The ArgoNeuT Experiment

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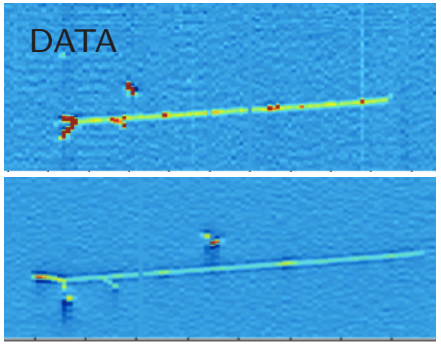
(on behalf of S. Farooq, KSU)
for the ArgoNeuT Collaboration

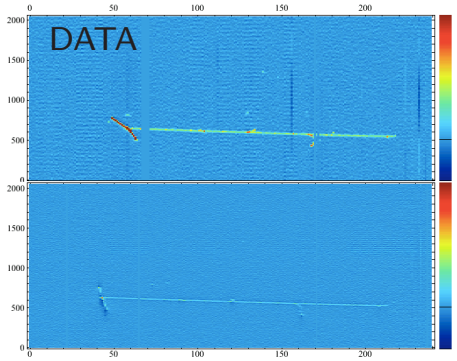
Yale University

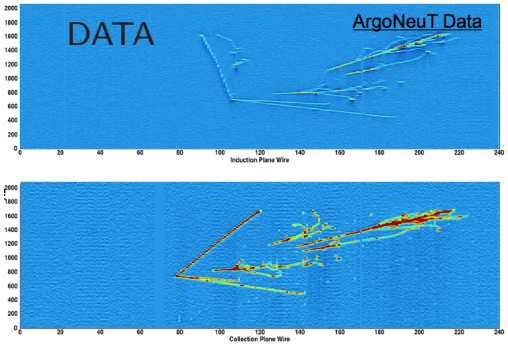
DPF2013, Santa Cruz

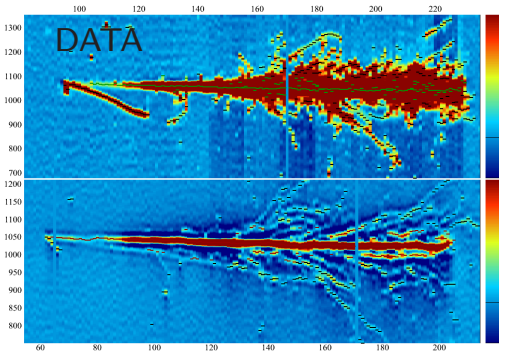
Liquid argon for ν detection

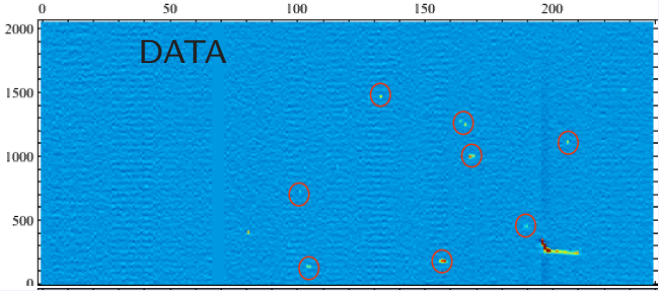
- Abundant ionization electrons and scintillation light can both be used for detection.
- Reasonably dense (1.4 g/cm^3) - a good target for neutrinos.
- Relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.
- Most importantly it gives us great opportunity to understand neutrino physics!





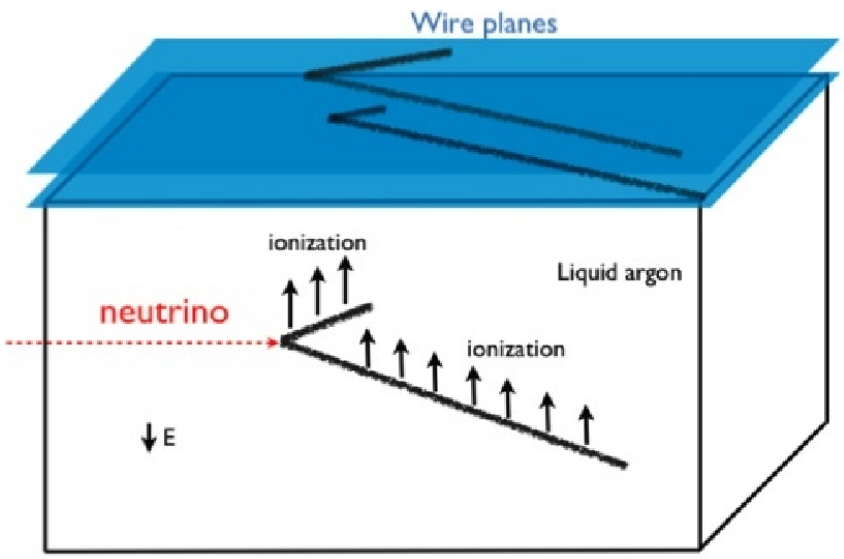


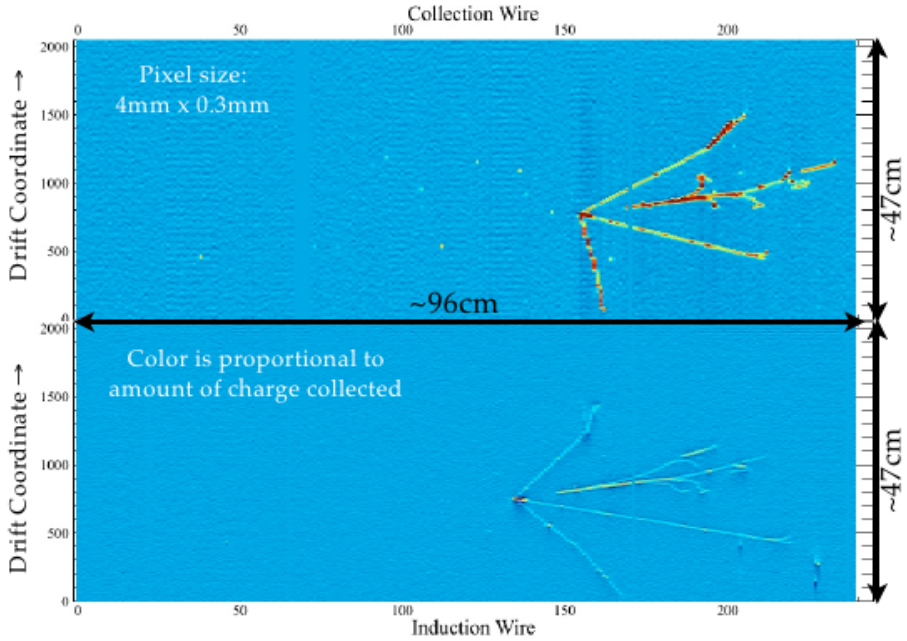




LArTPC Concept

- Energy deposition in argon results in ionization and scintillation
- Electrons are drifted in the Electric field towards the anode.
- Signal is induced and then collected on subsequent wire planes (2D location).
- Drift time provides 3rd coordinate → 3D reconstruction.
- Quantity of charge provides calorimetric reconstruction.

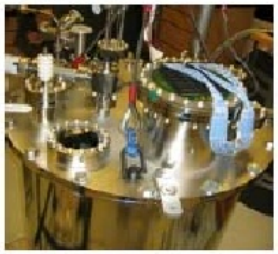




ArgoNeuT Data Event

LArTPC Program in the US

Yale TPC



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

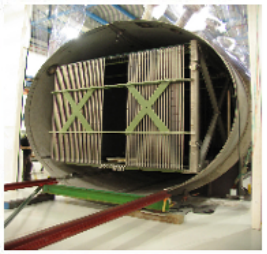
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

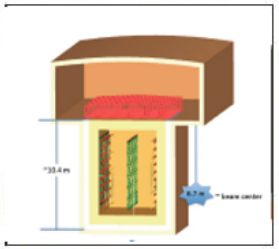
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



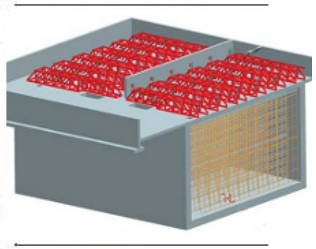
Location Fermilab
Active volume: 0.1 kton
Operational: 2014

LAr1



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

LBNE



Location: Homestake
Active volume: 10/35 kton
Construction start 202?

Luke

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

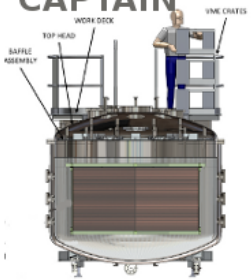
LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT

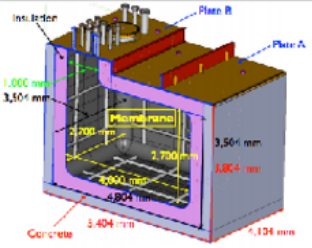
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN



Location: LANL
Purpose: LArTPC calibration
Operational: 2014

LBNE 35 Ton

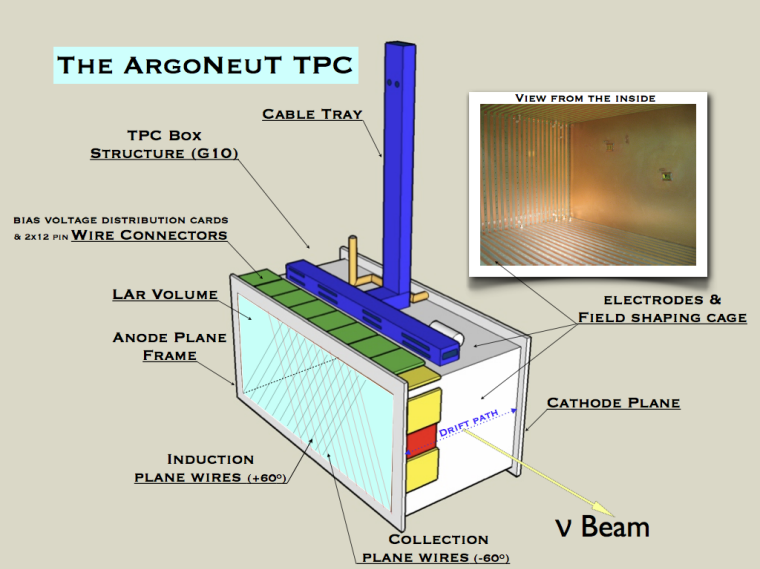


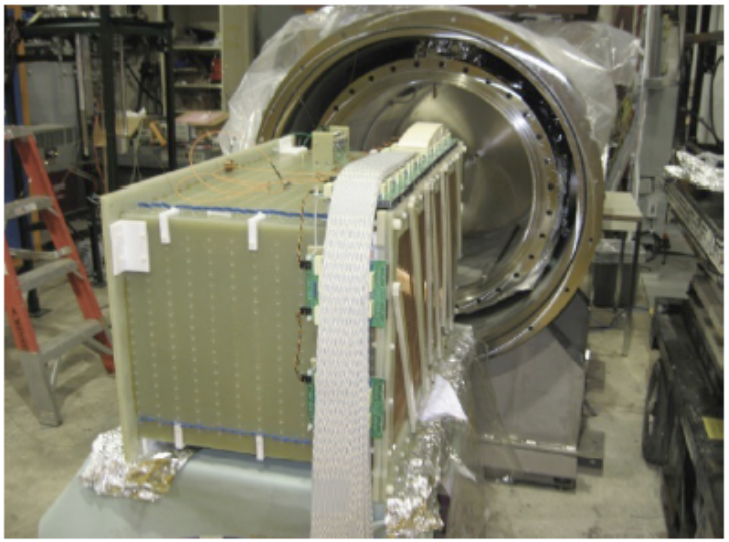
Location: Fermilab
Purpose: purity demo
Operational: 2013

ArgoNeuT Goals

- First TPC in a beam in the US LAr R&D program
- Measure CC cross sections on argon in the 1-10 GeV range.
- Examine effects of FSI using the TPC's great Granularity
- Examine dE/dx particle ID, especially e/γ separation, crucial for future ν experiments.
- Develop automated reconstruction techniques.

The ArgoNeuT TPC

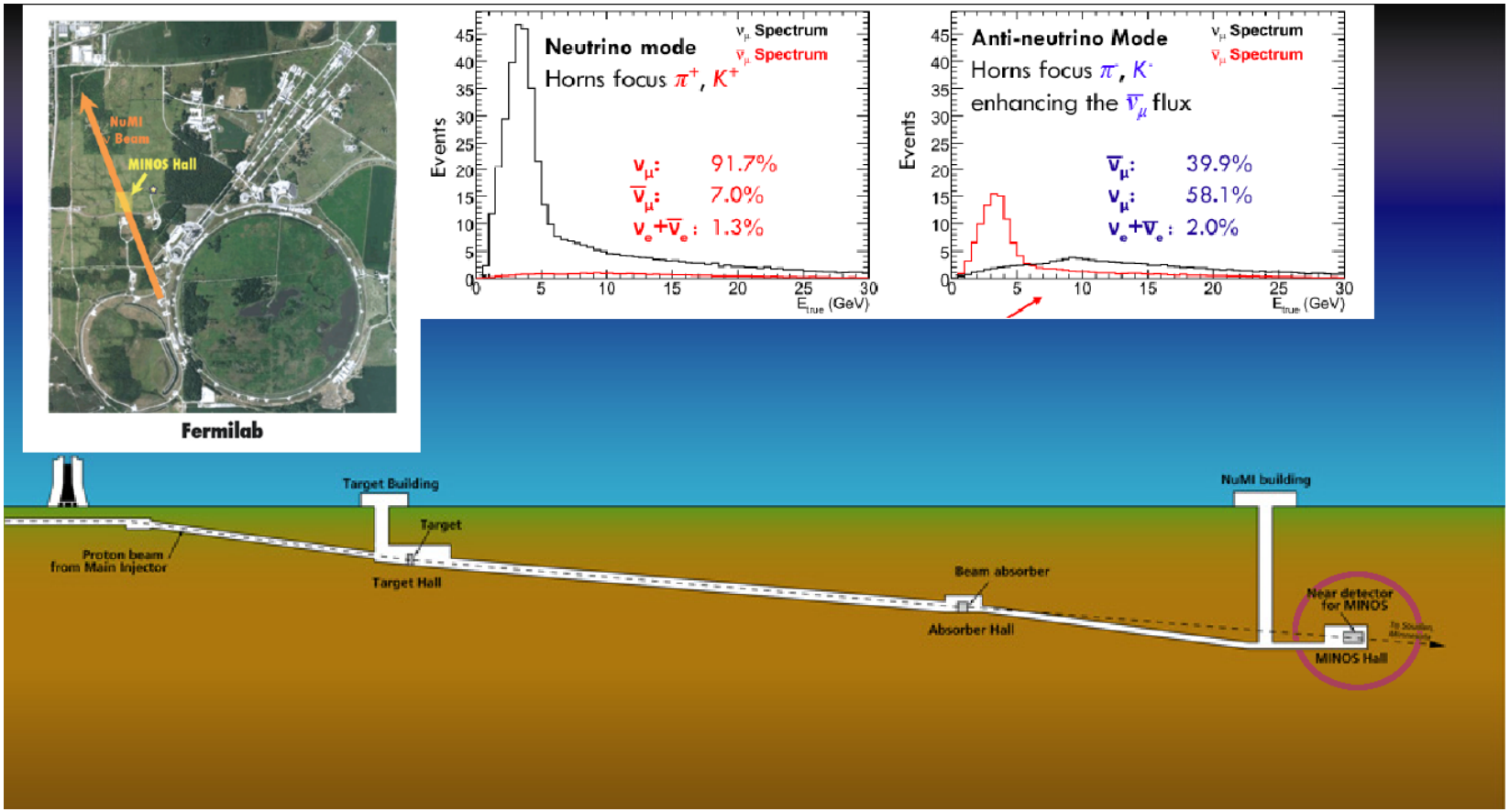




Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

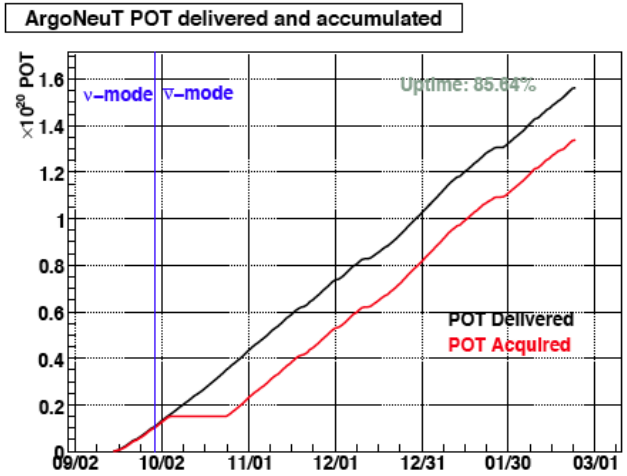
- Two wire planes instrumented (3 present)
- E-field between planes optimized to maximize transparency
- Wire spacing at 4mm.

NuMI Beam


NuMI ν Beam
MINOS Hall
Fermilab
Neutrino mode
Horns focus π+, K+
νμ Spectrum
ν̄μ Spectrum
νμ: 91.7%
ν̄μ: 7.0%
νe+ν̄e: 1.3%
Events
Etrue (GeV)
Anti-neutrino Mode
Horns focus π-, K-
enhancing the ν̄μ flux
ν̄μ: 39.9%
νμ: 58.1%
νe+ν̄e: 2.0%
Target Building
Target
Target Hall
Proton beam from Main Injector
Beam absorber
Absorber Hall
NuMI building
Near detector for MINOS
MINOS Hall

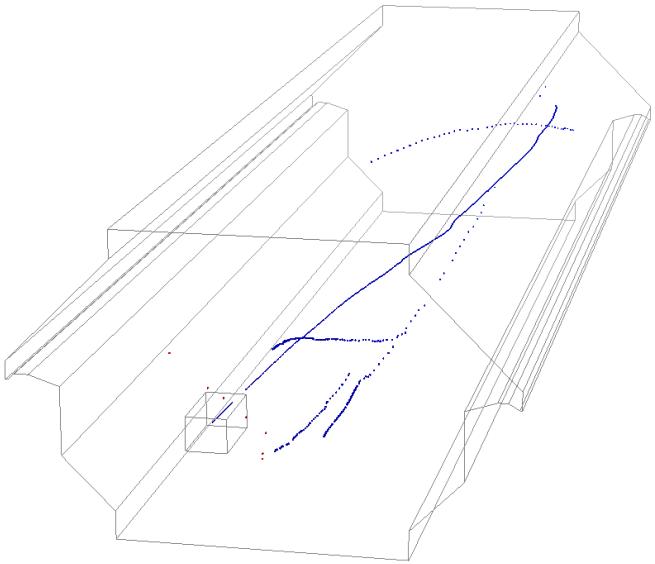
ArgoNeuT in the MINOS hall

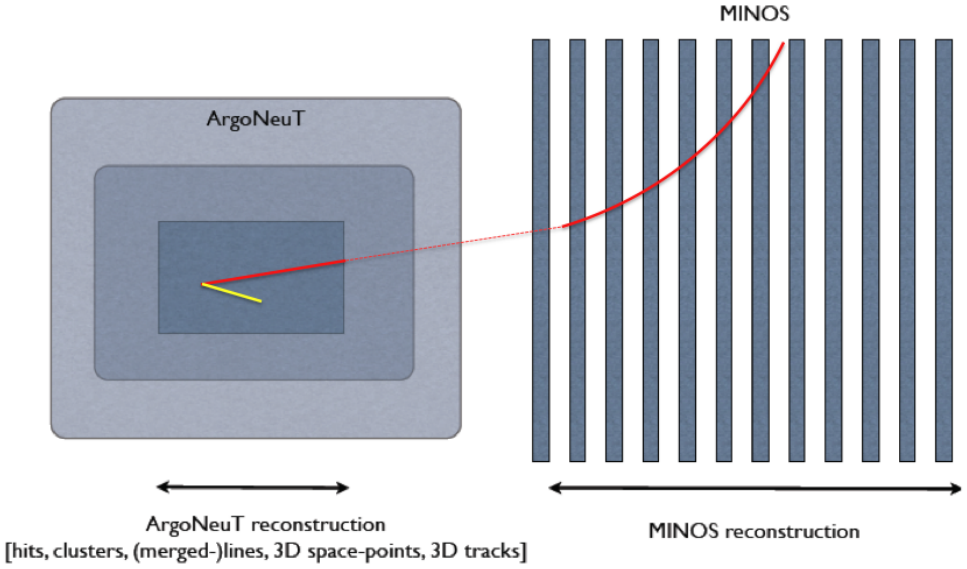
- Remote,shiftless operation for 5 months.
- Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode.
- Expect ~o(10k) CC events in ν_μ and $\bar{\nu}_\mu$



MINOS ND

- ArgoNeuT is too small to contain muons.
- Fortunately, the presence of the MINOS ND allows for their momentum reconstruction and charge identification (q).





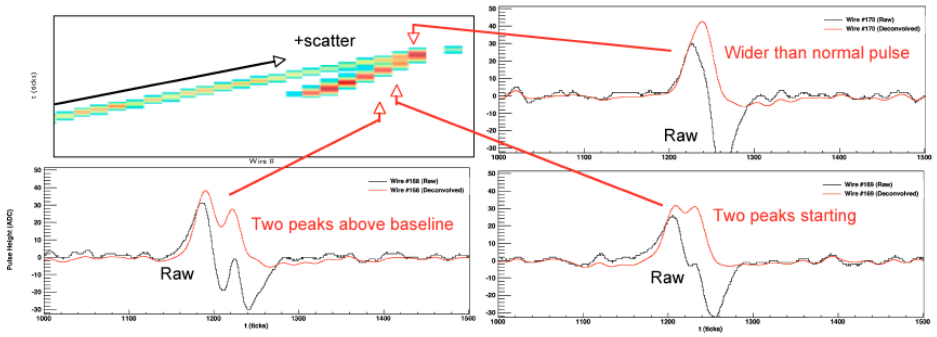
We gratefully acknowledge the help of the MINOS collaboration in these analyses.

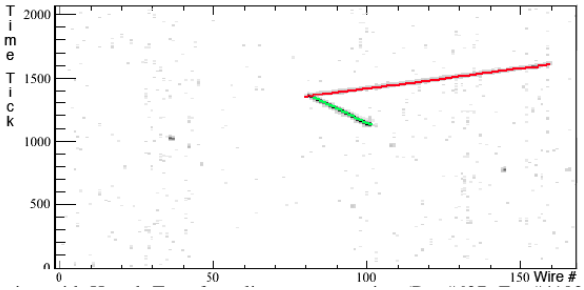
The ArgoNeuT Reconstruction

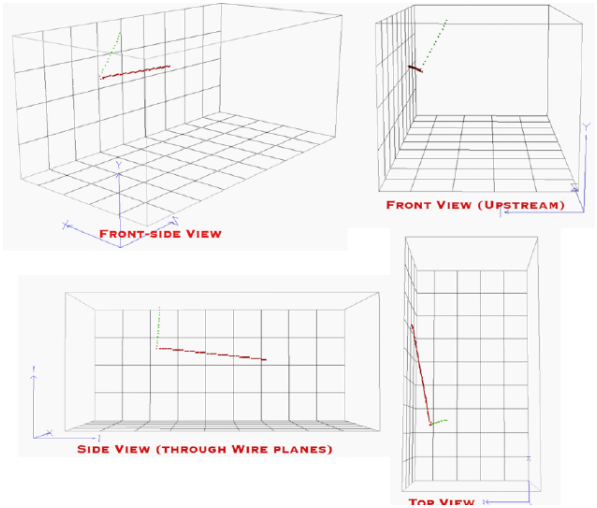
- The data acquired by ArgoNeuT is still being analyzed.
- The LArSOFT package, developed for US LAr TPCs is being used in the reconstruction.
- Use 3D and calorimetric reconstruction for efficient Particle Identification
- Excellent resolution for final states
- Possibility of "seeing" recoil proton(s)
- Good $p/\pi^{\pm}$ identification capability
- We can do nuclear physics!

The Reconstruction Process

- 1st stage - Hits (FFtHitFinder, GaussHitFinder)
- 2nd stage - Clustering (DBCluster, FuzzyCluster,...)
- 3rd stage - Combine into 3D tracks (KalmanTracker, BezierTracker,...)

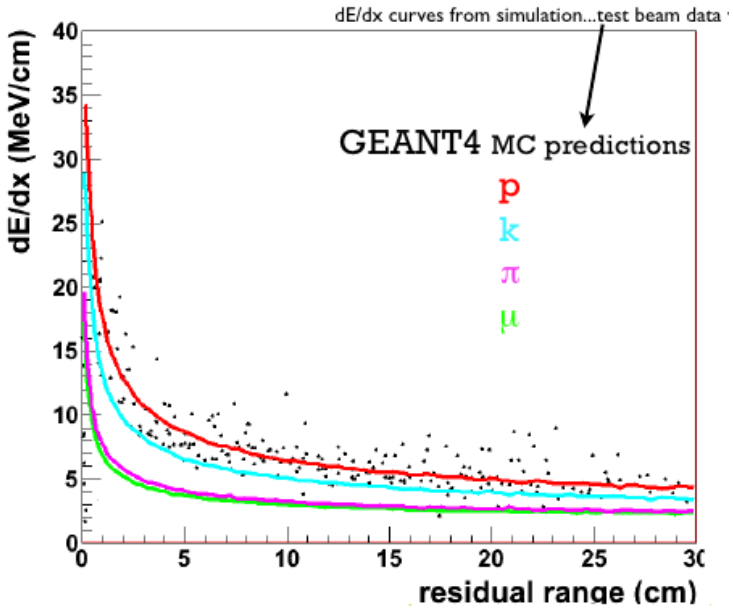


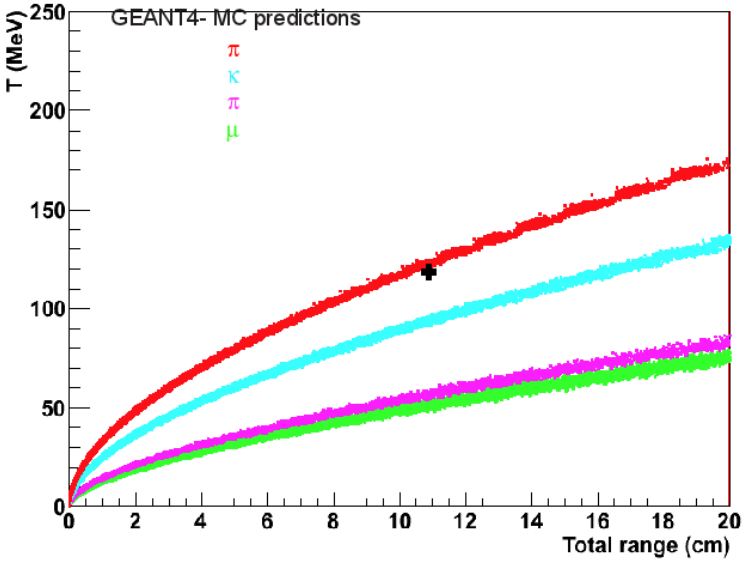




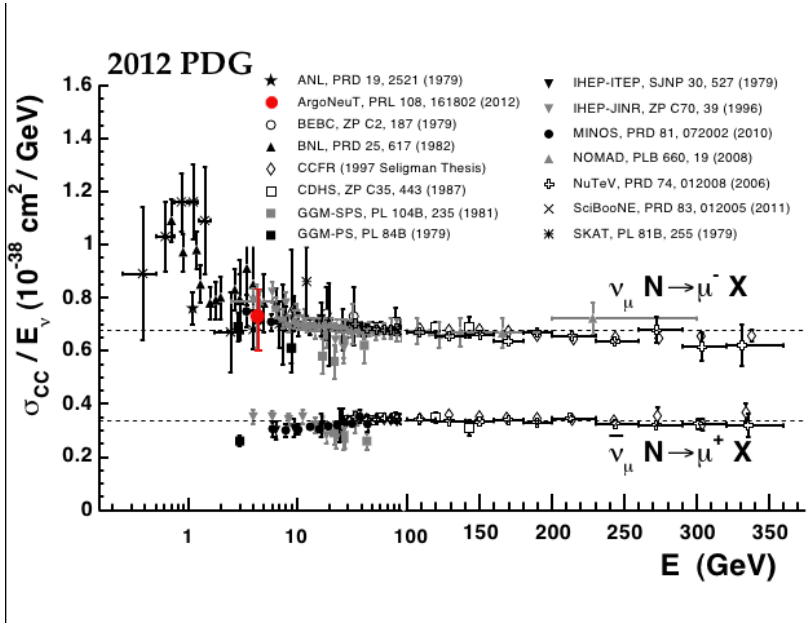
Calorimetry and PID

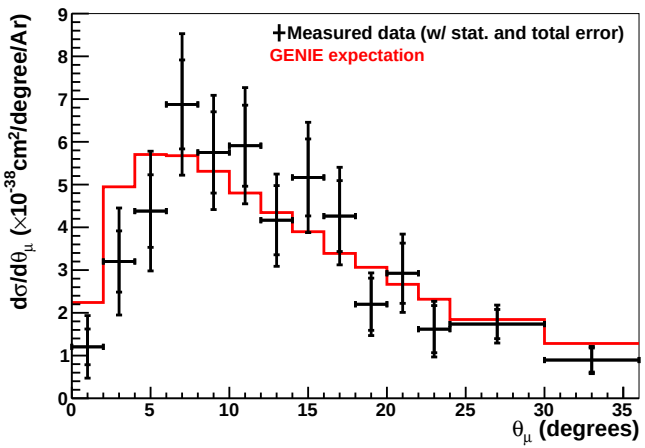
- Once we have the 3D track, we reconstruct the dE/dx
- This allows for Particle ID via total kinetic energy and residual range methods.

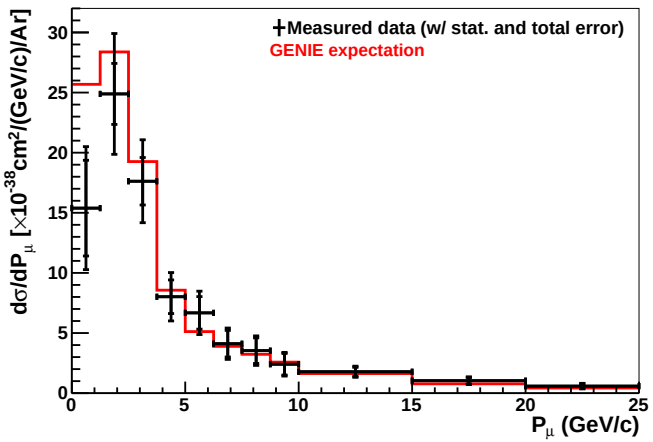




Measurement of the ν_μ CC inclusive Cross-section



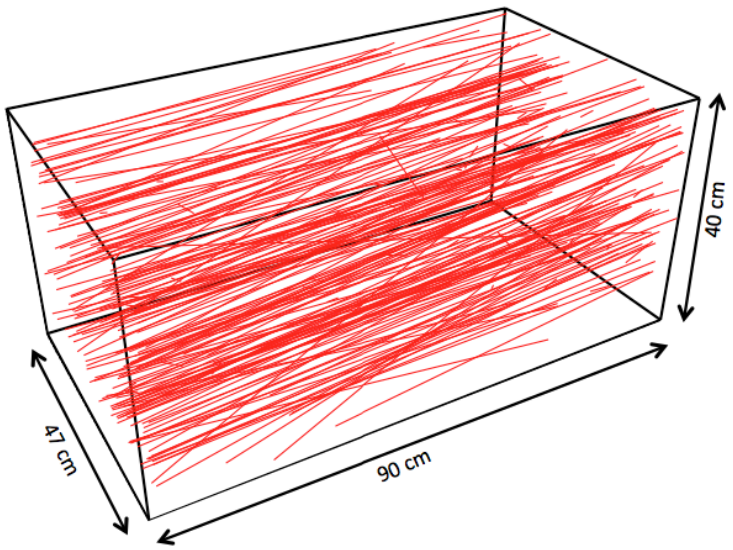


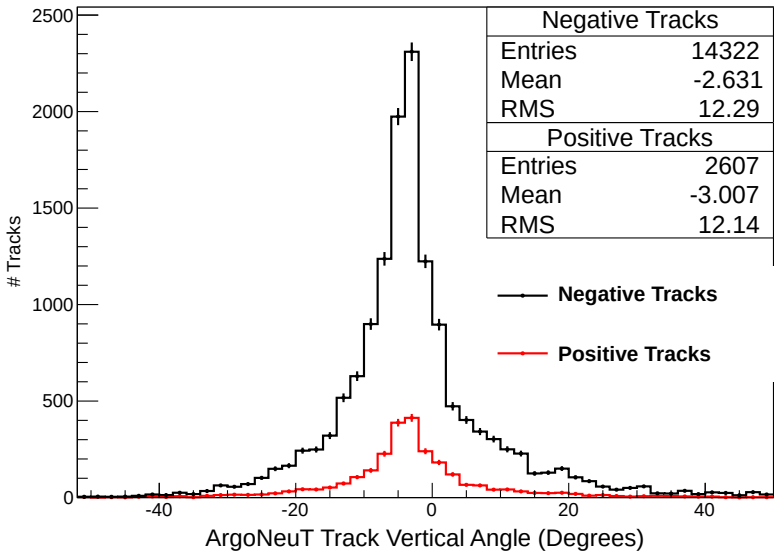


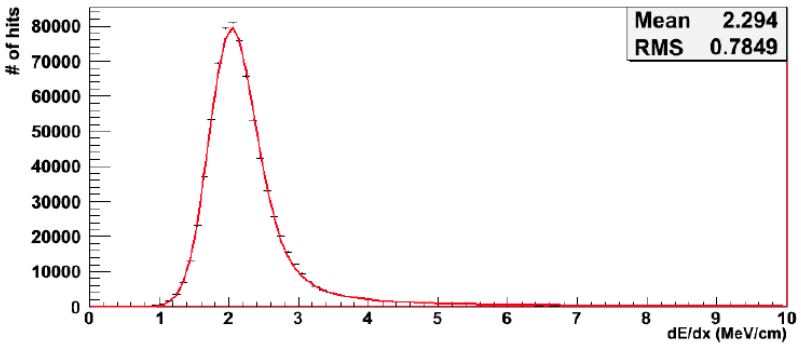
- Used data acquired in neutrino mode ($8.5x10^{18}$POT)
- C. Anderson et al., PRL 108, 2012
- Simple cuts applied:
  - vtx in fiducial volume
  - track matched to muon in MINOS ND
  - MINOS $q < 0$
- first CC-inclusive cross-section measurements in argon

Calorimetry on Through-going Muons

- Calorimetry tested on through going muons.
- Proves excellent calorimetric reconstruction capabilities of the LArTPC.
- C.Anderson et al., *2012 JINST 7 P10020*; arxiv.org:1205.6702,

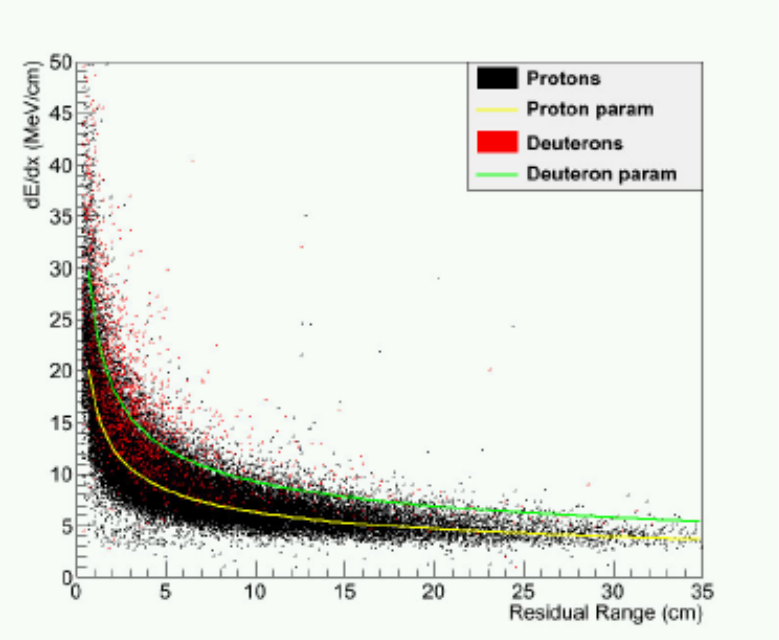


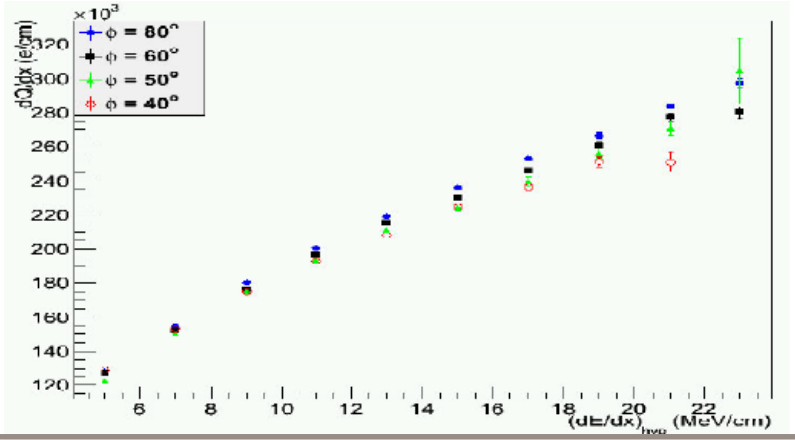




Recombination Study using Stopping Protons

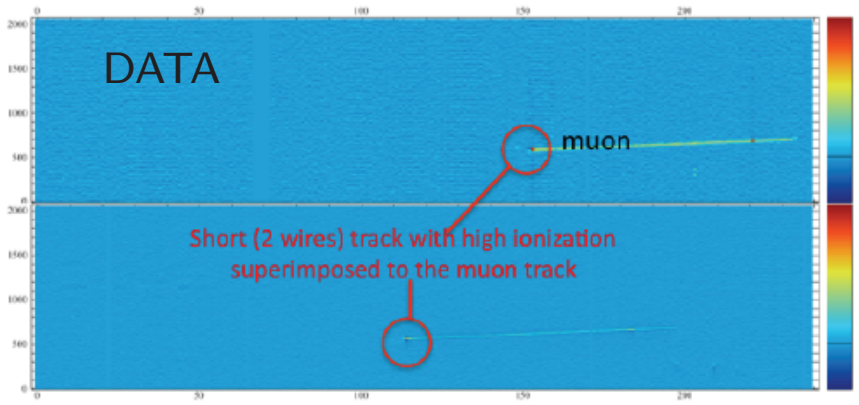
- Studied the recombination of electron-ion pairs produced in liquid argon by stopping protons and deutrons.
- Angular dependence of recombination - the collected charge by 5% - 10% at small angle (wrt to Electric Field) and high ionization.
- Significantly less than the 25% loss predicted by the Jaffe columnar theory and simulations.
- arXiv:1306.1712, accepted by JINST.

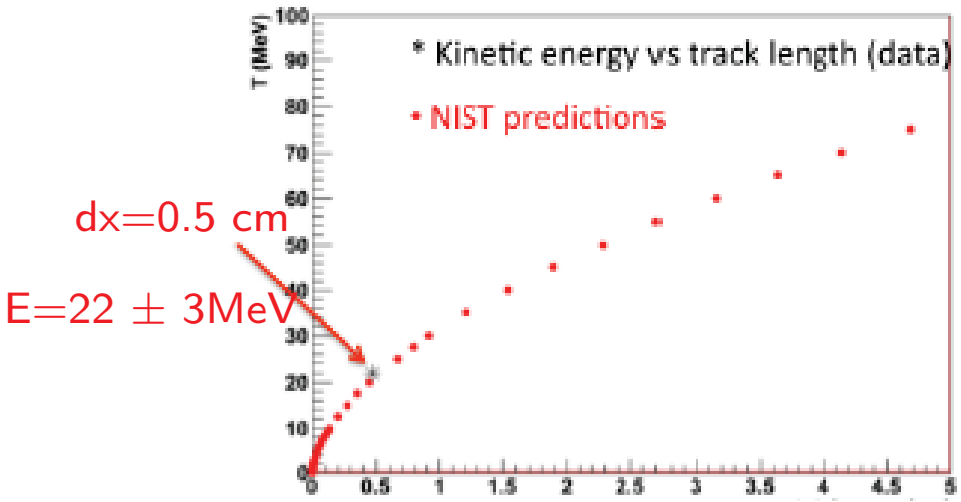




Studies of Nuclear Effects

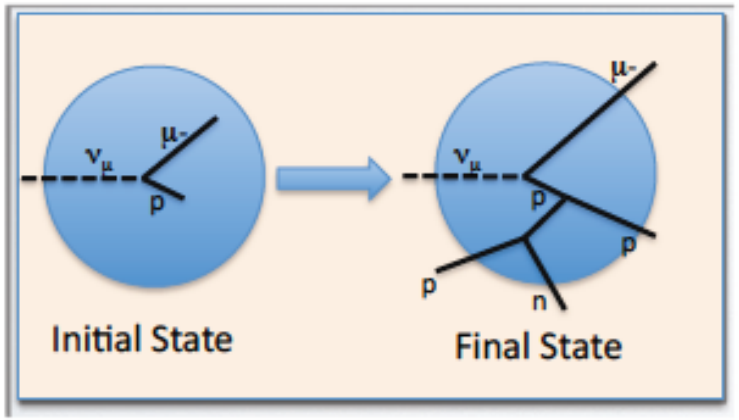
- LAr-TPC detectors can fully reconstruct exclusive topologies.
- Proton multiplicity and kinematics can be measured with a very low proton energy threshold (21 MeV).
- This will ultimately allow the reconstruction of the incoming neutrino energy from lepton AND proton kinematics.
- And it already allows studying nuclear effects!

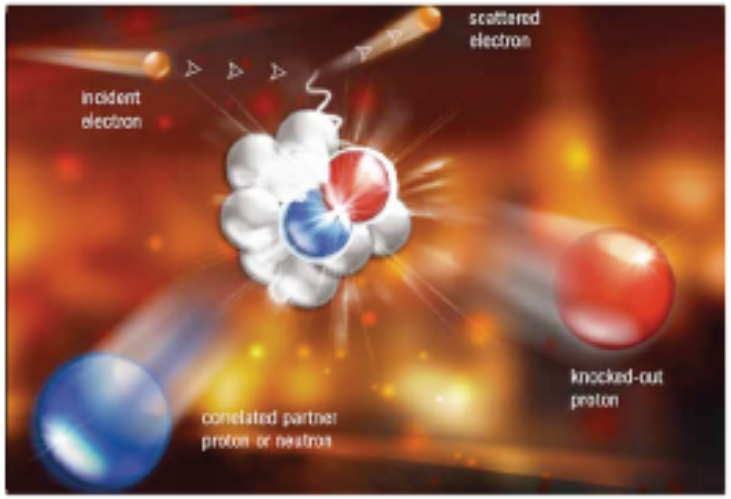




Studies of Nuclear Effects (2)

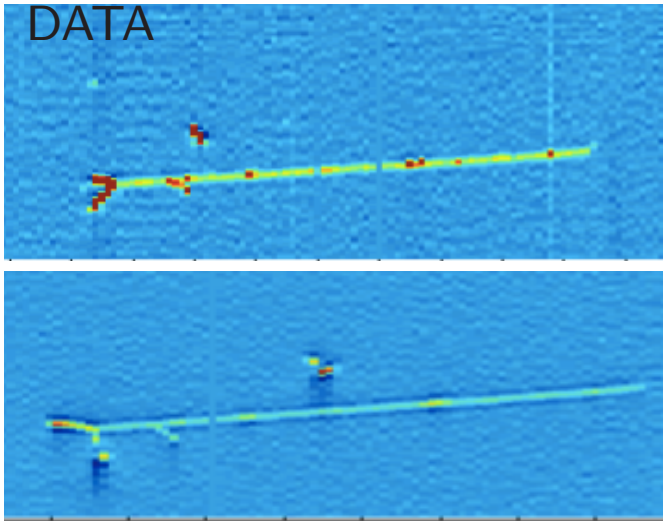
- Nuclear effects play a key role in neutrino-nucleus interactions in nuclear targets.
- Due to intra-nuclear re-scattering (FSI) Final State interactions and possible effects of correlation between target nucleons, a genuine QE interaction can often be accompanied by the ejection of additional nucleons, emission of many de-excitation γ's and sometimes by soft pions in the Final State.
- In ArgoNeuT we are able to observe these effects.

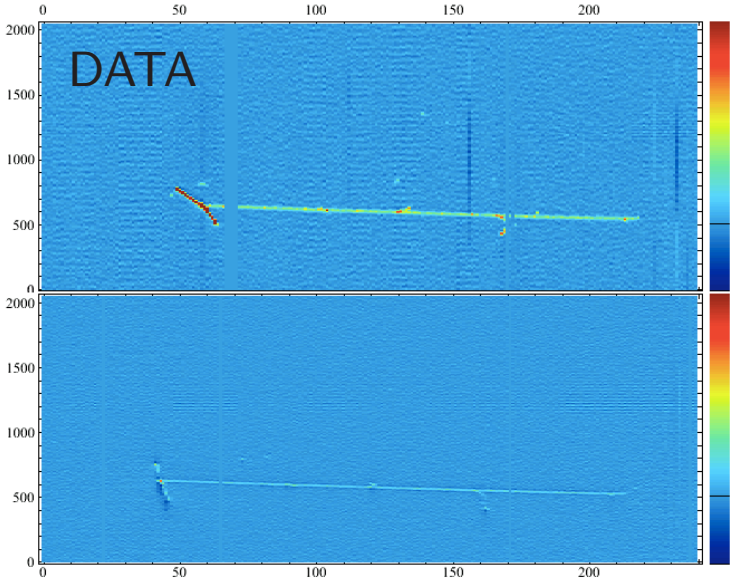




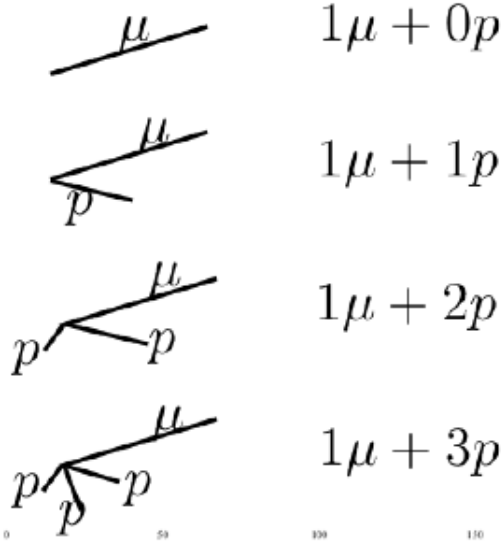
Studies of Nuclear Effects (3)

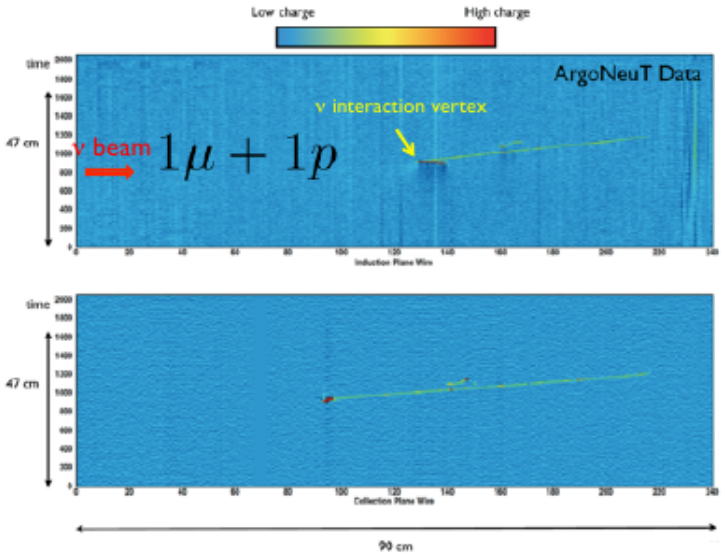
- Observed backwards going protons - kinematically forbidden in an interaction on a free and stationary nucleon.
- Can be an effect of intra-nuclear cascades or short range correlations.
- If nucleon in a correlated pair is knocked out of a nucleus, the "paired" nucleon is also emitted.
- Measuring back-to-back protons could be a "fingerprint of nucleon-nucleon correlations".
- p1: θ_1=67°
  L1=5.1 cm, p1=395±4 MeV/c
- p2: θ_2=116°
  L2=5.4 cm, p2=401±24 MeV/c
- Angle between two protons γ=183°

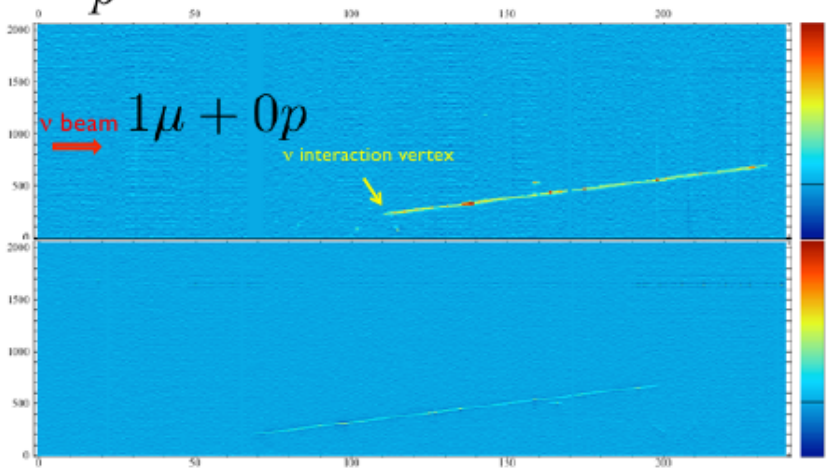


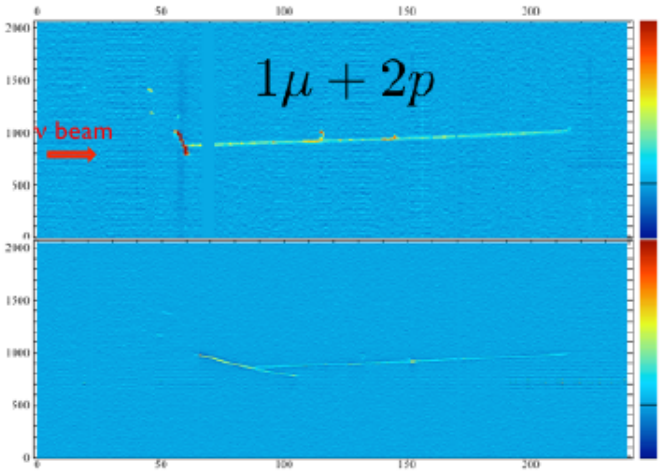


μ + N protons analysis

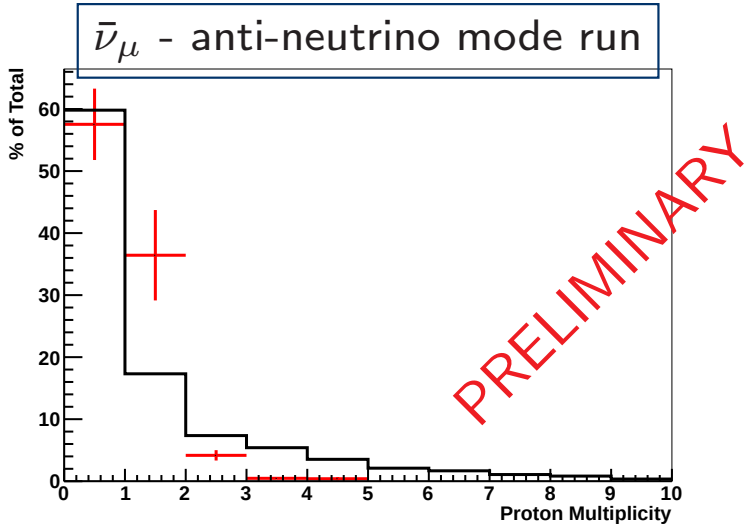


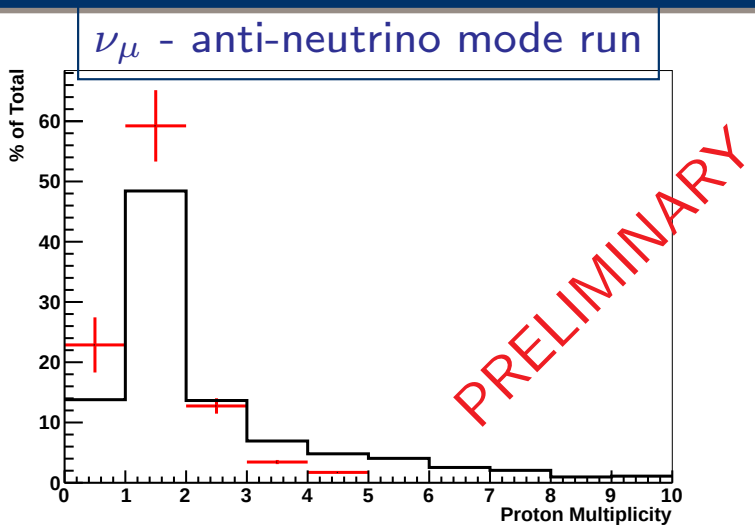


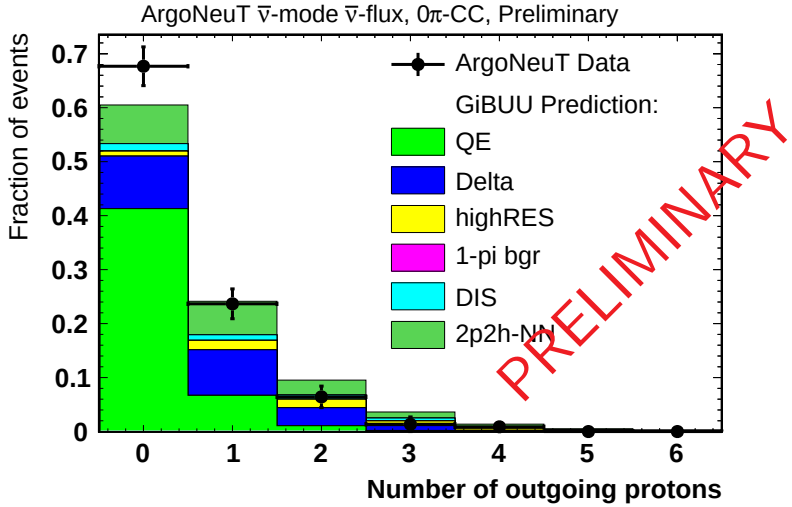




μ + N protons analysis (2)





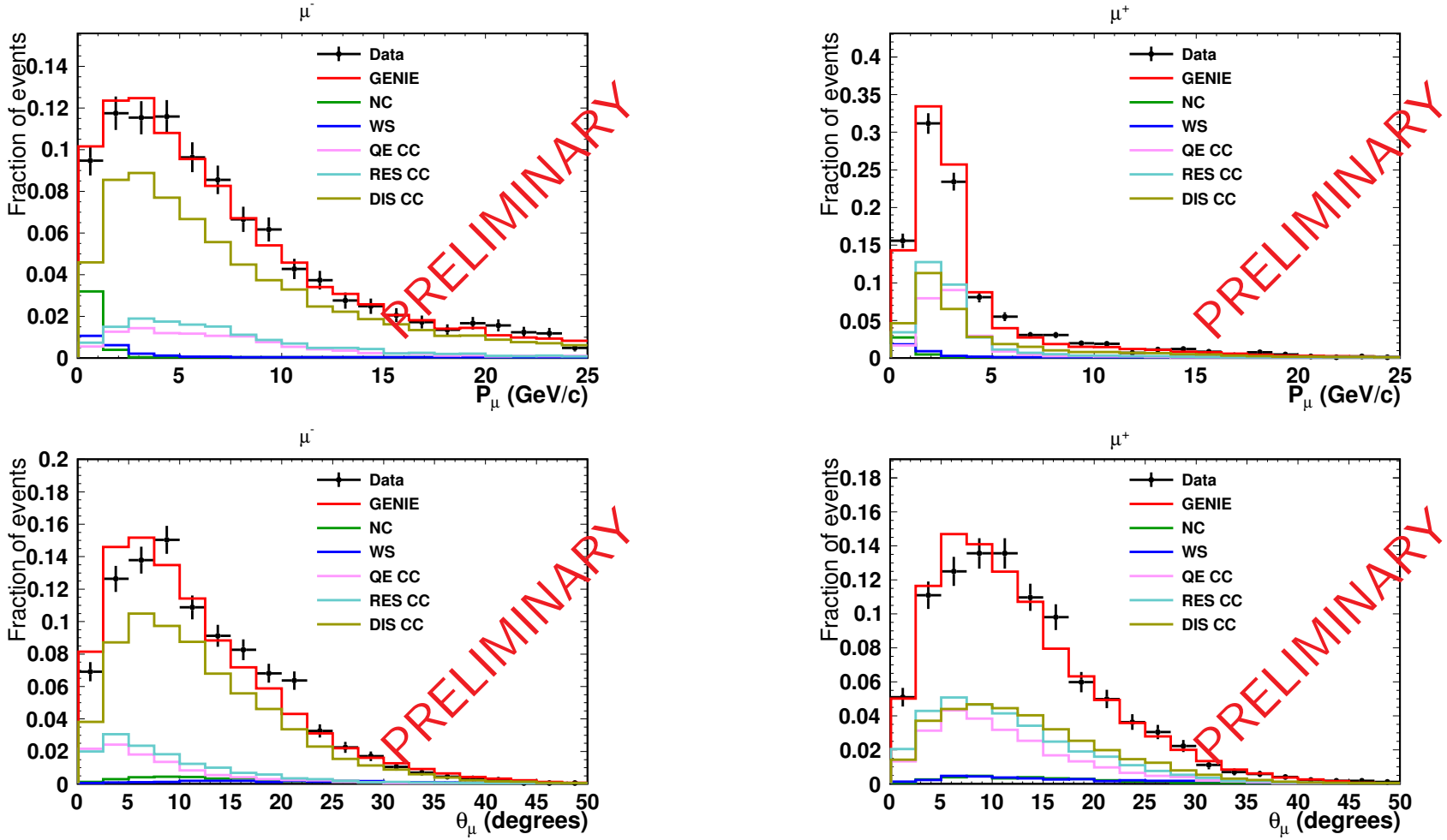


Default Fluka flux used.
Tuning in progress.

- The MC generators predict varying amounts of proton emission
- 30% of events in GENIE are not CCQE (FSI)
- LAr data can provide an important discriminator among models

CC - inclusive analysis of $\bar{\nu}_\mu$ data

- Sample size 8 times larger.
- CC inclusive measurements can be made on $\bar{\nu}_\mu$, but also on ν_μ due to beam composition.
- **Area normalized.**

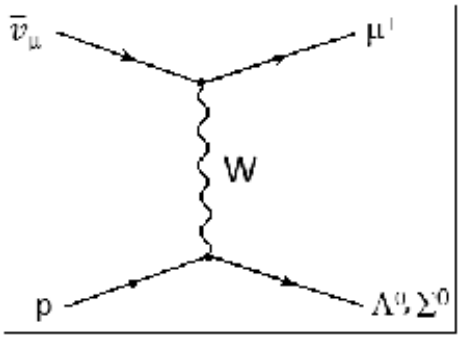


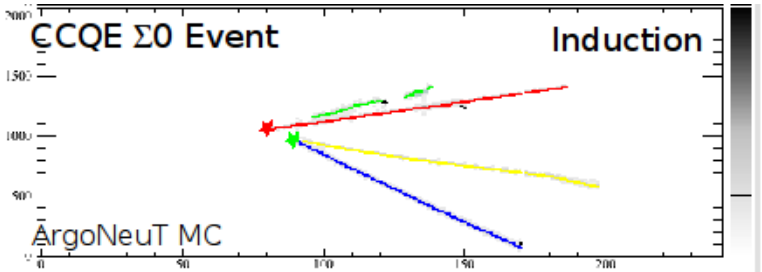
CCQE Neutral Hyperon Analysis

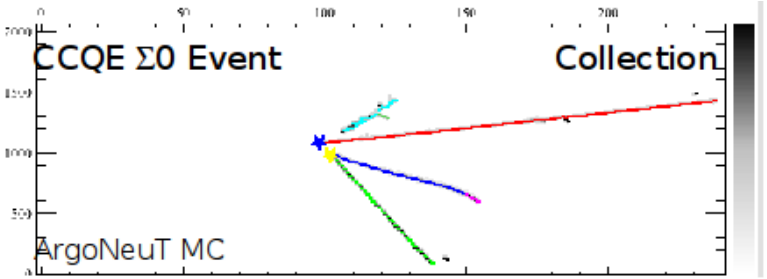
NUANCE Event Generator and GEANT4 are used to Simulate the CCQE Hyperon Events in the Detector

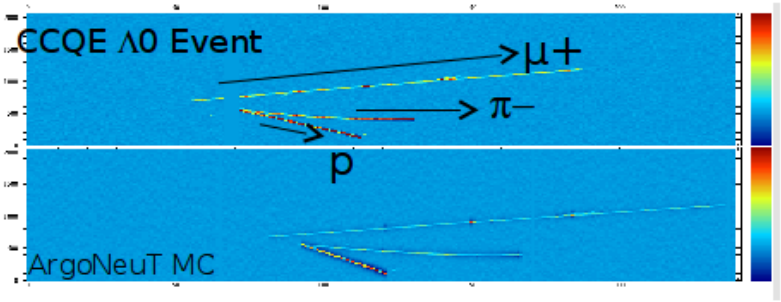
Cuts:

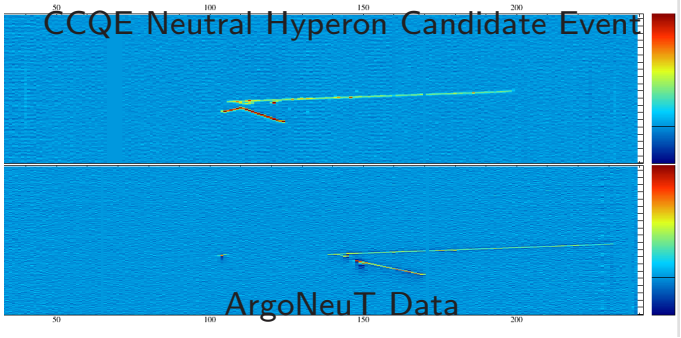
- Vertex in fiducial volume.
- Track match with positive muon track in MINOS.
- Use vertexing to detect a detached vertex.





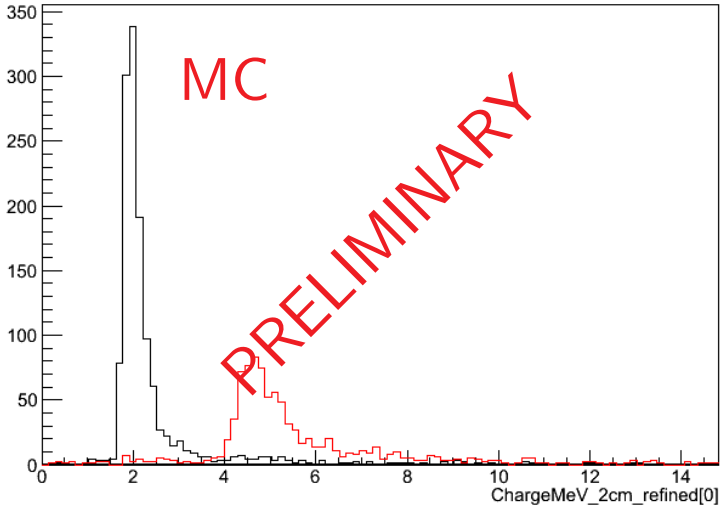


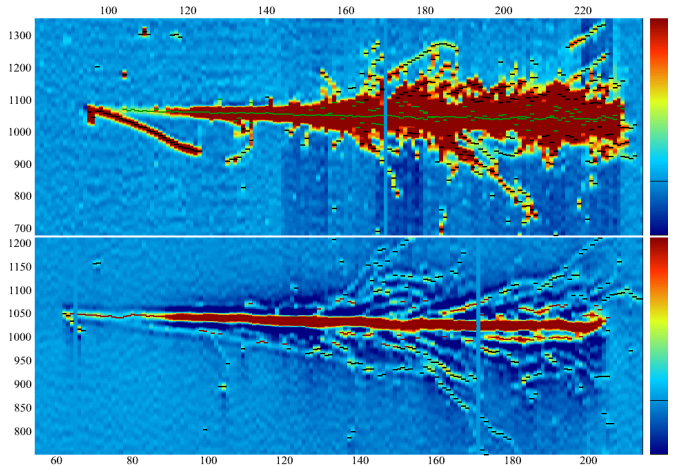




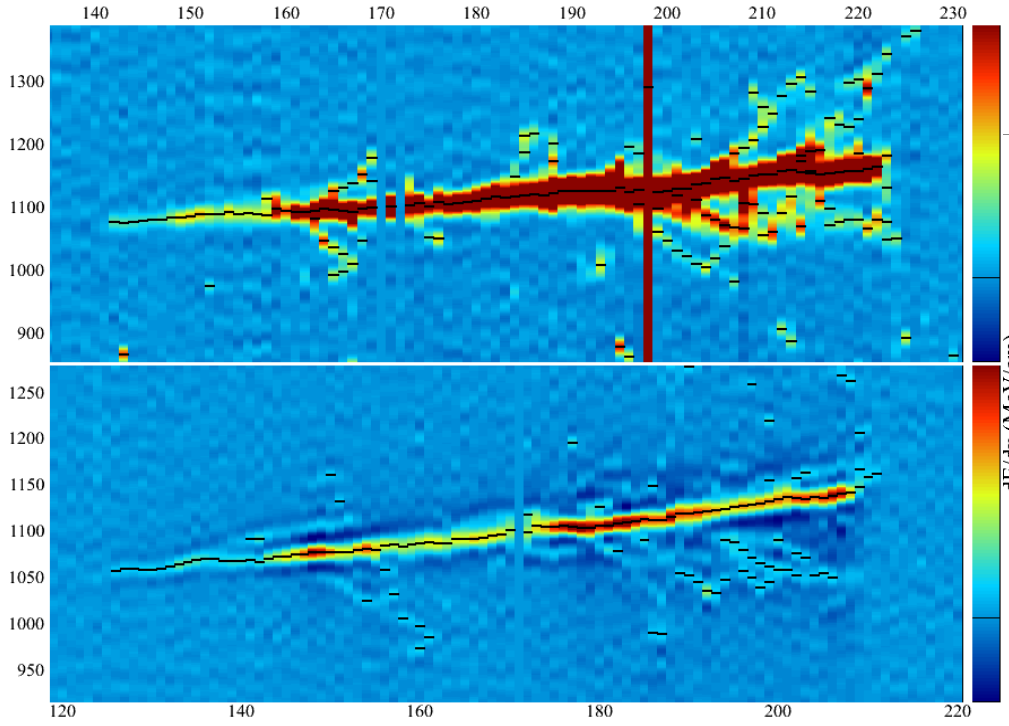
dE/dx e/γ ID

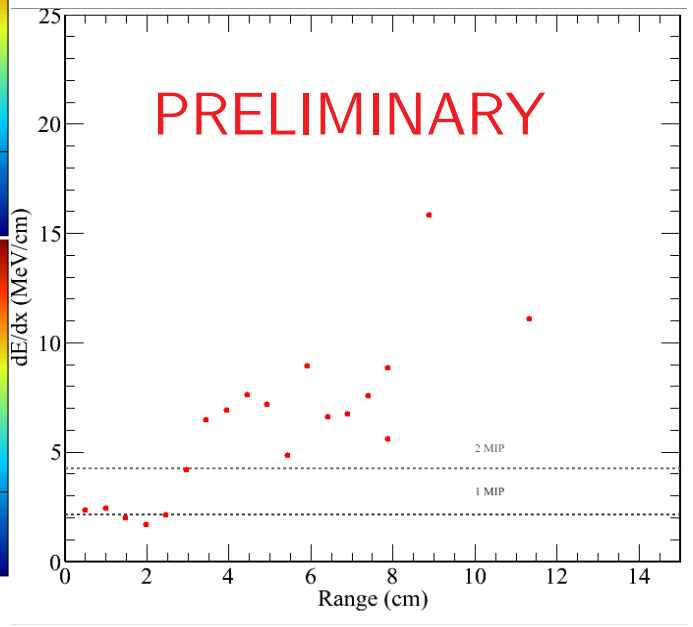
- Separating electrons from γs is important in precision ν measurements
- e.g. understanding whether the MiniBooNE anomaly is an effect of oscillation or background
- LongBaseline measurements e.g. CP violation etc.
- the dE/dx of a shower can be a powerful discrimination tool: an electron is a Minimum Ionizing Particle, a γ pair converts, so the ionization should be double.





dE/dx e/γ ID (2)

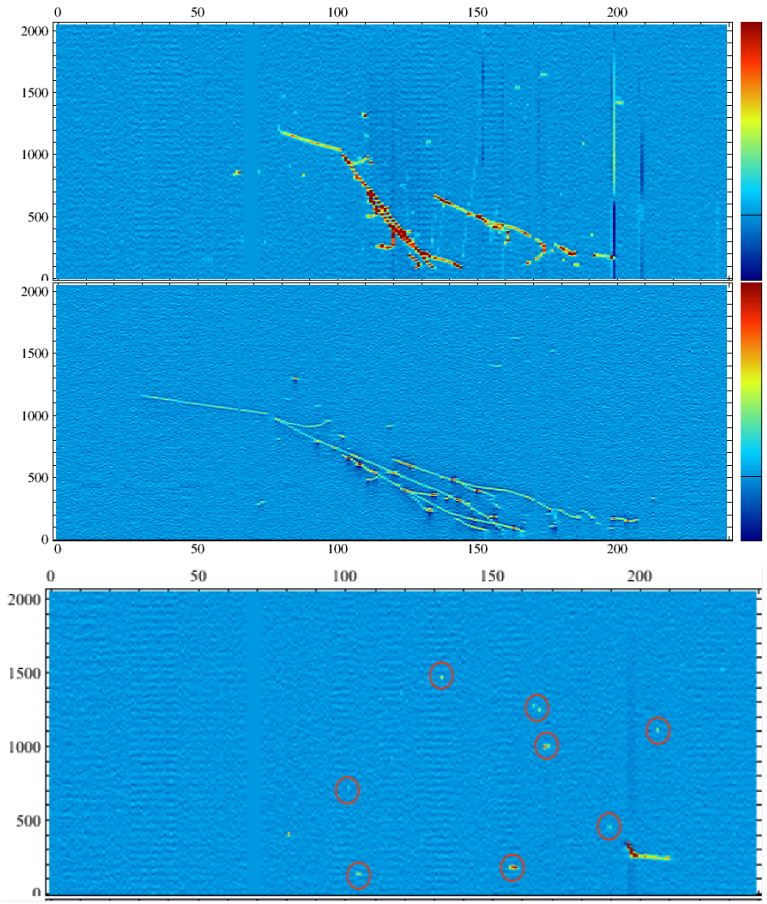




ν_e CC candidate

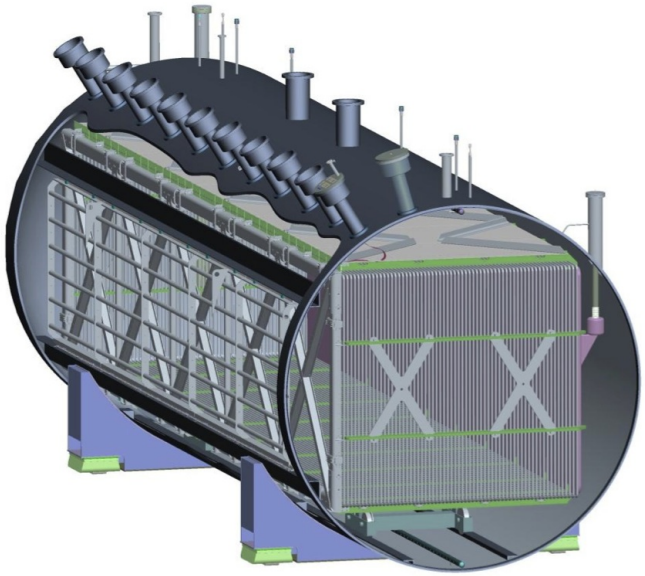
Other Ongoing Analyses

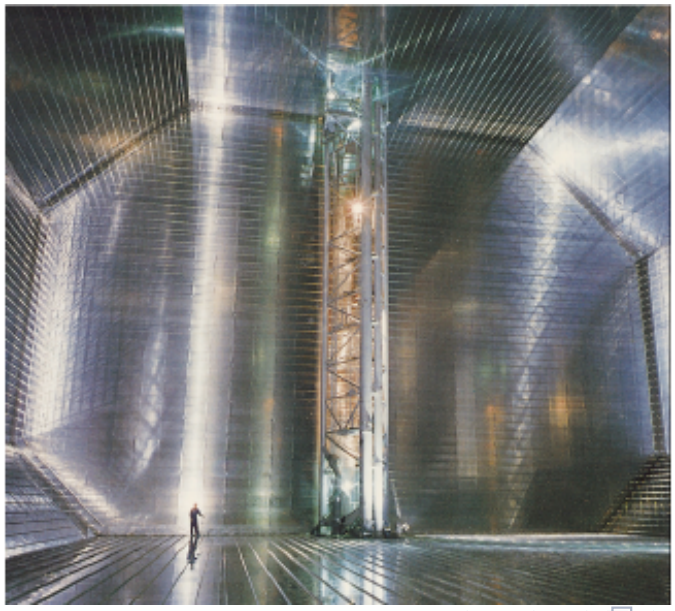
- NC π^0 cs
- Nuclear de-excitation gammas.
- Coherent pion production
- μ + nprotons + npions



Future LAr Experiments in the US

- LArIAT (in construction) - LAr in a TestBeam (talk in this session)
- MicroBooNE (in construction) - Short Baseline (talk in this session)
- LAr1 - 1kT detector (LOI) - Short Baseline
- LBNE - Long Baseline





Conclusions

- First LArTPC in a ν beam in the US.
- Provided important know-how used by subsequent LArTPC experiments.
- First ν data collected in the GeV region in Liquid Argon.
- First results already published.
- Data analysis is ongoing and more results should come soon.
- The detector itself will be reused as to calibrate the response of LArTPC to charged particles (see LArIAT talk).

Thank You

ArgoNeuT Collaboration
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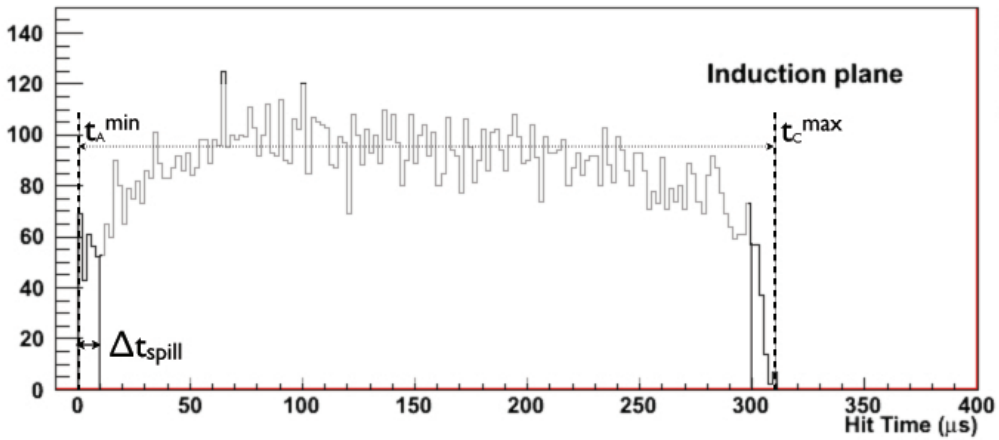
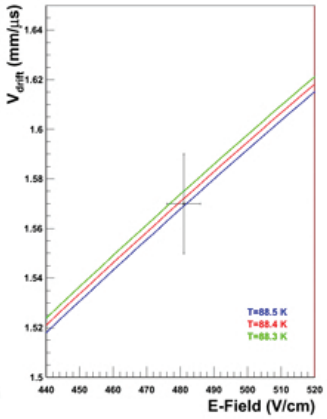
Back Up Slides

Measurement of electron drift speed

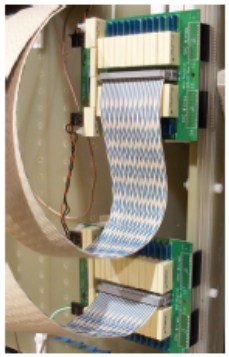
- Measurement of electron drift velocity confirms understanding of detector.
- Difference of maximum and minimum hit drift gives time.
- Distance is size of detector
- Corrected for different field strengths between planes.

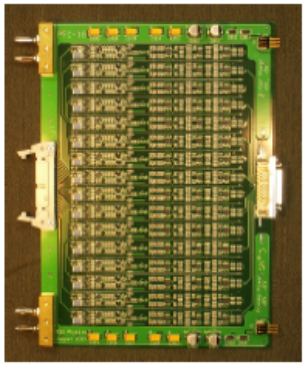


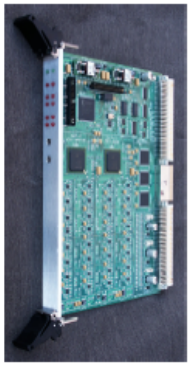


ArgoNeuT Electronics

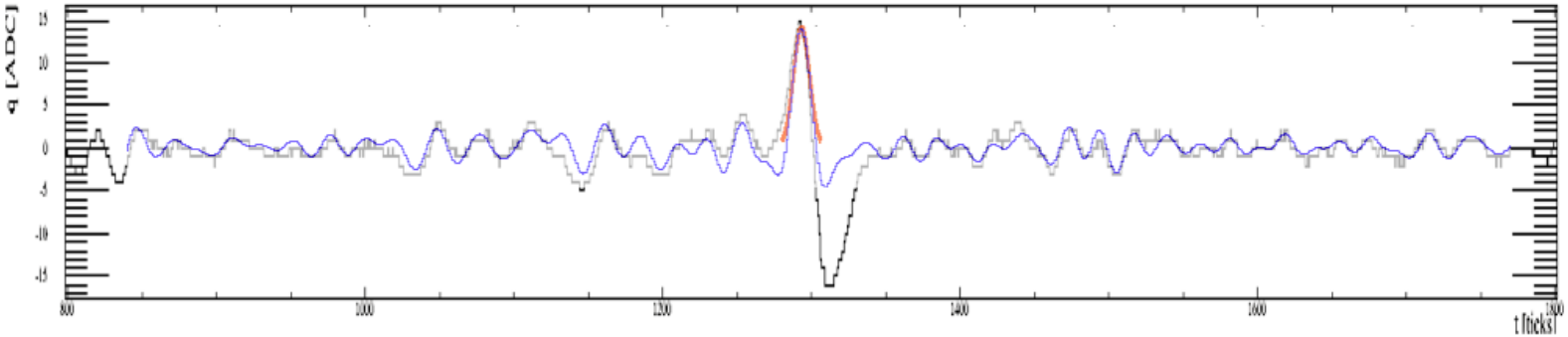
- "Warm" JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Currrent trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)





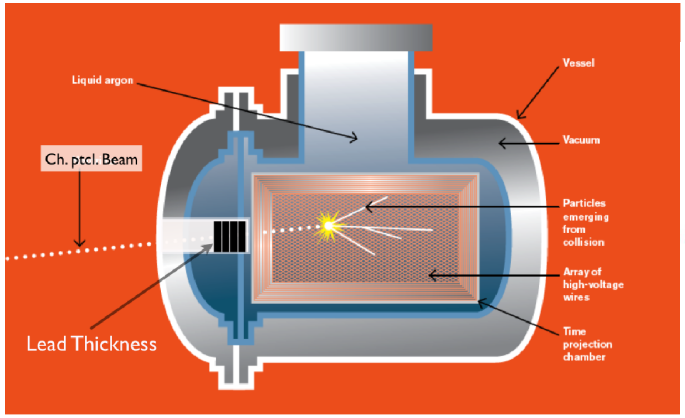


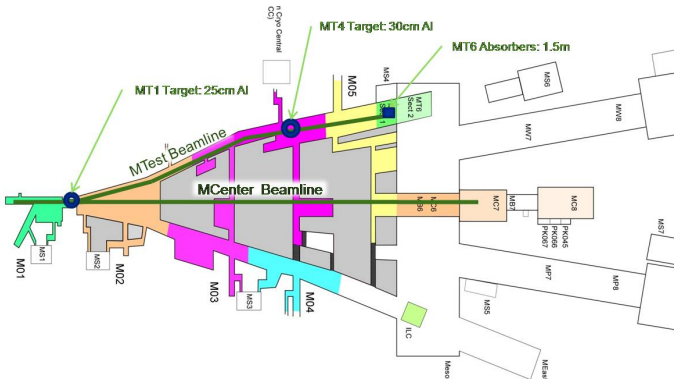
PreAmp stage - FET Voltage Gain	0.5 mV/fC
Digitizer Module (ADF-2)	
ADC range	10 bit
ADC Gain	0.1881 ADC/mV
Sampling Time (FPGA)	δt=198 ns (0.03cm)
Electronics Charge Sensitivity	7.49 ADC/fC
Tot. Capacitance (Det. and Cables)	230 pF
Response to mip (Coll. wires)	$S/N \geq 15$



LArIAT phase 1

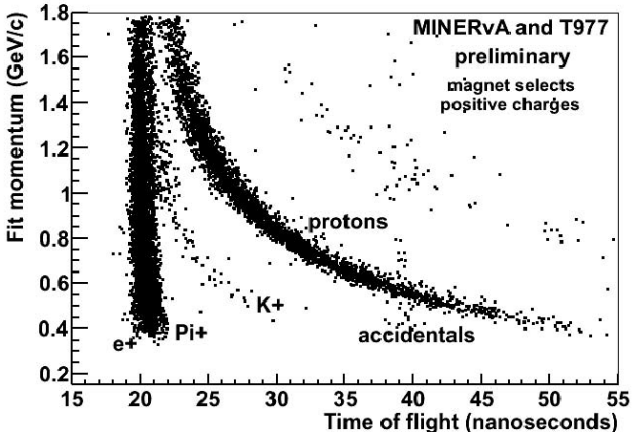
- The ArgoNeuT detector will be resurrected as LArIAT (Liquid Argon in a Testbeam) phase 1.
- The objective calibration of single tracks and collective topologies
- Characterization of response at a range of energies relevant for future experiments (MicroBooNE, LBNE, etc.)
- Known input particle type and energy → calibrated output response
- Done at Fermilab Test Beam Facility



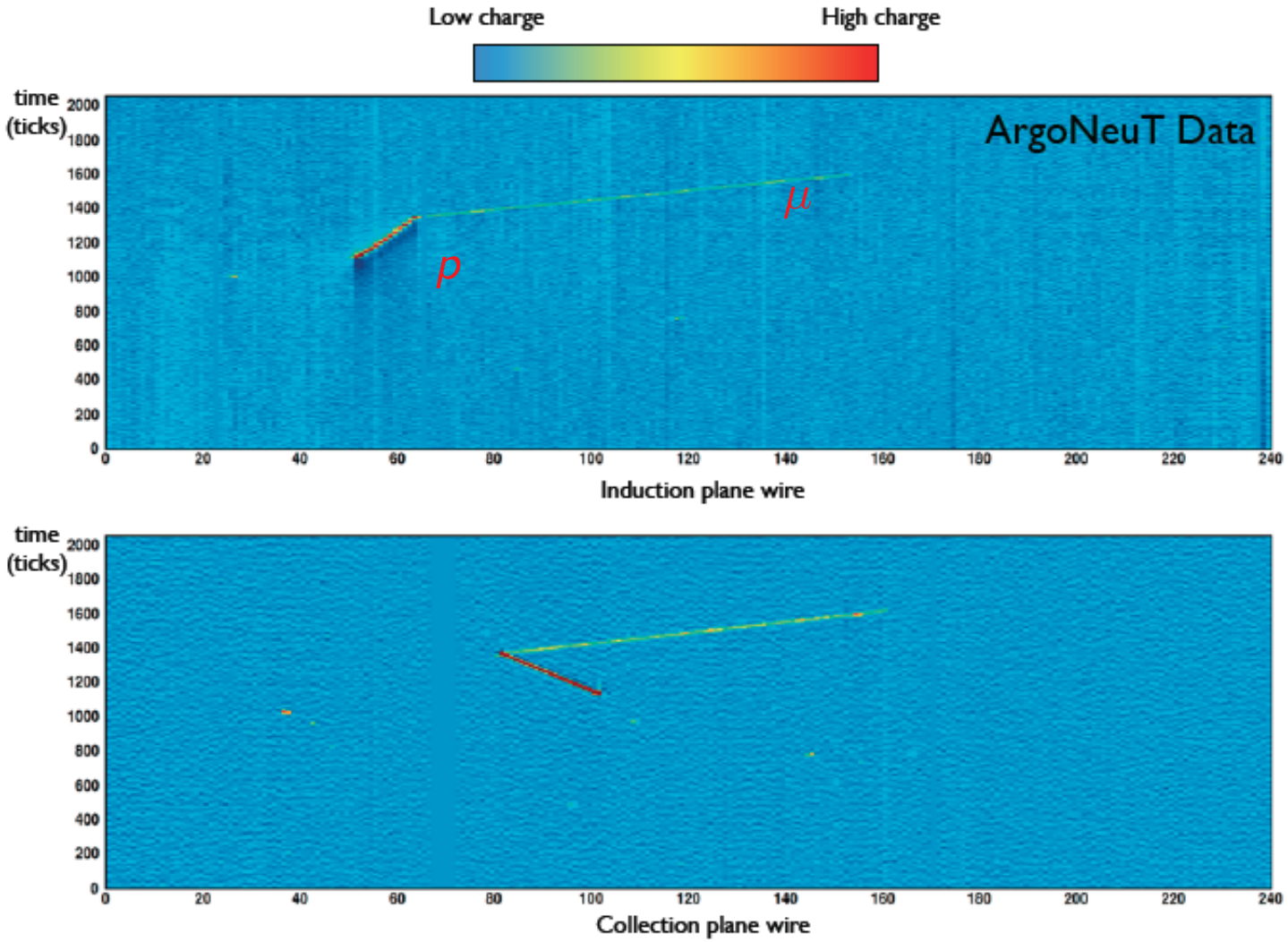


LArIAT phase 1

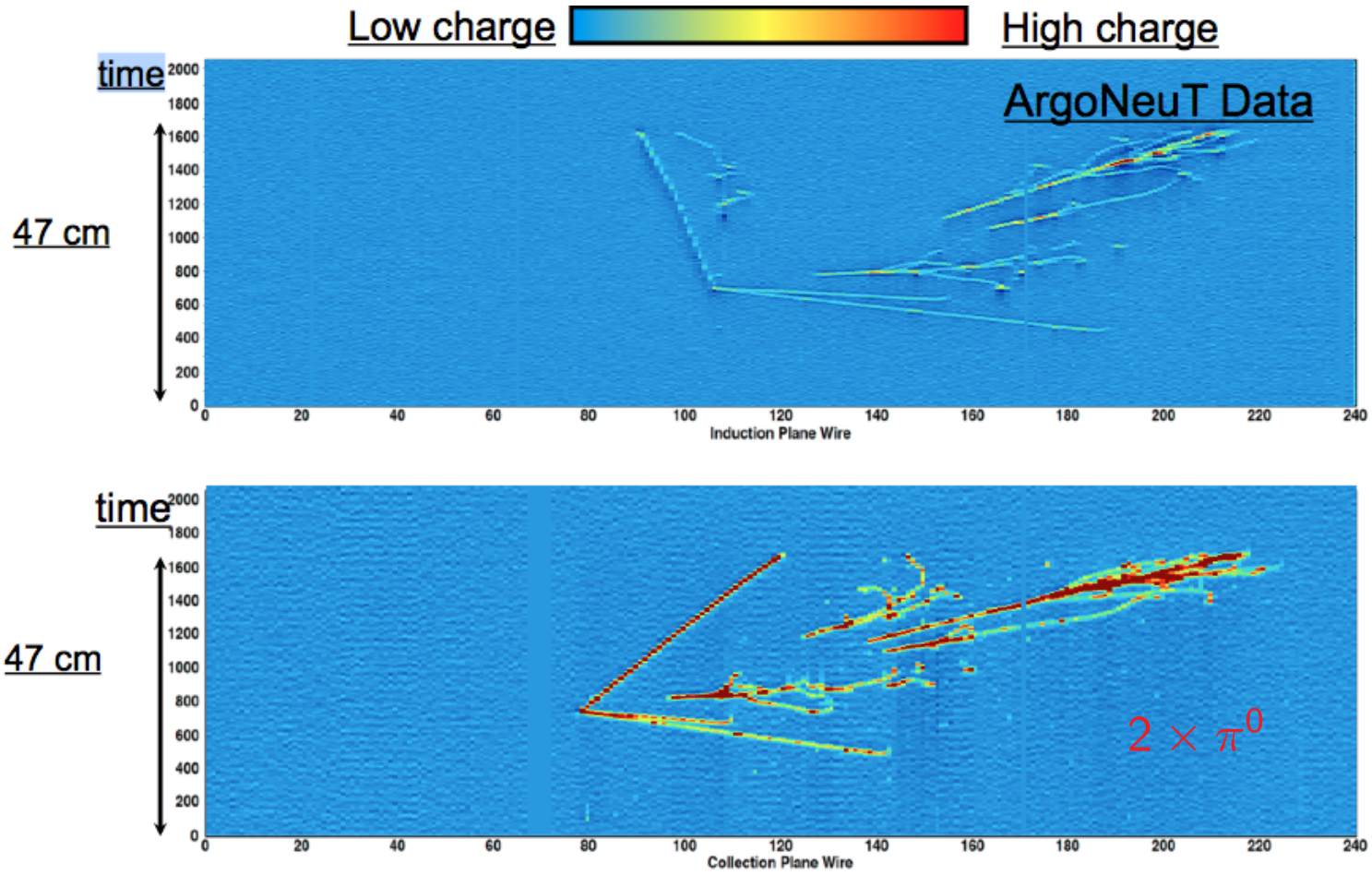
- Use Tertiary (low momentum) Beam developed by MINERVA collaboration.
- Provides protons, pions, electrons and muons.
- Modifications to the ArgoNeuT detector include a light readout system, recircuclation in liquid and front flange.
- Planned start of data taking - spring 2013.
- A larger TPC, geared towards hadronic shower containment is planned to follow as LArIAT phase 2.



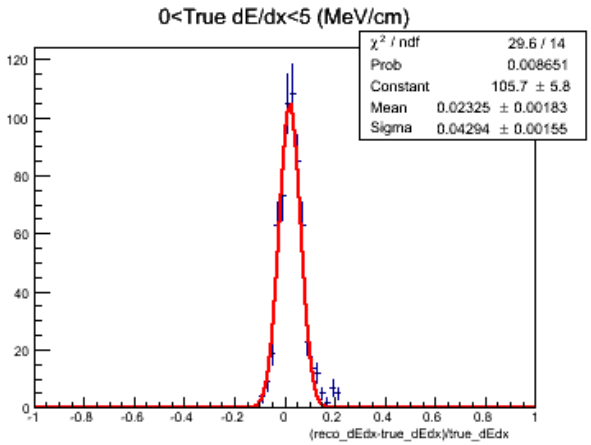
ArgoNeuT Events (1)

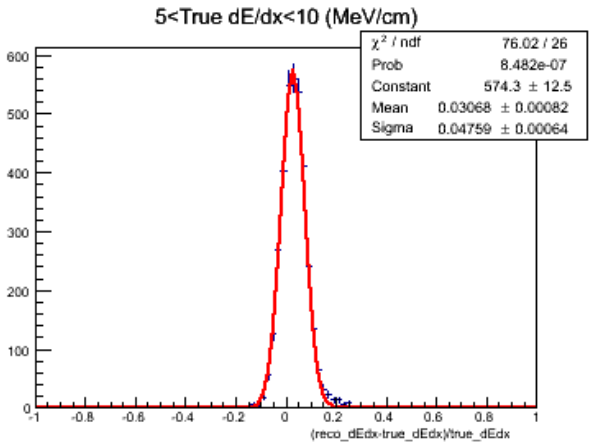


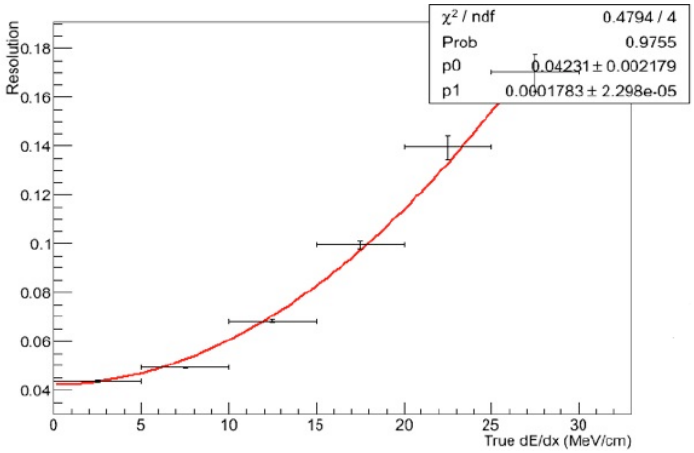
ArgoNeuT Events (2)



Energy resolution





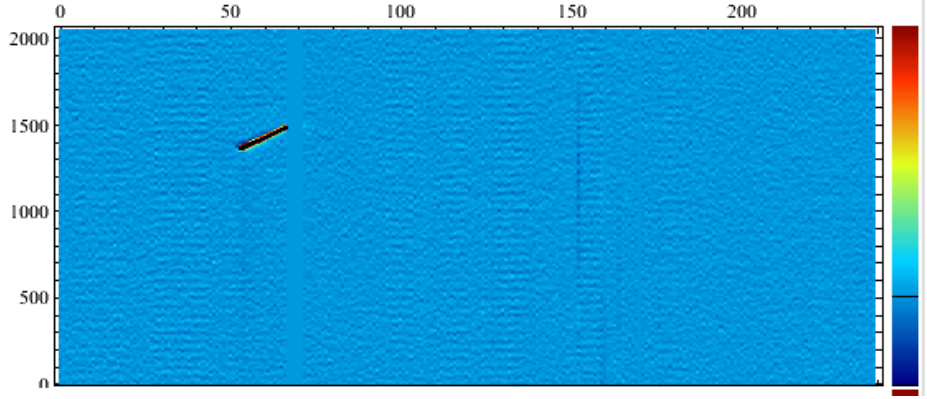


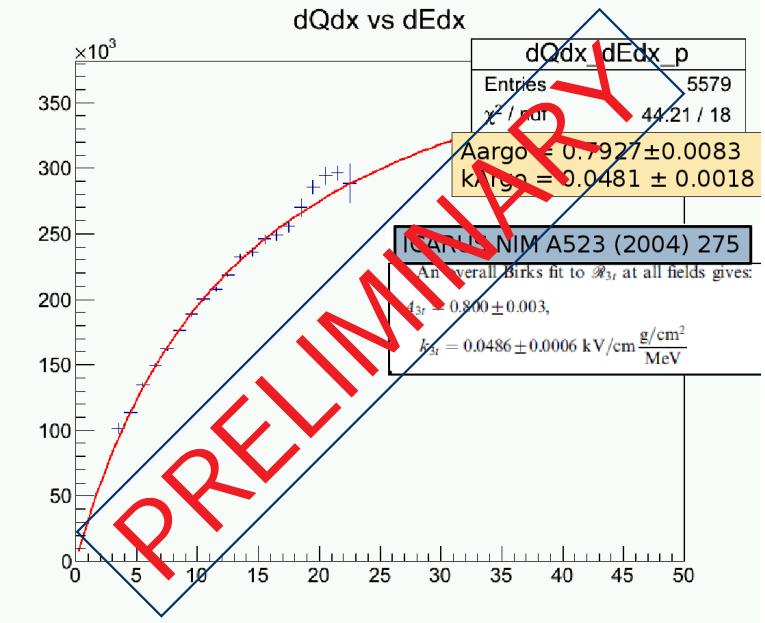
- Energy resolution $\simeq$5% for Minimum Ionizing Particles
- $\delta \frac{dE}{dx} = 0.042 + 1.78 \times 10^{-4} \frac{dE}{dx}^2$

Stopping Protons

- Electrons resulting from an energy deposition has a chance to reattach to the positive ions
- This effect depends on dE/dx and is nonlinear.
- Measurements in LAr are not very precise, especially at high dE/dx.
- ArgoNeuT observes many stopping proton events, mainly from background interactions.

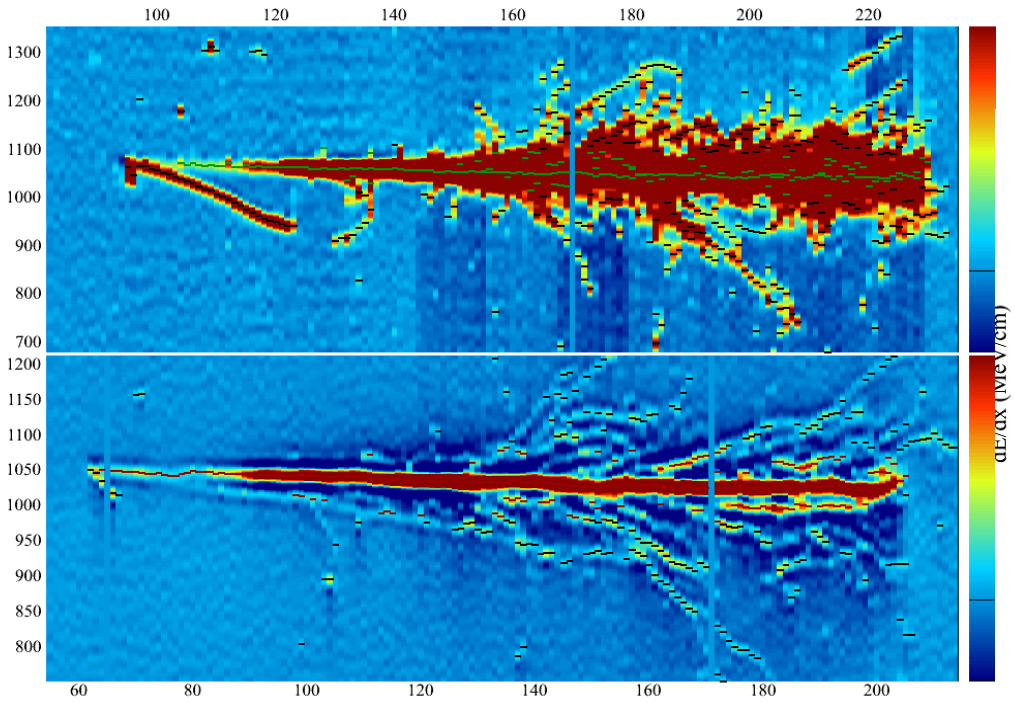
$$\frac{dE}{dx} = \frac{\frac{dQ}{dx}}{\frac{A}{W_{ion}} - \frac{K}{E_{field}}\frac{1}{\rho}\frac{dQ}{dx}}$$

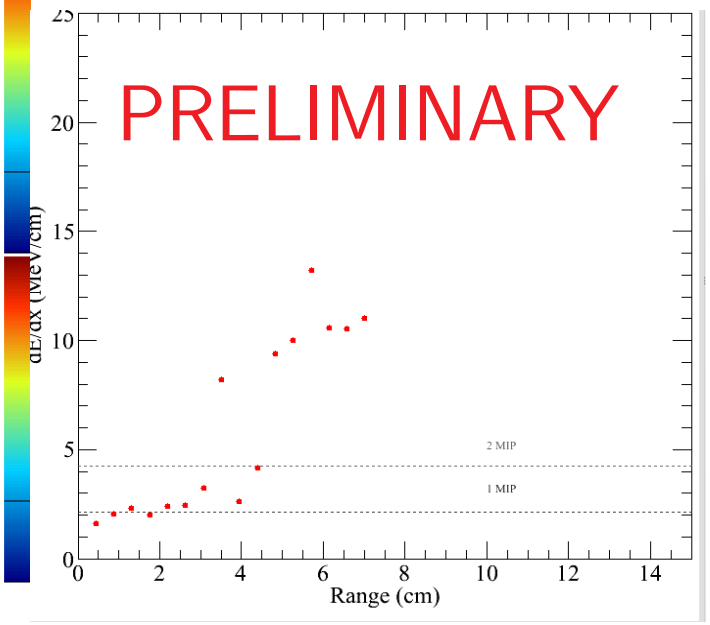




dE/dx e/γ ID (1)

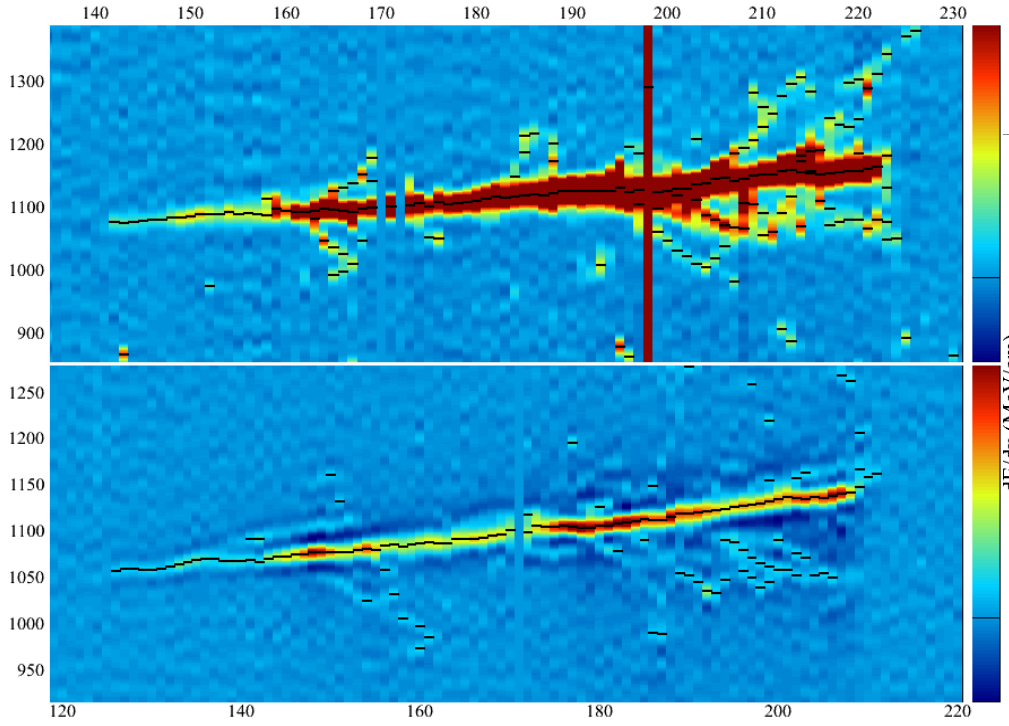
- 3D axis Showers calculated based on the angles ofthe 2D projections.
- Correction for Birk's recombination factor $f(dE/dx)$ and lifetime applied

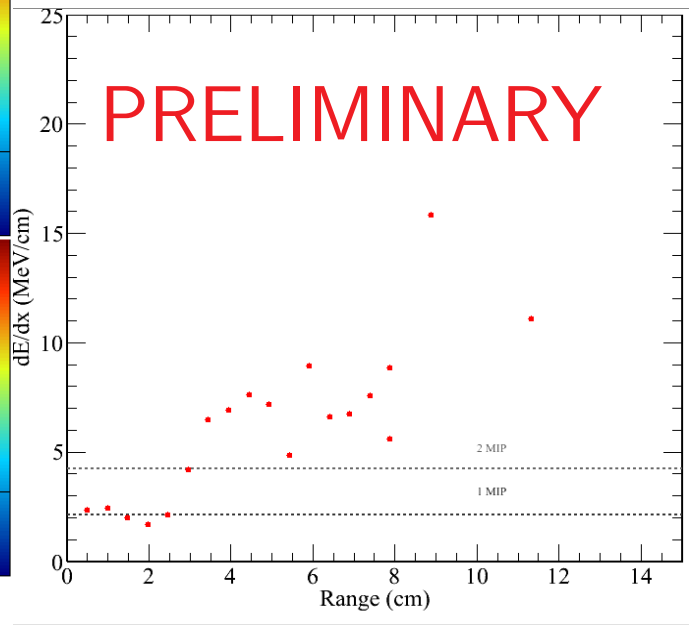




ν_e CC candidate.

dE/dx e/γ ID (2)

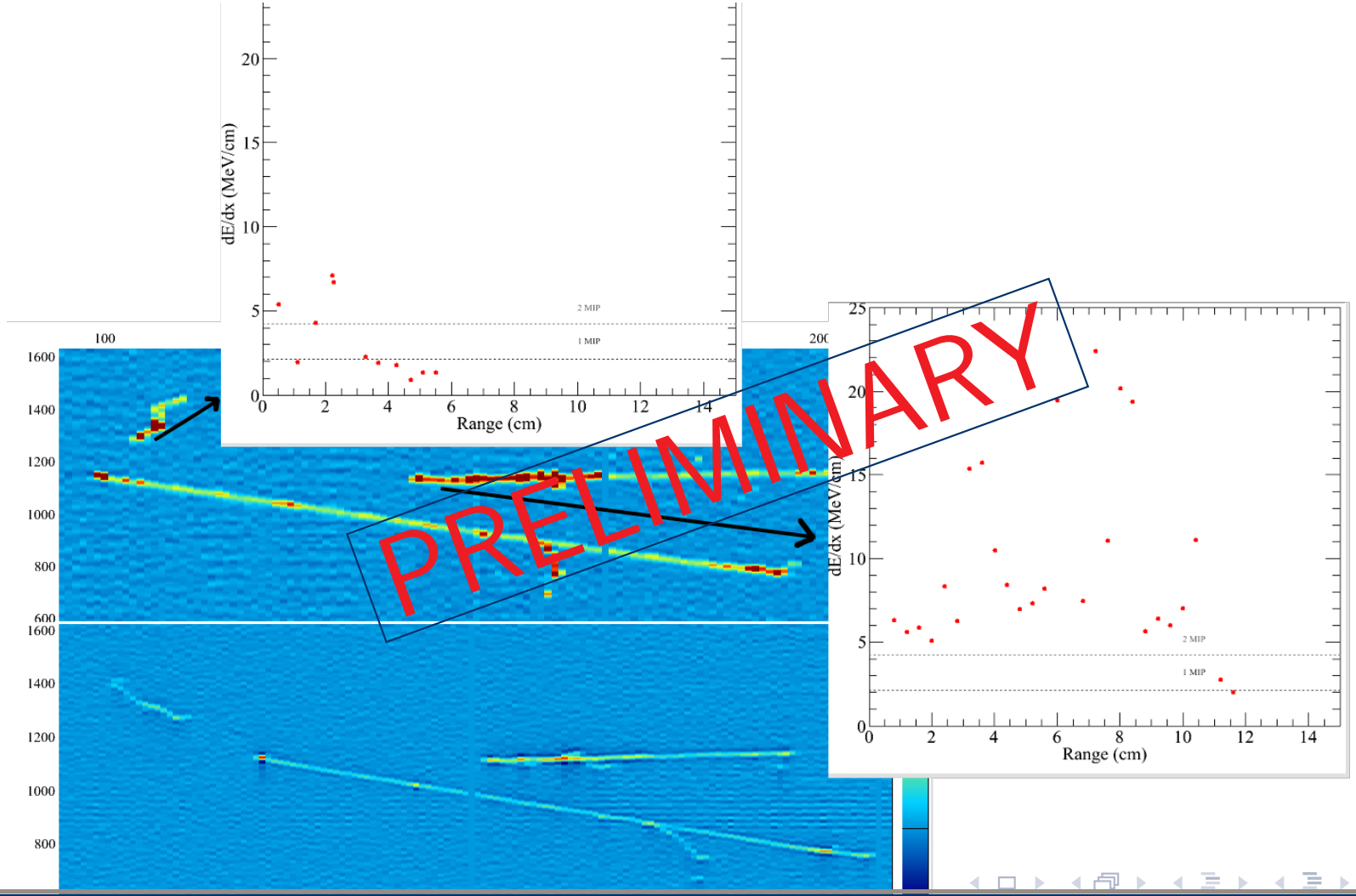




ν_e CC candidate

dE/dx e/γ ID (3)

ν_μ CC + π^0 candidate

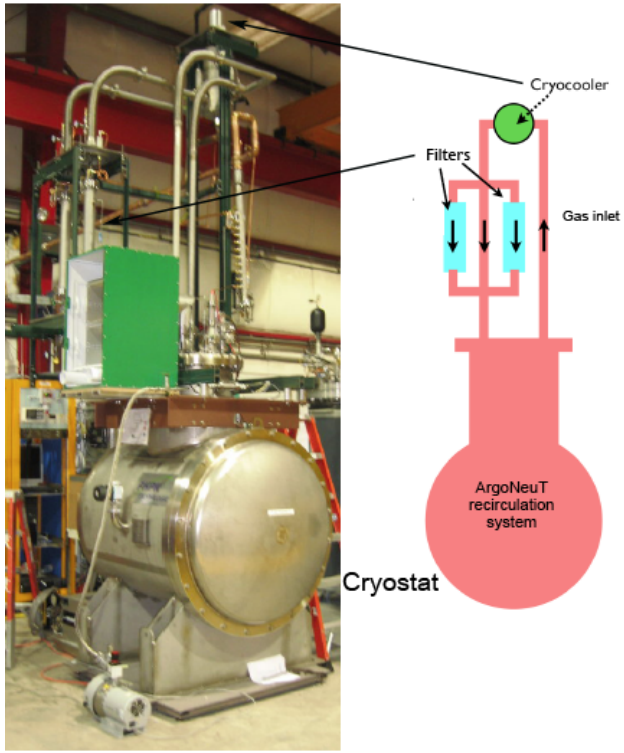


Noble liquids for ν detection

- Abundant ionization electrons and scintillation light can both be used for detection.
- Noble liquids are dense, so they make a good target for neutrinos.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.

	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
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150	175	

Cryogenics + Recirculation System

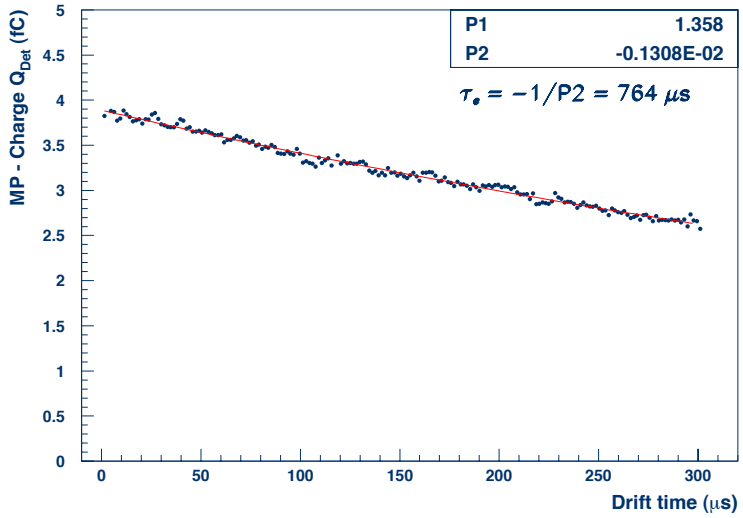


LAr volume (mass)	550 liters (0.77 t)
Insulation	Vacuum Jacket (10^{-4} mbar) with SuperInsulation
Total Heat Load	$\approx$ 120 W
Cooling	CryoCooler (330 W cool. capacity)
Ar Recondensation	LAr Flow Rate: $\approx$ 3 lt/hr
P, T (set point)	GAr P=2 psig, LAr T=88.4 K

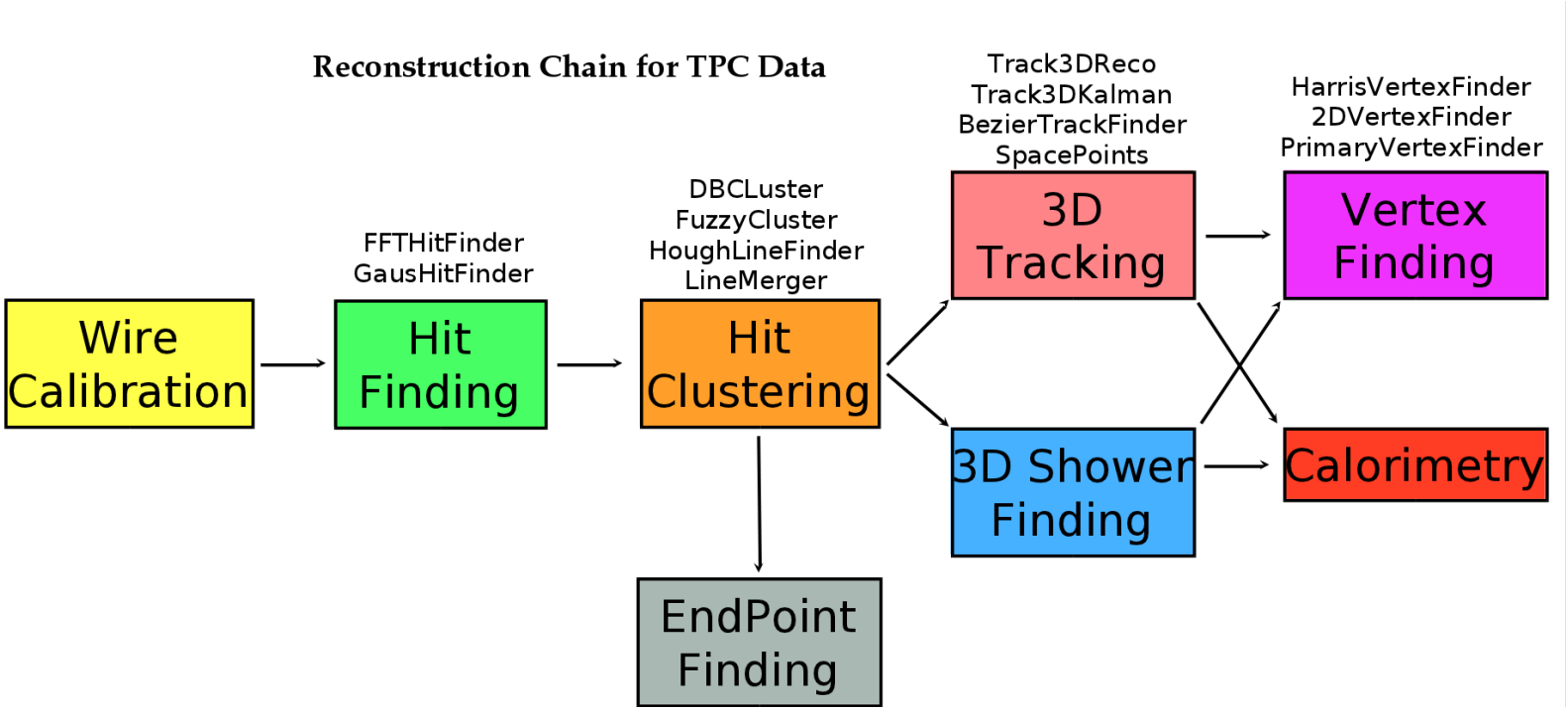
- Cooling with 330W CryoCooler
- Electronegative impurities, like O_2 and H_2O attach drifting electrons weakening the signal on the wires.
- Their quantity in argon can be diminished by pushing the argon through filters.
- Used regenerated filters developed at Fermilab $\rightarrow$

  Nucl.Instrum.Meth.A605:306-311,2009
- Obtained sufficient purity ($\simeq$700 μs) using gas recirculation (330 μs drift).

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.

LArSOFT structure

- LArSOFT is a software package developed for LArTPCs
- Detector agnostic
- Constructed from separate modules - highly configurable