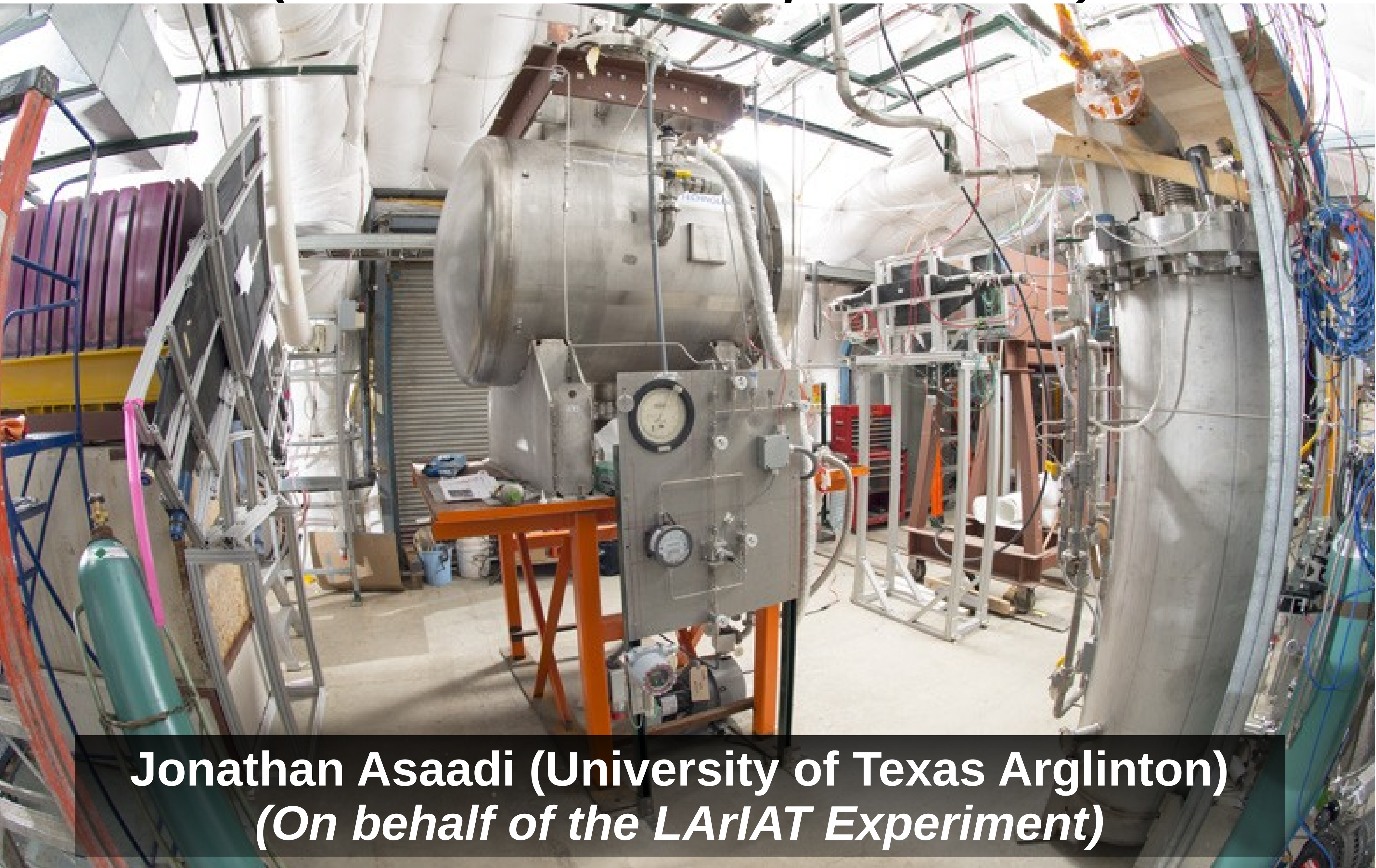
<u>**Liquid Argon In A Testbeam Experiment**</u>

(The LArIAT Experiment)

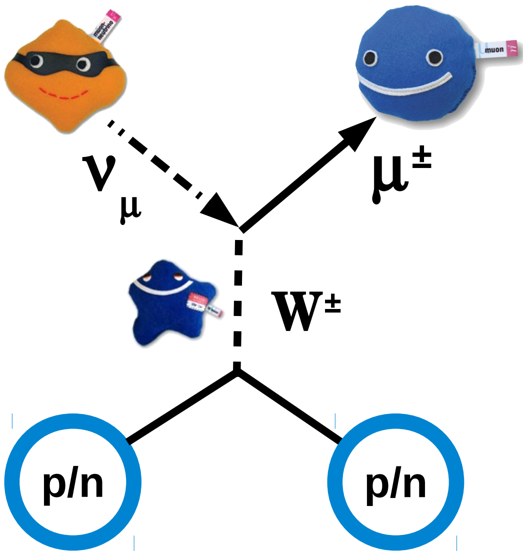


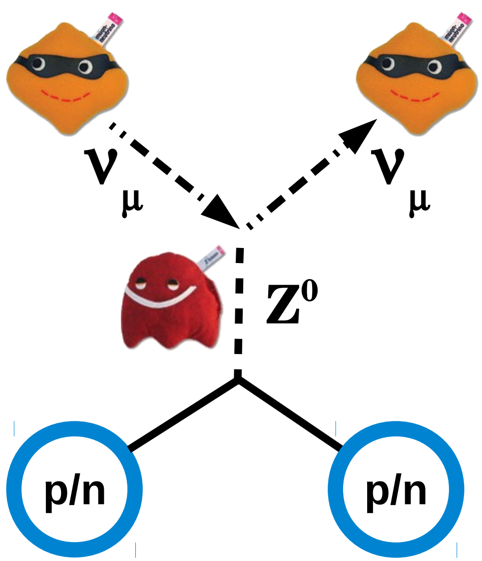
Jonathan Asaadi (University of Texas Arglinton)

(On behalf of the LArIAT Experiment)

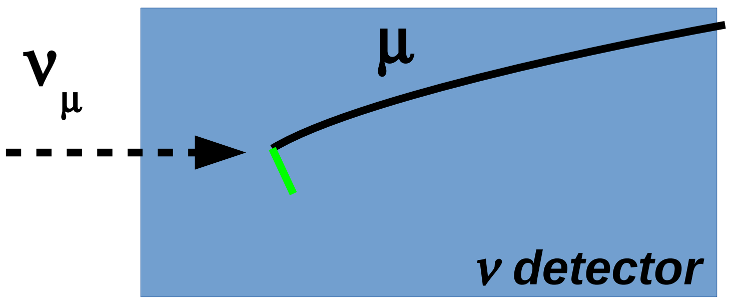
Neutrino physics in a simple world

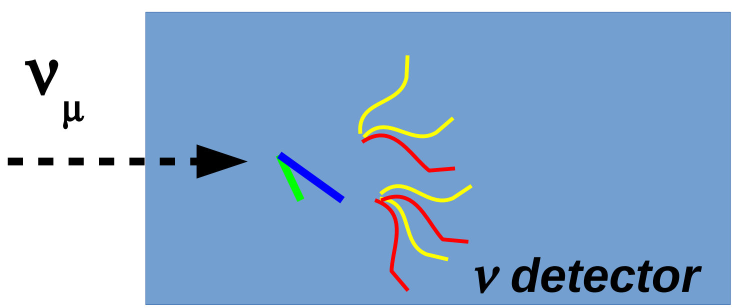
From theorists...





... to experimentalists



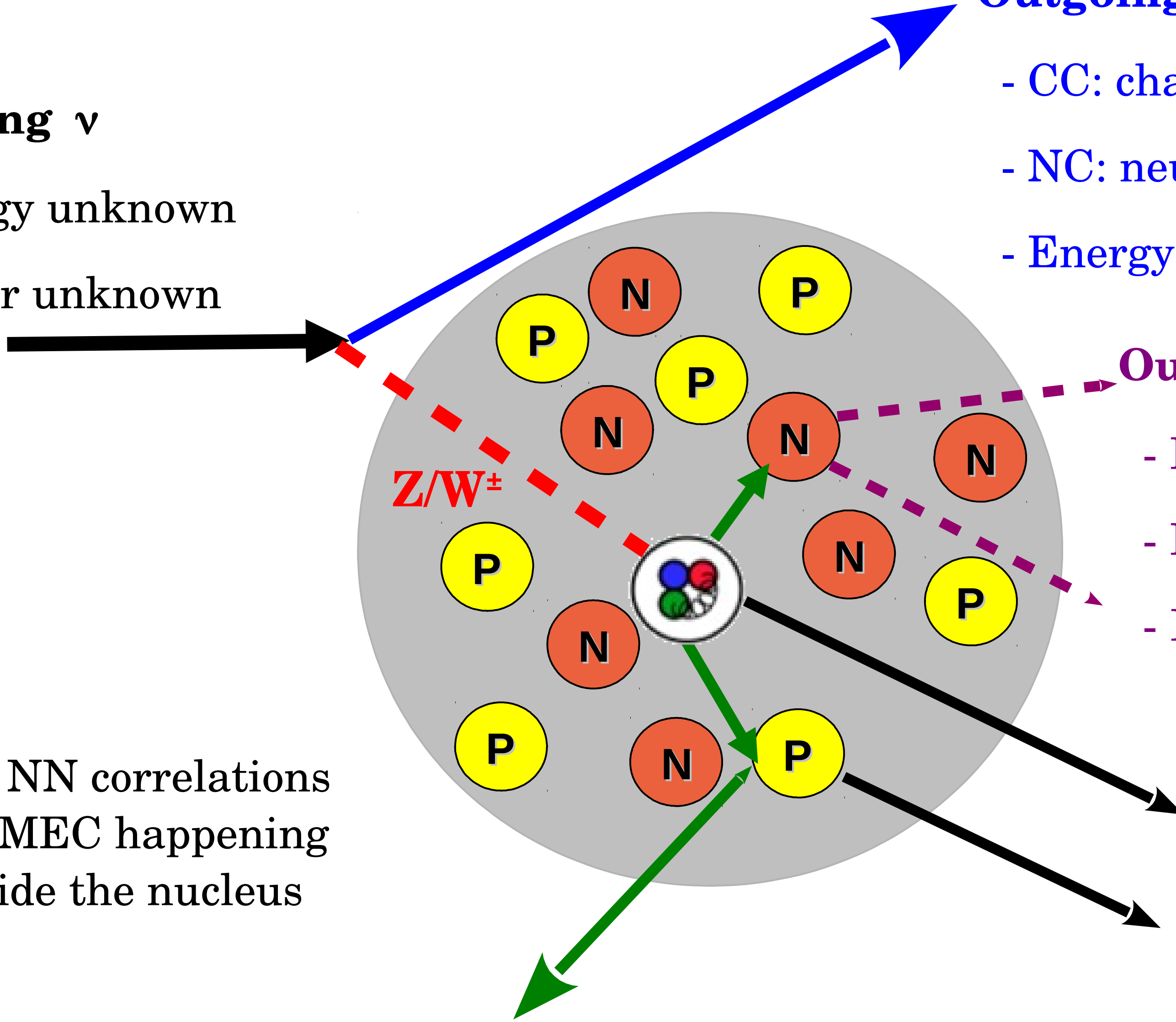


- ✔ *Shoot a neutrino beam into your detector*
- ✔ *Detect the particle produced in the interaction*
- ✔ *Reconstruct the neutrino information measure important physics quantities*

Neutrino physics in a more real-like world

Incoming ν

- Energy unknown
- Flavor unknown



Outgoing Lepton

- CC: charged lepton
- NC: neutral lepton
- Energy to be measured

Outgoing Mesons

- Final State Interactions
- Energy?
- Identity?

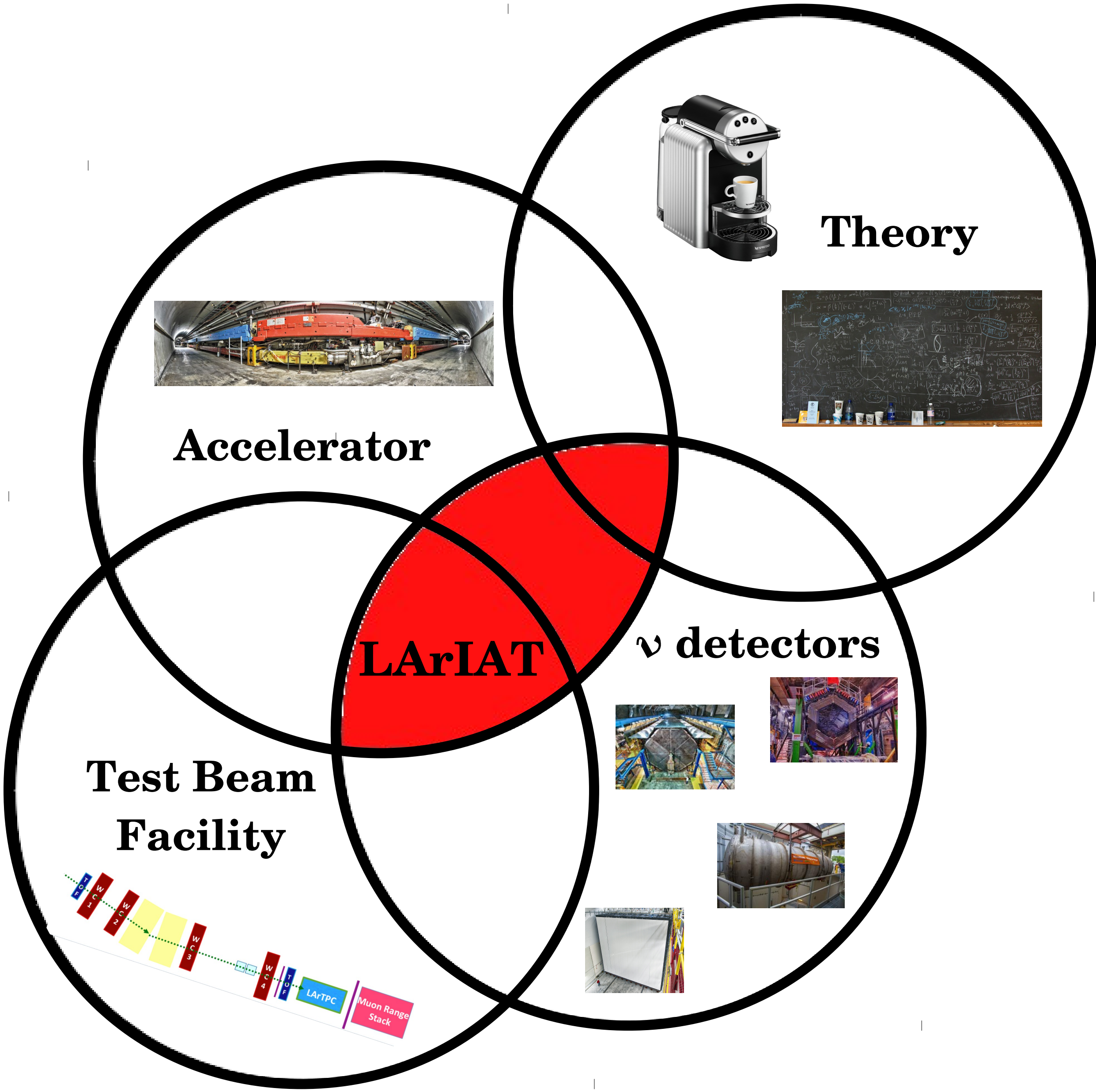
Outgoing Nucleons

- Visible?
- Energy?

Also NN correlations and MEC happening inside the nucleus

Credit: M. Kordosky

LArIAT at the cross-section of ν-physics



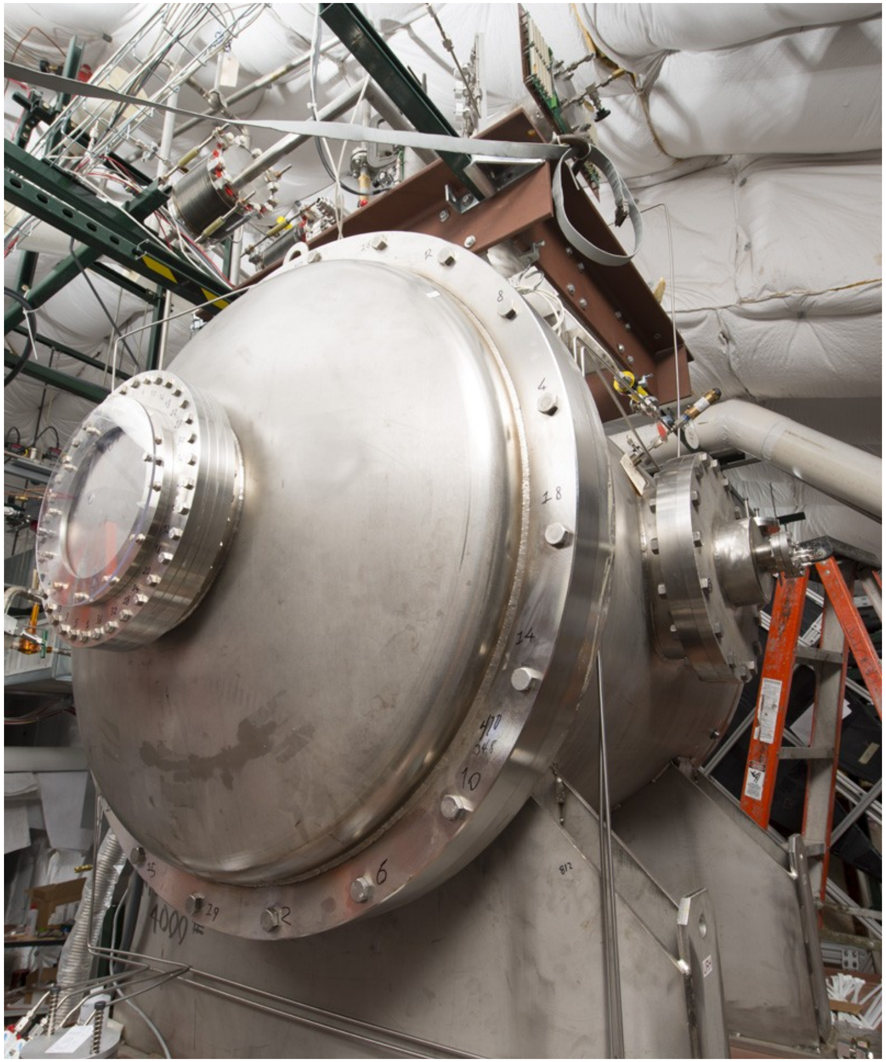
More than just neutrino detectors!

Synergy between all the fields

We are in the "precision era" of neutrino physics: a complete characterization of detection techniques and secondary particle interactions is ***fundamental***

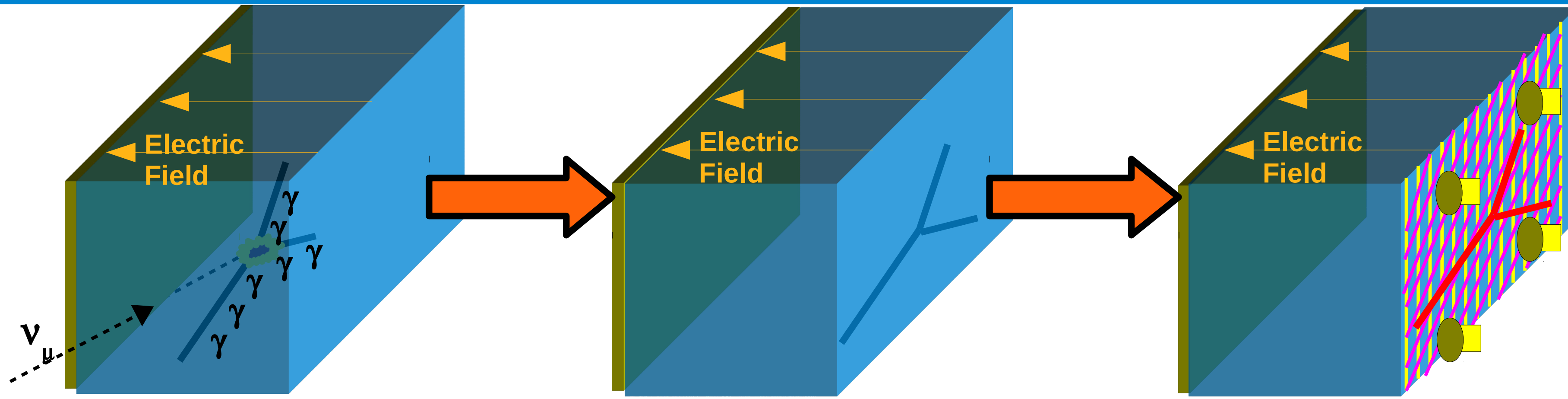
The LArIAT Mission

Executing a comprehensive program designed to characterize LArTPC performance and charged particles interaction in argon in the energy range relevant to the forthcoming neutrino experiments



LArIAT: The experiment the LArTPC community needs

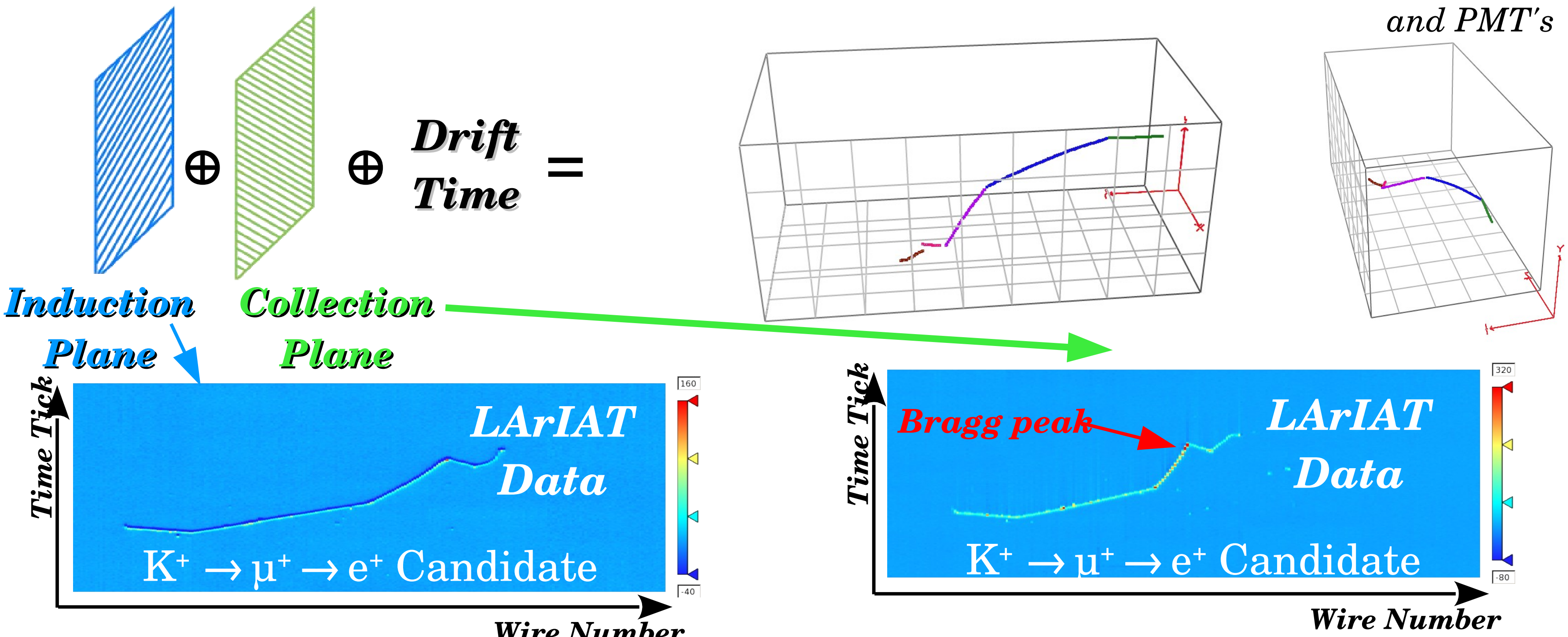
Liquid Argon Time Projection Chamber



Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

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

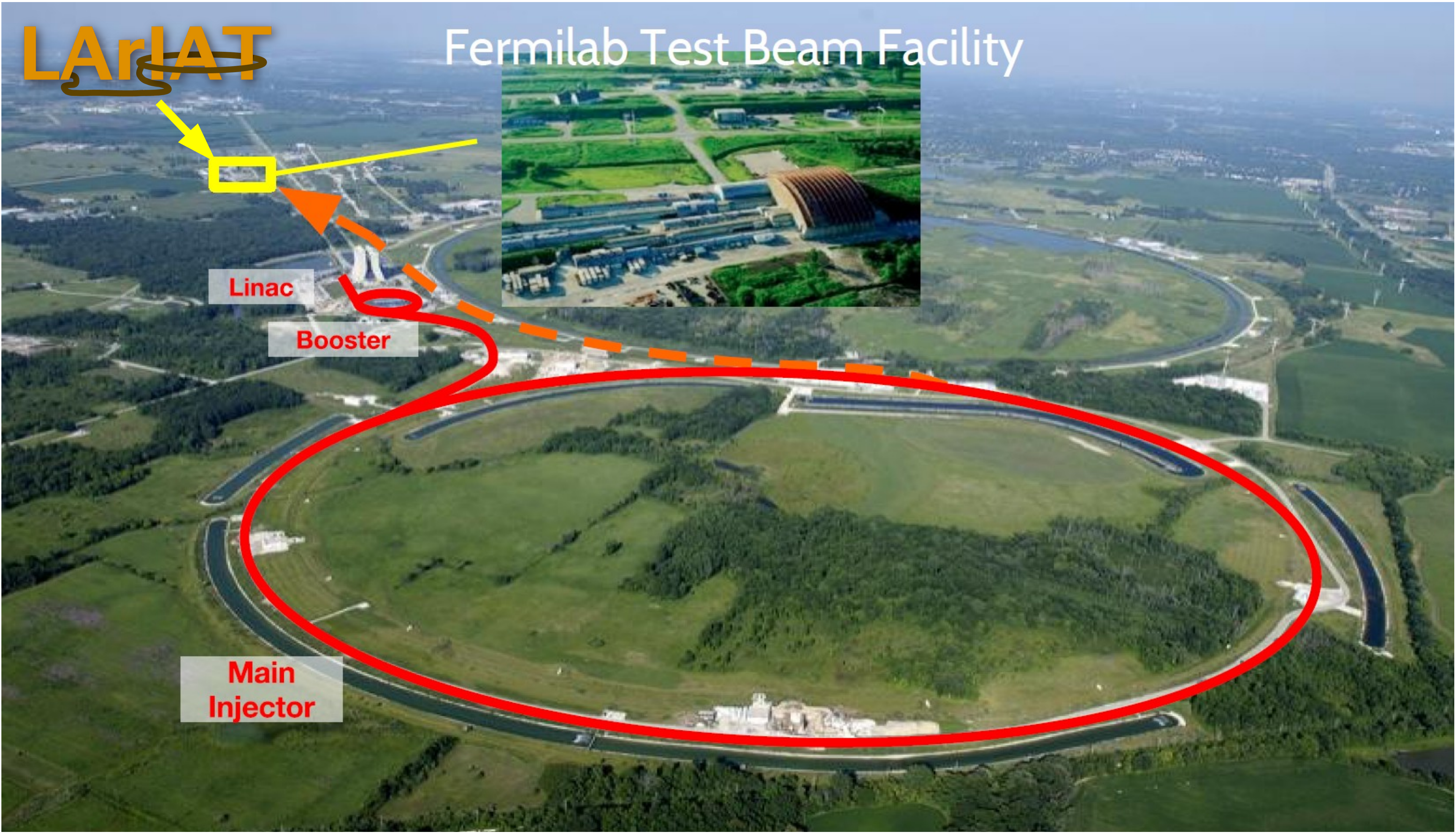


✔ **3D imaging with mm space resolution**

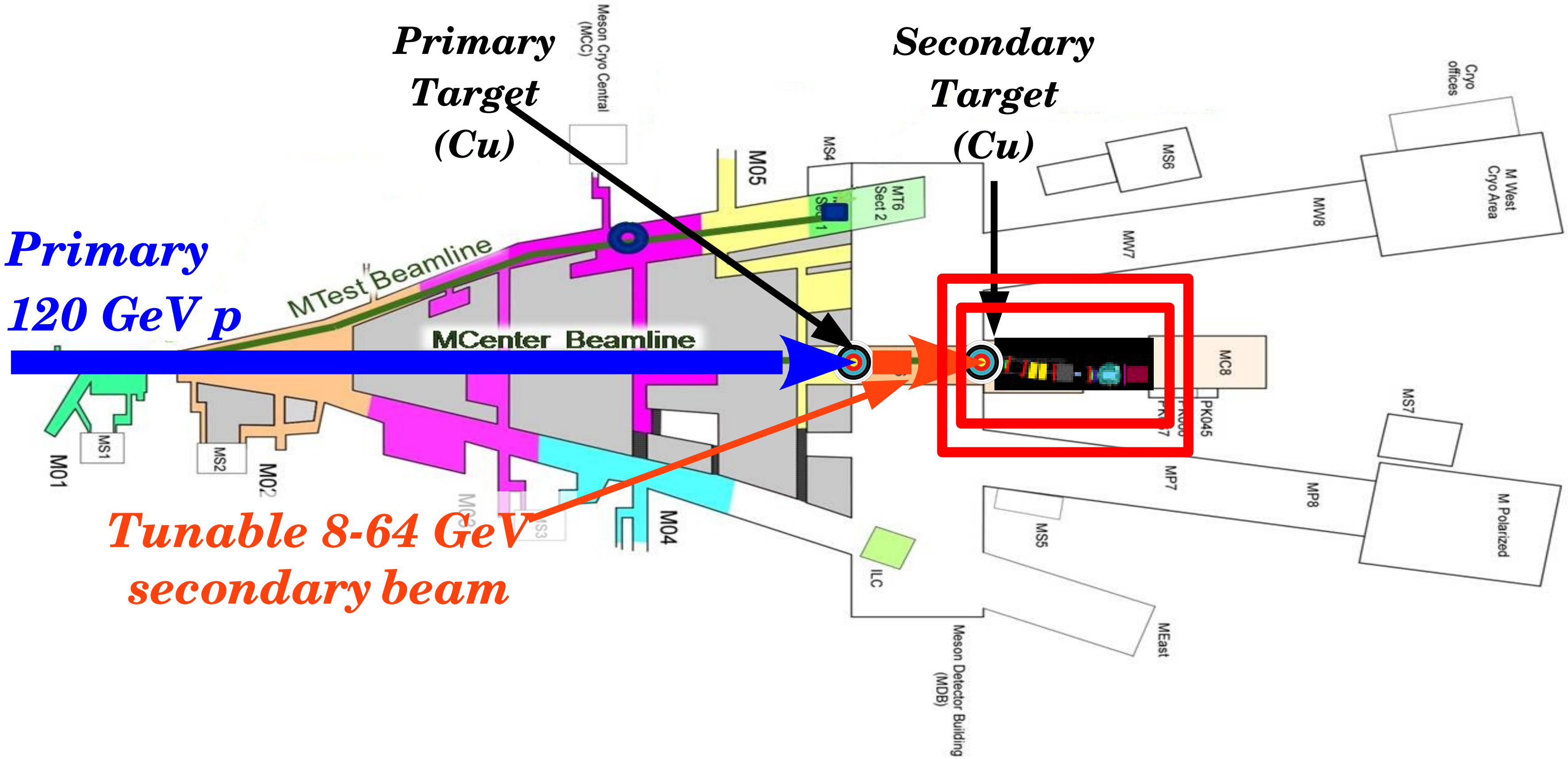
✔ **Calorimetry information**

✔ **PID capabilities**

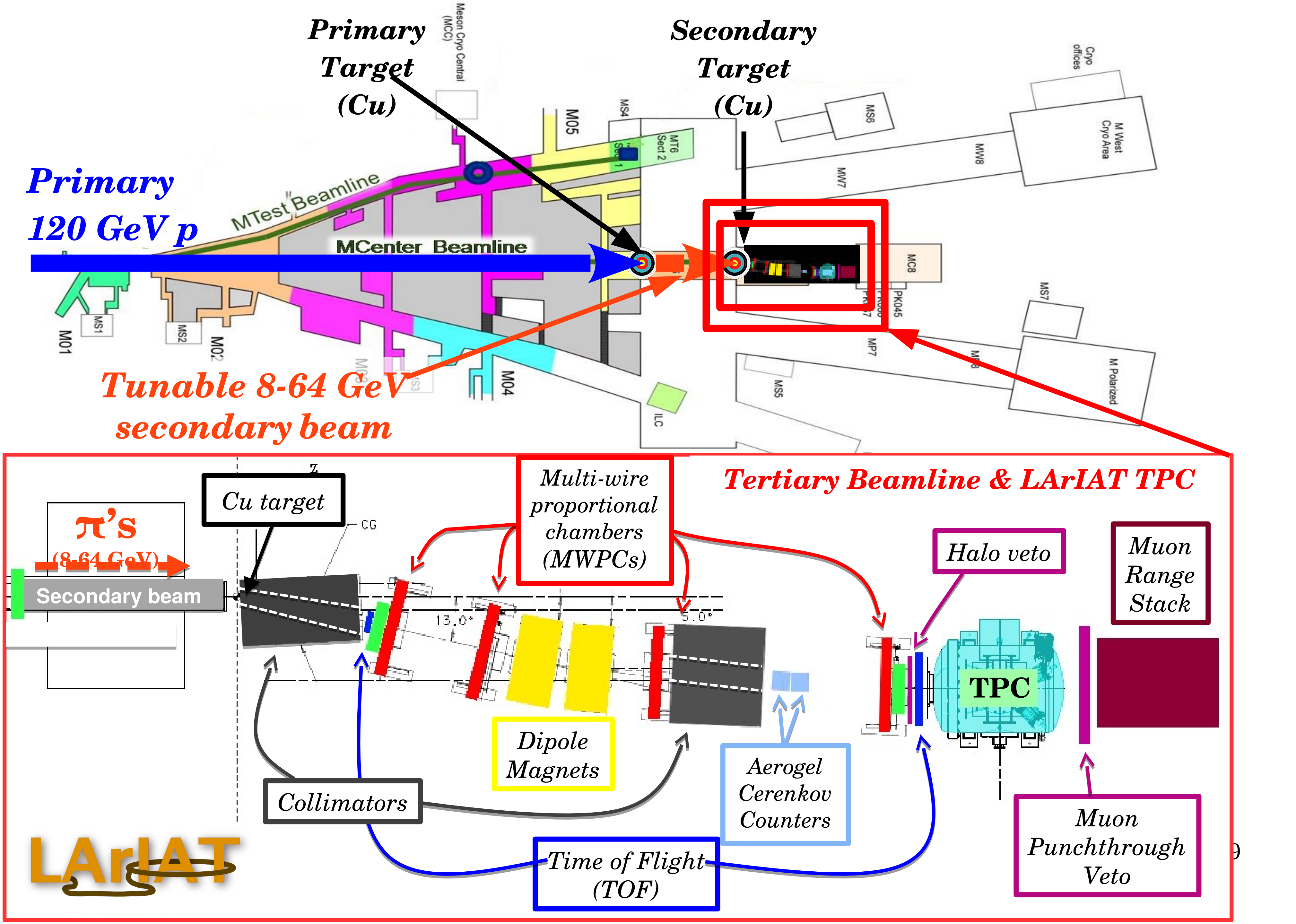
LArIAT's Home



Bird's eye view of LArIAT beamline

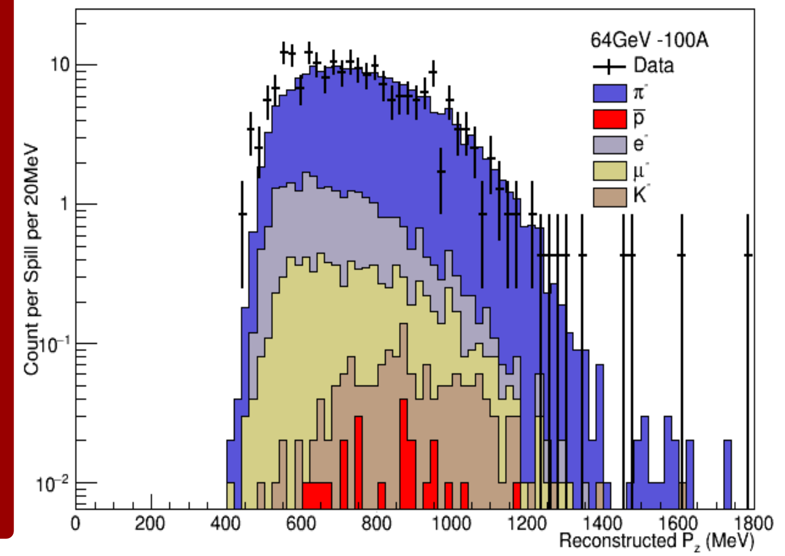


Bird's eye view of LArIAT beamline

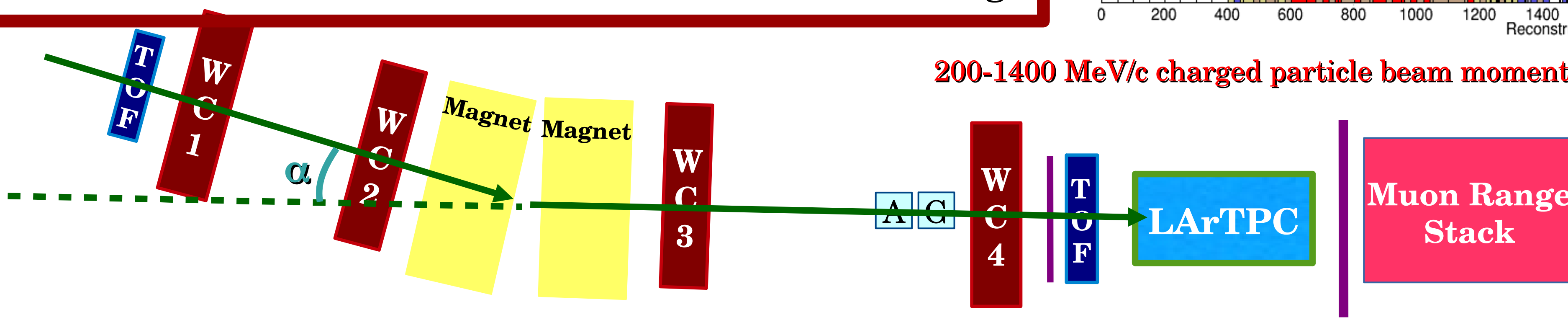


LArIAT Beamline Detectors

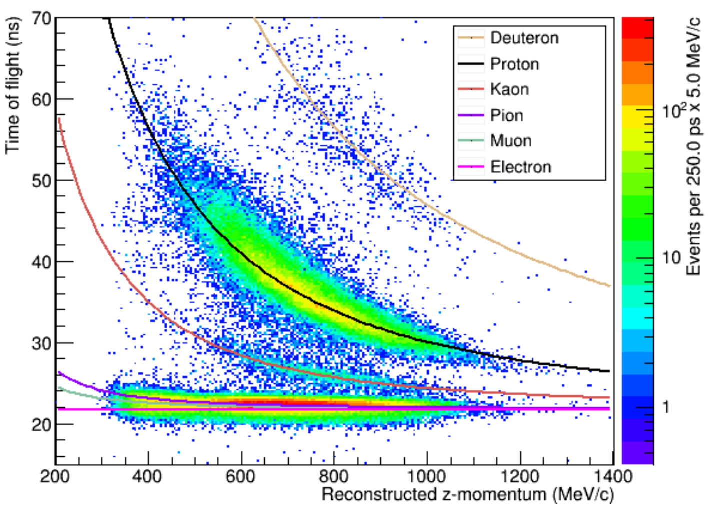
- ✔ WC pairs used to define particle tracks before and after the magnets
- ✔ The angle α between the two tracks determines the momentum reconstruction
- ✔ Momentum reconstruction possible even if information from one of the two inner WC is missing



200-1400 MeV/c charged particle beam momentum range

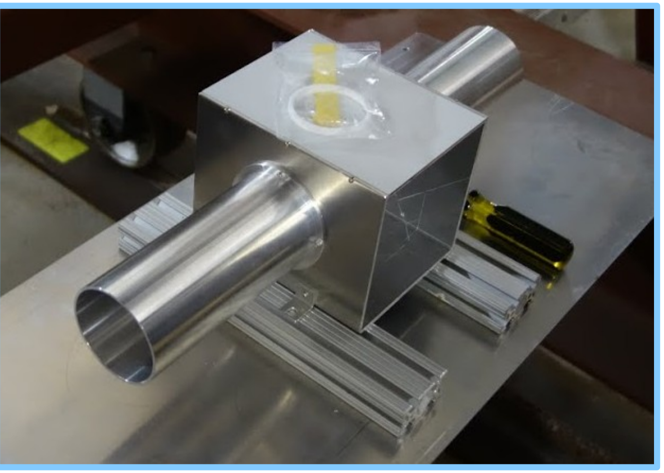


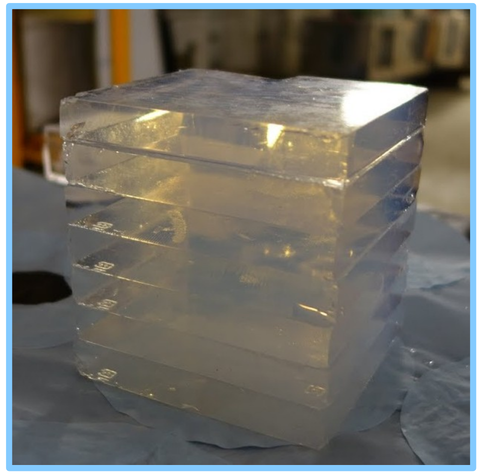
TOF vs reconstructed momentum



- ✔ 2 scintillator counters with 1 ns sampling provides TOF
- ✔ In conjunction with momentum derived by MWPCs, discrimination of π&μ&e/K/p is possible

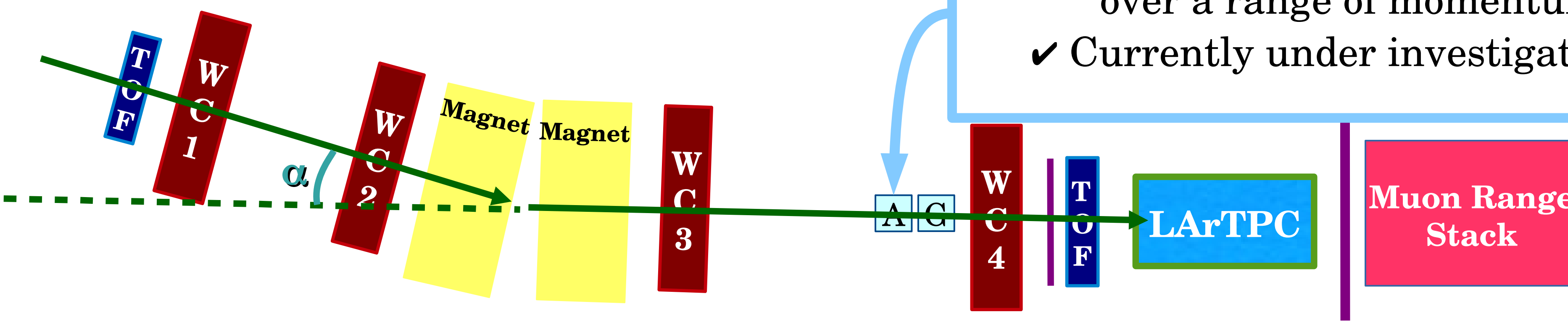
LArIAT Beamline Detectors



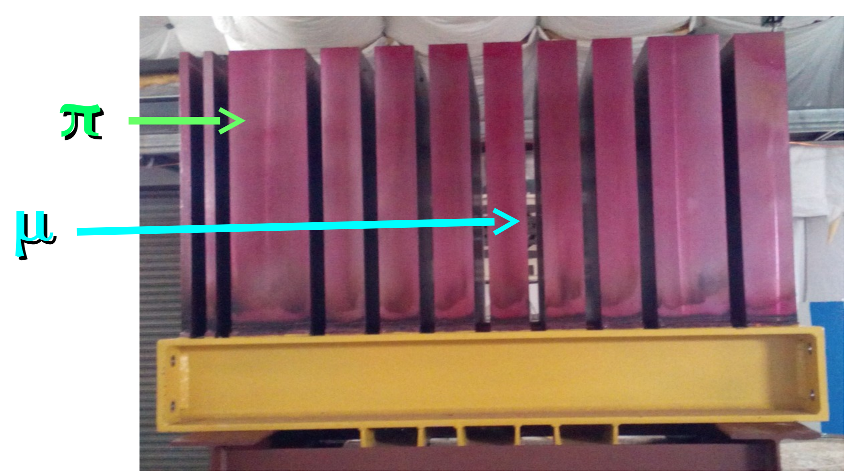


	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

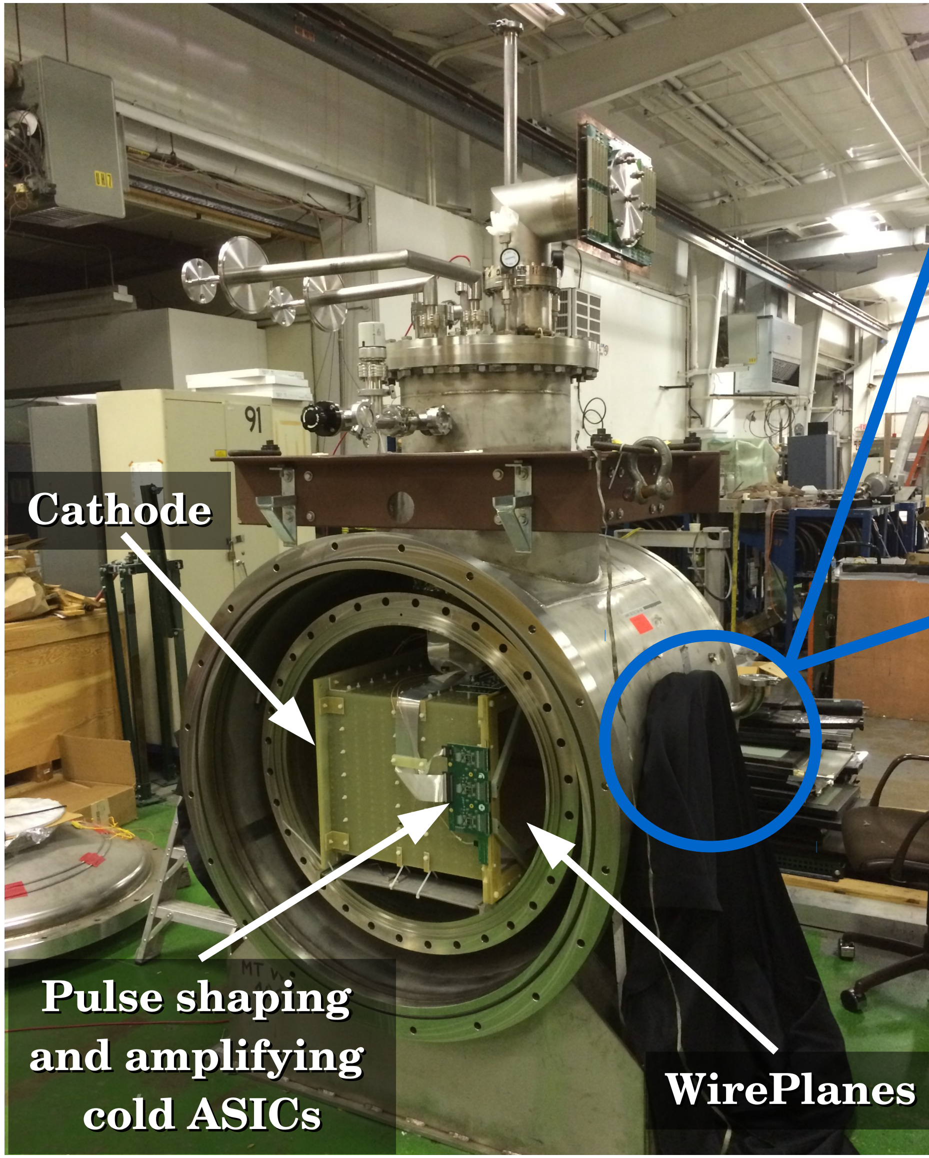
✔ Allows to perform π/μ separation over a range of momentum
✔ Currently under investigation

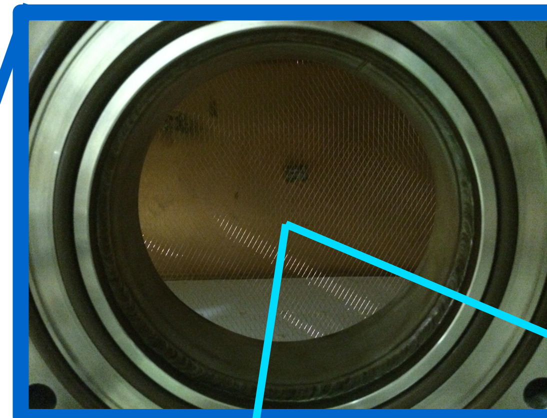


- ✔ Four layers of XY planes sandwiched between (pink) steel slabs
- ✔ Each plane is composed by 4 scintillating bars connected to a PMT
- ✔ Allows to discriminate π/μ exiting the cryostat
  - ✔ Currently under investigation

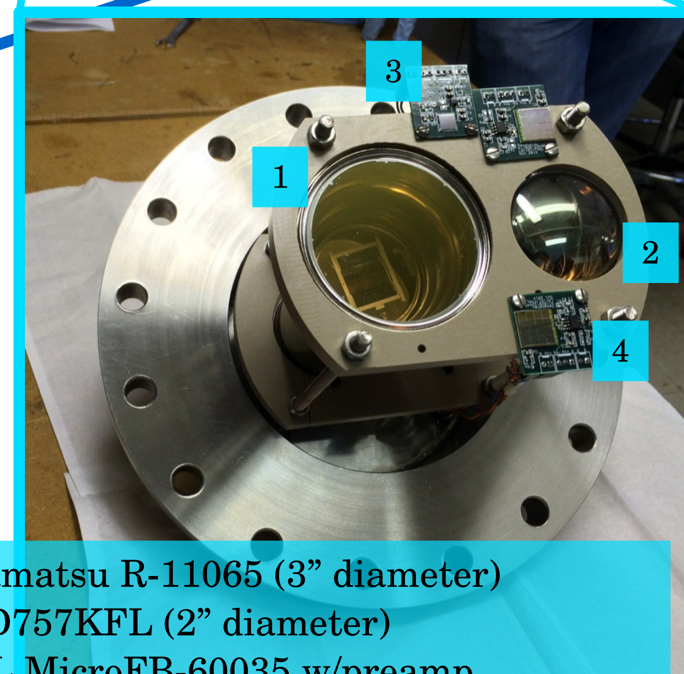


Inside the cryostat: TPC and light collection system



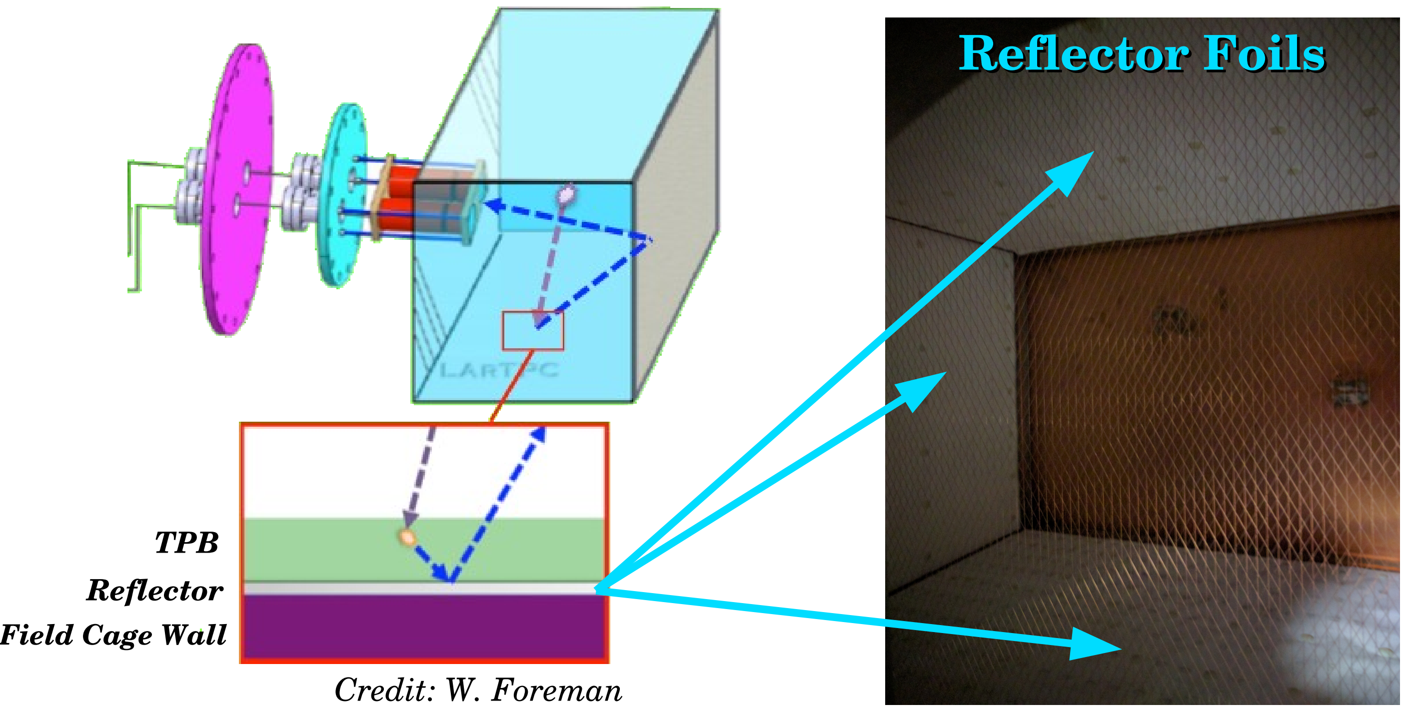


Light Collection System port

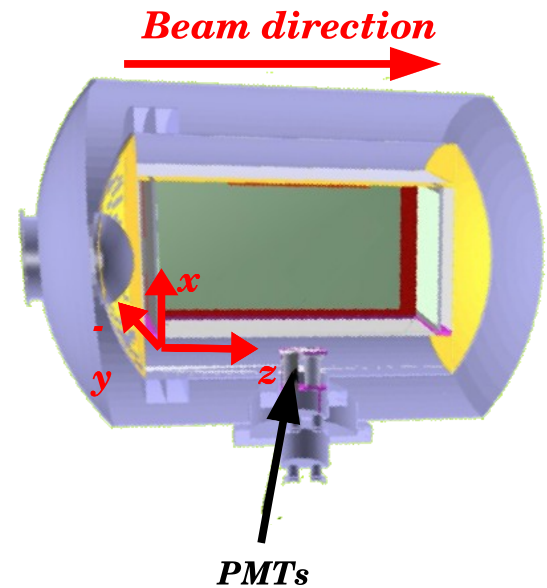


1. PMT: Hamamatsu R-11065 (3” diameter)
2. PMT: ETL D757KFL (2” diameter)
3. SiPM: SensL MicroFB-60035 w/preamp
4. SiPM: Hmm. S11828-3344M 4x4 array (Run I)
   SiPM: Hmm. VUV-sensitive (Run II)

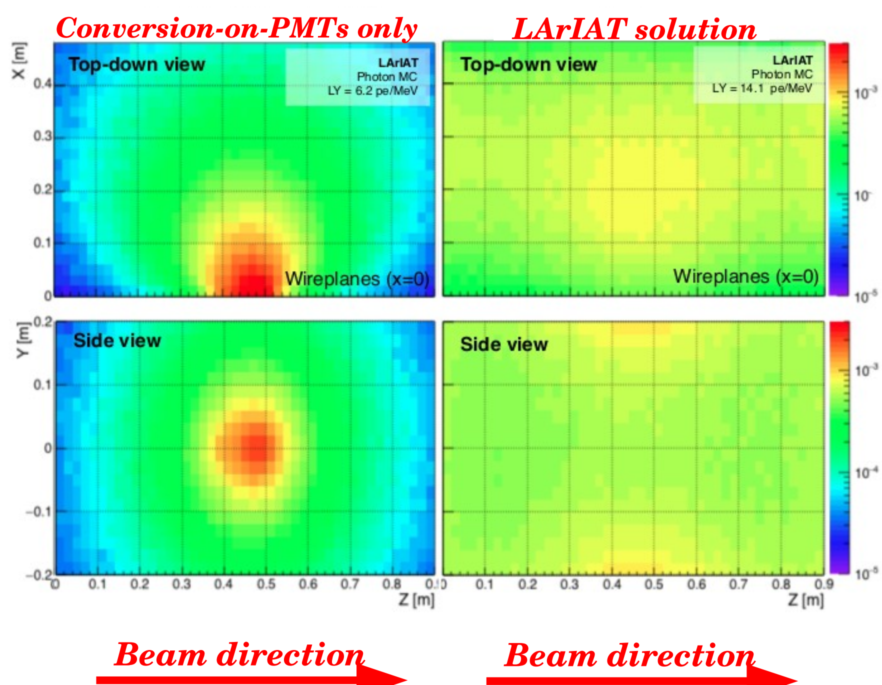
Light Collection System



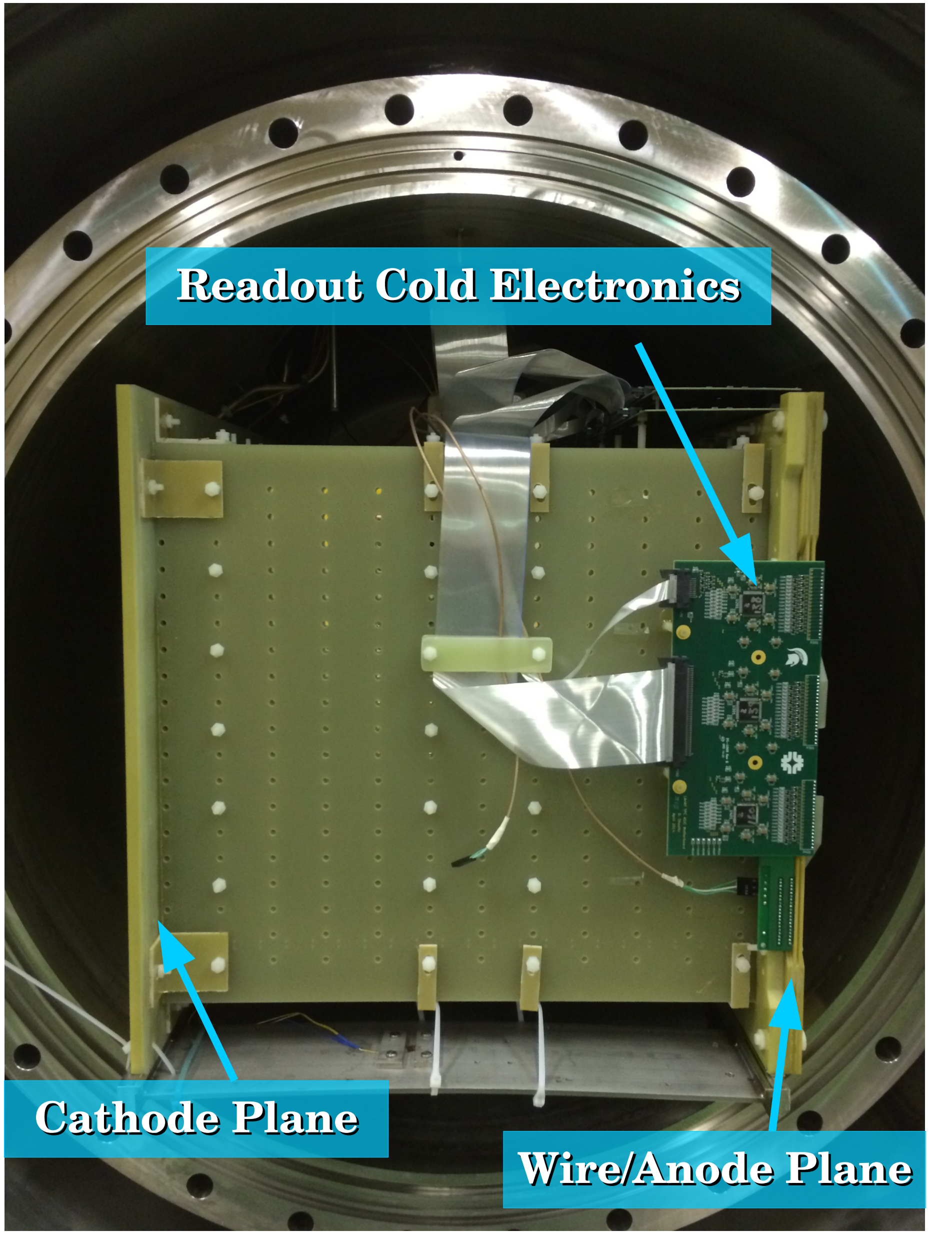
Credit: W. Foreman



- **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**

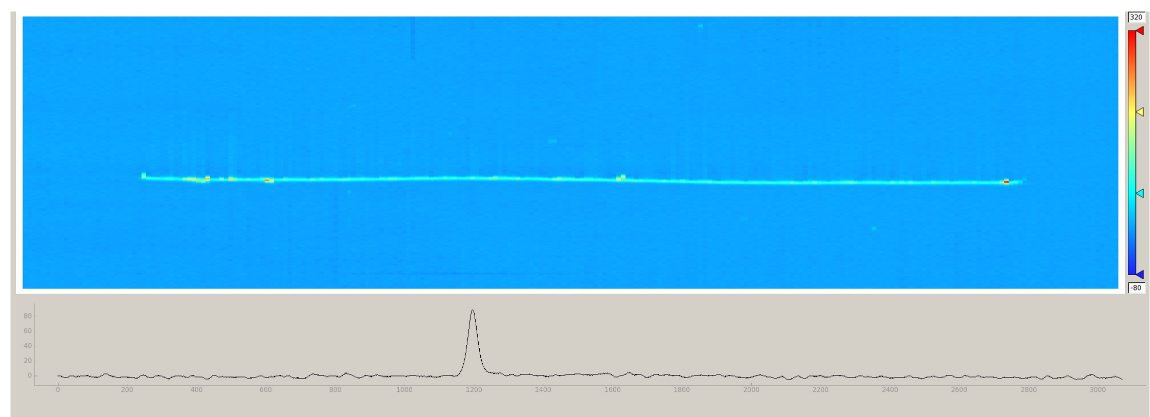


LArTPC

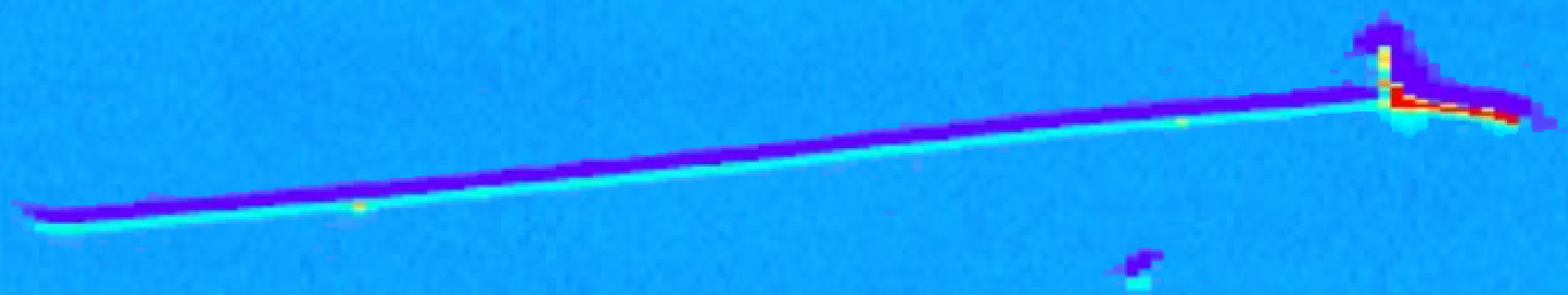


- **Refurbished ArgoNeuT TPC**
  - ✔ 2 Readout planes
  - ✔ 240 wires/plane, ±60° respect to beam, 4 mm pitch
  - ✔ 500 V/cm nominal drift field

- **Cold Electronics: MicroBooNE preamplifying ASICs on custom motherboards**
  - ✔ Signal to Noise ratio (MIP pulse height compared to pedestal RMS)
    - **Run 1** ~50:1 (ArgoNeuT warm electronics ~15:1)
    - **Run 2** ~70:1

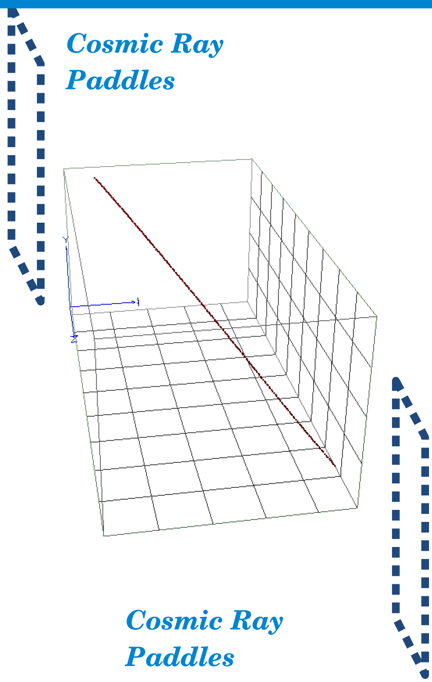


First Physics with LArIAT

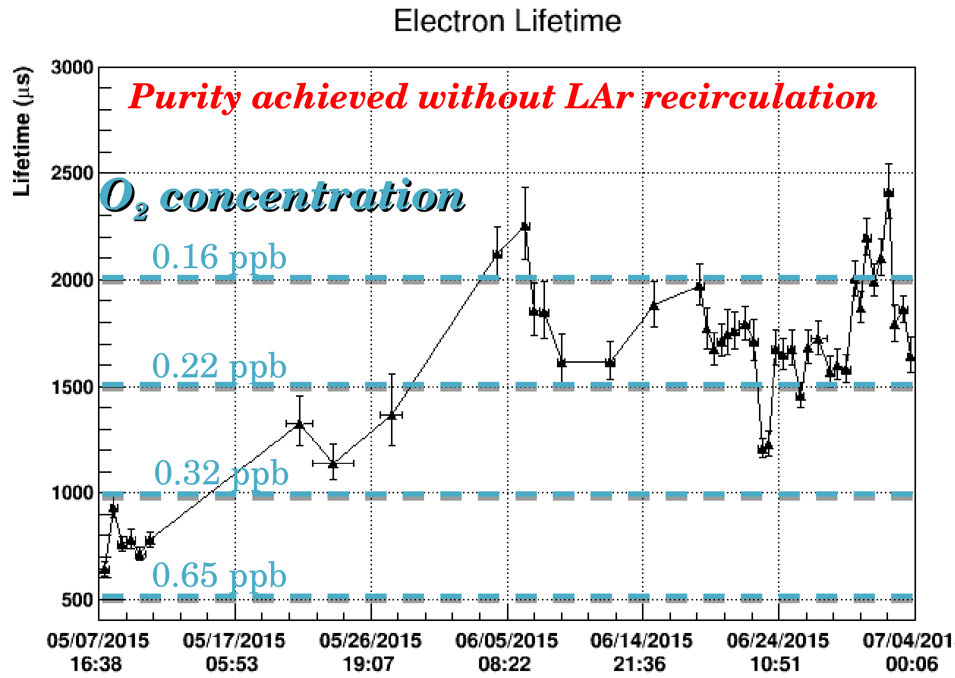


- **Our first physics measurements that put together all the various aspects of the LArIAT experiment**
  - ***Note: I can't show all the analyses currently underway in the time alloted, so this is just a sampling***

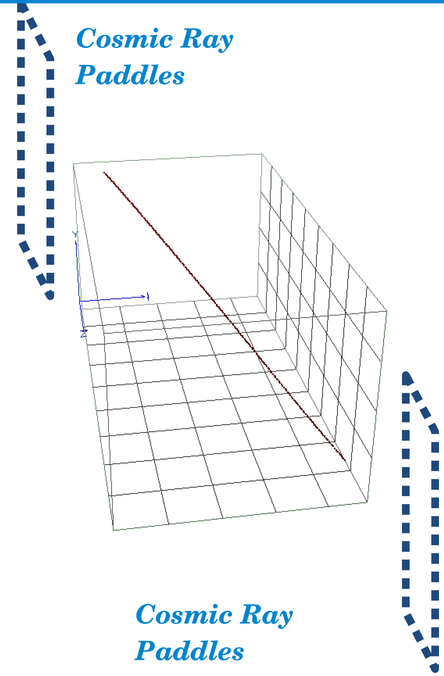
Physics w/o the charged particle beam



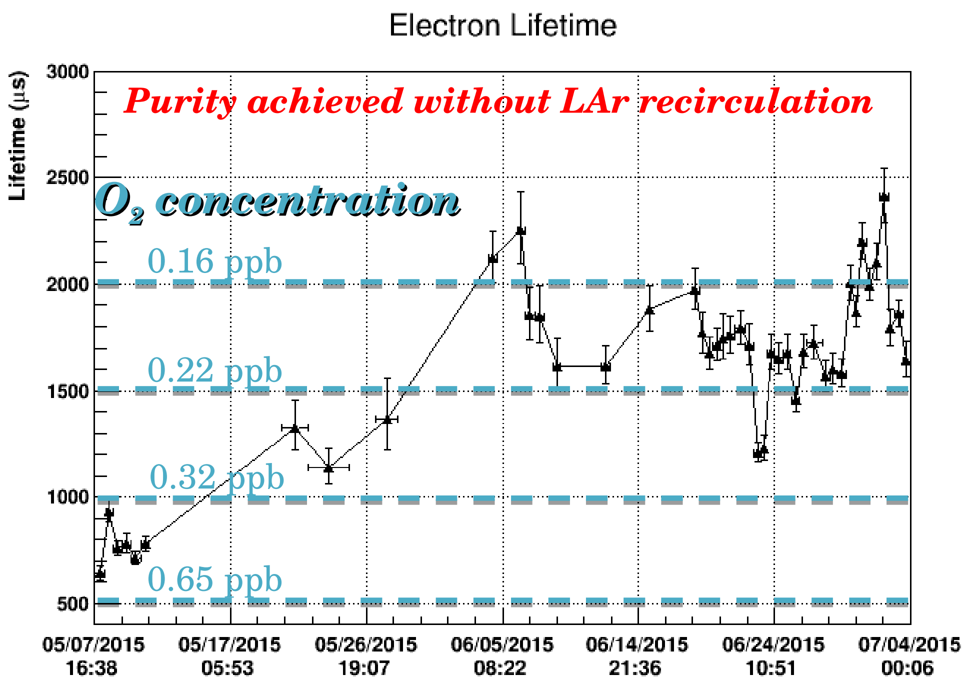
- **Using a sample of crossing and stopping cosmic muons LArIAT is already doing physics measurements**
  - Automated electron lifetime

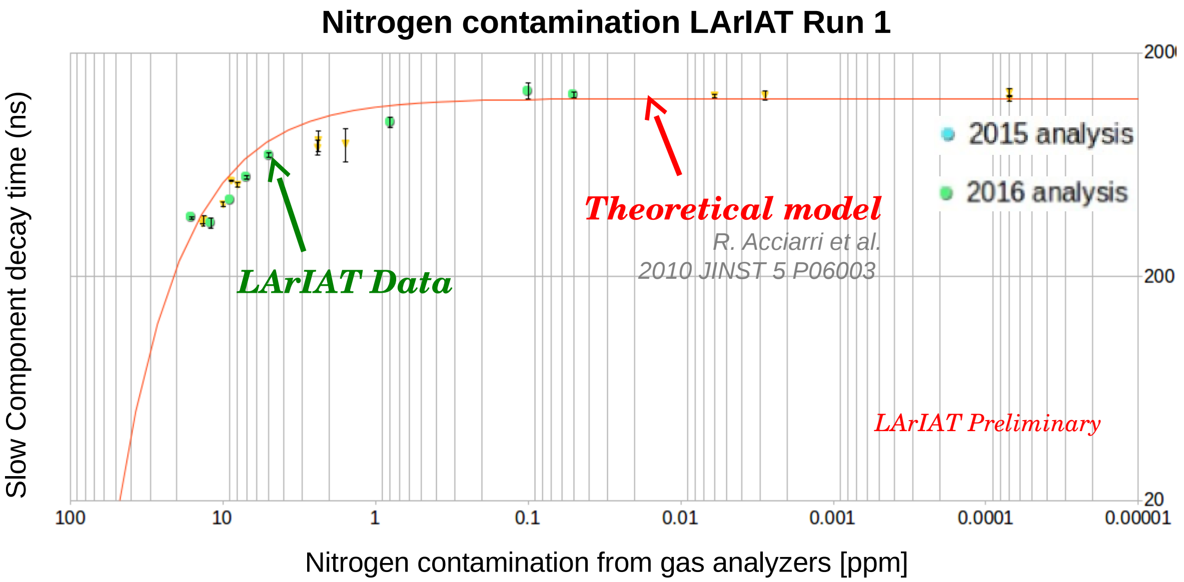


Physics w/o the charged particle beam

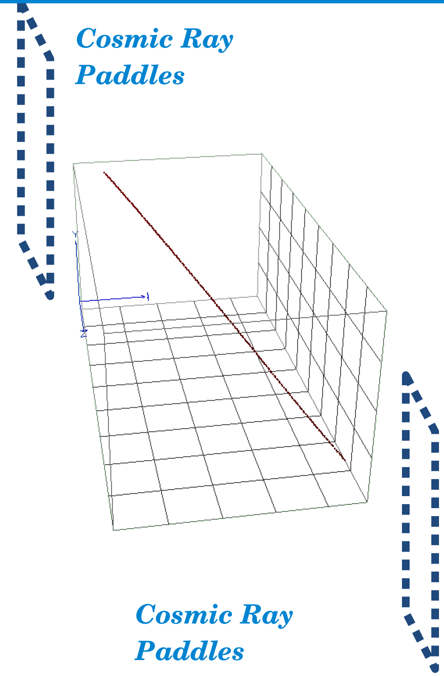


- **Using a sample of crossing and stopping cosmic muons LArIAT is already doing physics measurements**
  - Automated electron lifetime
  - Nitrogen Contamination from the "slow" light

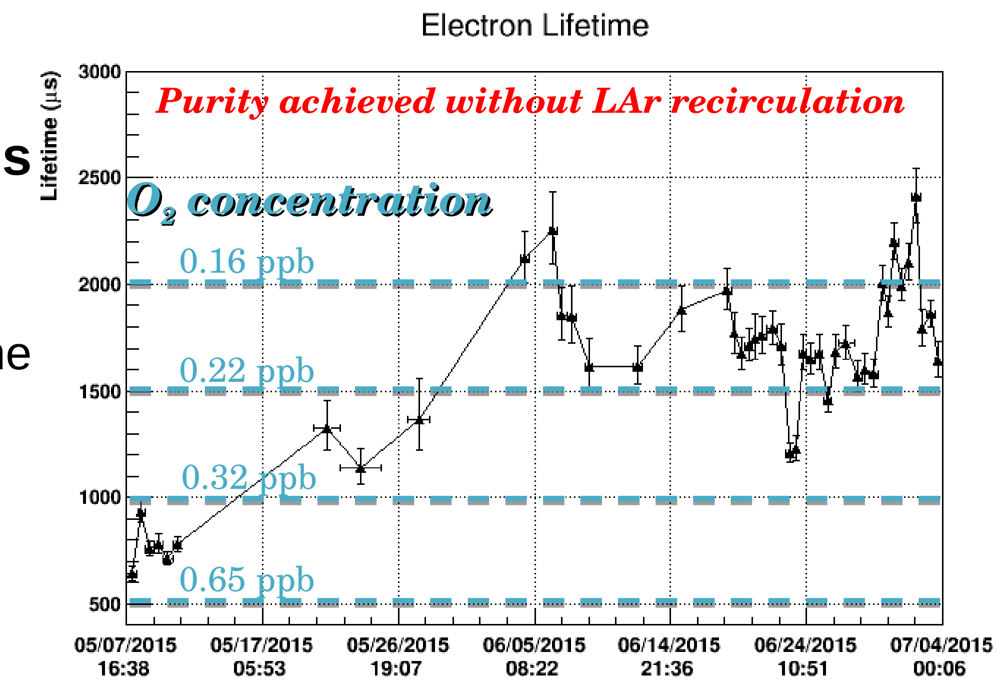


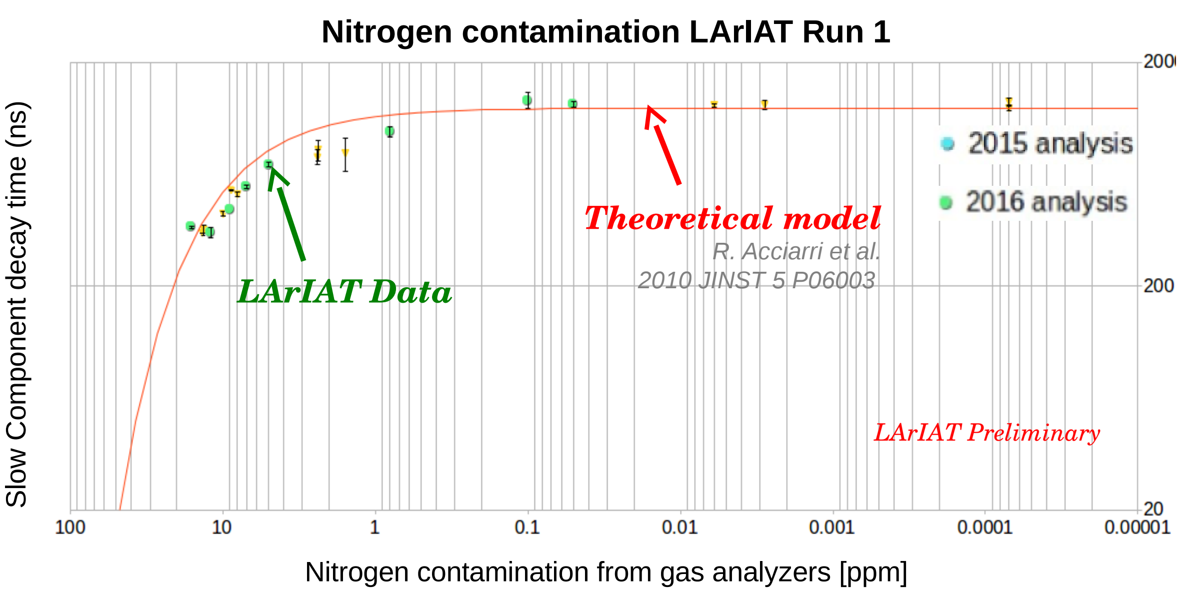


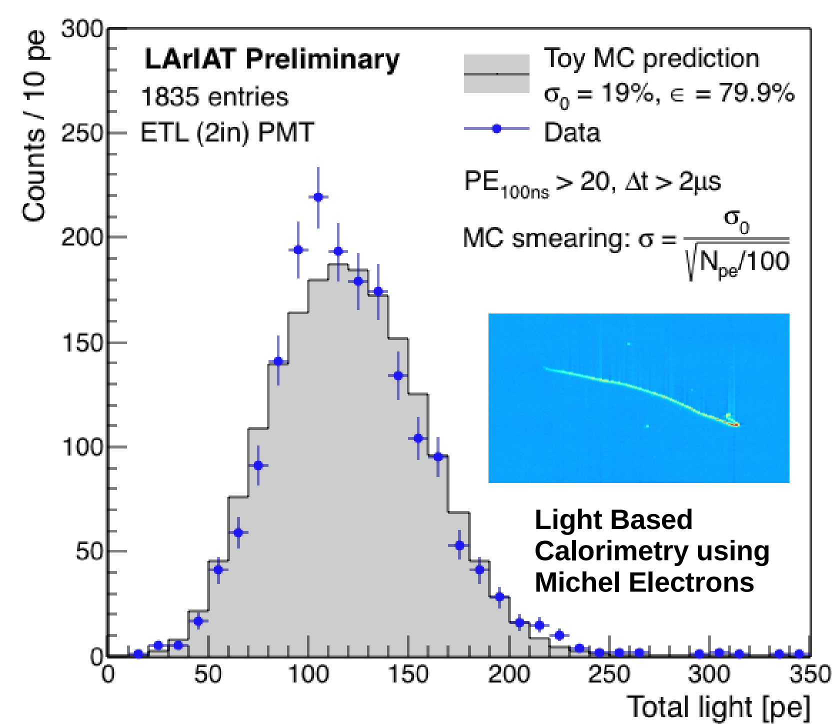
Physics w/o the charged particle beam



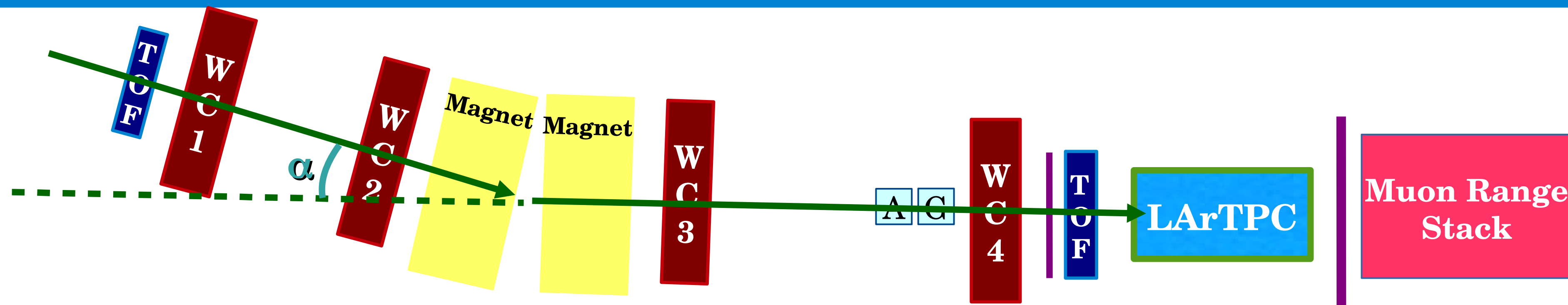
- **Using a sample of crossing and stopping cosmic muons LArIAT is already doing physics measurements**
  - Automated electron lifetime
  - Nitrogen Contamination from the "slow" light
  - Michel Electron energy measurements using scintillation light
  - Muon capture lifetime

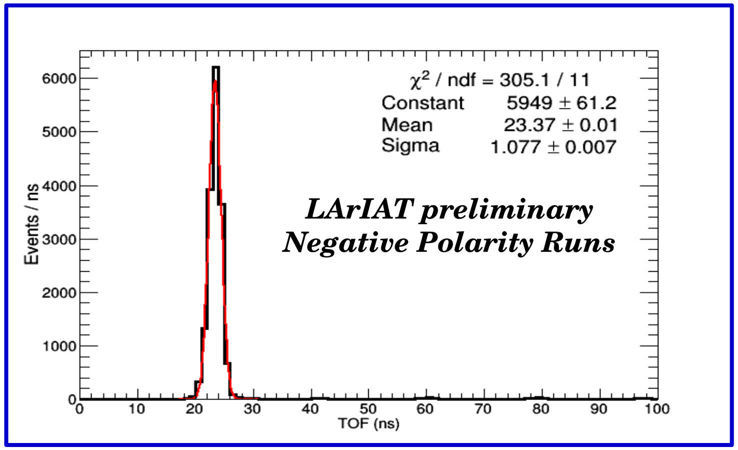


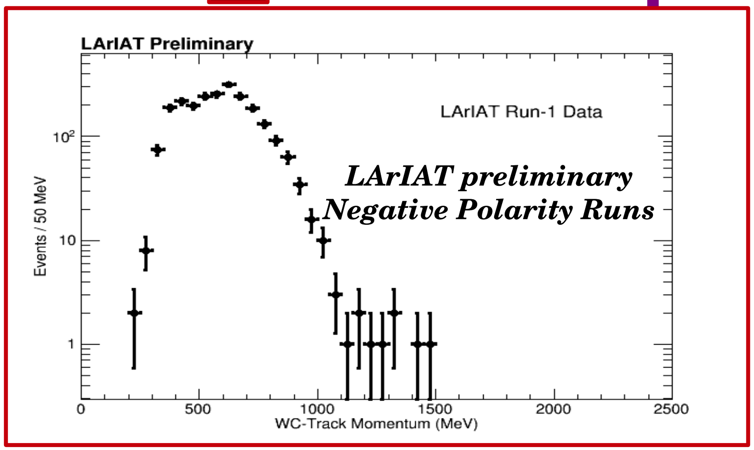




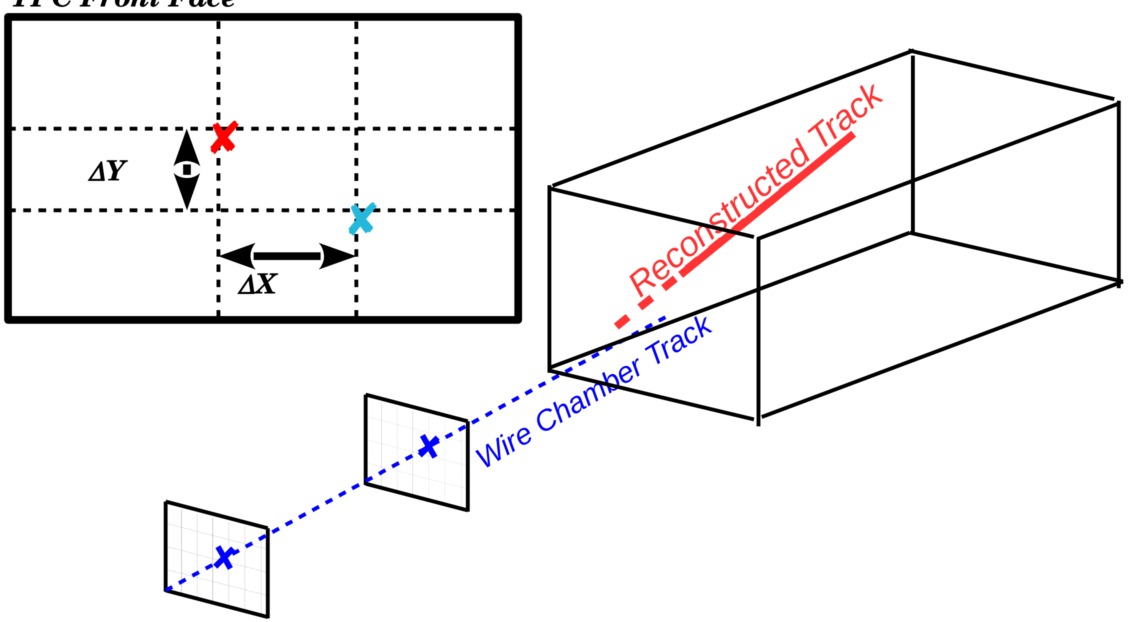
π^-–Argon Cross-Section

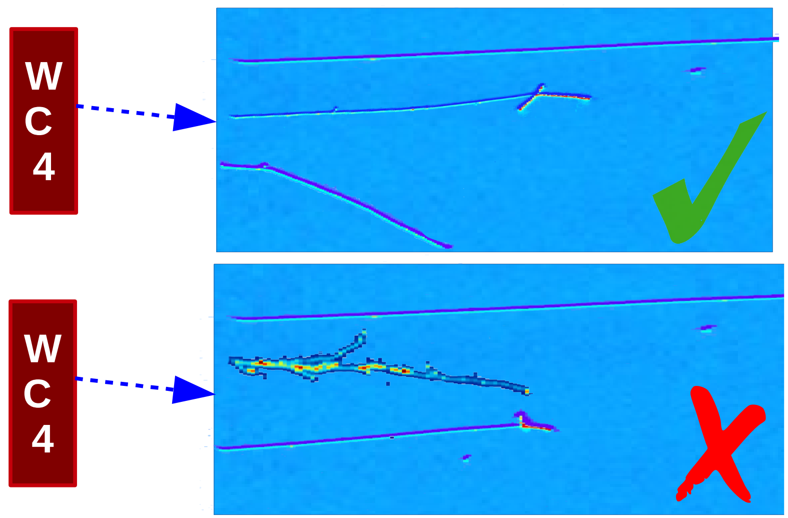






TPC Front Face

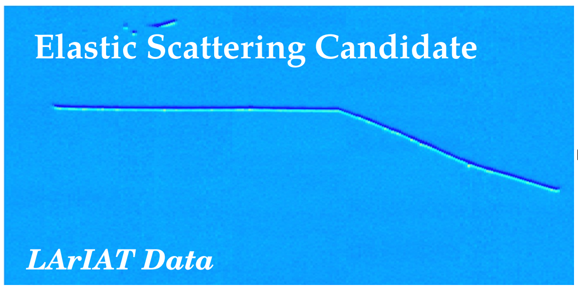




π^-–Argon Cross-Section

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

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



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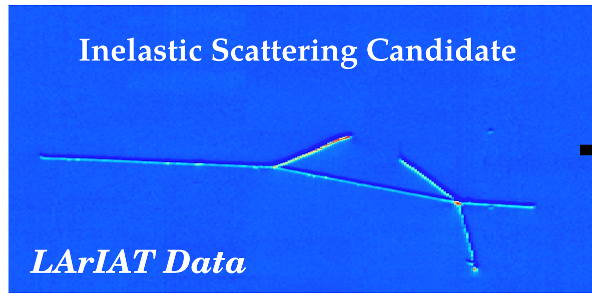

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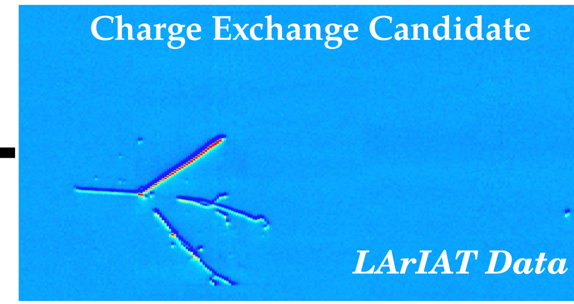

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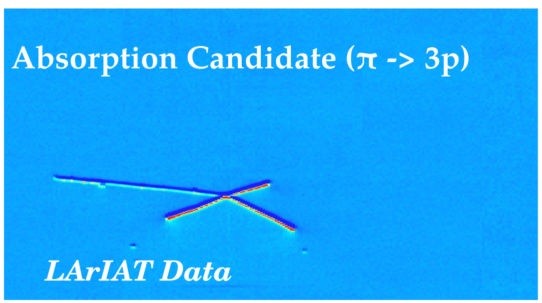

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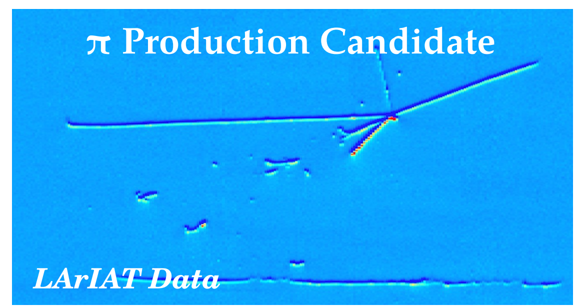
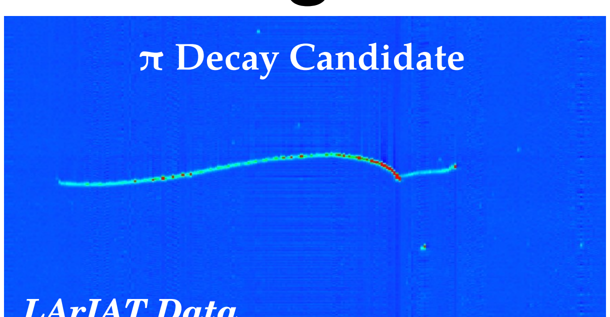
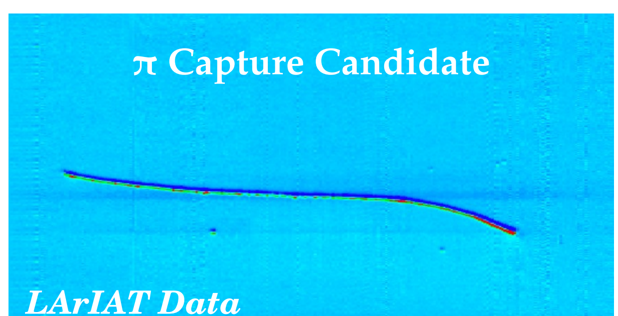
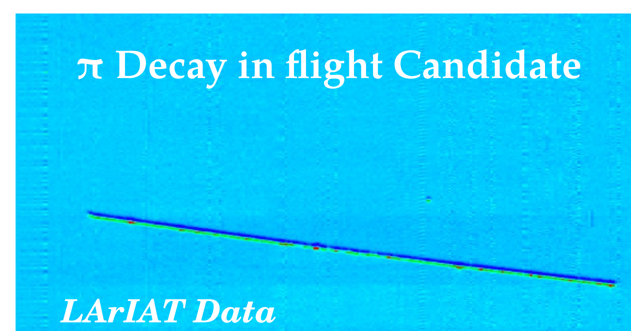


- **Backgrounds are:**







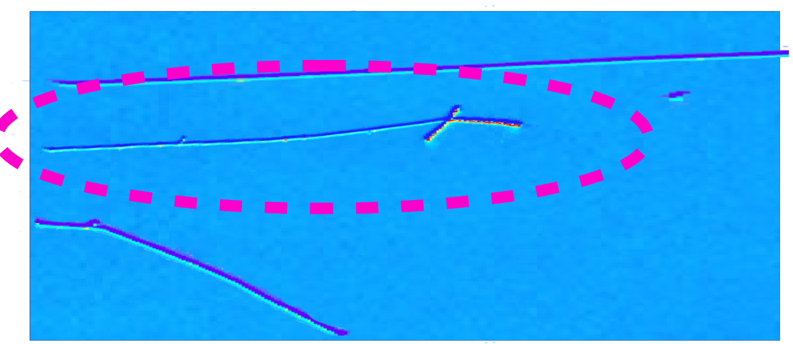
Note: These backgrounds are still included in the forthcoming plots

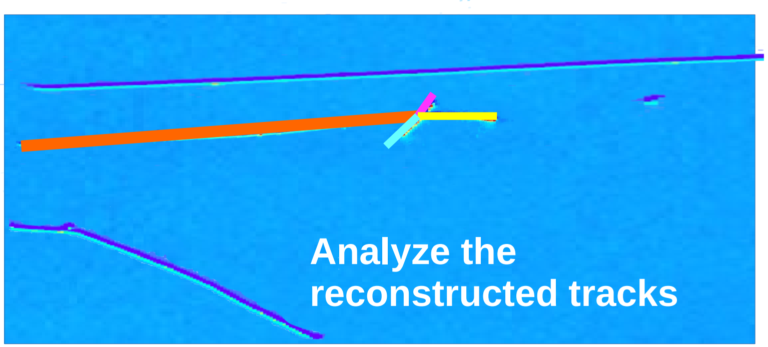
π^- –Argon Cross-Section

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

	π^-	e^-	γ	μ^-	K^-	$\bar{p}$
Beam Composition before cuts	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 %





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

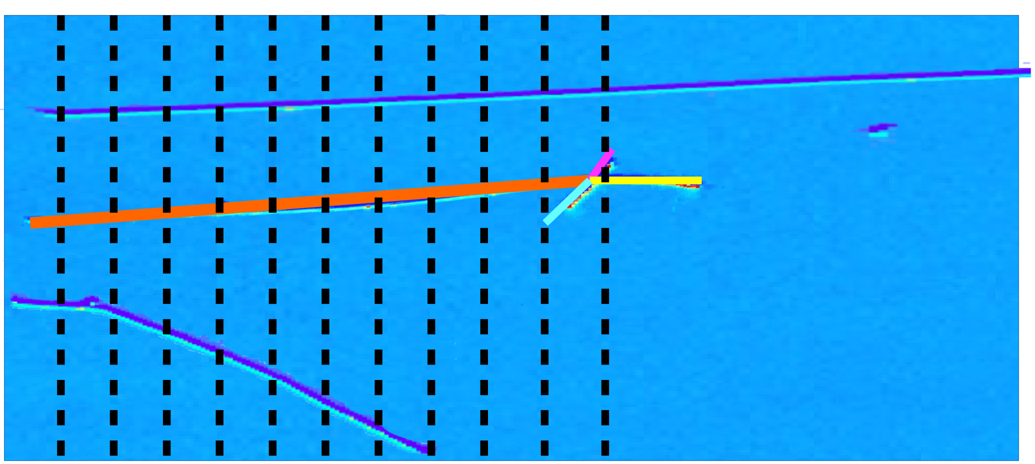
$$KE_i = \sqrt{p^2 + m_\pi^2} - m_\pi - E_{\text{Flat}}$$

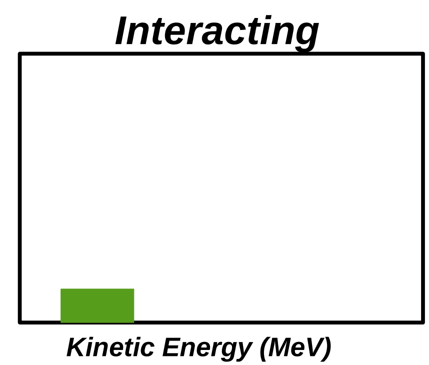
we take into account energy loss due to material upstream of the TPC (argon, steel, beamline detectors, etc)

π^-–Argon Cross-Section

- **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**
  - **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
    - **Yes:** Calculate the kinetic energy at this point and put that in both the **interacting** and **incident** histograms

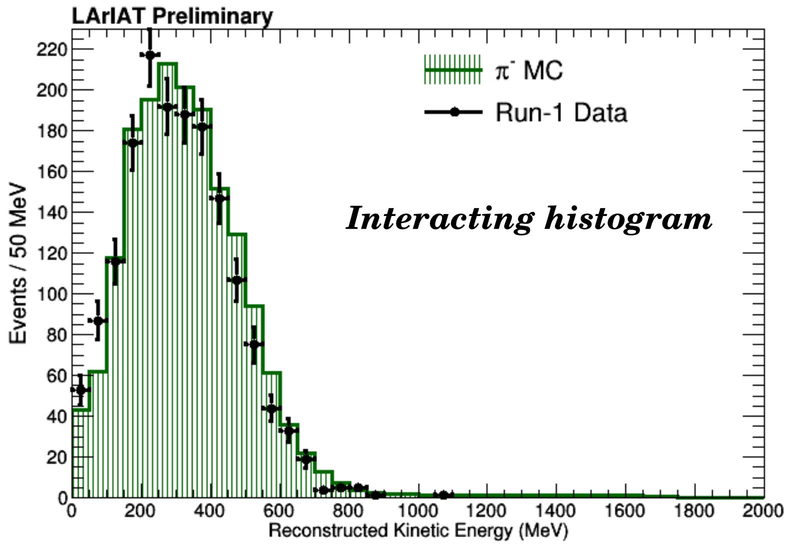
$$KE_{Interaction} = KE_i - \sum_{i=0}^{nSpts} dE/dX_i \times Pitch_i$$





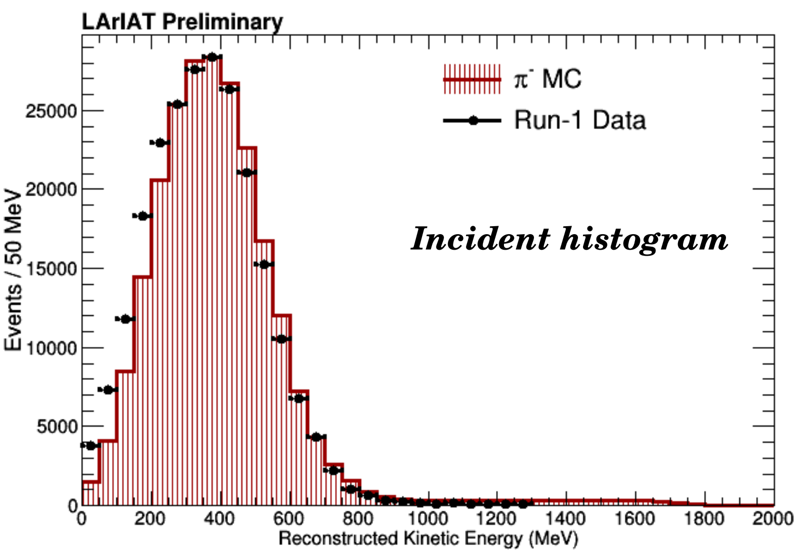
π^- –Argon Cross-Section

- **Repeat this process for your entire sample of π^-**
- **Use the thin slab approach and calculate the cross-section**



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

Where $n = \rho N_A / A$
Z = slab depth



$$= \frac{1}{nz}$$

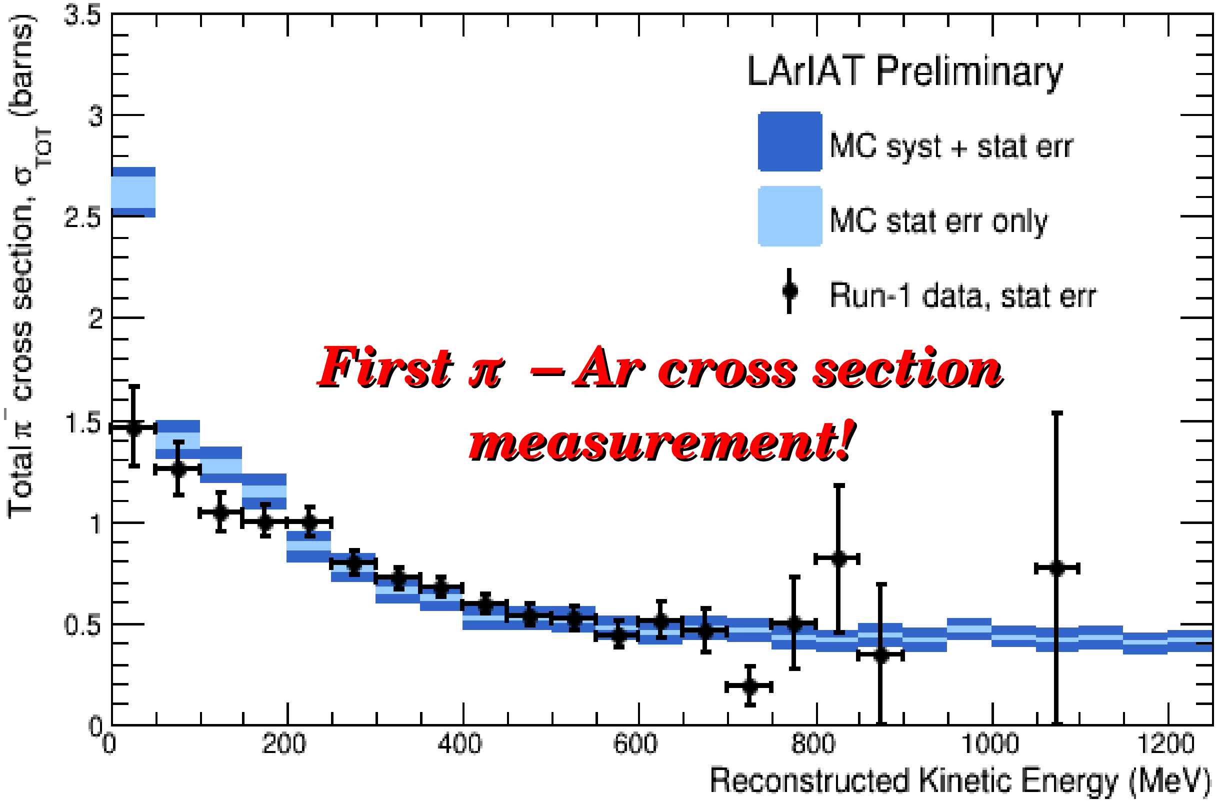
Cross-section (barns)

Reminder:
Cross section still contains capture and decay processes.

We are currently utilizing the data and MC to estimate the relative fraction of abs/decay and employing methods to remove this from our sample

Kinetic Energy (MeV)

π^-–Argon Cross-Section



Systematics Considered Here

dE/dX Calibration: 5%

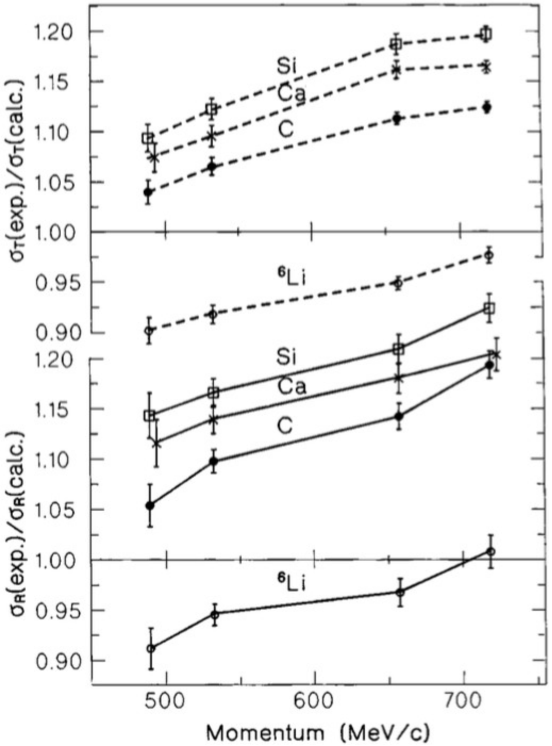
Energy Loss Prior to entering the TPC: 3.5%

Through Going Muon Contamination: 3%

Wire Chamber Momentum Uncertainty: 3%

- **Next steps for this analysis**
  - Remove pion capture/decay background
  - Improve energy calibration
  - Investigate utilizing the Aerogel and Muon Range Stack to remove muon contamination

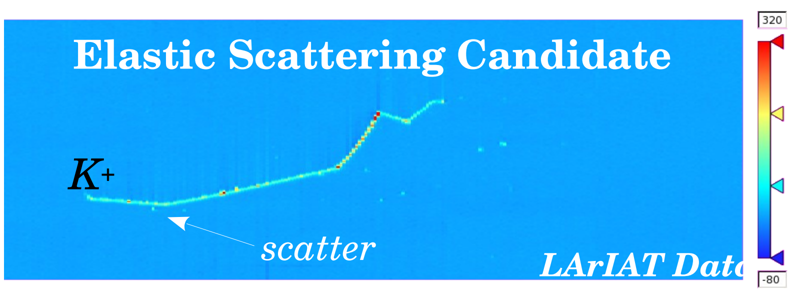
Towards a K^+ – Ar cross section measurement

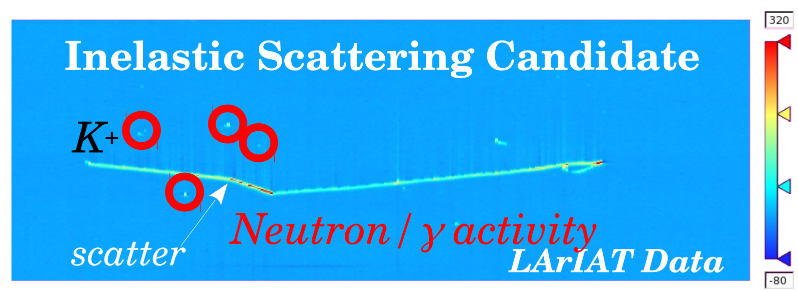


- Like for Pion, Kaon cross section never measured on argon before, and scarcely measured in general

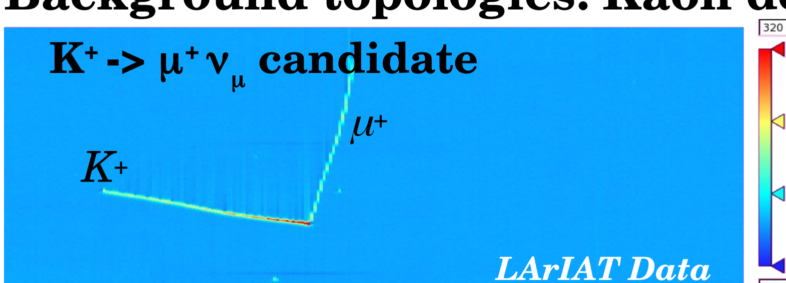
- This study concentrate on K^+ cross section, given its relevance to proton decay searches in DUNE - $p \to \upsilon K^+$ Golden channel for proton decay in LAr

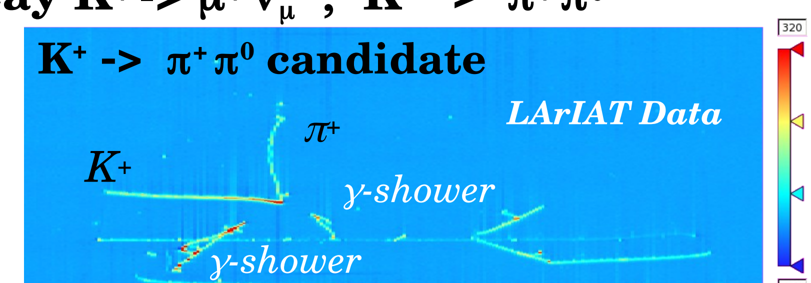
Signal topologies: $\sigma_{Tot} = \sigma_{Elastic} + \sigma_{Reaction}$



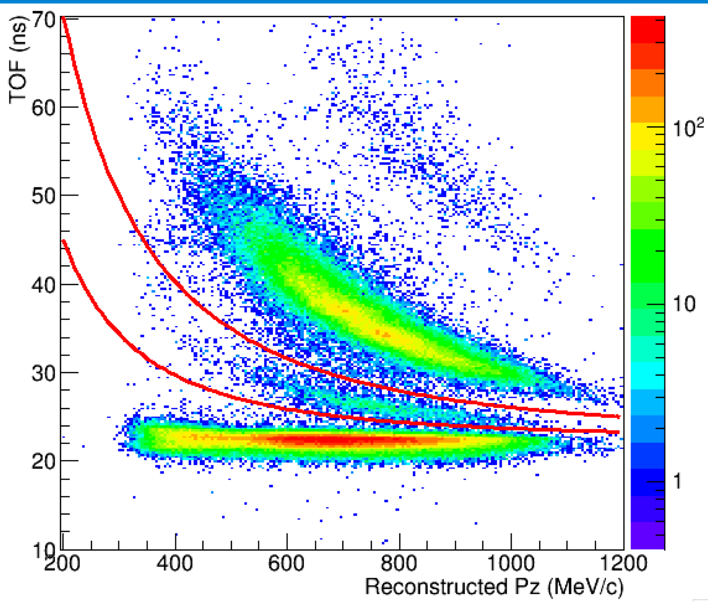


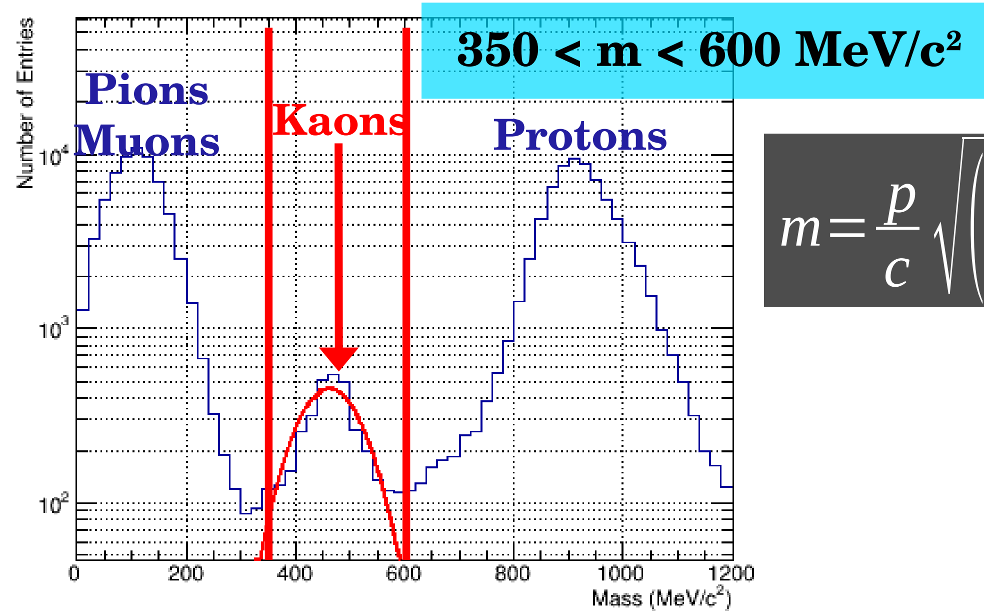
Background topologies: Kaon decay $K^+ \to \mu^+ \nu_\mu$; $K^+ \to \pi^+ \pi^0$





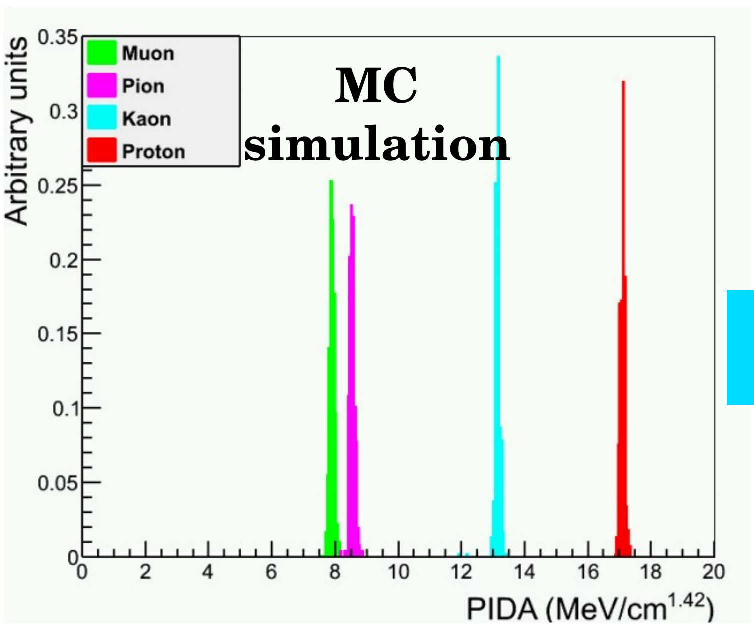
Towards a K^+ – Ar cross section measurement





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

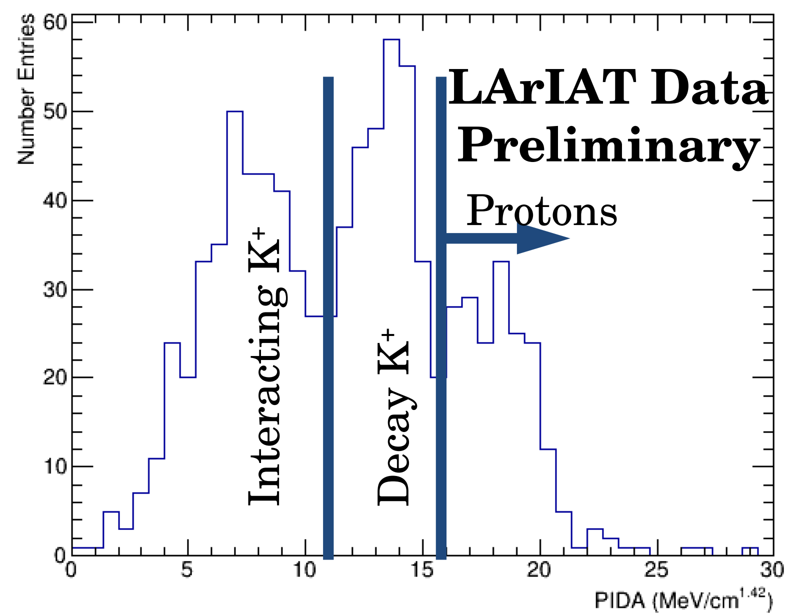
- **We can use beamline selections to enrich our sample of Kaon candidates using TOF vs Pz**
- **Next use calorimetry within the TPC to separate interacting Kaons from Kaon decay and proton contamination**



$$\frac{dE}{dx} \approx AR^{-0.42}$$

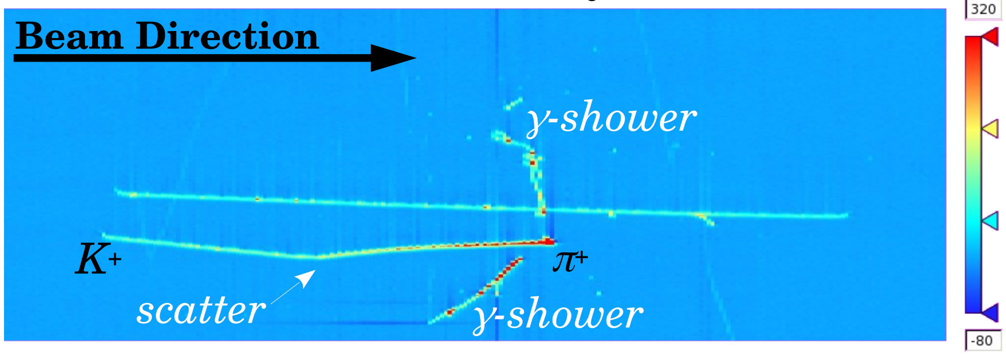
$$A = \frac{1}{N}\sum_{1}^{N}\left(\frac{dE}{dx}\right)_{calo,i} R_i^{0.42}$$

A tag for Kaon decay!

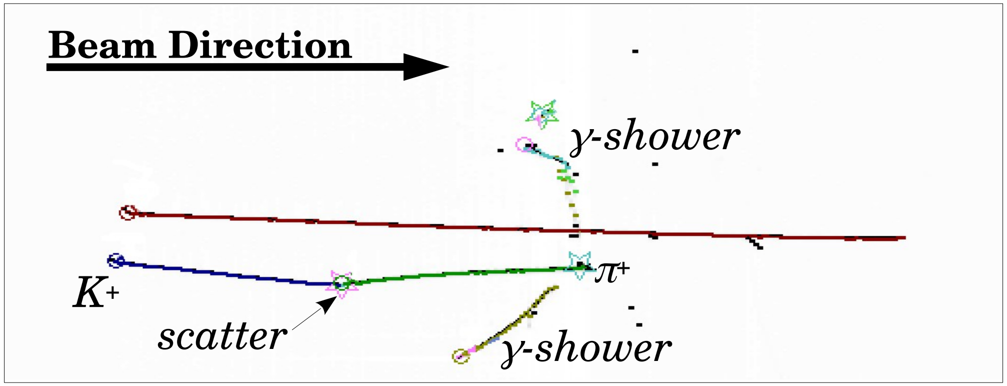


Towards a K^+ – Ar cross section measurement

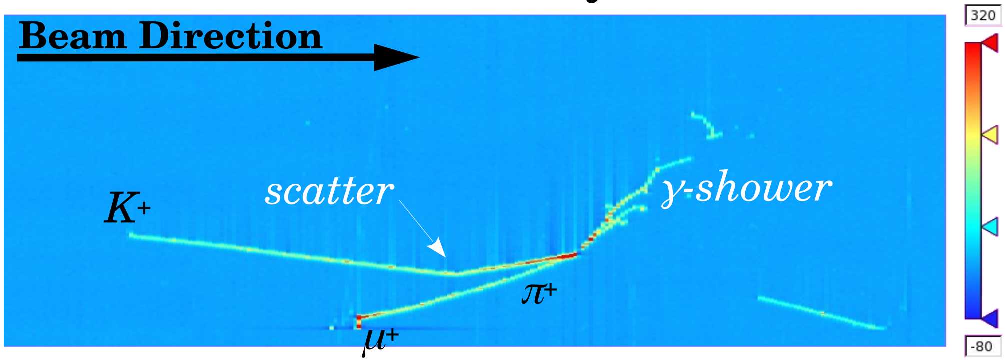
LArIAT Data Preliminary K^+ Candidate



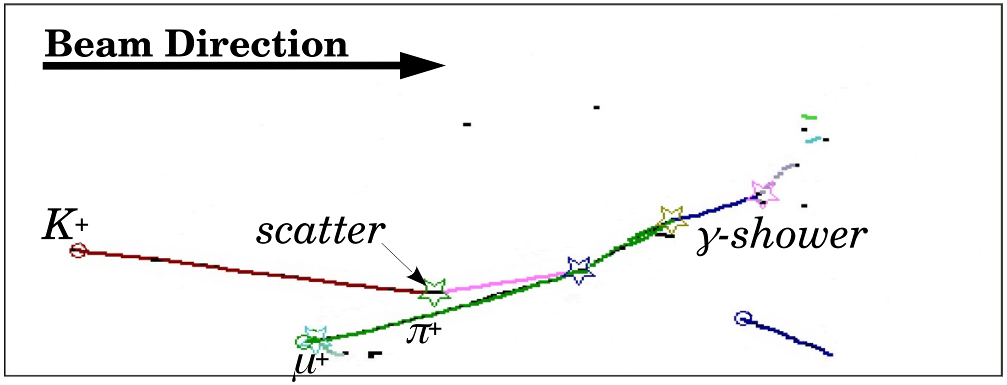
LArIAT Data Preliminary Reconstruction



LArIAT Data Preliminary K^+ Candidate



LArIAT Data Preliminary Reconstruction



- **The analysis has demonstrated the ability to automatically identify, tag, and reconstruct Kaon events in LArIAT**
- **Now working to improve our statistics in our sample and make a measurement of the Kaon Cross-Section!**

Conclusions

- **LArIAT has recently completed two successful beam runs and has collected a large number of charged particle events**
  - We have made the first inclusive pion-Argon cross-section (publication in preparation)
  - Kaon identification and reconstruction has been successfully demonstrated
    - Cross-section measurement forthcoming soon!
  - Has begun to explore the full depth of light-augmented calorimetry capable inside a LArTPC
- **LArIAT has a large number of additional analyses in the pipeline**
  - p+ inclusive cross-section
  - Exclusive pion cross-sections (charge exchange, elastic, absorption, etc...)
  - Will also do similar measurements for other charged particle species (proton, K-, μ/π separation studies, e/γ characterization, etc...)
- **LArIAT is preparing for a Run-III**
  - Will implement 3mm and 5mm wire pitch for detailed reconstruction studies of various wire spacings
  - Additional upgrades to the light collection system under consideration
    - e.g. Implementing the ARAPUCA
  - Also working in collaboration with the Bern group to explore deploying a ~500 channel pixel based readout for LArTPC R&D

Thank YOU from the LArIAT collaboration!!!

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- **U. Cincinnati** Randy Johnson, Jason St. John
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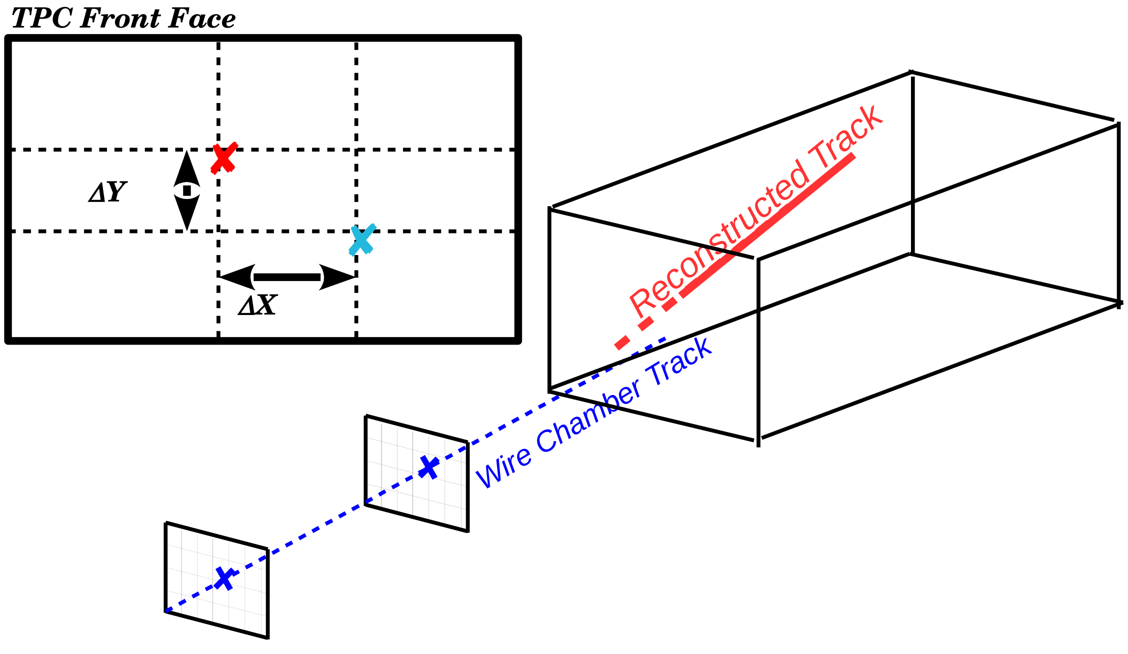
- **U. Minnesota, Duluth** Rik Gran, Alec Habig
- **U. Pittsburgh** Steve Dytman, Matthew Smylie
- **Syracuse University** Jessica Esquivel, Pip Hamilton, Greg Pulliam, Mitch Soderberg
- **U. Texas, Arlington** Jonathan Asaadi, Animesh Chatterjee, Amir Farbin, Sepideh Shahsavarani, Jae Yu
- **U. Texas, 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


TODAY'S MENU
Backup Slides $1.50
Questions $ 5.35
Coffee $ 1.00
Special
Applause free!!!!


TPC Front Face
ΔY
ΔX
Reconstructed Track
Wire Chamber Track

Thin-Sliced TPC Method

- **Generally the survival probability of a pion traveling through a thin slab of argon is given by**

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

Where σ_{TOT} is the cross-section per nucleon and z is the depth of the slab and n is the density

- **The probability of the pion interacting is thus**

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

where we measure the probability of interacting for that thin slab as the ratio of the number of interacting pions to the number of incident pions

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

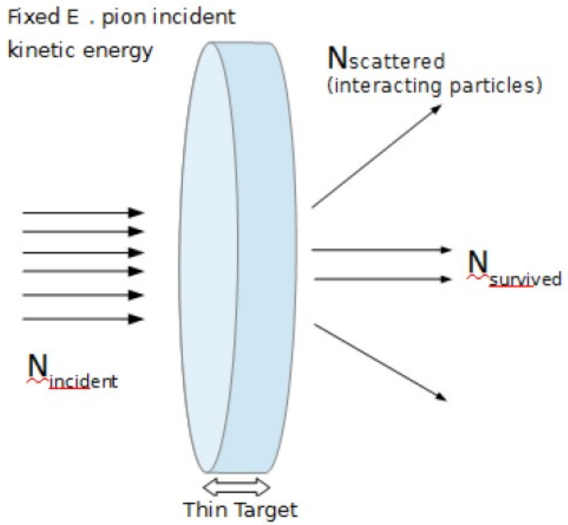
Thin-Sliced TPC Method

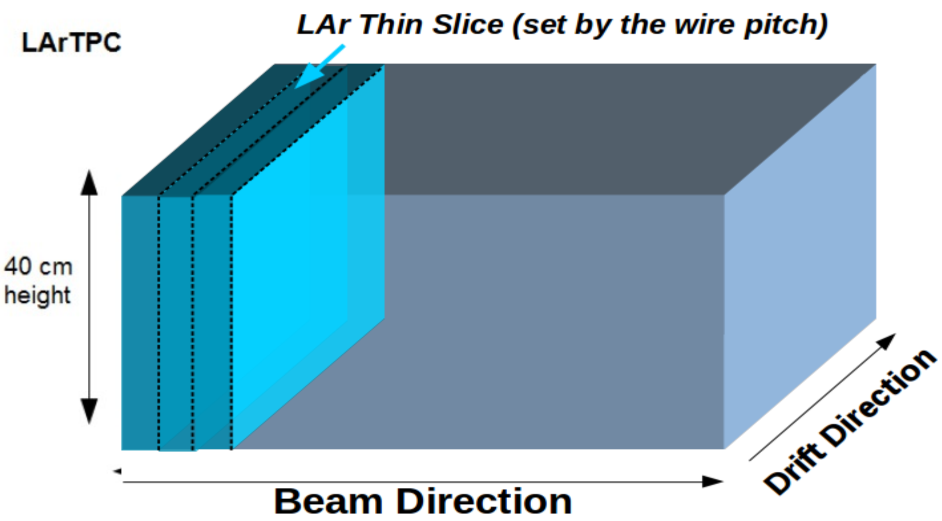
- **Thus you can extract the pion cross-section as a function of energy as**

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

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

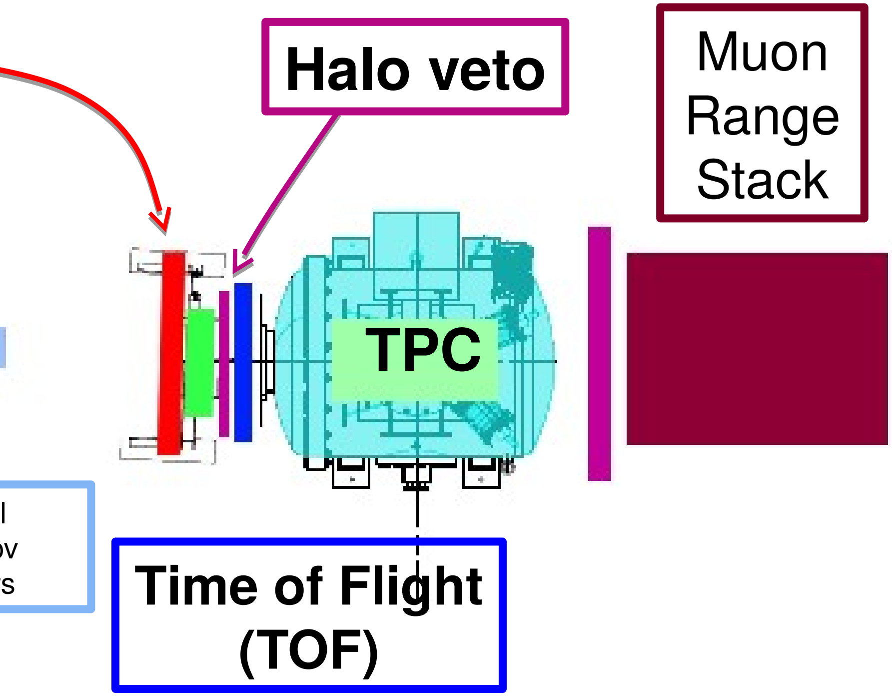
Where $n = \rho N_A / A$



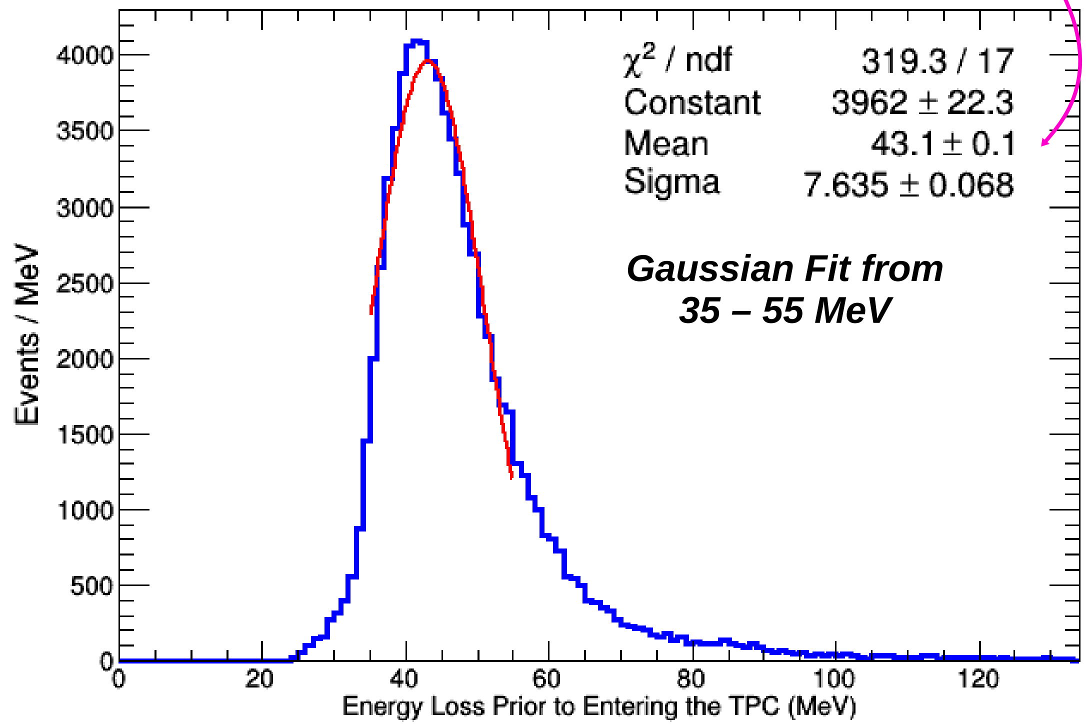


- **Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of "thin-slab" targets if we know the energy of the pion incident to that target**

Energy Corrections



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

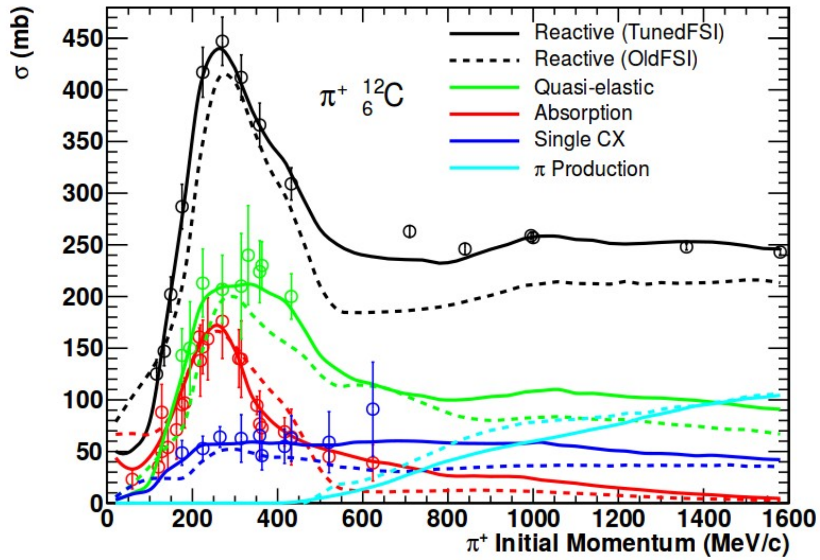


- Adding up all the energy which a pion loses in the region before it enters the TPC (**TOF**, **Halo**, **Cryostat**, **Argon**) gives us the "energy loss" by the pion in the upstream region

Hadron – Ar interaction cross sections: π – Ar

π^+ scattering data on ^{12}C

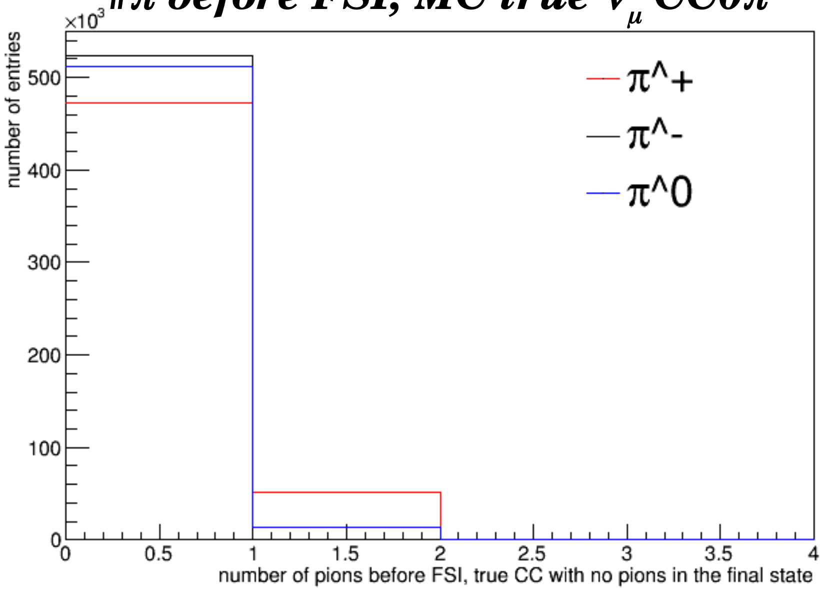
arXiv:1405.3973 [nucl-ex]



✔ In the energy range of 100-500 MeV pion interactions are dominated by Δ resonances

✔ Cross section is boosted in this energy range, the same range where most of the pions produced by few GeV ν interactions lie

#π before FSI, MC true ν_μ CC0π

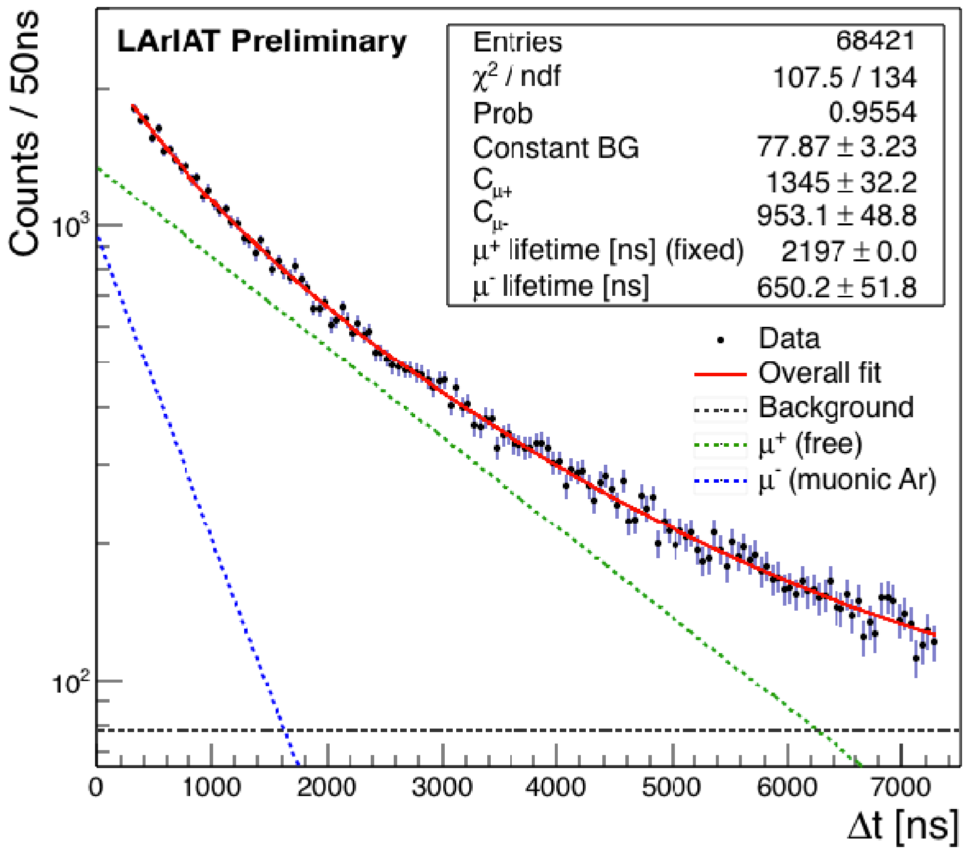


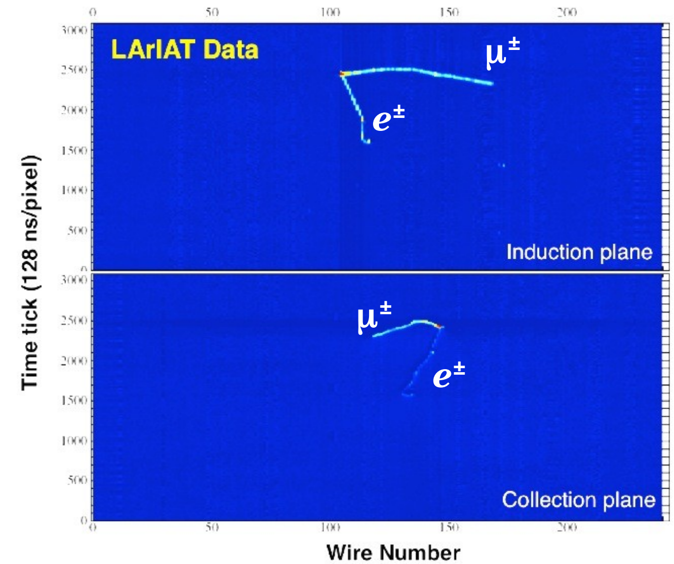
✔ A non-negligible fraction of pion produced in ν_μCC interaction don't exit the Ar nucleus, thus modifying the kinematic distribution of final state particles

Pion interaction represents an important systematic in the neutrino cross section!

Measurements with light: Michel electrons

- Michel electrons can be used for energy calibration, PID of stopping $\mu^{\pm}$
- Real-time triggering on Michel e's from stopping cosmic μ's using light signals





$\tau_{\mu-}$ = 650 ± 52 ns from fit

$$1/\tau_{\mu-} = 1/\tau_{free} + 1/\tau_{capture}$$

T_{free} = 2197 ns (fixed)

$\tau_{capture}$ **= 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)

Event selection: reduction table

Event Sample	Number of Events
Single beamline particle fully reconstructed	187463
# tracks > 0 in first 2 cm TPC && < 5 in first 14 cm	117710
Unique WC – TPC track matching	70801
TOF cut	28303
PIDA cut	8231
Invariant Mass Cut	**882**