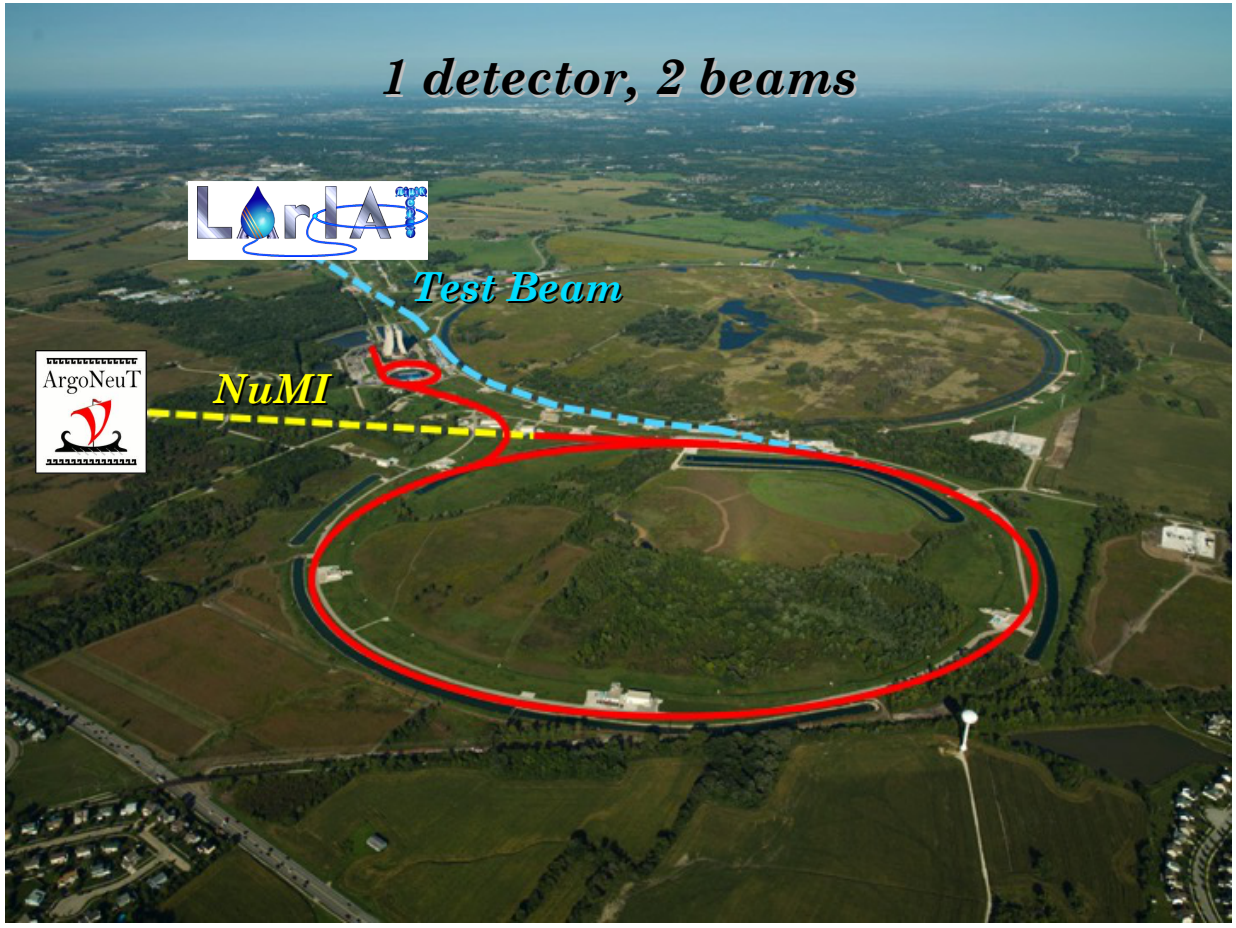
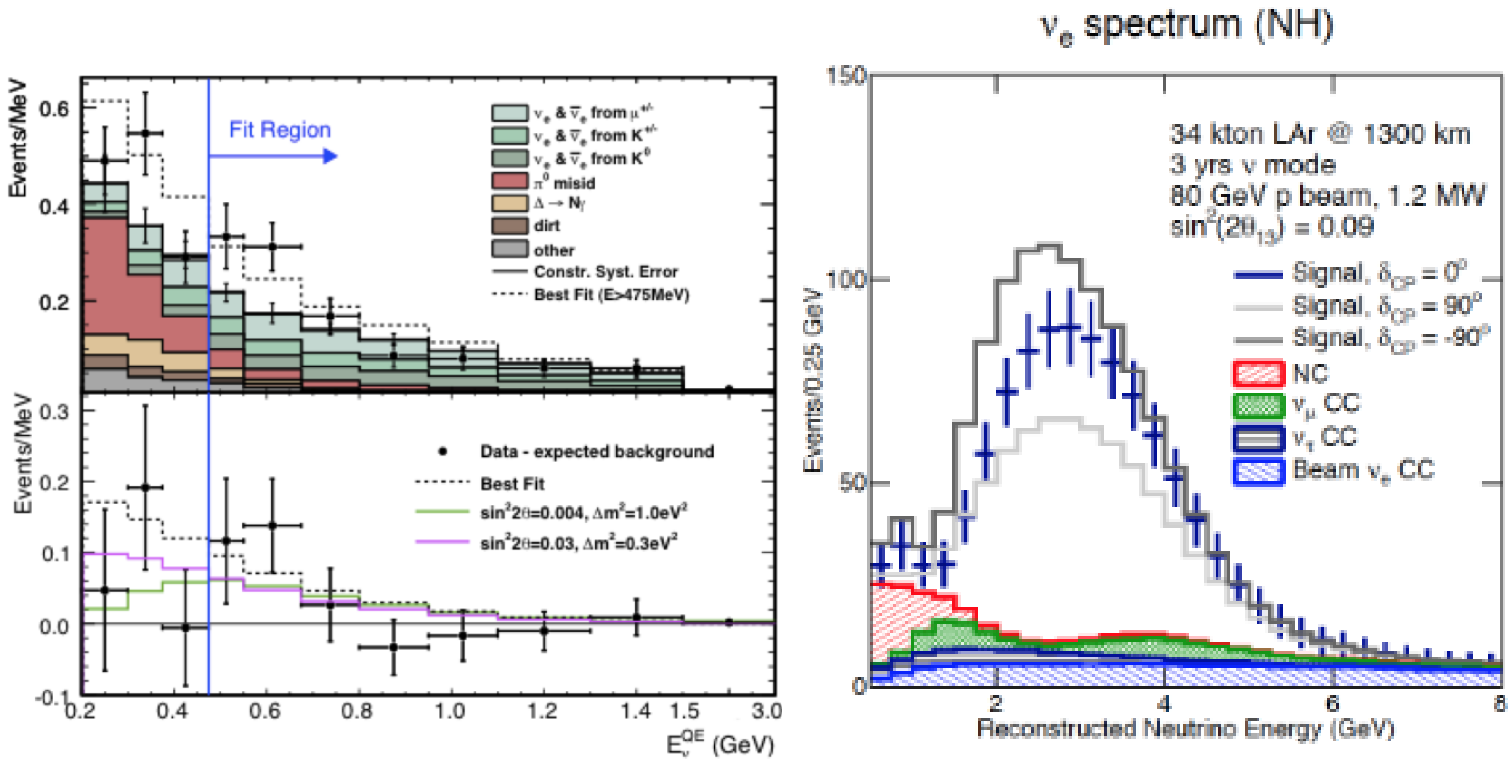
ArgoNeuT and LArIAT: Status and Progress on Measurements Relevant for DUNE

Will Flanagan, University of Texas, on behalf of the
ArgoNeuT and LArIAT Collaborations

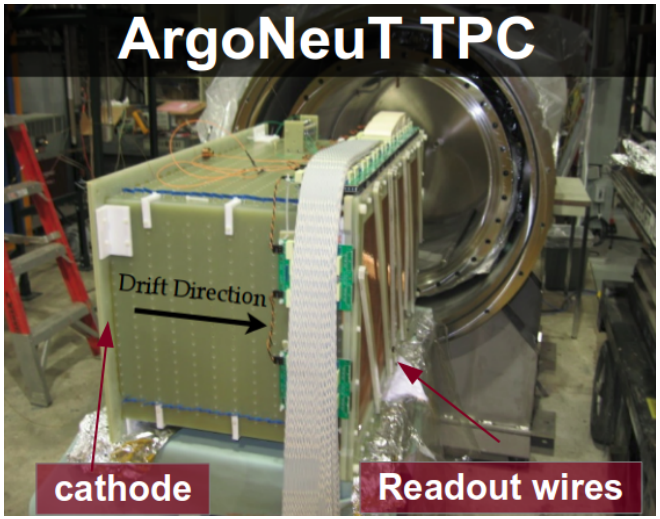


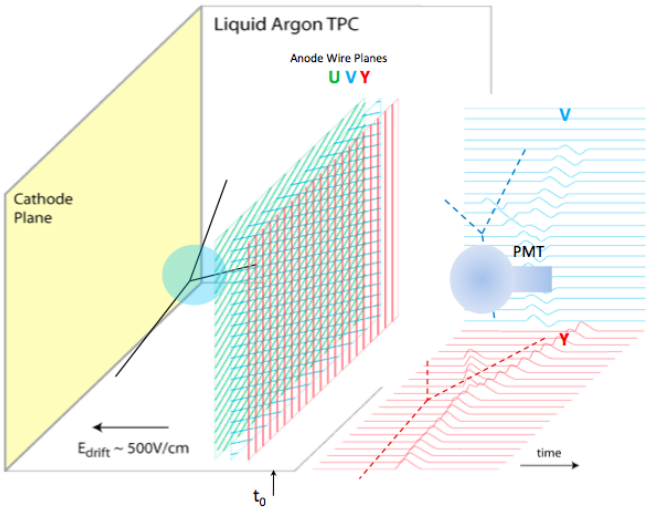
Physics Motivation

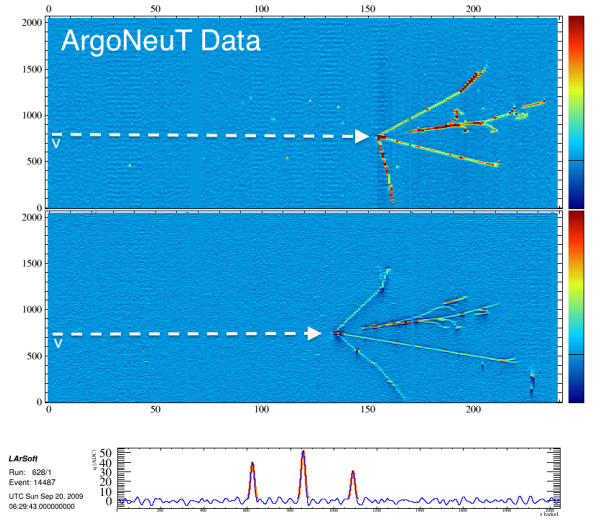


- Thanks to the capability of **LAr detectors**, we have an opportunity to measure **CP violation** and **neutrino mass ordering** and search for **new fundamental particles**.
- This is an exciting time in physics with important implications!
- But we first need to measure neutrino nucleus cross sections (**ArgoNeuT**) and better understand interaction processes of charged particles on argon (**LArIAT**).

ArgoNeuT Overview

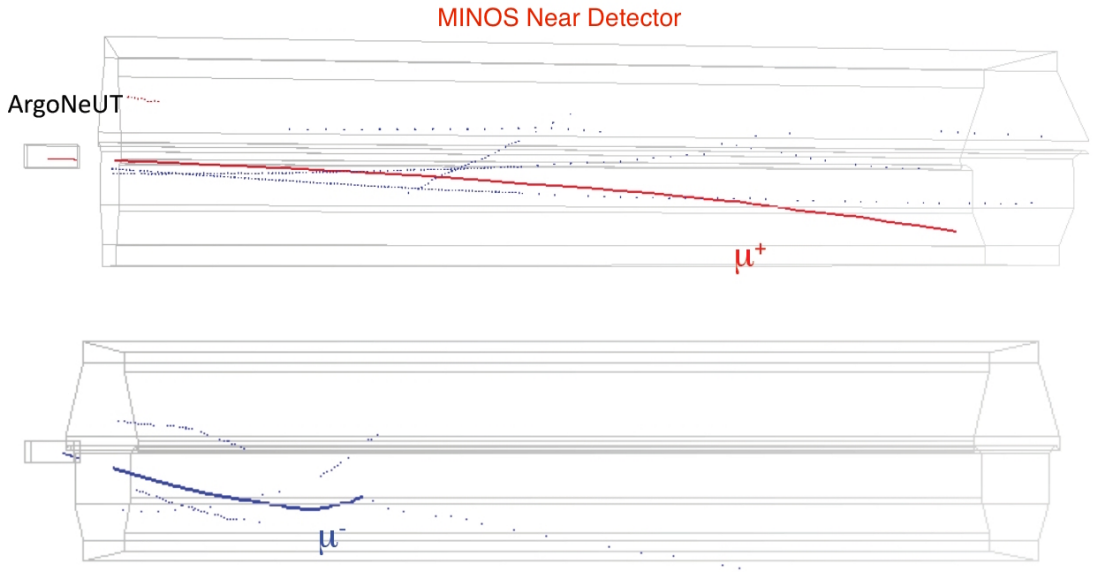






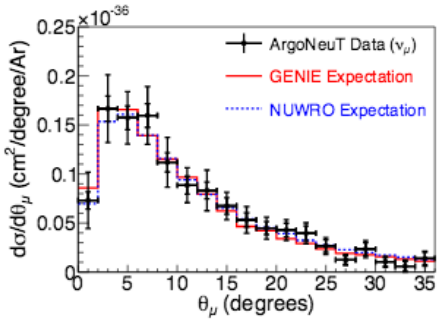
- 175 L of liquid argon (47x40x90 cm^3) is contained in the TPC.
- 500 V/cm electric field drifts electrons from ionization tracks to induction and collection wire planes.
- 3D reconstruction of tracks combining electron drift time and wire planes information.
- No light detection system in ArgoNeuT. This has been added as part of LArIAT upgrades.

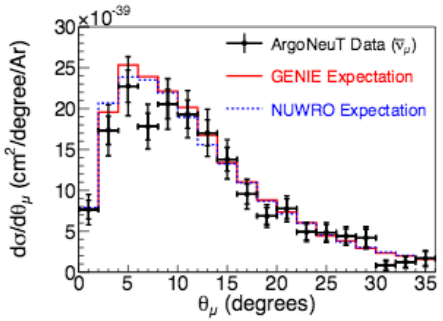
ArgoNeuT Overview (II)

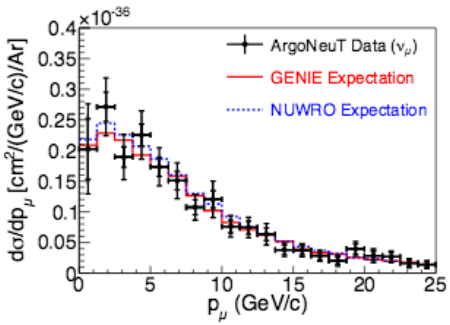


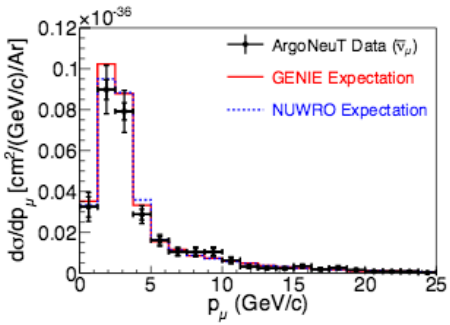
- Located in the NuMI beamline, upstream of the MINOS ND.
- Data collected from September 2009 to February 2010.
- (1.2)0.1x10^{20} PoT collected in (anti)neutrino mode (<E>=4GeV).

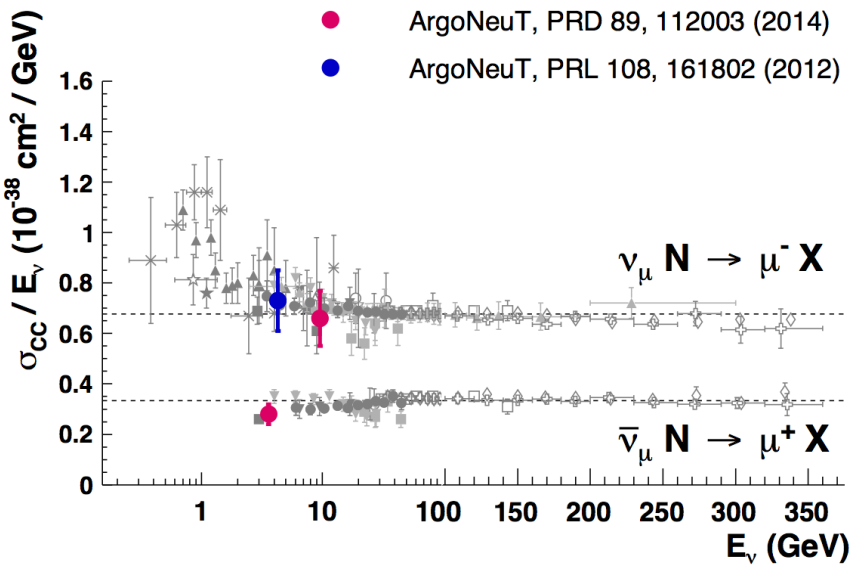
ArgoNeuT Results (ν_μ and $\bar{\nu}_\mu$ CC-inclusive)





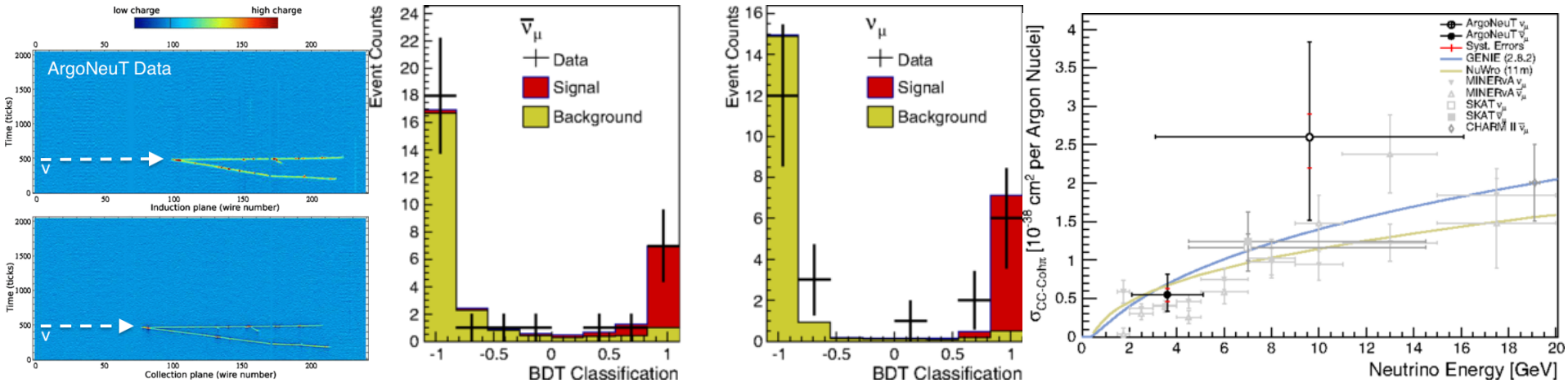






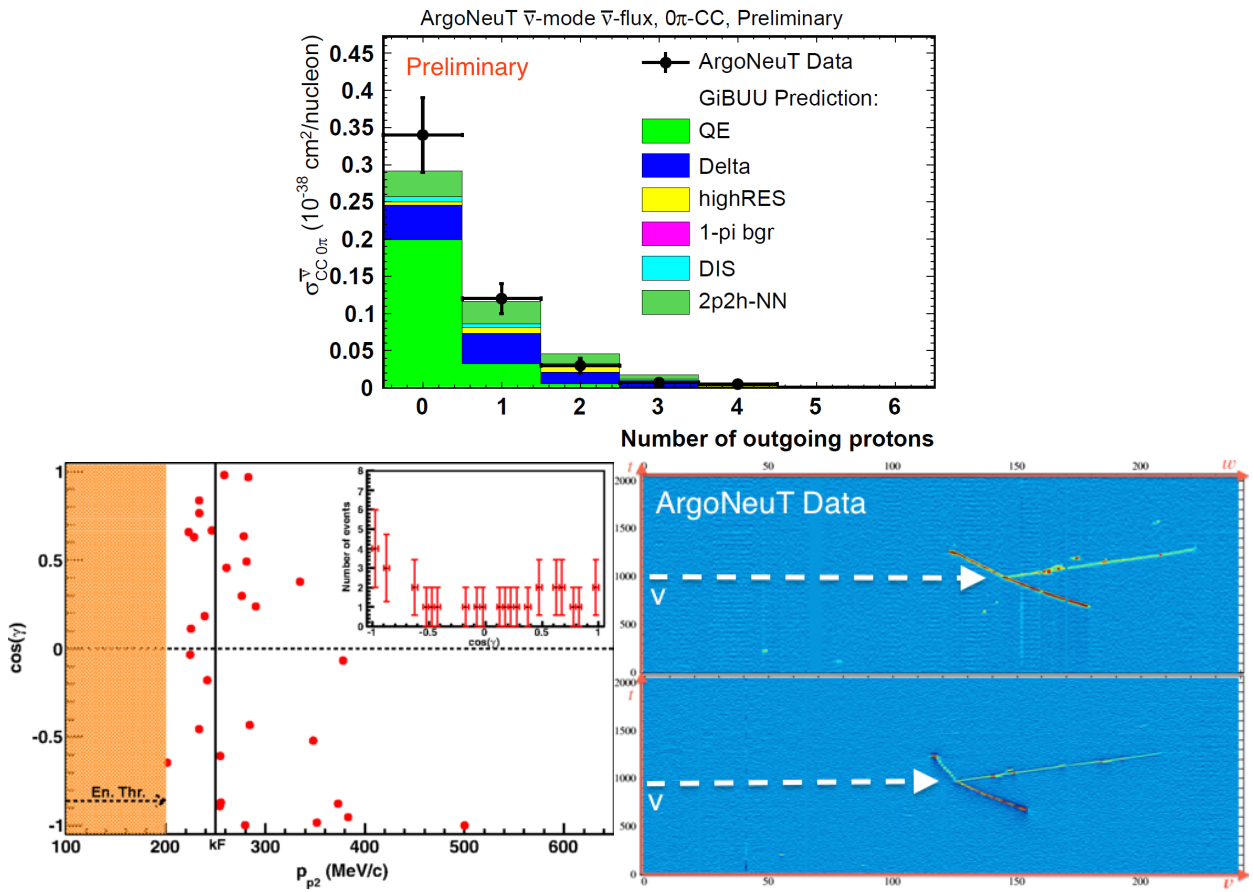
- First inclusive cross section measurement with an argon target.
- C. Anderson et al., PRL 108 (2012) - ν_μ CC-incl. σ
- R. Acciarri et al., PRD 89, 112003 (2014) - ν_μ and $\bar{\nu}_\mu$ CC-incl. σ

ArgoNeuT Results (CC Coherent $\pi^{\pm}$ Production)



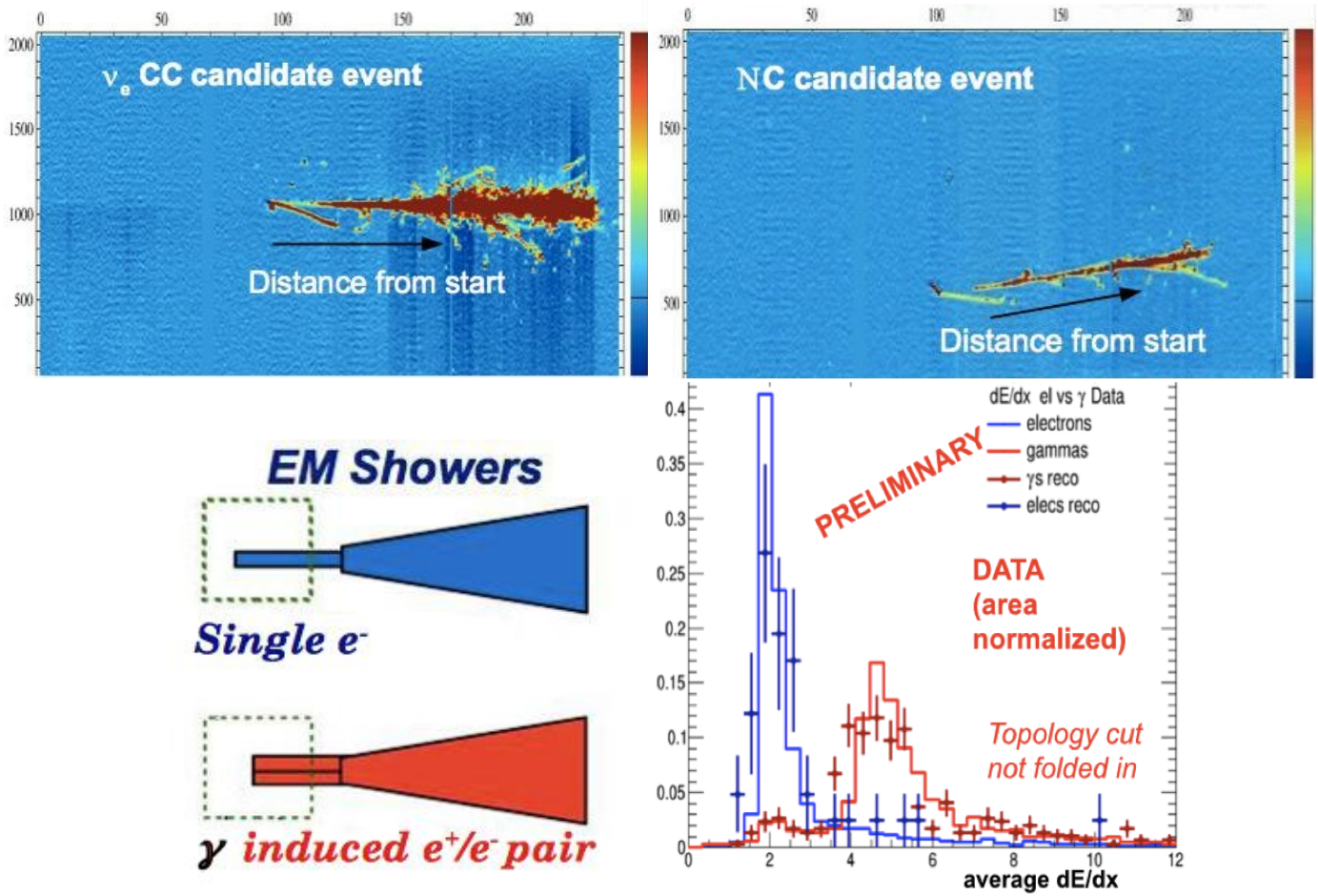
- This is the first measurement of CC coherent pion production on argon.
- This is also the first time that machine learning techniques (BDT) have been applied to LArTPC data analysis.
- R. Acciarri et al., PRL 113, 261801 (2014)

ArgoNeuT Results (Nuclear Effects)



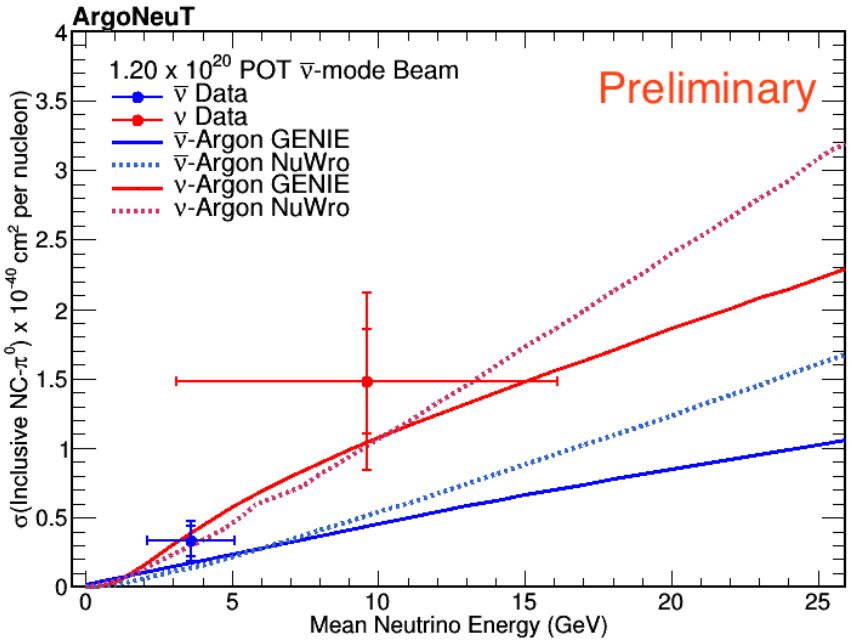
- Nuclear effects were explored using the number of outgoing protons in pionless events.
- The 0π $2p^+$ events show an excess of back-to-back protons consistent with CC RES pionless reactions involving pre-existing SRC np pairs - R. Acciarri et al., PRD 90, 012008 (2014).

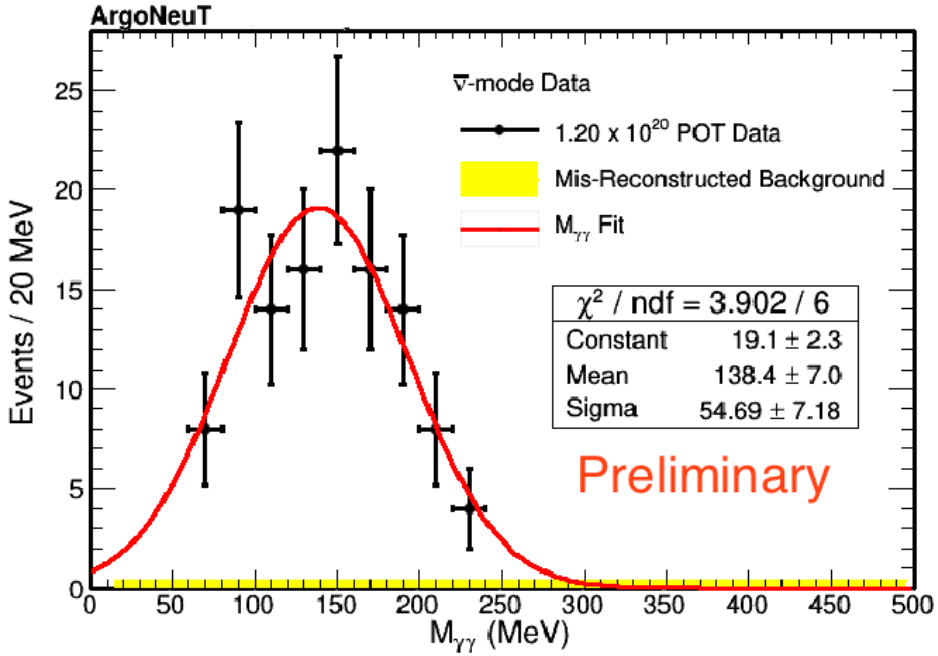
ArgoNeuT Results (e/γ Separation Using dE/dx)



- This measurement is critical for distinguishing ν_e CC events from NC events containing a π^0.
- Paper is under review.

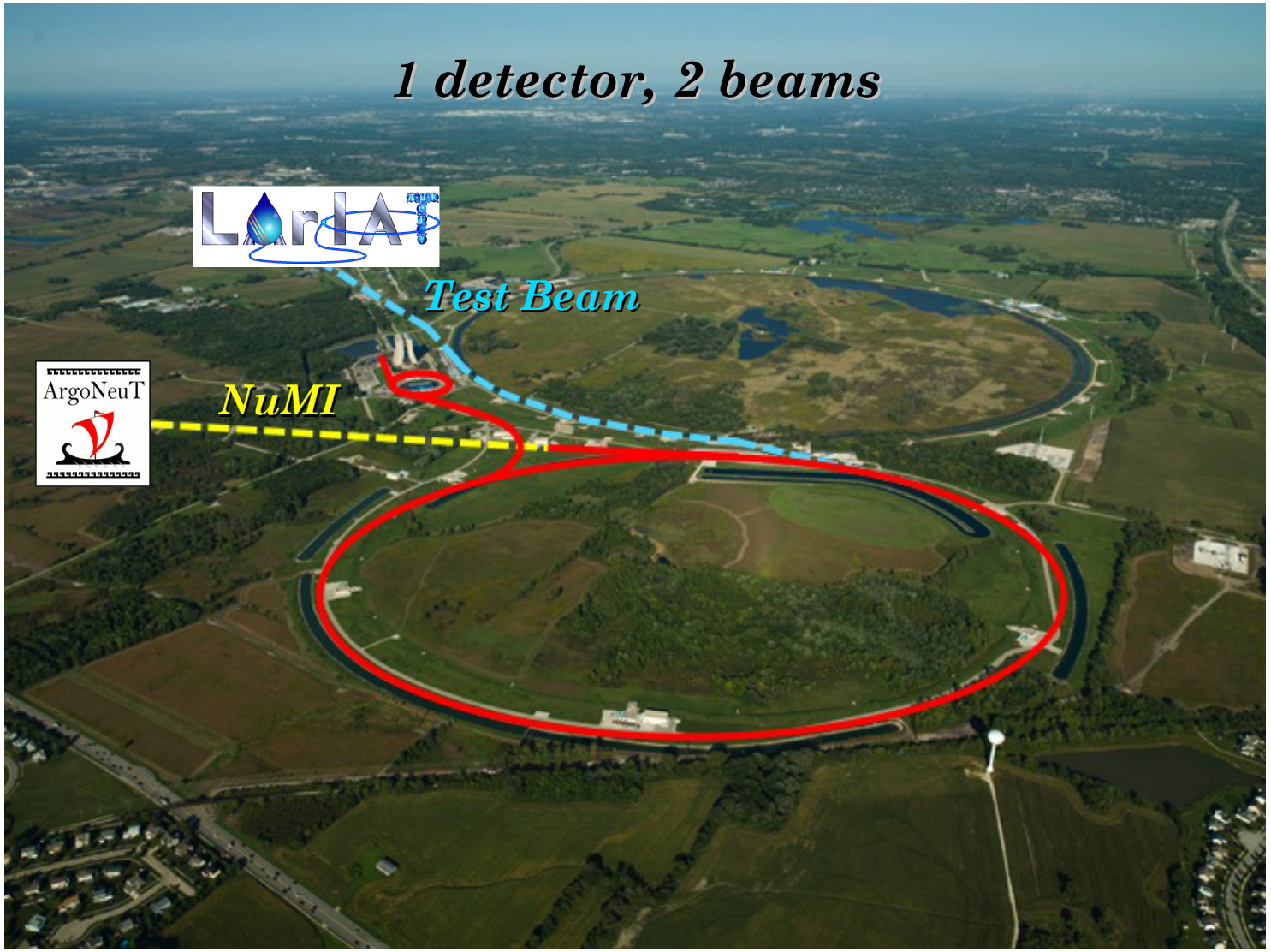
ArgoNeuT Results (Neutral Current π^0 Study)





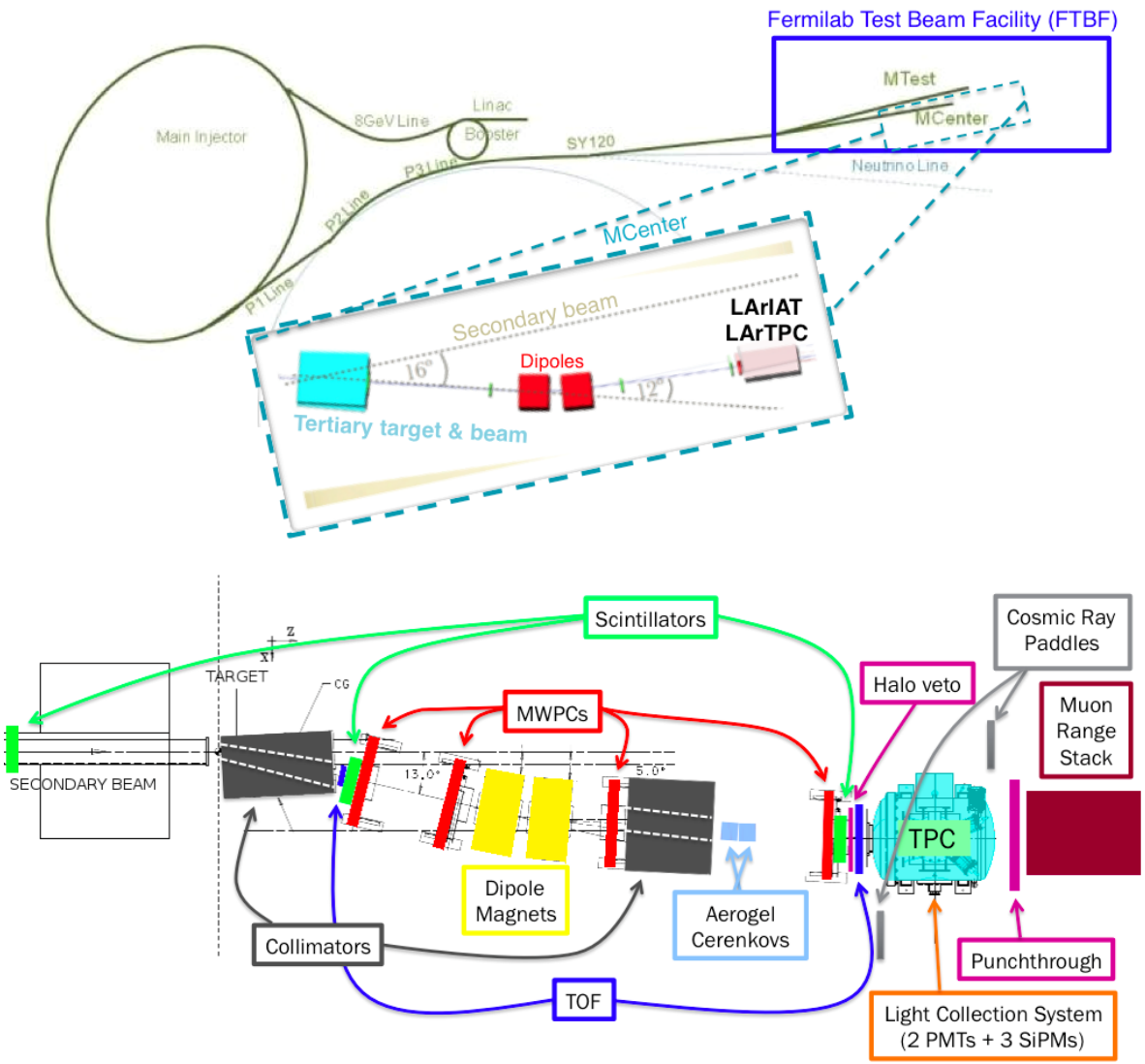
- Larger LAr detectors with better photon containment will be able to further improve this measurement.
- Energy corrections are applied which utilize ArgoNeuT's fine grain shower resolution.
- Paper is under review.

From ArgoNeuT to LArIAT



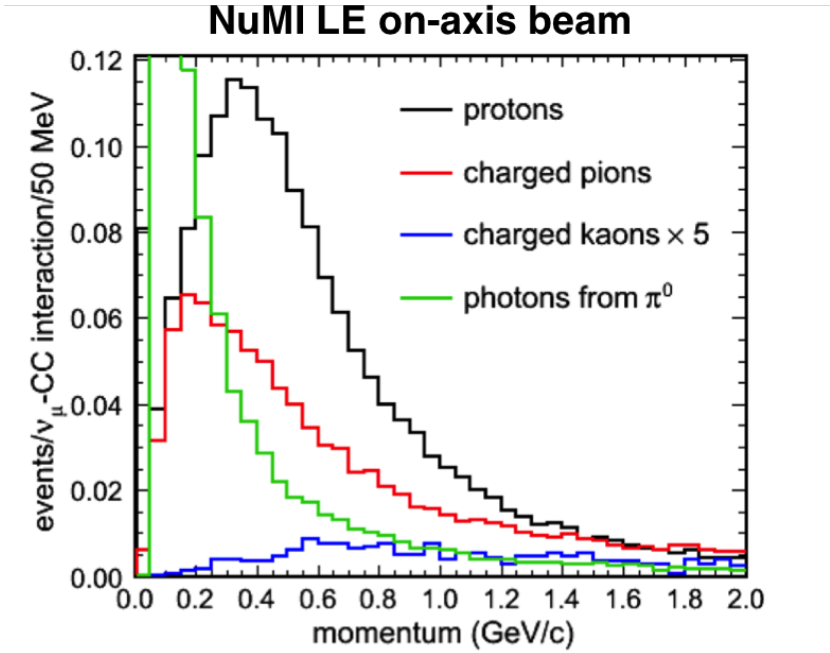
- Same great TPC, from a neutrino to a charged particle beam...

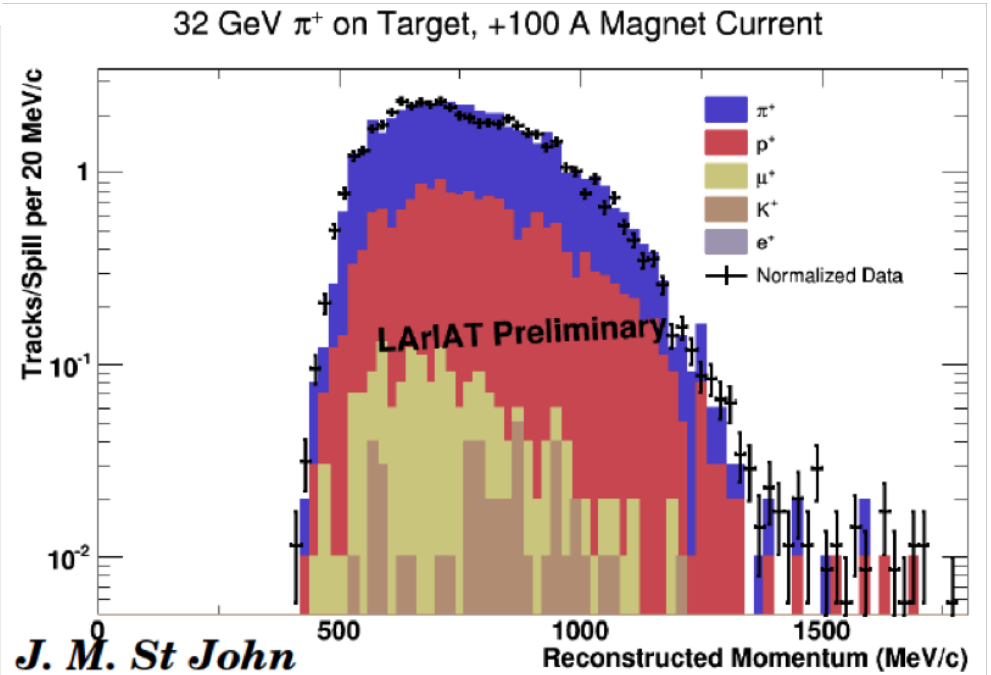
From ArgoNeuT to LArIAT



- Same great TPC, from a neutrino to a charged particle beam...

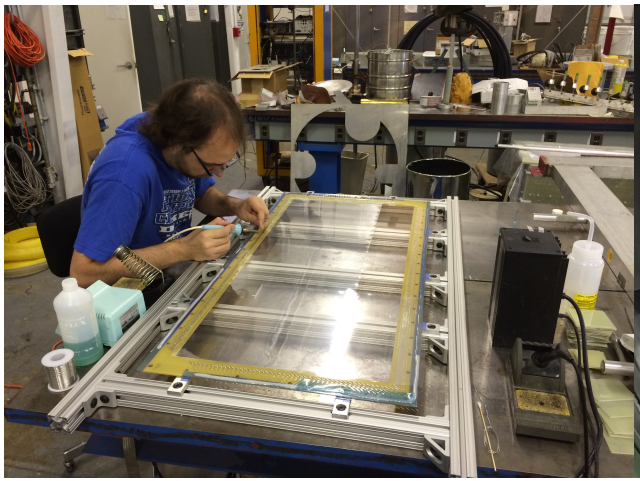
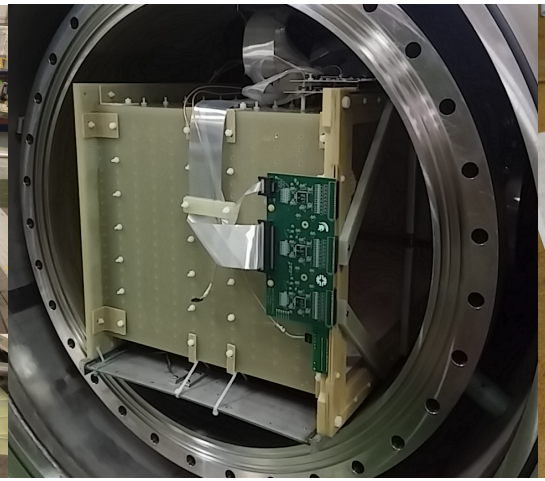
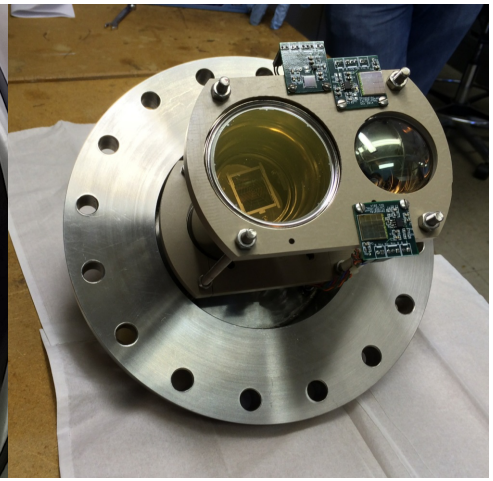
From ArgoNeuT to LArIAT (II)





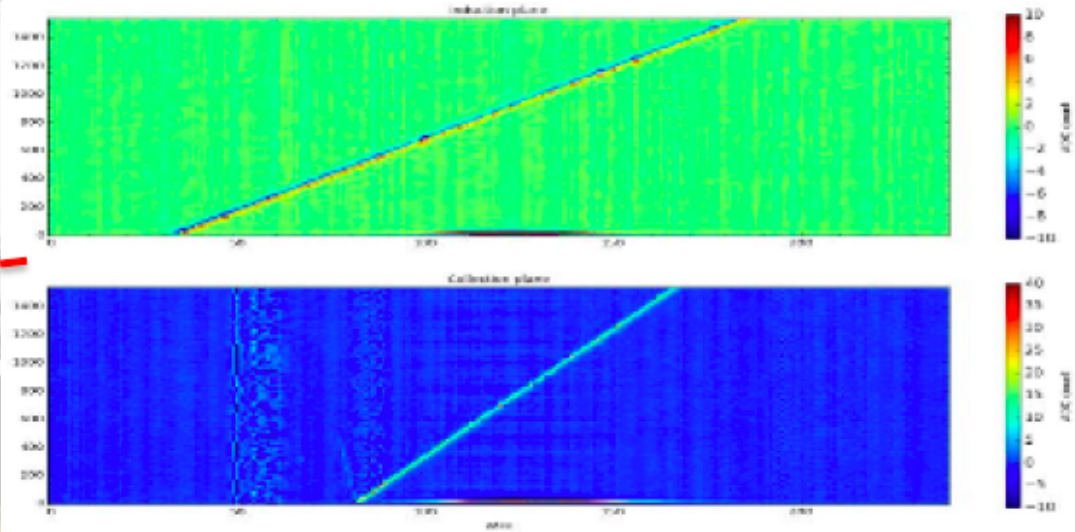
- The LArIAT beam is composed mainly of $\pi^{\pm}$, p^{+}, $\mu^{\pm}$, $e^{\pm}$, and $K^{\pm}$.
- Momentum and beam polarity adjustable using tertiary beam magnets.
- 200 MeV to 2 GeV coverage allows us to focus on:
  - Matching DUNE/BNB momenta of interest
  - Stopping muons and pions
  - Kaons

LArIAT Upgrades

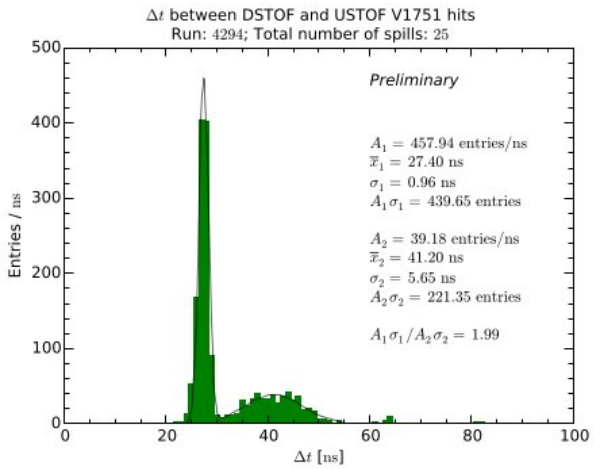
- Upgrades to the ArgoNeuT detector include:
  - Titanium beam window
  - New cold electronics
  - New wire planes
  - New tensioning bars and RC components
  - New HV feedthrough
  - Optical system including 2 PMTs, 3 SiPMs, reflector and wavelength shifting lining
  - Dedicated filling and purification system
  - This is all in addition to various contributions to our DAQ and beamline detectors!

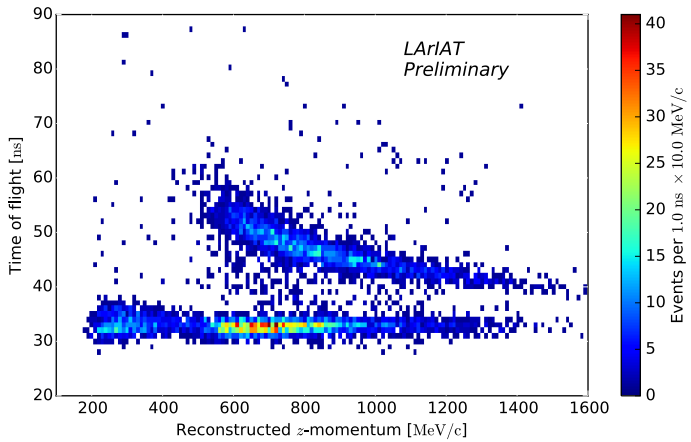
LArIAT Data Collected So Far

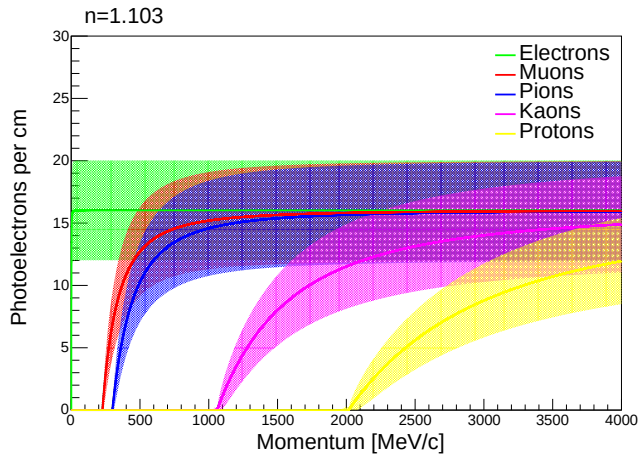


- Our first track (Run 5215, Event 1) was recorded at 3pm on April 30, 2015.
- Since then we accrued 9 weeks of data (~44k spills), including both beam polarities, 3 secondary beam energies, and six tertiary beam settings!
- Average 5-10 events per spill

LArIAT Physics and R&D Goals







- Now that we have data, LArIAT physics goals include:
  - π-Ar interaction cross sections (total and exclusive channels)
  - Kaon identification (and possibly interaction cross section)
  - e/γ separation
  - Muon sign identification via decay vs capture
  - Geant4 validation
- LArIAT R&D goals include:
  - Establish relationship between energy deposited to charge and light collected, for stopping tracks of known energy
  - Optimization and development of PID, 2D & 3D event reconstruction
  - This is part of a common effort within the LAr community.

LArIAT (π-Ar Cross Sections)

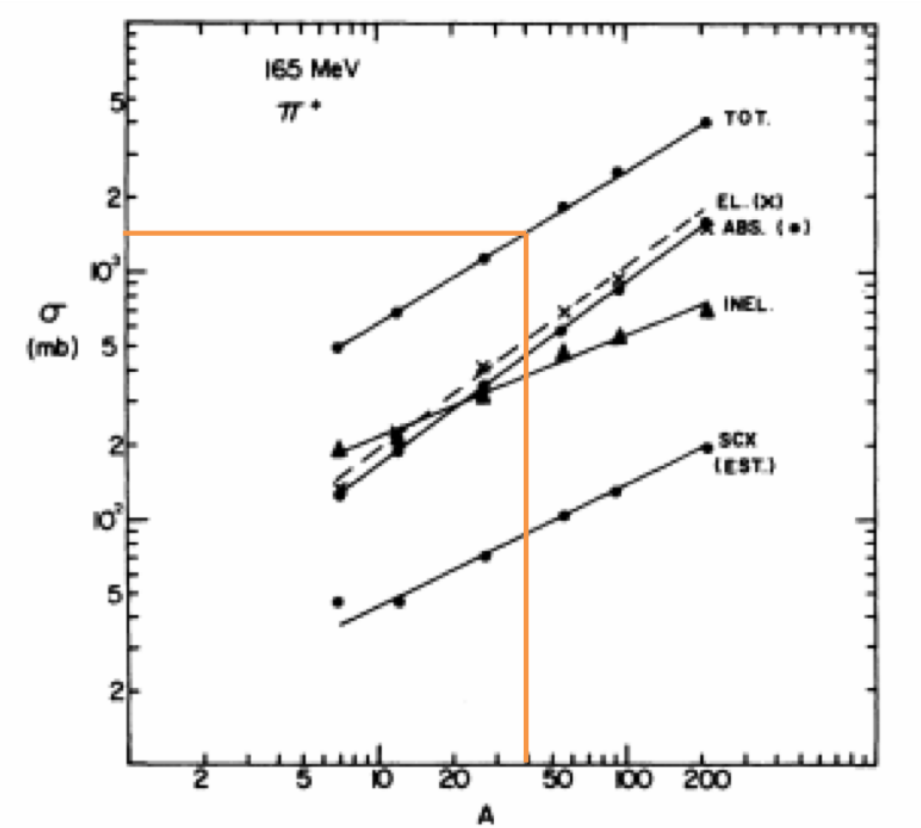
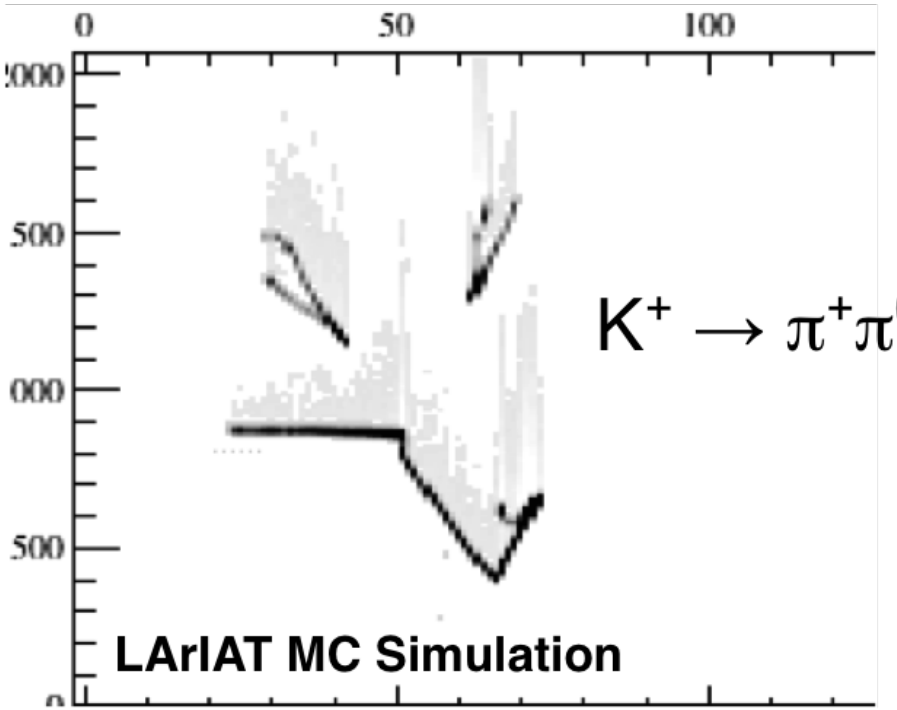
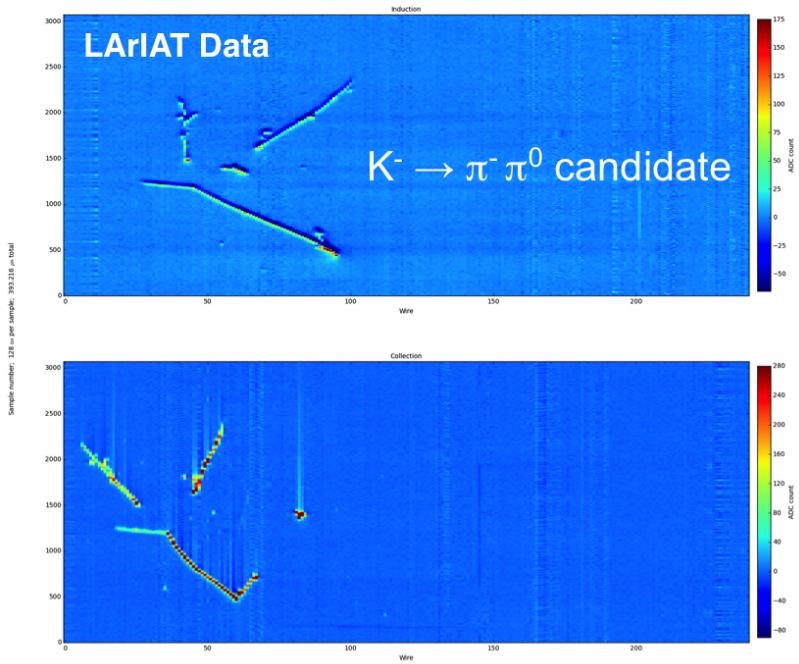


FIG. 9. Decomposition of the total π^+-nucleus cross section at 165 MeV. The lines are least squares fits to power laws.

- There are no measurements of $\pi^{\pm}$-^{40}Ar cross sections yet. See D. Ashery et al. Phys. Rev. C23, 2173 (1981).
- Pion cross sections within argon are a large source of systematic uncertainty for neutrino oscillation analyses.

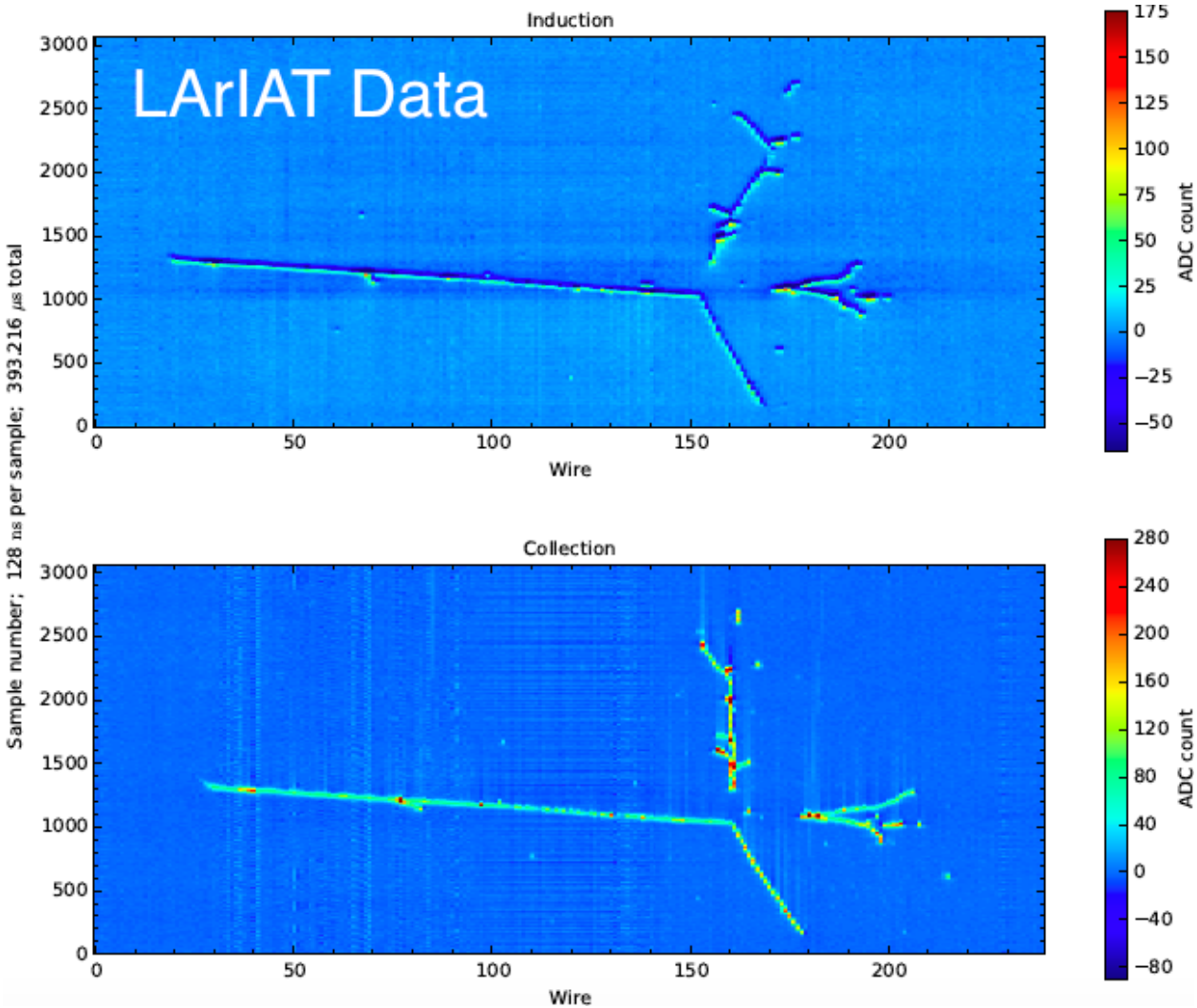
LArIAT ($K^{\pm}$ Identification)





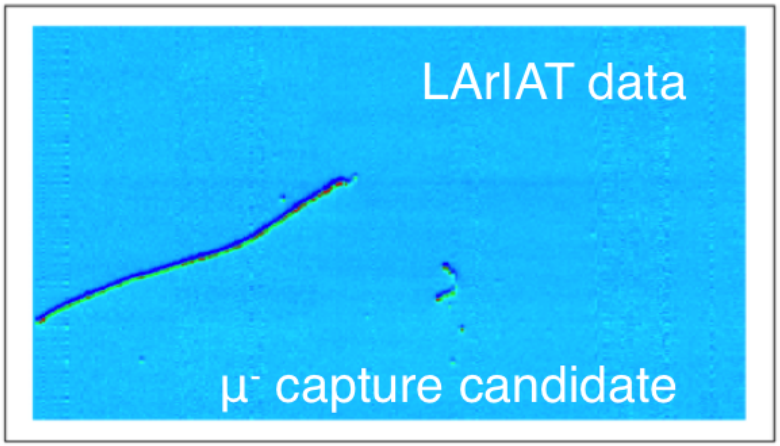
- We are studying kaon reconstruction and identification.
- This is a critical measurement for future proton decay measurements in LAr.

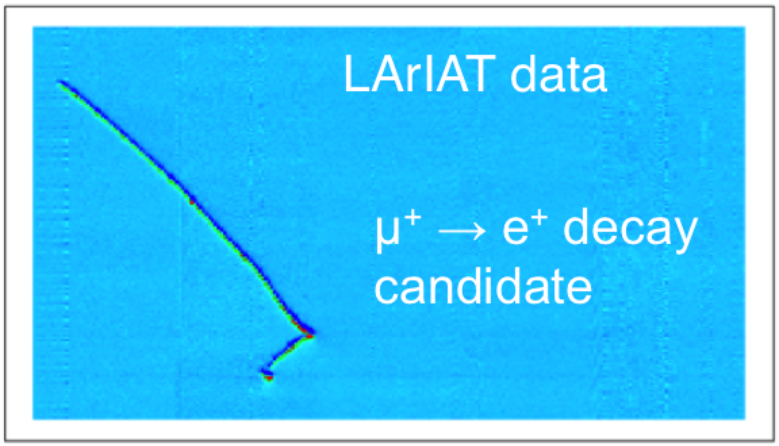
LArIAT (Nuclear Effects and Final State Interactions)

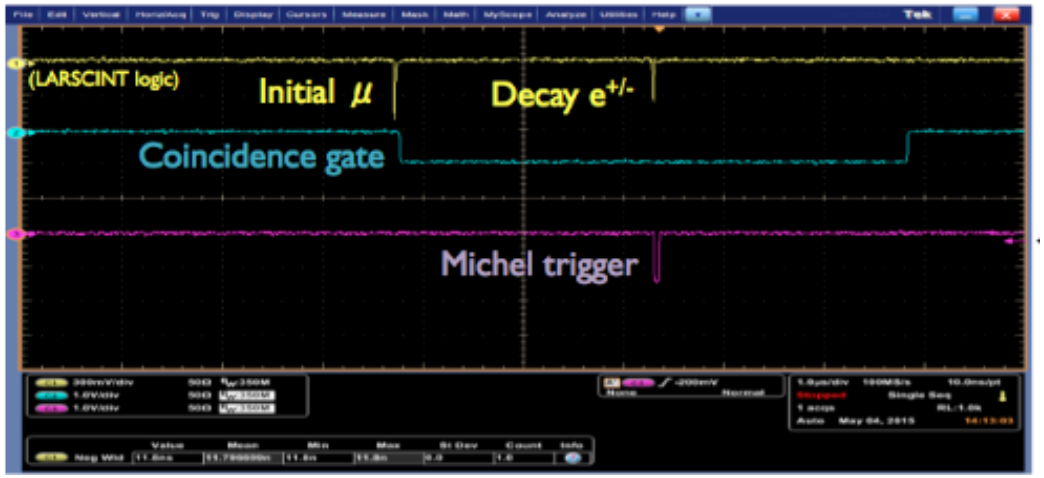


- Above is an example of a $\pi^{\pm} \rightarrow \pi^{0}$ charge exchange candidate.
- Our goldmine of data will allow us to validate and tune Geant4 and Monte Carlo generators.

LArIAT (Michel Electrons)

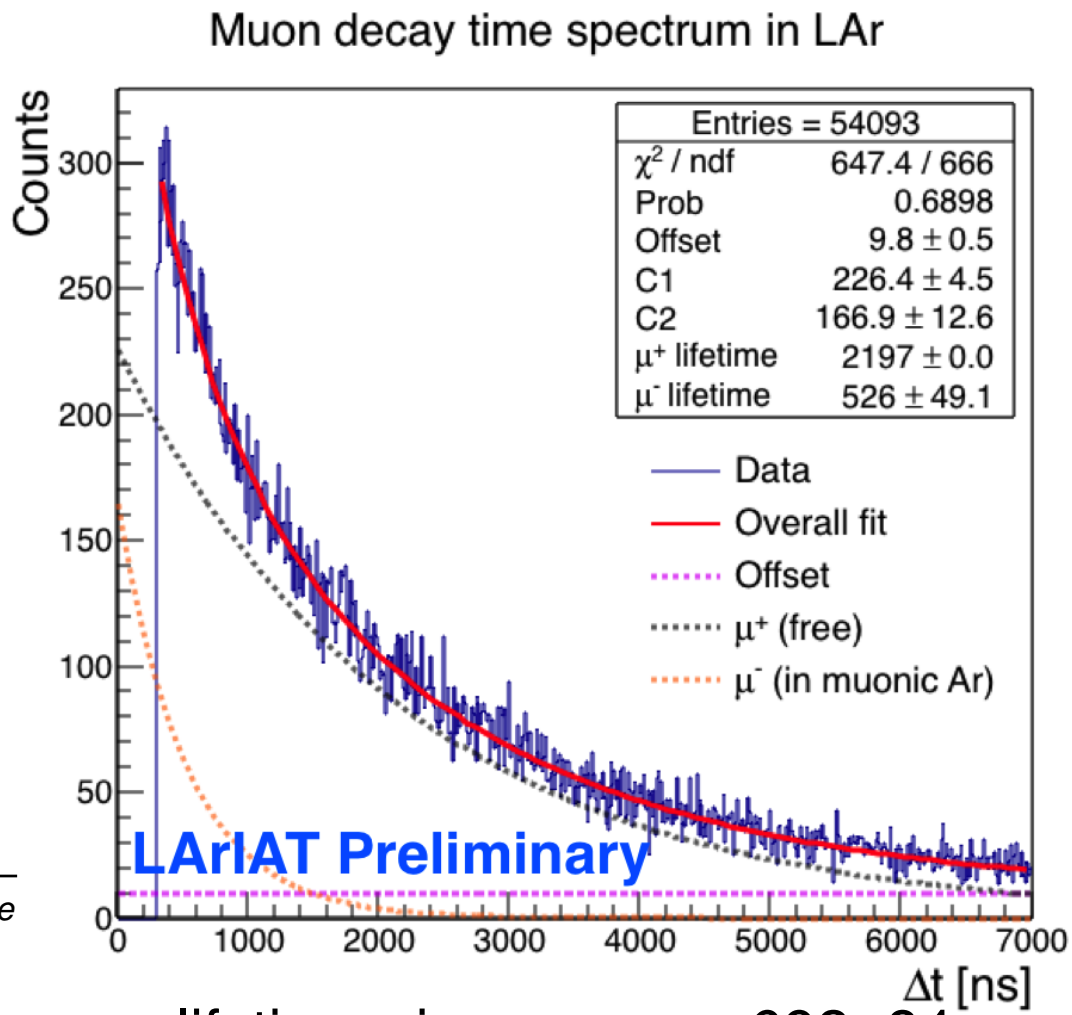






- μ capture and decay are critical for sign determination.
- Michel electrons also serve as an energy calibration source for both the TPC and light collection systems.
- Triggered on Michel candidates using a cosmic muon coinciding with a delayed electron.

LArIAT (Michel Electrons)

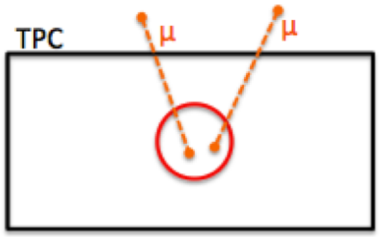


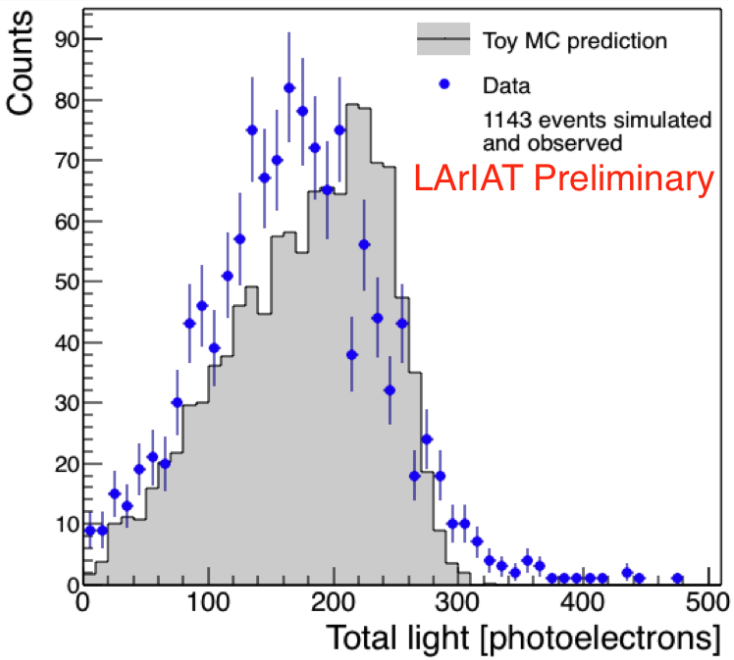
$$\frac{1}{\tau_{\mu^-}} = \frac{1}{\tau_{free}} + \frac{1}{\tau_{capture}}$$

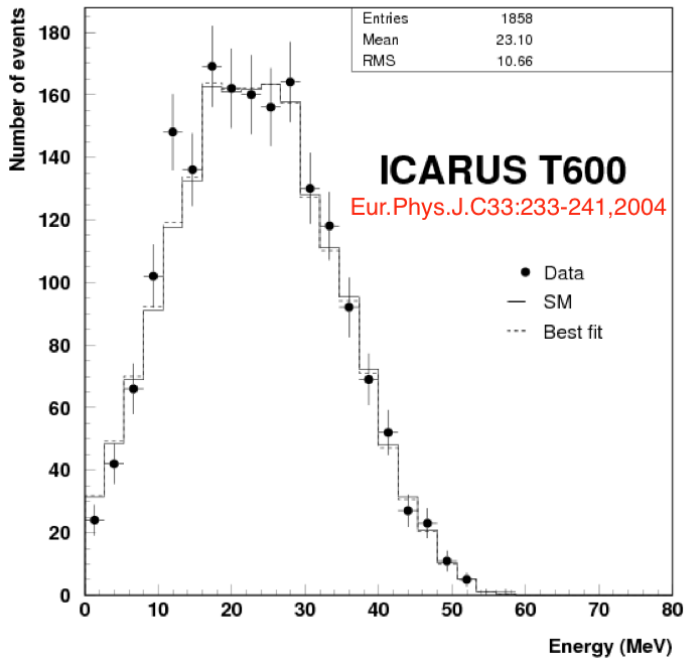
$$P_{capture} = 1 - \frac{\tau_{\mu^-}}{\tau_{free}}$$

- A fit of the muon lifetime gives $\tau_{capture}$=692±84ns
- 833±55ns and 709±56ns was measured by Bertin, A. et al., PRD 8 (1973) and Carboni et al., PLB 96 (1980), respectively.
- $P_{capture}$=76.1±2.2%

LArIAT (Michel Electrons)







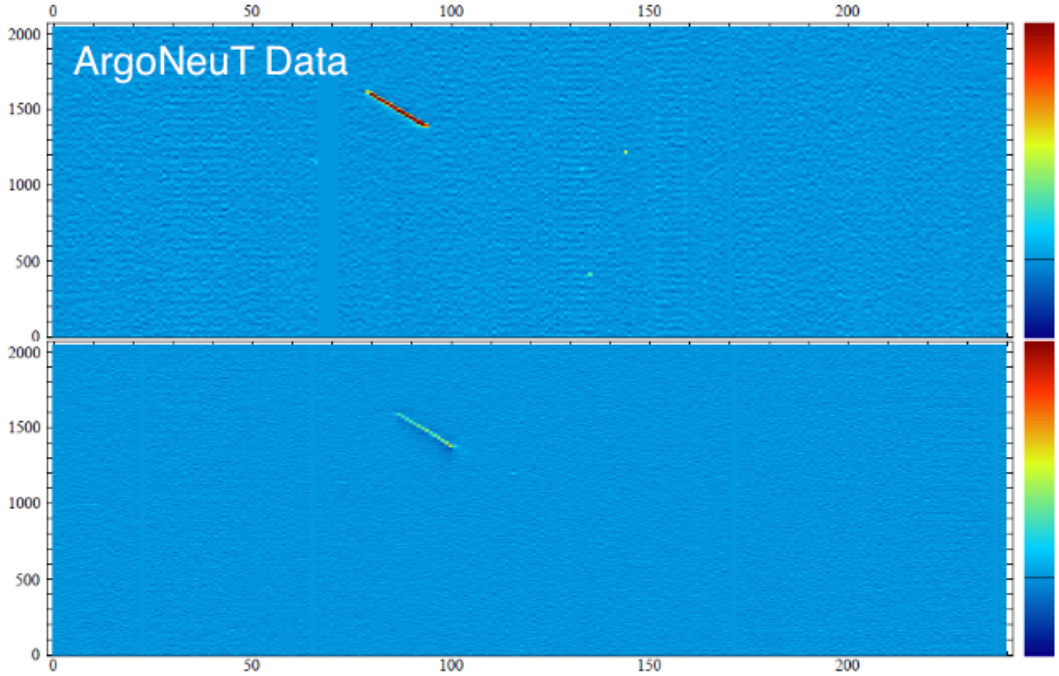
- Above is the Michel spectrum for muons which stop in the central 20cm of our TPC.
- Current analysis assume uniform visibility... adding position dependence to MC and detector systematics
- The above comparison with ICARUS is not an apples-to-apples comparison, but worth noting the similar smearing...
- Optimizing track/shower reconstruction for measurement of ionization energy spectrum

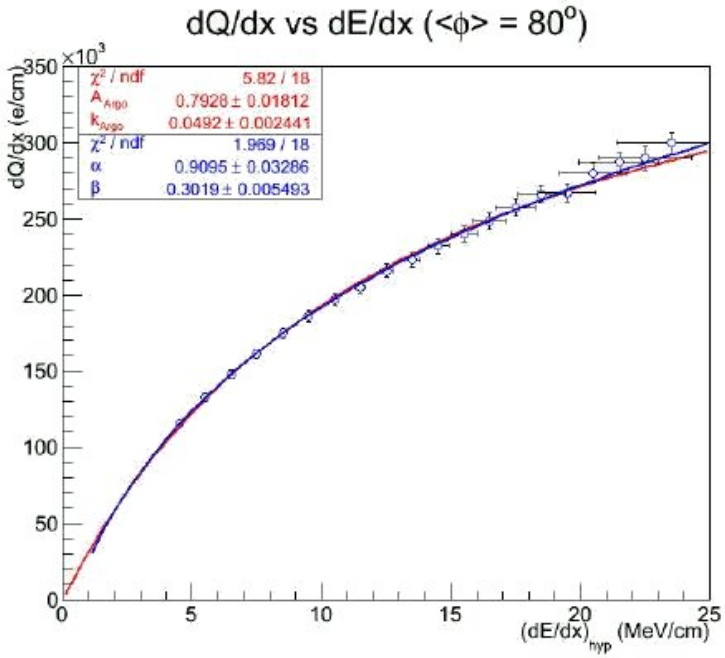
Conclusions

- **ArgoNeuT** has measured many important neutrino nucleus cross sections (ν_μ and $\bar{\nu}_\mu$ CC-inclusive, CC coherent $\pi^\pm$ production, nuclear effects).
  - Many more exciting measurements on the way (neutral current π^0 cross section, e/γ separation using dE/dx)
- **LArIAT** continues this work in a complementary manner by measuring cross sections of charged hadrons.
  - Run-I (Completed: April 30, 2015 to July 7, 2015)
    - All detectors installed and operational
    - Focus is currently on Run-I analysis to inform data-taking for Run-II
    - Many exciting results are in the pipeline including $\pi^\pm$-Ar cross sections, $K^\pm$ interactions in LAr, muon decay vs capture, e/γ experimental separation study, etc.
  - Run-II (Expected start: February 2016)
    - Currently completing small modifications for optimized performance
- Both **ArgoNeuT** and **LArIAT** measurements address one of the dominant systematic uncertainties towards measurements of **CP violation**, **neutrino mass ordering**, and **new fundamental particles**.

Backup

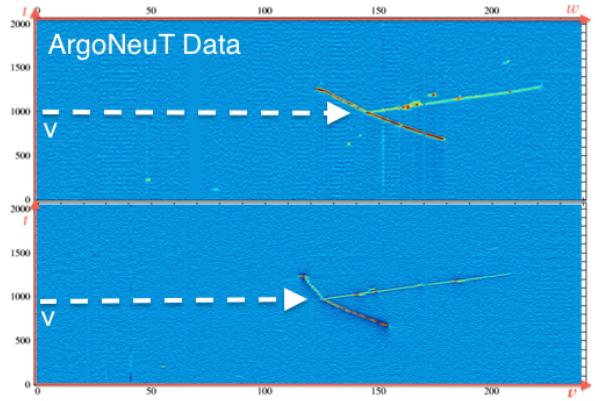
ArgoNeuT Results (Charge Recombination)

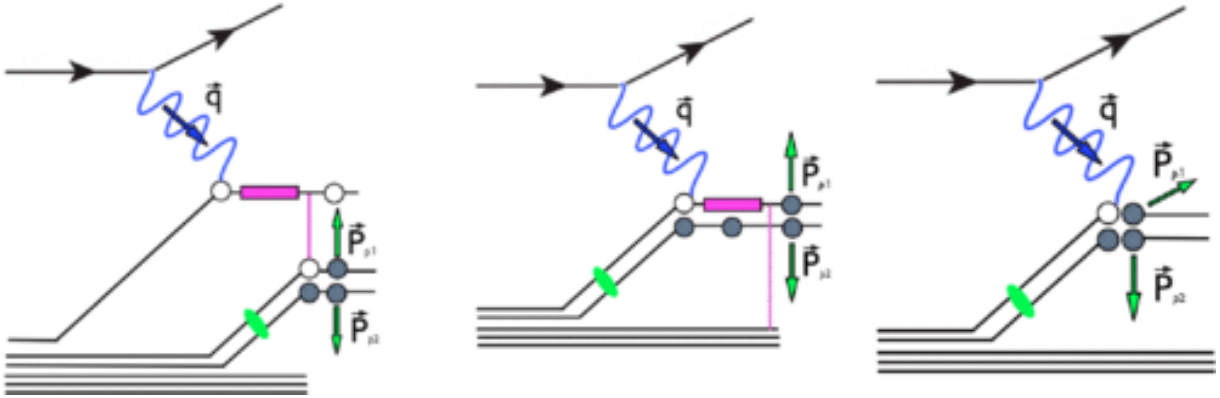




- The data are well modeled by a Birks model and modified form of the Box model.
- An understanding of impurities is critical to future calorimetry in LAr.
- R. Acciarri et al., JINST 8 P08005 (2013)

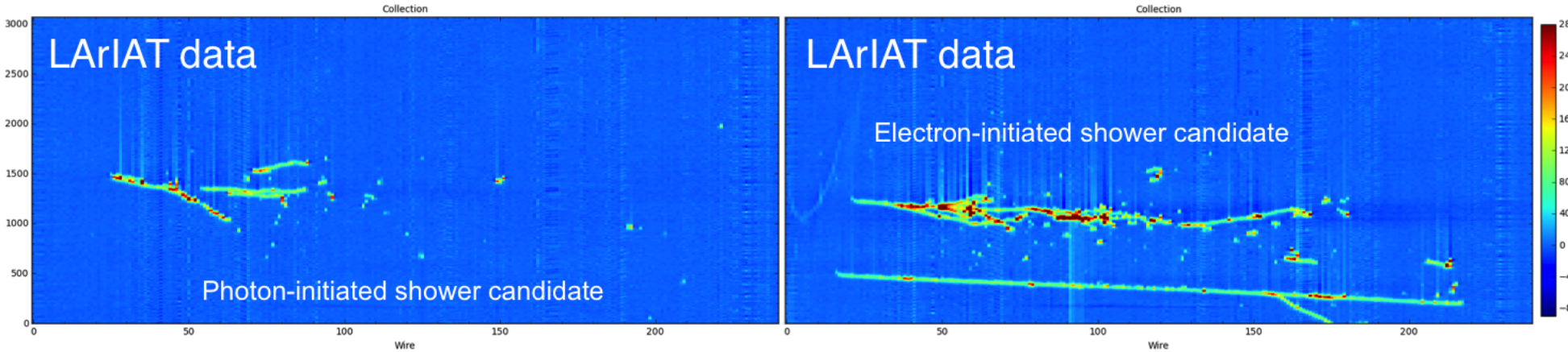
ArgoNeuT Results (Back-To-Back Protons)





- Back-to-back protons provide an excellent probe of short range correlations and final state interactions in argon nuclei.
- CC pionless resonance reactions involving a SRC pair may produce back-to-back protons in the Lab frame (Left, Center).
- CC QE interaction on a neutron in a SRC pair is expected to produce back-to-back protons in the CM frame (Right).

LArIAT (e/γ Separation)



- We are comparing topological cuts with dE/dx discrimination of electrons and photons.