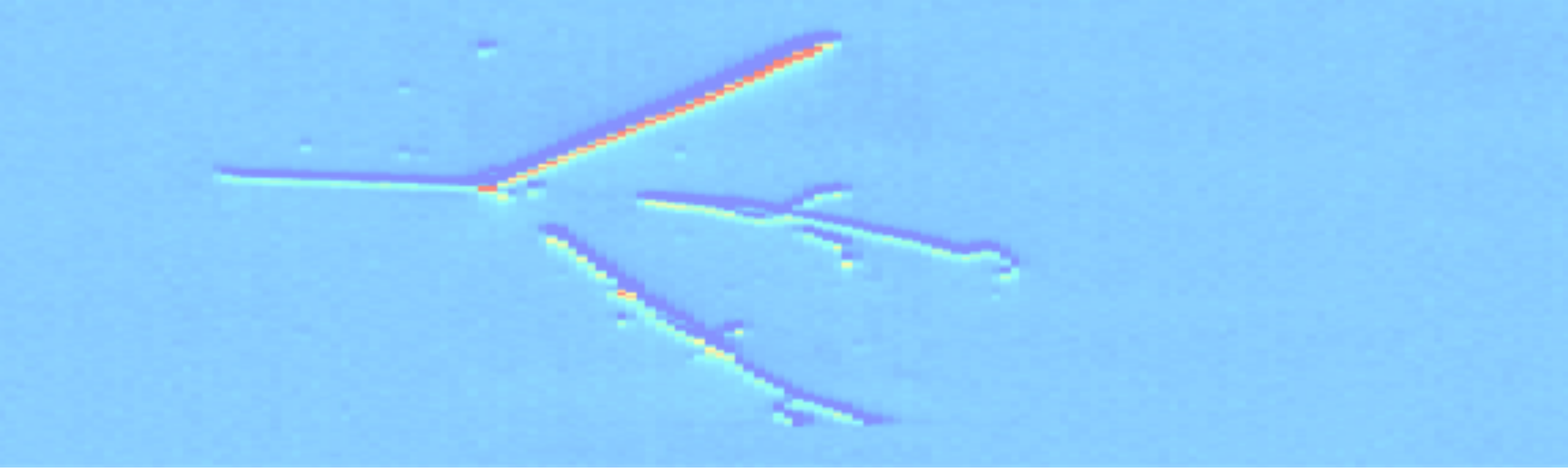
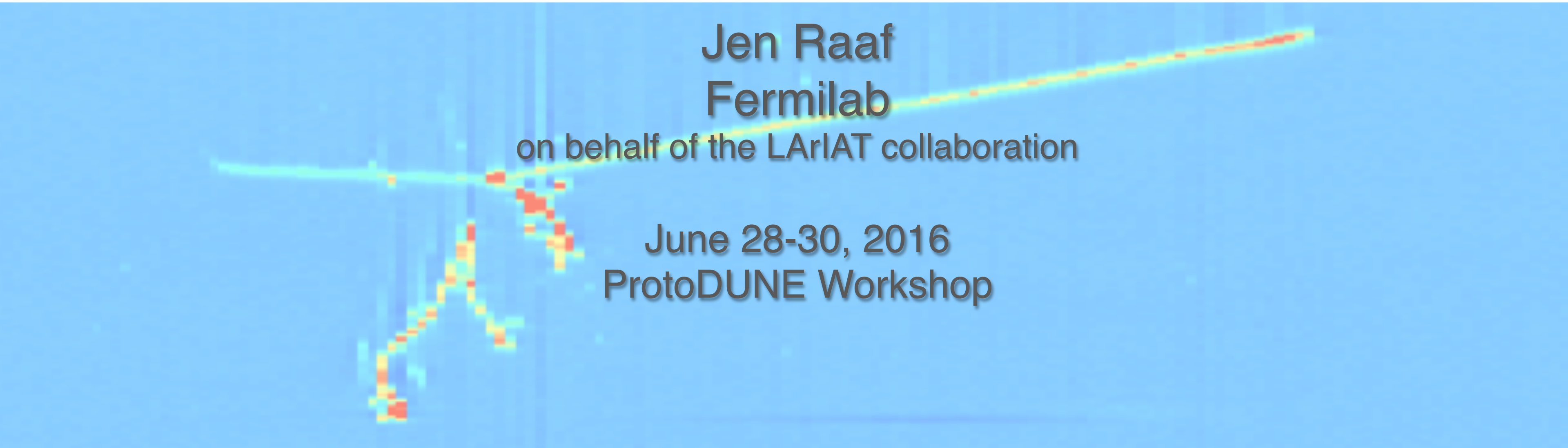


LArIAT

LArTPC In A Testbeam



Jen Raaf
Fermilab
on behalf of the LArIAT collaboration

June 28-30, 2016
ProtoDUNE Workshop

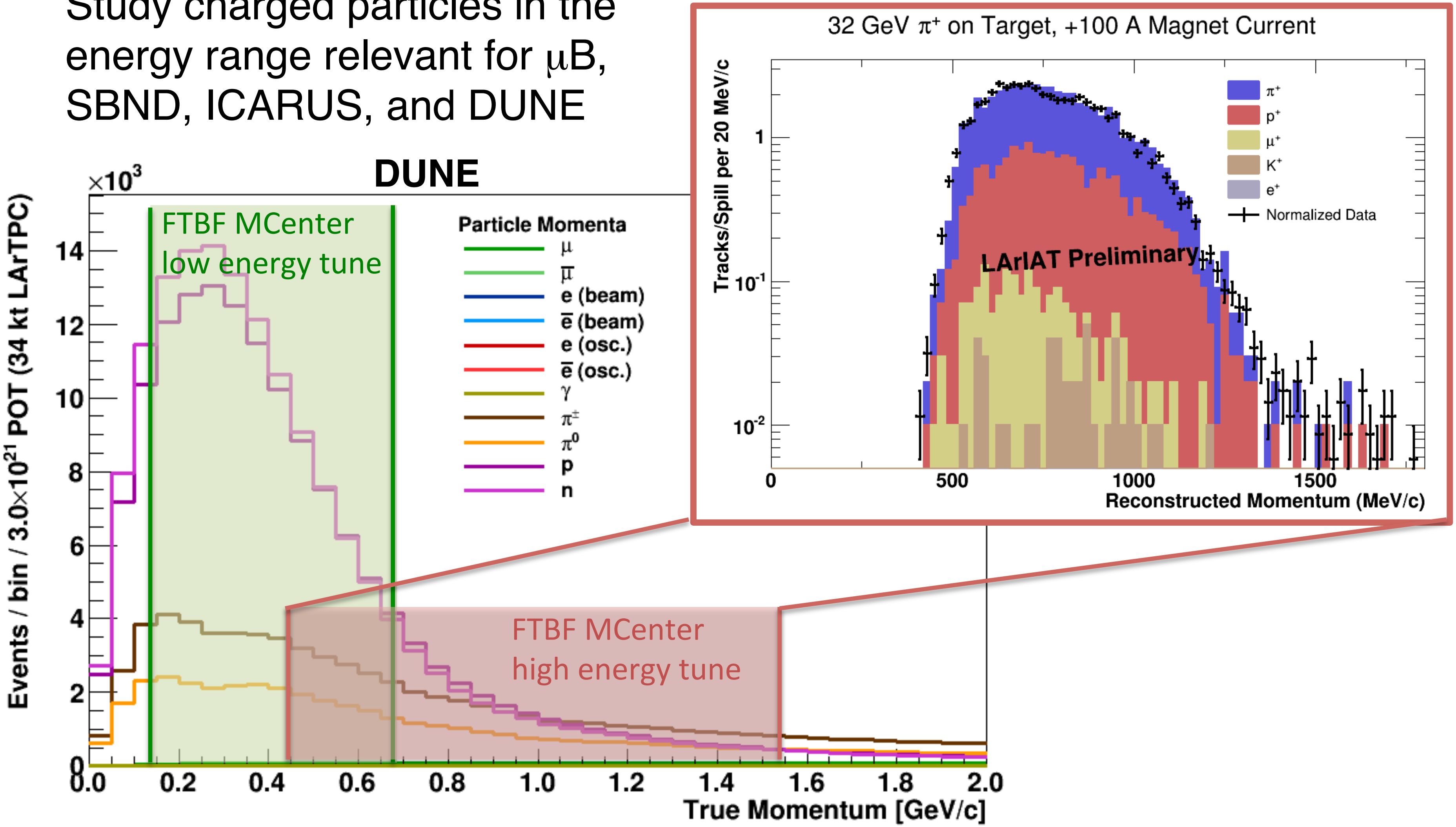
Motivation and Method

LArTPC in the Fermilab Test Beam Facility

Study charged particles in the energy range relevant for μB, SBND, ICARUS, and DUNE

LArIAT

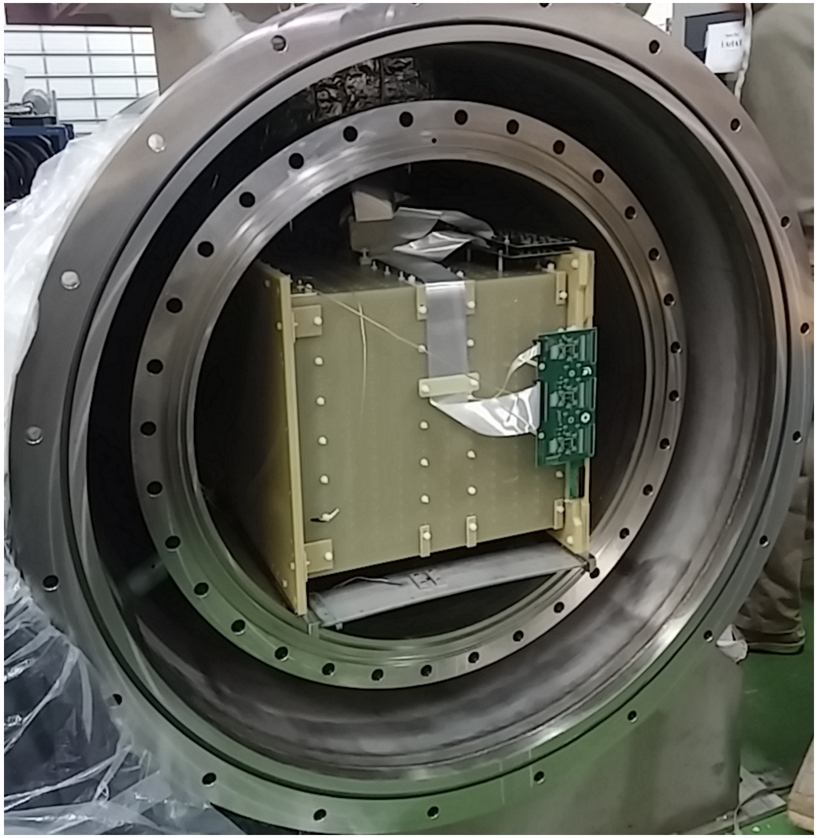
DUNE



LArIAT Goals

Program for comprehensive characterization of LArTPC performance in the range of energies relevant to upcoming neutrino experiments.

- Physics goals
  - Hadron-Ar interaction cross sections (π,K)
  - Study of nuclear effects
  - Geant4 validation
  - Develop criteria for determining particle charge based on topology (decay vs. capture), without magnetic field
  - Electron/photon shower ID
- R&D goals
  - Ionization and light production properties
    - Establish relationship between energy deposited to charge and light collected, for stopping tracks of known energy
  - Optimization of particle ID methods
  - 2D & 3D event reconstruction



Pion-Argon Cross Sections

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

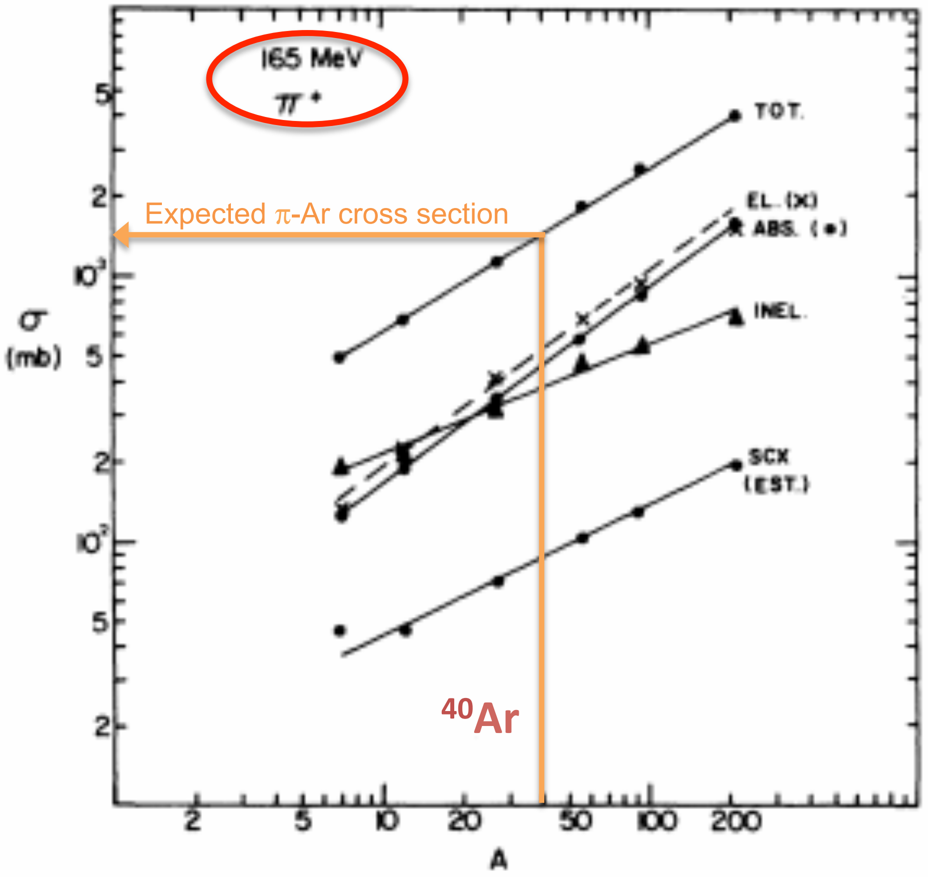


FIG. 9. Decomposition of the total π^+-nucleus cross section at 165 MeV. The lines are least squares fits to power laws.

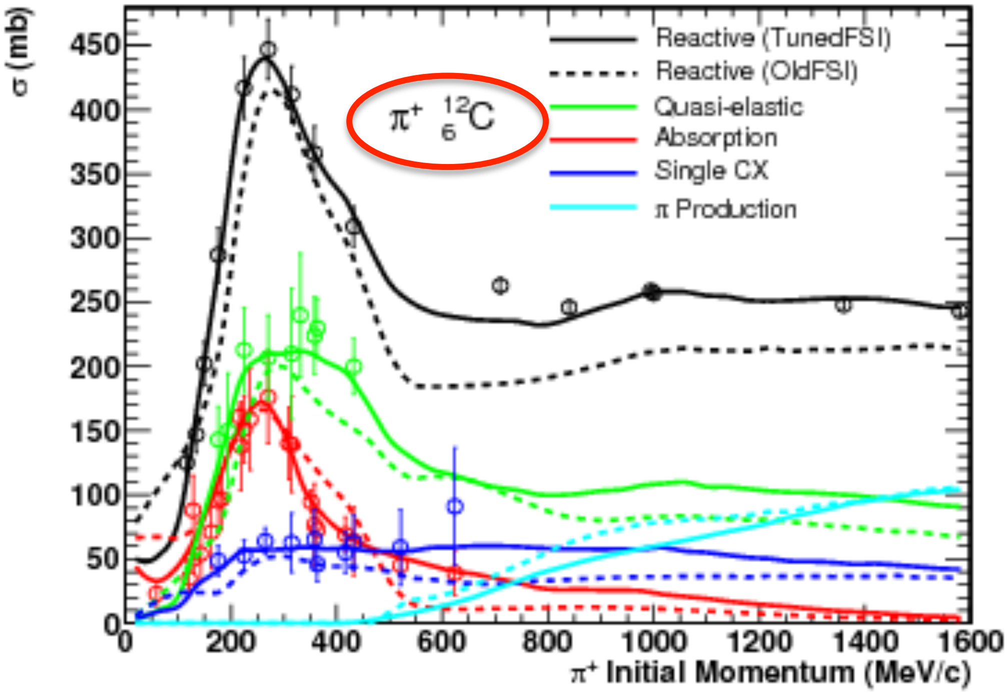
- Predictions for ^{40}Ar come from interpolation between heavier/lighter nuclei

LArIAT measurements:
- Total interaction cross section
- Exclusive interaction channels
    - Absorption
    - Charge exchange
    - Inelastic & elastic scattering

Charged Pions in LAr

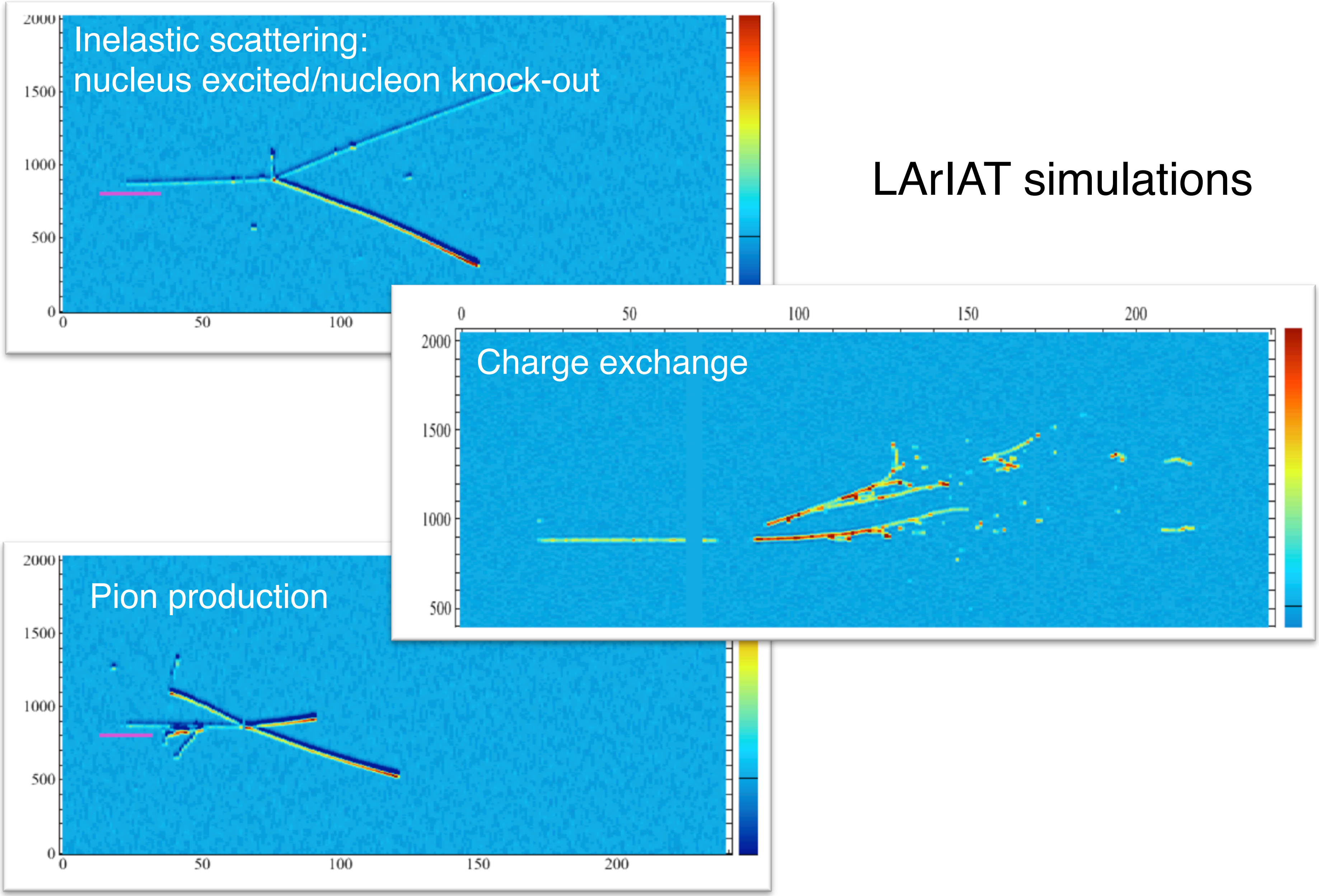
- In the intermediate energy range (~100-500 MeV), pion interactions are dominated by Δ resonance
- Four main components to pion-nucleus interactions:
  - Elastic Scattering: nucleus remains in ground state
  - Inelastic Scattering: nucleus excited/nucleon knock-out
  - Absorption: no pion in the final state
  - Charge exchange: $\pi^{\pm} \longrightarrow \pi^0$
- Above 500 MeV, pion production

AIP Conf.Proc. 1405 (2011) 223-228
arXiv:1405.3973 [nucl-ex]



NEUT pion final state interaction model, tuned to data from pion scattering on various nuclei.

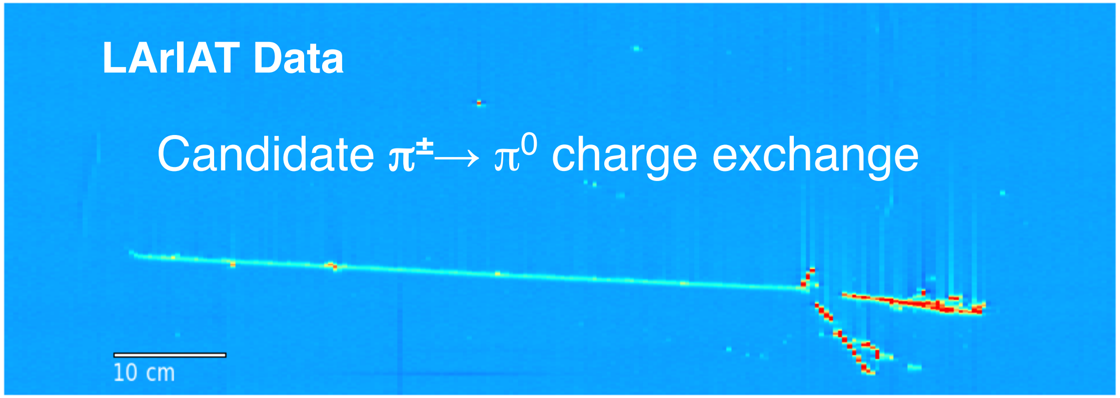
LArIAT simulations

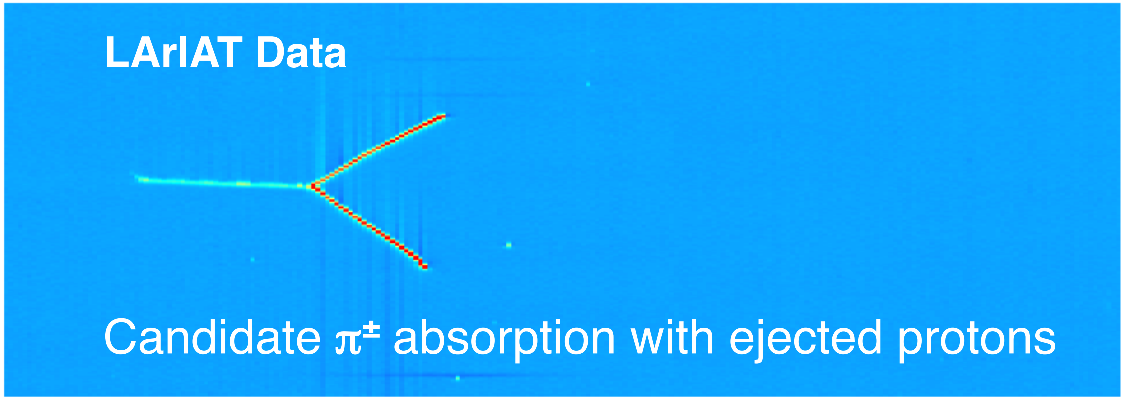

Inelastic scattering: nucleus excited/nucleon knock-out

Charge exchange

Pion production

Nuclear Effects & Final State Interactions





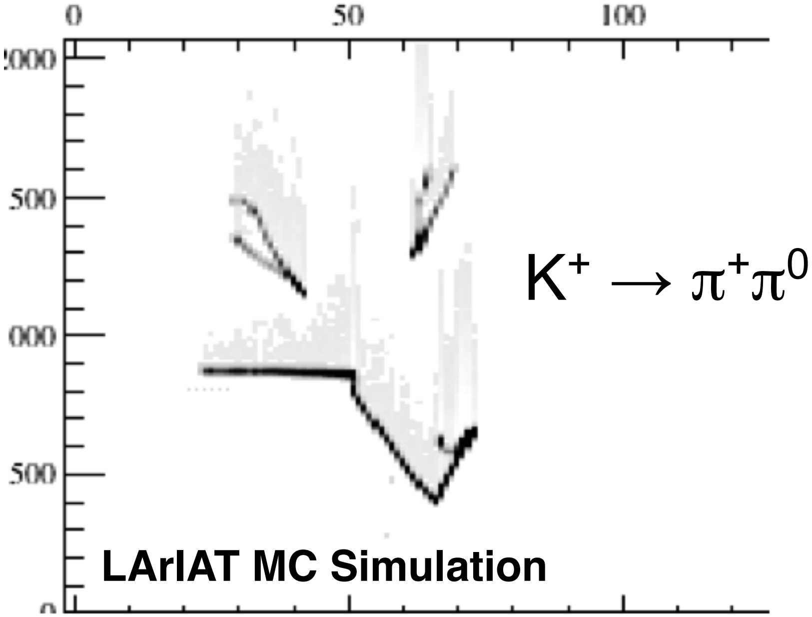
- Tune hadron-nucleus interaction models in Geant4 and neutrino generators
- Study reconstruction systematics and calorimetry

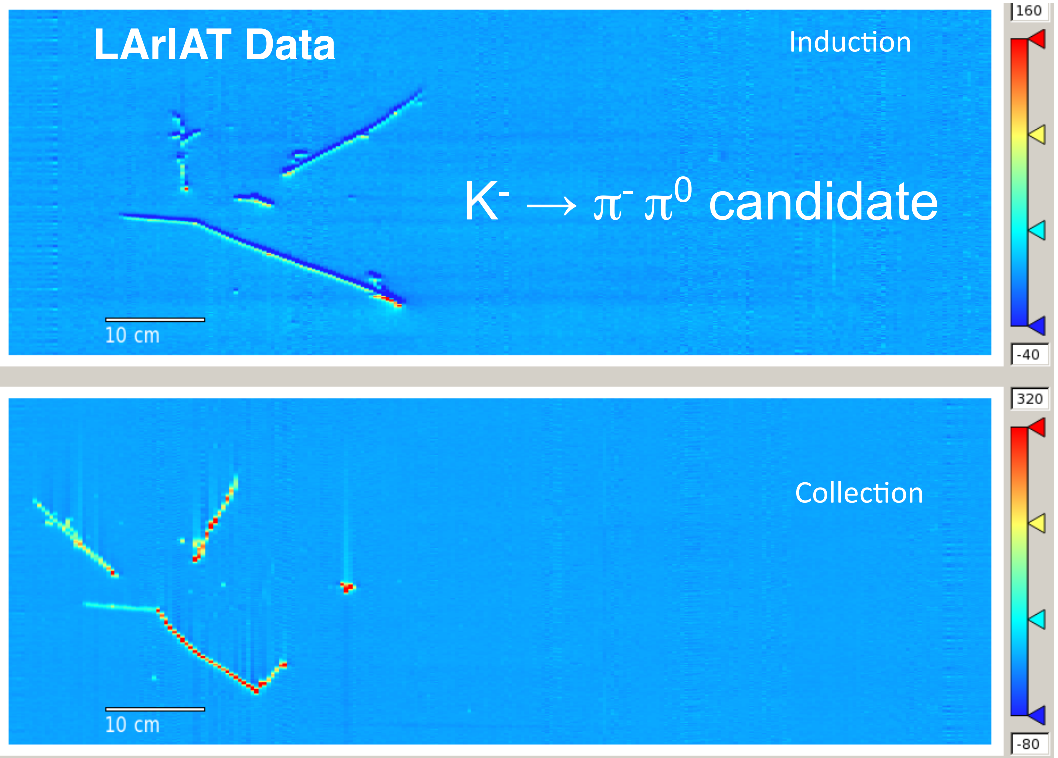
Important for oscillation experiments:

Study and constrain features of backgrounds to ν oscillation

Cross section systematics begin to dominate for precision oscillation measurements

Kaon ID and reconstruction

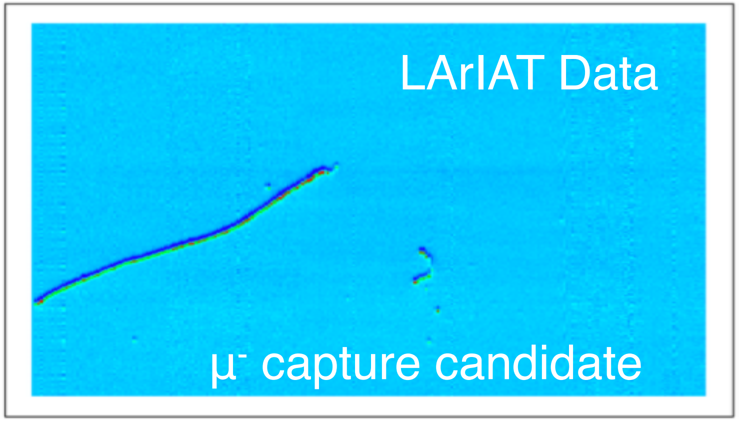


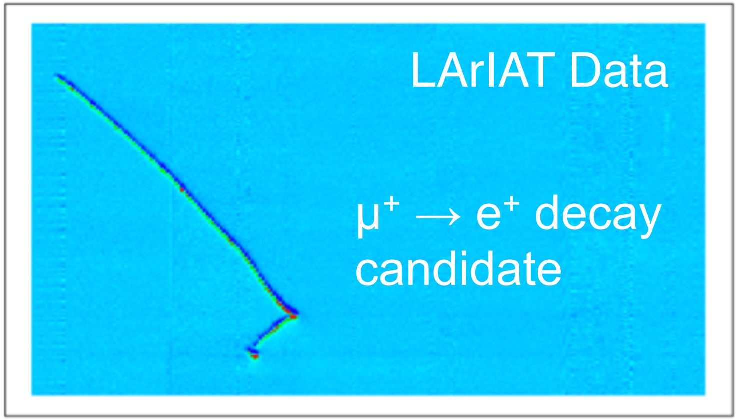


- $K^\pm$ reconstruction
- Study recombination
- Kaon-argon interaction cross section measurement
- Understand kaon/pion and kaon/proton discrimination

Important for baryon-number-violation searches: Relevant to proton decay searches in DUNE

Muon Sign Determination (w/o magnetic field)

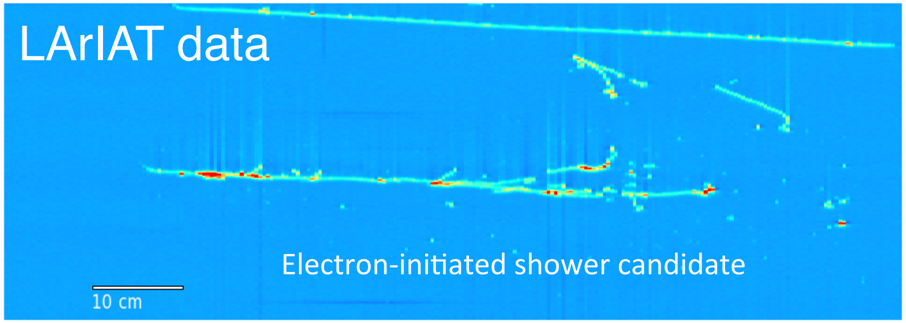


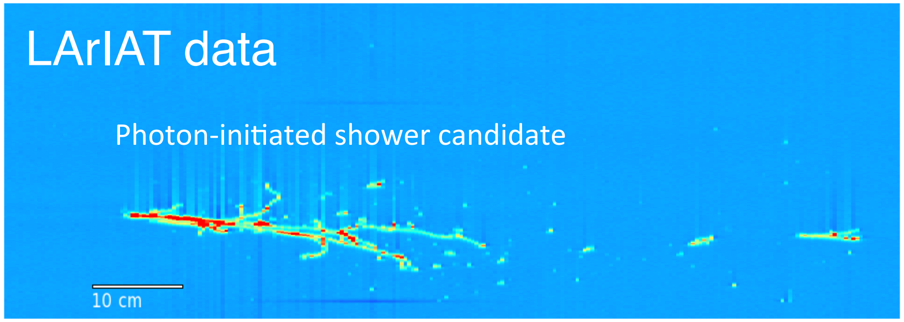


- Explore a LArTPC feature never before (systematically) studied
    - Decay vs. capture in LAr
    - μ^+ only decay, with e^+ emission of known energy spectrum
    - μ^- capture on nuclei followed by γ/n emission (76%) or decay (24%)
    - Capture rate higher in Ar than in lighter elements
- Statistical analysis of fully-contained muons, via timing & pattern recognition

Important for oscillation experiments: Constrain capability to charge-ID primary lepton in ν_μ CC interactions of particular interest for CP violation w/ DUNE

Electron/Gamma Discrimination





- First few cm of show used to separate electron-initiated showers 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 NC π^0 background

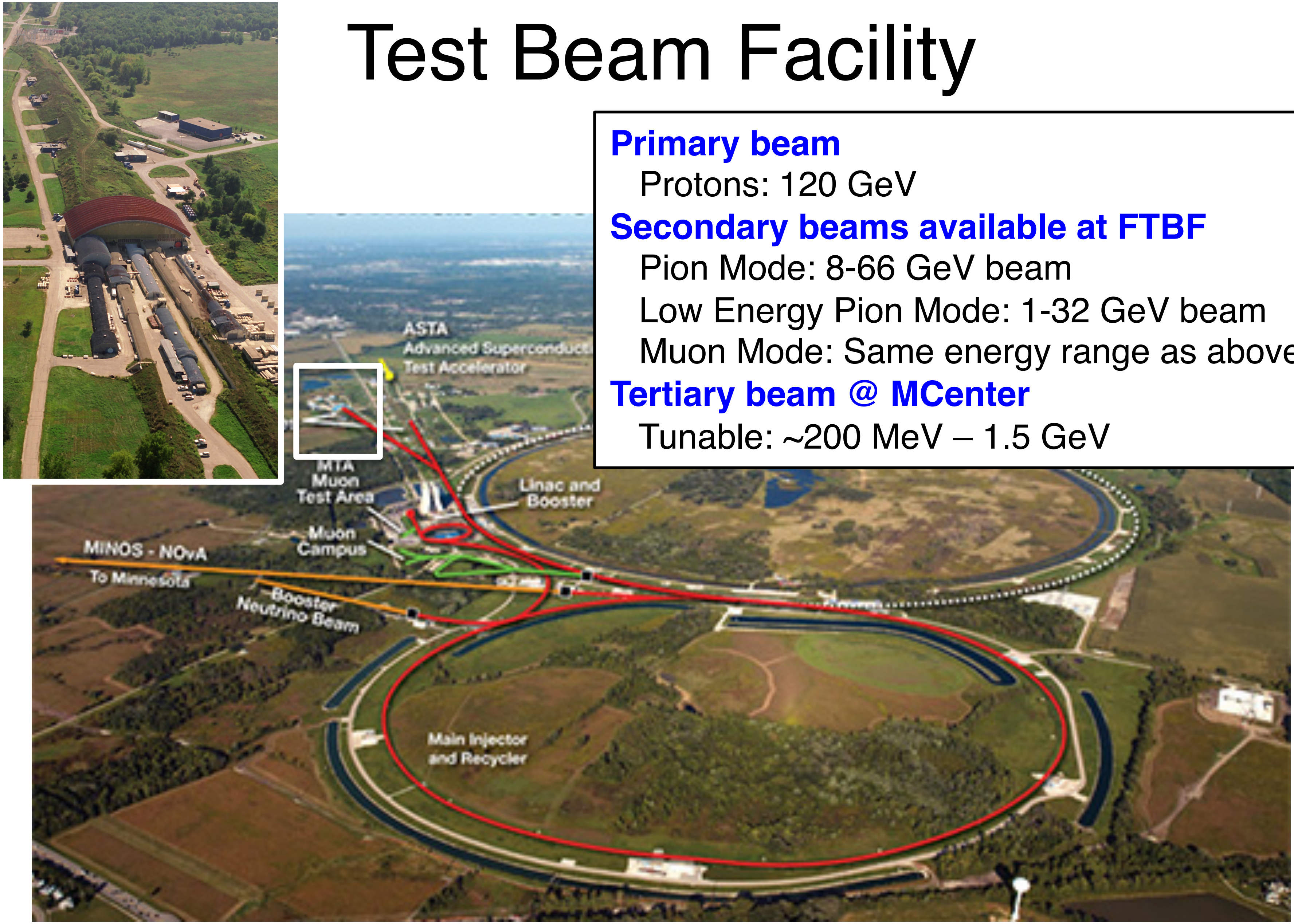
THE EXPERIMENT

Test Beam Facility

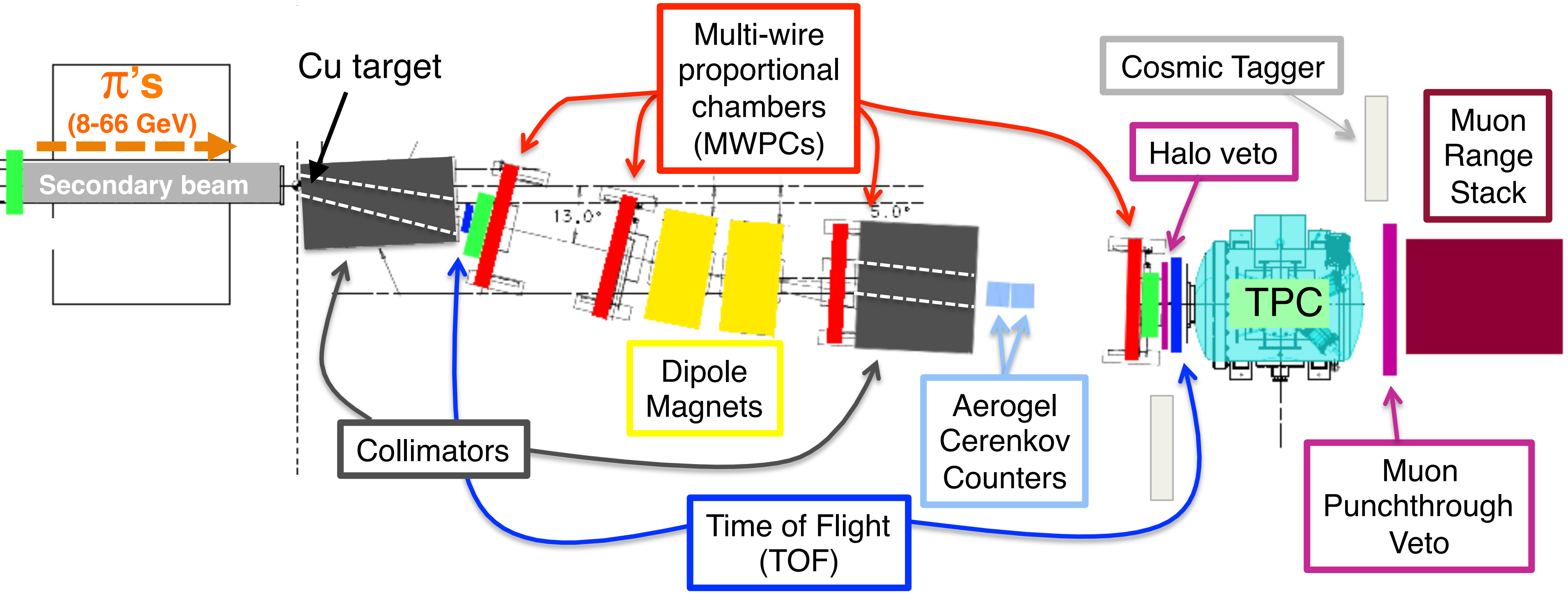
Primary beam
- Protons: 120 GeV

Secondary beams available at FTBF
- Pion Mode: 8-66 GeV beam
- Low Energy Pion Mode: 1-32 GeV beam
- Muon Mode: Same energy range as above

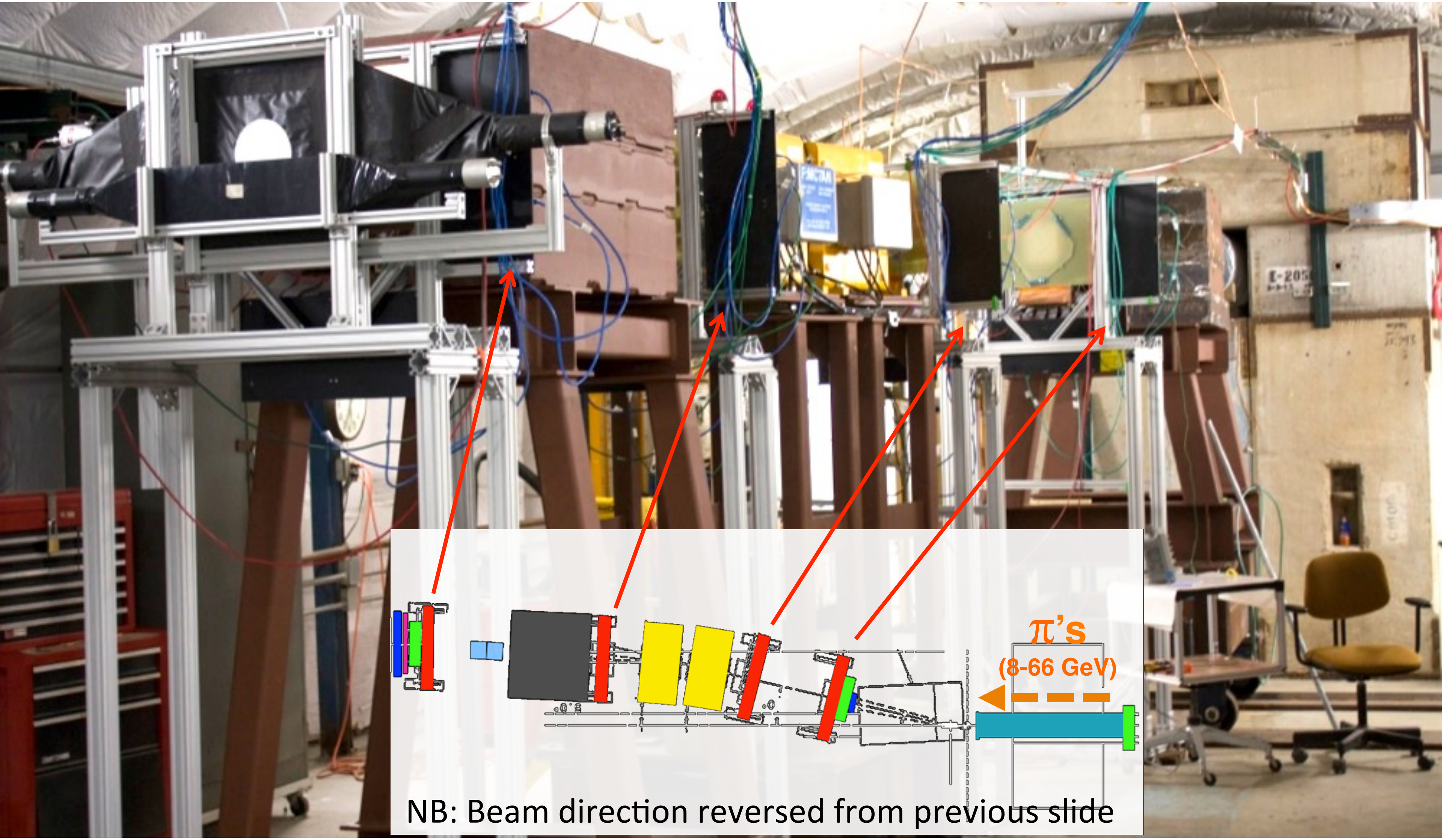
Tertiary beam @ MCenter
- Tunable: ~200 MeV – 1.5 GeV



MCenter Tertiary Beam

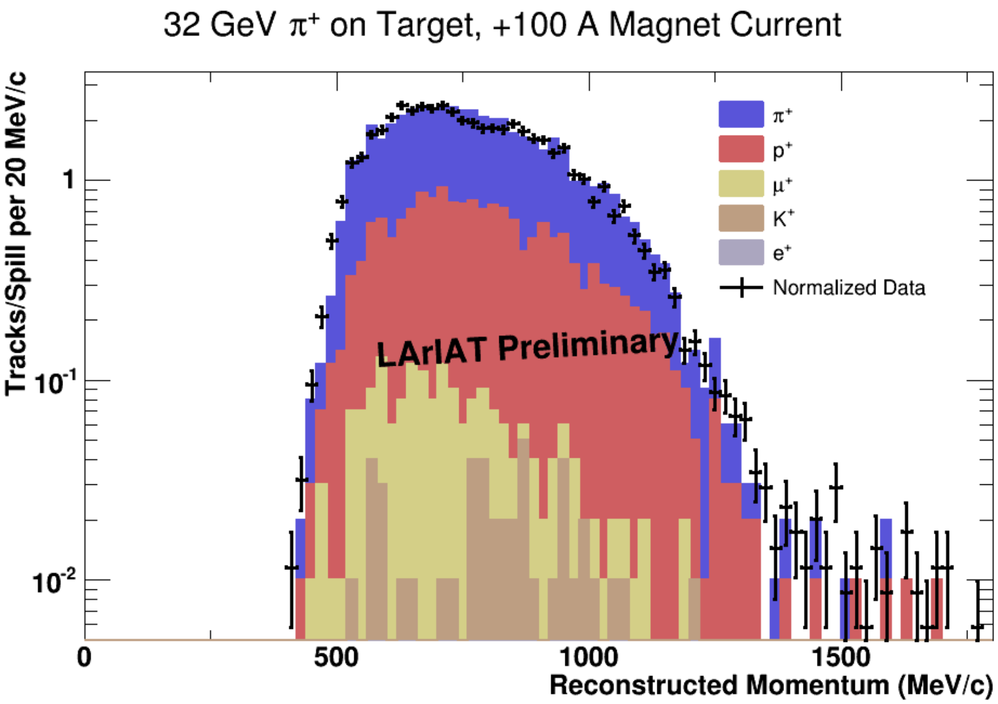


MCenter Tertiary Beam



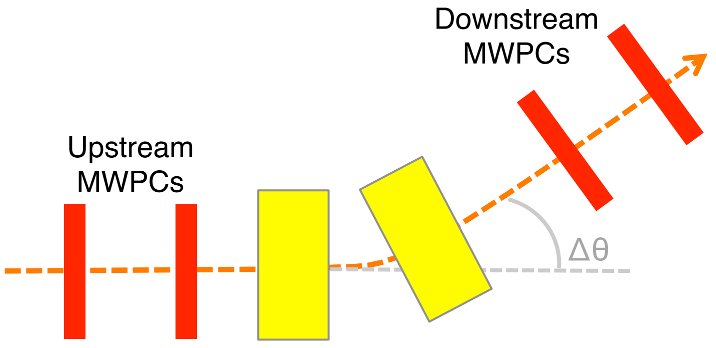
NB: Beam direction reversed from previous slide

Beamline Detectors



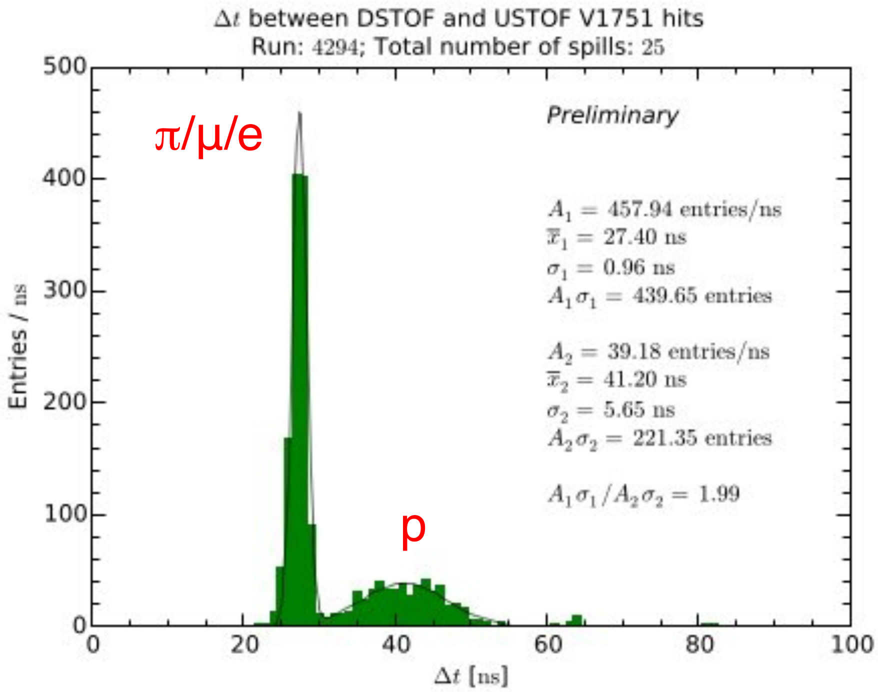
32 GeV π^+ on Target, +100 A Magnet Current

- ☐ **MWPCs** + bending magnet for momentum reconstruction



- ☐ Excellent agreement with simulation

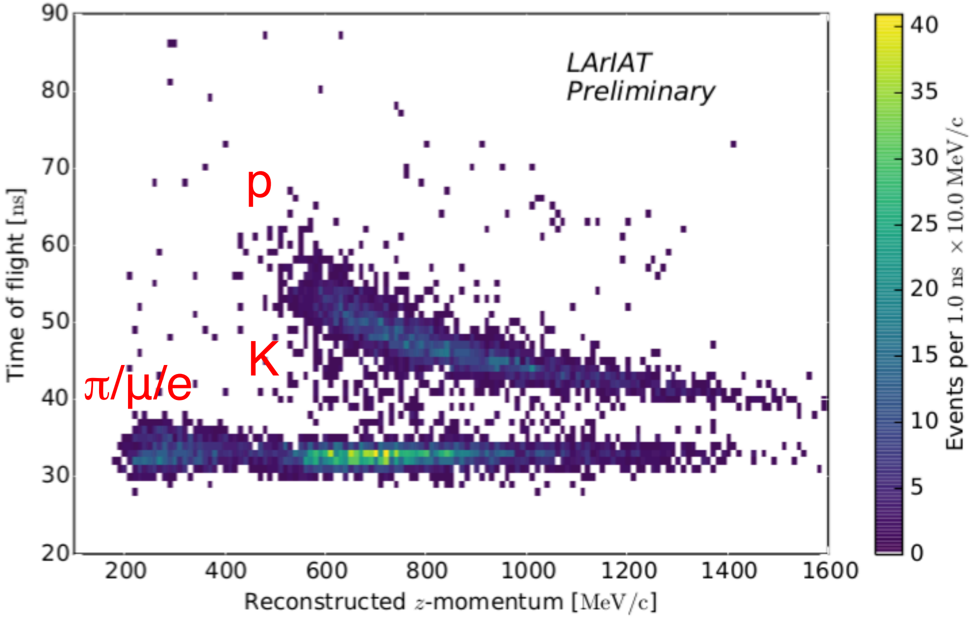
Beamline Detectors



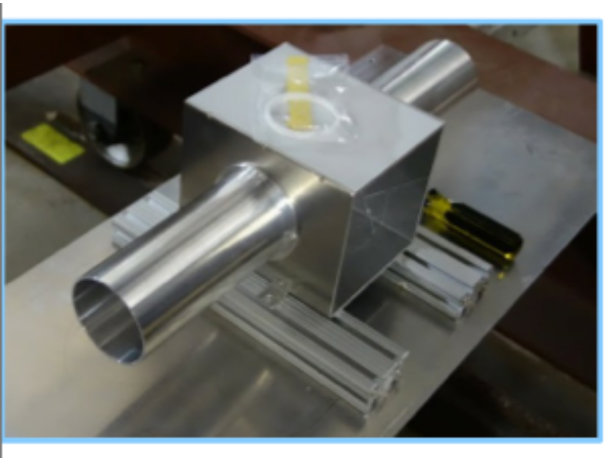
☐ **Time of flight (TOF)** for separation of π/μ/e's from heavier species

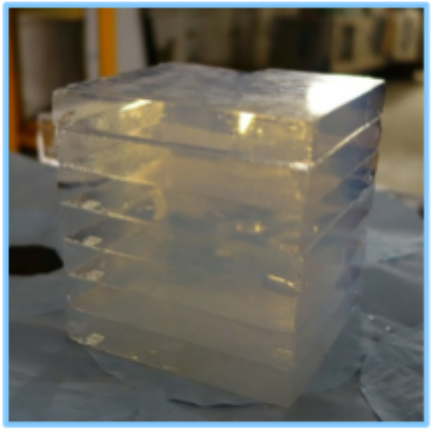
- 2:1 ratio of π:p

☐ **TOF vs. reconstructed momentum**



Beamline Detectors

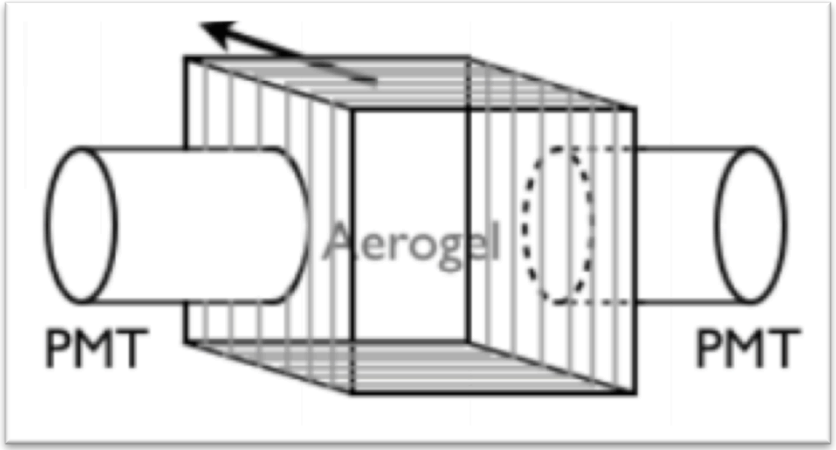


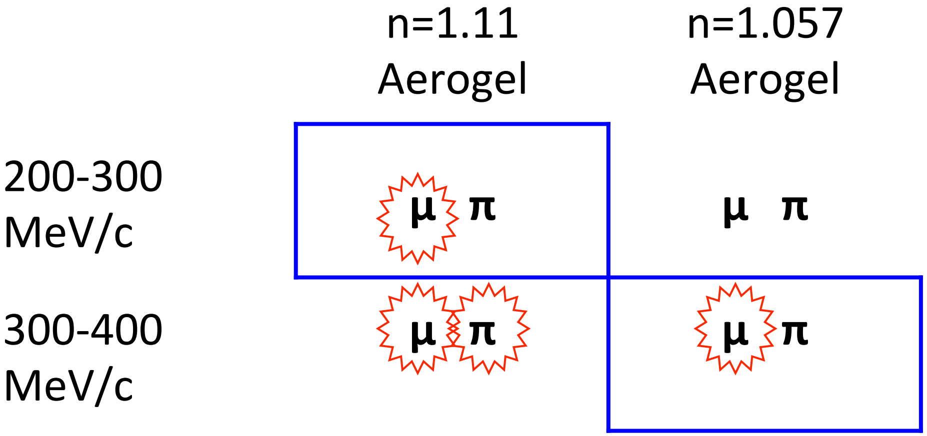


Aerogel Cherenkov counters for further PID

π vs. μ discrimination

Effective for TPC-contained π/μ range: 230-400 MeV/c



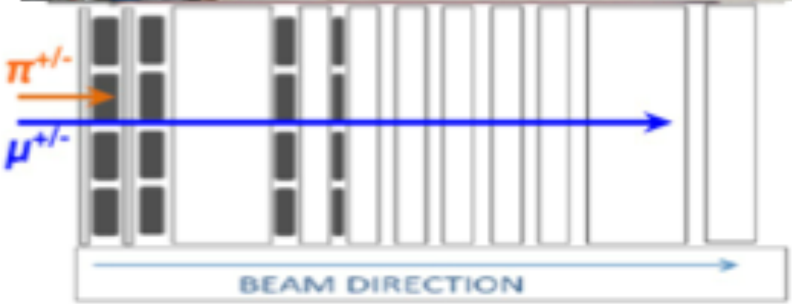


	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

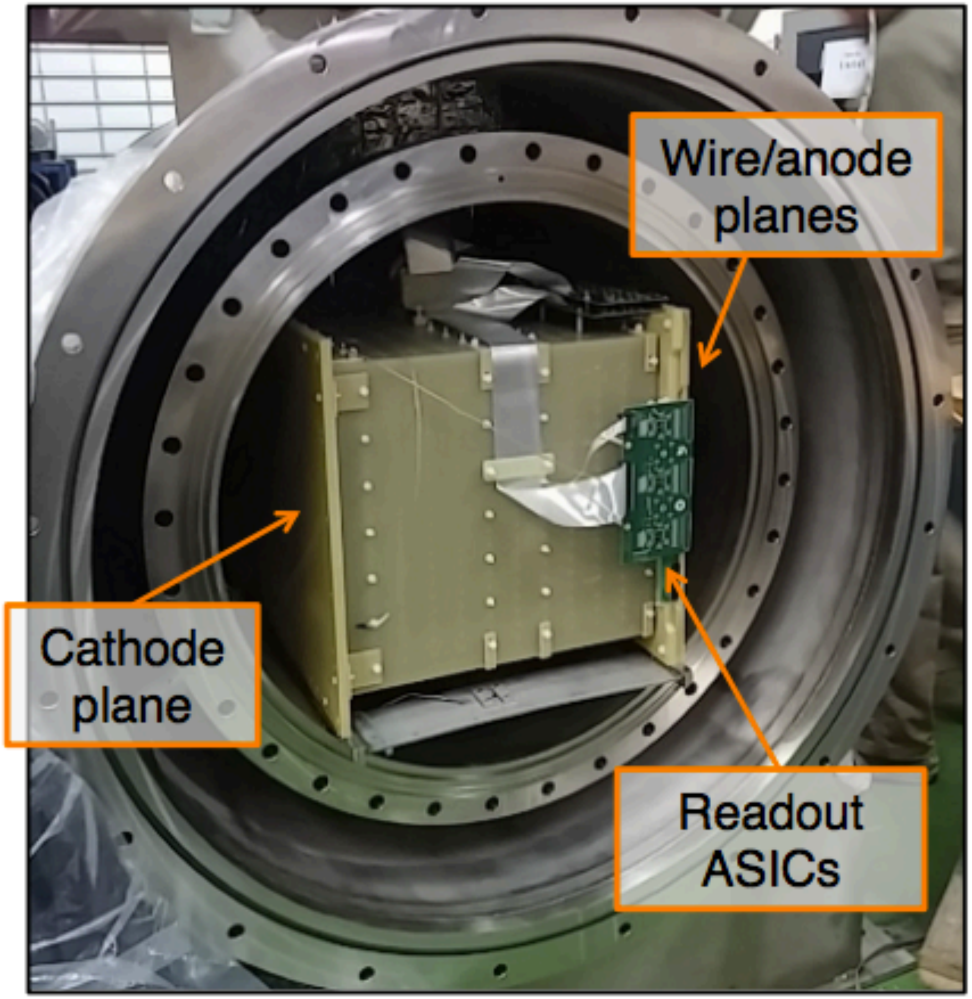
Beamline Detectors

Muon Range Stack to discriminate TPC-through-going pions from muons

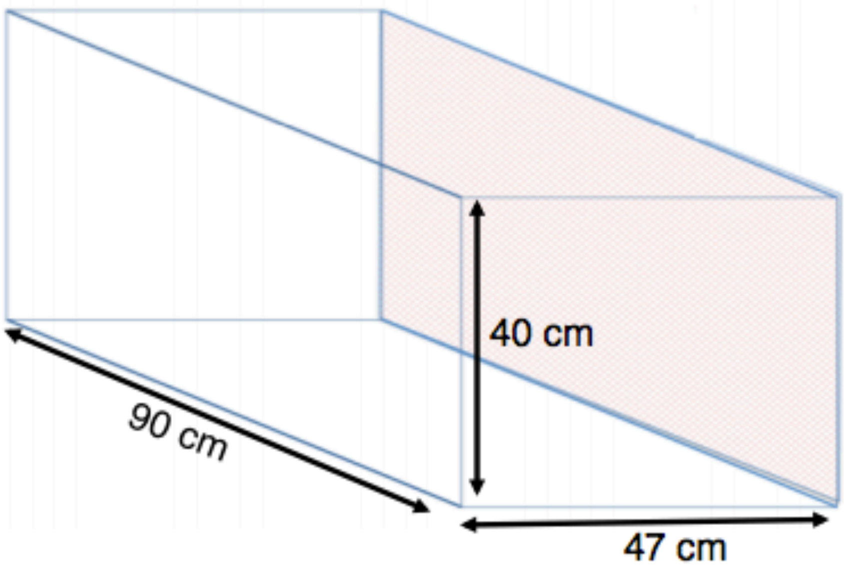
Not in use in analyses yet, but coming soon.



LArIAT TPC

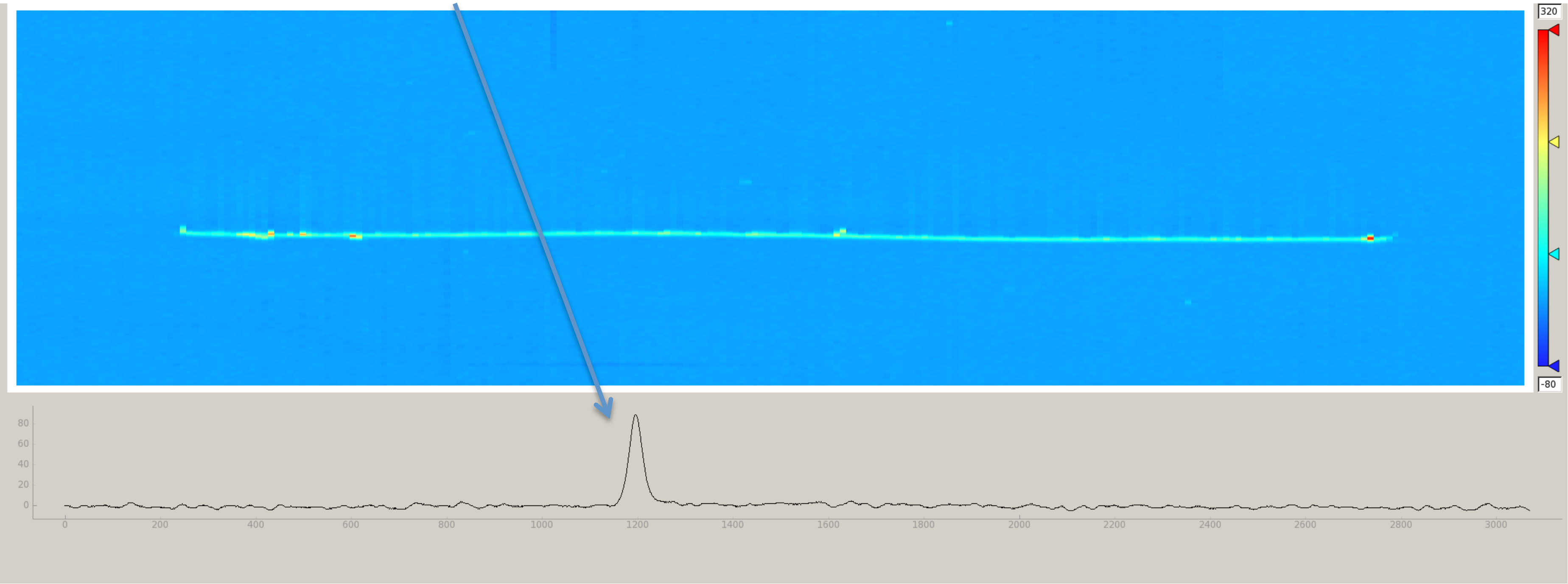


- **The time projection chamber**
  - Repurposed from ArgoNeuT
  - New wireplanes & cold readout electronics
    - 1 (non-instrumented) shield plane: 225 vertical wires
    - 2 readout planes: 240 wires each, +/-60°, 4mm pitch
  - Drift field ~500 V/cm (nominal)
    - Currently doing drift field scan at request of MicroBooNE for PID studies.



Cold Electronics

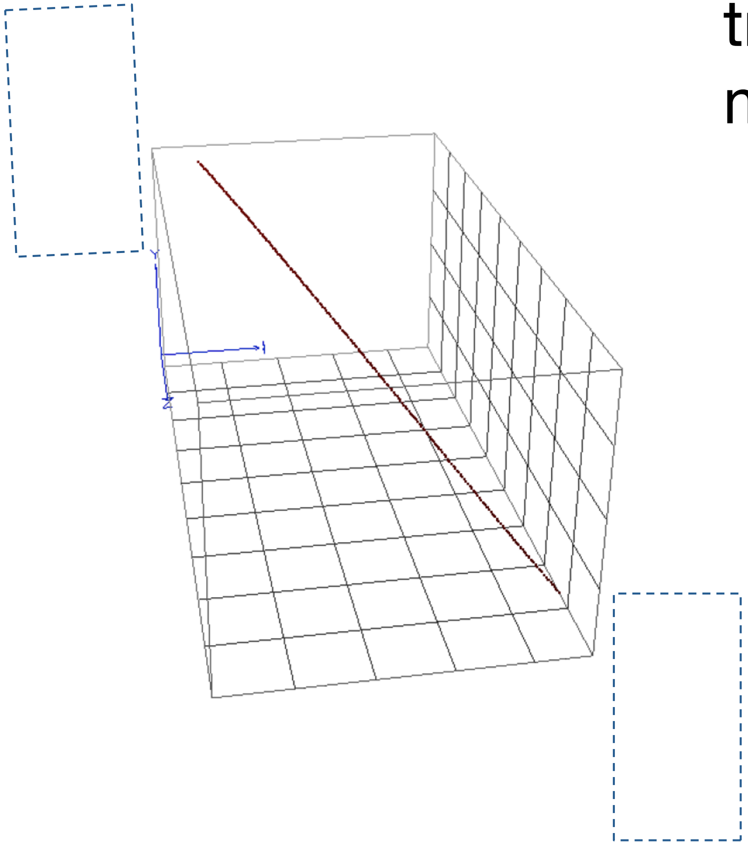
- LArIAT uses the MicroBooNE preamplifying ASIC on a similar custom-designed motherboard
- Signal-to-Noise (MIP pulse height compared with pedestal RMS)
  - Run-I: ~50:1 (ArgoNeuT warm electronics value 15:1)
  - Run-II: ~70:1



LArIAT Data-Taking Periods

- LArIAT Run-I (Apr. 30 – Jul. 4, 2015)
  - 9 weeks beam data (~3 weeks LE + ~5 weeks HE tune)
    - 28k negative polarity spills + 31k positive polarity spills
    - ~10-20 events/spill including cosmics & other non-beam triggers
      - mix of π/μ/K/p/e in beam triggers
      - Collected ~5000 clean π^- (conservatively), ~100 kaons
- LArIAT Run-II (Feb. 18 – Aug. 1, 2016)
  - Expect 21 weeks beam data
    - So far, 51k negative polarity + 56k positive polarity spills
      - Beam tune chosen to increase kaon fraction
      - Estimate $\gtrsim$1000 K^+ collected in this run + many π, p, etc.

Purity Measurement with Muons

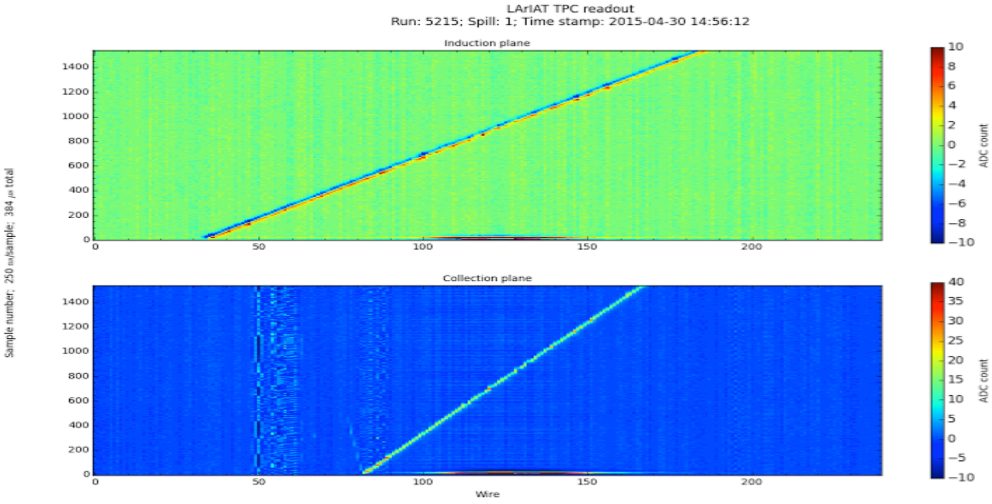


Cosmic tagger paddle

Cosmic tagger paddle

Cosmic tagger paddles for triggering on diagonal cosmic-ray muons (cathode ⟷ anode)

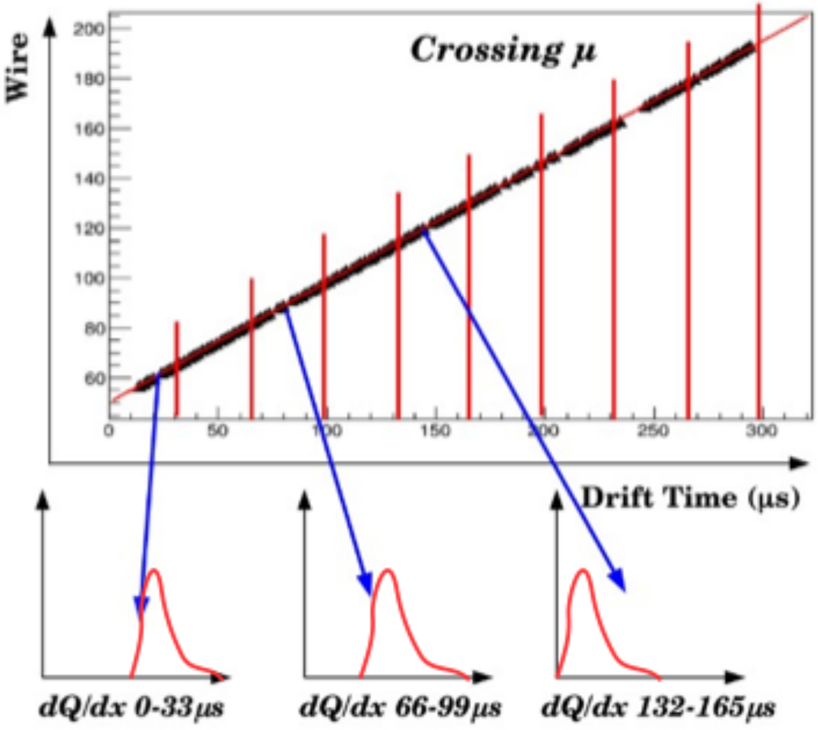
- April 30, 2015 – First cosmic-triggered track within minutes of turning on TPC



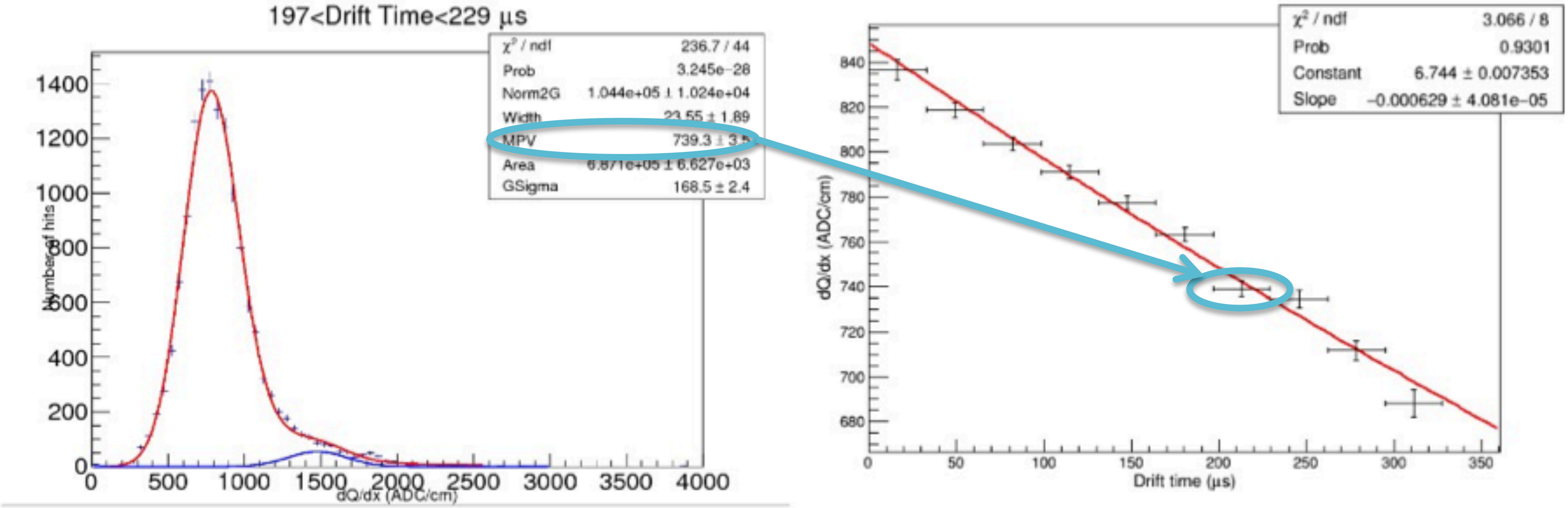
Purity Measurement with Muons

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 exhibits exponential decay trend as a function of drift time ("electron lifetime")
  - Charge deposited near the wire planes will be collected with little or no quenching due to contaminants
  - Charge deposited near the cathode will be maximally quenched as it drifts over to the wire planes

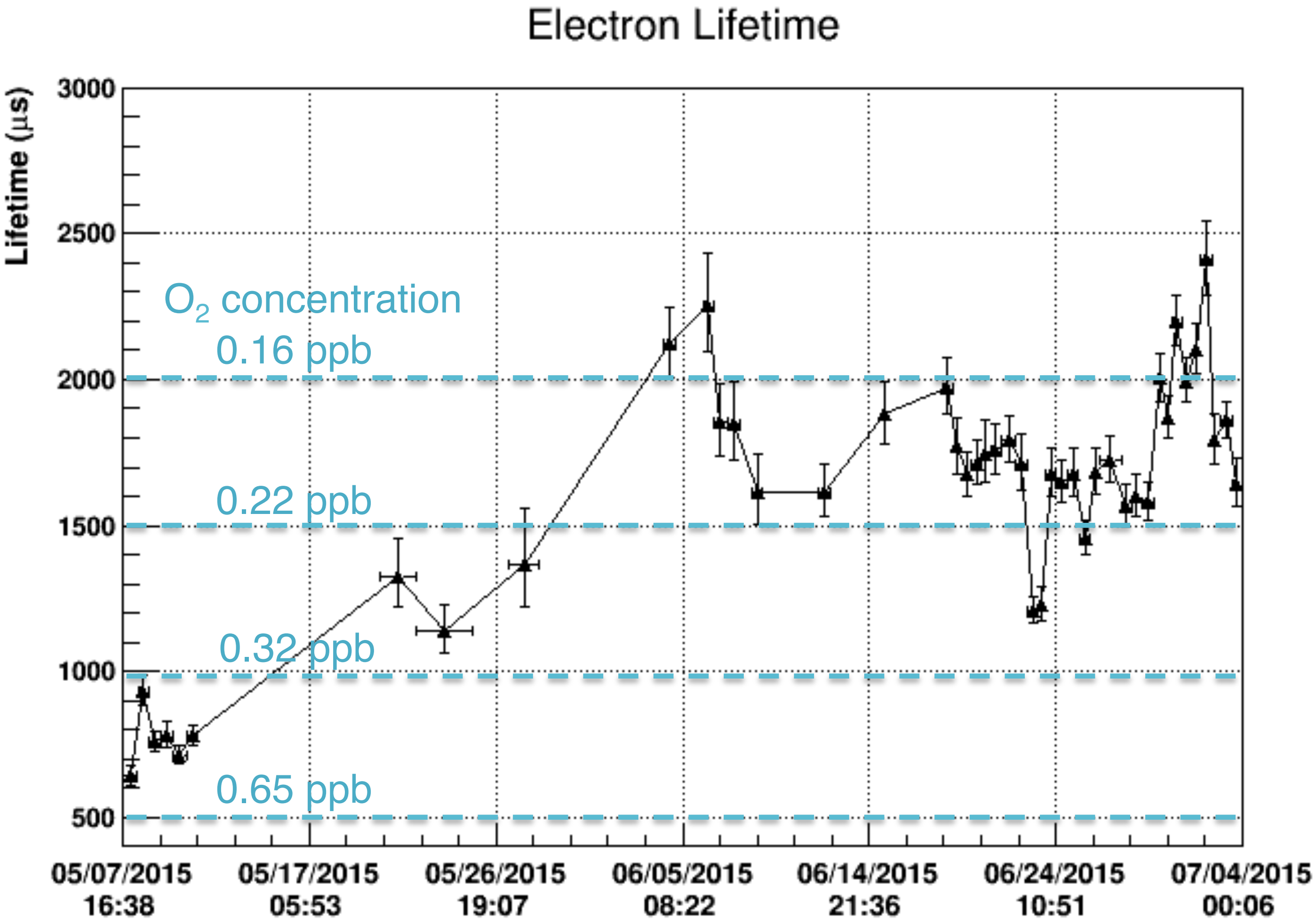


Purity Measurement with Muons



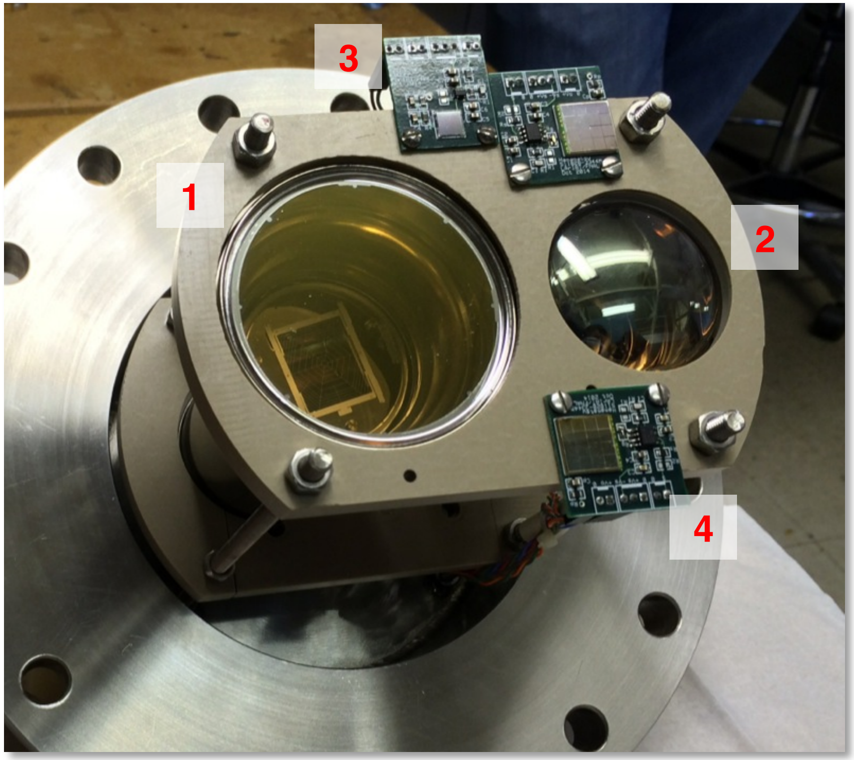
- Each bin in right histogram comes from result of a fit like that on left
- Exponential fit to right plot gives electron lifetime

Run-I Electron Lifetime via Cosmic Muons



Purity achieved without LAr recirculation

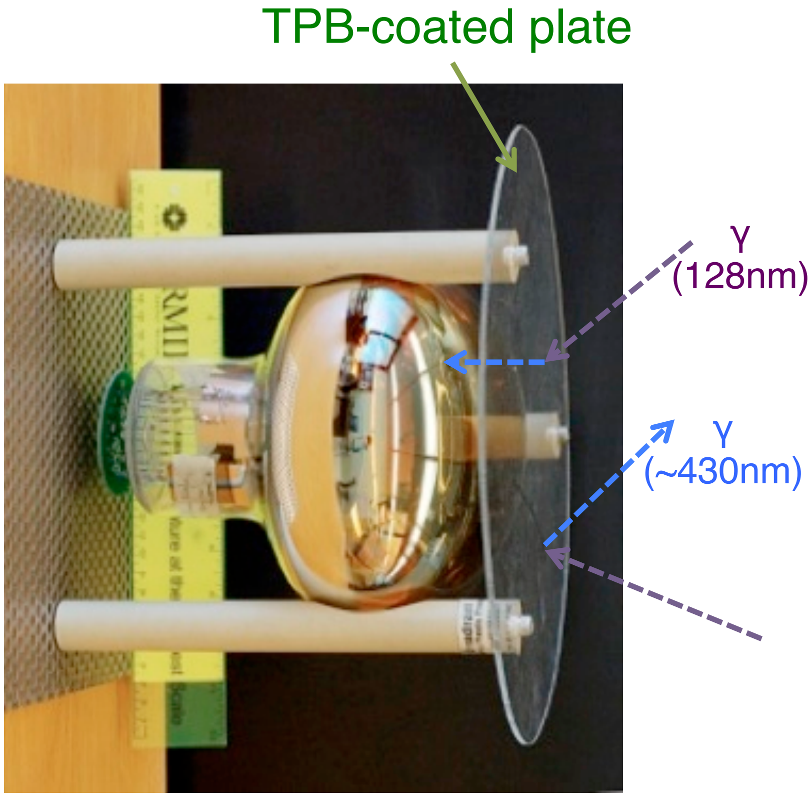
Light Collection System



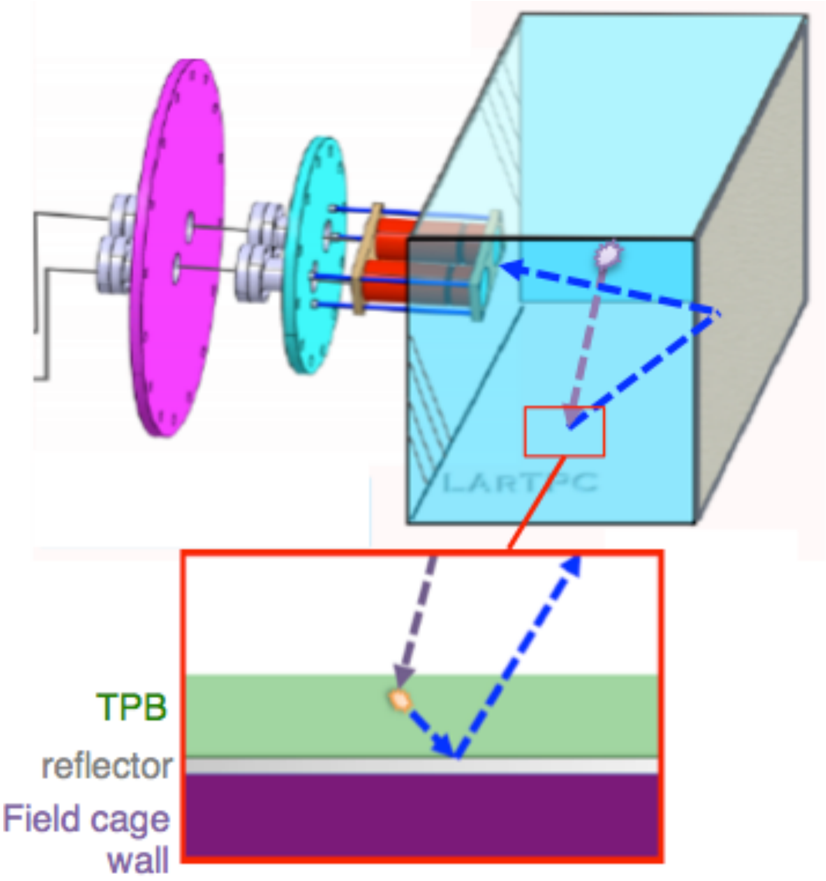
1. Hamamatsu PMT R-11065 (3” diameter)
2. ETL PMT D757KFL (2” diameter)
3. SensL MicroFB-60035 SiPM w/preamp
4. Hmm. S11828-3344M 4x4 SiPM array (*Run I*)
   Hmm. VUV-sensitive SiPM (*Run IIa*)

Light Collection System

Standard LArTPC approach (e.g., ICARUS, MicroBooNE)

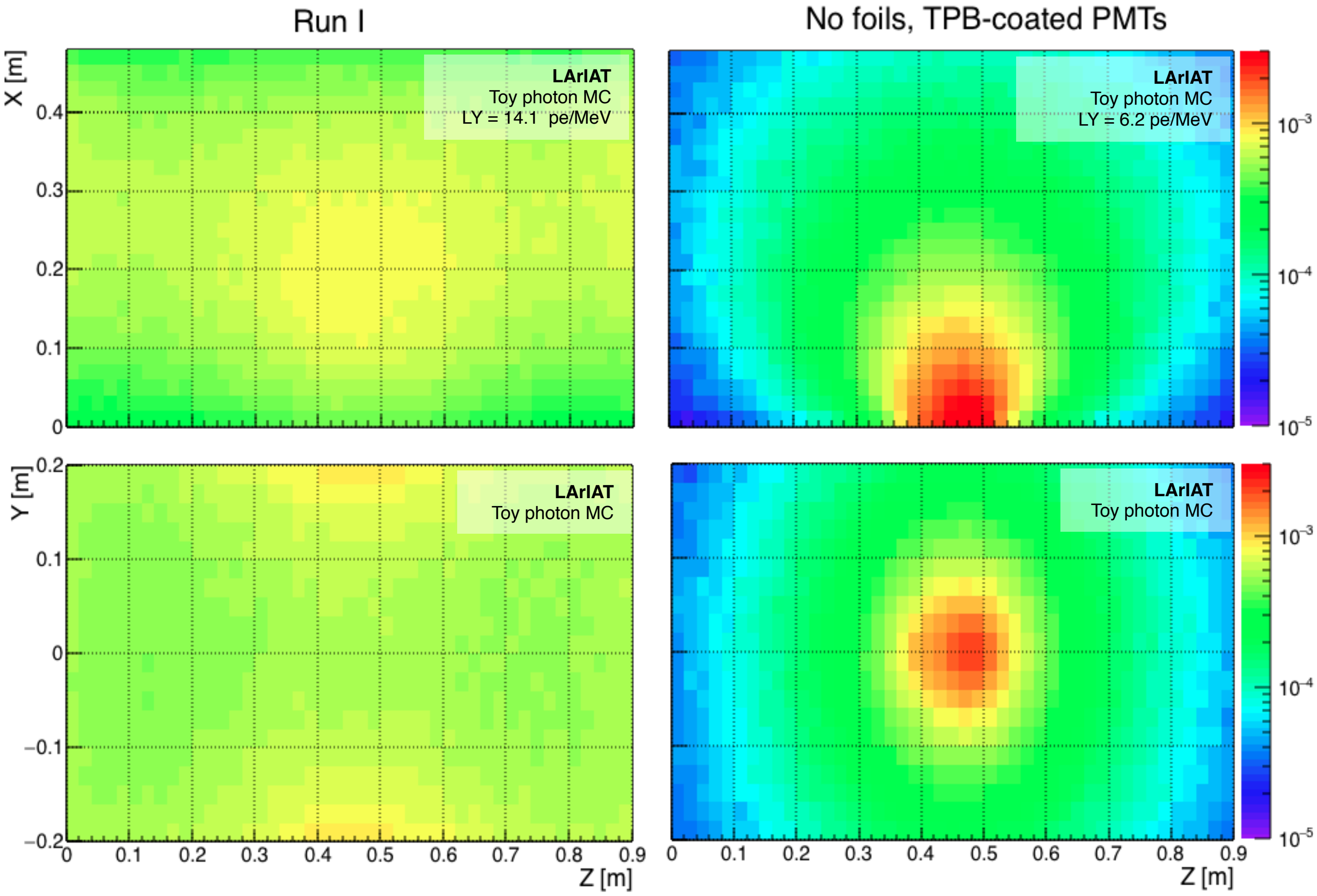


Reflector-based solution (LArIAT)



Visibility Map (Simulation)

Fractional photon visibility for LArIAT Run I vs. a traditional setup



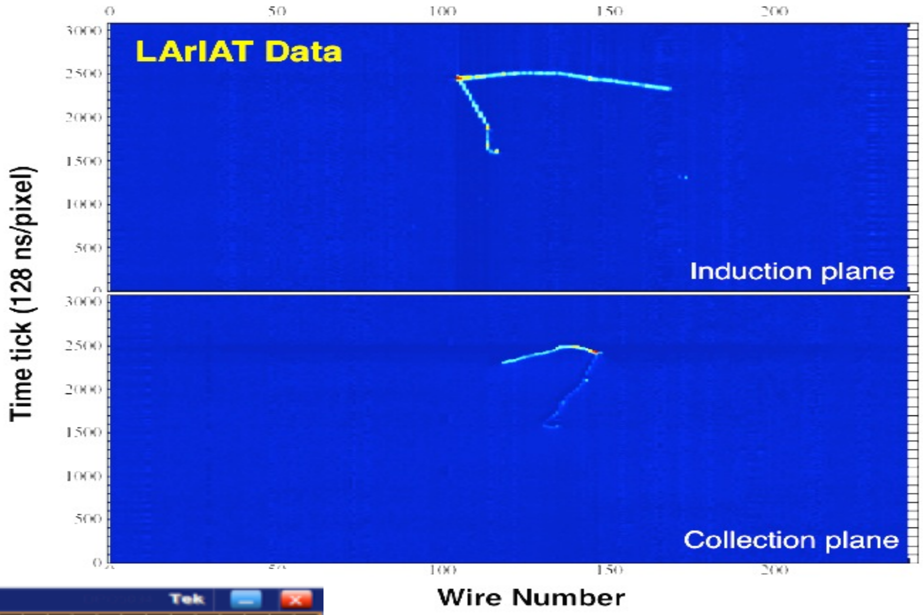
> 2x light and **more uniform response** compared to a scenario w/ no reflector foil and TPB-coating on both PMTs

Michel electron trigger

$\mu^{+/-}$ (at rest) → $\mathbf{e^{+/-}}$ + ν_μ + $\overline{\nu}_e$

Useful for…

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



Real-time triggering on Michel e's from stopping cosmic μ's using light signals

Muon decay time

- Stopping $\mu^{+/-}$ can decay to electron with $\tau_{free} = 2.2\mu s$
- … but μ^- can also be *captured* by Ar nucleus with competing time constant τ_c

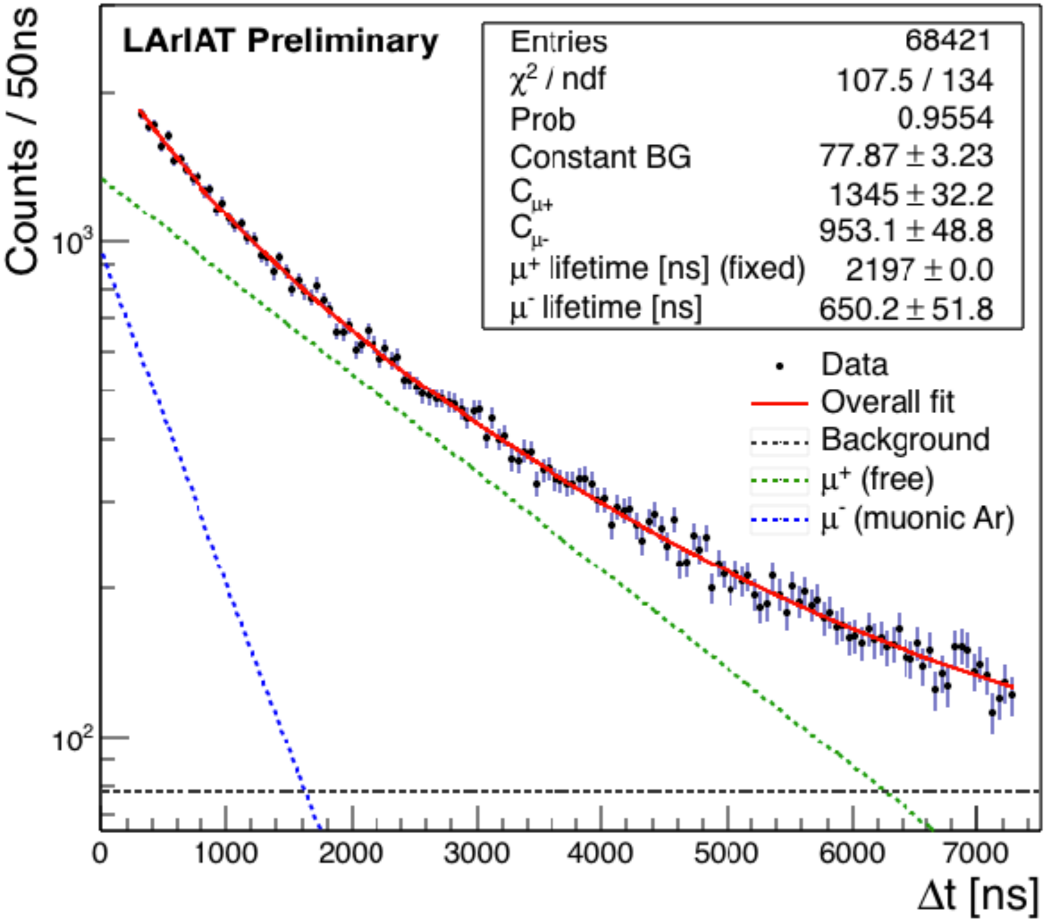
$$\boxed{\tau_{\mu-}} = \left(\frac{1}{\tau_c} + \frac{Q}{\boxed{\tau_{free}}}\right)^{-1}$$

650 ± 52 ns
(from fit result, preliminary)

918 ± 109 ns

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

Muon decay time spectrum in LAr



LIDINE 2015 Proceedings, JINST 11 C01037

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

Next Steps with Light Collection System

- **Michel energy spectra** from
  - Scintillation light (from PMTs)
  - Charge (from TPC wires)
  - Charge + light *combined*

Data-driven energy calibration source for detector

Requires:

- ✧ Improved 3D $\mu^{+/-}$ track and $e^{+/-}$ shower reconstruction
- ✧ Accurate photon visibility map from full-scale MC

- Light/charge-based selection of stopping μ from beam →

Non-magnetic sign determination of $\mu^{+/-}$

- Other studies enabled by abundant sample of low-E $e^{+/-}$ →

dE/dx, low-energy shower reconstruction, scintillation-yield as function of E-field, etc…

TPC “Thin-Slice” Cross Section Measurement

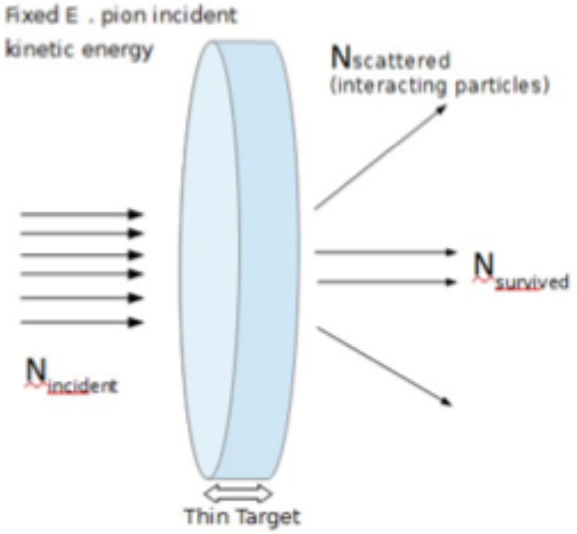
- Survival probability of a pion traveling through a thin slab of argon is given by:

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

- Interaction probability is *1-P*$_{survival}$
- Measure interaction probability directly as ratio of number of interacting pions to number of incident pions:

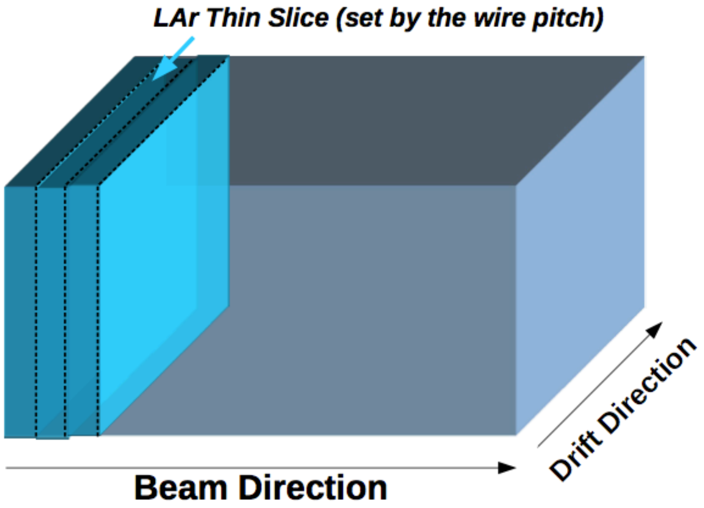
$$\frac{N_{interacting}}{N_{incident}} = P_{interaction} = 1 - e^{-\sigma n z}$$

“Thin-Slice” Cross Section



$$P_{interaction} \approx 1-(1-\sigma n \delta z+\ldots)$$

$$\sigma(E) \approx \frac{1}{nz} P_{interaction} = \frac{1}{nz} \frac{N_{interacting}}{N_{incident}}$$

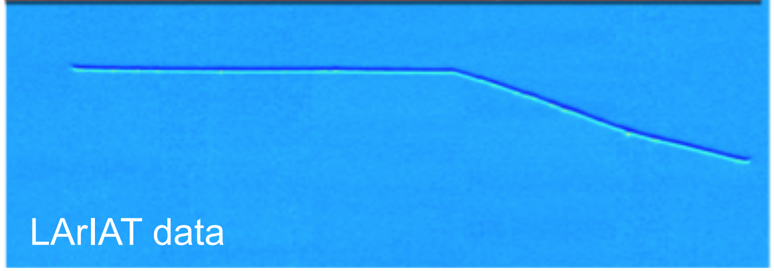


We can treat TPC wire-to-wire spacing as a series of “thin slab” targets, as long as we know the energy of the pion as it is incident on each target.

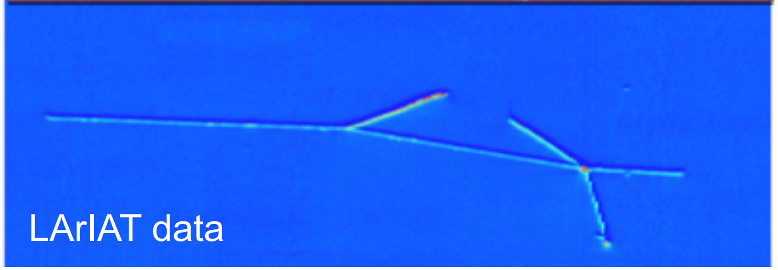
Total π^--Ar Cross Section

$$\sigma_{tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{chgx} + \sigma_{absorption} + \sigma_{\pi-prod}$$

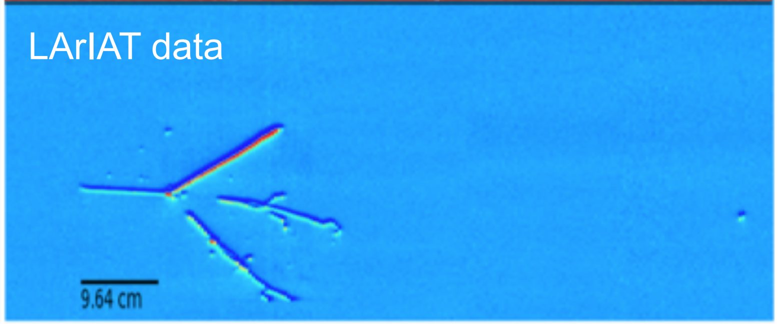
Pion - Elastic Scattering Candidate



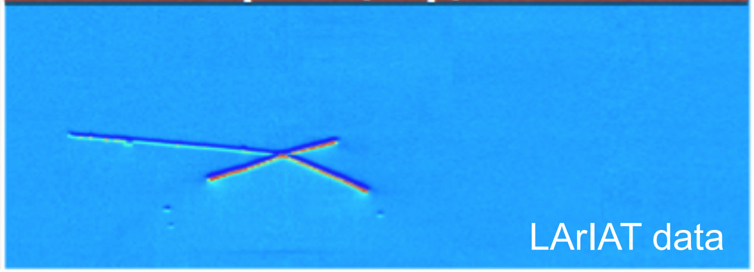
Pion - Inelastic Scattering Candidate

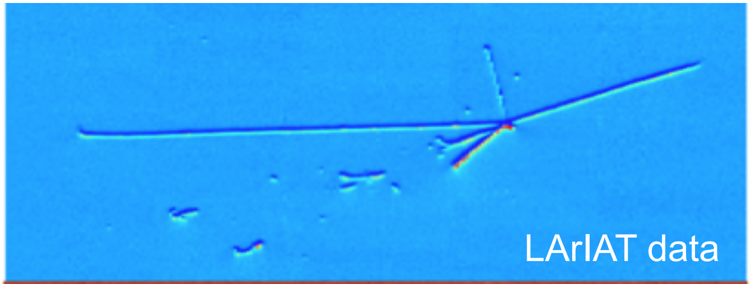


Pion - Charge Exchange Candidate



Pion - Absorption (→3p) Candidate

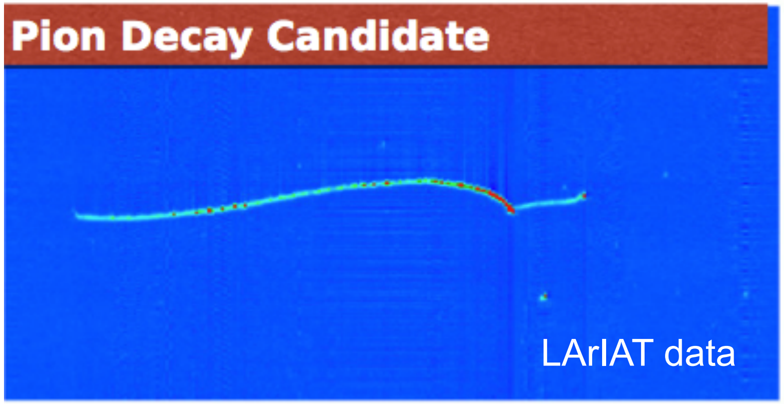




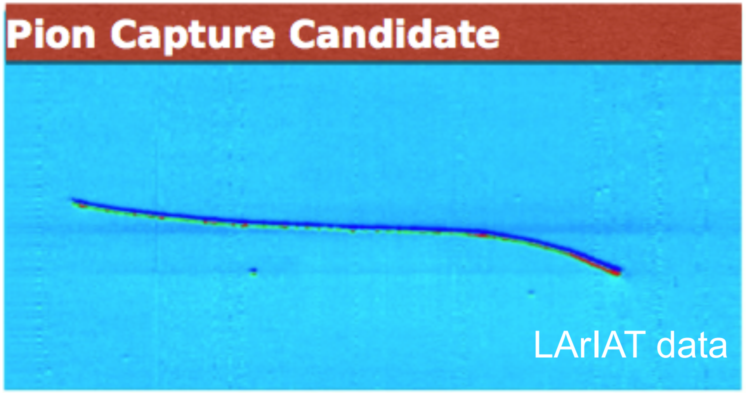
Pion Production Candidate

Total π^--Ar Cross Section

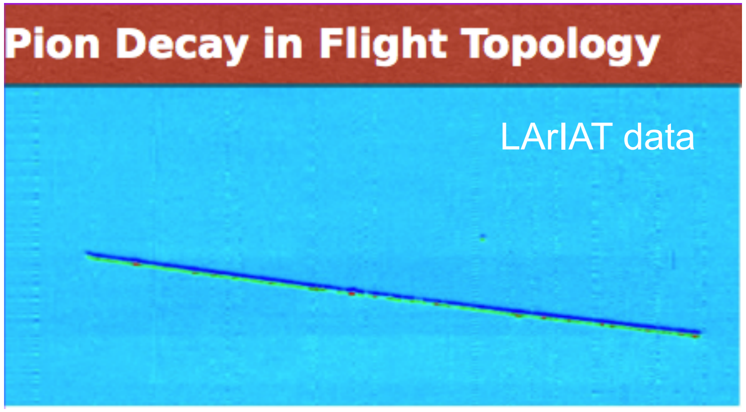
- Some backgrounds still included in this preliminary analysis. Work is underway to remove them


Pion Decay Candidate

LArIAT data

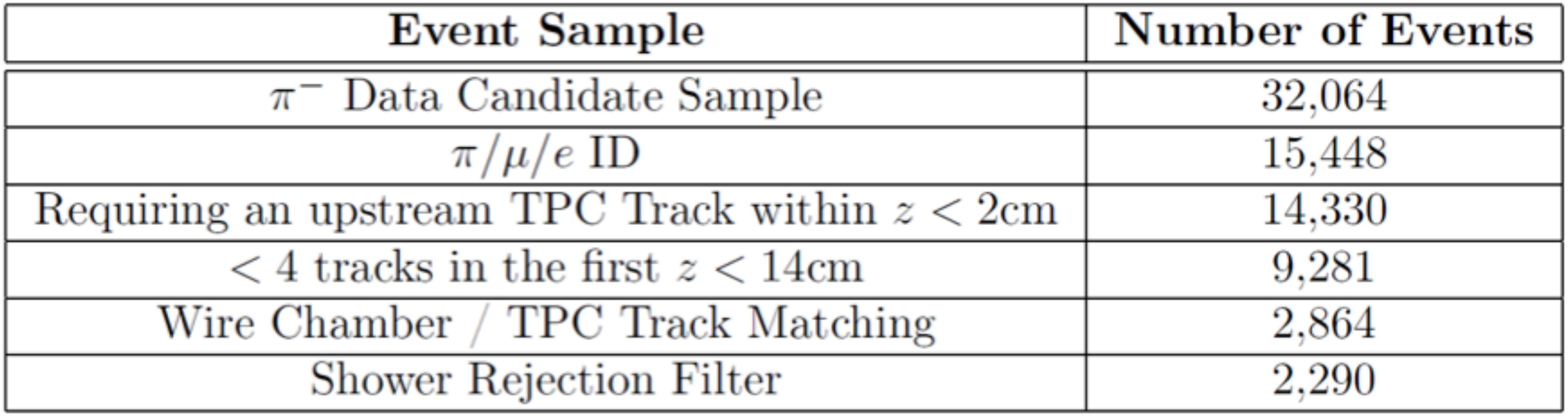

Pion Capture Candidate

LArIAT data

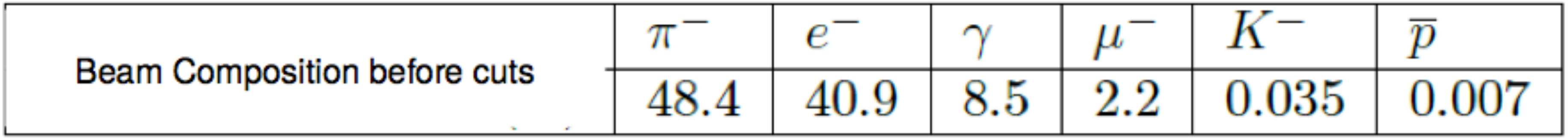

Pion Decay in Flight Topology

LArIAT data

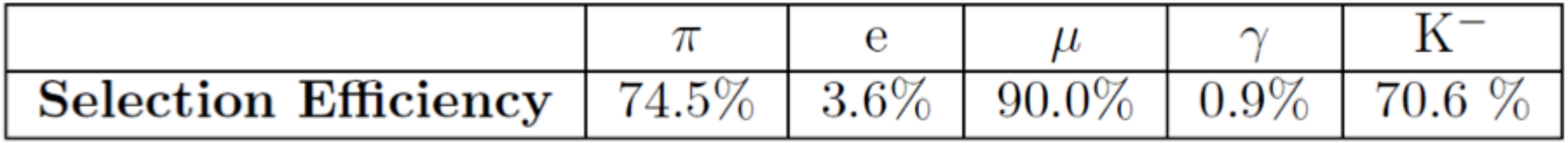
Event Selection



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



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

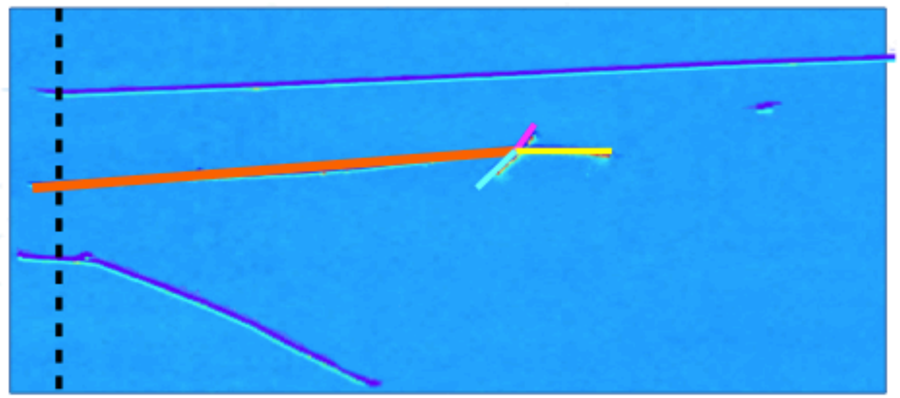


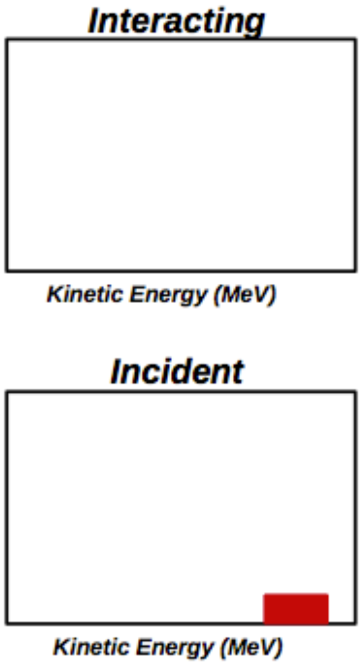
	π	e	μ	γ	K^-
Selection Efficiency	74.5%	3.6%	90.0%	0.9%	70.6 %

Pion Analysis

- **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

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

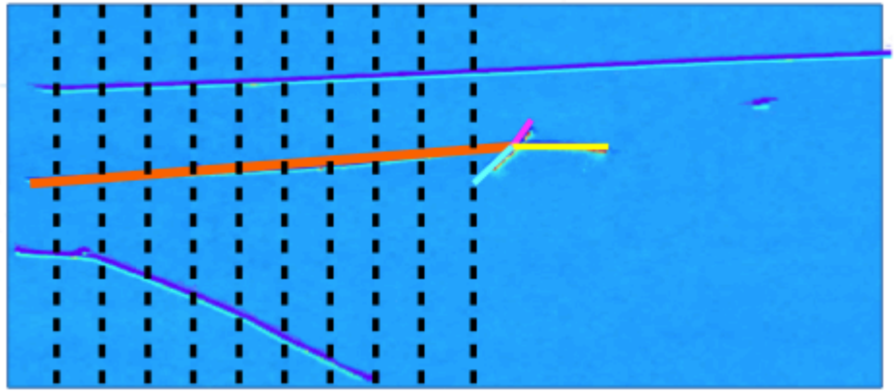


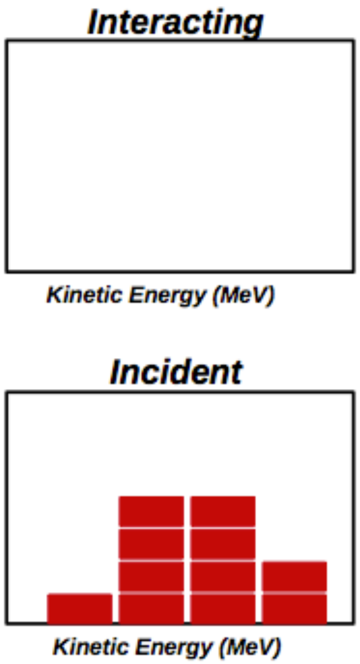


Pion Analysis

- **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

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

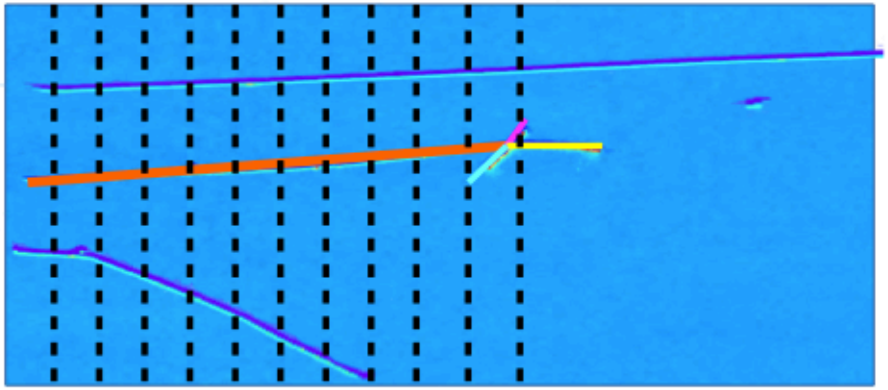


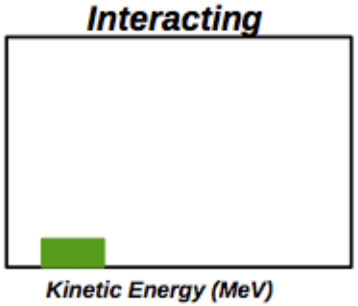


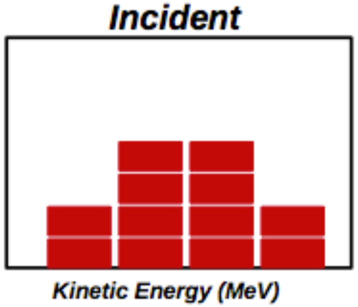
Pion Analysis

- **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

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

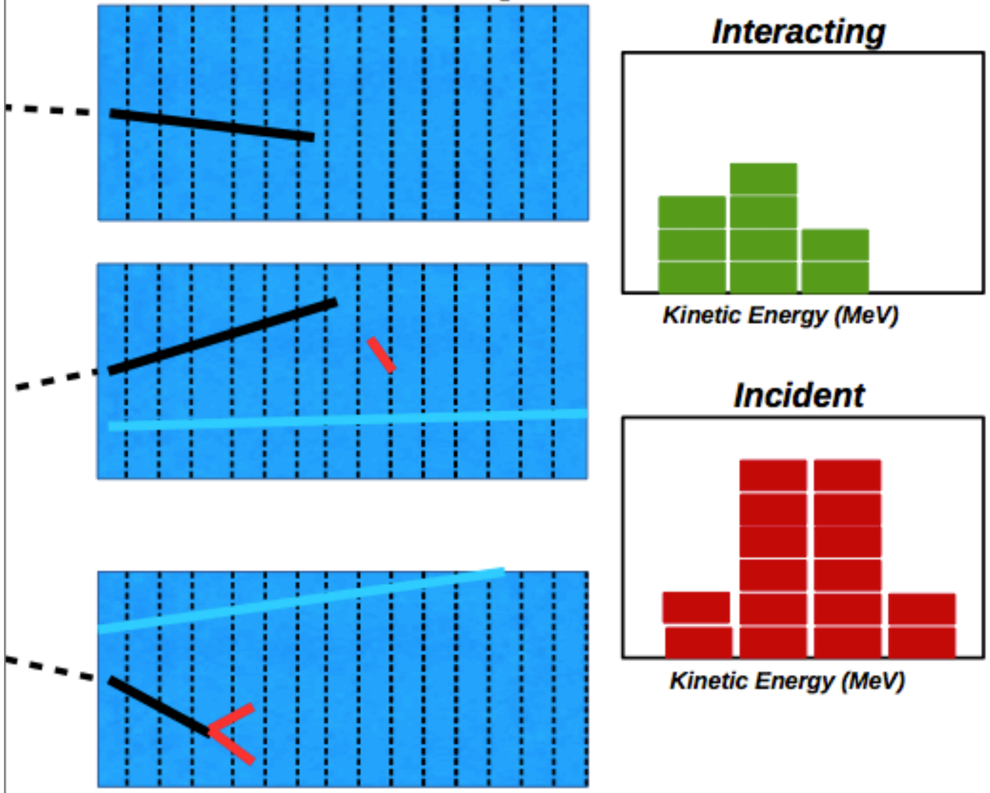




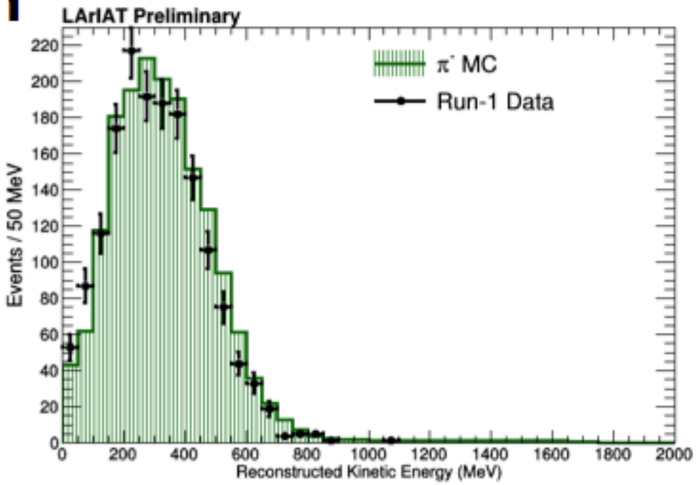


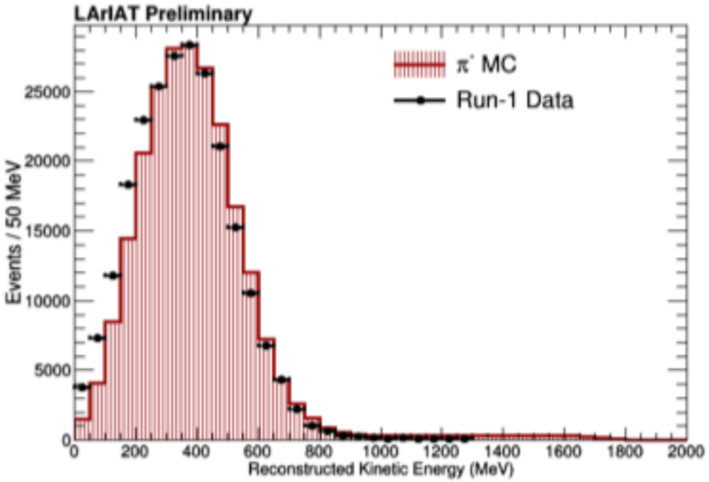
Pion Analysis

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

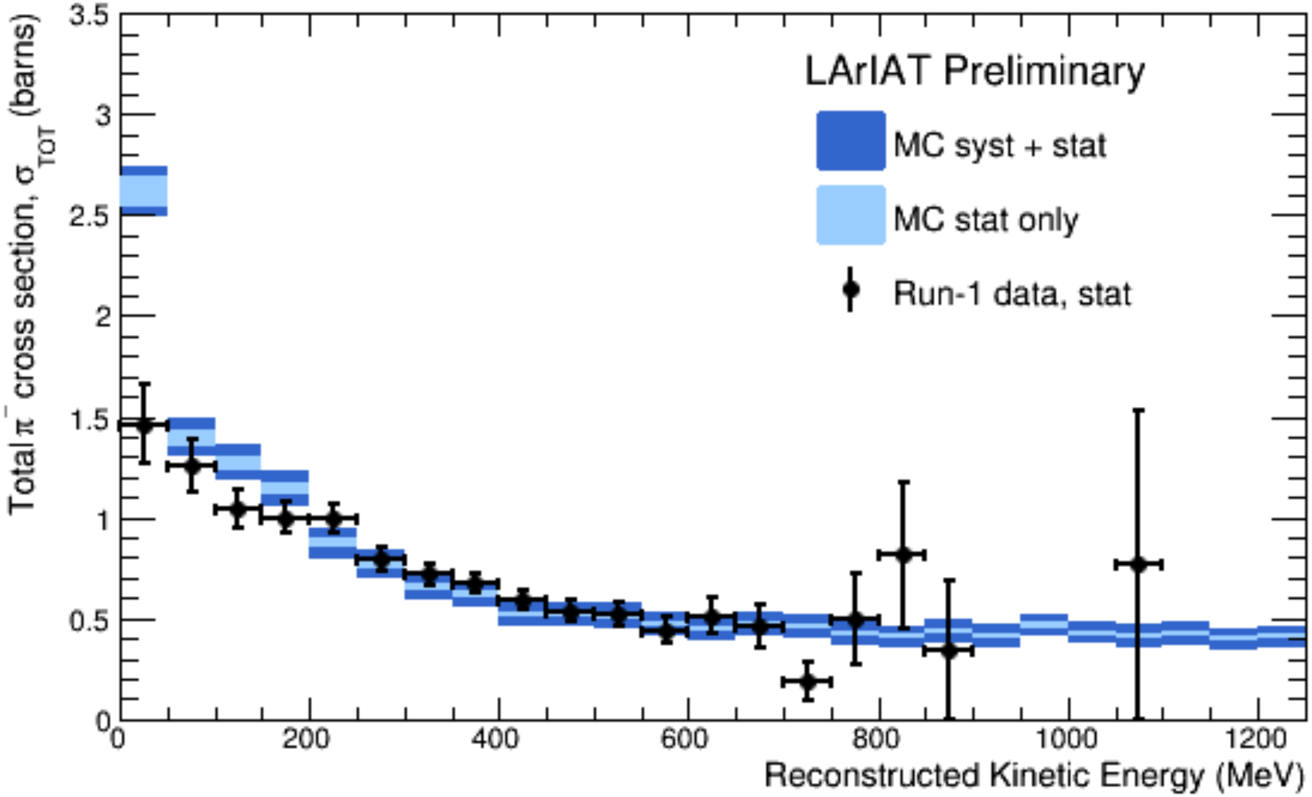


We ignore other tracks in the event not matched to the Wire Chamber Track





Total Pion Cross Section in Argon



Systematics considered

dE/dx calibration: 5%
Energy loss prior to entering TPC: 3.5%
Through-going muon contamination: 3%
Wire chamber momentum uncertainty: 3%

Kaons

- Analysis of K-Ar interaction cross section currently underway
- Starting from positive polarity Run-II data
  - Select on MWPC tracks matched with TPC track + TOF cut + mass cut
  - Remaining sample contains both decaying and interacting kaons, some proton contamination
  - Estimate ≥1000 K^+
    - (Expect we have similar number of K^-, but analysis not yet started)

Cleaning up the Kaon Sample

- Remove stopping particles (K^+ decays and stopping protons)
  - “PIDA” module developed by ArgoNeuT (arXiV:1306.1712)

Uses expected power-law dependence of dE/dx for **stopping particles** as described by the Bethe-Bloch equation. Can be approximated using:

$$(dE/dx)_{hyp} = A\,R^{b}$$

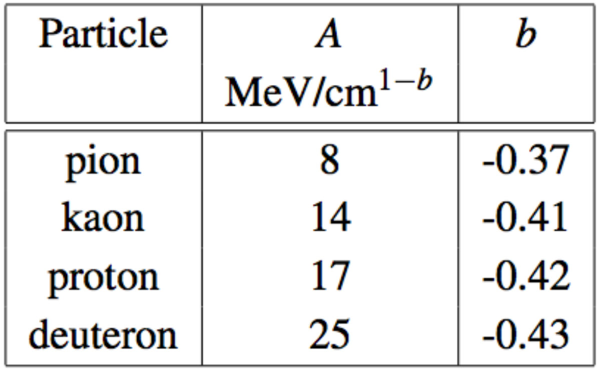
where R is residual range, and A and b are parameterization variables.

Setting b = -0.42, the module finds A by taking the average of all spacepoints in the track using:

$$A_i = (dE/dx)_{calo,i} R_i^{0.42}$$

This number A is unique for a stopped particle:

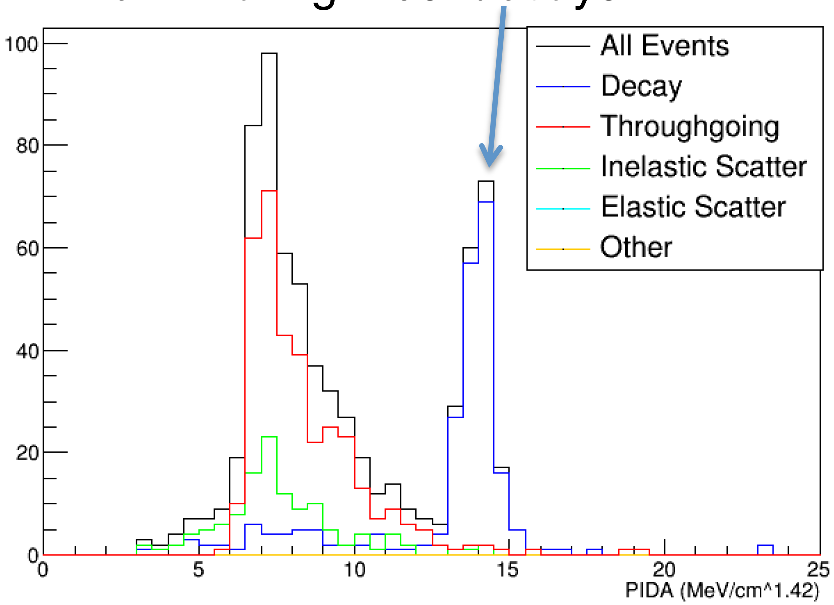
Error from fixed b is negligible compared to ionization fluctuations.



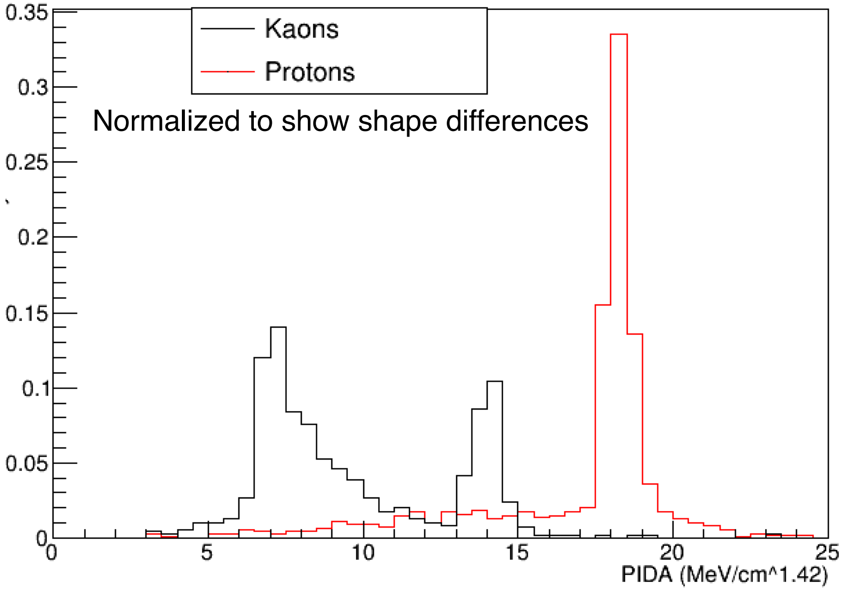
Particle	A $\mathrm{MeV/cm}^{1-b}$	b
pion	8	-0.37
kaon	14	-0.41
proton	17	-0.42
deuteron	25	-0.43

PIDA in LArIAT

Potential to tag stopping K⁺, eliminating most decays



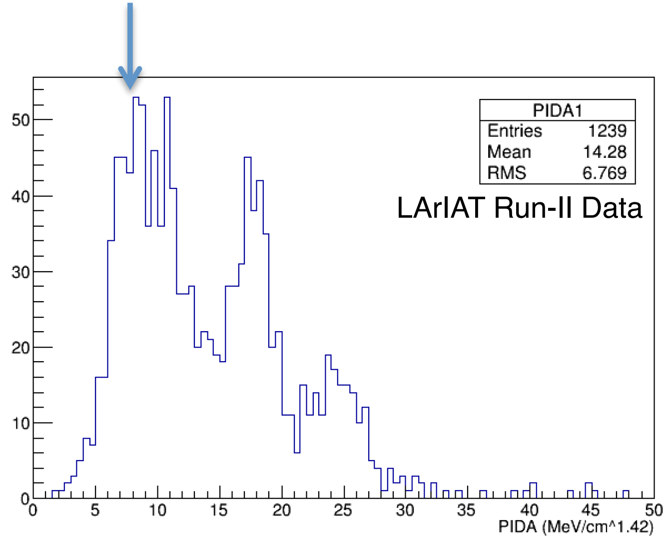
Potential to remove proton contamination since most protons stop in LAr.



Normalized to show shape differences

Particle	A $\mathrm{MeV/cm}^{1-b}$	b
pion	8	-0.37
kaon	14	-0.41
proton	17	-0.42
deuteron	25	-0.43

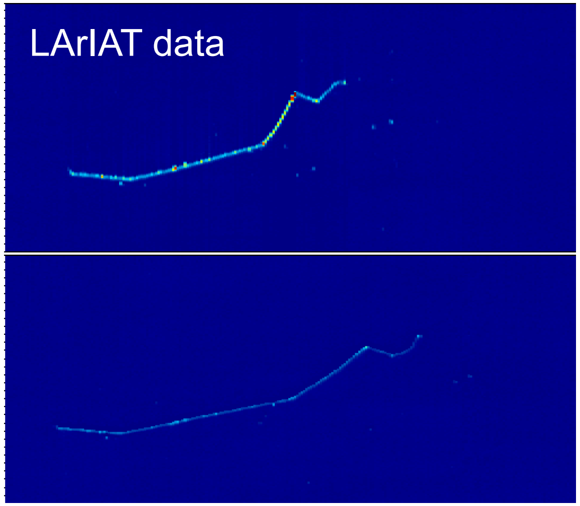
First Look at K^+ Data (Work In Progress)



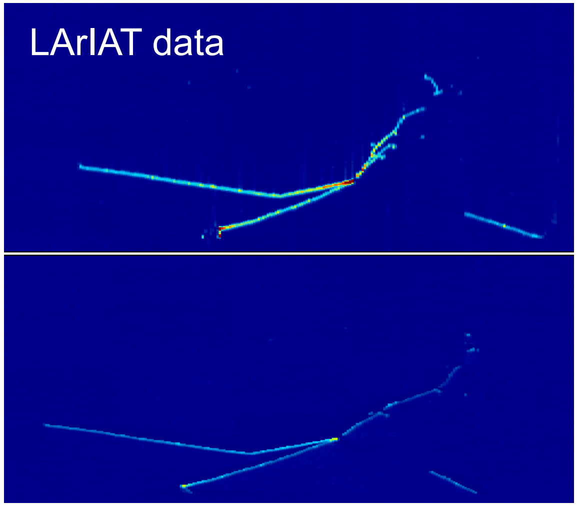
PIDA < 15

First peak should represent tracks that did not stop (interacted or exited TPC)

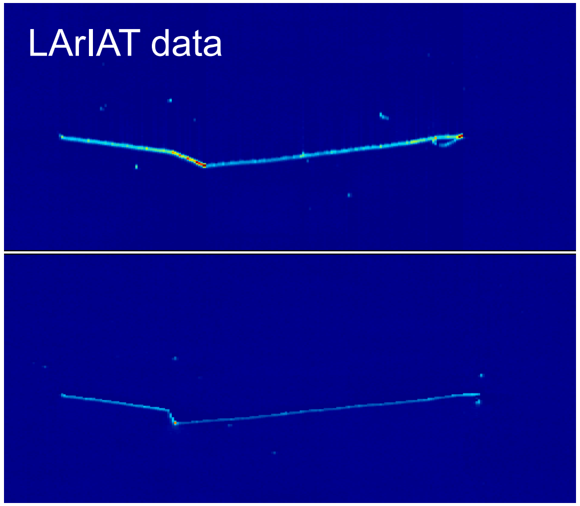
PIDA: 7.4



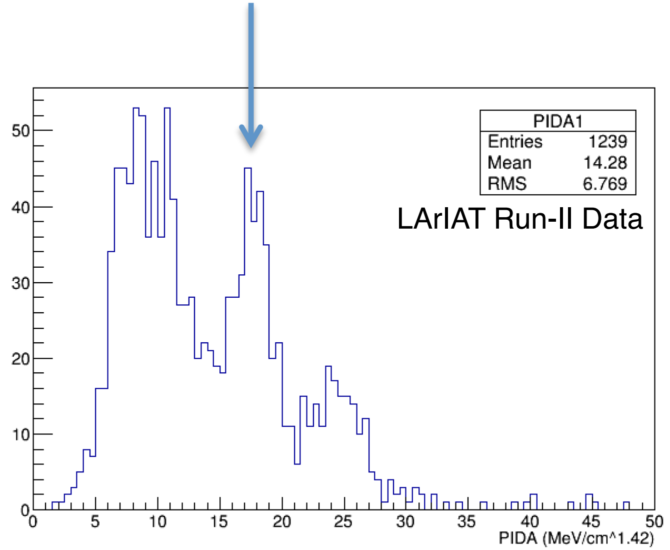
PIDA: 11.5



PIDA: 12.7



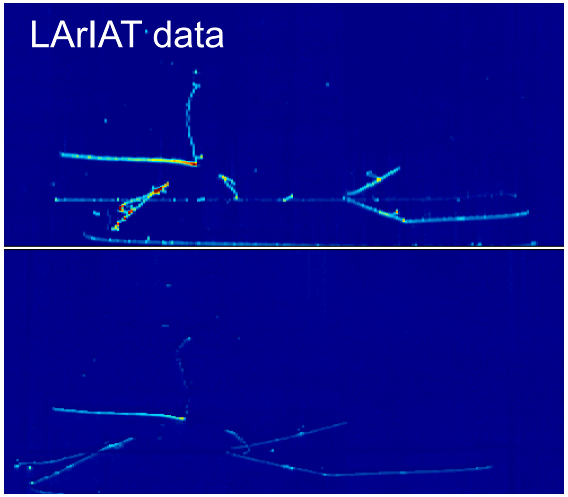
First Look at K+ Data (Work In Progress)



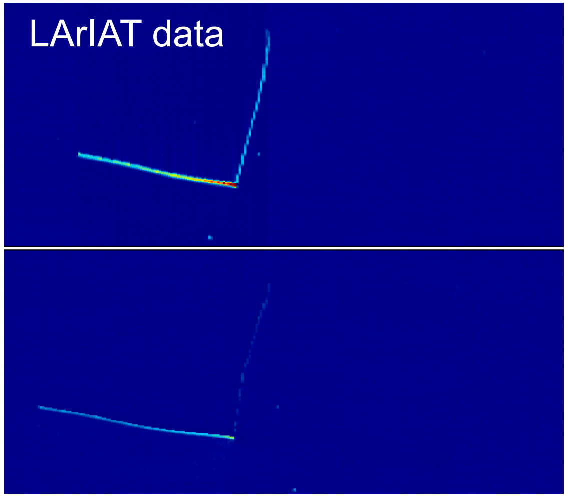
15 < PIDA < 21

These should be kaons that stopped in the TPC, depositing all of their energy on the way and fitting perfectly to the parameterized Bethe-Bloch equation

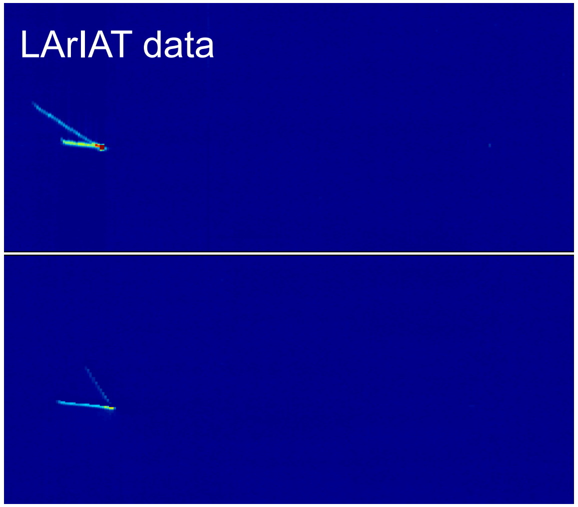
PIDA: 16.9



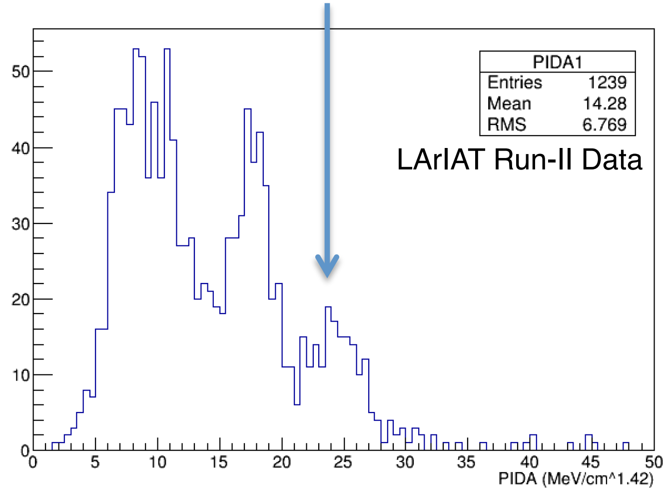
PIDA: 16.2



PIDA: 16.2



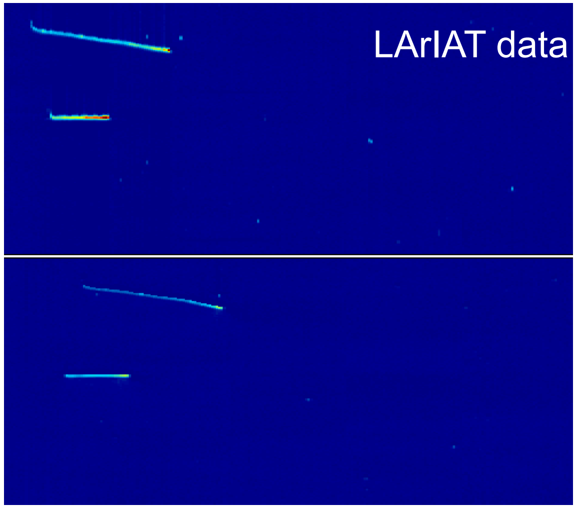
First Look at K^+ Data (Work In Progress)



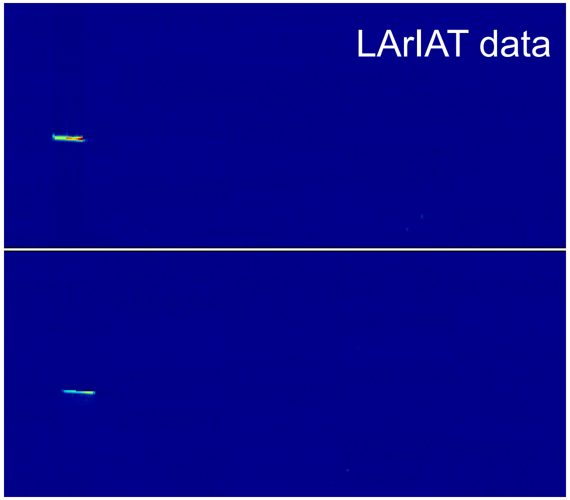
PIDA > 21

These values are unlikely for kaons and represent contamination from protons that enter and stop inside the TPC

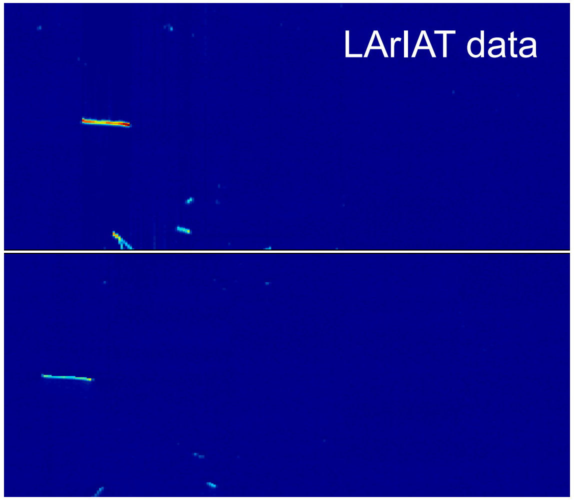
PIDA: 22.2



PIDA: 23.8



PIDA: 25.0

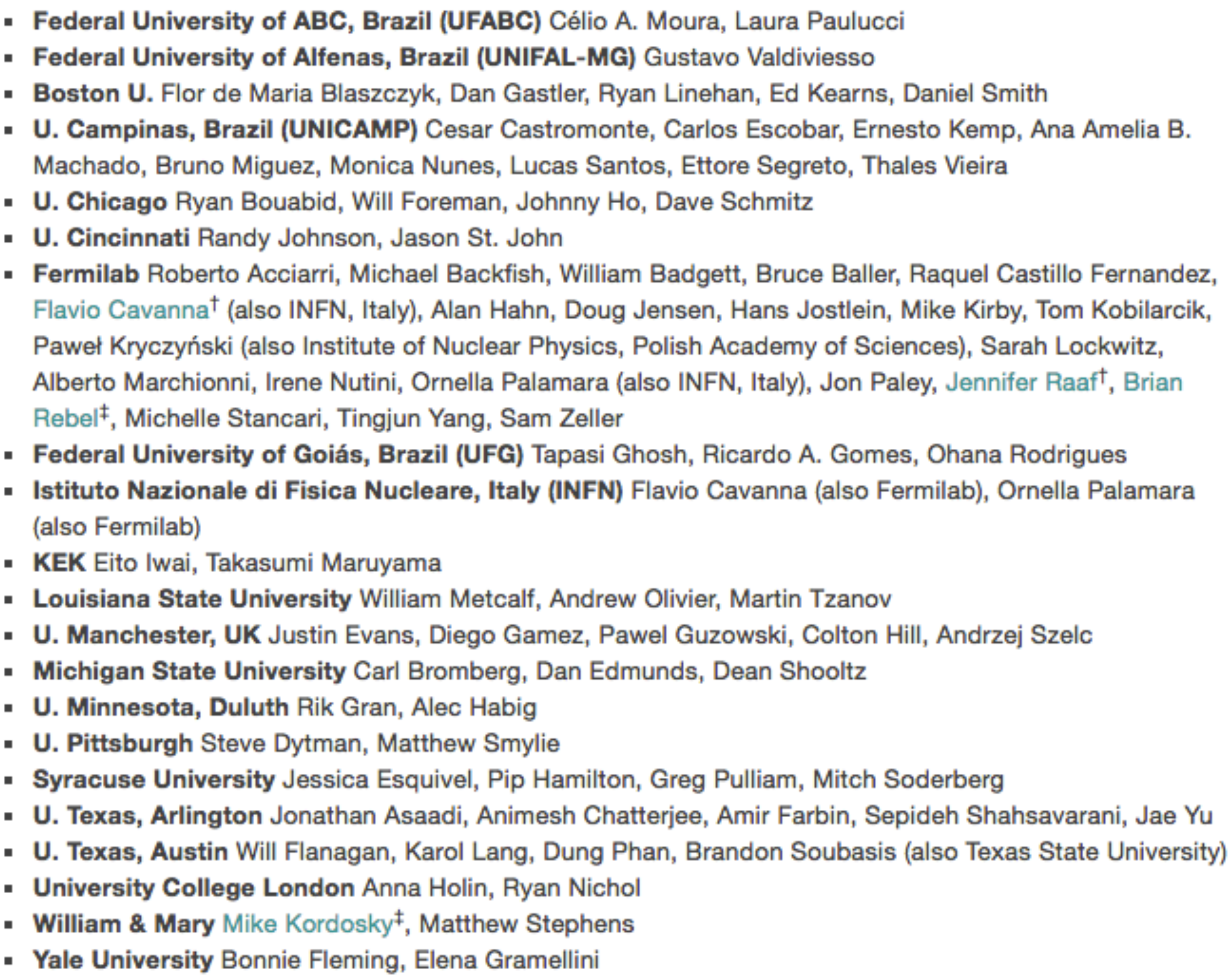


What's Next

- **Analyses in progress/starting:**
    - Exclusive pion-Ar cross section channels
    - Kaon-Ar cross section
    - Michel e^- analysis with light + charge
    - Charge-sign ID
    - Electron/gamma separation
    - Particle ID and reconstruction studies
- **LArIAT Current Data-taking**
    - E-field scan < 500 V/cm for PID studies
- **LArIAT Future**
    - Short-run R&D tests
        - Various light-collection ideas
        - 3mm vs. 5mm wire plane spacing

LArIAT Collaboration

LArIAT Collaboration

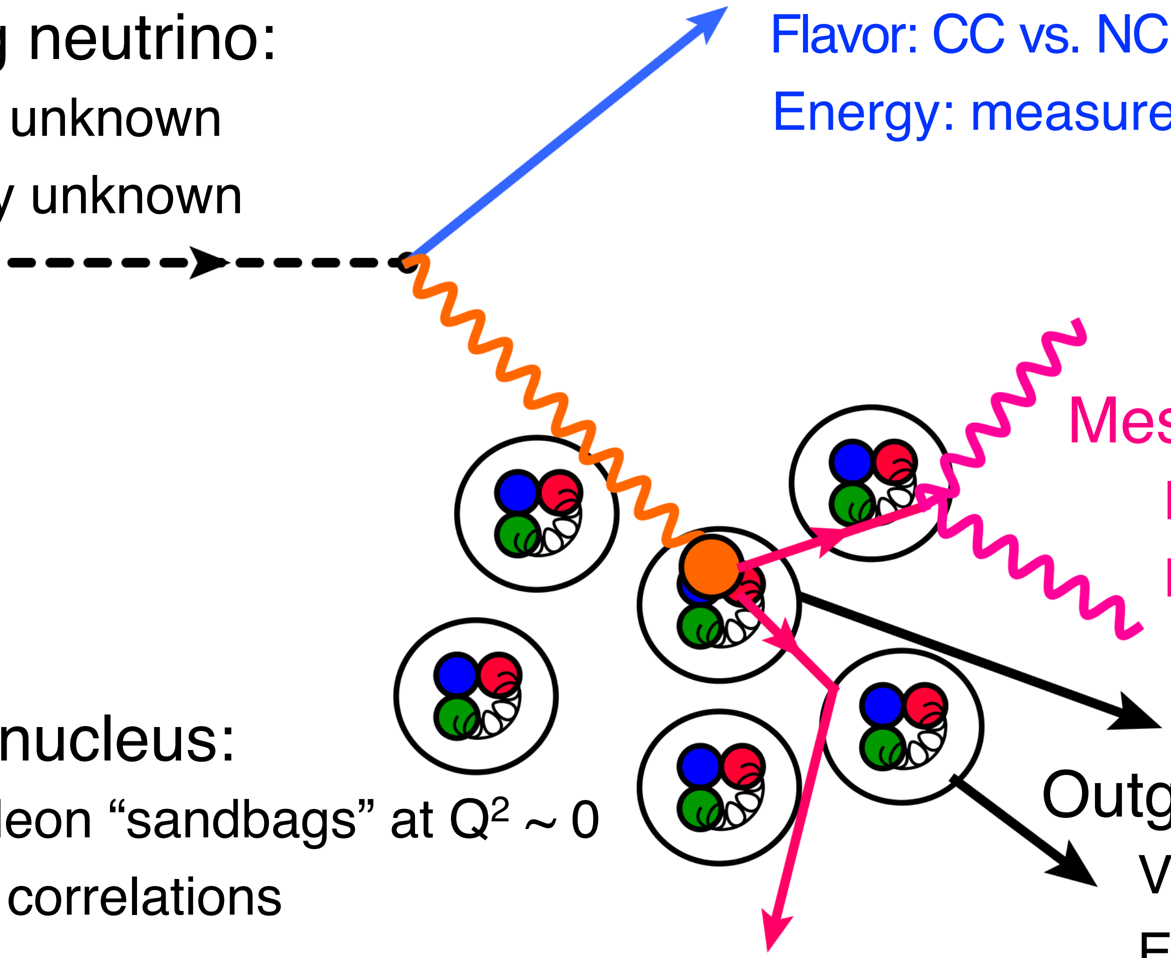


- **Federal University of ABC, Brazil (UFABC)** Célio A. Moura, Laura Paulucci
- **Federal University of Alfenas, Brazil (UNIFAL-MG)** Gustavo Valdiviesso
- **Boston U.** Flor de Maria Blaszczyk, Dan Gastler, Ryan Linehan, Ed Kearns, Daniel Smith
- **U. Campinas, Brazil (UNICAMP)** Cesar Castromonte, 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

SPARES

Motivation: Needs of Neutrino Experiments

Typical neutrino event



Incoming neutrino:

- Flavor unknown
- Energy unknown

Outgoing lepton:

- Flavor: CC vs. NC, μ^+ vs. μ^-, e vs. γ
- Energy: measure

Mesons:

- FSI!
- Energy? Identity?

Target nucleus:

- Nucleon "sandbags" at $Q^2 \sim 0$
- N-N correlations

Outgoing nucleons:

- Visible?
- Energy?

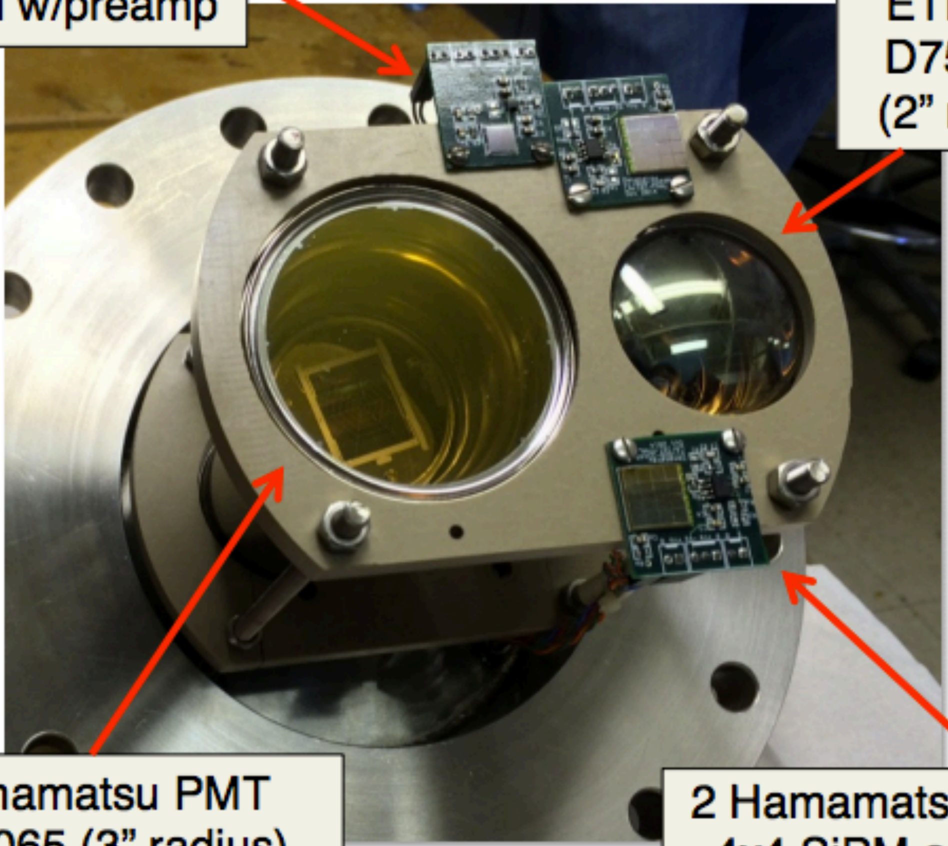
Run-I Summary

- Total: 9 weeks beam data + 1 week special runs
  - Data from first 3 weeks not entirely good physics quality, mostly beam tuning
  - Final 6 weeks: ~44k beam spills with good 2^{ndary} beam recorded to tape
  - ~20 events/spill, of which ~25% are "good" events (without pileup)

→ average ~5 good events/spill with a mix of particle types

Secondary beam energy	Tertiary beam magnet setting	Number of spills recorded
16 GeV	+100A	7950
16 GeV	-100A	10843
16 GeV	-60A	6573
32 GeV	-60A	91
32 GeV	-100A	2252
32 GeV	+100A	3287
64 GeV	+100A	1315
64 GeV	-100A	5205
64 GeV	-40A	3149
64 GeV	-20A	497
64 GeV	+40A	2189

Light Collection System



SensL MicroFB-60035
SiPM channel w/preamp

ETL PMT
D757KFL
(2" radius)

Hamamatsu PMT
R-11065 (3" radius)

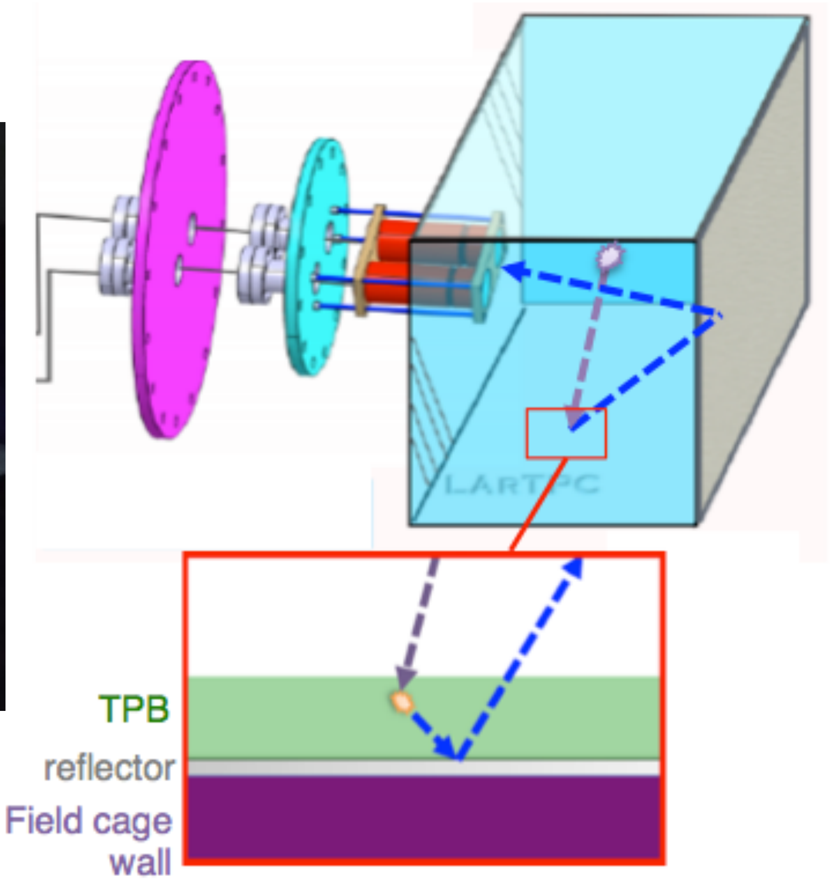
2 Hamamatsu S11828-3344M
4x4 SiPM arrays, w/preamp

Light Collection System

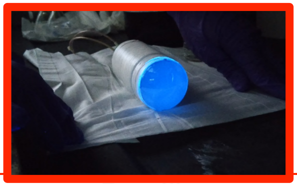
Experimented with a TPB-coated PMT as well during Run II


TPB-coated ETL PMT under a UV lamp (just prior to Run 2)

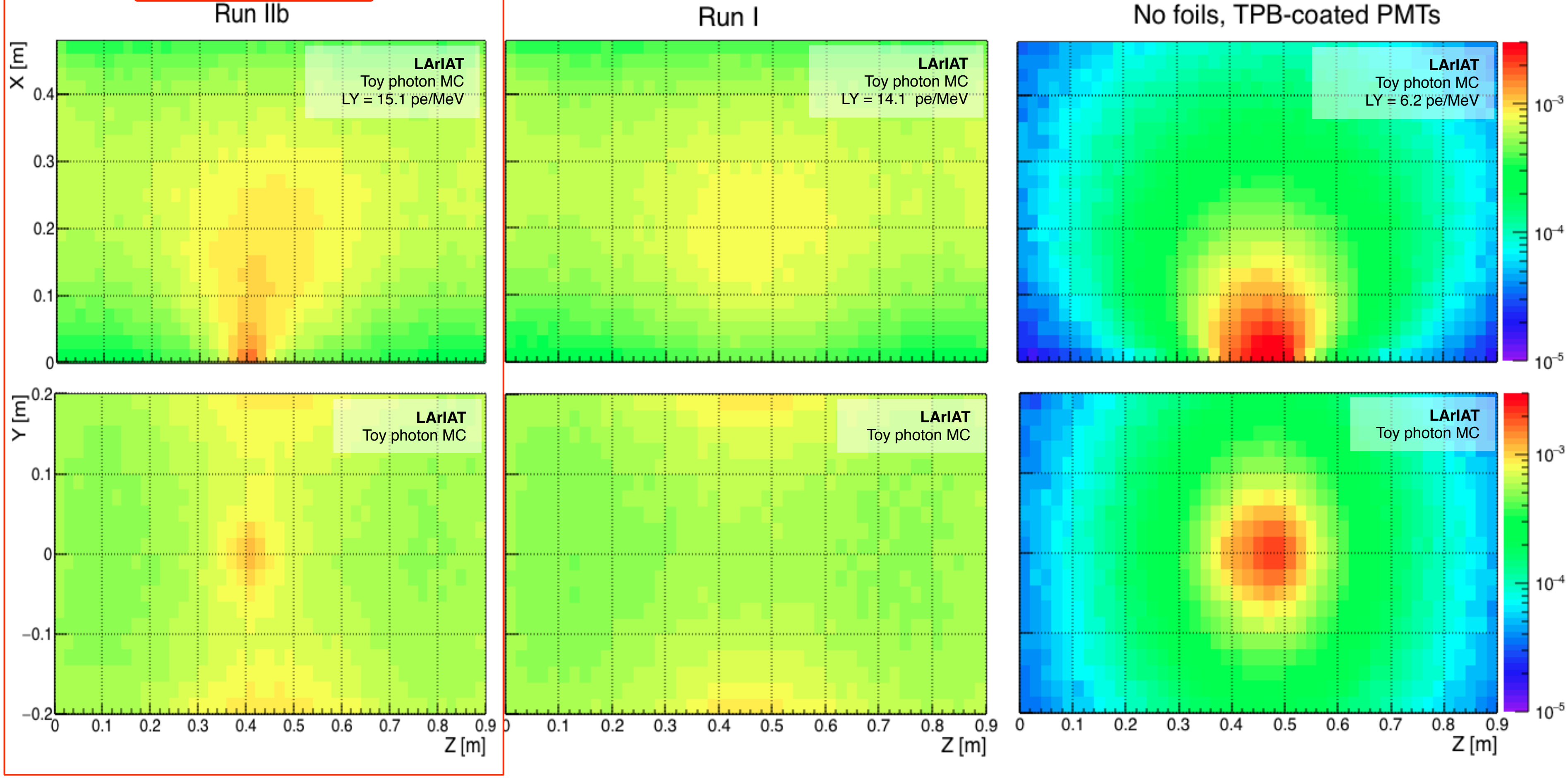
Reflector-based solution (LArIAT)



Visibility Map (Simulation)

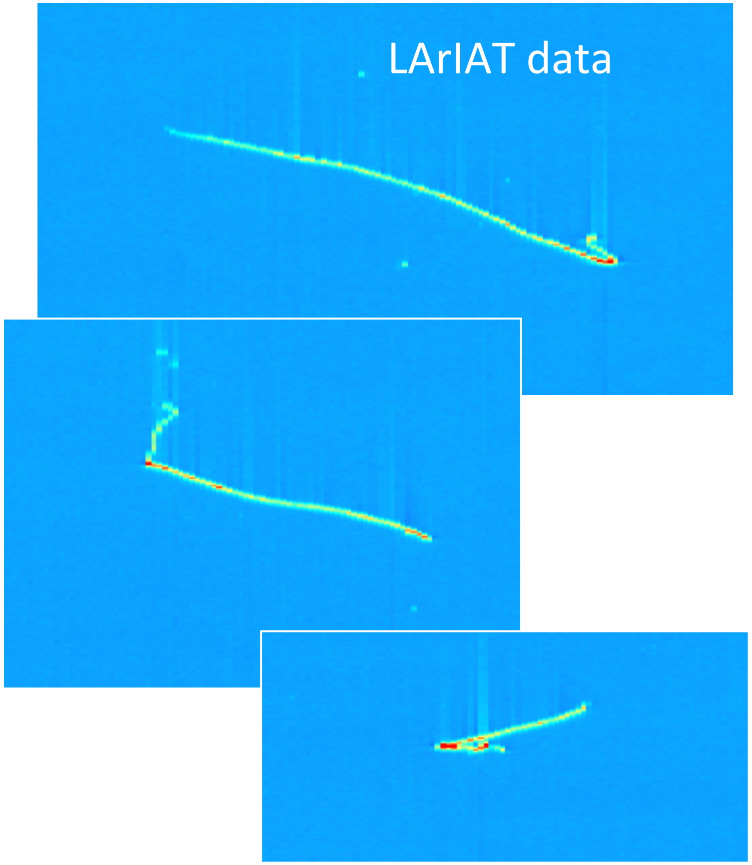


Fractional photon visibility for LArIAT Run I vs. a traditional setup

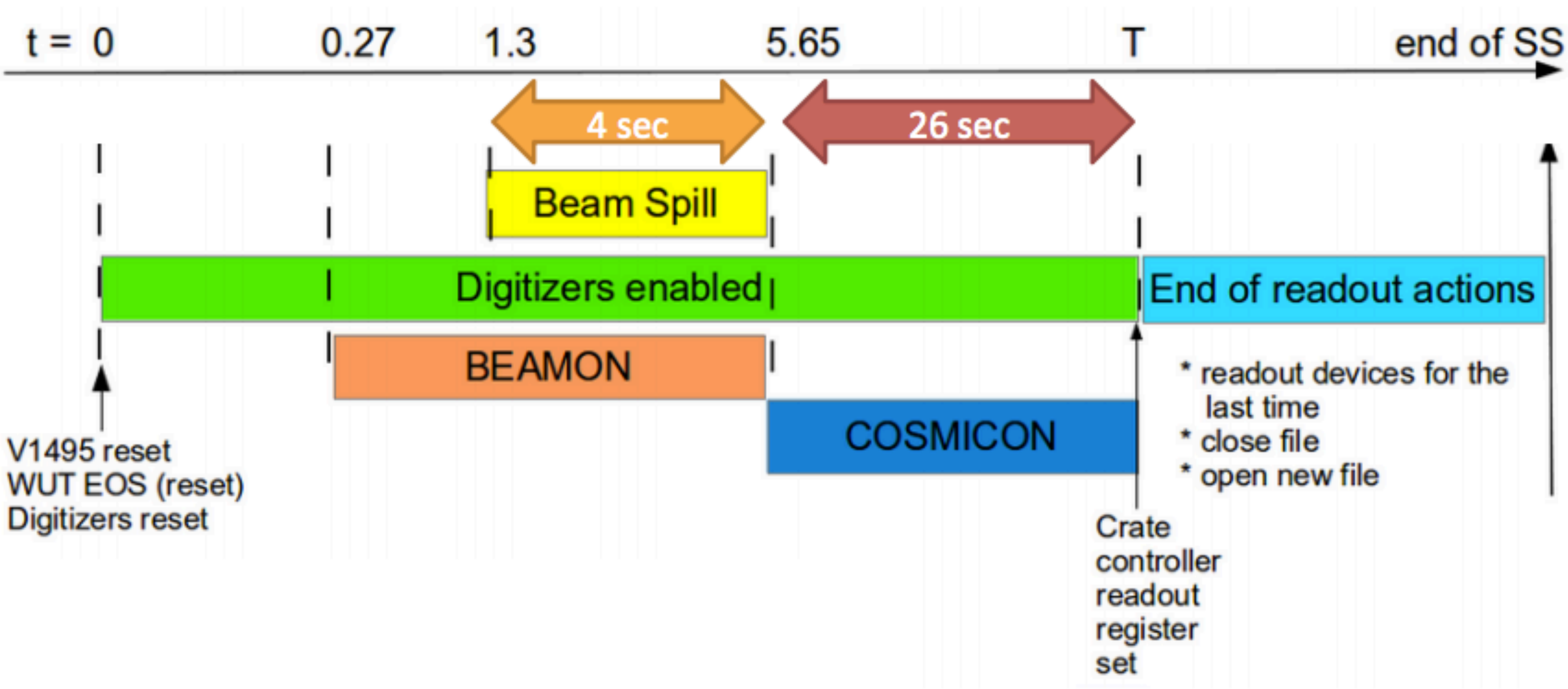


Calibration with Michel electrons

- Light-based trigger
  - Source of stopping muons and low energy electrons
- Energy calibration source for TPC and photodetectors
- Measurement of μ^- nuclear capture probability in LAr
- Muon sign determination studies



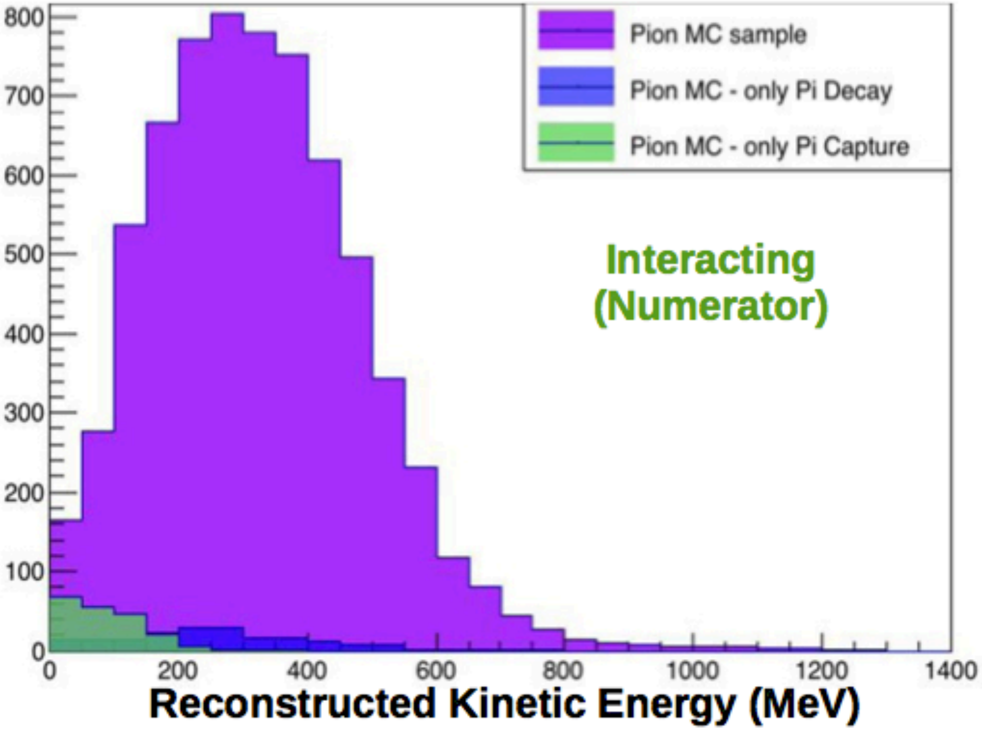
Supercycle



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

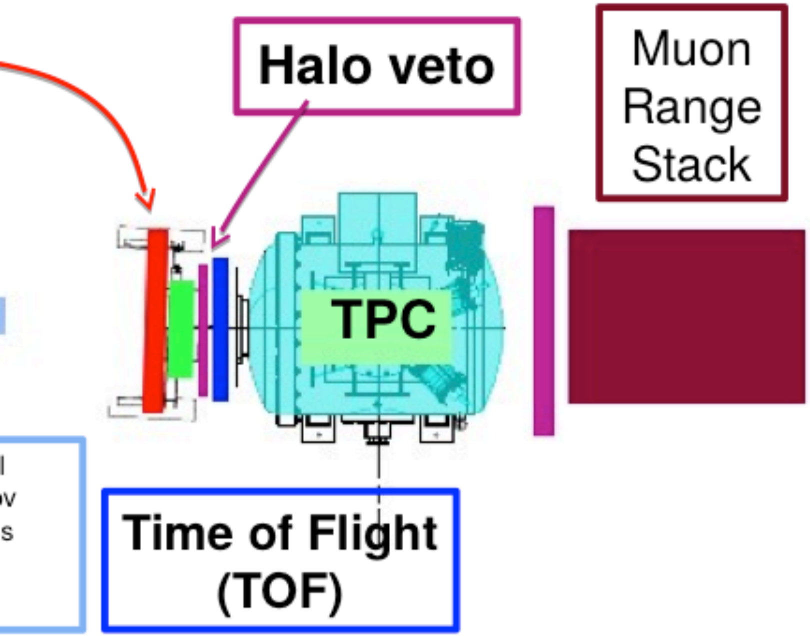
- ~ 5-20 beam triggers per supercycle (depending on beam intensity)
- ~0-2 cosmic muon paddle triggers per supercycle
- ~20 Michel events per supercycle

Background Contamination

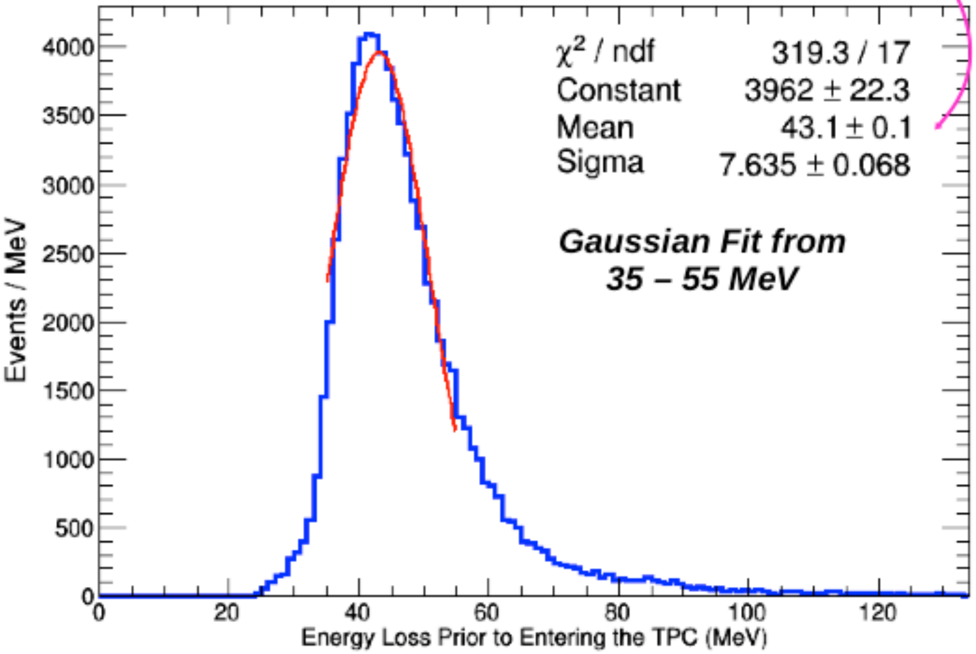


- Interacting sample contains ~9% capture and 2% decay
- 34% crossing particles (pi/mu) and 66% interacting
- ~10% muon contamination uniformly distributed (not shown here)

Energy Corrections



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



- 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