The ArgoNeuT Experiment

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for the ArgoNeuT Collaboration

Yale University

NuINT 2012, Rio de Janeiro

Outline

1. Introduction
   - The LArTPC
2. The ArgoNeuT Detector
3. ArgoNeuT@NuMI
4. Physics Results and Analyses
   - The LArSOFT Software package
   - On-Going analyses
5. The Future
6. Conclusions

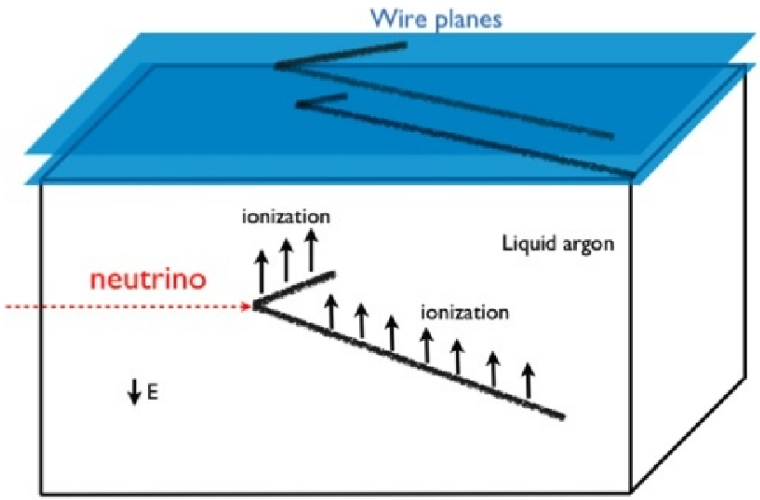
Noble liquids for ν detection

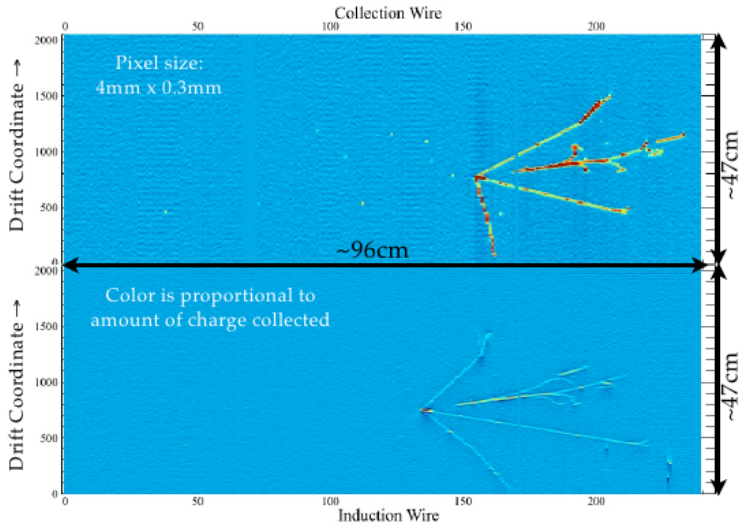
- Abundant ionization electrons and scintillation light can both be used for detection.
- Noble liquids are dense, so they make a good target for neutrinos.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.

	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	

LArTPC Concept

- Pioneered by the ICARUS collaboration
- 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 $\rightarrow$ 3D reconstruction.
- Quantity of charge provides calorimetric reconstruction.

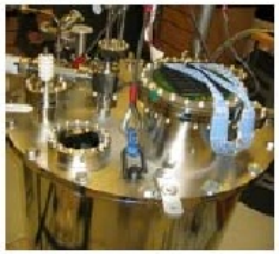




ArgoNeuT Data Event

LArTPC Program in the US

Yale TPC



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

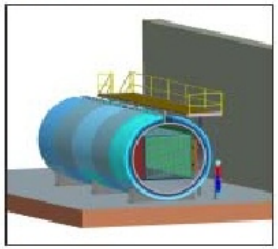
Bo

Location: Fermilab
Active volume: 0.02 ton
operational 2008

ArgoNeuT

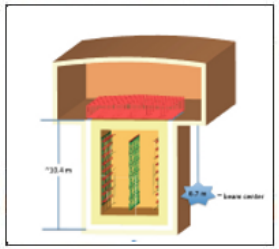
Location: Fermilab
Active volume: 0.3 ton
operational: 2008
First neutrinos: June 2009

MicroBooNE



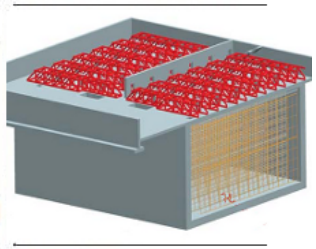
Location Fermilab
Active volume: 0.1 kton
Construction start: 2011

LAr1



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

LBNE



Location: Homestake
Active volume: 10 kton
Construction start 2020

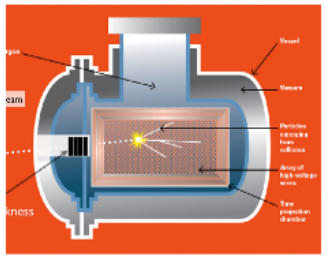
Luke

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)

ArgoNeuT Goals

- First TPC in a beam in the US LAr R&D program
- Measure CC cross-sections on argon in the 1-5 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.

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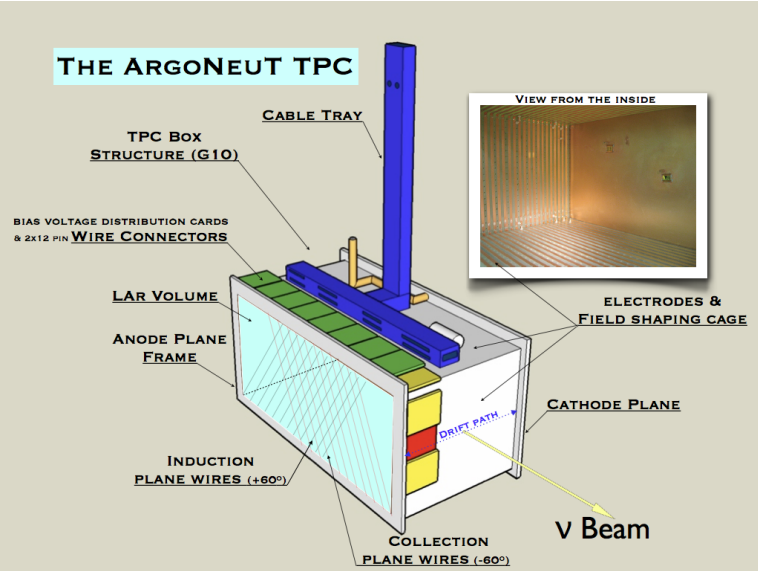
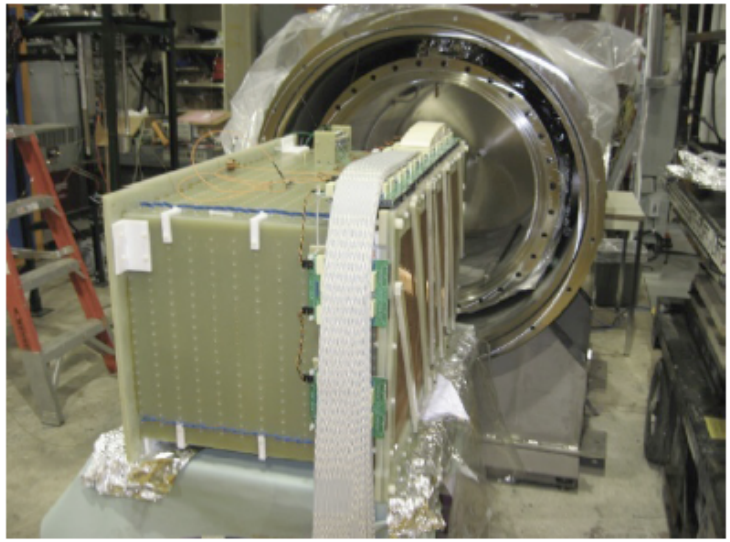
The ArgoNeuT TPC



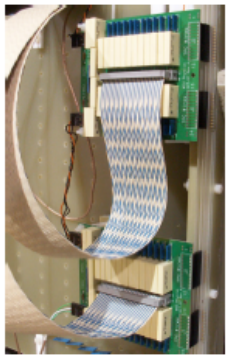
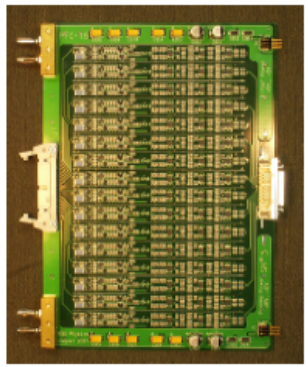
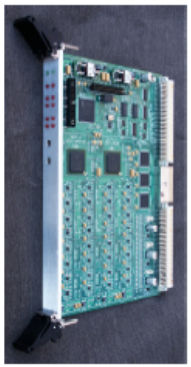


Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

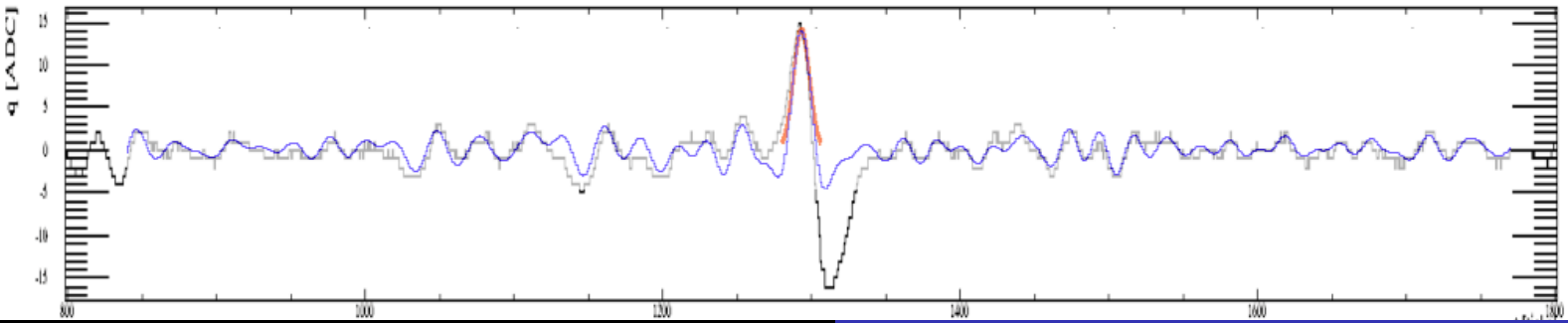
- Two wire planes instrumented (3 present)
- E-field between planes optimized to maximize transparency
- Wire spacing at 4mm. MicroBooNE will use 3mm.

ArgoNeuT Electronics

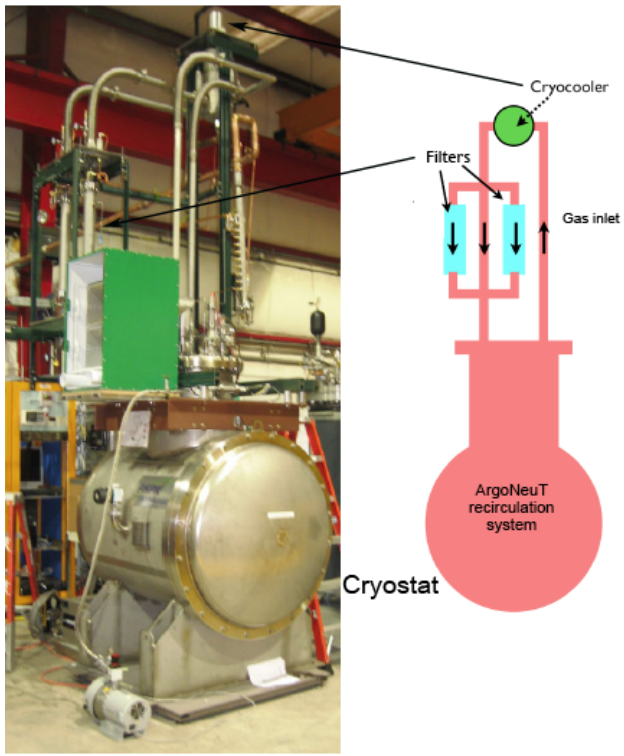
- "Warm" JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Currrent trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)

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)	$S/N \geq 15$



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

- 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. Liquid is faster.

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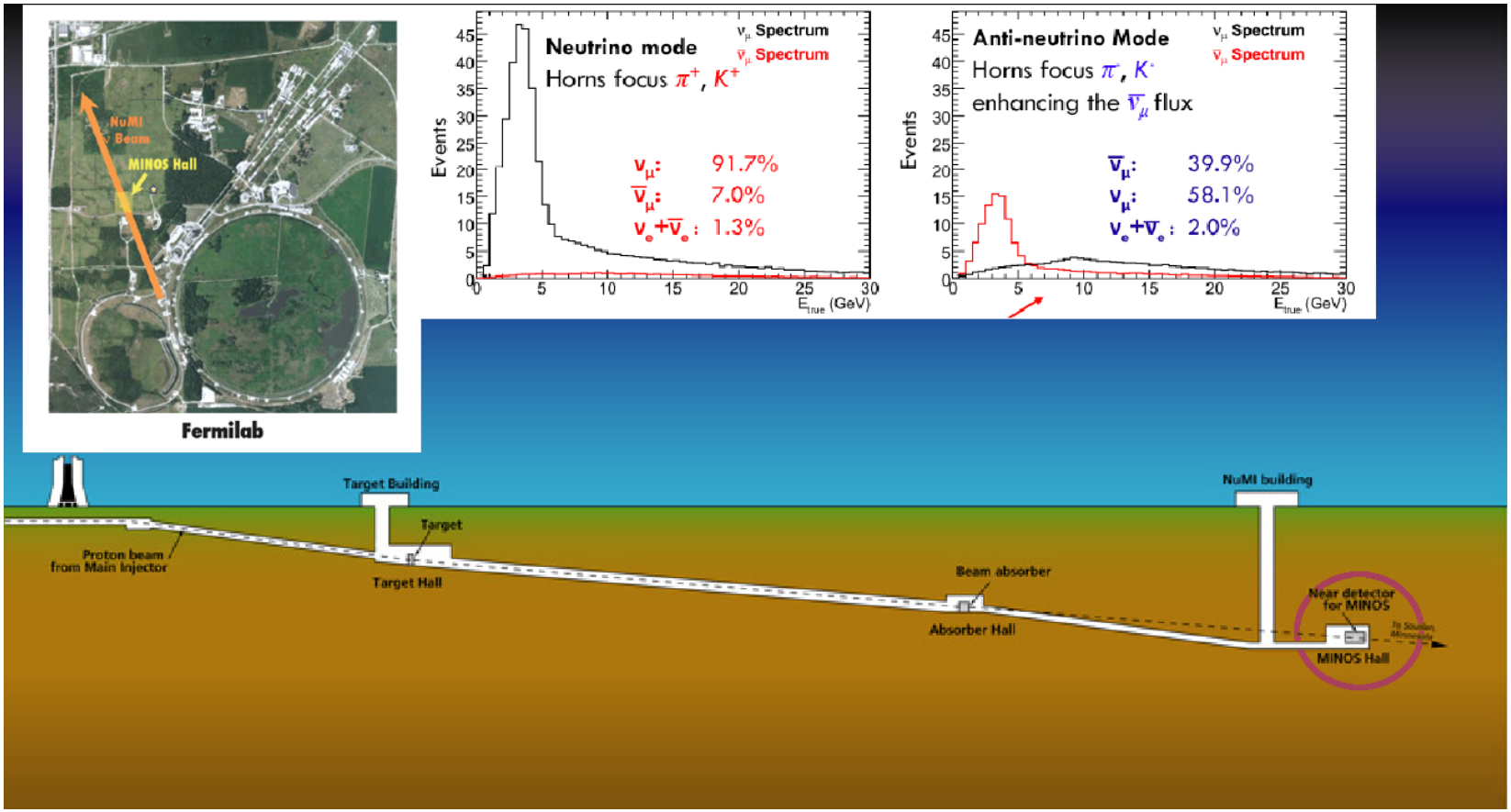
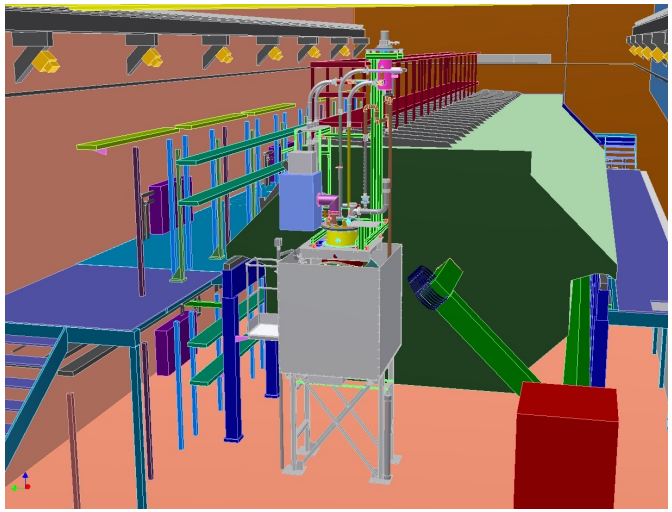
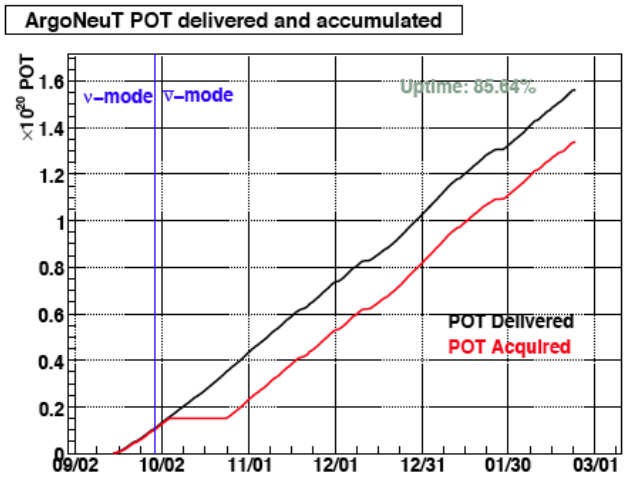
NuMI Beam


NuMI ν Beam
MINOS Hall
Fermilab
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%
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

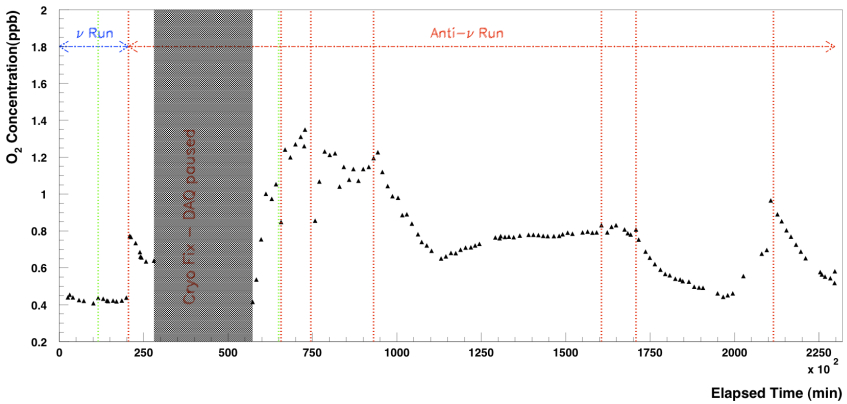


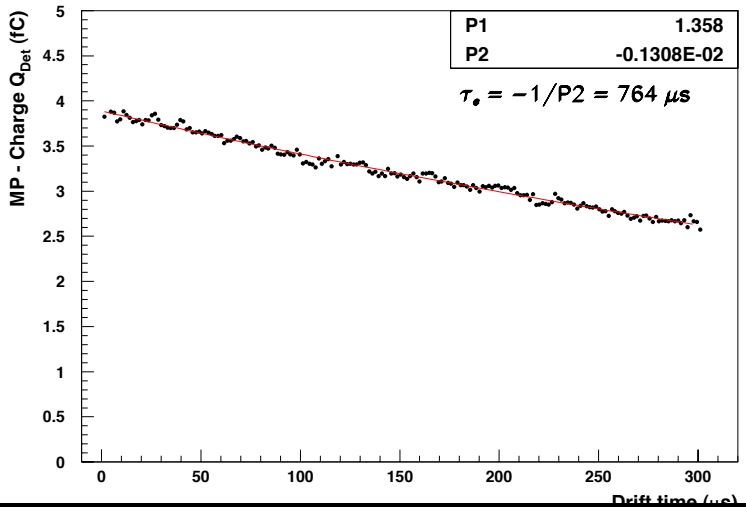


- Remote,shiftless operation for 5 months.
- Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode.

Reaction	#events in AV (~1.35E20 POT)
ν_μ CC	~6600
$\overline{\nu}_\mu$ CC	~4900

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
- Lesson learned: purity is important $\rightarrow$ Material Test Stand and LAPD

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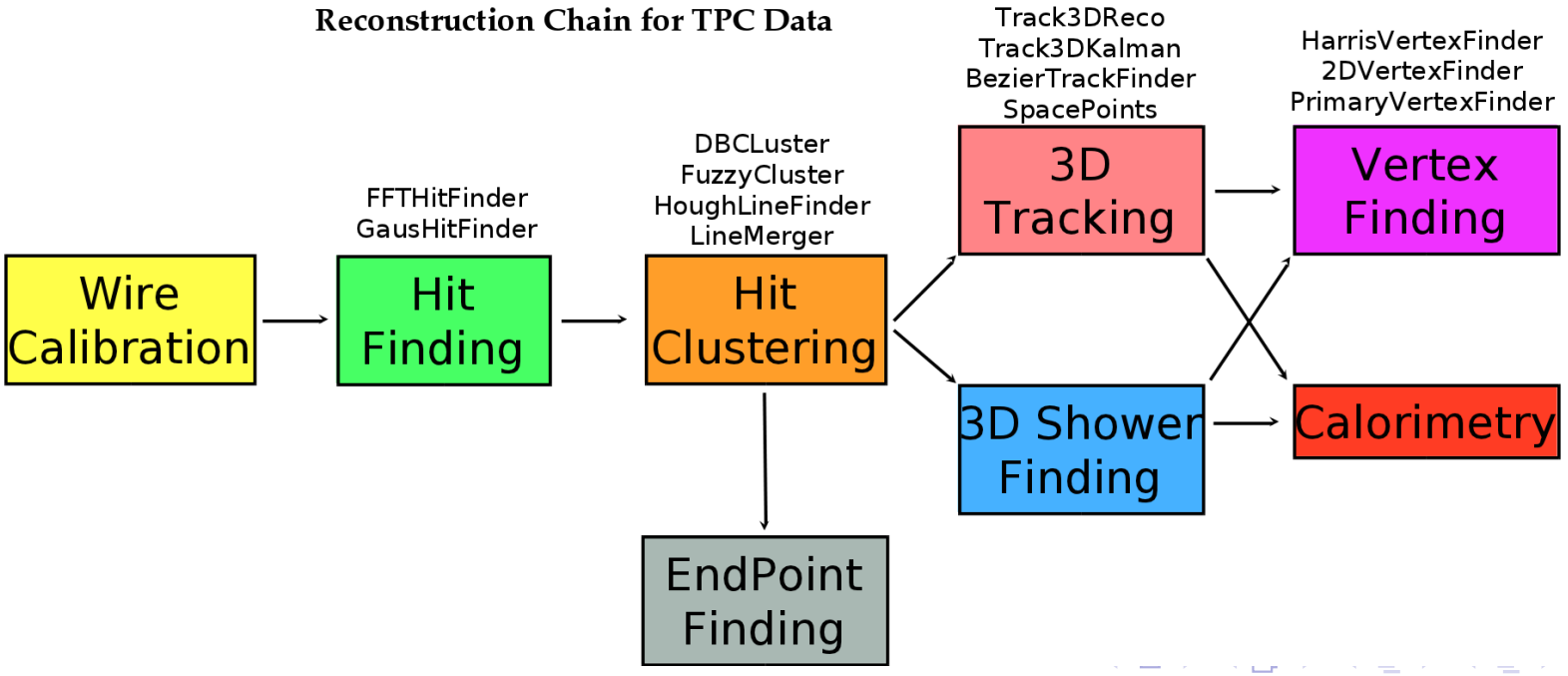
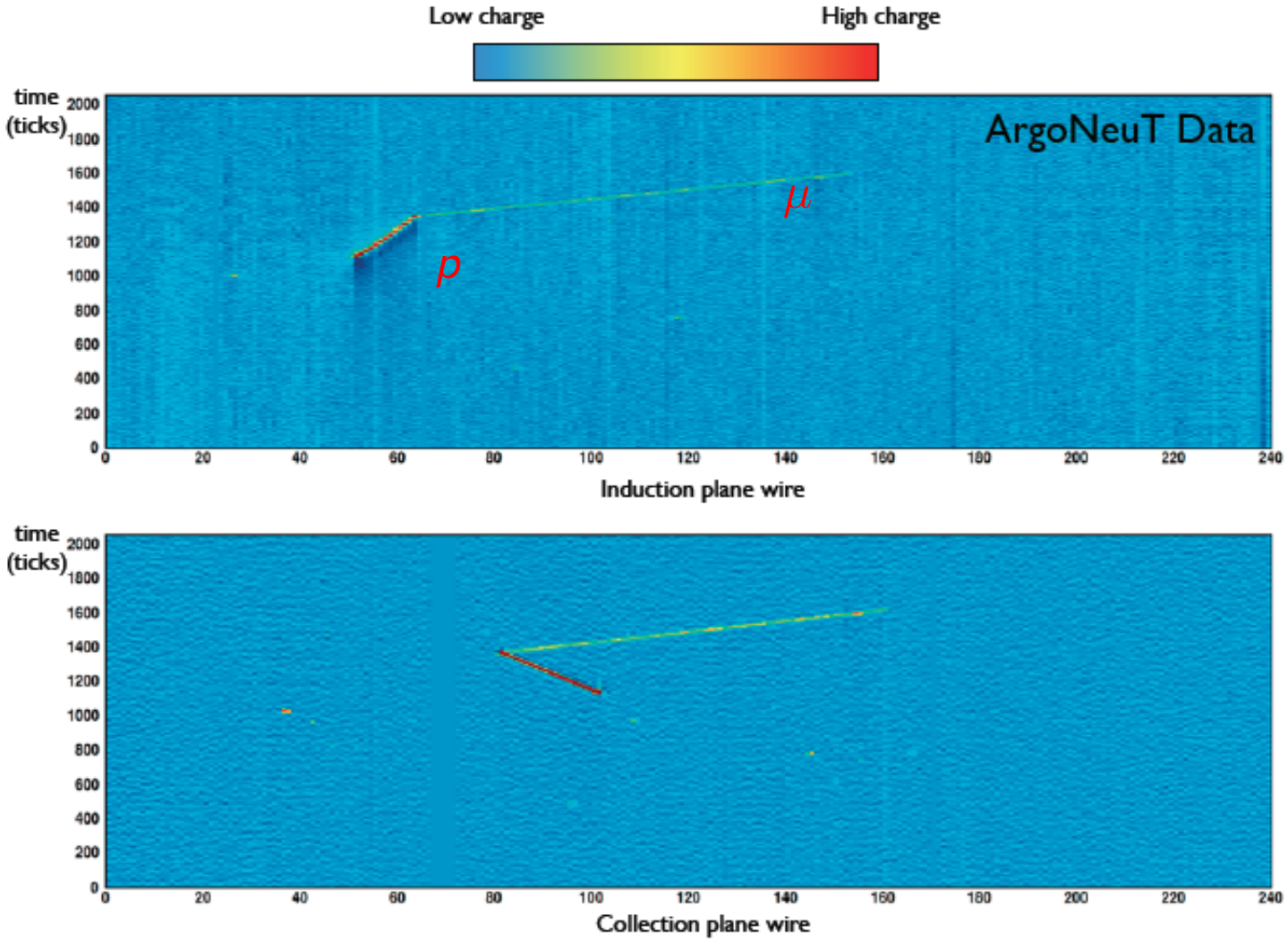
LArSOFT structure

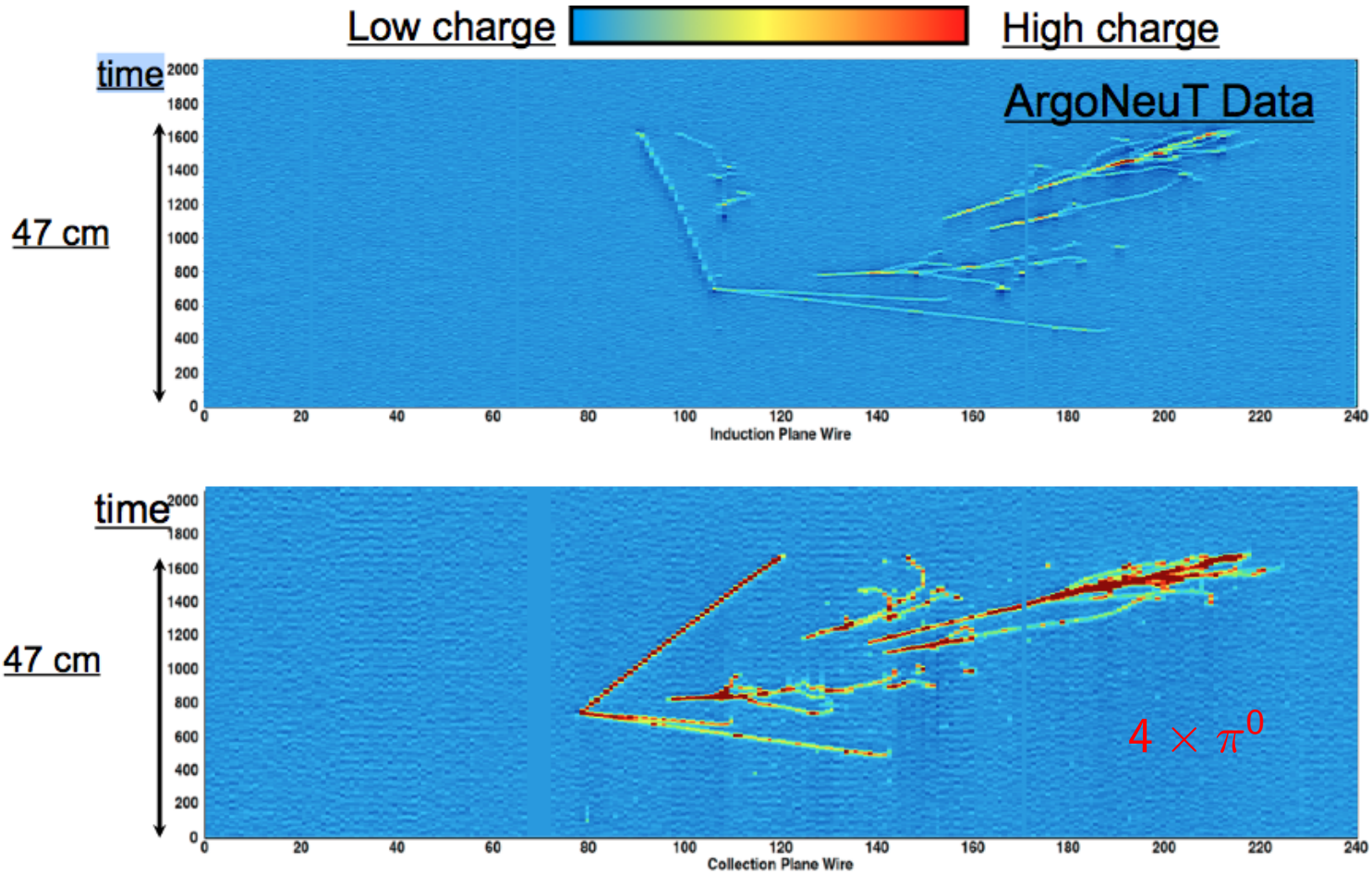
- LArSOFT is a software package developed for LArTPCs
- Detector agnostic
- Constructed from separate modules - highly configurable



ArgoNeuT Events (1)

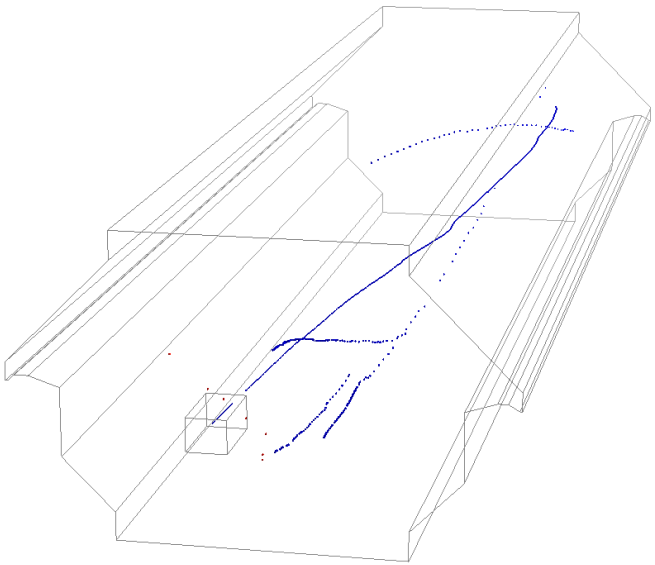


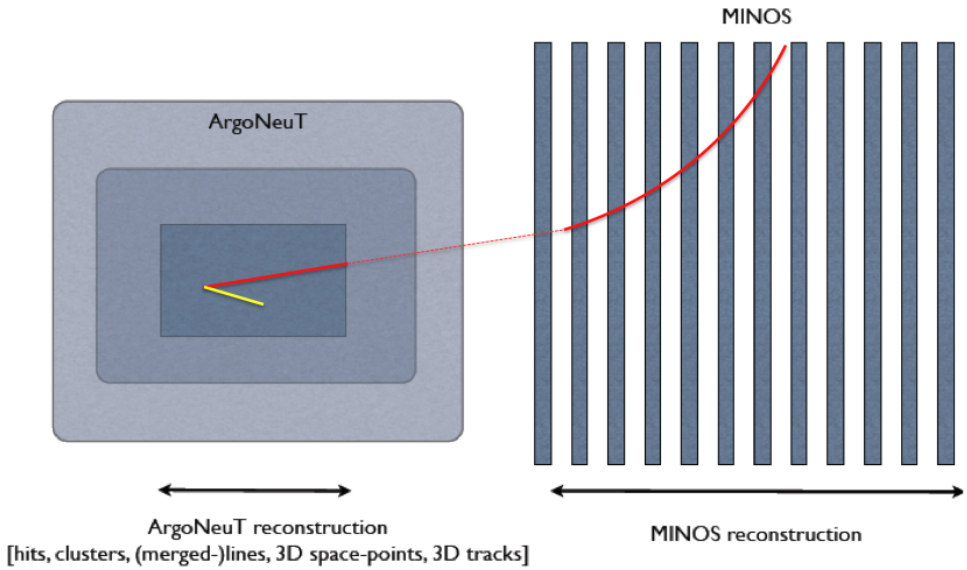
ArgoNeuT Events (2)



MINOS ND

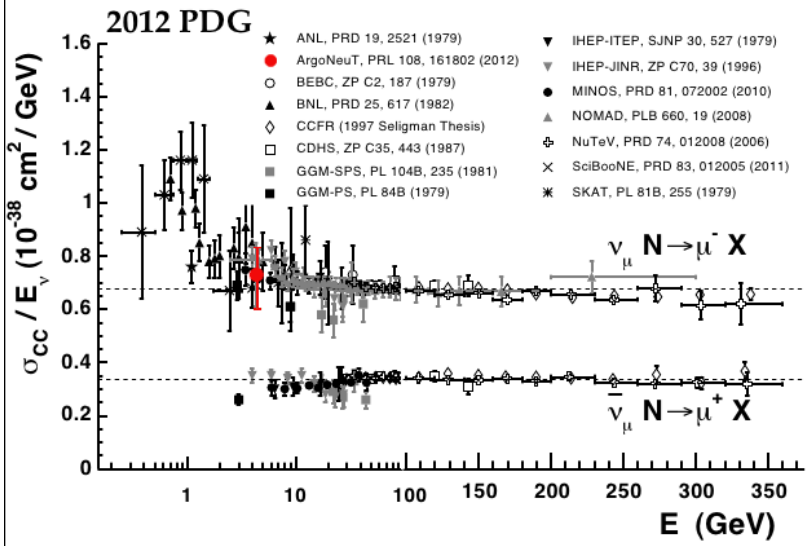
The presence of the MINOS ND allows for energy reconstruction and charge identification (q) of muons.

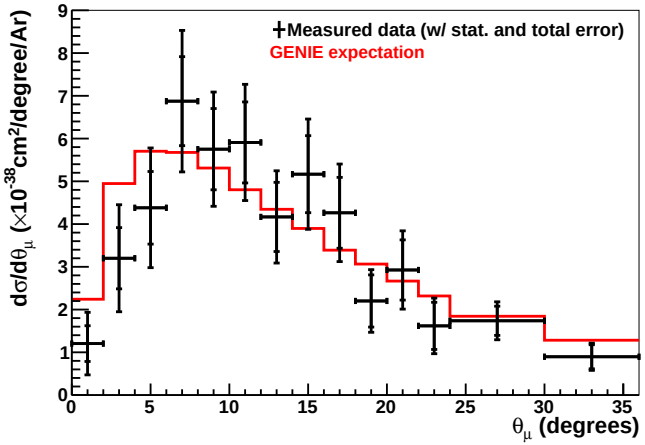


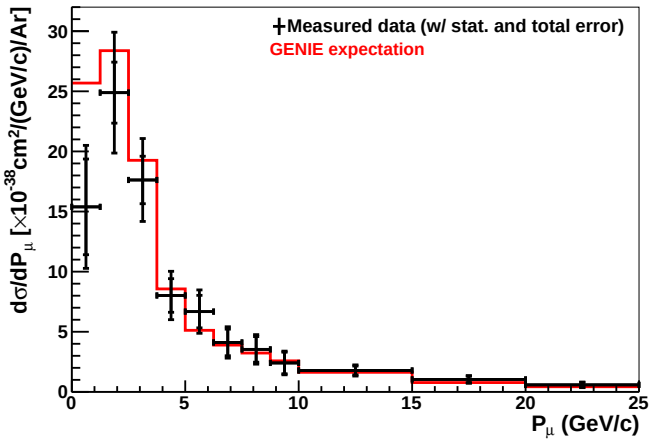


We gratefully acknowledge the help of the MINOS collaboration in these analyses.

Measurement of the ν_μ CC inclusive Cross-section



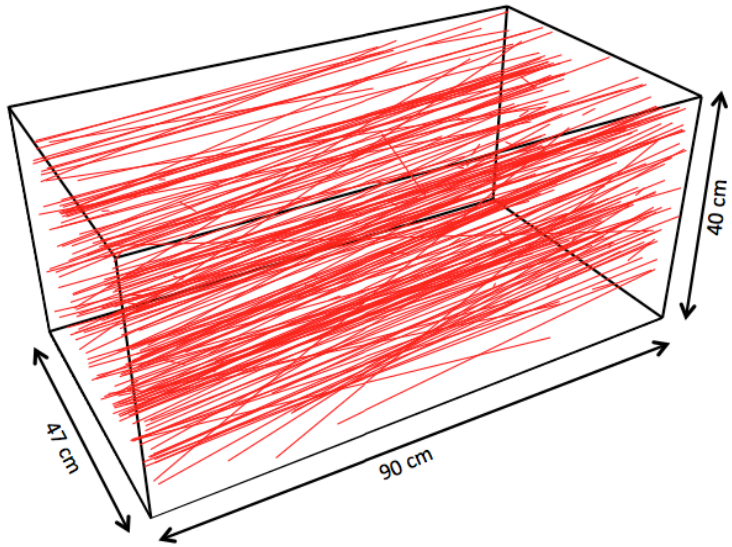


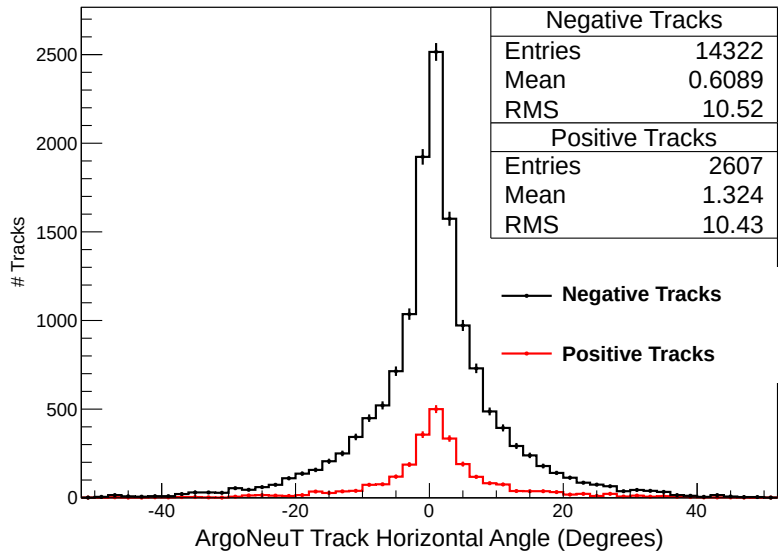


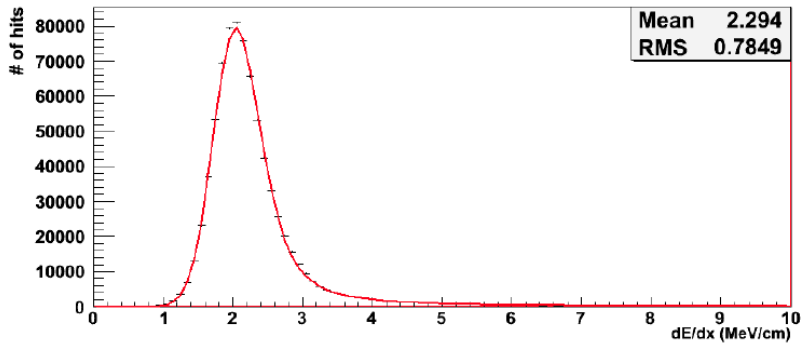
- Used data acquired in neutrino mode ($8.5x10^{18}$POT)
- C. Aderson et al., PRL 108, 2012
- Simple cuts applied:
  - vtx in fiducial volume
  - track matched to muon in MINOS ND
  - MINOS $q < 0$
- first CC-inclusive cross-section measurements in argon

Calorimetry on Through-going Muons

- Calorimetry tested on through going muons.
- The final sample contains 14322 μ^- and 2607 μ^+.
- C.Anderson et al., arxiv.org:1205.6702, accepted by JINST





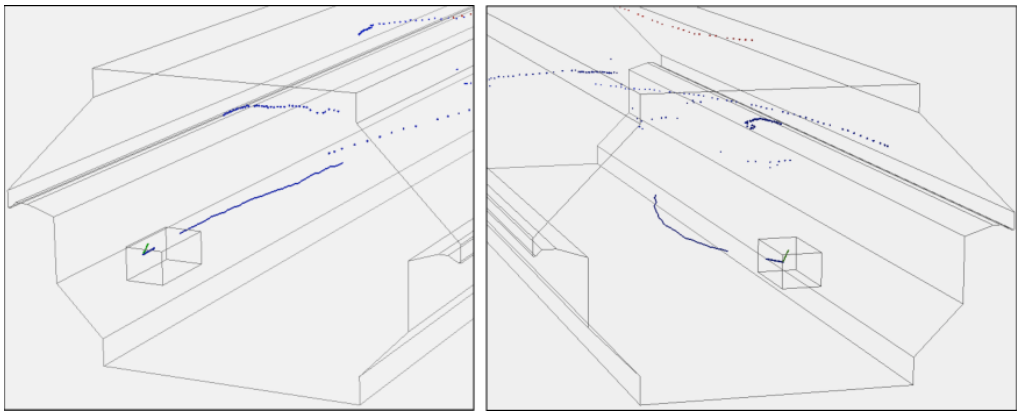


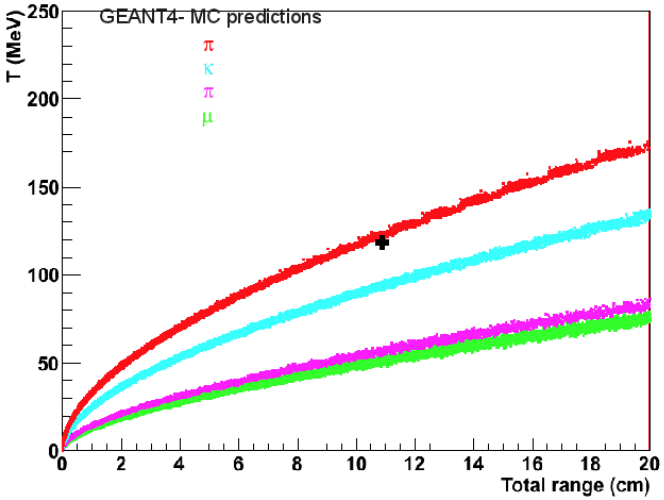
μ + N protons analysis

See talk by K. Partyka on Friday.

- Muon (ArgoNeut+MINOS reconstruction): p=2.85 GeV/c
- Proton (ArgoNeuT reconstruction): track length= 10.88 cm, T=118 MeV, p=0.485 GeV/c
- Reconstructed Neutrino Energy $\simeq$ 3.1 GeV
  $E_\nu = p_\mu cos\theta_\mu + p_h cos\theta_h$

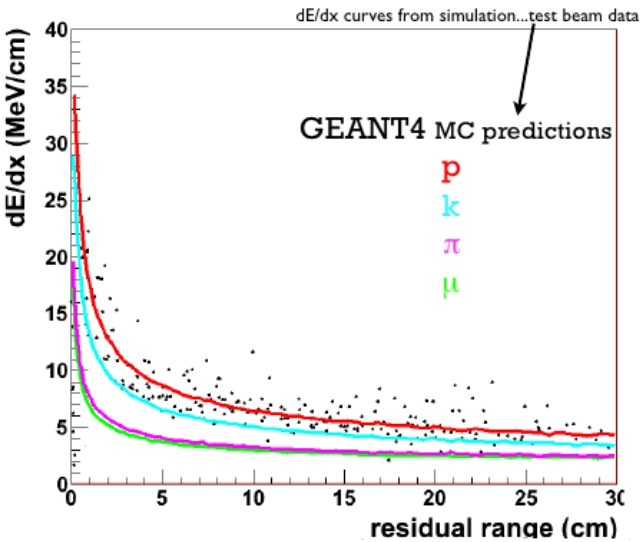
see event on slide 17

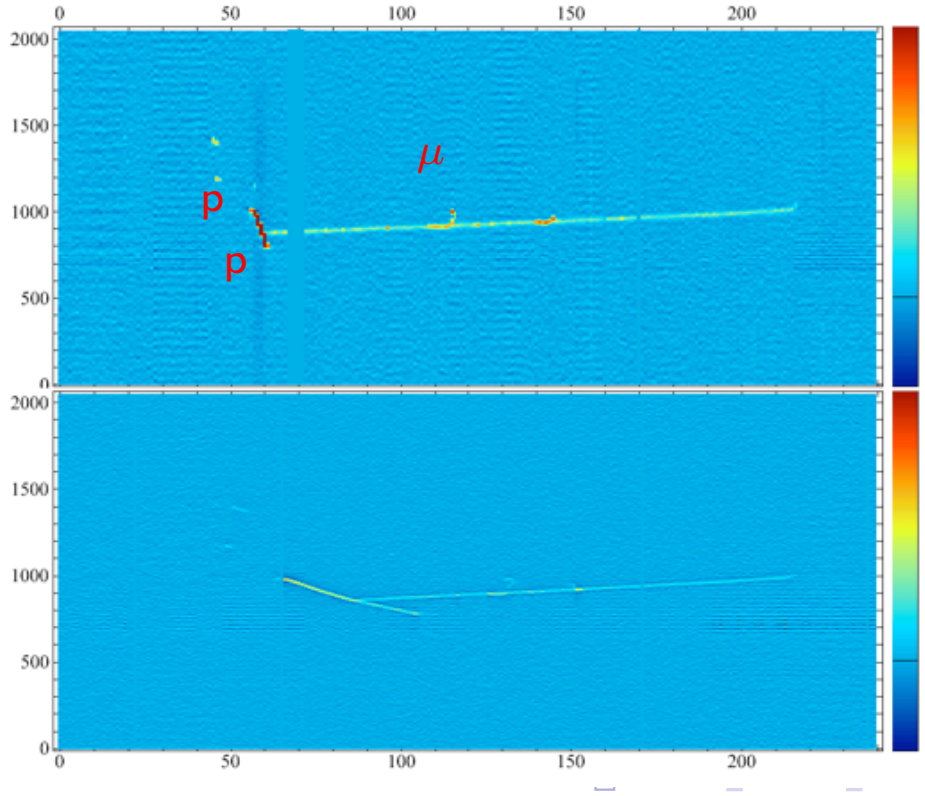




Nuclear Effects in ArgoNeut

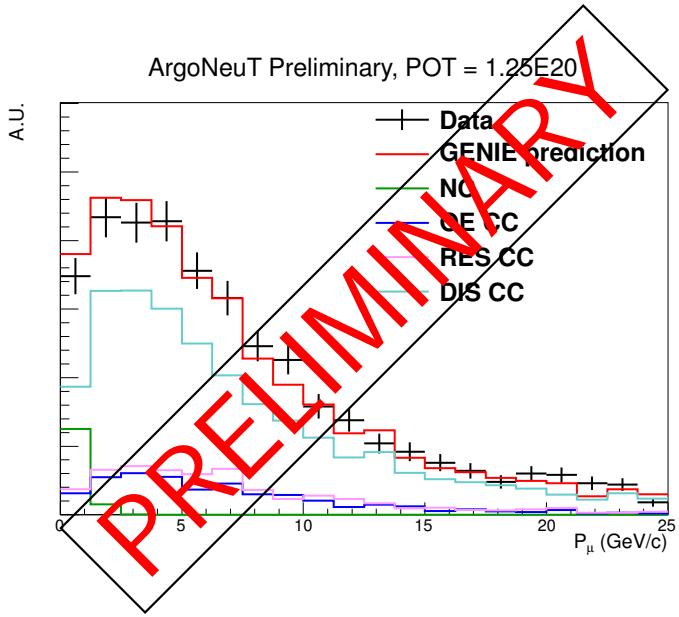
- (See talk by O. Palamara on Friday)
- Due to the LArTPC's excellent granularity ArgoNeuT is able to shed some light on vertex activity and multiple proton events
- Residual Range (distance from end of track) allows for Particle ID

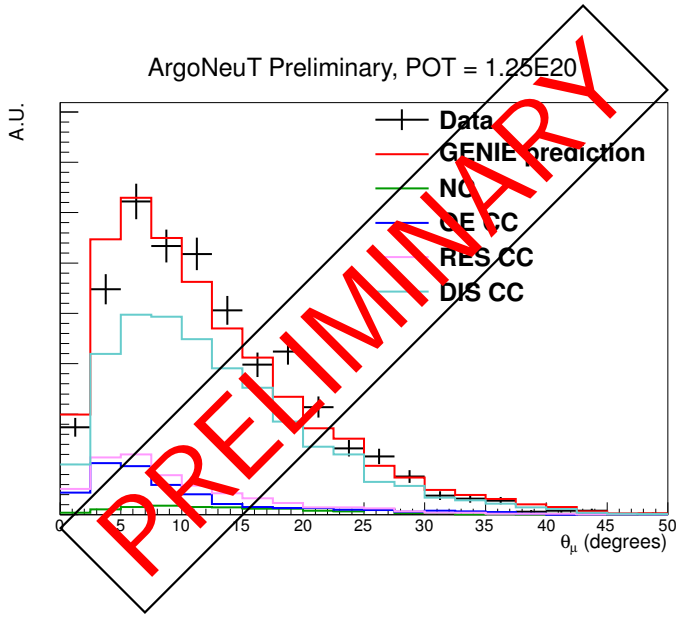




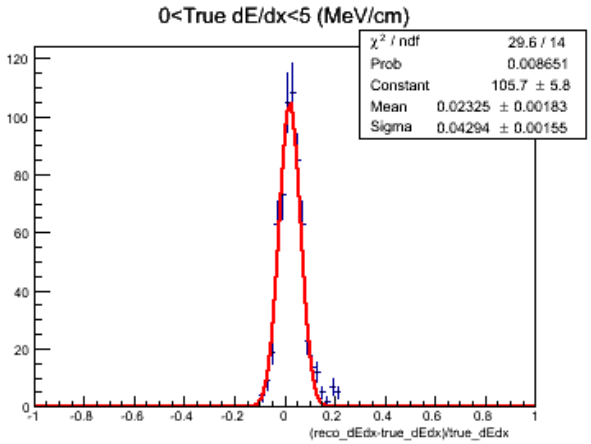
CC - inclusive analysis of $\bar{\nu}_\mu$ data

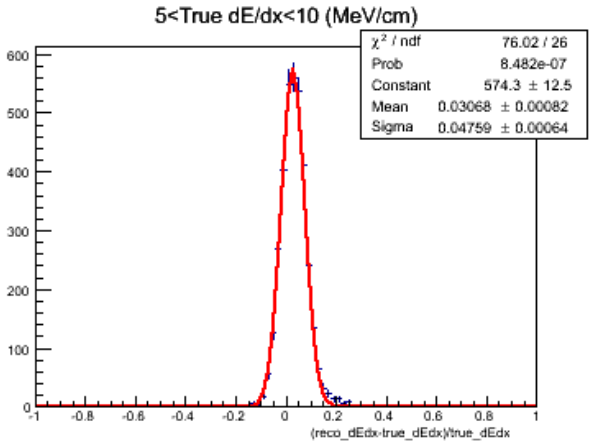
- Sample size 8 times larger.
- CC inclusive measurements can be made on $\bar{\nu}_\mu$, but also on ν_μ due to beam composition.
- Sample shown here is ν_μ !

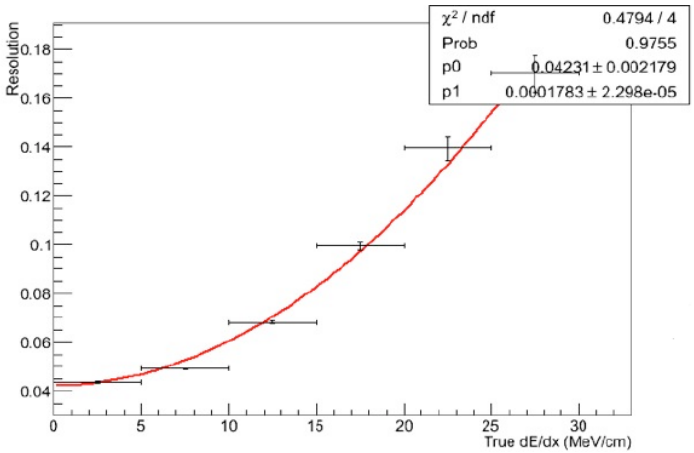




Energy resolution





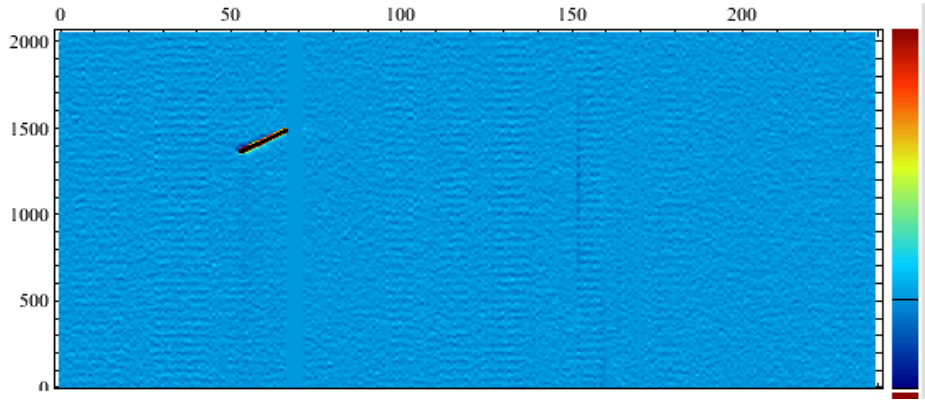


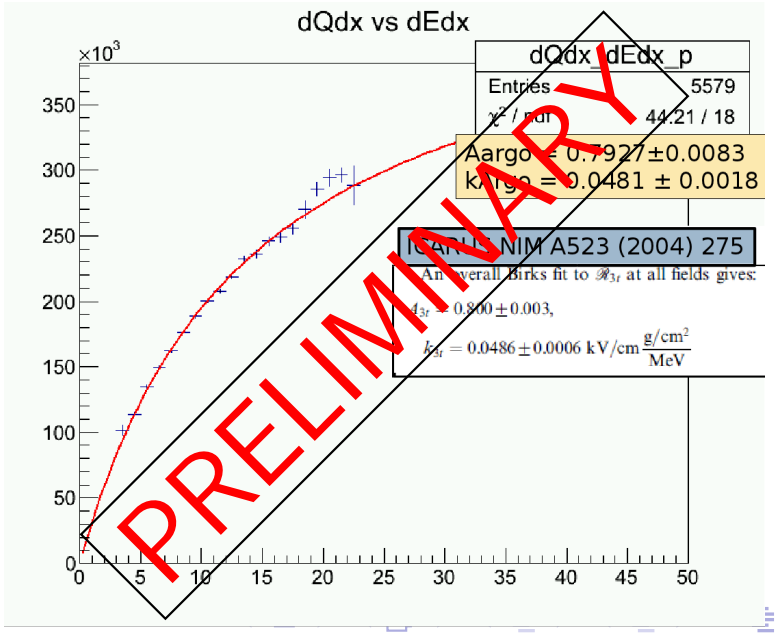
- Energy resolution $\simeq$5% for Minimum Ionizing Particles
- $\delta \frac{dE}{dx} = 0.042 + 1.78 \times 10^{-4} \frac{dE}{dx}^2$

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.

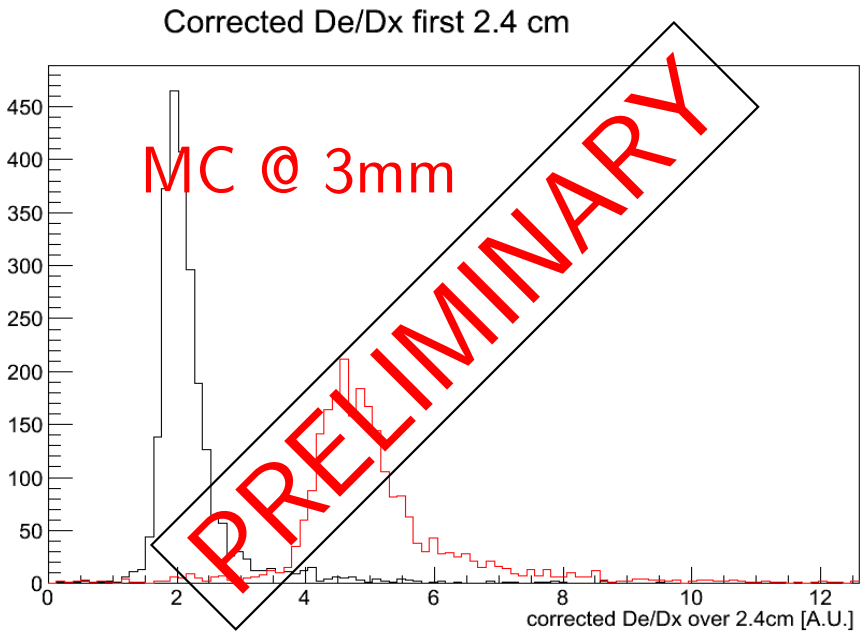
$$\frac{dE}{dx} = \frac{\frac{dQ}{dx}}{\frac{A}{W_{ion}} - \frac{K}{E_{field}}\frac{1}{\rho}\frac{dQ}{dx}}$$





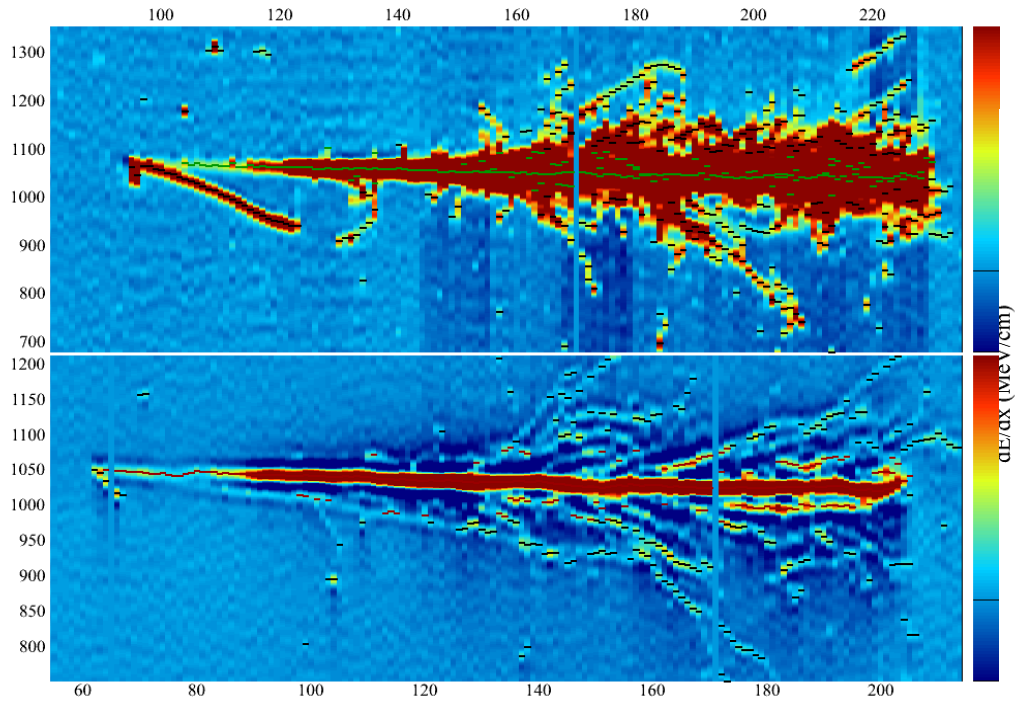
dE/dx e/γ ID

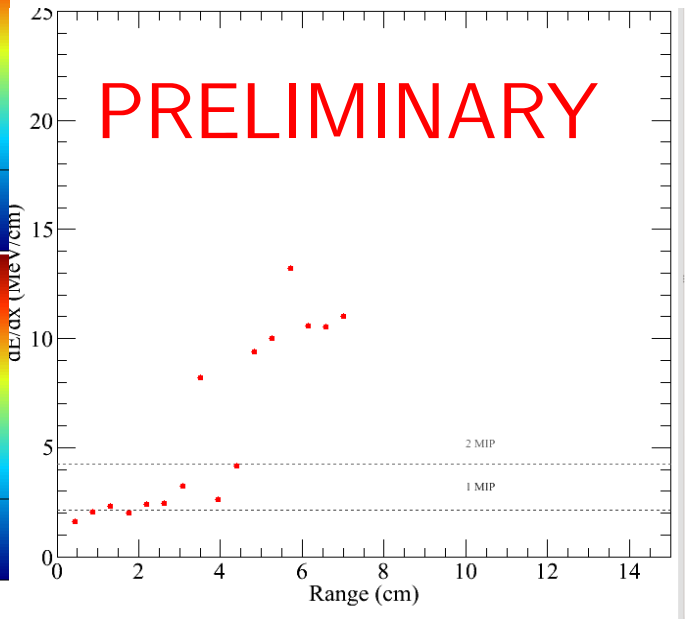
- Separating electrons from γs is important in precision ν measurements
- e.g. understanding whether the MiniBooNE anomaly is an effect of oscillation or background
- LongBaseline measurements e.g. CP violation etc.
- the dE/dx of a shower can be a powerful discrimination tool: an electron is a Minimum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



dE/dx e/γ ID (1)

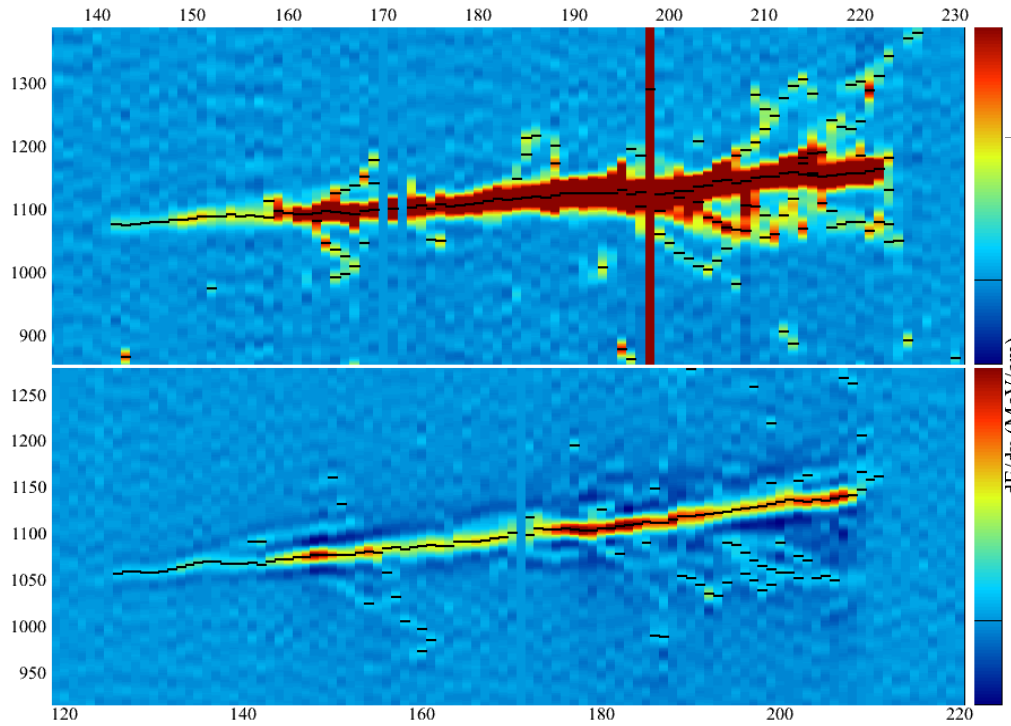
- 3D axis Showers calculated based on the angles ofthe 2D projections.
- Correction for Birk's recombination factor $f(dE/dx)$ and lifetime applied

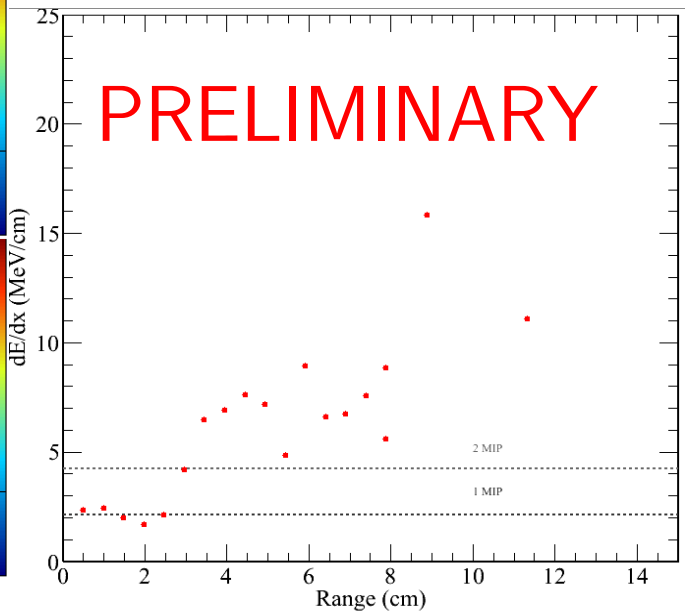




ν_e CC candidate.

dE/dx e/γ ID (2)

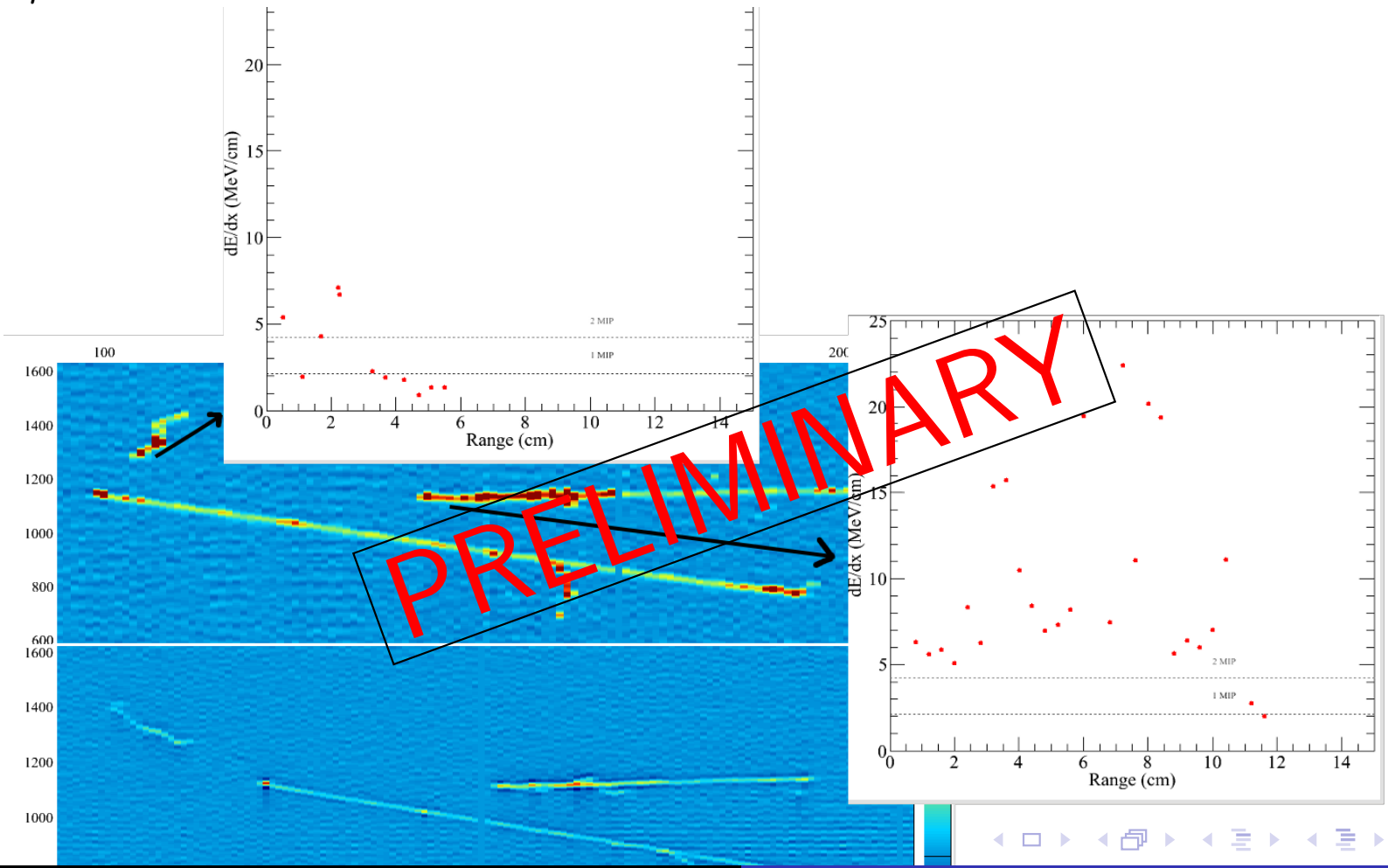




ν_e CC candidate

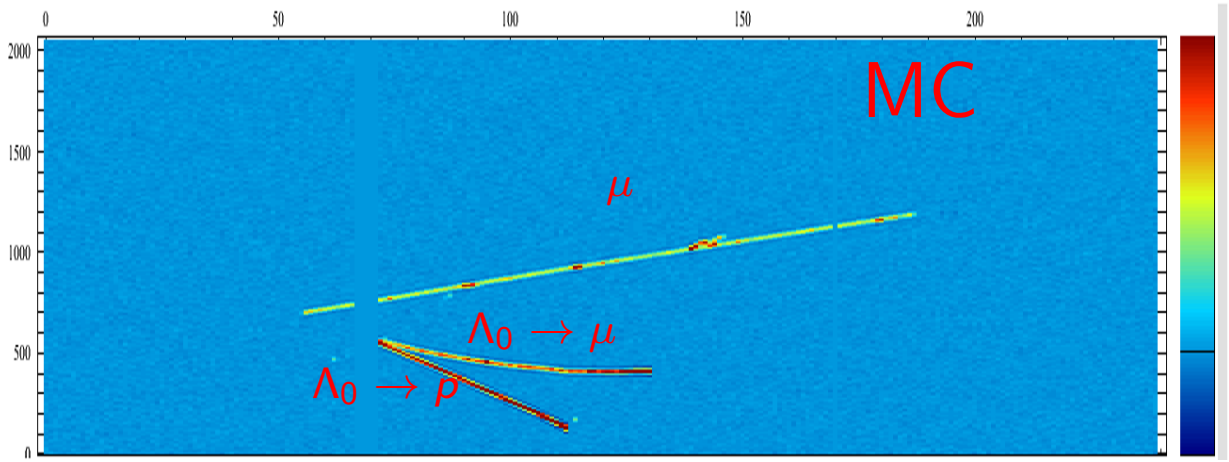
dE/dx e/γ ID (3)

ν_μ CC + π^0 candidate



Other Ongoing Analyses

- NC π^0 cs
- Hyperon Production



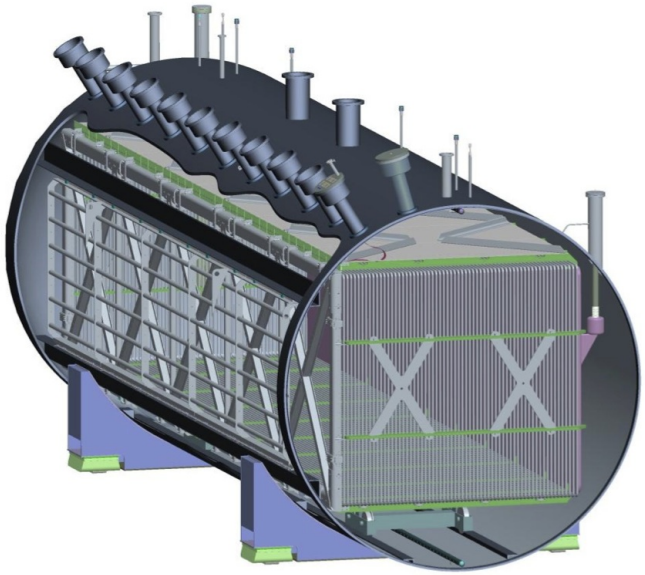
- μ + nprotons + npions

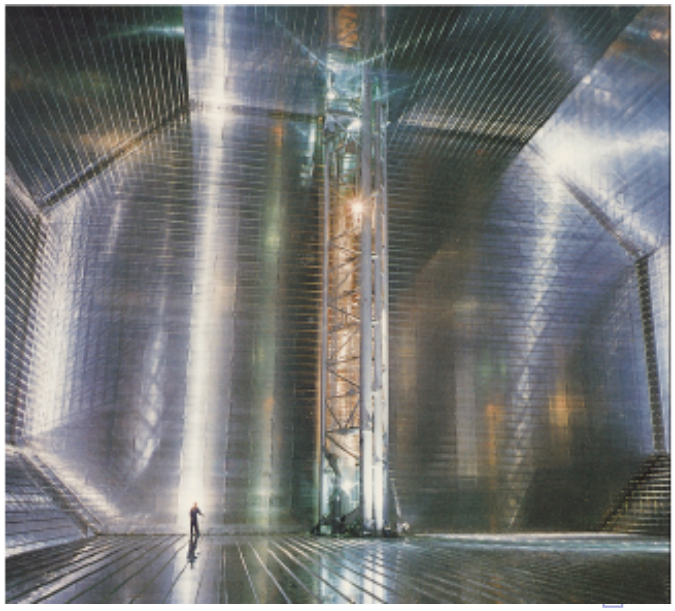
Outline

1. Introduction
   - The LArTPC
2. The ArgoNeuT Detector
3. ArgoNeuT@NuMI
4. Physics Results and Analyses
   - The LArSOFT Software package
   - On-Going analyses
5. The Future
6. Conclusions

Future LAr Experiments in the US

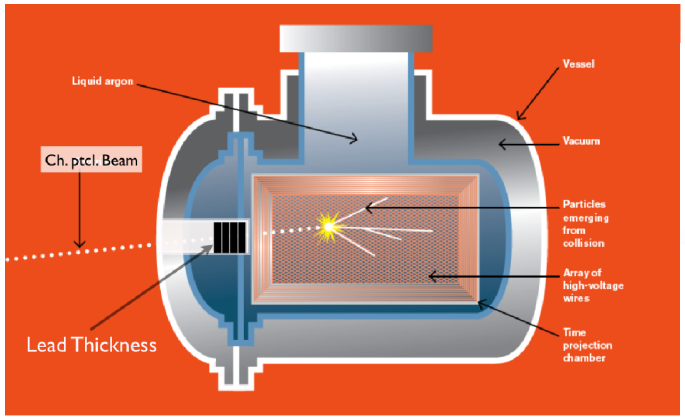
- See talk by G. Karagiorgi (Friday)
- LAriAT (in construction) - LAr at a TestBeam
- MicroBooNE (in construction) - Short Baseline
- LAr1 - 1kT detector (LOI) - Short Baseline
- LBNE - Long Baseline

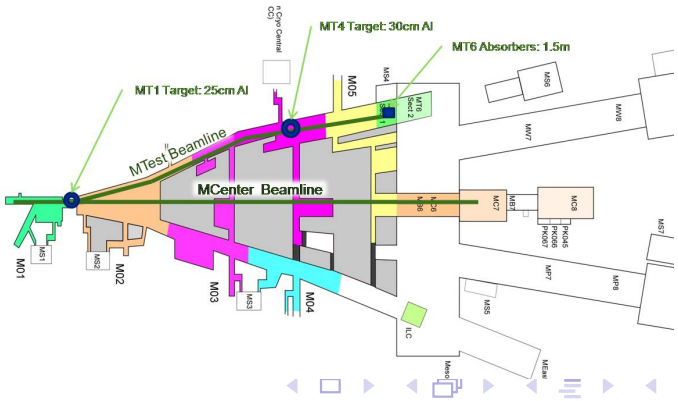




LArIAT phase 1

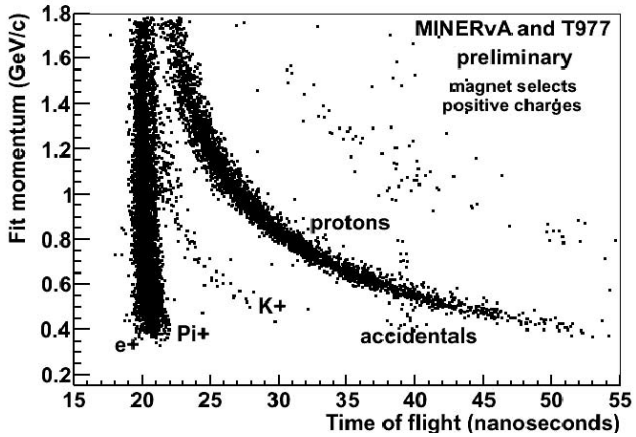
- The ArgoNeuT detector will be resurrected as LArIAT (Liquid Argon in a Testbeam) phase 1.
- The objective calibration of single tracks and collective topologies
- Characterization of response at a range of energies relevant for future experiments (MicroBooNE, LBNE, etc.)
- Known input particle type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



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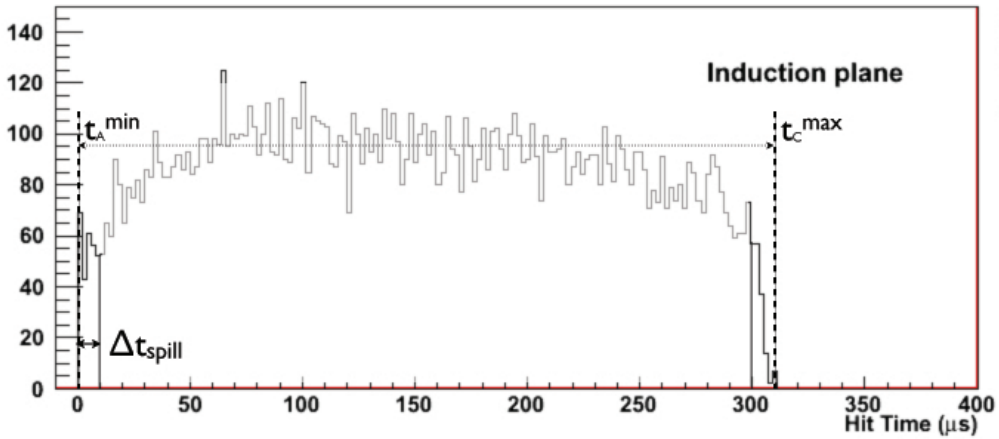
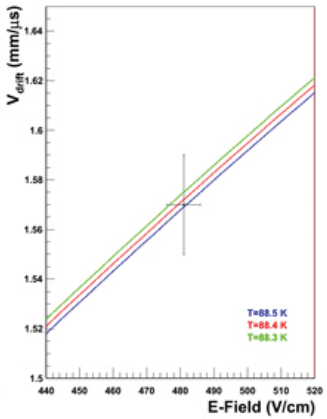
Conclusions

- First LArTPC in a ν beam in the US
- Provided important know-how which is 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.

Conclusions

Muito Obrigado

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.