The ArgoNeuT Experiment

ArgoNeuT

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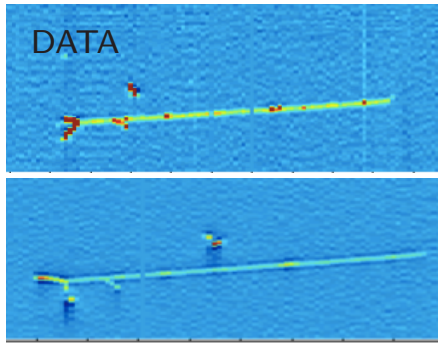
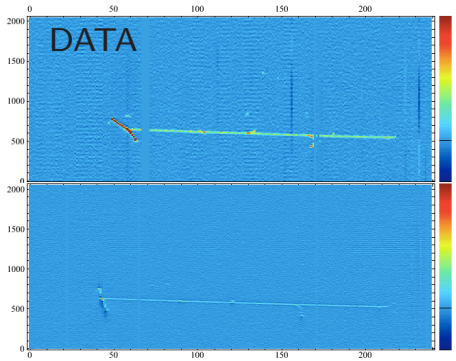
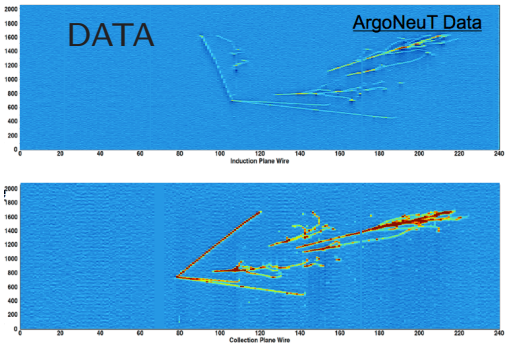
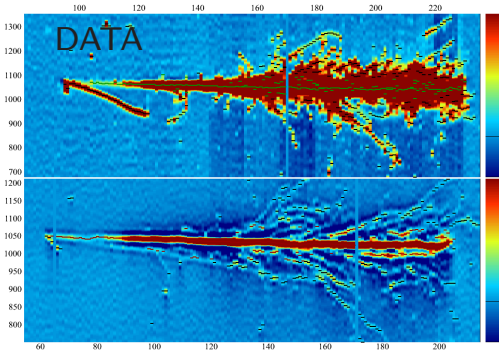
Liquid argon for ν detection (a reminder)

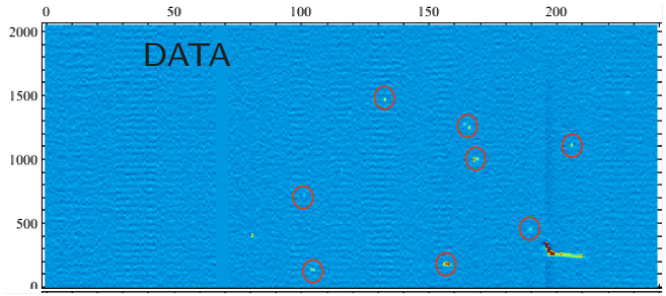
- Abundant ionization electrons and scintillation light can both be used for detection.
- Reasonably dense (1.4 g/cm^3) - a good target for neutrinos.
- Relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks (or opportunities)...no free protons...nuclear effects.





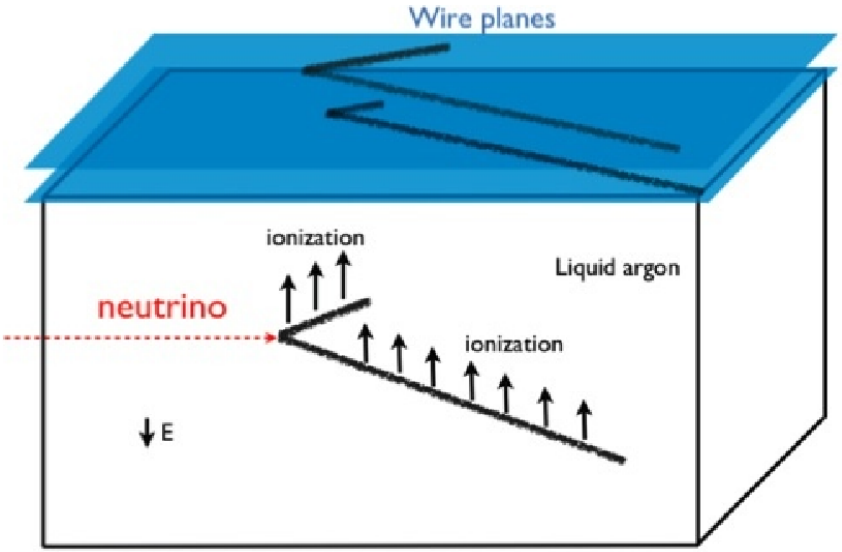


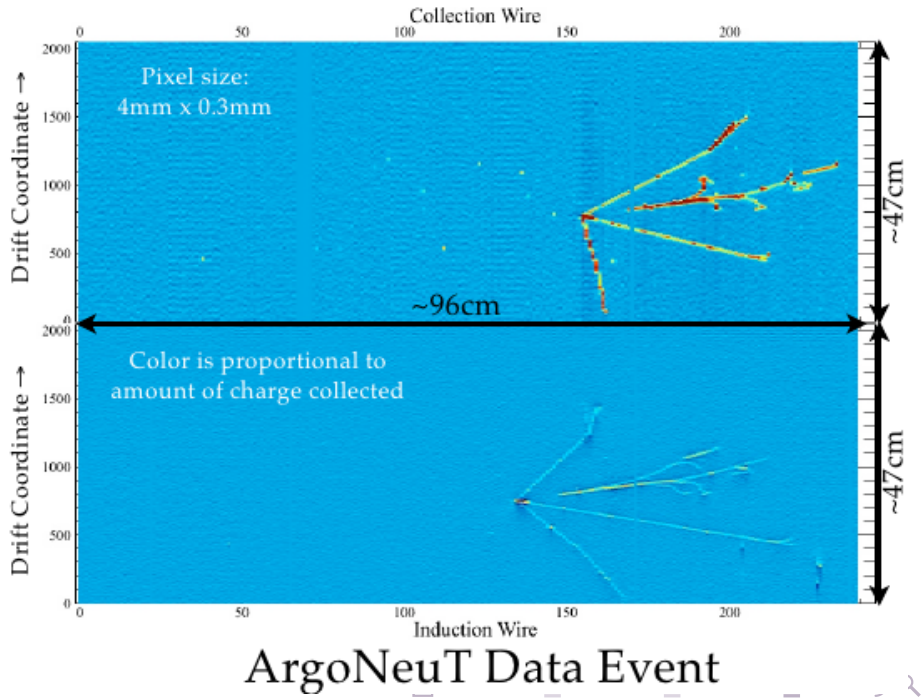




How LArTPCs Work

- 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

ArgoNeuT

- First TPC in a beam in the US LAr R&D program.
- A relatively short run (1 + 6 months).
- Pioneered the use of liquid argon for low/medium energy neutrinos.
- Much bigger detectors are online (see talks by Anne, Marco, Joel, Colton and Raquel on Tuesday; Roberto on Monday) or coming online soon.
- ArgoNeuT is not history yet.

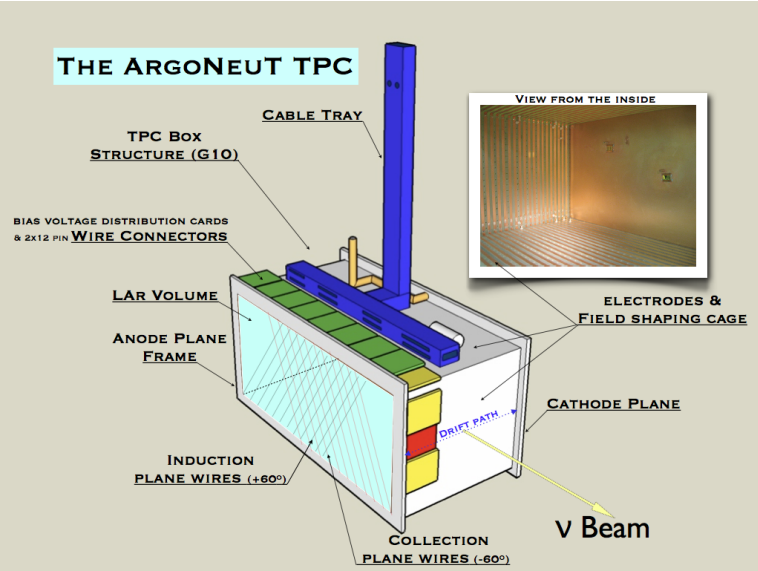
ArgoNeuT Goals When we started

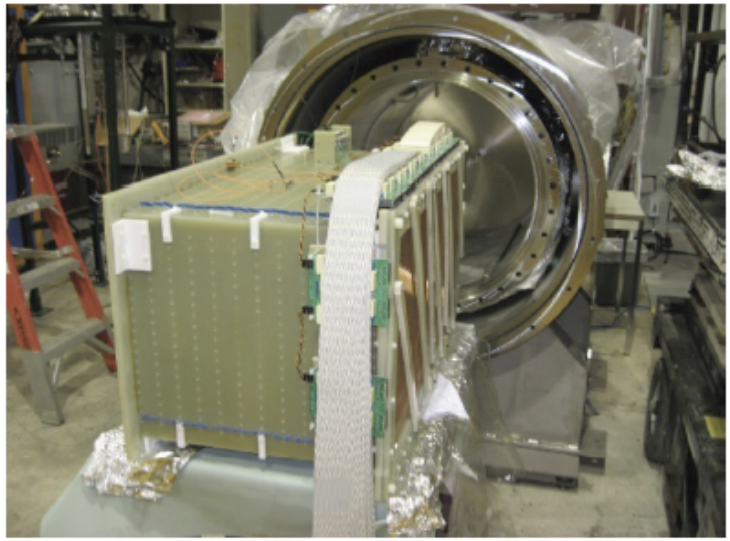
- Measure CC cross sections on argon in the 1-10 GeV range.
- Examine effects of FSI using the TPC's granularity.
- Examine dE/dx particle ID, especially e/γ separation, crucial for future ν experiments.
- Develop automated reconstruction techniques.

How did that go?

- C. Anderson et al., Phys.Rev. Lett. 108, (2012) (ν_μ CC inclusive Cross-section)
- C.Anderson et al., *2012 JINST 7 P10020*; (arxiv.org:1205.6702), (Calorimetry with throughgoing muons)
- C.Anderson et al., JINST 7 (2012) P10019, (arXiv:1205.6747), (Detector Paper)
- R. Acciarri et al., JINST 8 (2013) P08005, (arXiv:1306.1712) (Recombination with stopping protons)
- R. Acciarri et al., Phys.Rev. D89 (2014), 112003, (arXiv:1404.4809) (CC-inclusive with $\bar{\nu}$ beam mode)
- R. Acciarri et al., Phys.Rev. D90 (2014), 012008, (arXiv:1405.4261) (b-to-b 2-proton events)
- R. Acciarri et al., Phys.Rev.Lett. 113 (2014), 261801 (arXiv:1408.0598) (CC coherent charged π production)
- R. Acciarri et al., Phys.Rev. D95 (2017), 072005, (arXiv:1610.04102) (electron-photon separation)
- R. Acciarri et al., Phys.Rev. D96 (2017), 012006 ,(arXiv:1511.00941) (NC-π^0 cross-section)
- more in this talk....

The ArgoNeuT TPC

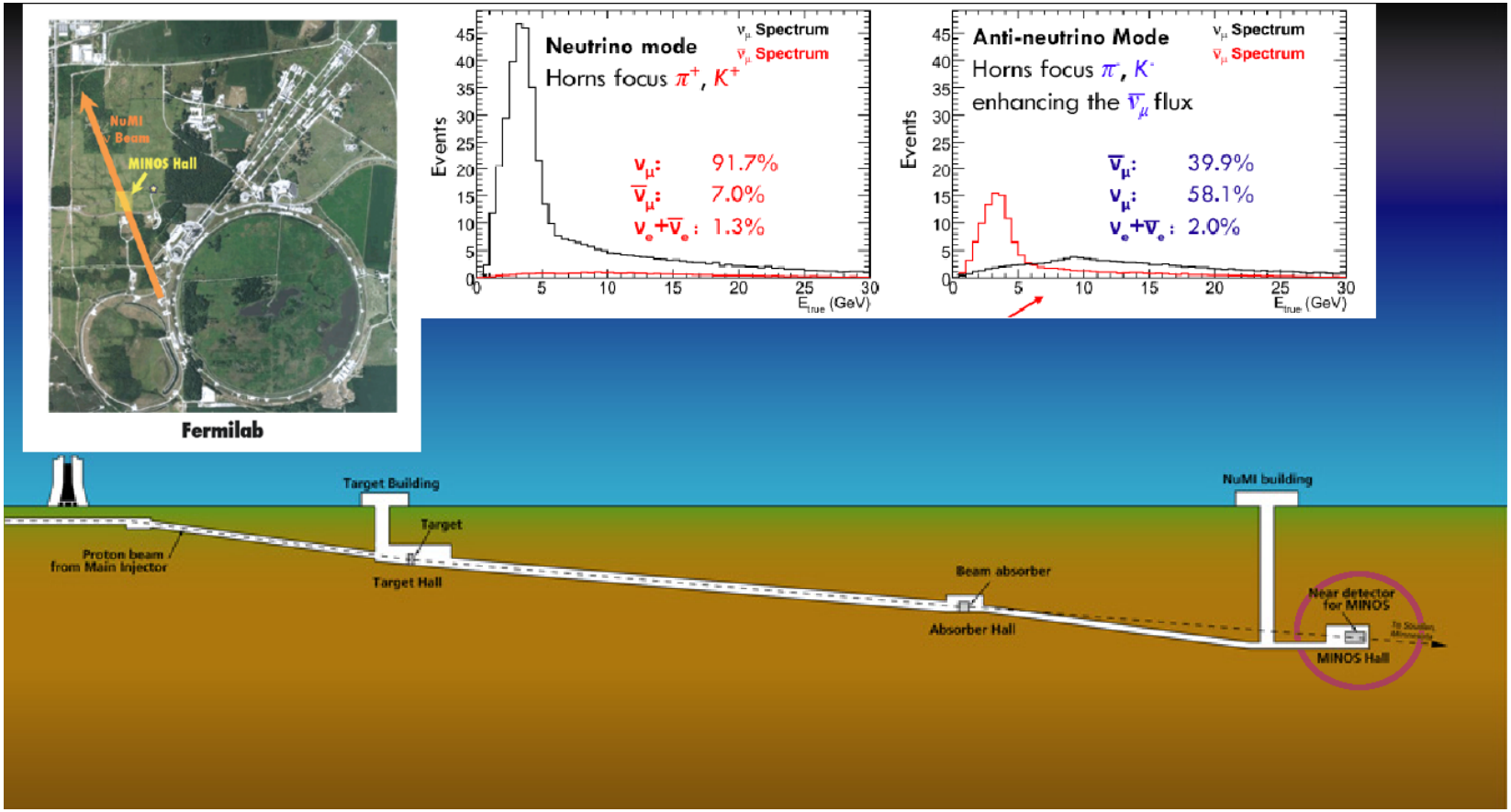




Cryostat Volume	500 Liters
TPC Volume	175 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length (Time)	0.5m (330μs)
Light Collection	None

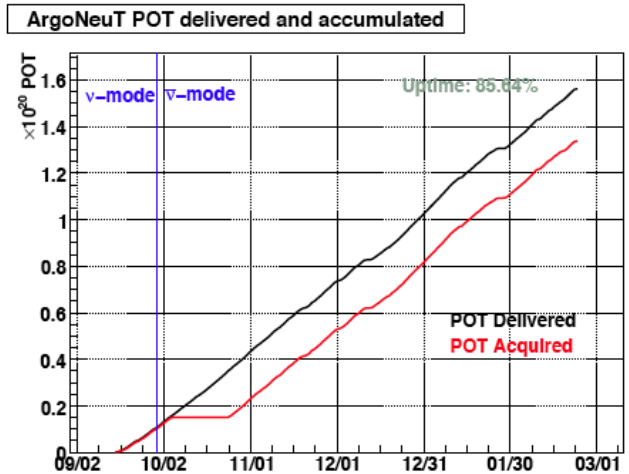
- Two wire planes instrumented (3 present).
- E-field between planes optimized to maximize transparency.
- Wire spacing at 4mm.

NuMI Beam


NuMI
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
ν_μ Spectrum
$\bar{\nu}_\mu$ Spectrum
$\bar{\nu}_\mu$: 39.9%
ν_μ: 58.1%
$\nu_e+\bar{\nu}_e$: 2.0%
Events
E_{true} (GeV)
Target Building
Target
Proton beam
from Main Injector
Target Hall
Beam absorber
Absorber Hall
NuMI building
Near detector
for MINOS
MINOS Hall

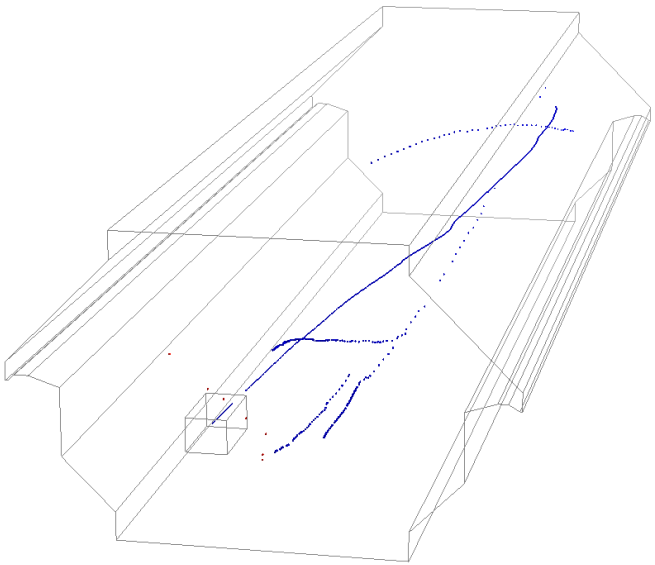
ArgoNeuT in the MINOS hall

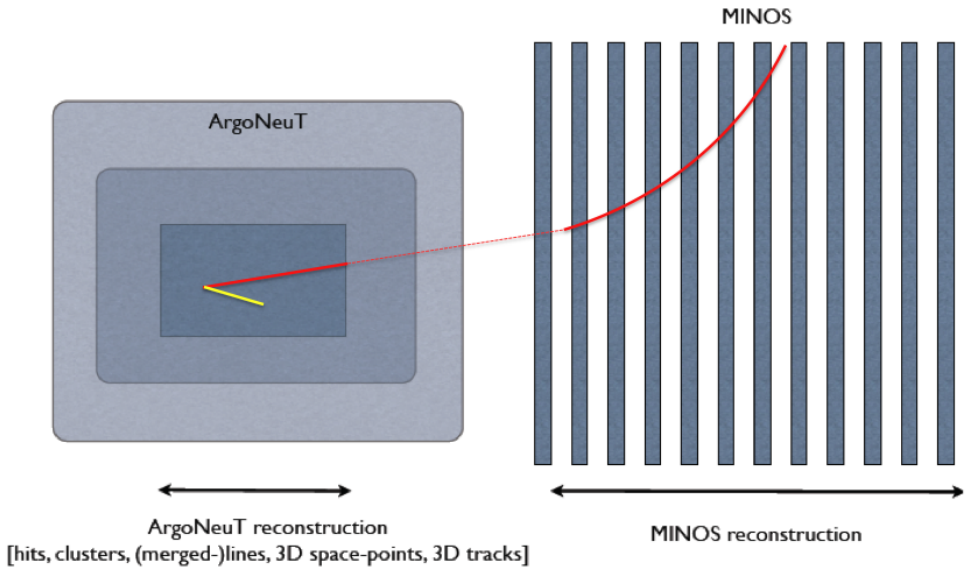
- Remote,shiftless operation for 5 months.
- Acquired 1.35×10^{20} POT, mainly in $\bar{\nu}_\mu$ mode.
- Expected $\sim$o(10k) CC events in ν_μ and $\bar{\nu}_\mu$.



MINOS ND

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





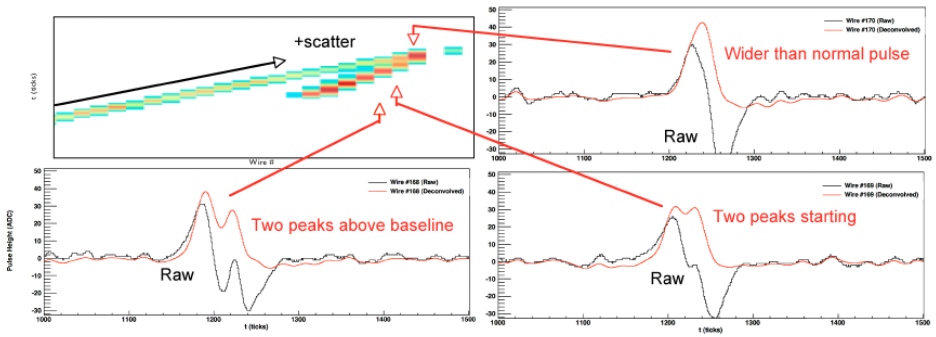
We gratefully acknowledge the help of the MINOS collaboration in these analyses.

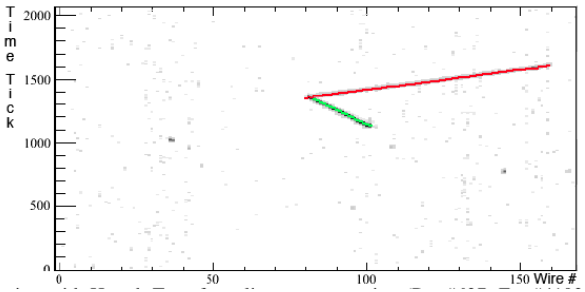
The ArgoNeuT Reconstruction

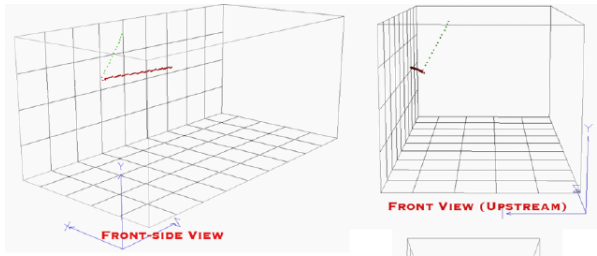
- The data acquired by ArgoNeuT continues to be used in analyses.
- ArgoNeuT was the first experiment to use The LArSOFT package developed for US LArTPCs.
- Use 3D and calorimetric reconstruction for efficient Particle Identification.
- Excellent resolution for final states.
- Possibility of "seeing" recoil proton(s).
- Good p/$\pi^{\pm}$ identification capability.
- First proof that LArTPCs could be used to do nuclear physics!

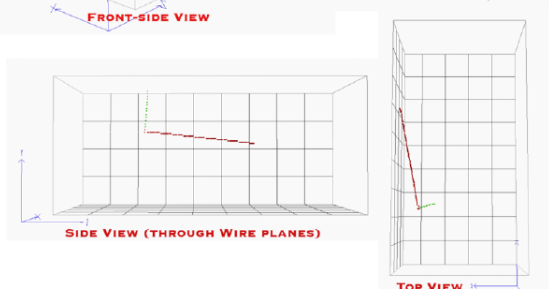
The Reconstruction Process

- 1^{st} stage - Hits (GausHitFinder)
- 2^{nd} stage - Clustering (TrajCluster)
- 3^{rd} stage - Combine into 3D tracks (PMATracker)
- 4^{th} stage - Use dQ/dx information from hits for PID and energy reco









So, what's new in ArgoNeuT World?

FERMILAB-PUB-18-142-ND

First measurement of the cross section for ν_μ and $\bar{\nu}_\mu$ induced single charged pion production on argon using ArgoNeuT

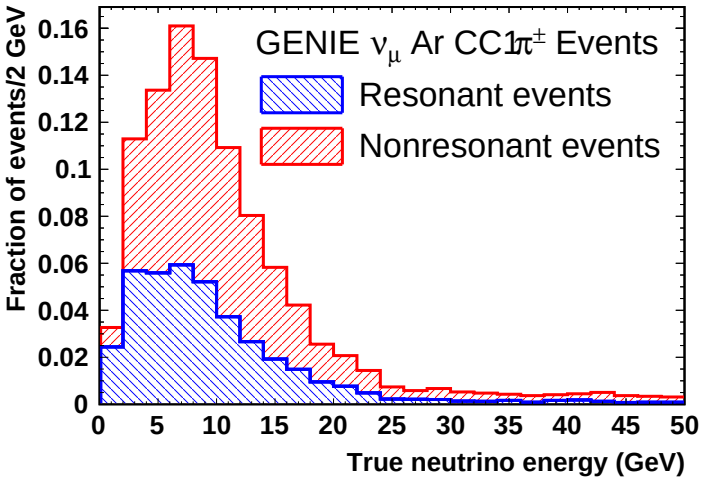
R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] E. Church,[6] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] R.S. Fitzpatrick,[8] B. Fleming,[2] A. Hackenburg,[2] G. Horton-Smith,[4] C. James,[1] K. Lang,[9] I. Lepetic,[10] B.R. Littlejohn,[10] X. Luo,[2] R. Mehdiyev,[9] B. Page,[5] O. Palamara,[1] B. Rebel,[1] A. Schukraft,[1] G. Scanavini,[2] M. Soderberg,[11] J. Spitz,[8] A.M. Szelc,[12] M. Weber,[7] W. Wu,[1] T. Yang,[1,*] and G.P. Zeller[1]
(The ArgoNeuT Collaboration)

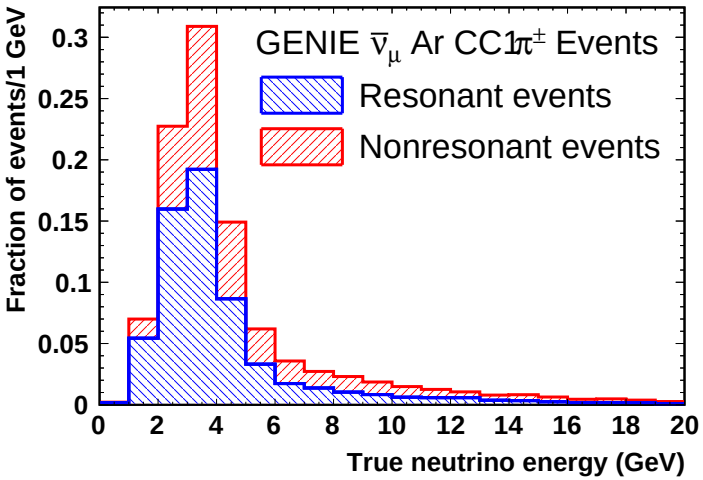
Phys. Rev. D 98, 052002 (2018) and *arXiv:1804.10294*

CC 1 π what to to expect?

According to GENIE:

- Resonant pion: 39% (and 61%) of ν_μ (and $\bar{\nu}_\mu$) c-s
- Rest predominantly through DIS 89% (and 97%) contain $\pi^\pm$
- Coherent π production contributes 3% (and 5%)

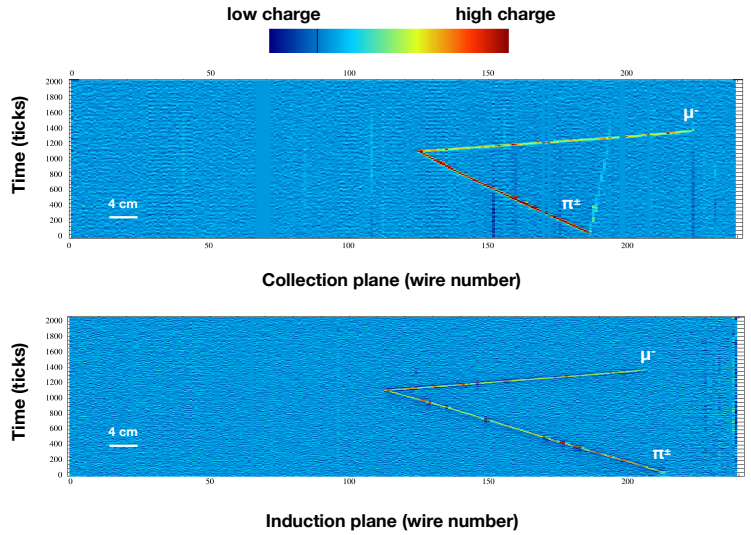


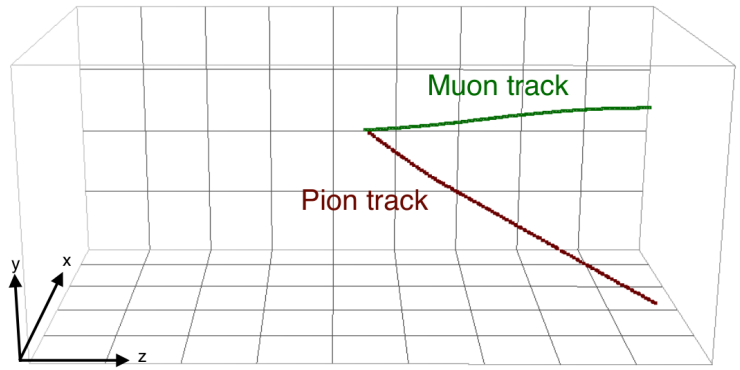


Events we're looking for

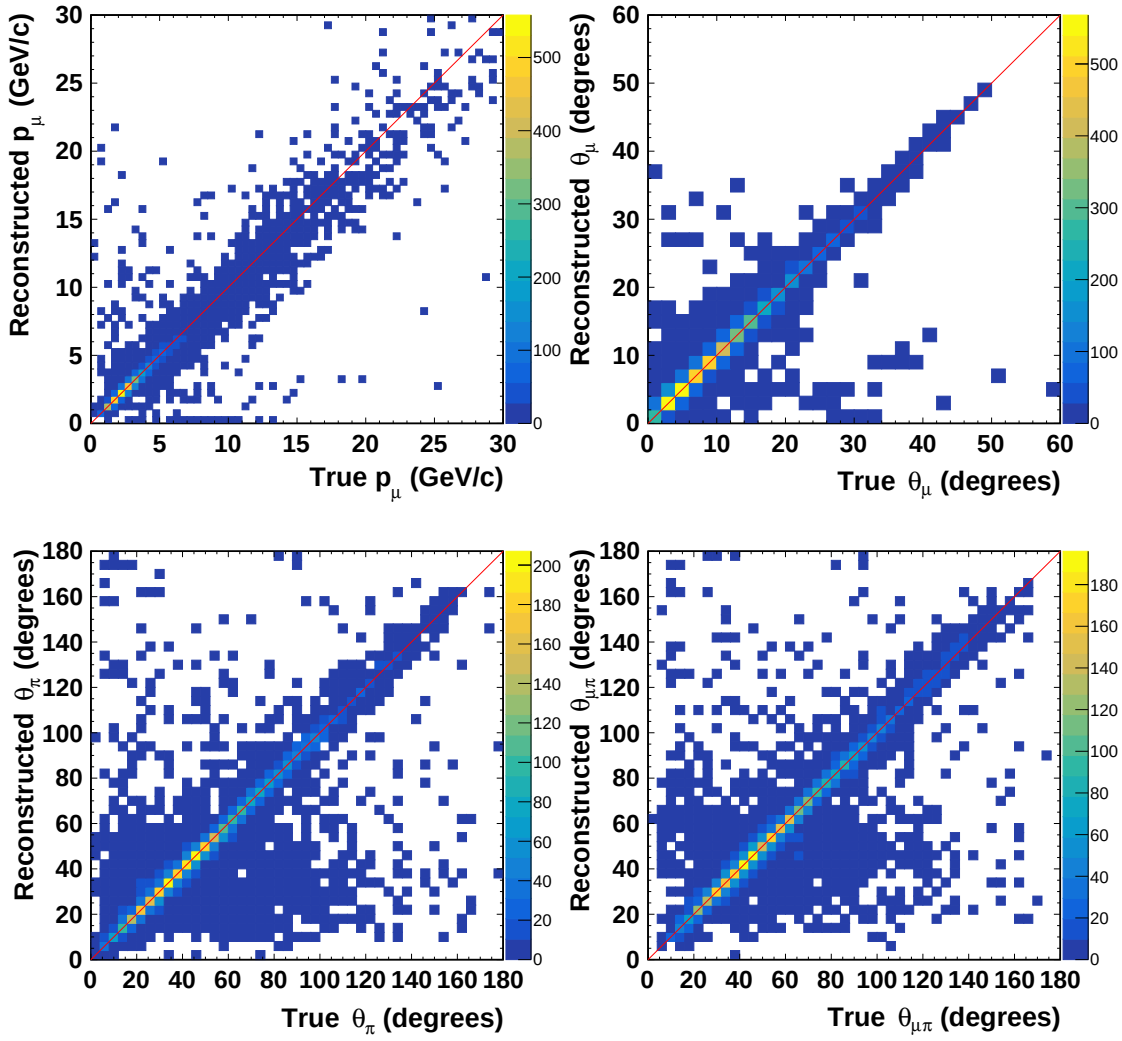
- Searching for at least two minimum ionizing tracks.
- Track matched to MINOS must be muon.
- Reject pairs at $> 170^o$ to reject "broken" through-going muons.
- Request at least 4cm of pion track (effective 100 MeV/c threshold on p_π)

Caveat: ArgoNeuT's small size means that exiting protons, can be mis-id'ed as pions. 16% of CC 1π events are reconstructed with more than one muon/pion ID'ed track.
Solution: extend selection to events with two MIP tracks apart from the muon. The lower average dE/dx track becomes the pion candidate.



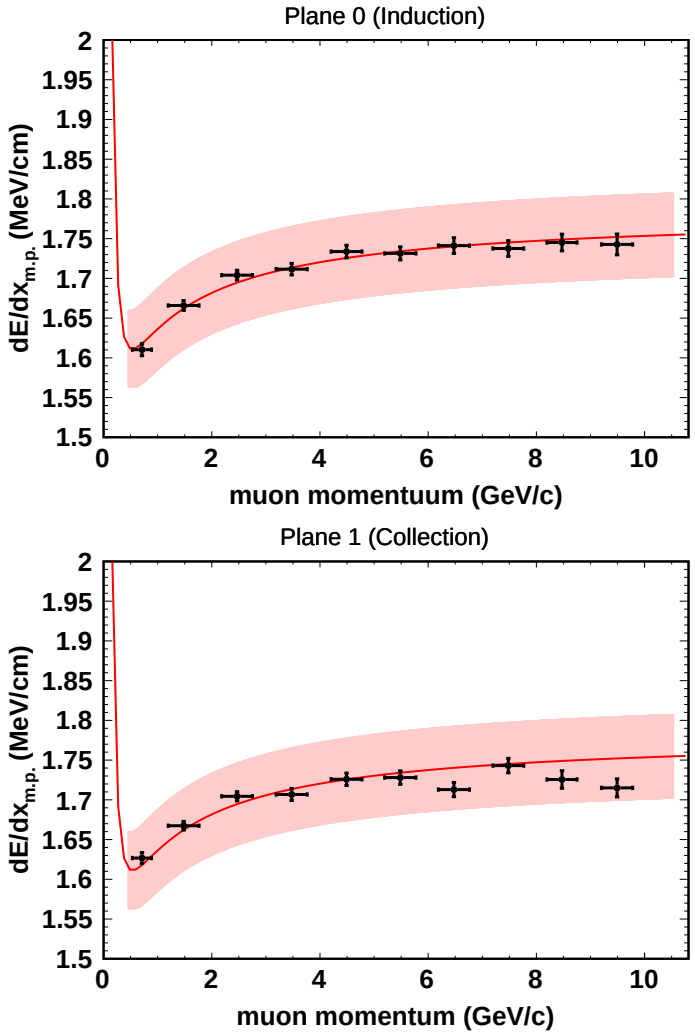


Reconstruction Performance



Reconstruction Performance Continued

- dE/dx calculation corrects for electronics, impurities etc...
- Stopping particles identified as muon/pion are kept in the selection.
- For exiting tracks use the average of last 5cm in detector.



BDT Event Selection

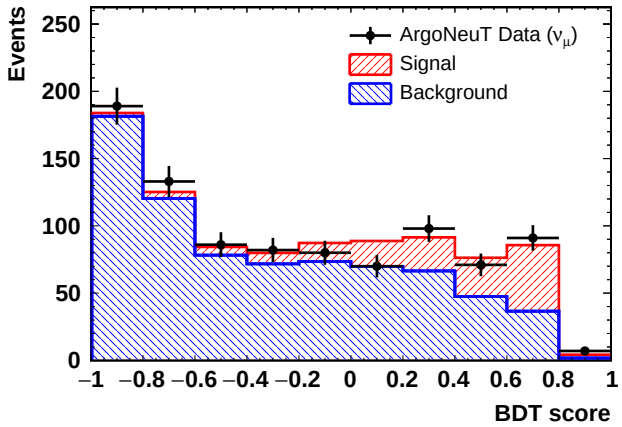
Variables used in th BDT:

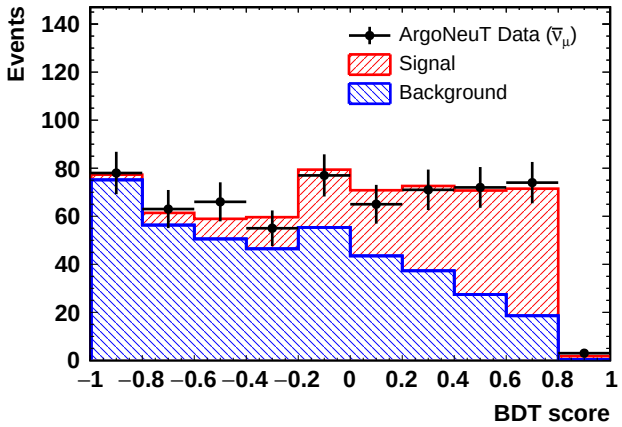
- Average dE/dx calculated using the last 5 cm of the candidate pion track;
- Number of tracks identified as charged pion or muon;
- Number of reconstructed vertices;
- Fraction of total measured charge that is associated with all reconstructed tracks;
- Fraction of total measured charge that is associated with reconstructed tracks originating from the reconstructed neutrino interaction vertex.

Last three variables designed to remove DIS events.

	ν_μ	$\bar{\nu}_\mu$
$\nu_\mu/\bar{\nu}_\mu$ CC selection	1862	1756
One or two MIP-like tracks	907	624
BDT score > 0	337	285
BDT score < 0	570	339

BDT Selection Results





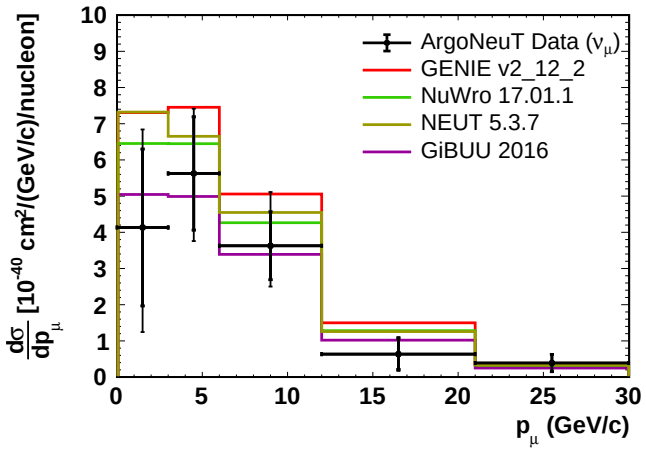
	ν_μ			
	Data	Fitted MC	Fitted Signal	Fitted Background
Total (after cuts)	907	907	160	747
BDT score > 0	337	346	124	222
BDT score < 0	570	561	36	525

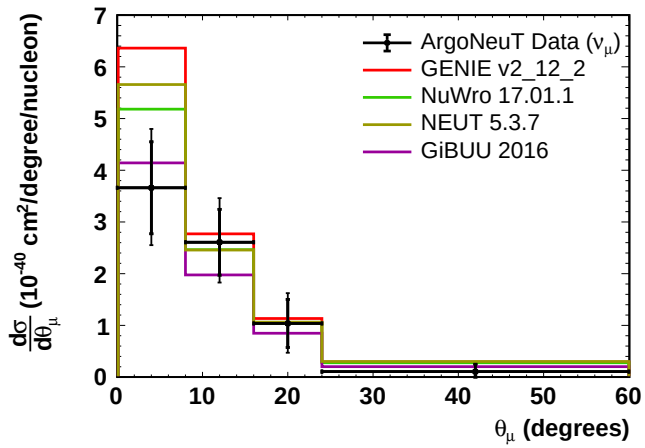
	$\bar{\nu}_\mu$			
	Data	Fitted MC	Fitted Signal	Fitted Background
Total (after cuts)	624	624	213	411
BDT score > 0	285	287	160	127
BDT score < 0	339	337	53	284

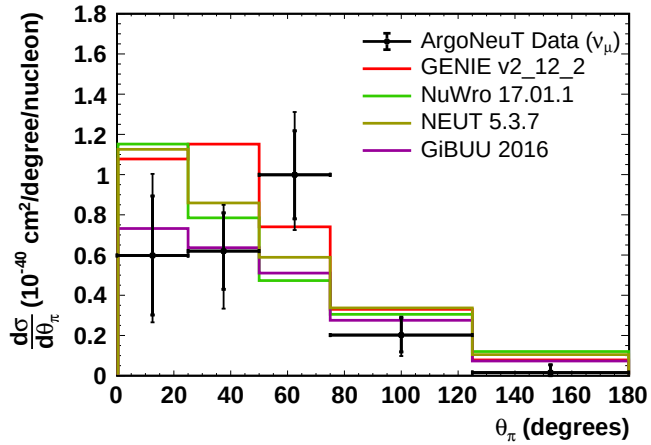
Summary of Systematic Errors

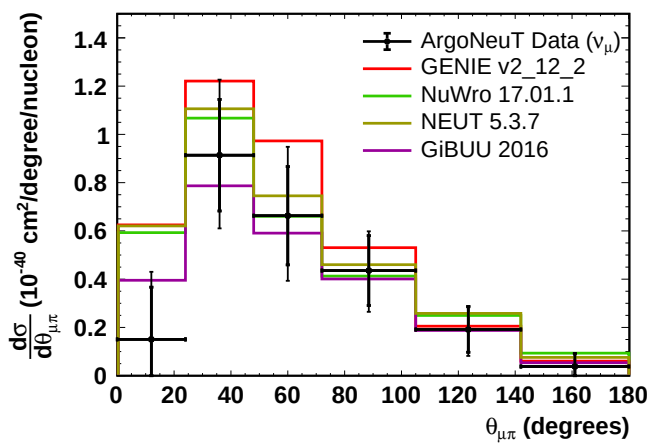
	Cross section uncertainty (%)	
Systematic Uncertainty	ν_μ	$\overline{\nu}_\mu$
Flux Normalization	$^{+11.0}_{-9.0}$	$^{+8.0}_{-7.0}$
GENIE modeling	$^{+14.5}_{-16.6}$	$^{+5.5}_{-5.2}$
Energy scale	$^{+7.7}_{-0.0}$	$^{+7.2}_{-1.8}$
Number of argon targets	± 2.0	± 2.0
POT	± 1.0	± 1.0
Total systematics	$^{+19.9}_{-19.0}$	$^{+12.3}_{-9.2}$

ν_μ CC1$\pi^\pm$ cross section results

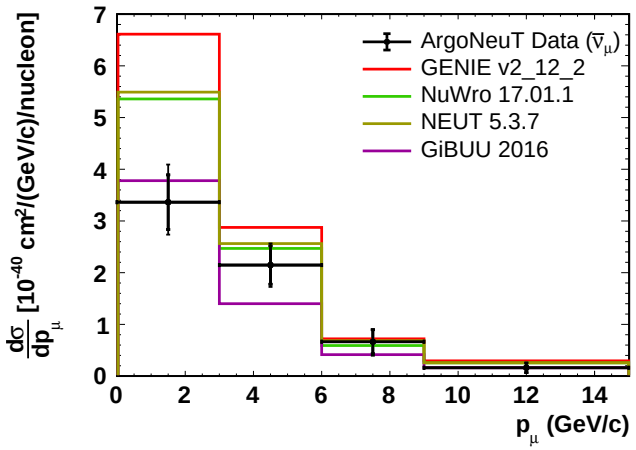


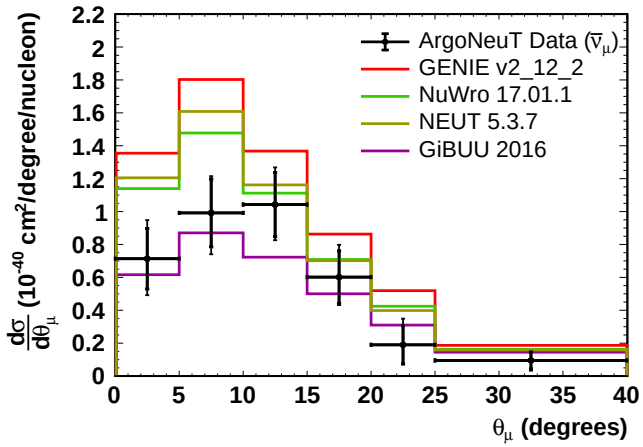


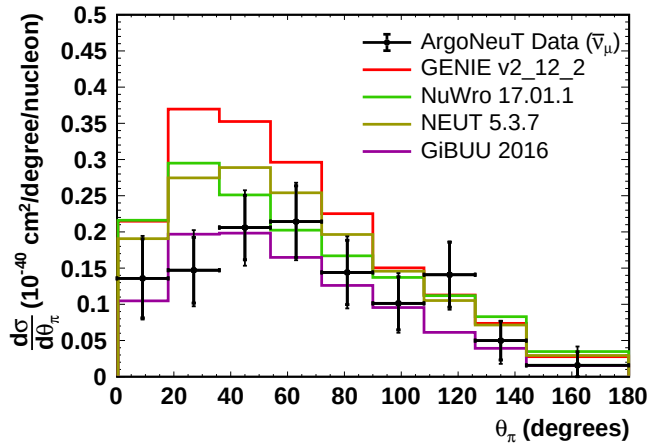


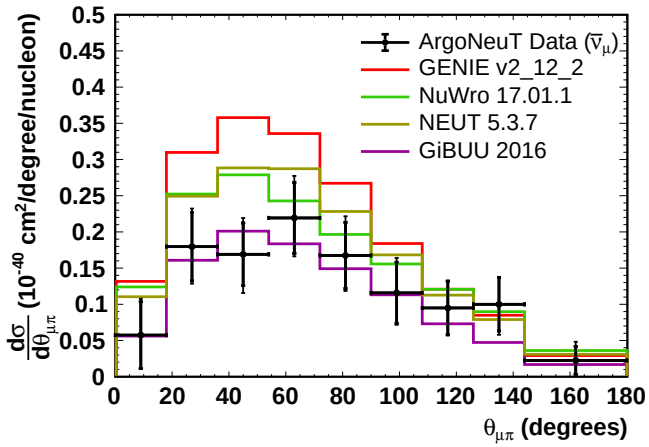


$\bar{\nu}_\mu$ CC1$\pi^\pm$ cross section results





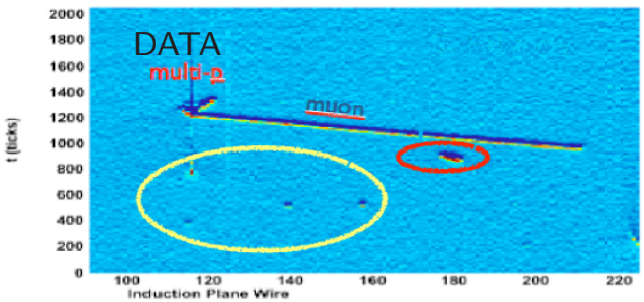


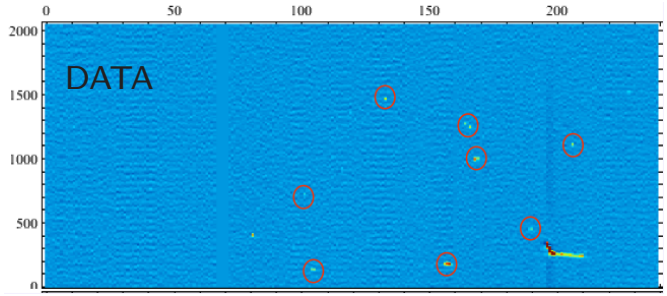


And now, fresh off the press...

γ from nuclear de-excitation?

These images, showcasing the possibility of reconstructing de-excitation gammas, have been around for some time.





Reconstructing low energy gammas crucial for supernova, solar and beam neutrinos.
Also a tool for BSM searches.
Now, we can make a quantitative statement: **arXiv:1810.06502**

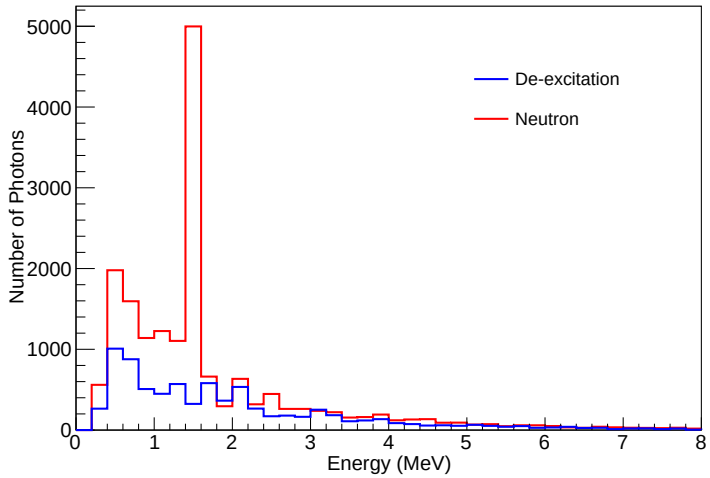
FERMILAB-PUB-18-559-ND

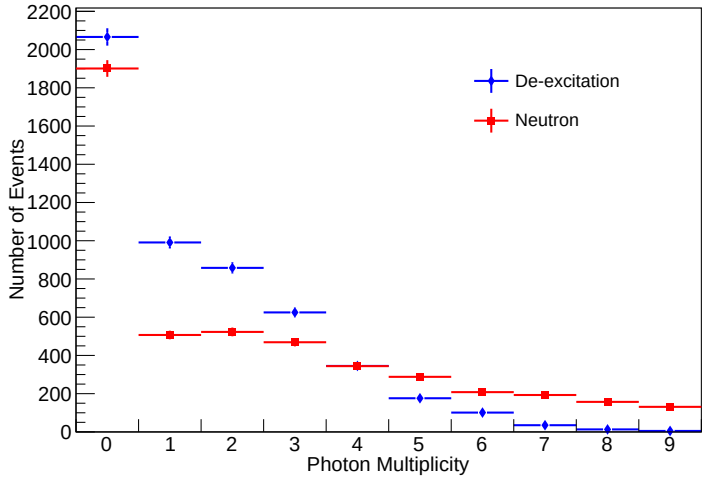
Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT

R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] E. Church,[6] D. Edmunds,[5] A. Ereditato,[7] S. Farooq,[4] A. Ferrari,[8] R.S. Fitzpatrick,[9] B. Fleming,[2] A. Hackenburg,[2] G. Horton-Smith,[4] C. James,[1] K. Lang,[10] M. Lantz,[11] I. Lepetic,[12,*] B.R. Littlejohn,[12,†] X. Luo,[2] R. Mehdiyev,[10] B. Page,[5] O. Palamara,[1] B. Rebel,[1] P.R. Sala,[13] G. Scanavini,[2] A. Schukraft,[1] G. Smirnov,[8] M. Soderberg,[14] J. Spitz,[9] A.M. Szelc,[15] M. Weber,[7] W. Wu,[1] T. Yang,[1] and G.P. Zeller[1]
(The ArgoNeuT Collaboration)

Modelling De-excitation γ in ArgoNeuT

- De-excitation γs should be present in neutrino interactions when the nucleus ends up in an excited state (and have been observed in T2K).
- They can show up as blips (Compton Scatters) in LArTPCs.
- Neutron interactions will look identical - need to consider both.
- To model both of these components, we use FLUKA as it includes de-excitation gammas in its interactions.



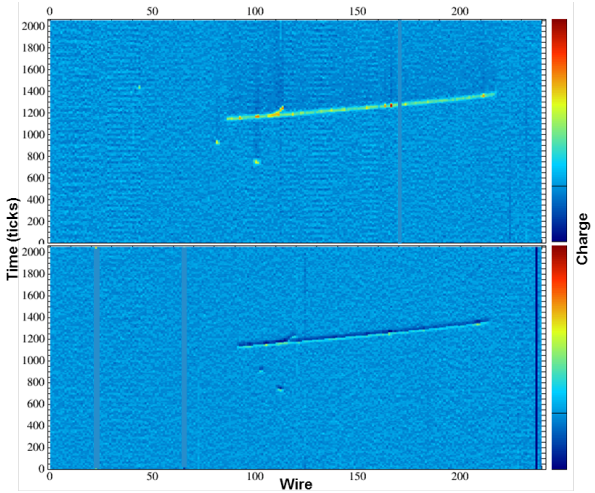


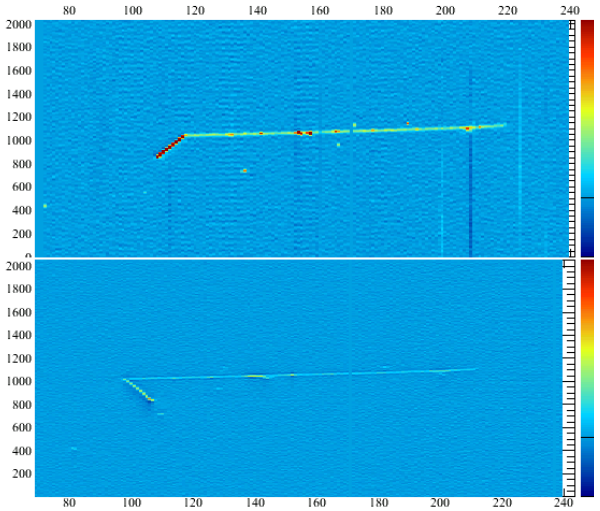
Event Samples Used

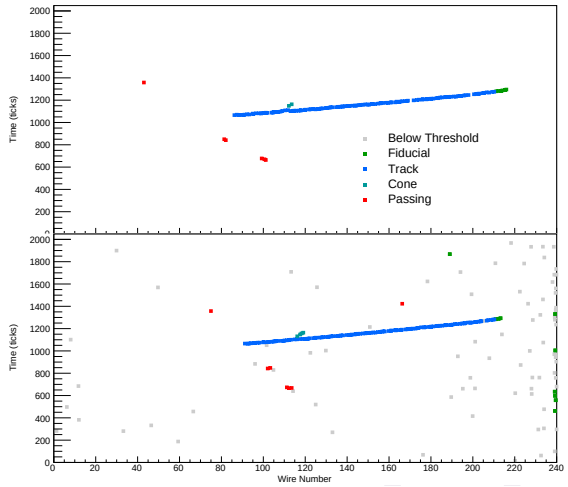
Use the well defined sample of CC $0p$ or $1p$ and 0π and search for de-excitation blips.

Use empty trigger events to remove any intrinsic electronics noise or ^{39}Ar activity.

Blips grouped into charge "clusters". Compare their multiplicity,energy and distance from neutrino vtx with MC Generator predictions.



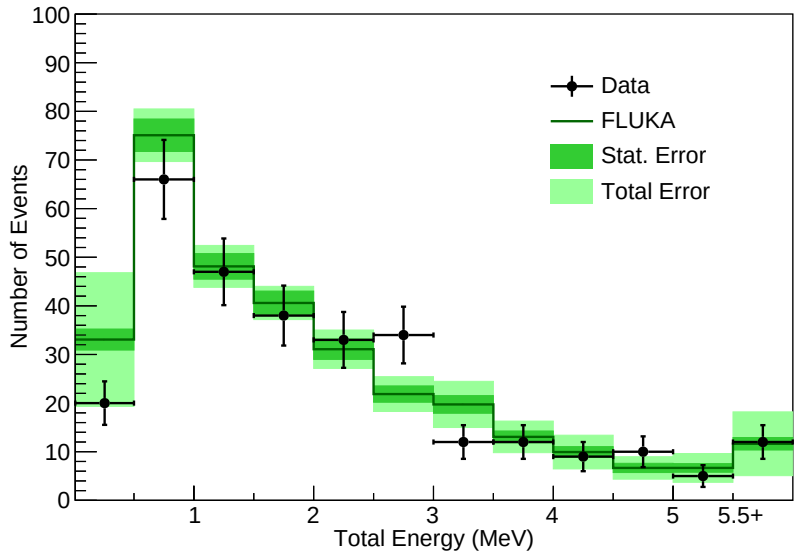




Jumping to results

- We observe a clear surplus of de-excitation gamma/neutron events over the background sample.
- The observed energy spectrum is in good agreement with predictions from FLUKA
- These combine de-excitation photons and neutrons.
- can we tell which one it is?

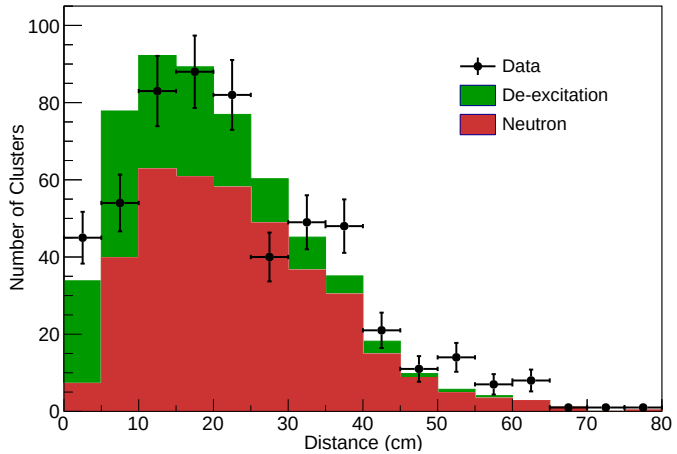
Metric	ν Events	Background
Hits/event	1.30	0.21
Clusters/event	1.00	0.16
Av. Tot. Energy (MeV)	1.11	0.19
Events with > 0 hits	54%	12%
Av. dist. from vtx	22.4	–

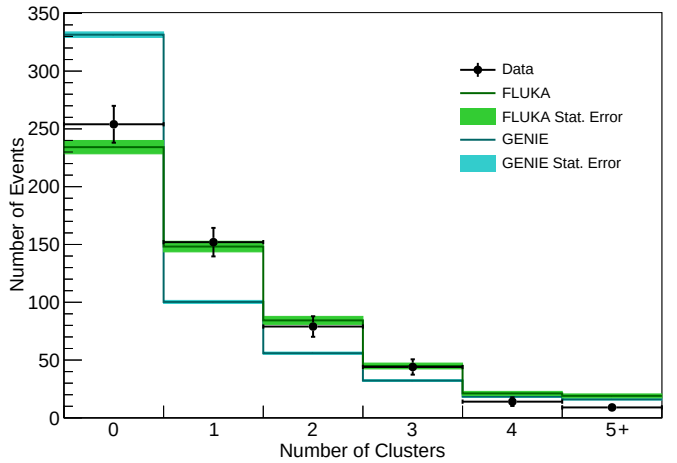


The Nature of the Blips

- Shape comparisons can determine whether the blips are de-excitation gammas or neutron interactions.
- The answer is **both**: removing either component results in significant worsening of agreement.
- Comparison with GENIE (no de-excitation photons) a good example of this. (Using cluster number for comparison as differs more between the two populations)

Full details of this analysis will be presented at Wine & Cheese on November 30th.





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.
- ArgoNeuT is still done running (but kicking).
- First measurements ν_μ and $\bar{\nu_\mu}$ CC $1\pi^\pm$ cross section.
- First reconstruction of de-excitation γs in a LArTPC.
- For current and future adventures of the ArgoNeuT cryostat and TPC, see Elena's talk about the LArIAT TestBeam experiment next.

Thank You

ArgoNeuT Collaboration

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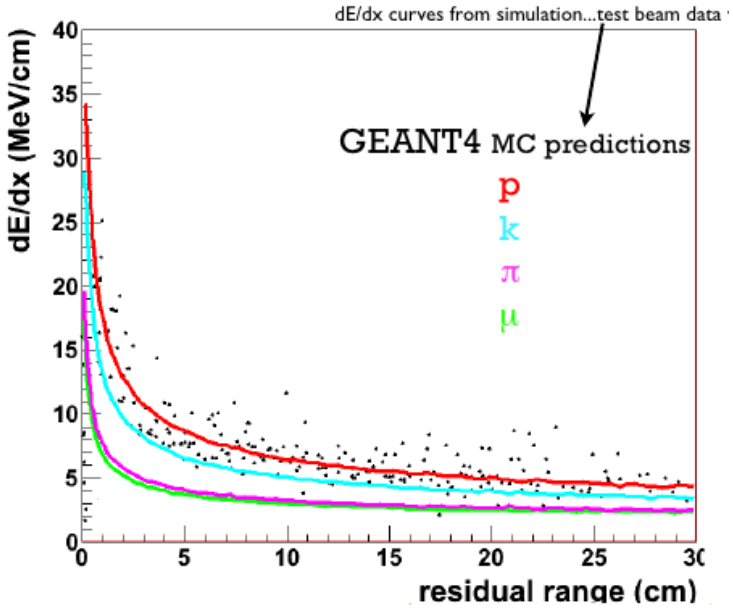
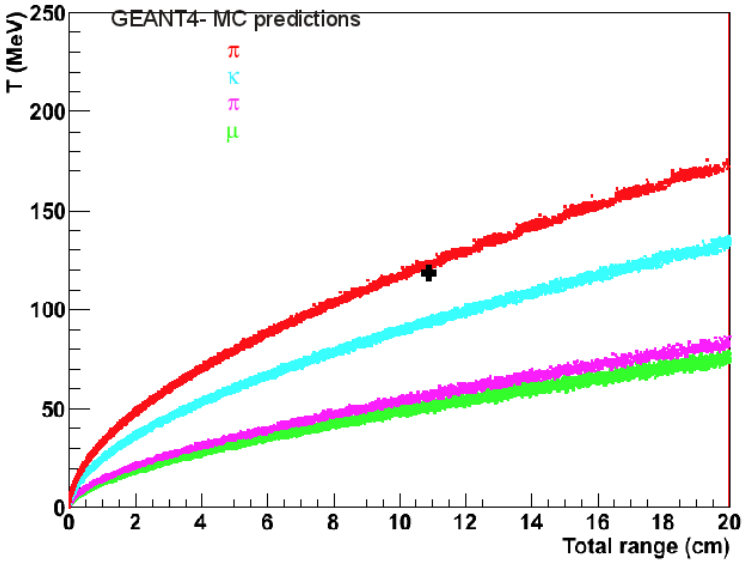
Back Up Slides

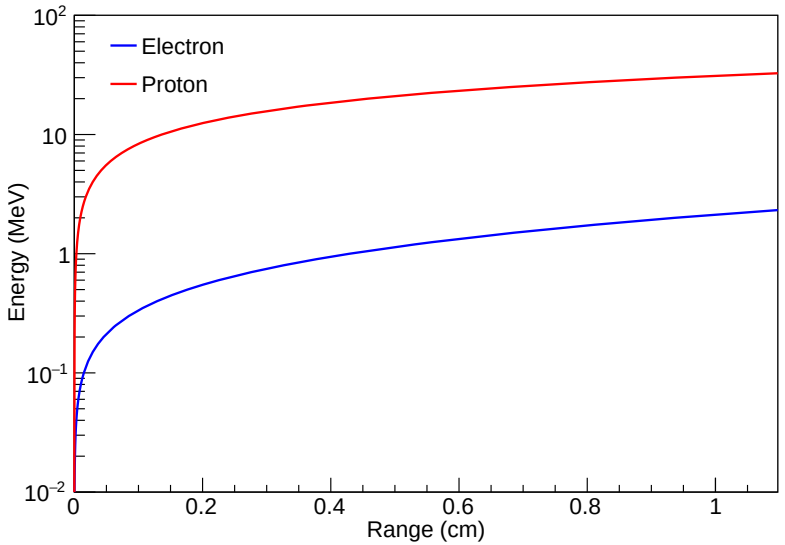
Calorimetry and PID

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



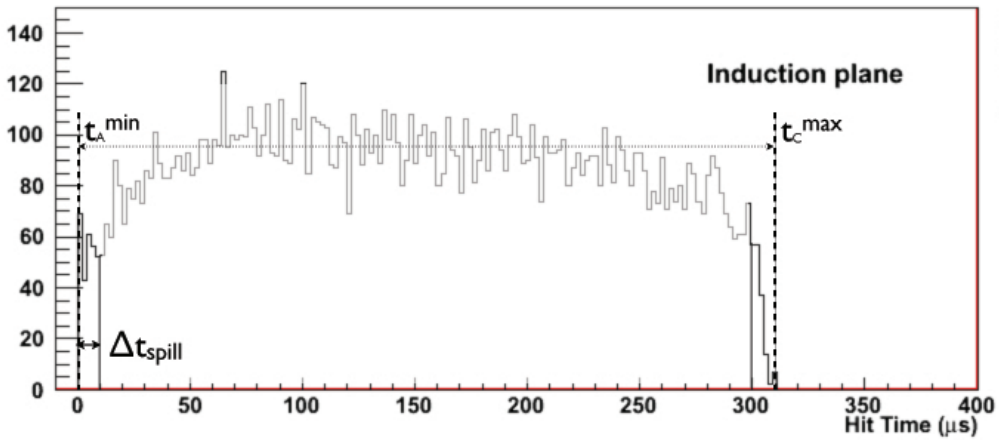


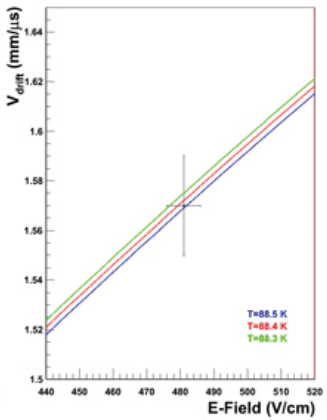
Low Energy Reconstruction



Measurement of electron drift speed

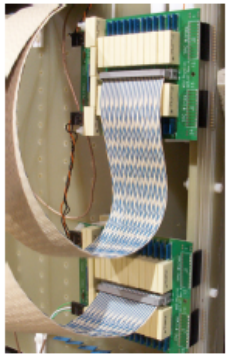
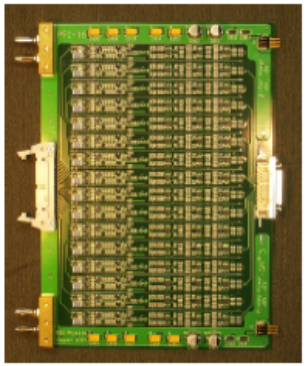
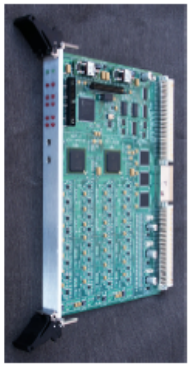
- Measurement of electron drift velocity confirms understanding of detector.
- Difference of maximum and minimum hit drift gives time.
- Distance is size of detector
- Corrected for different field strengths between planes.



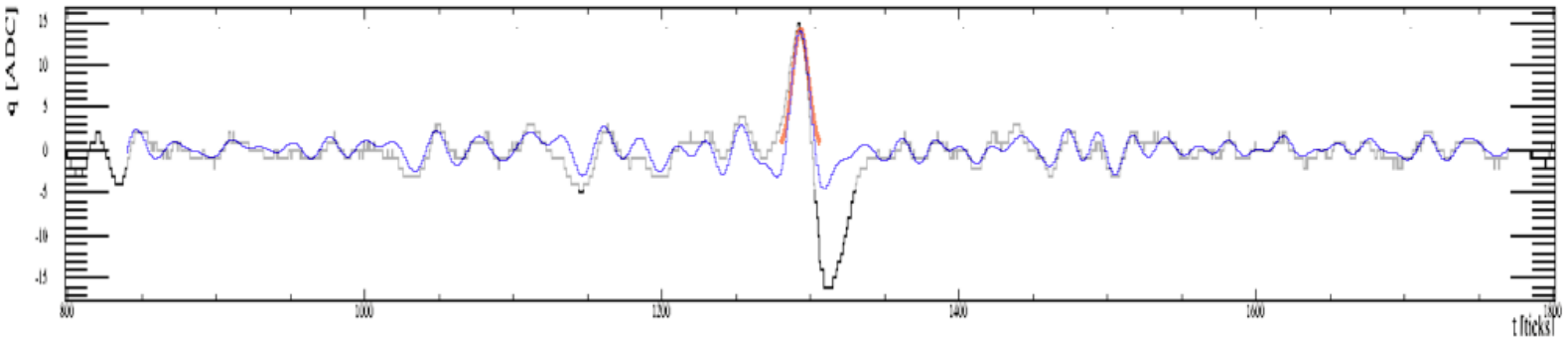


ArgoNeuT Electronics

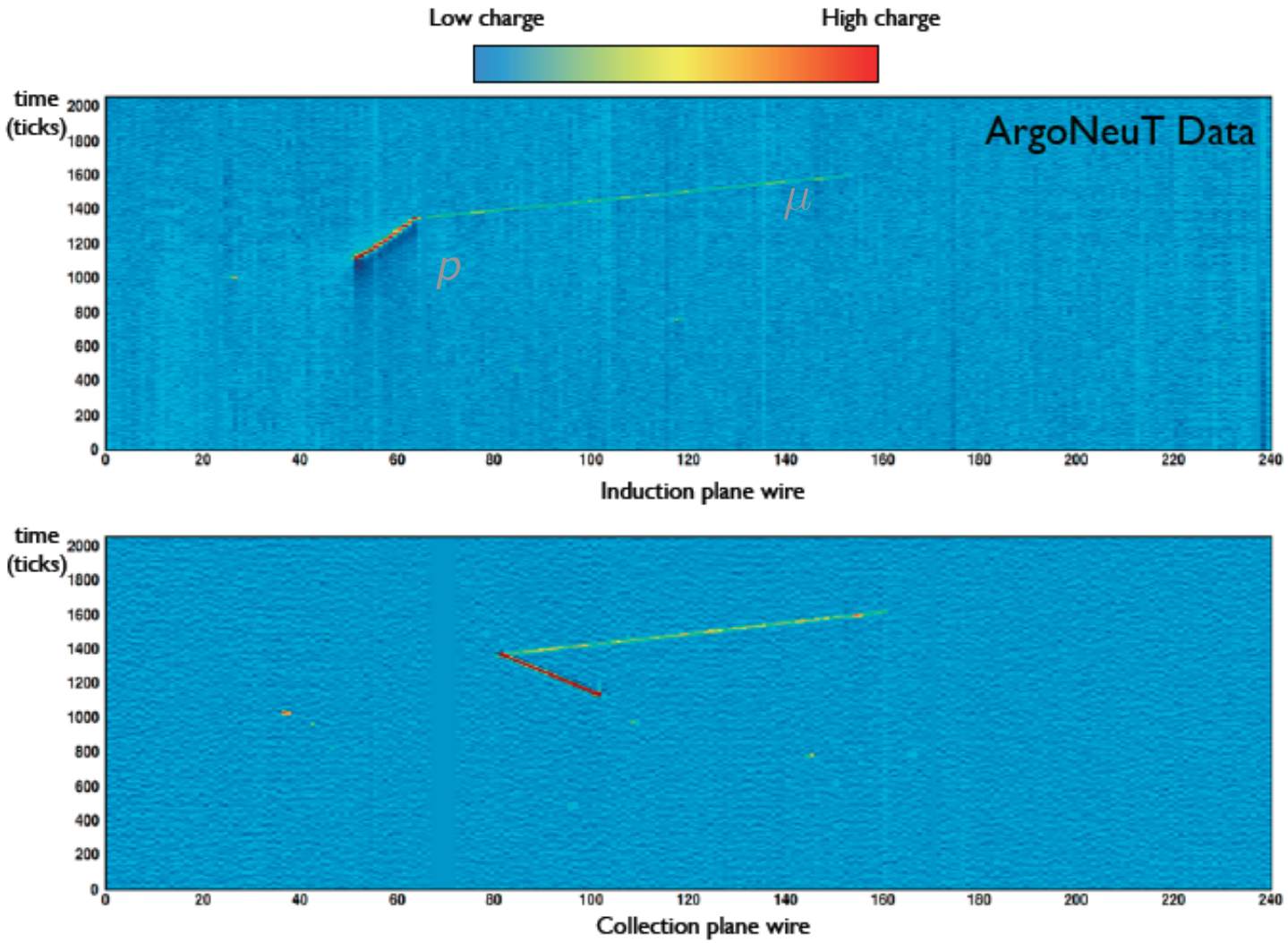
- "Warm" JFET Preamplifiers
- Shaped signal registered by ADF-2 ADCs
- Currrent trend is to go with lower noise, cold CMOS electronics (MicroBooNE, LBNE)

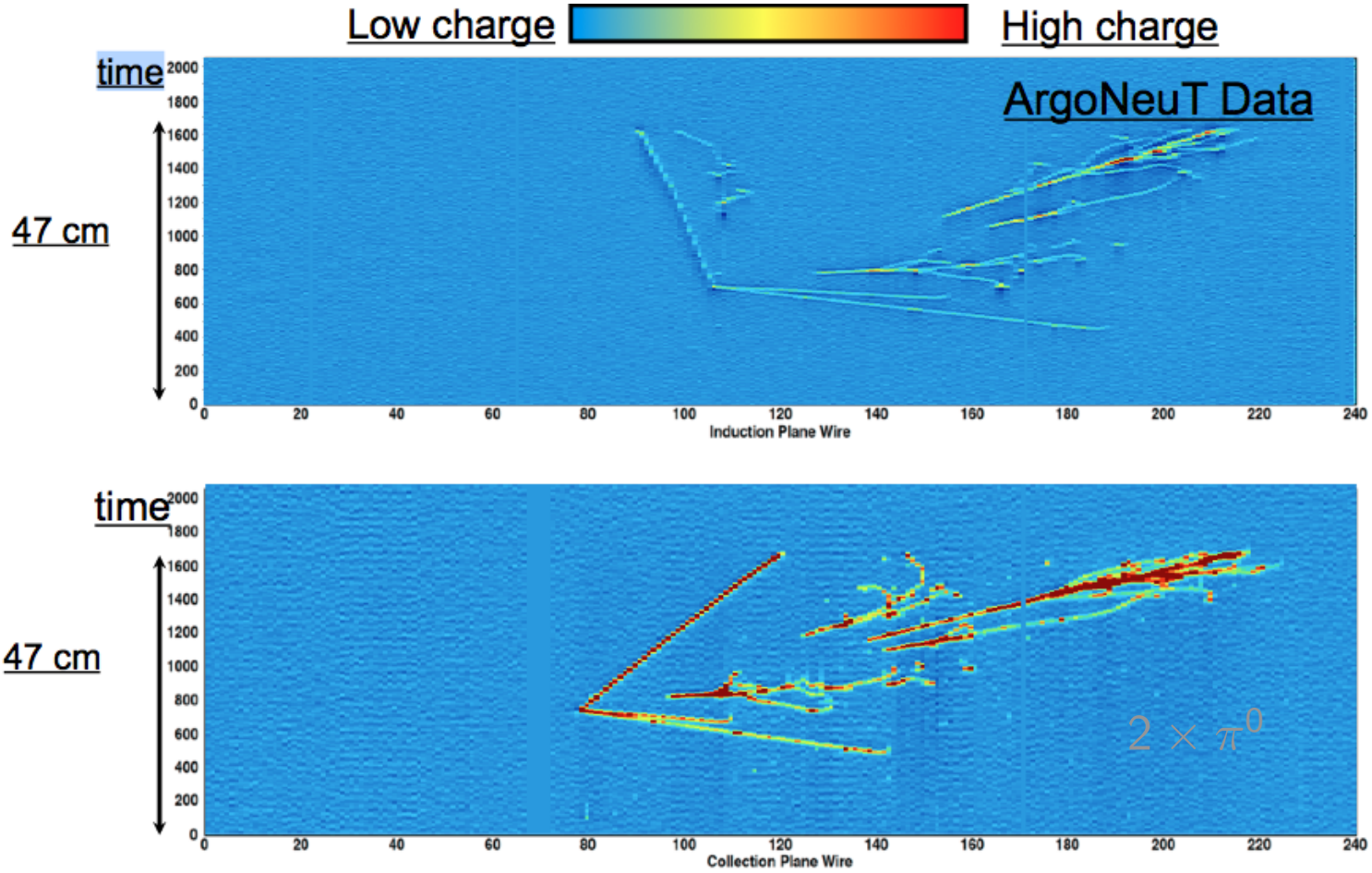
PreAmp stage - FET Voltage Gain	0.5 mV/fC
Digitizer Module (ADF-2)	
ADC range	10 bit
ADC Gain	0.1881 ADC/mV
Sampling Time (FPGA)	δt=198 ns (0.03cm)
Electronics Charge Sensitivity	7.49 ADC/fC
Tot. Capacitance (Det. and Cables)	230 pF
Response to mip (Coll. wires)	$S/N \geq 15$



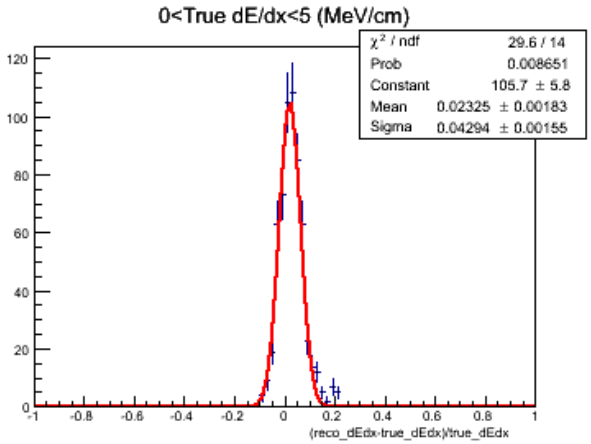
ArgoNeuT Events (1)

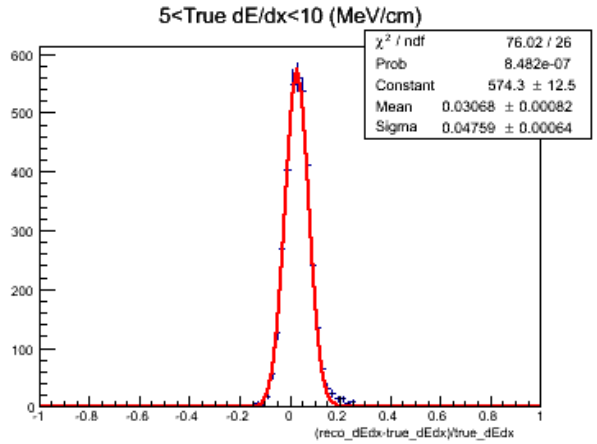


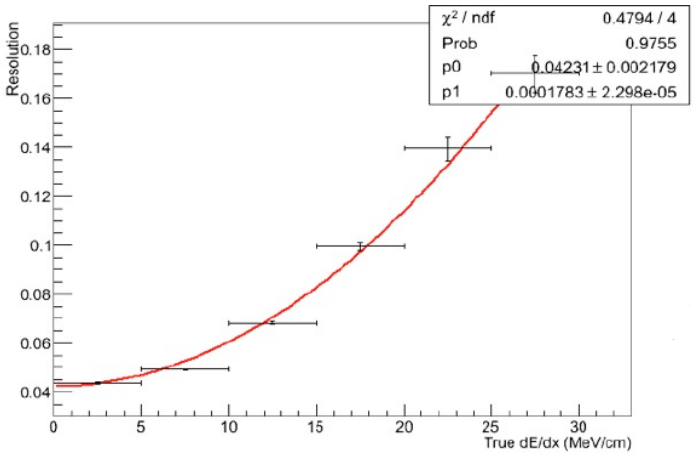
ArgoNeuT Events (2)



Energy resolution







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