The ArgoNeuT Experiment

ArgoNeuT

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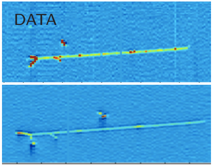
(on behalf of S. Farooq, KSU)
for the ArgoNeuT Collaboration

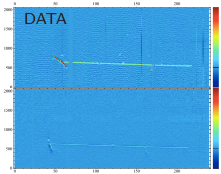
Yale University

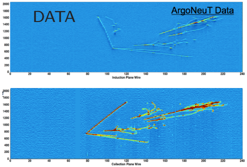
DPF2013, Santa Cruz

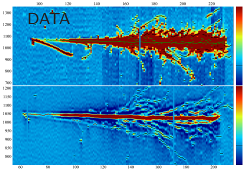
Liquid argon for ν detection

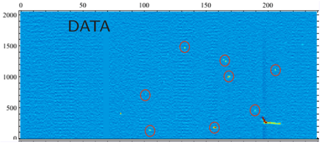
- Abundant ionization electrons and scintillation light can both be used for detection.
- Reasonably dense (1.4 g/cm^3) - a good target for neutrinos.
- Relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.
- Most importantly it gives us great opportunity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





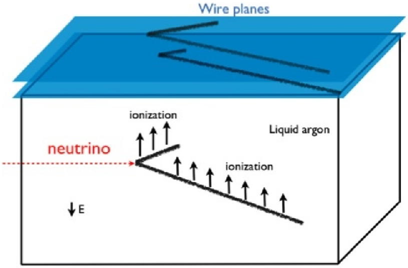


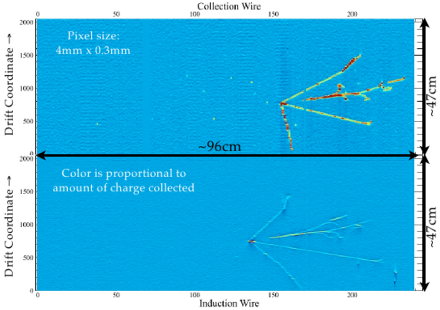




LArTPC Concept

- 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.

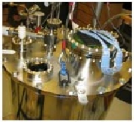




ArgoNeuT Data Event

LArTPC Program in the US

Yale TPC



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

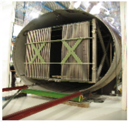
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

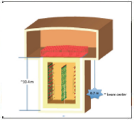
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



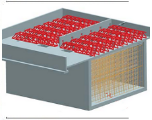
Location Fermilab
Active volume: 0.1 kton
Operational: 2014

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

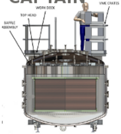
LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2011

LArIAT

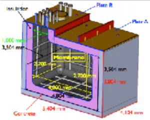
Location: Fermilab
Purpose: LArTPC calibration
Operational: 2014 (phase 1)

CAPTAIN



Location: LANL
Purpose: LArTPC calibration
Operational: 2014

LBNE 35 Ton

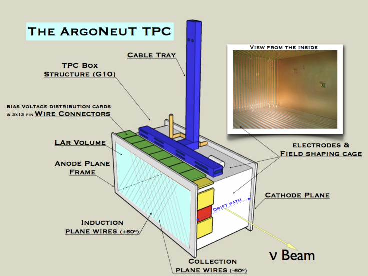


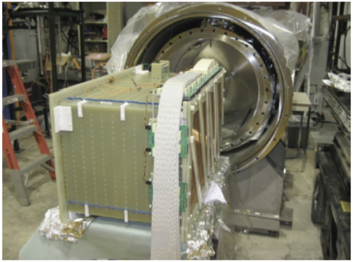
Location: Fermilab
Purpose: purity demo
Operational: 2013

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

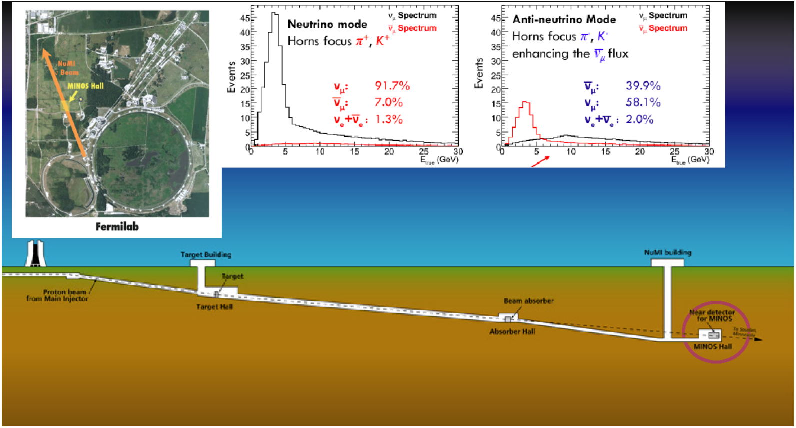




Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

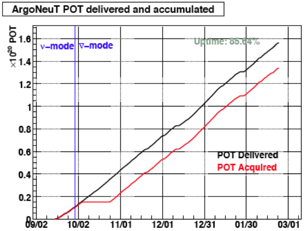
- Two wire planes instrumented (3 present)
- E-field between planes optimized to maximize transparency
- Wire spacing at 4mm.

NuMI Beam


Neutrino mode
Horns focus π^+, K^+
ν_μ Spectrum
$\bar{\nu}_\mu$ Spectrum
ν_μ: 91.7%
$\bar{\nu}_\mu$: 7.0%
$\nu_e+\bar{\nu}_e$: 1.3%
Events
E_{true} (GeV)
Anti-neutrino Mode
Horns focus π^-, K^-
enhancing the $\bar{\nu}_\mu$ flux
$\bar{\nu}_\mu$: 39.9%
ν_μ: 58.1%
$\nu_e+\bar{\nu}_e$: 2.0%
NuMI Beam
MINOS Hall
Fermilab
Target Building
Target
Proton beam from Main Injector
Target Hall
Beam absorber
Absorber Hall
NuMI building
Near detector for MINOS
MINOS Hall

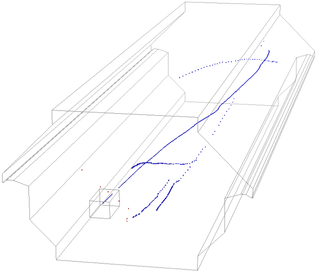
ArgoNeuT in the MINOS hall

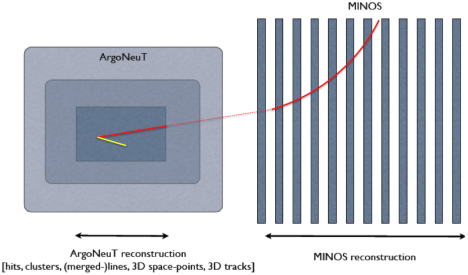
- Remote,shiftless operation for 5 months.
- Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode.
- Expect $\sim$o(10k) CC events in ν_μ and $\bar{\nu}_\mu$



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).





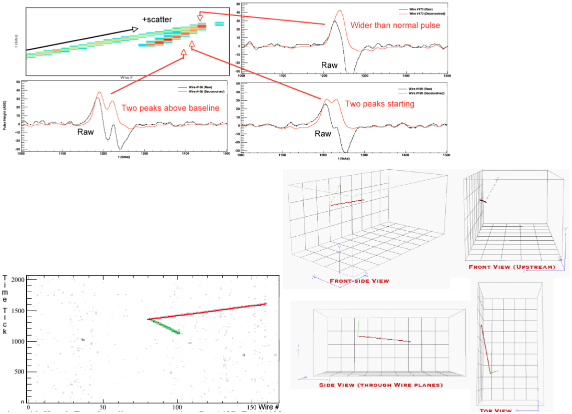
We gratefully acknowledge the help of the MINOS collaboration in these analyses.

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!

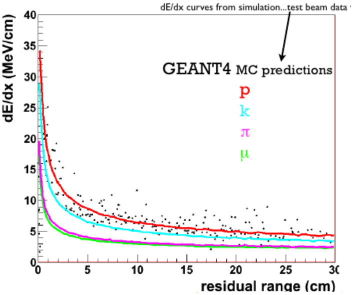
The Reconstruction Process

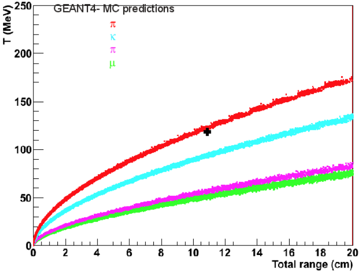
- 1st stage - Hits (FFtHitFinder, GaussHitFinder)
- 2nd stage - Clustering (DBCluster, FuzzyCluster,...)
- 3rd stage - Combine into 3D tracks (KalmanTracker, BezierTracker,...)



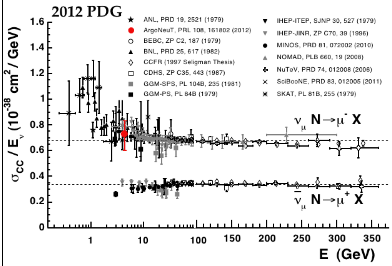
Calorimetry and PID

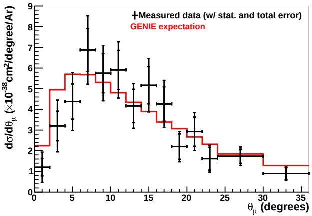
- Once we have the 3D track, we reconstruct the dE/dx
- This allows for Particle ID via total kinetic energy and residual range methods.

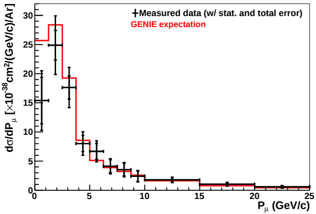




Measurement of the ν_μ CC inclusive Cross-section



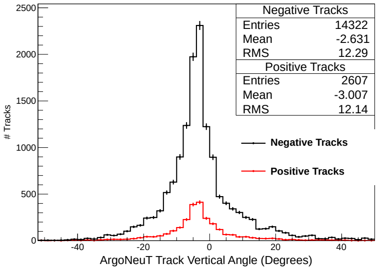


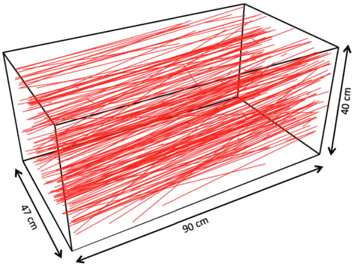


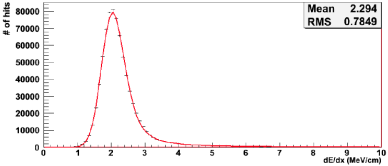
- Used data acquired in neutrino mode (8.5x10^{18}POT)
- C. Anderson et al., PRL 108, 2012
- Simple cuts applied:
  - vtx in fiducial volume
  - track matched to muon in MINOS ND
  - MINOS $q < 0$
- first CC-inclusive cross-section measurements in argon

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,

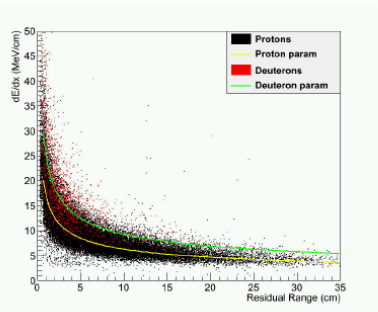


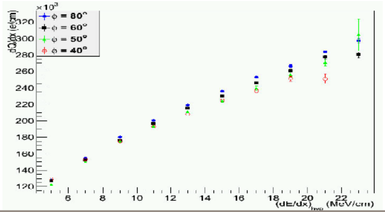




Recombination Study using Stopping Protons

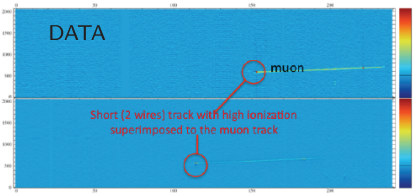
- Studied the recombination of electron-ion pairs produced in liquid argon by stopping protons and deutrons.
- Angular dependence of recombination - the collected charge by 5% - 10% at small angle (wrt to Electric Field) and high ionization.
- Significantly less than the 25% loss predicted by the Jaffe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

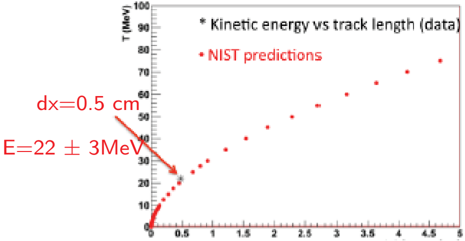




Studies of Nuclear Effects

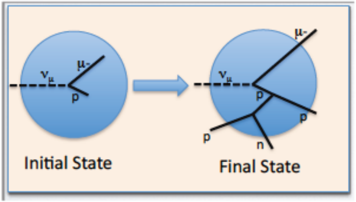
- LAr-TPC detectors can fully reconstruct exclusive topologies.
- Proton multiplicity and kinematics can be measured with a very low proton energy threshold (21 MeV).
- This will ultimately allow the reconstruction of the incoming neutrino energy from lepton AND proton kinematics.
- And it already allows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

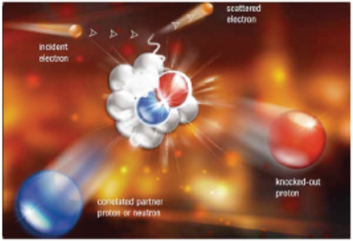




Studies of Nuclear Effects (2)

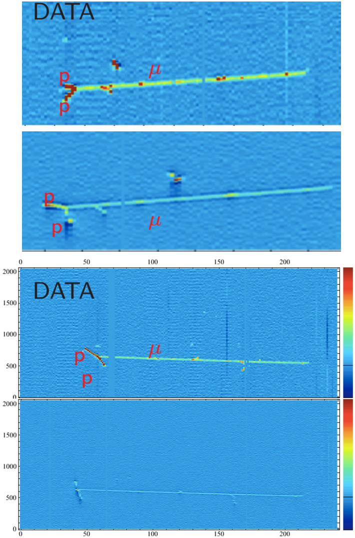
- Nuclear effects play a key role in neutrino-nucleus interactions in nuclear targets.
- Due to intra-nuclear re-scattering (FSI) Final State interactions and possible effects of correlation between target nucleons, a genuine QE interaction can often be accompanied by the ejection of additional nucleons, 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.



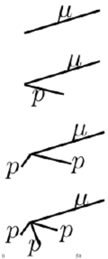


Studies of Nuclear Effects (3)

- 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^o
  L1=5.1 cm, p1=395±4 MeV/c
- p2: θ_2=116^o
  L2=5.4 cm, p2=401±24 MeV/c
- Angle between two protons γ=183^o



μ + N protons analysis

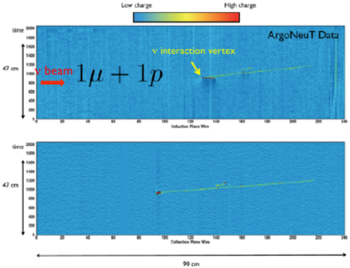


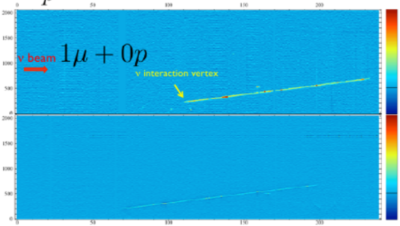
$1\mu + 0p$

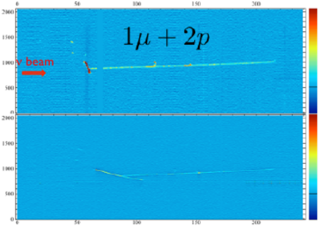
$1\mu + 1p$

$1\mu + 2p$

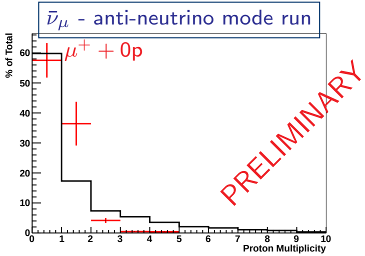
$1\mu + 3p$

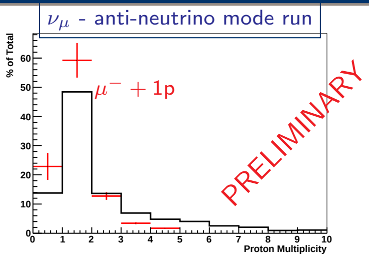


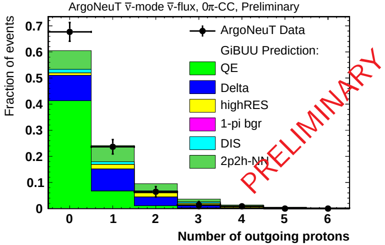




μ + N protons analysis (2)





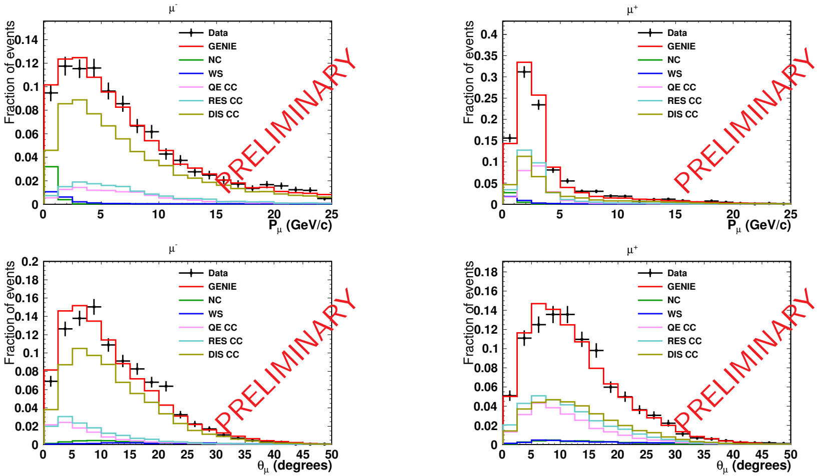


Default Fluka flux used.
Tuning in progress.

- 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.**

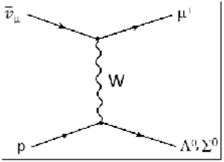


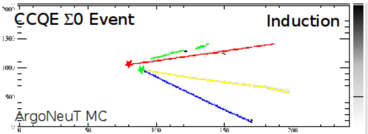
CCQE Neutral Hyperon Analysis

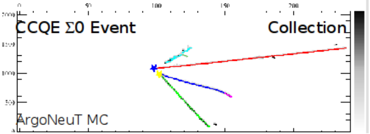
NUANCE Event Generator and GEANT4 are used to Simulate the CCQE Hyperon Events in the Detector

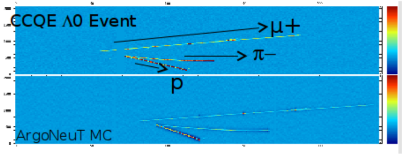
Cuts:

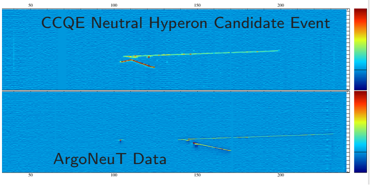
- Vertex in fiducial volume.
- Track match with positive muon track in MINOS.
- Use vertexing to detect a detached vertex.





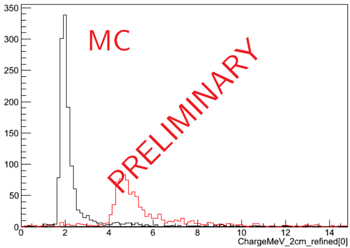


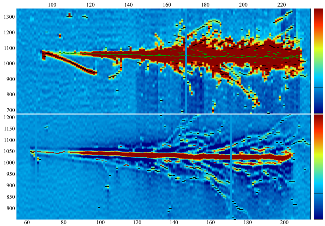




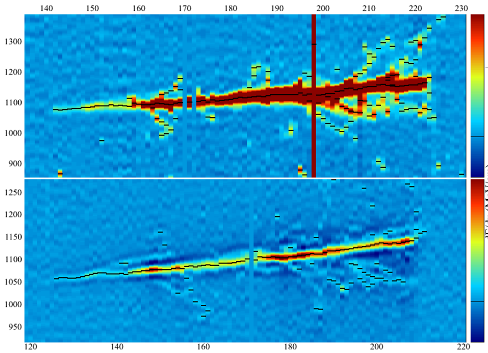
dE/dx e/γ ID

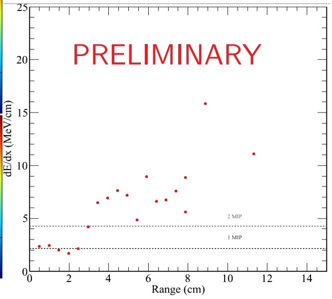
- Separating electrons from γs is important in precision ν measurements
- e.g. understanding whether the MiniBooNE anomaly is an effect of oscillation or background
- LongBaseline measurements e.g. CP violation etc.
- the dE/dx of a shower can be a powerful discrimination tool: an electron is a Minimum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





dE/dx e/γ ID (2)

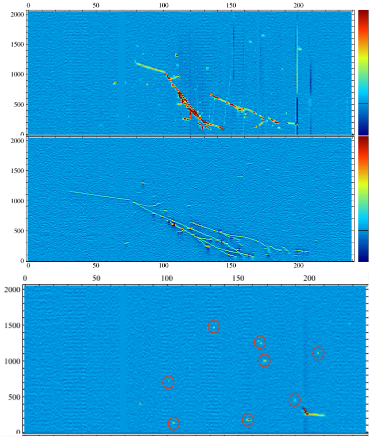




ν_e CC candidate

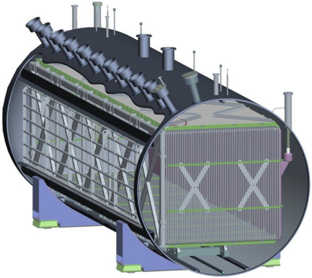
Other Ongoing Analyses

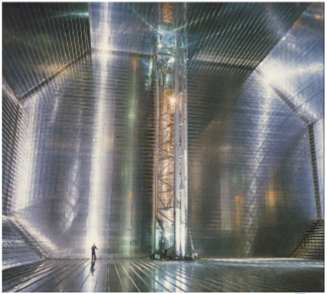
- NC π^0 cs
- Nuclear de-excitation gammas.
- Coherent pion production
- μ + nprotons + npions



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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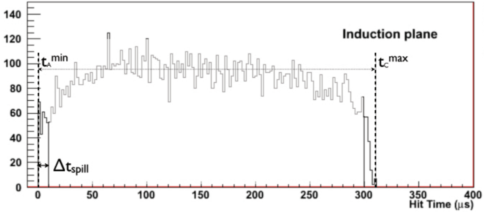
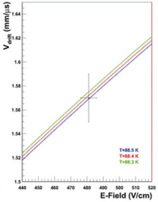
Back Up Slides

Measurement of electron drift speed

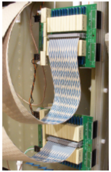
- Measurement of electron drift velocity confirms understanding of detector.
- Difference of maximum and minimum hit drift gives time.
- Distance is size of detector
- Corrected for different field strengths between planes.

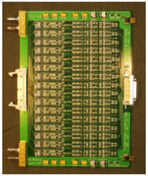


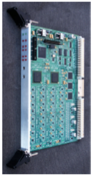


ArgoNeuT Electronics

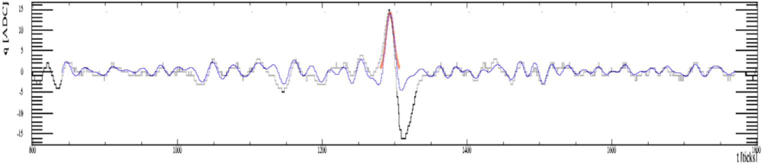
- "Warm" JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Currrent trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)





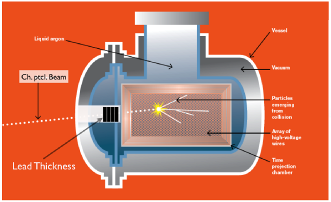


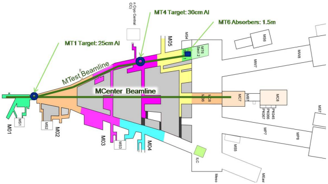
PreAmp stage - FET Voltage Gain	0.5 mV/fC
Digitizer Module (ADF-2)	
ADC range	10 bit
ADC Gain	0.1881 ADC/mV
Sampling Time (FPGA)	δt=198 ns (0.03cm)
Electronics Charge Sensitivity	7.49 ADC/fC
Tot. Capacitance (Det. and Cables)	230 pF
Response to mip (Coll. wires)	$S/N \geq 15$



LArIAT phase 1

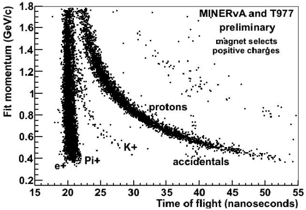
- The ArgoNeuT detector will be resurrected as LArIAT (Liquid Argon in a Testbeam) phase 1.
- The objective calibration of single tracks and collective topologies
- Characterization of response at a range of energies relevant for future experiments (MicroBooNE, LBNE, etc.)
- Known input particle type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



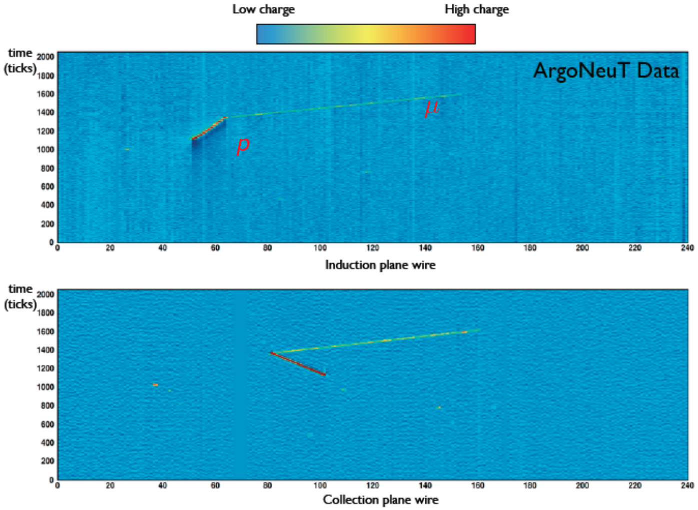


LArIAT phase 1

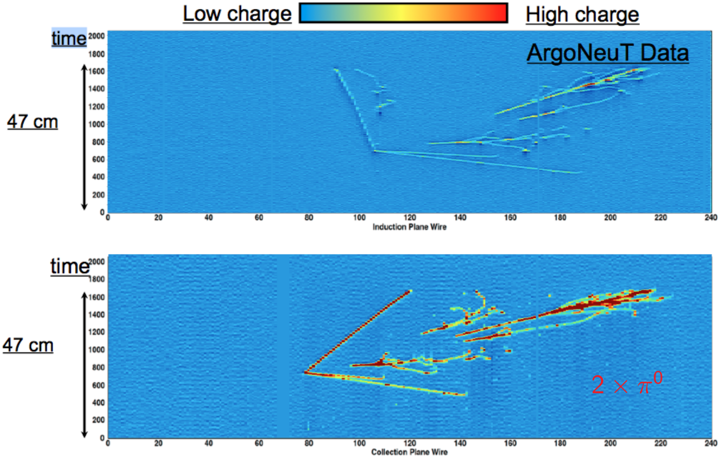
- Use Tertiary (low momentum) Beam developed by MINERVA collaboration.
- Provides protons, pions, electrons and muons.
- Modifications to the ArgoNeuT detector include a light readout system, recircuclation in liquid and front flange.
- Planned start of data taking - spring 2013.
- A larger TPC, geared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



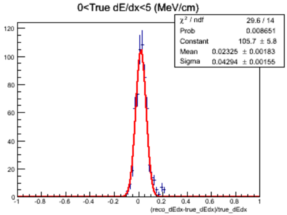
ArgoNeuT Events (1)

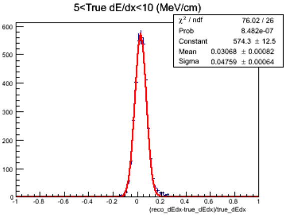


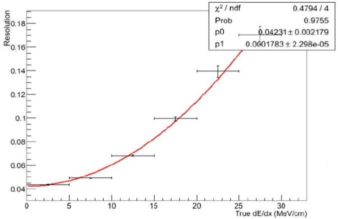
ArgoNeuT Events (2)



Energy resolution





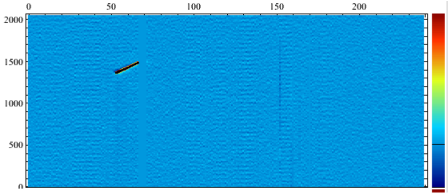


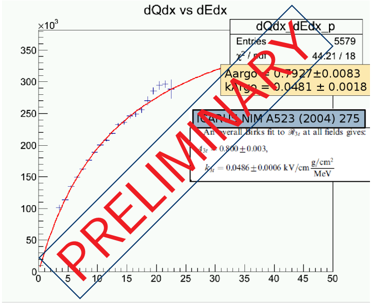
- Energy resolution ≃5% for Minimum Ionizing Particles
- $\delta \frac{dE}{dx} = 0.042 + 1.78 \times 10^{-4} \frac{dE}{dx}^2$

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.

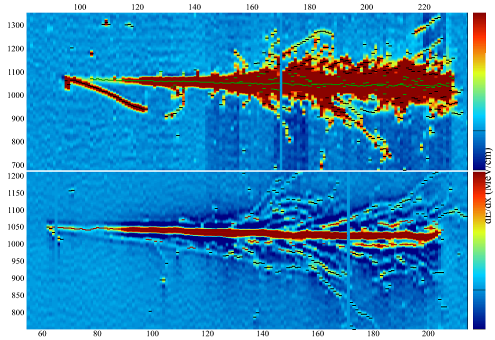
$$\frac{dE}{dx} = \frac{\frac{dQ}{dx}}{\frac{A}{W_{ion}} - \frac{K}{E_{field}}\frac{1}{\rho}\frac{dQ}{dx}}$$

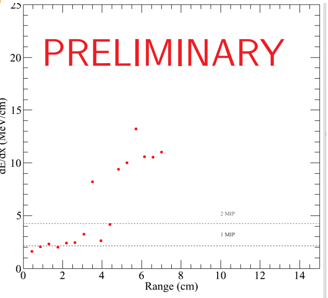




dE/dx e/γ ID (1)

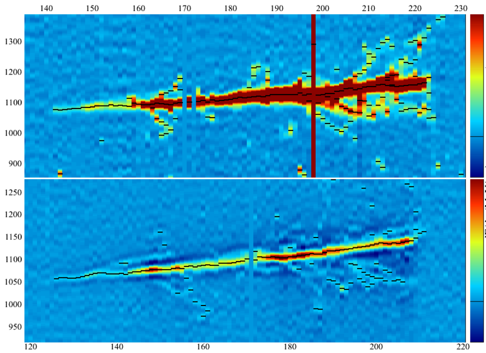
- 3D axis Showers calculated based on the angles ofthe 2D projections.
- Correction for Birk's recombination factor $f(dE/dx)$ and lifetime applied

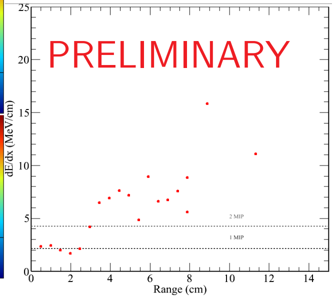




ν_e CC candidate.

dE/dx e/γ ID (2)

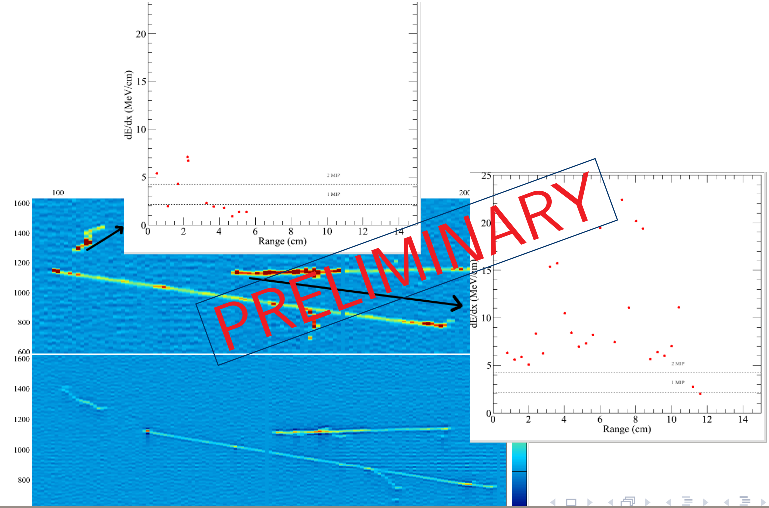




ν_e CC candidate

dE/dx e/γ ID (3)

ν_μ CC + π^0 candidate

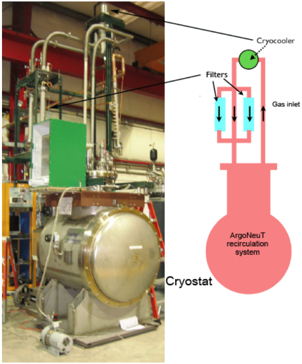


Noble liquids for ν detection

- 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

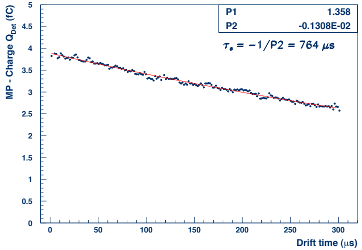


LAr volume (mass)	550 liters (0.77 t)
Insulation	Vacuum Jacket (10^{-4} mbar) with SuperInsulation
Total Heat Load	$\approx$ 120 W
Cooling	CryoCooler (330 W cool. capacity)
Ar Recondensation	LAr Flow Rate: $\approx$ 3 lt/hr
P, T (set point)	GAr P=2 psig, LAr T=88.4 K

- 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