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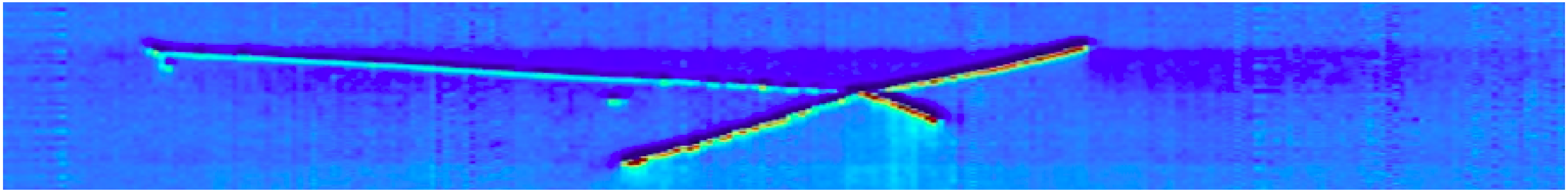
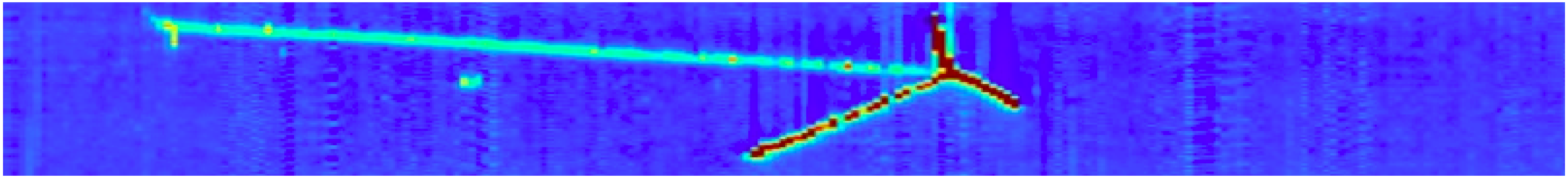


LArIAT: World's First Pion-Argon Cross-Section

Pip Hamilton
on behalf of the LArIAT collaboration



Overview

- **Introducing LArIAT**
  - Studying charged particles on Ar
  - The test beam
  - The beamline
  - The LArIAT TPC
- **How to measure a π-Ar cross-section**
- **Selection**
- **Results**
- **Conclusions and Future Work**

Introducing LArIAT

Studying Charged Particles on Ar

- Ar: the target nucleus of the future for ν experiments.

- Interactions of pions (+ other charged particles) on nucleons in Ar nuclei are the same interactions that occur when those pions are produced by neutrinos interacting inside the nucleus.

- By observing π-Ar interactions in LArIAT we can:
  - Tune hadron-nucleus interaction models in Geant4 and neutrino generators.
  - Study reconstruction systematics and calorimetry.

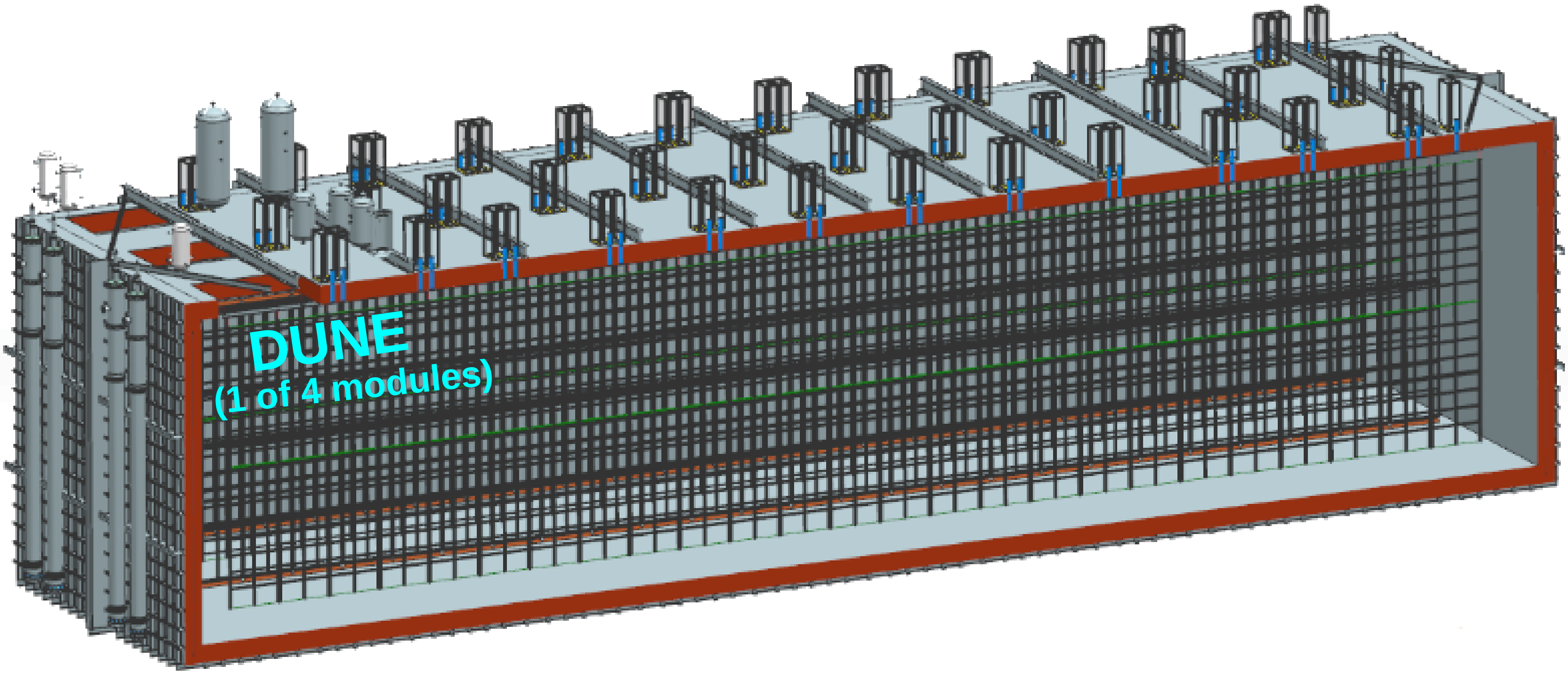
  ⇒ **constrain cross-section systematics for oscillation measurements**

The LArIAT Experiment

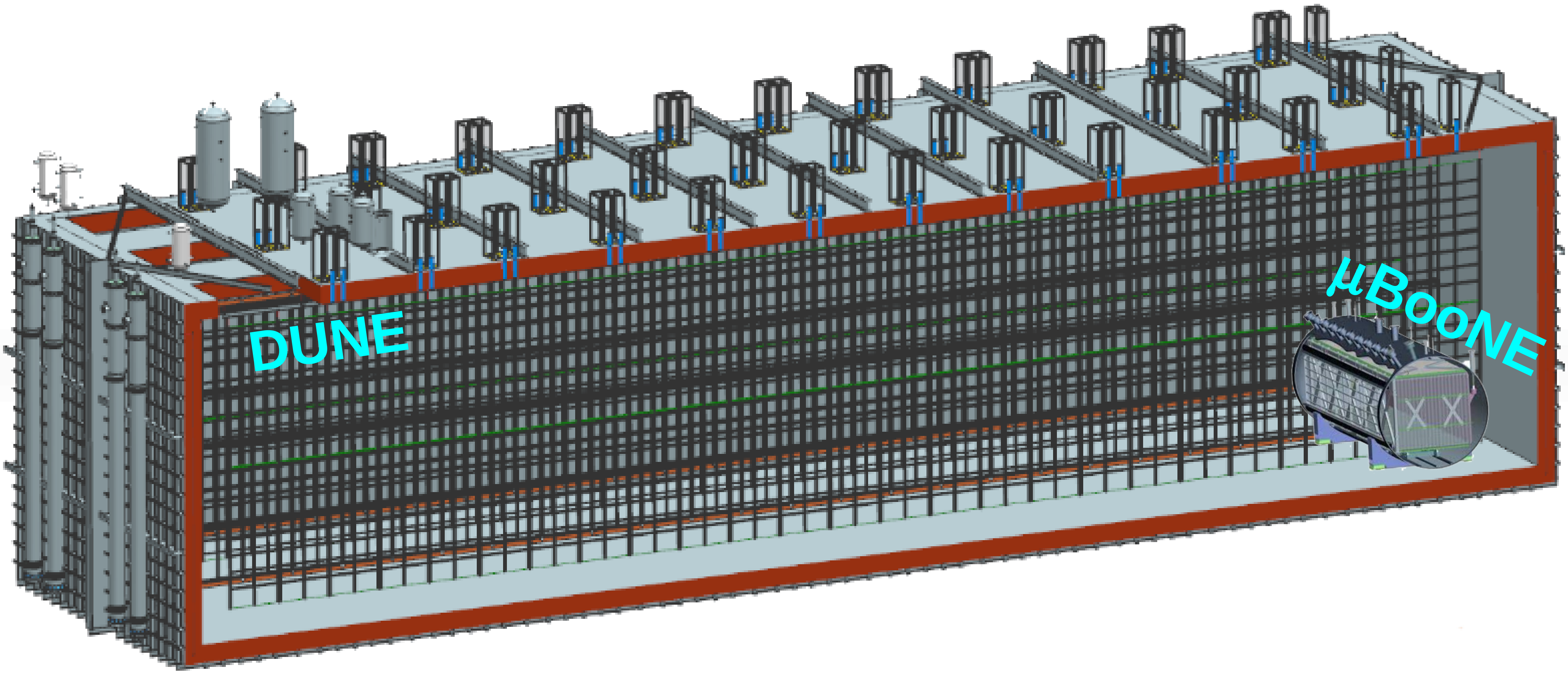
Liquid **Ar**gon **I**n **A** **T**est Beam

- LArIAT uses the refurbished ArgoNEUT TPC to take data in the Fermilab test beam.
- LArIAT began taking data in May 2015.
  - **Run 1:** 3 months
  - **Run 2:** 5.5 months

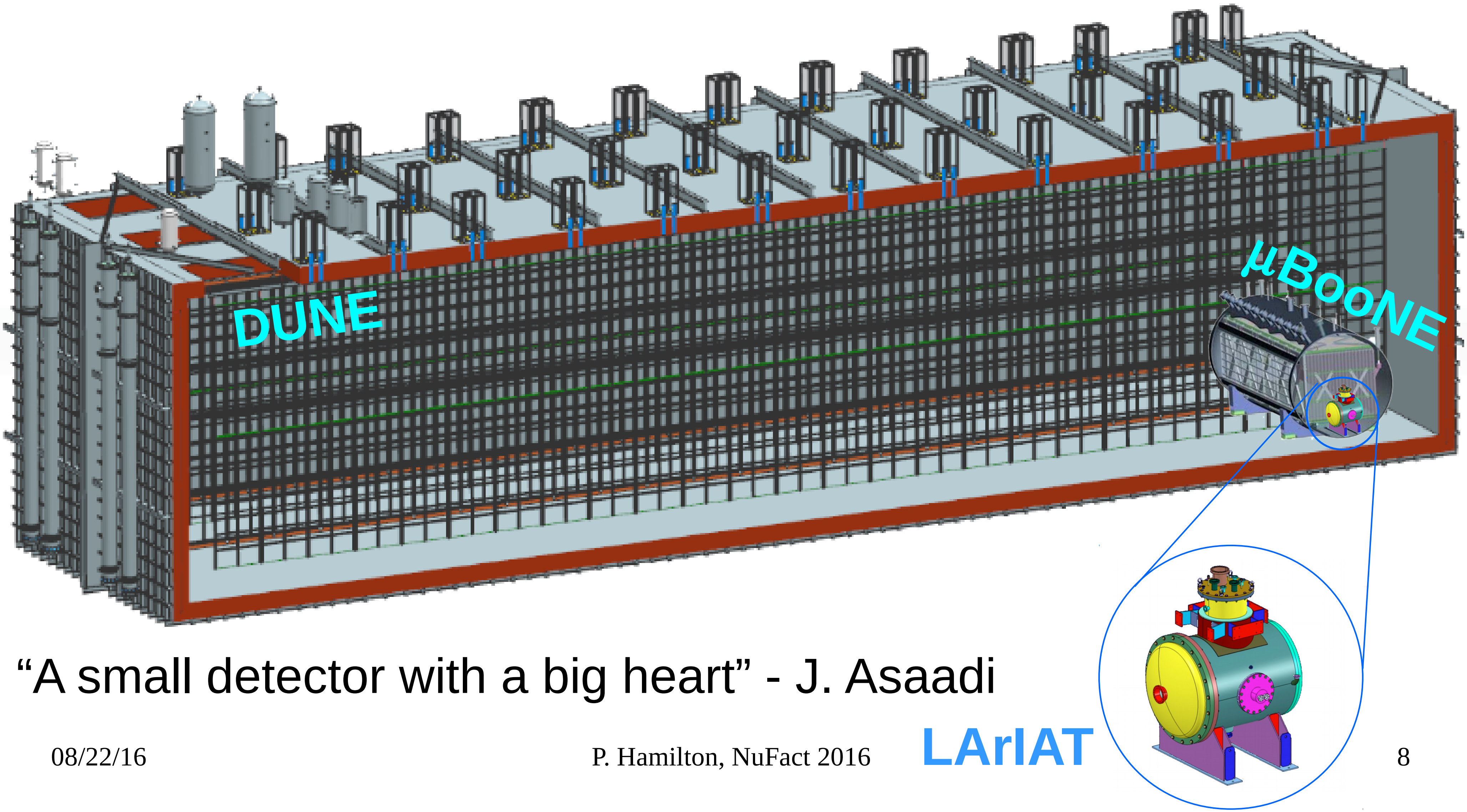
LArIAT in Perspective



LArIAT in Perspective

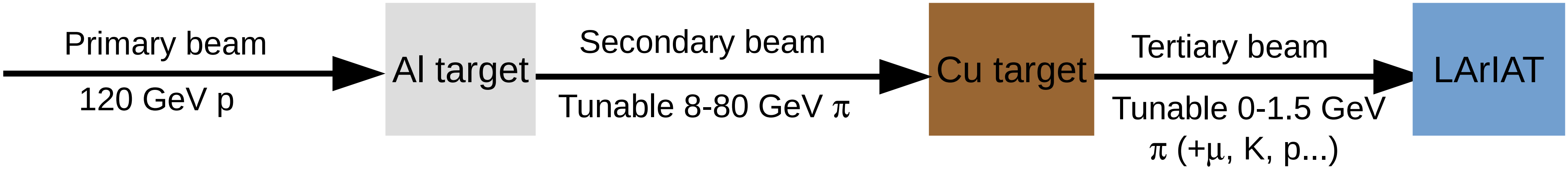


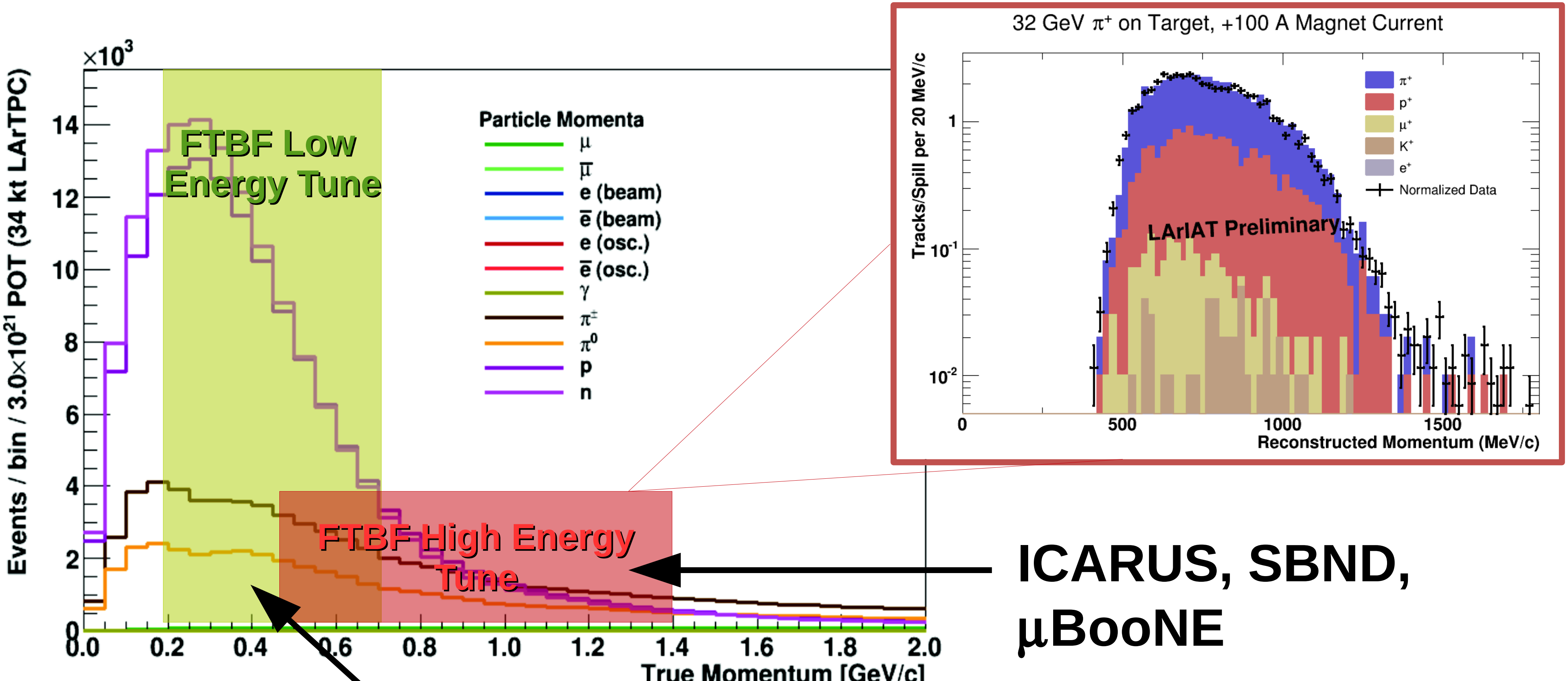
LArIAT in Perspective



"A small detector with a big heart" - J. Asaadi

The Test Beam

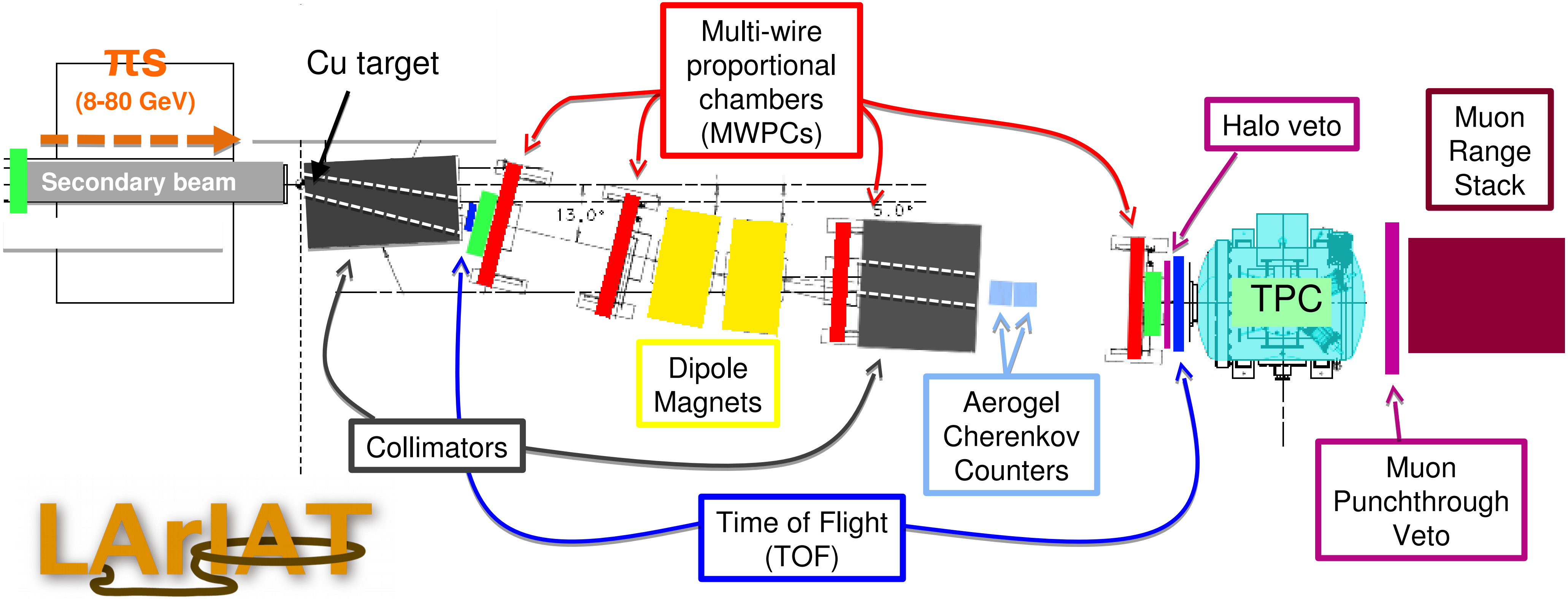




ICARUS, SBND, µBooNE

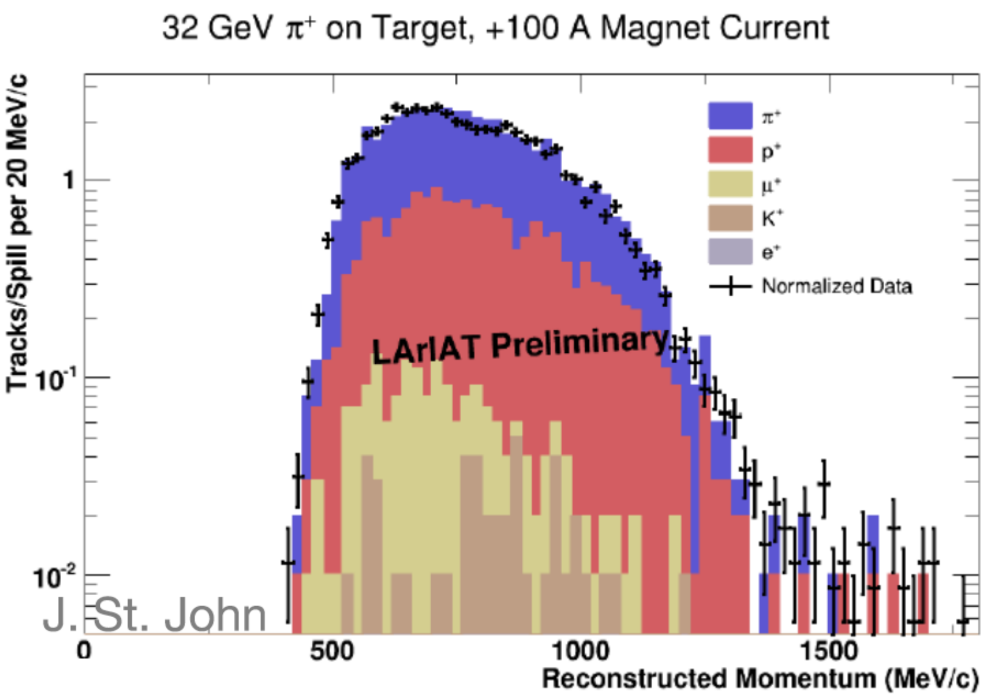
DUNE, µBooNE

The Beamline



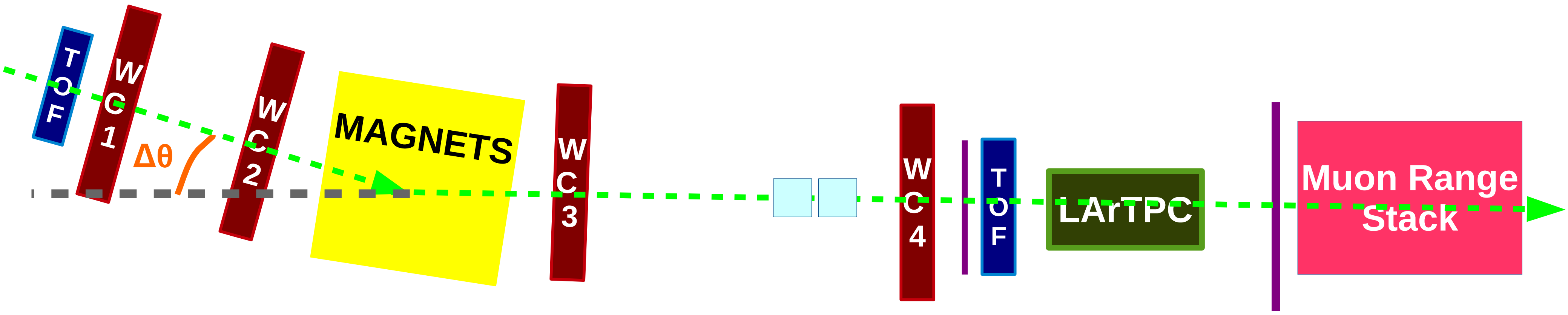
A number of auxiliary detectors are deployed to parameterise the tertiary beam impinging on the TPC.

Beamline: MWPCs and Magnets



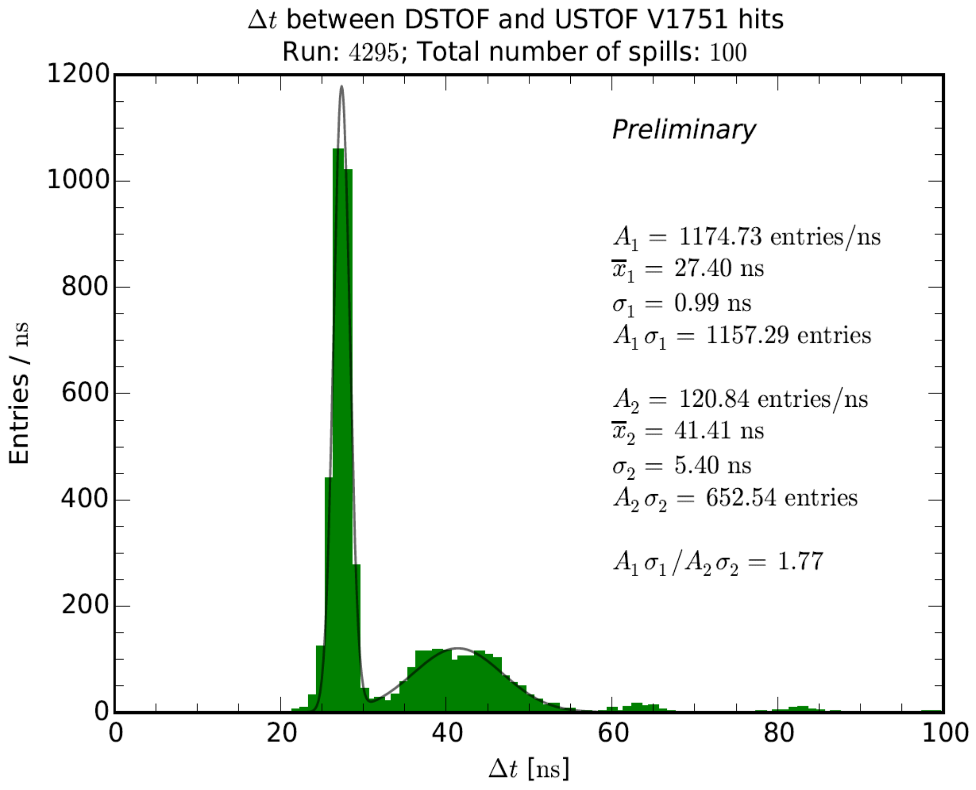
4 MWPCs allow us to measure particle's deflection due to bending magnet B-field

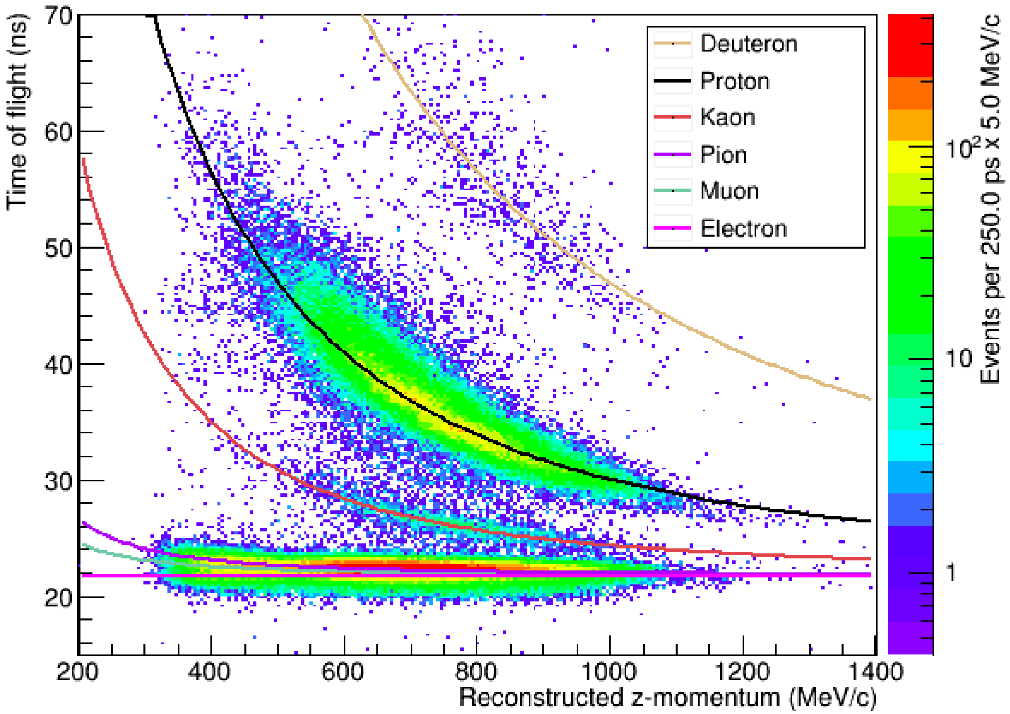
⇒ measure momentum of incident particle



Beamline: Time of Flight

Time of flight detectors at the start and end of the tertiary beamline allow us to separate μ/π/e from p/K.

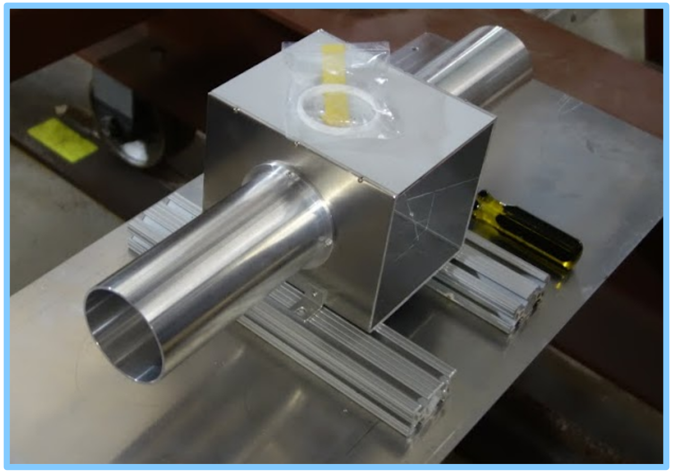


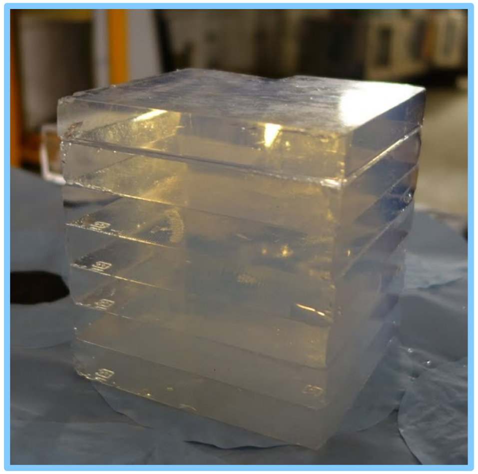


Beamline: Aerogel Cherenkov

Two Cherenkov counters of differing indices of refraction give μ/π separation in combination with the momentum measurement from the MWPCs.

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

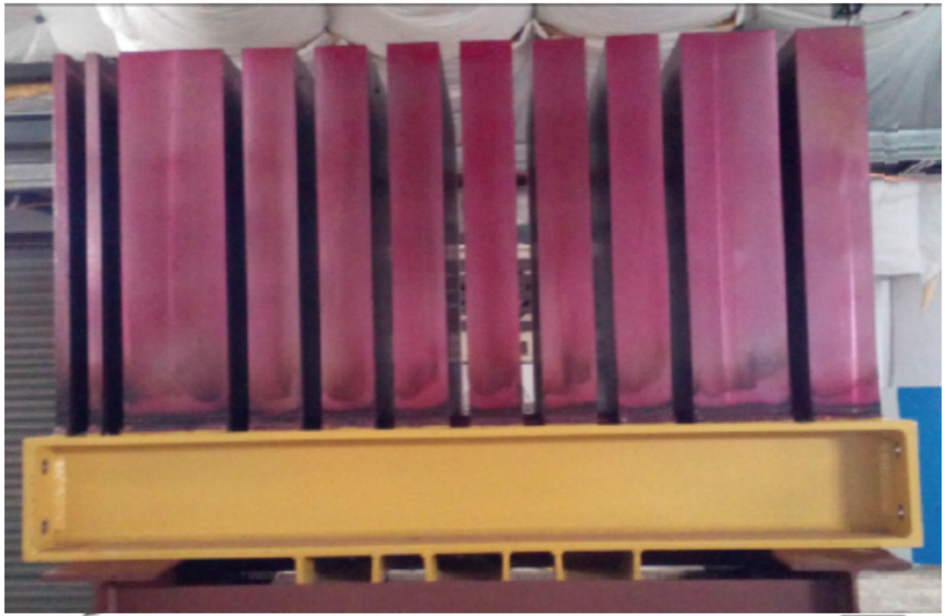


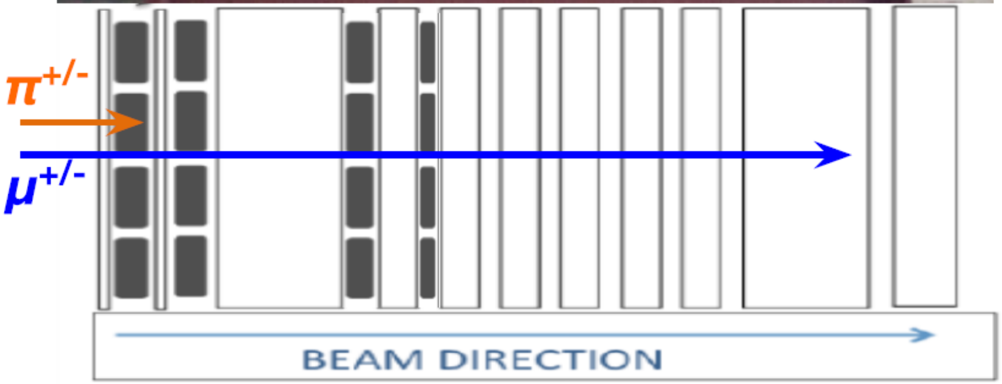


Beamline: Muon Range Stack

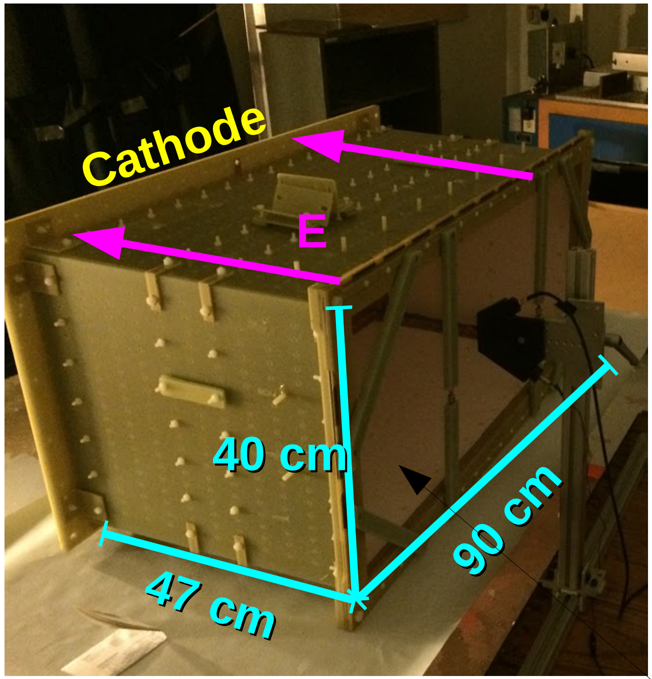
Positioned behind TPC

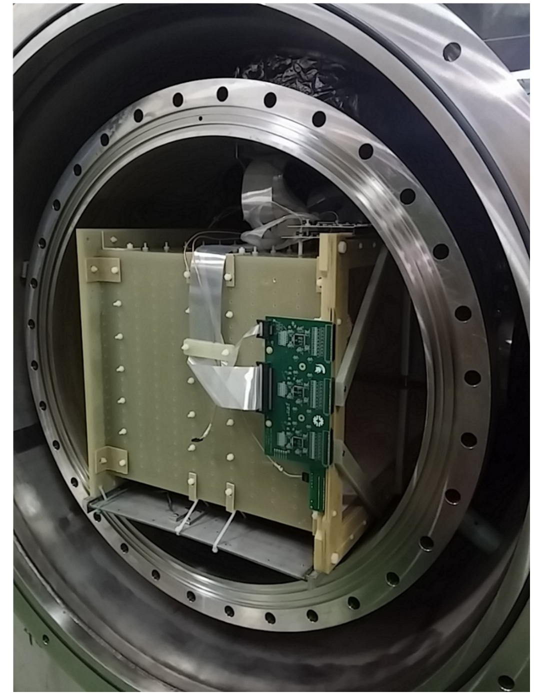
Layers of steel and PMT-instrumented scintillator paddles discriminate between through-going μ and π via penetration depth.





The TPC





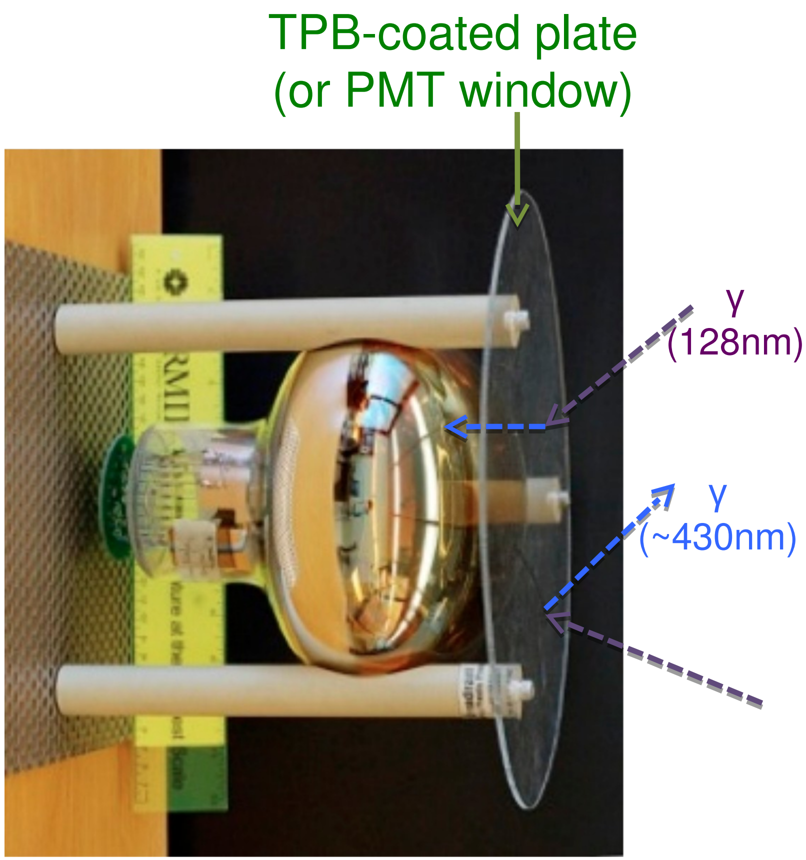
Light collection foil

- 170 L of Ar
- 2 planes of readout wires
  - +/- 60° orientation, 4 mm pitch
- Drift field ~500 V/cm

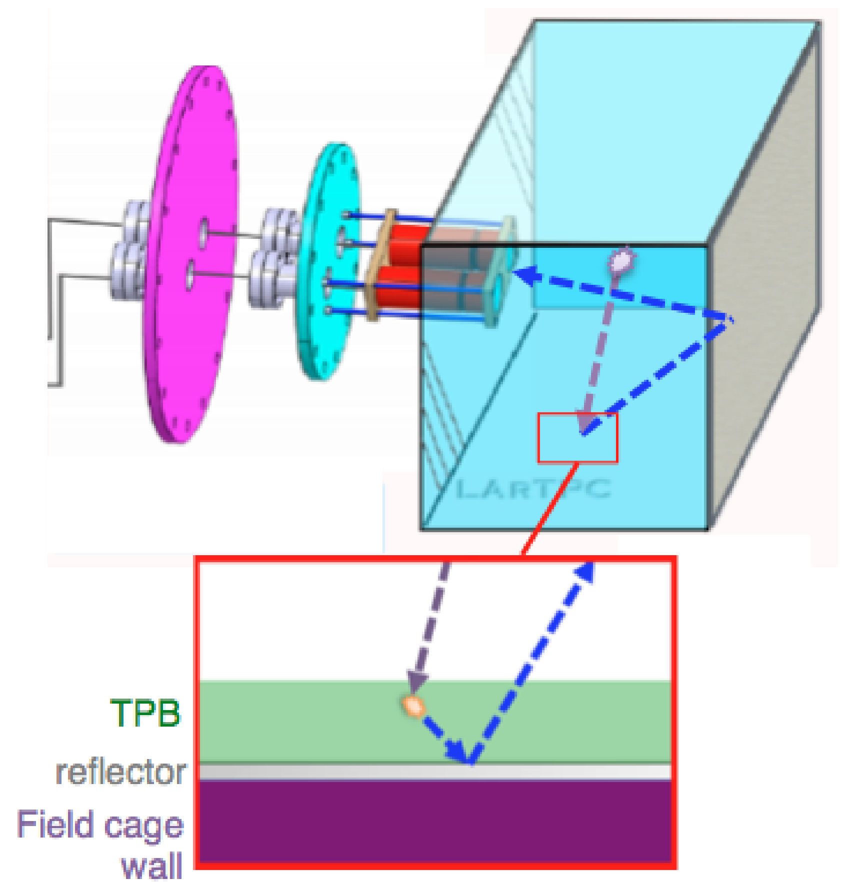
For TPC operation principles see μBooNE slides.

Light Collection

Standard LArTPC approach
(ie, ICARUS, MicroBooNE)



Reflector-based approach
(LArIAT)



Simulated Visibility

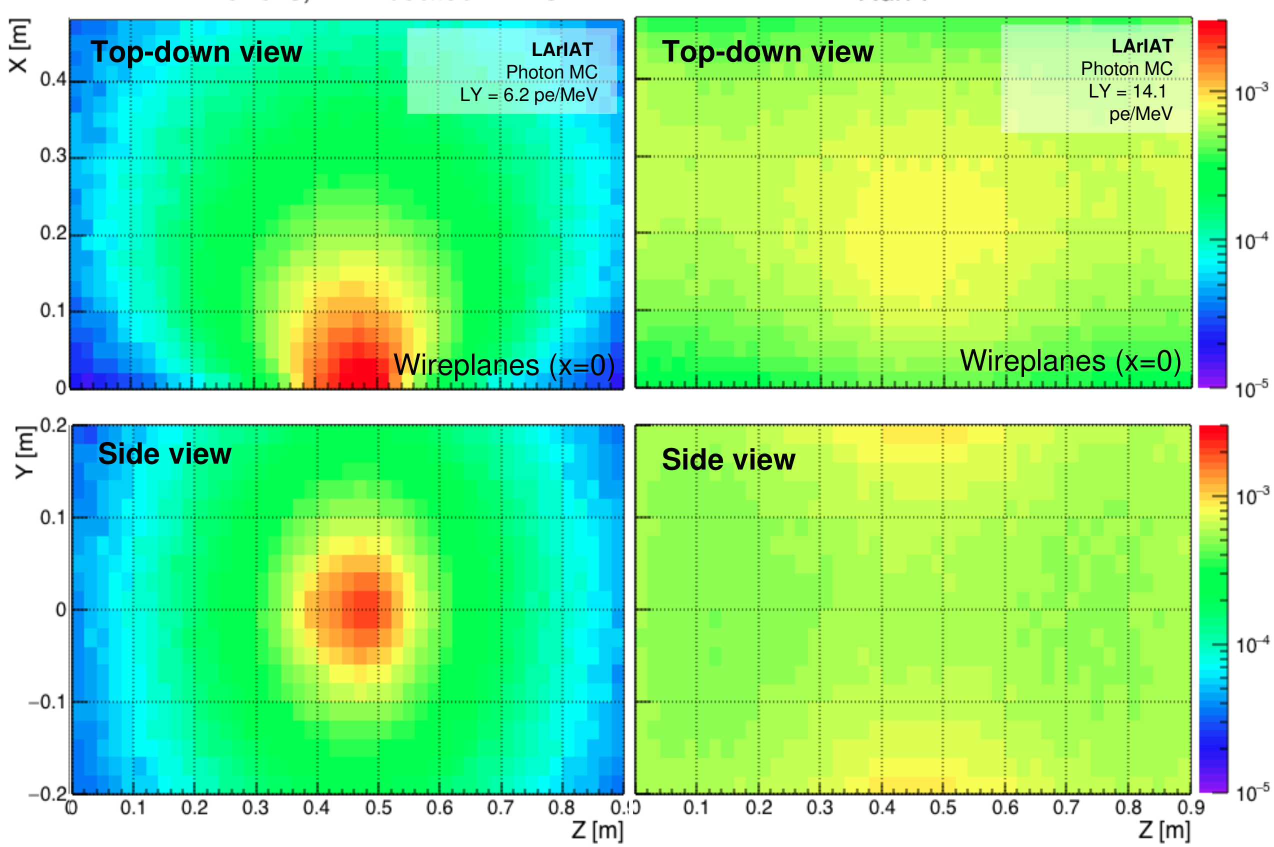
Fractional photon visibility for a standard setup vs. LArIAT

Standard Setup

No foils, TPB-coated PMTs

LArIAT Setup

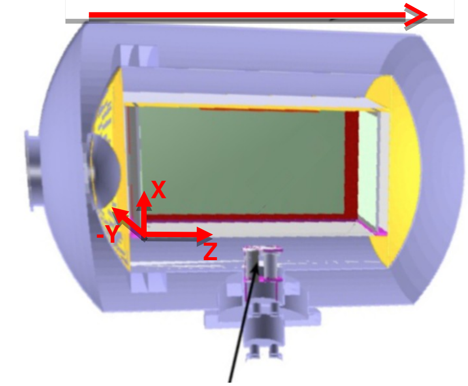
Run I



Beam direction

Beam direction

Beam direction



PMTs

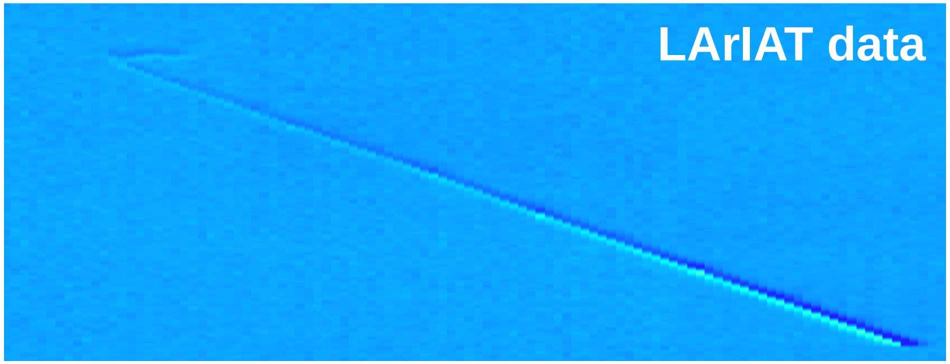
> 2x light & **more uniform visibility** compared to case with no foils and TPB-coated PMTs

This method being tested in LArIAT for use in future ν experiments (e.g. SBND).

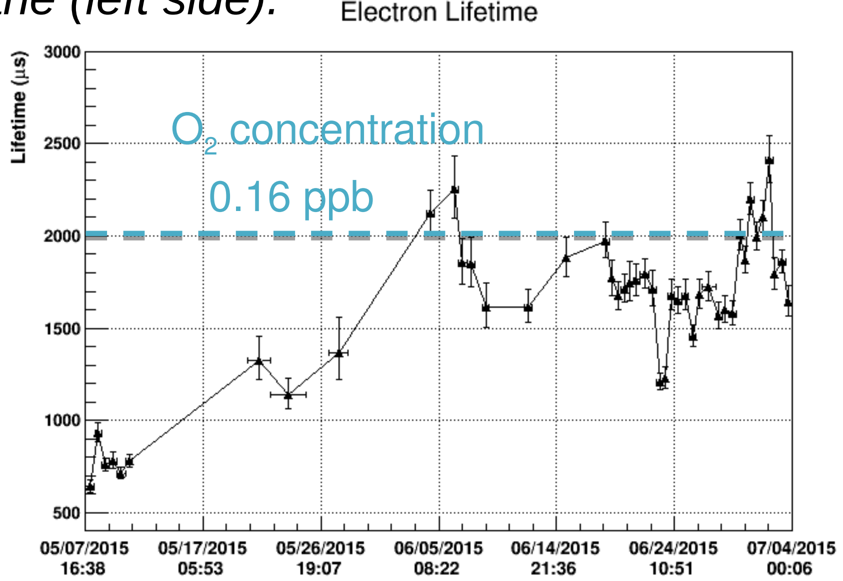
LAr Purity

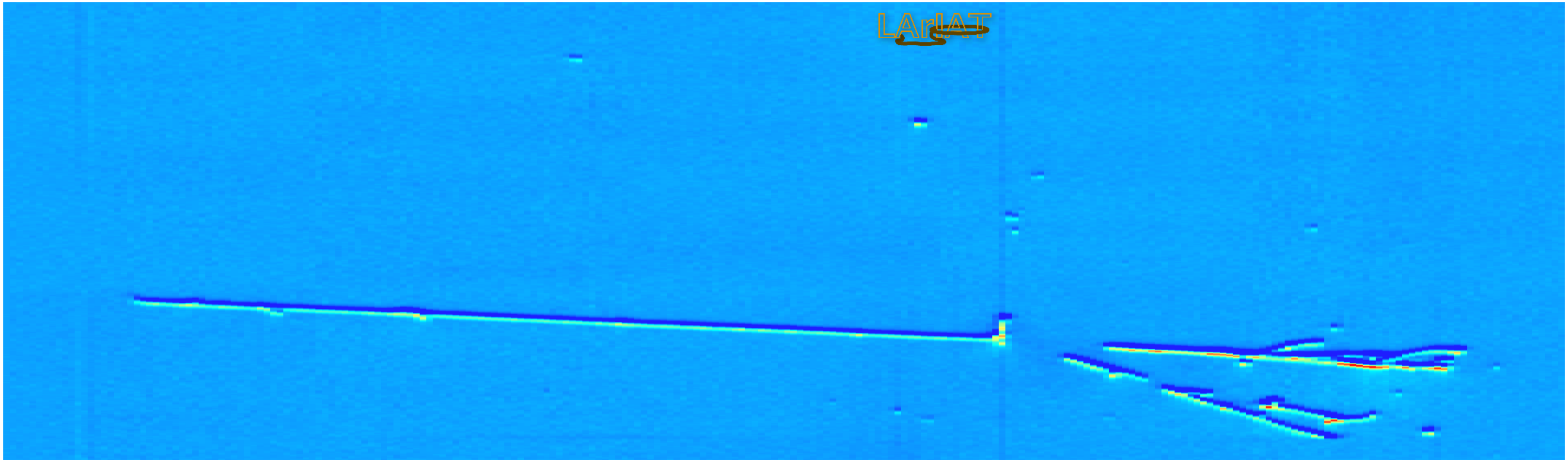
- Besides light, the other key thing to get out of a TPC is charge.
- Impurities in LAr quench the charge from a track as the electrons drift ⇒ more drift distance, less charge.

  ⇒ important for large-scale detectors!
- We measure this effect by fitting dQ/dX against drift time along crossing μ tracks.
- LArIAT maintains high LAr purity **without** LAr recirculation.

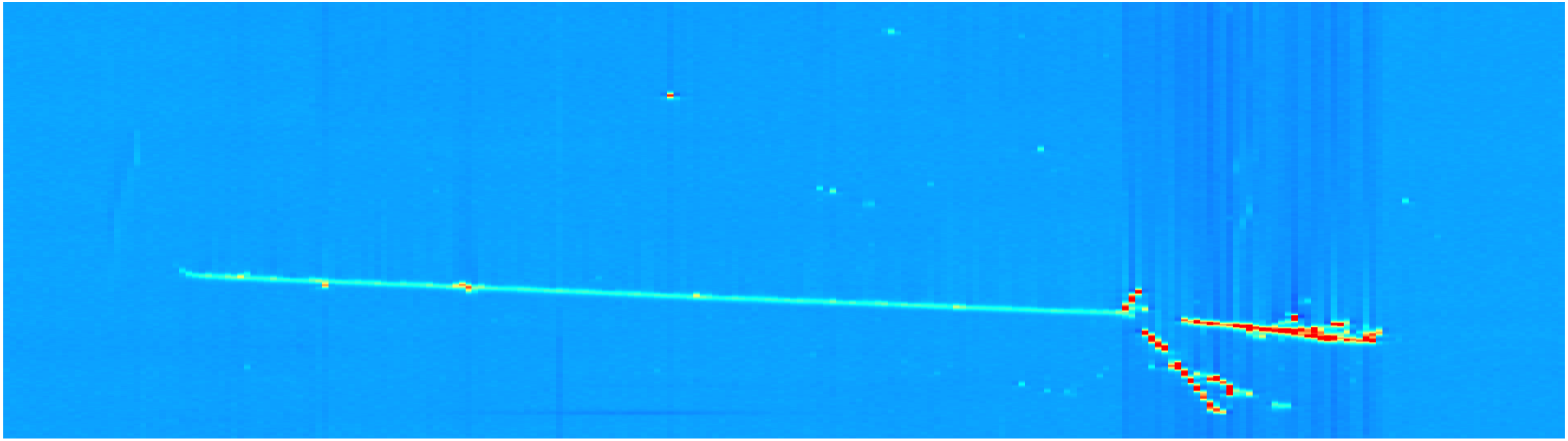


Muon track with Michel from period of low Ar purity, fading out towards end furthest from wire plane (left side).





Charge exchange candidate in LArIAT, 1st April 2016



How to measure a π-Ar cross-section

Cross-Section Measurement

- **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 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**

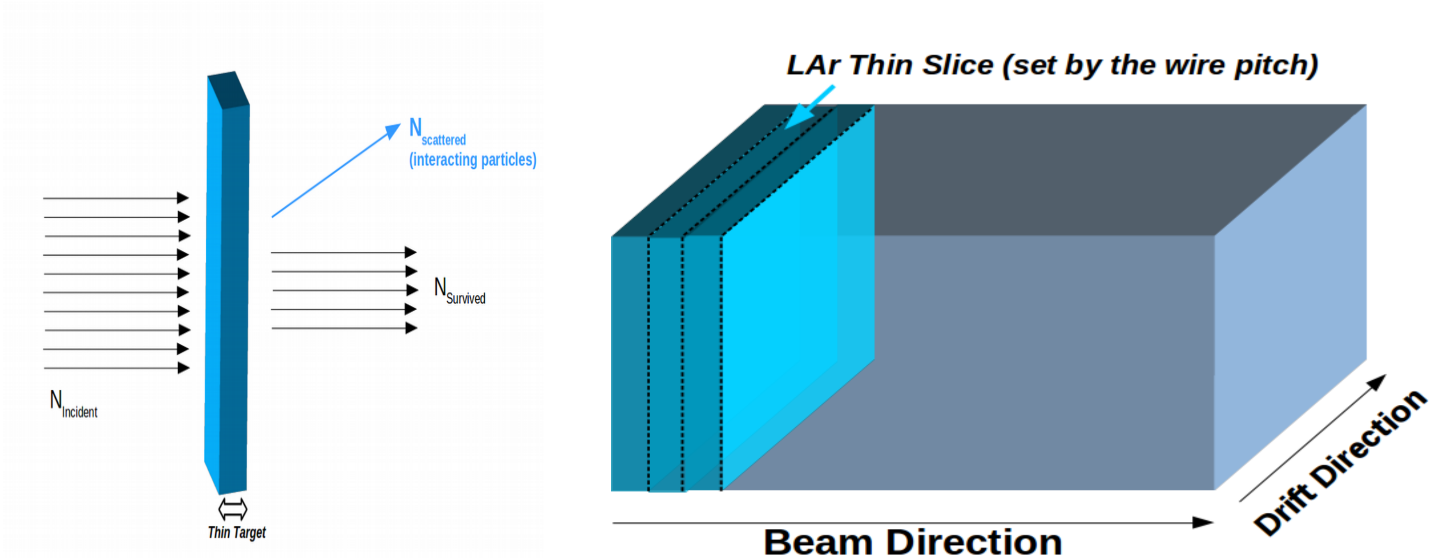
$$P_{\text{Interacting}} = 1 - P_{\text{Survival}}$$

which can be re-expressed as the ratio of interacting to incident pions:

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

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

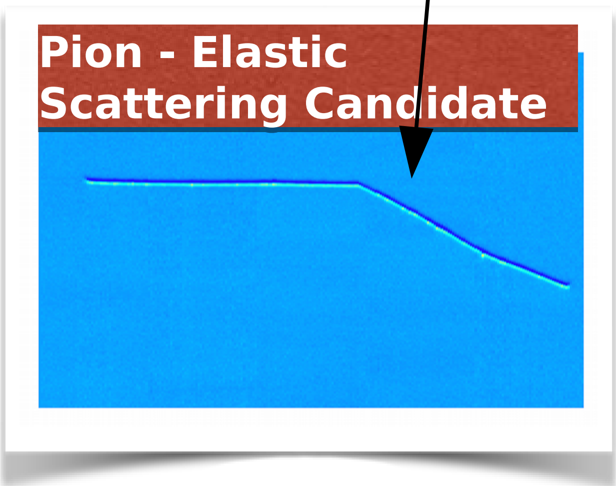
$$\boxed{\begin{aligned} P_{\text{Interacting}} &= 1-(1-\sigma n \delta z+\ldots) \\ \sigma(E) &\approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz}\frac{N_{\text{interacting}}}{N_{\text{Incident}}} \end{aligned}}$$

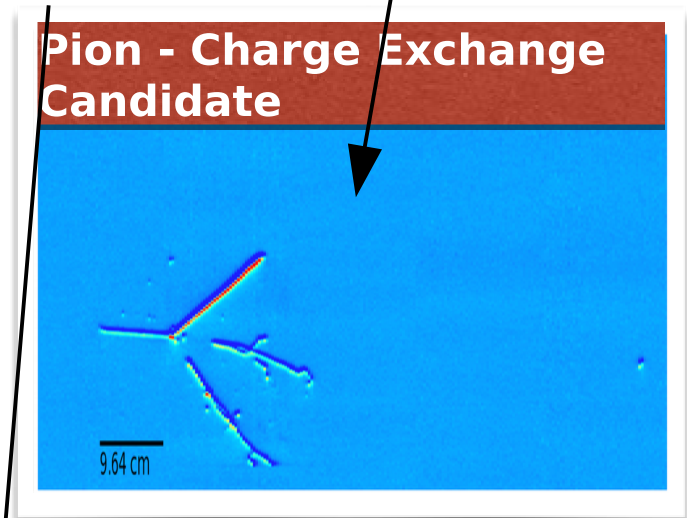


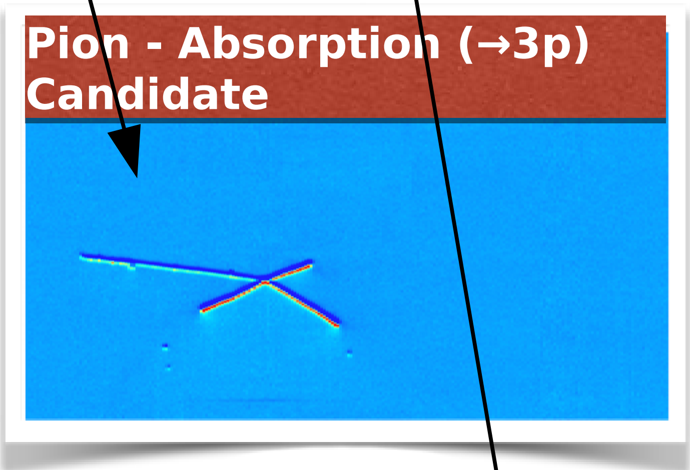
Treat the **wire-to-wire spacing** in the TPC as a series of “thin slab” targets (⇒ depth 4 mm).

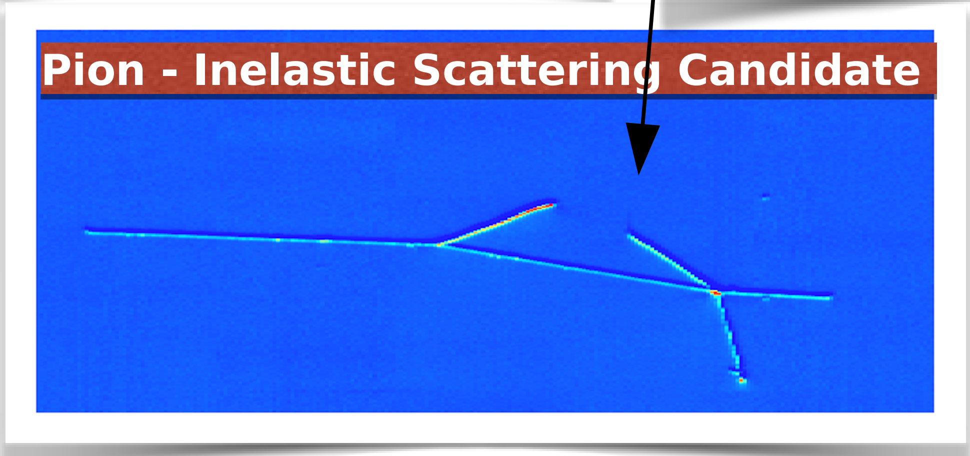
LArIAT defines a **total** cross-section containing multiple processes:

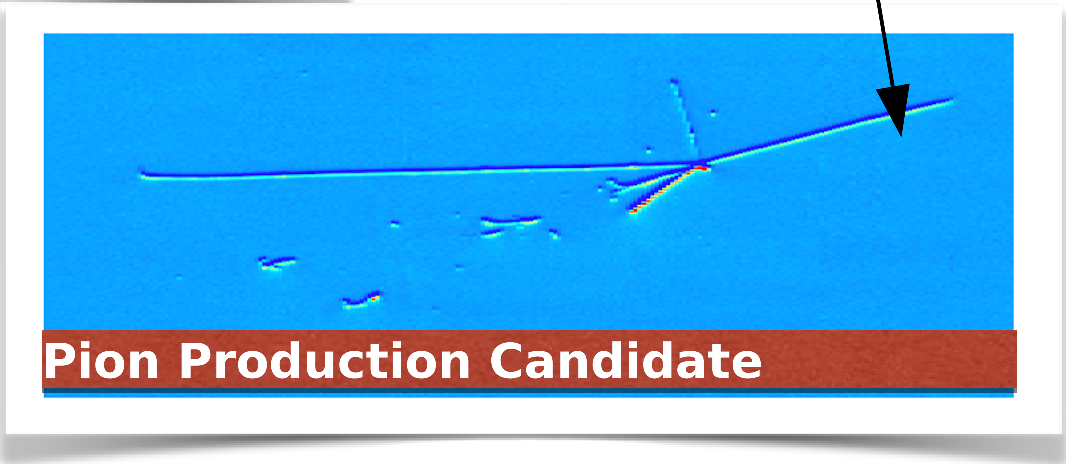
$$\sigma_{\text{Total}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{ch-exch}} + \sigma_{\text{absorp.}} + \sigma_{\pi\text{-production}}$$



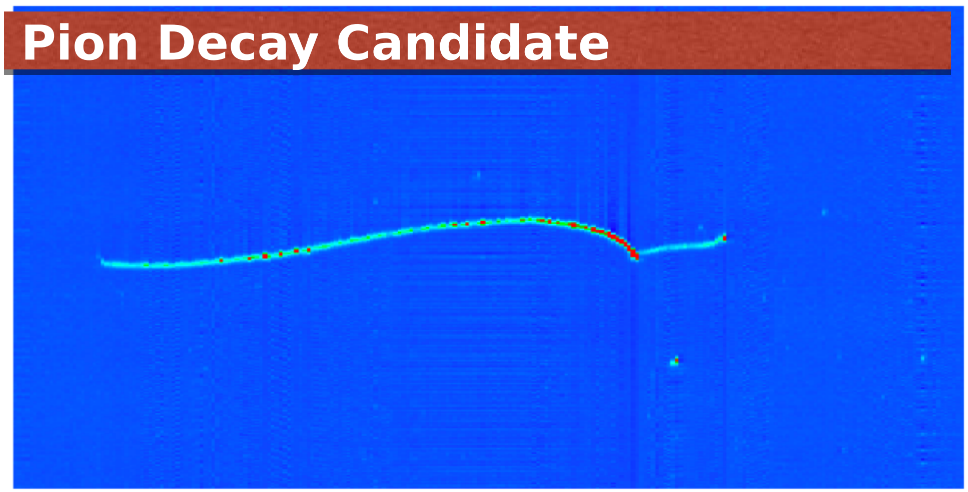


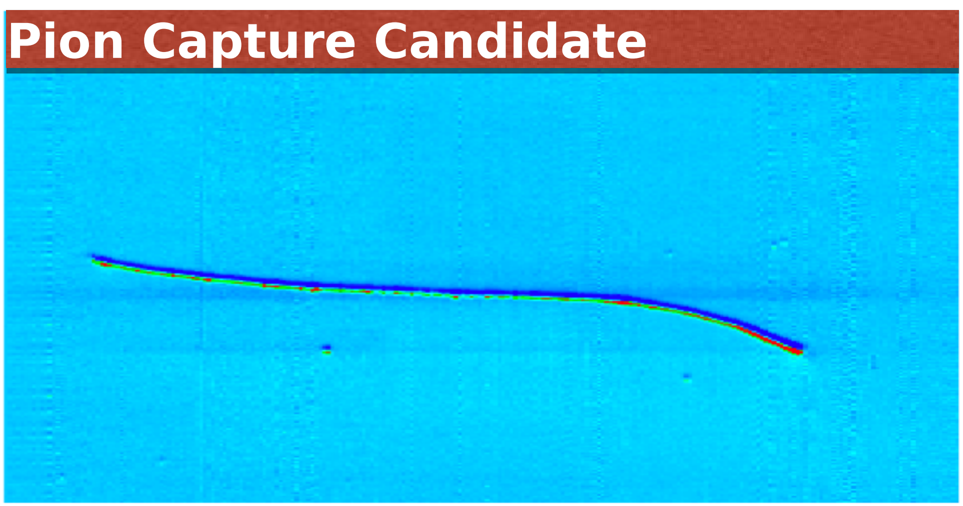


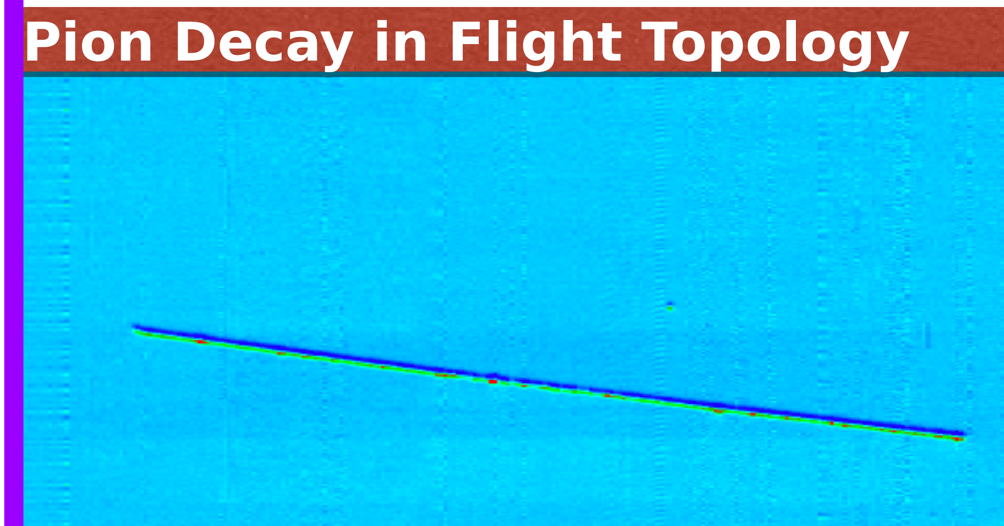




Backgrounds







LarIAT aims to remove these backgrounds through **background subtraction** rather than cuts.

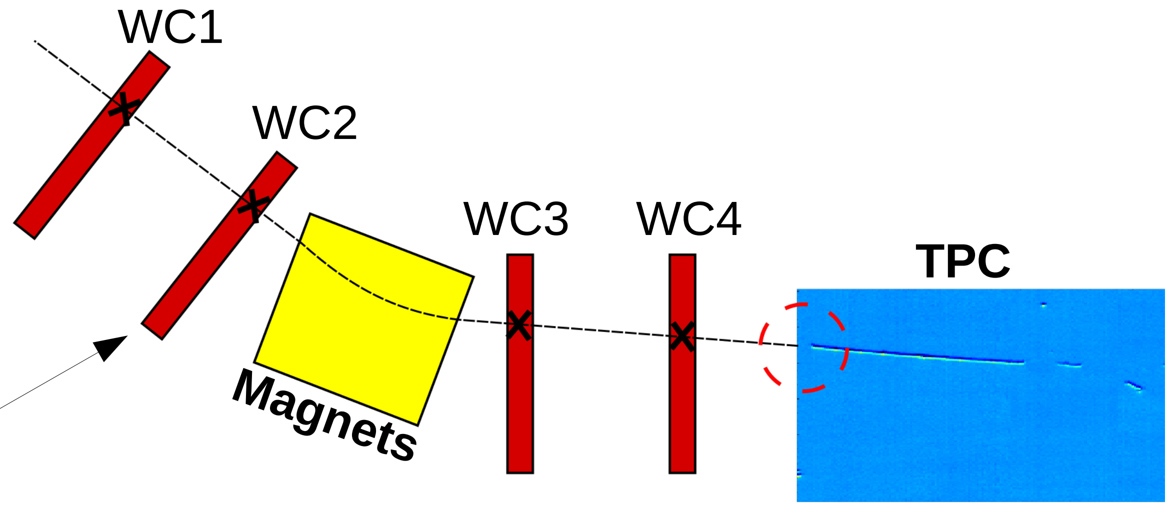
Currently they are not subtracted (⇒ implicitly included in the total cross-section).

Selection

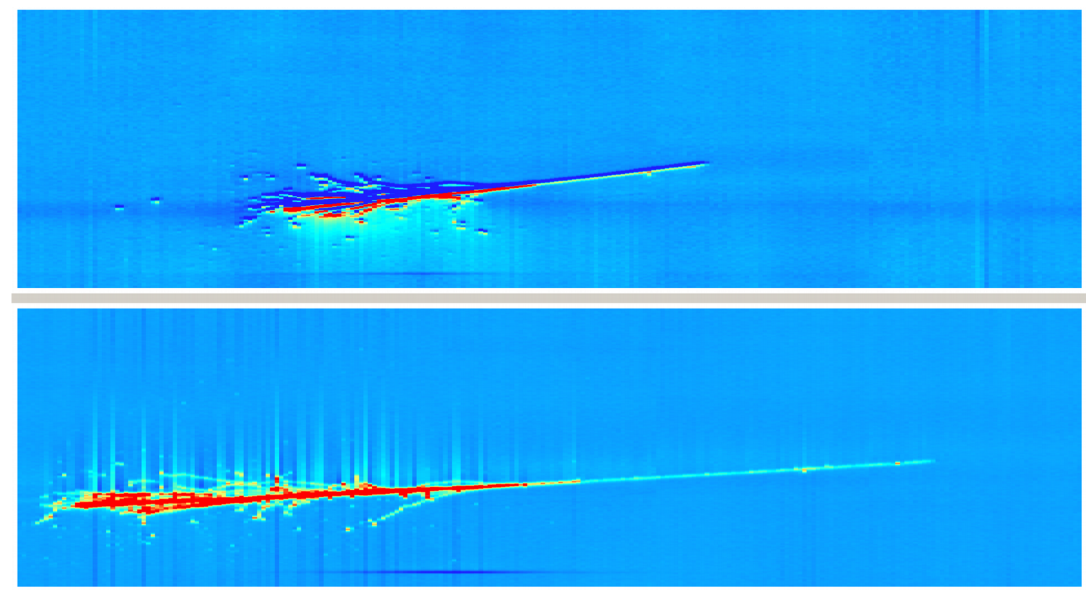
Selection

1) Using TOF detectors, require particles with a μ/π/e PID.

2) Require a clean match between extrapolated wire chamber track and start of TPC track.



3) Veto events with an EM shower profile in the TPC to remove electrons from the selected sample.



Selection Performance

	π^-	e^-	γ	μ^-	K^-	$\bar{p}$
Beam composition before cuts	48.4%	40.9%	8.5%	2.2%	0.035%	0.007%
Selection efficiency	74.5%	3.6%	0.9%	90.0%	70.6%	

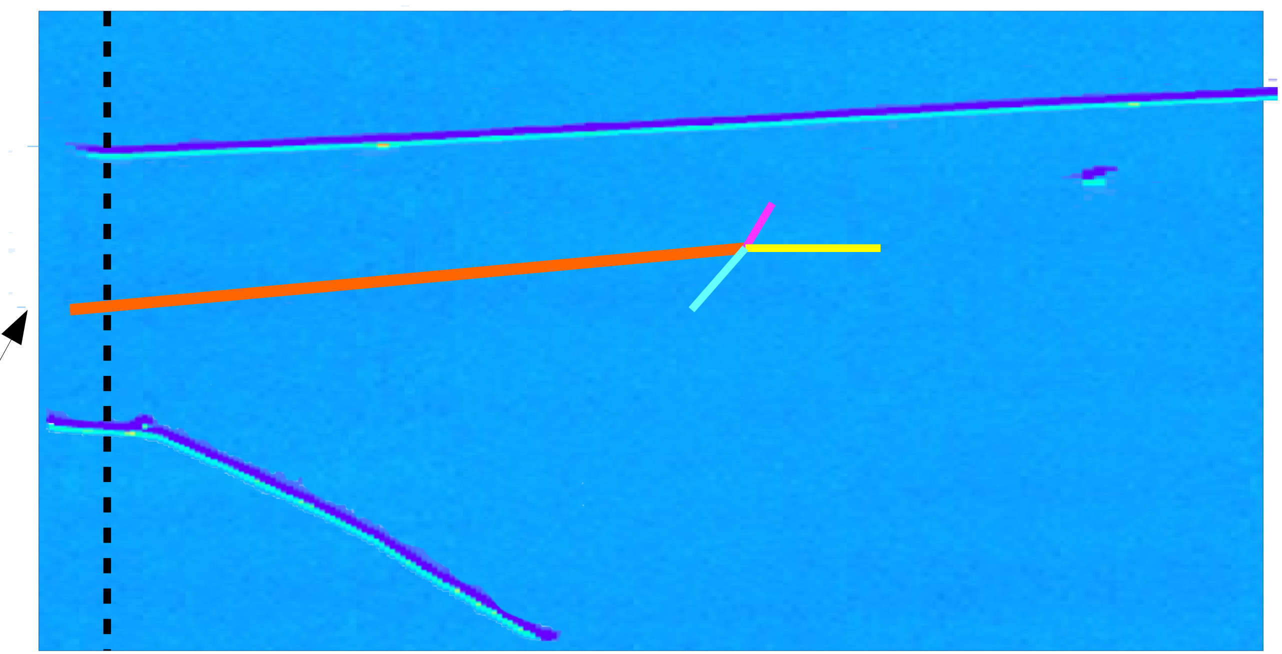
From the data used for this result (Run 1 π^-; ~3 weeks at low-energy tune, ~5 weeks at high energy tune), survival rates are:

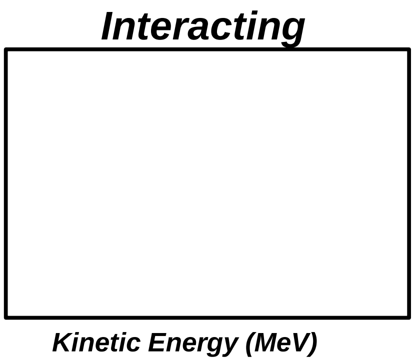
Event Sample	Number of Events
π^- Data Candidate Sample	32,064
$\pi/\mu/e$ ID	15,448
Requiring an upstream TPC Track within $z < 2$cm	14,330
< 4 tracks in the first $z < 14$cm	9,281
Wire Chamber / TPC Track Matching	2,864
Shower Rejection Filter	2,290

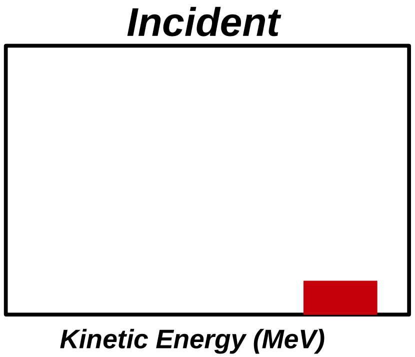
Cross-Section Calculation

Follow selected track in slices, recalculating KE for each slice:

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







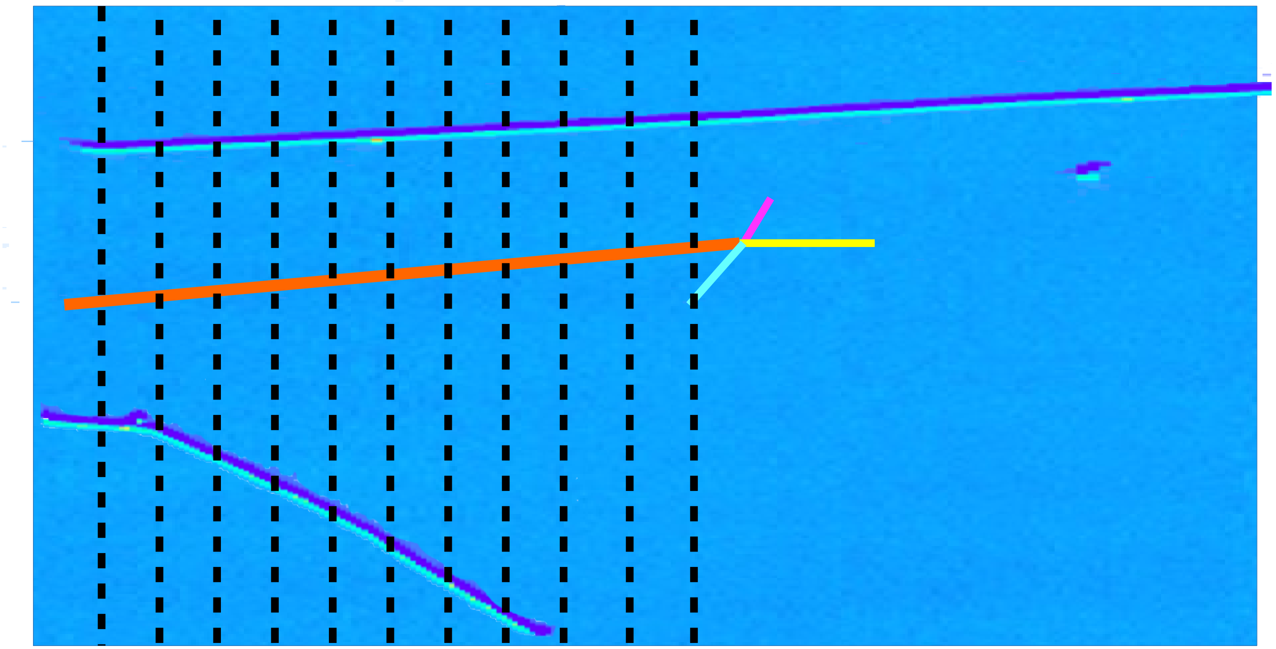
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\mathrm{Flat}}$$

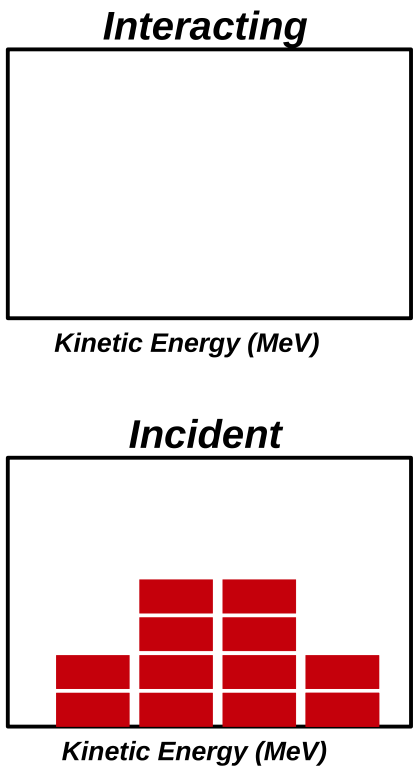
Accounts for energy loss from material upstream of TPC

Cross-Section Calculation

For each slice before interaction, fill incident histogram.

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

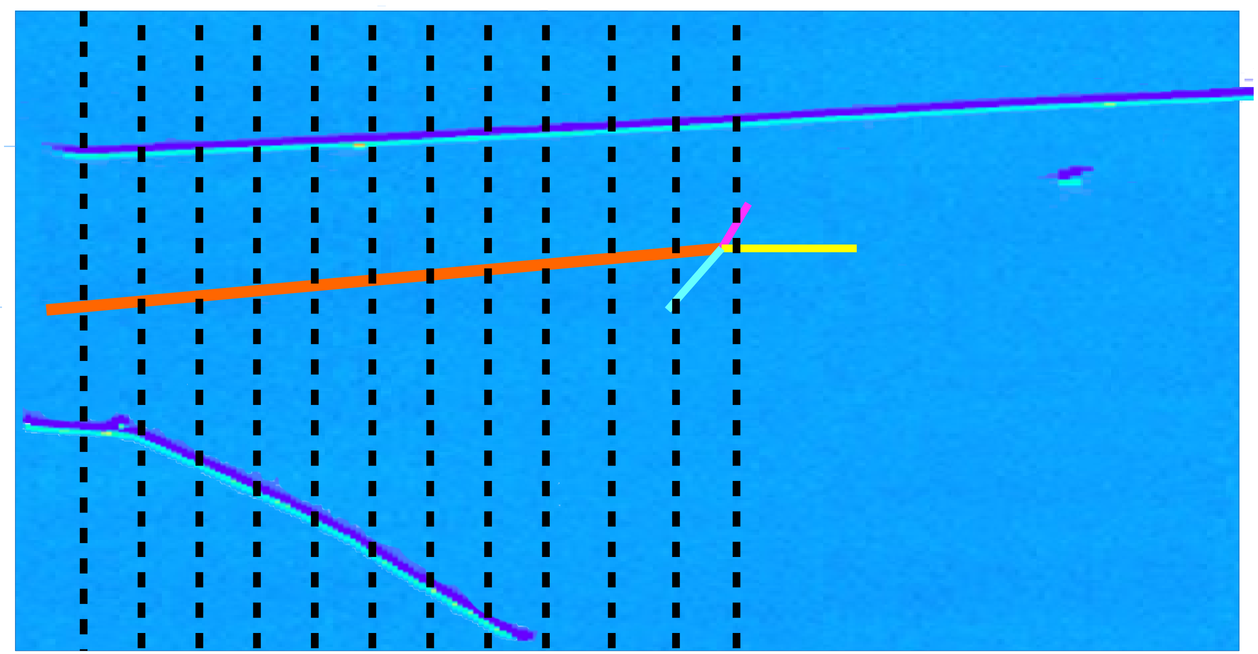


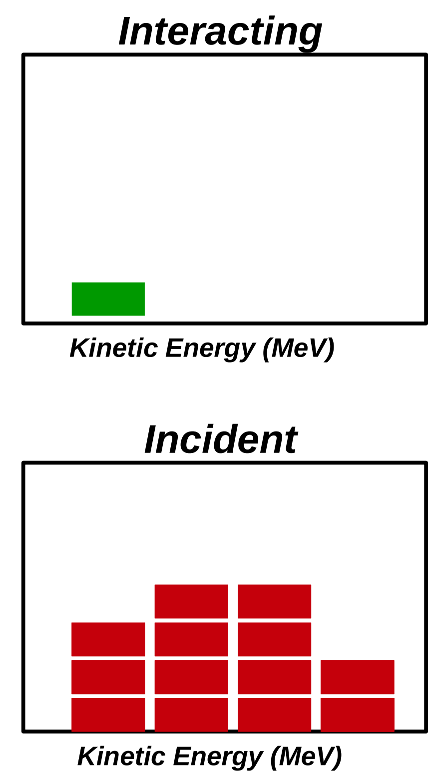


Cross-Section Calculation

For the interacting slice, fill incident **and** interacting histograms.

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





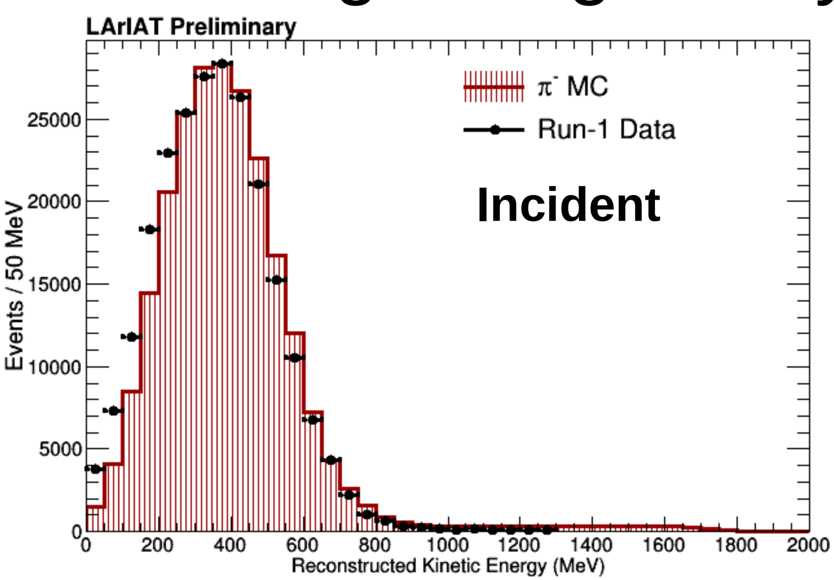
Repeat event by event, until we have gone through the entire sample.

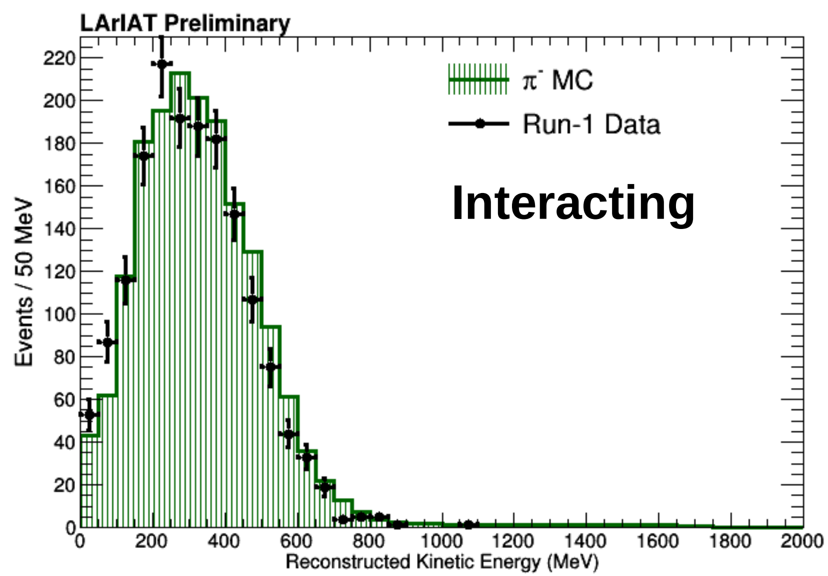
Cross-Section Calculation

Recalling that

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

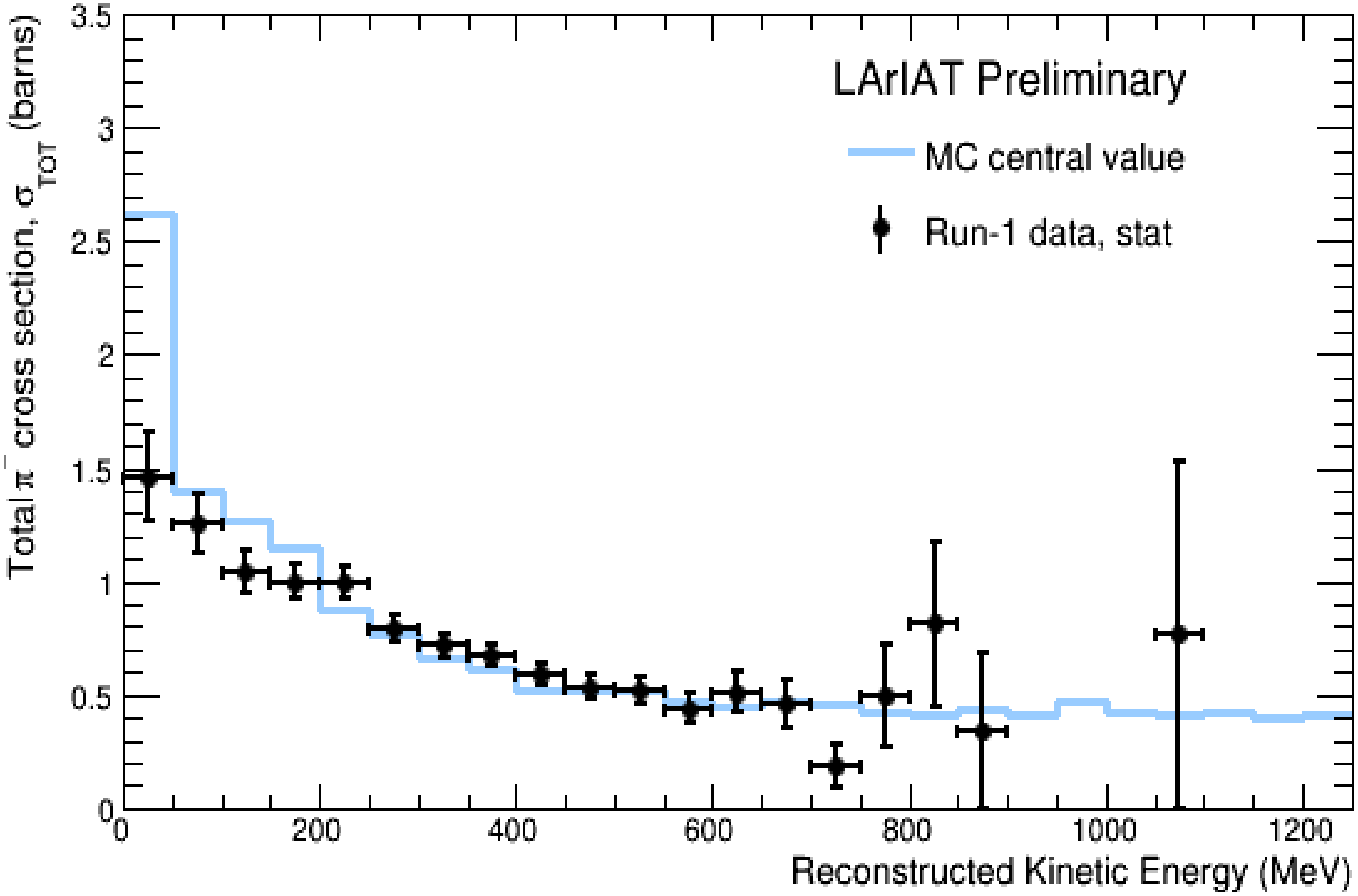
The cross-section can be derived by dividing the interacting histogram by the incident histogram.





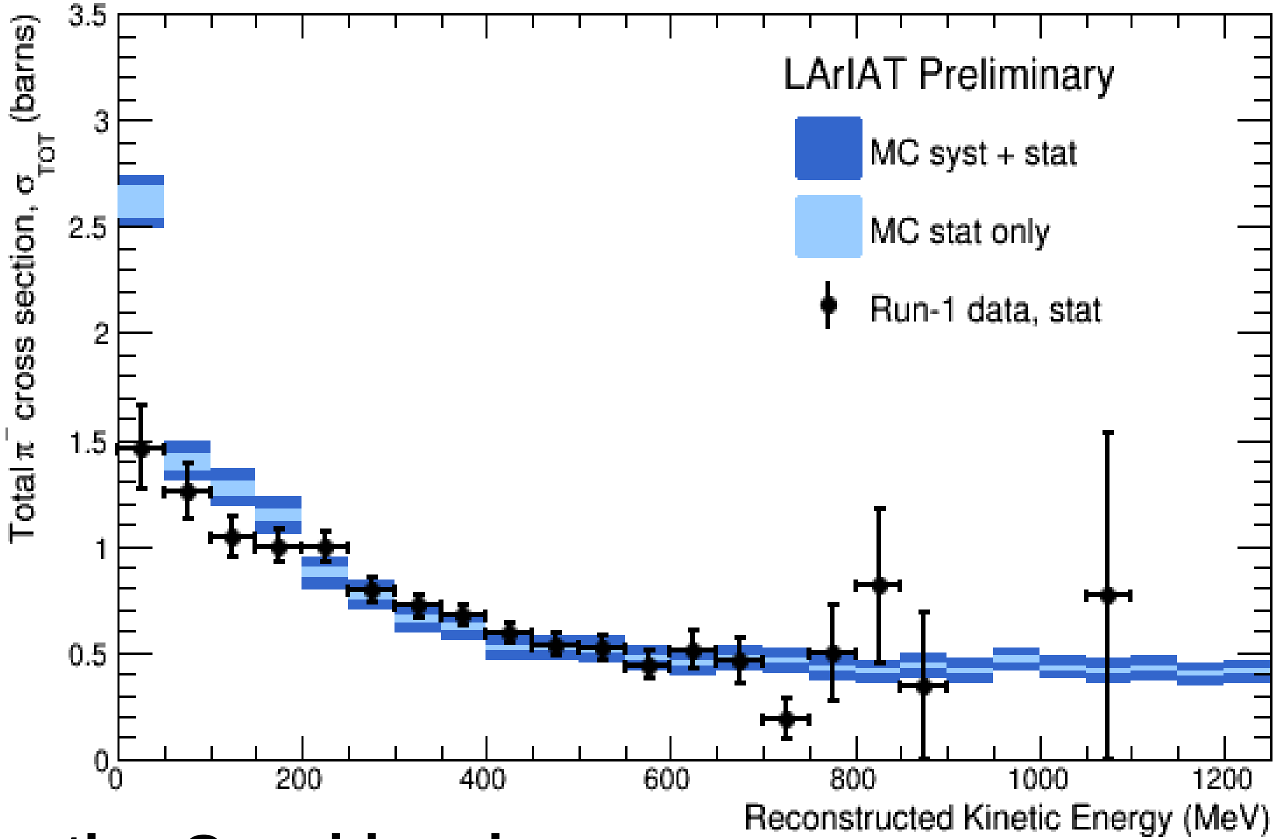
Result

Result



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

Uncertainties



Systematics Considered:

- dE/dX calibration: 5%
- Energy loss prior to entering the TPC: 3.5%
- Through-going μ contamination: 3% (π decay and capture still present)
- Wire chamber momentum uncertainty: 3%

Assessing Systematics: Momentum Uncertainty & Backgrounds

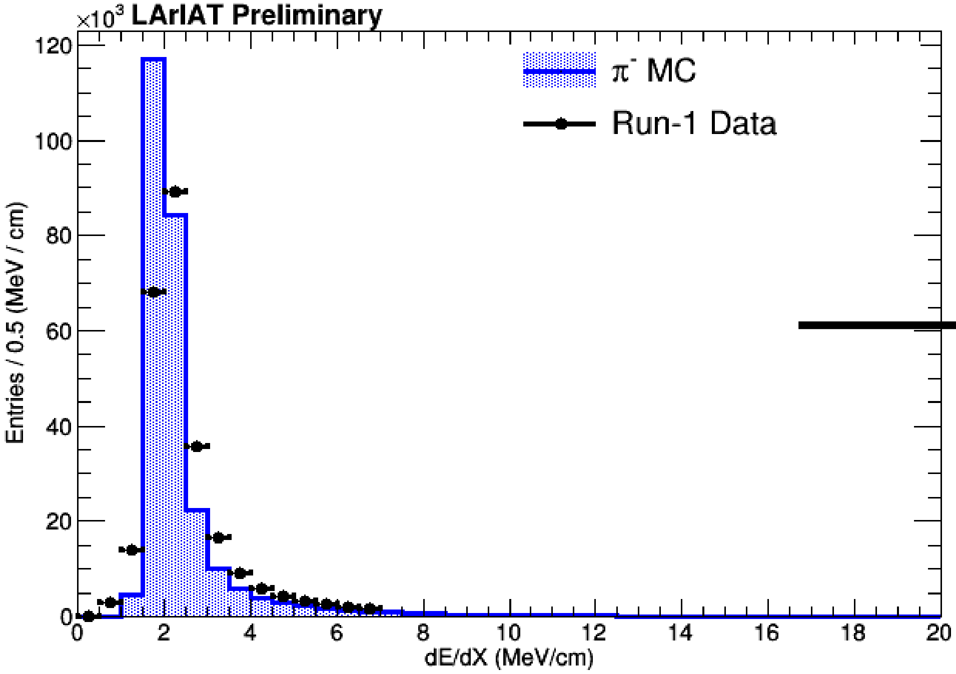
Momentum Uncertainty

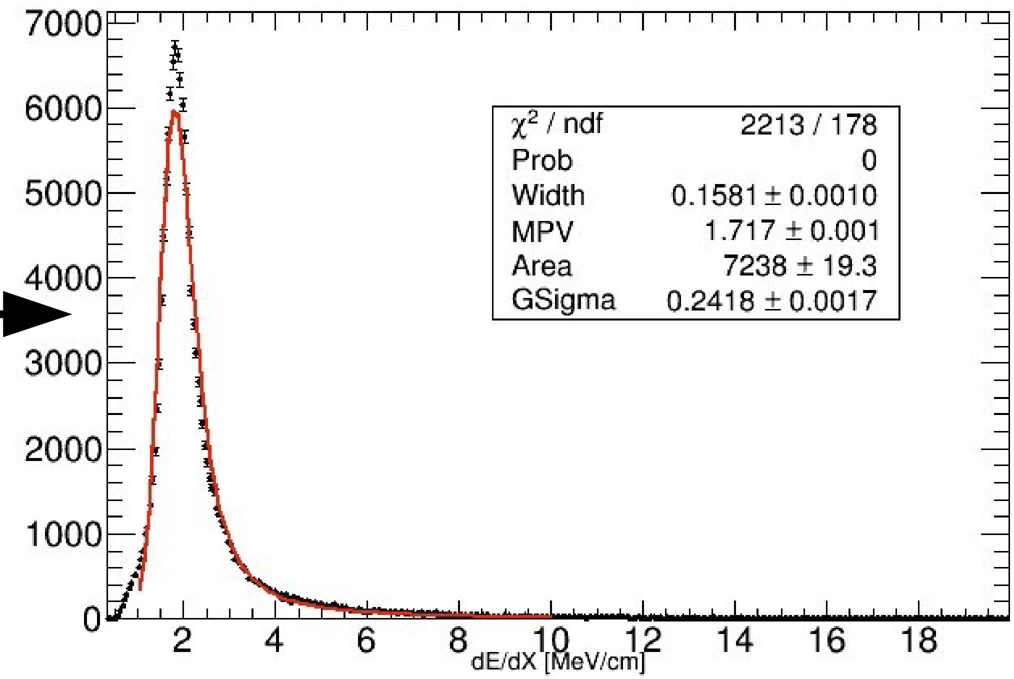
- Simple geometric consideration from uncertainty on wire chamber alignment.
- Assessed with data tracks (varying assumed wire chamber positions).

Background Contamination

- ~10% muon contamination (uniformly distributed in energy).
- ~9% π-capture and 2% π-decay (not uniformly distributed) – not yet accounted for.
- Assessed using MC.

Assessing Systematics: dE/dX Calibration



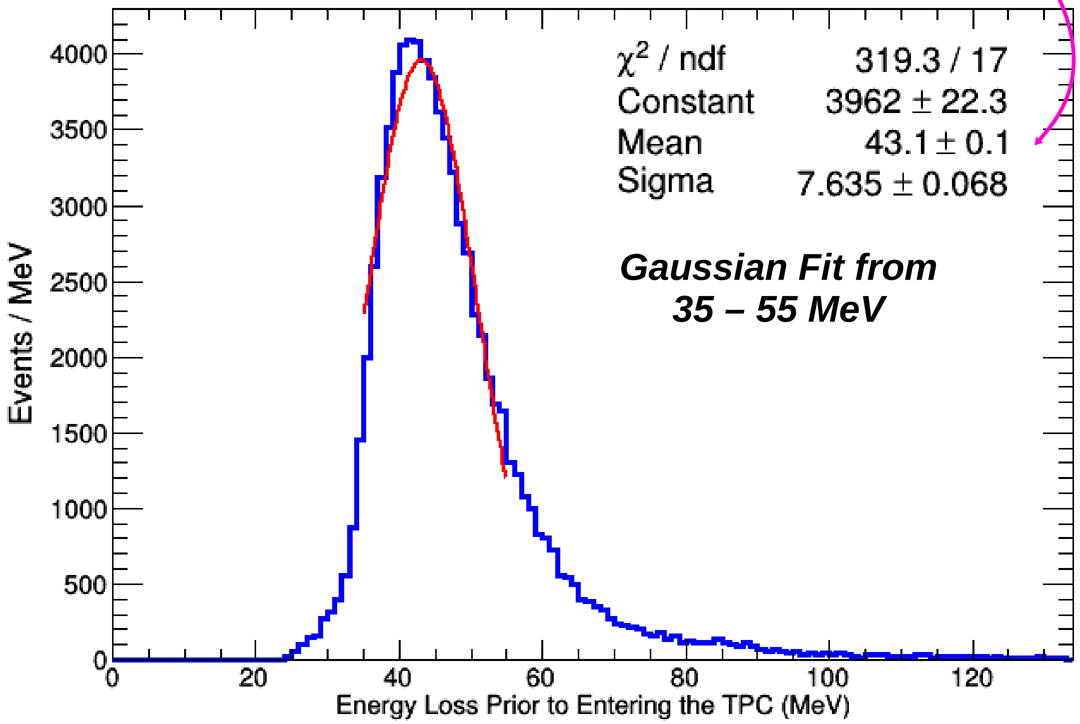


The uncertainty on dE/dX is assessed with a simple fit to the data.

Assessing Systematics: Energy Loss Before TPC

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

The uncertainty on the upstream energy loss is assessed purely from MC (using a particle gun simulation of the beamline).



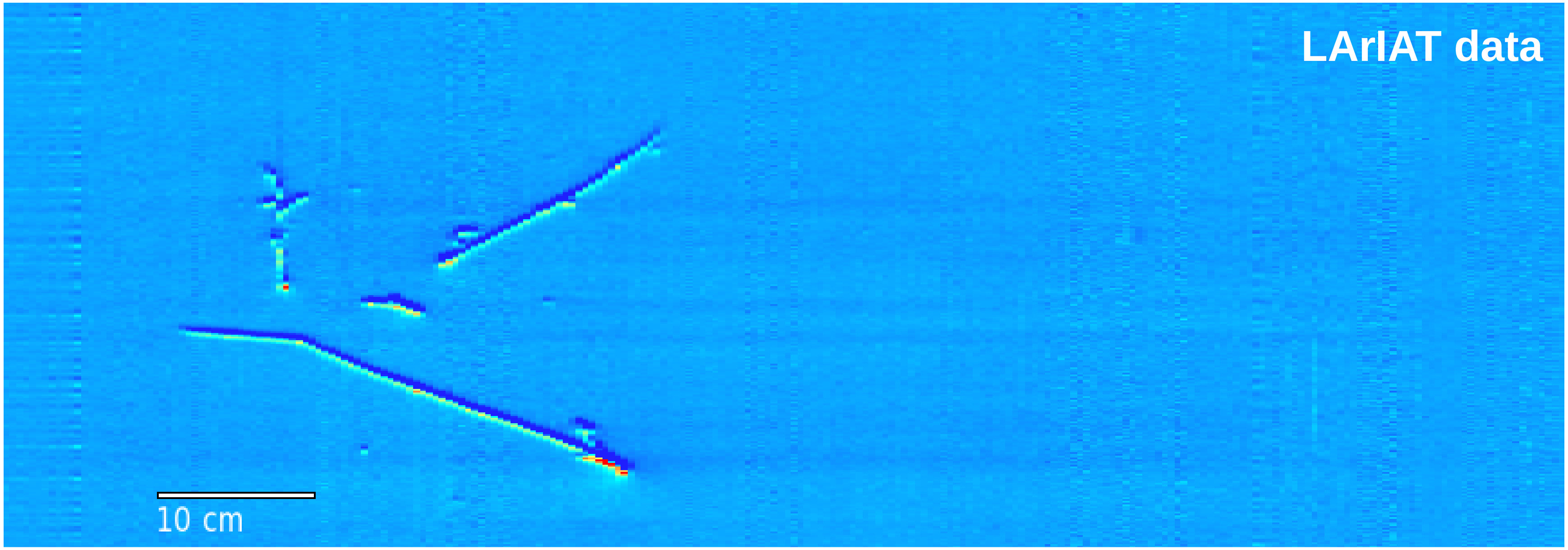
Conclusions and Future Work

Summary

- LArIAT has performed the world's first π-Ar cross-section measurement.
- The measurement uses fully automated reconstruction of interactions in liquid Ar.
  - Common tools for all LAr experiments.
- Next steps for analysis:
  - Full treatment of π decay/capture backgrounds.
  - Possible introduction of aerogel and muon range stack to bring down through-going μ background.

Coming Soon from LArIAT

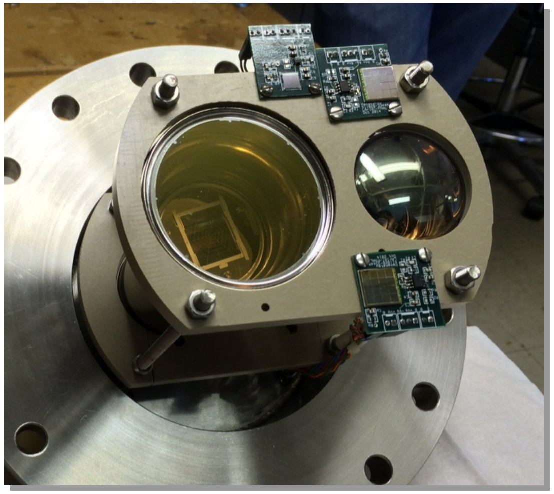
- **More data!**
  - Results shown here are purely from Run 1.
  - Run 2 recently completed.
    - 5× statistics of Run 1.
    - Improved beam tuning ⇒ higher-quality data.
  - Run 3 inbound.
    - R&D focused.
- **More cross-sections!**
  - Exclusive channels: π-Ar absorption, charge exchange, CC-elastic, CC-inelastic (both π^- and π^+)
  - Kaon interactions (inclusive analysis already underway)
  - Proton interactions
  - etc etc.
- **More R&D!**
  - e/γ discrimination studies
  - Light collection studies
  - Low-energy studies (with radioactive sources)
  - Wire pitch studies



Stay Tuned!

Backup Slides

Light Collection Components



Two cryogenic PMTs

Three silicon photomultipliers (SiPMs)* on custom preamp boards.

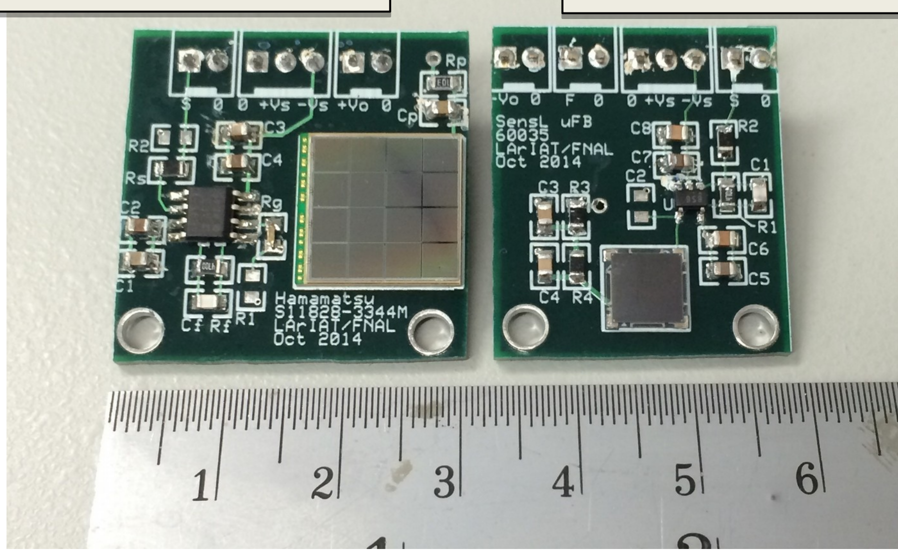
*VUV SiPM not shown

Hamamatsu PMT
R-11065
(3” diameter)

ETL PMT
D757KFL
(2” diameter)

Hamamatsu S11828-3344M,
4x4 array, w/preamp

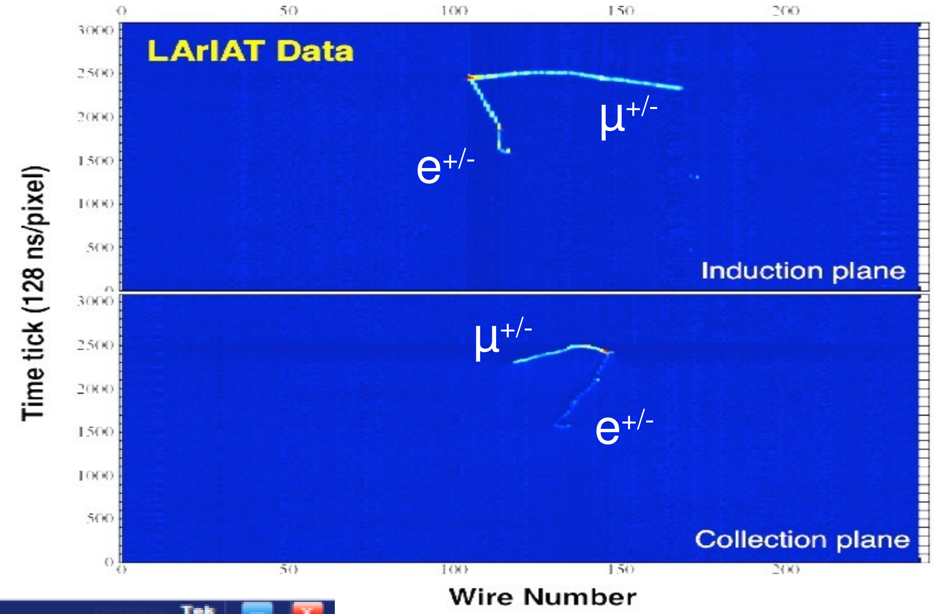
SensL MicroFB-60035
w/preamp

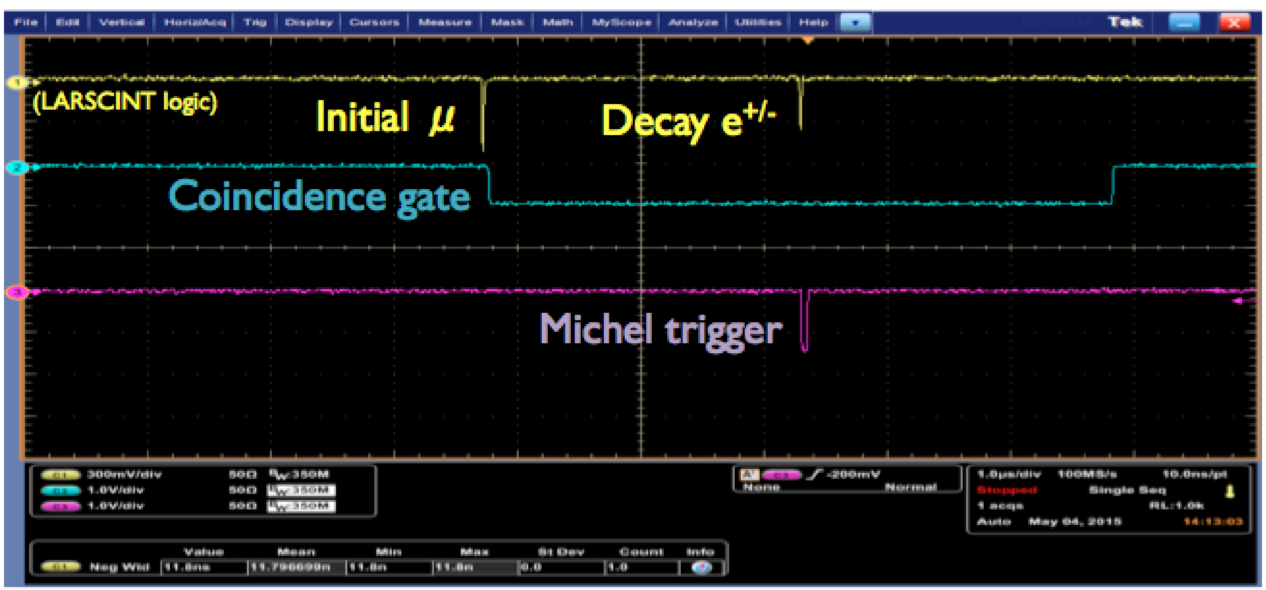


Michel Electrons: Triggering

$\mu^{+/-}$ (at rest) $\rightarrow$ $e^{+/-} + \nu_\mu + \overline{\nu}_e$

- Energy calibration
- PID of stopping $\mu^{+/-}$
- Training ground for shower reco, dE/dx measurements..





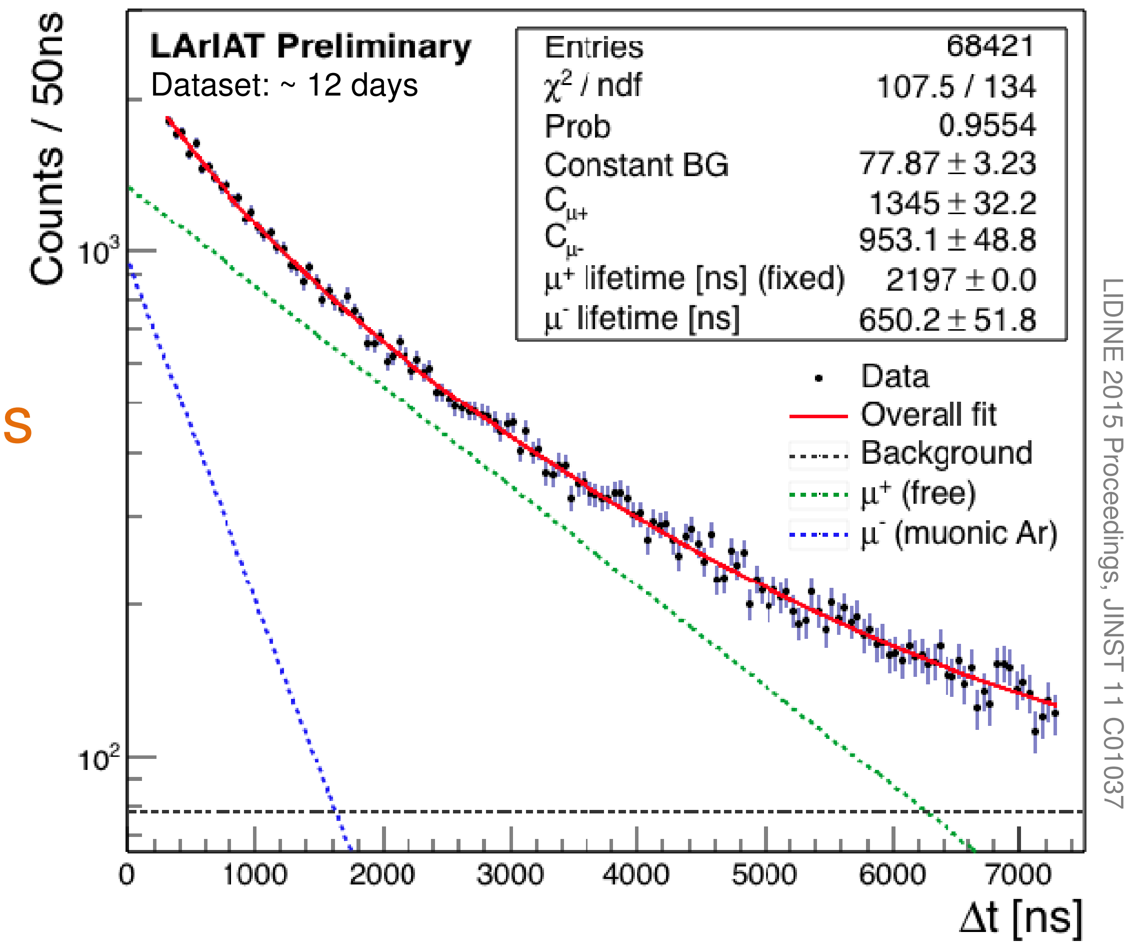
Real-time triggering on Michel es from stopping cosmic μs using **light signals**

Michel Electrons: μ capture lifetime in Ar

$$\boxed{\tau_{\mu-}} = \left(\frac{1}{\tau_c} + \frac{Q}{\boxed{\tau_{free}}} \right)^{-1}$$

650 ± 52 ns
(from fit result, preliminary)

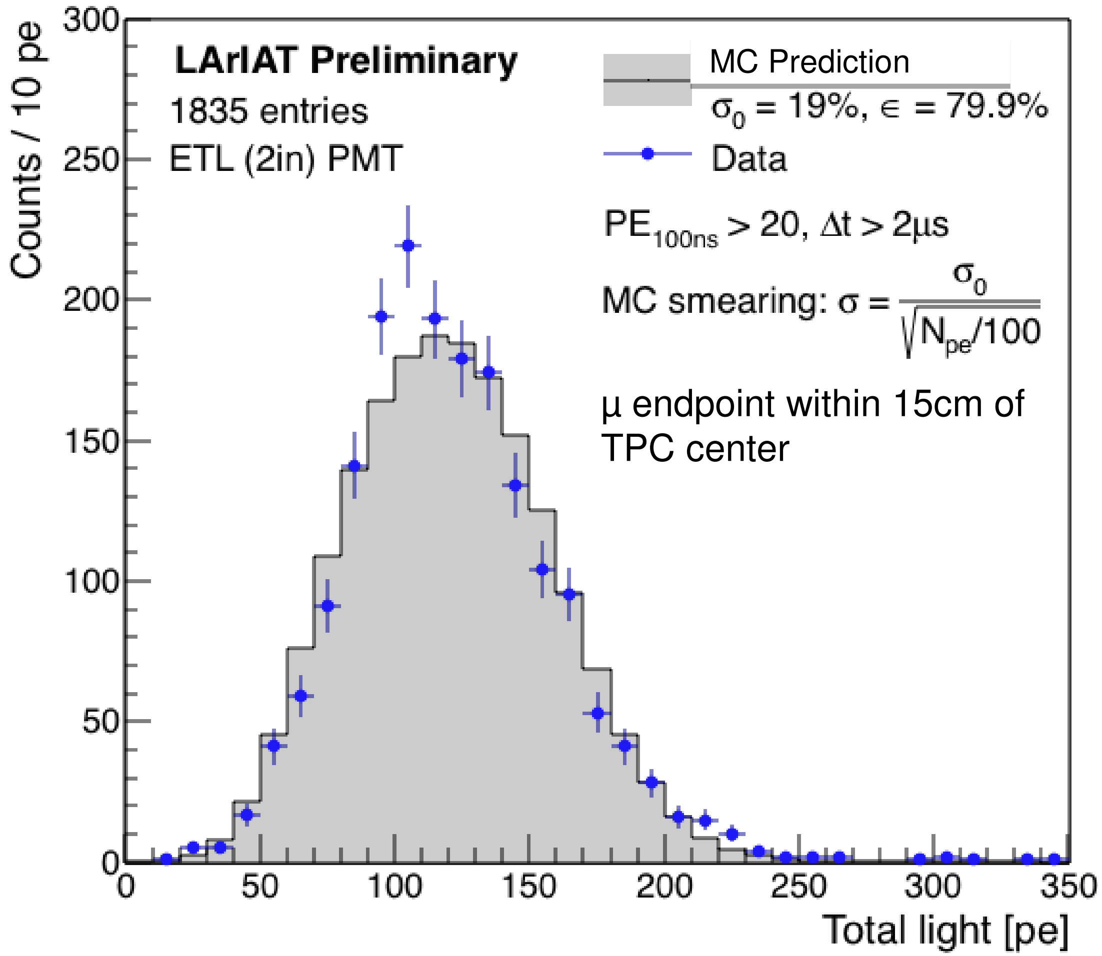
918 ± 109 ns



Early results agree w/ recent measurement[1] (854 ± 13 ns) and theory prediction[2] (851ns)

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

Michel Electrons: Photoelectron Spectrum



- Michel-candidate signals integrated to get PE spectrum
- Data in approximate agreement with preliminary MC
  - Gives confidence in MC-predicted LY: 2.4 pe/MeV for 2" ETL PMT (Run I)

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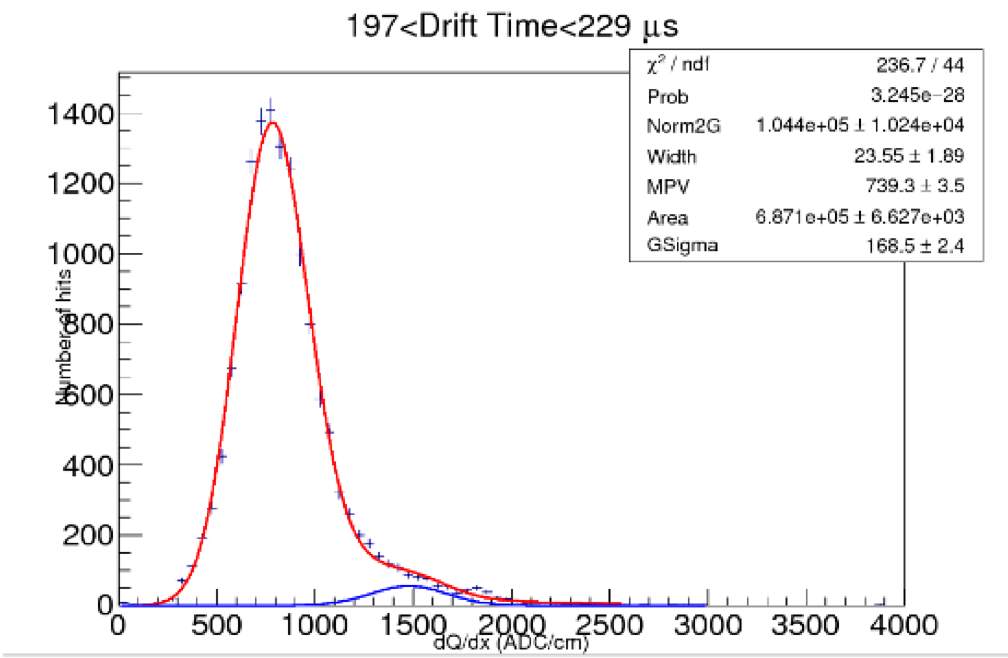
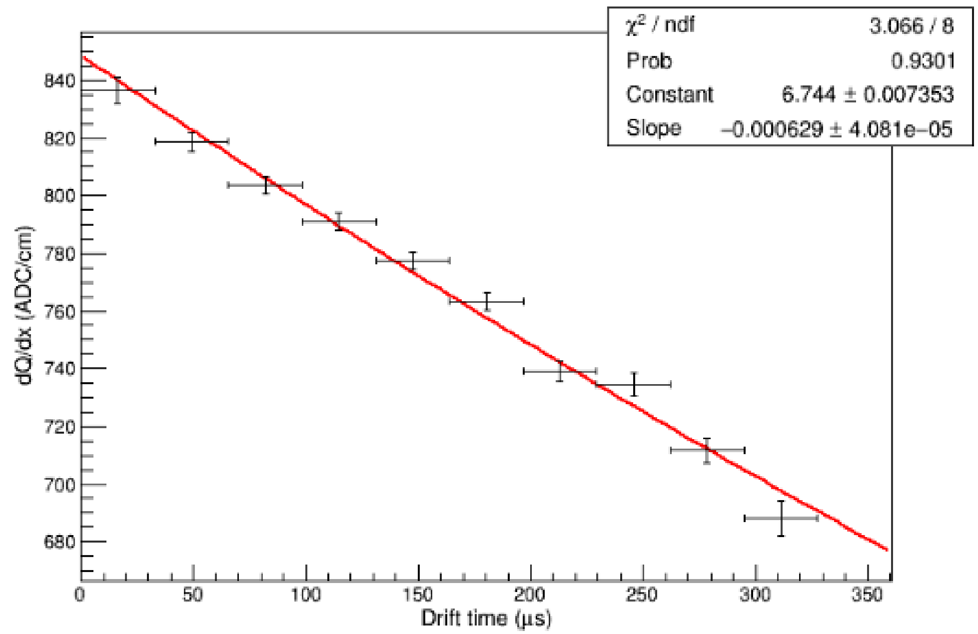
Purity Measurement Method





- Each bin in the histogram on the right comes from result of a fit as shown on the left.
- An exponential fit to the right-hand plot gives the electron lifetime.

Pion Backgrounds