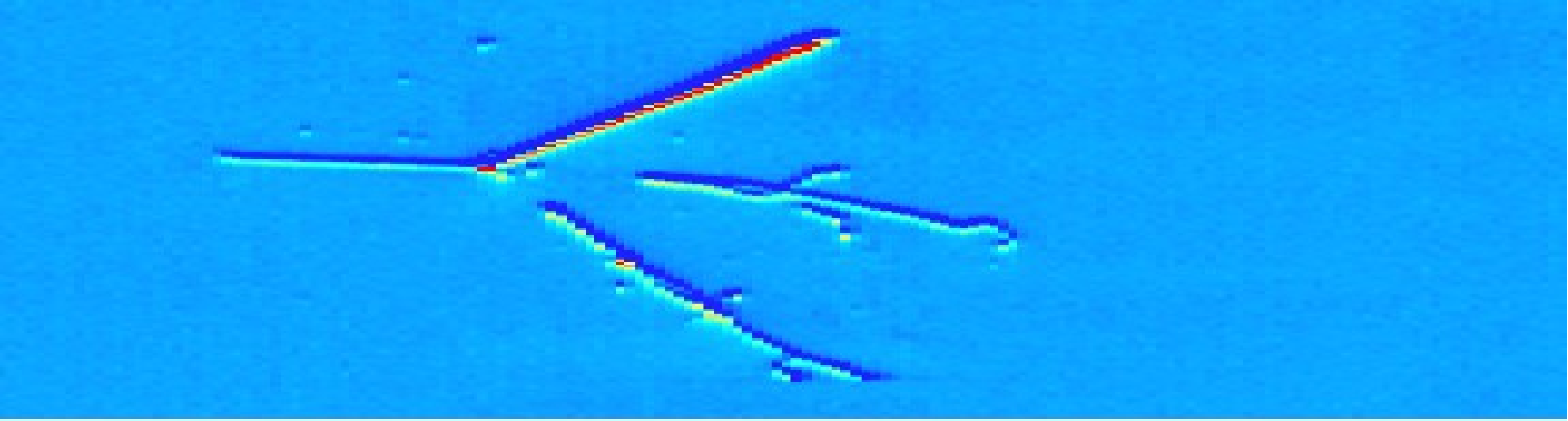


LArIAT

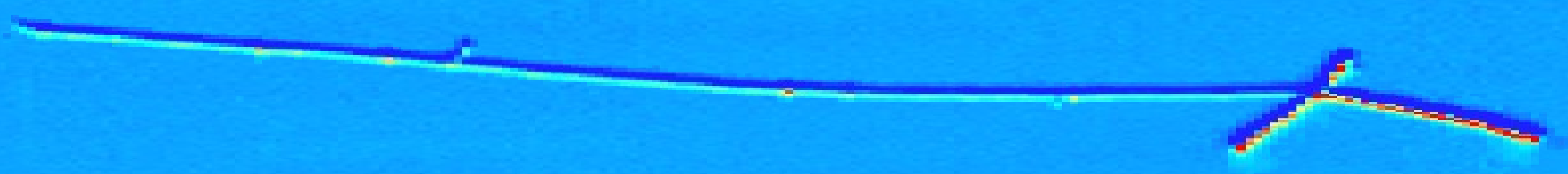
Liquid **Ar**gon TPC **I**n **A** **T**estbeam

First Total π-Ar Cross Section Measurement

Jonathan Asaadi

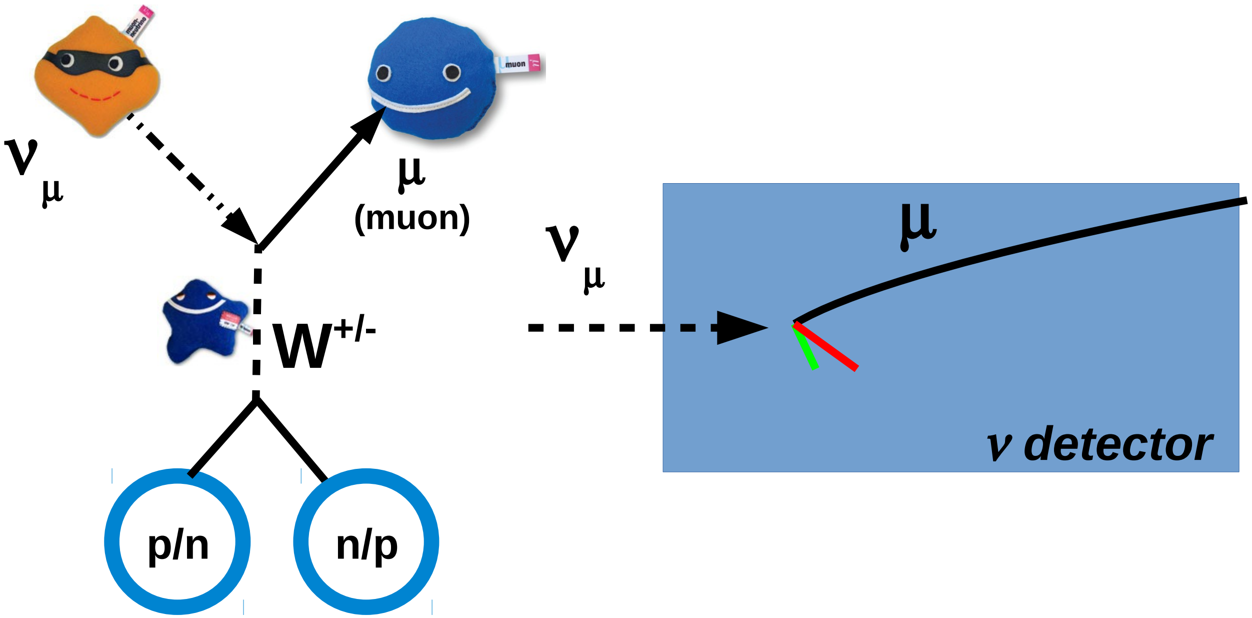
University of Texas Arlington

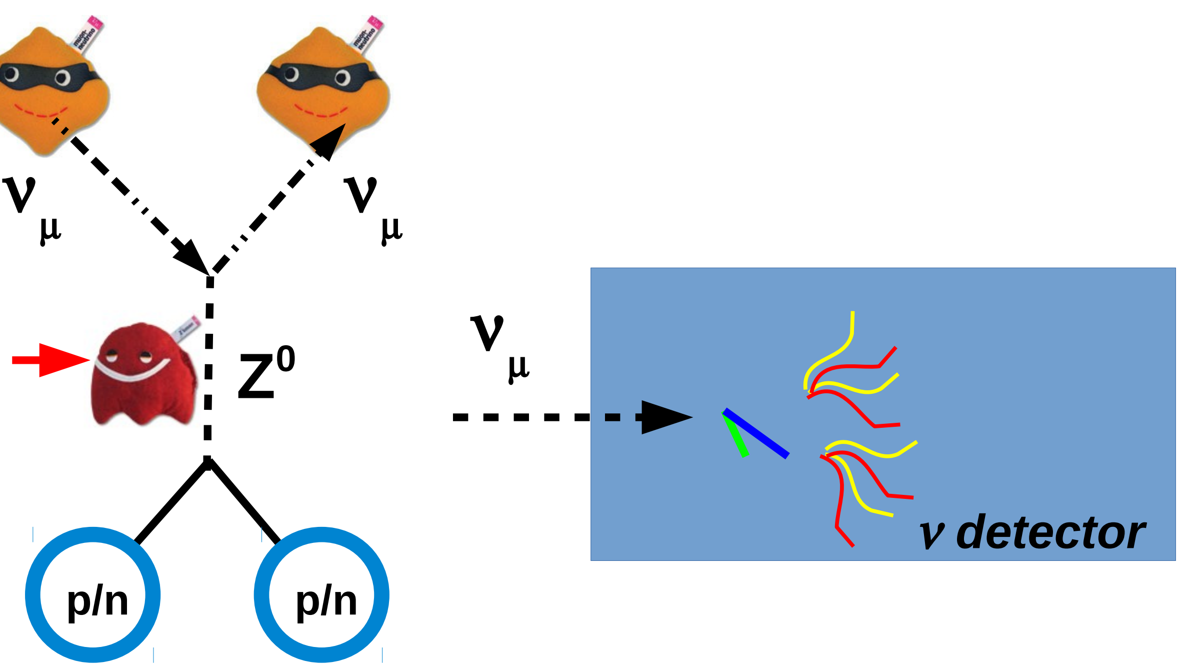
On behalf of the LArIAT Collaboration



Fermilab Wine & Cheese Seminar April 8, 2016

Motivation: Needs of ν-experiments





- **Simplified view of how we do neutrino experiments goes like:**
  - Fire a beam of neutrinos into your detector
  - Detect the particles that come out from the interaction
  - Reconstruct the information about the neutrino
- **But we all know that the world is a much more complicated place....**

Motivation: Needs of ν-experiments

Typical neutrino event

Outgoing lepton:

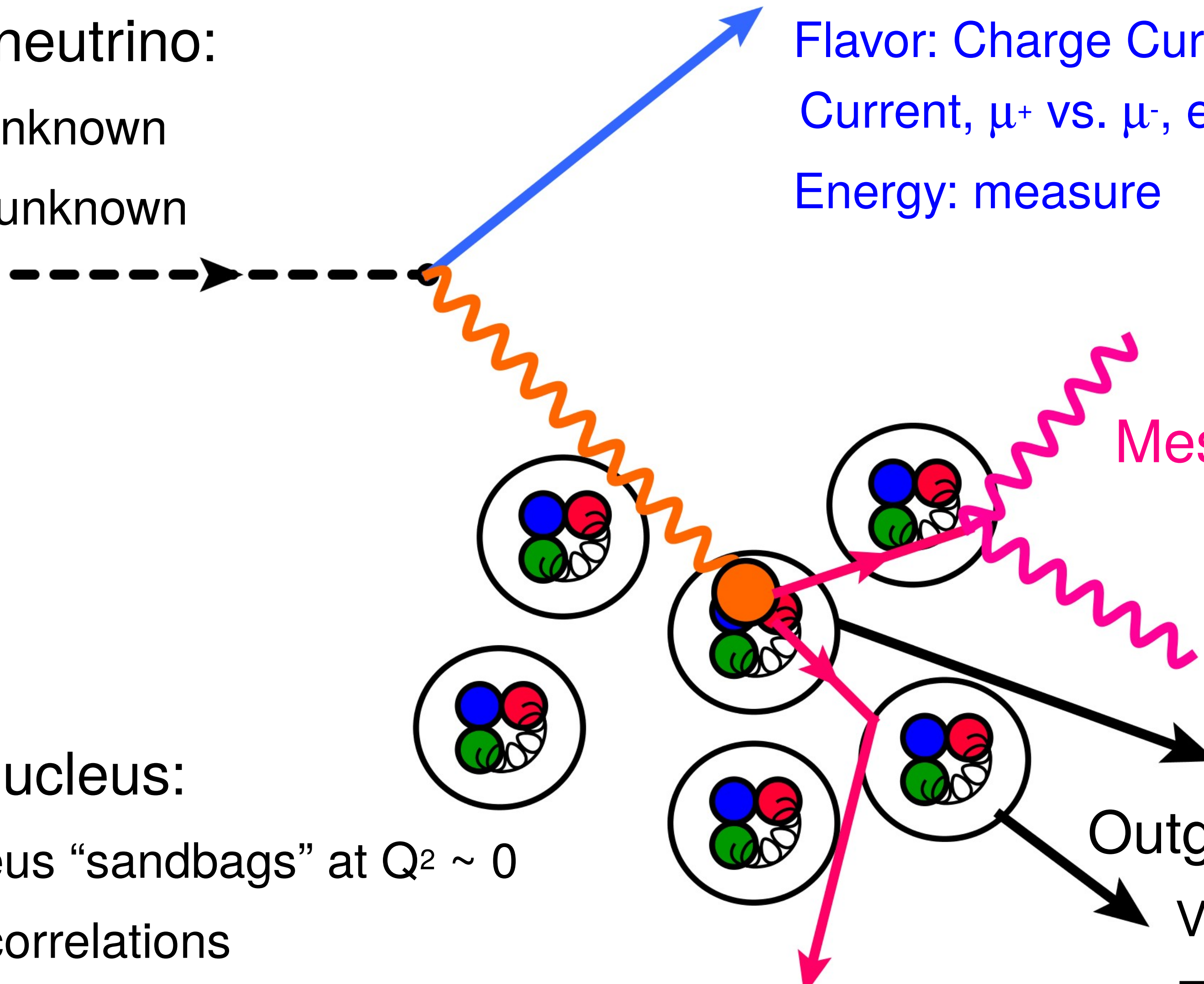
Flavor: Charge Current vs. Neutral Current, μ^+ vs. μ^-, e vs. γ

Energy: measure

Incoming neutrino:

Flavor unknown

Energy unknown



Mesons:

Final State Interactions!

Energy? Identity?

Target nucleus:

Nucleus “sandbags” at $Q^2 \sim 0$

N-N correlations

Outgoing nucleons:

Visible?

Energy?

Liquid Argon Time Projection Chamber

Liquid Argon is an excellent choice for neutrino detectors:

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	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
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Note: This table was first produced by Mitch Soderberg and if he had patented it he would have 10's of dollars because it shows up in every LAr talk I've ever seen!

→ Dense

40% more dense than water

→ Abundant

1% of the atmosphere

→ Ionizes easily

55,000 electrons / cm

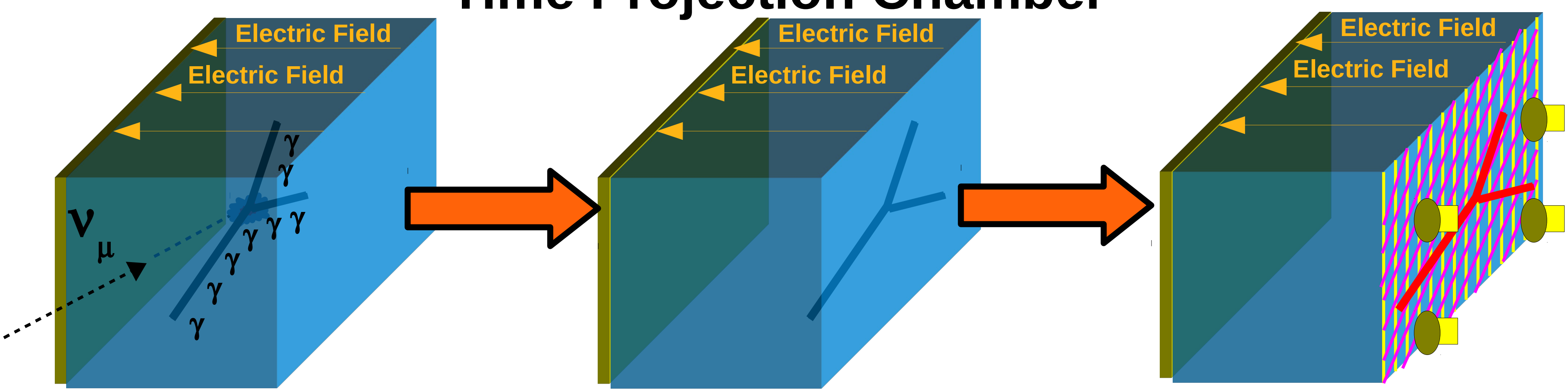
→ High electron lifetime

Greek name means "inactive"

→ Produces copious scintillation light

Transparent to light produced

Time Projection Chamber

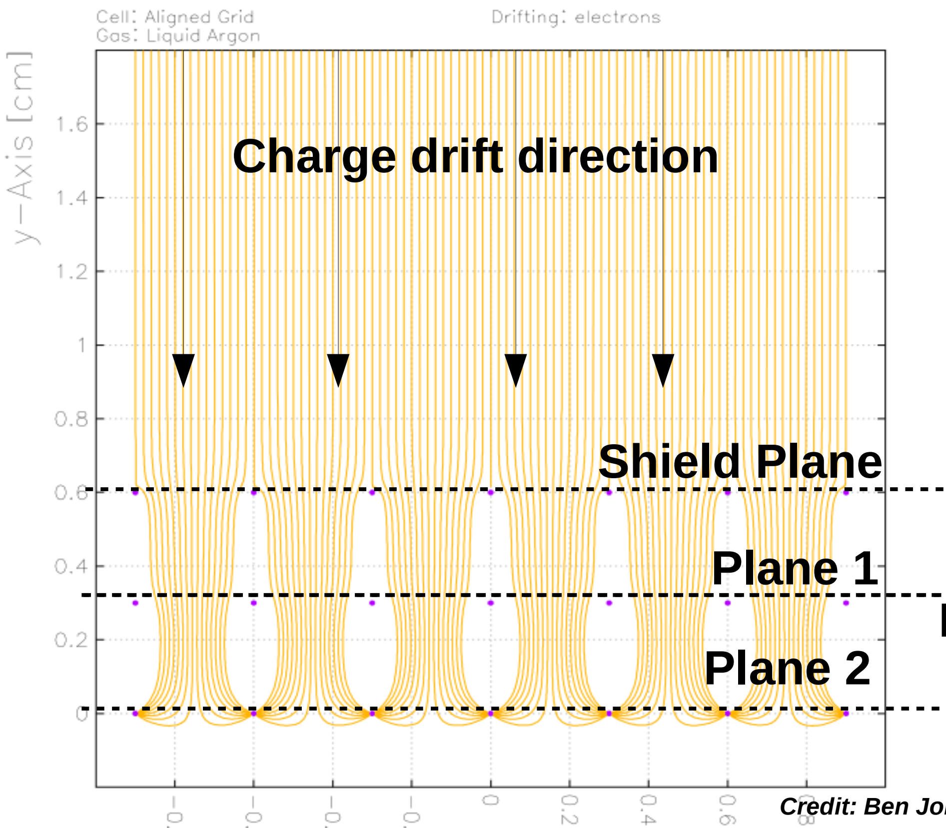


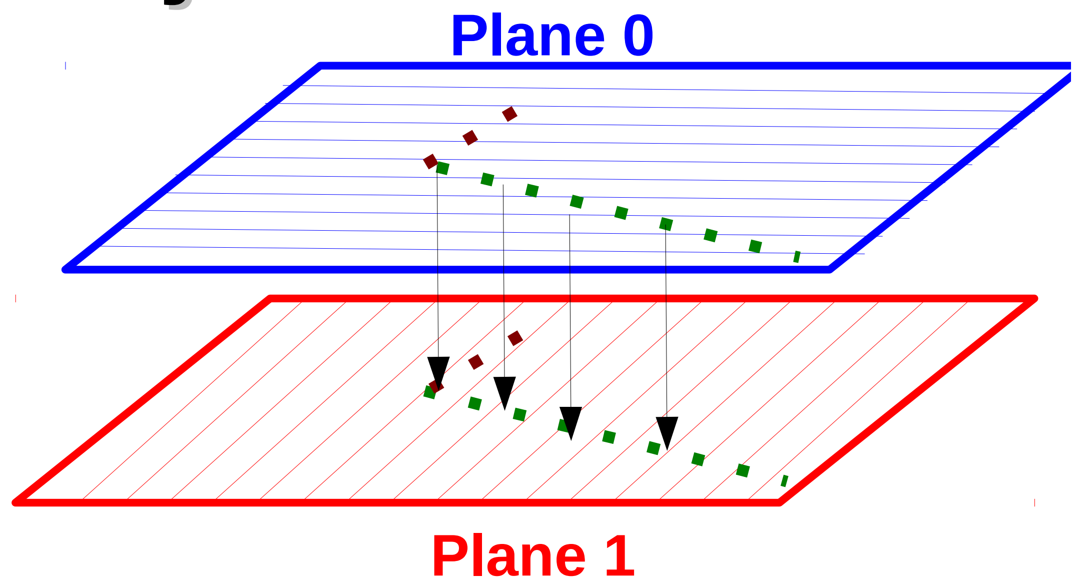
Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

Read out charge and light produced using precision wires and PMT's

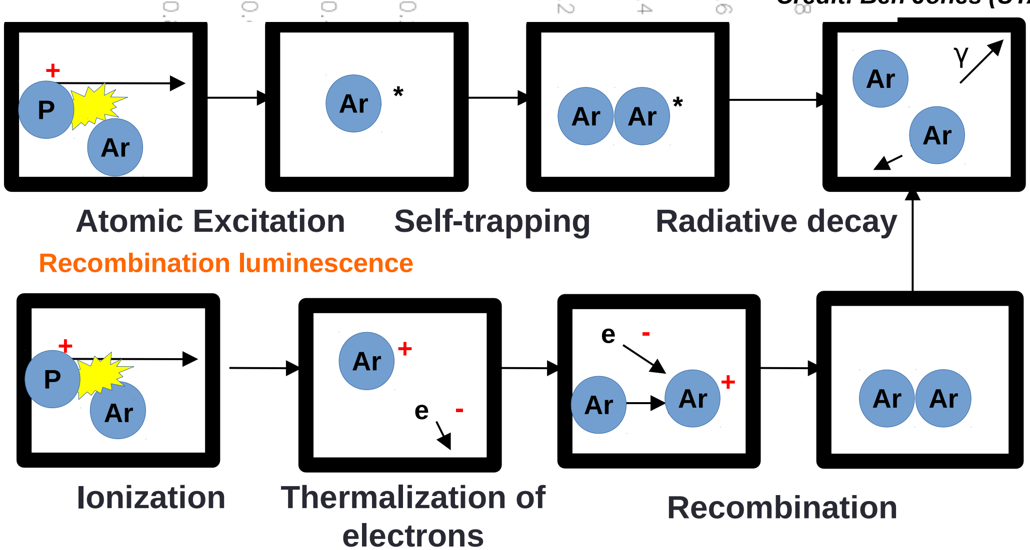
Liquid Argon Time Projection Chamber

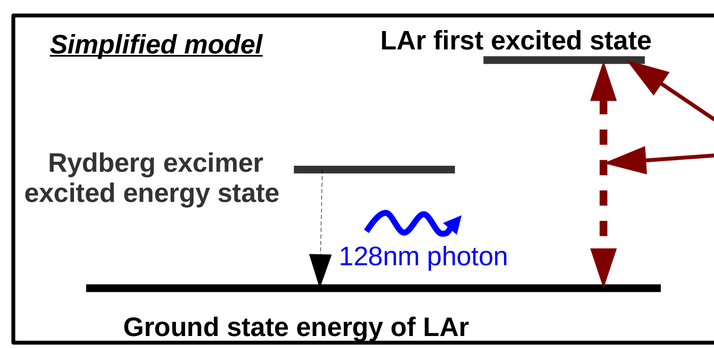




Matching charge locations across different angled wire planes allows for 3d reconstruction

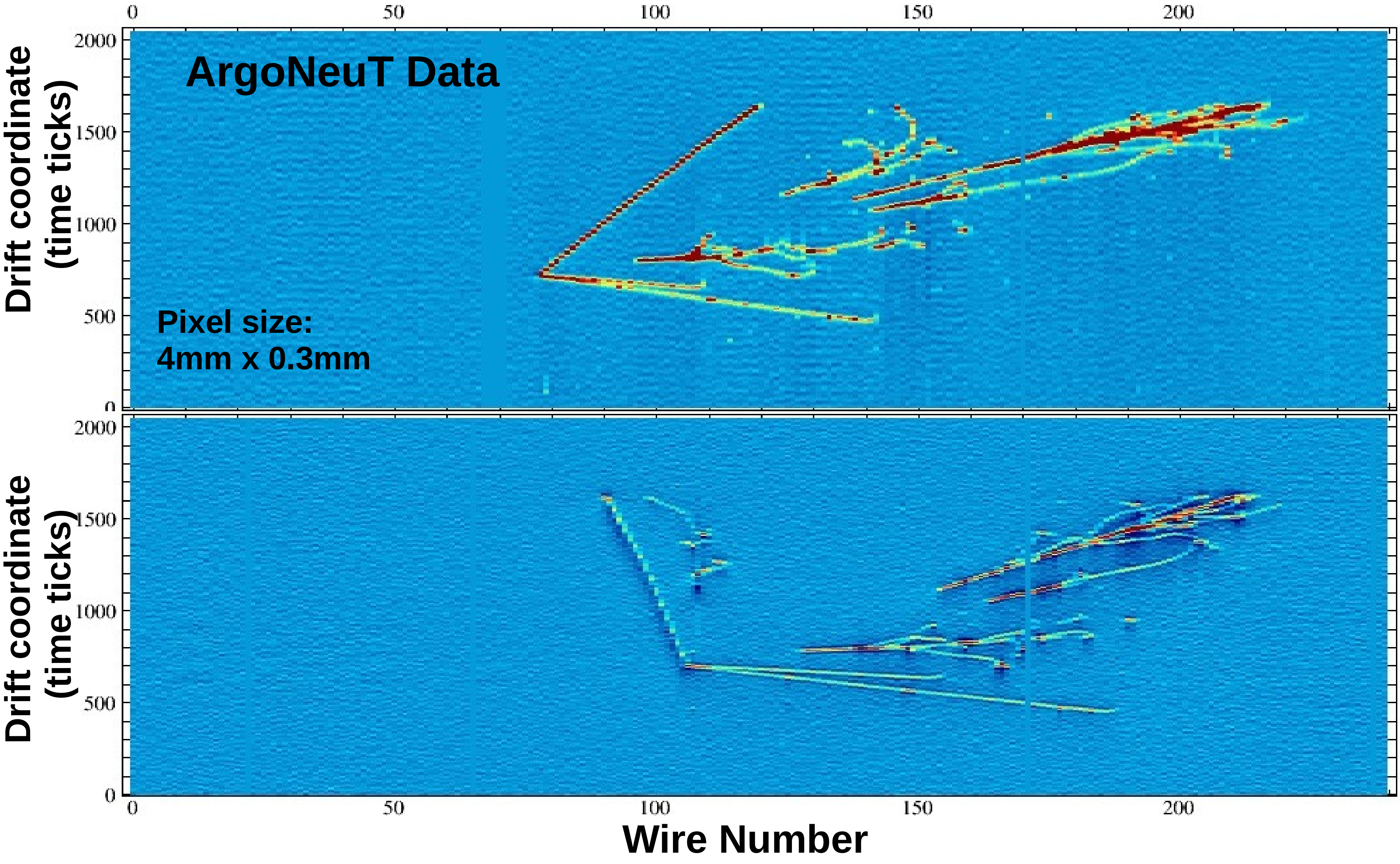
Credit: Ben Jones (UTA) for image



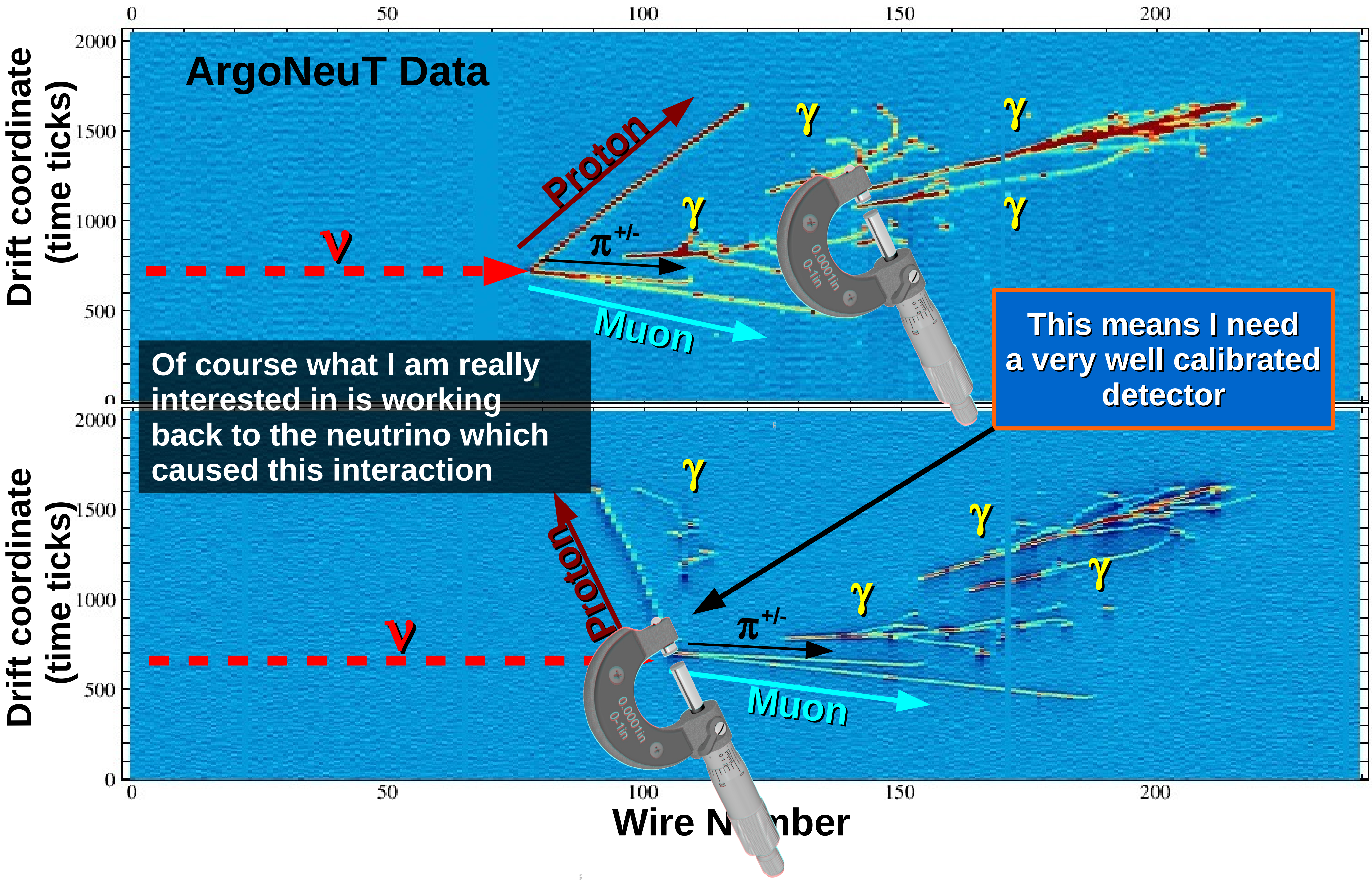


This difference between the energy levels is why LAr is transparent to the scintillation light it produces

Liquid Argon Time Projection Chamber

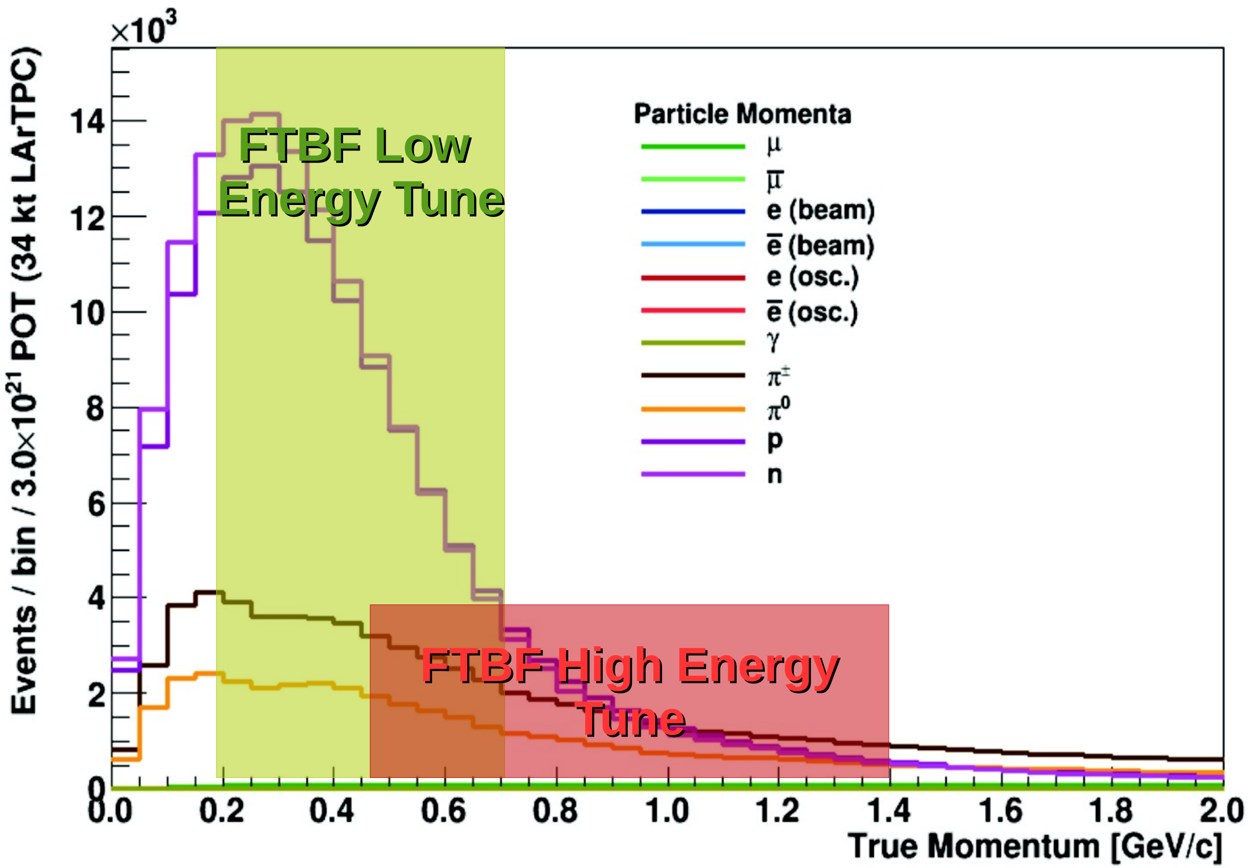


Liquid Argon Time Projection Chamber



Motivation: Needs of ν-experiments

- **A LArTPC in the Fermilab Test Beam Facility is well suited to study charged particles in the energy range relevant to both the short-baseline (uBooNE, SBND, ICARUS) and Long-Baseline (DUNE) experiments**



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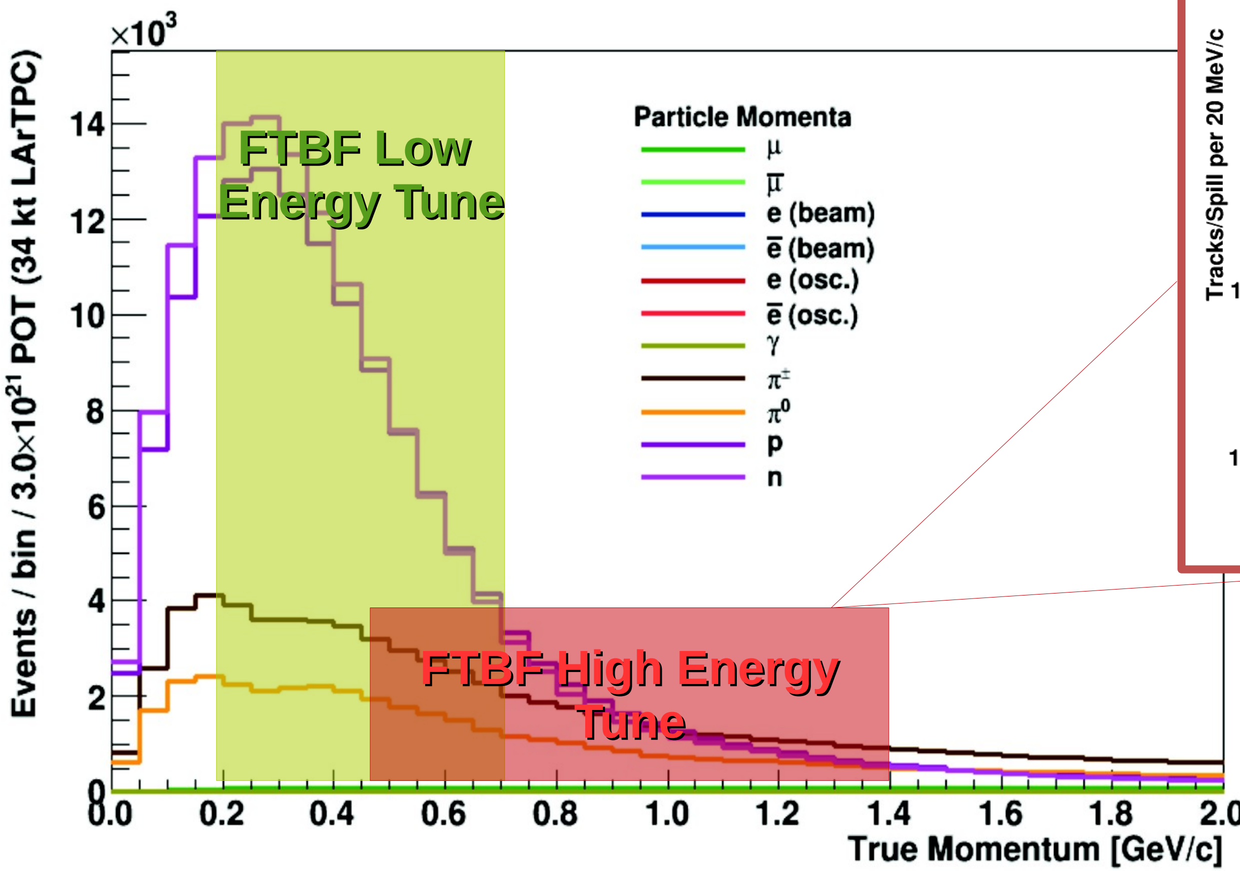
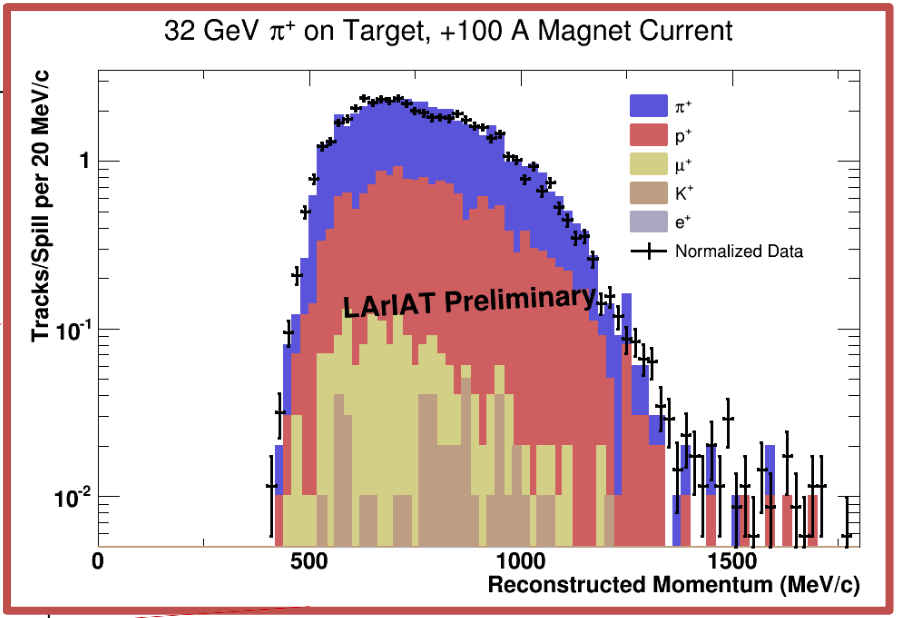
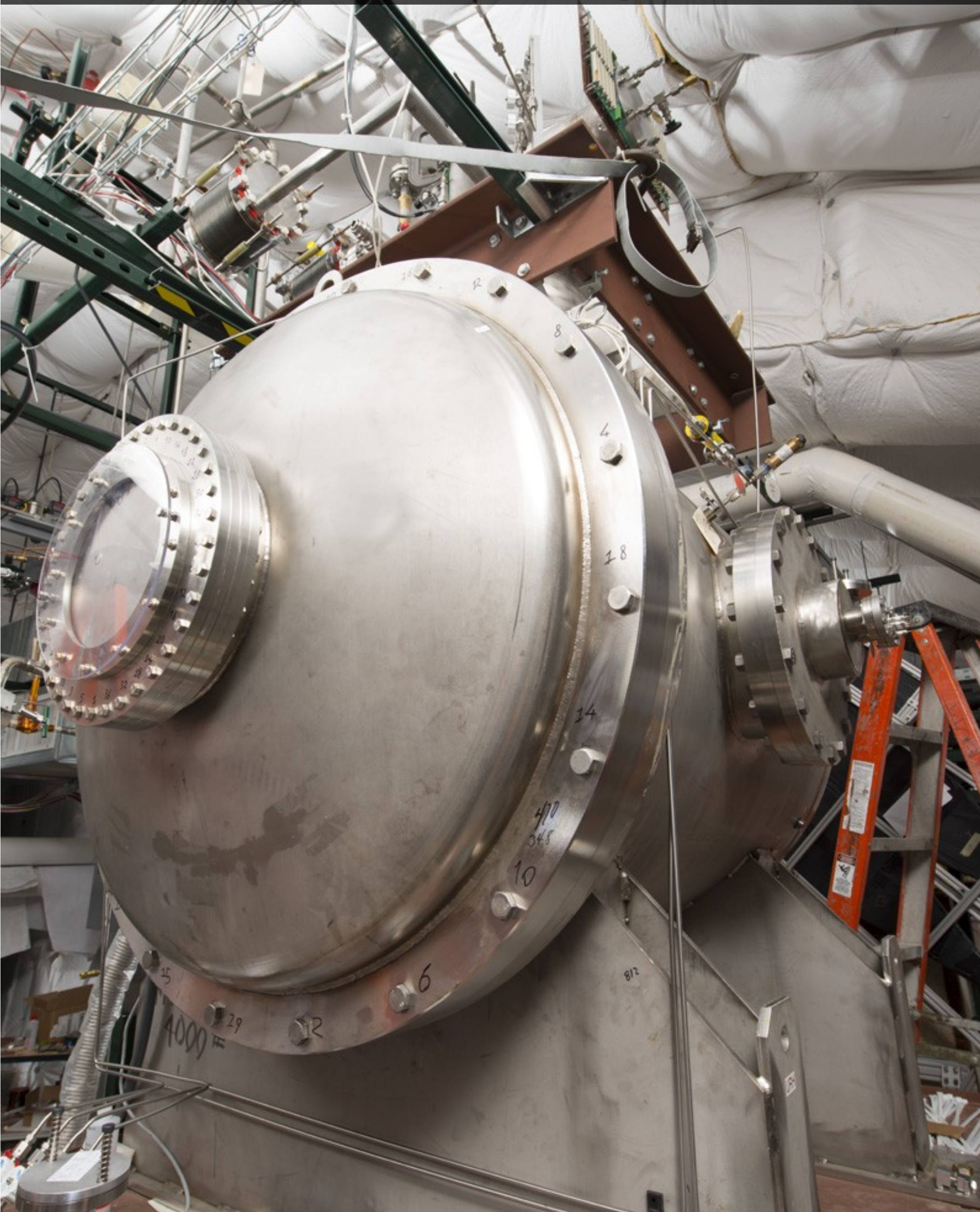




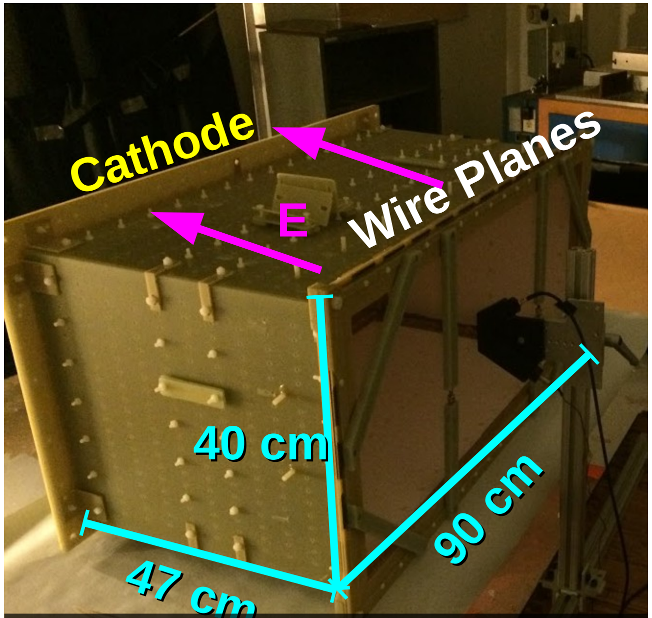
Calibrating a new particle detector



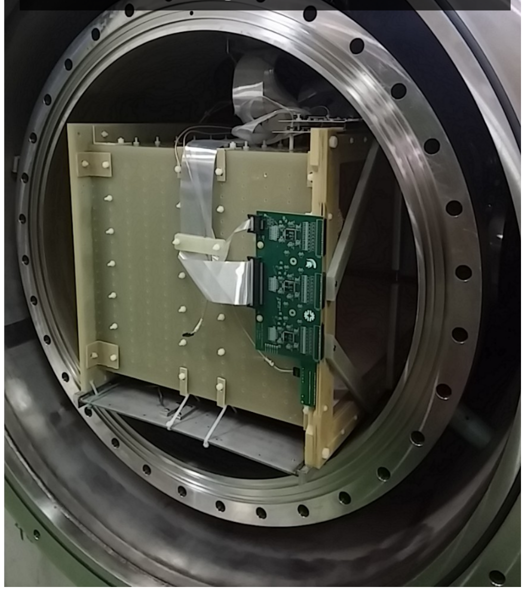
Executing a comprehensive program designed to characterize LArTPC performance in the energy range relevant to the forthcoming neutrino experiments

LArIAT: Liquid Argon In A Testbeam

LArIAT



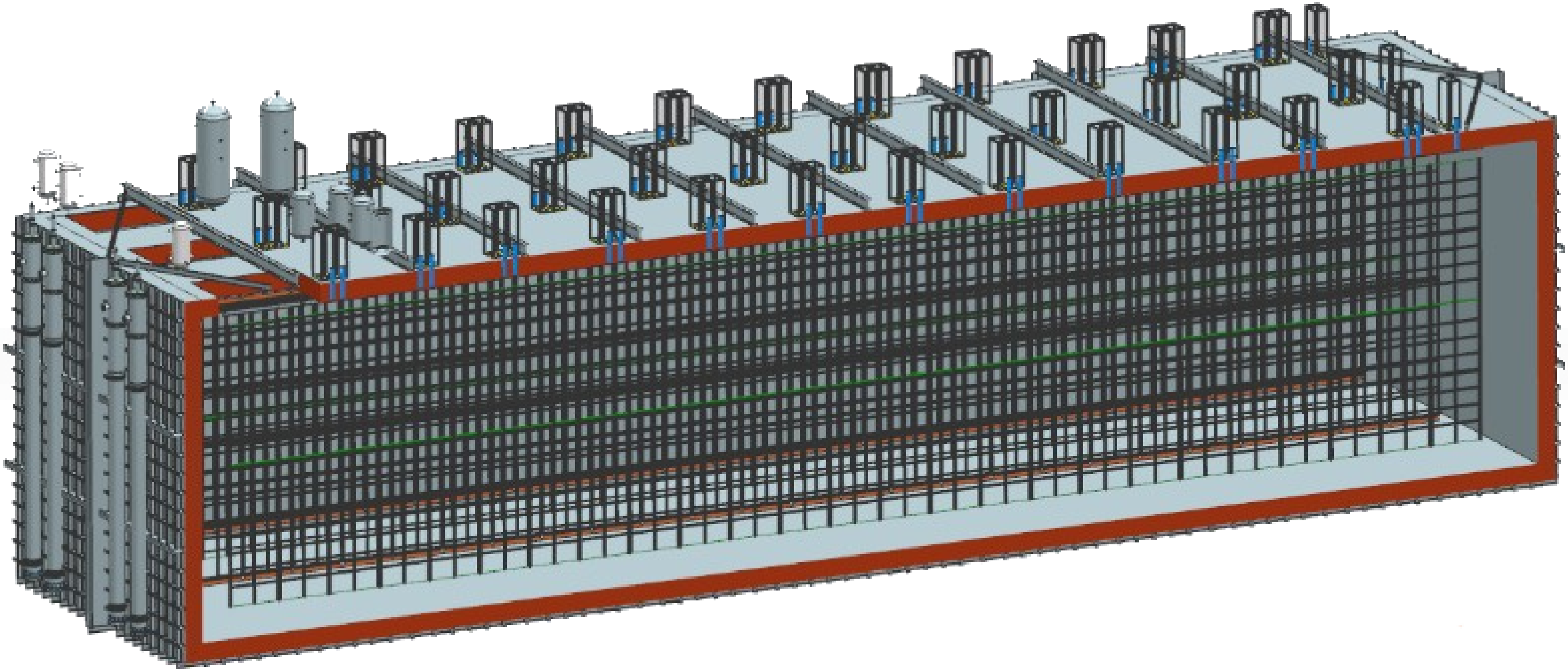
LArIAT TPC before installation


LArIAT TPC inside the cryostat

LArIAT is small (170 liters {0.25 tons} of Ar) LArTPC designed for calibrating detector response in a charged particle beam

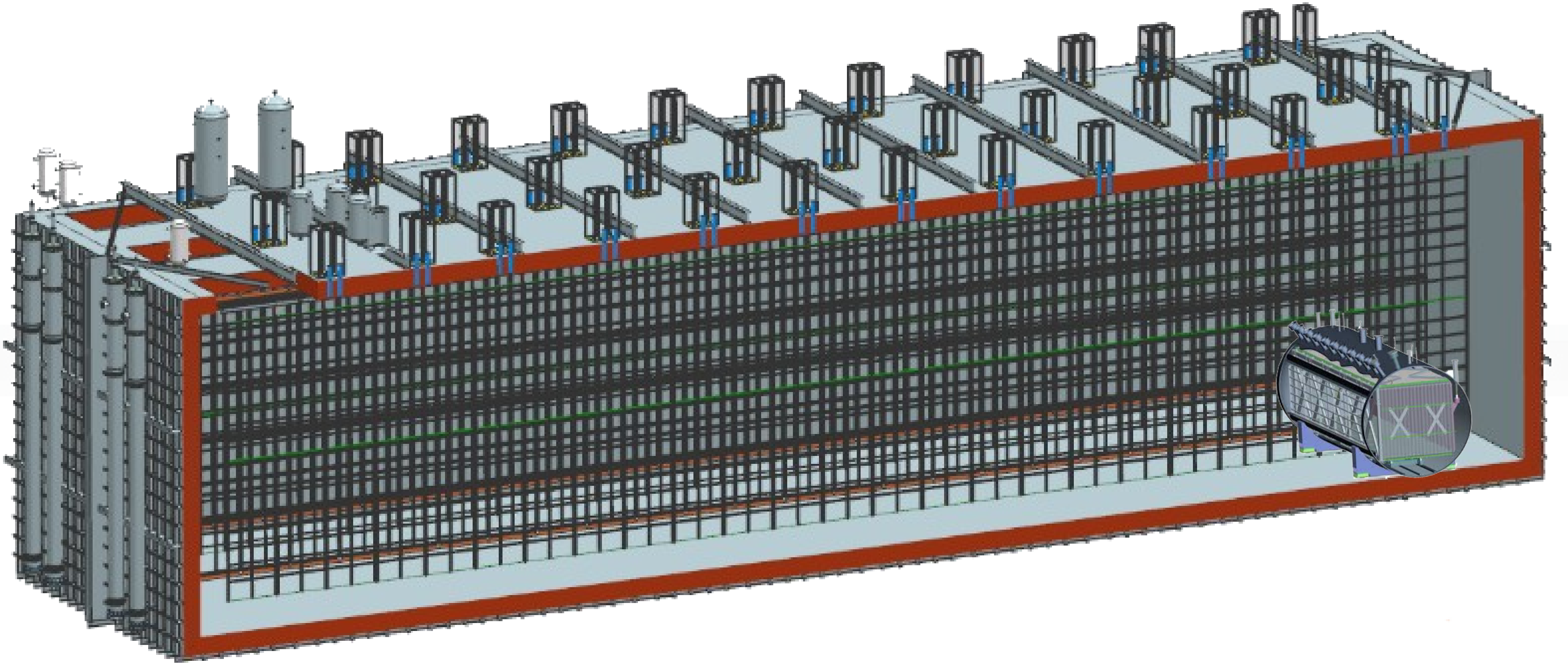
- **Physics Goals**
  - Hadron-Ar interaction cross sections
  - Study of nuclear effects in Ar
  - e/γ shower identification
  - Particle sign determination in the absence of a magnetic field, utilizing topology
    - e.g. decay vs capture
  - Geant4 validation
- **R&D Goals**
  - Ionization and scintillation light studies
    - Charge deposited vs. light collected for stopping particles of known energy
  - Optimization of particle ID techniques
  - LArTPC event reconstruction

The Scale of Things....



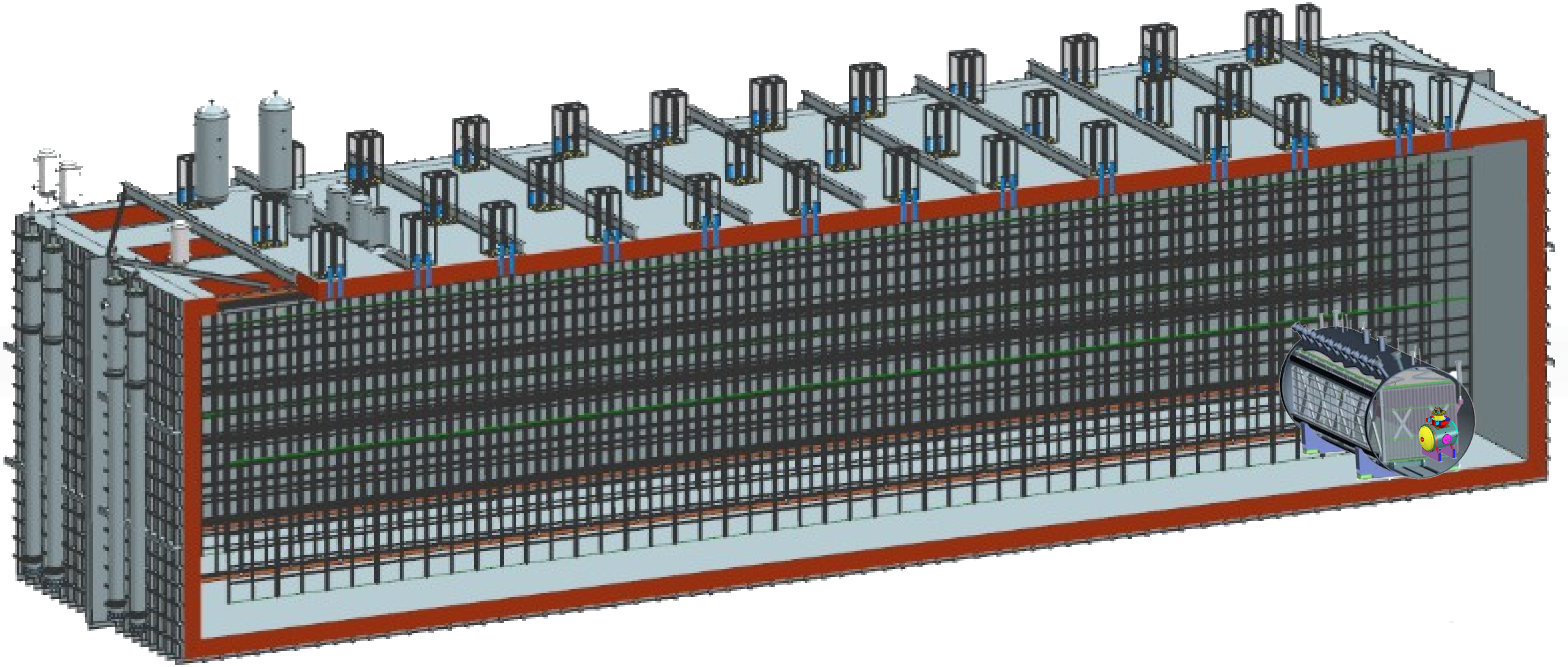
- **One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)**
  - ¼ the total size of DUNE

The Scale of Things....



- **One MicroBooNE TPC (80 tons) (2.2 m x 2.5 m x 10 m)**
  - Largest operating LArTPC in the US

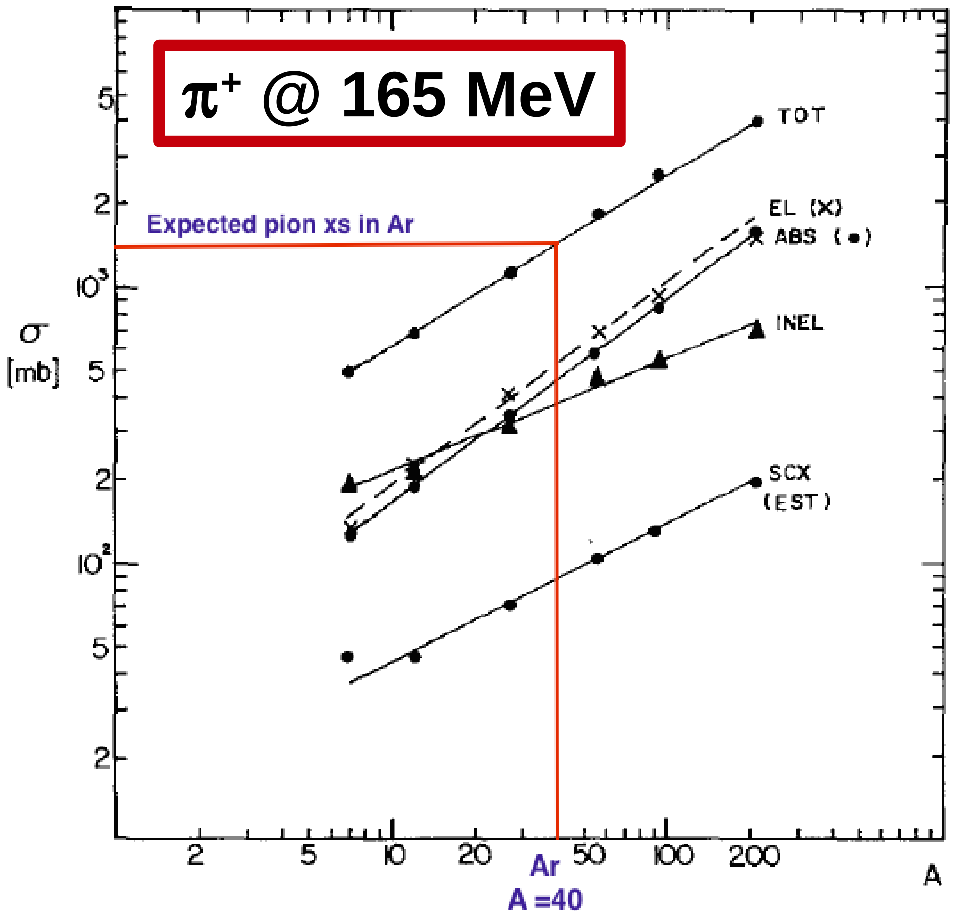
The Scale of Things....



- **One LArIAT TPC (0.25 tons) (0.4 m x 0.47 m x 0.9 m)**
  - Small detector with a big heart!

π-Ar Cross-Sections

D. Ashery et al. Phys. Rev. C23, 2173 (1981)



$$\sigma_{tot} = \sigma_{el} + \sigma_{reac}$$

$$\sigma_{reac} = \sigma_{inel} + \sigma_{abs} + \sigma_{chex} + \sigma_{\pi prod}$$

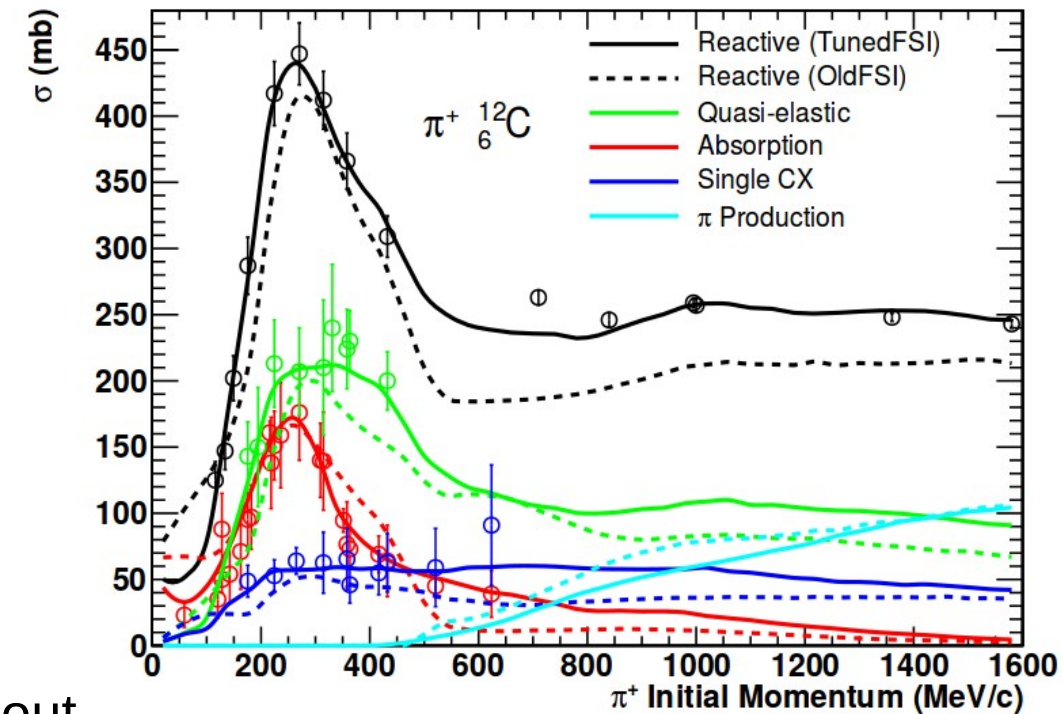
- **No measurement for Argon (until today!)**
- **Predictions come from interpolation between lighter and heavier nuclei**
- **LArIAT's Measurements:**
  - Total π-Ar interaction cross-section
  - Exclusive π-Ar interaction channels
    - Absorption
    - Charge Exchange
    - Inelastic & Elastic Scattering

Charged Pions in Argon

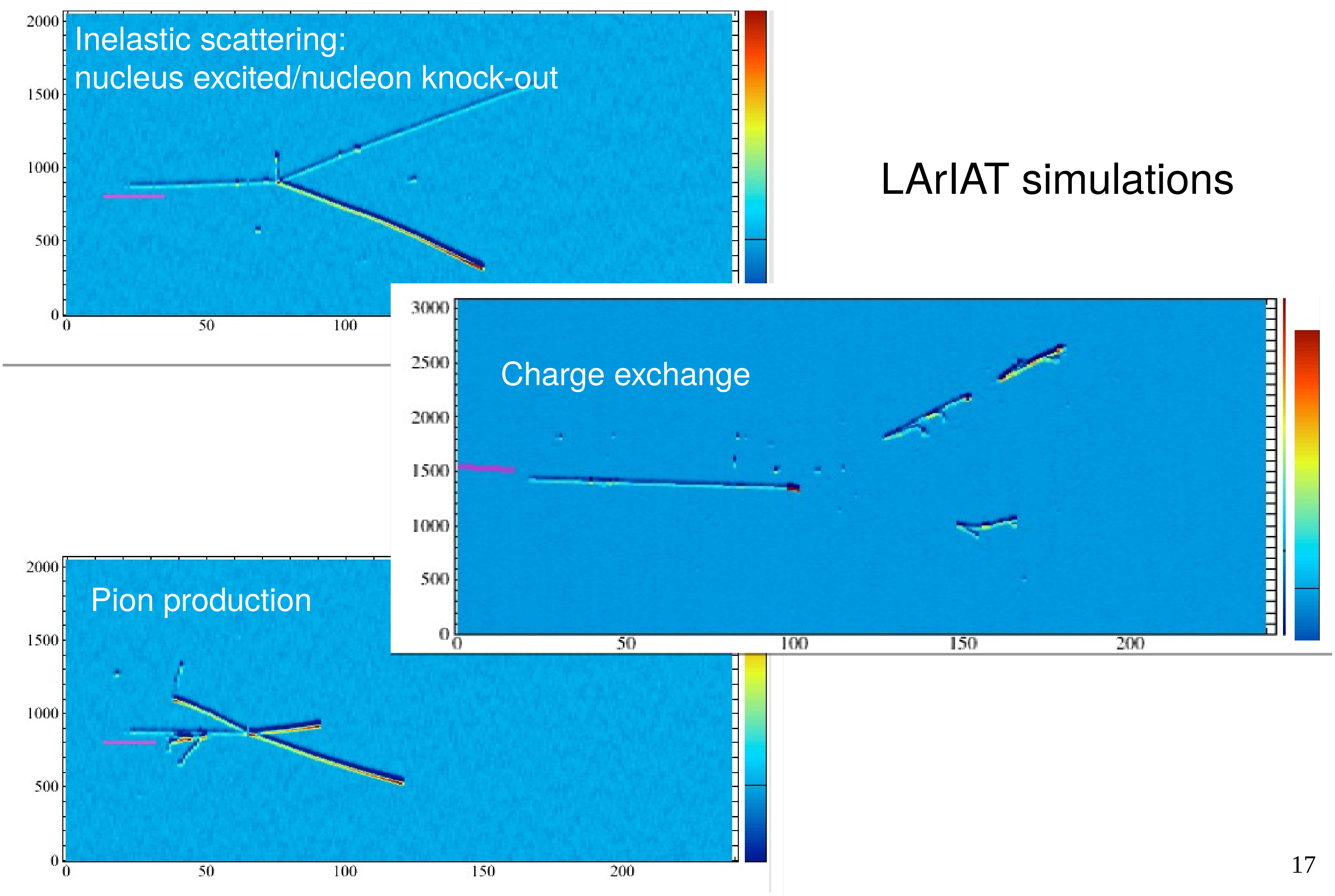
- **In the energy range of 100-500 MeV, pion interactions are dominated by Δ resonances**
- **Four main components for π/N interactions**
  - Elastic Scattering:
    - Nucleus remains in the ground state
  - Inelastic Scattering
    - Nucleus excited/nucleon knock-out
  - Absorption
    - No π in the final state
  - Charge exchange
    - $\pi^+ \rightarrow \pi^0$

π^+ scattering data on ^{12}C

arXiv:1405.3973 [nucl-ex]

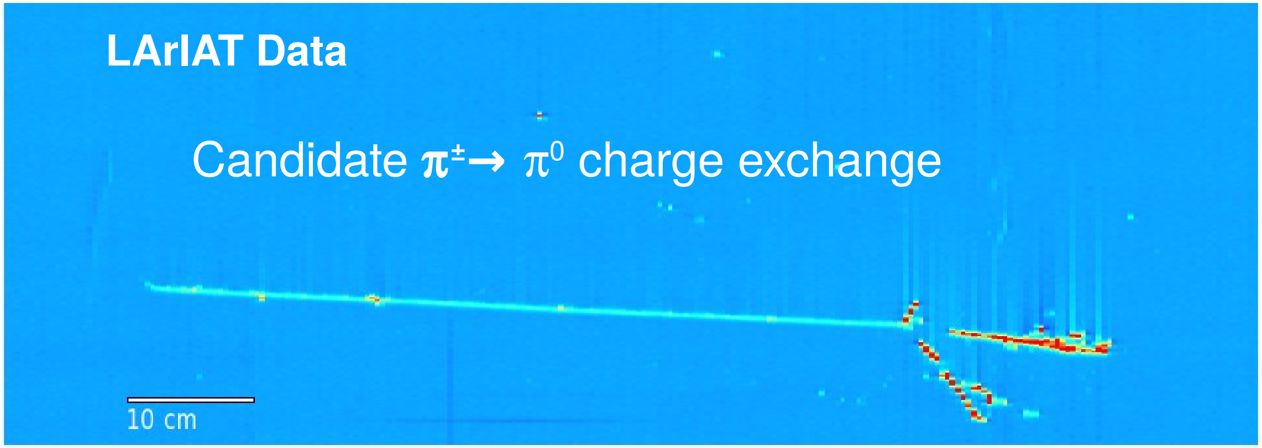


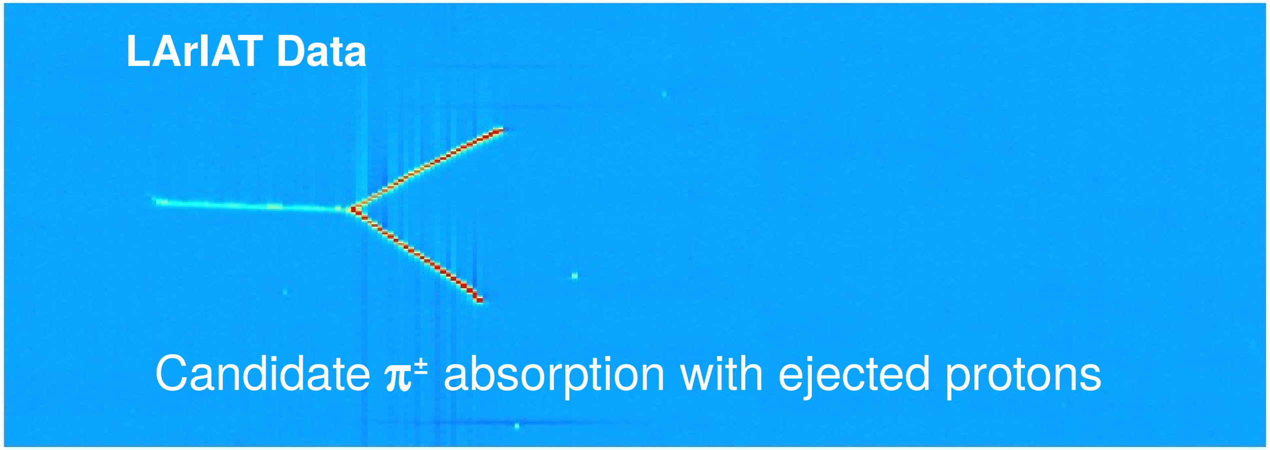
Charged Pions in Argon (MC)



LArIAT simulations

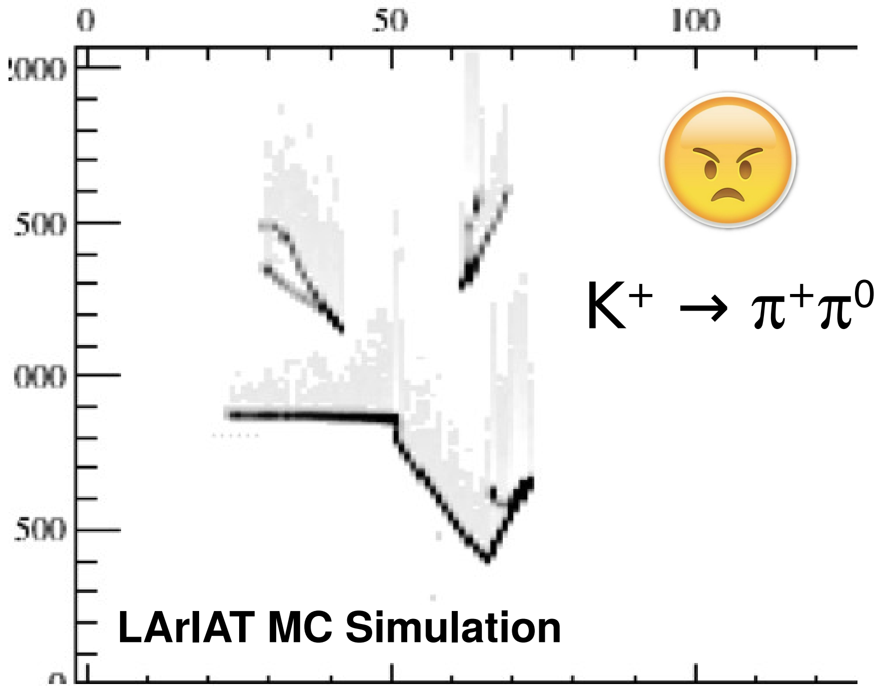
Nuclear Effects and Final State Interactions

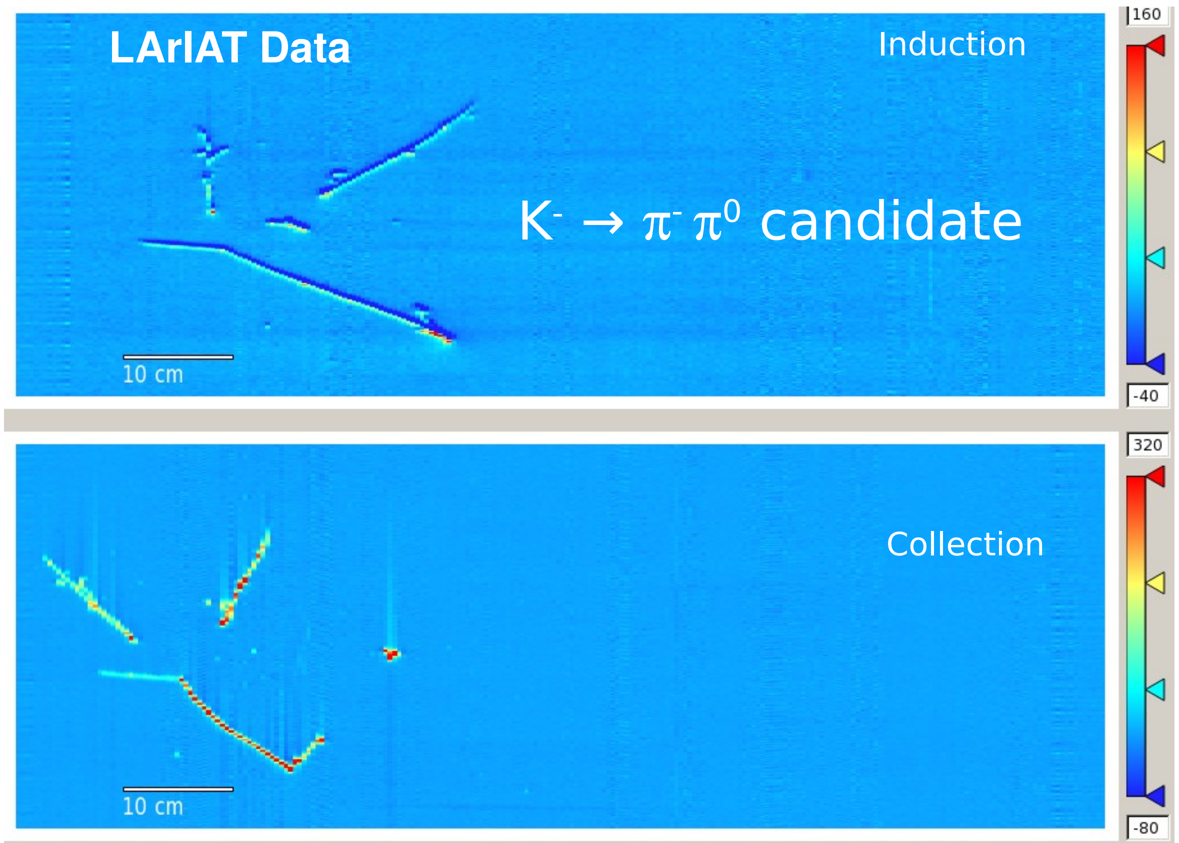




- **Utilize LArIAT data to:**
  - Tune hadron-nucleus interaction models Geant4 and neutrino generators
  - Study reconstruction systematics and calorimetry
- **Features are important to ν-oscillation experiments**
  - Constrain features of the ν-interaction channels for oscillation
  - Cross-section systematics begin to dominate for precision oscillation measurements

Kaon Identification and Reconstruction



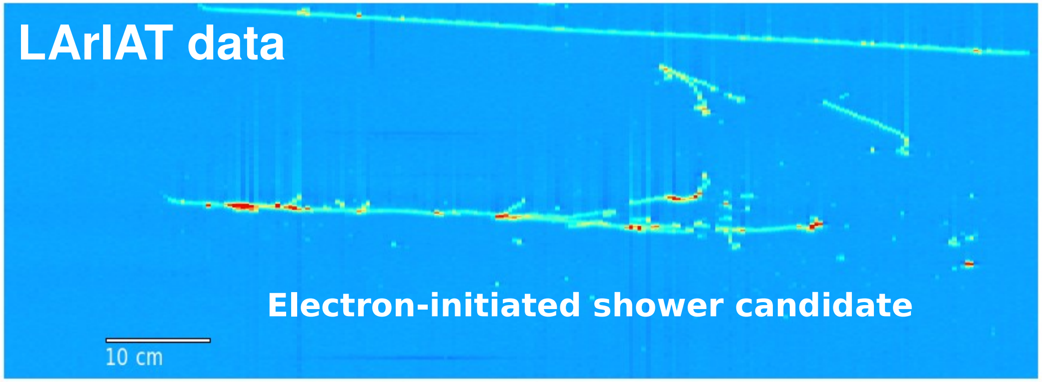


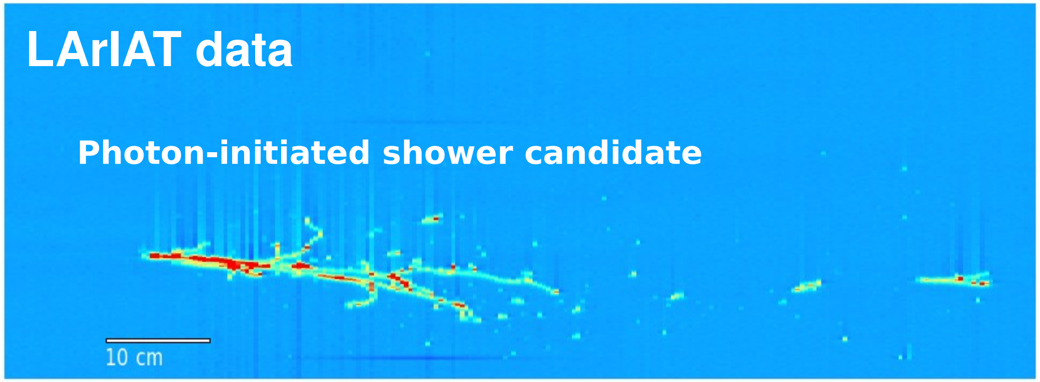
- **LArIAT Data will enable:**
  - Study of $K^{+/-}$ reconstruction in LArTPC
  - Measure Kaon-Ar interaction cross section (analysis in progress!)
  - Understand K/π and K/p discrimination

Important channel for baryon-number violation searches!

  - Relevant to proton decay searches in DUNE ($p \rightarrow K^+ \bar{\nu}$)

e/γ Discrimination

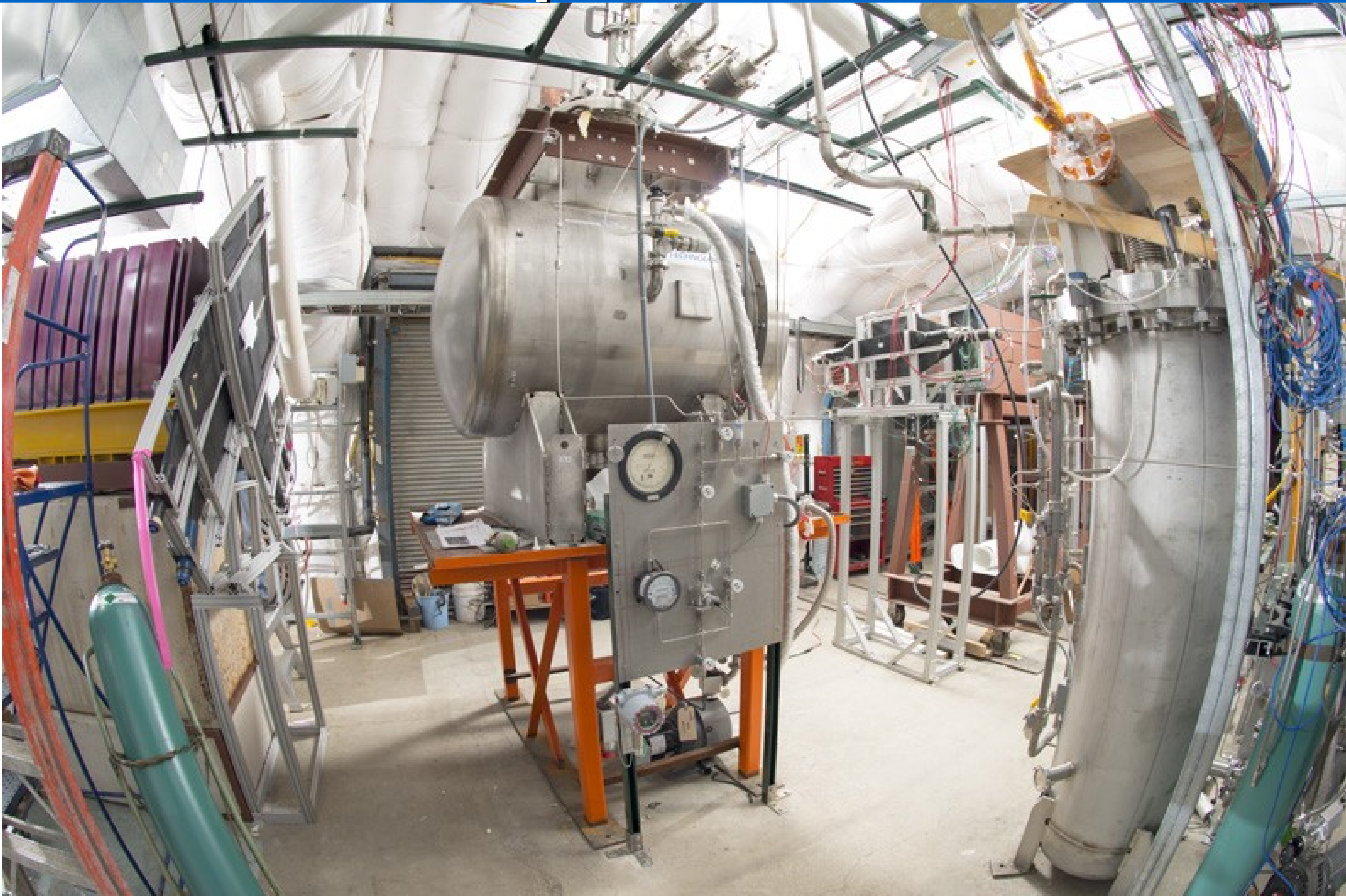




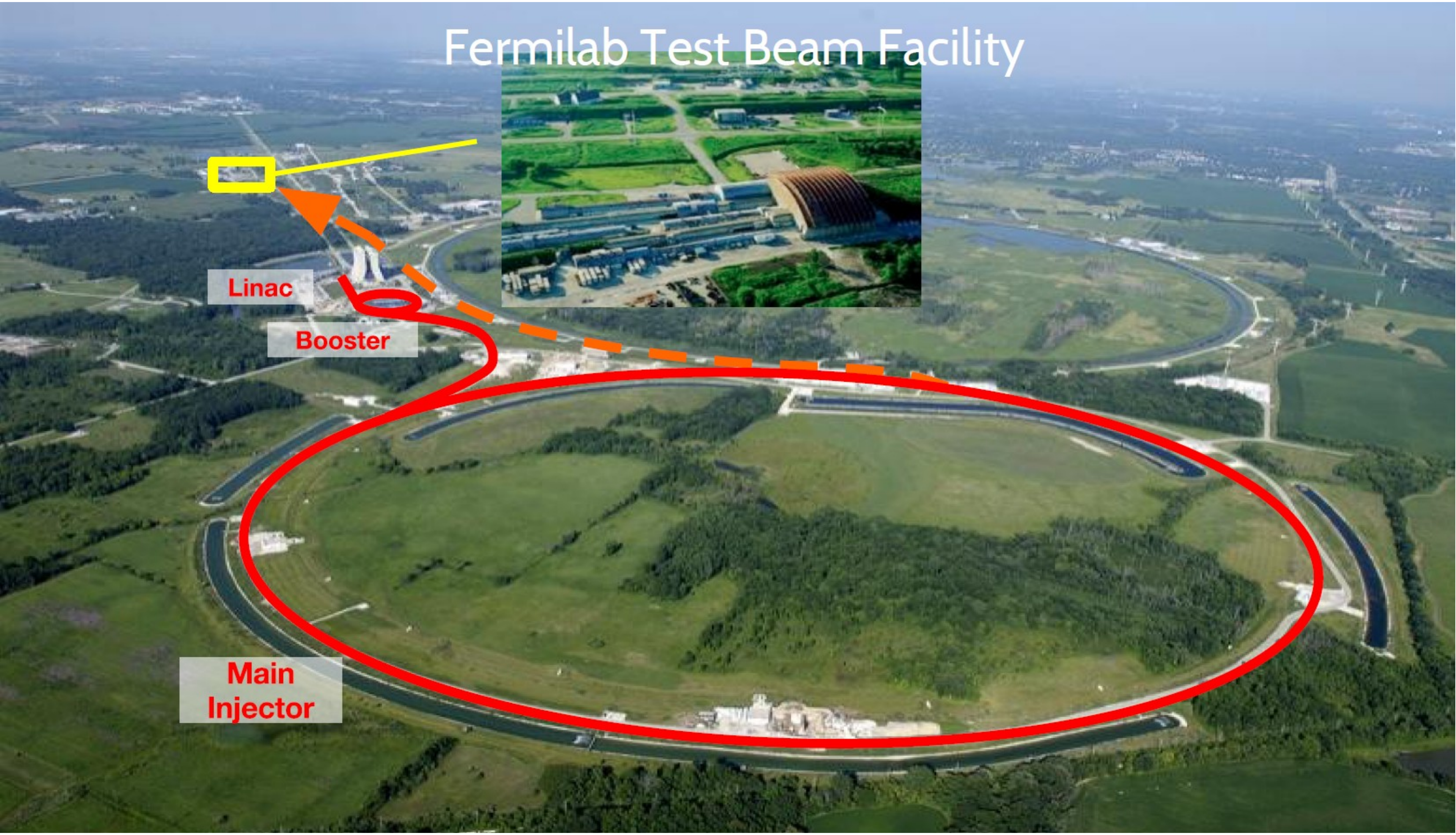
- First few cm are used to separate electron-initiated from photon-initiated showers (single vs. double ionization)
- Direct experimental measurement of the (MC-estimated) separation efficiencies and purities
- Enable development of reliable separation criteria/algorithms in the LArSoft offline reconstruction code

Important for oscillation experiments: support measurement of the low-energy e-like excess from MiniBooNE (primary goal of MicroBooNE), and for DUNE separation of ν_e CC signal from NCπ^0 background

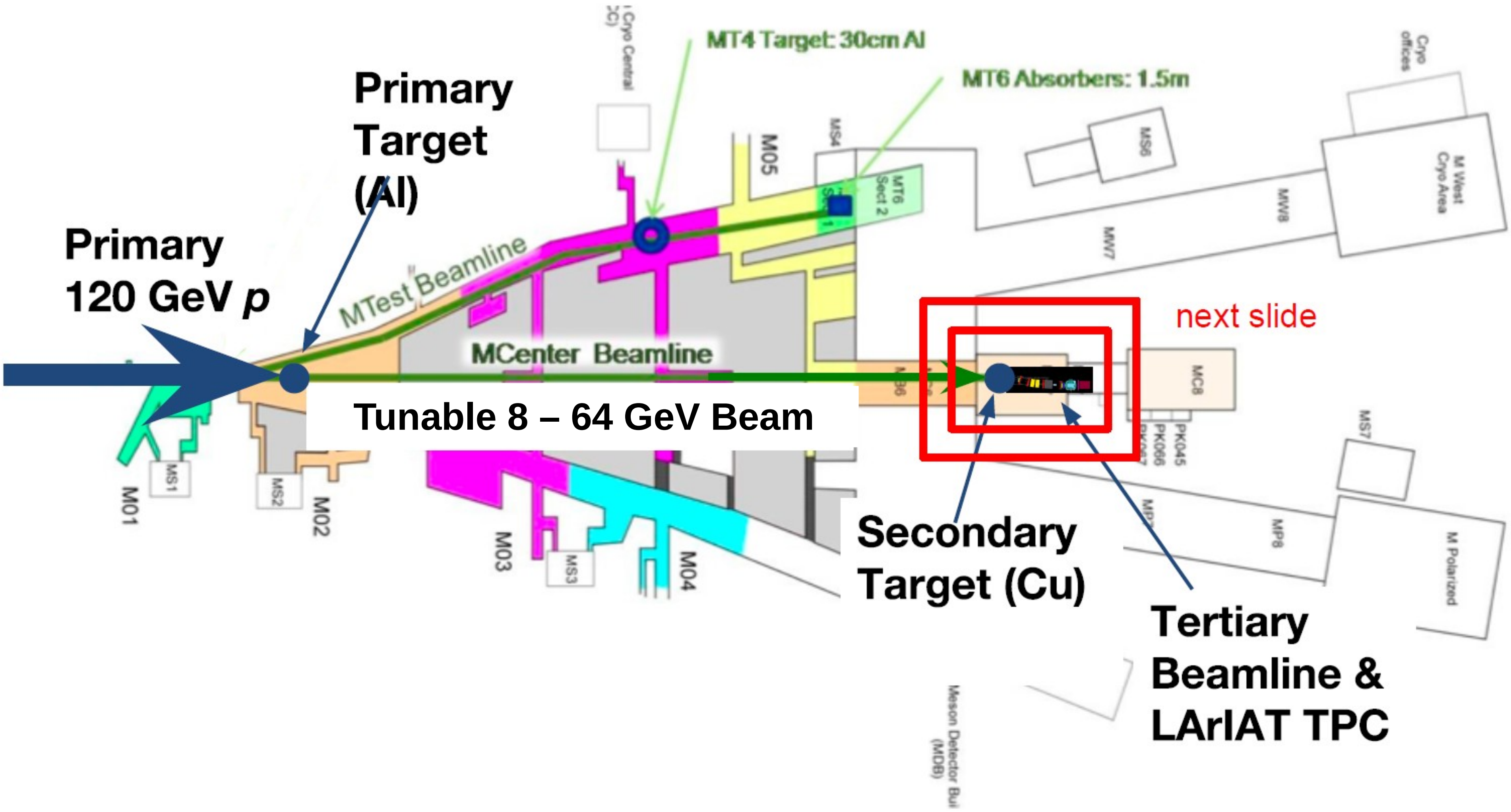
LArIAT: The Experiment



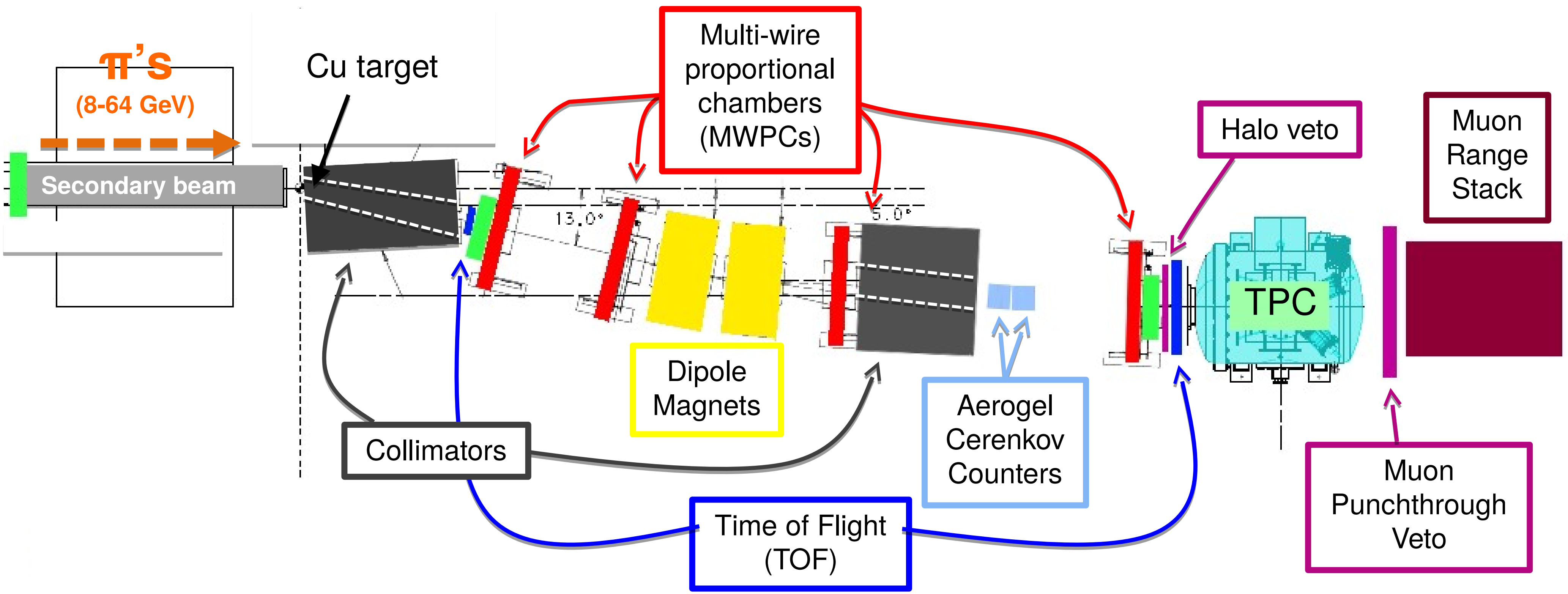
Where LArIAT Lives....



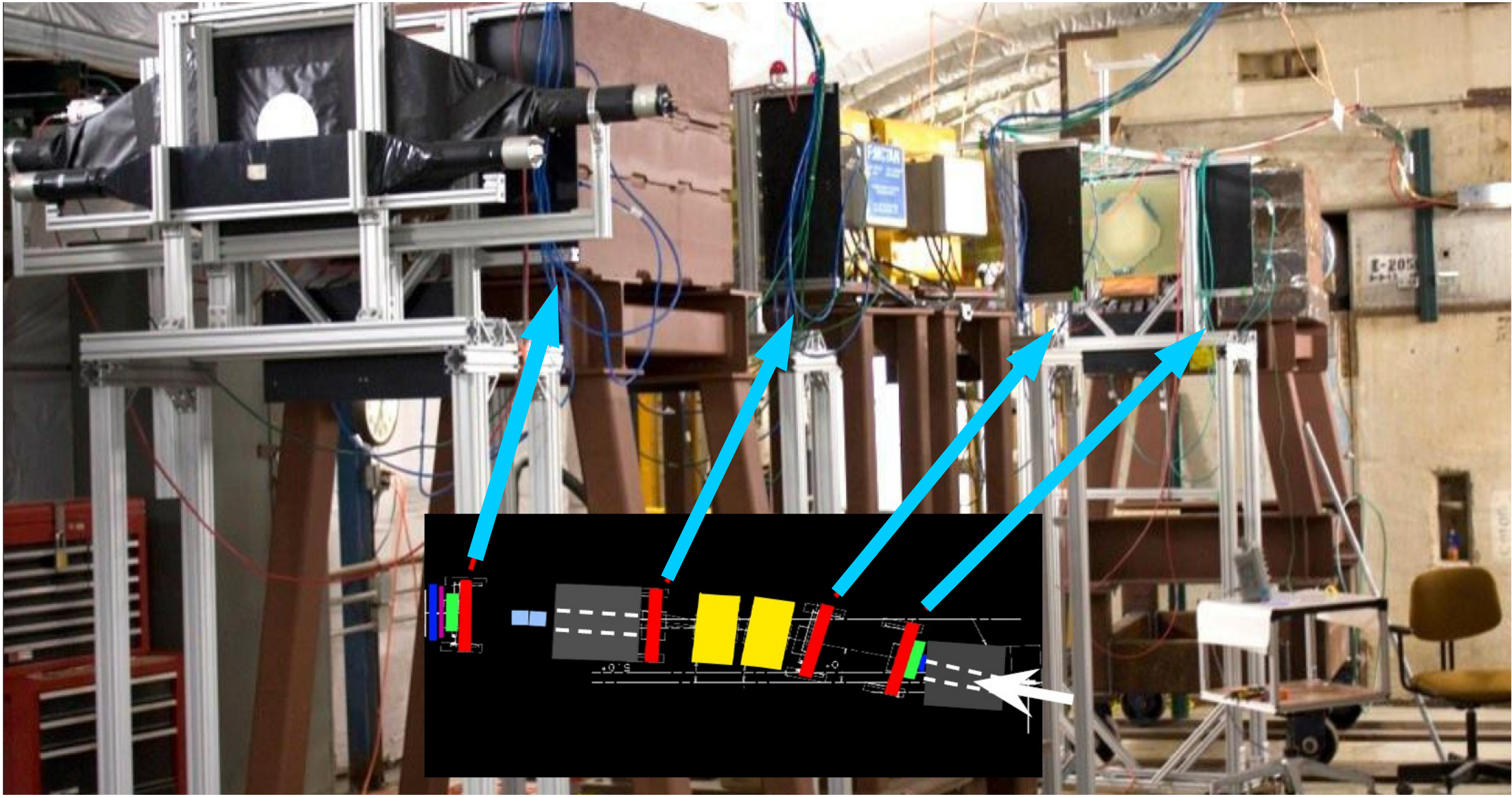
The LArIAT Beamline



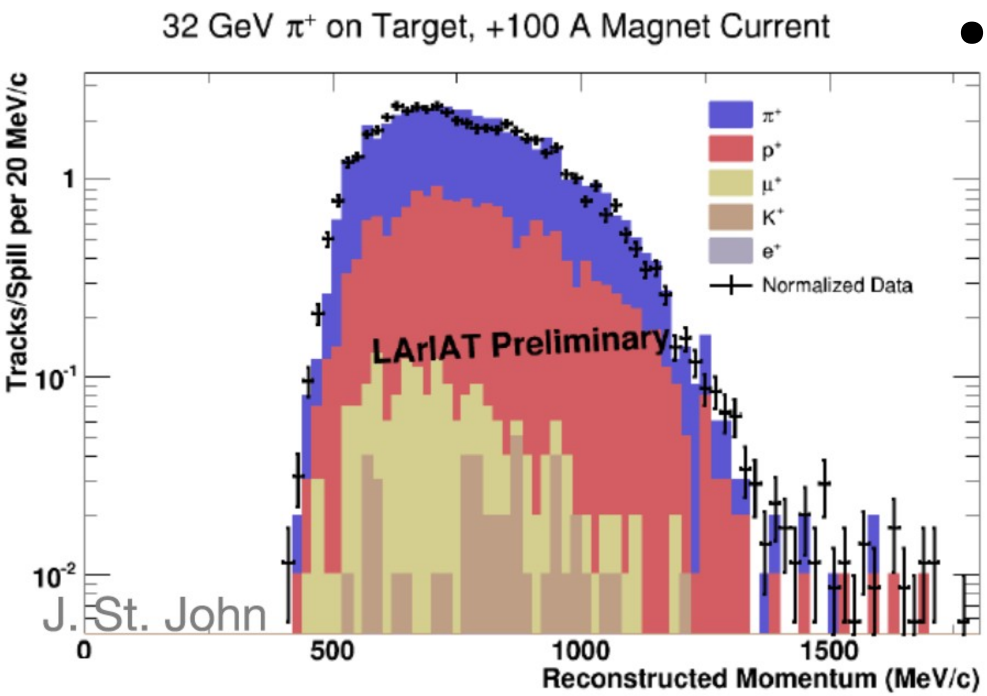
Tertiary Beamline



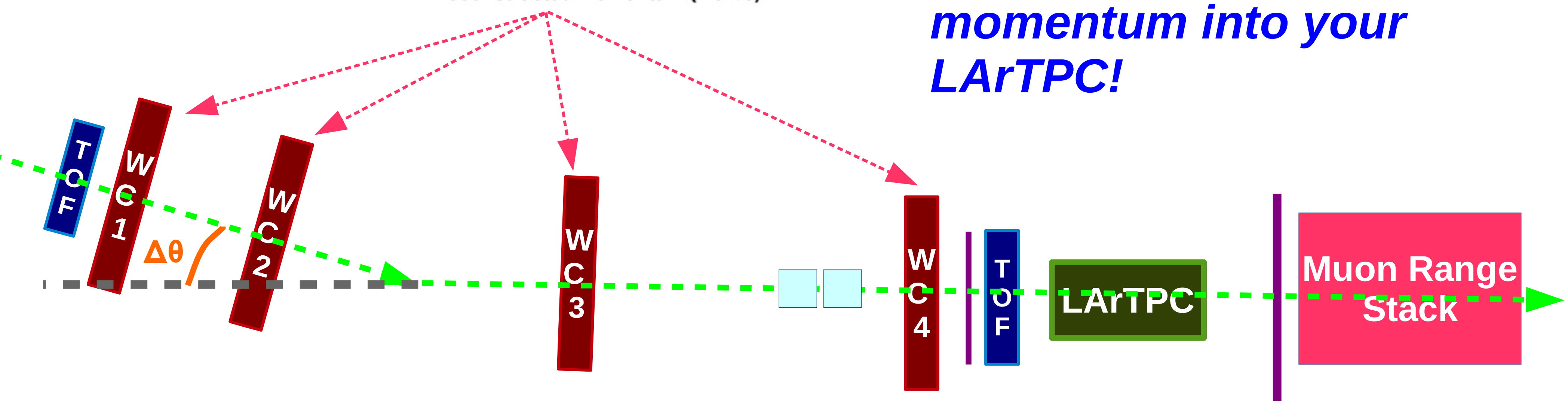
Multi-Wire Proportional Chambers MWPC's



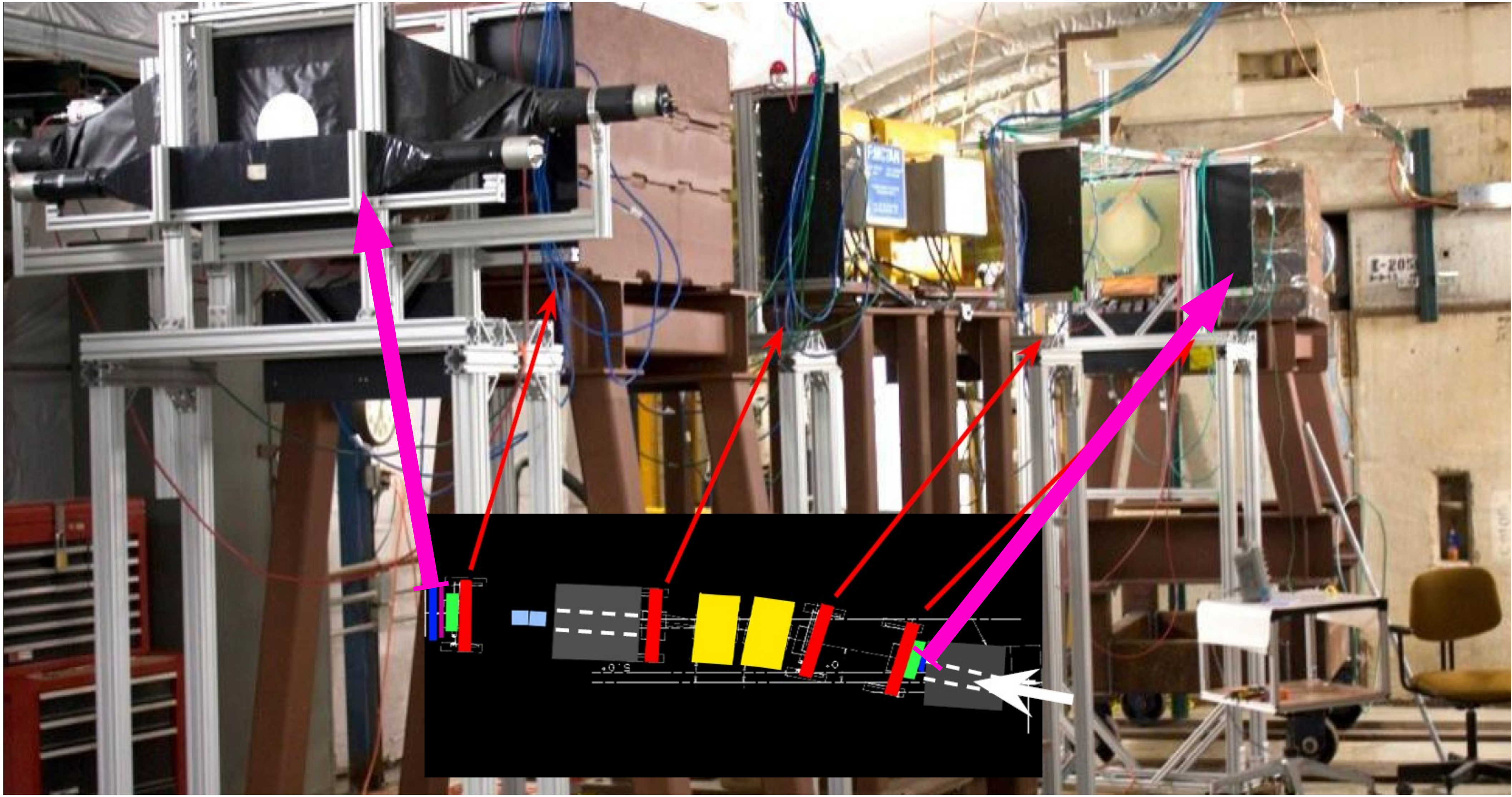
Multi-Wire Proportional Chambers



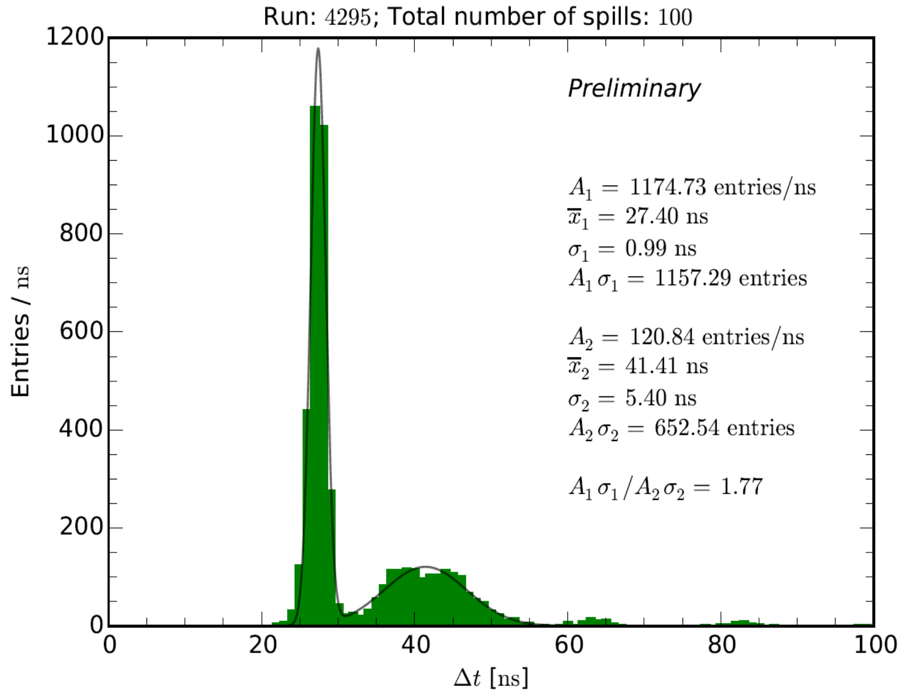
- **MWPCs + Bending Magnets**
  - Charged particle beam 200 – 1400 MeV/c
  - Single particle momentum measurement
    - ***You know the incident momentum into your LArTPC!***

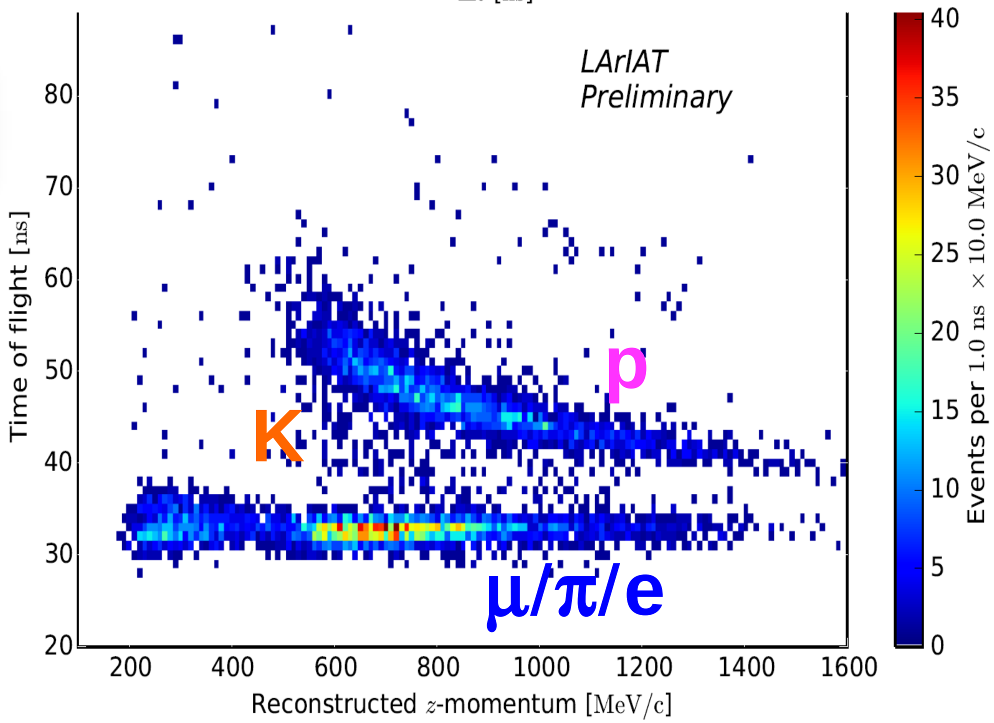


Time of Flight (TOF)



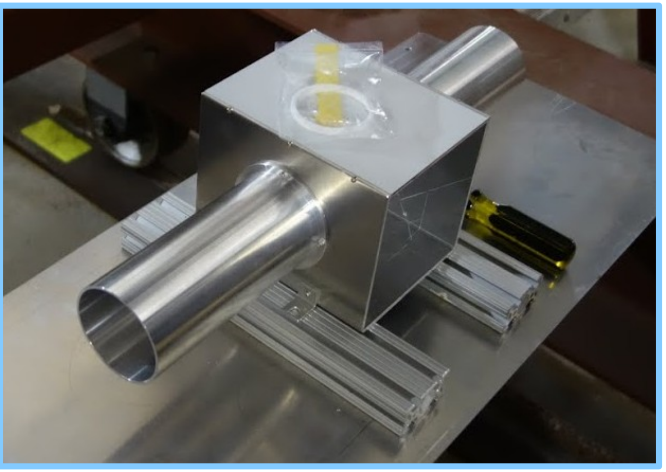
Time of Flight

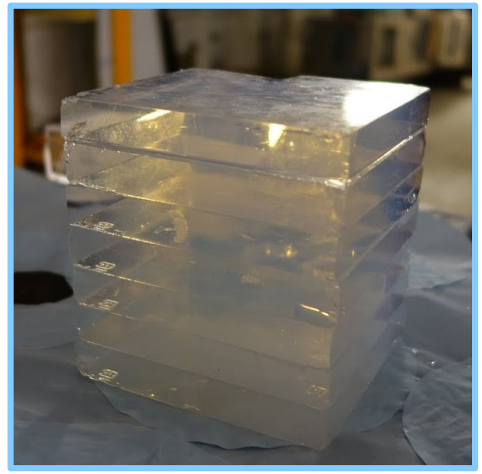




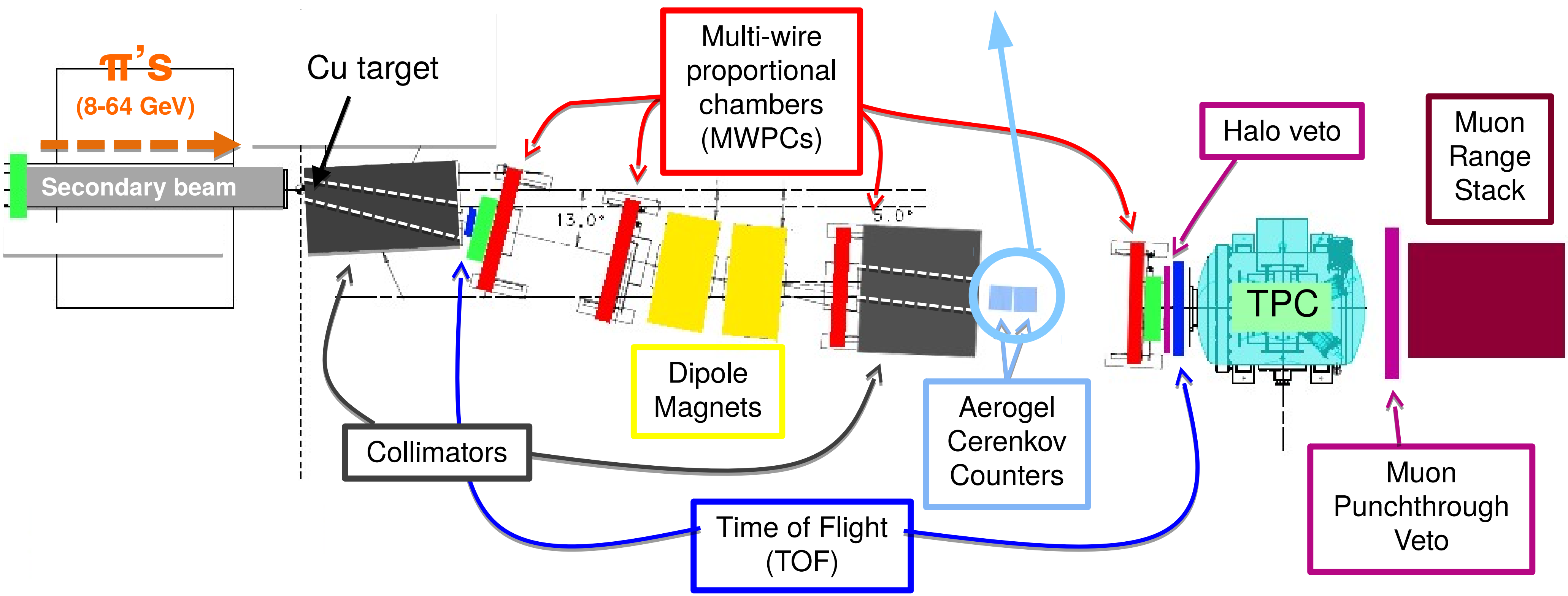
- **TOF separates μ/π/e from protons and kaons**
  - Given the timing of the readout of the **TOF + MWPC's** you can do particle ID (μ/π/e, p, K) before the particle enters your LArTPC
    - ***Now you know the particle species and momentum!***

Aerogel Cherenkov Detector

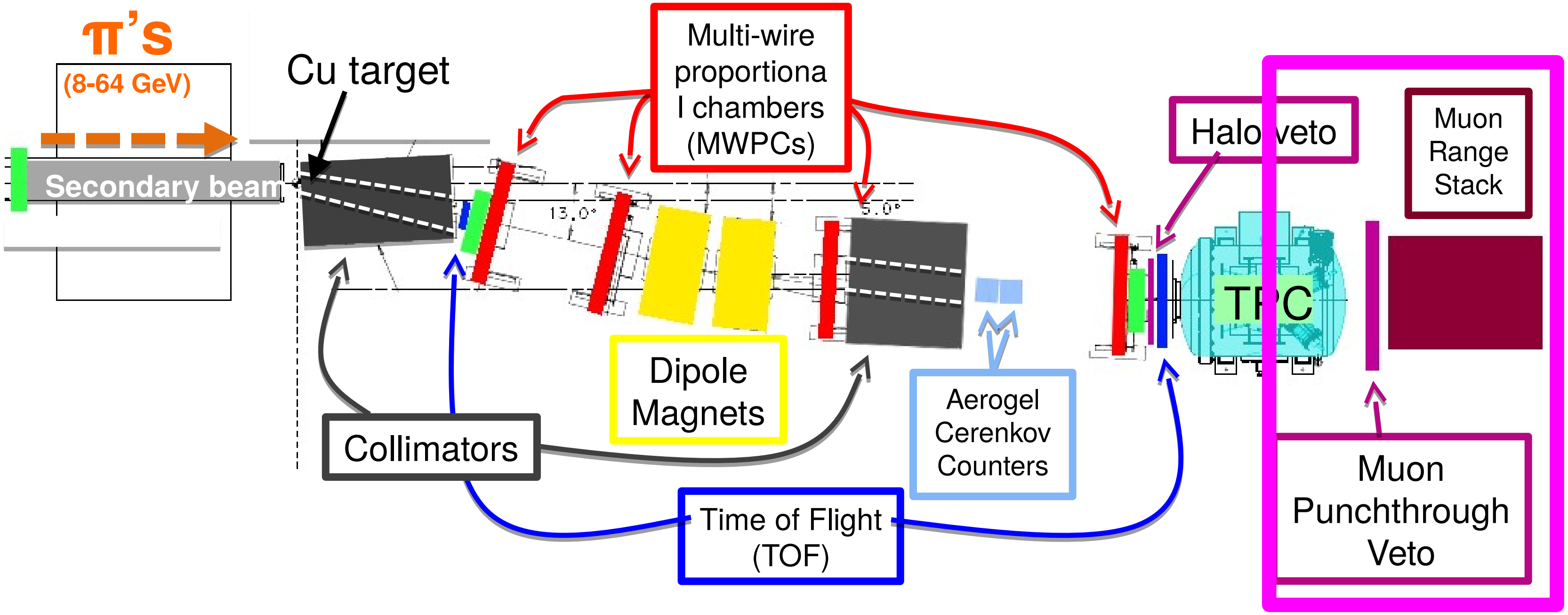




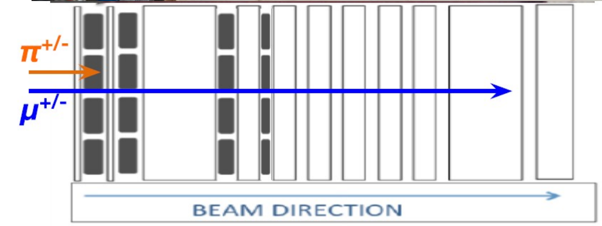
	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π



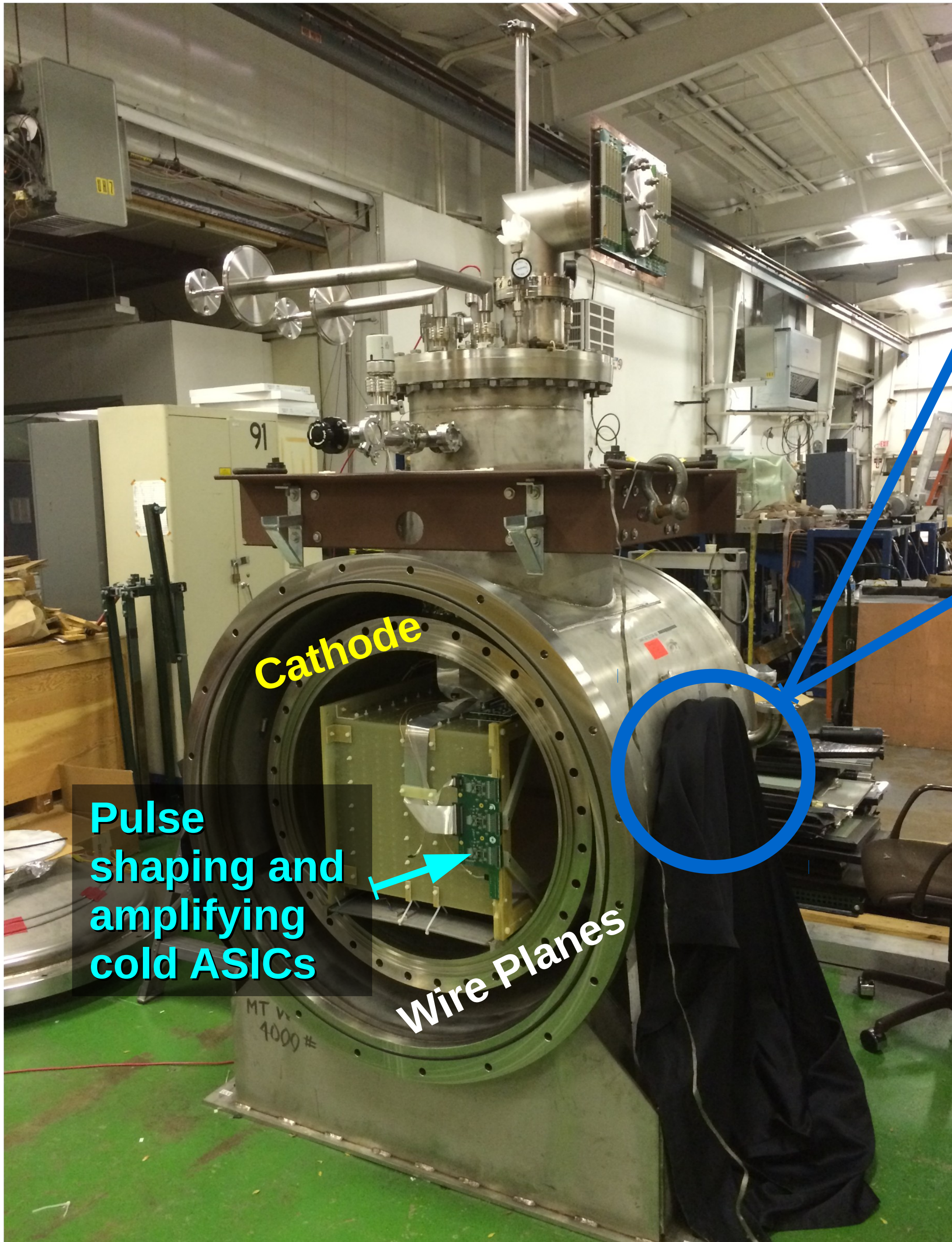
Muon Range Stack

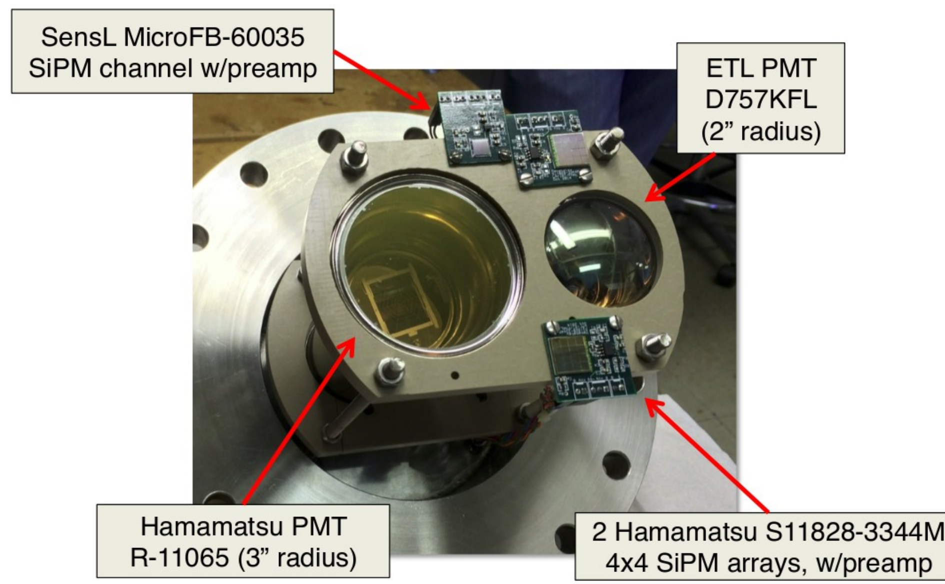


- **Muon range stack is for discriminating through going μ/π**
  - Essentially a segmented block of (pink) steel with scintillator bars and PMTs
  - Muons can penetrate further than pions
  - Match this activity to the rest of the beamline and the TPC



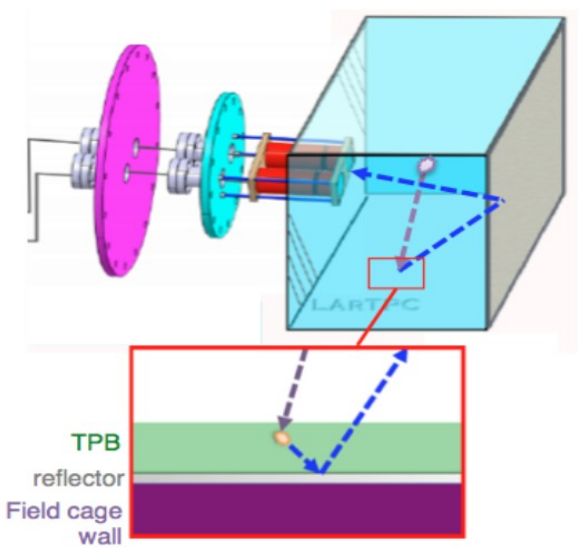
Inside the cryostat

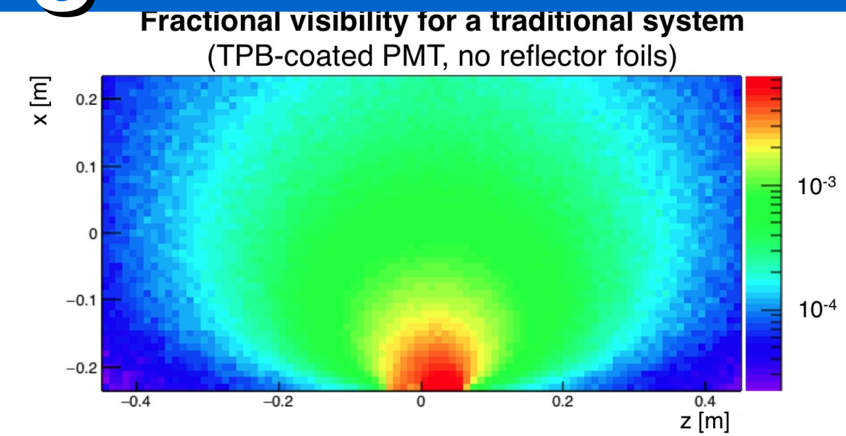


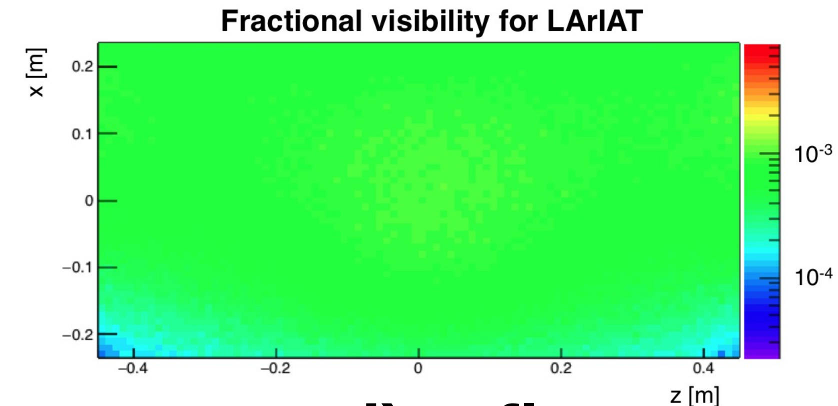


Inside the cryostat: Light Collection

Reflector-based solution (LArIAT)



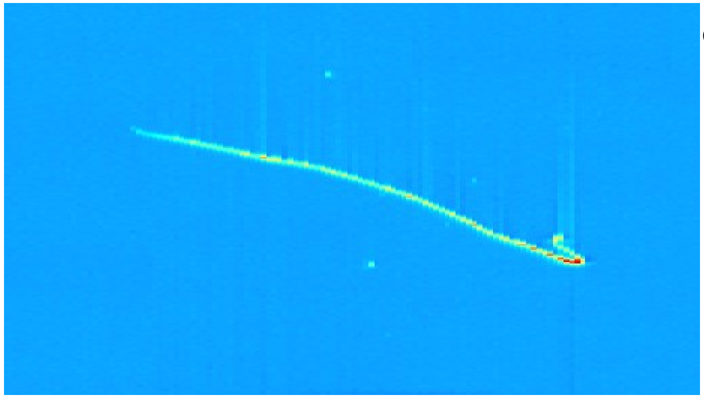




- **LArIAT uses wavelength shifting (evaporated) reflector foils to shift the scintillation light into the visible spectrum**
  - Provides better light yield
    - ~40 pe / MeV @ zero field
  - Light is more uniform
    - Good for calorimetry

Idea adapted from dark matter experiments and being tested in LArIAT for possible use in future neutrino experiments (e.g. SBND)

Measurements with Michel Electrons



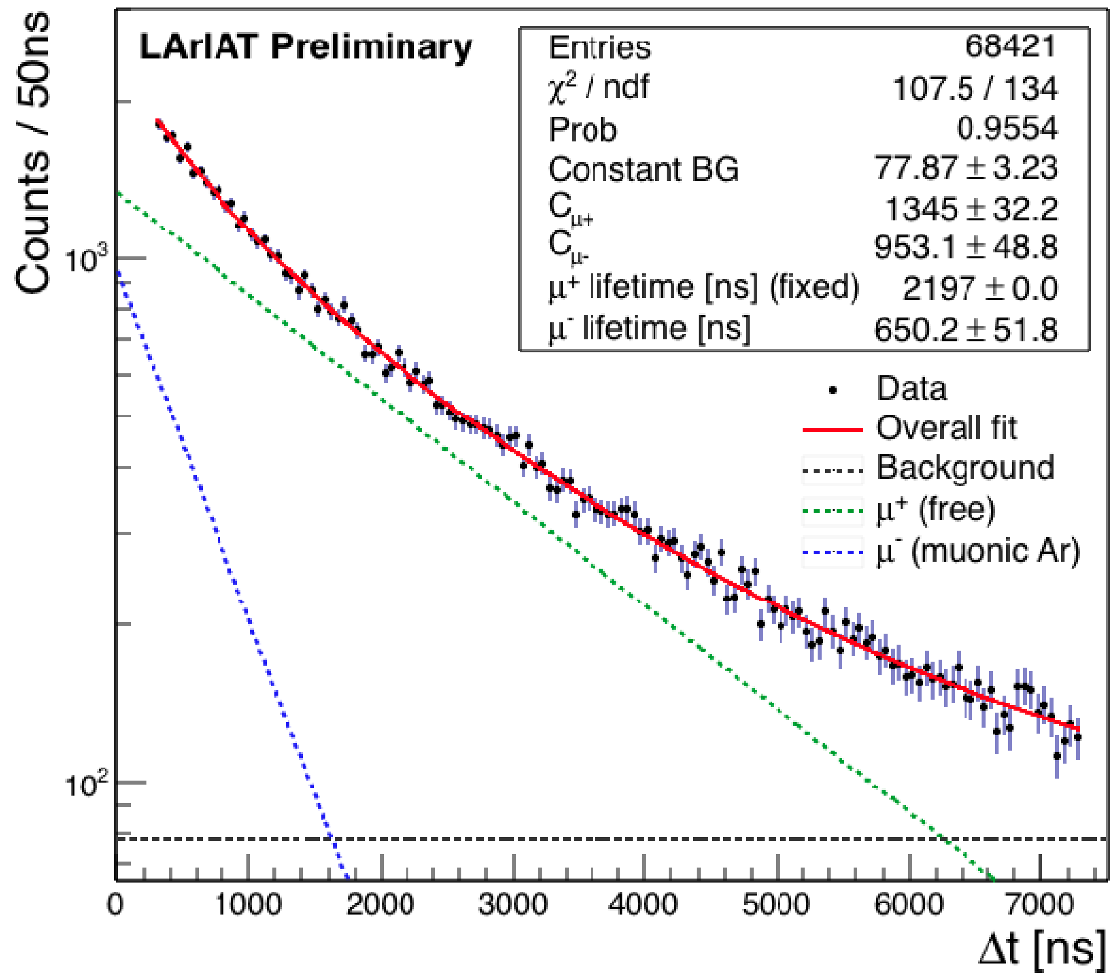
- **Utilize a light based trigger for calibration of TPC and photodetectors**
  - Source is stopping μ and low energy electron

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

Fit shown here gives
$\tau_{\mu-}$ = 650 ± 52 ns

$\tau_{capture}$ = 918 ± 109 ns

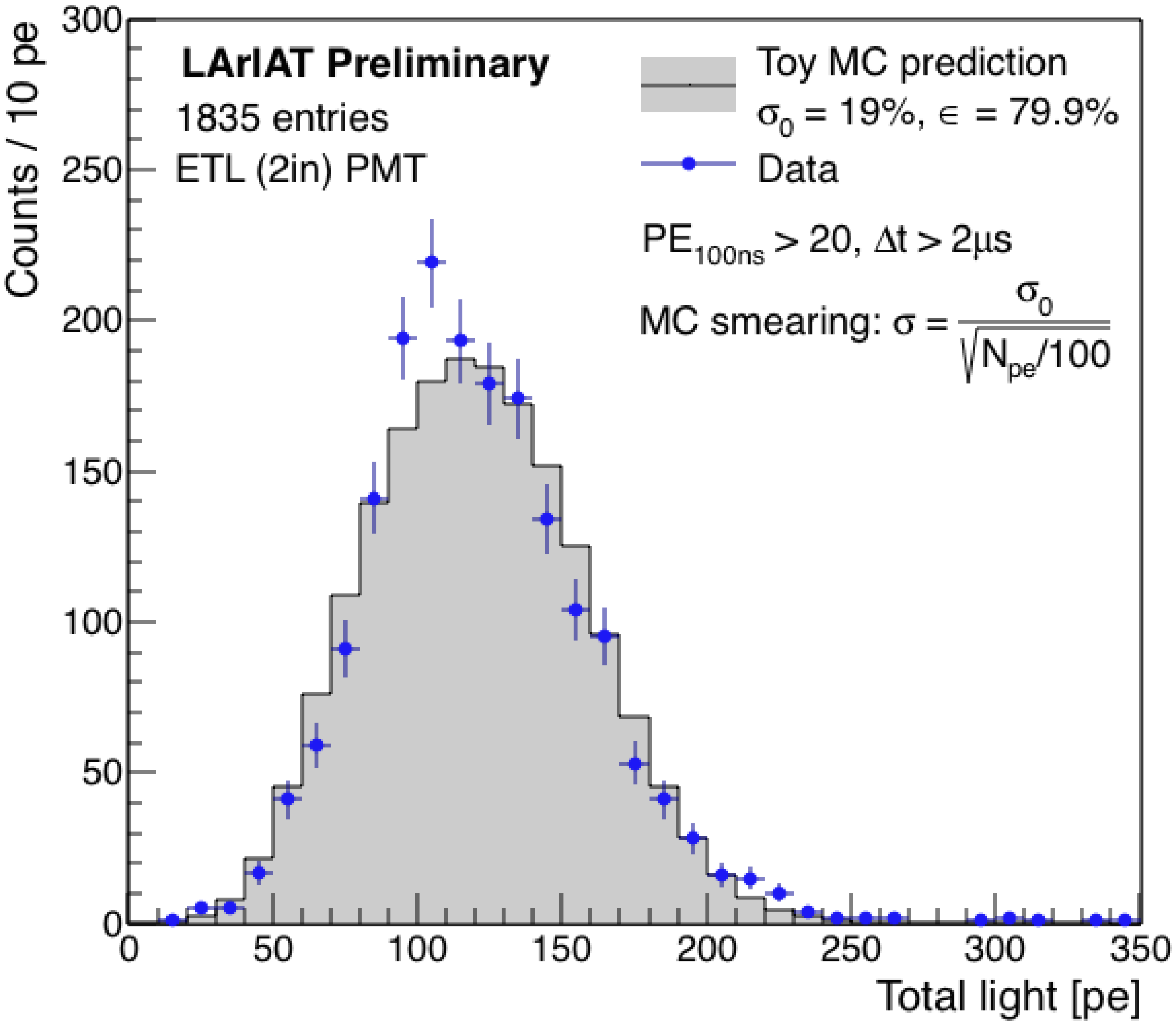
Early results agree w/ recent measurement[1] and theory prediction[2] (851ns)



LIDINE 2015 Proceedings, JINST 11 C01037

[1](Klinskih et al., 2008)
[2](Suzuki & Measday, 1987)

Measurements with Michel Electrons



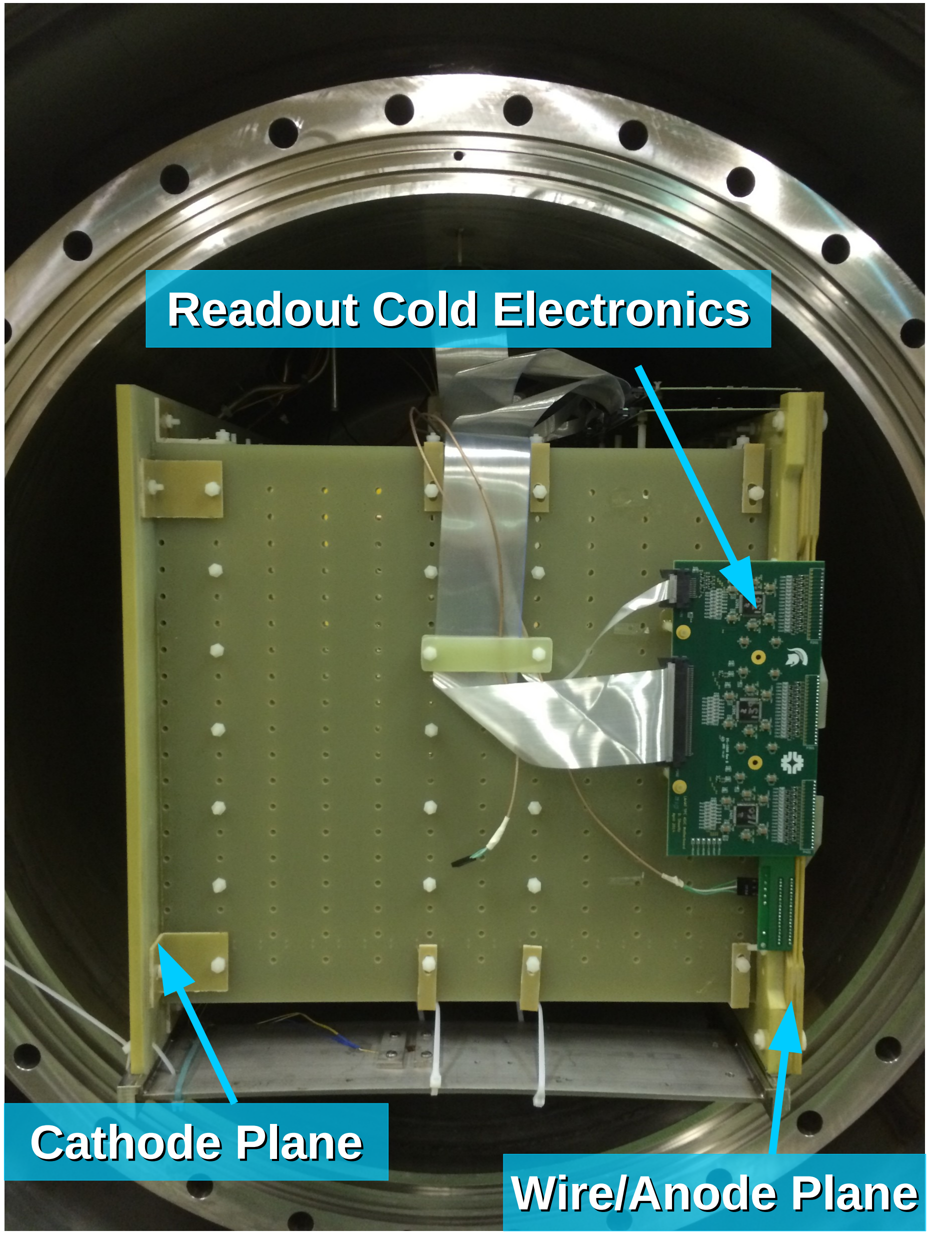
Data & toy MC in close agreement

Working to improve more realistic simulation

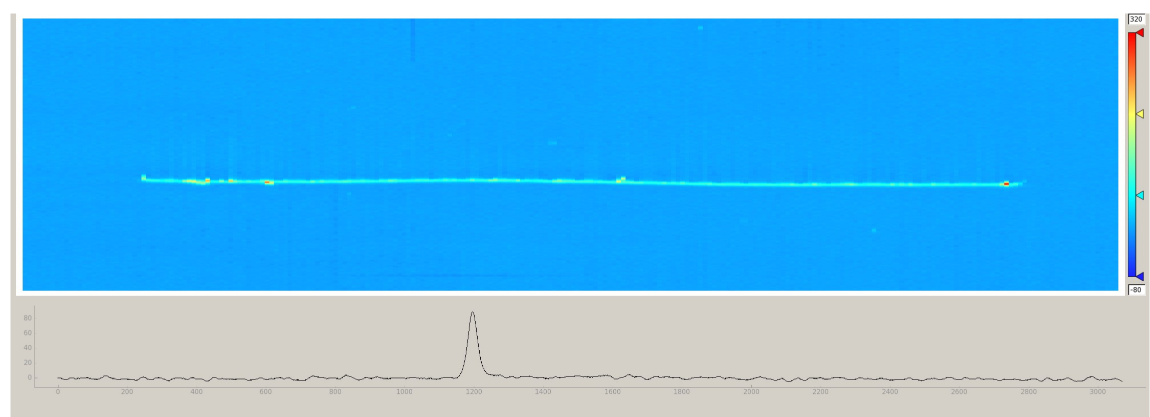
Photoelectron spectrum from 2" ETL PMT compared to toy light propagation MC (w/point-like events)

Smearing resolution σ_0 and PMT "collection efficiency" factor ε tuned to match data via χ^2 minimization

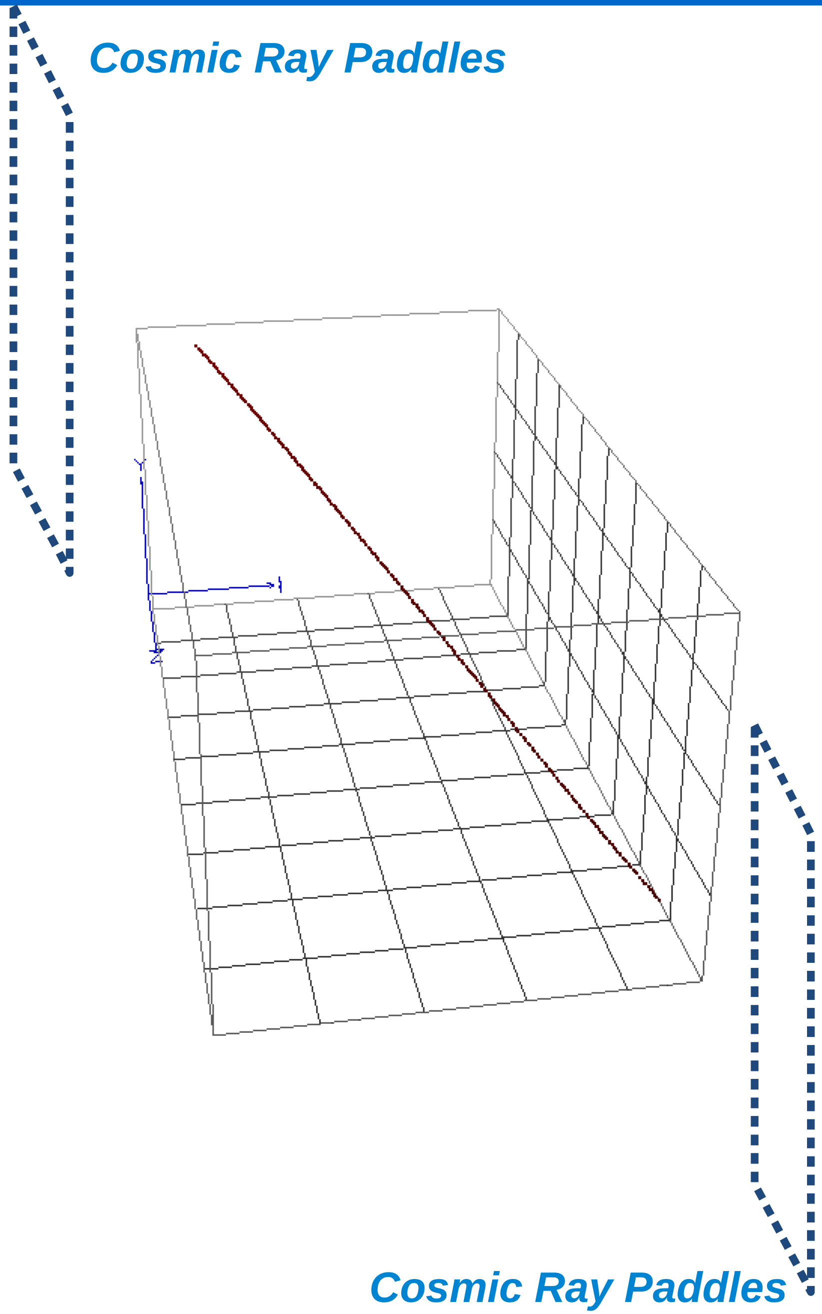
Inside the cryostat: TPC



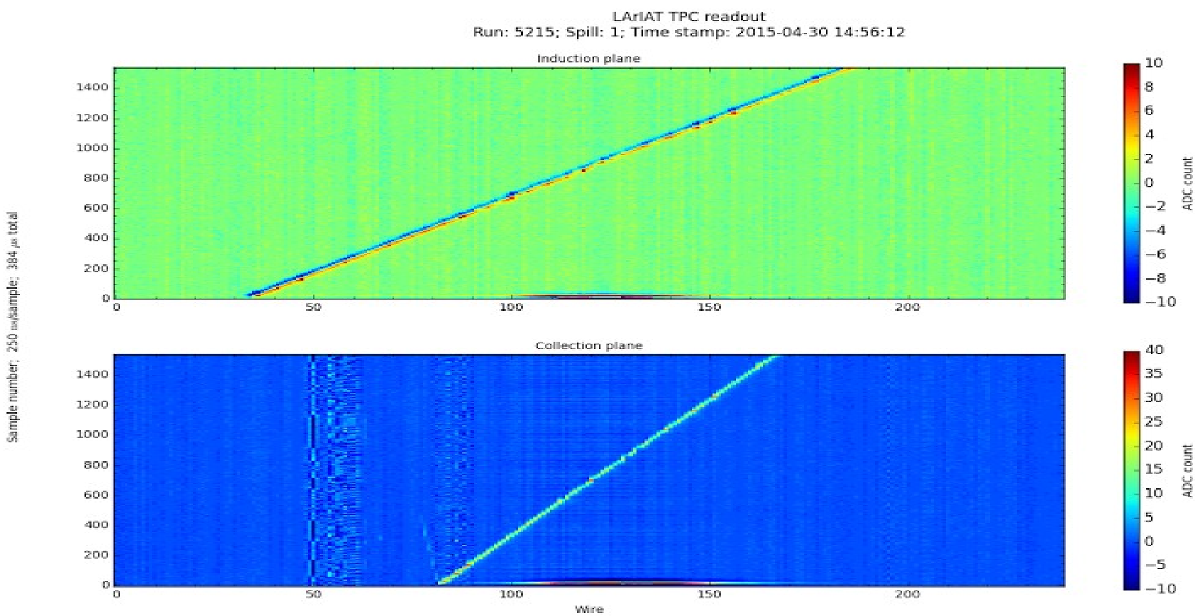
- **LArIAT uses the refurbished ArgoNeuT TPC**
  - 2 Readout planes
    - 240 wires / plane +/- 60o, 4mm pitch
  - Drift field ~500 V/cm
- **LArIAT uses MicroBooNE preamplifying ASICs on custom motherboards**
  - Signal-to-noise (MIP pulse height compared to the pedestal RMS
    - Run-1: ~50:1 (ArgoNeuT value 15:1)
    - Run-2: ~70:1



First LArIAT Event!

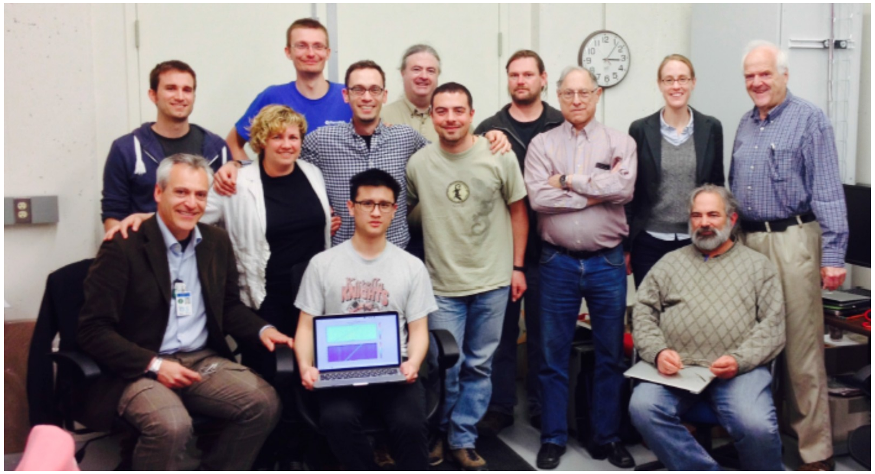


- LArIAT uses a pair of **cosmic ray paddles** to trigger on diagonal cosmic ray muons (going cathode to anode)
  - **April 30th 2015:** LArIAT's first event was one of these cosmic ray muons



Start of LArIAT Run 1

- **This began our first run which lasted ~9 weeks of beam data.**
  - Whenever we weren't taking beam we were collecting cosmics which we use for our purity measurement and detector studies



Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
May 2015					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31	Notes:					

May 2015 Calendar Printable calendars available from www.calendarcraze.com

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
June 2015						
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	Notes:			

June 2015 Calendar Printable calendars available from www.calendarcraze.com

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
July 2015						
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	Notes:

July 2015 Calendar Printable calendars available from www.calendarcraze.com

We filled the cryostat, ramped up the HV, and began taking data in less than 1 day (April 30th) and immediately saw our first event

LArIAT Run 1

- **~3 Weeks at Low energy Tune**
  - **Taking data in both the positive and negative polarity**
- **~5 Weeks at High energy tune**
  - **Taking data in both the positive and negative polarity**

Example of our running table

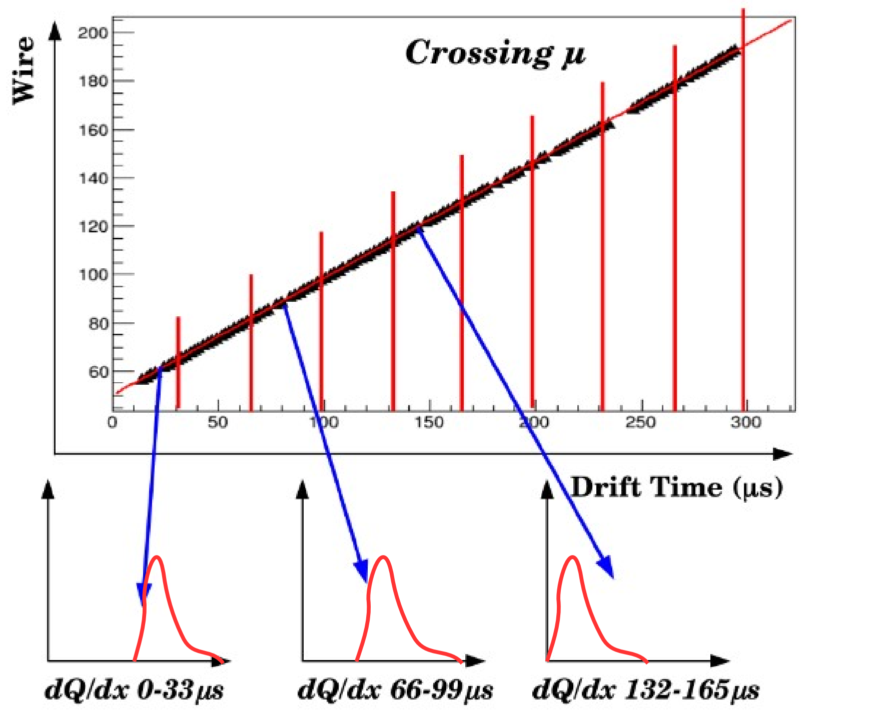
Beam Request	Tertiary Beam Magnet Polarity/Current	Trigger Configuration	Duration
+16 GeV, 18,000 @ SC1	-60 A	BEAMON+USTOF+DSTOF+WCCOINC3OF4-HALO COSMICON+COSMIC BEAMON+USTOF+DSTOF+WCCOINC3OF4+PUNCH-HALO BEAMON+USTOF+DSTOF+WCCOINC3OF4+MURS-HALO	Days **Starting 2015.05.30**
+16 GeV, 18,000 @ SC1	100 A	BEAMON+USTOF+DSTOF+WCCOINC3OF4-HALO COSMICON+COSMIC BEAMON+USTOF+DSTOF+WCCOINC3OF4+PUNCH-HALO BEAMON+USTOF+DSTOF+WCCOINC3OF4+MURS-HALO	Days **Done 2015.05.30**
-16 GeV, 15,000 @ SC1	-100 A	BEAMON+USTOF+DSTOF+WCCOINC3OF4 COSMICON+COSMIC BEAMON+USTOF+DSTOF+WCCOINC3OF4+PUNCH BEAMON+USTOF+DSTOF+WCCOINC3OF4+MURS COSMICON+MICHEL MICHEL-BEAMON Veto:	Days (Beginning 2015.06.05 from run 6042)
16 GeV pi+, maximizing MC7SC5	+100 A	Trigger0: on: (BEAMON USTOF DSTOF WCCOINC3OF4) Trigger1: on: (COSMICON COSMIC)	Establish trigger rate per SC5 counts. ~Few spills.

The pion analysis you will be shown uses both low energy and high energy tune in the negative polarity configuration (π^- configuration)

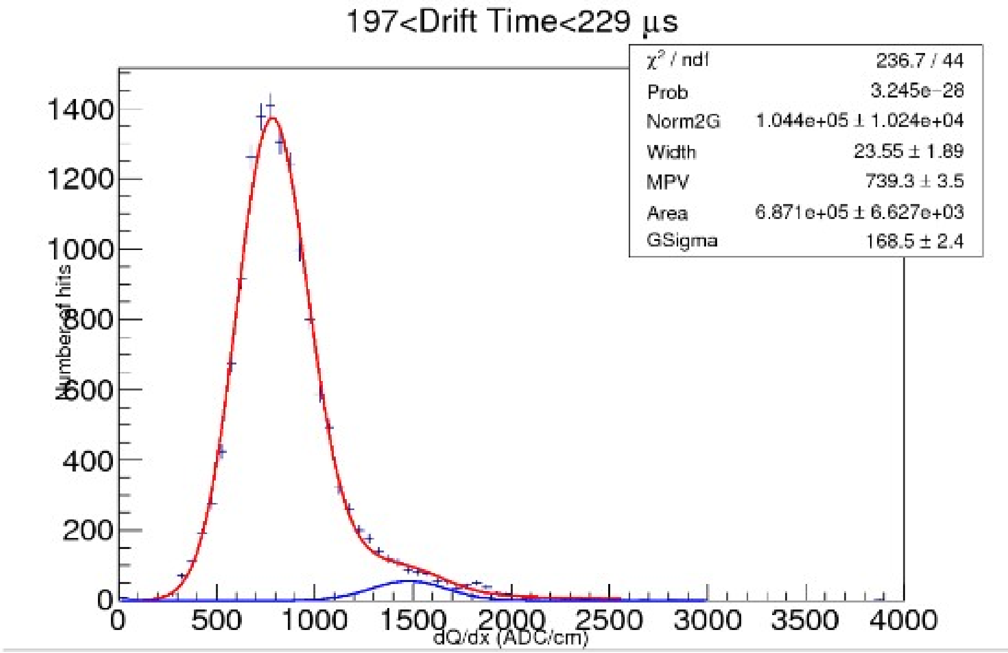
Purity Measurement with Muons

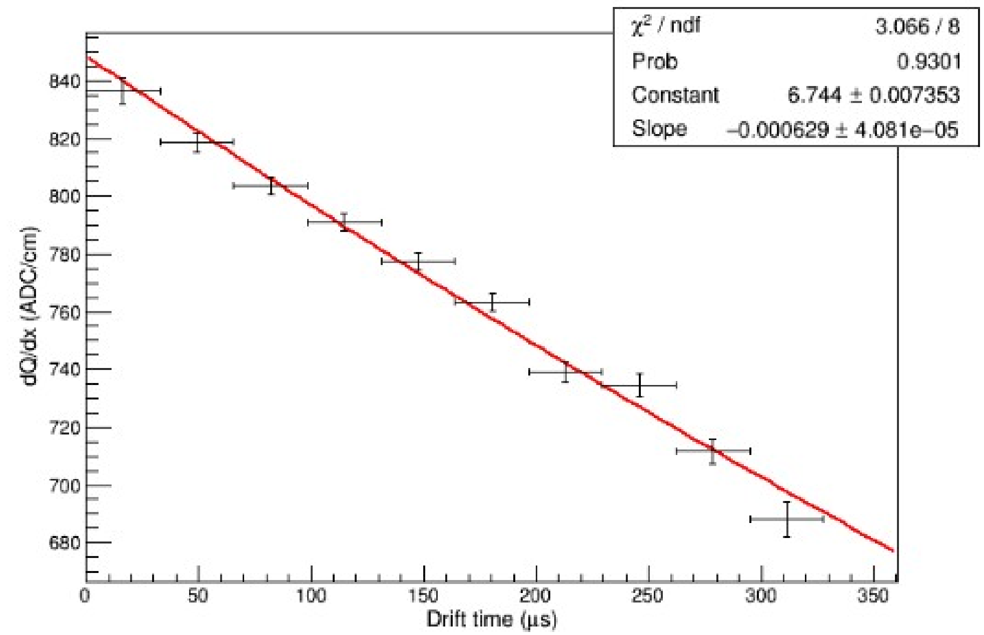
Electronegative contaminants in the liquid argon (e.g., O_2 and H_2O) quench the charge produced by interacting particles

- Amount of charge per unit length (dQ/dx) collected at wire planes depends on distance it drifted
- For a given charge deposited in the LAr, the amount of charge collected at the wire planes will exhibit an exponential decay trend as a function of drift time (called "electron lifetime")
  - Charge deposited near the wire planes will be collected with little or no quenching
  - Charge deposited near the cathode will be maximally quenched



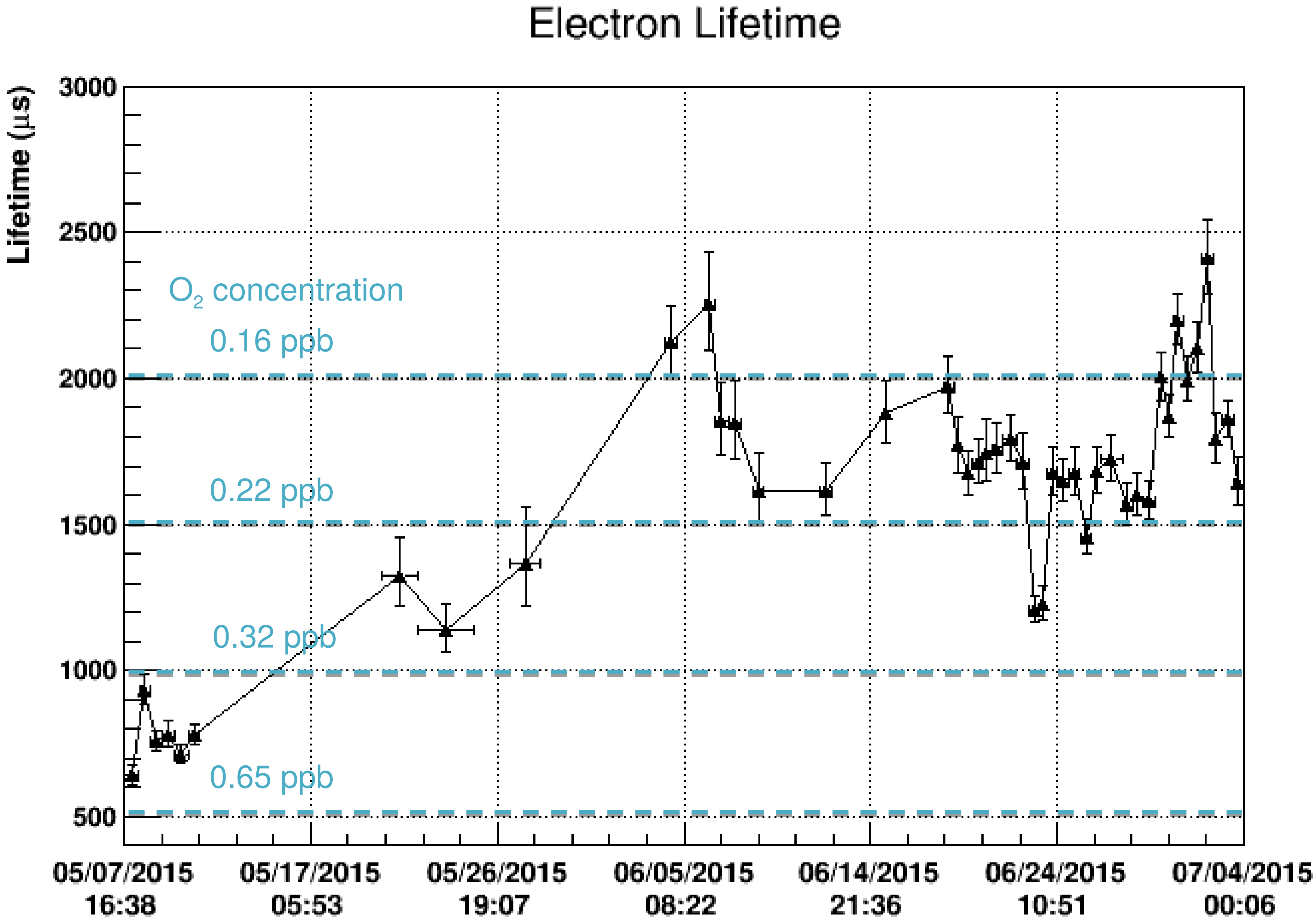
Purity Measurement with Muons





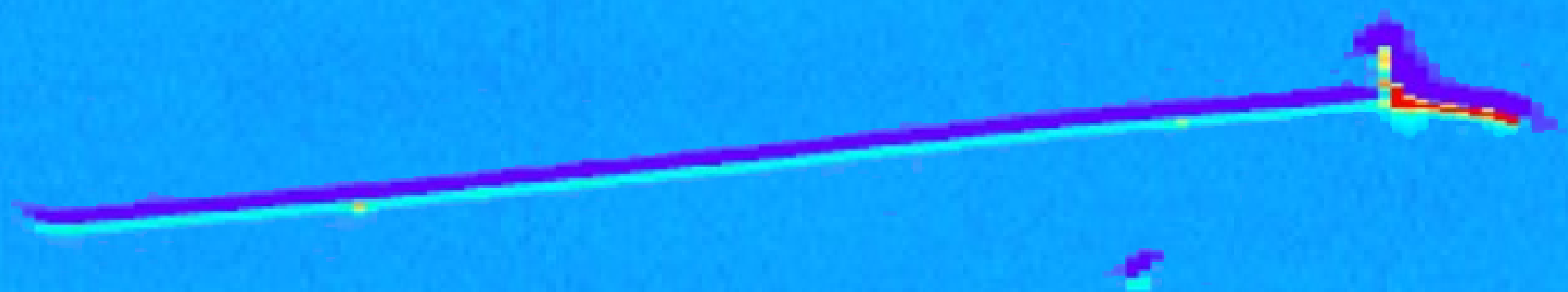
- **Each bin in right histogram comes from result of a fit like that on left**
- **Exponential fit to right plot gives electron lifetime**

Run-1 Lifetime



Purity achieved without LAr recirculation

First Total π-Ar Cross Section Measurement



- **Our first physics measurement puts together all the various aspects of the LArIAT experiment**
  - While this result is preliminary, we wanted to show where we are and demonstrate the analysis techniques

Thin-Sliced TPC Method

- **Generally the survival probability of a pion traveling through a thin slab of argon is given by**

$$P_{\text{Survival}} = e^{-\sigma n z}$$

Where σ_{TOT} is the cross-section per nucleon and z is the depth of the slab and n is the density

- **The probability of the pion interacting is thus**

$$P_{\text{Interacting}} = 1 - P_{\text{Survival}}$$

where we measure the probability of interacting for that thin slab as the ratio of the number of interacting pions to the number of incident pions

$$\frac{N_{\text{interacting}}}{N_{\text{Incident}}} = P_{\text{Interacting}} = 1 - e^{-\sigma n z}$$

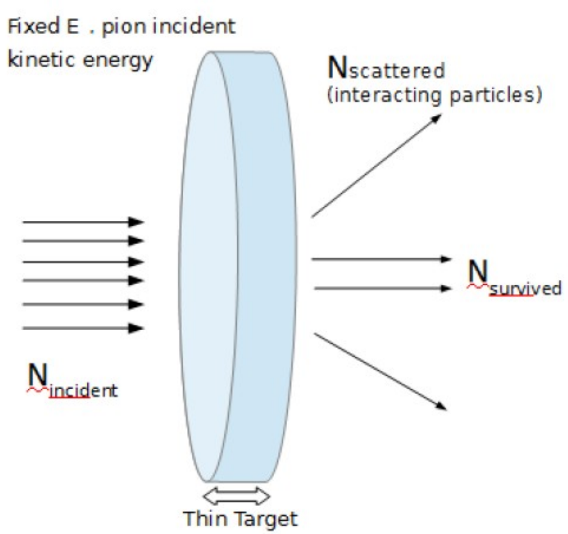
Thin-Sliced TPC Method

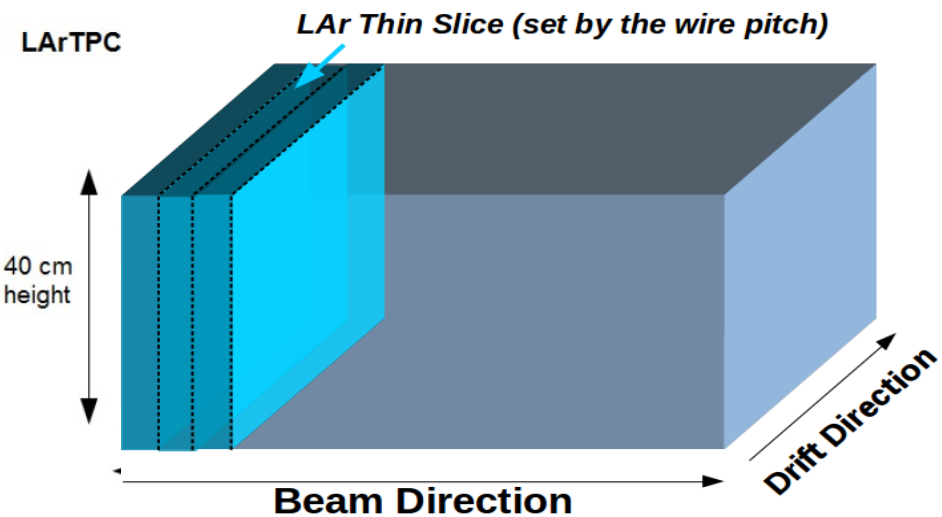
- **Thus you can extract the pion cross-section as a function of energy as**

$$P_{\text{Interacting}} = 1 - \left(1 - \sigma n \delta z + \ldots\right)$$

$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

Where $n = \rho N_A / A$



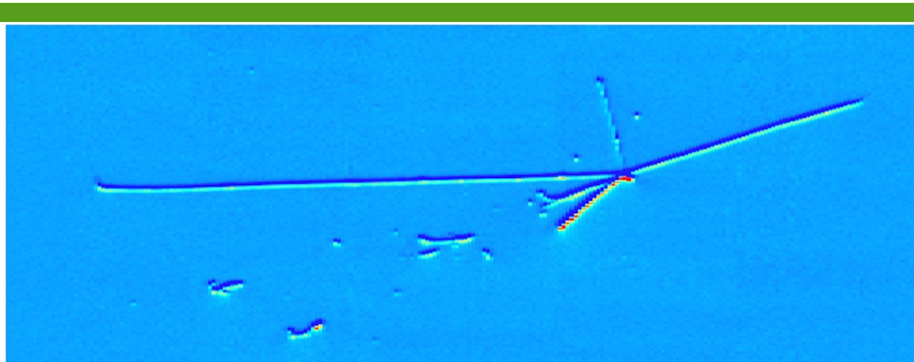


- **Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of "thin-slab" targets if we know the energy of the pion incident to that target**

Total π-Ar Cross Section

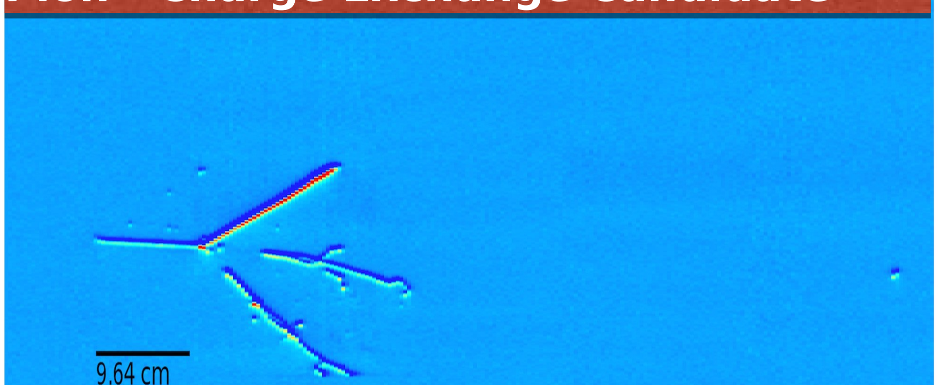
$$\sigma_{Total} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{ch\text{-}exch} + \sigma_{absorp.} + \sigma_{\pi\text{-}production}$$

- Our inclusive cross section definition currently includes the **traditional processes** as well as **background processes**

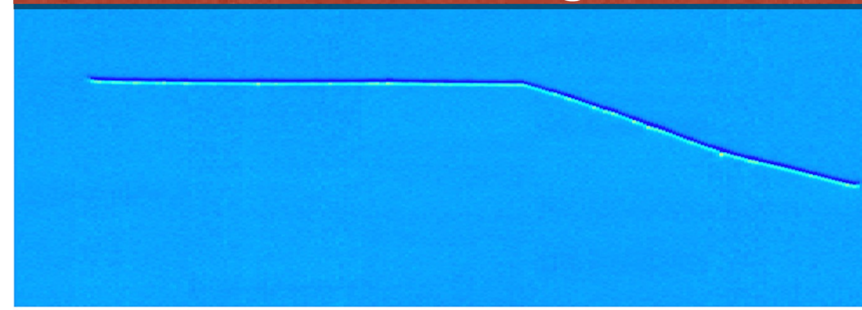


Pion Production Candidate

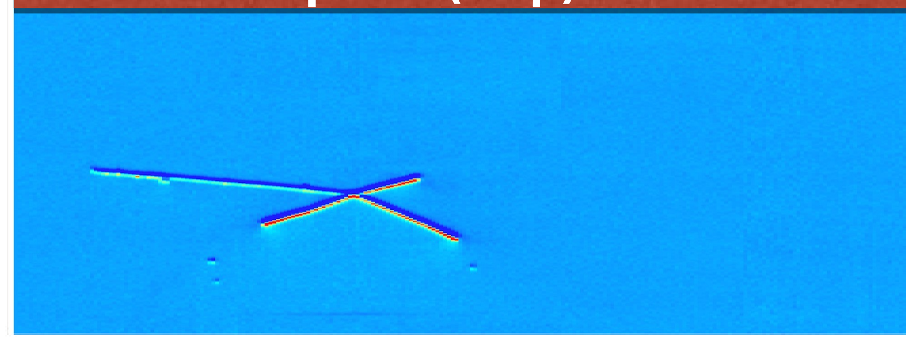
Pion - Charge Exchange Candidate



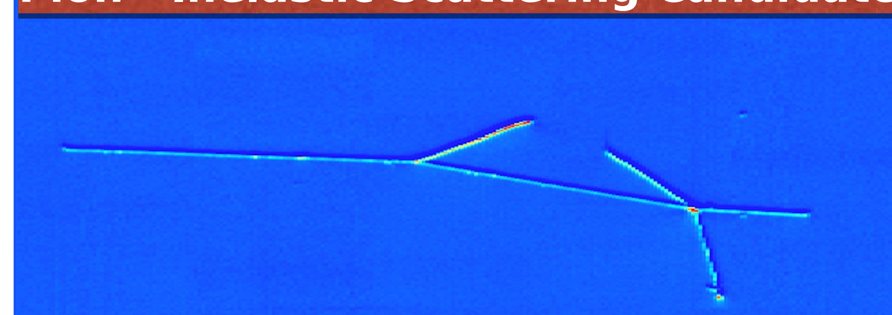
Pion - Elastic Scattering Candidate



Pion - Absorption (→3p) Candidate



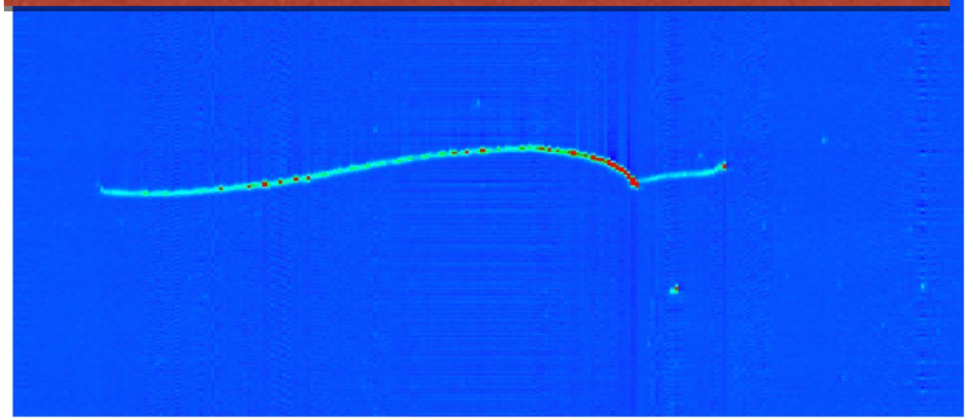
Pion - Inelastic Scattering Candidate



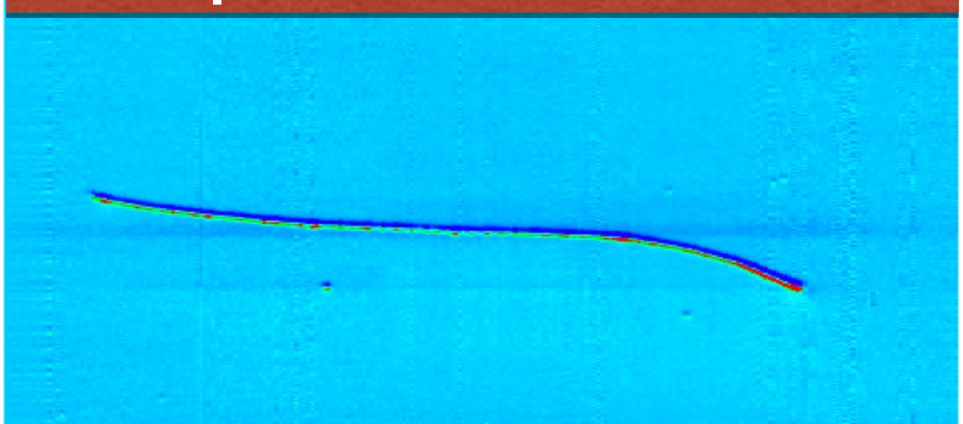
Total π-Ar Cross Section

- **Example** **background processes** **that are currently included in this analysis**
  - These processes will be estimated and removed

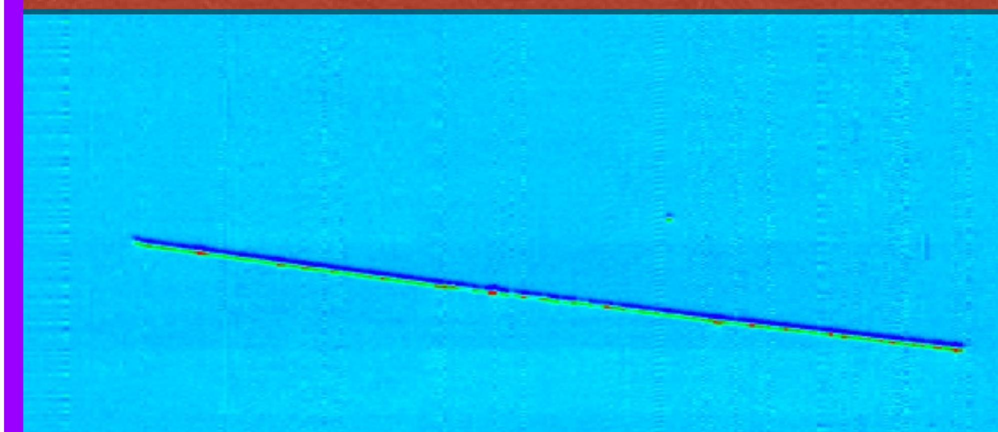
Pion Decay Candidate



Pion Capture Candidate

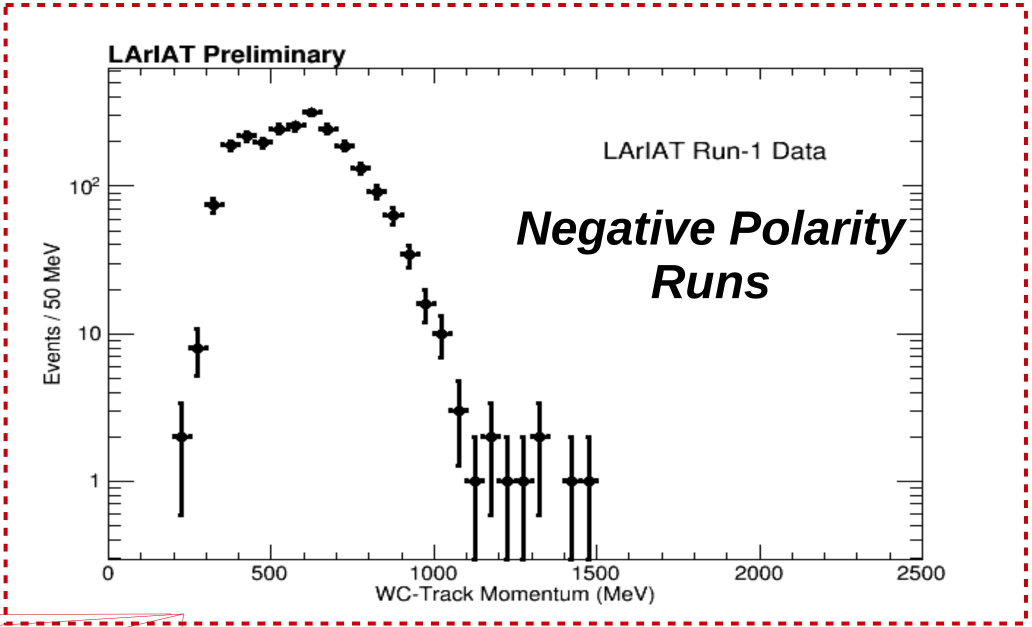


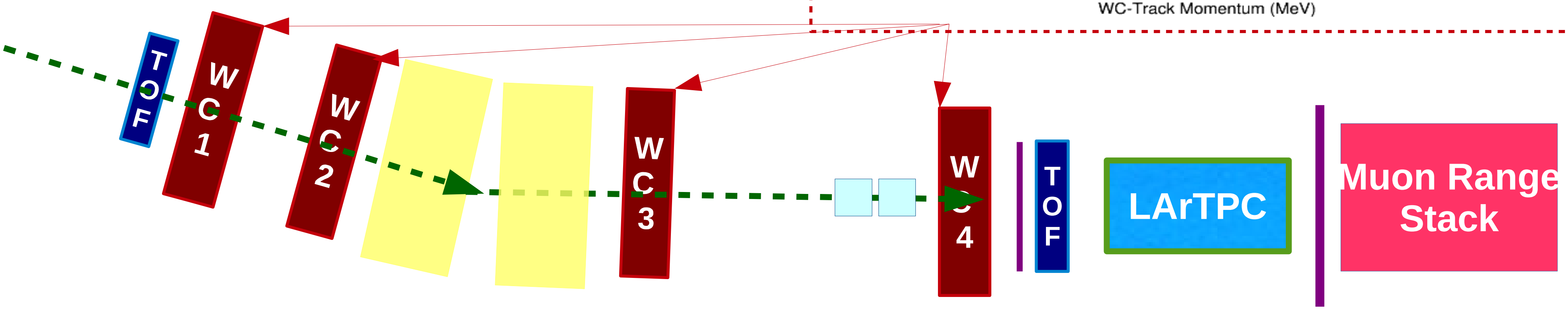
Pion Decay in Flight Topology



Total π-Ar Cross Section

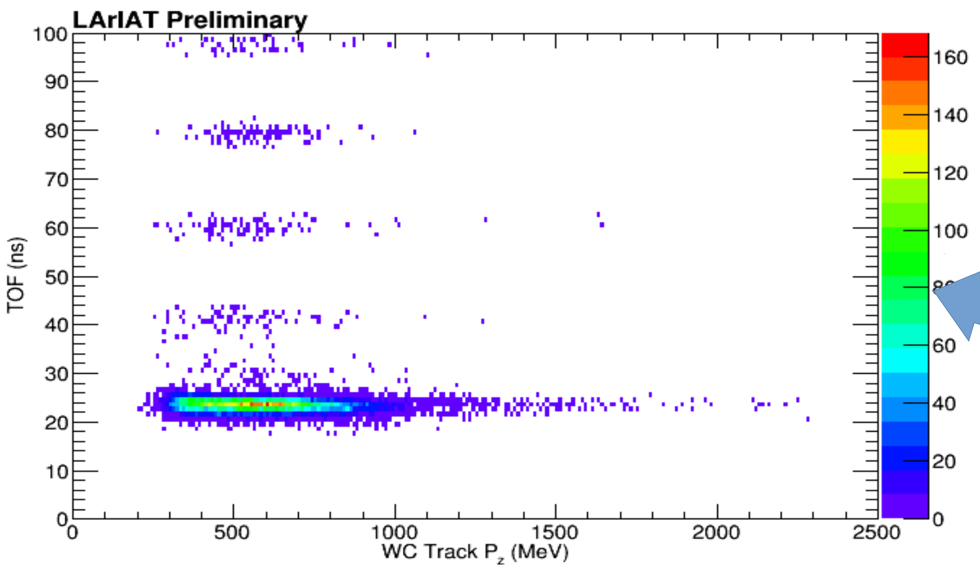
- **LArIAT measures the momentum of the incoming pions utilizing the Wire Chambers**
  - We reconstruct a “Wire Chamber Track” and use the bend in the track to measure the momentum

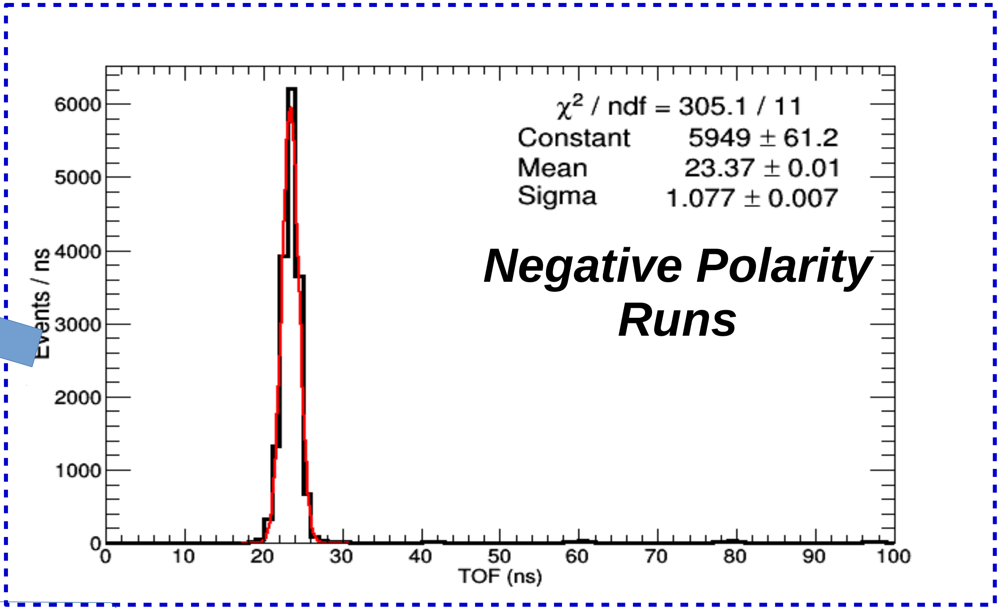


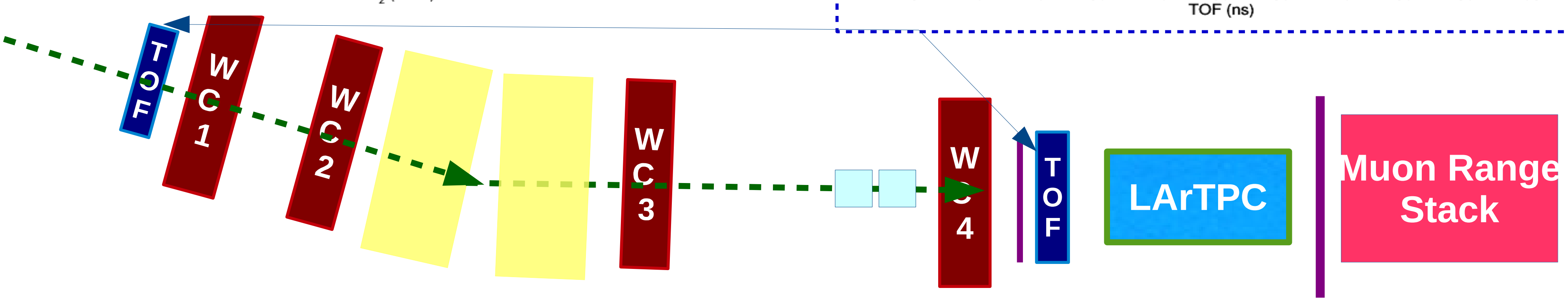


Total π-Ar Cross Section

- We then utilize the Time-of-Flight detectors to separate π/μ/e candidates (all have a similar TOF) from protons, kaons, and late particles

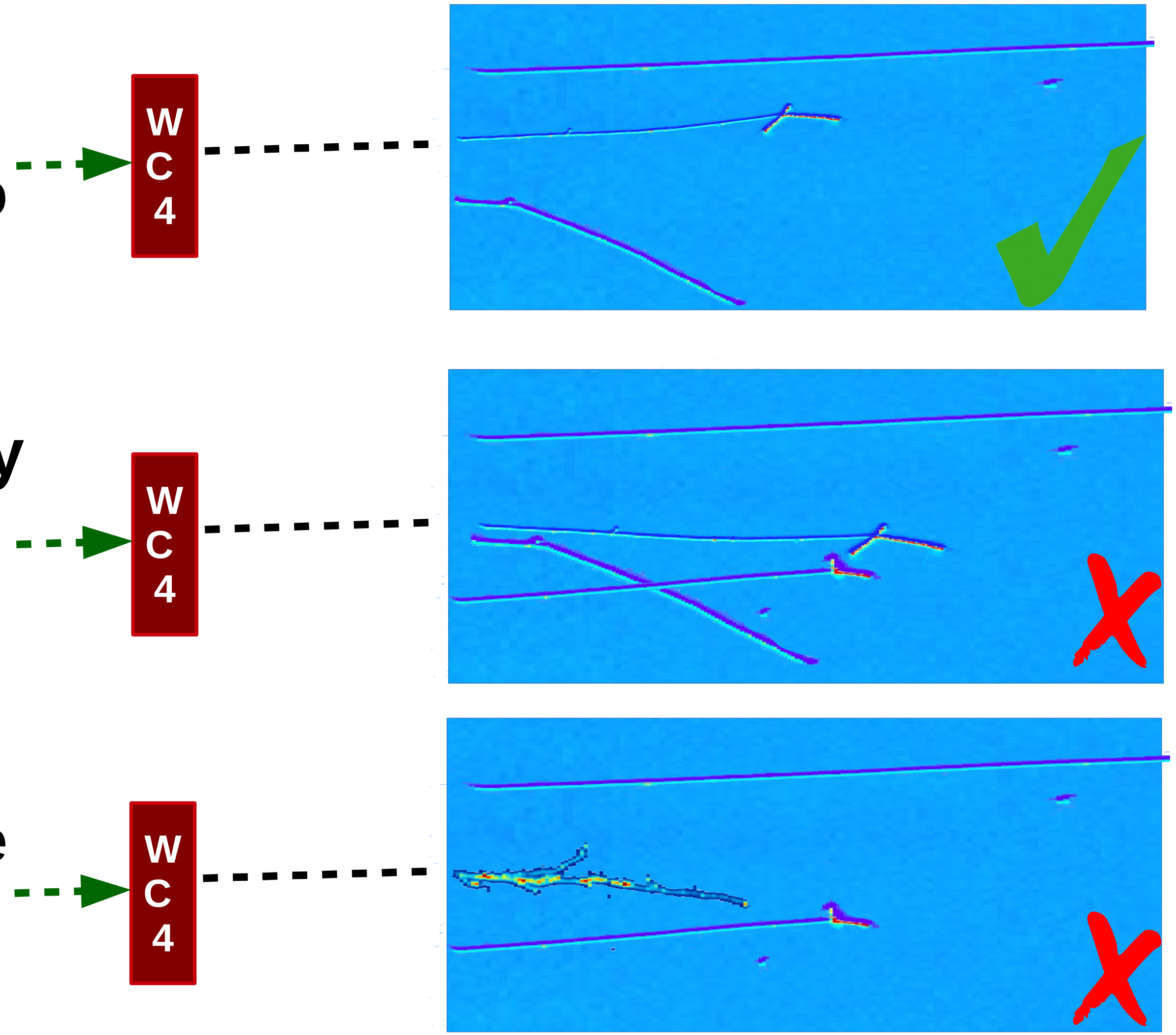


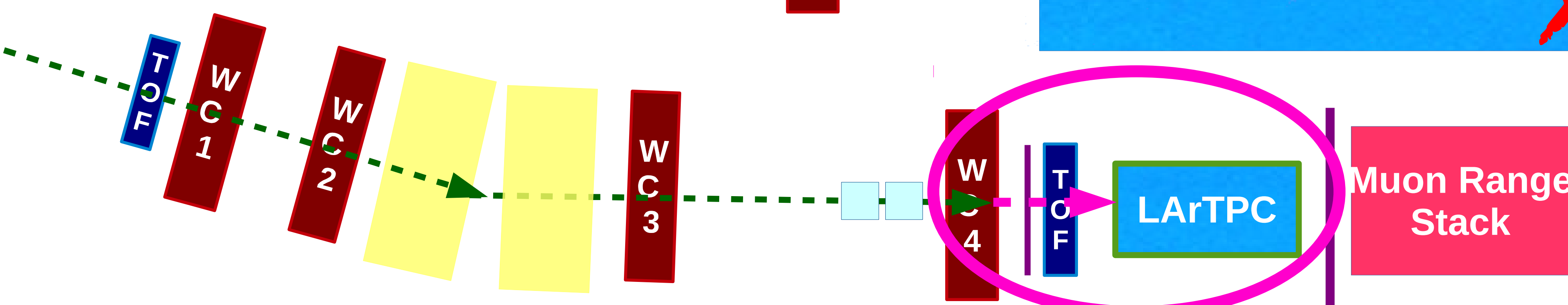




Total π-Ar Cross Section

- **We then take the Wire Chamber Track and extrapolate its position to the front face of the TPC**
- **We only select events that we can unequivocally match a TPC track to a Wire Chamber track**
  - We also veto events which have an EM-Shower profile to remove electrons from the beam





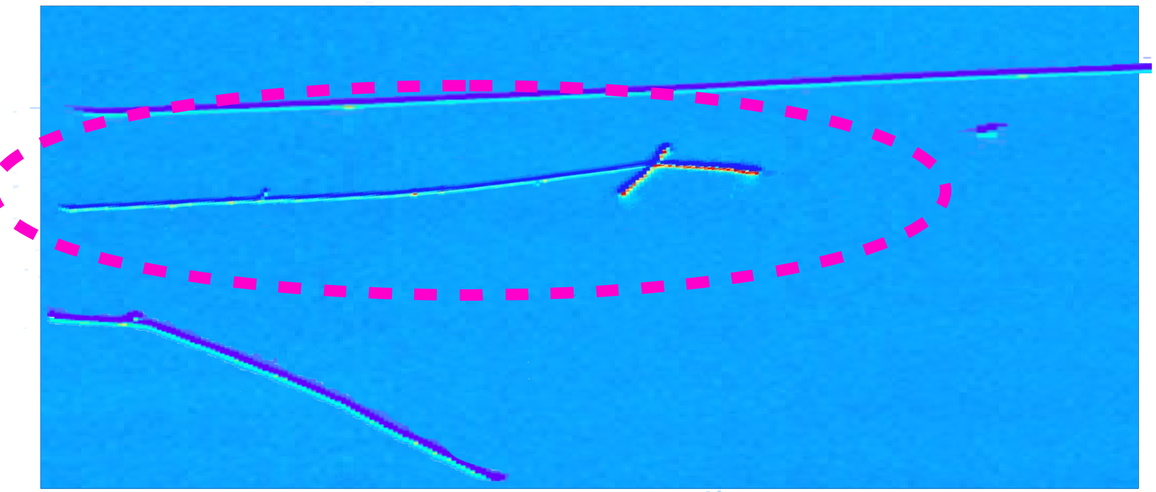
π-Ar Event Selection

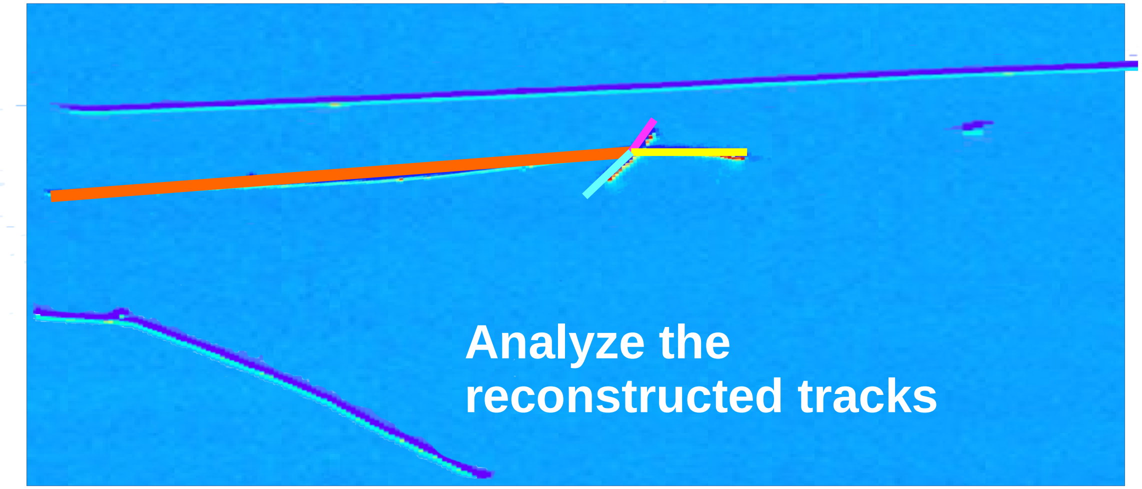
Event Sample	Number of Events
π^- Data Candidate Sample	32,064
$\pi/\mu/e$ ID	15,448
Requiring an upstream TPC Track within $z < 2$cm	14,330
< 4 tracks in the first $z < 14$cm	9,281
Wire Chamber / TPC Track Matching	2,864
Shower Rejection Filter	2,290

	π^-	e^-	γ	μ^-	K^-	$\overline{p}$
Beam Composition before cuts	48.4	40.9	8.5	2.2	0.035	0.007

	π	e	μ	γ	K^-
Selection Efficiency	74.5%	3.6%	90.0%	0.9%	70.6 %

π-Ar Event Selection





- Now we have a matched WC track and TPC track
- We calculate the π-candidate's initial kinetic energy as

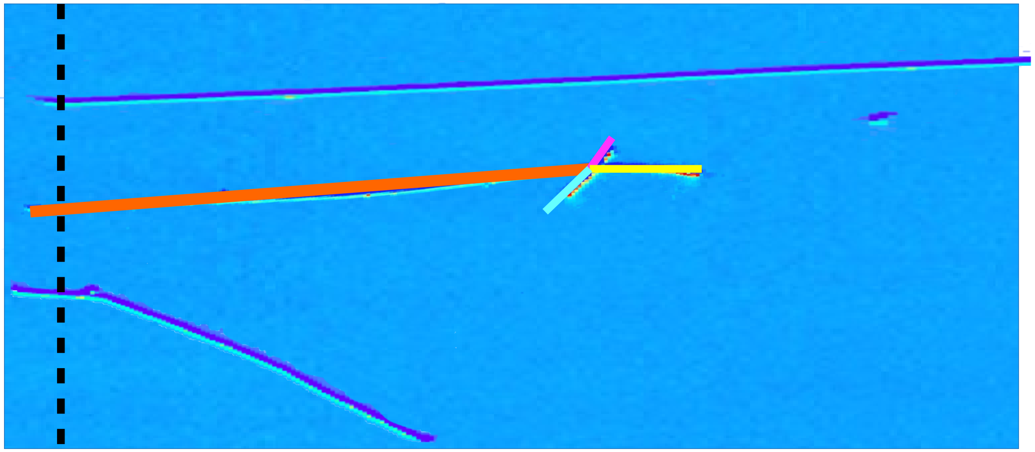
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

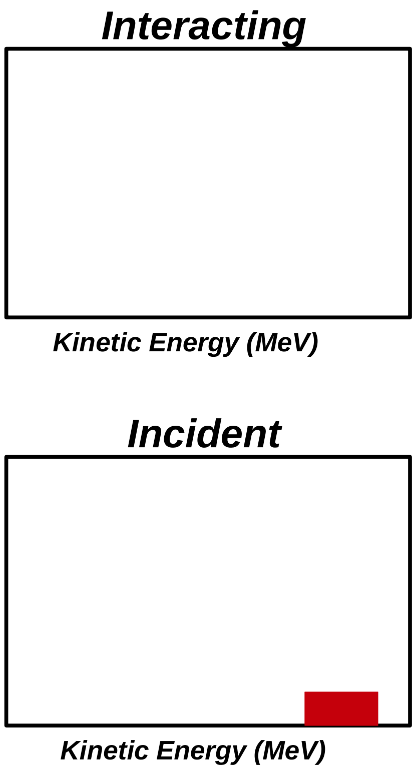
we take into account energy loss due to material upstream of the TPC (argon, steel, beamline detectors, etc)

π-Ar Interaction

- **We have a wire chamber track (with an initial kinetic energy) matched to a TPC track, we follow that TPC track in slices**
  - The slice represents the distance between each 3D point in the track
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$

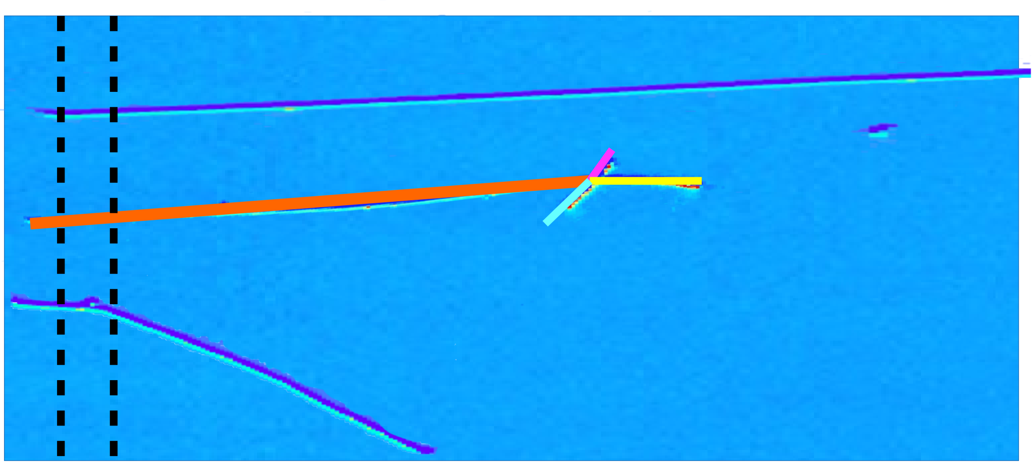


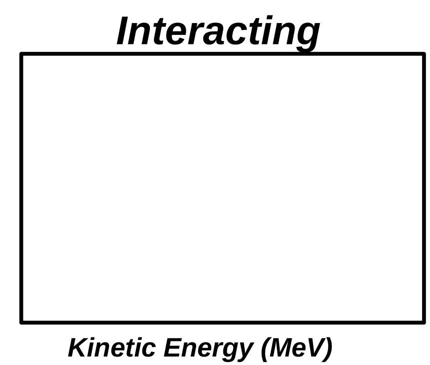


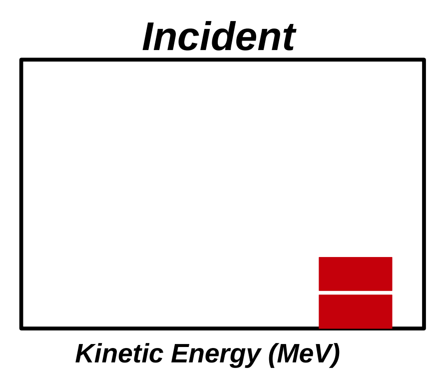
π-Ar Interaction

- **We have a wire chamber track (with an initial kinetic energy) matched to a TPC track, we follow that TPC track in slices**
  - The slice represents the distance between each 3D point in the track
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$



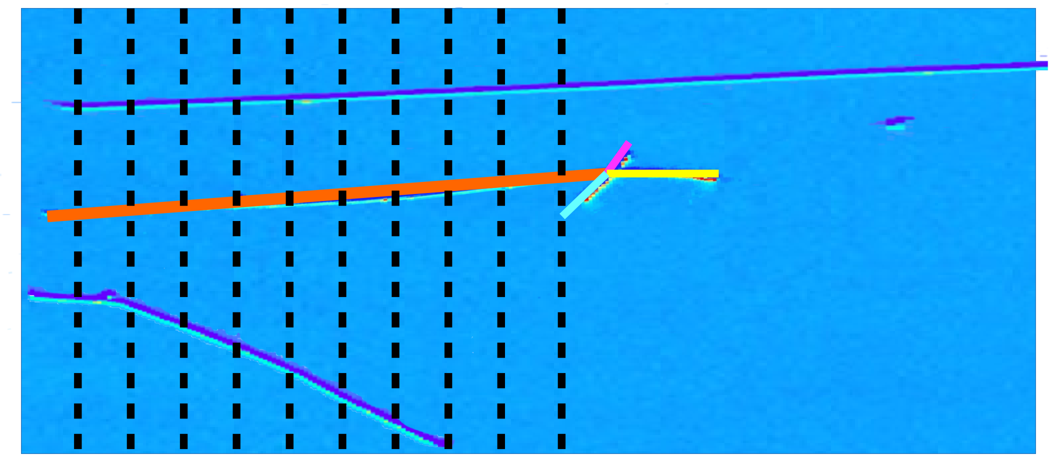


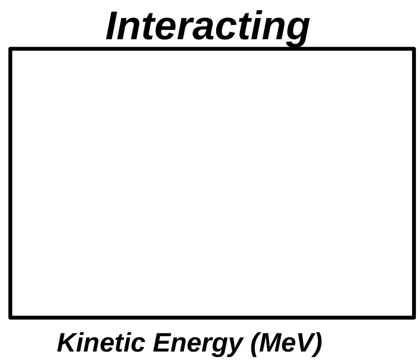


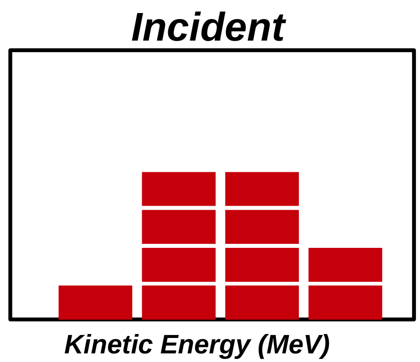
π-Ar Interaction

- **We have a wire chamber track (with an initial kinetic energy) matched to a TPC track, we follow that TPC track in slices**
  - The slice represents the distance between each 3D point in the track
  - For each slice we ask: “Is this the end of the track?”
    - **NO:** Calculate the kinetic energy at this point and put that in our “non-interacting” histogram

$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$



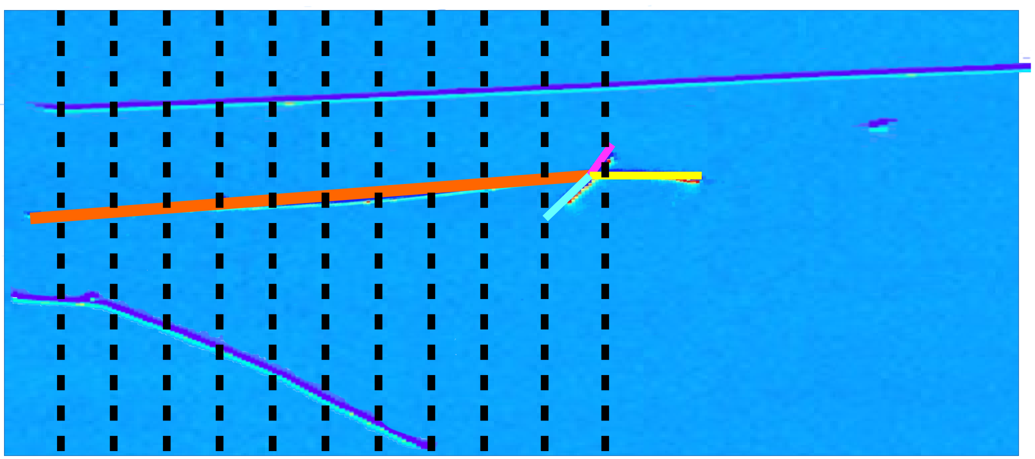


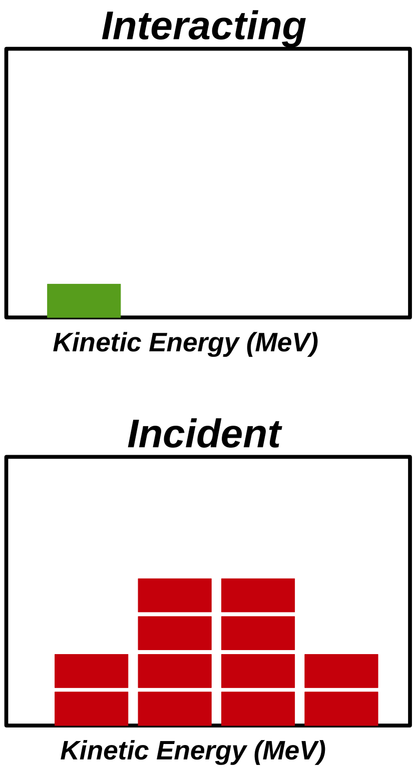


π-Ar Interaction

- **Now that we have a wire chamber track (with an initial kinetic energy measured from the wire chambers) matched to a TPC track, we follow that TPC track in slices**
  - **Yes:** Calculate the kinetic energy at this point and put that in our "interacting" histogram
    - This is kinetic energy in put in both the **interacting** and **incident** histograms

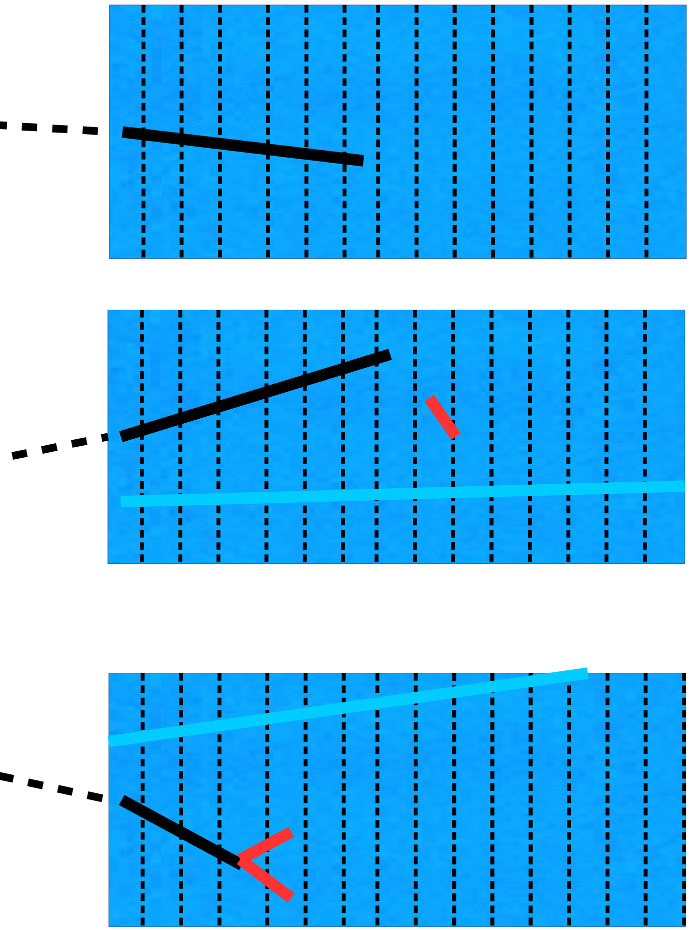
$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$

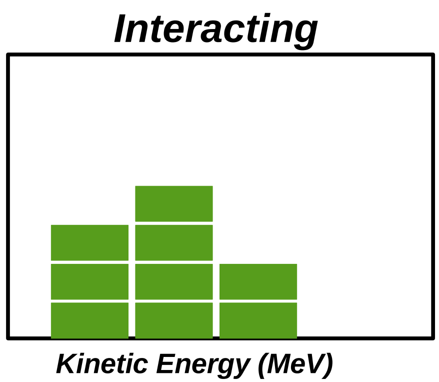


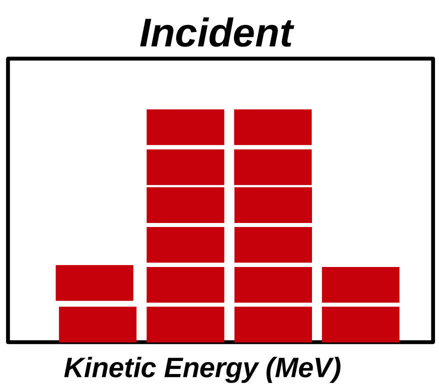


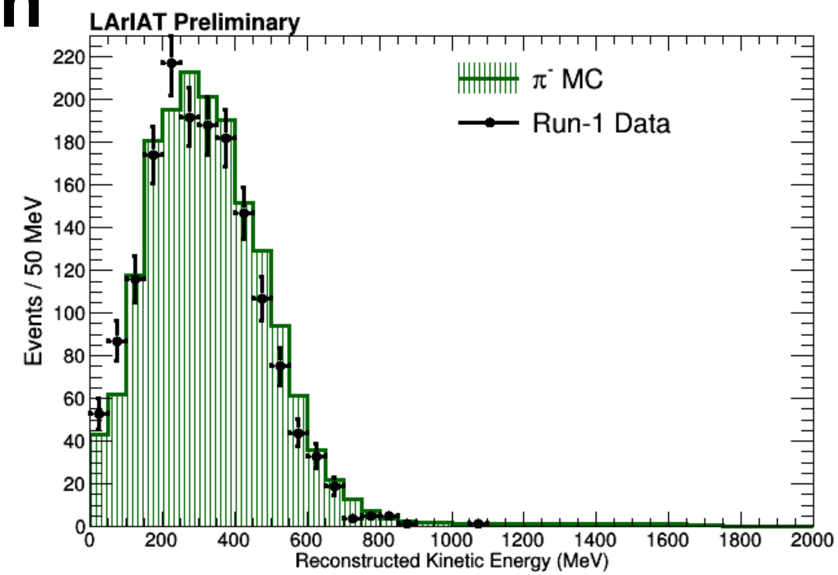
π-Ar Interaction

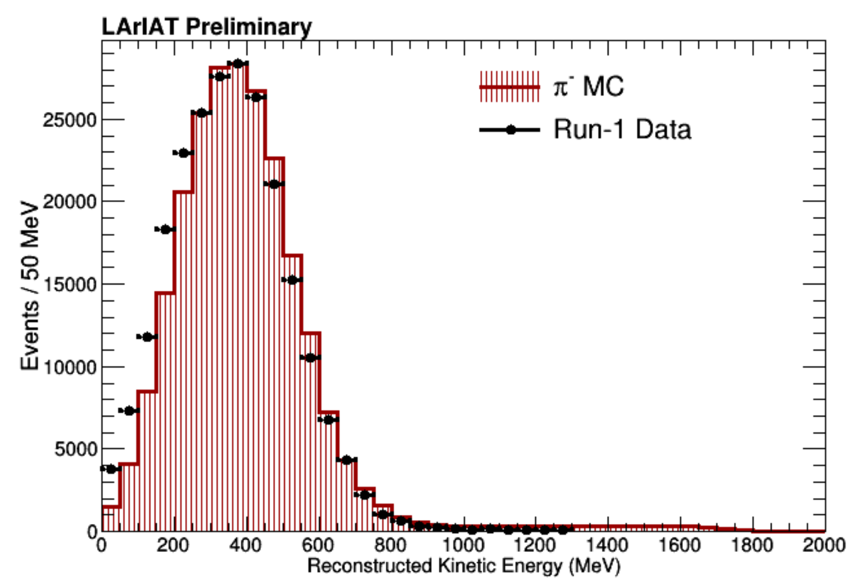
- We repeat this process event-by-event until we have gone through our entire sample





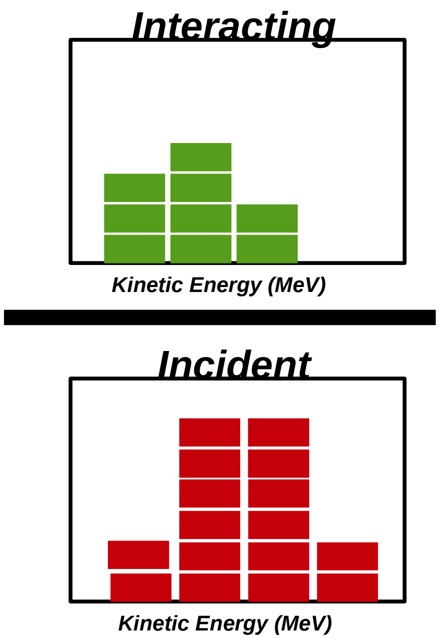




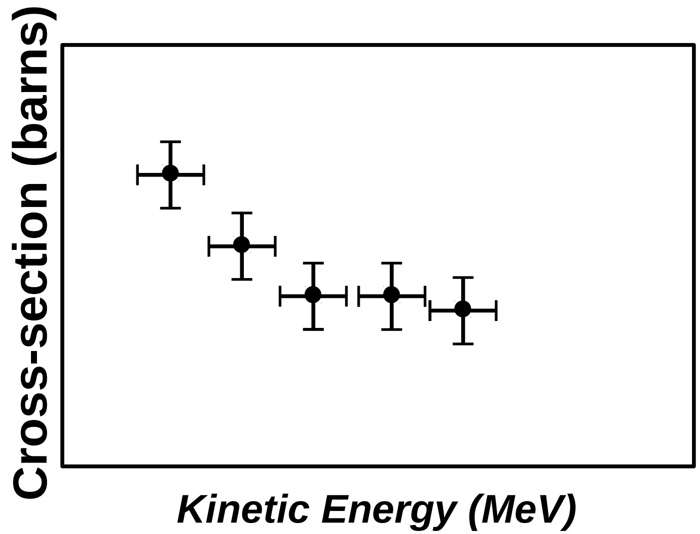


We ignore other tracks in the event not matched to the Wire Chamber Track

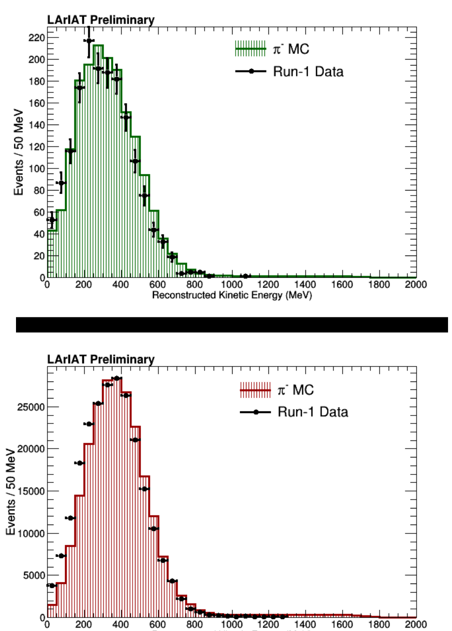
Total π-Ar Cross Section



$$= \frac{1}{nz}$$



- Finally we take the ratio of the two histograms and calculate the cross section



$$= \frac{1}{nz}$$

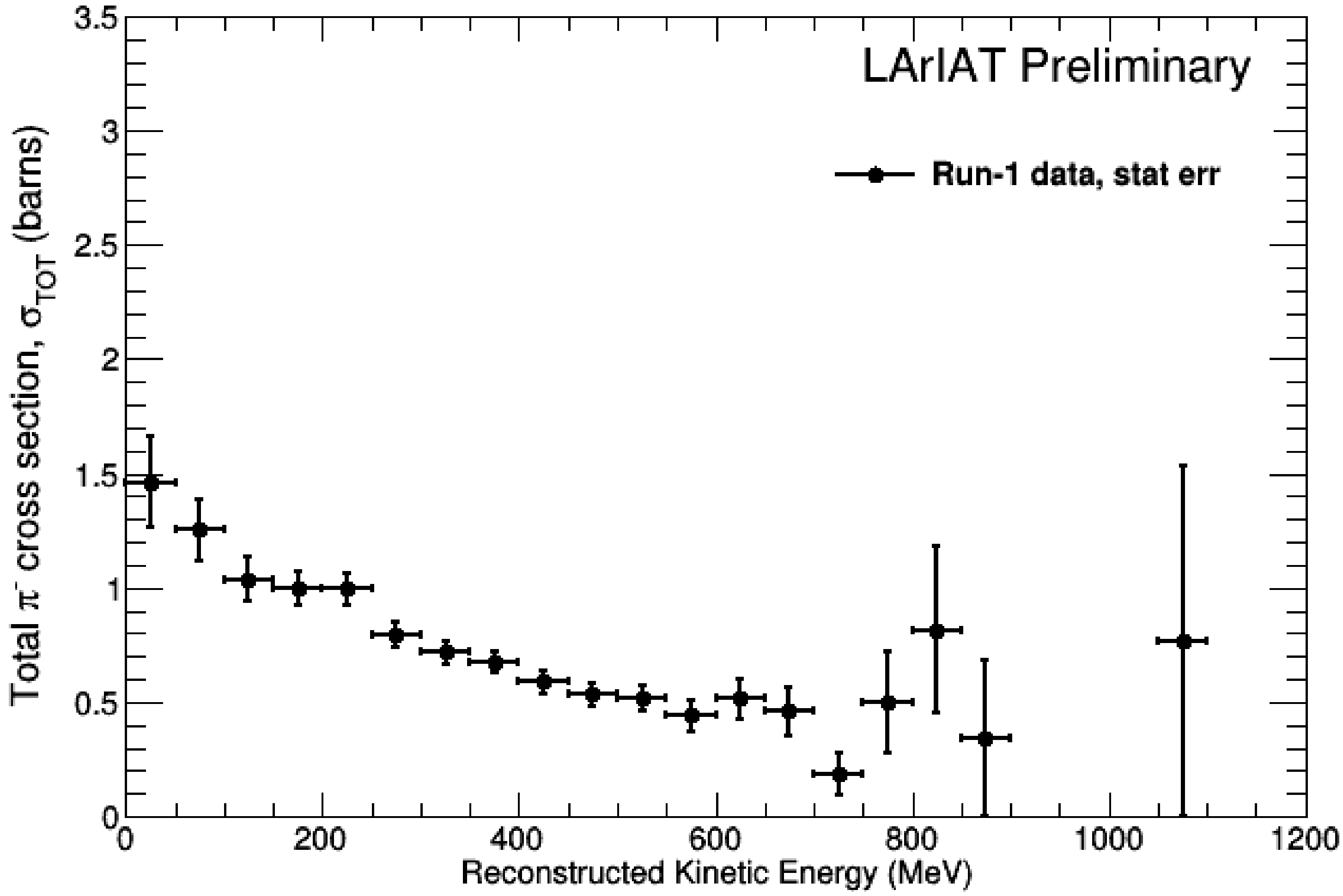
Cross-section (barns)

Reminder:
Cross section still contains capture and decay processes.

We are currently utilizing the data and MC to estimate the relative fraction of abs/decay and employing methods to remove this from our sample

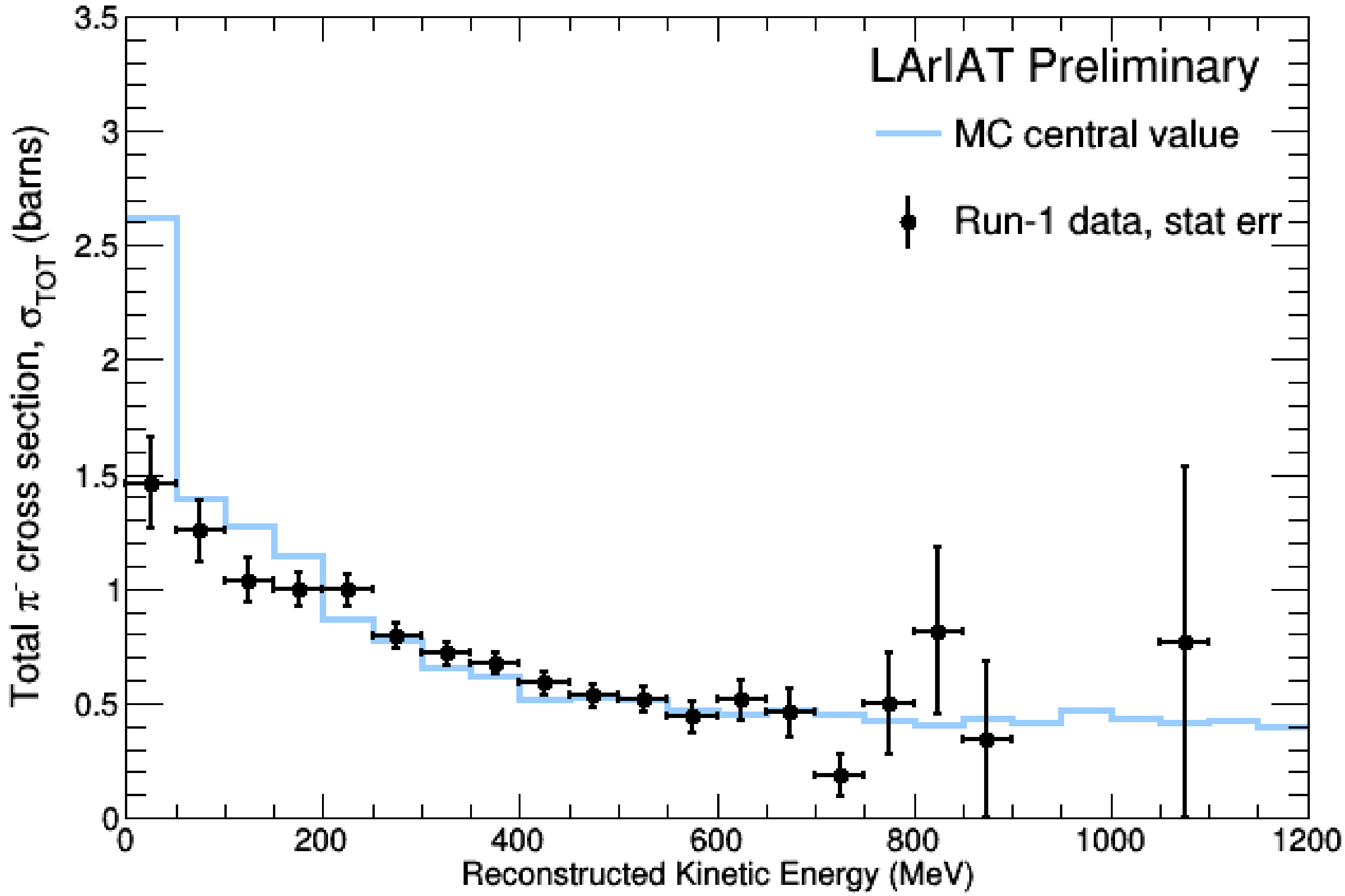
Kinetic Energy (MeV)

Total π-Ar Cross-Section



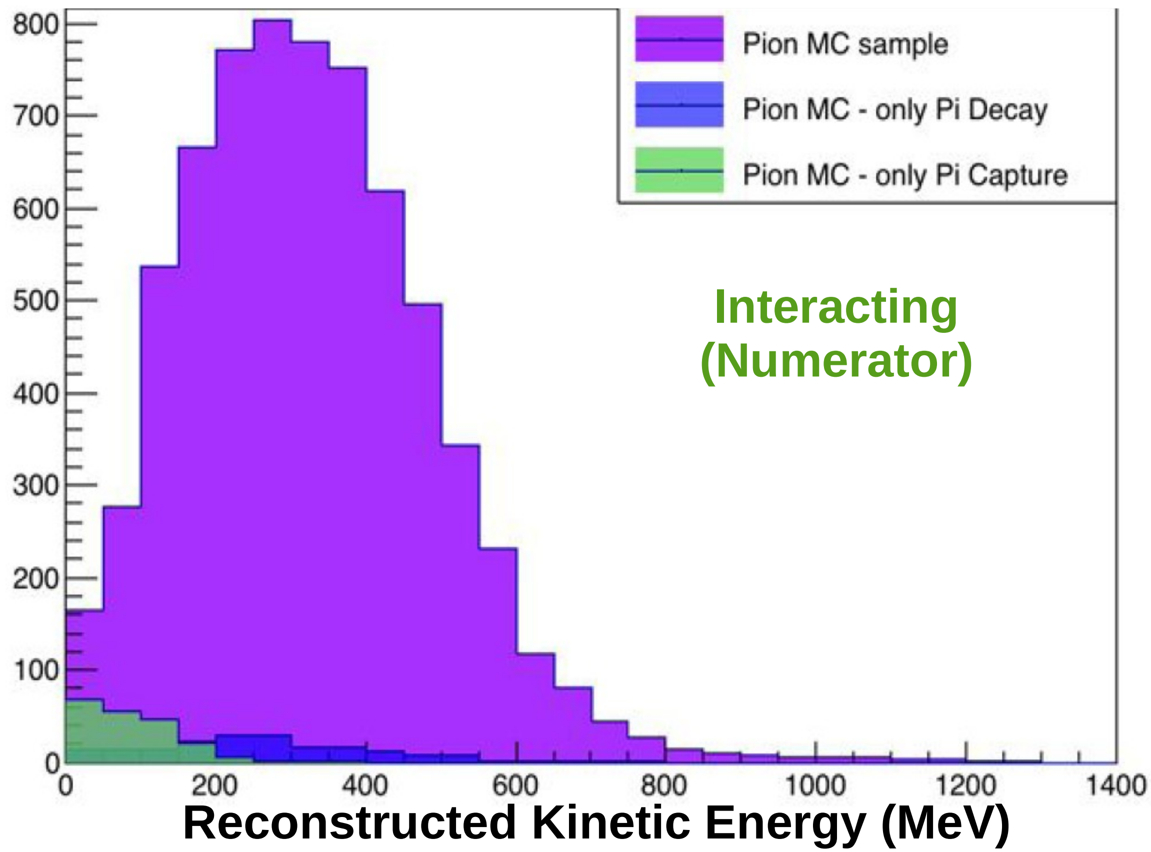
- **First measurement of π-Ar cross-section!**

Total π-Ar Cross Section



Comparing our result to π^- MC

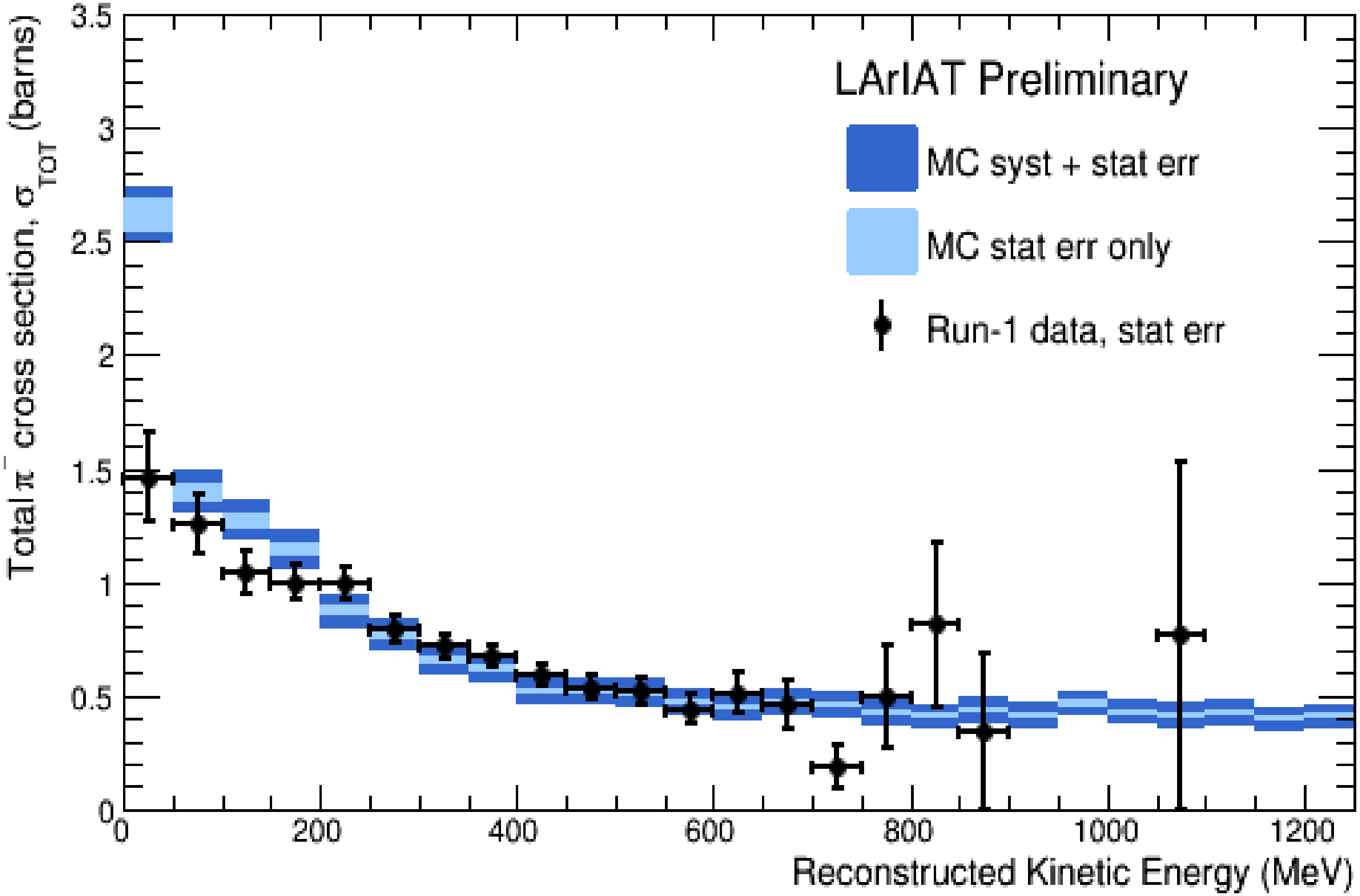
Background Contamination



- **Approximately 9% π-capture and 2% π-decay in the interacting sample**
- **34% crossing particles (π/μ) and 66% interacting particles in the TPC**
- **~10% muon contamination uniformly distributed (not shown here)**

Total π-Ar Cross-Section

Adding on Systematics



<u>Systematics Considered Here</u>

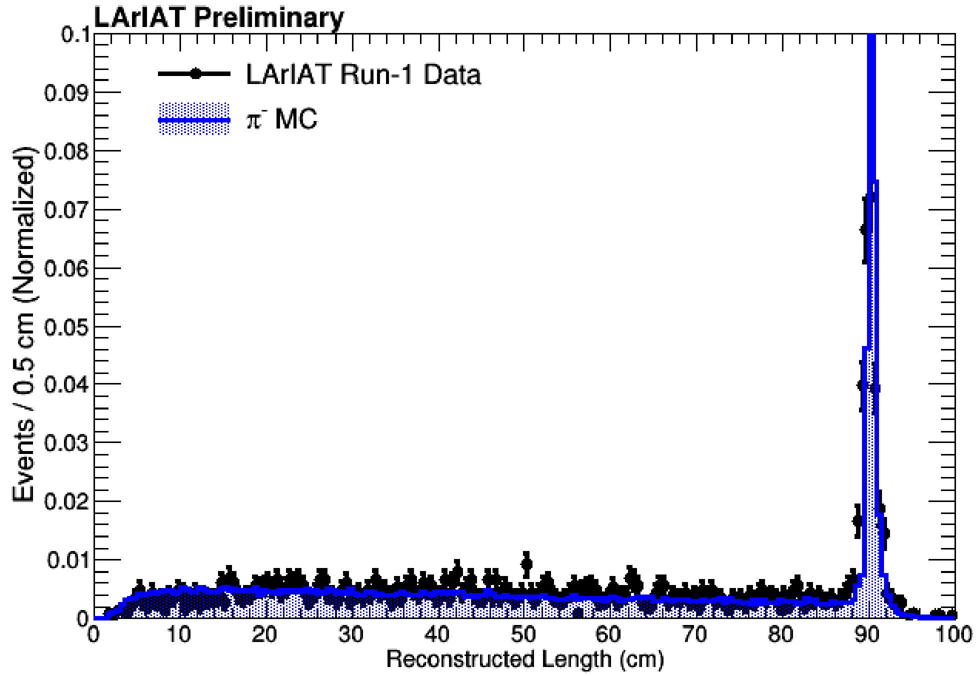
dE/dX Calibration: 5%

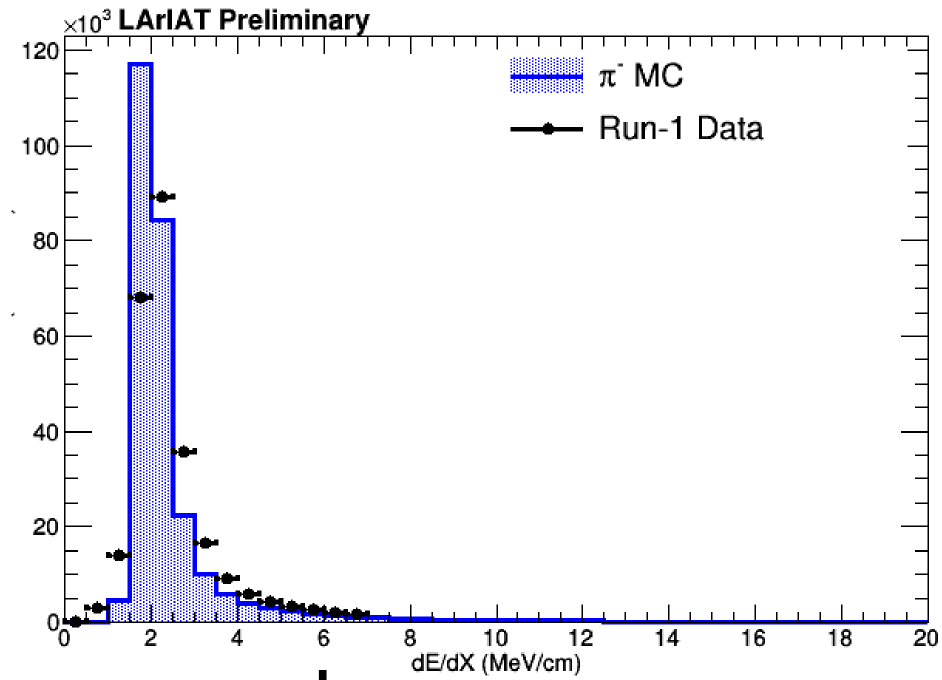
Energy Loss Prior to entering the TPC: 3.5%

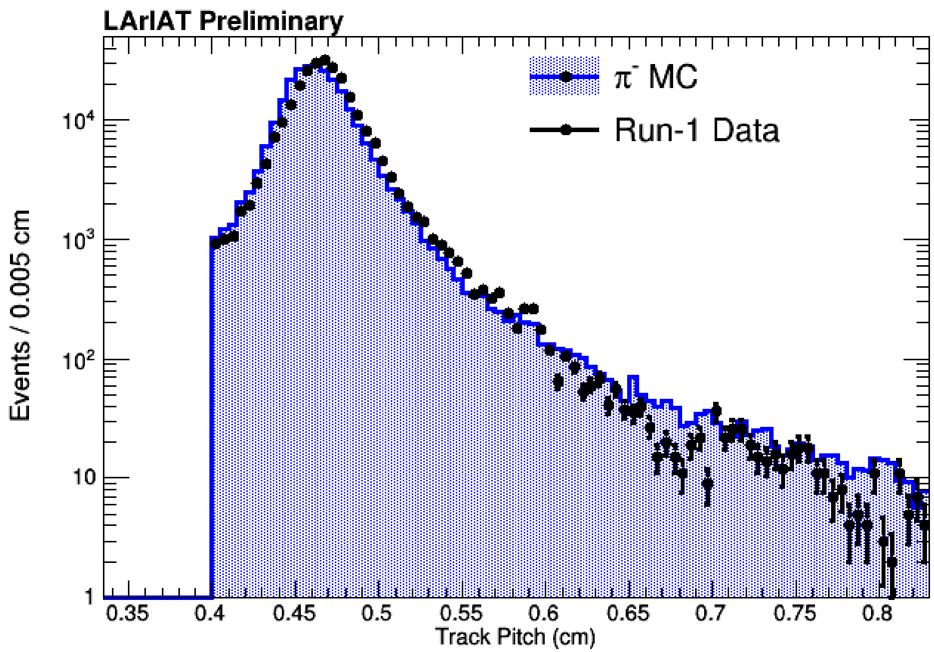
Through Going Muon Contamination: 3%

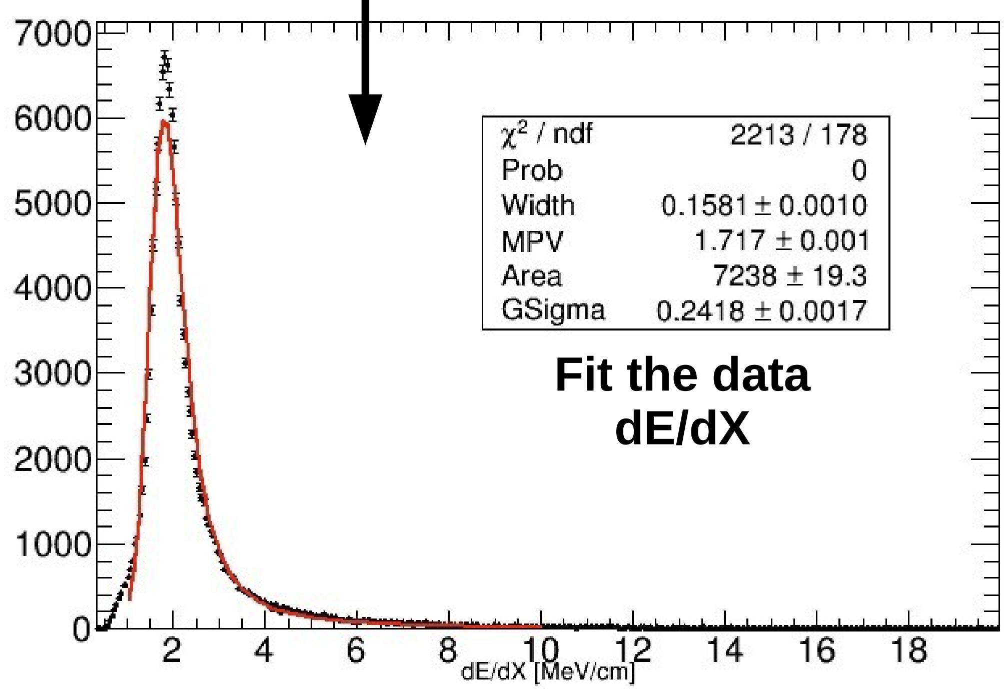
Wire Chamber Momentum Uncertainty: 3%

π-Ar Interaction



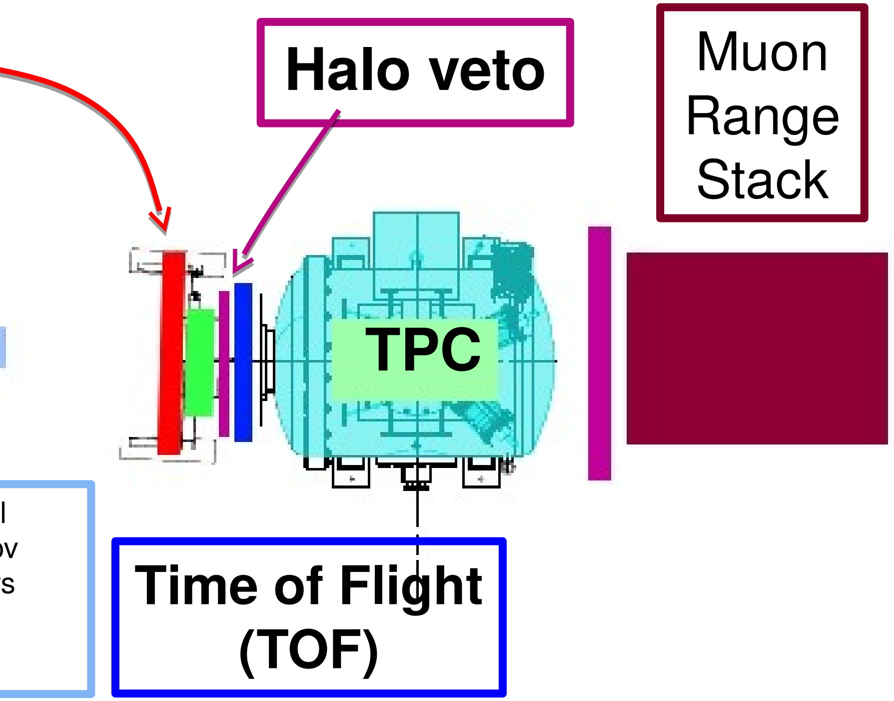




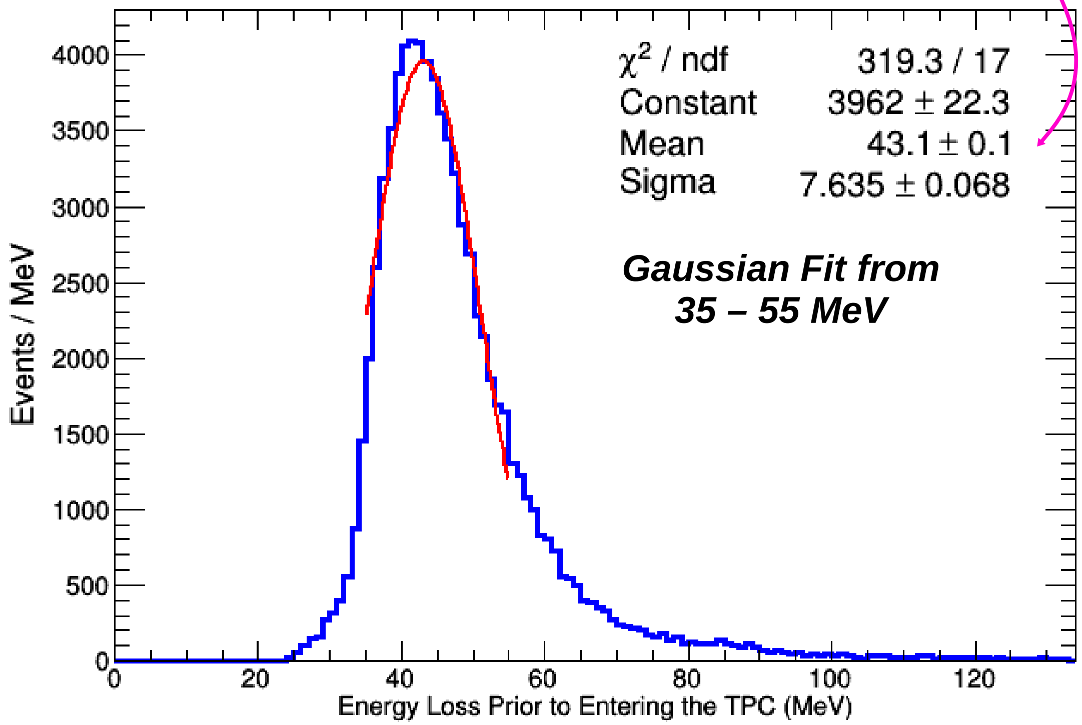


Fit the data dE/dX

Energy Corrections



$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - \boxed{E_{\mathrm{Flat}}}$$



- Adding up all the energy which a pion loses in the region before it enters the TPC (**TOF**, **Halo**, **Cryostat**, **Argon**) gives us the “energy loss” by the pion in the upstream region

Total π-Ar Cross Section

- **First analysis from LArIAT**
  - Total Pion cross section on argon never before measured
  - Fully automated LArSoft reconstruction
    - Common tool set for all liquid argon experiments
- **Next steps for the analysis**
  - Treatment of pion capture and decay processes
  - Investigate Aerogel and Muon Range Stack for through-going muon removal

Conclusions and future plans

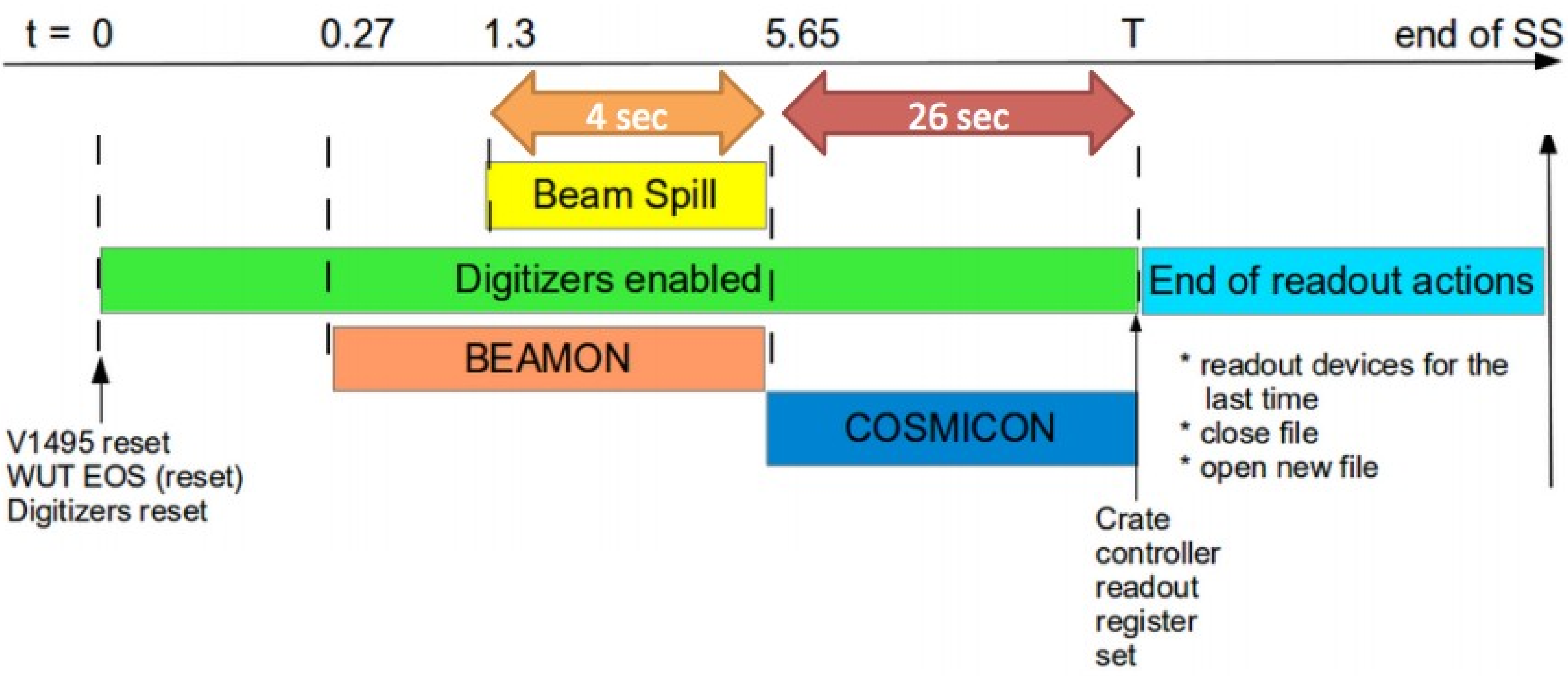
- **Run 1 collected a wonderful dataset**
  - Special thank you to the Accelerator Division (beautiful beam), FTBF (for hosting and support), Scientific Computing (support for our DAQ and offline software) and support from PPD and ND (material, engineering, and technical support)!!!
- **More analyses to come from LArIAT**
  - Cross section analyses
    - Exclusive π-Ar absorption and charge exchange channels as well as elastic, inelastic are all underway
    - All of the above for π^+'s as well
    - Kaon (Total and possibly exclusive channels analysis)
    - proton, etc...
  - e/γ, muon sign determination, scintillation light studies
- **Run 2 currently underway**
  - Began February 18th and will continue until the shutdown (July 2016)
  - 5x more statistics to be collected
  - Improvements in tuning the beam (higher quality data!)
  - Treasure trove of data to be analyzed!!!!

LArIAT Collaboration

- **Federal University of ABC, Brazil (UFABC)** Célio A. Moura, Laura Paulucci
- **Federal University of Alfenas, Brazil (UNIFAL-MG)** Gustavo Valdiviesso
- **Boston U.** Flor de Maria Blaszczyk, Dan Gastler, Ryan Linehan, Ed Kearns, Daniel Smith
- **U. Campinas, Brazil (UNICAMP)** Cesar Castromonte, Carlos Escobar, Ernesto Kemp, Ana Amelia B. Machado, Bruno Miguez, Monica Nunes, Lucas Santos, Ettore Segreto, Thales Vieira
- **U. Chicago** Ryan Bouabid, Will Foreman, Johnny Ho, Dave Schmitz
- **U. Cincinnati** Randy Johnson, Jason St. John
- **Fermilab** Roberto Acciarri, Michael Backfish, William Badgett, Bruce Baller, Raquel Castillo Fernandez, Flavio Cavanna† (also INFN, Italy), Alan Hahn, Doug Jensen, Hans Jostlein, Mike Kirby, Tom Kobilarcik, Paweł Kryczyński (also Institute of Nuclear Physics, Polish Academy of Sciences), Sarah Lockwitz, Alberto Marchionni, Irene Nutini, Ornella Palamara (also INFN, Italy), Jon Paley, Jennifer Raaf†, Brian Rebel‡, Michelle Stancari, Tingjun Yang, Sam Zeller
- **Federal University of Goiás, Brazil (UFG)** Tapasi Ghosh, Ricardo A. Gomes, Ohana Rodrigues
- **Istituto Nazionale di Fisica Nucleare, Italy (INFN)** Flavio Cavanna (also Fermilab), Ornella Palamara (also Fermilab)
- **KEK** Eito Iwai, Takasumi Maruyama
- **Louisiana State University** William Metcalf, Andrew Olivier, Martin Tzanov
- **U. Manchester, UK** Justin Evans, Diego Gamez, Pawel Guzowski, Colton Hill, Andrzej Szelc
- **Michigan State University** Carl Bromberg, Dan Edmunds, Dean Shooltz
- **U. Minnesota, Duluth** Rik Gran, Alec Habig
- **U. Pittsburgh** Steve Dytman, Matthew Smylie
- **Syracuse University** Jessica Esquivel, Pip Hamilton, Greg Pulliam, Mitch Soderberg
- **U. Texas, Arlington** Jonathan Asaadi, Animesh Chatterjee, Amir Farbin, Sepideh Shahsavarani, Jae Yu
- **U. Texas, Austin** Will Flanagan, Karol Lang, Dung Phan, Brandon Soubasis (also Texas State University)
- **University College London** Anna Holin, Ryan Nichol
- **William & Mary** Mike Kordosky‡, Matthew Stephens
- **Yale University** Bonnie Fleming, Elena Gramellini

Back up

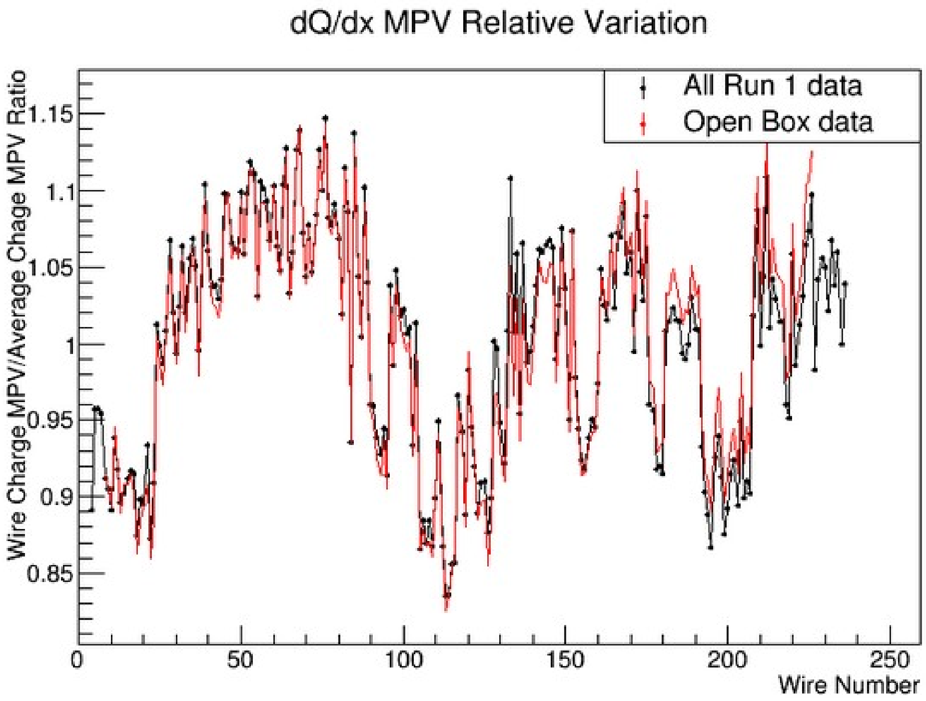
Supercycle

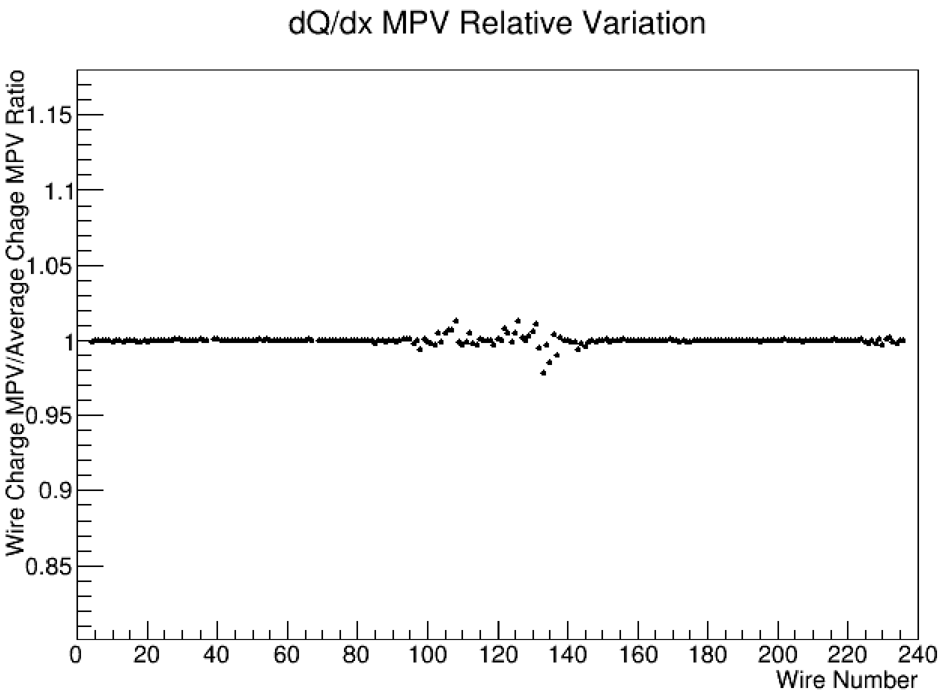


Spill supercycle = **4s beam + 26s cosmics & light-based Michel triggers**

- ~ 5-20 beam triggers per supercycle (depending on beam intensity)
- ~0-2 cosmic muon paddle triggers per supercycle
- ~20 Michel events per supercycle

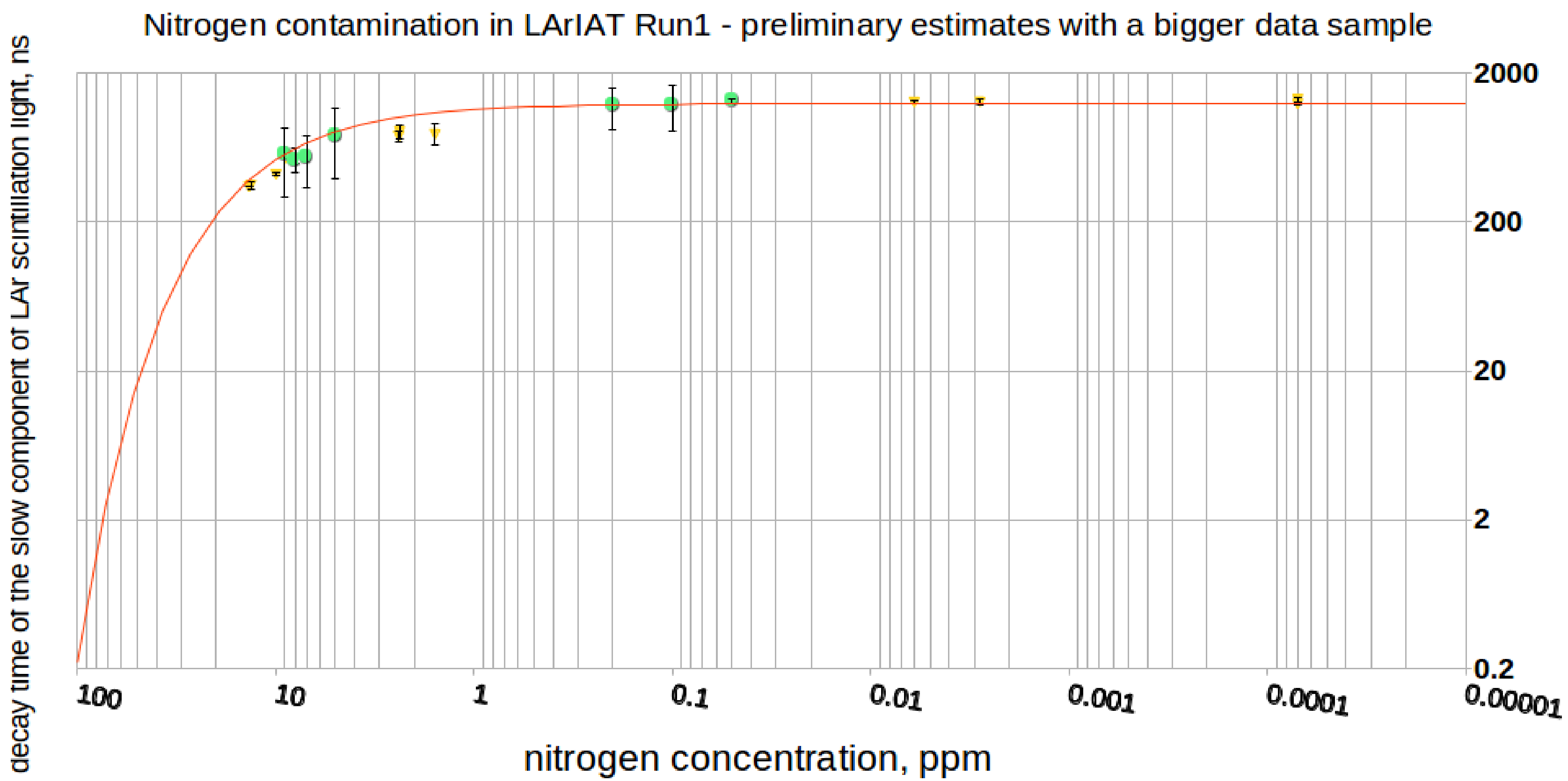
Wire-By-Wire Corrections

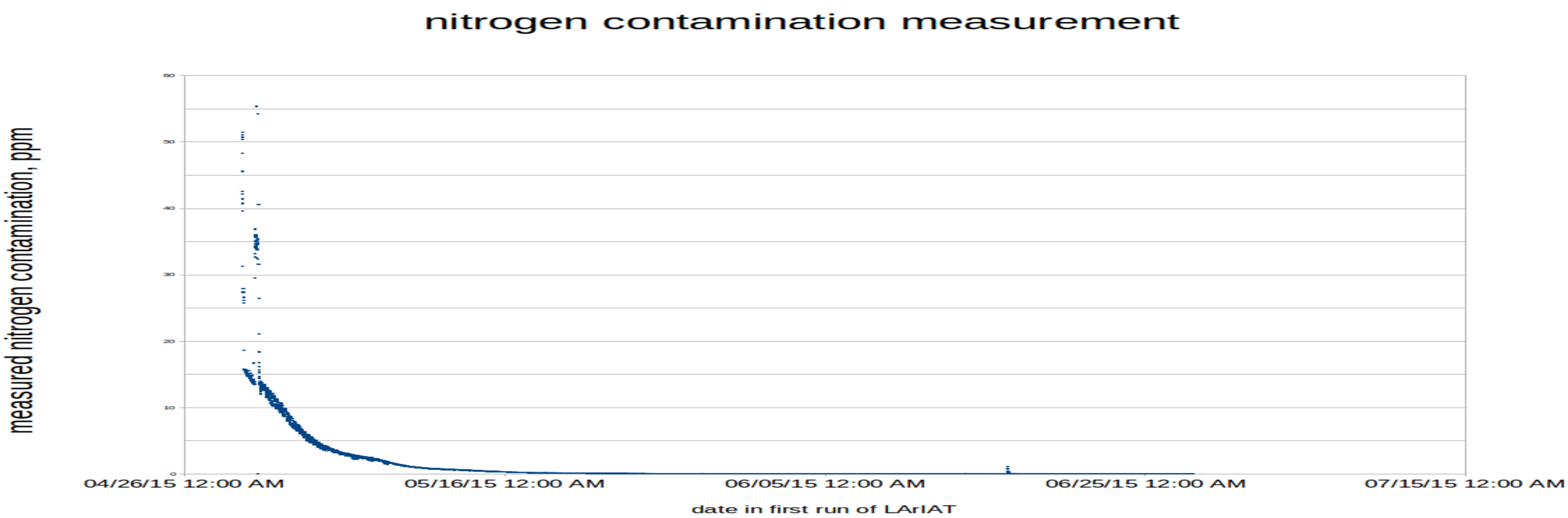




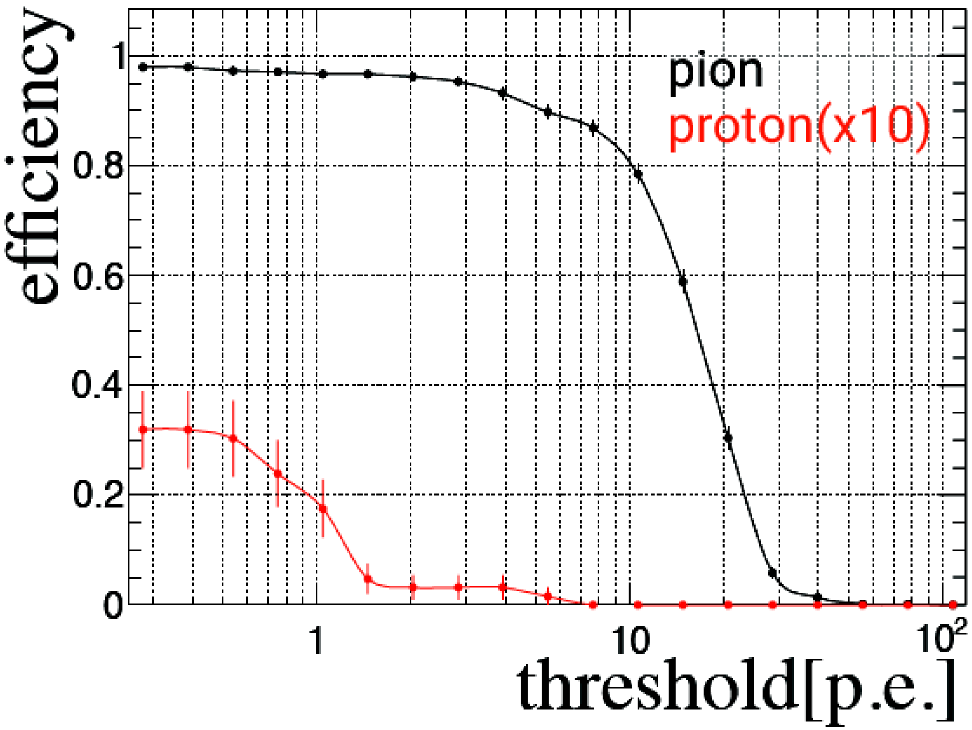
- **A notable variation of the charge collected wire-by-wire was observed during Run 1**
- **In order to mitigate the effect of this variation an Wire-by-wire correction was derived and applied**
  - Note: we do calorimetry using the collection plane in this analysis
- **Here we explore the impact the wire-by-wire correction has on the analysis**

Run-1 Nitrogen Contamination



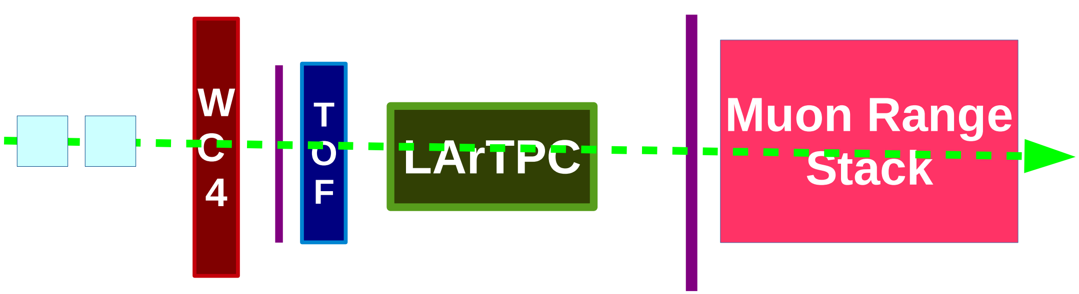


Aerogel Cherenkov Detector

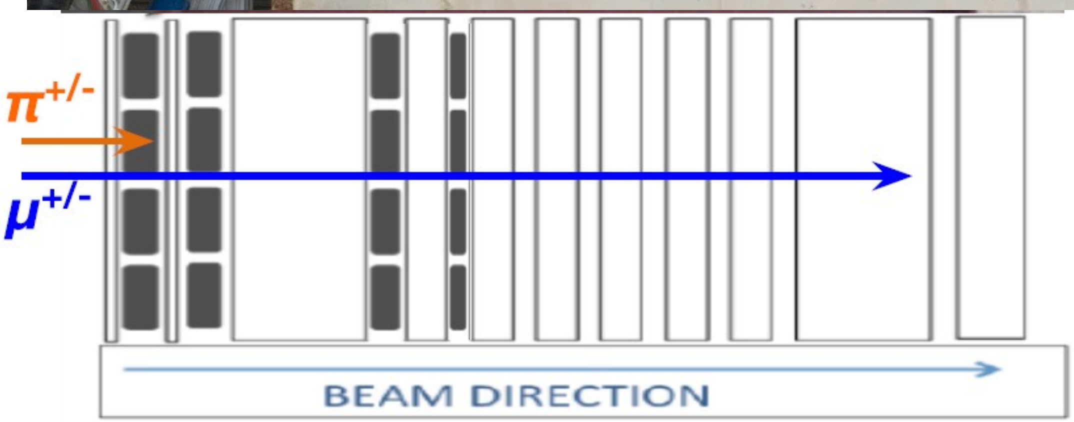


- **By having two Aerogel detectors with different incidences of refraction you can begin to separate μ/π**
  - Demonstrated efficiency for pions of 97% @ 1.5 pe threshold
  - Proton fake rate of 0.5% @ 1.5 pe threshold
  - μ/π studies ongoing now

	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

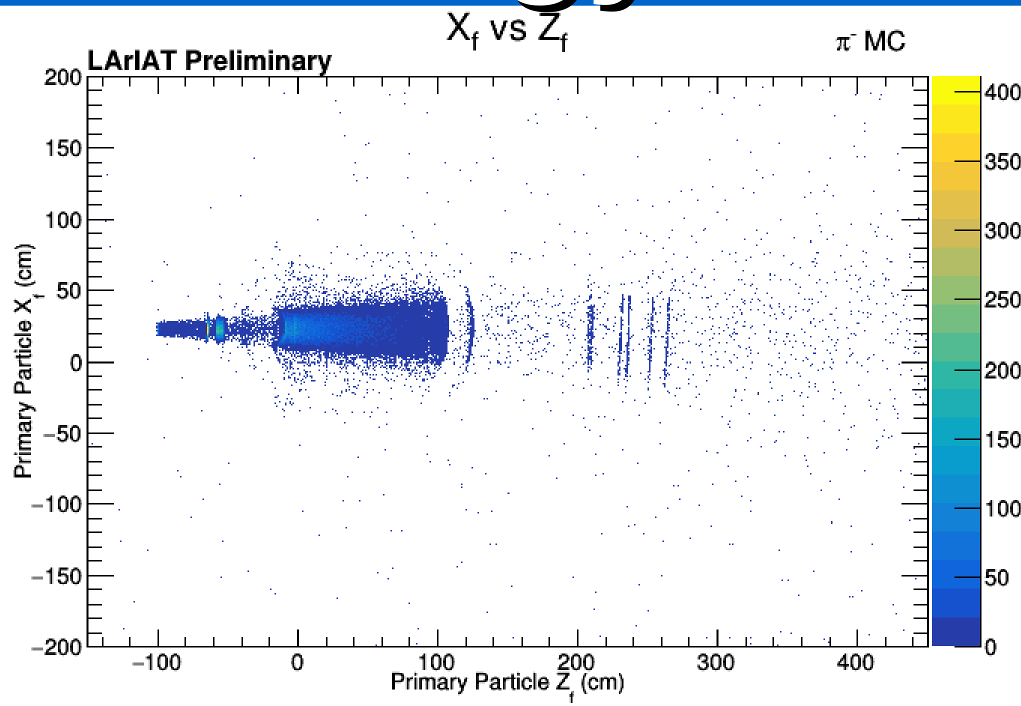


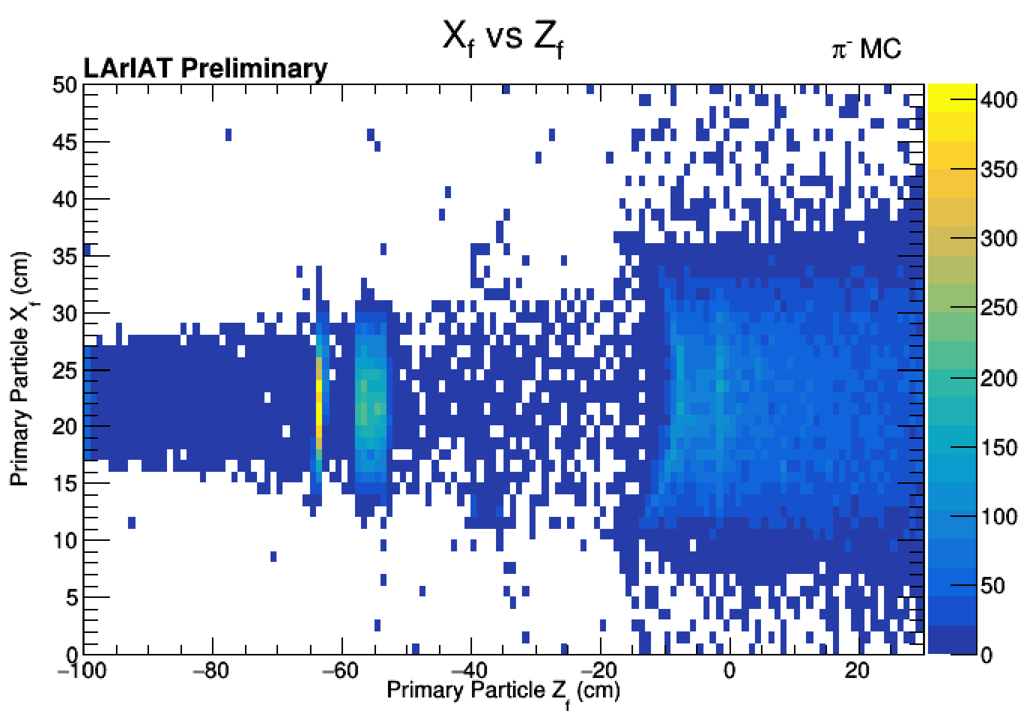
Muon Range Stack



- **Muon range stack is for discriminating through going μ/π**
  - Essentially a segmented block of (pink) steel with scintillator bars and PMTs
  - Muons can penetrate further than pions
  - Match this activity to the rest of the beamline and the TPC

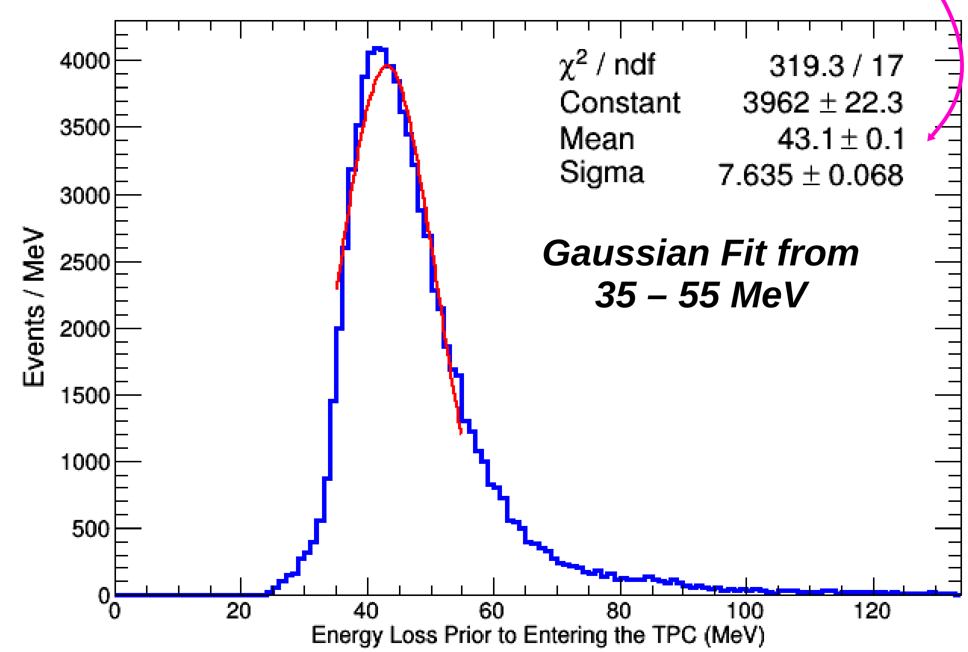
Energy Loss Corrections



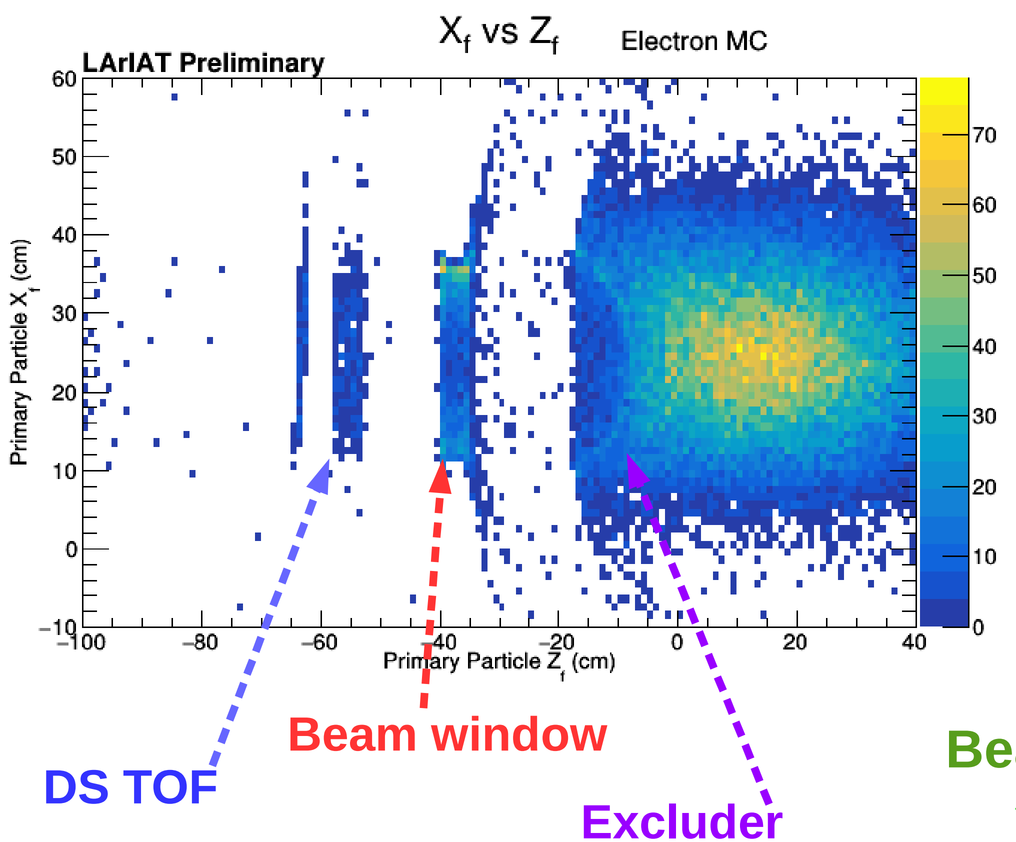


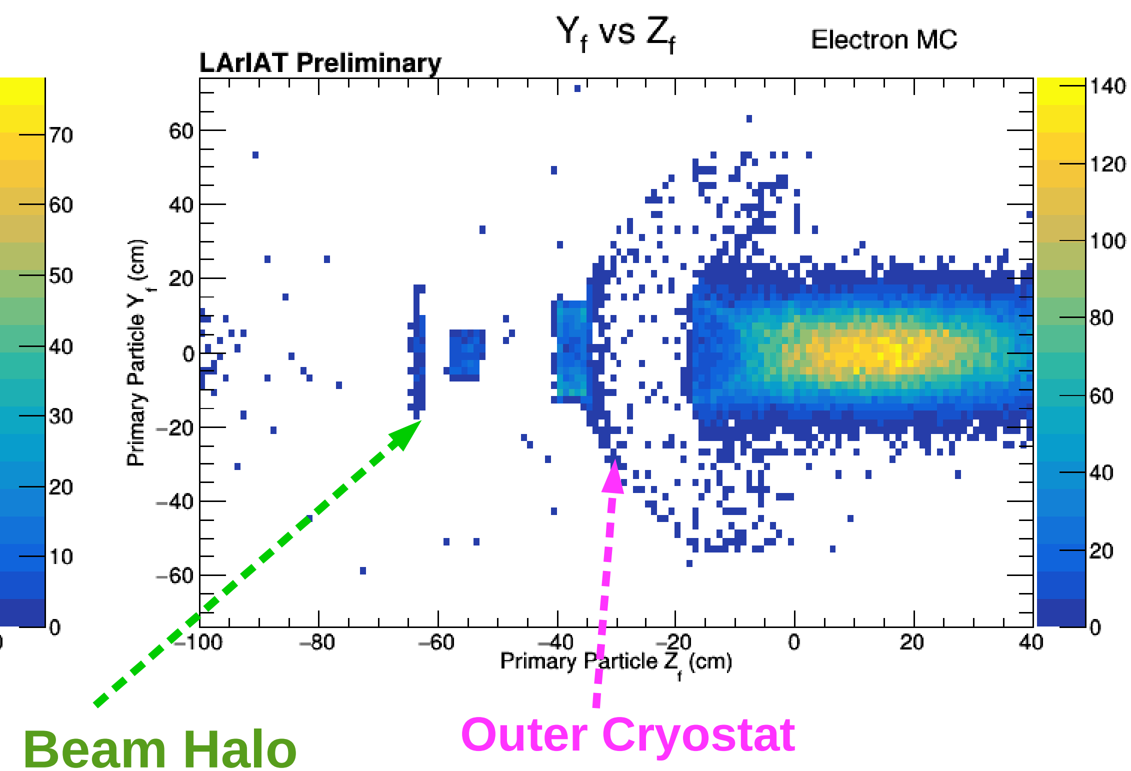
- Adding up all the energy which a pion loses in the region before it enters the TPC gives us the “energy loss” by the pion in the upstream region

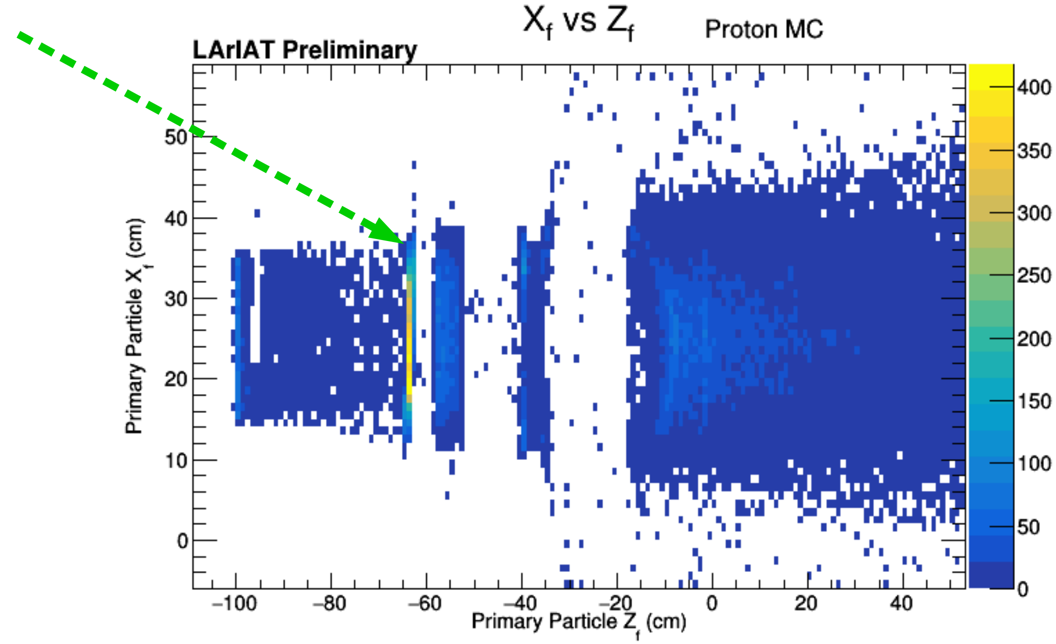
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - \boxed{E_{\mathrm{Flat}}}$$



Energy Corrections
(looking at other particle species)



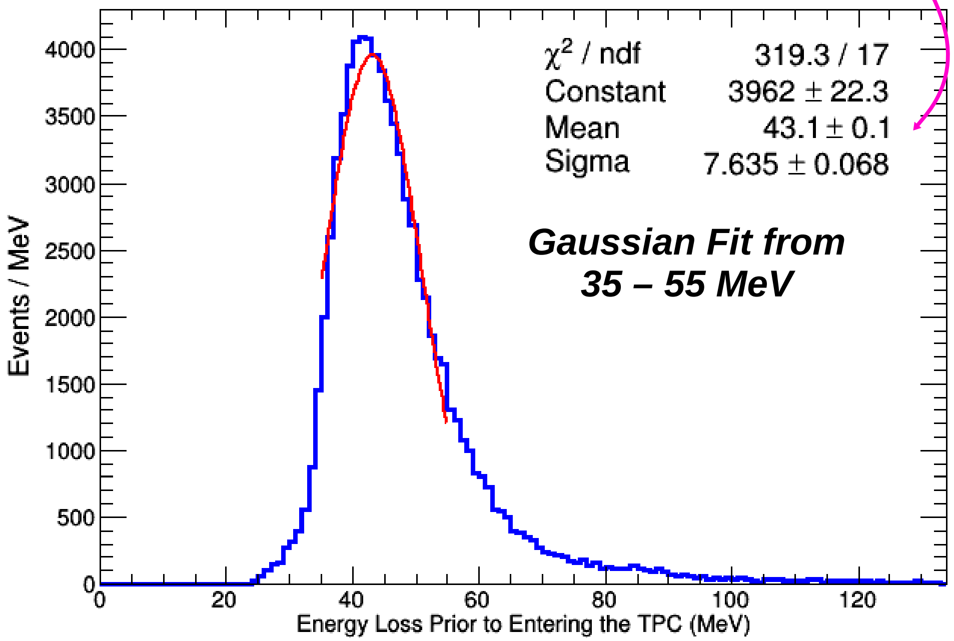




- **Looking at single particle electron and proton we can get a better sense of the material that is being simulated**

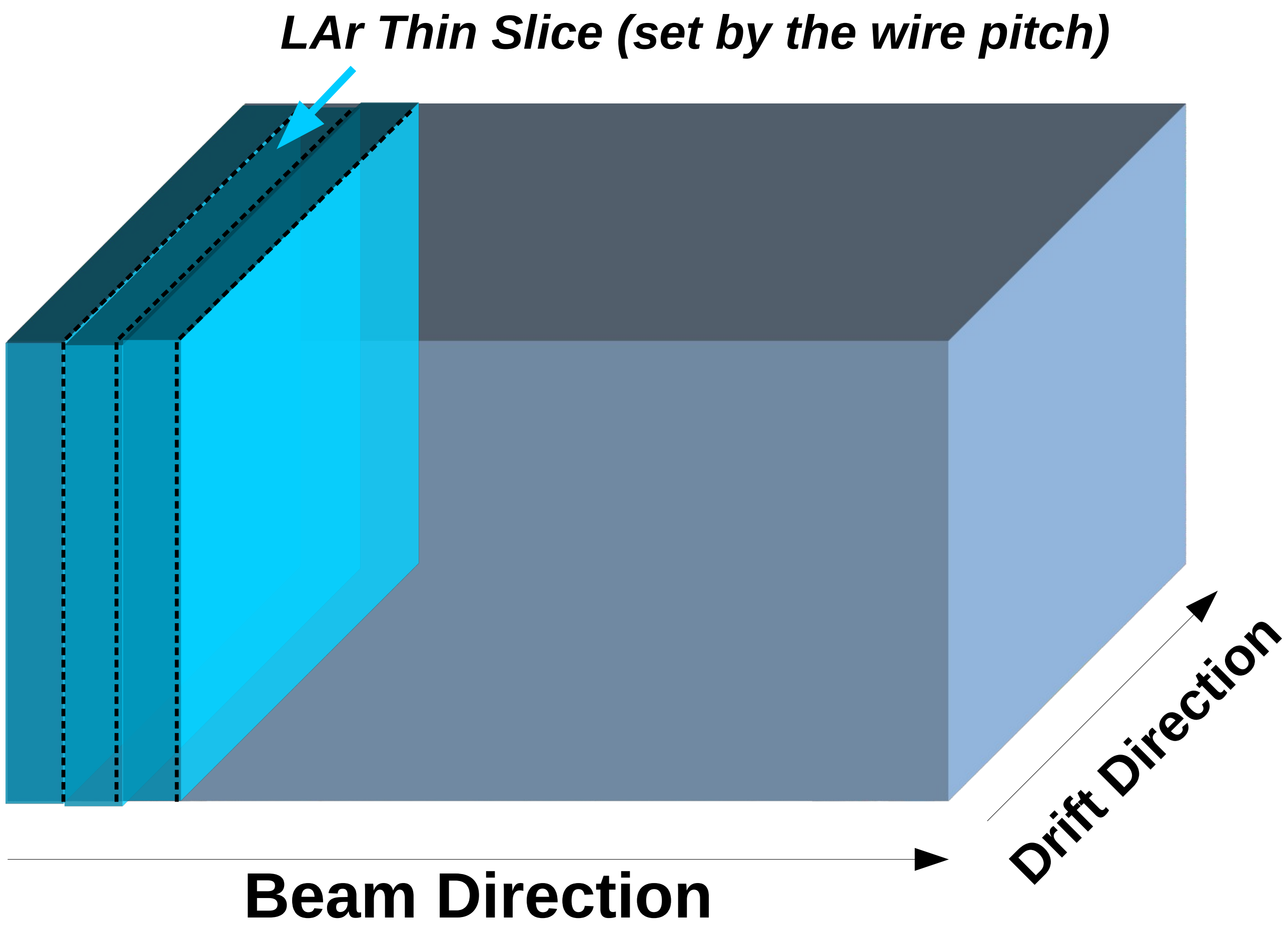
Energy Corrections

$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi + \boxed{E_{\text{Flat}}}$$



- **The uncertainty of this energy correction we take as σ(E) = 7.6 MeV and then propagate this into the uncertainty in the Kinetic Energy**

This is a 5% uncertainty applied to the K.E.


LAr Thin Slice (set by the wire pitch)
Beam Direction
Drift Direction