LArIAT

Fermilab PAC Meeting

November 11, 2016

Jen Raaf

PAC Charge

3. LArIAT

We ask the committee to comment on the LArIAT Collaboration's proposal to continue data taking in the latter part of FY 2017 (Run 3), and whether this initiative can be considered as part of a coherent LAr R&D program. Specifically:

i) Is the proposed LArIAT Run 3 program unique and well motivated scientifically?

ii) Is the proposed LArIAT Run 3 program well aligned with the needs of DUNE and the LAr neutrino community.

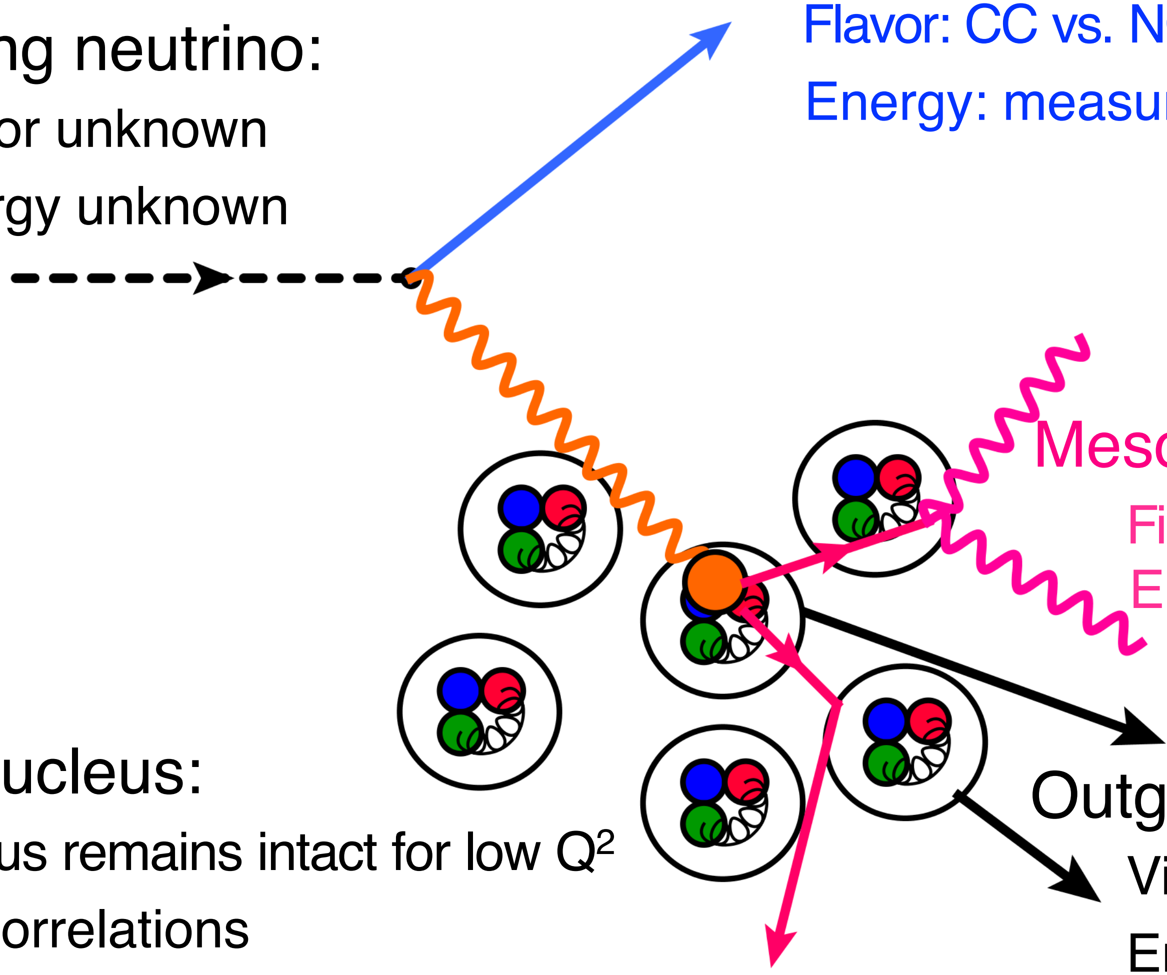
iii) Is it likely that a continued LArIAT effort will take important effort away from the protoDUNE activities?

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

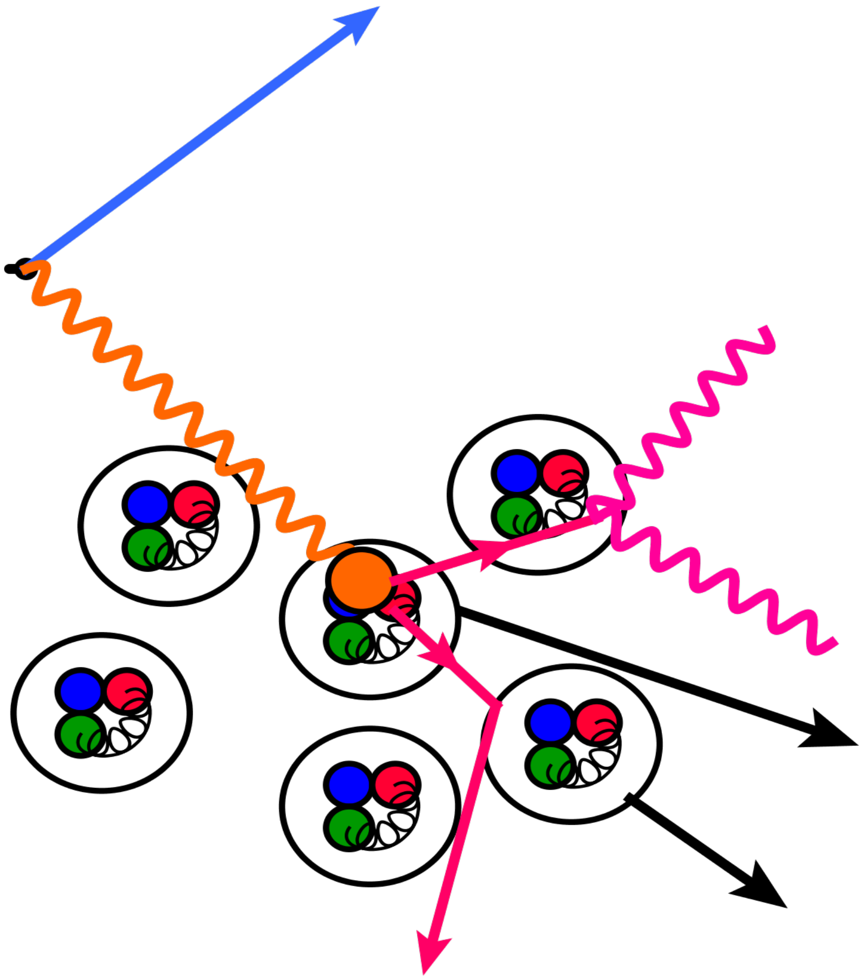


Mesons:
- Final State Interactions
- Energy? Identity?

Target nucleus:
- Nucleus remains intact for low Q^2
- N-N correlations

Outgoing nucleons:
- Visible?
- Energy?

LArIAT: Study Final State Particles



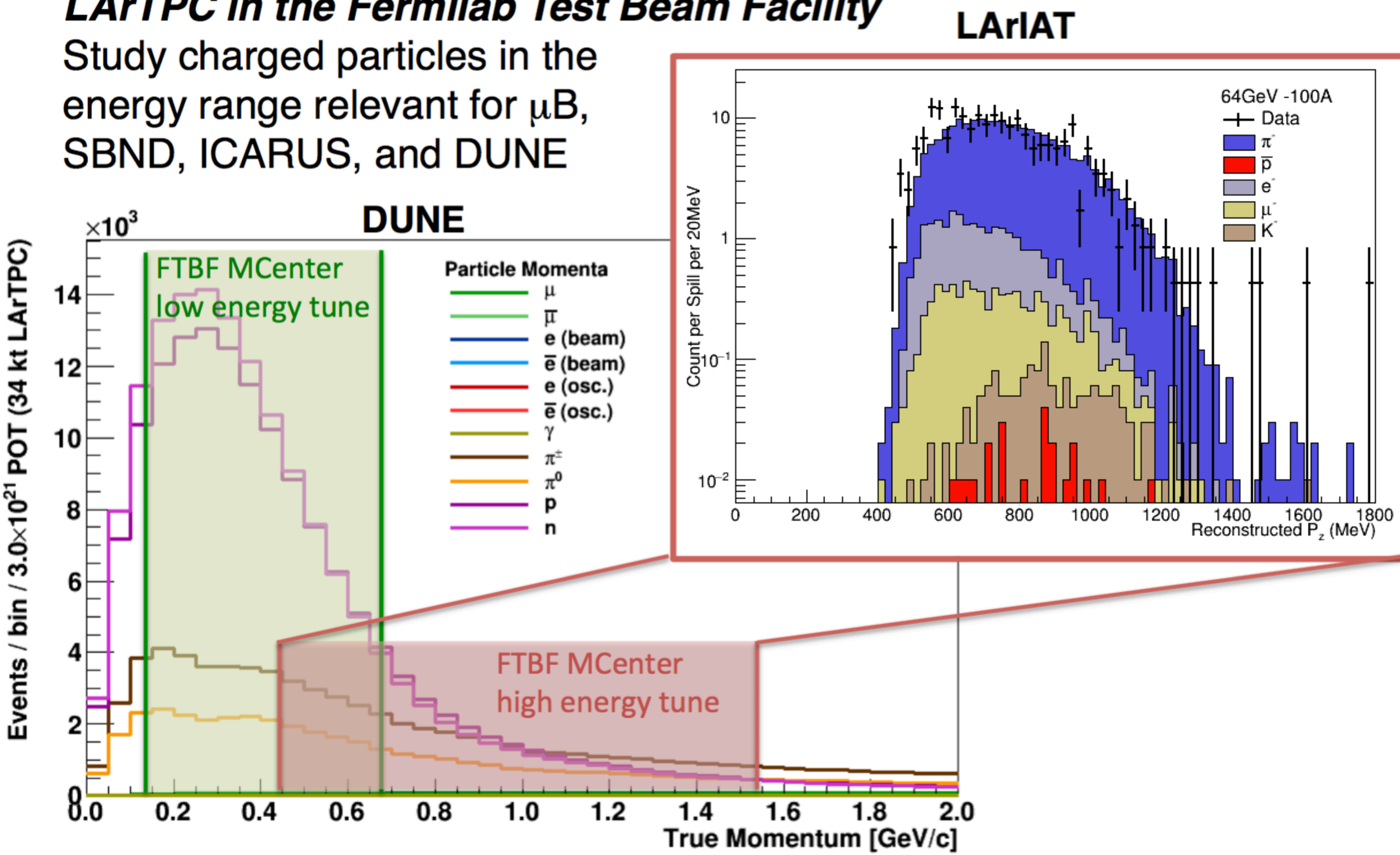
- Visible energy calibration
- Calorimetric response and resolution
- Particle identification
- Event reconstruction
- Hadron-argon scattering cross sections

LArTPCs enable us to study these topics in unprecedented detail.

Motivation & Method

LArTPC in the Fermilab Test Beam Facility

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



Test Beam Facility

Primary beam

Protons: 120 GeV

Secondary beams available at FTBF

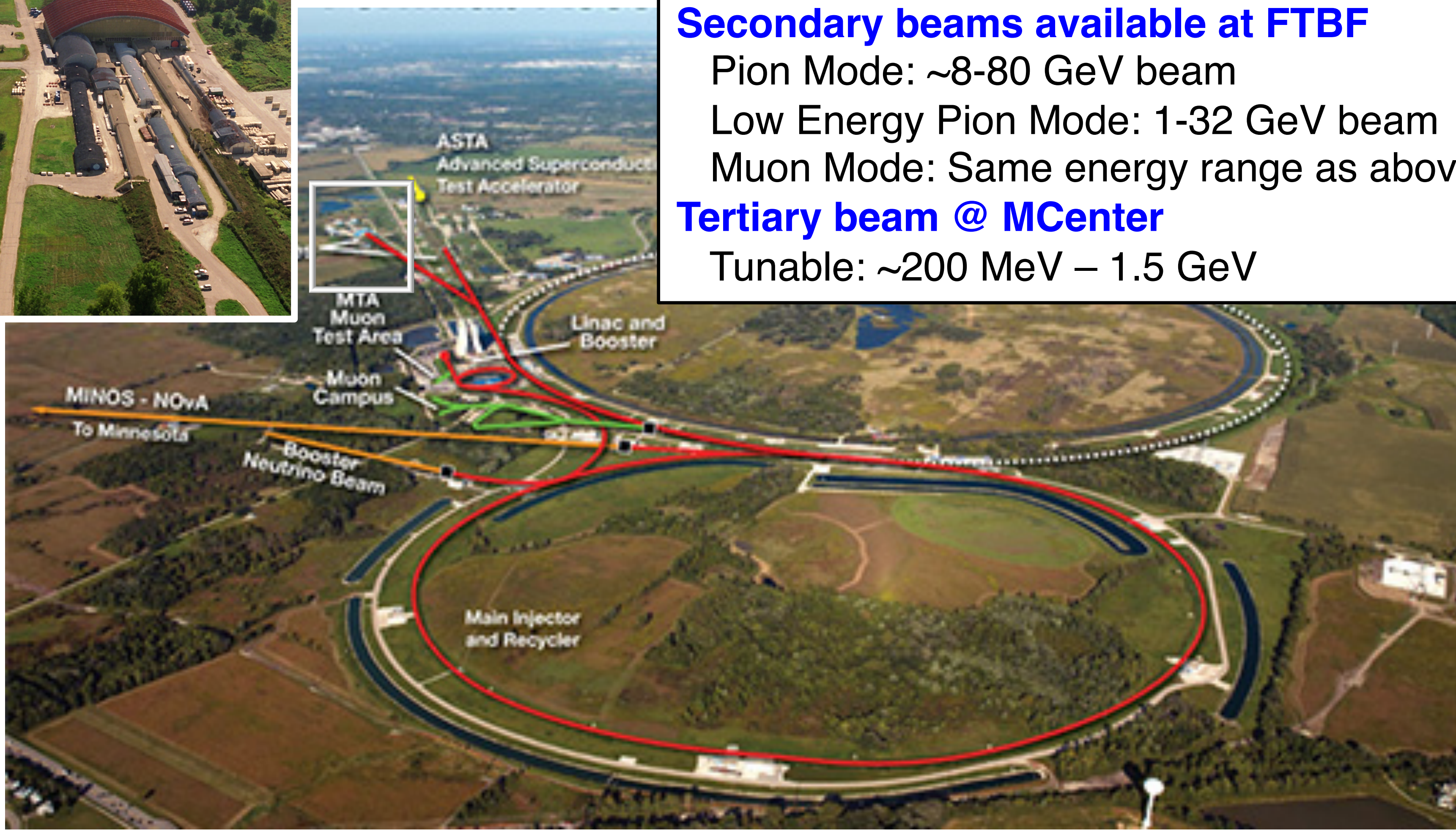
Pion Mode: ~8-80 GeV beam

Low Energy Pion Mode: 1-32 GeV beam

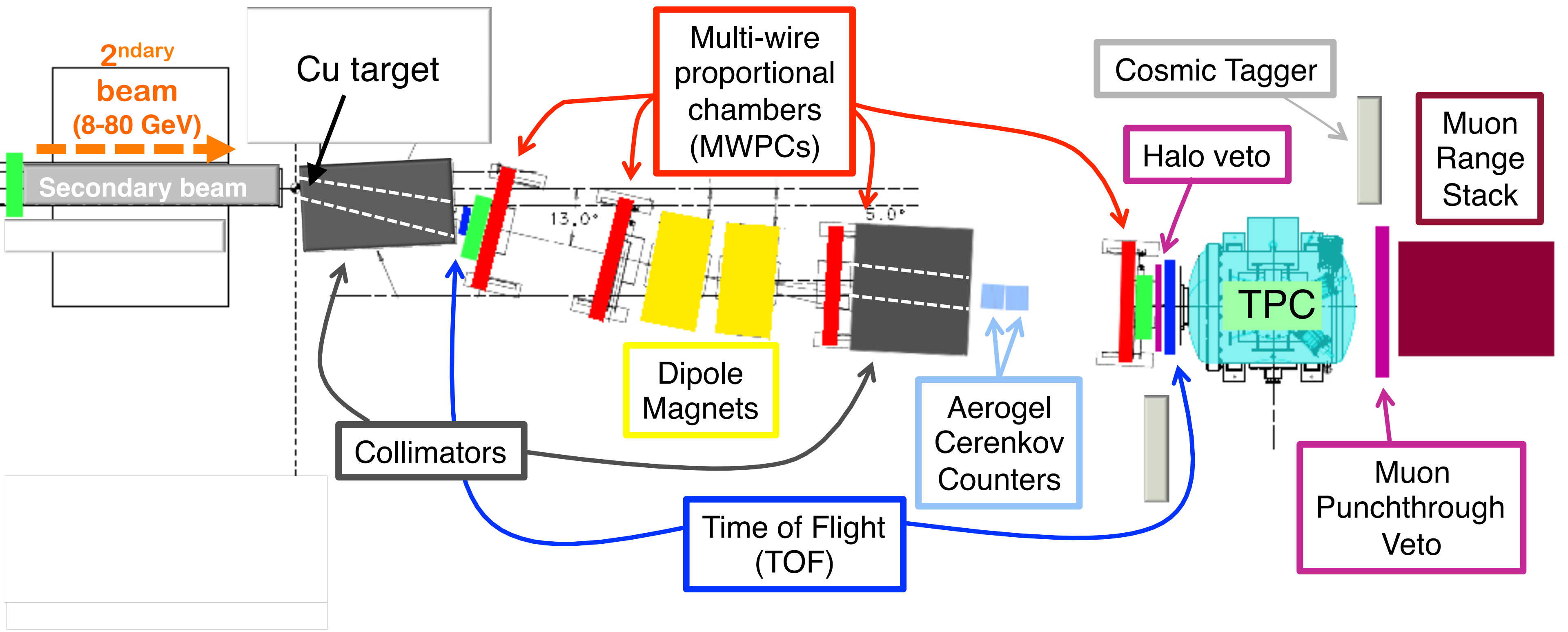
Muon Mode: Same energy range as above

Tertiary beam @ MCenter

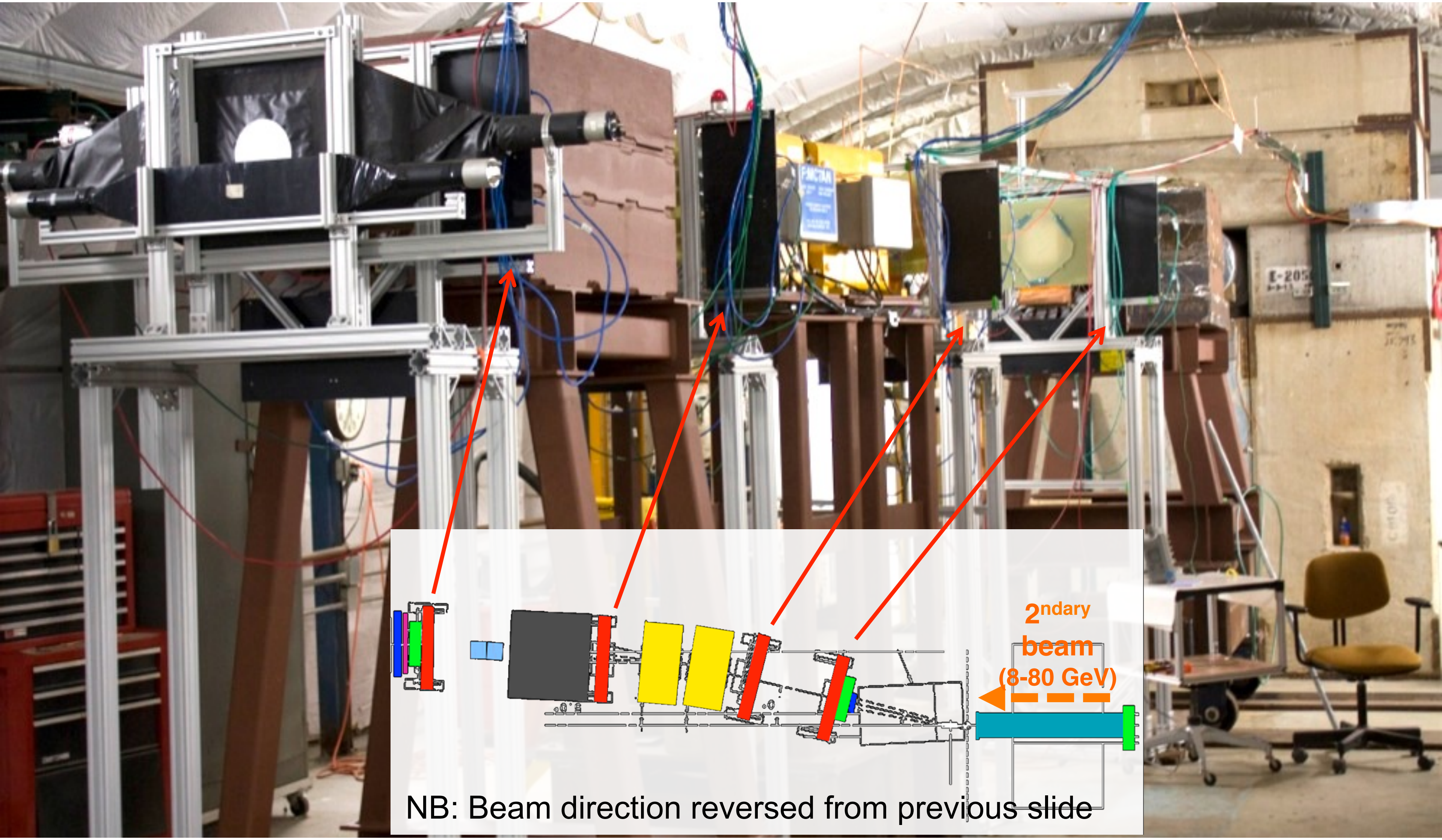
Tunable: ~200 MeV – 1.5 GeV



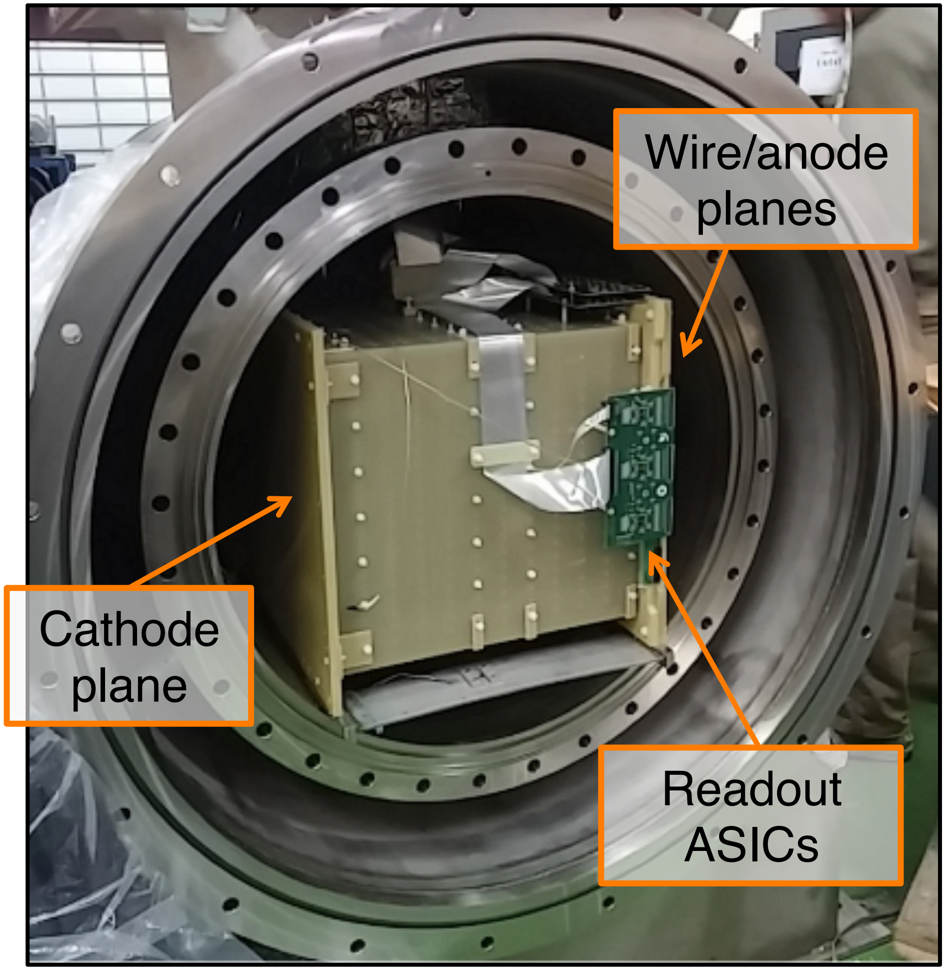
Experiment Overview



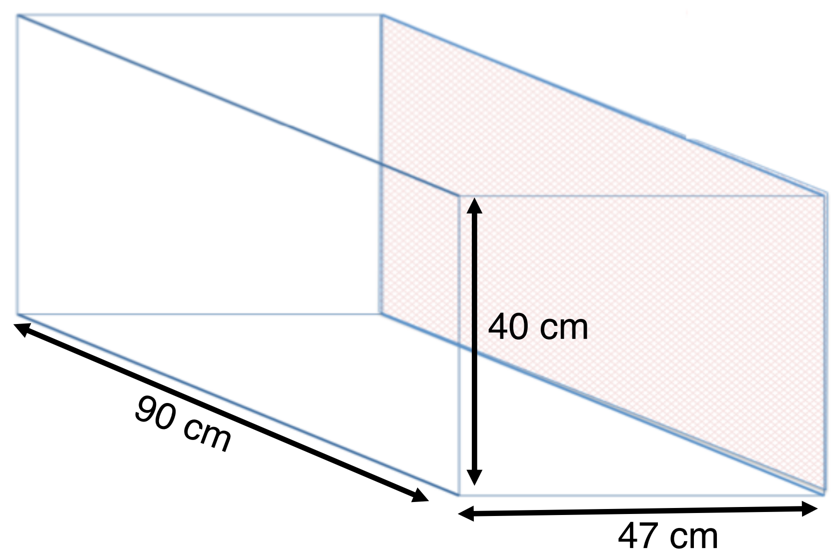
MCenter Tertiary Beam



LArIAT TPC



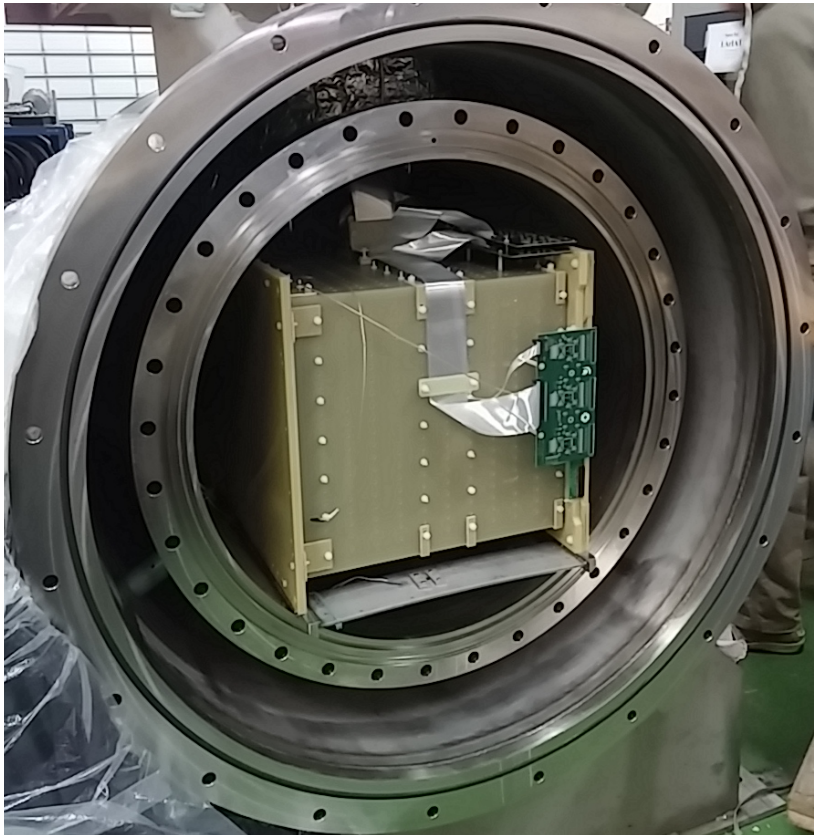
- **The time projection chamber**
  - Repurposed from ArgoNeuT
  - New wireplanes
    - 1 shield plane: 225 vertical wires
    - 2 readout planes: 240 wires each, +/-60°, 4mm pitch
  - Drift field ~500 V/cm



LArIAT Goals

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

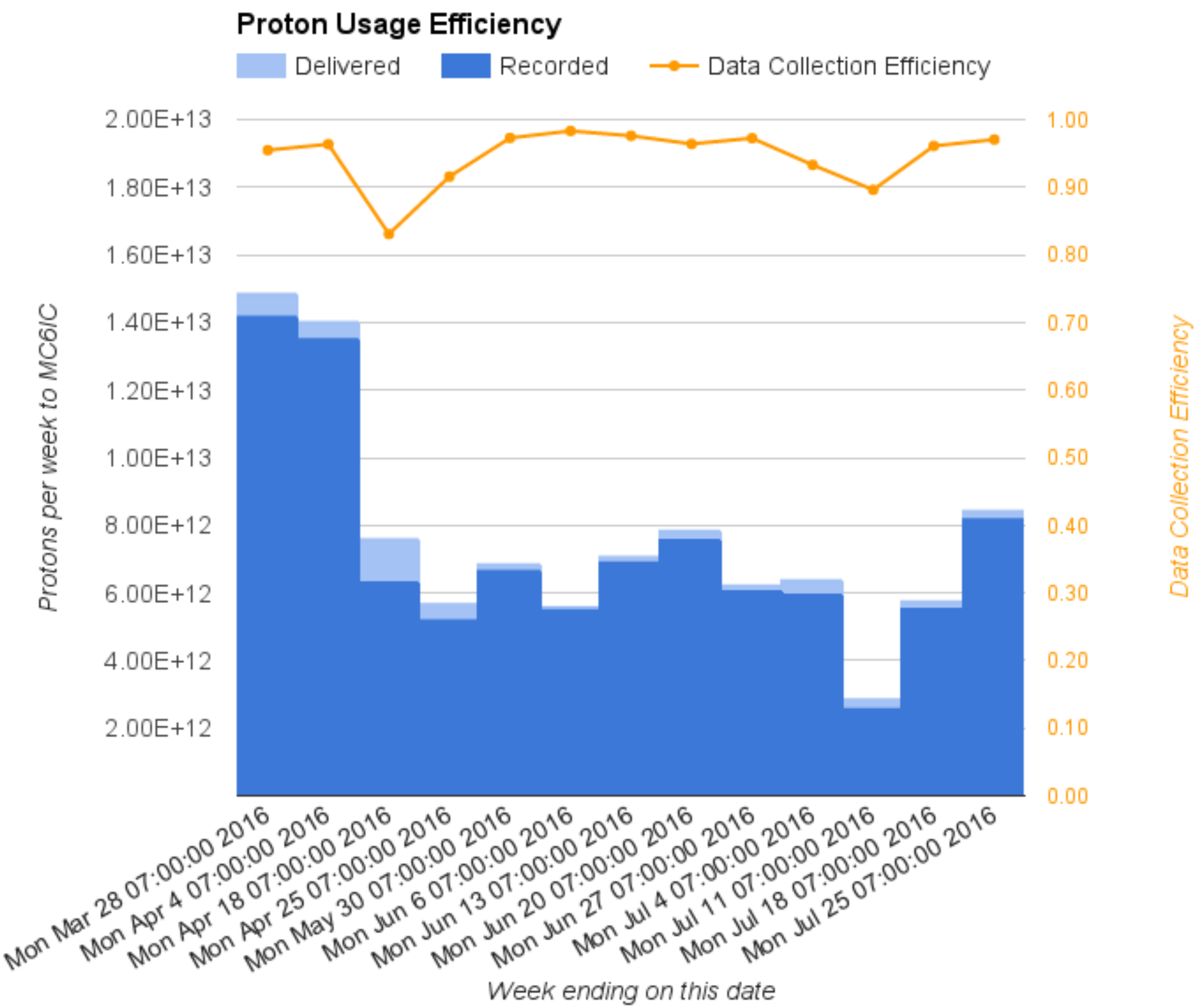
- Physics goals
  - π-Ar interaction cross sections
  - Kaon interaction cross sections
  - Geant4 validation
  - Develop criteria for determining particle charge based on topology (decay vs. capture), without magnetic field
  - Electron/photon shower ID
- R&D goals
  - Ionization and light production 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



Run-I and Run-II (Completed)

- **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. 19 – Jul. 25, 2016)**
  - 24 weeks beam data
    - 73k negative polarity spills + 57k positive polarity spills
    - ~80 events/spill including cosmics & other non-beam triggers
      - Increased Michel trigger rate (improvements to DAQ)
      - Beam tune chosen to increase kaon fraction
      - Estimate ~1000 K^+ collected in this run + many π, p, etc.

Run-II Proton Usage Efficiency



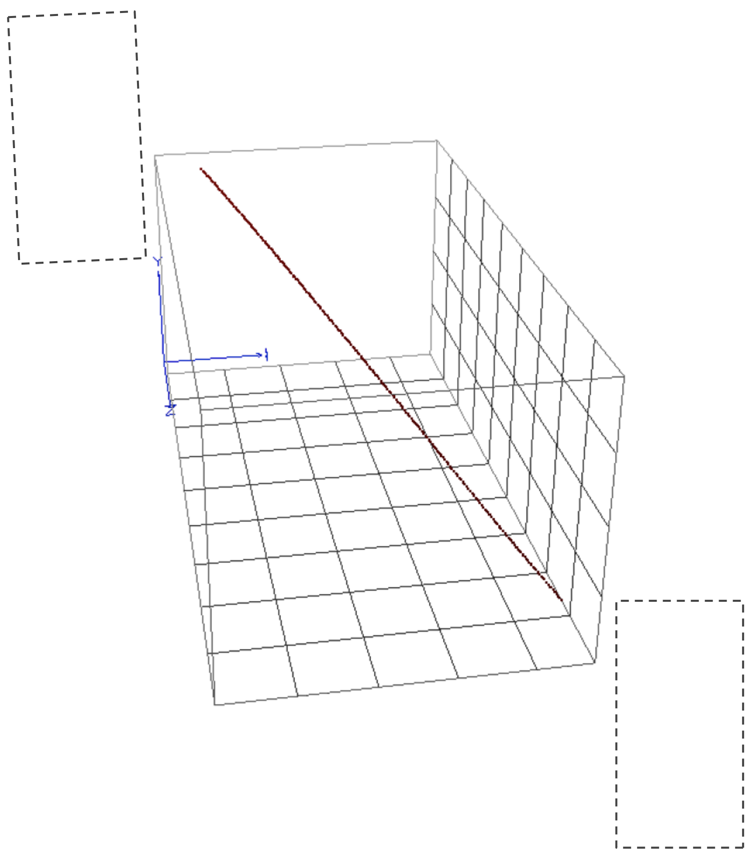
Run-I & -II Analysis Highlights

- In-situ impurity measurements
  - O_2-equivalent concentration via cosmic rays
  - N_2 concentration via slow component of light
- Light-based triggering/PID for Michel electrons
- Pion-Ar total cross section measurement
  - Publication currently in preparation
  - Exclusive interaction channel cross section measurements in progress
- Kaon ID & Kaon-Ar cross section
  - In progress

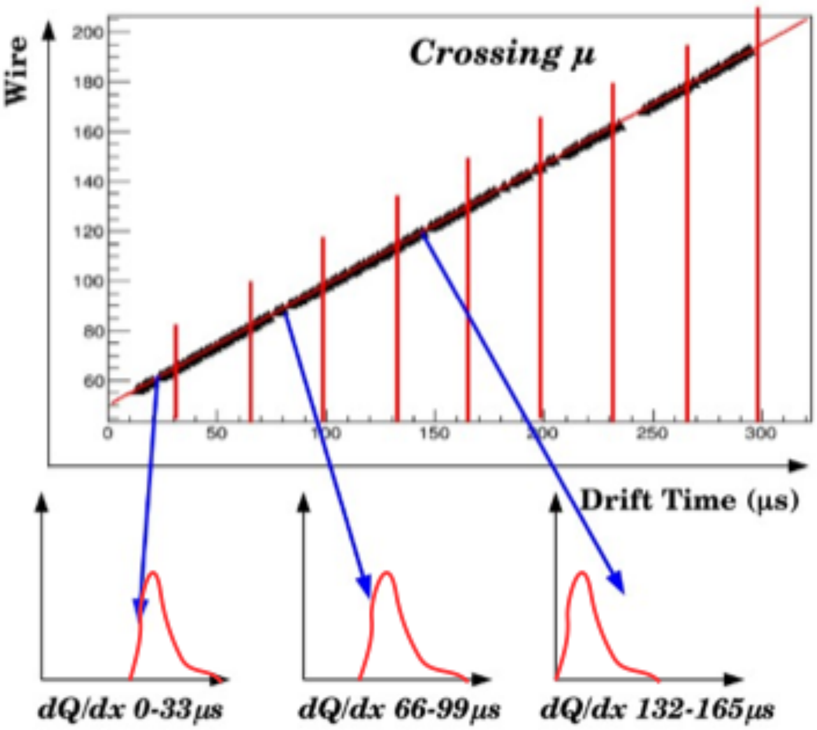
Highlight: Oxygen Contamination

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

Cosmic tagger paddle

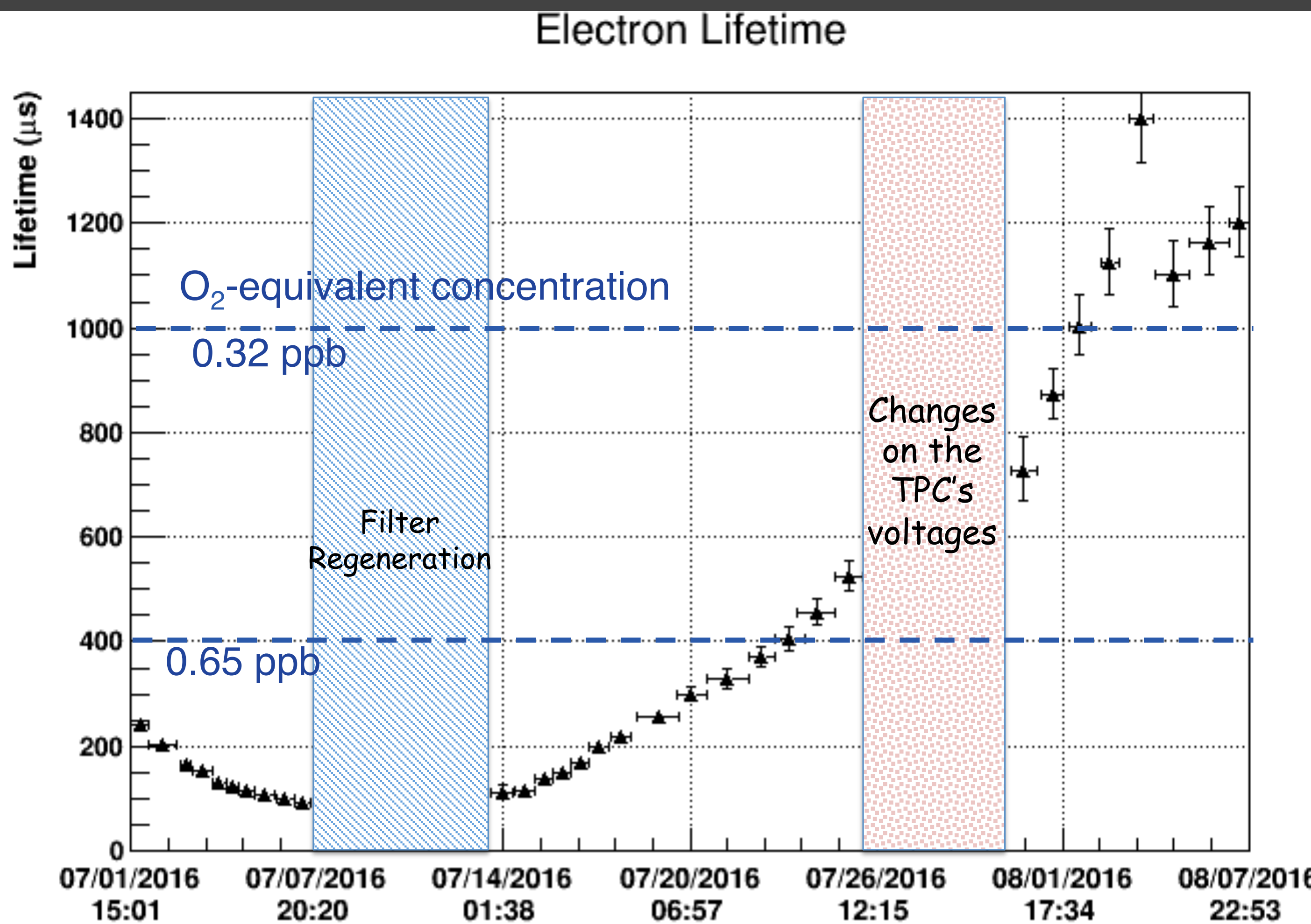


Cosmic tagger paddle



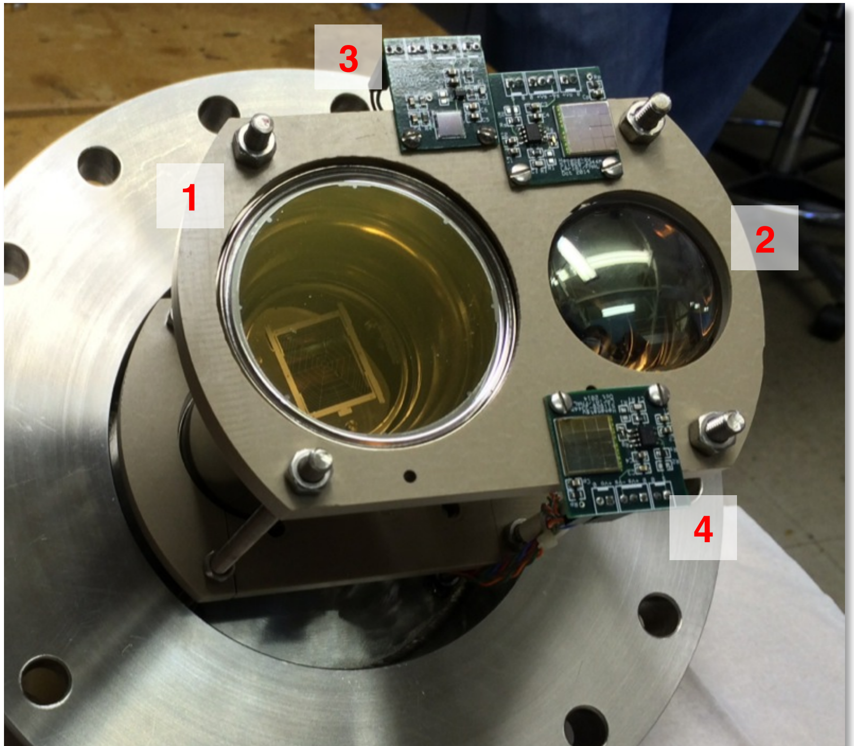
Amount of charge per unit length (dQ/dx) collected at wire planes depends on distance it drifted

Run-II Lifetime via Crossing Muons

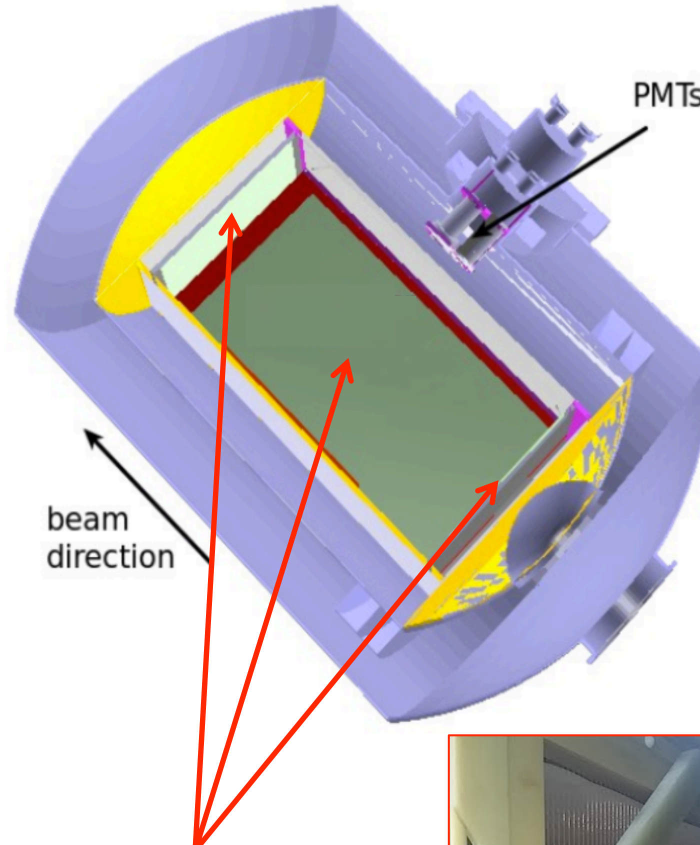


Our LArSoft module for measuring electron lifetime (O_2-equivalent concentration) using crossing muons can be easily adapted for use by other LArTPCs.

LArIAT Light Collection System



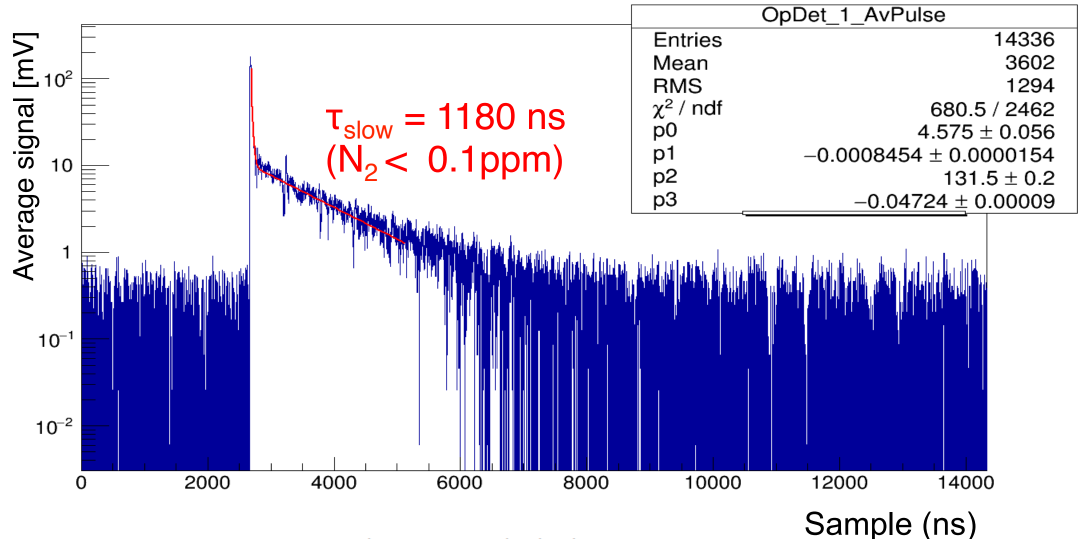
1. PMT: Hamamatsu R-11065 (3" diameter)
2. PMT: ETL D757KFL (2" diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (*Run I*)
   SiPM: Hmm. VUV-sensitive (*Run II*)

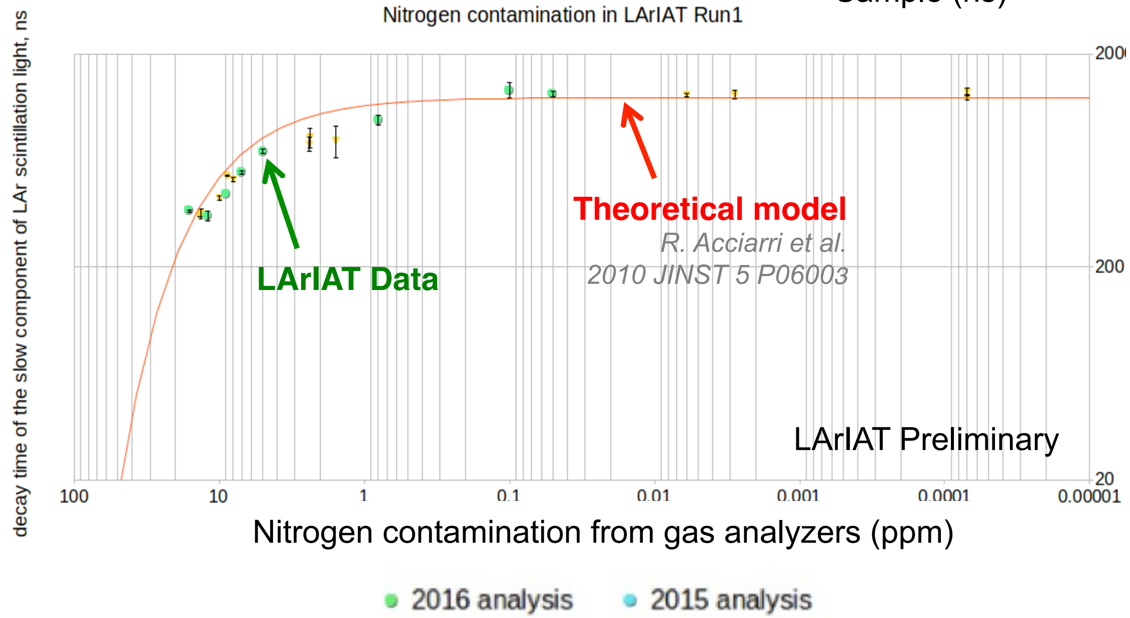


TPB-coated reflector foils on field cage walls

Highlight: Nitrogen Contamination

- N_2 in LAr suppresses scintillation light
- From fits to scintillation, can extract "slow" light time component and determine N_2 concentration
- Results agree with trend from model

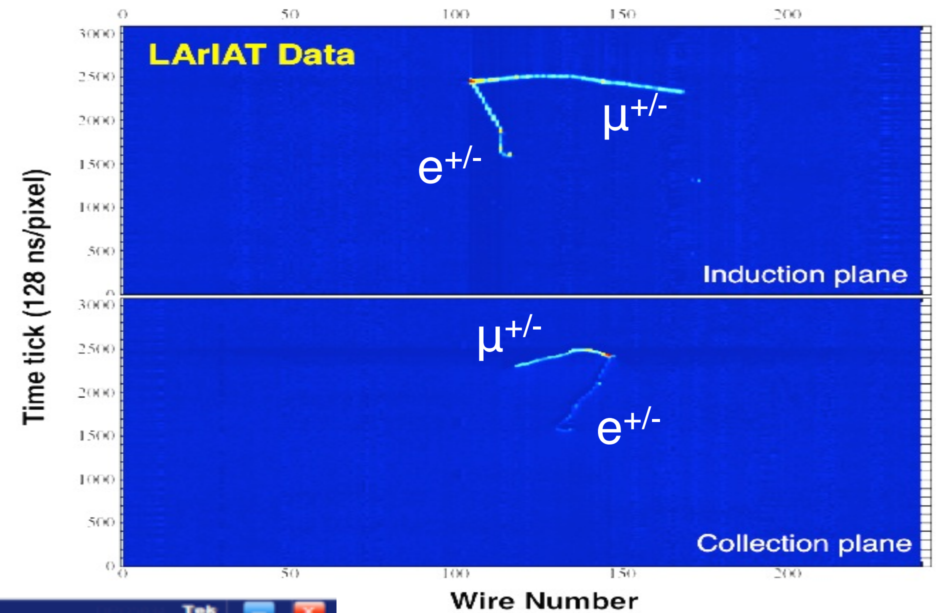


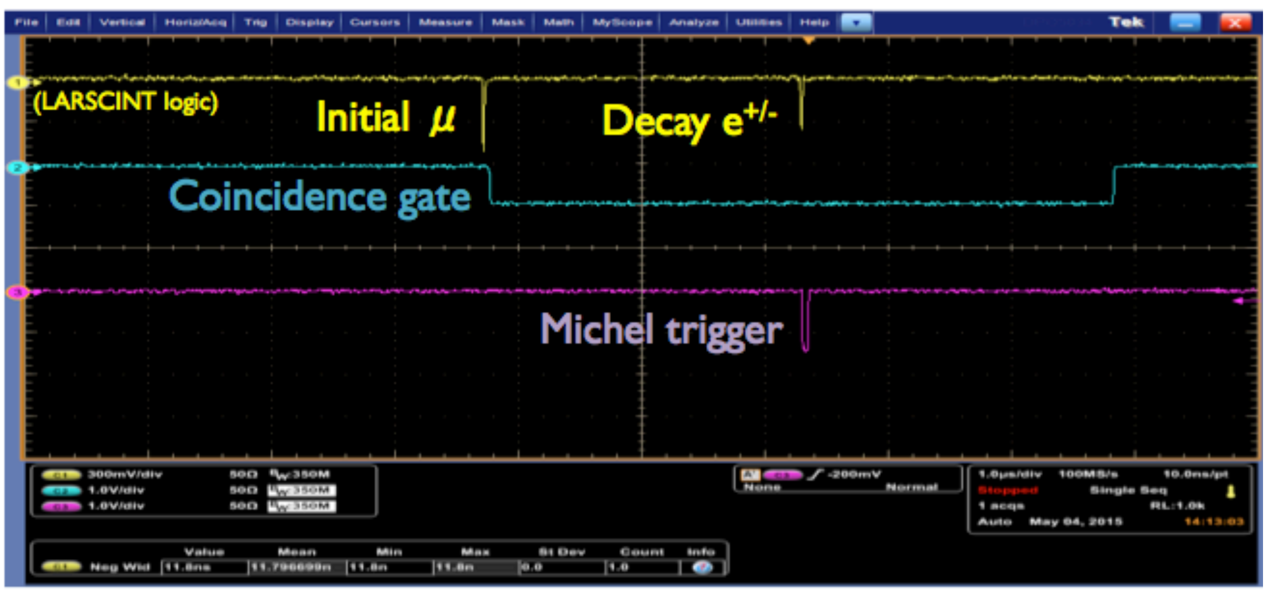


Highlight: Michel electron trigger

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

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





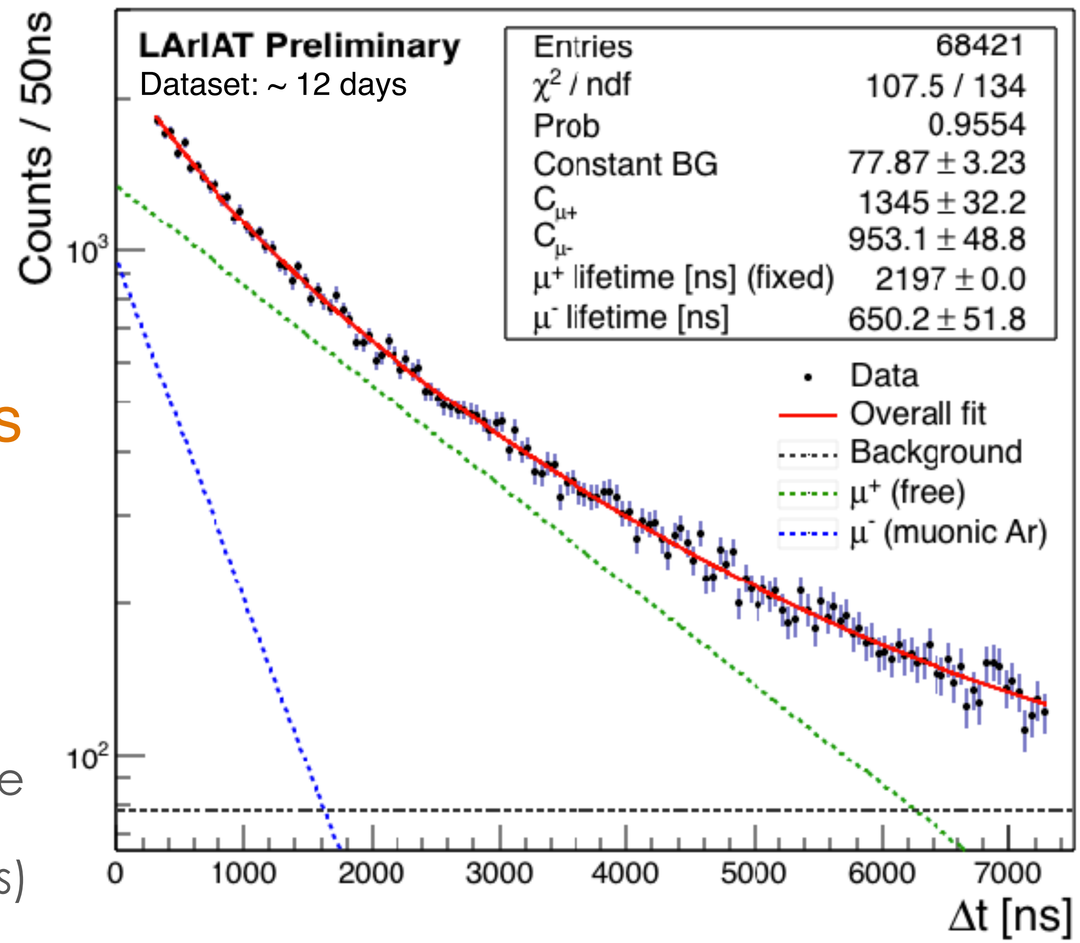
Real-time triggering on Michel e's from stopping cosmic μ's using **light signals**

Highlight: 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

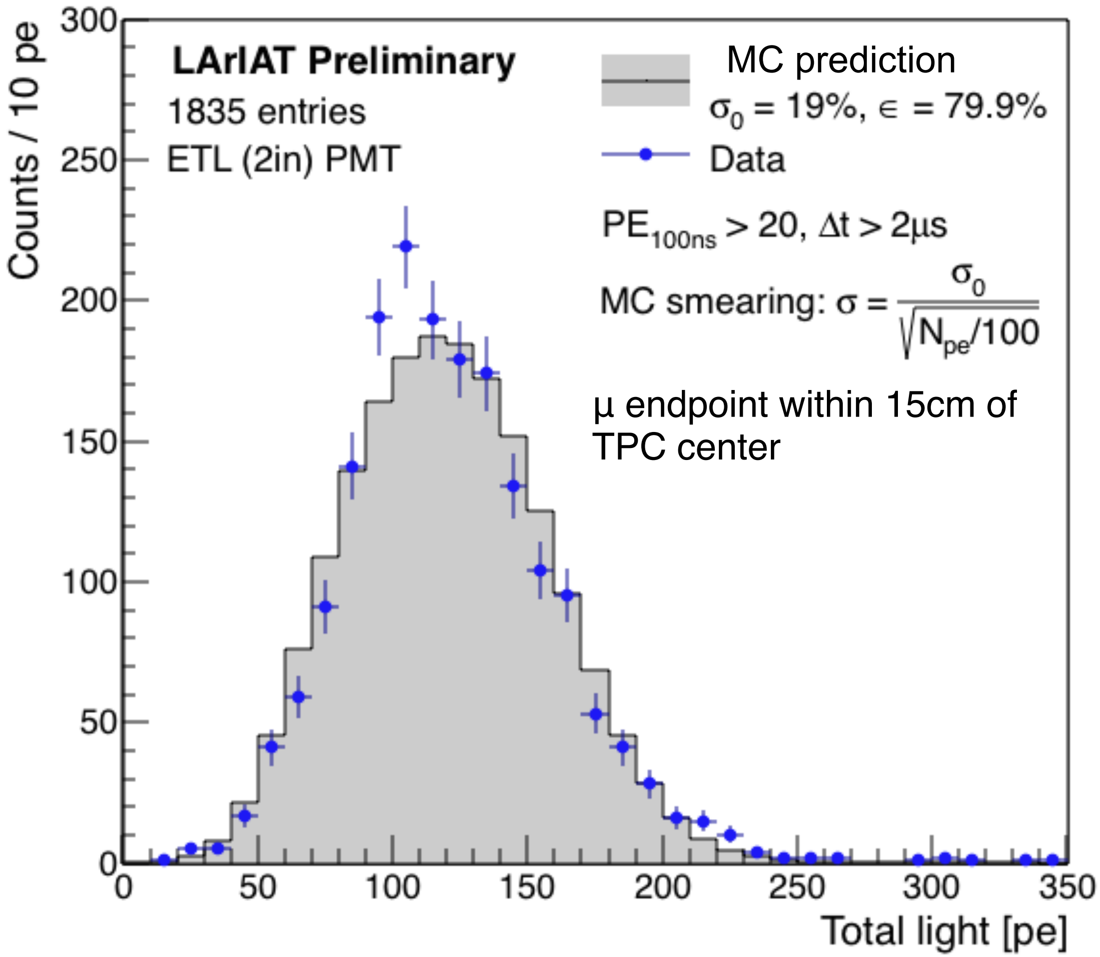


LIDINE 2015 Proceedings, JINST 11 C01037

- Fit results agree with recent measurement[1] (616.9 ± 6.7 ns)
- Translates to a capture lifetime of 918 ± 109 ns, in agreement with theory prediction[2] (851 ns)

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

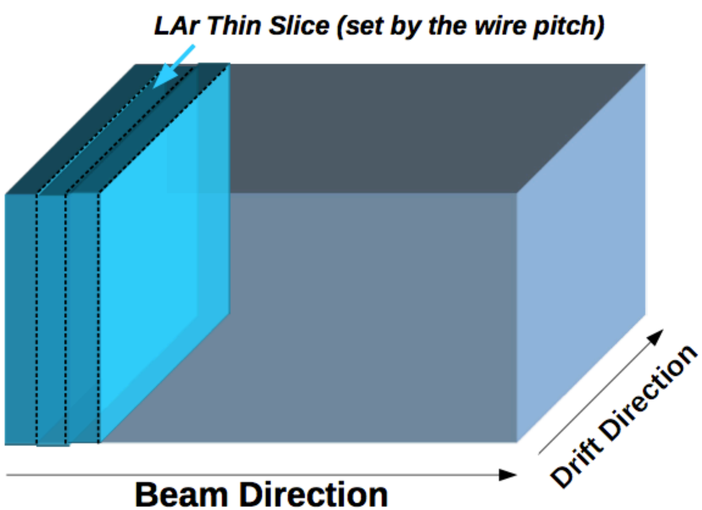
Highlight: Michel e PE spectrum



- Michel-candidate signals integrated to get photoelectron (PE) spectrum
- Data agree reasonably well with preliminary MC
  - Gives confidence in MC-predicted light yield: 2.4 pe/MeV for 2" ETL PMT (Run-I)

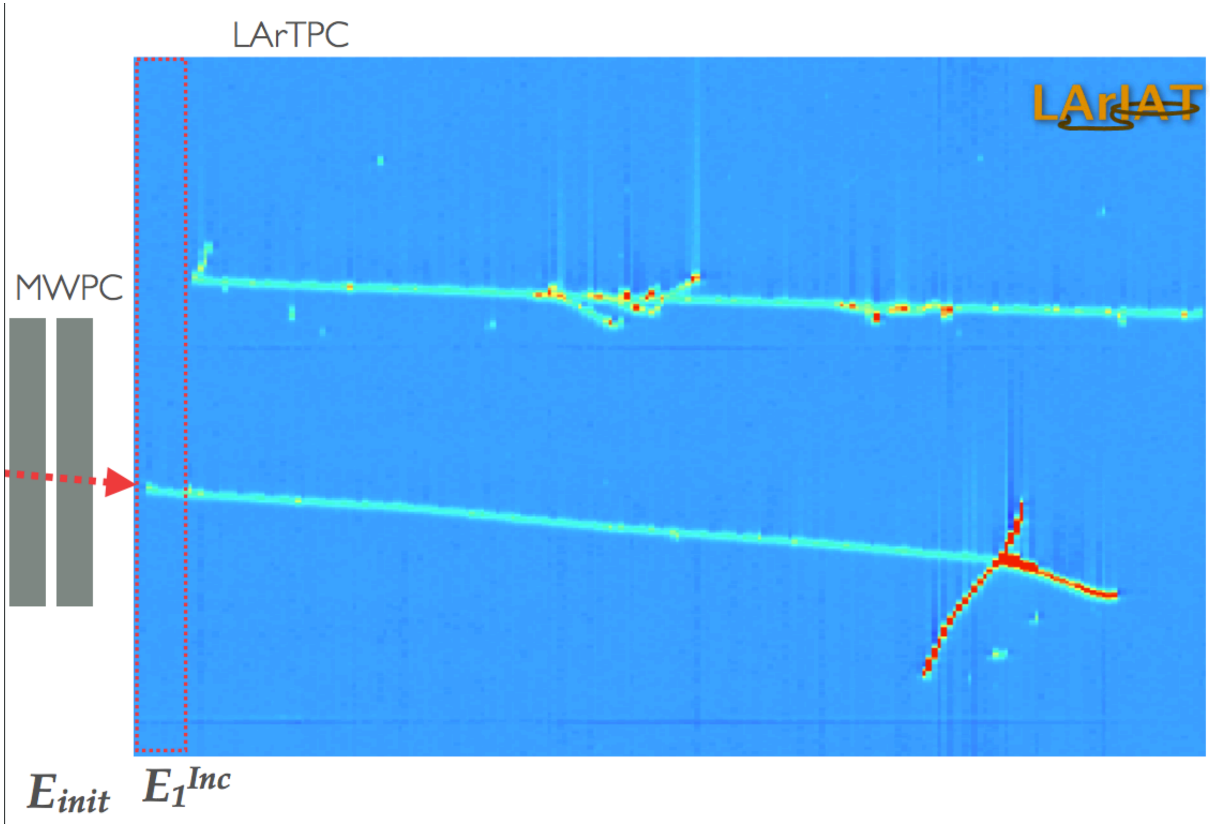
Highlight: "Sliced-TPC" Cross Section Measurement

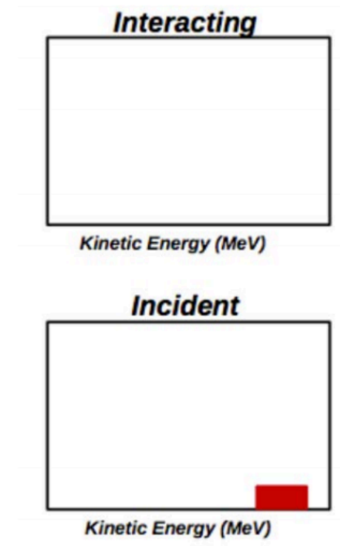
- TPC wire spacing allows us to divide the (90 cm) thick LAr volume into a sequence of (~200) adjacent thin slices (~4.5 mm) orthogonal to the beam direction of the incident pion
- Incident pion's kinetic energy is known at each slice
  - Entering pion's KE ($E_{initial}$) is known from tertiary beam instrumentation
  - At each successive TPC slice, energy incident on that slice is determined by subtraction of calorimetric energy (dE/ds) released by pion in previous slices



$$E_k^{incident} = E_{initial} - \sum_{s=0}^{k-1} dE_s$$

Sliced-TPC Method



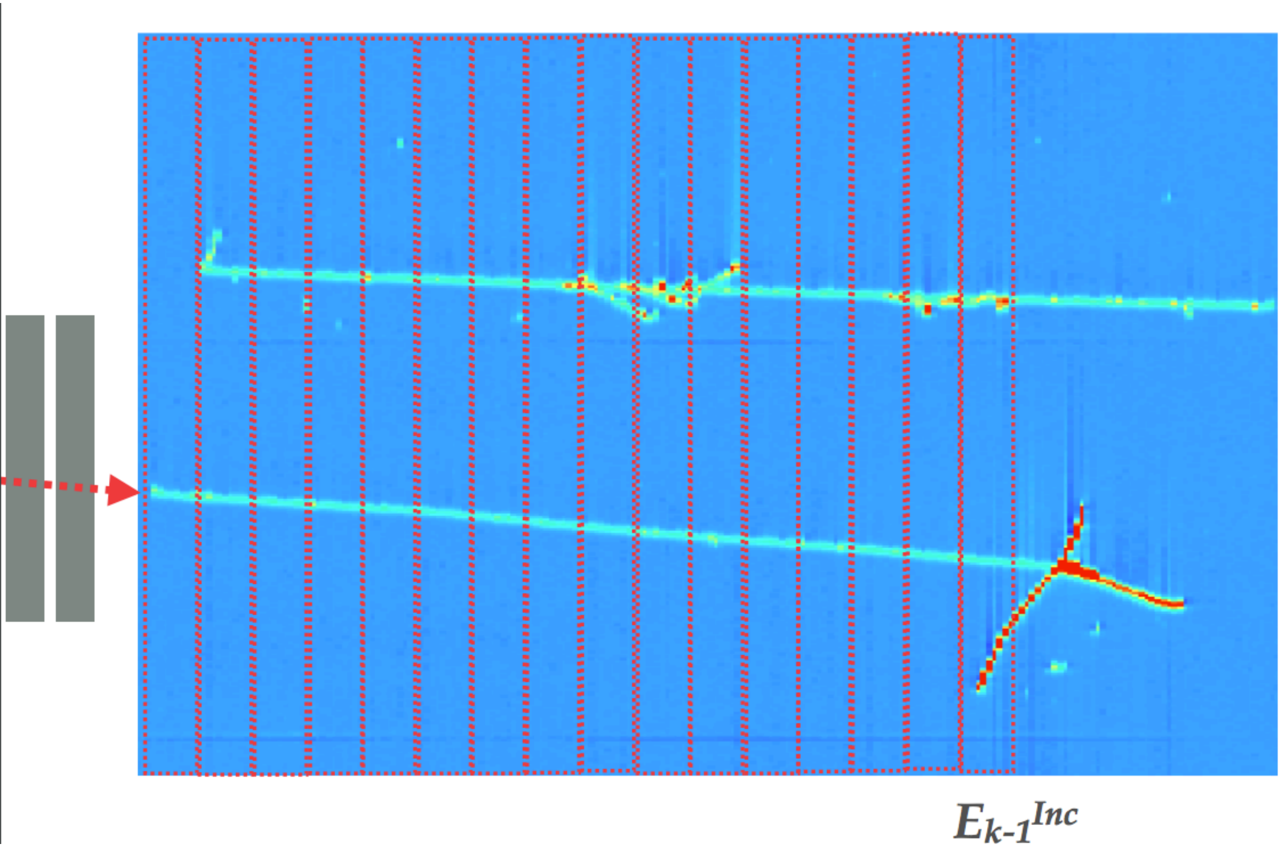


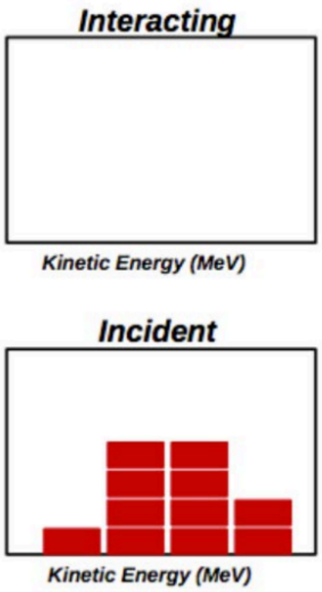
If NO interaction in the slice, fill only $\mathbf{N_{incid}}$ histo

If YES, fill both hisograms

- Sample each pion multiple times along its trajectory through the TPC
- Each time it crosses a slice, fill 2 histograms ($\mathbf{N_{incid}}$ & $\mathbf{N_{interact}}$)

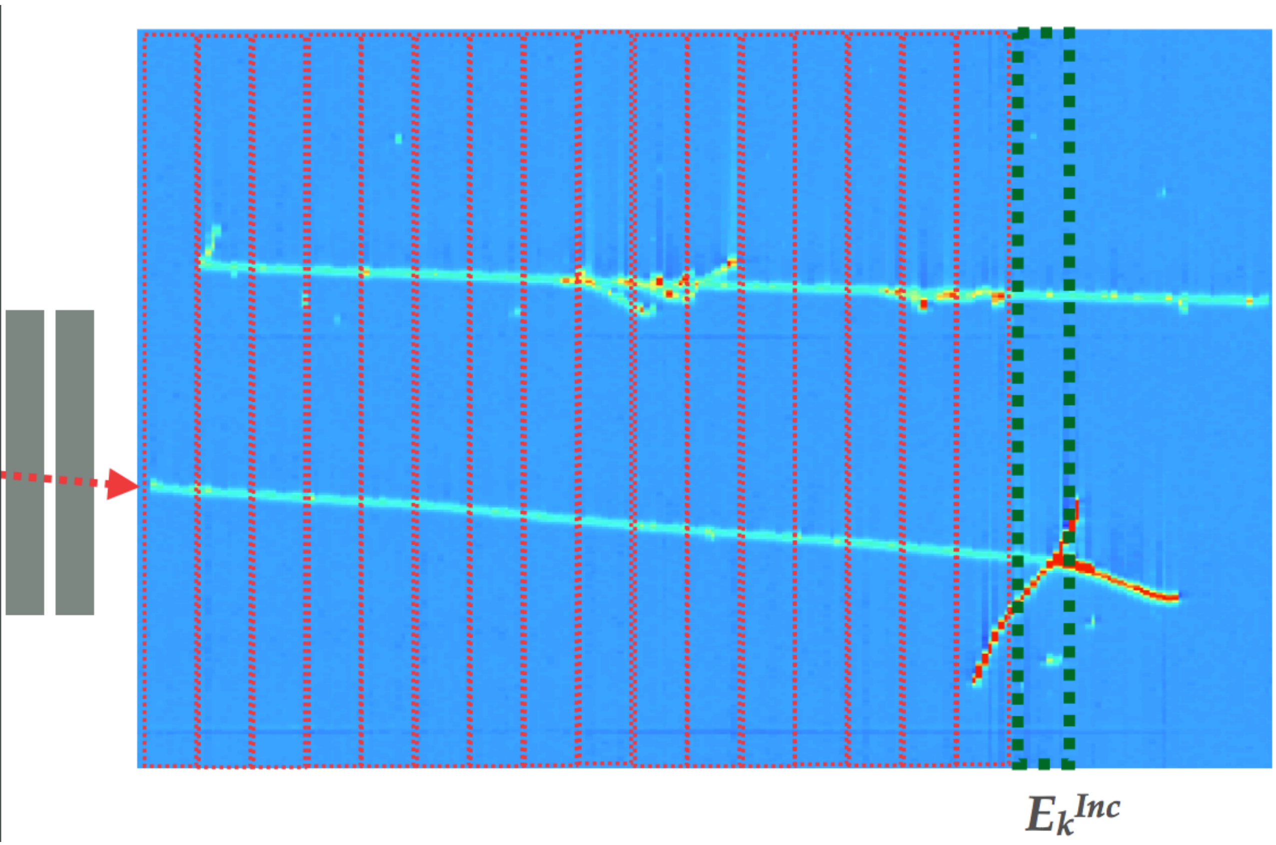
Sliced-TPC Method

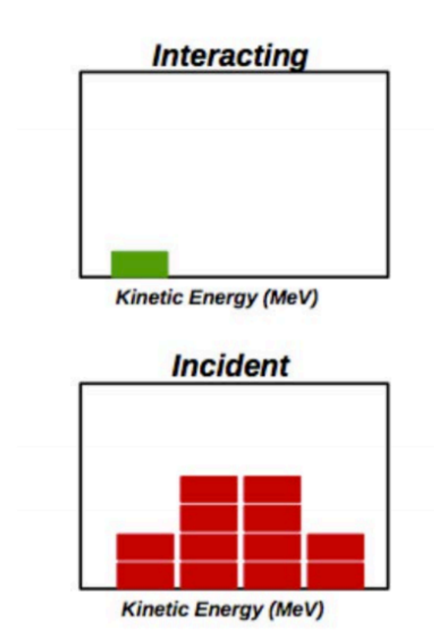




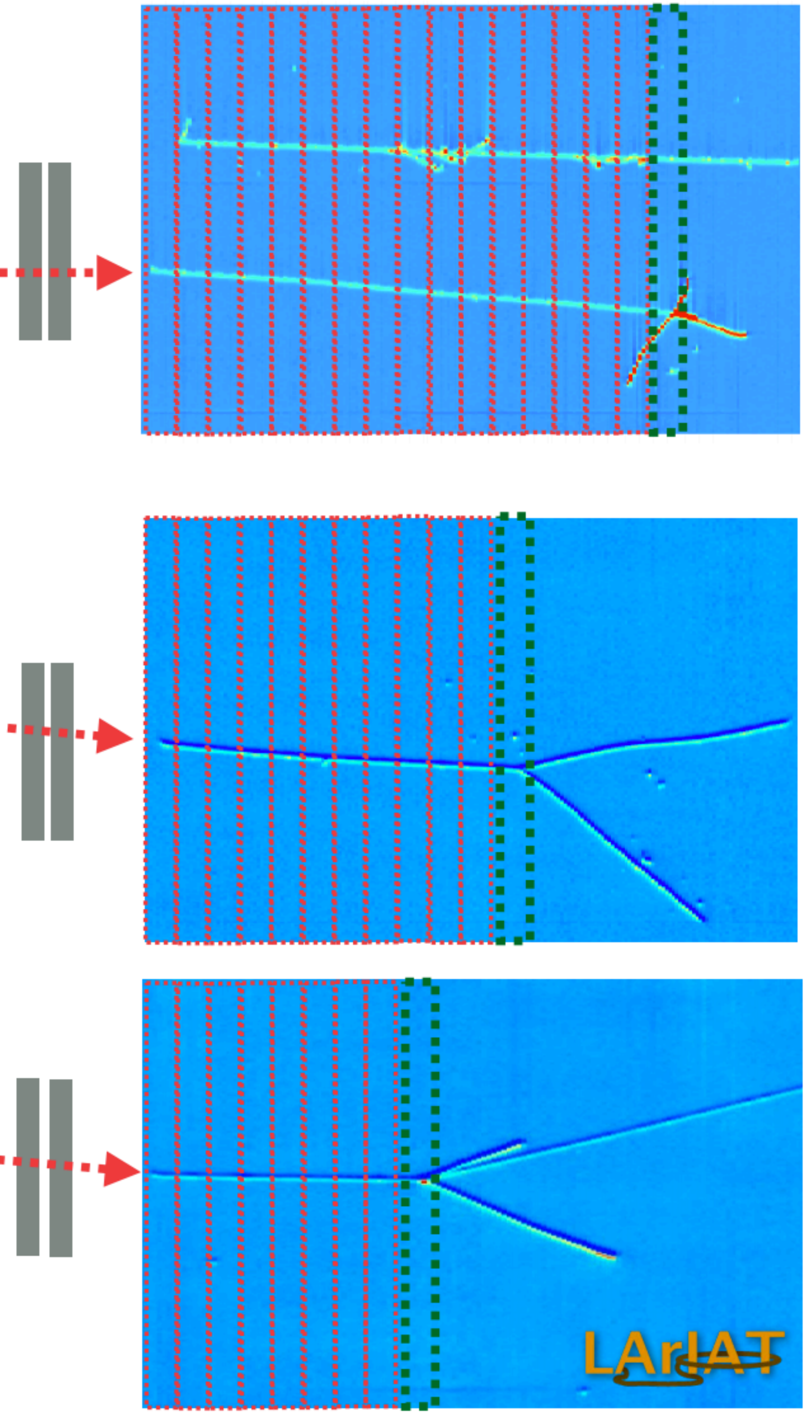
If NO interaction in the slice, fill only $\mathbf{N_{incid}}$ histo

Sliced-TPC Method



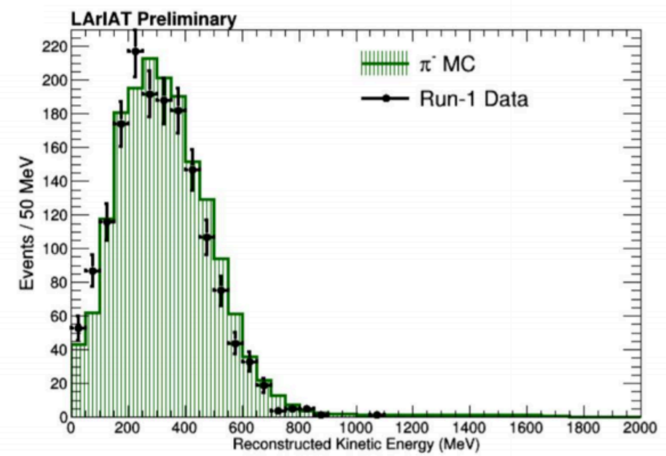


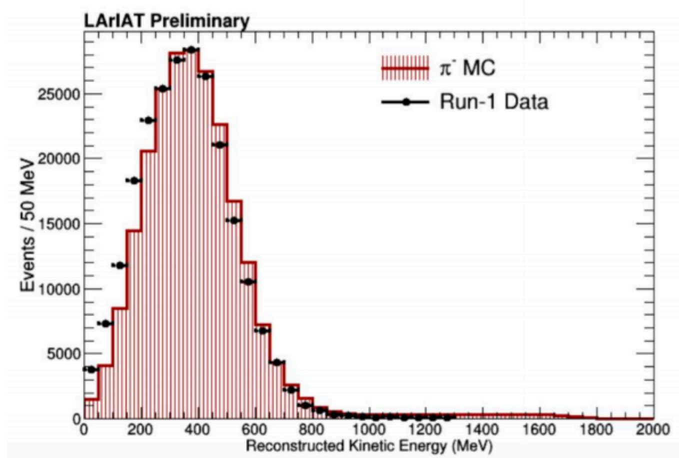
YES!!
Interaction in the slice!
Fill both hisograms



Sliced-TPC Method

- Repeat the process for the entire collected sample of pions

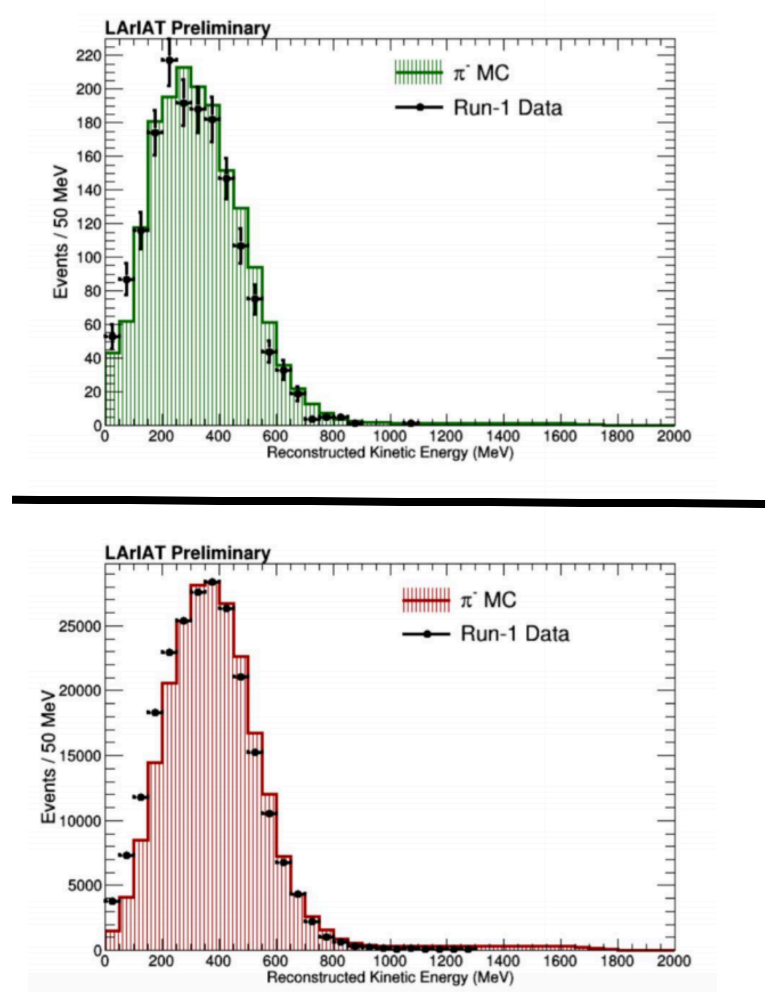




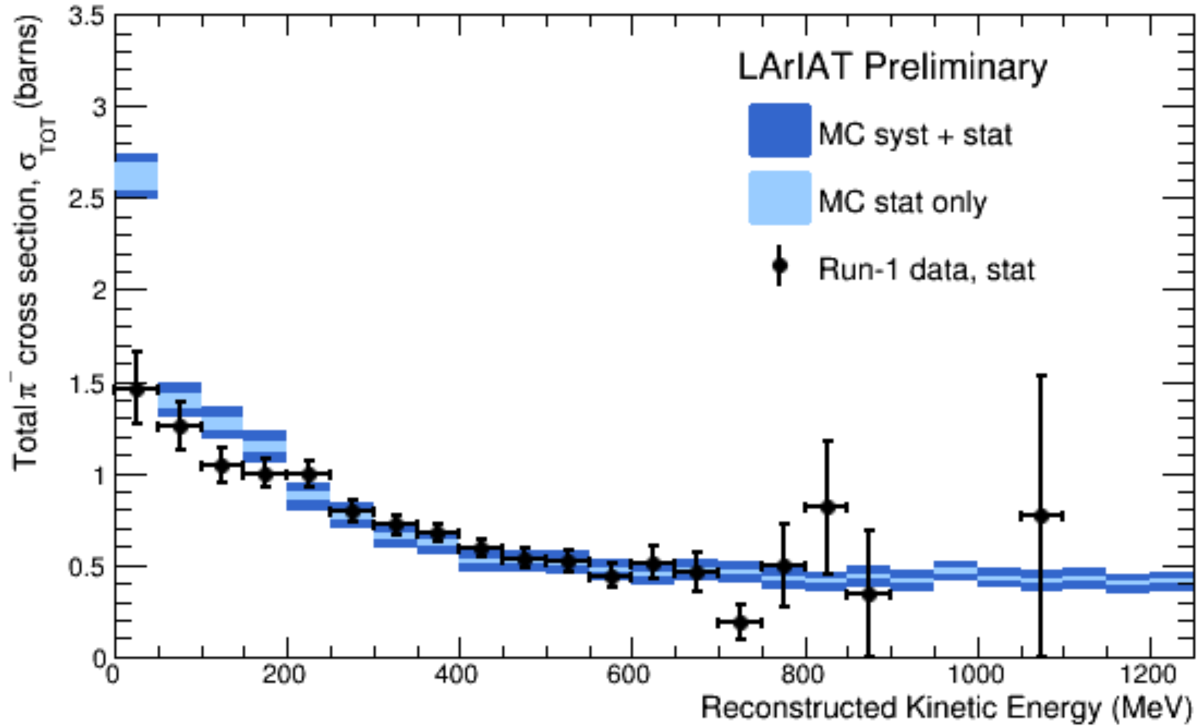
Cross Section

- Take the bin-to-bin ratio and calculate the cross section

$$\sigma_{tot}(E_{kin}) = \frac{1}{n\delta z}$$



Highlight: "Sliced-TPC" Pion Cross Section

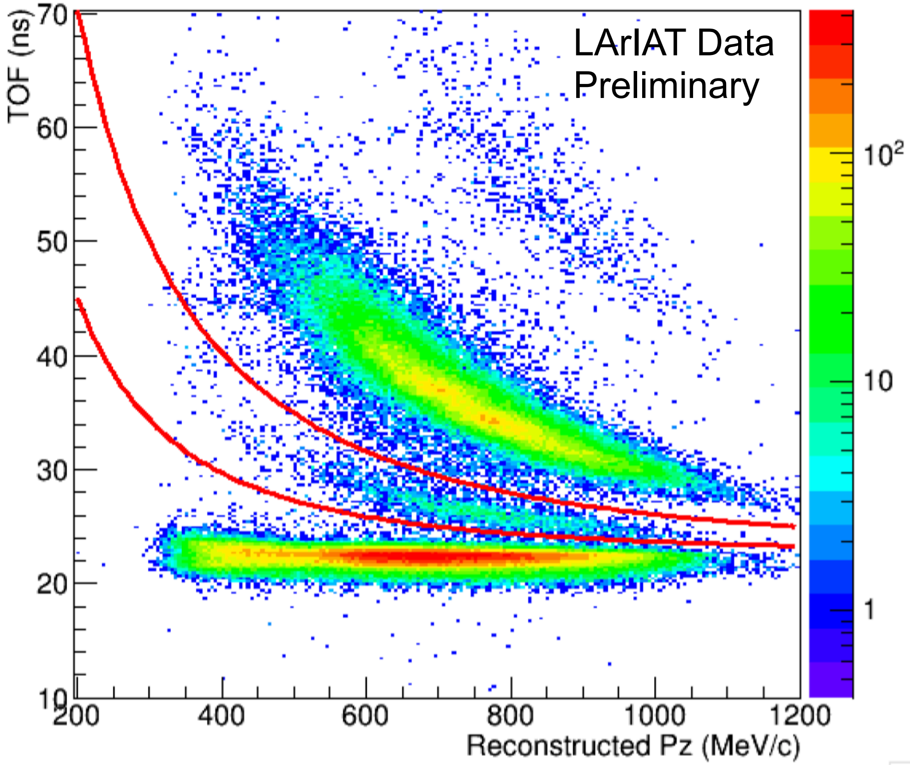


- Systematics considered:
  - dE/dx calibration: 5%
  - Energy loss prior to entering TPC: 3.5%
  - Through-going muon contamination: 3%
  - Wire chamber momentum uncertainty: 3%

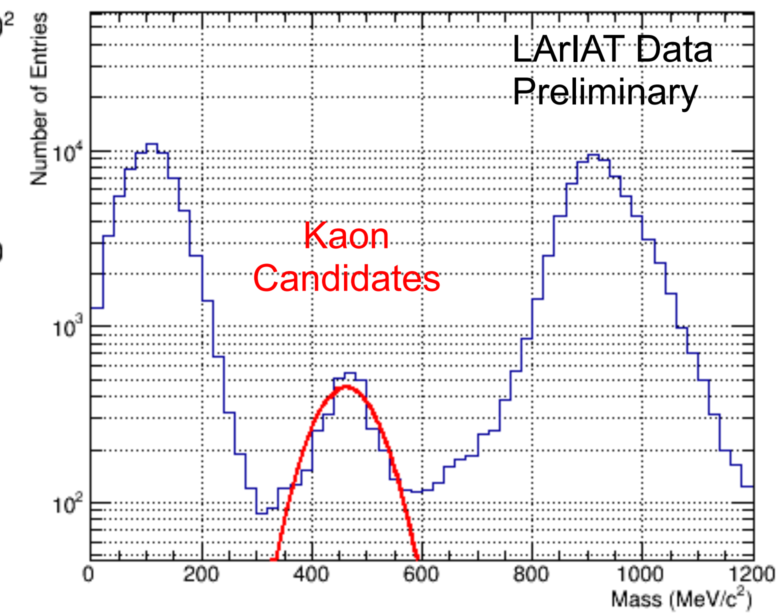
Presented at Fermilab Wine & Cheese Seminar, April 2016 and ICHEP 2016

Paper in preparation

Highlight: Kaons

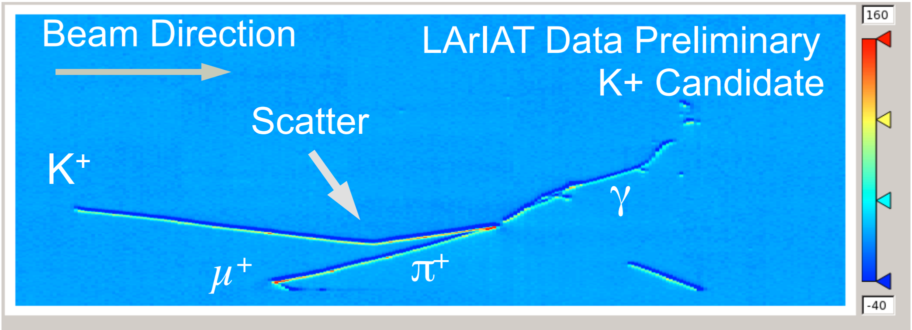


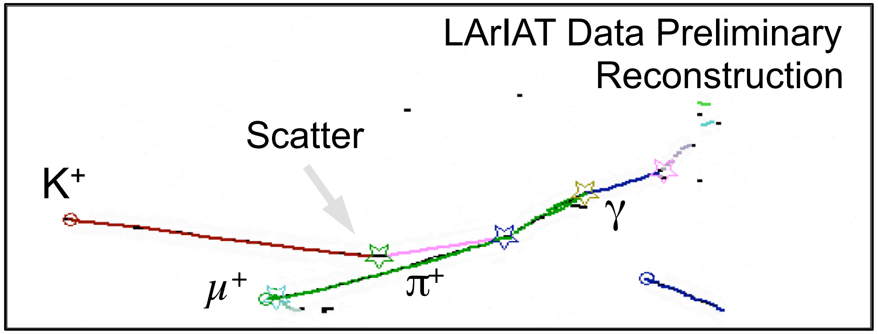
$$m = \frac{p}{c}\sqrt{\left(\frac{c \cdot TOF}{\ell}\right)^2 - 1}$$

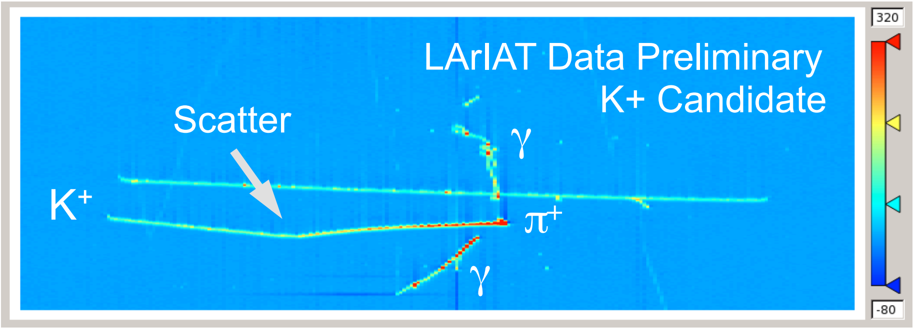


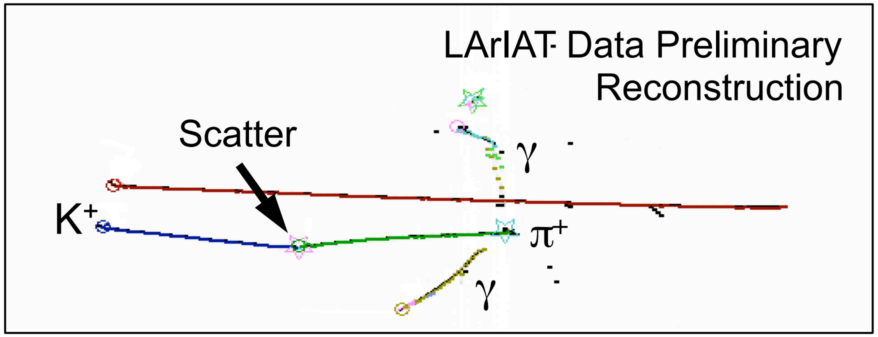
- Select kaons using tertiary beam TOF and magnetic spectrometer (wire chambers + magnets)

Highlight: Kaons









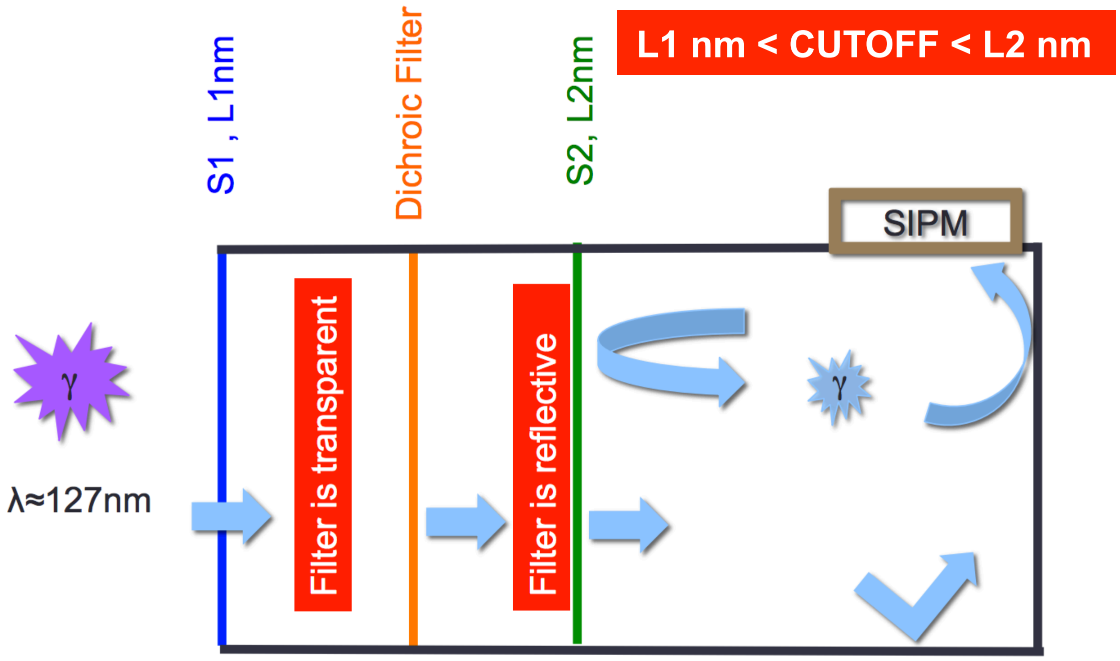
- Tagged as kaons entering TPC, then do PID by dE/dx-based "PIDA" algorithm (developed by ArgoNeuT)
- Demonstrated ability to automatically identify, tag, and reconstruct kaon events
- Next step: Kaon-Ar cross section

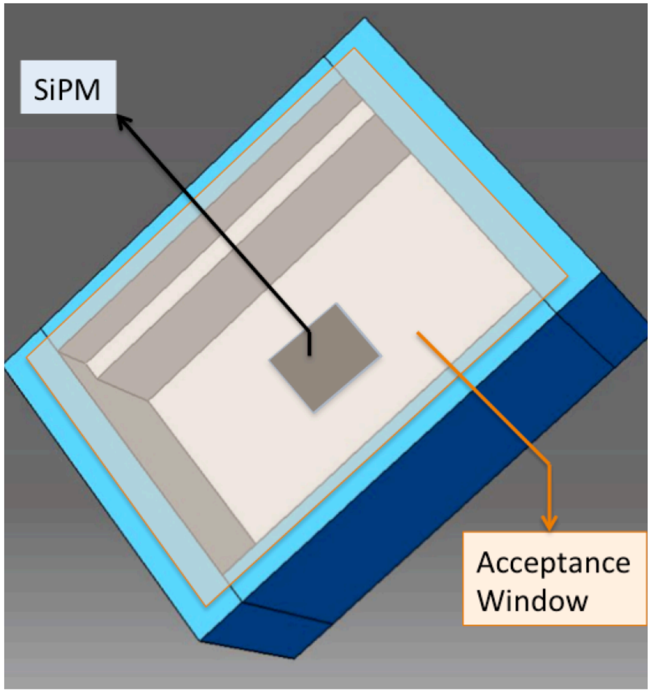
LArIAT Run-III

- Goals
  - Direct measurement of 5mm vs. 3mm wire pitch
  - Test novel light collection device (ARAPUCA)
- Additional possibilities (if funding and timing allow)
  - Test of “transparent” (mesh) cathode a la SBND
  - Test of SBND-style roll-formed field cage tubes

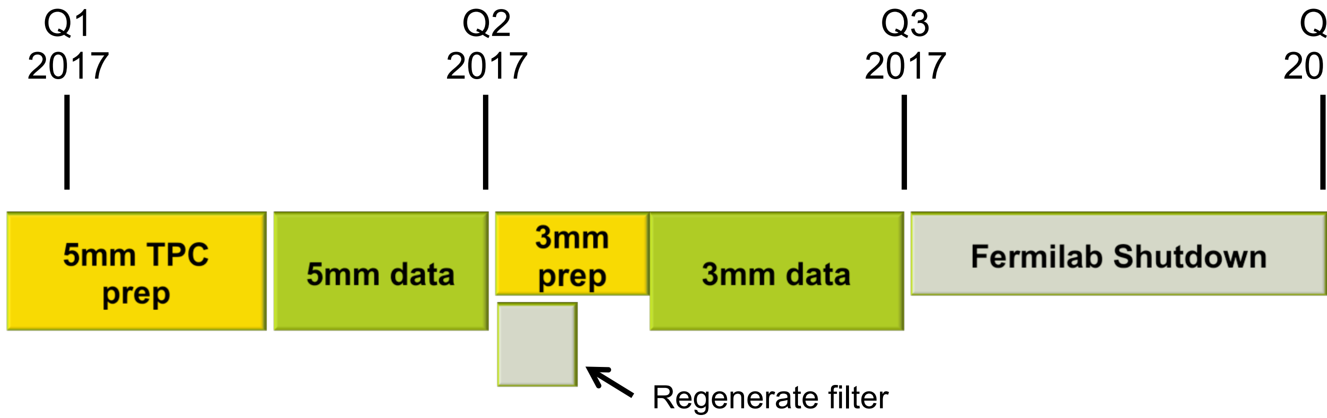
ARAPUCA (U. Campinas)

- Flattened box with highly reflective internal surfaces, and one open side with a dichroic filter (entrance for light)
- SiPM inside box detects trapped light





Run-III Timeline



- LArIAT Run-III construction & commissioning will be finished before protoDUNE construction begins in earnest
- Operations support by collaborators is only required until start of Fermilab shutdown in Summer 2017 (and it is minimal)

> I can definitely state that in the current stage of design, construction and preparation for assembly at CERN, the main protoDUNE needs are for mechanical, electric and cryogenic engineers.
> It is also very evident to me that the continued data analysis effort does not represent any risk of taking resources away from protoDUNE. On the contrary, the LArIAT analysis effort is very functional in opening the way for the protoDUNE test beam data analysis. In fact, a joint effort for code development is actively pursued by members of the two collaborations.
>
> flavio

i) Is the proposed LArIAT Run 3 program unique and well motivated scientifically?

- **This is the only program which will test the wire pitch options discussed for the SBND and DUNE detectors.**
  - Directly test, in identical conditions, how PID efficiencies and purities change with wire pitch
  - Determine how those changes affect the energy reconstruction for EM showers and hadrons
- **The light collection system tests may also inform the designs of SBND and DUNE photon detection systems**
  - First test of ARAPUCA in a beam environment

ii) Is the proposed LArIAT Run 3 program well aligned with the needs of DUNE and the LAr neutrino community?

- **At the time we proposed to Run-III to Neutrino Division, the DUNE spokespeople (Mark, Andre) agreed that it was useful for DUNE**
  - LArIAT continues to be the only available experiment in which to test design choices with quick turnaround
- **Due to its small size and ability to quickly change components, it is the ideal test stand for these studies**
  - ProtoDUNE is not as nimble, due to the large volume of argon required for operation
- **We are responsive to requests from the rest of the LAr community as well, for example:**
  - Electric field studies requested by MicroBooNE (took data from 0 V/cm → 700 V/cm in steps, PID studies underway now)
  - Test of LAPPDs as TOF in MCenter beam (effort led by J. Paley), in preparation for their use in protoDUNE

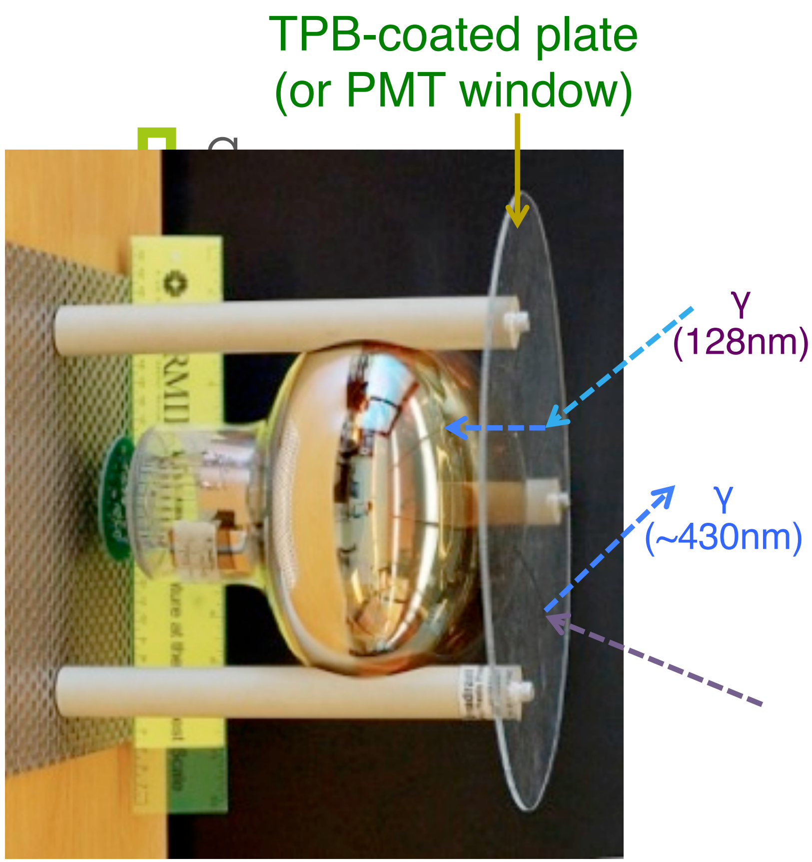
iii) Is it likely that a continued LArIAT effort will take important effort away from the protoDUNE activities?

- **LArIAT Run III construction & commissioning will be finished before protoDUNE construction begins in earnest**
  - Minimal person-power needs for LArIAT operations (shift-taker + a few on-call experts)
  - All LArIAT effort will then be scientific, for data analysis
- **Students and postdocs trained in LArTPC analysis with LArIAT data will benefit protoDUNE (and all LArTPC experiments…)**
  - Easy transition to protoDUNE analysis when it has collected data, (assuming they work at an institution which is also participating in protoDUNE)

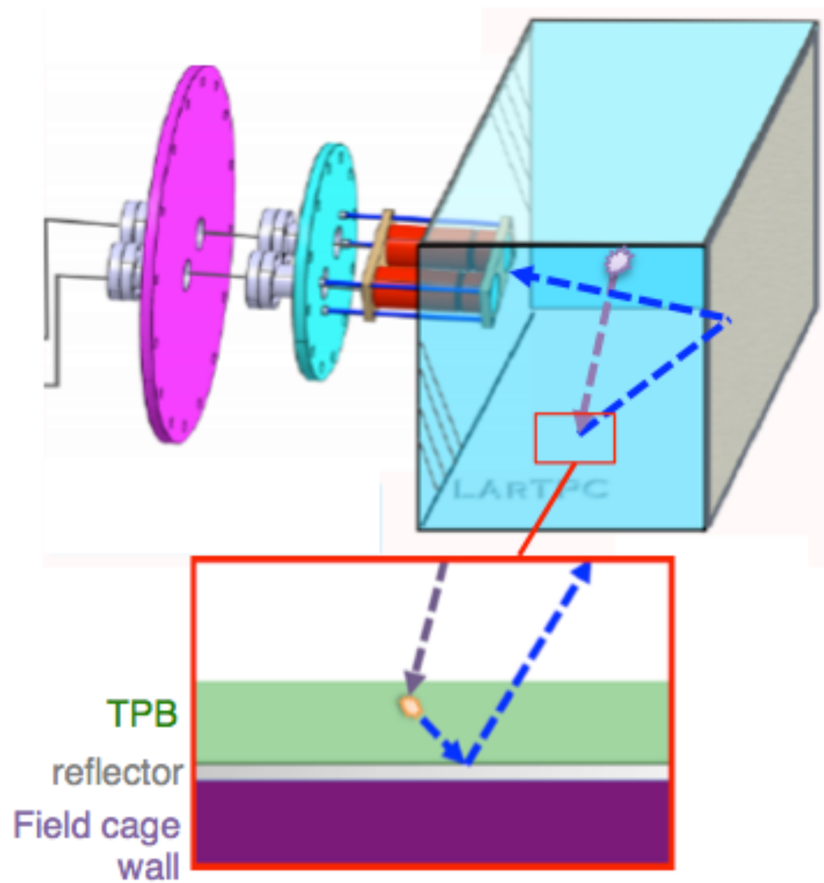
Thank you

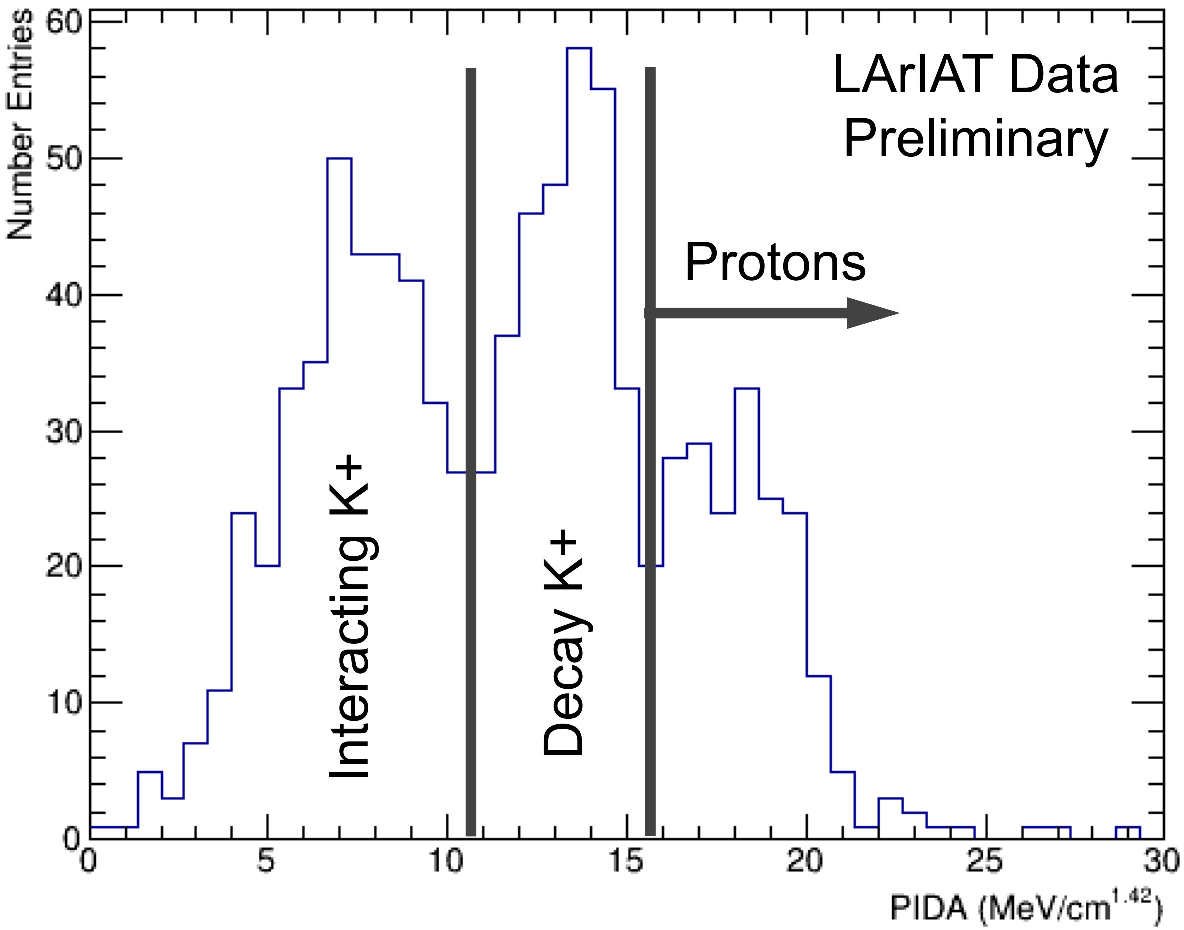
Extras

Standard LArTPC approach (ie, ICARUS, MicroBooNE)



Reflector-based approach (LArIAT)





LArIAT Data
Preliminary
Protons
Interacting K+
Decay K+
Number Entries
PIDA (MeV/cm^1.42)
0
10
20
30
40
50
60
0
5
10
15
20
25
30

"Sliced-TPC" Cross Section Meas.

The Survival (Interaction) Probability of a particle (pion) traveling through a slab of matter (Ar in the LArTPC volume) of depth **z** and density ***n*** is given by:

$$P_{Surv} = exp(-\sigma_{Int}\ n\ z) \quad \rightarrow \quad P_{Int} = 1 - P_{Surv}$$

If the slab is a thin slice (i.e. **z → δz**) so that the energy loss by ionization while crossing the slice is negligible (and ***n*** **δ**z is effectively a surface density):

$$P_{Int} = 1 - (1 - \sigma_{Int}\ N\ \delta z + ...) \simeq \sigma_{Int}\ n\ \delta z$$

We experimentally estimate the Probability $\mathbf{P}_{Int}$ by the Interaction Frequency and extract the Interaction Cross Sec $\boldsymbol{\sigma}_{Int}$:

$$P_{Int} \leftarrow \frac{N_{Int}}{N_{incid}} \quad \Rightarrow \quad \sigma_{Int} = \frac{N_{Int}}{N_{incid}} \frac{1}{n\ \delta z}$$

where N_{Int} is the number of events where the pion interacts in the slice and N_{incid} is the total number of incident pions on the slice.

Pion-argon cross sections

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

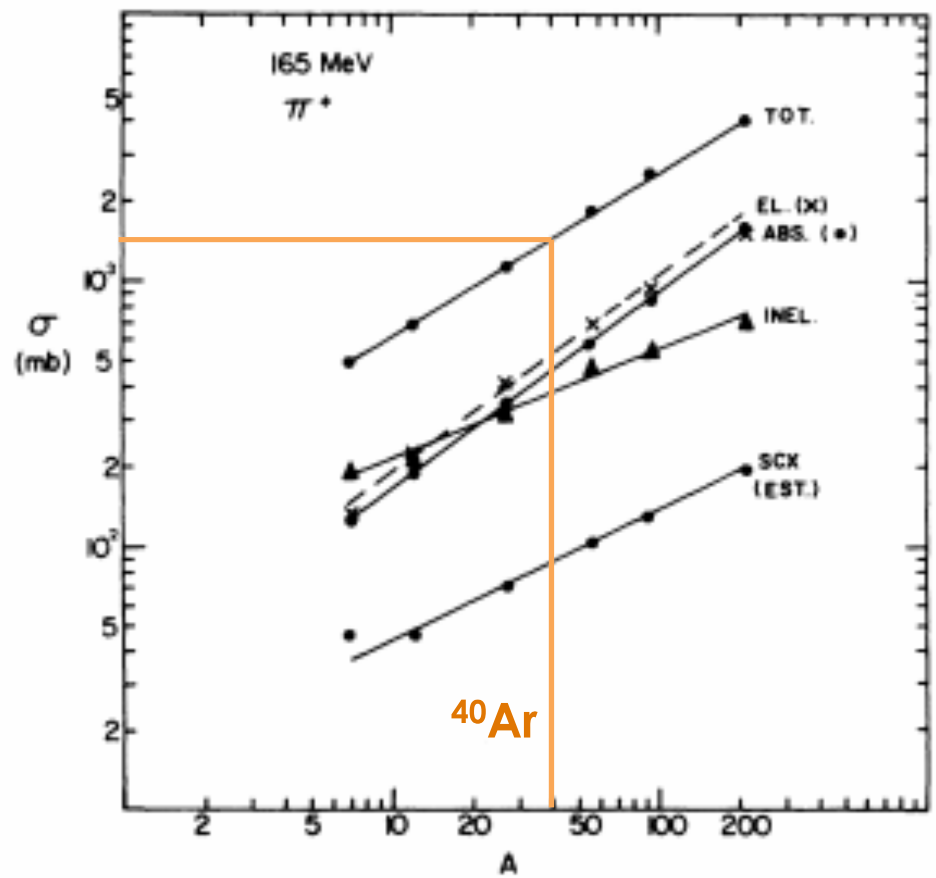


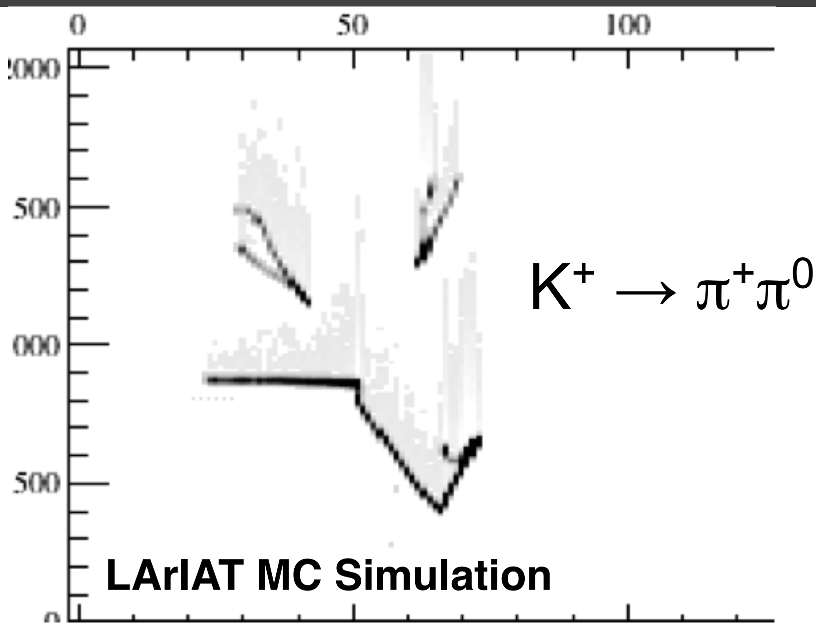
FIG. 9. Decomposition of the total π^+-nucleus cross section at 165 MeV. The lines are least squares fits to power laws.

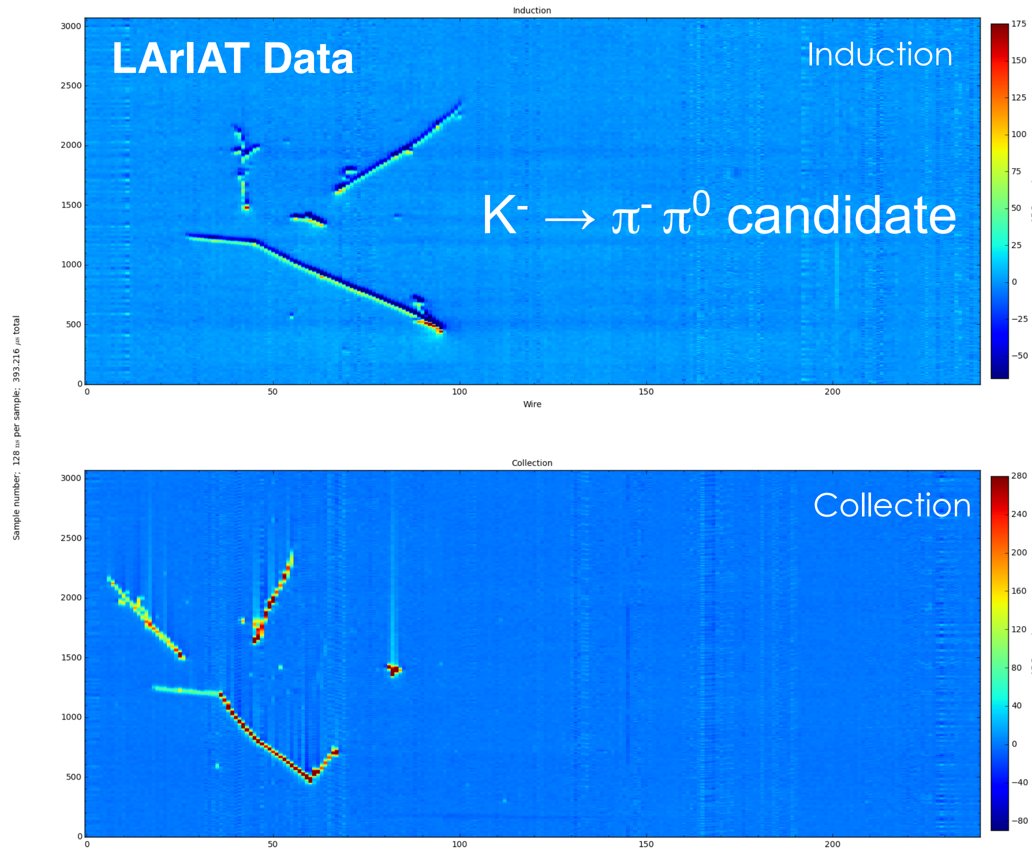
- No measurements for ^{40}Ar
- Predictions come from interpolation between heavier/lighter nuclei

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

Preliminary results of this analysis were presented at a Wine & Cheese Seminar in April and at ICHEP in August

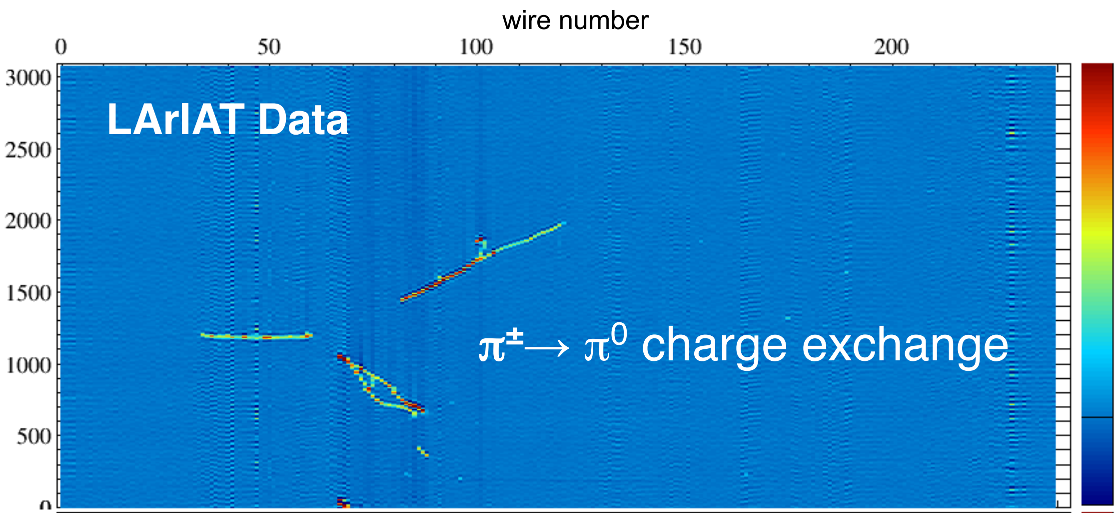
Kaon ID and reconstruction

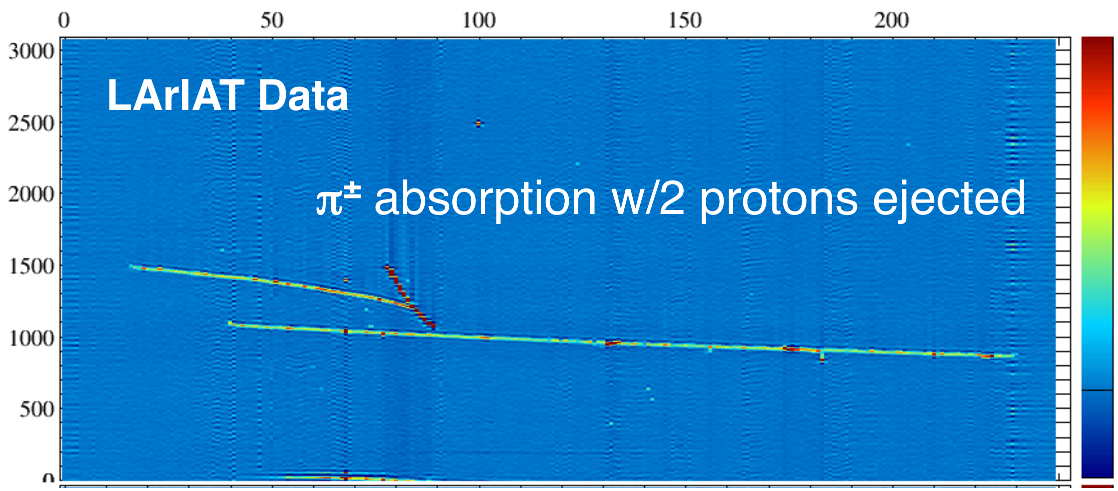




- $K^{\pm}$ reconstruction
- Study recombination
- Kaon-argon interaction cross section measurement
- Understand kaon/pion and kaon/proton discrimination
- ***Important for baryon-number-violation searches:*** relevant to proton decay searches in future experiments

Nuclear Effects & Final State Interactions



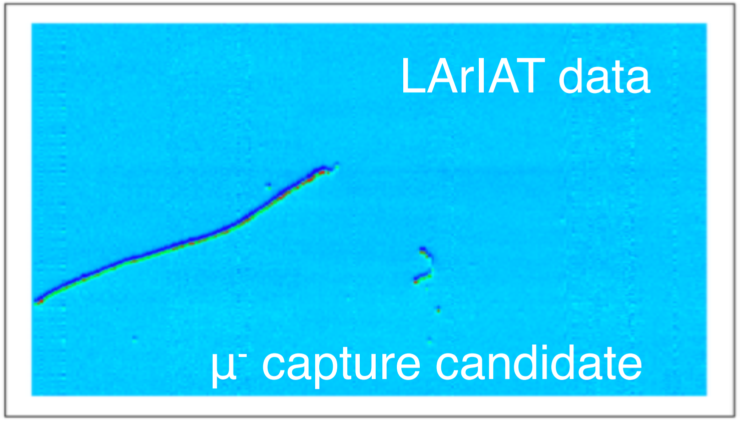


- Tune hadron-nucleus interaction models in Geant4 and neutrino generators
- Study reconstruction systematics & calorimetry
- ***Important for oscillation experiments:*** study/ constrain features of backgrounds to ν oscillation

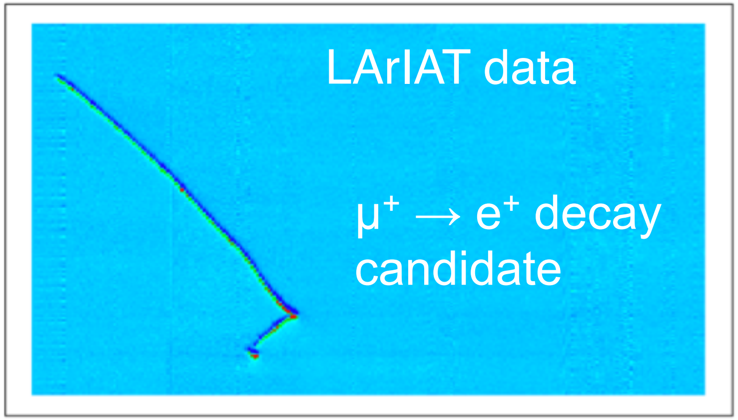
Charge Sign Determination (w/o magnetic field)

Explore a LArTPC feature never before (systematically) studied

- decay vs. capture in LAr
- μ^+ only decay, μ^- capture (76%) or decay (24%)



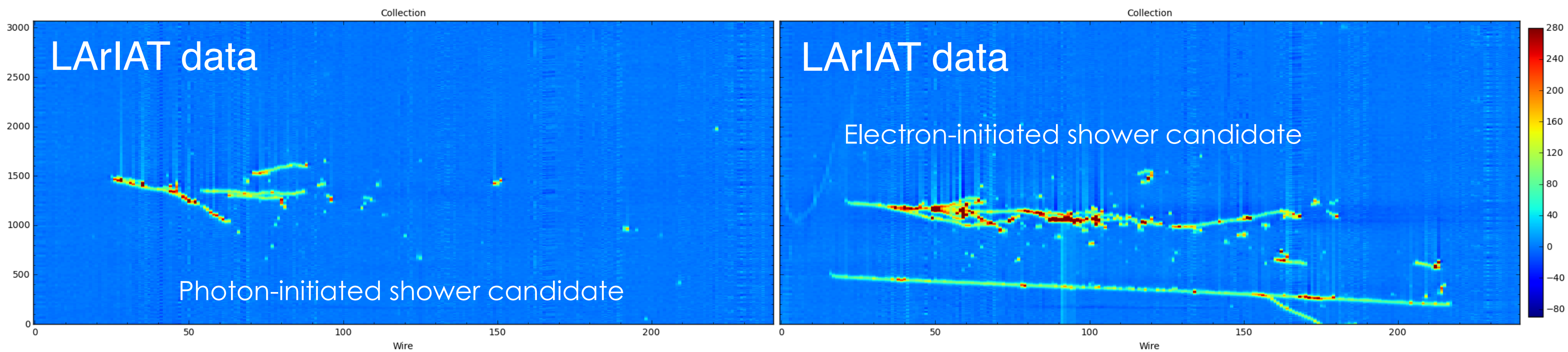
Timing & pattern recognition



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 shower used to separate electron-initiated showers from photon-initiated showers (single vs. double ionization)
- Direct experimental measurement of the (MC-estimated) separation efficiencies
- 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 BG