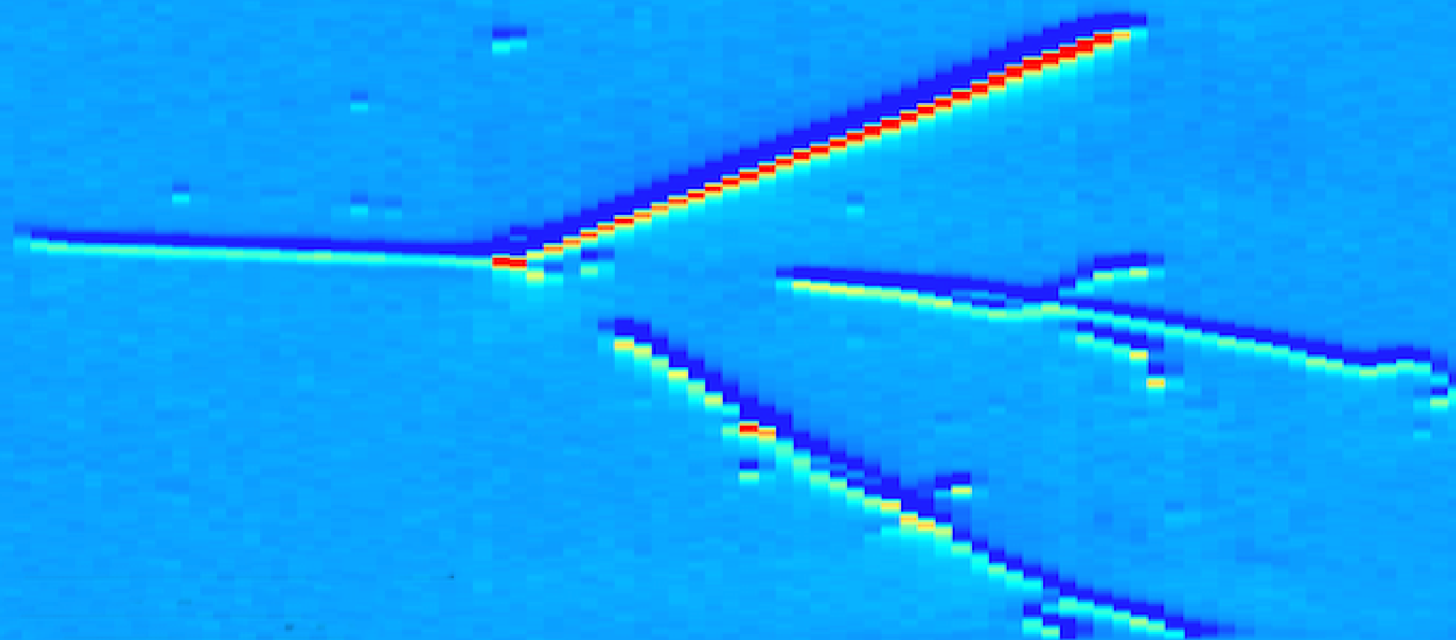
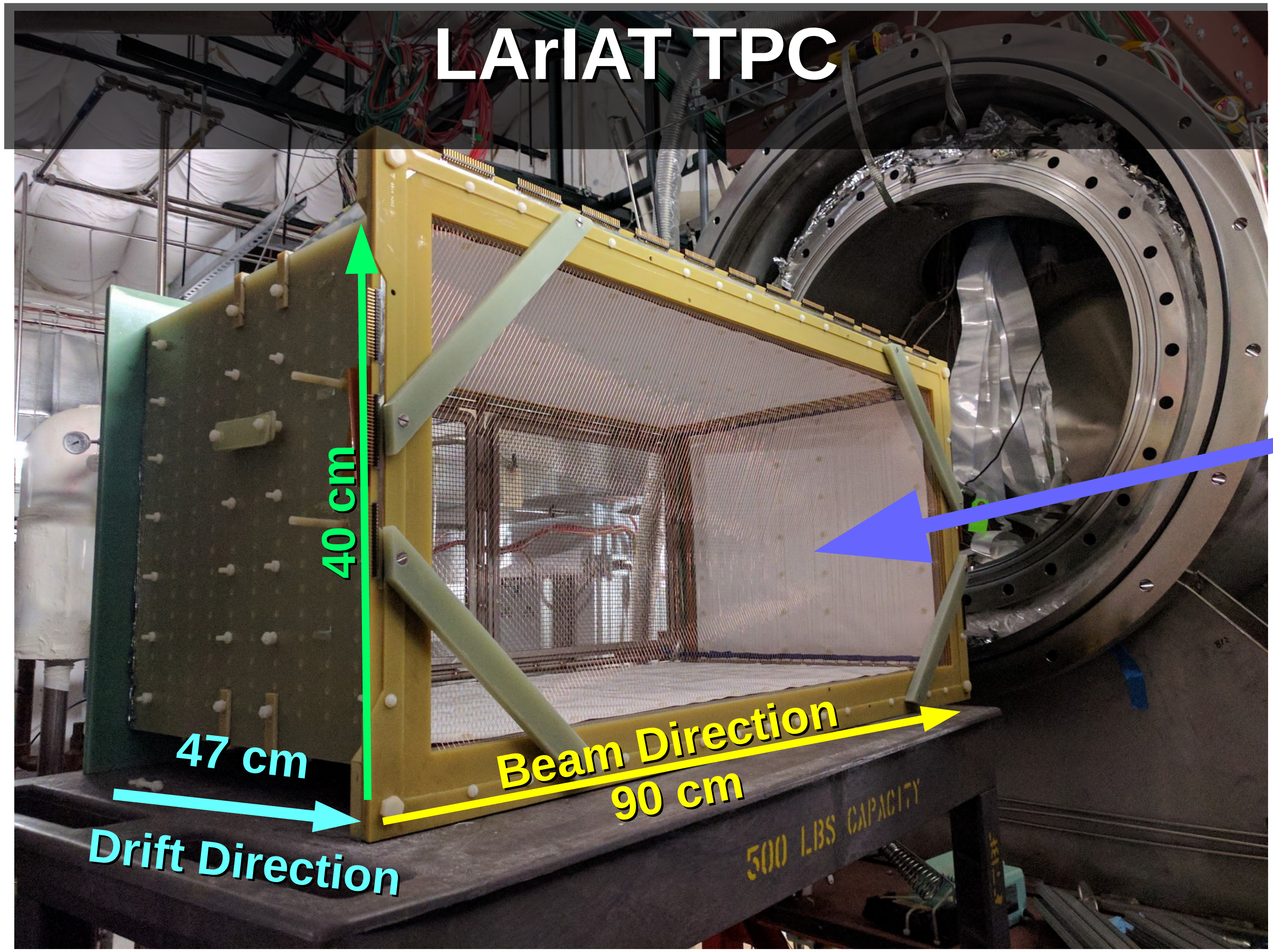
Pion scattering with the LArIAT experiment



Justin Hugon
(On behalf of the LArIAT experiment)
Louisiana State University

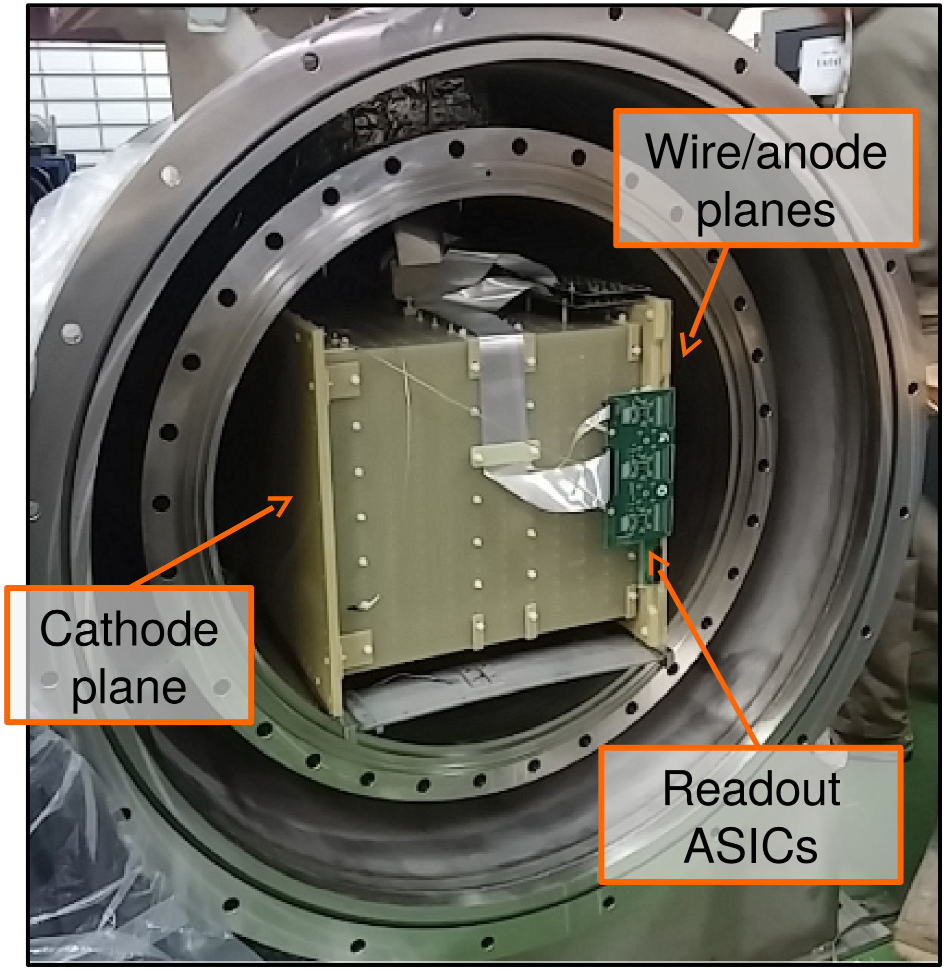
Liquid Argon in a Test Beam (LArIAT)



170 L
0.25 tons of LAr

Reuse the ArgoNEUT TPC in a charged particle beam at Fermilab

Liquid Argon in a Test Beam (LArIAT)

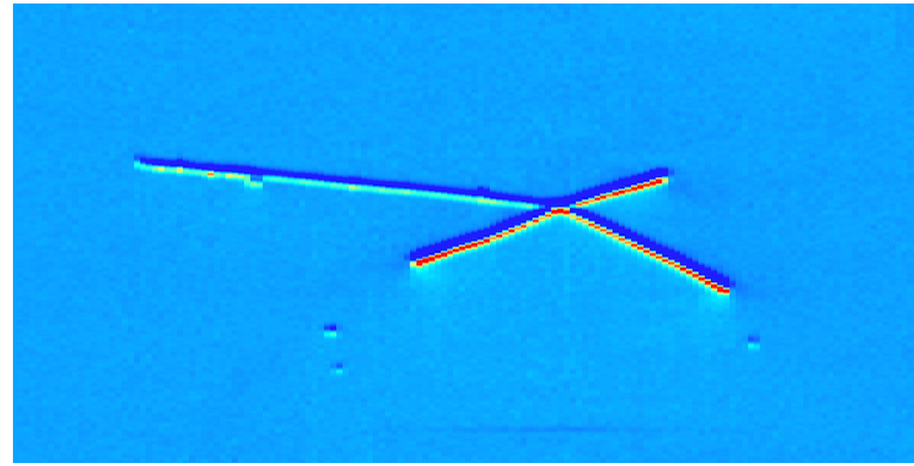


Changes from ArgoNEUT:

- **New wireplanes**
- **Cold front-end electronics fom MicroBooNE**

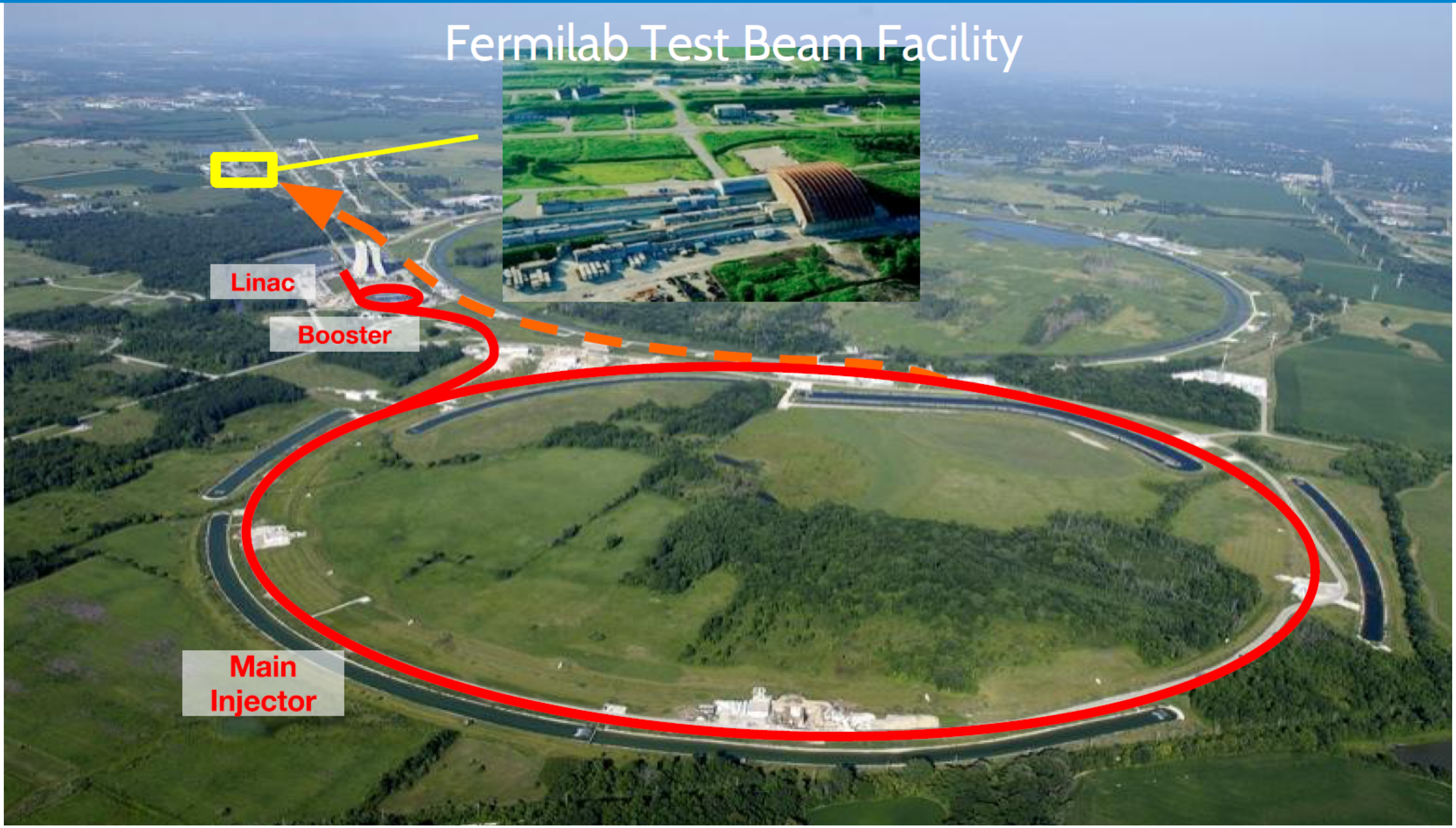
LArIAT Goals

- **Physics Goals**
  - Hadron-Ar interaction cross sections
    - $\pi^{+/-}$-Ar to support ν cross-sections
    - $K^{+/-}$ - Ar, supporting nucleon decay
    - Geant4 validation
  - e/γ shower identification capabilities
  - Anti-proton annihilation at rest
    - Similar to BSM n-$\bar{n}$ oscillation signature
  - Particle sign determination in the absence of a magnetic field, utilizing topology
    - e.g. decay vs capture



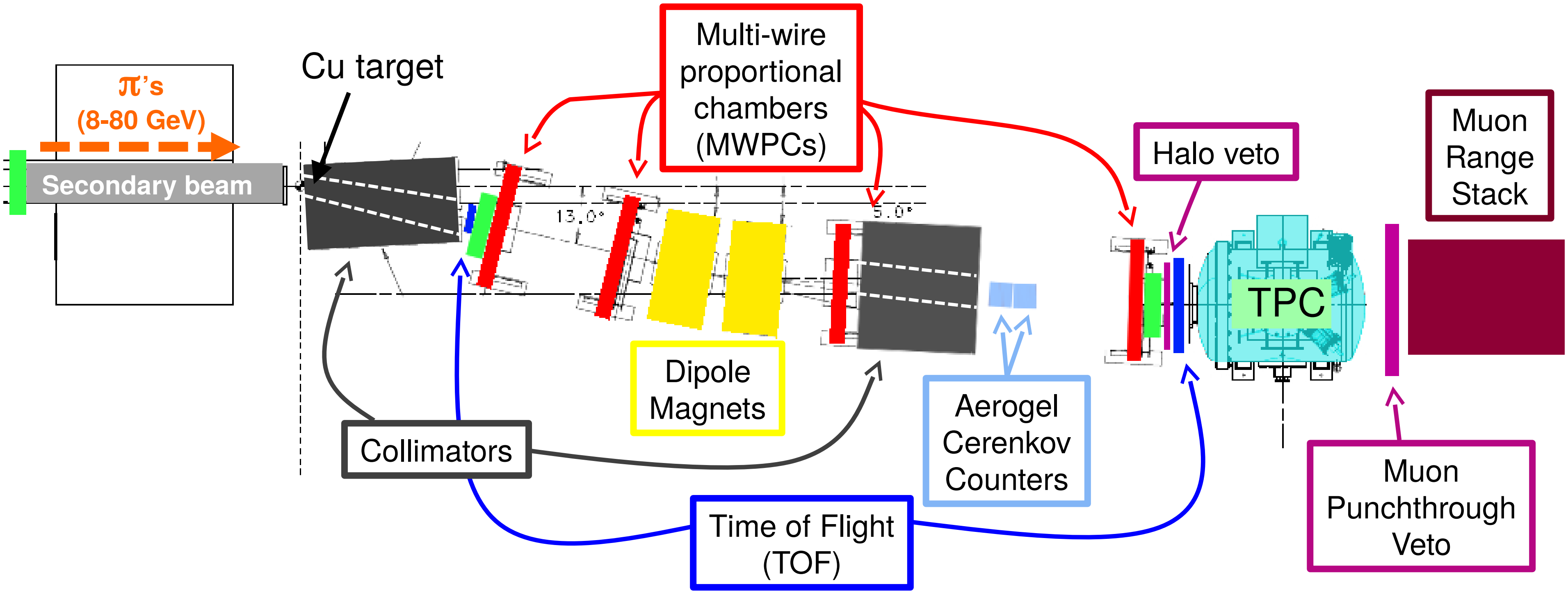
- **R&D Goals**
  - Ionization and scintillation light studies
    - Charge deposited vs. light collected for stopping particles of known energy
  - Optimization of particle ID techniques
  - LArTPC event reconstruction
    - Compare 3mm, 4mm, 5mm wire pitch

LArIAT Testbeam



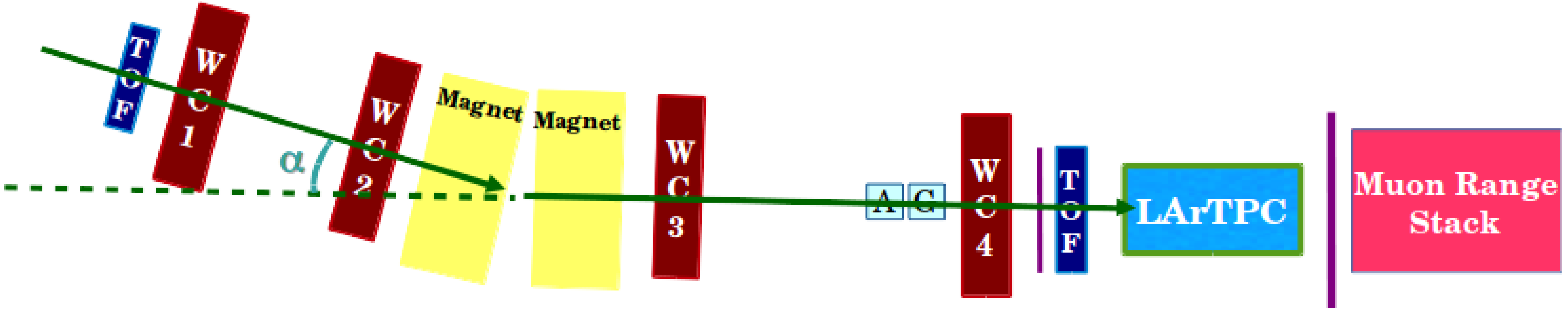
- **Fermilab's main injector sends 120 GeV protons to the Fermilab test-beam facility (FTBF)**
- **FTBF creates a tunable secondary beam, 8 GeV to 80 GeV, directed toward the LArIAT experimental hall**

LArIAT Tertiary Beamline

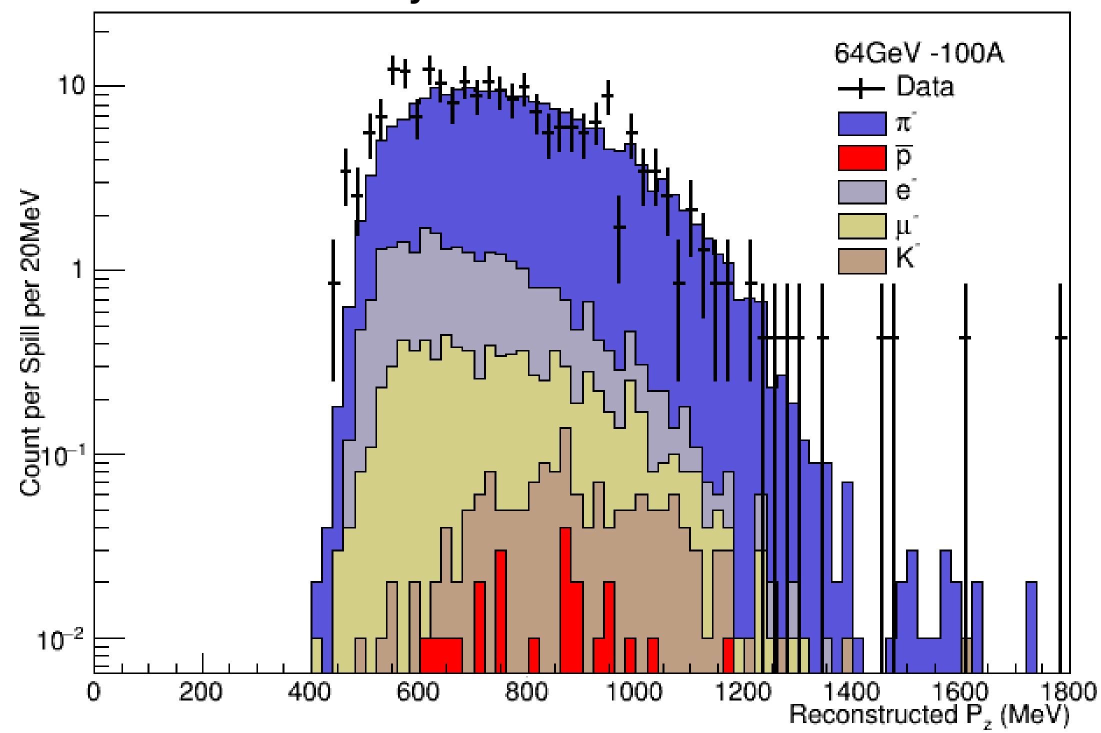


- **Secondary target further reduces beam energy**
- **Instrumented beamline identifies and characterizes particles**

LArIAT Beamline: Wire Chambers

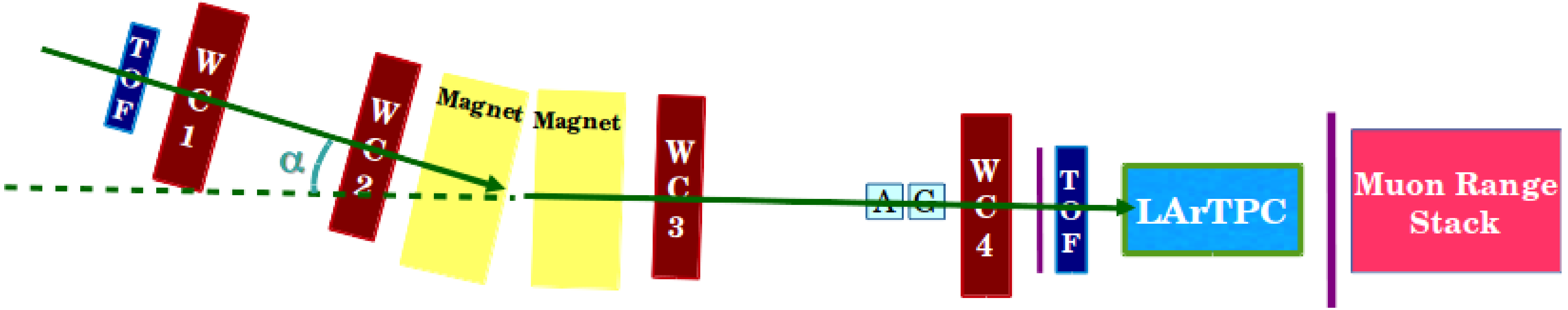


Wire chambers reconstruct the position and momentum of the particles in the beamline

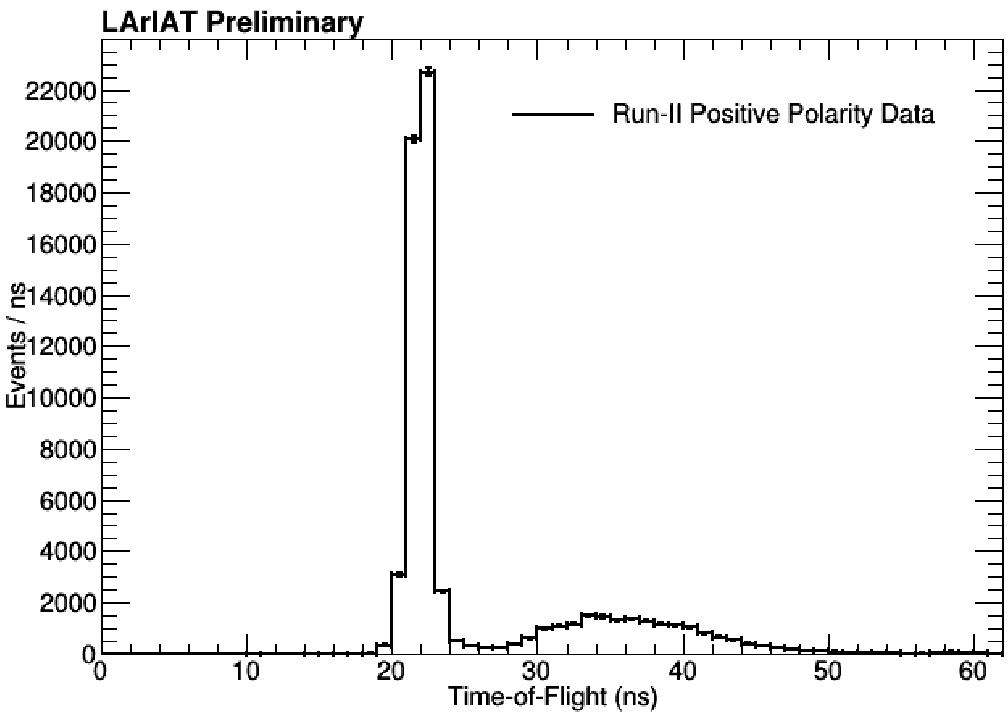


Wire chamber reconstructed momentum compared to simulation

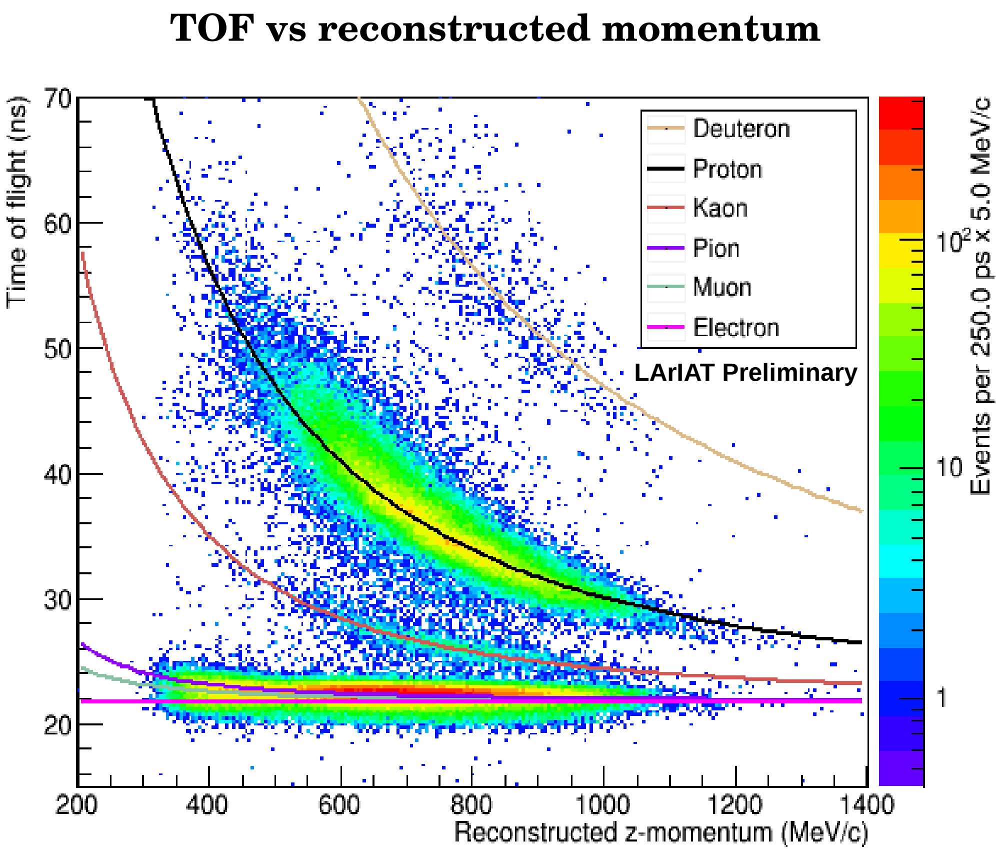
LArIAT Beamline: Time of Flight

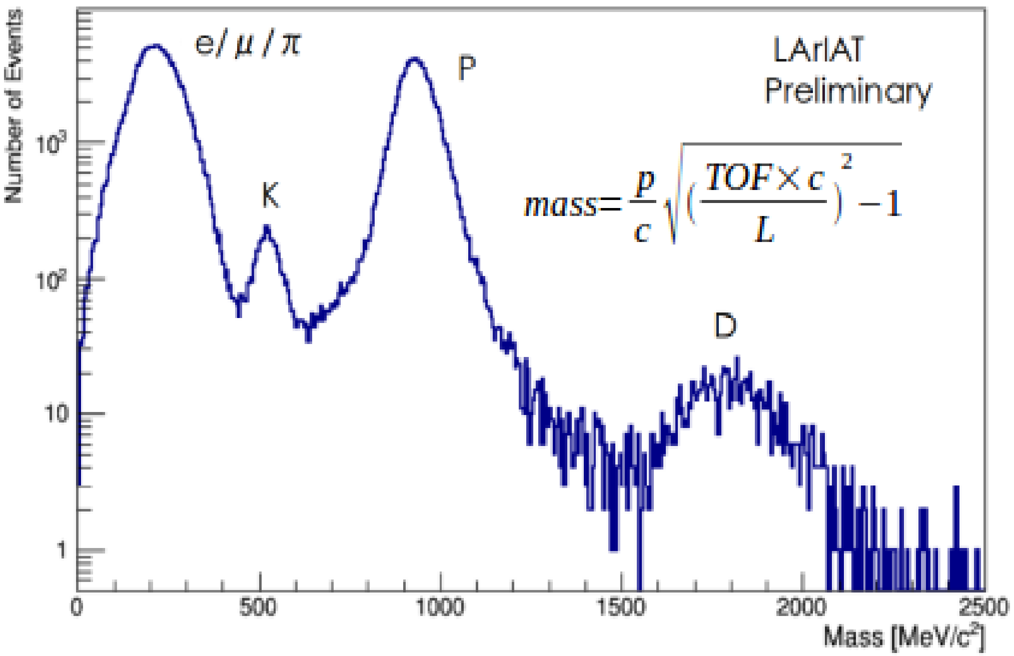


2 scintillator counters w/ ~1ns sampling, provide the time of flight (TOF)



LArIAT Beamline Detectors

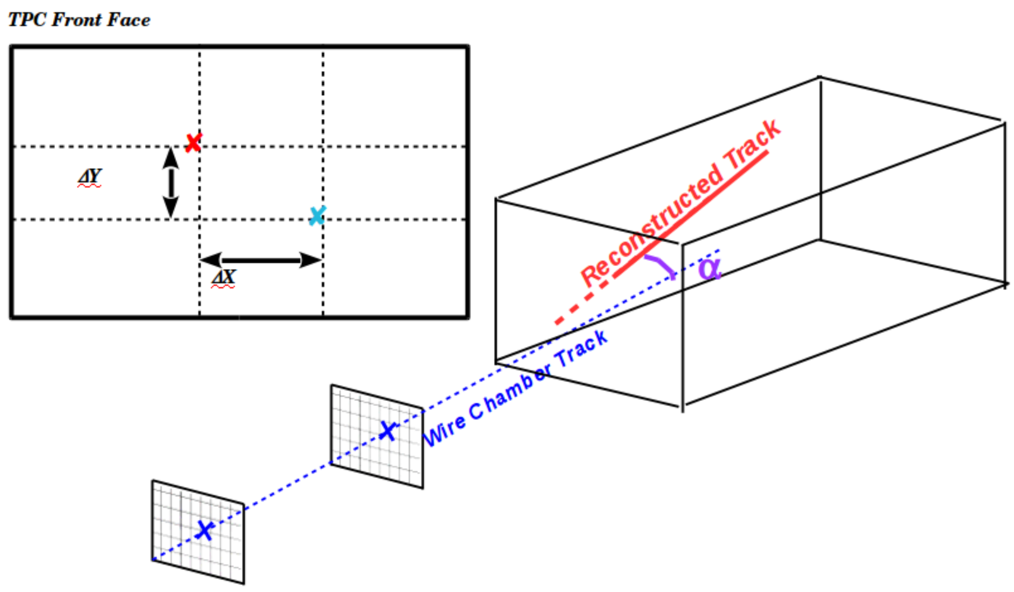




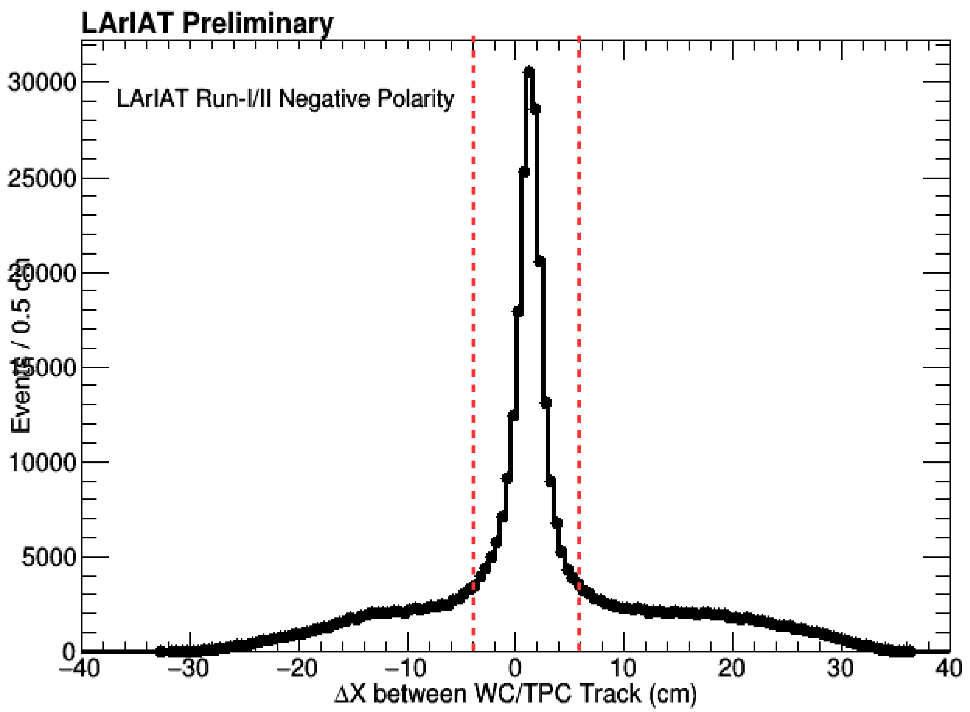
Combining the momentum and TOF allows for π/μ/e, K, proton separation

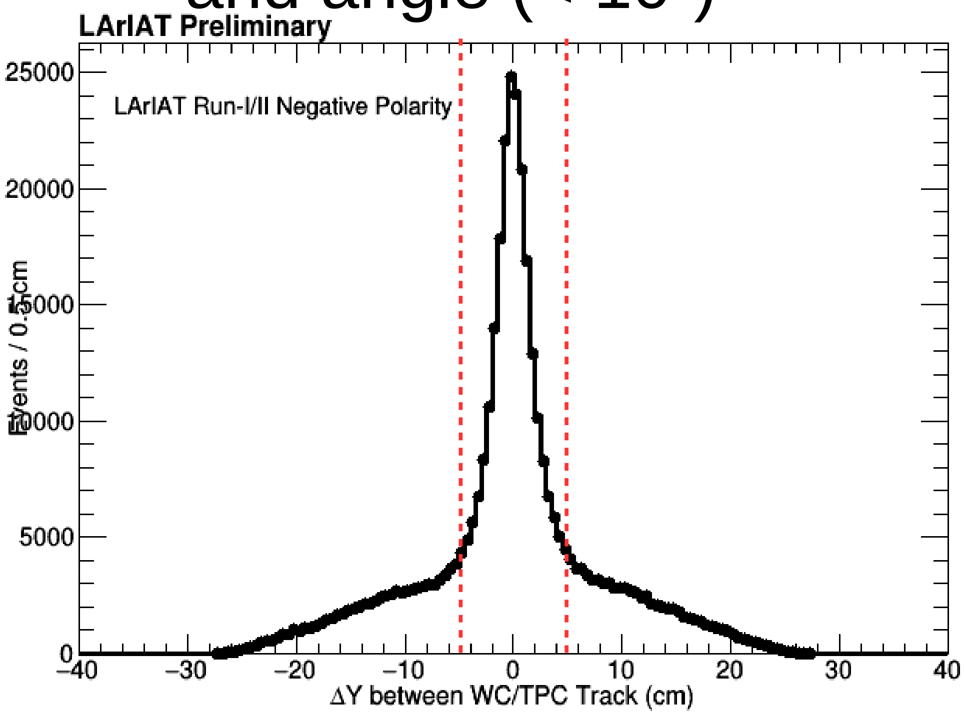
Additionally, using the known masses of the K and proton we can constrain the momentum scale to 1.5%

Matching Beamline to the TPC

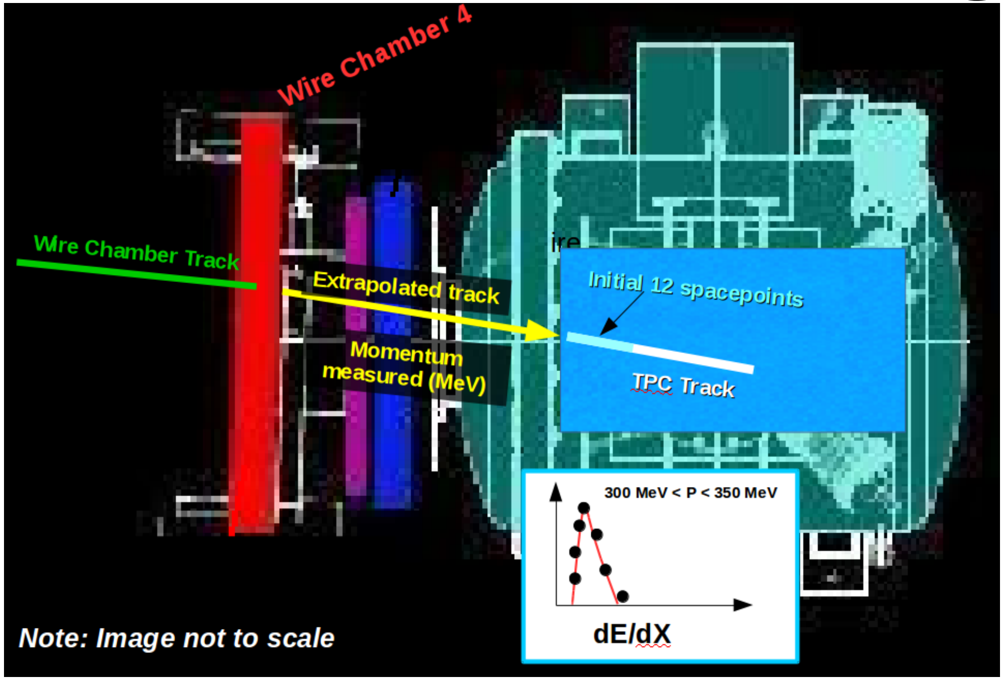


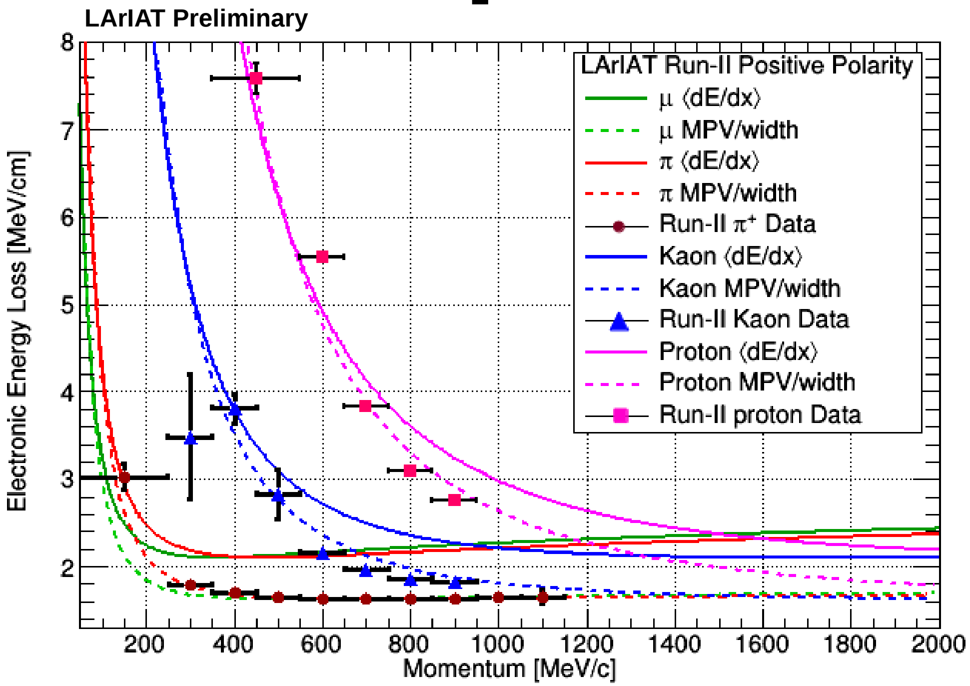
- **We can take this track reconstructed in the beamline and extrapolate it to the LArTPC and look for a match**
  - We match in both position (+/- 5cm about the mean) and angle (< 10°)





Calibrating our sample

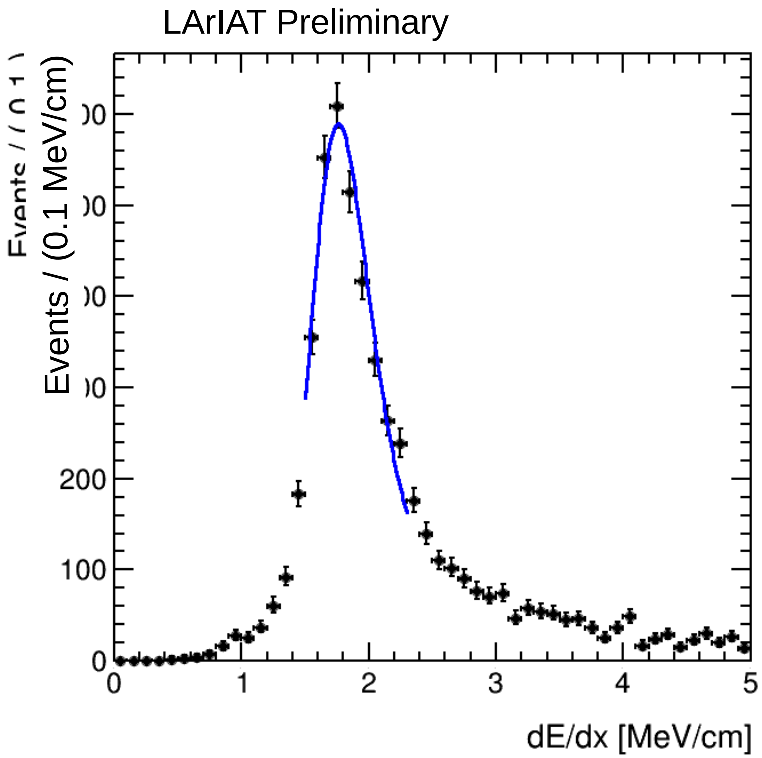


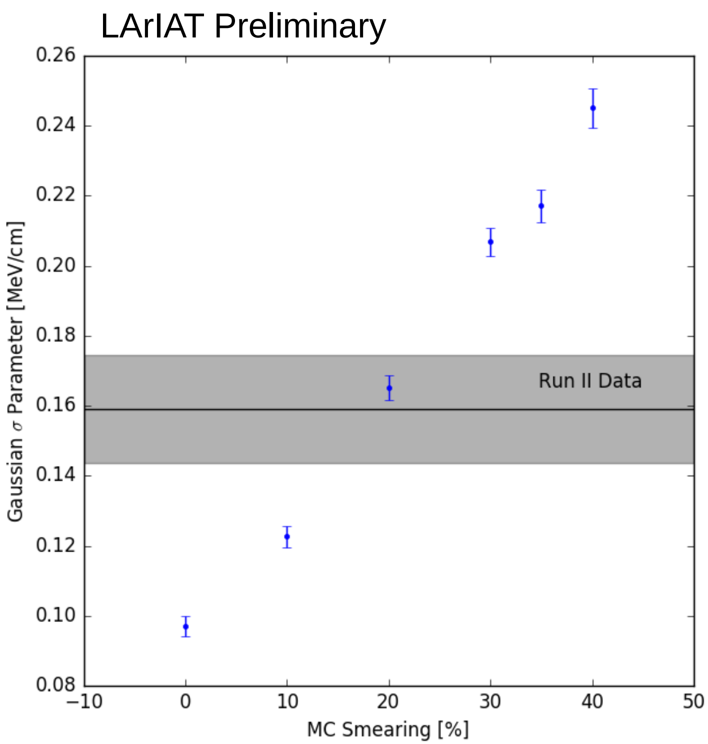


- **Using the first few centimeters of a matched track we can characterize the dE/dX response as a function of the track's initial momentum in both data and simulation**
- **Calibrate detector response to follow Bethe-Block formula by selecting events with different particle type and momentum**
- **Calibrate using pions; check on kaons/protons**

Smearing Simulated Data

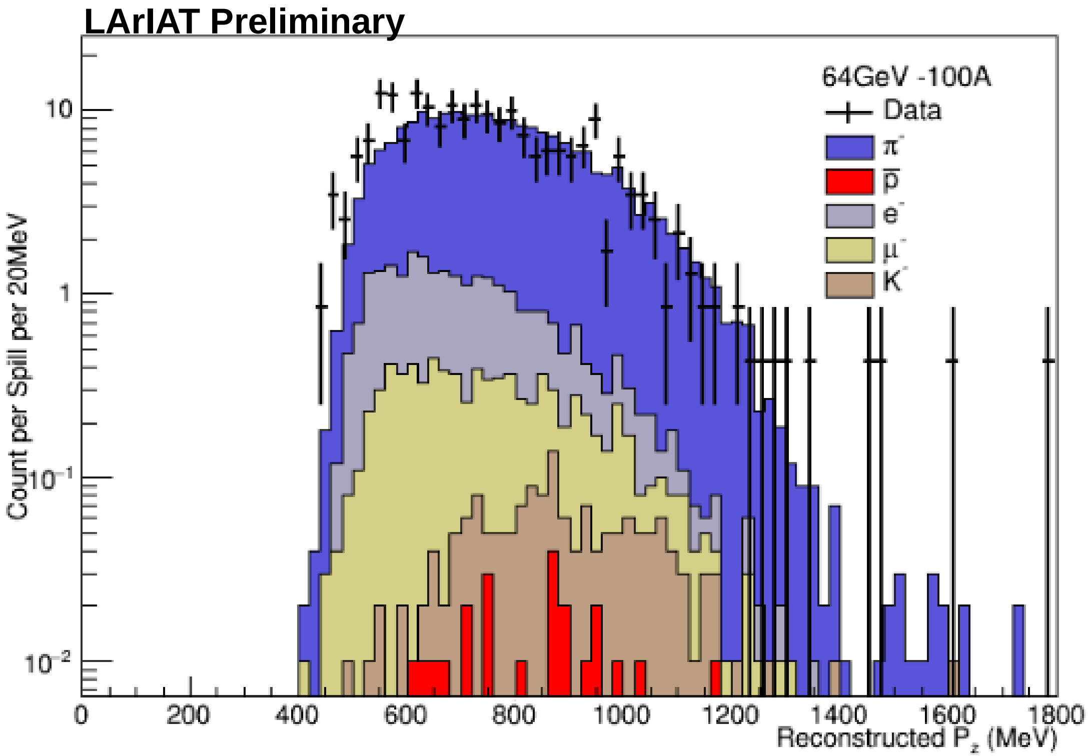
- **Cosmic-ray muons provide another calibration sample**
  - **Width of dE/dx distribution can be compared between data and simulation**





- **Additional 20% smearing makes the simulation match the data**

Pion Event Selection



- Our MC allows us to estimate what our fractional beam composition and our selection efficiencies are for the various particle species

	π^-	e^-	γ	μ^-	K^-	$\bar{p}$
Beam Composition (%)	48.4	40.9	8.5	2.2	0.035	0.007

Table 1: Beam Composition - Negative polarity configuration (from MC)

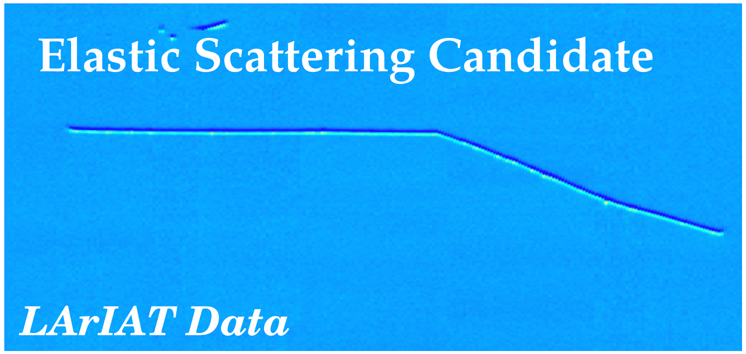
	π^- MC	e^- MC	γ MC	μ^- MC	K^- MC
Percent of events passing cut	73.5%	14.2 %	2.3%	73.4%	70.6%

Table 8: Fraction of MC Events passing inclusive pion analysis cuts.

Pion Cross-Section

- **The total π^-–Argon Cross-Section includes**

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



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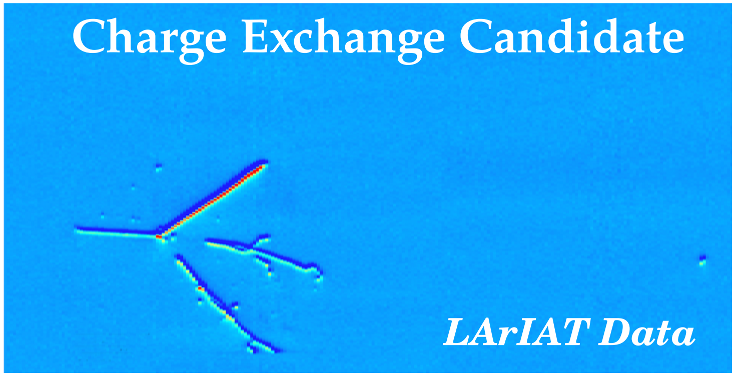

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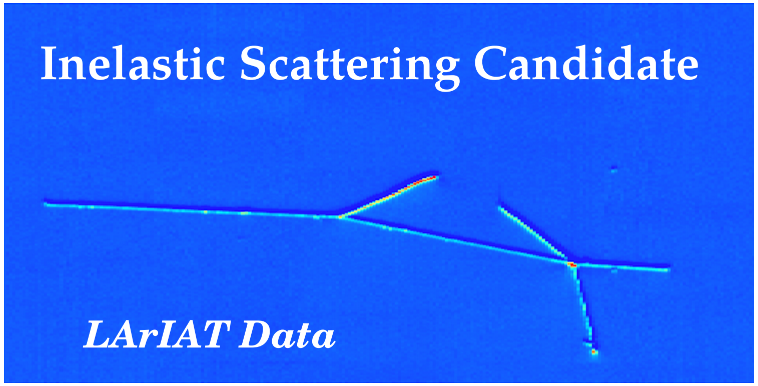

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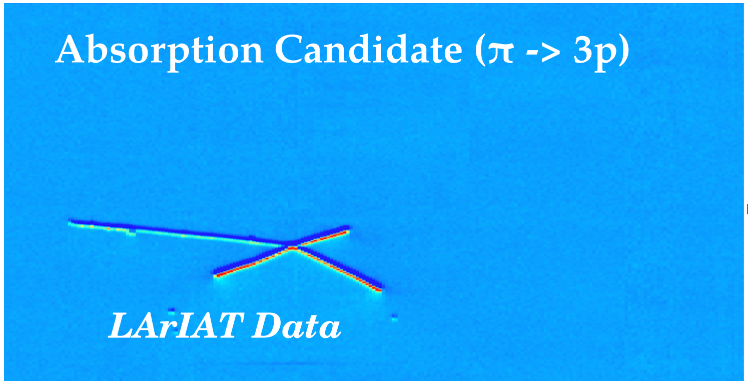

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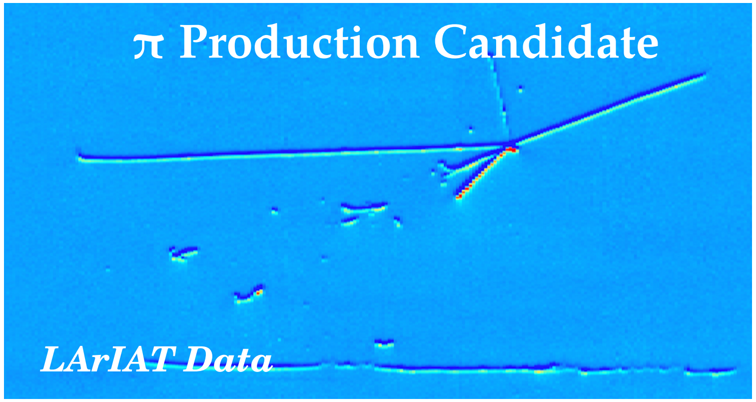
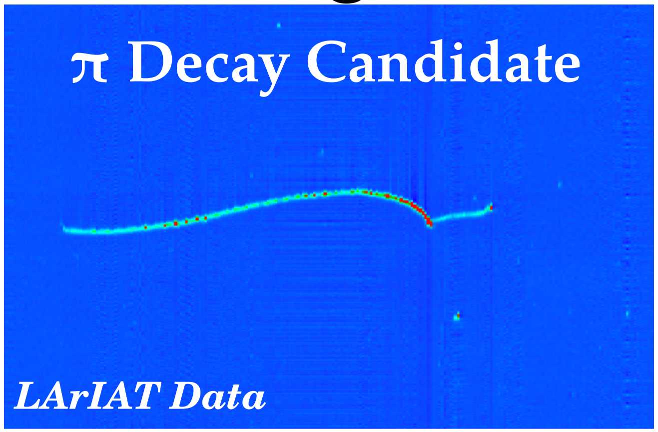
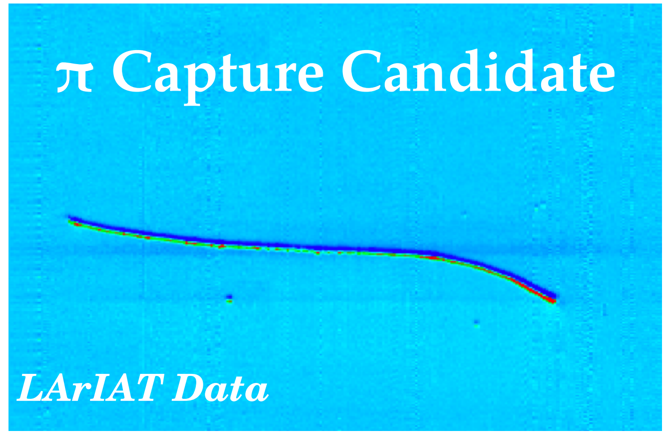
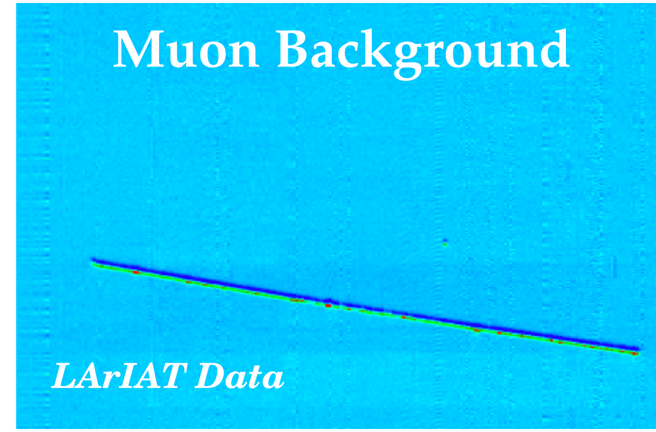


Pion Cross-Section

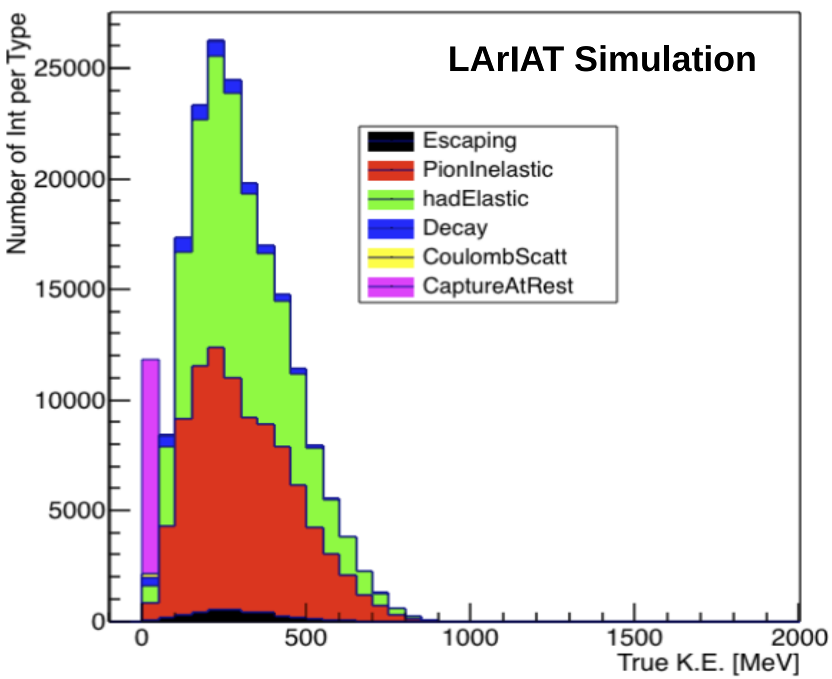
- **Backgrounds are:**



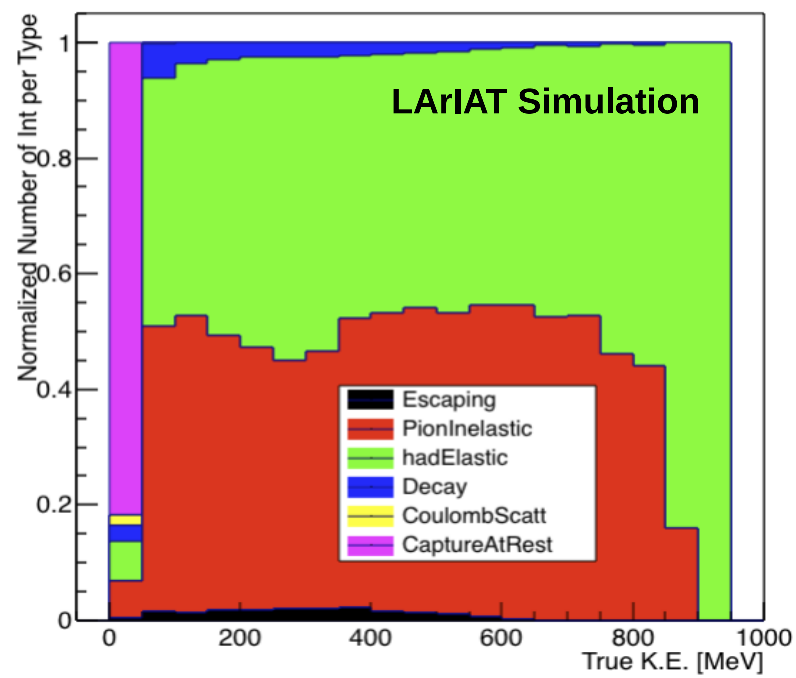




Pion Interaction Type per Kinetic Energy



Pion Interaction Fraction per Kinetic Energy



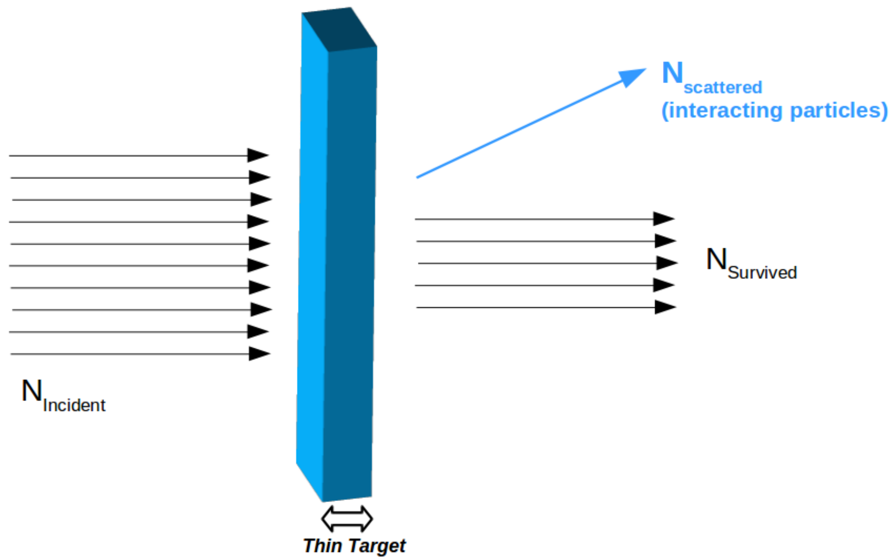
Note: Pion decay backgrounds are small component which remain in our result. Capture dominates the lowest energy bin and is thus excluded

Thin Slice 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, 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:

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

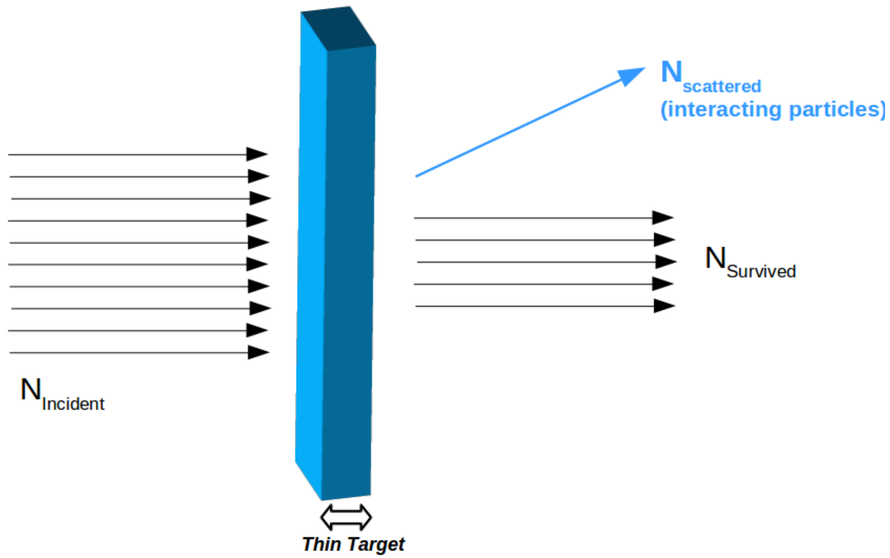
Thin Slice TPC Method

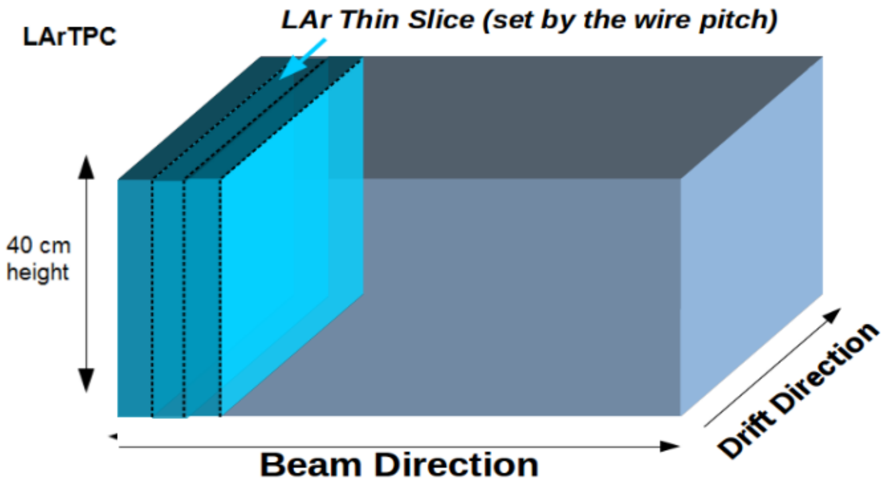
- **Thus you can extract the pion cross-section as a function of energy as**

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

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

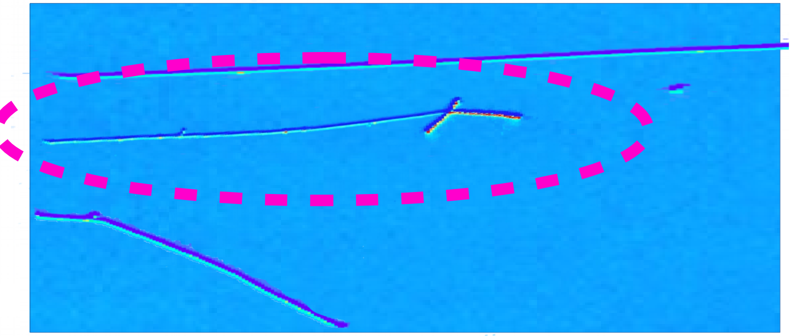
Where $n = \rho N_A / A$

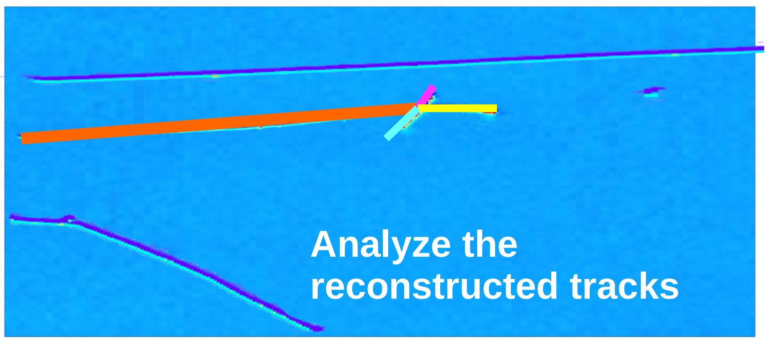




- **Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of “thin-slab” targets if we know the energy of the pion incident to that target**

Pion Cross-Section





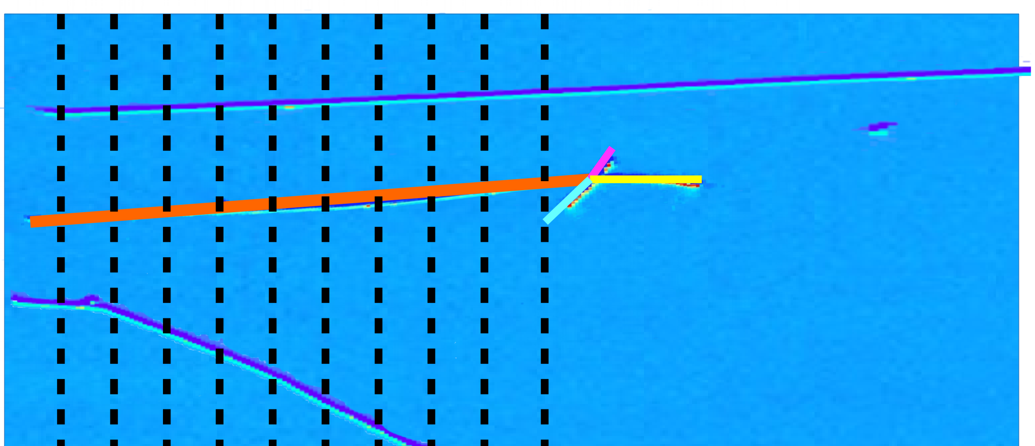
- Now we have a matched WC track and TPC track
- We calculate the π-candidate's initial kinetic energy as

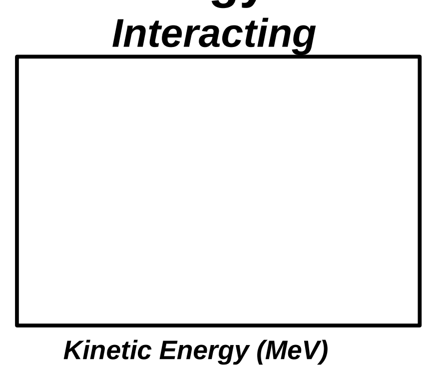
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

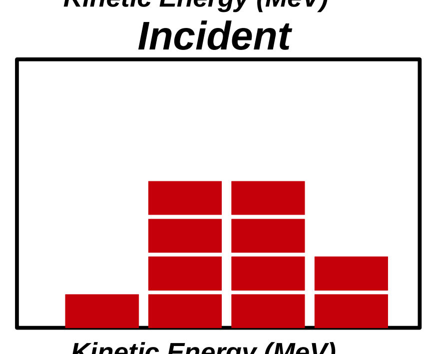
we take into account energy loss due to material upstream of the TPC (argon, steel, beamline detectors, etc)

- We then follow π-candidate track treating each point as a “thin slice” of argon which the pion is incident to at a known energy

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







Pion Cross-Section

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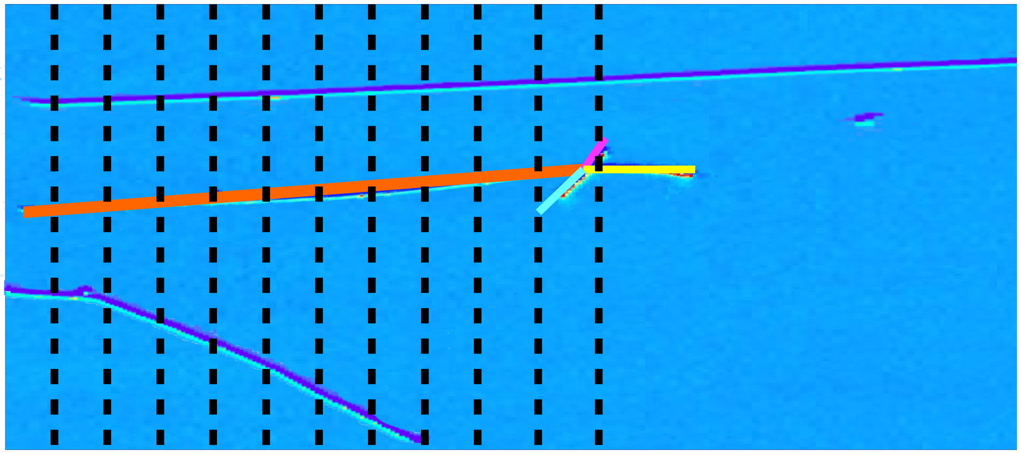
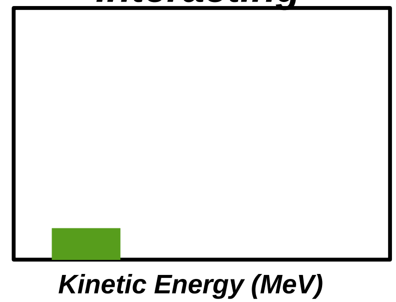
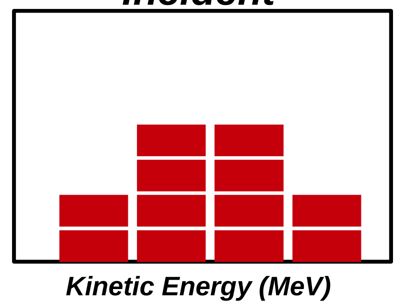


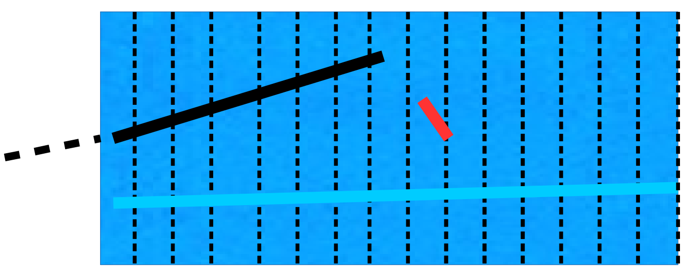
Interacting

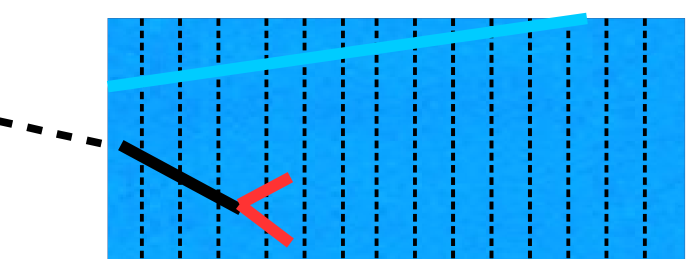


Incident

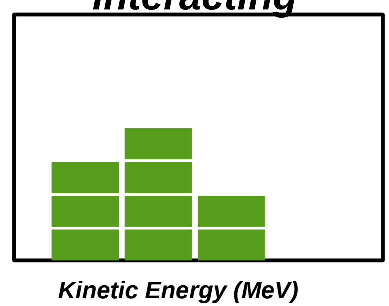


When you encounter the interaction point you now fill the interacting and incident histogram for the energy the pion has at that point

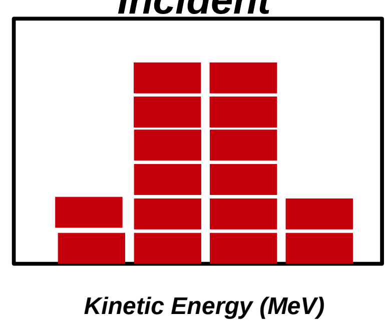




Interacting



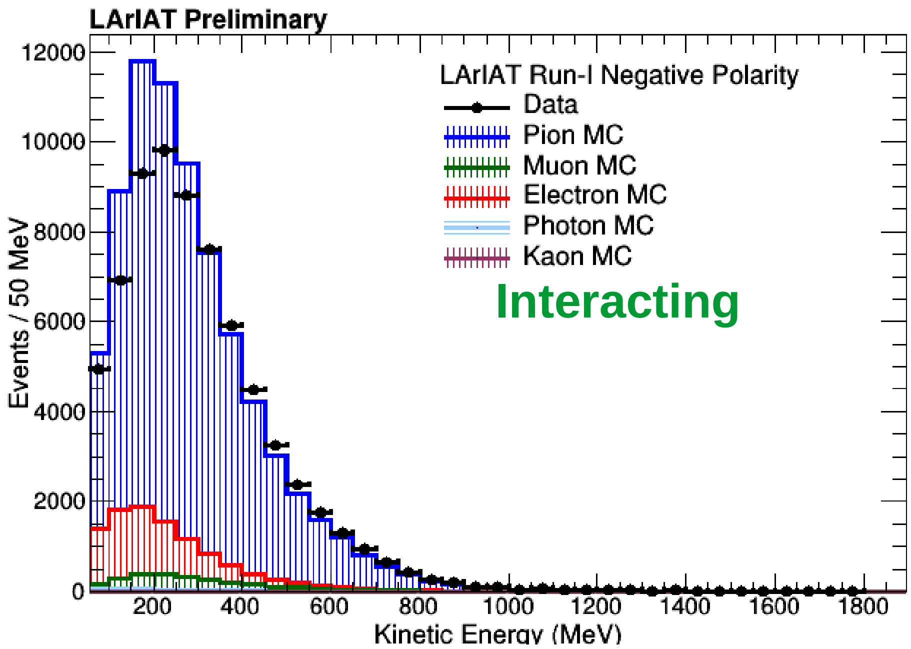
Incident



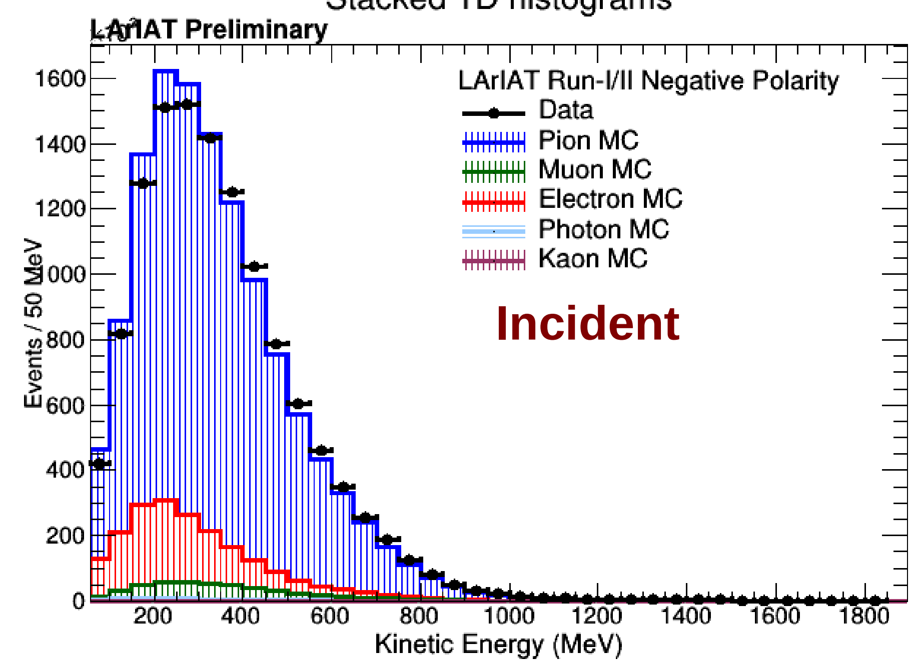
You now repeat this process for your entire sample

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

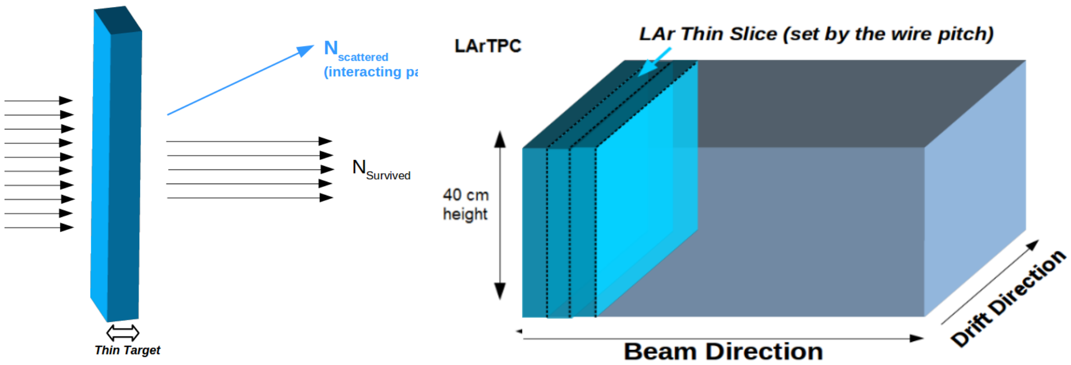
Pion Cross-Section



Stacked 1D histograms



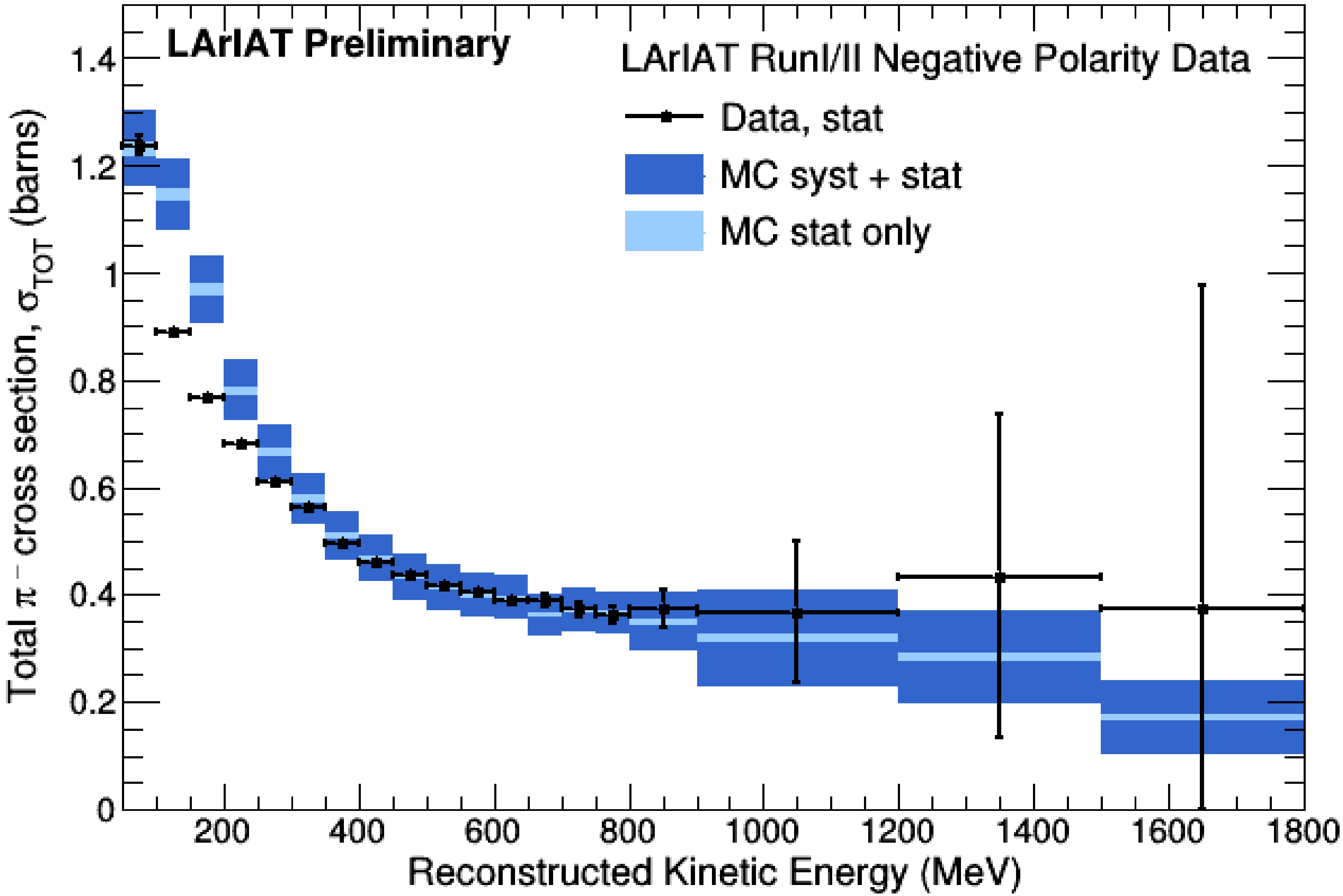
- You now take the ratio of these two histograms to extract the cross-section



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

Where n = $\rho N_A / A$

Pion Cross-Section



<u>Systematics Considered Here</u>

dE/dX Calibration: 3% *(previously was 5%)*

Energy Loss Prior to entering the TPC: 3.5%

Through Going Muon Contamination: 3%

Wire Chamber Momentum Uncertainty: 3%

Toward Exclusive Pion Channels

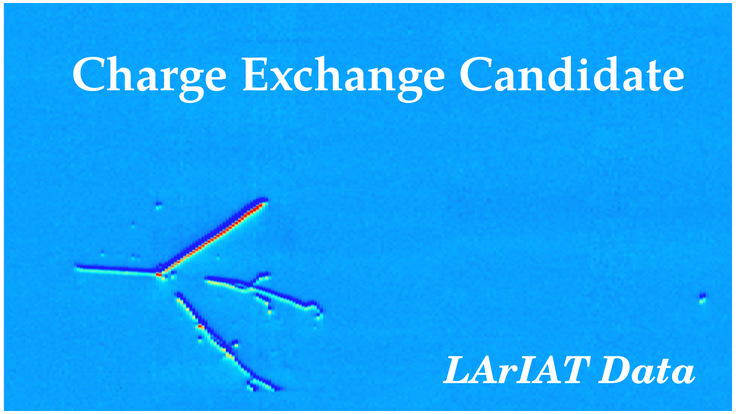
- **Working on absorption + charge exchange:**

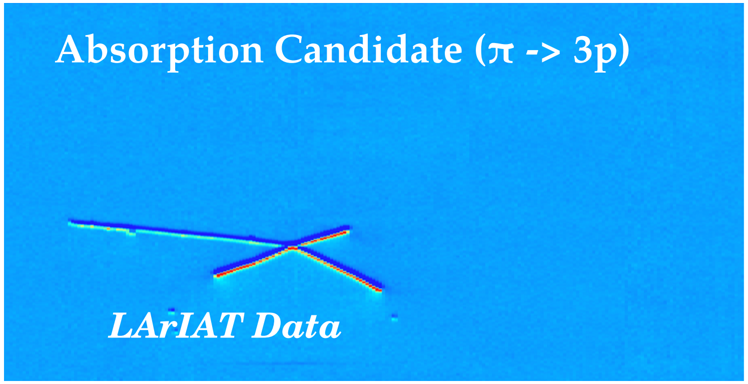
  p + Ar $\rightarrow$ 0$\pi^{\pm}$ + X

  - Useful for modeling contamination of ν CC QE from CC RES where a π is absorbed in the interaction nucleus
  - Need to identify outgoing pions v. protons

Signal Events:

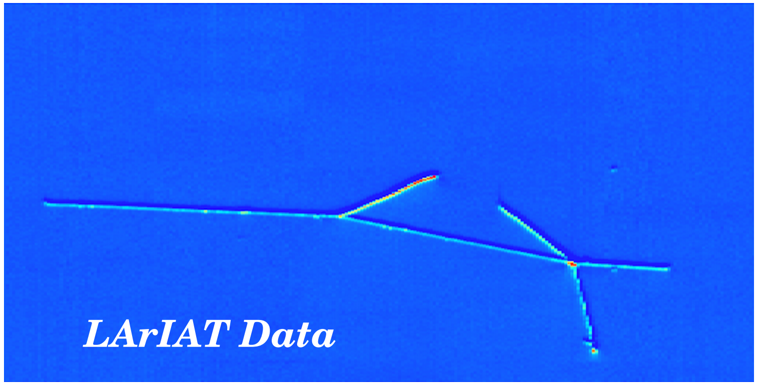
0 Secondary $\pi^{\pm}$



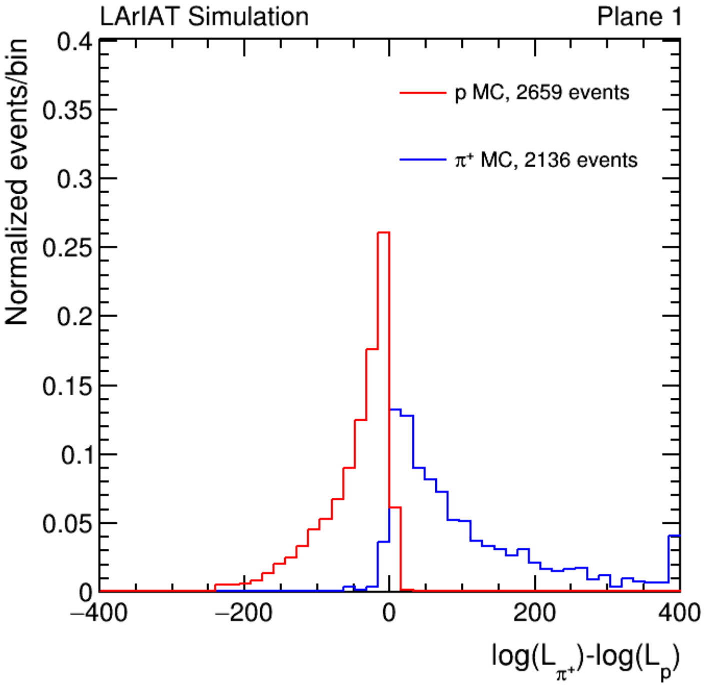


Background Events:

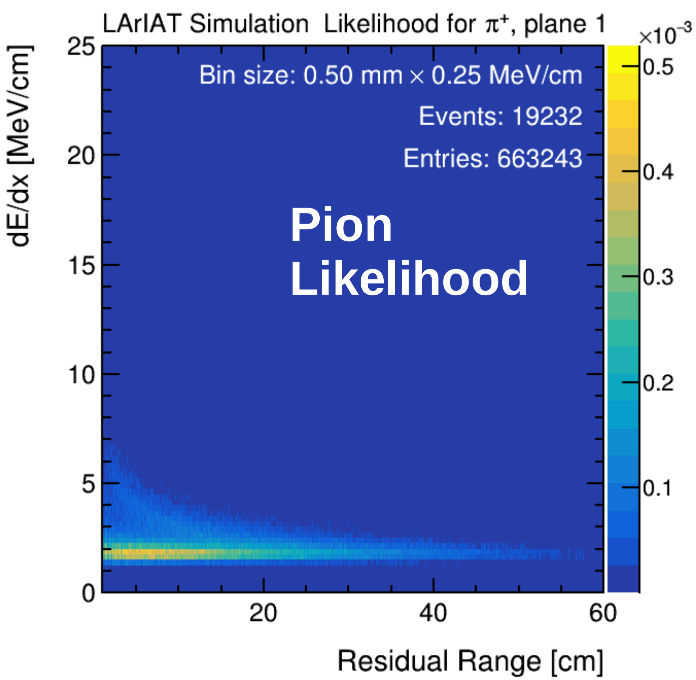
Contain Secondary $\pi^{\pm}$

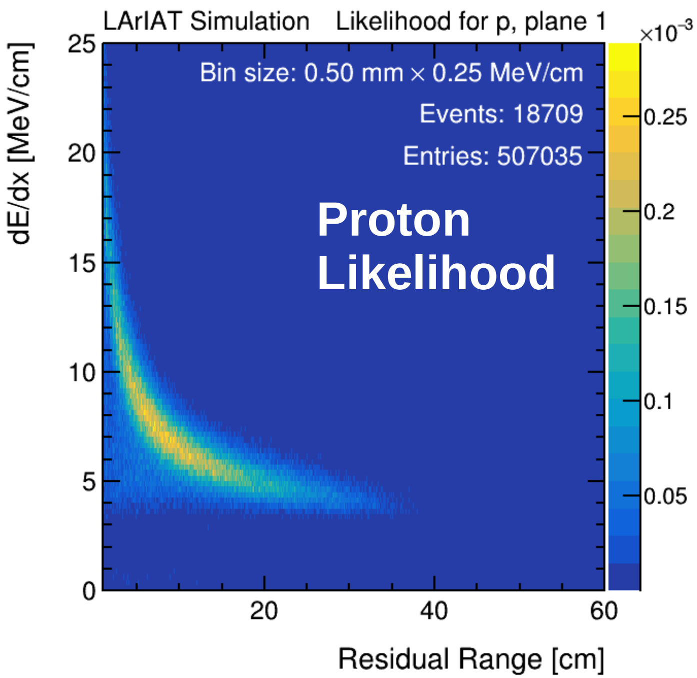


Likelihood-Based Particle ID

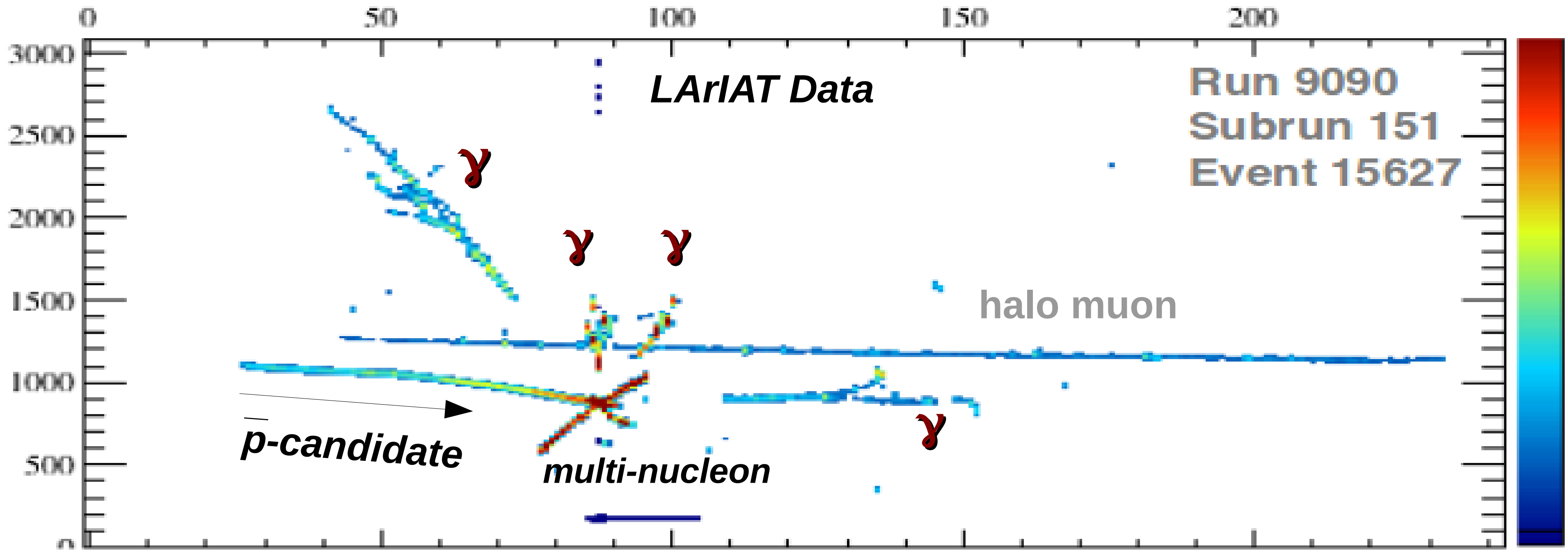


- **Likelihood of dE/dx versus residual range of each track hit**
  - Constructed from simulated tracks
  - Evaluate using likelihood-ratio of all hits on a track

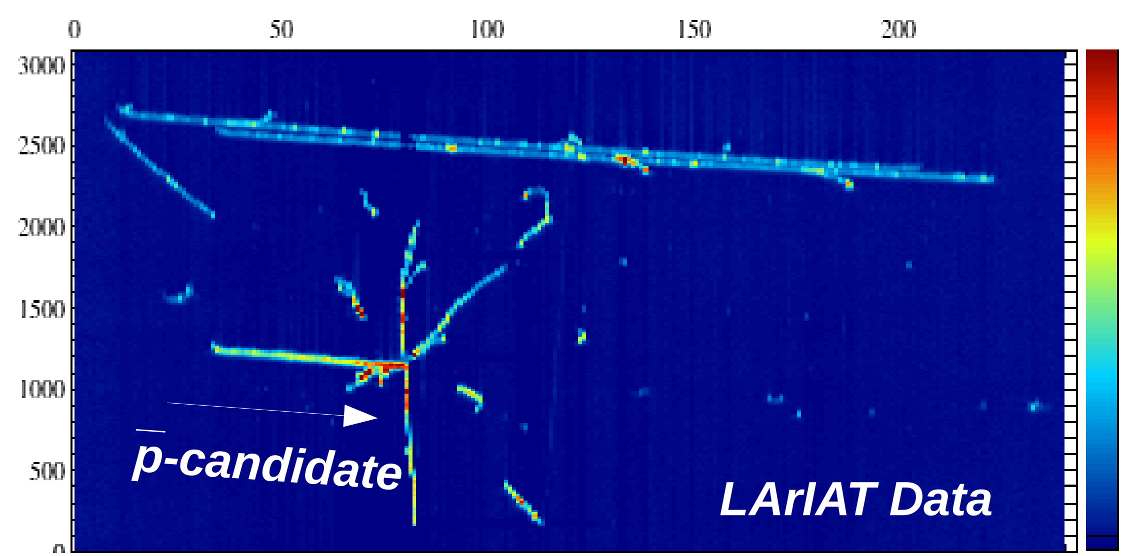




Anti-proton Annihilation

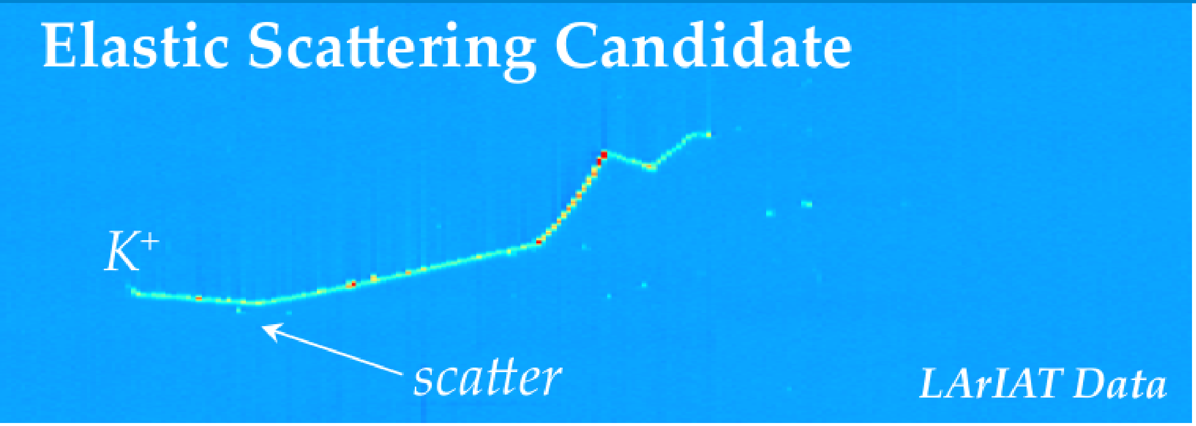


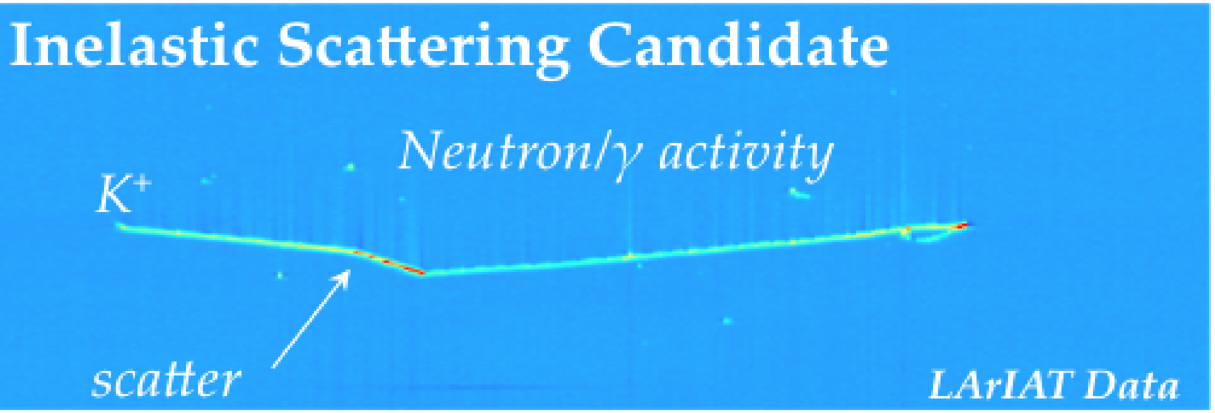
- **LArIAT has identified O(20) anti-proton annihilation at rest candidates**
  - O(70) annihilation in flight
- **Similar to BSM n-$\bar{n}$ oscillation signature**
  - DUNE planning search



Work ongoing to reconstruct these final state topologies

Kaon Cross-sections





- **Inclusive K+ cross-section has O(2000) Elastic/Inelastic interactions identified**
  - Inclusive cross-section coming soon
    - First time measured on argon
  - Work ongoing to reconstruct these final state topologies

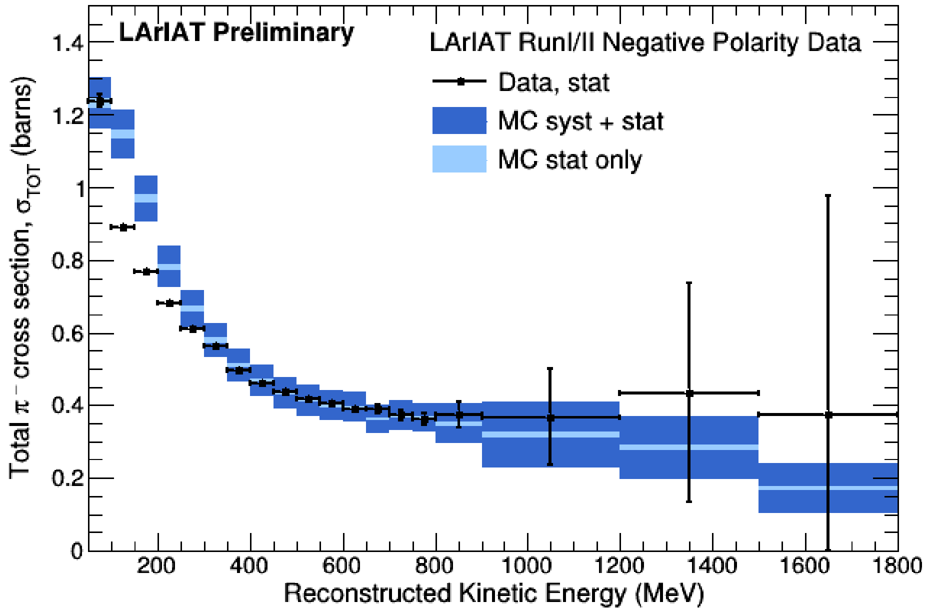
- **DUNE plans search for proton decay:**

$$p \rightarrow K^{+}\bar{\nu}$$

- **Cross-section information will help ensure signal efficiency is modeled properly**

Conclusions

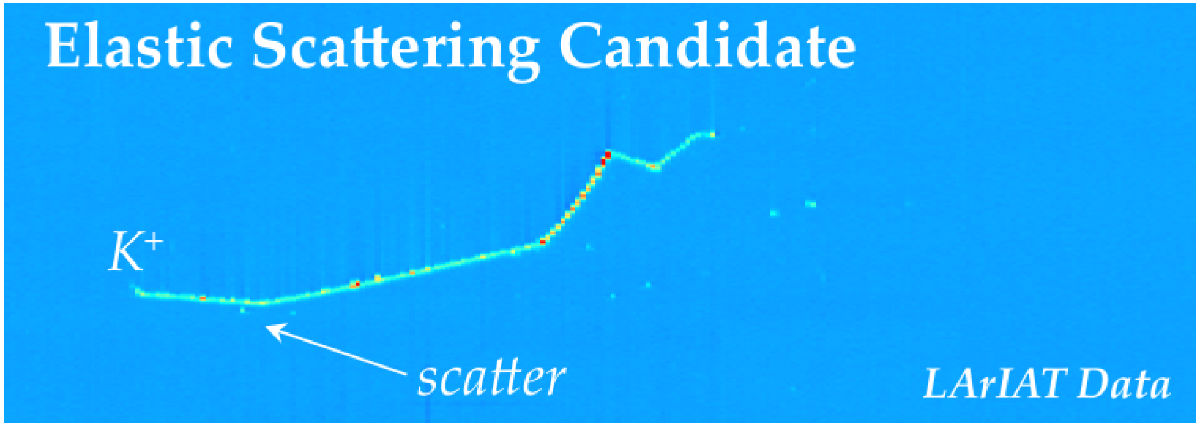
- **LArIAT recently completed its 3rd physics run**
  - Run-I / Run-II: 4mm wire pitch
    - Hadronic cross-sections
    - Scintillation Light R&D
  - Run-III: 3mm / 5mm wire pitch comparison
    - LArTPC particle ID R&D
    - New mesh cathode
    - New ARAPUCA Light Detection System



- **Inclusive π^--Argon Cross-section**
  - New result has x100 the initial statistics
    - Inclusion of Run-II data
    - Tuning of reconstruction cuts and improvement in dE/dX calibration
  - Paper in preparation

Future Plans

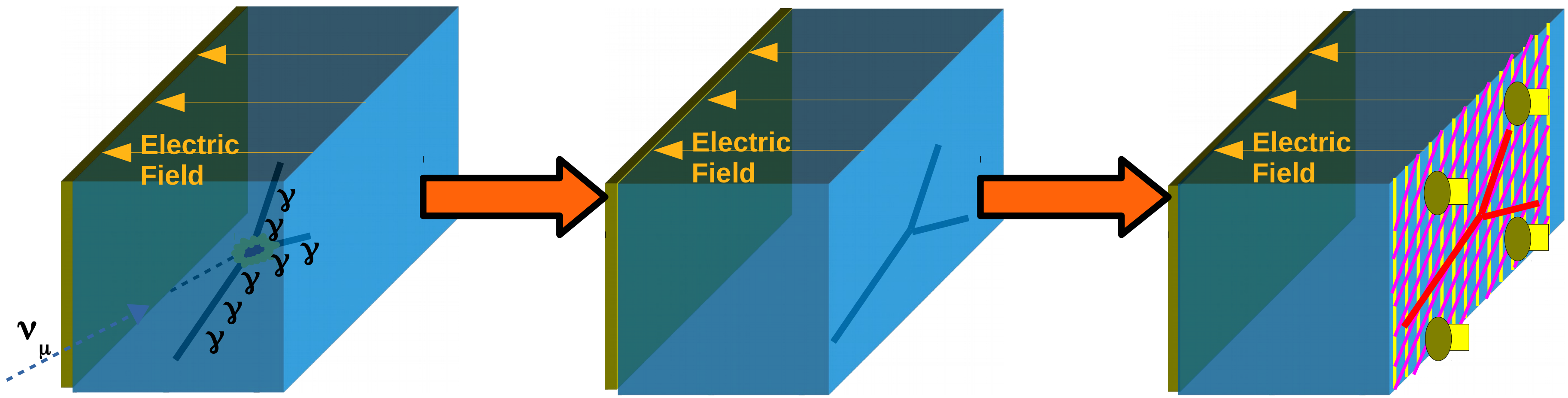
- **Many other physics results following close behind this result**
  - Inclusive K+ Cross-section
  - Inclusive π+ Cross-section
    - Absorption and charge exchange exclusive channels coming along too
  - Anti-proton annihilation at rest
  - e/γ shower characterization
    - Inclusion of 3mm/5mm wire pitch comparisons



Thank you!

Backup Slides

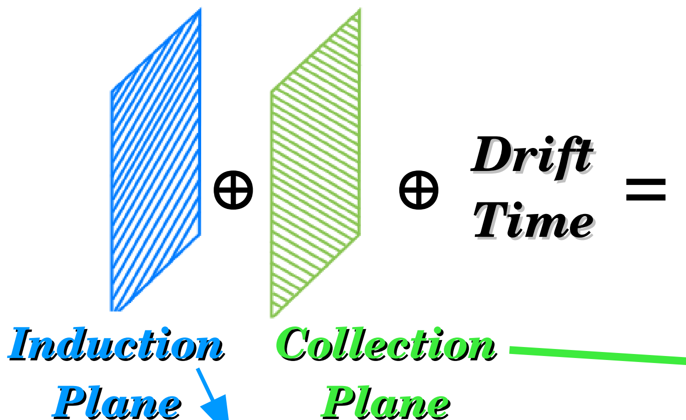
Liquid Argon Time Projection Chamber

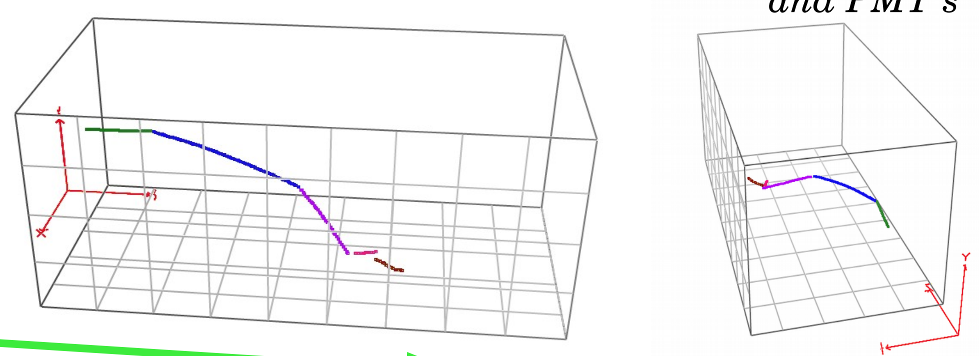


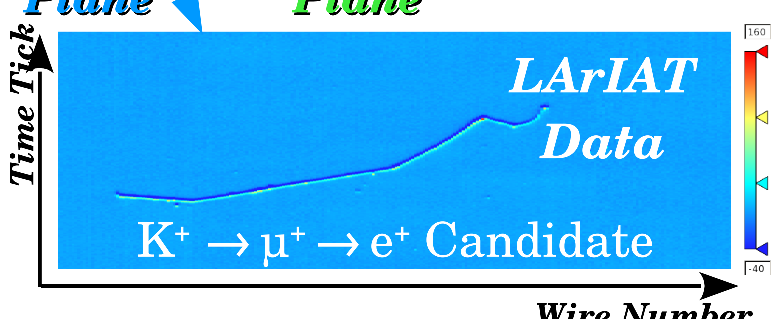
Neutrino interaction in LAr produces ionization and scintillation light

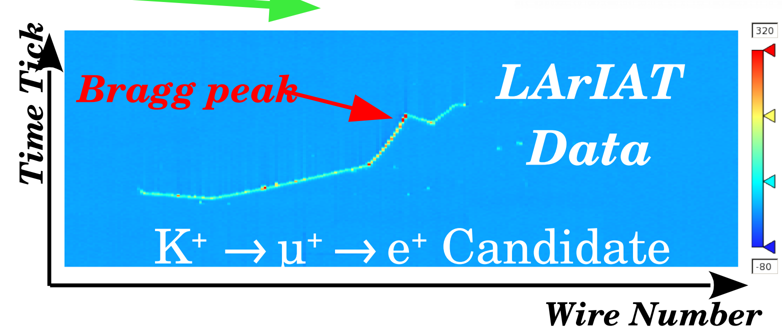
Drift the ionization charge in a uniform electric field

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









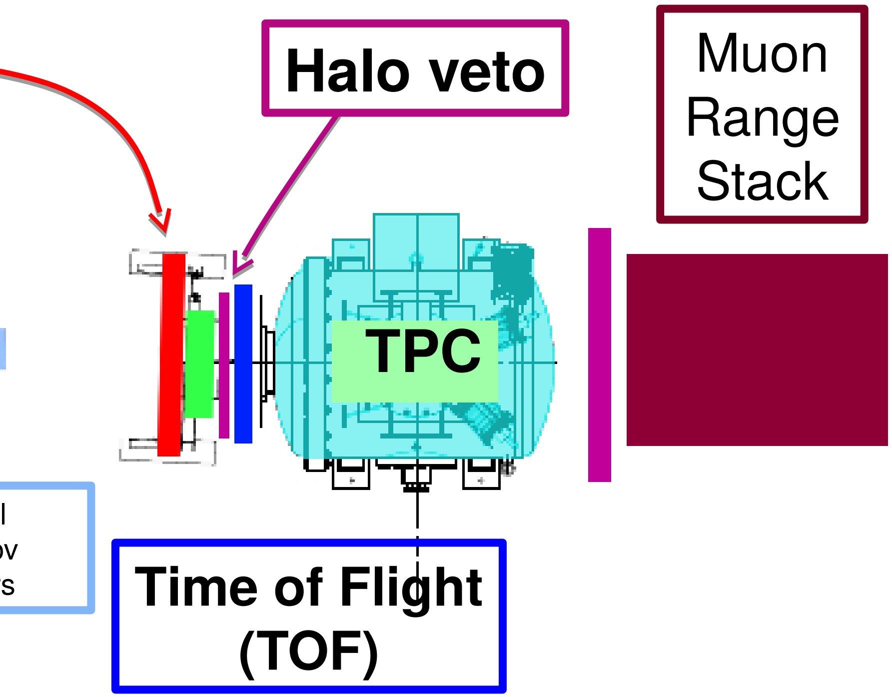
✔ **3D imaging with mm space resolution**

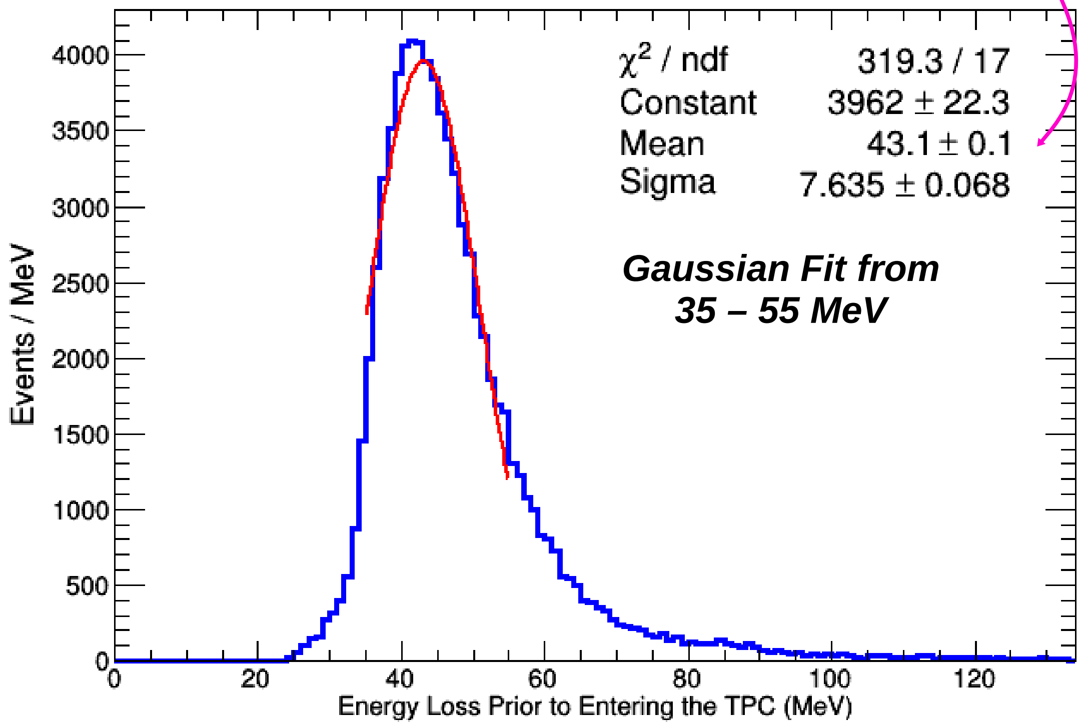
✔ **Calorimetry information**

✔ **PID capabilities**

Energy Corrections

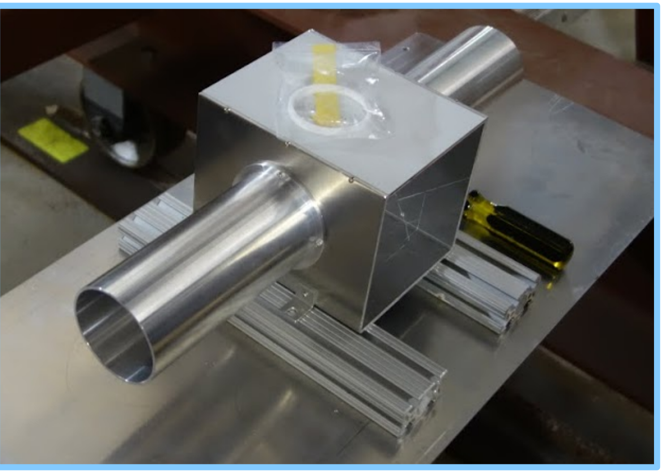
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi + \boxed{E_{Flat}}$$

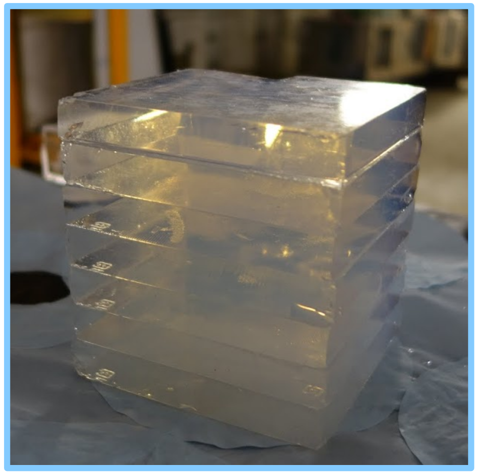




- Adding up all the energy which a pion loses in the region before it enters the TPC (**TOF**, **Halo**, **Cryostat**, **Argon**) gives us the “energy loss” by the pion in the upstream region

LArIAT Beamline Detectors

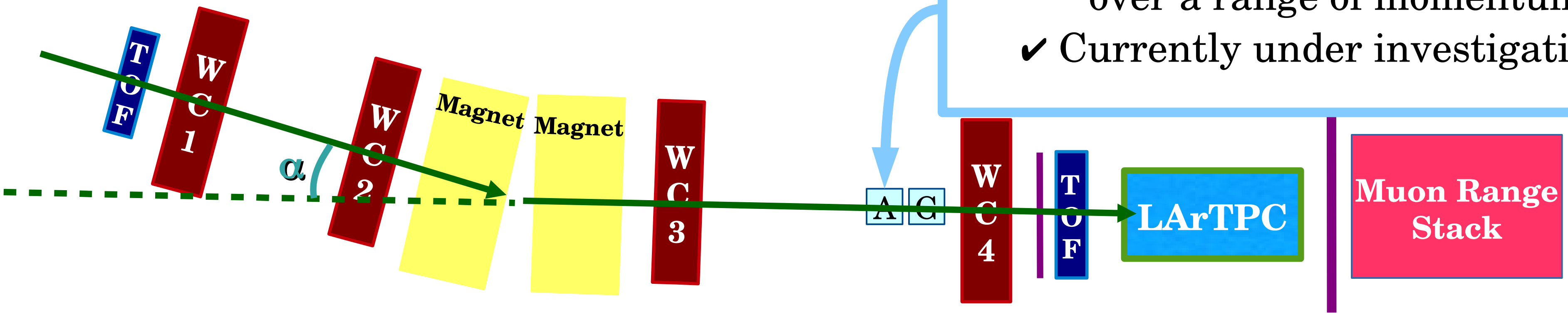




	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

✔ Allows to perform π/μ separation over a range of momentum

✔ Currently under investigation

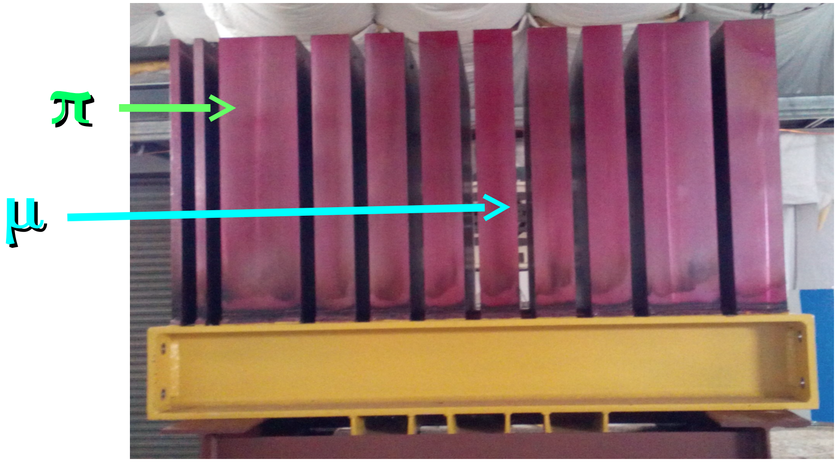


✔ Four layers of XY planes sandwiched between (pink) steel slabs

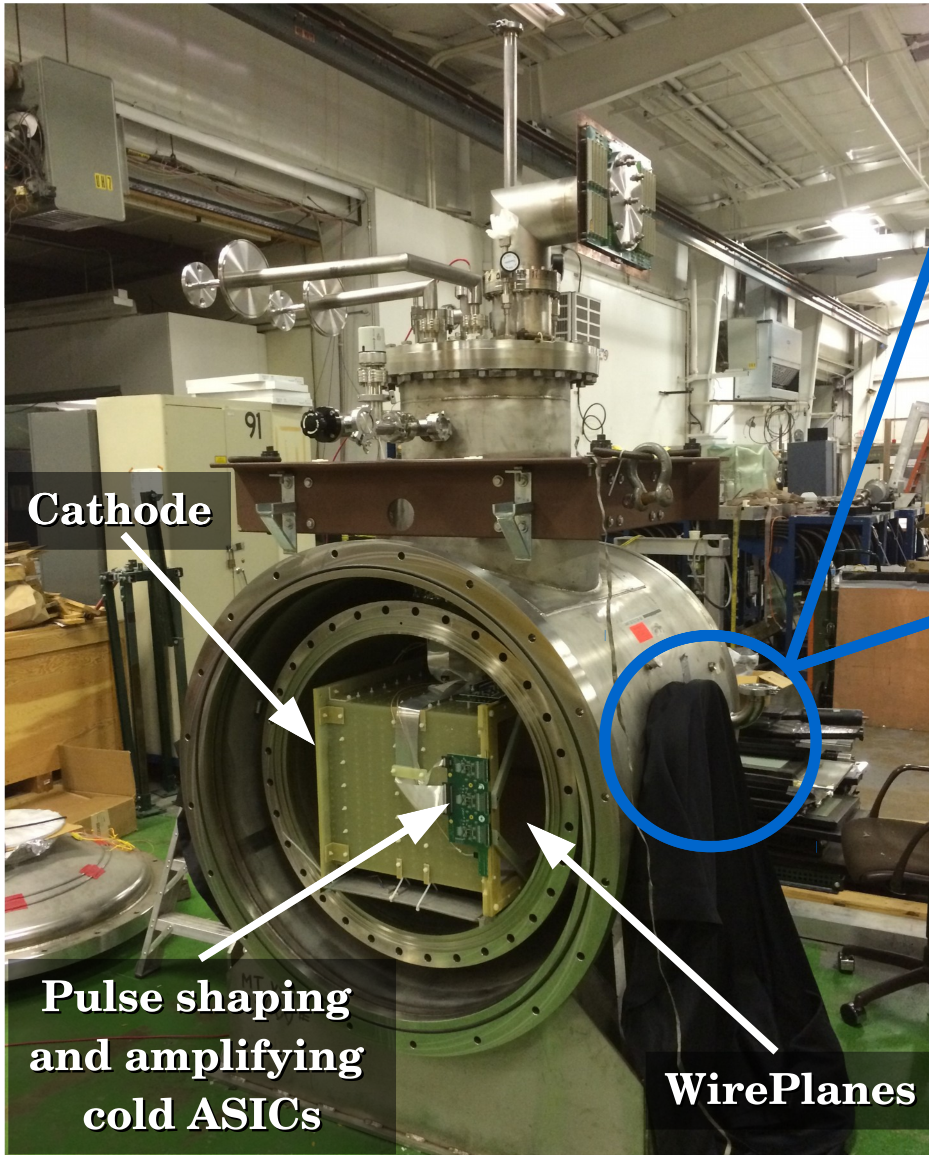
✔ Each plane is composed by 4 scintillating bars connected to a PMT

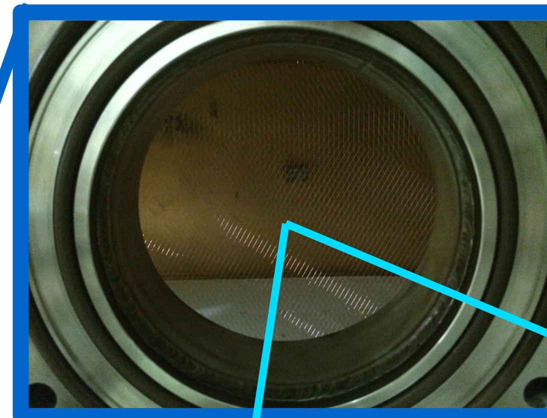
✔ Allows to discriminate π/μ exiting the cryostat

✔ Currently under investigation

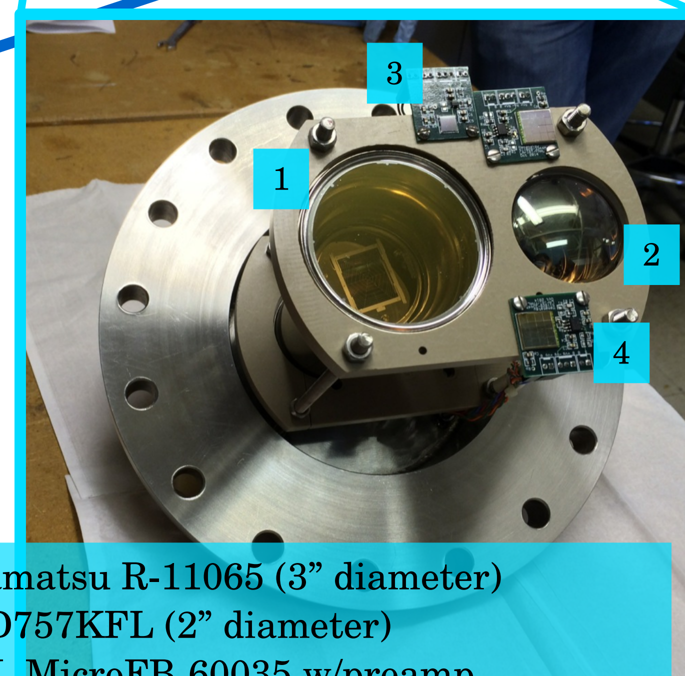


Inside the cryostat: TPC and light collection system



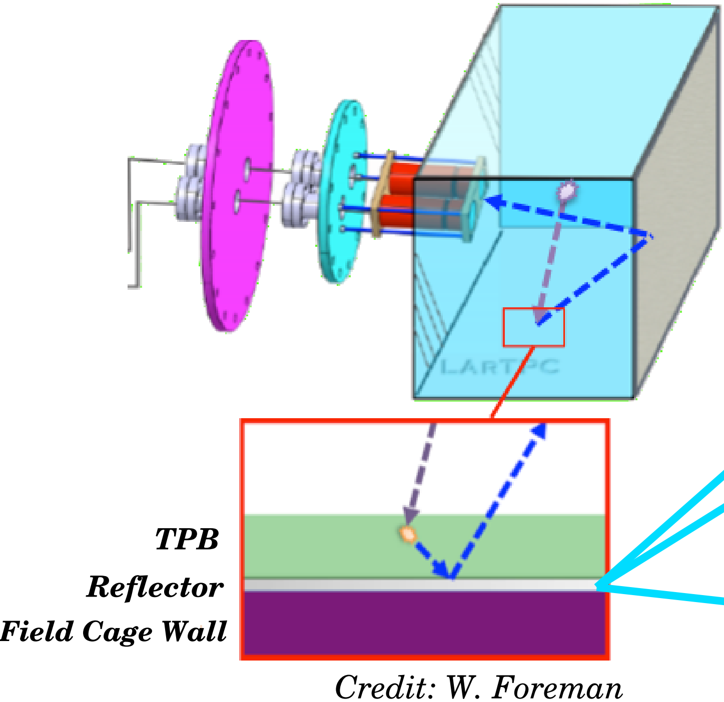


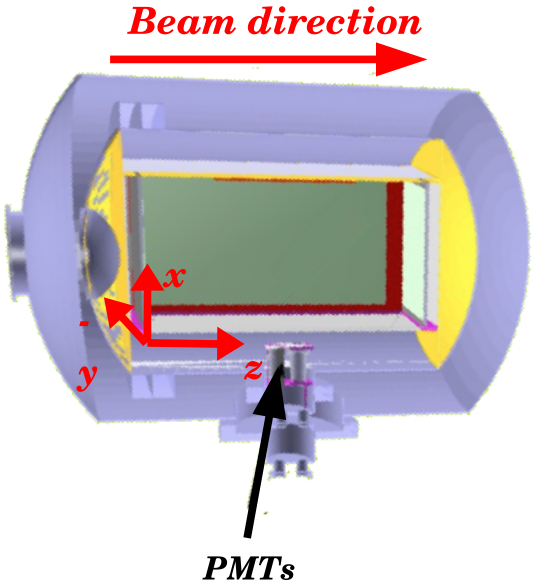
Light Collection System port



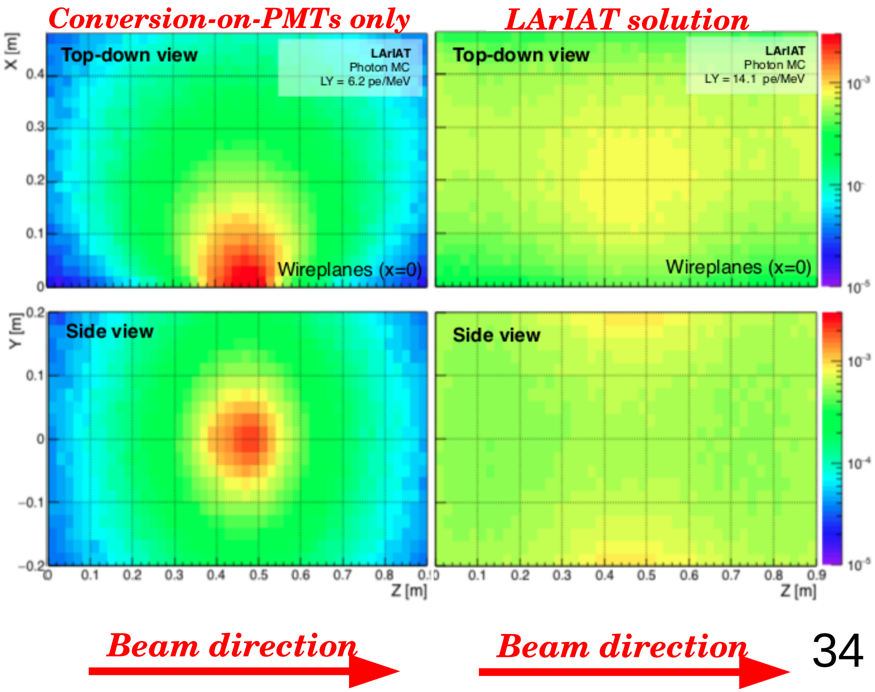
1. PMT: Hamamatsu R-11065 (3” diameter)
2. PMT: ETL D757KFL (2” diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (Run I)
   SiPM: Hmm. VUV-sensitive (Run II)

Light Collection System

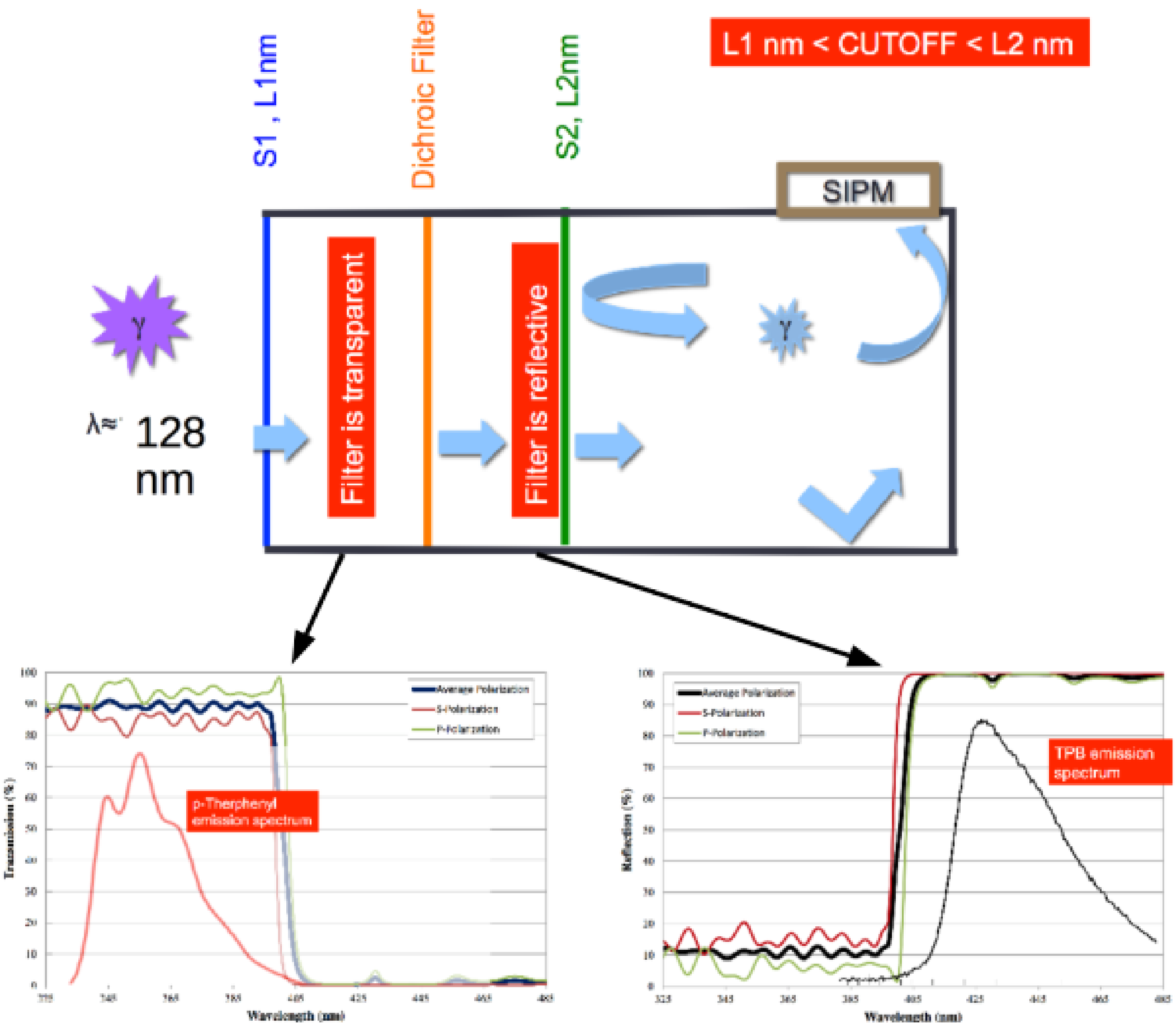


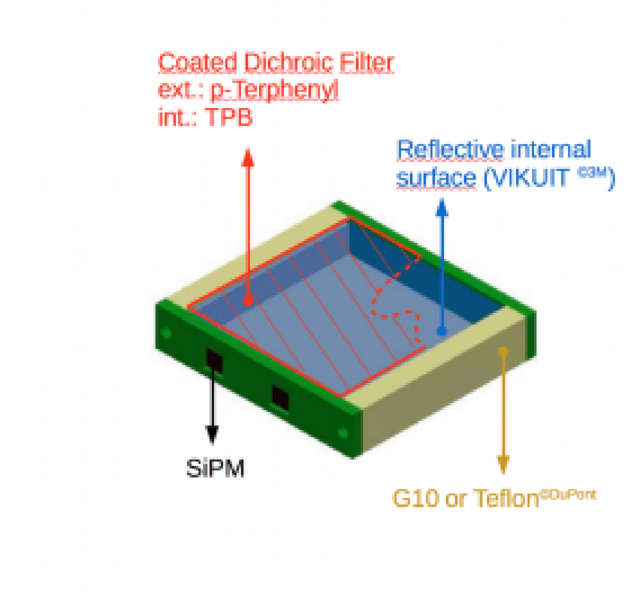


- **Wavelength shifting (evaporated) reflected foils on the four field cage walls**
  - *Technique borrowed from dark matter experiments*
- **Provides greater (~ 40 pe/MeV at zero field) and more uniform light yield respect to "conversion-on-PMTs-only" light systems**
- **R&D for future neutrino experiments as a way to improve calorimetry and triggering**



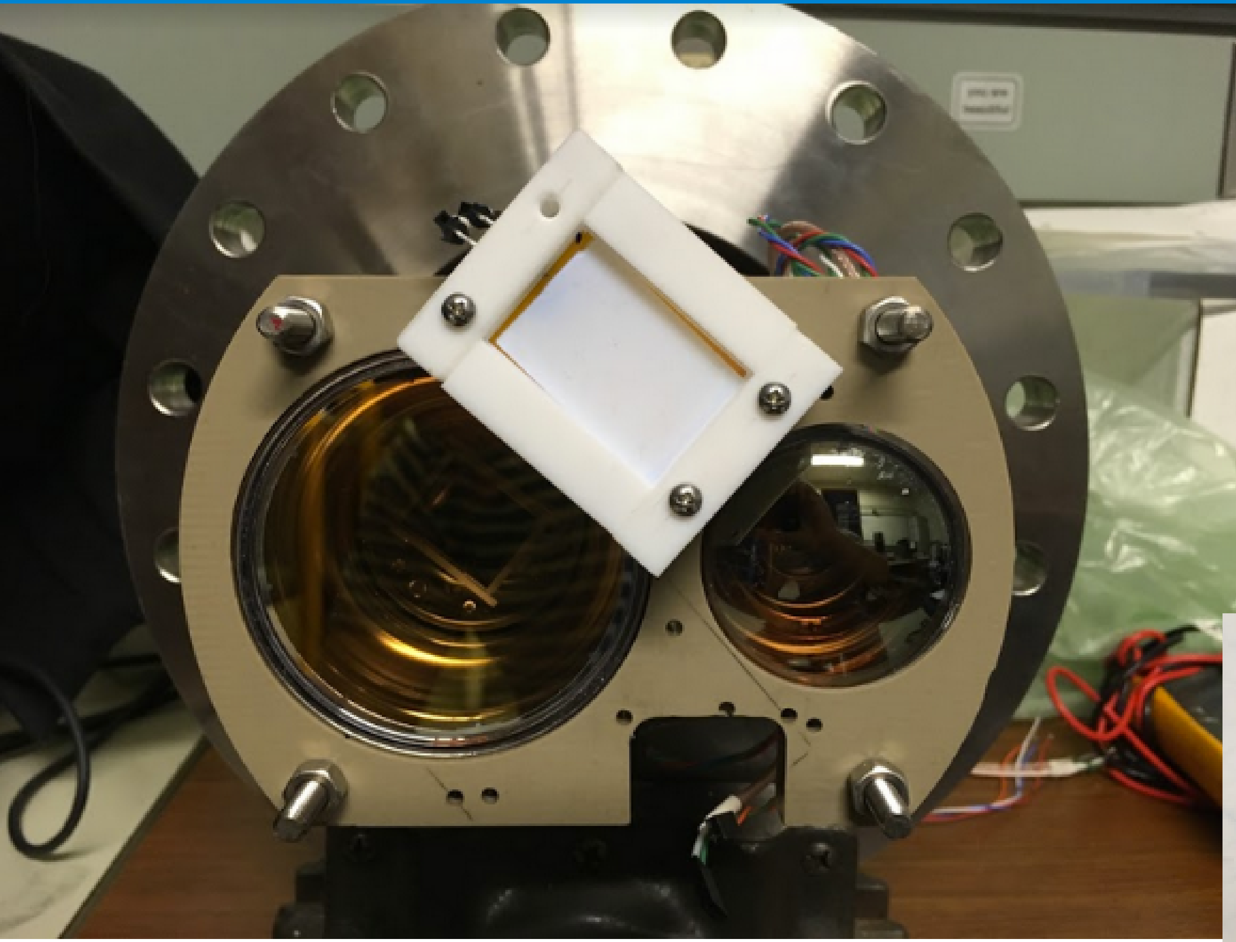
New ARAPUCA Light Collection System





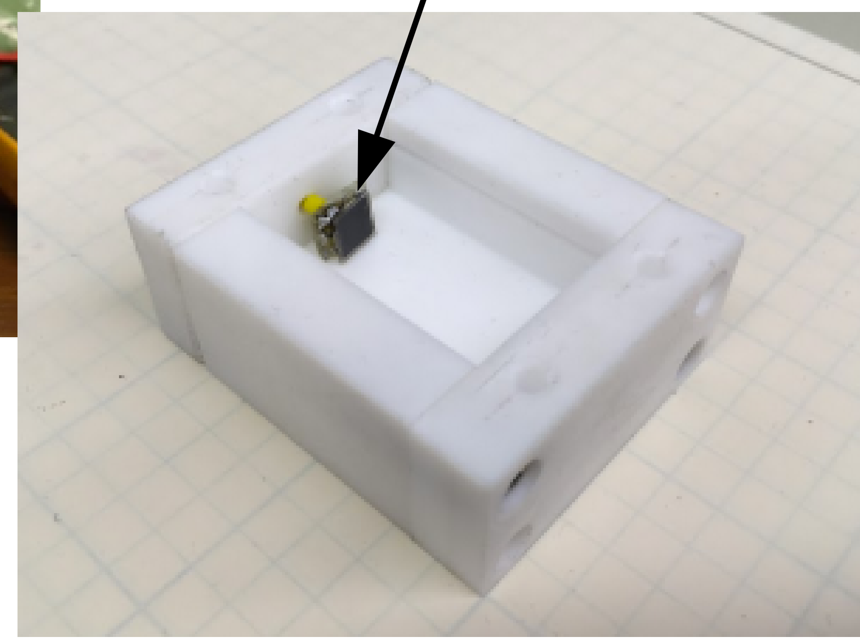
- **Dichoric filter + wavelength shifter**
  - Trap light inside device
- **Inner walls made of Teflon**
  - Trapped light reflected until detected by SiPM

New ARAPUCA Light Collection System



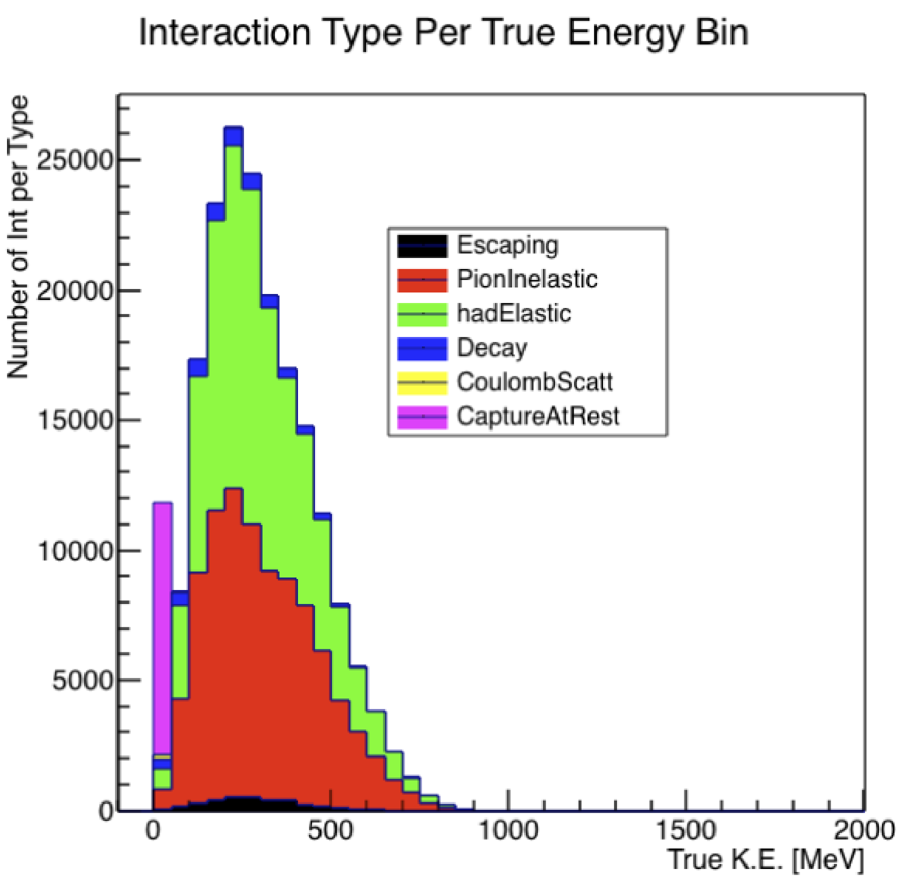
- **ARAPUCA mounted near existing PMTs**
  - Compare ARAPUCA performance to PMTs

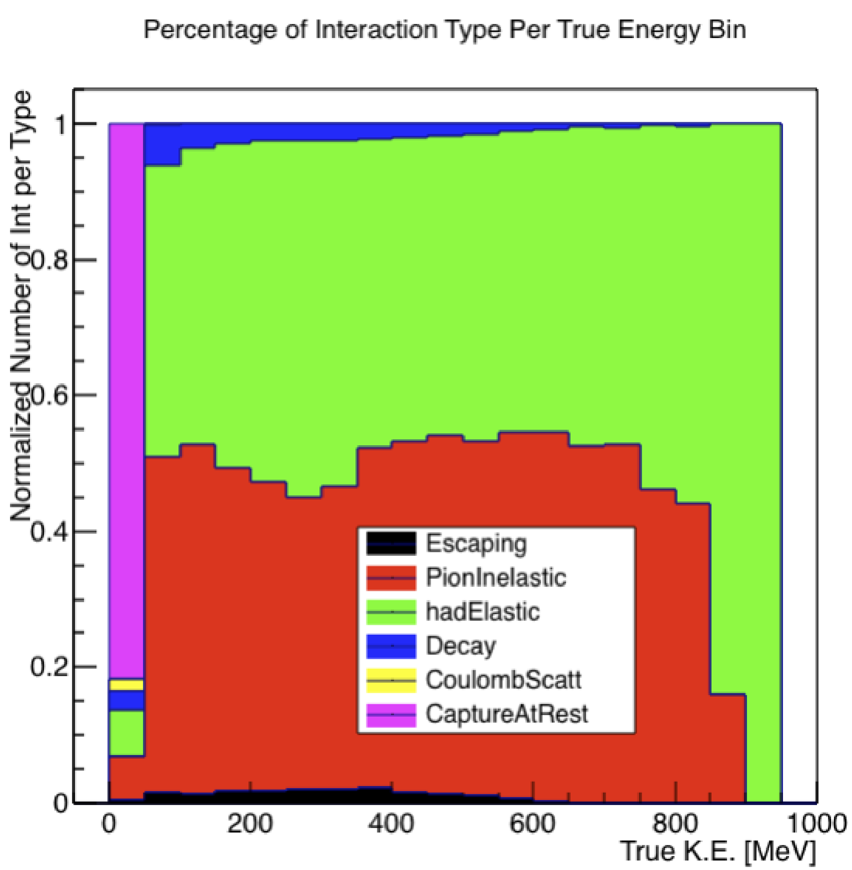
2x Ganged SiPM



Cross-Section

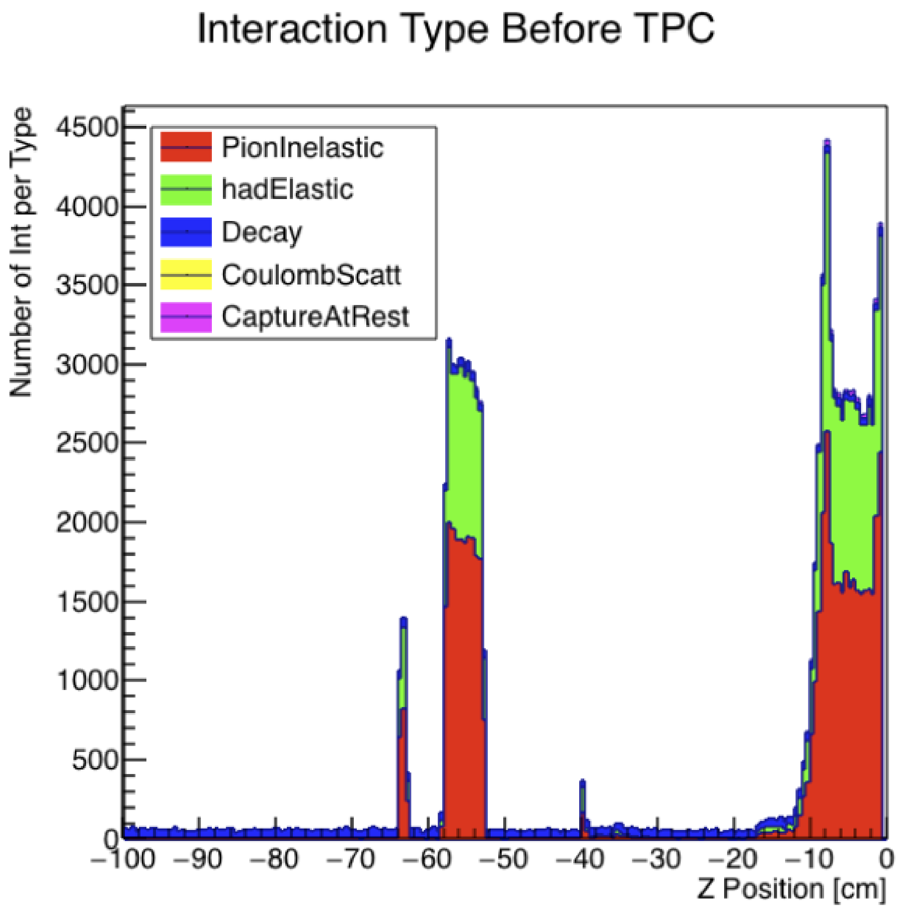
- **We begin by looking at the bin content of the cross-section from MC**
  - Here we show events / 50 MeV bin to mimic the binning used in the data
  - Plot the true kinetic energy
- **Pion captrure-at-rest dominate in the lowest energy bin (0 MeV < KE < 50 MeV)**
  - Constitutes ~80% of the interactions in that bin
  - This is not a process we want to include in the cross-section measurement

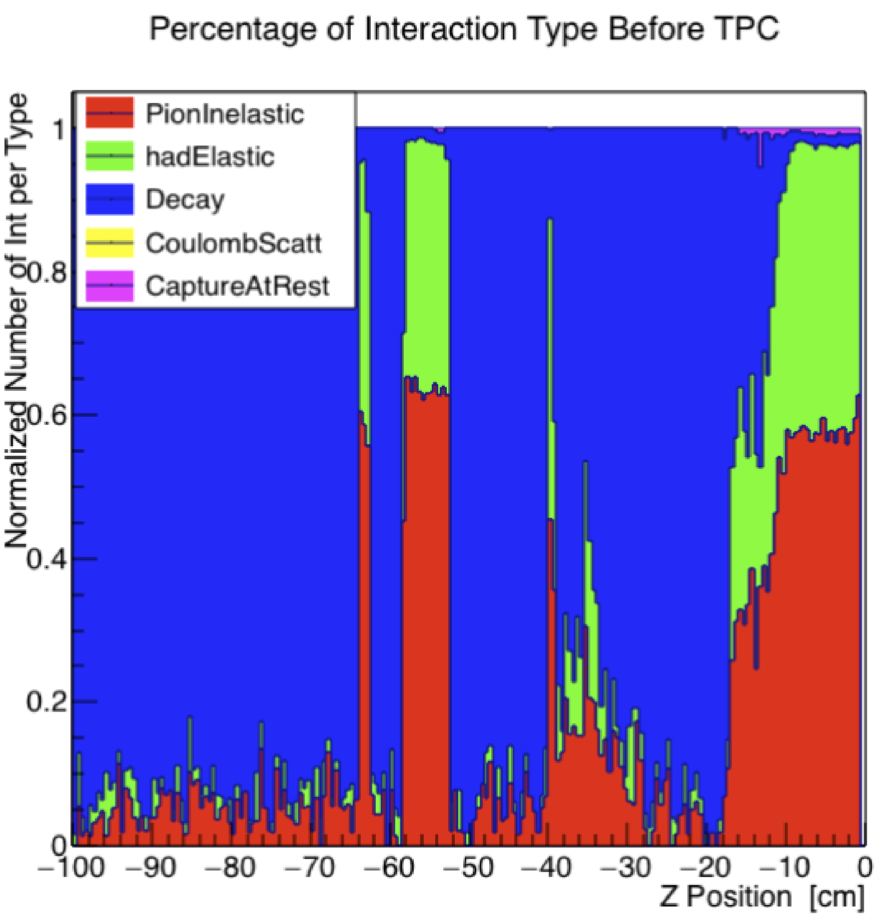




What happens in the upstream

- **About 1% of the time the pion actually stops before reaching the TPC**
  - The remaining portion there is actually an interaction





Validation Plots