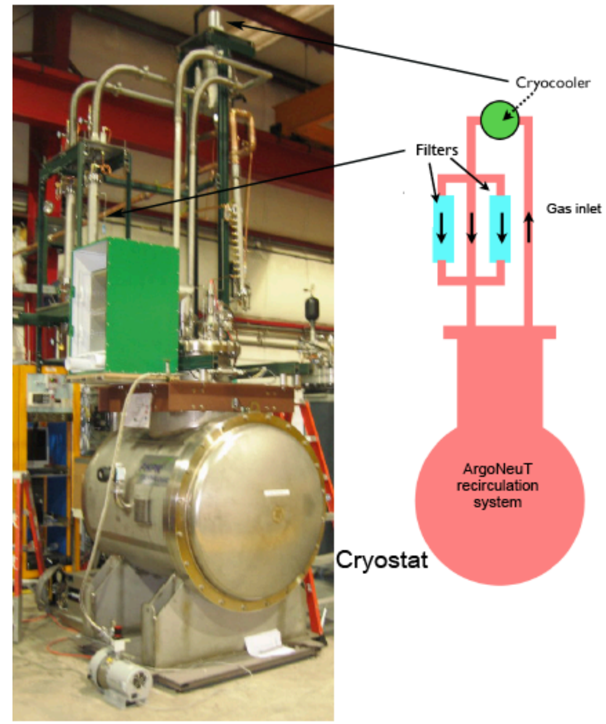
ArgoNeuT TPC and cryostat

JINST 7 (2012) P10019



The TPC, about to enter the inner cryostat

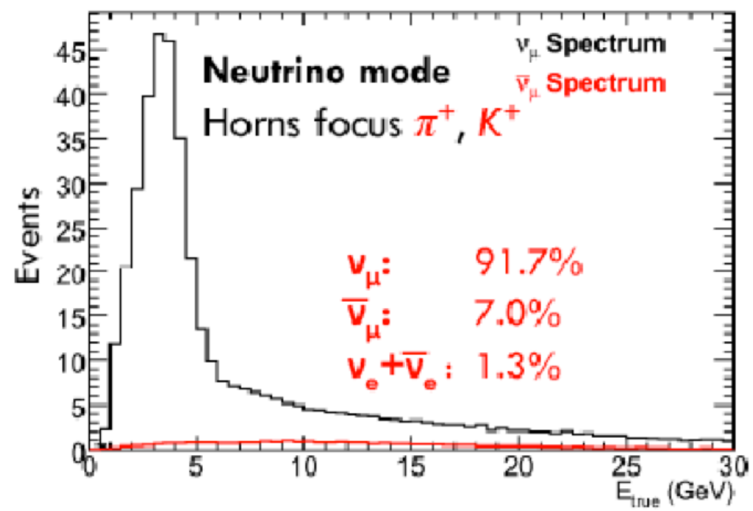
Cryostat Volume	500 Liters
TPC Volume	170 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length	47 cm
Light Collection	None



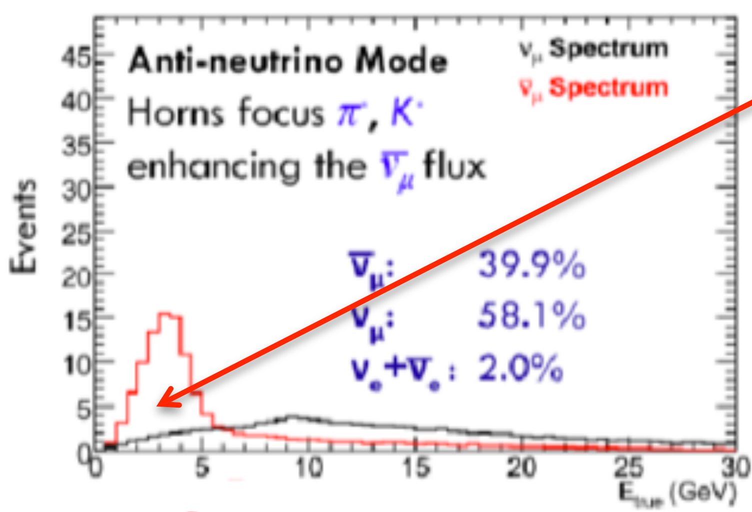
- Self contained system.
- Recirculate argon through a copper-based filter.
- Cryocooler used to recondense boil-off gas.

ArgoNeuT's Physics Run

0.085e20 POT



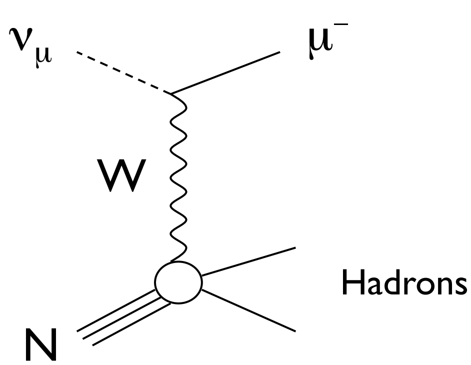
1.2e20 POT

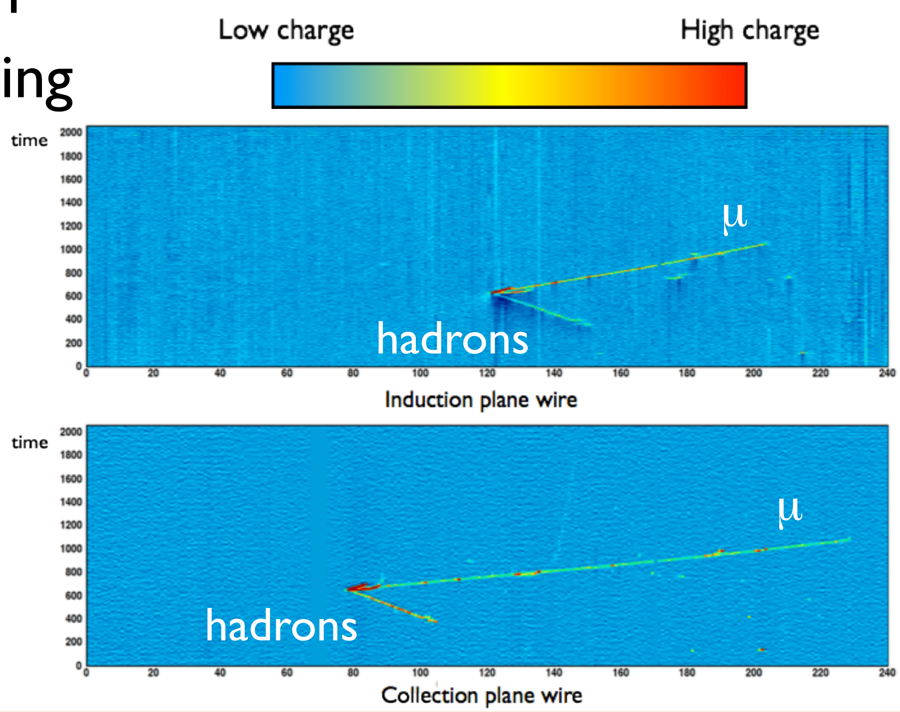


- ArgoNeuT completed taking data. (9/14/2009-2/22/2010).
- Collected events in the 0.1 to ~20 GeV range.
  - First low energy neutrino interactions in LArTPC
- Results based on $\bar{\nu}_\mu$'s in the anti-neutrino beam
  - Inclusive Charged-Current (CC) cross section
  - Exclusive CC 1μ+Np topological cross section

Muon neutrino inclusive charged current cross sections

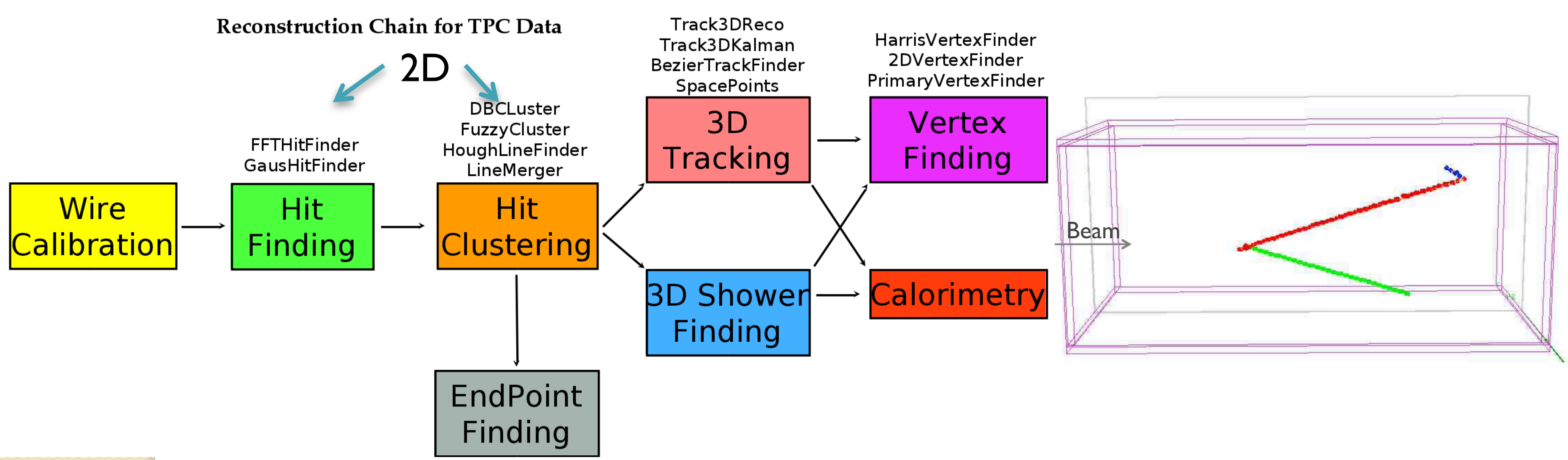
- First results based on 8.5e18 POT neutrino data published in PRL 108 (2012) 161802.
- Currently working on measurements using 1.2e20 POT antineutrino data.
  - Event reconstruction
  - MINOS track matching
  - MC simulation
  - Preliminary results



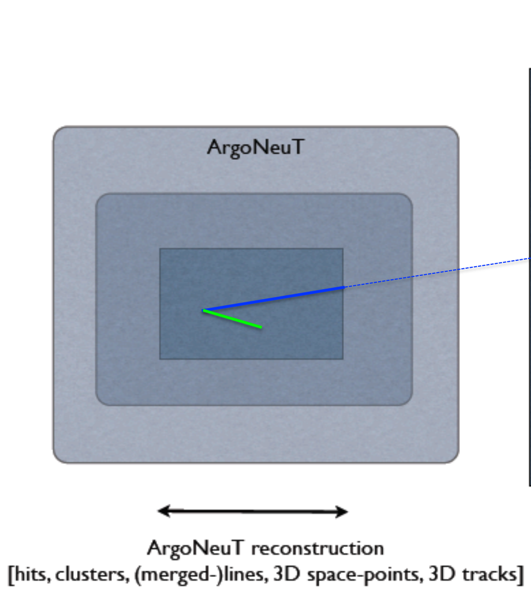


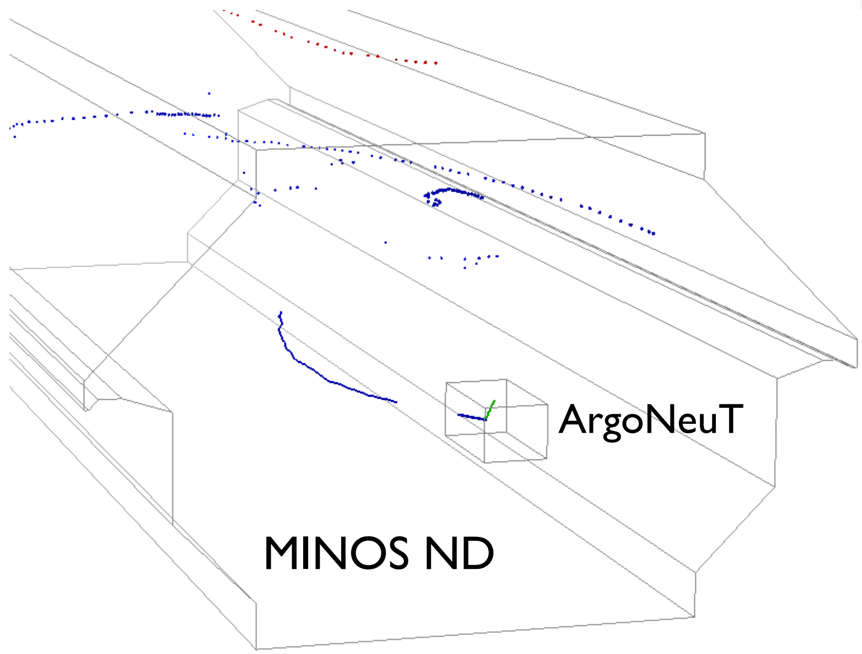
Reconstruction

- Reconstruction is done using LArSoft in the ART framework: https://cdcvs.fnal.gov/redmine/projects/larsoftsvn
  - A software package developed for LArTPCs.
  - Used for several experiments: ArgoNeuT, MicroBooNE, LBNE, etc.
  - Constructed from separate modules - highly configurable.



MINOS track matching



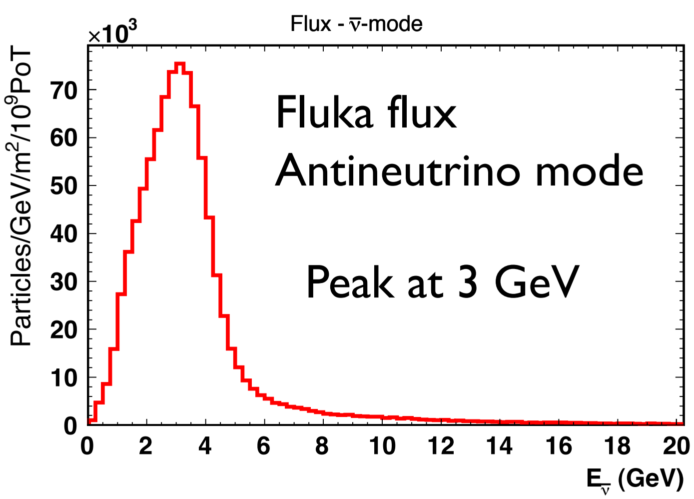


JINST 7 (2012) P10020

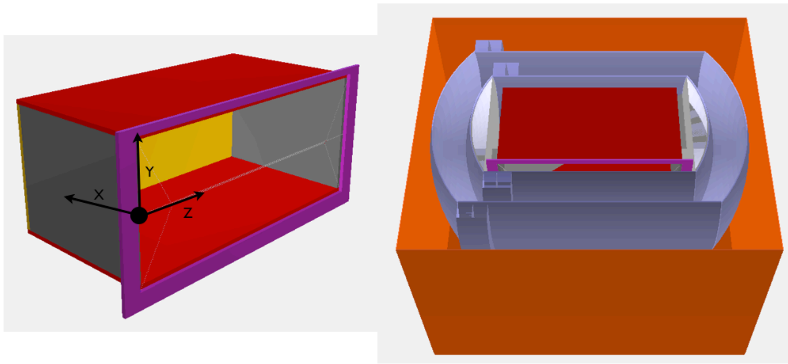
- The presence of the MINOS ND allows for energy reconstruction and charge identification (q) of muons.
- We gratefully acknowledge the help of the MINOS collaboration for providing simulated NuMI flux, ND data, simulation and reconstruction code.

MC Simulation

- Monte Carlo simulation is also done in LArSoft
  - NuMI flux
    - Neutrino mode – Low-ν flux: PRD 81 (2010) 072002
    - Anti-neutrino mode – Fluka08
  - Neutrino interaction: GENIE r3470
    - Neutrino cross sections and final state interactions (FSI)
  - Particle propagation: GEANT4
  - Detector response: LArSoft
  - MINOS ND: MINOS code



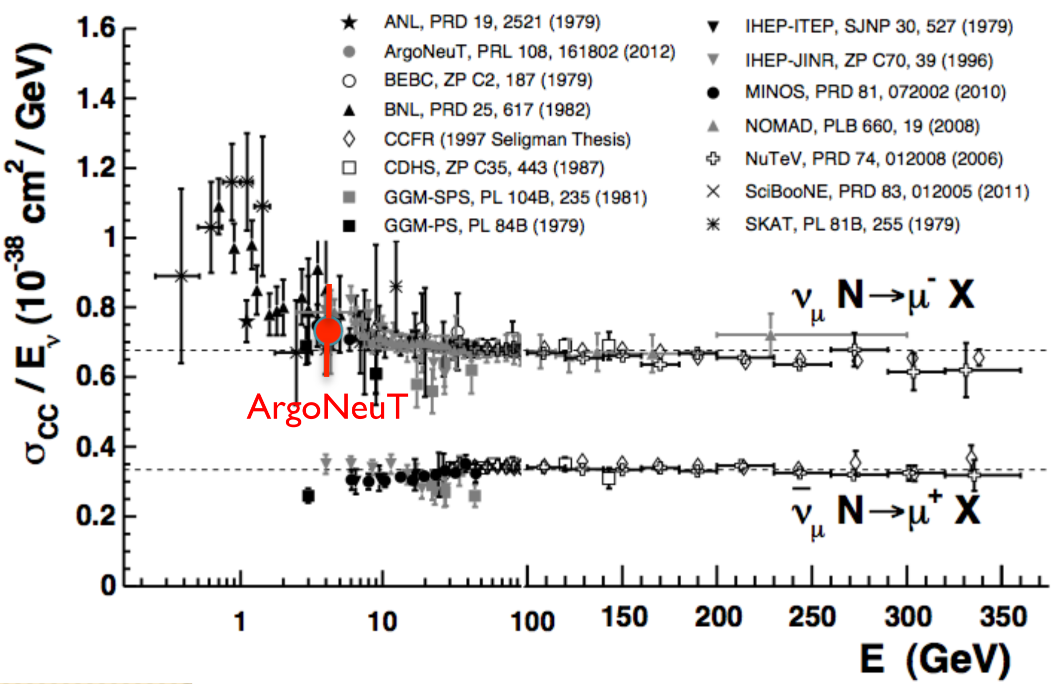
PRL 107 (2011) 021801

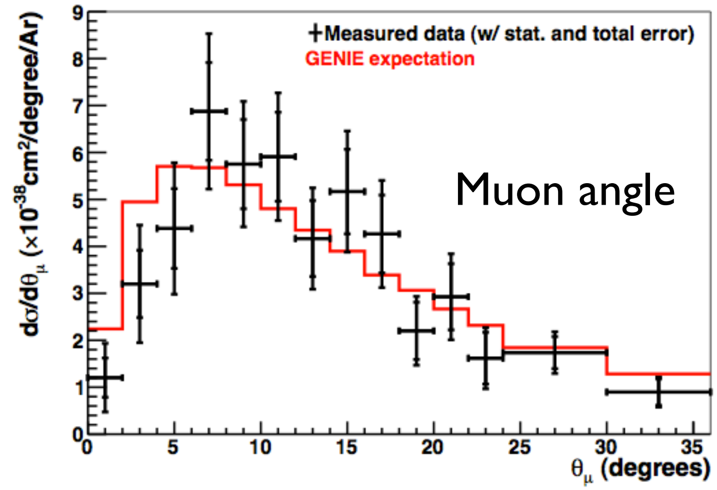


Geometry

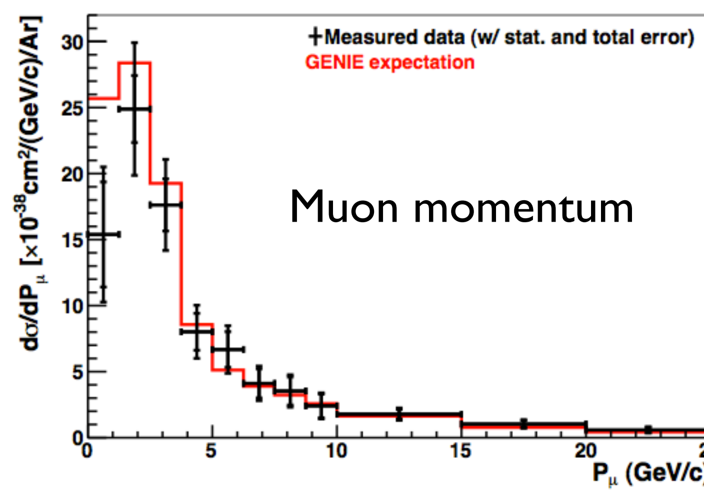
Previous results in ν mode (8.5e18 POT)

PRL 108 (2012) 161802

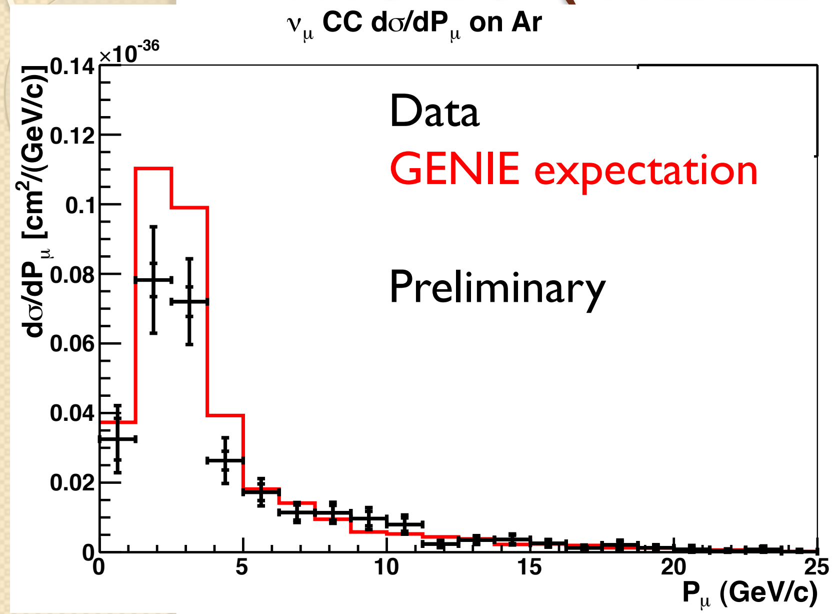


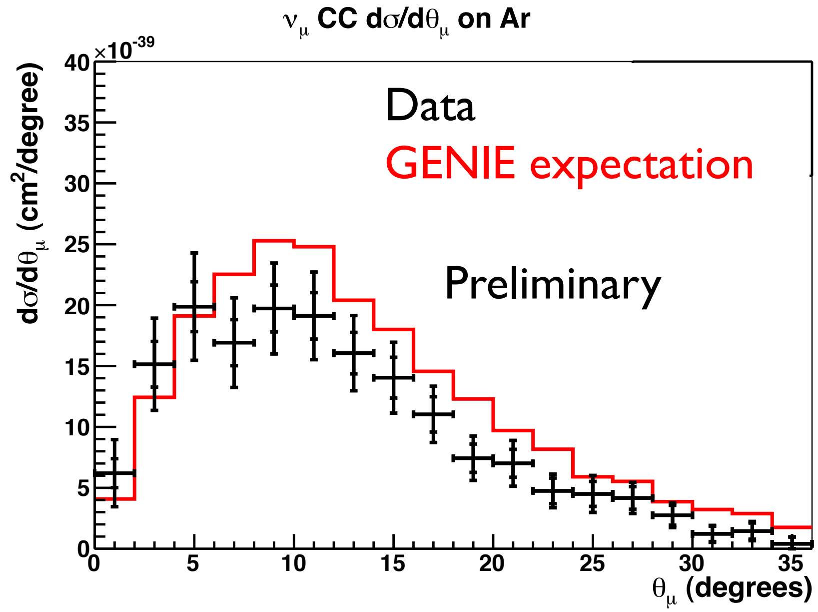


- Interaction vertex in fiducial volume.
- Track matched to muon in MINOS ND.
- Negatively charged muon in MINOS.



Anti-neutrinos in the Anti-neutrino mode (1.2E20)

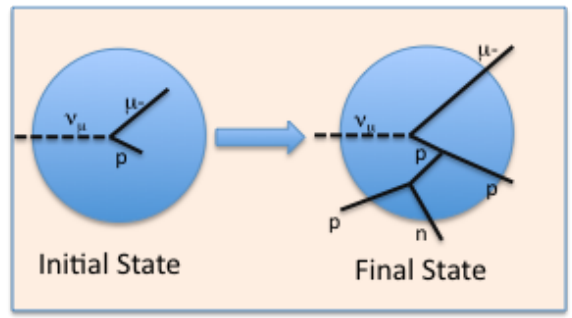




- Similar inclusive CC selection
  - Interaction vertex in fiducial volume.
  - Track matched to muon in MINOS ND.
  - Positively charged muon in MINOS ND.
- Efficiency and background evaluated using a full MC simulation.
- Working on measurements using neutrinos in the antineutrino mode.

Topological Analysis 1μ+Np

- Conventional measurement of exclusive channels: quasi-elastic (QE), resonance pion production (RES) etc.
- Difficulties in comparing with theoretical predictions
  - Large uncertainties in transition region (e.g. RES->DIS)
  - Final state interaction (FSI)
- Instead: Topological Analysis
  - Measure what we see in detector
  - 1μ+Np where N=0,1,2...
  - 1μ+π+Np
  - etc.
- LArTPC allows for FSI exploration and exclusive topology recognition with extraordinary sensitivity

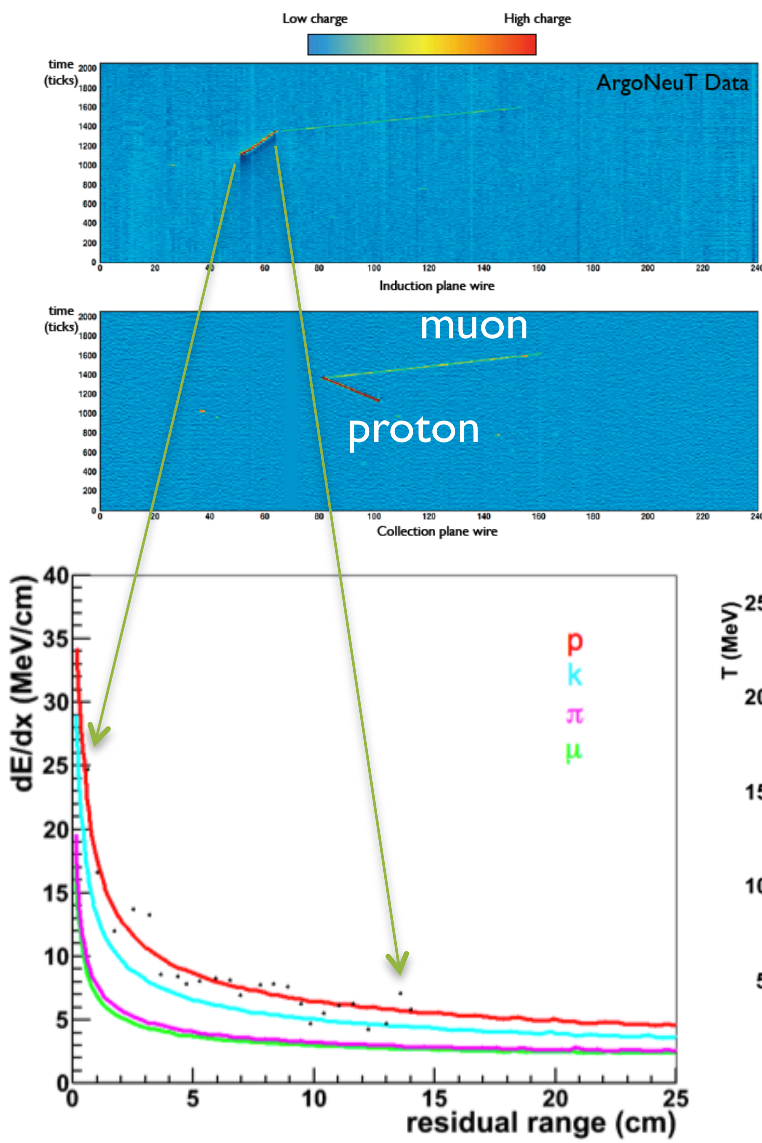


Focus of the talk →

Analysis strategy (1μ+Np)

- Event selection
  - Automated cuts – select CC events with distinct tracks
    - Similar to inclusive CC analysis with additional cuts
  - Visual scanning – select events with only muon and contained proton tracks (no pion).
- Correct for efficiency and purity for different proton multiplicities evaluated using a full MC simulation.
  - Take proton containment into account.

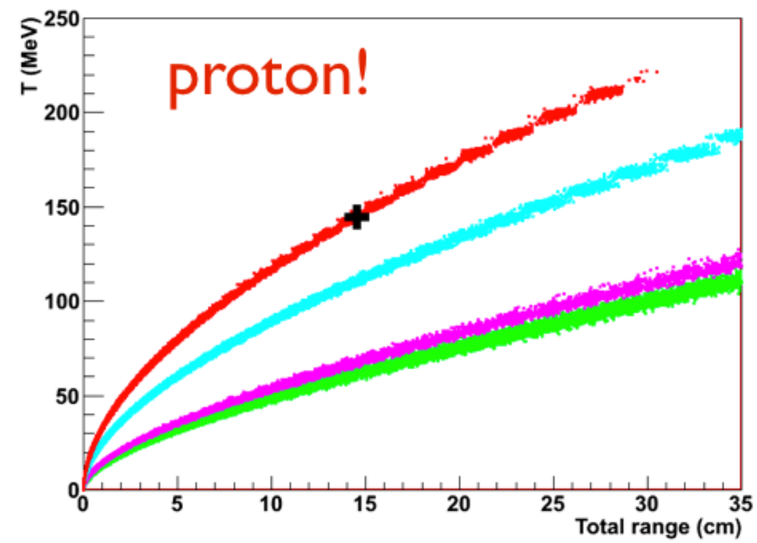
Calorimetry particle ID



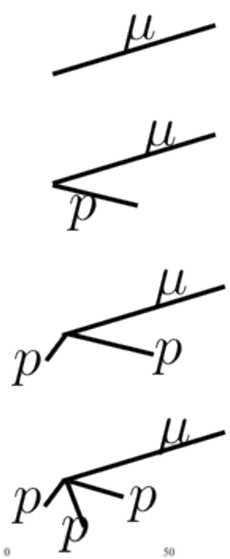
Pixel size of
(4.0 x 0.3) mm^2

4mm wire pitch
198 ns sampling time

Energy resolution ≈5% for
Minimum Ionizing Particles



Event topology

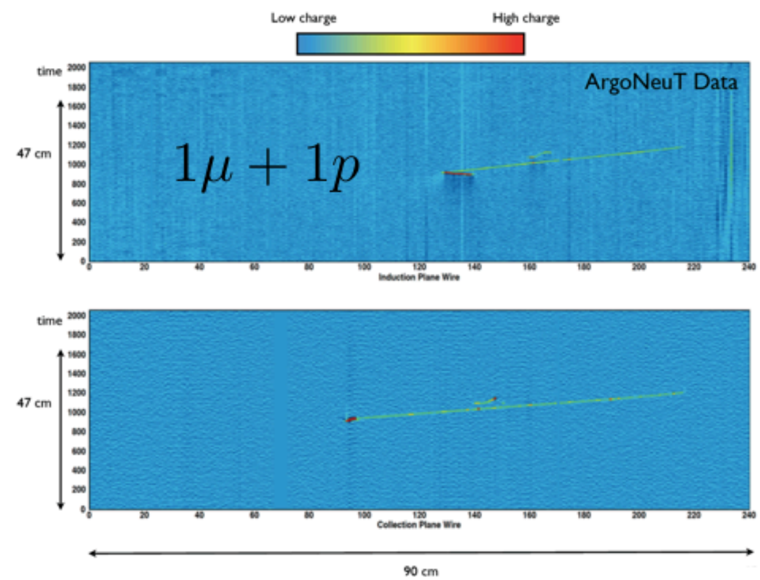


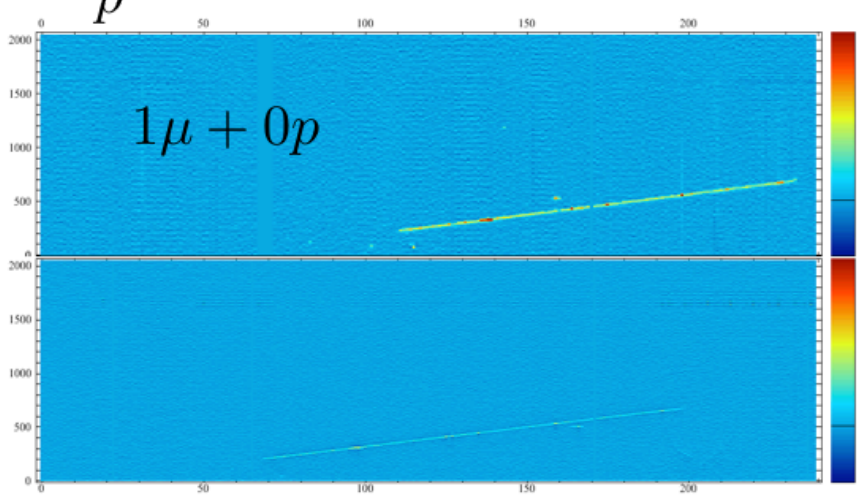
$1\mu + 0p$

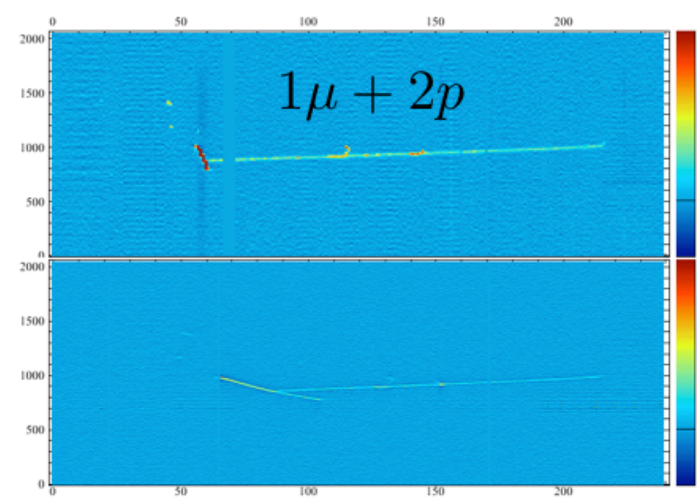
$1\mu + 1p$

$1\mu + 2p$

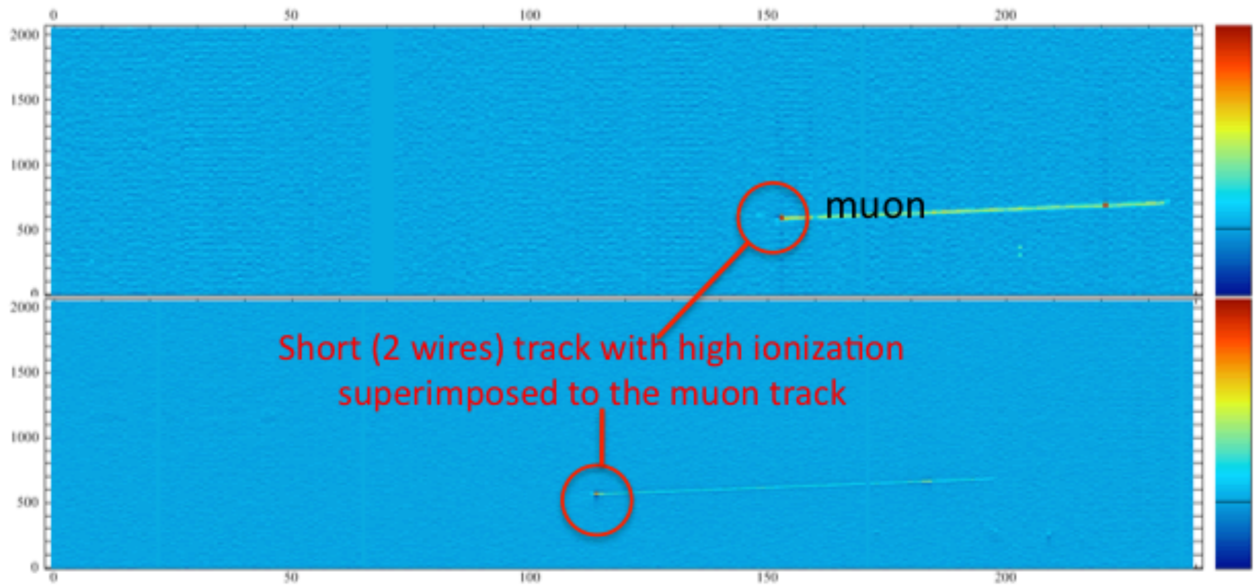
$1\mu + 3p$







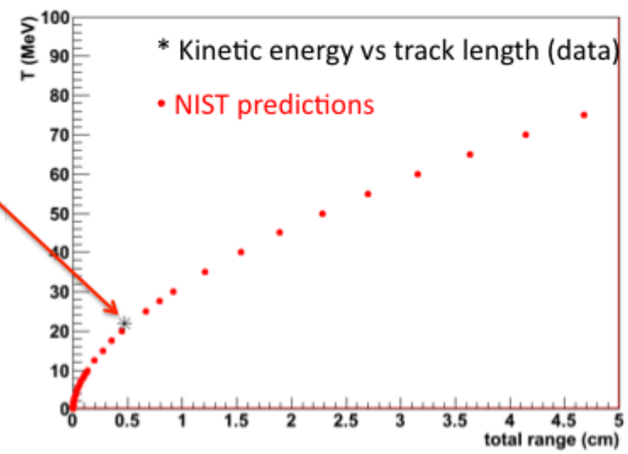
Proton threshold



The short track behaves like proton

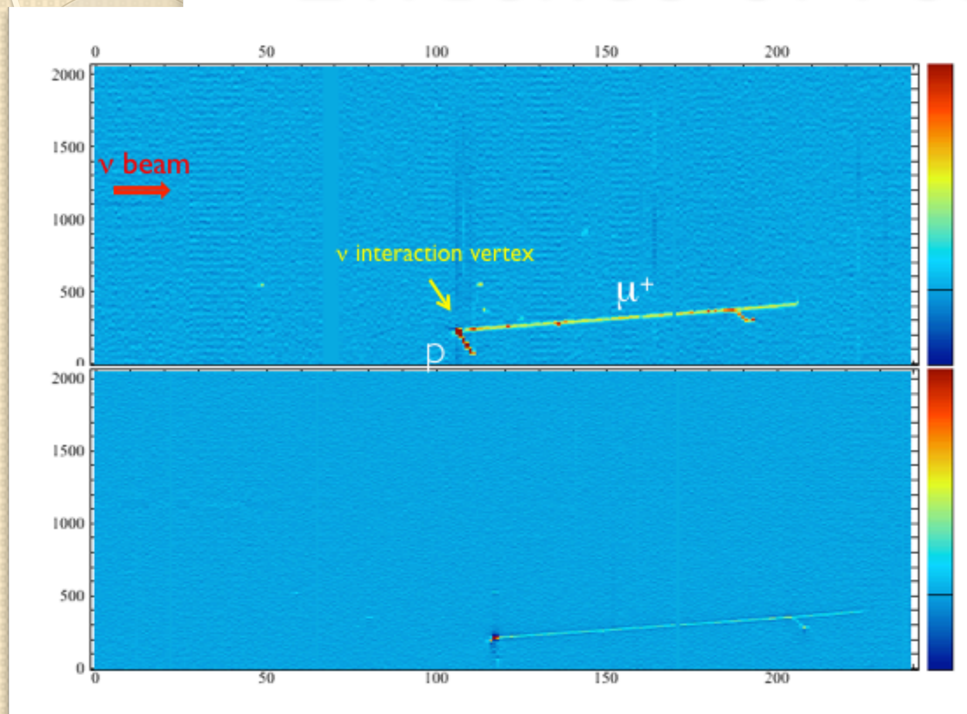
Length=0.5 cm

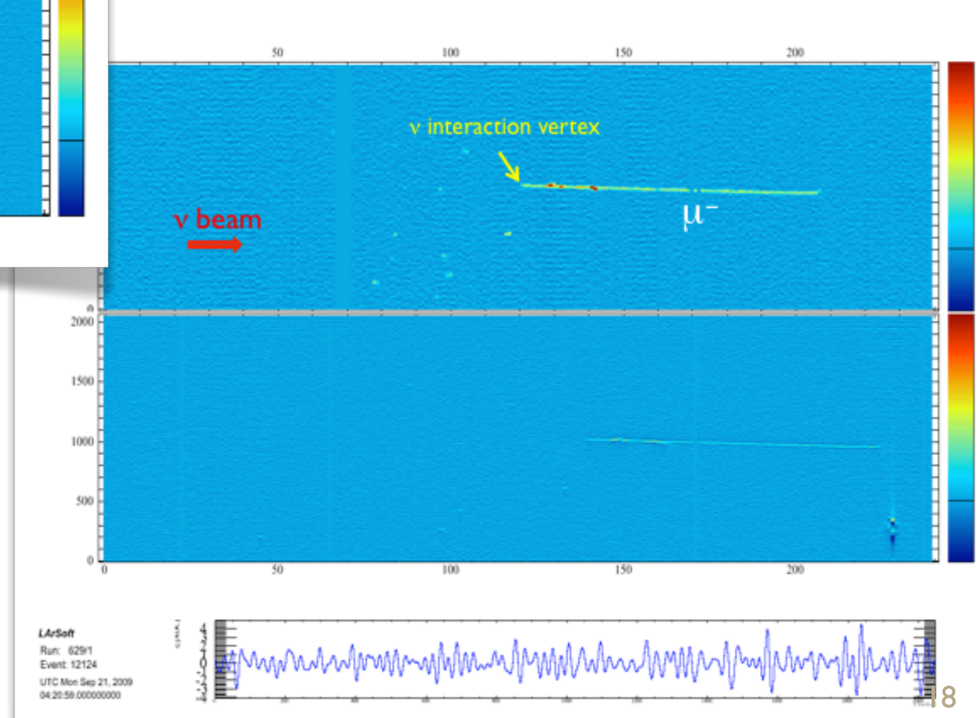
KE=22±3 MeV



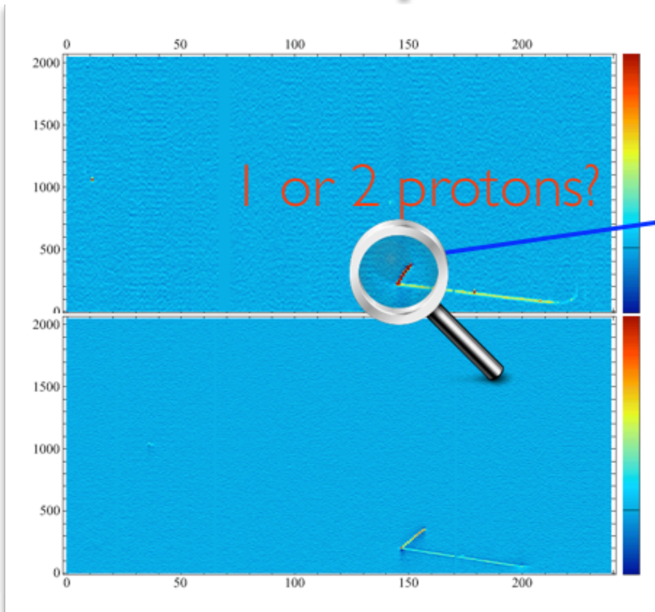
- Proton threshold is 21 MeV

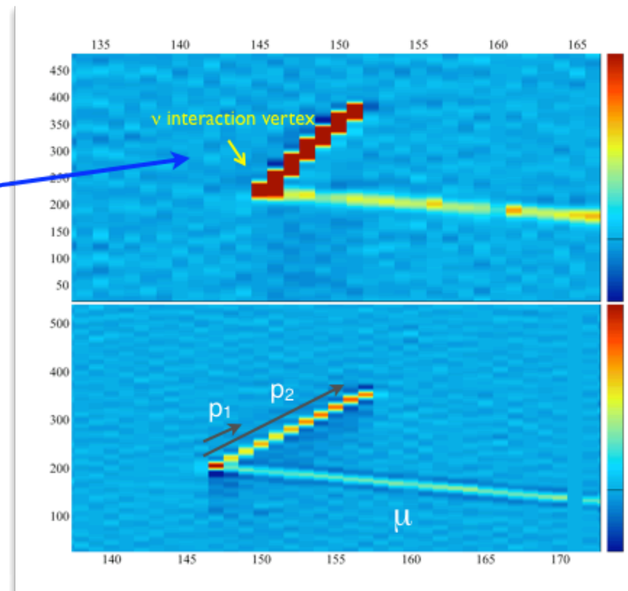
Evidence of FSI

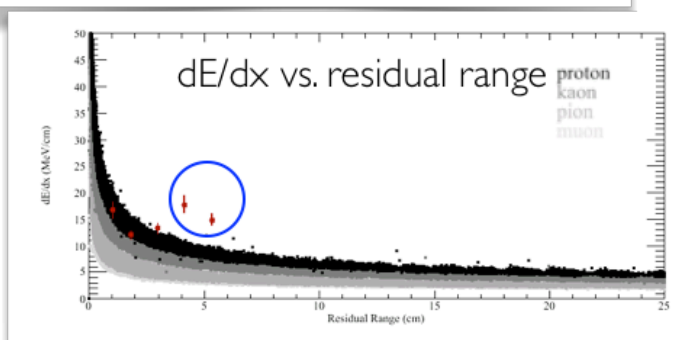




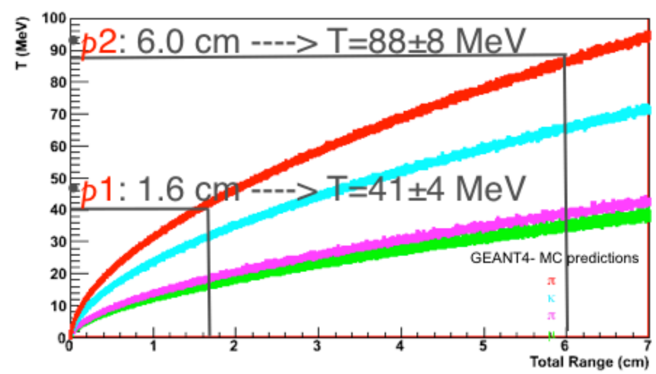
A multi-proton event







compatible with
1 μ 2p

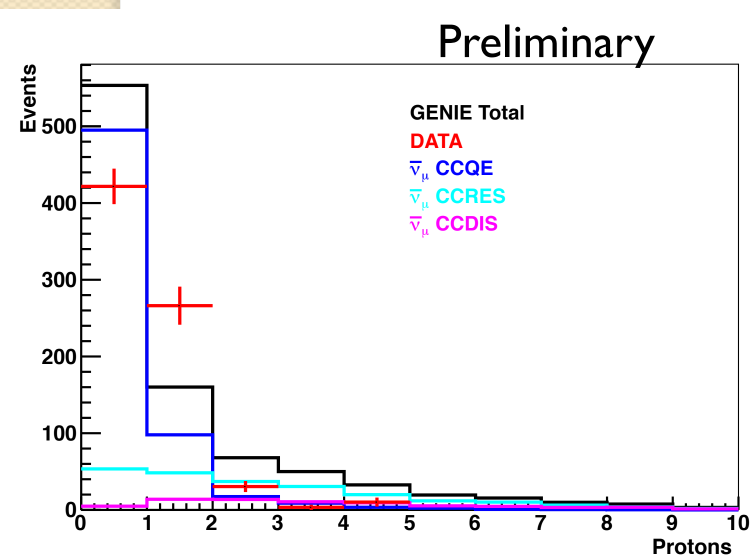


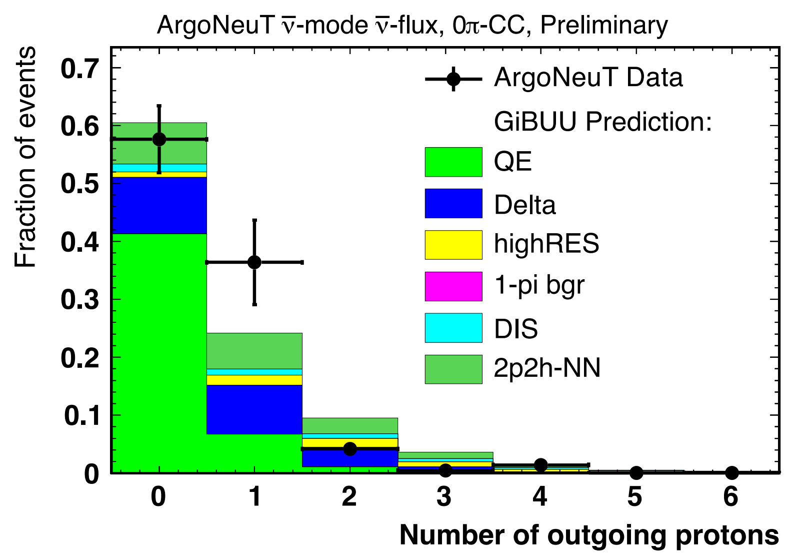
Comparison with MC

- GENIE - Generates Events for Neutrino Interaction Experiments
  - FSI: Intranuclear Cascade mode (INC)
  - Meson exchange (MEC) channel in the future
- GiBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project
  - FSI: Transport model
  - 2p2h-NN channel included
    - 2-particle-2-hole interaction with 2 nucleons produced
  - We are grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions.

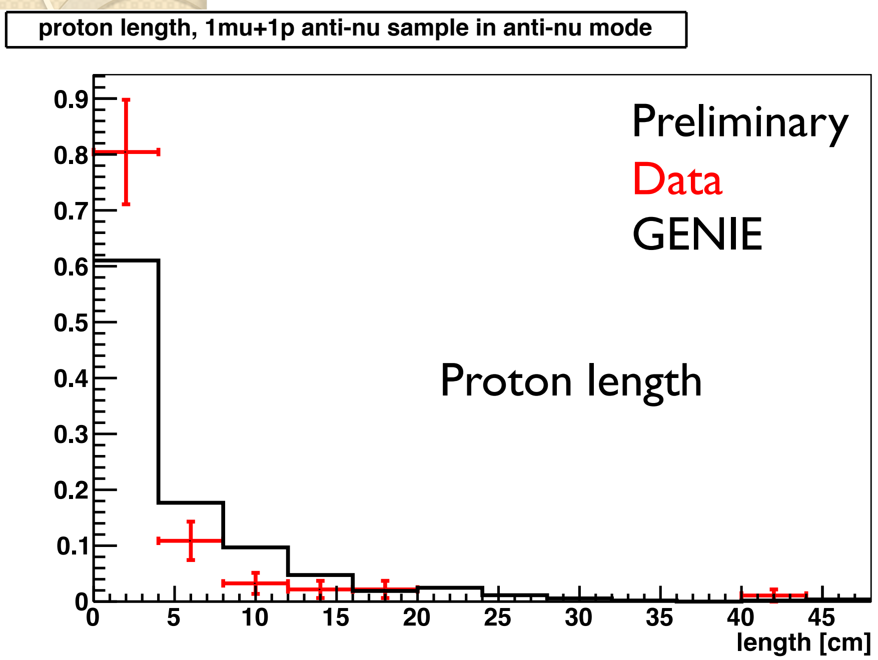
Proton multiplicity (1μ+Np)

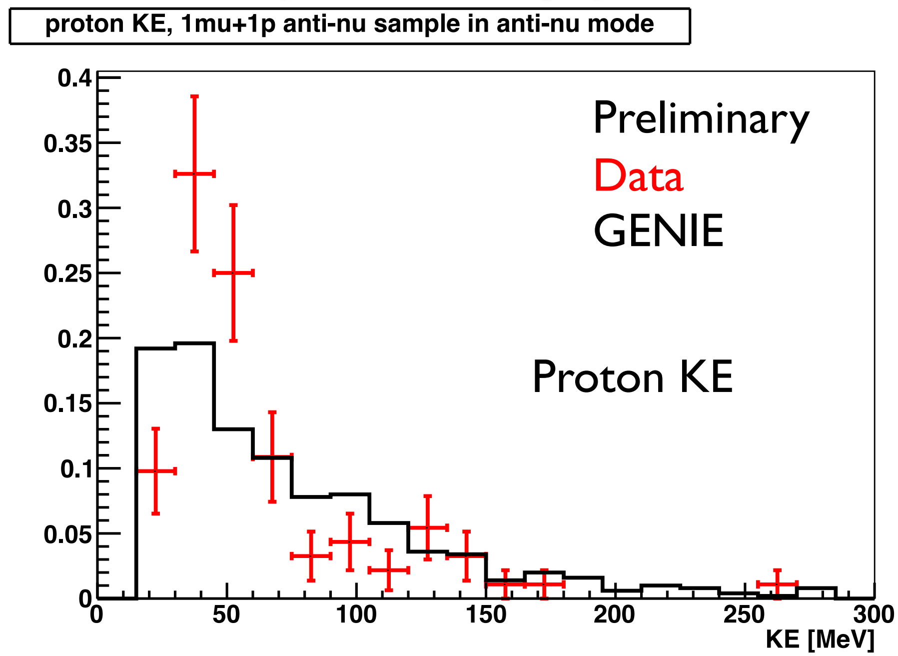
Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	Data/MC Ratio
0p+1mu	553±11	60%	422±42	58%	0.76
1p+1mu	160±6	17%	266±53	37%	1.66
2p+1mu	68±4	7%	30±6	4%	0.44
3p+1mu	50±3	5%	3±1	0.4%	0.06
4p+1mu	32±3	4%	3±1	0.4%	0.09
TOTAL (including >4p)	925±15	-	727±68	-	0.79





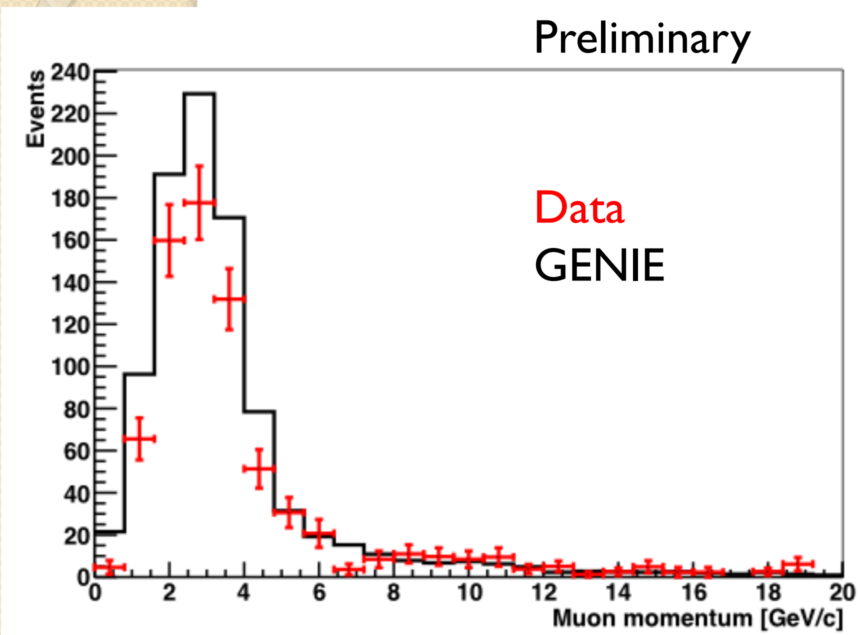
Proton kinematics (1μ+1p)

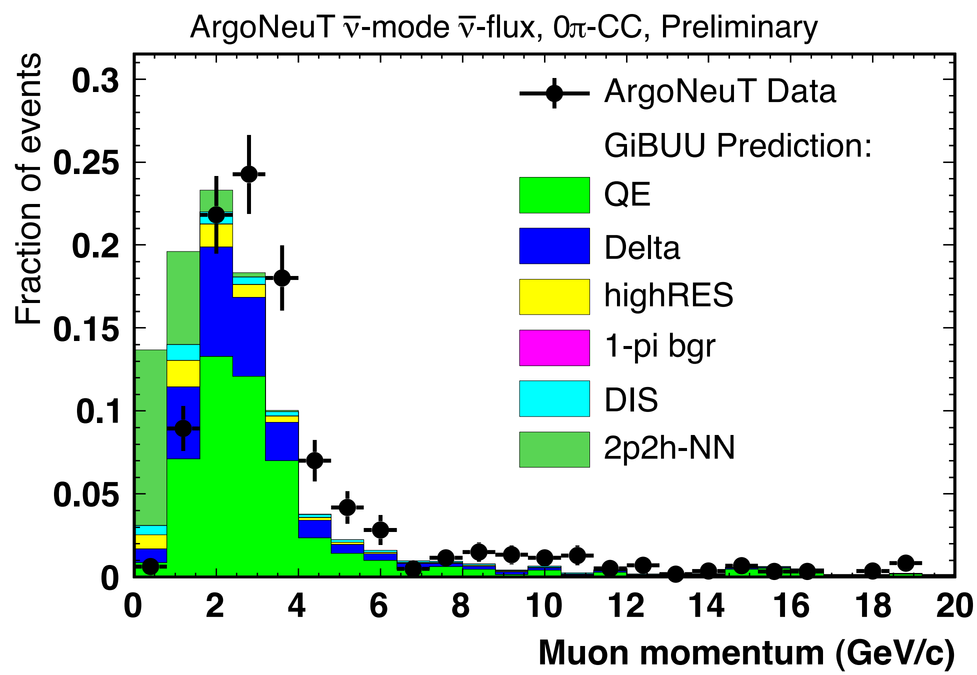




- Area normalized, comparison inside detector with contained protons, no efficiency/acceptance corrections

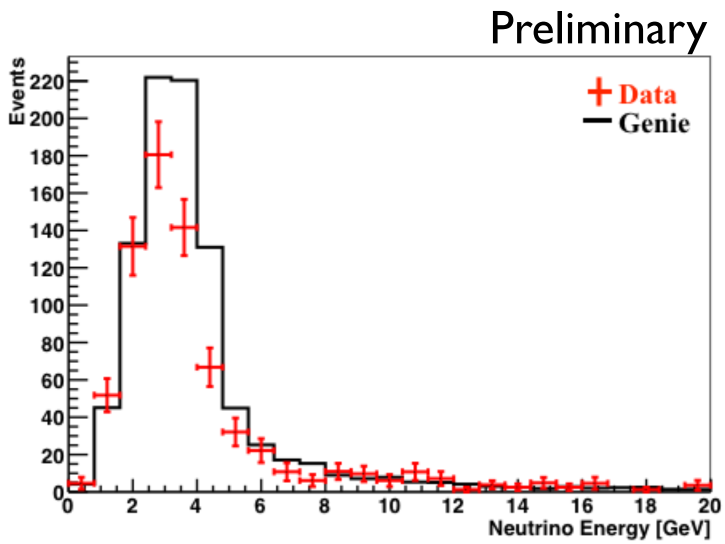
Muon momentum (1μ+Np)

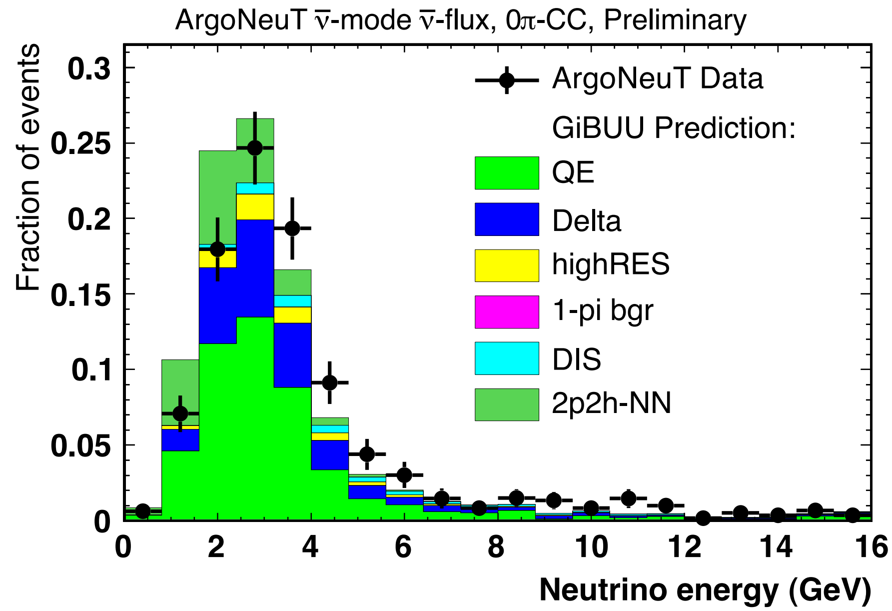




- The 2p2h-NN component has large uncertainties.

Neutrino energy (1μ+Np)





$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

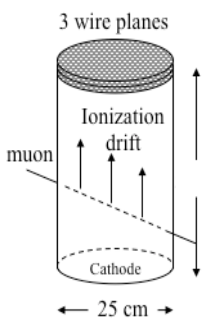
- Data energy reconstructed with the QE formula.
- Improved energy reconstruction including proton kinematics in progress.

Conclusions

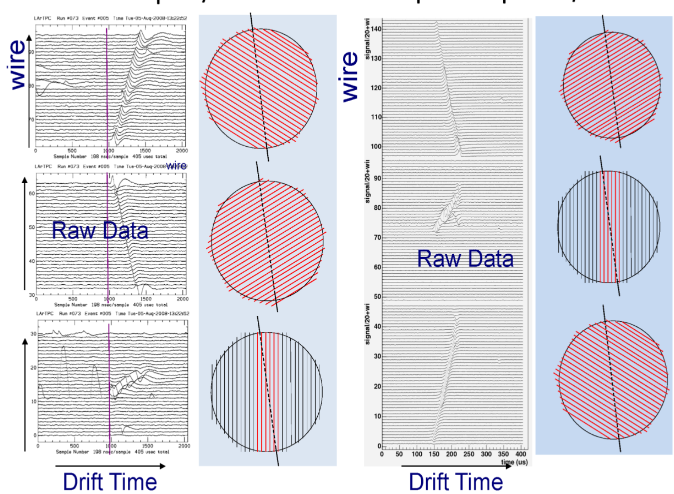
- ArgoNeuT collected first ever data for low energy neutrino interactions with a LArTPC.
- Measurement of inclusive CC cross sections using high statistics anti-neutrino data.
- Analysis of 1μ+Np events provides valuable information to event generator developments.
  - Please let us know which topology your model favors.
- Working on measurements using neutrinos in the anti-neutrino beam.

New developments in technology

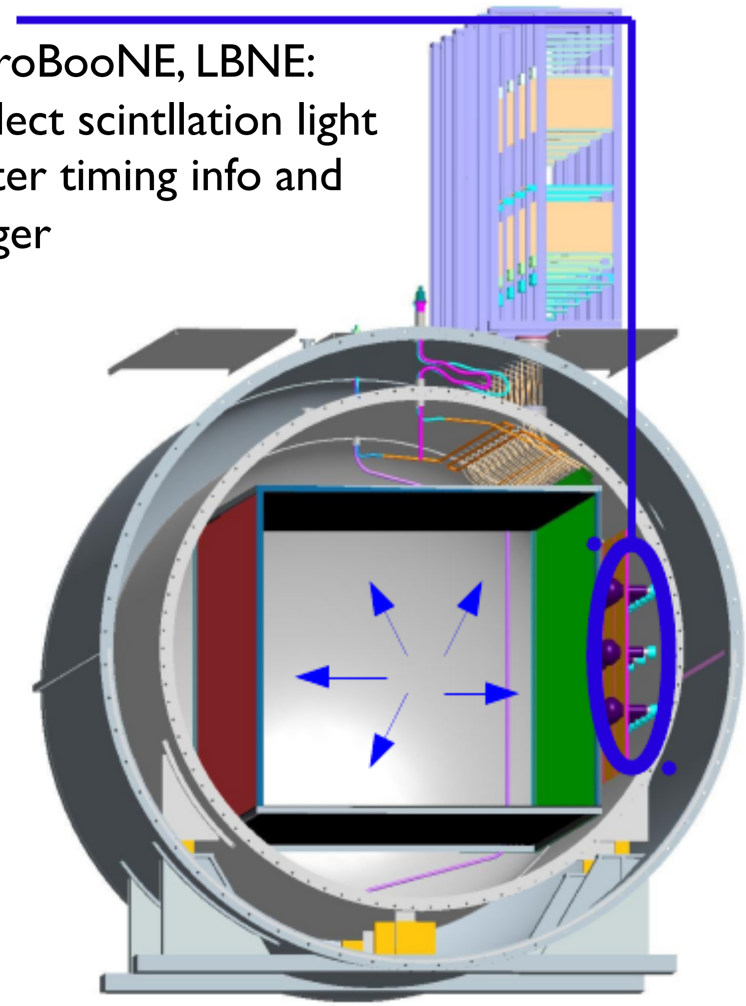
Electronics: JFET -> CMOS

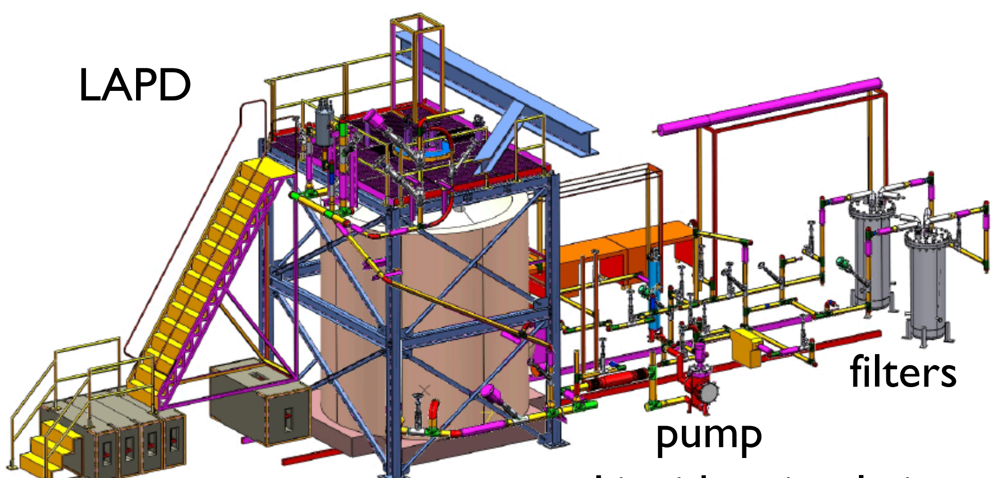


Warm amps S/N = 15 | Amps in liquid S/N >30

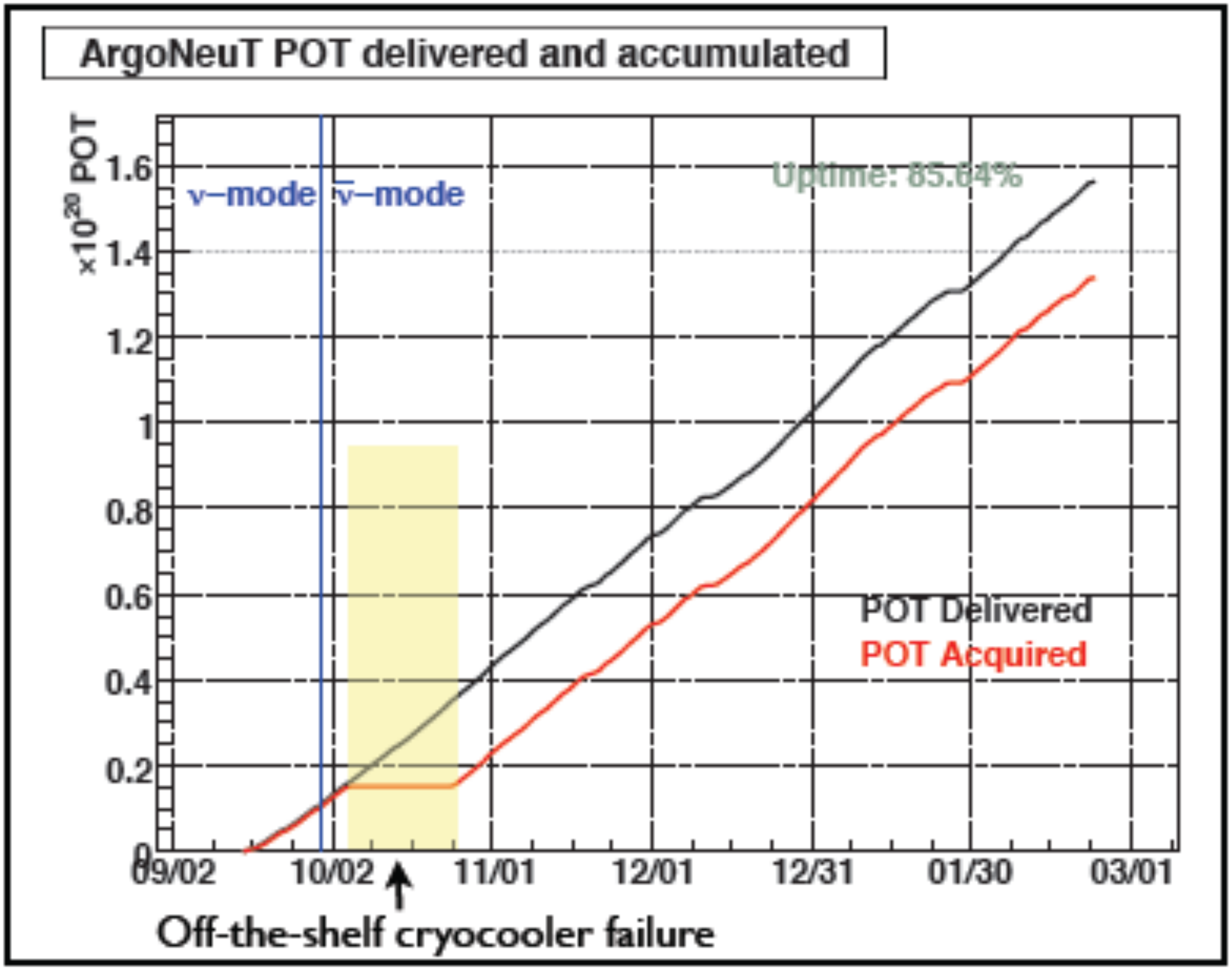


MicroBooNE, LBNE:
Collect scintllation light
Better timing info and trigger

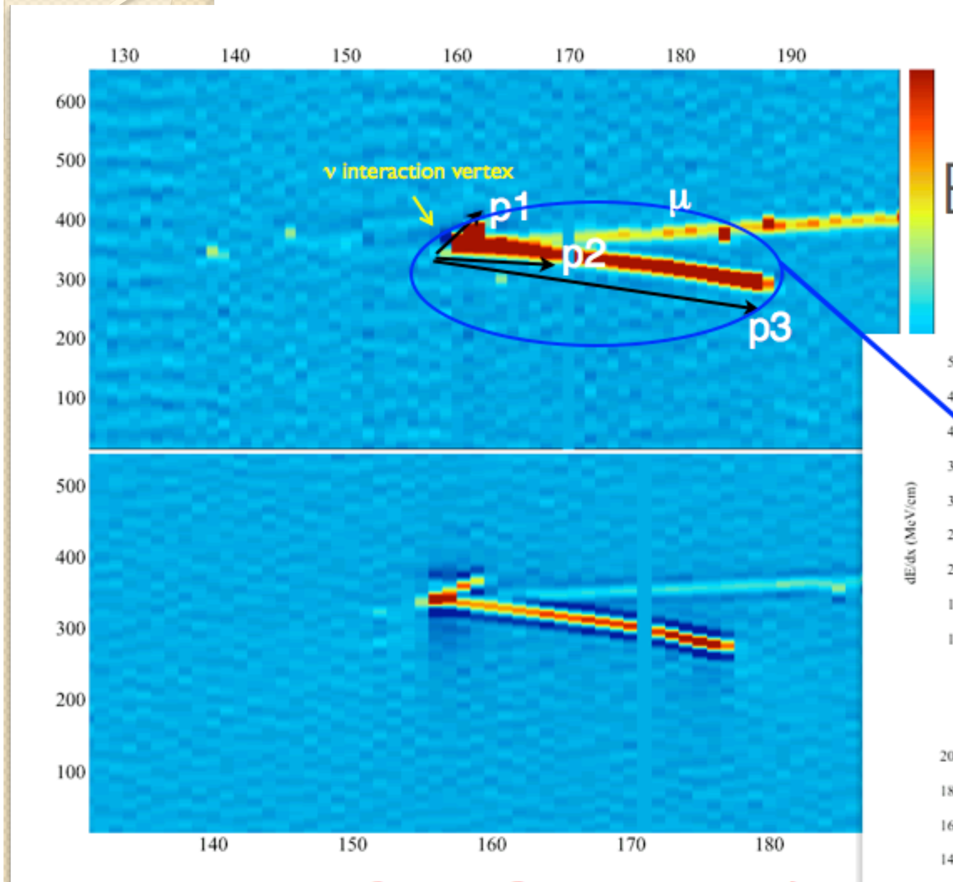


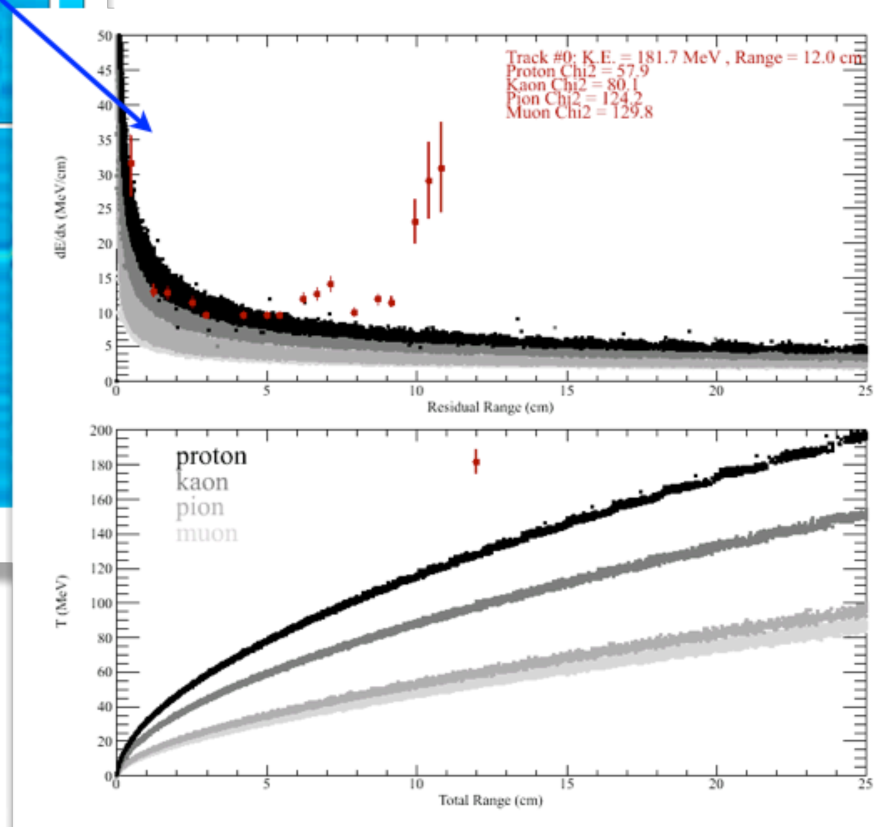


Liquid recirculation


ArgoNeuT POT delivered and accumulated
×10^20 POT
ν−mode
ν̄−mode
Uptime: 85.64%
POT Delivered
POT Acquired
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
09/02
10/02
11/01
12/01
12/31
01/30
03/01
Off-the-shelf cryocooler failure

DATA: EXCLUSIVE TOPOLOGIES

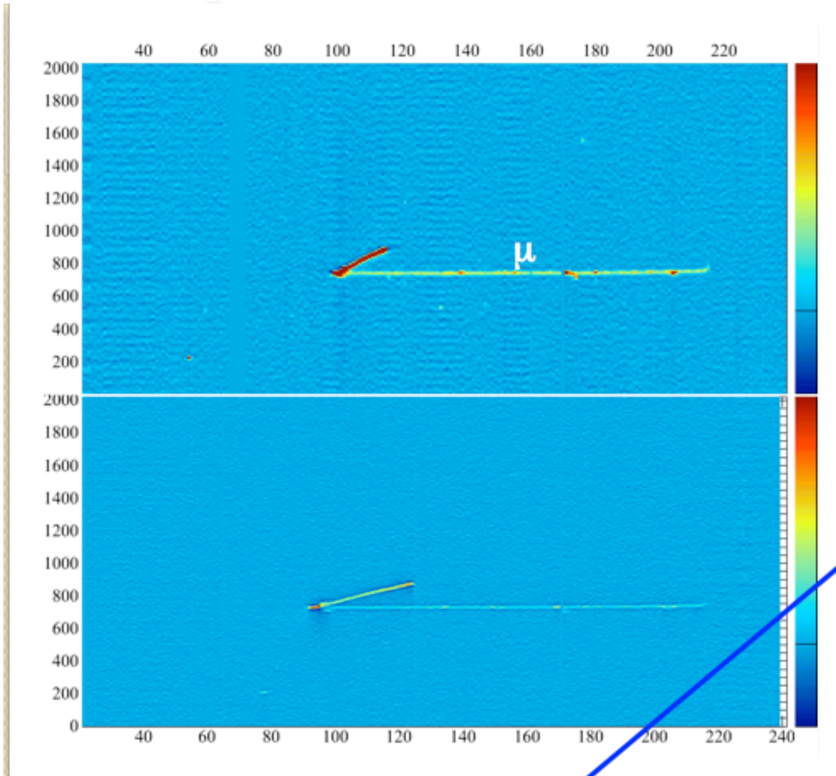


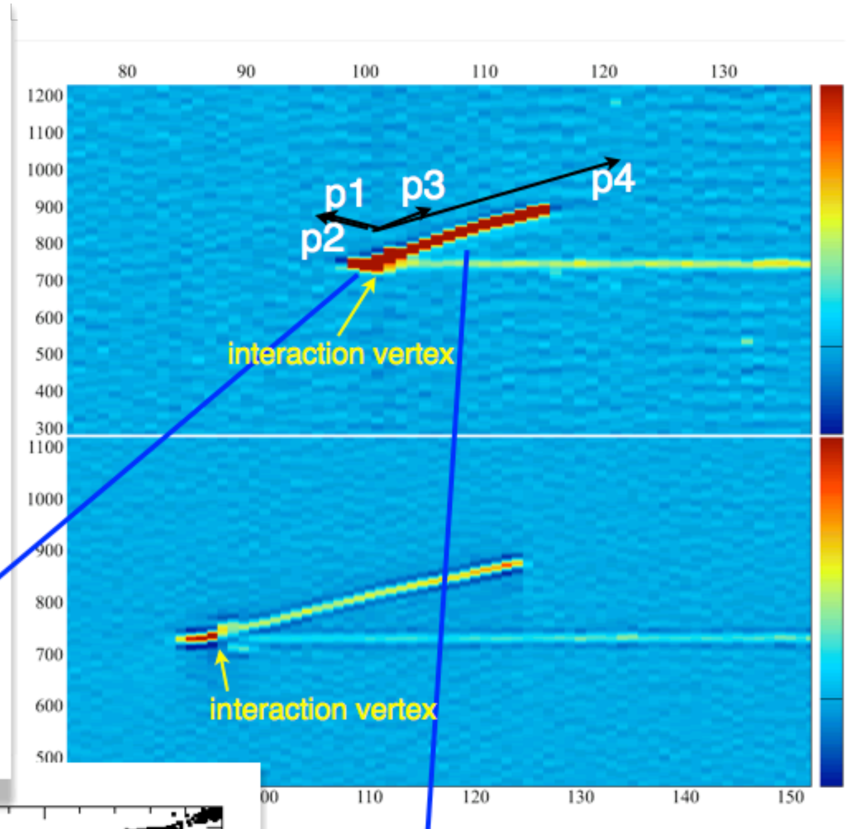


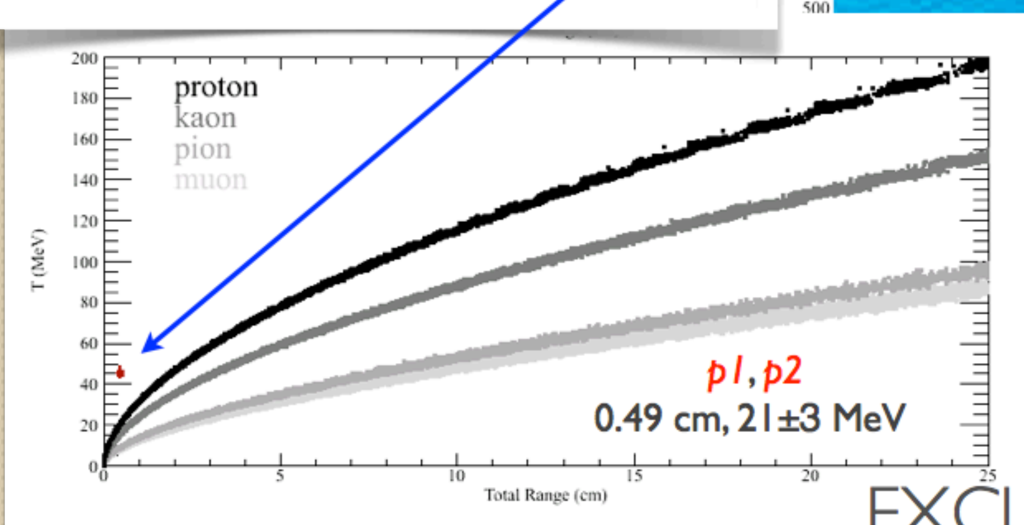
2 or 3 protons?

compatible with
1 μ 3p

- *p1*: 1.7 cm ----> T=42±4 MeV
- *p2*: 3.6 cm ----> T=64±5 MeV
- *p3*: 11.9 cm ----> T=126±7 MeV



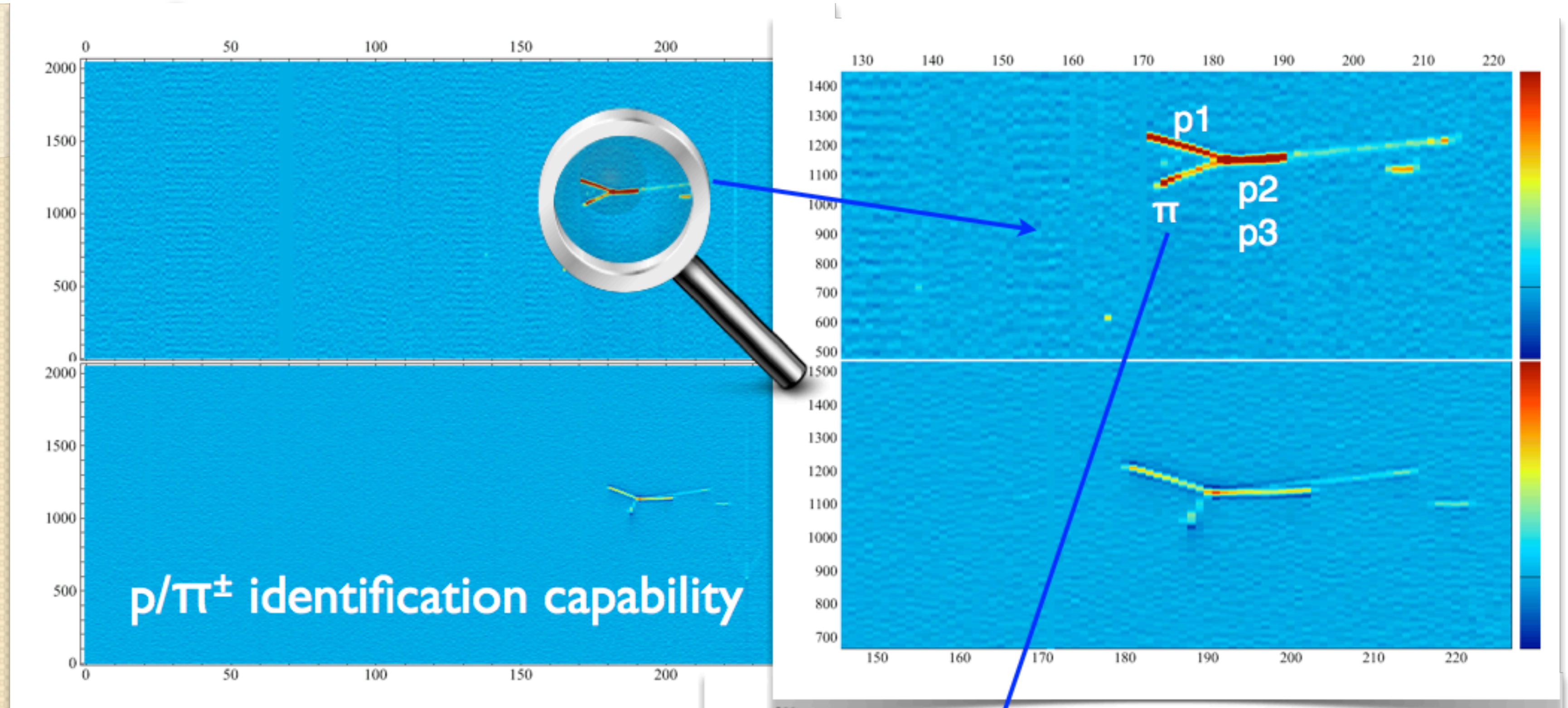




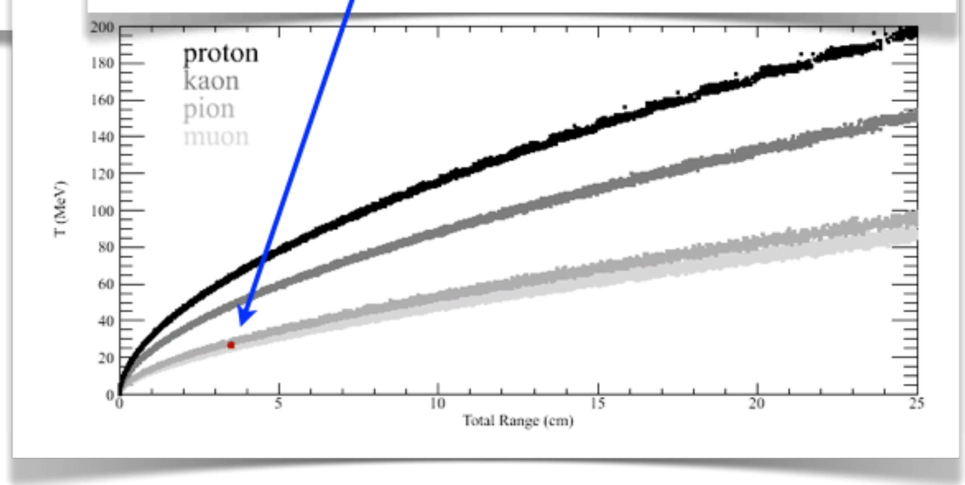
p4: 12 cm, 128±7 MeV
p3: 0.6 cm, 24±3 MeV

compatible with
1 μ 4p

DATA:
EXCLUSIVE TOPOLOGIES



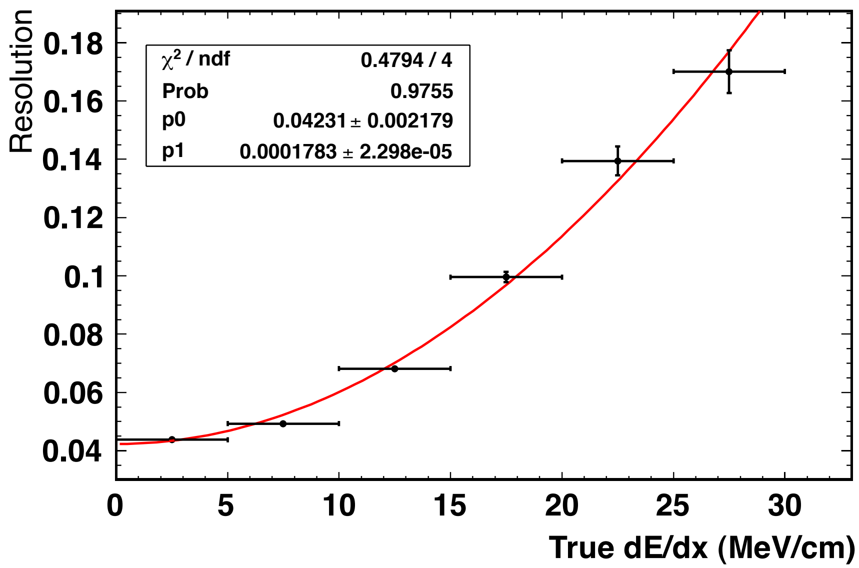
- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- π: 3.5 cm ----> T=26±3 MeV



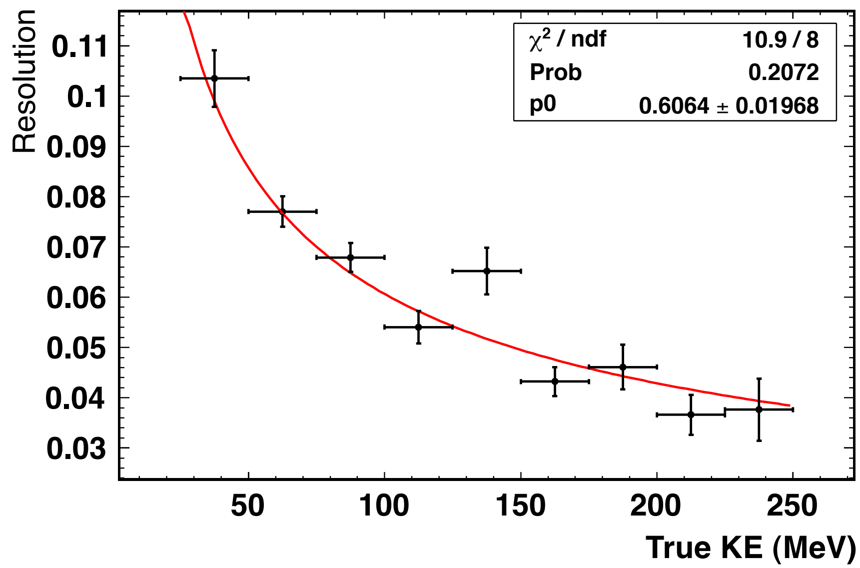
compatible with

1 μ 3p 1 π

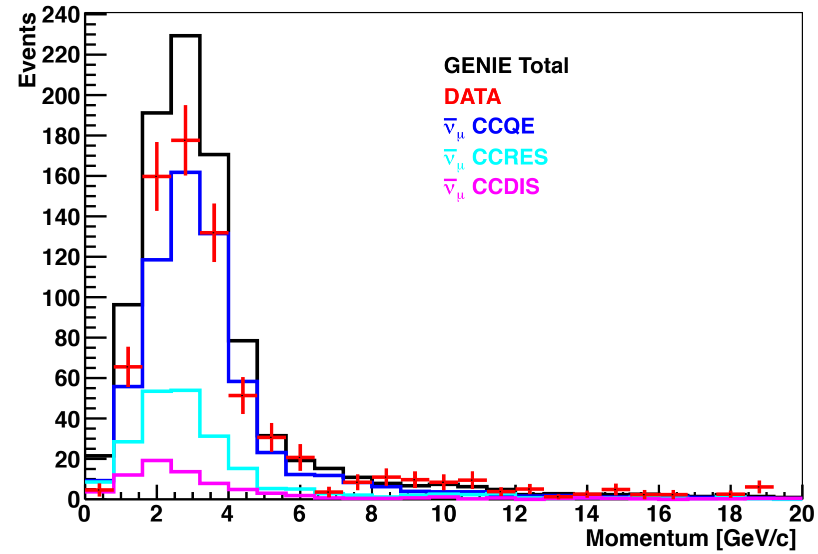
Event not in the muon+Np sample

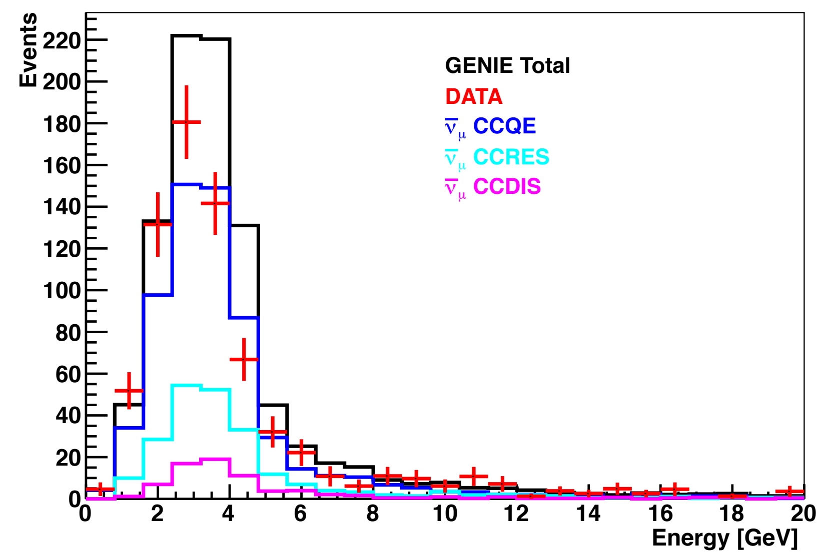


χ^2 / ndf 0.4794 / 4
Prob 0.9755
p0 0.04231 ± 0.002179
p1 0.0001783 ± 2.298e-05
Resolution
True dE/dx (MeV/cm)



χ^2 / ndf 10.9 / 8
Prob 0.2072
p0 0.6064 ± 0.01968
Resolution
True KE (MeV)


Events
Momentum [GeV/c]
GENIE Total
DATA
$\bar{\nu}_\mu$ CCQE
$\bar{\nu}_\mu$ CCRES
$\bar{\nu}_\mu$ CCDIS


Events
Energy [GeV]
GENIE Total
DATA
$\bar{\nu}_\mu$ CCQE
$\bar{\nu}_\mu$ CCRES
$\bar{\nu}_\mu$ CCDIS

dE/dx e/γ ID

- Separating electrons from γs is important in precision ν 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: an electron is a Minimum Ionizing Particle, a γ pair converts, so the ionization should be double.