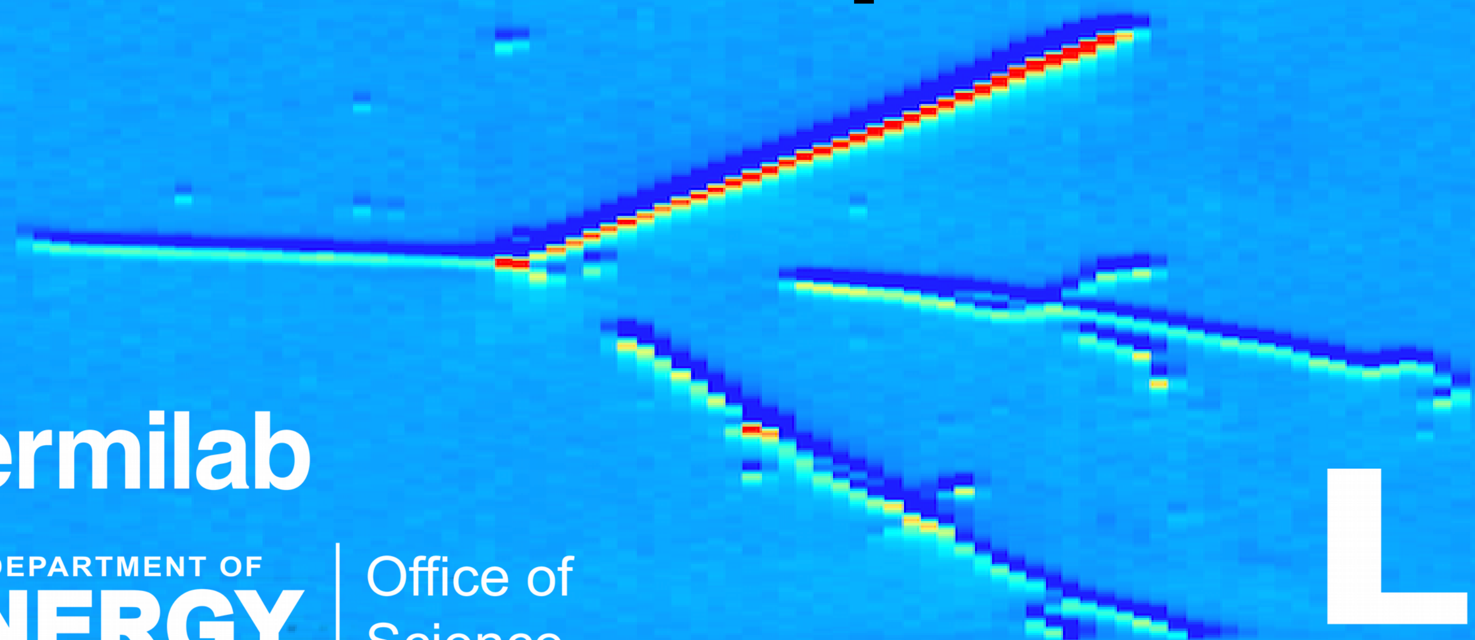
Fermilab Test Beam Facility and LArIAT Experiment



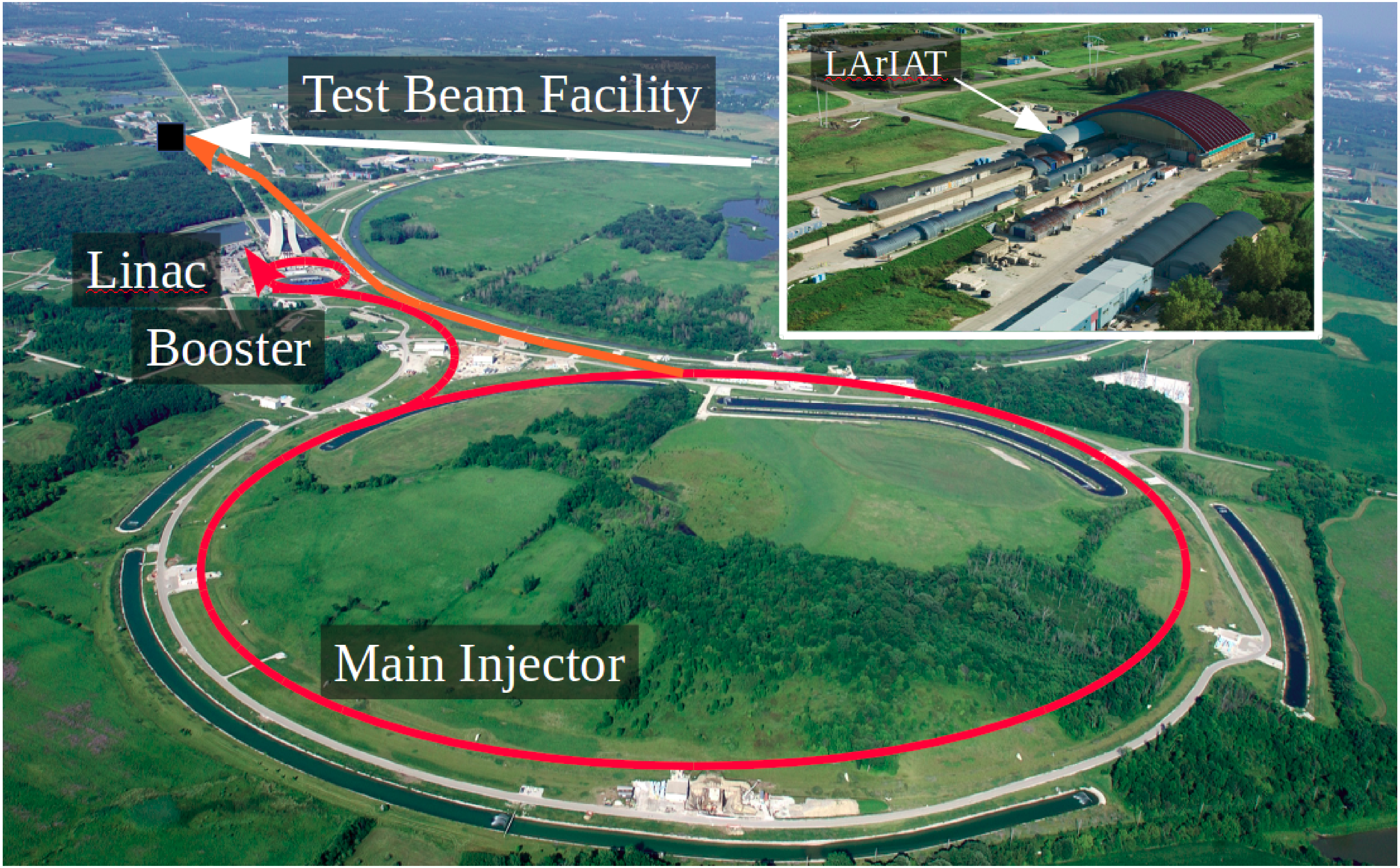
Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

LSU
LOUISIANA STATE UNIVERSITY

Justin Hugon
Louisiana State University
On behalf of the Fermilab Test Beam Facility and LArIAT experiment

Fermilab Test Beam Facility (FTBF)

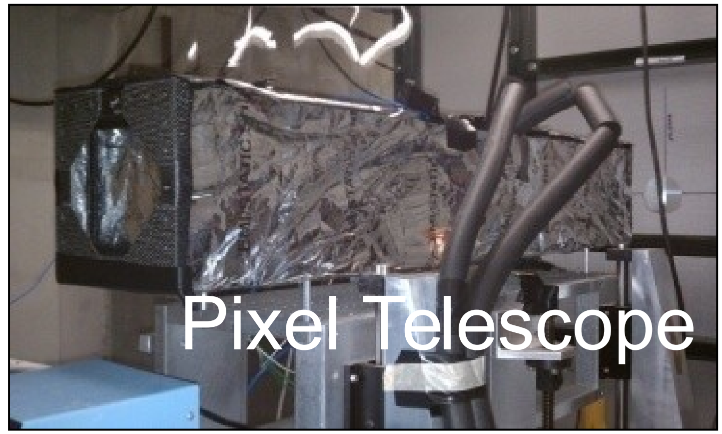


Fermilab Test Beam Facility (FTBF)

- Full details can be found: http://ftbf.fnal.gov/beam-overview/
  - 4 sec spill every 60 seconds
  - Tunable rate (100 Hz – 100,000 Hz)
  - Beam available 24/7
- MTest Beamline
  - 120 GeV protons (primary)
  - 1 – 60 GeV secondary beam
  - Spot size about 2cm
- MCenter Beamline
  - Tertiary beamline down to 200 MeV
  - Currently have cryogenic support for LArIAT (Liquid Argon In A Test Beam)

Facility Instrumentation

Cherenkov Detector

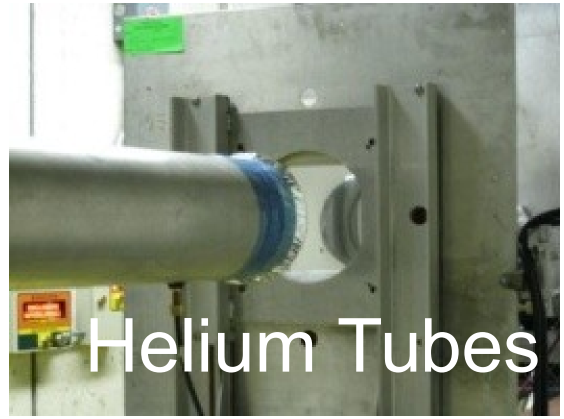


+ Assorted Trigger Scintillators

4 MWPC Trackers

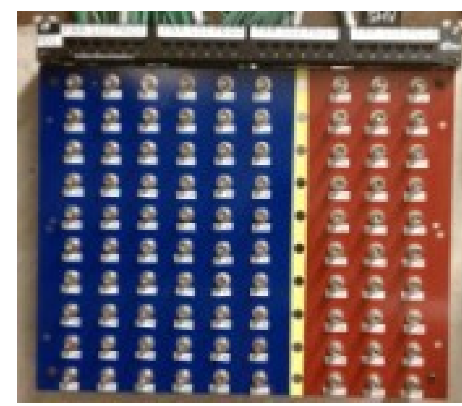
Infrastructure in MTest

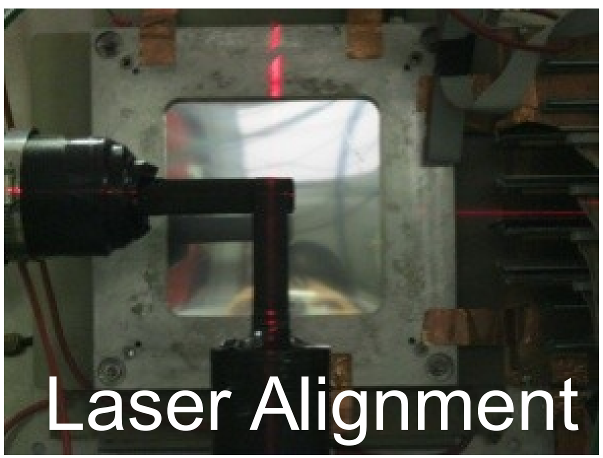
ACNET Controlled Motion Tables



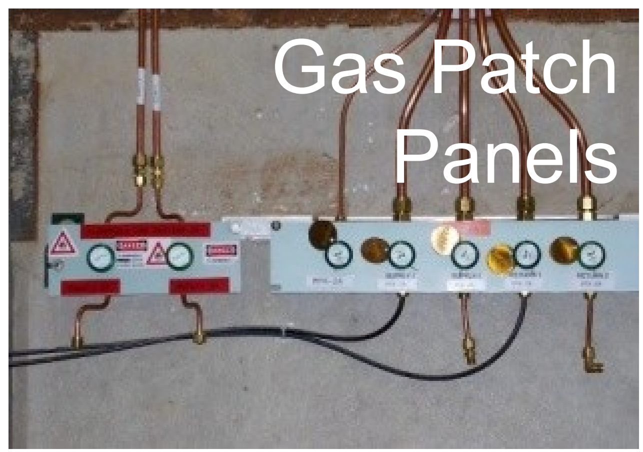
Helium Tubes

Signal, Network, & High Voltage Patch Panels





Laser Alignment

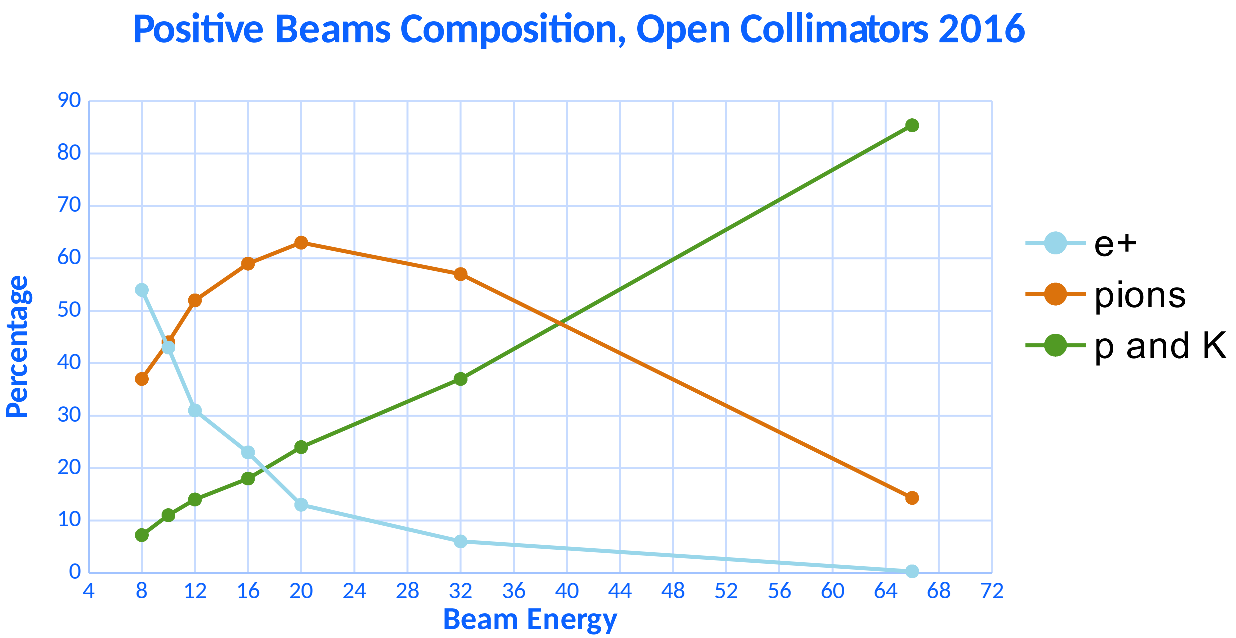


Gas Patch Panels

Web Cameras

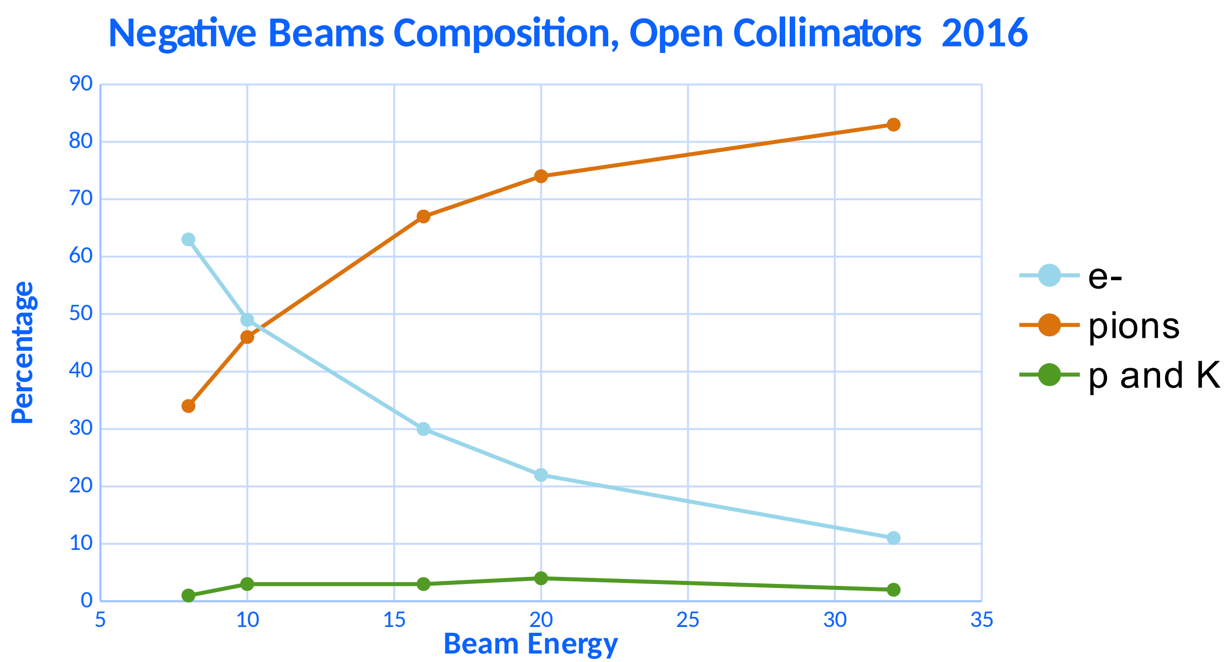
Climate Controlled Huts & 30 Ton Crane

Beams Composition Studies—In Progress



Studies done by E. Skup and D. Jensen

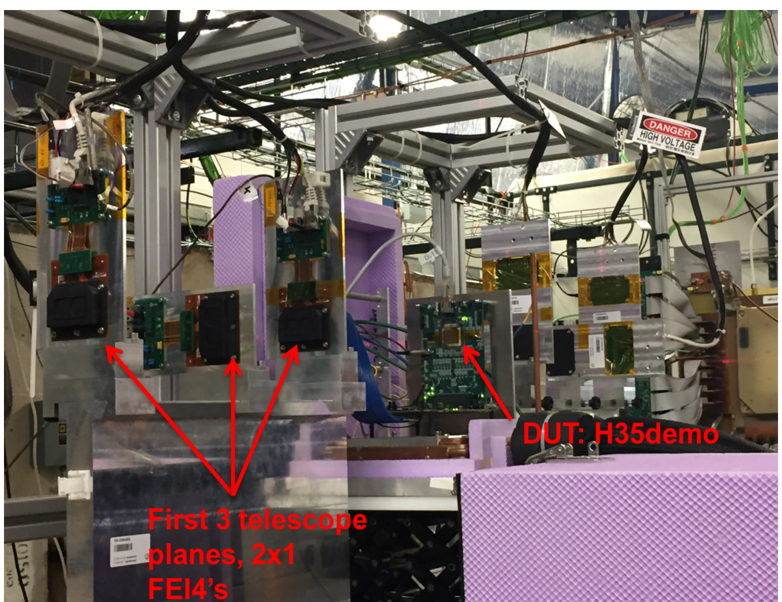
- **MTest Secondary Beam**
- Plans to continue this study as schedule allows
- Put into a database with all running conditions recorded



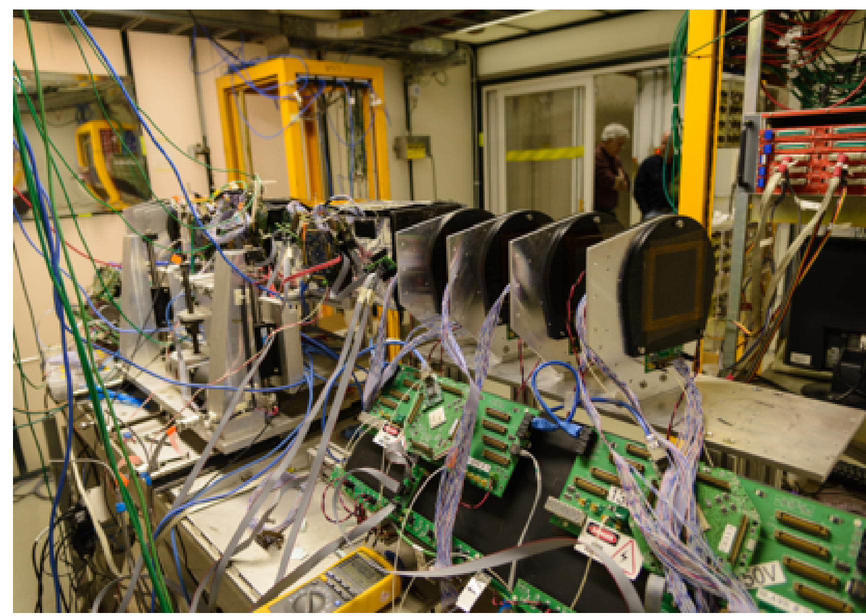
Tests for LHC Experiments (CMS, ATLAS)

- CMS Outer Tracker, CMS Pixels, CMS timing all had test beams this year
- ATLAS pixels also ran for several weeks.
- Both groups used the test beam heavily this year.

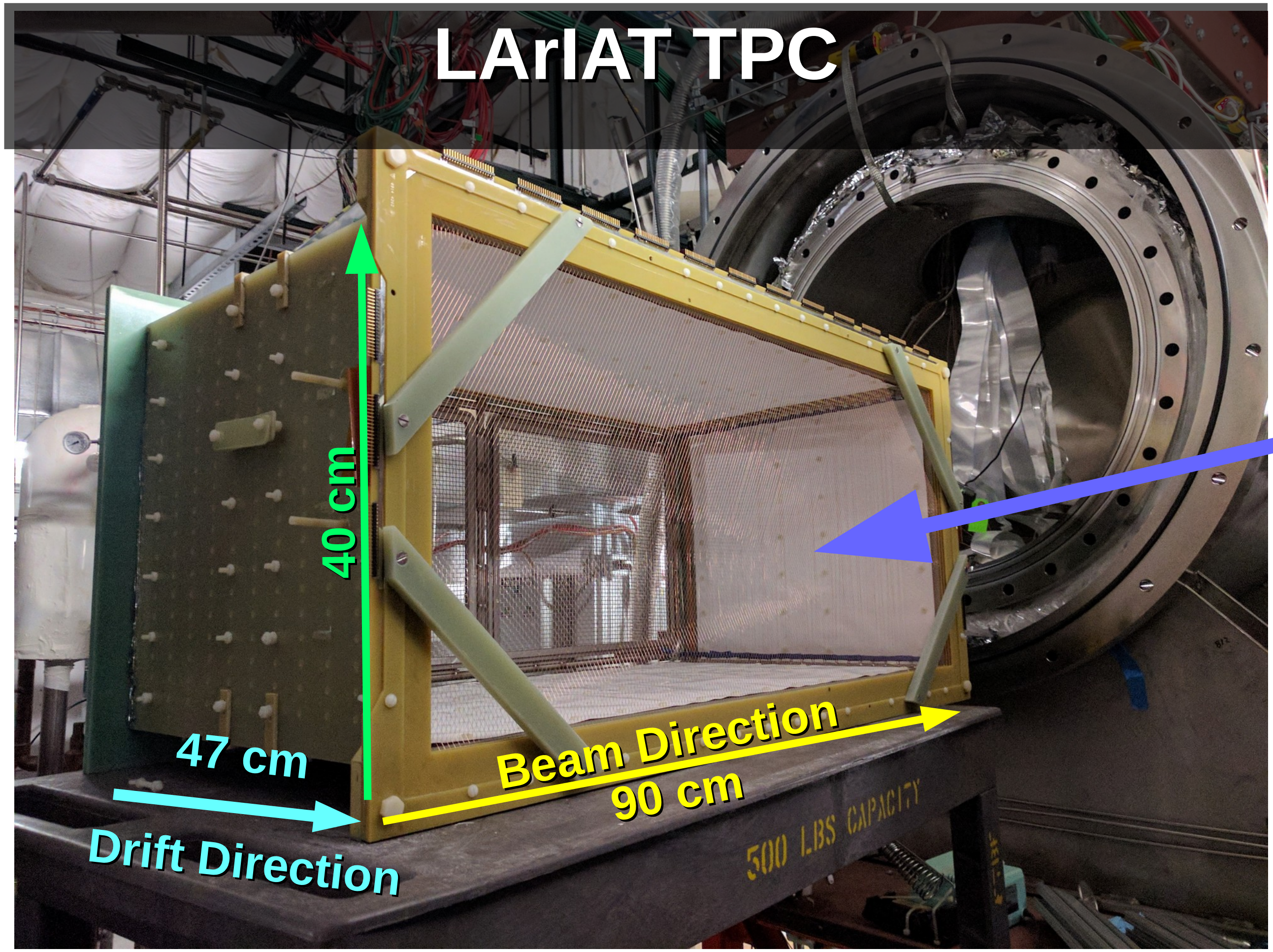
ATLAS Test Beam Setup



CMS Test Beam Setup



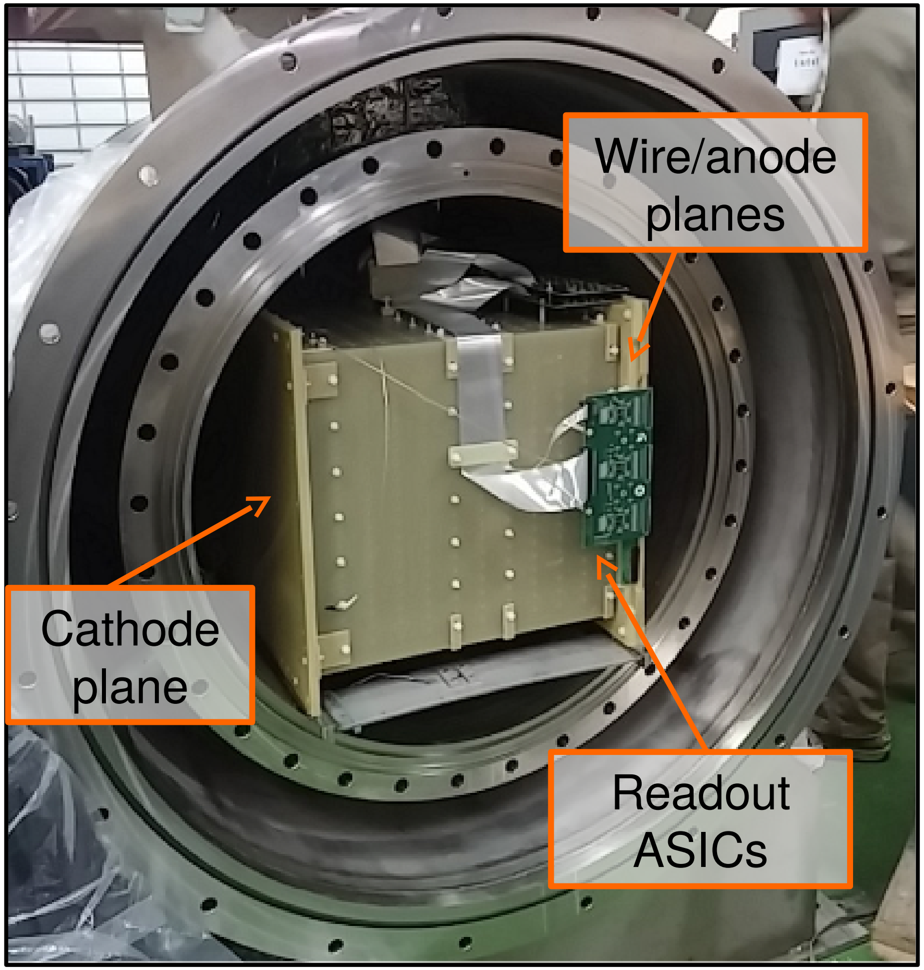
Liquid Argon in a Test Beam (LArIAT)



170 L
0.25 tons of LAr

Reuse the ArgoNeuT TPC in the MCenter (long-duration test) beamline

Liquid Argon in a Test Beam (LArIAT)

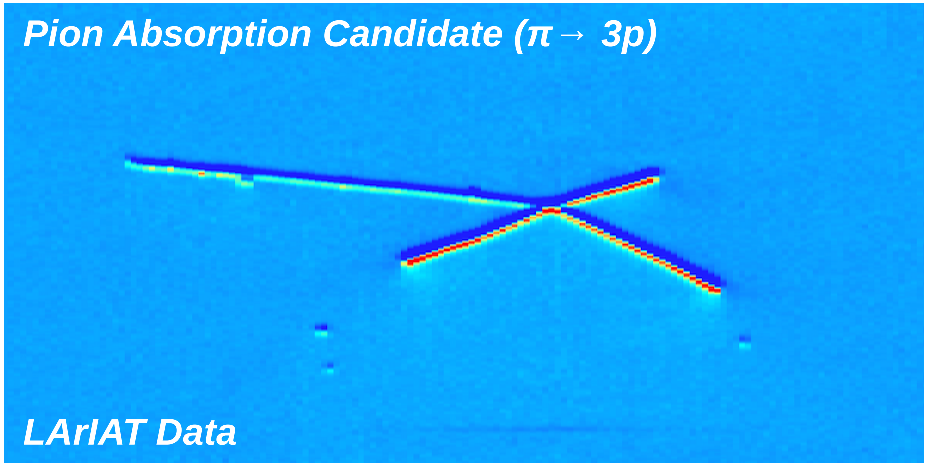


Changes from ArgoNeuT:

- **New wireplanes**
- **Cold front-end electronics ASICs from MicroBooNE**

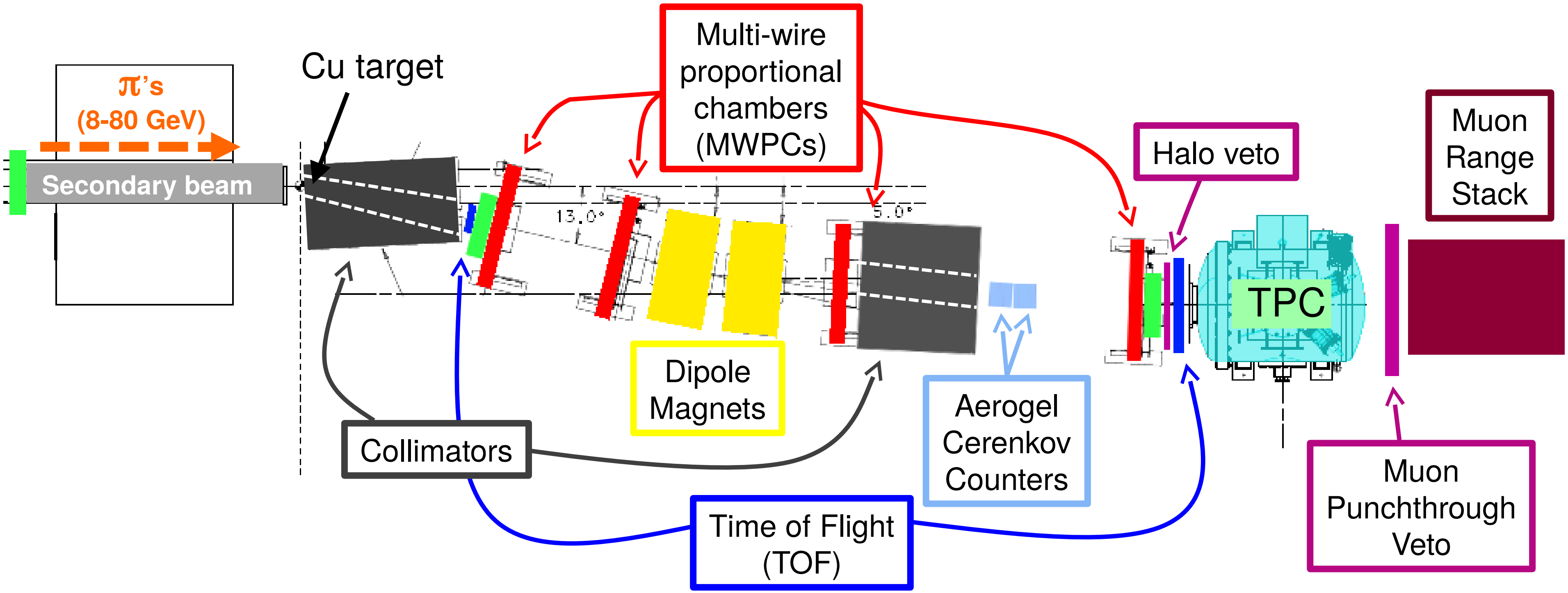
LArIAT Goals

- **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



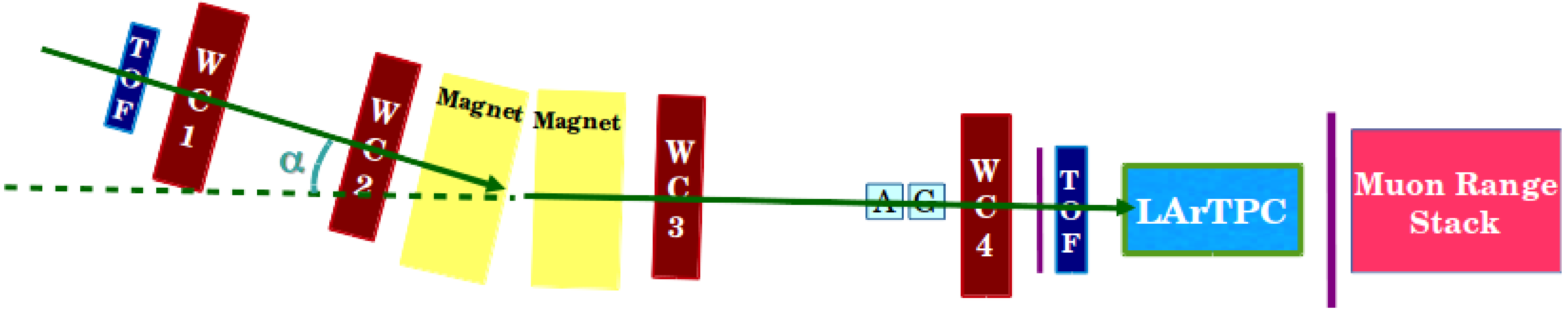
- **R&D Goals**
  - Ionization and scintillation light studies
    - Charge deposited vs. light collected for stopping particles of known energy
  - Optimization of particle ID techniques
  - LArTPC event reconstruction
    - Compare 3mm, 4mm, 5mm wire pitch

LArIAT Tertiary Beamline

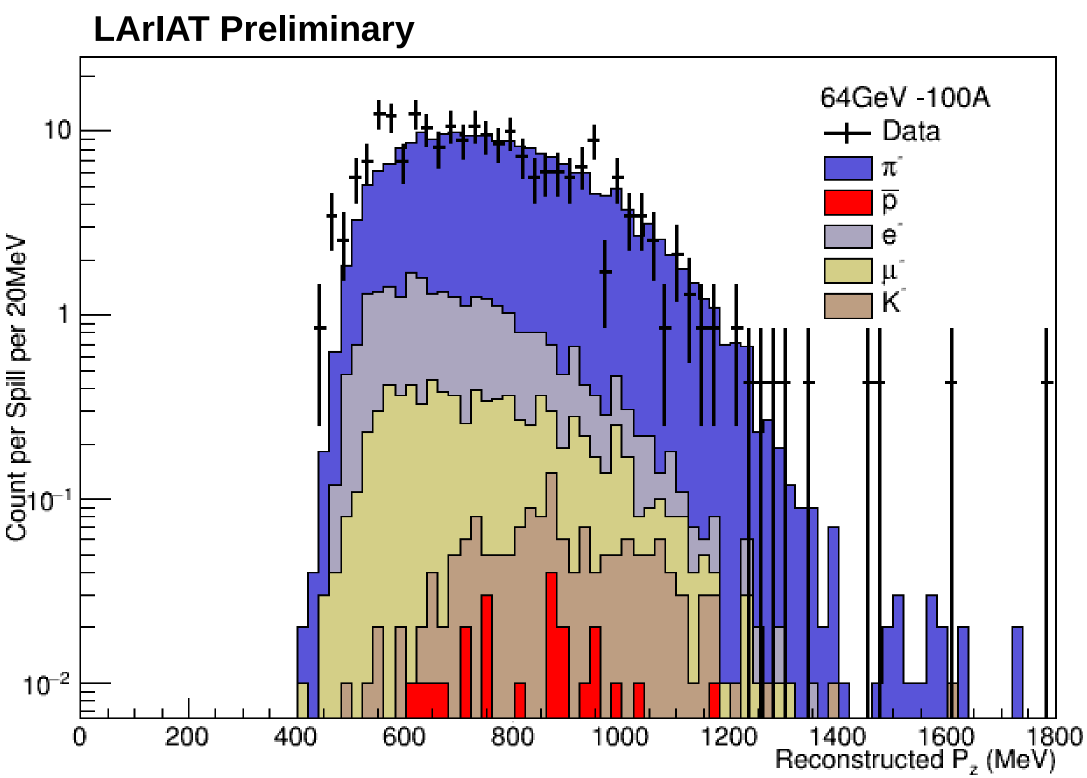


Instrumented beamline identifies and characterizes particles both online and offline

LArIAT Beamline: Wire Chambers

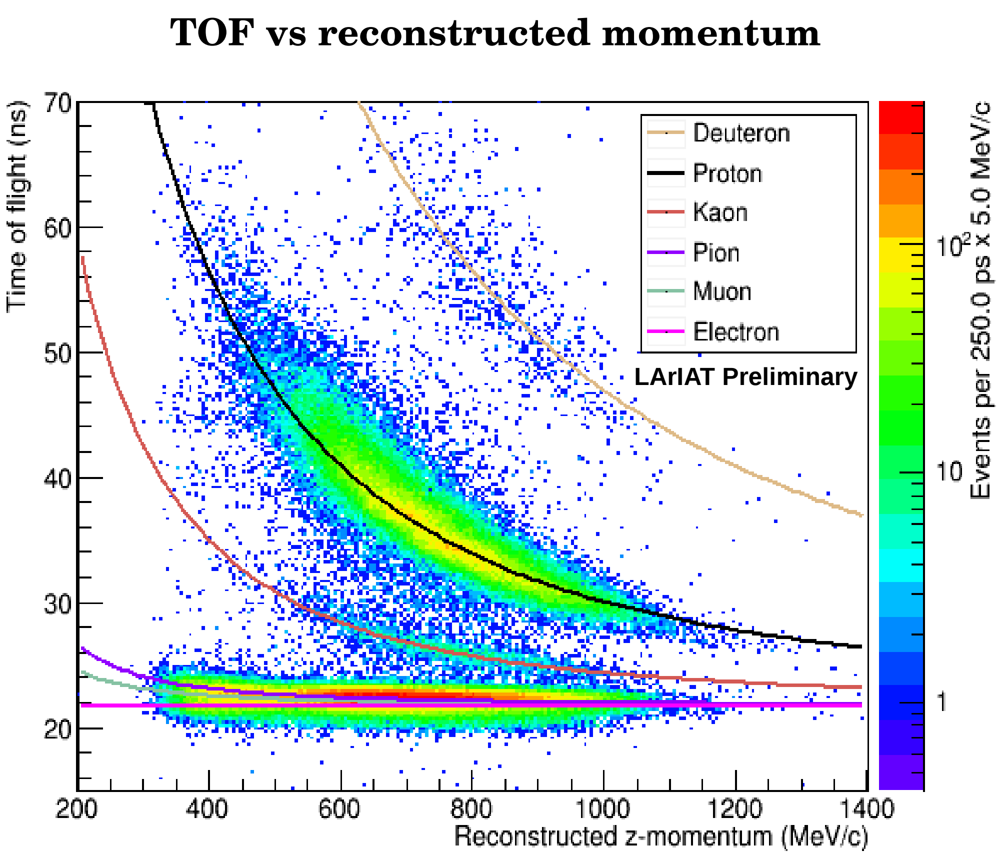


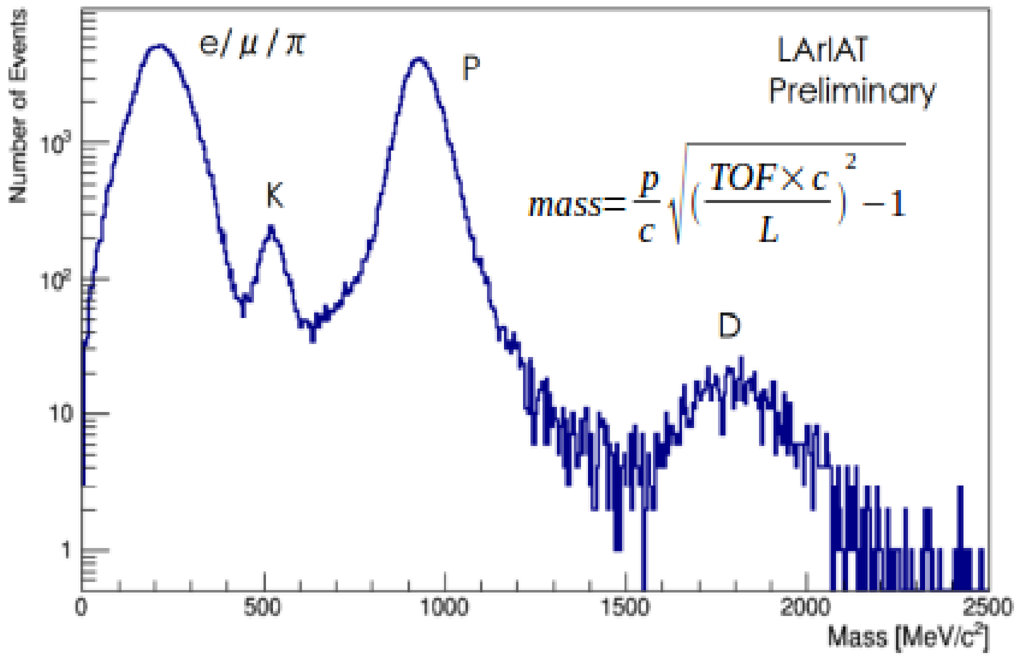
Wire chambers reconstruct the position and momentum of the particles in the beamline



Wire chamber reconstructed momentum compared to simulation

LArIAT Beamline Detectors

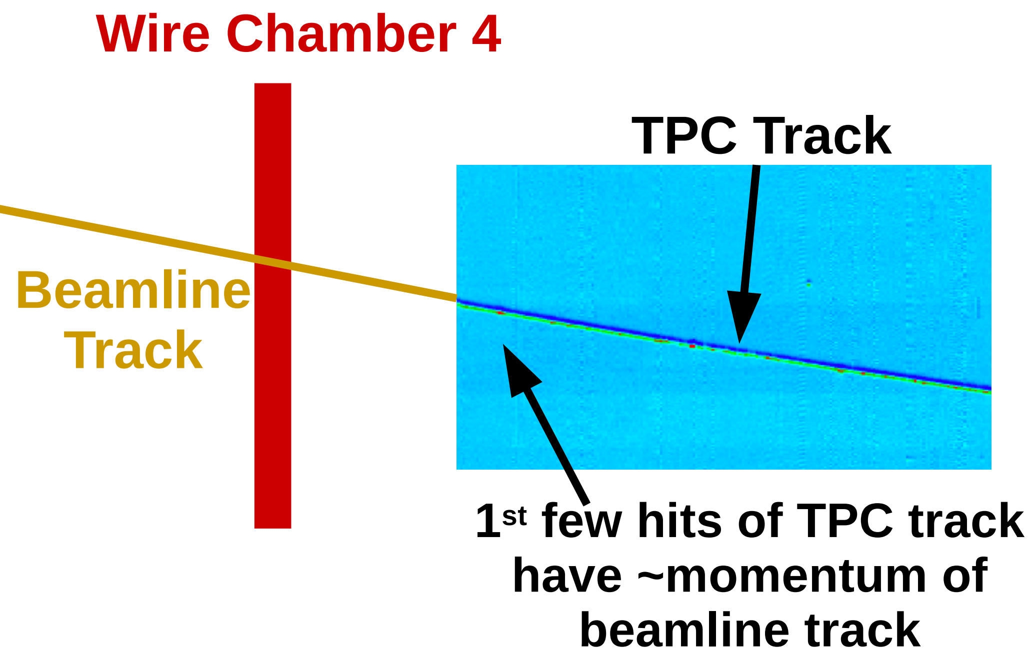


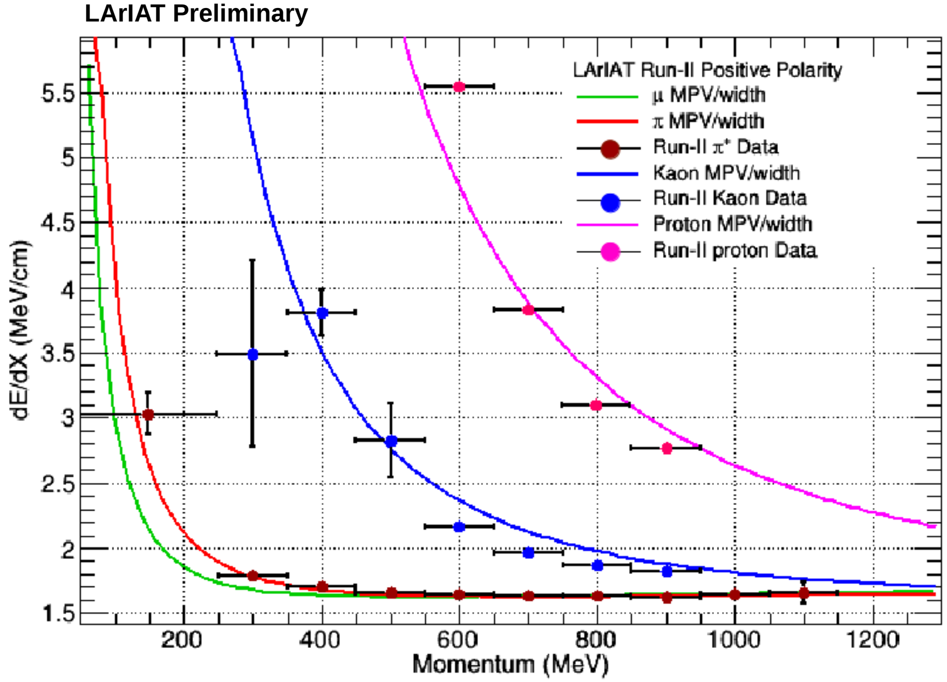


Combining the momentum and TOF allows for π/μ/e, K, proton separation

Additionally, using the known masses of the K and proton we can constrain the momentum scale to 3%

Calibrating the TPC



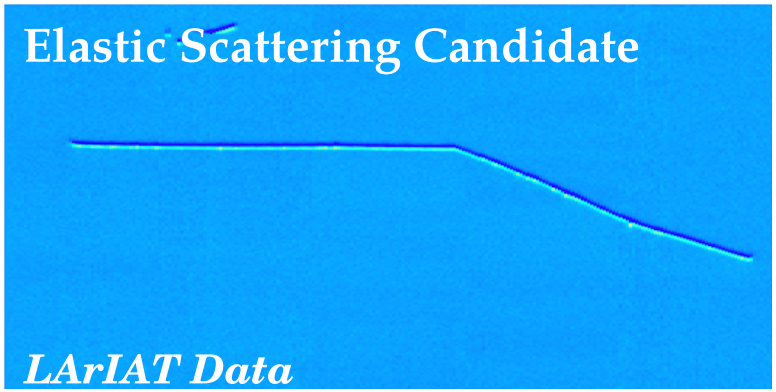


- Match beamline track to TPC track
- Fit dE/dx for various beamline momenta
- Calibrate detector response to follow Bethe-Bloch formula
- Calibrate using pions; check on kaons/protons

Pion Cross-Section

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

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



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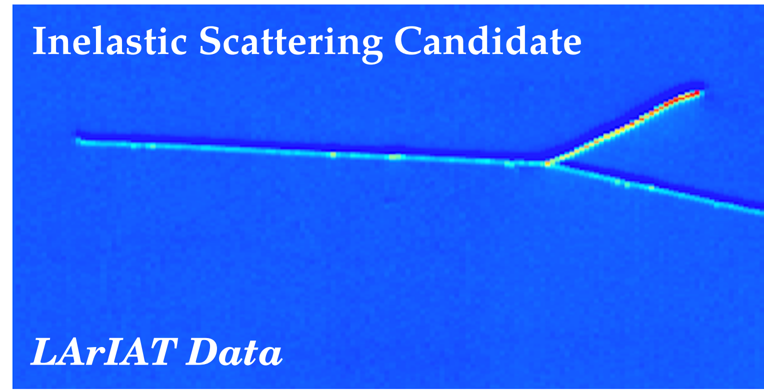

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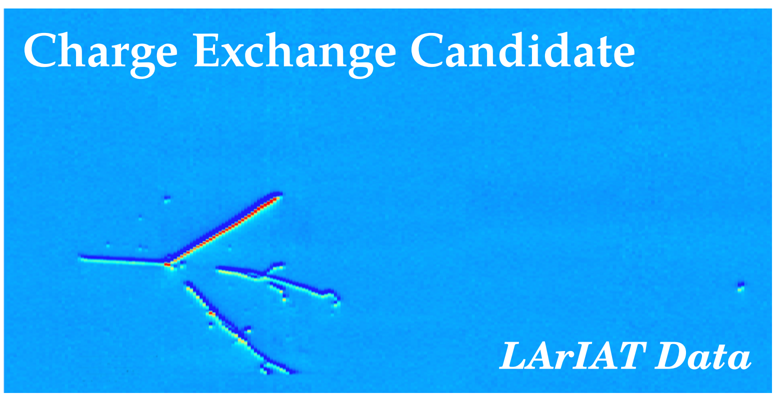

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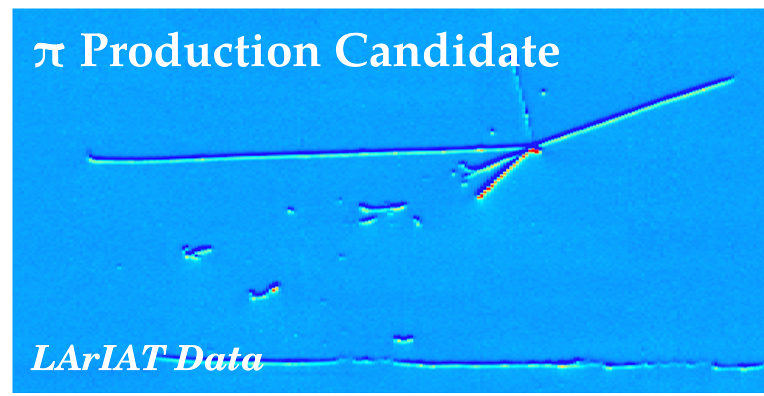

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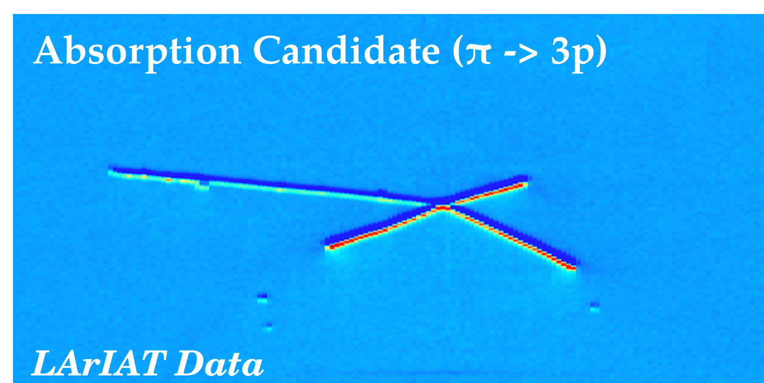
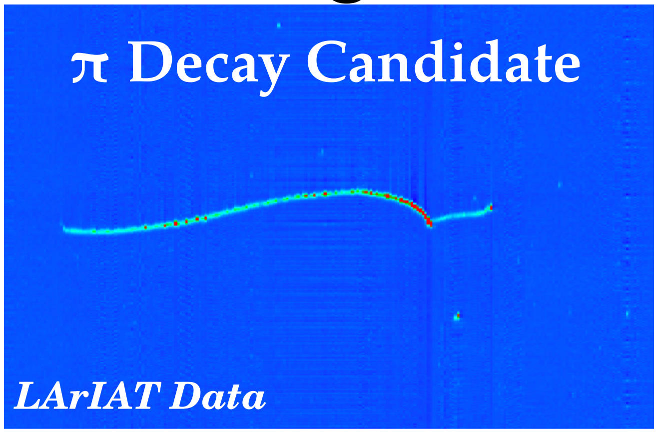
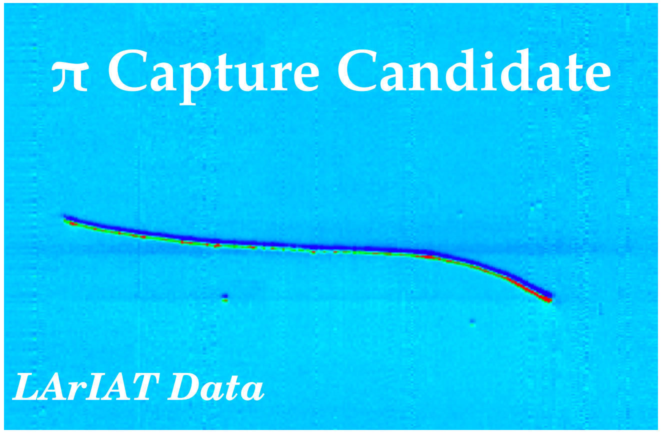
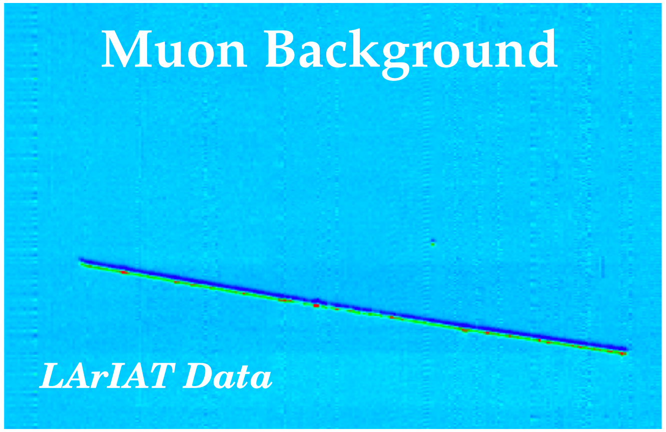


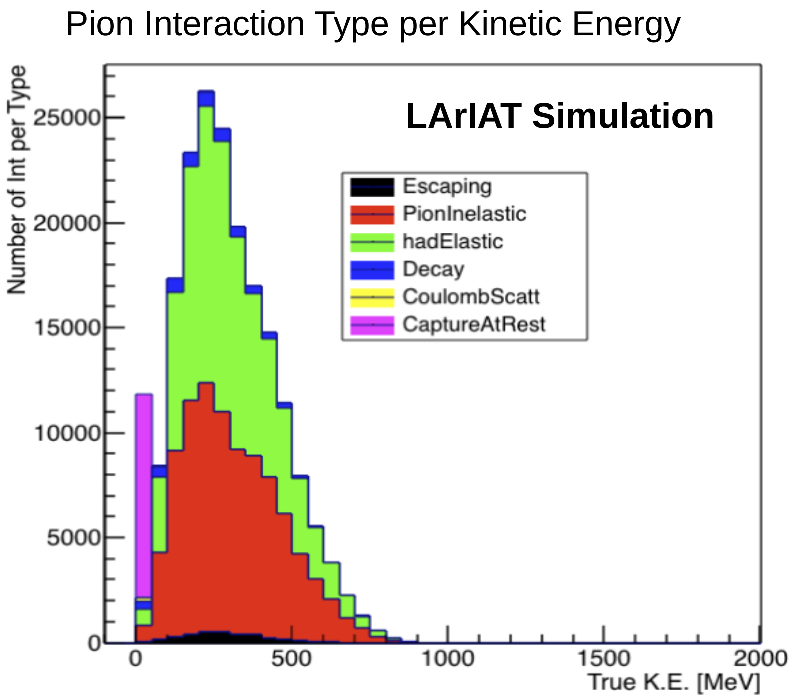
Pion Cross-Section

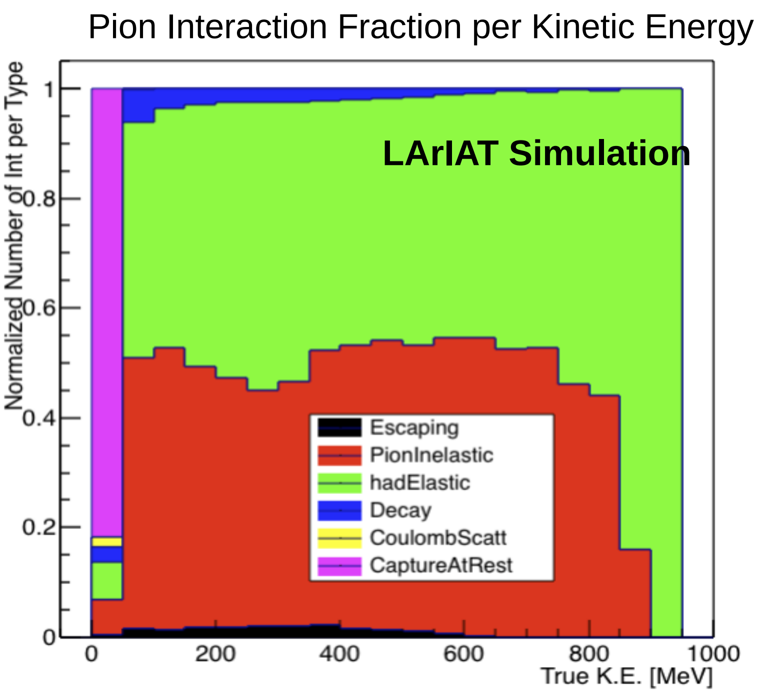
- **Backgrounds are:**









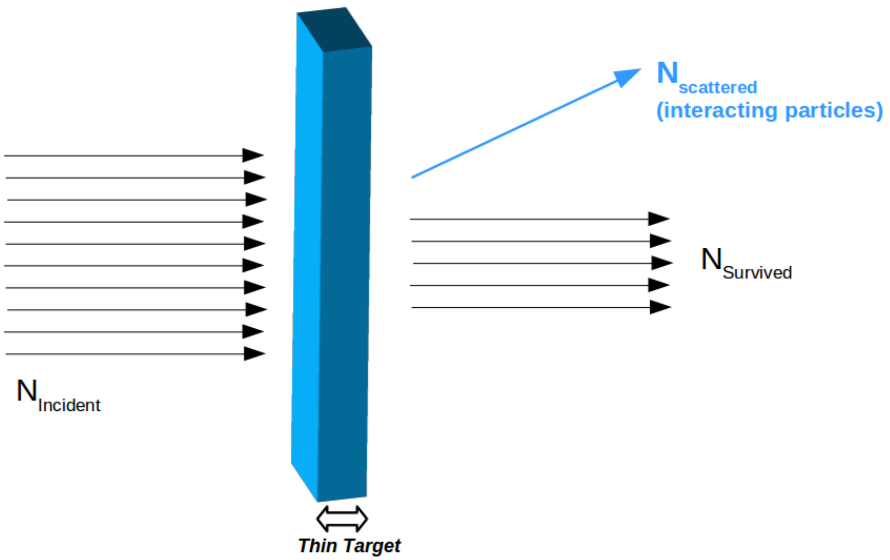


Note: Pion decay backgrounds are small component which remain in our result. Capture dominates the lowest energy bin and is thus excluded

Thin Slice Cross-Section

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

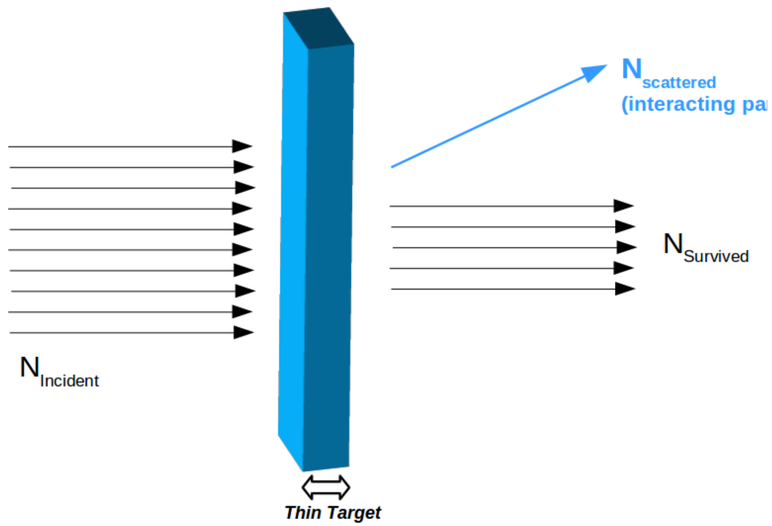
$$P_{\text{Interacting}} = 1 - P_{\text{Survival}} = 1 - e^{-\sigma n z}$$

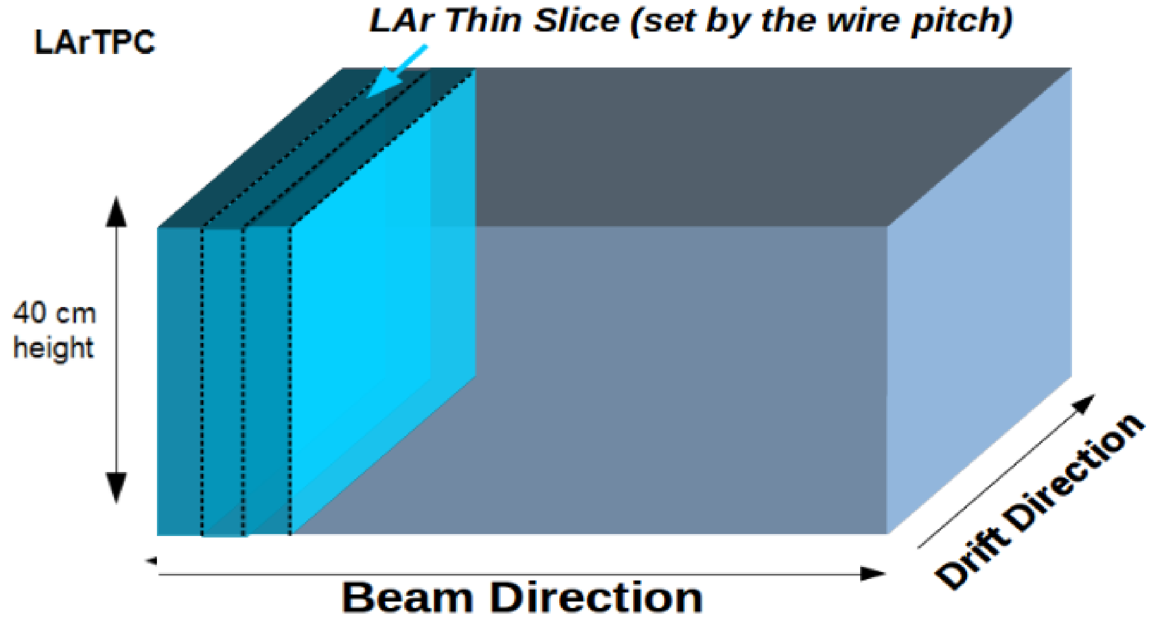


$$\frac{N_{\text{interacting}}}{N_{\text{Incident}}} = P_{\text{Interacting}} = 1 - e^{-\sigma n z} \approx 1 - \left(1 - \sigma n z + \ldots\right)$$

$$\boxed{\sigma \approx \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}}$$

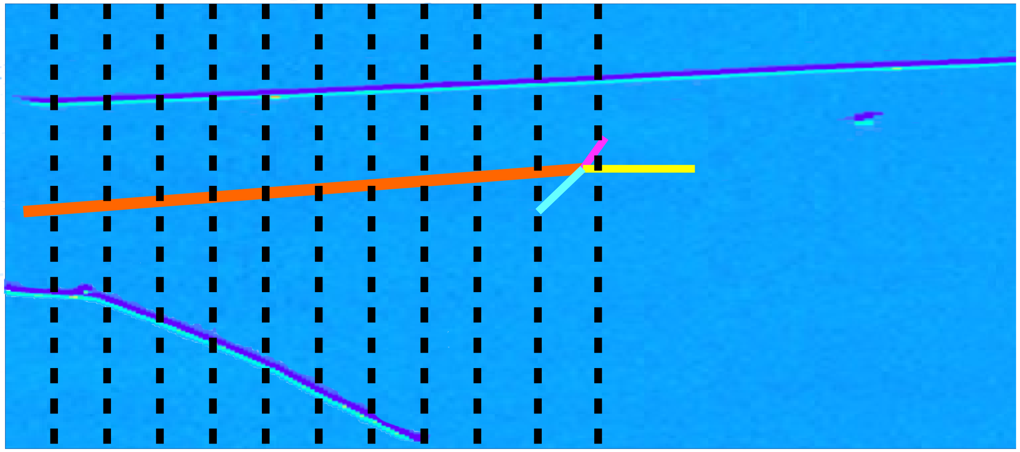
Thin Slice TPC Method



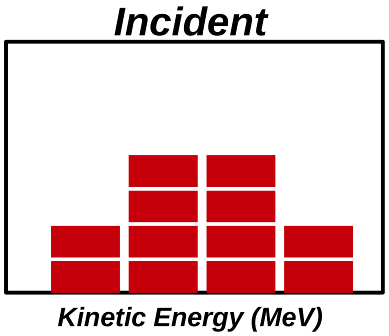


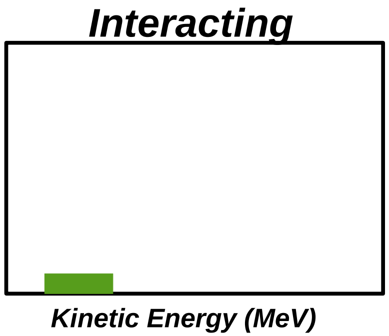
Treat the TPC wire-to-wire spacing as a series of "thin-slice" targets

Pion Cross-Section



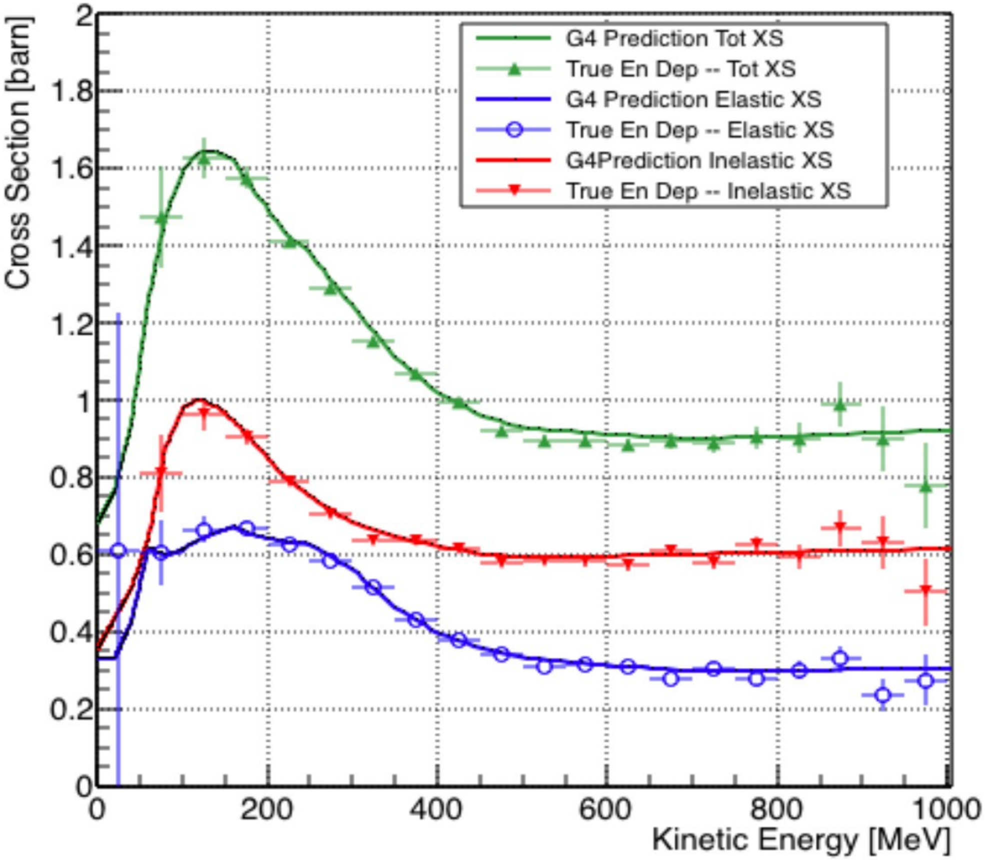
$$KE_i = KE_{beamline} - \sum_{j=0}^{i-1} dE/dX_j \times Pitch_j$$



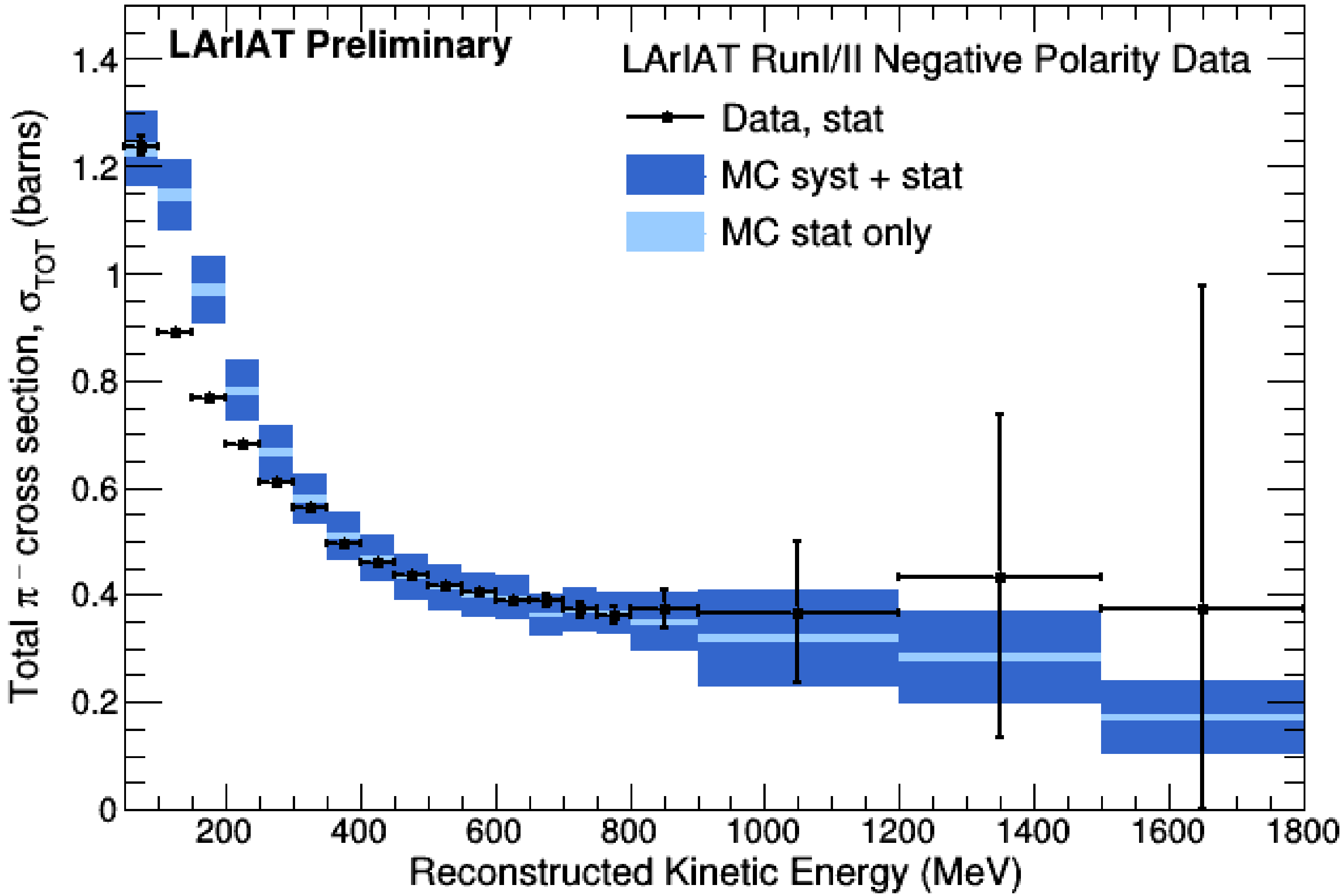


$$\sigma \approx \frac{1}{nz}\frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

Simulation Test of the Method for $\pi^- + Ar$



Pion Cross-Section



Systematics Considered Here

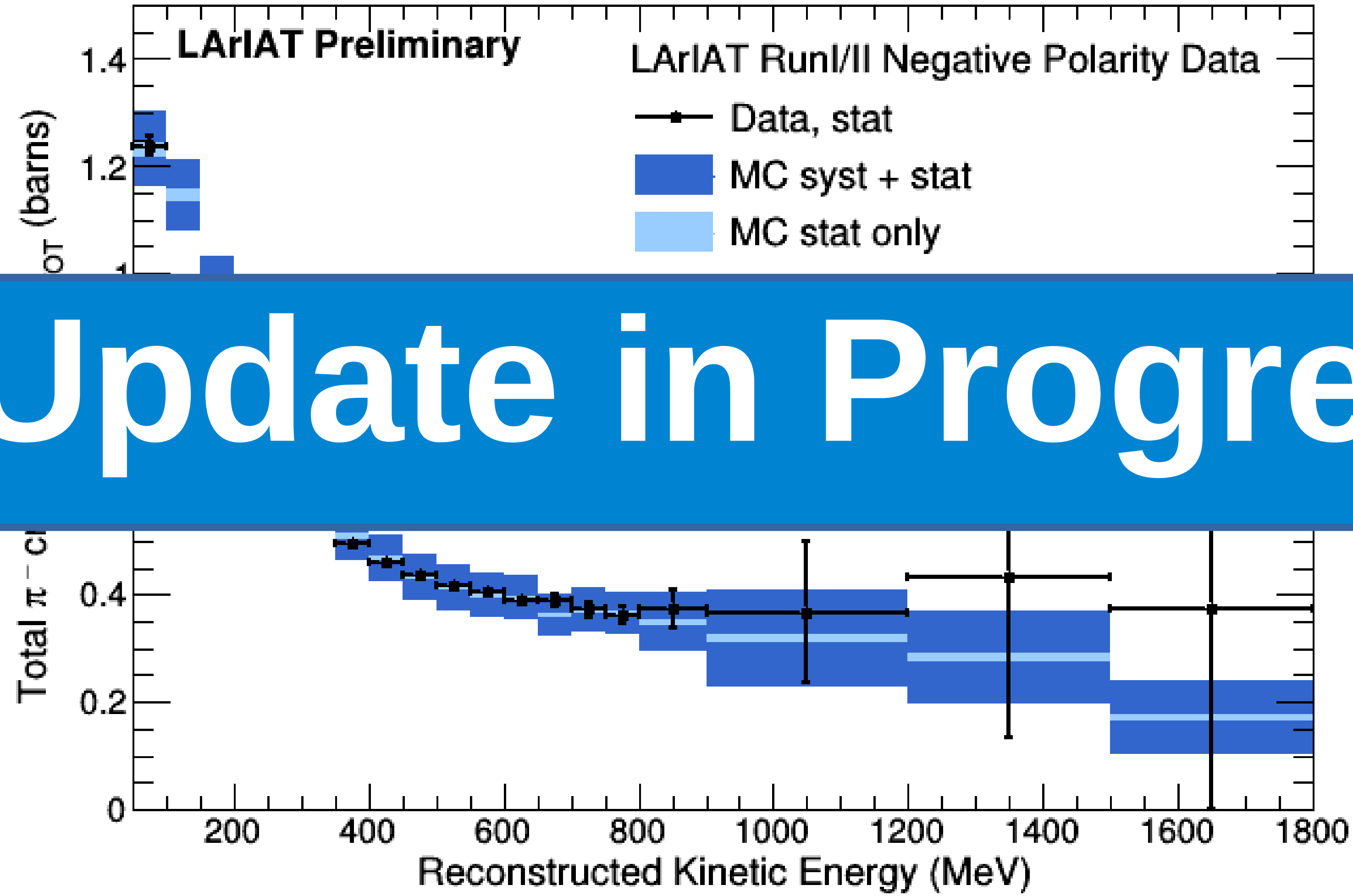
dE/dX Calibration: 3%

Energy Loss Prior to entering the TPC: 3.5%

Through Going Muon Contamination: 3%

Wire Chamber Momentum Uncertainty: 3%

Pion Cross-Section



Update in Progress

<u>Systematics Considered Here</u>

dE/dX Calibration: 3%

Energy Loss Prior to entering the TPC: 3.5%

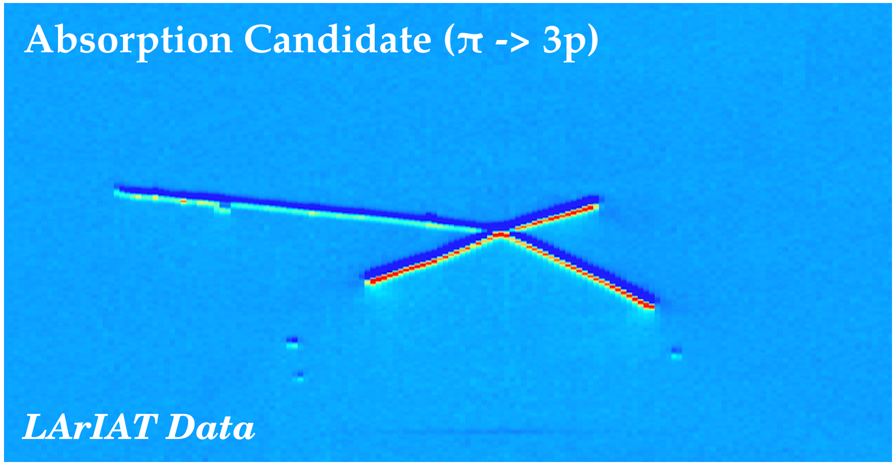
Through Going Muon Contamination: 3%

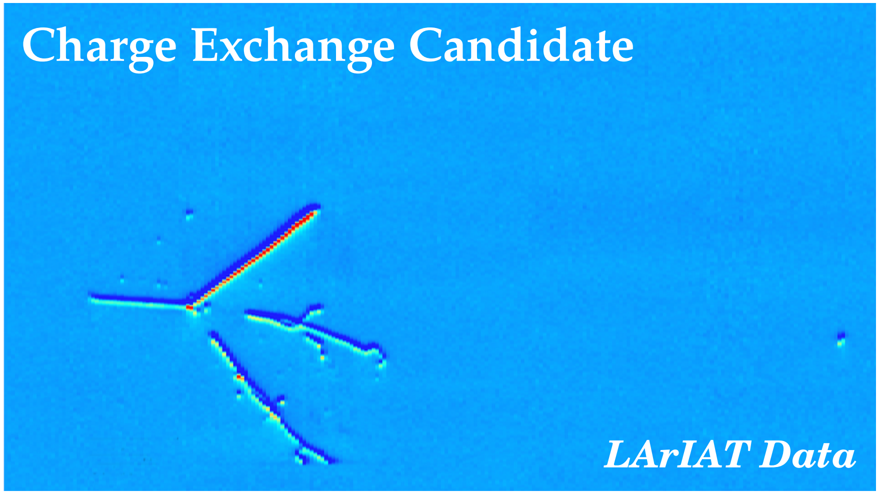
Wire Chamber Momentum Uncertainty: 3%

Toward Exclusive Pion Channels

Signal Events:

0 Secondary $\pi^{\pm}$





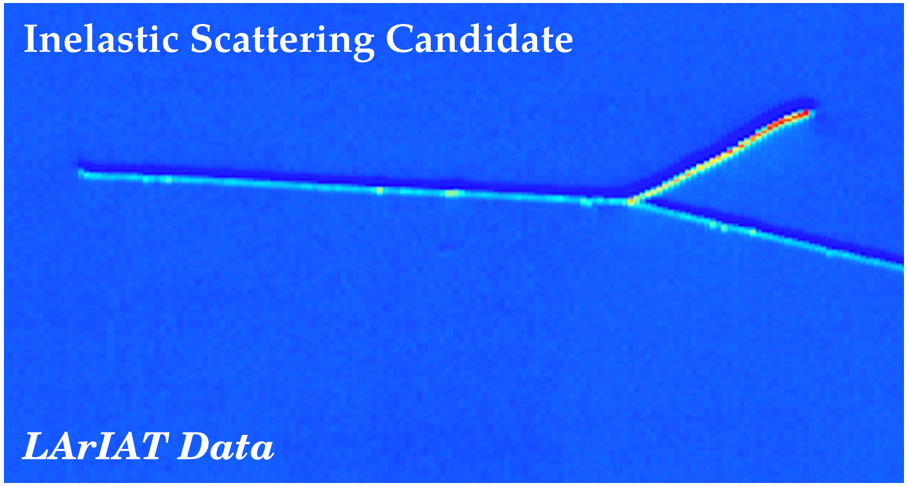
- **Working on absorption + charge exchange:**

  π^{+} + Ar → $0\pi^{\pm}$ + X

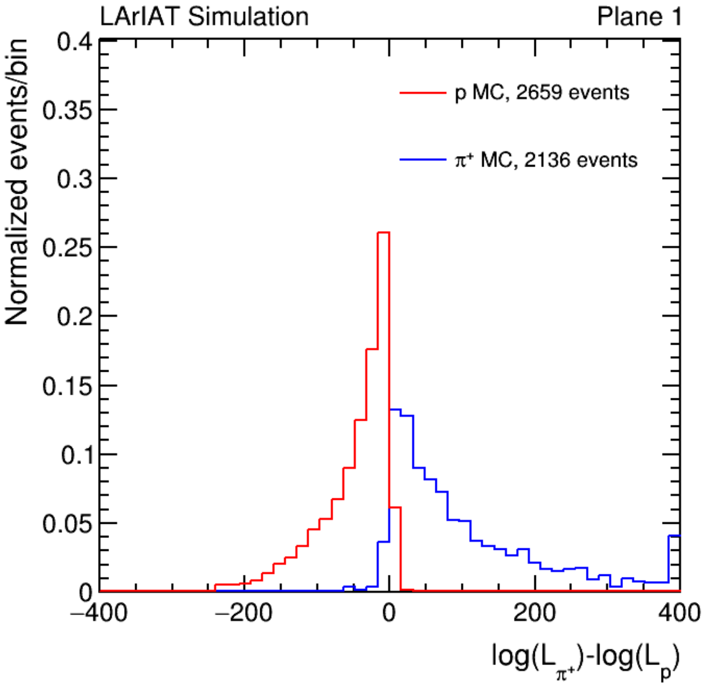
  - Useful for modeling contamination of ν CC QE from CC RES
  - Need to identify outgoing pions v. protons

Background Events:

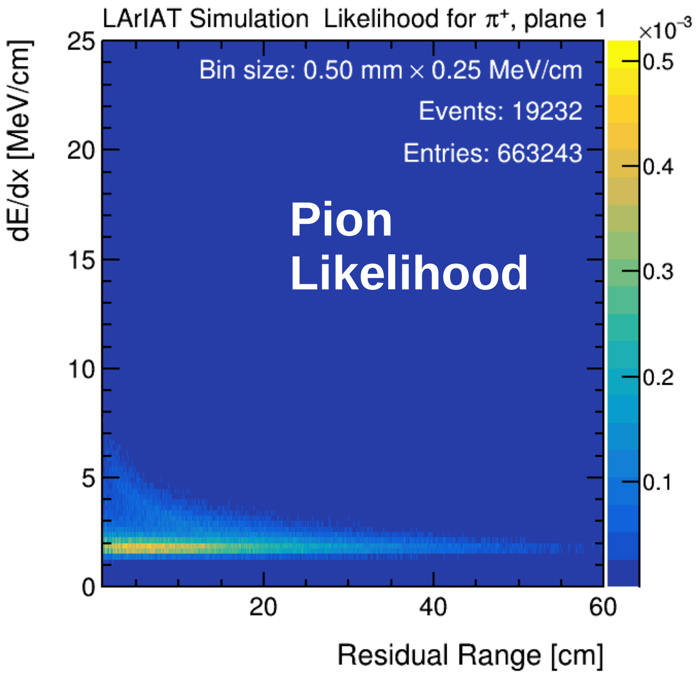
Contain Secondary $\pi^{\pm}$

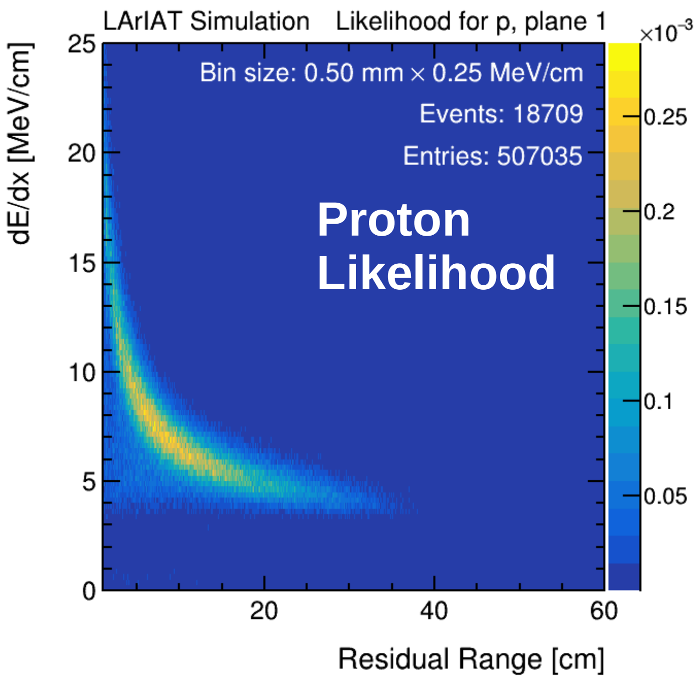


Likelihood-Based Particle ID

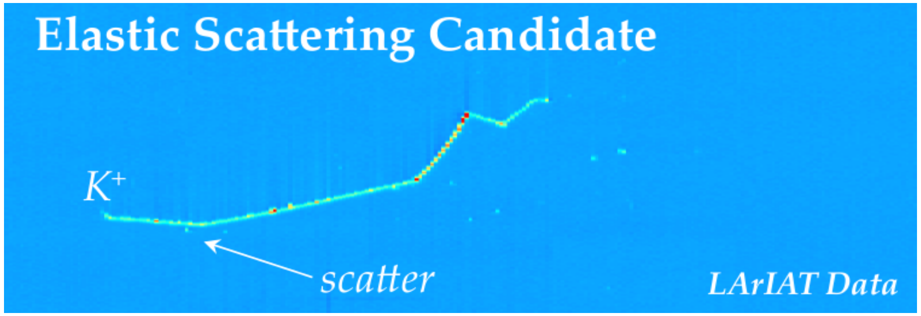


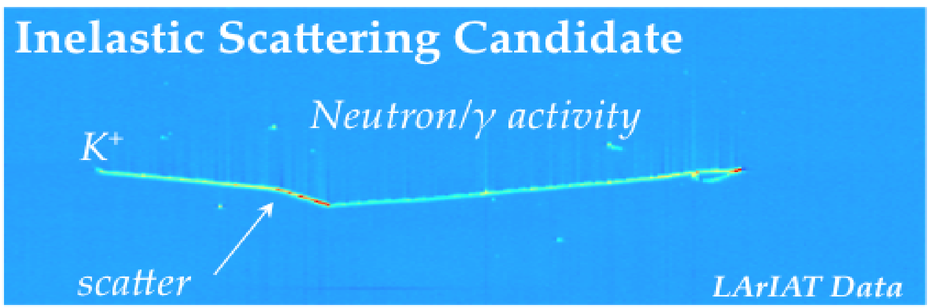
- **Likelihood of dE/dx versus residual range of each track hit**
  - Constructed from simulated tracks
  - Evaluate using likelihood-ratio of all hits on a track

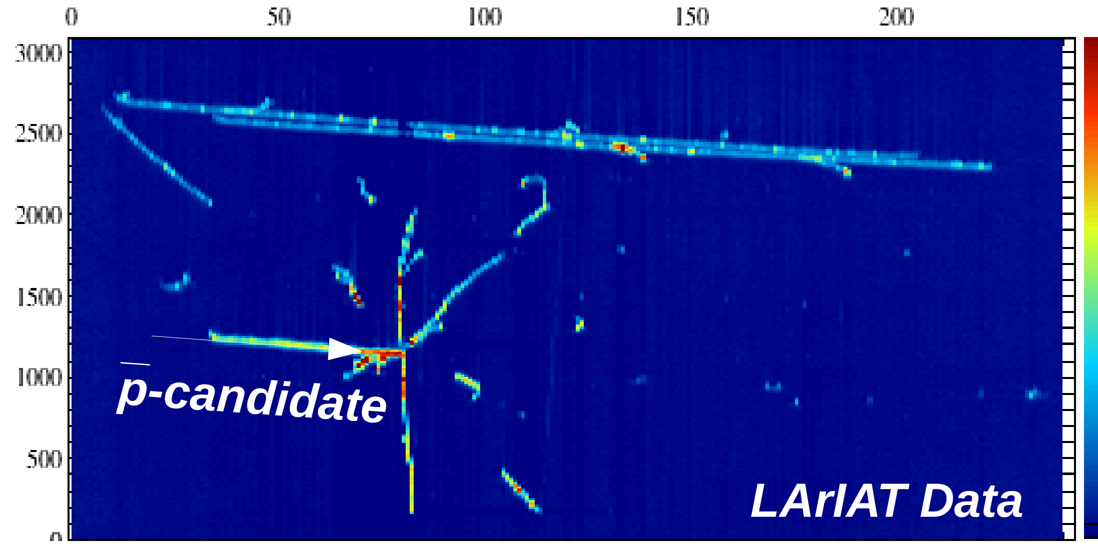




Kaon Cross-section & Anti-proton Anihilation at Rest







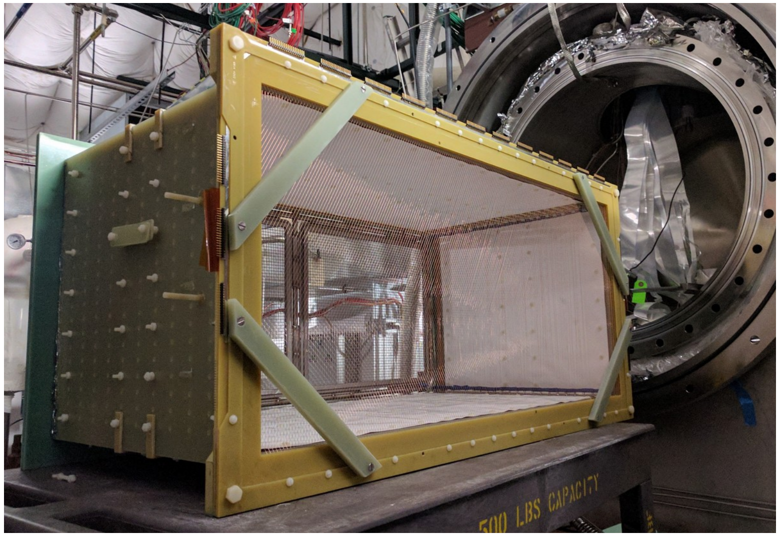
- **Inclusive K+ cross-section has $\mathcal{O}(2000)$ Elastic/Inelastic interactions identified**
  - Inclusive cross-section coming soon
    - First time measured on argon
- **DUNE plans search for proton decay:**

  $p \to K^+ \bar{\nu}$
- **Cross-section information will help ensure signal efficiency is modeled properly**

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

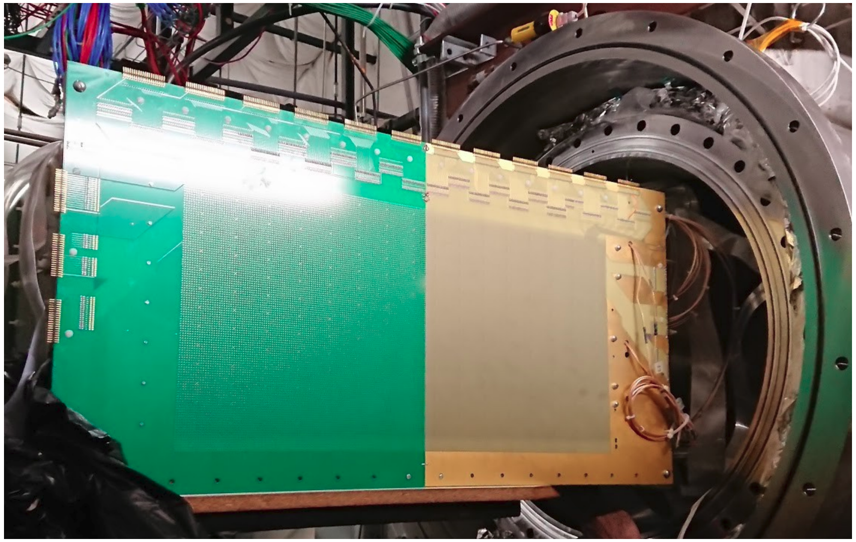
PixLAr & Detector R&D

LArIAT → Wires

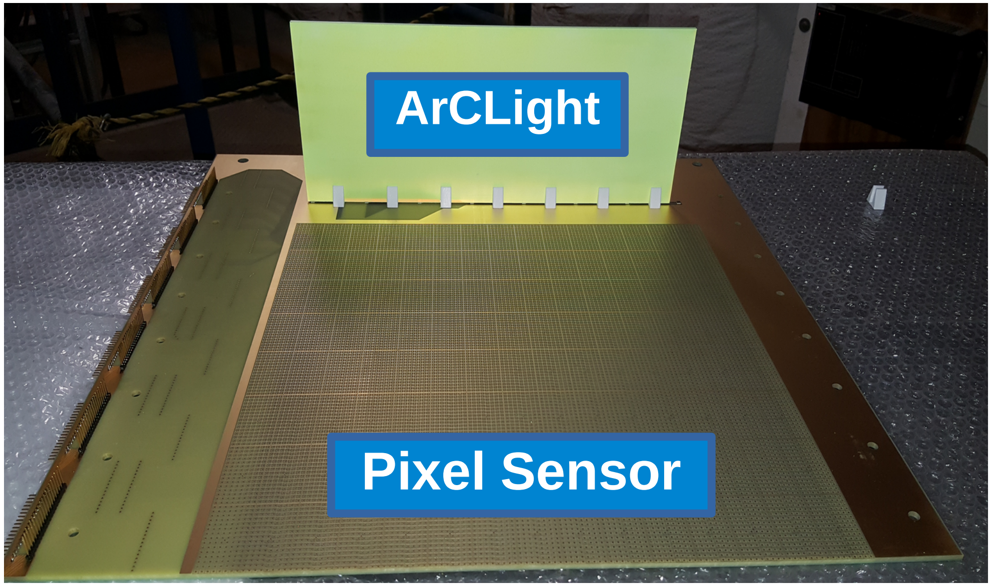


- **LArIAT ran with few different wire spacings and light detector configurations**
  - Run-I / Run-II: 4mm wire pitch
    - Hadronic cross-sections
    - Scintillation Light R&D
  - Run-III: 3mm / 5mm wire pitch comparison
    - LArTPC particle ID R&D
    - New mesh cathode (for SBND)
    - New ARAPUCA Light Detection System

PixLAr → Pixels

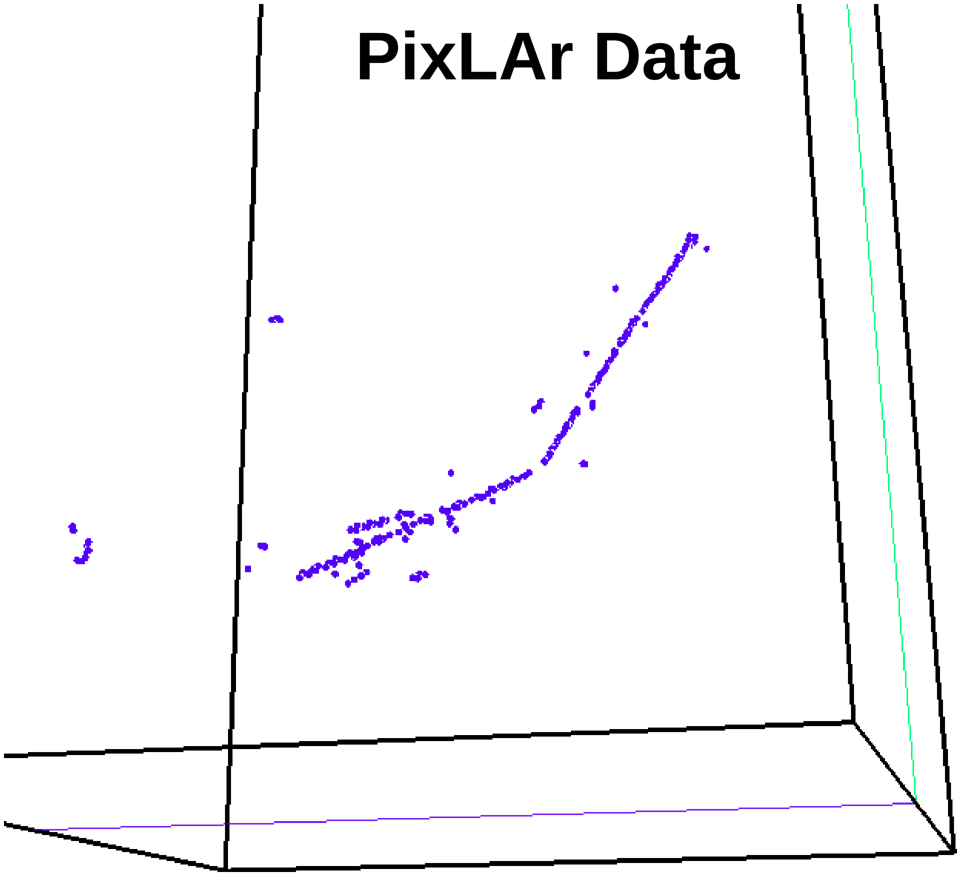


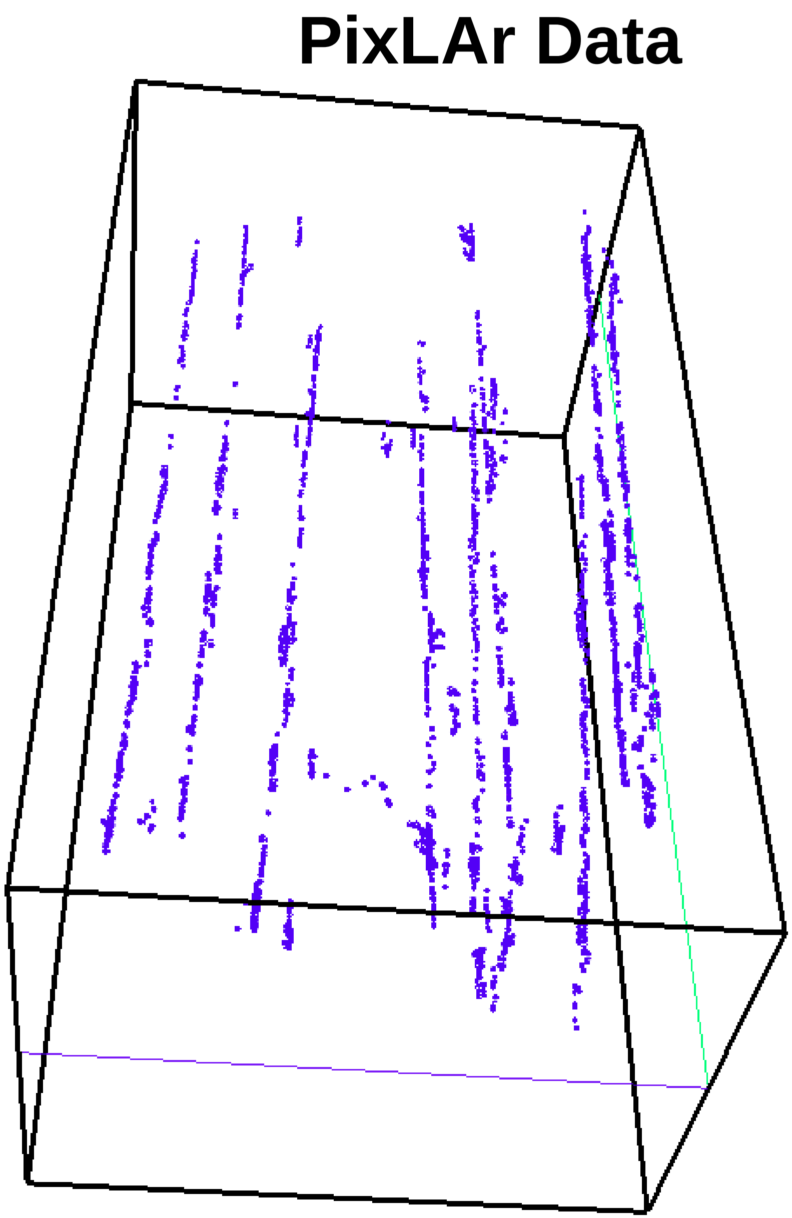
PixLAr Readout Plane



PixLAr Data

- PixLAr event displays demonstrate pixel readout
- PixLAr ganged-pixel readout worked even with high particle multiplicity





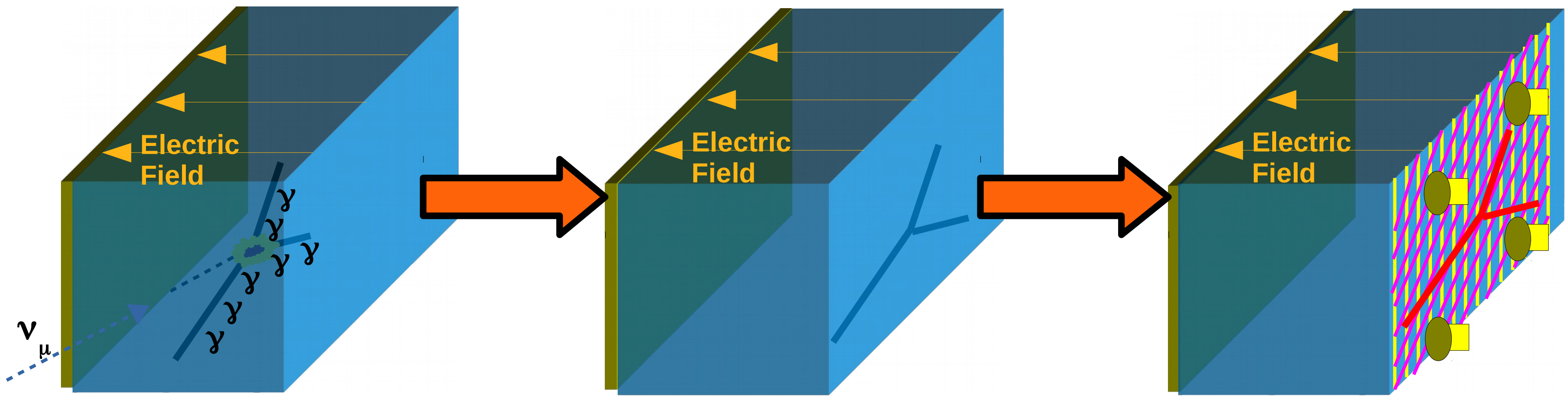
Conclusions

- **FTBF busy with:**
  - **LHC upgrades**
  - **sPHENIC/EIC upgrades**
  - **Veriety of neutrino programs**
  - **Generic detector R&D**
- **FTBF has many instruments available to users**
- **LArIAT working on many physics results**
  - **Inclusive cross-sections for π- K+ and exclusive cross-sections**
- **LArIAT & PixLAr working on detector results**
  - **3mm/4mm/5mm wires and pixel reconstruction**
  - **Scintillation light collection with PMTs, SiPMs, ARAPUCA, ArCLight detectors**

Thank you!

Backup Slides

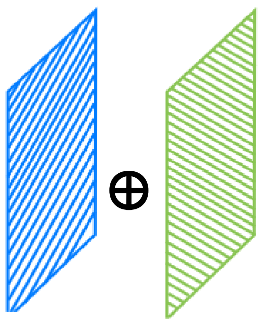
Liquid Argon Time Projection Chamber



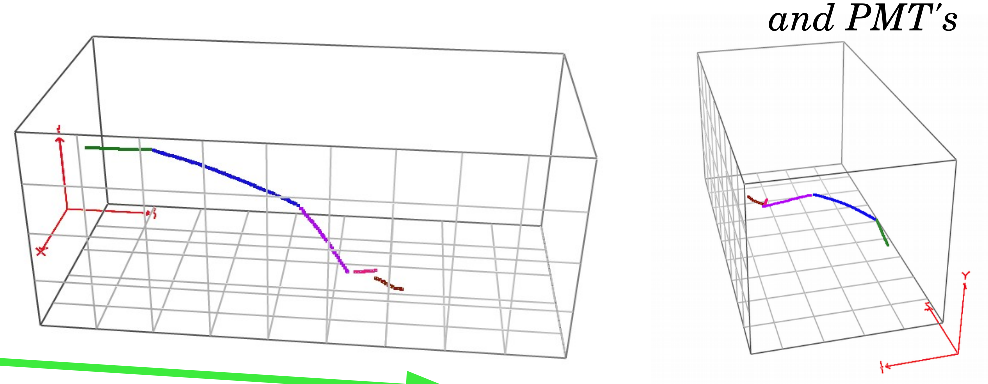
Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

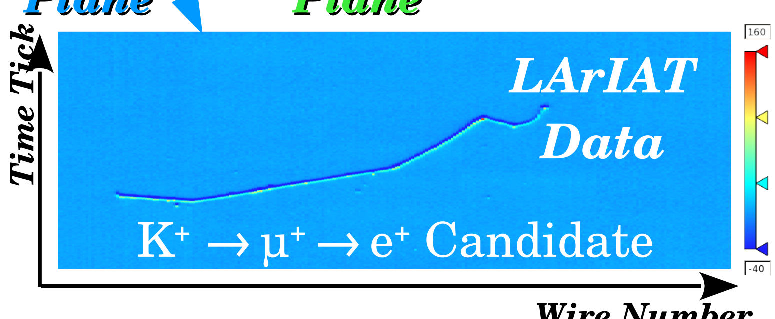
Read out charge and light produced using precision wires and PMT's

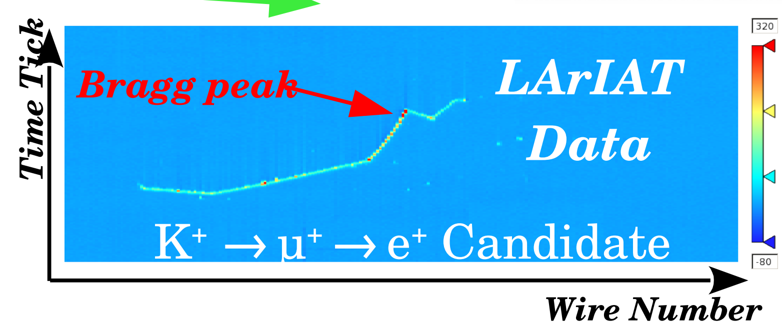


⊕ ⊕ ***Drift Time*** =



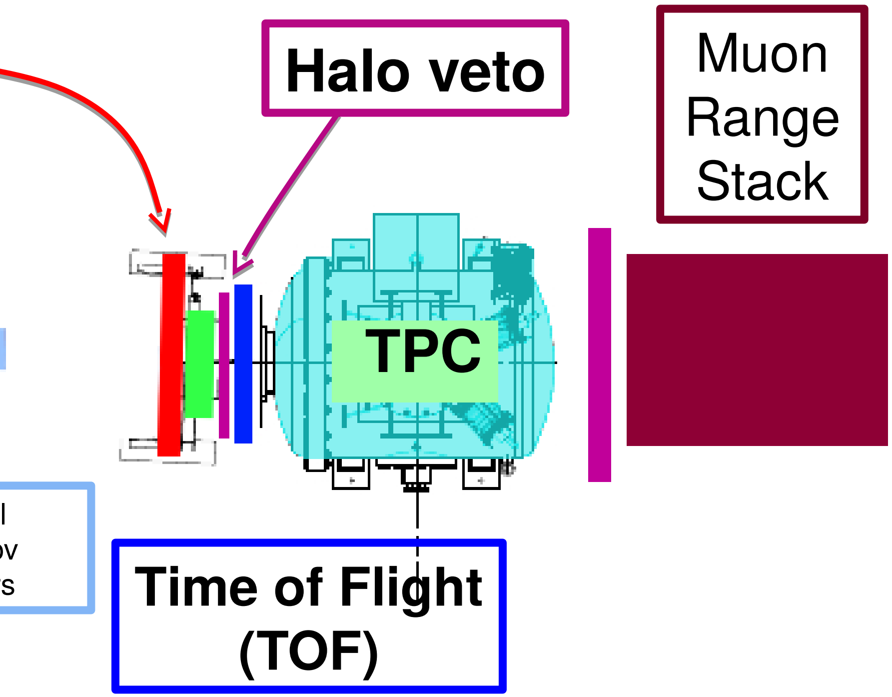
Induction Plane ***Collection Plane***



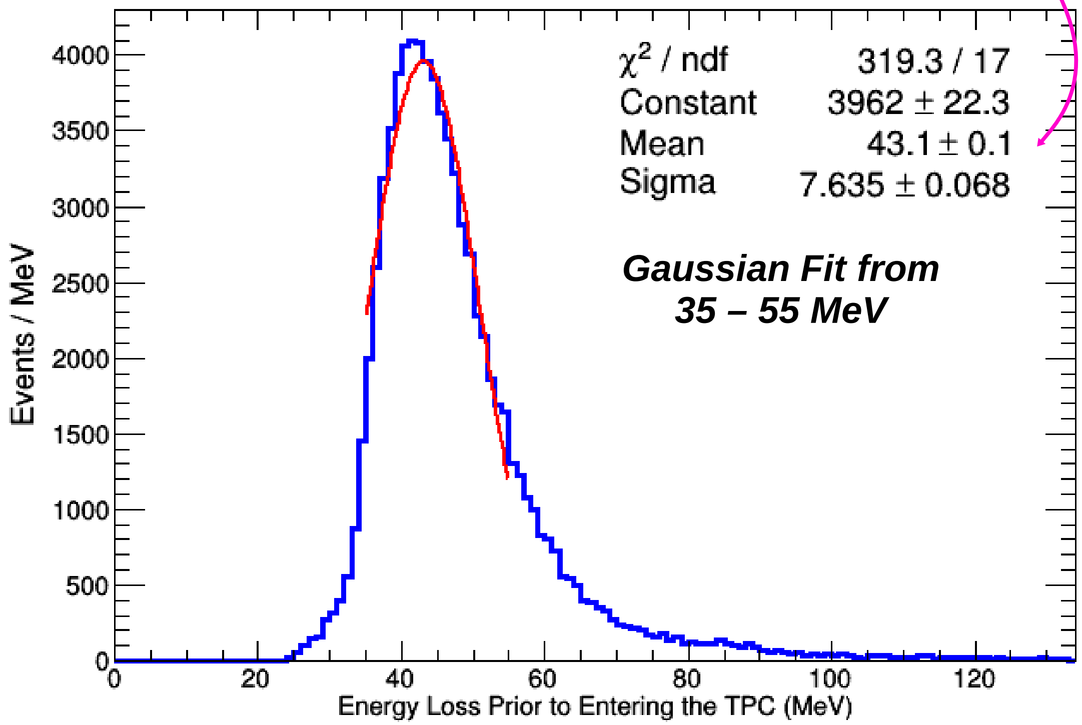


- ✔ ***3D imaging with mm space resolution***
- ✔ ***Calorimetry information***
- ✔ ***PID capabilities***

Energy Corrections

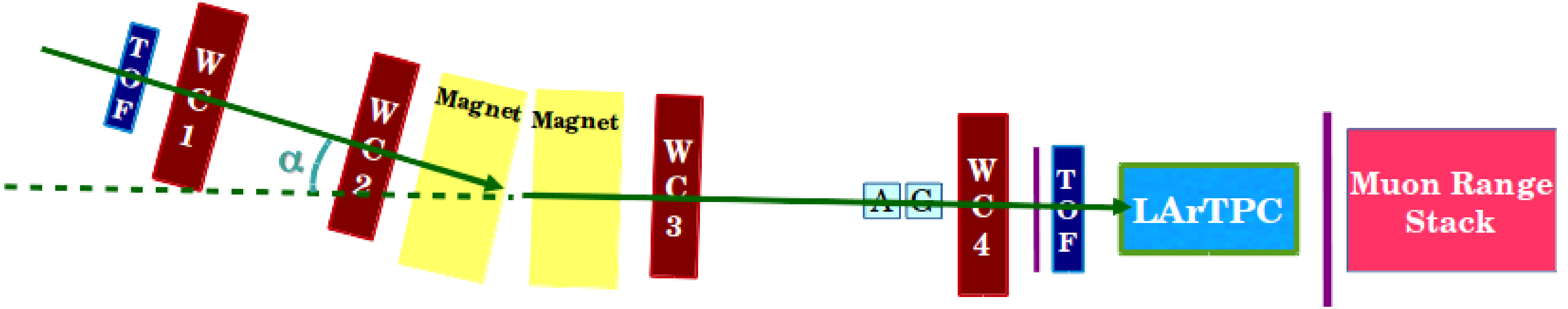


$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{Flat}$$

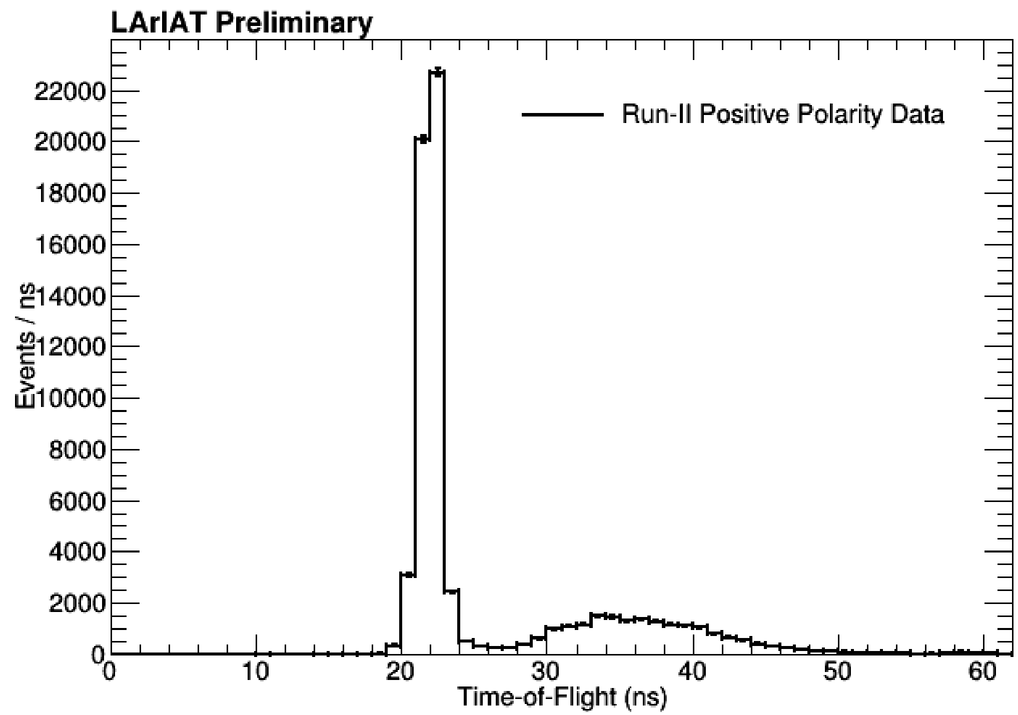


- Adding up all the energy which a pion loses in the region before it enters the TPC (**TOF**, **Halo**, **Cryostat**, **Argon**) gives us the "energy loss" by the pion in the upstream region

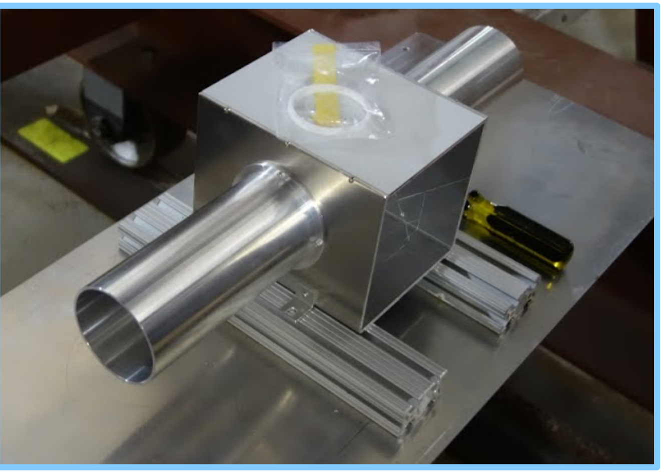
LArIAT Beamline: Time of Flight

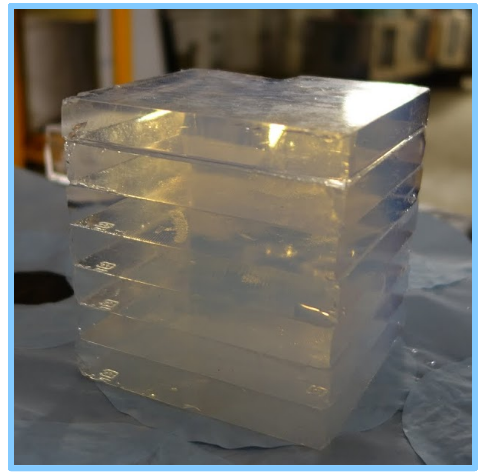


2 scintillator counters w/ ~1ns sampling, provide the time of flight (TOF)



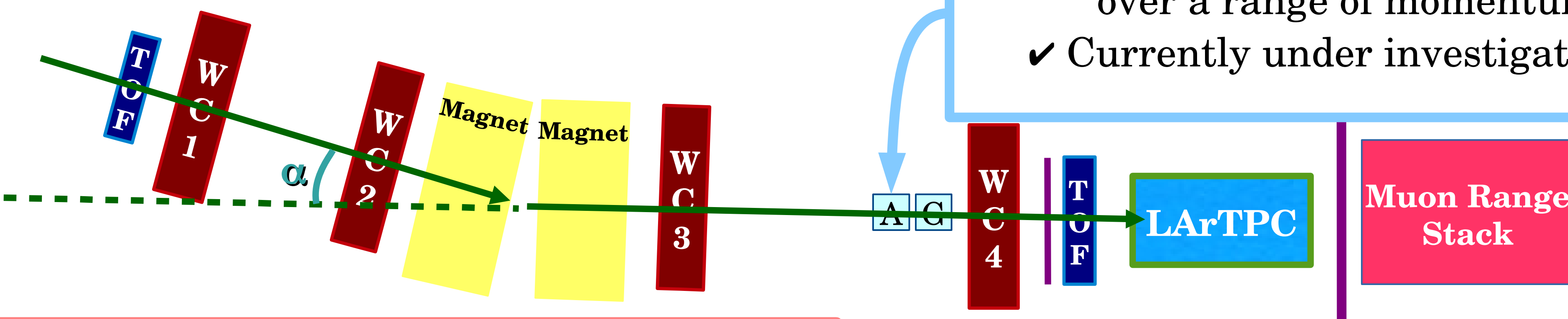
LArIAT Beamline Detectors





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

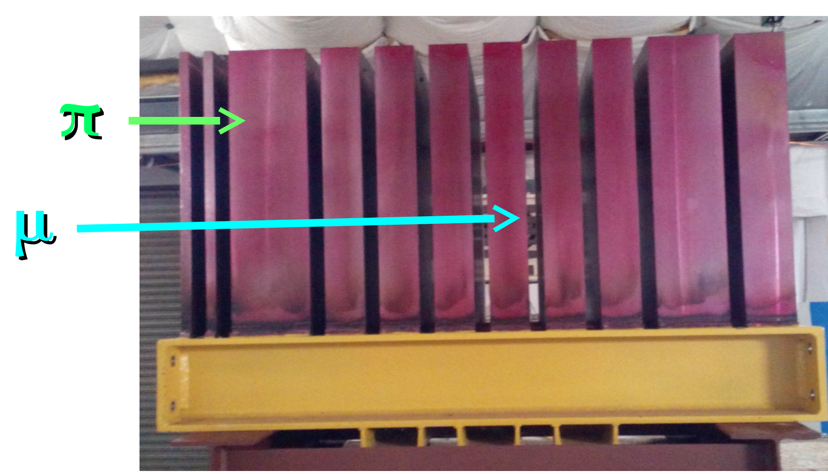
✔ Allows to perform π/μ separation over a range of momentum
✔ Currently under investigation



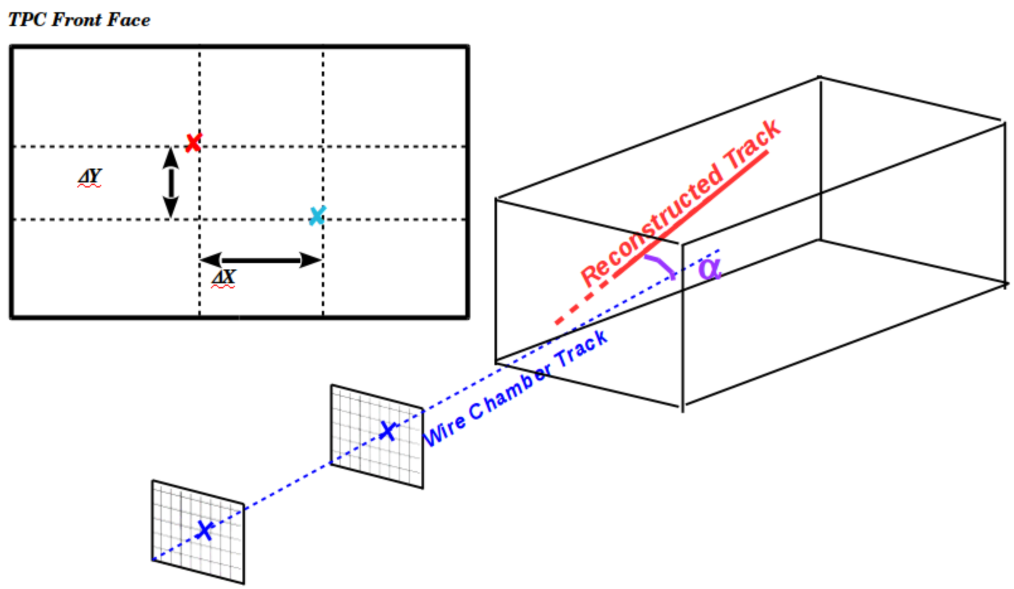
✔ Four layers of XY planes sandwiched between (pink) steel slabs

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

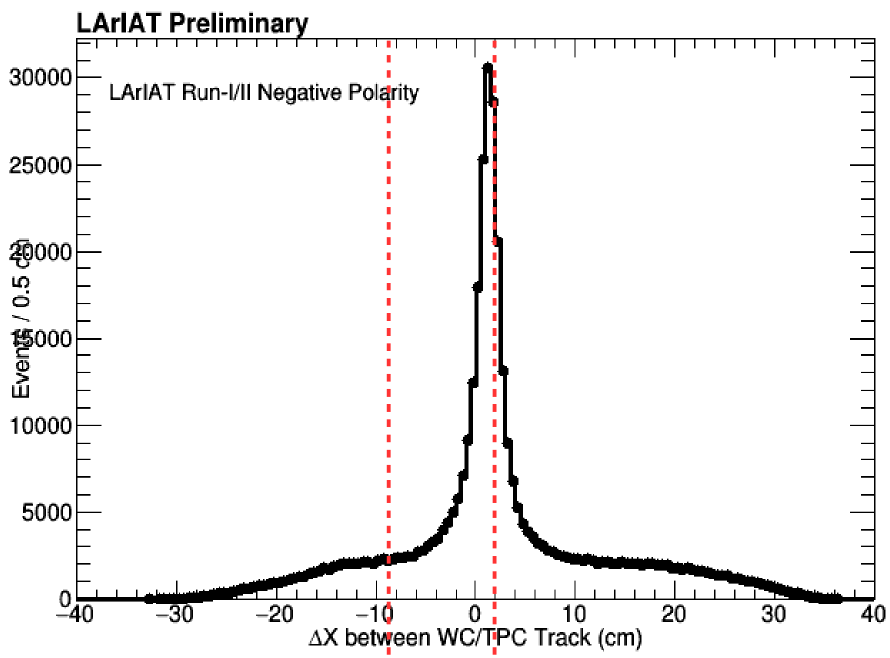
✔ Allows to discriminate π/μ exiting the cryostat
✔ Currently under investigation

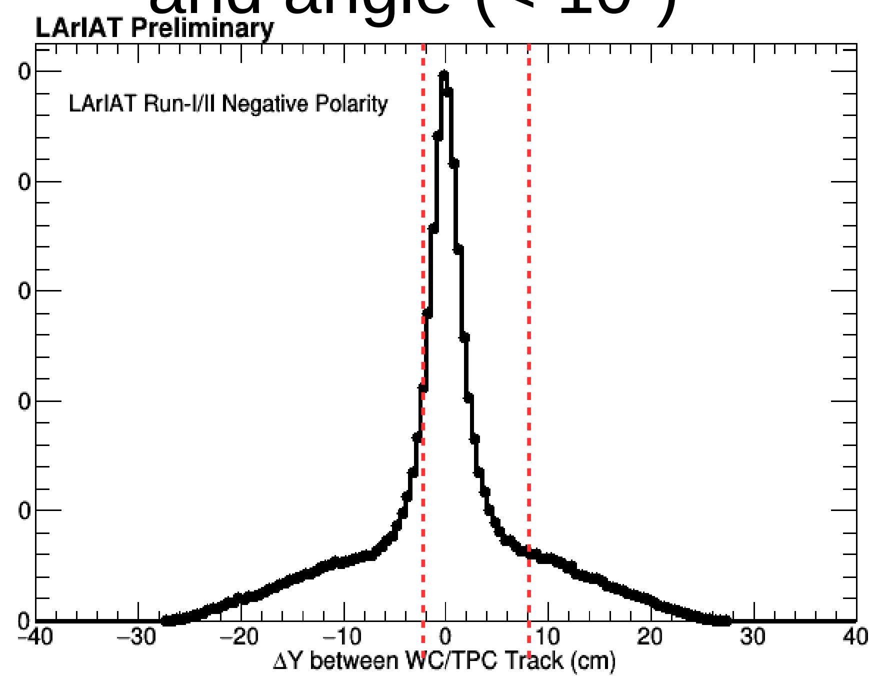


Matching Beamline to the TPC

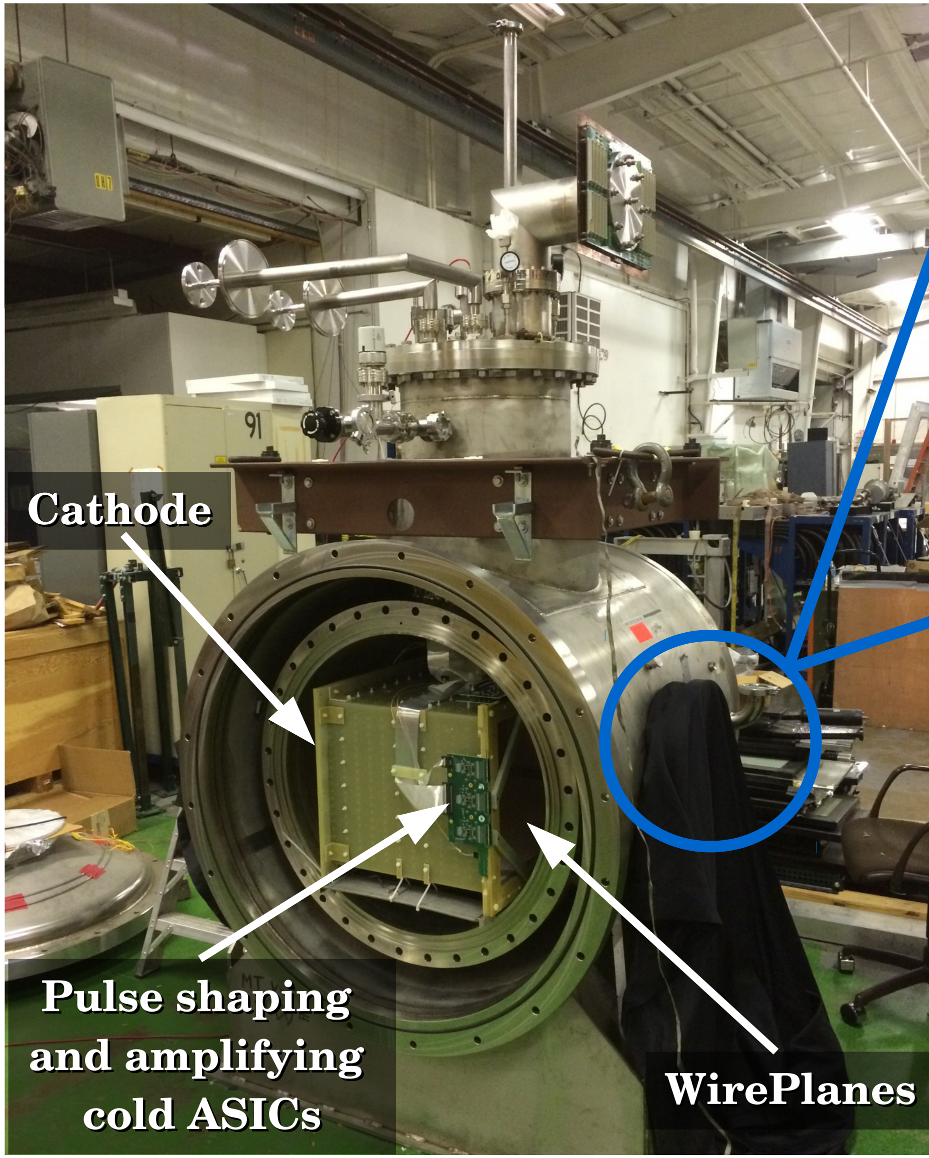


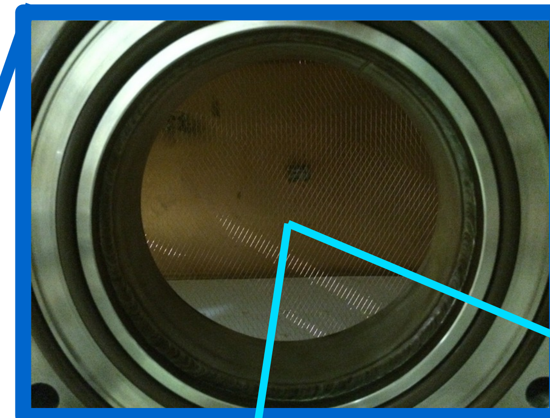
- **We can take this track reconstructed in the beamline and extrapolate it to the LArTPC and look for a match**
  - We match in both position (+/- 5cm about the mean) and angle (< 10^{o})



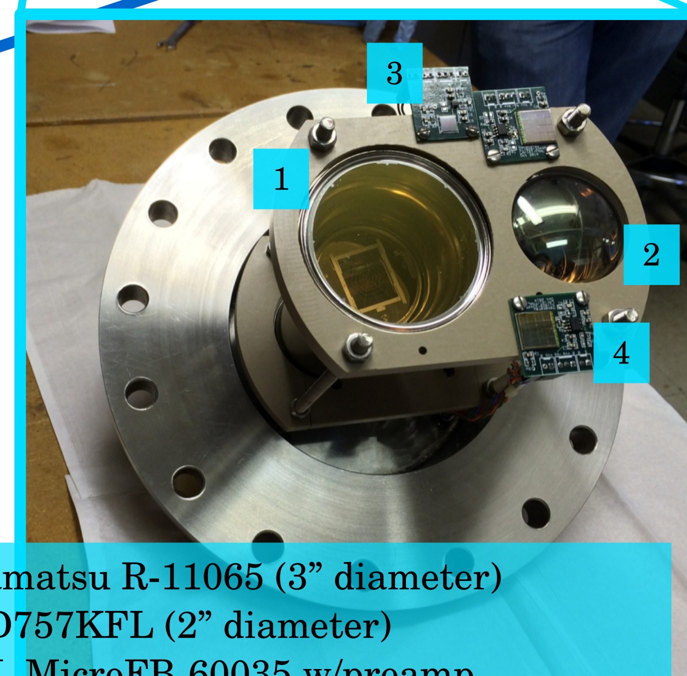


Inside the cryostat: TPC and light collection system



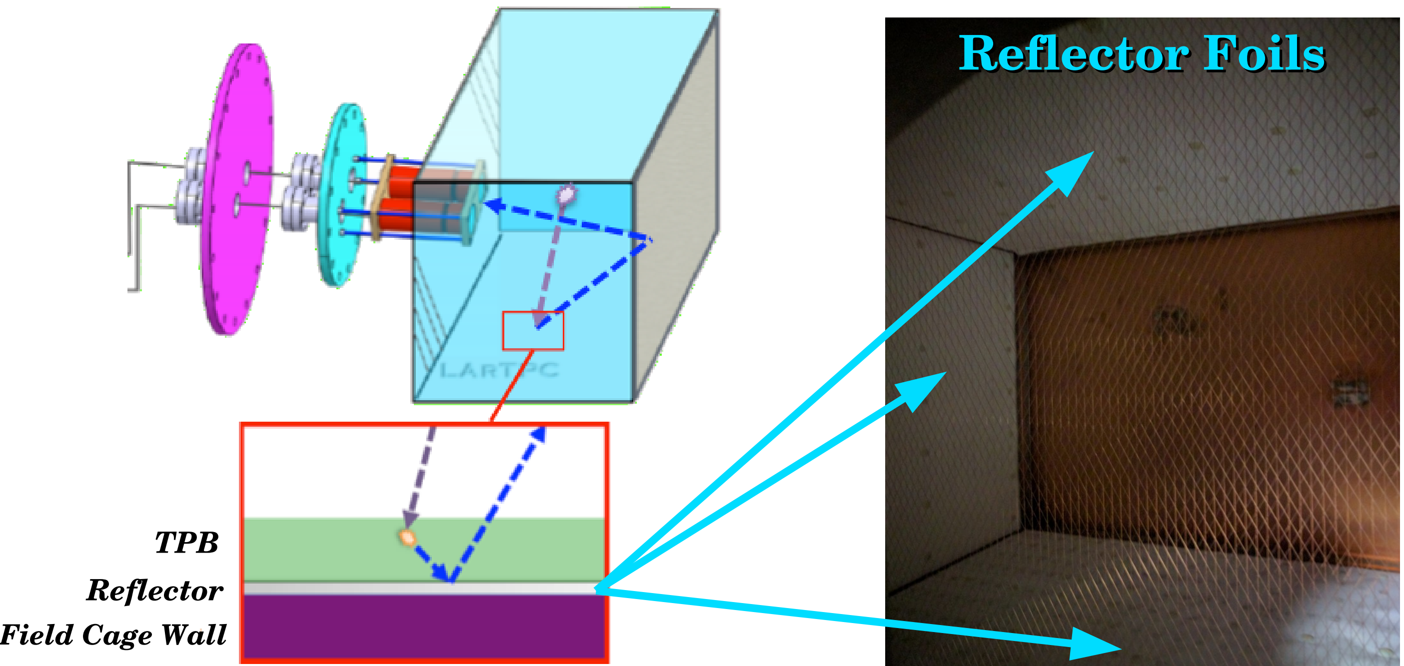


Light Collection System port

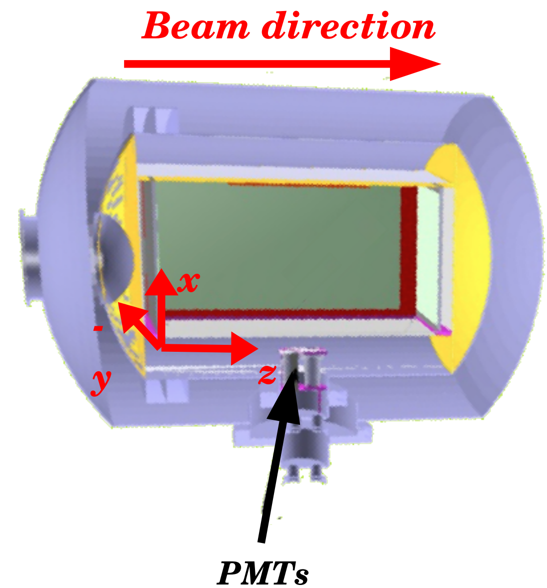


1. PMT: Hamamatsu R-11065 (3” diameter)
2. PMT: ETL D757KFL (2” diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (Run I)
   SiPM: Hmm. VUV-sensitive (Run II)

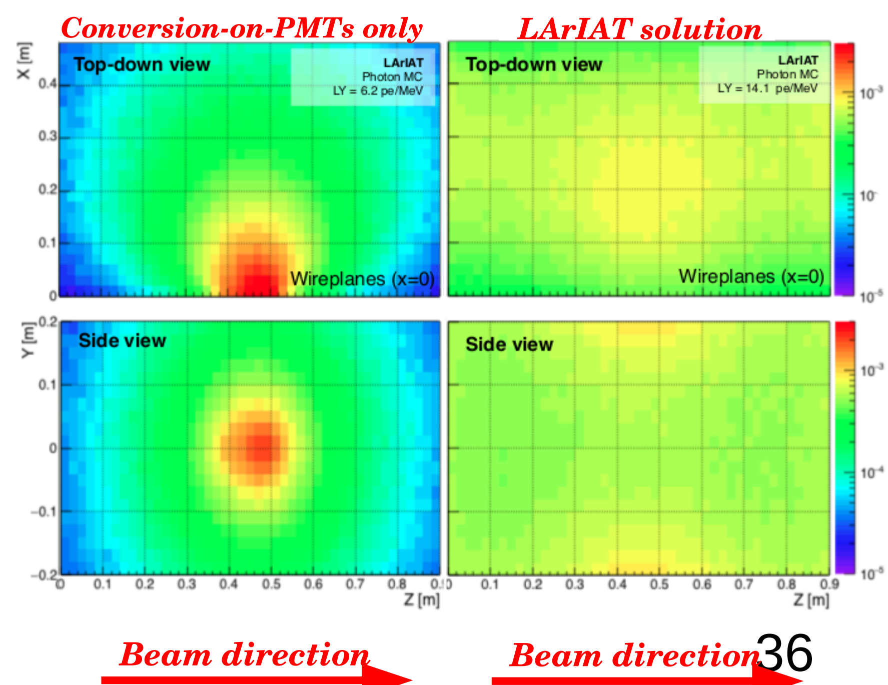
Light Collection System



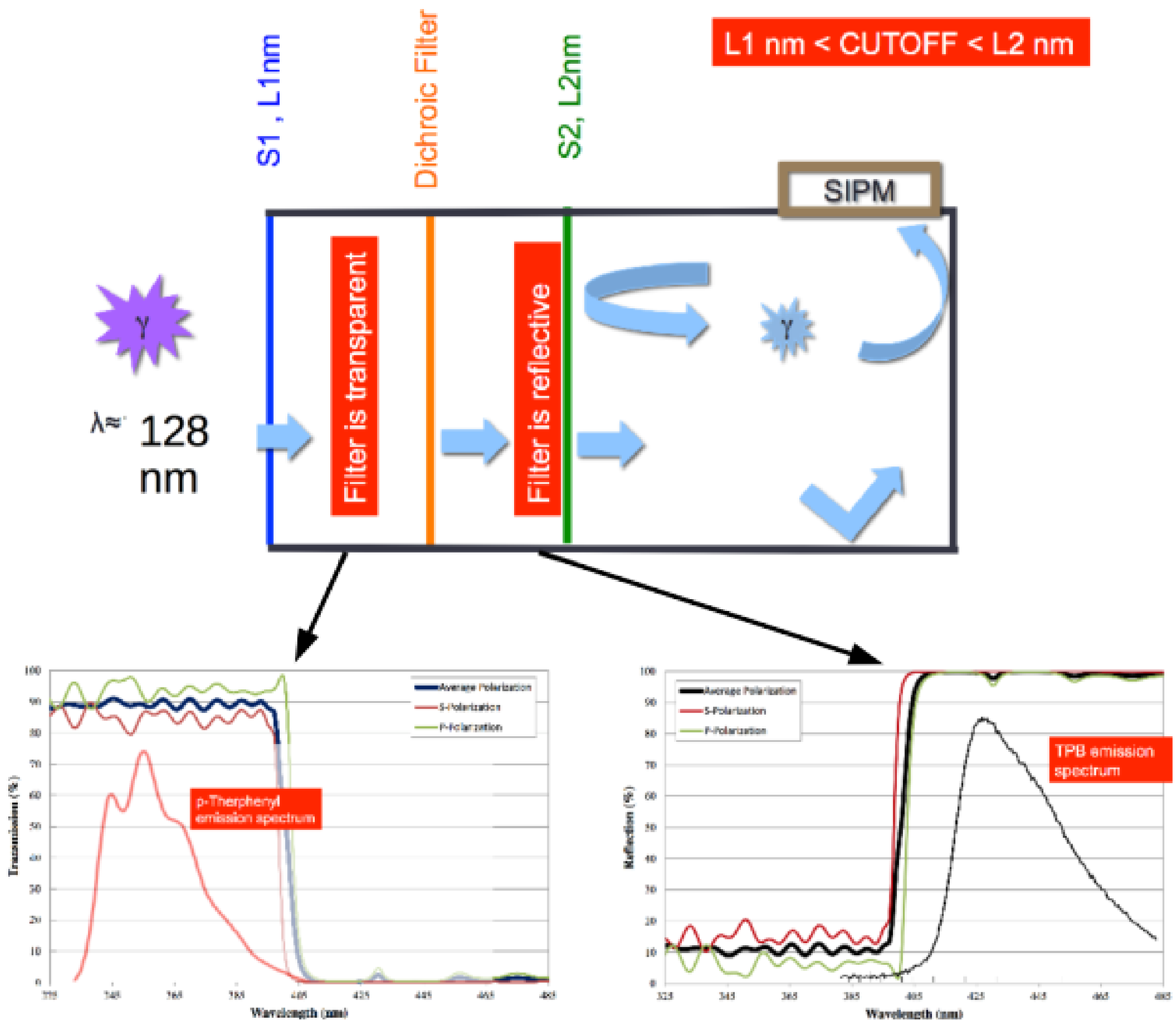
Credit: W. Foreman

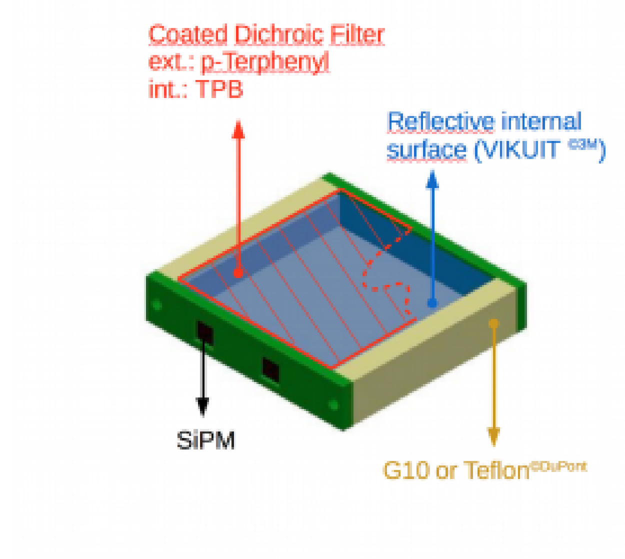


- **Wavelength shifting (evaporated) reflected foils on the four field cage walls**
  - *Technique borrowed from dark matter experiments*
- **Provides greater (~ 40 pe/MeV at zero field) and more uniform light yield respect to "conversion-on-PMTs-only" light systems**
- **R&D for future neutrino experiments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



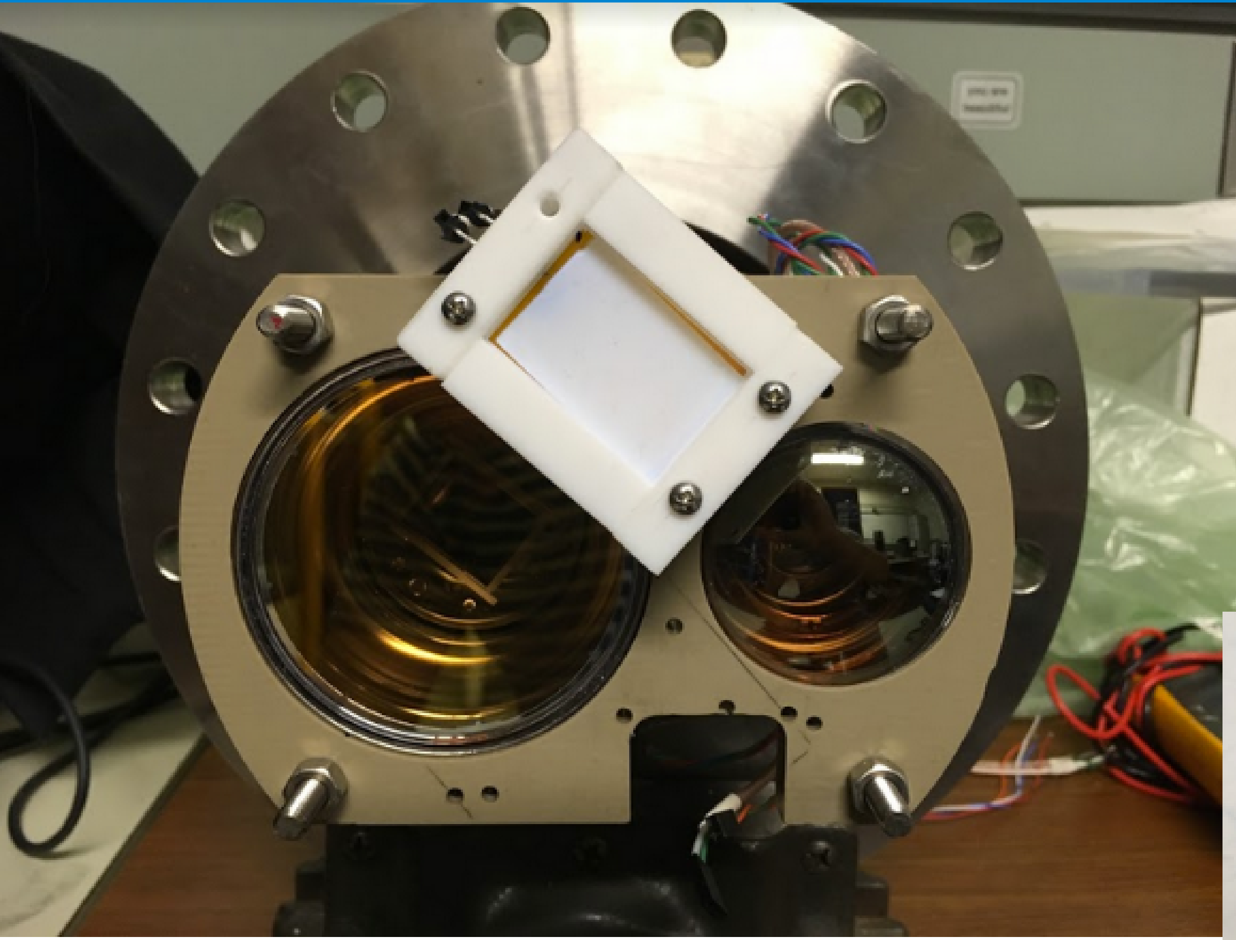
New ARAPUCA Light Collection System



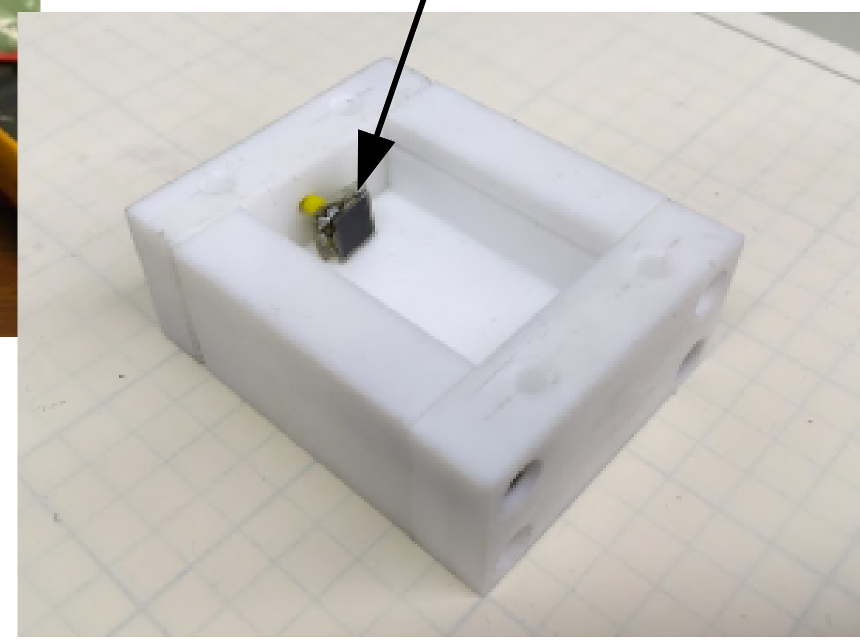


- **Dichoric filter + wavelength shifter**
  - Trap light inside device
- **Inner walls made of Teflon**
  - Trapped light reflected until detected by SiPM

New ARAPUCA Light Collection System



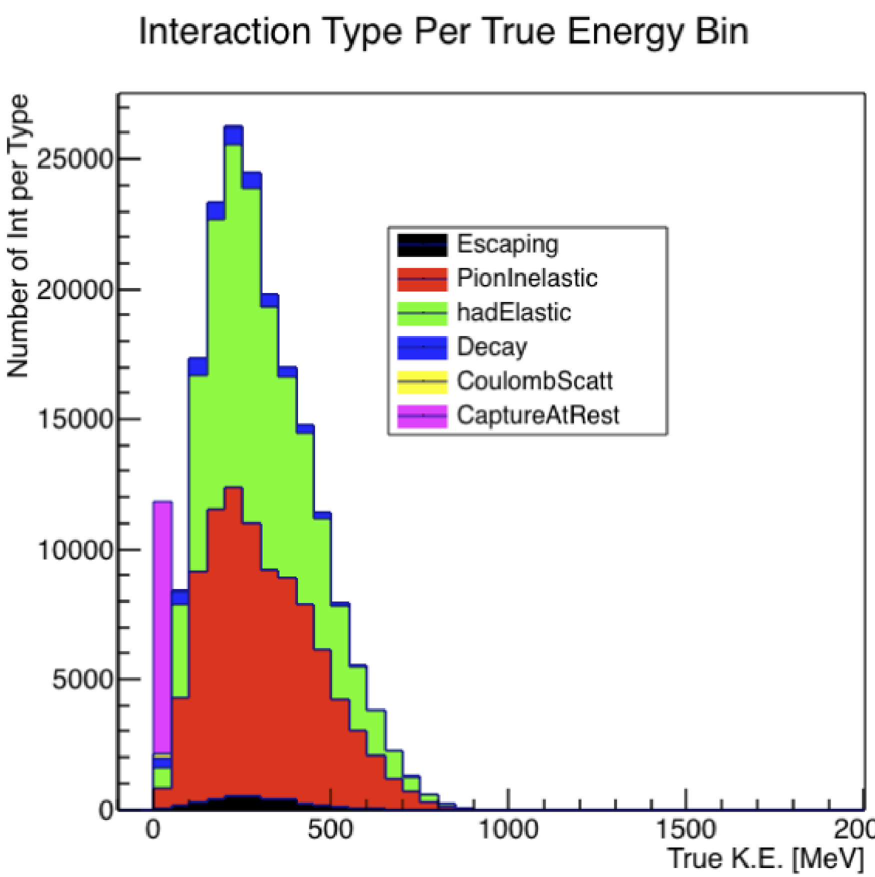
2x Ganged SiPM

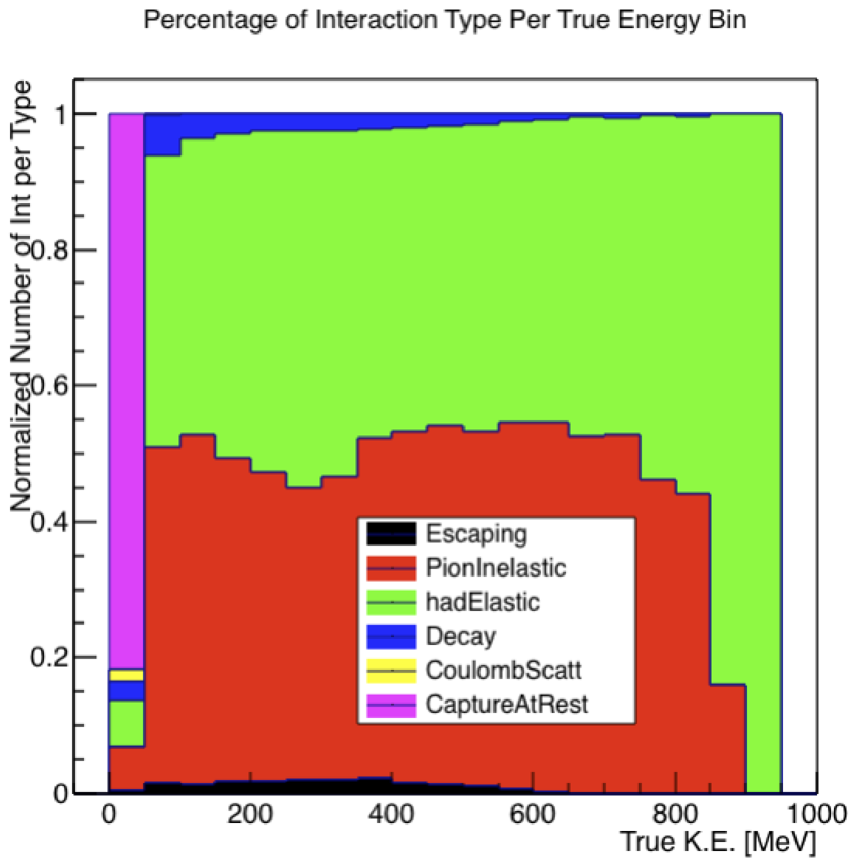


- **ARAPUCA mounted near existing PMTs**
  - Compare ARAPUCA performance to PMTs

Cross-Section

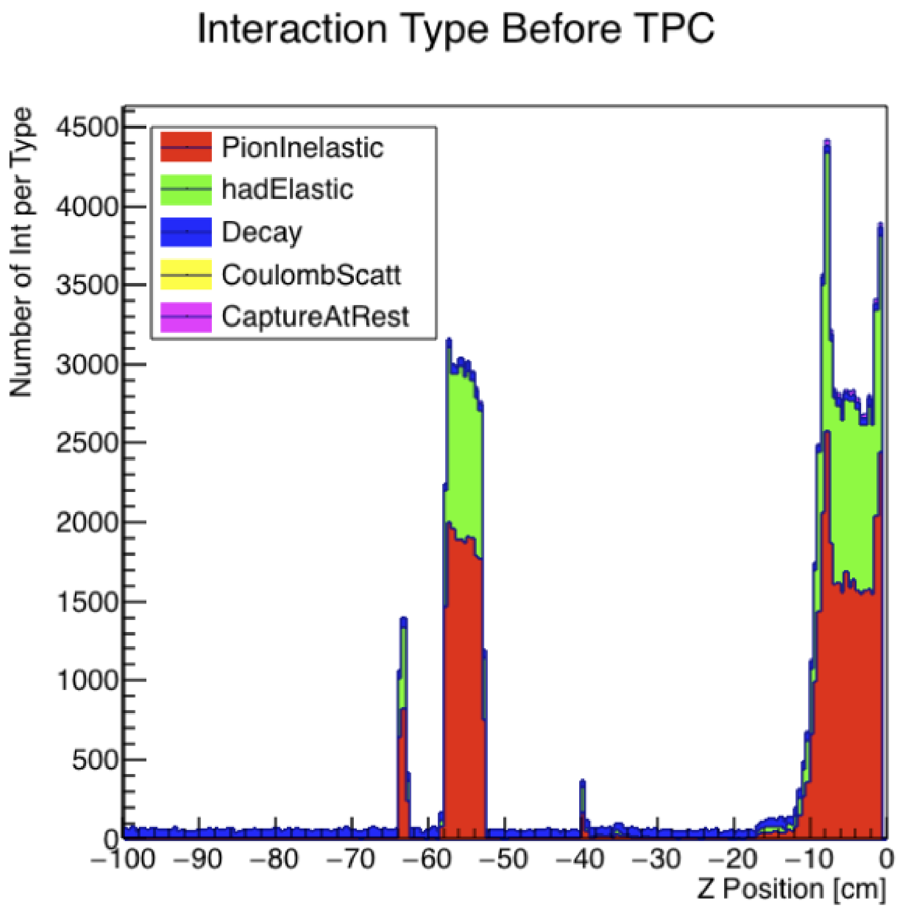
- **We begin by looking at the bin content of the cross-section from MC**
  - Here we show events / 50 MeV bin to mimic the binning used in the data
  - Plot the true kinetic energy
- **Pion captrure-at-rest dominate in the lowest energy bin (0 MeV < KE < 50 MeV)**
  - Constitutes ~80% of the interactions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

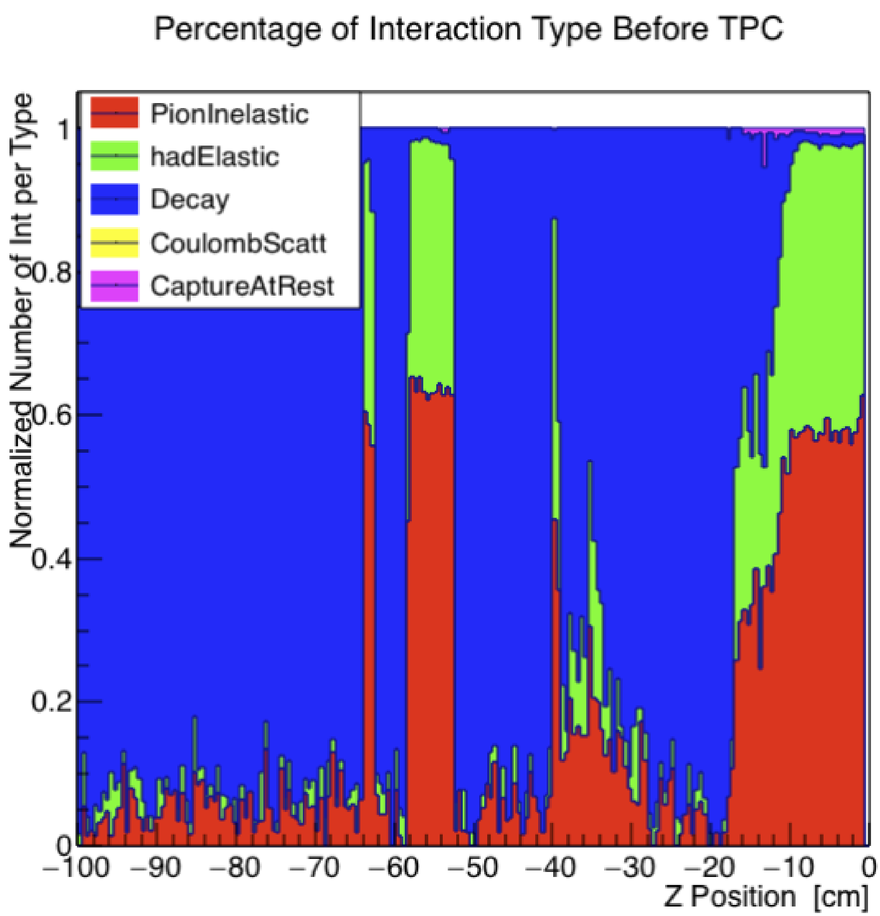




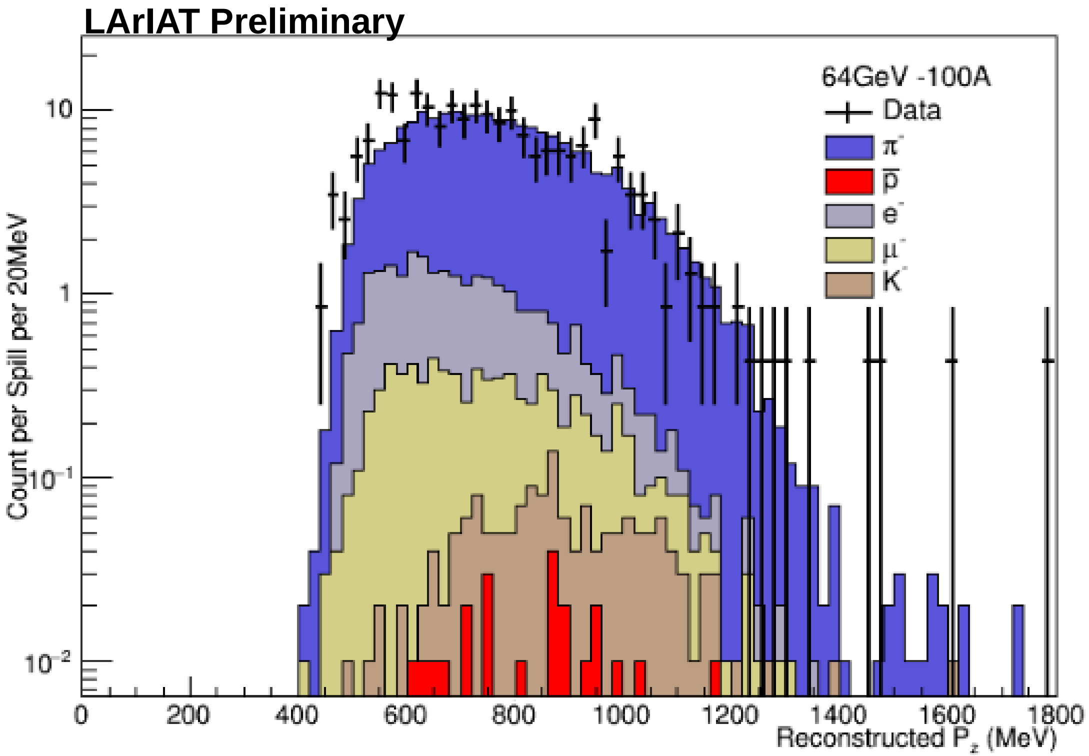
What happens in the upstream

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





Pion Event Selection



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

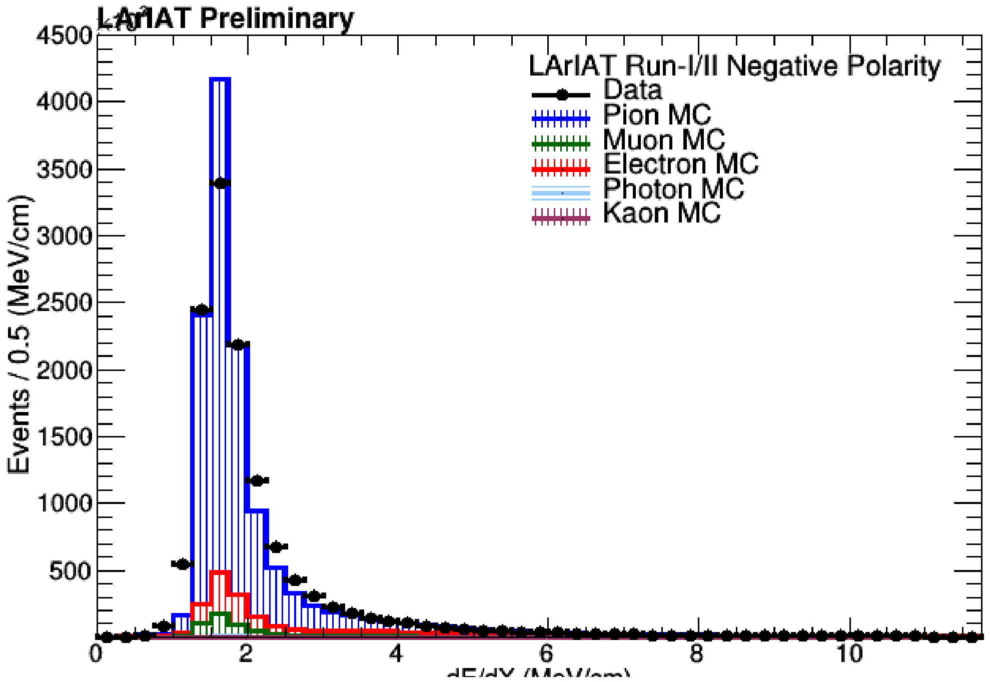
	π^-	e^-	γ	μ^-	K^-	$\overline{p}$
Beam Composition (%)	48.4	40.9	8.5	2.2	0.035	0.007

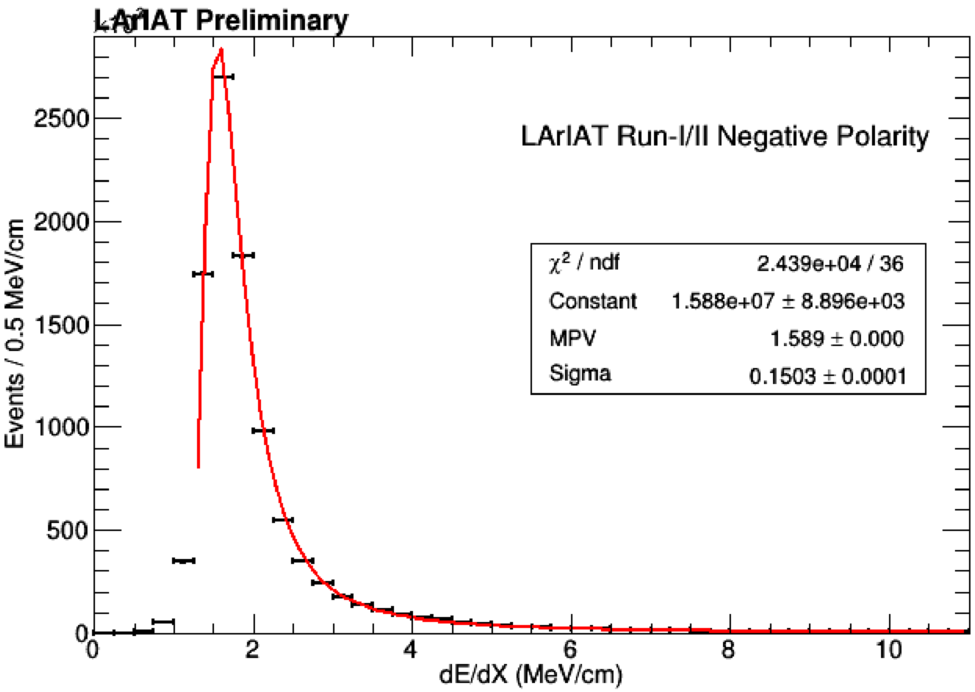
Table 1: Beam Composition - Negative polarity configuration (from MC)

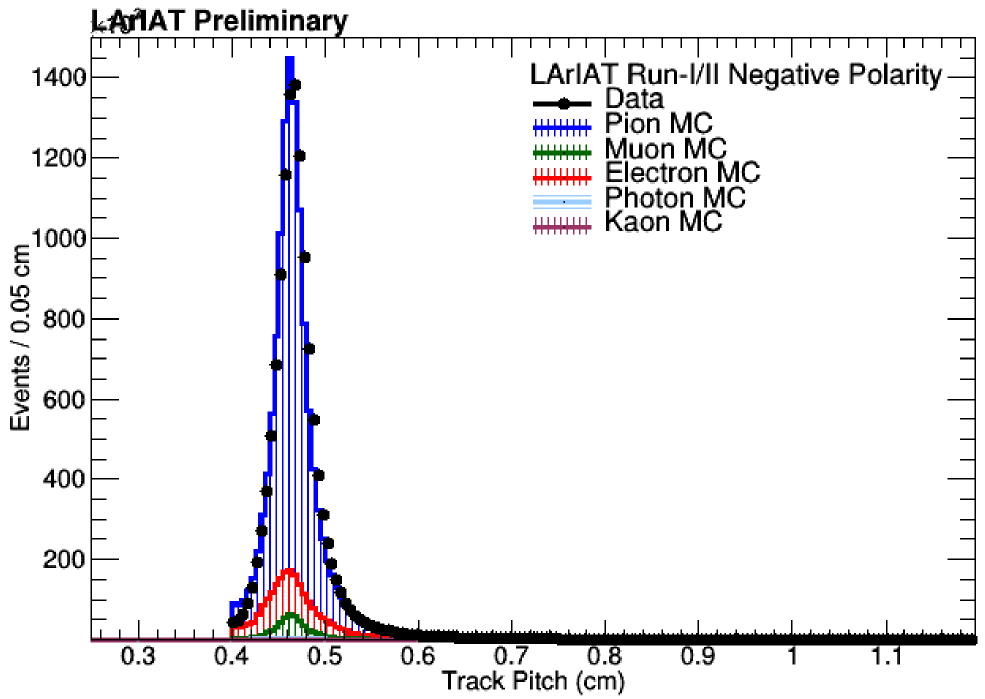
	π^- MC	e^- MC	γ MC	μ^- MC	K^- MC
Percent of events passing cut	73.5%	14.2 %	2.3%	73.4%	70.6%

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

Validation Plots

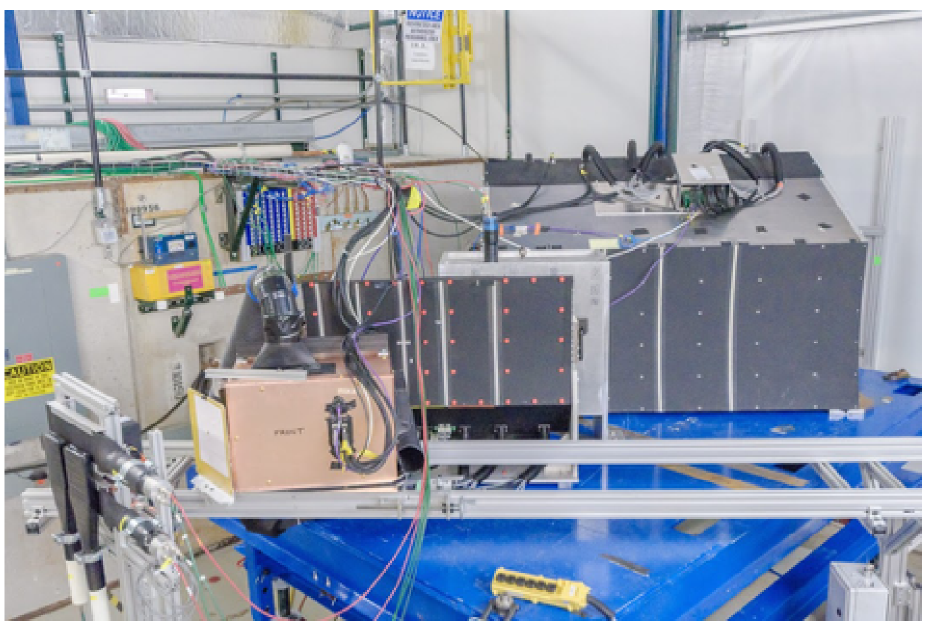




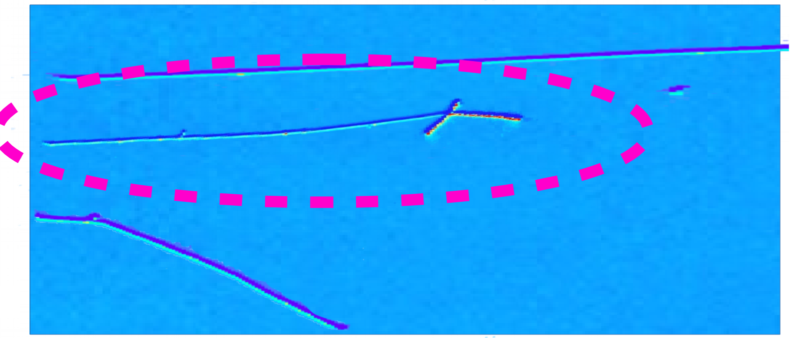


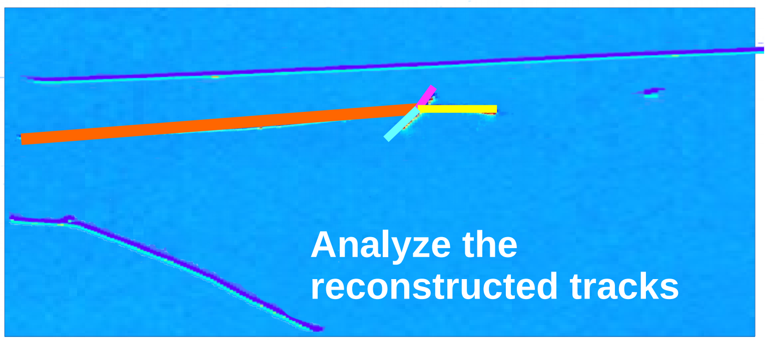
Non-LHC Collider Tests

- sPHENIX (Brookhaven)
  - Continuing tests of EMCal and Hadronic calorimeter including new readout electronics
  - Used the results for their CD review.
  - Will be returning next year
  - Continues to send other users our way as well.



Pion Cross-Section





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

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

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

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