LArIAT:
Liquid Argon In a Testbeam

Roberto Acciarri – Fermilab
On behalf of the LArIAT collaboration

Fermilab Neutrino Seminar Series – September 29th, 2016

YES

This is the usual neutrino seminar

AND YES

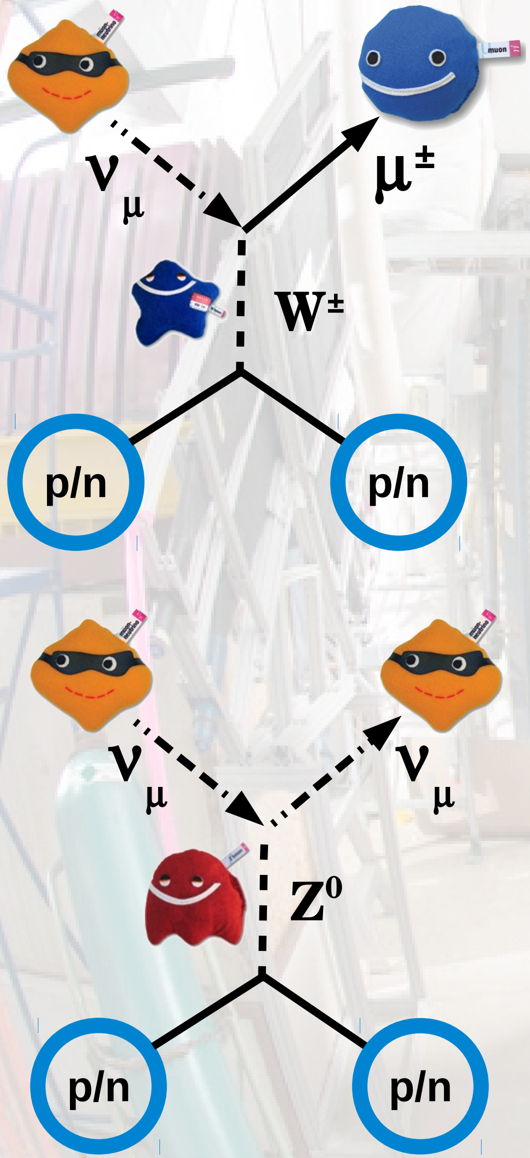
Our liquid argon detector is in a test beam, we don't see any neutrinos

SO WHY LARIAT?

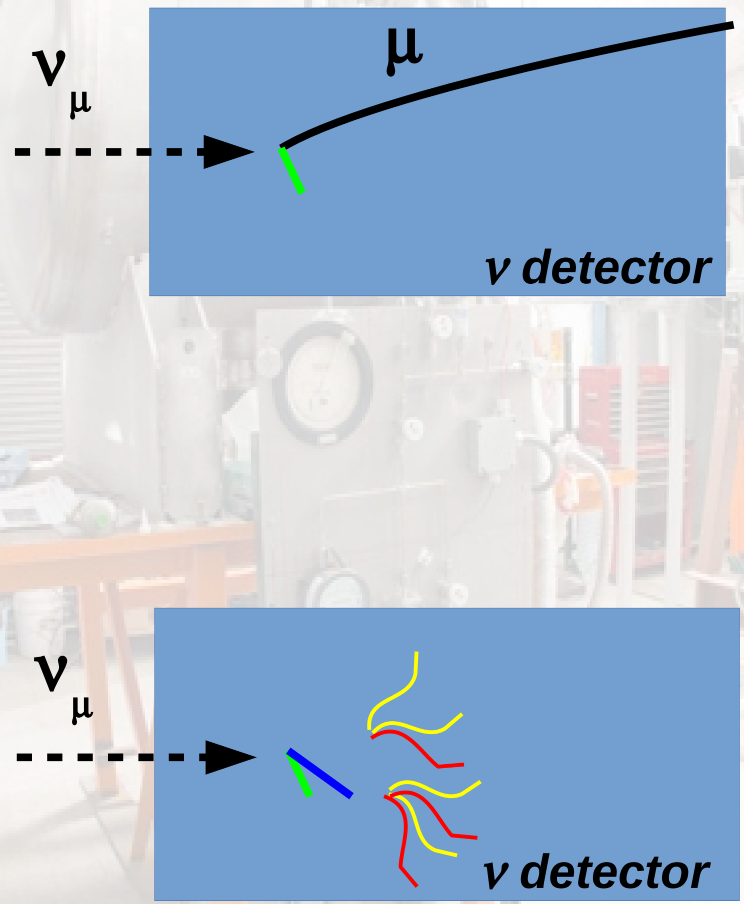
'Cause life isn't easy. Neutrino physics neither.

Neutrino physics in a simple world

From theorists...



... to experimentalists



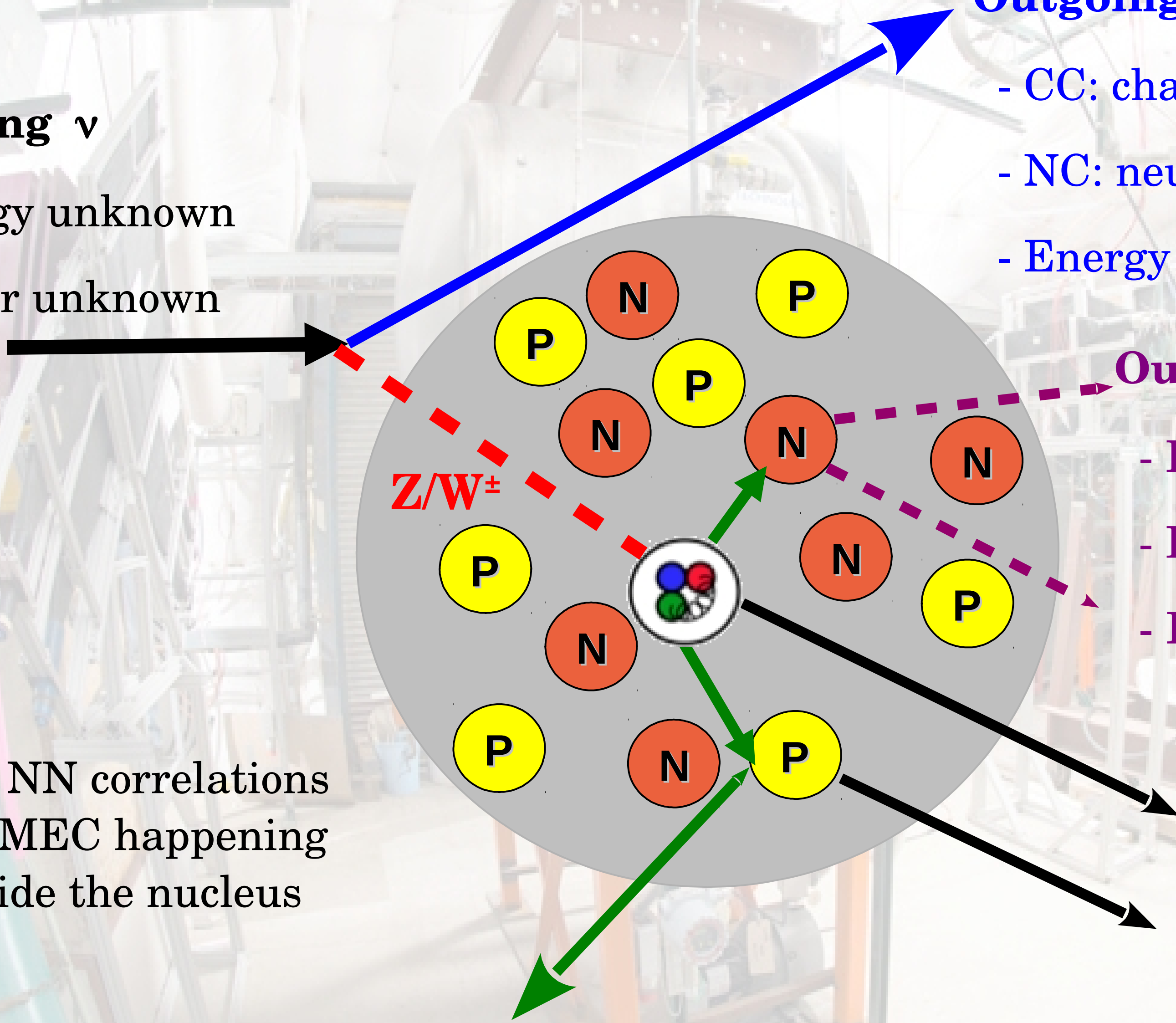
Credit: J. Asaadi

- ✔ *Shoot a neutrino beam into your detector*
- ✔ *Detect the particle produced in the interaction*
- ✔ *Reconstruct the neutrino information and make cool plots*

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?

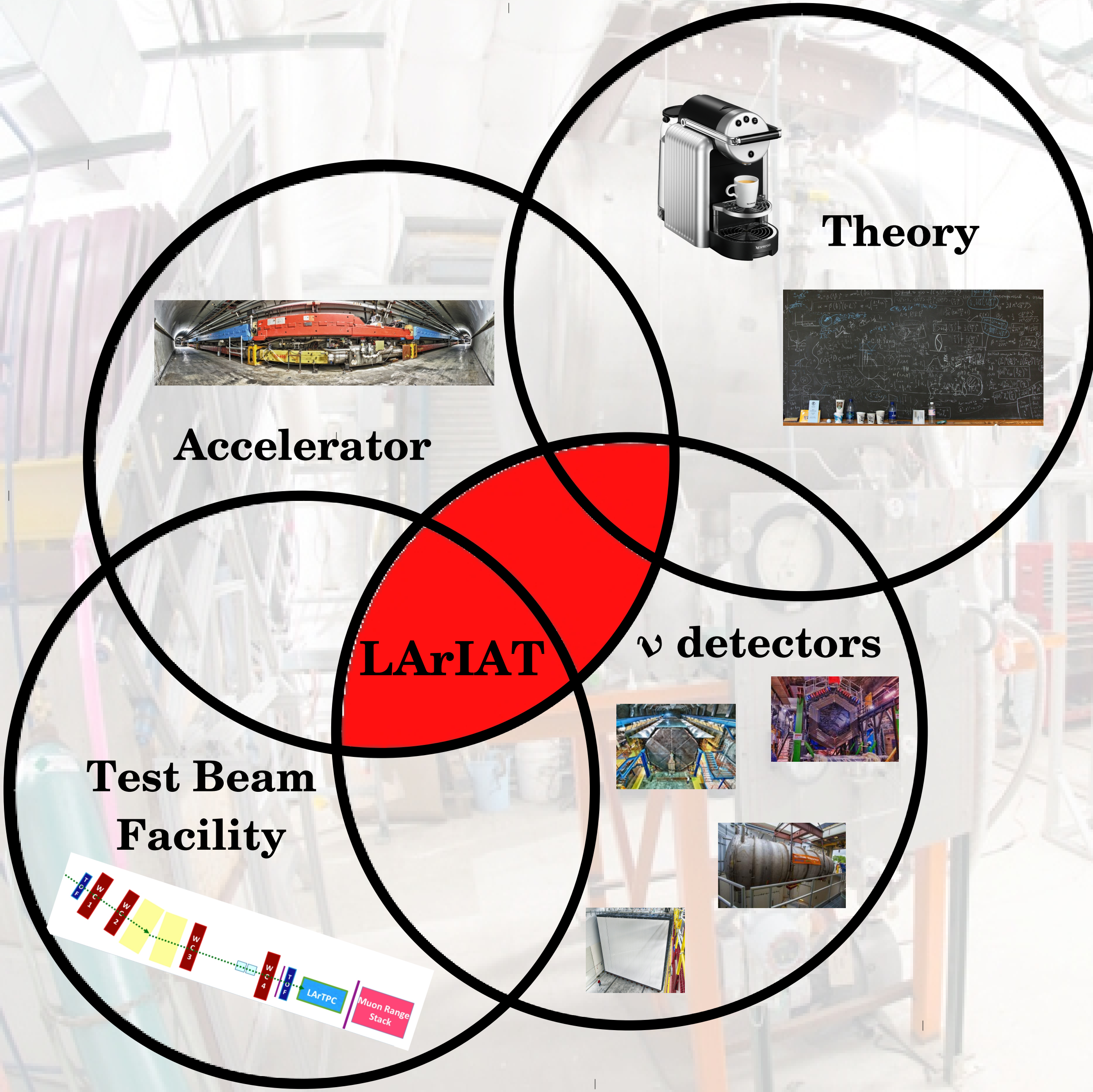
Outgoing Nucleons

- Visible?
- Energy?

Also NN correlations and MEC happening inside the nucleus

Credit: M. Kordosky

ν community as a mirror of the ν physics



More than just neutrino detectors!

Synergy between all the fields

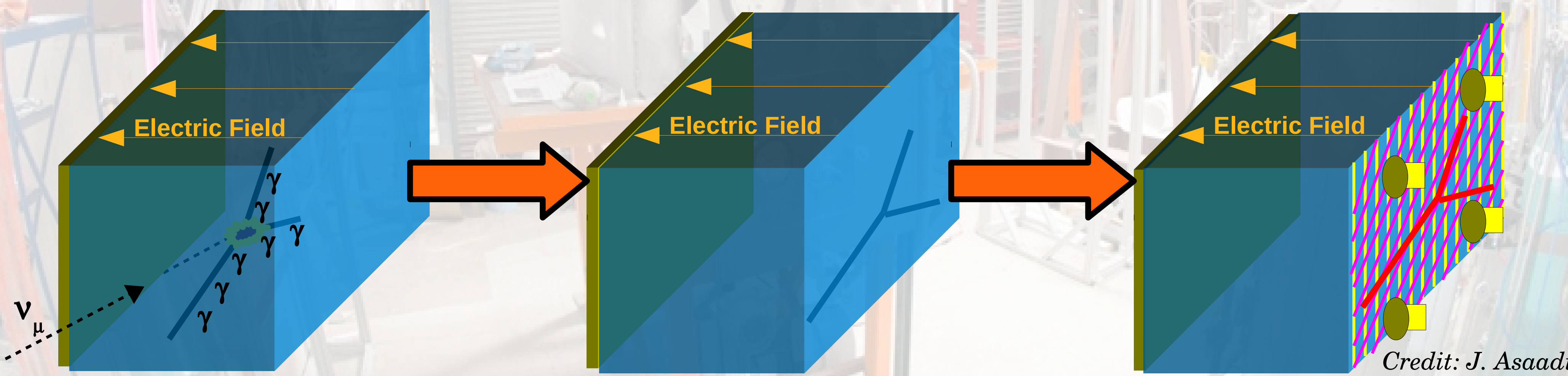
We are in the "precision era" of neutrino physics: a complete characterization of detection techniques and secondary particle interactions is ***fundamental***

Why a liquid argon detector in a test beam?

- **Dense** *40% more than water*
- **Abundant** *1% of the atmosphere*
- **Ionizes easily** *55k e^-/cm*
- **High electron lifetime**
- **High scintillation light yield** *40k γ/MeV (null E field), transparent to light produced*

Liquid argon TPC technology is excellent for neutrino detectors!

Time Projection Chamber

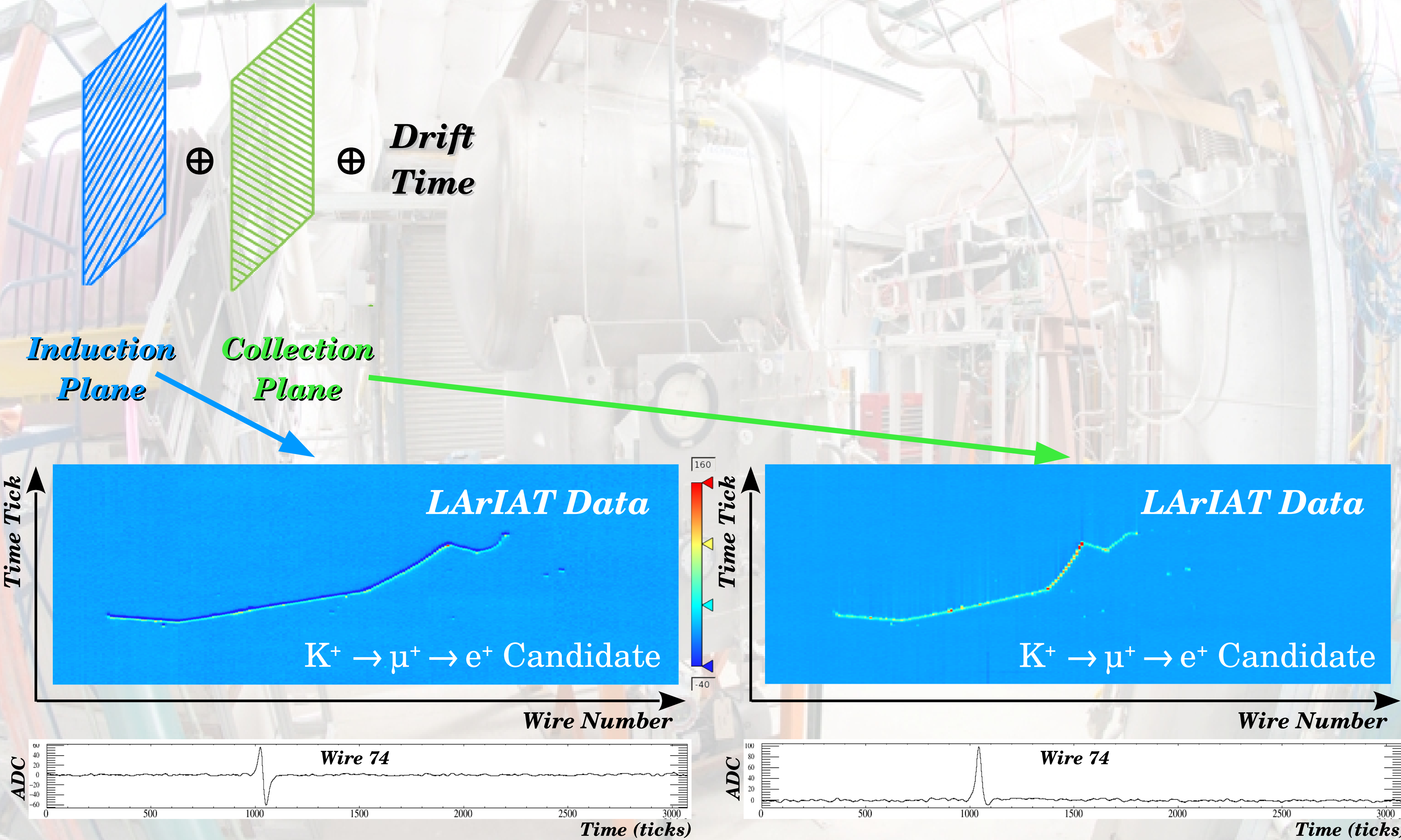


Neutrino interaction in LAr produces ionization and scintillation light

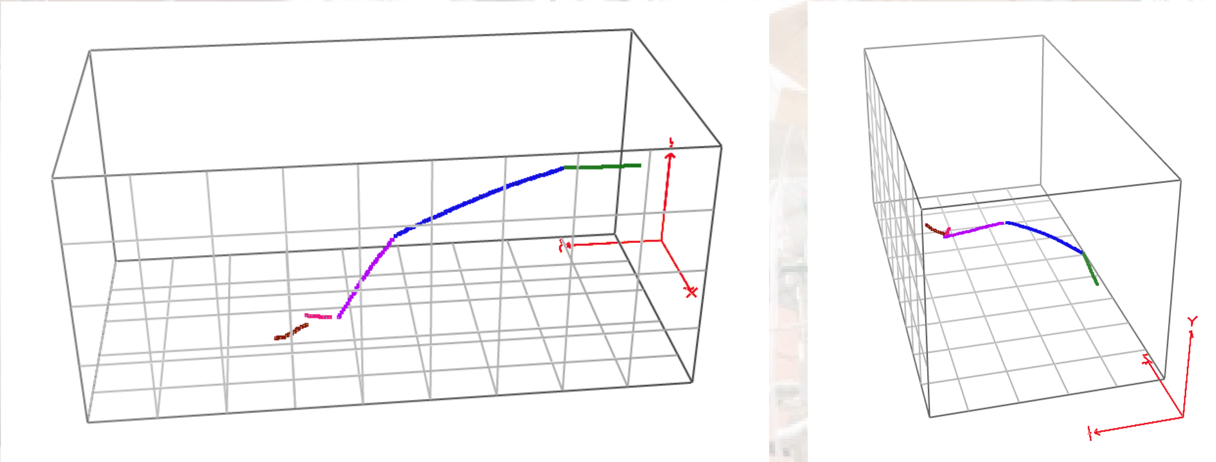
Drift the ionization charge in a uniform electric field

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

Why a liquid argon detector in a test beam?

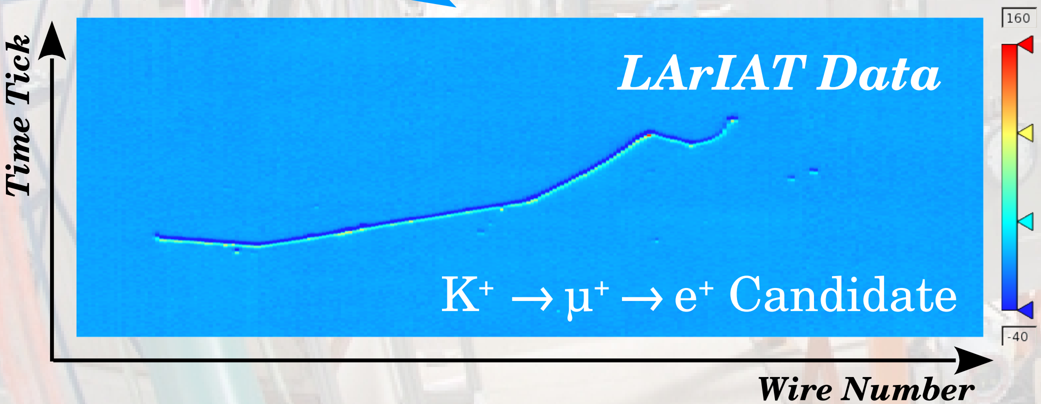


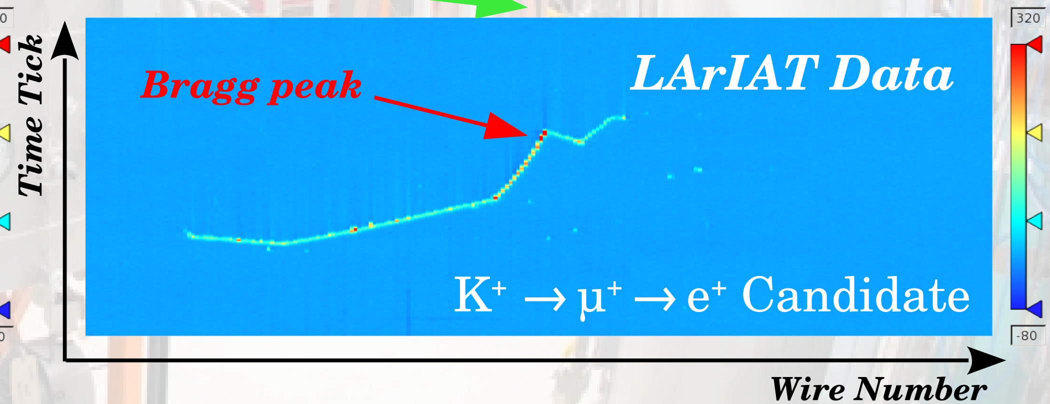
Why a liquid argon detector in a test beam?



Induction Plane

Collection Plane



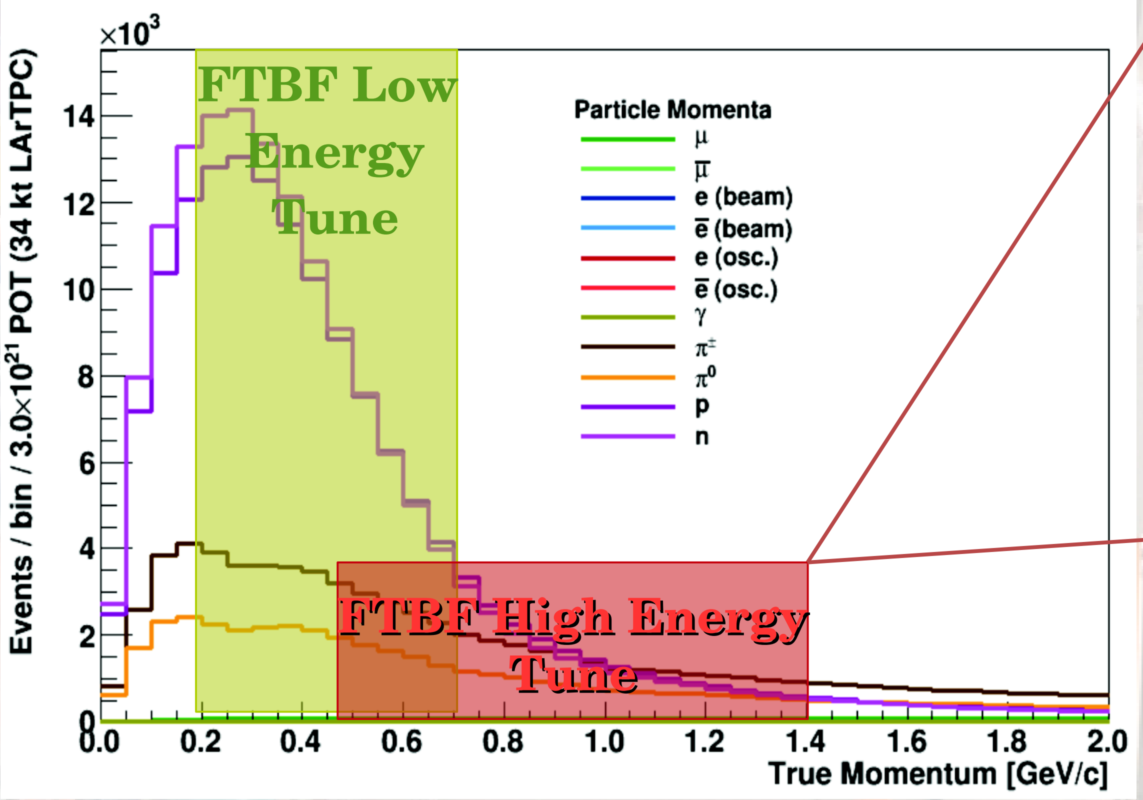


- ✔ 3D imaging with mm space resolution
- ✔ Calorimetry information
- ✔ PID capabilities

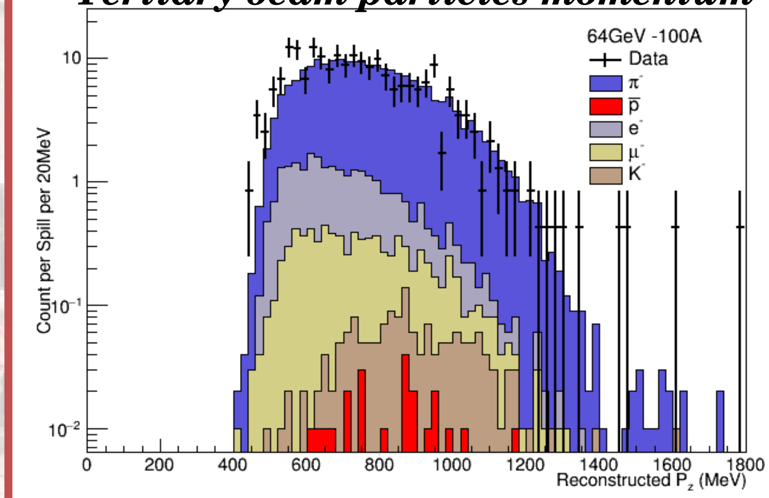
Why a liquid argon detector in a test beam?

A LArTPC in the Fermilab Test Beam Facility is well suited to study charged particles in the energy range relevant to both the short-baseline (uBooNE, SBND, ICARUS) and Long-Baseline (DUNE) experiments

DUNE SIMULATION for ν_e CC analysis

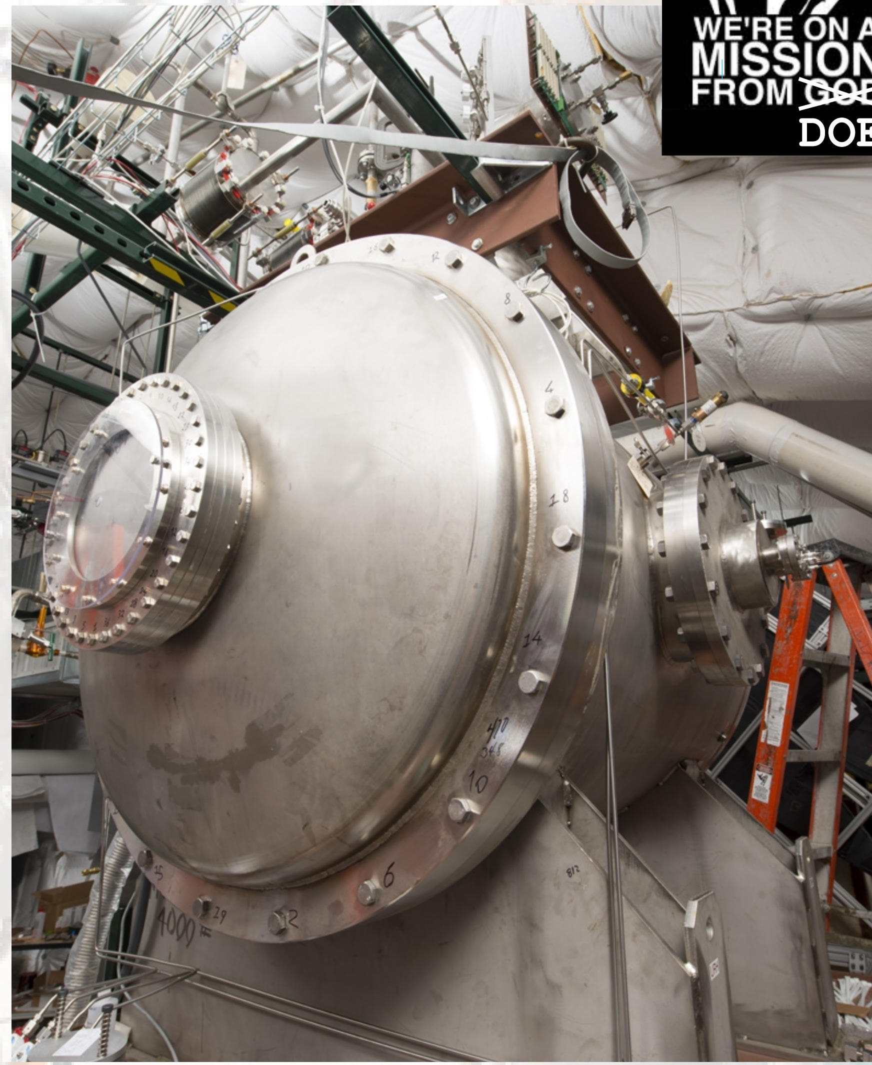


Tertiary beam particles momentum



The LArIAT Mission

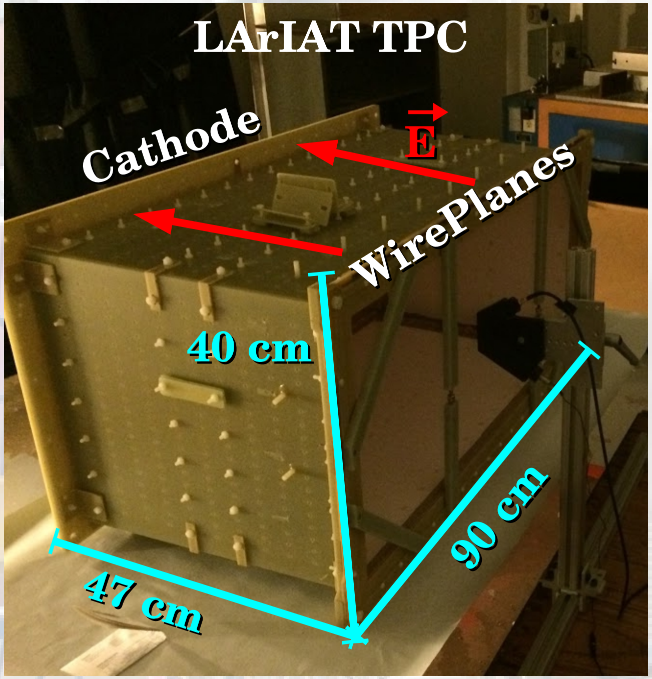
Executing a comprehensive program designed to characterize LArTPC performance and charged particles interaction in argon in the energy range relevant to the forthcoming neutrino experiments



LArIAT: You need us... and you know it!

The LArIAT goal bullet-pointed

170 lt (0.24 ton) LArTPC designed to calibrate detector response in a charged particle beam

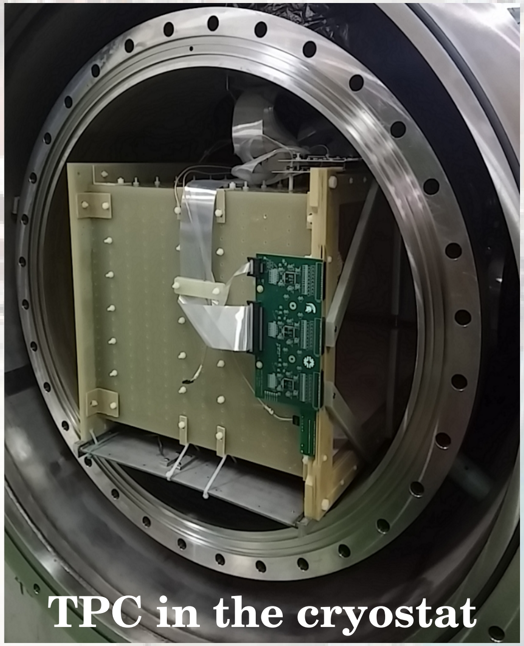


Physics Goals

- Hadron – Ar interaction cross sections and nuclear effects
- e/γ shower identification
- Particle sign determination in the absence of magnetic field, using topology
- Geant 4 validation

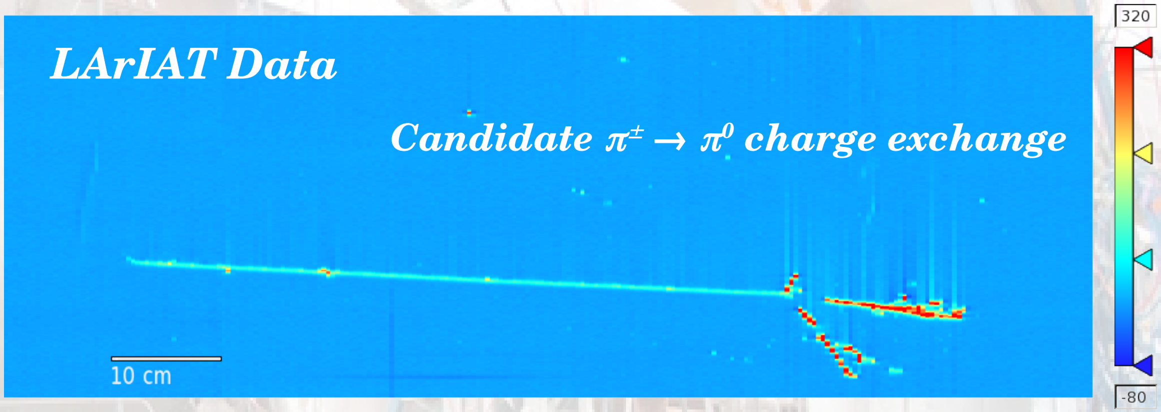
R&D Goals

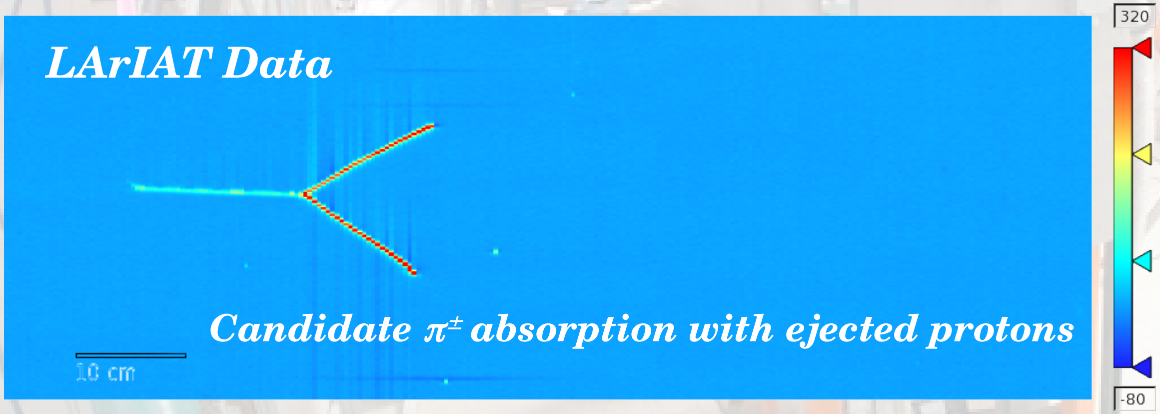
- Improvement of the energy resolution through the combination of scintillation light and ionization charge signals
- Optimization of particle ID techniques
- Study of LArTPC event reconstruction and calorimetry systematics


TPC in the cryostat

Hadron – Ar interaction cross sections: π – Ar

Tune hadron – nucleus interaction and nuclear structure models through inclusive and exclusive cross section measurements

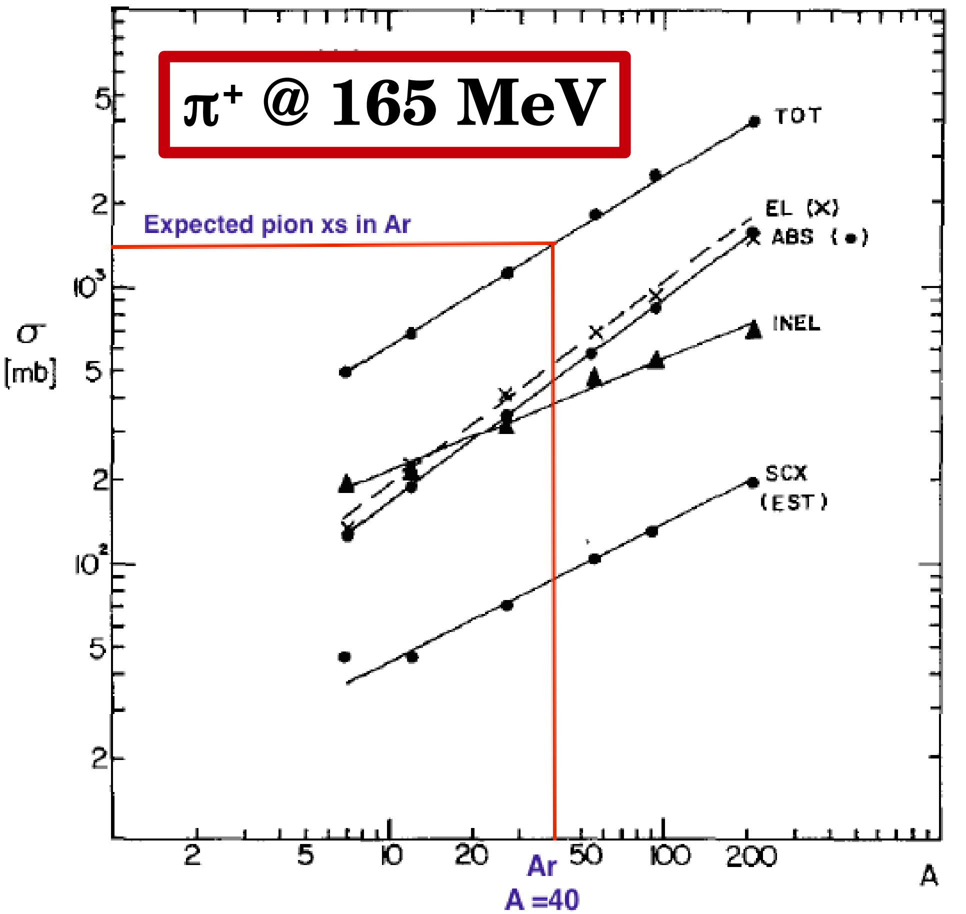




Neutrino interactions in the few GeVs energy range produce many pions: π – Ar cross sections will play an important in the systematics of neutrino measurements

Hadron – Ar interaction cross sections: π – Ar

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



$$\sigma_{tot} = \sigma_{el} + \sigma_{reac}$$

$$\sigma_{reac} = \sigma_{inel} + \sigma_{abs} + \sigma_{chex} + \sigma_{\pi prod}$$

- No existing measurement before LArIAT!
- Prediction come from interpolation between lighter and heavier nuclei
- LArIAT measurements:
  - total π – Ar cross section
  - Exclusive π – Ar interaction channels
    - ✔ Absorption
    - ✔ charge exchange
    - ✔ elastic and inelastic

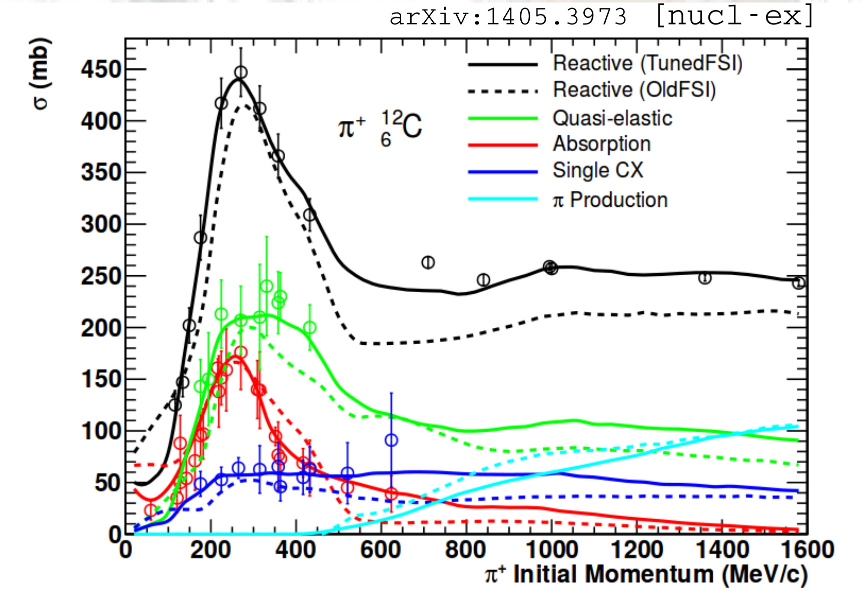
Hadron – Ar interaction cross sections: π – Ar

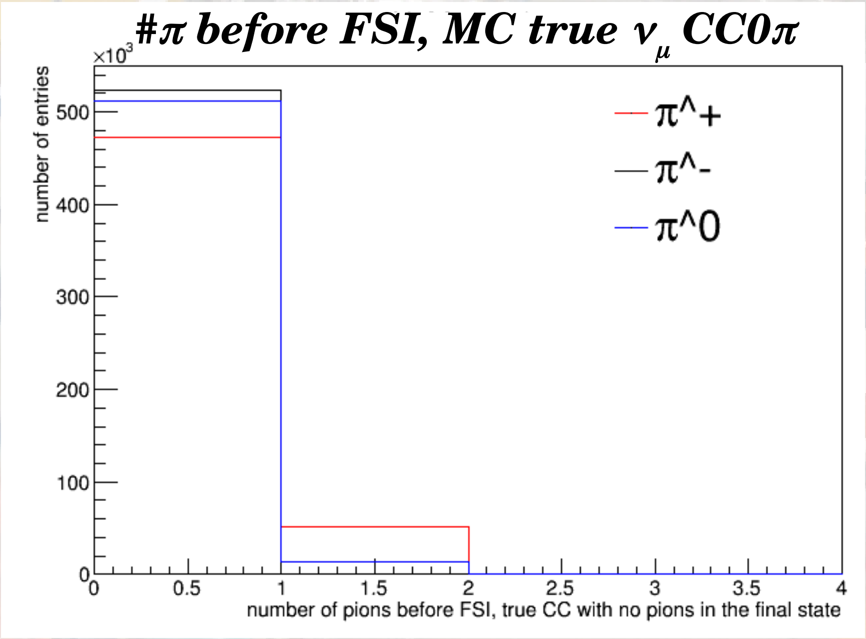
✔ In the energy range of 100-500 MeV pion interactions are dominated by Δ resonances

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

π^+ scattering data on ^{12}C

arXiv:1405.3973 [nucl-ex]

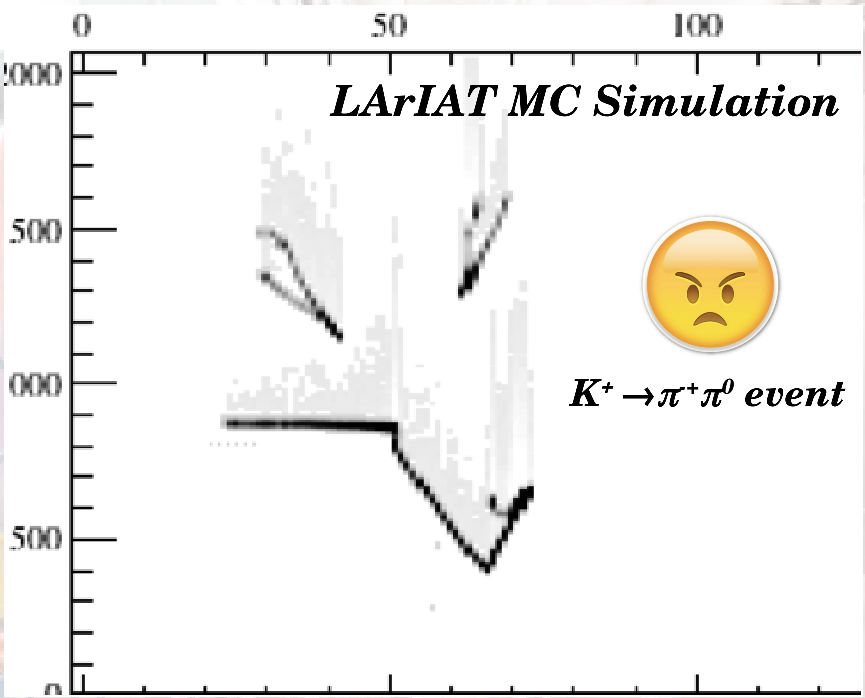


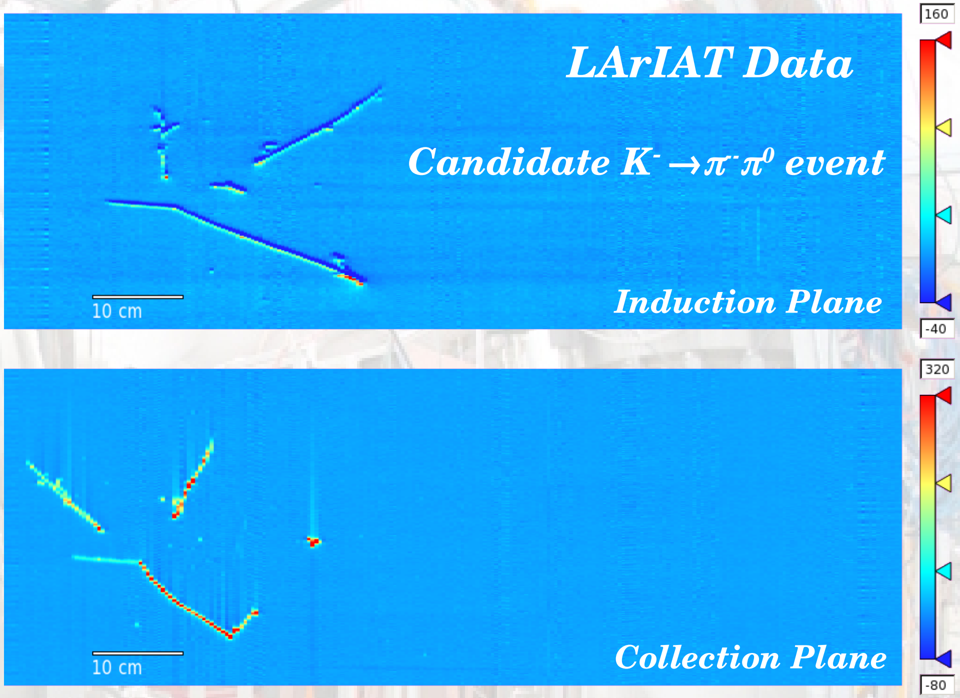


✔ A non-negligible fraction of pion produced in ν_μCC interaction don't exit the Ar nucleus, thus modifying the kinematic distribution of final state particles

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

Hadron – Ar interaction cross sections: K – Ar





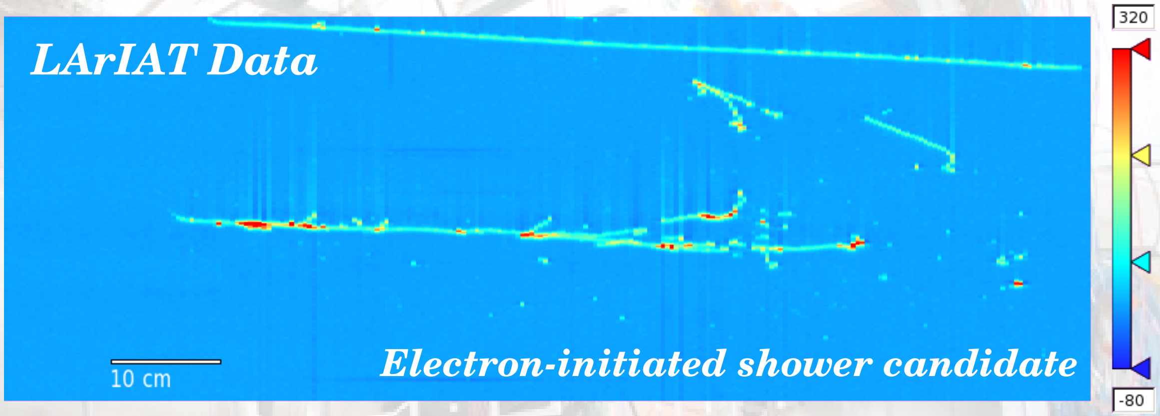
- Tune hadron – nucleus interaction models
- Relevant to proton decay searches in DUNE ($p \rightarrow K^+ \bar{\nu}$)

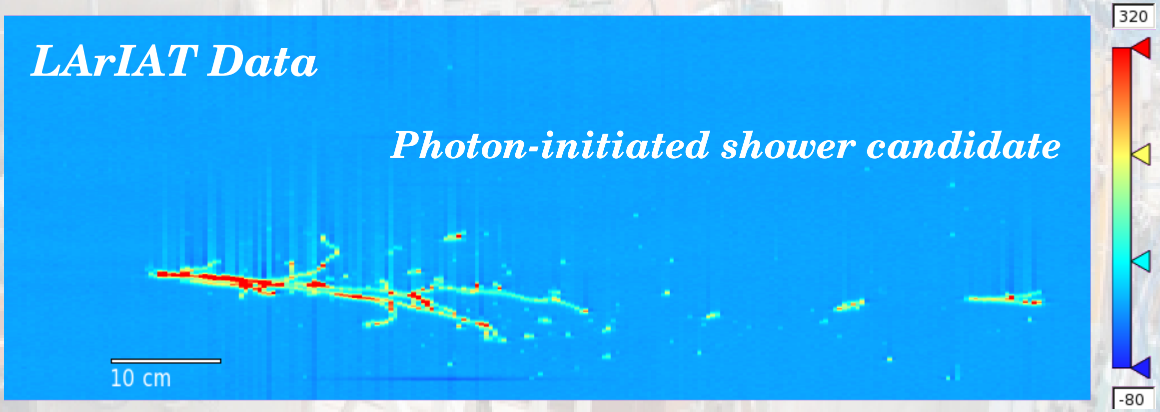
Not only cross-section!

- Study of $K^{+/-}$ reconstruction in LArTPC
- Understand K/π and K/p discrimination

e/γ discrimination

- First few cm are used to separate electron-initiated 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!

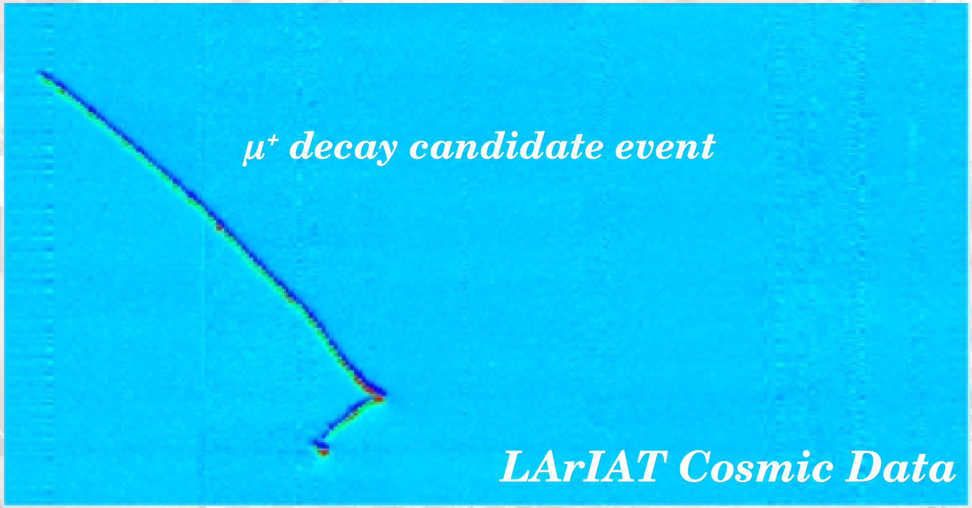
To support measurement of the low-energy e-like excess from MiniBooNE (primary goal of MicroBooNE), and for DUNE separation of ν_e CC signal from NC π^0 background

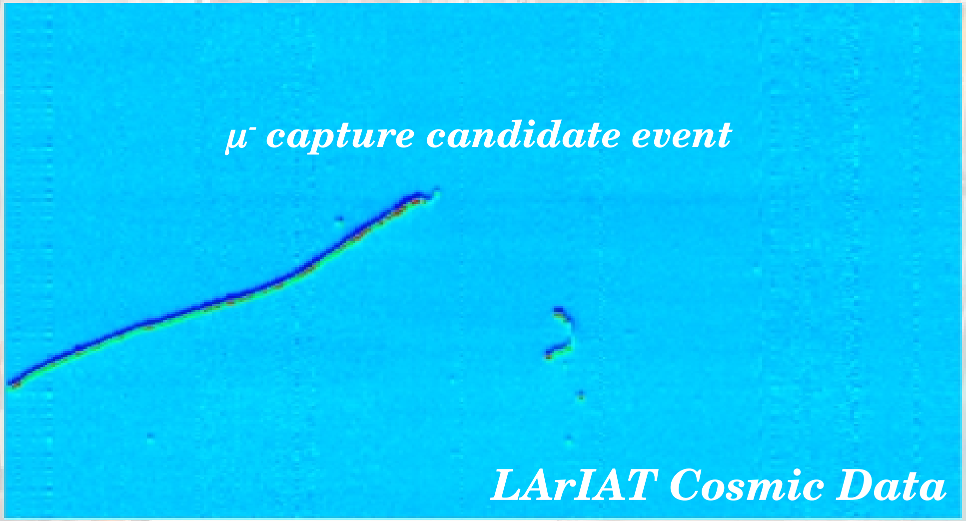
Sign determination without magnetic field

- μ^- undergo both capture on nuclei (76%) and decay (24%)
- μ^+ undergo decay (100%)
- Topological differences can allow for sign determination in absence of magnetic field on a statistical basis

Important for future ν experiments!

To develop techniques for $\nu_\mu/\bar{\nu}_\mu$ discrimination in non-magnetized LArTPC



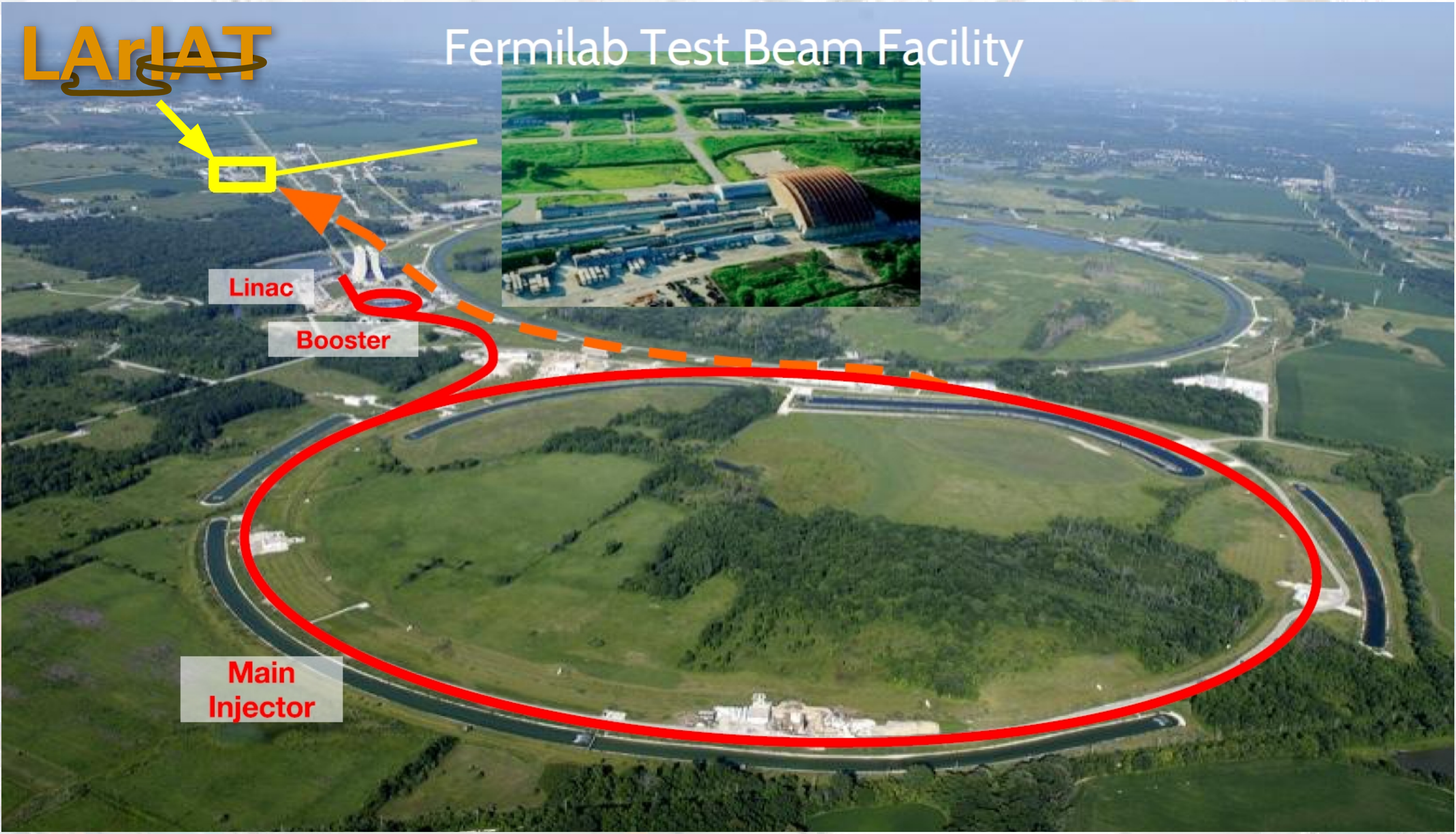


From goals declaration....

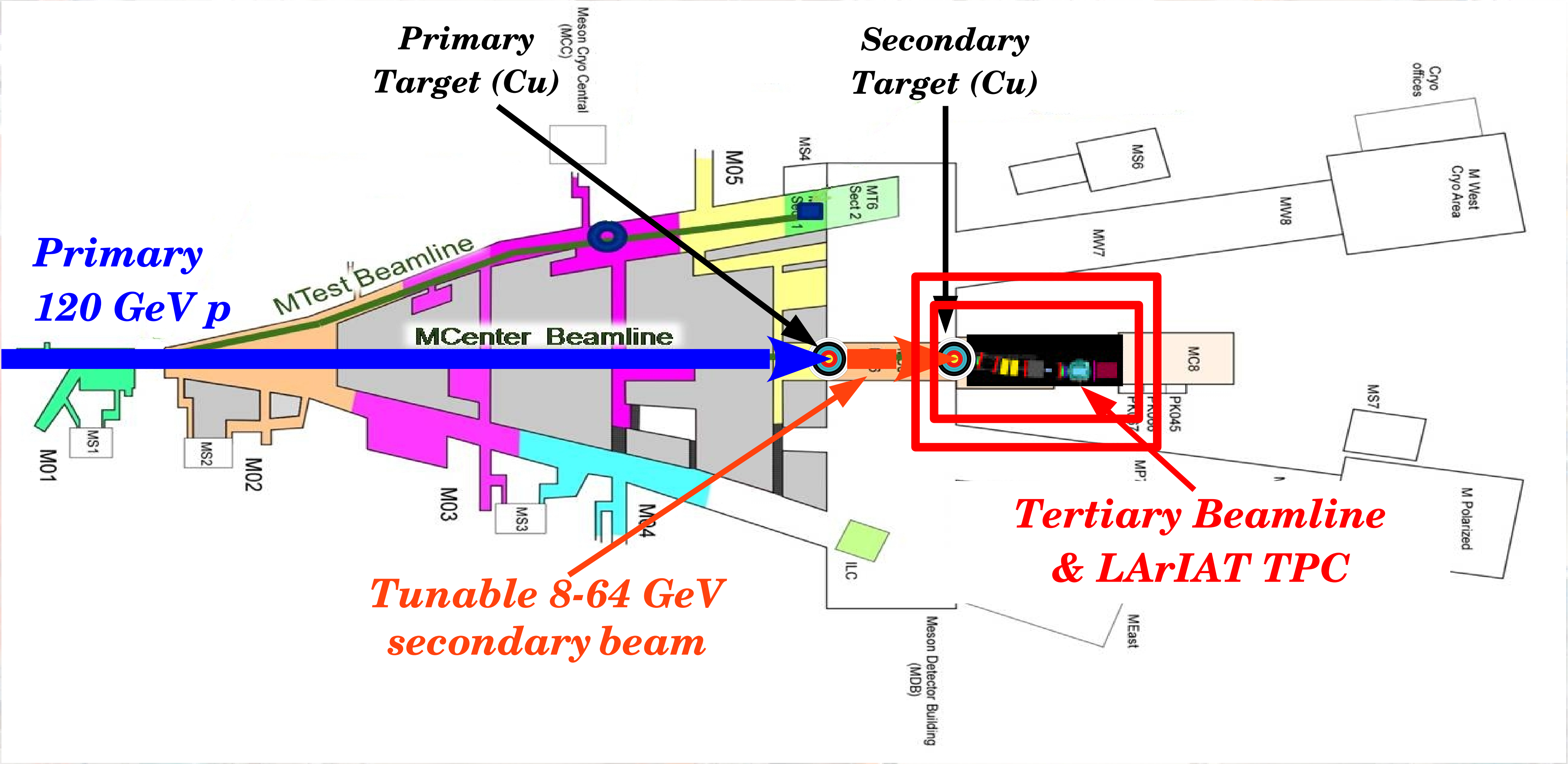
...to goals realization:

a closer look at the experiment

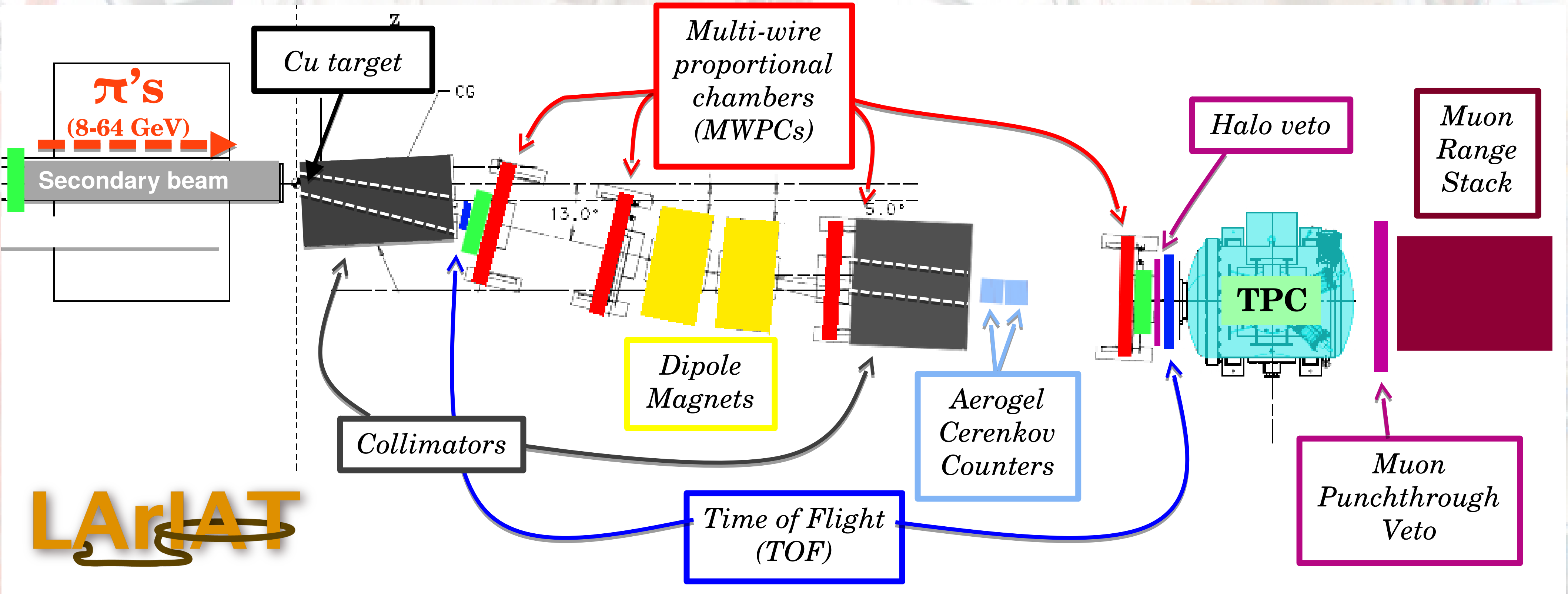
Sweet home FTBF



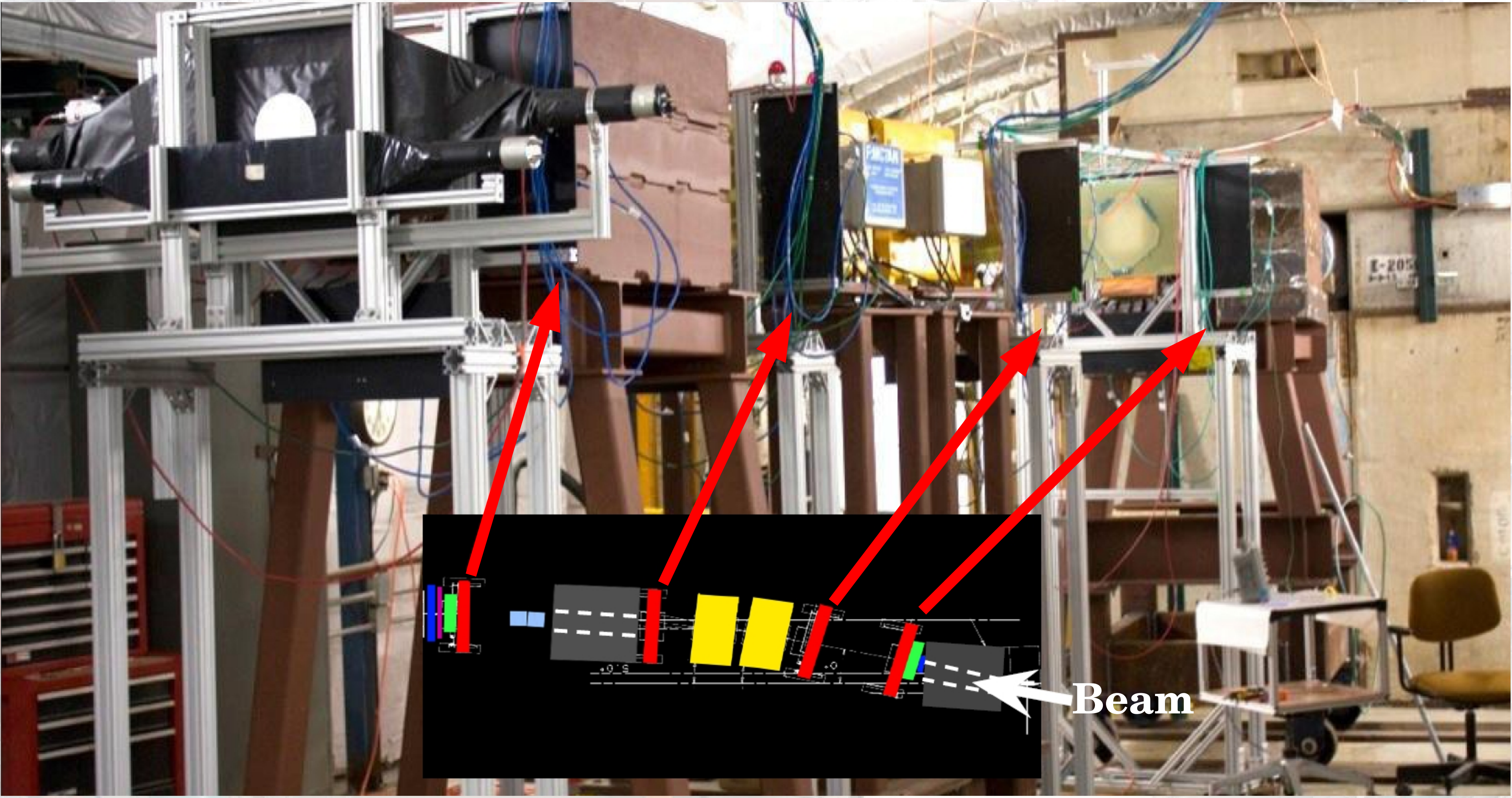
Bird's eye view of LArIAT beamline



Zoom-in on the tertiary beamline



Multi-Wire Proportional Chambers (MWPCs)



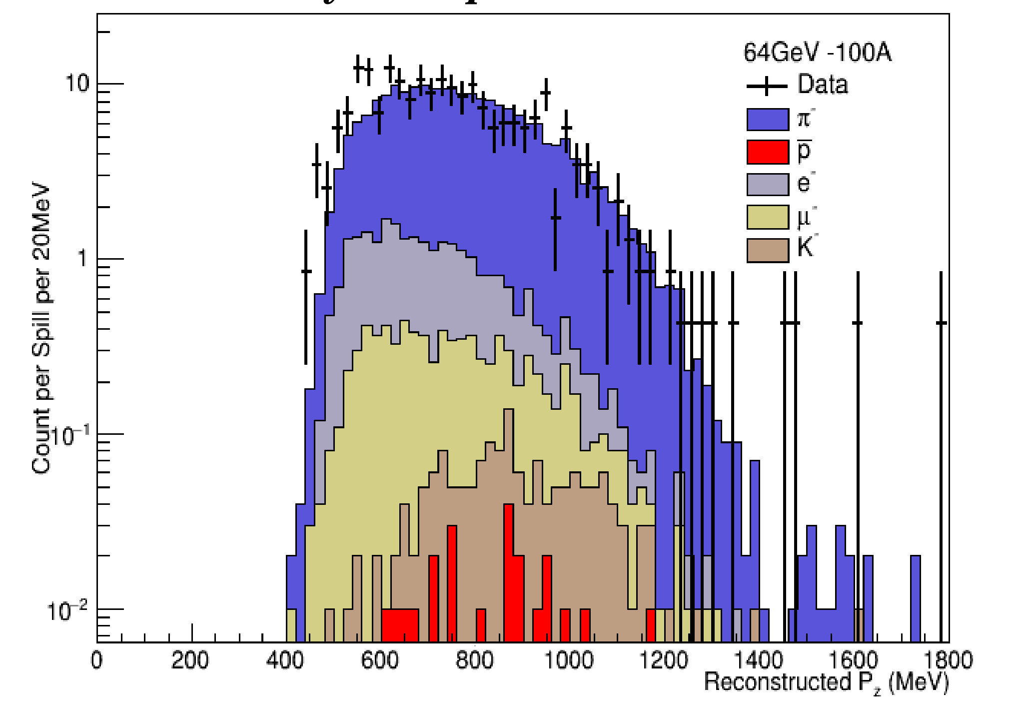
Multi-Wire Proportional Chambers

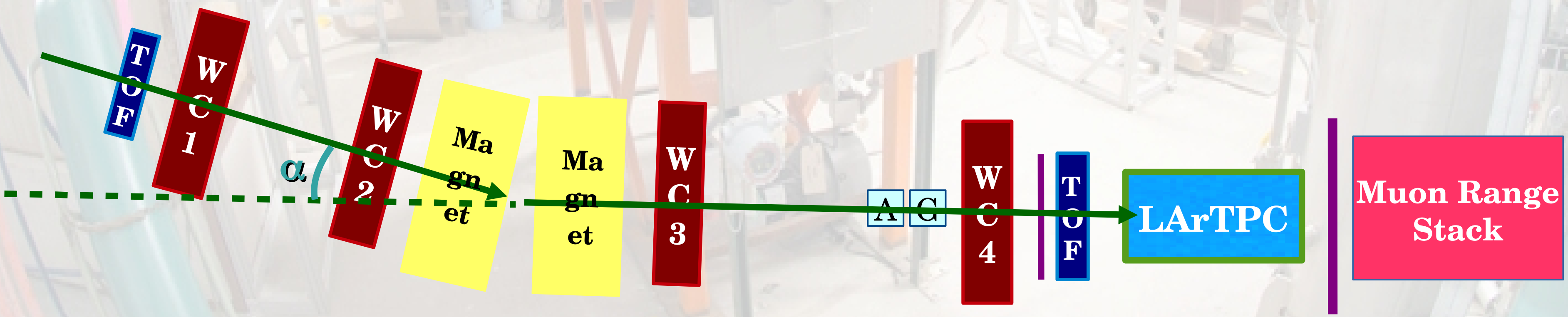
MWPCs + bending magnets allow to reconstruct particles momentum before entering the LArTPC

- ✔ 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

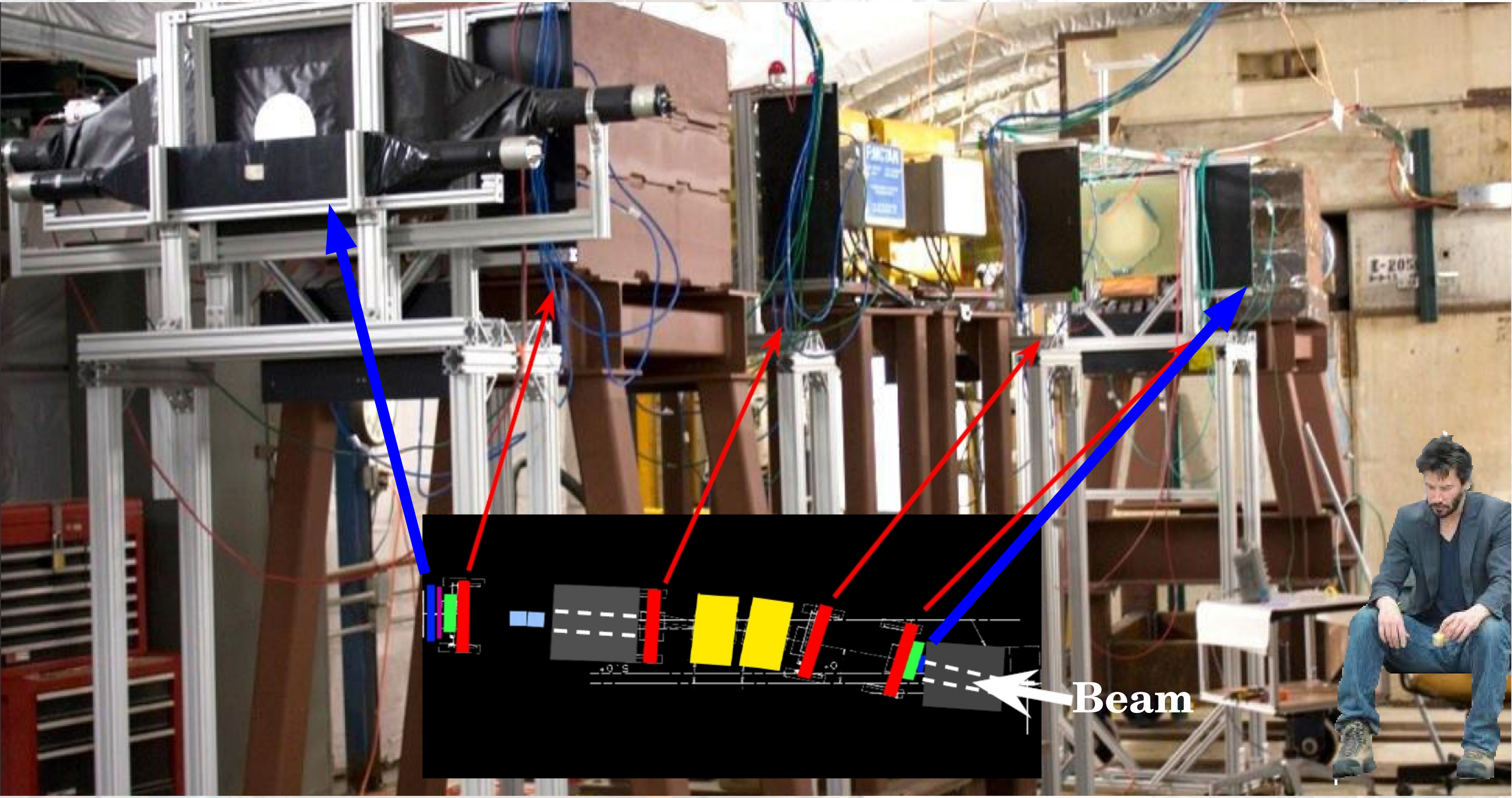
200-1400 MeV/c charged particle beam momentum range

Tertiary beam particles momentum





Time Of Flight (TOF)

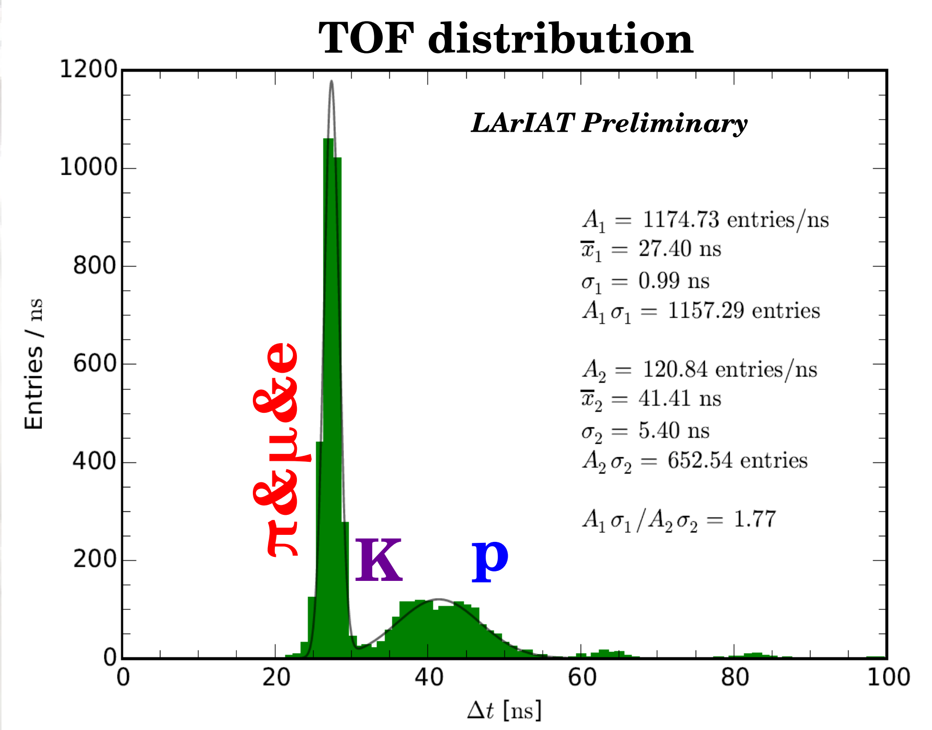


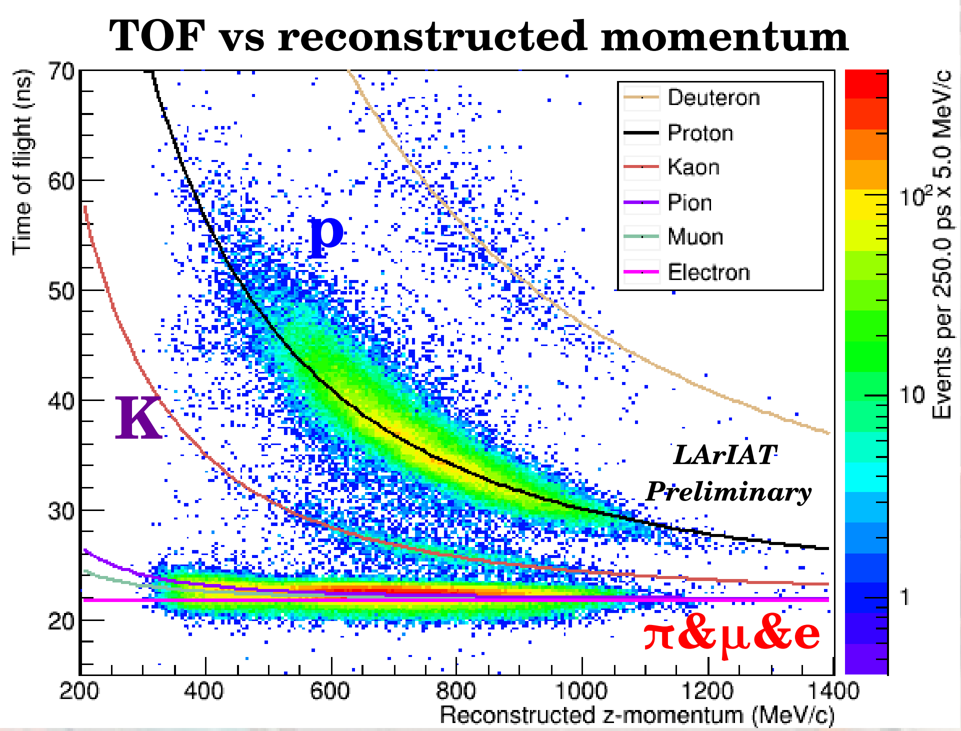
Credit: E. Gramellini

Time Of Flight (TOF)

✔ 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

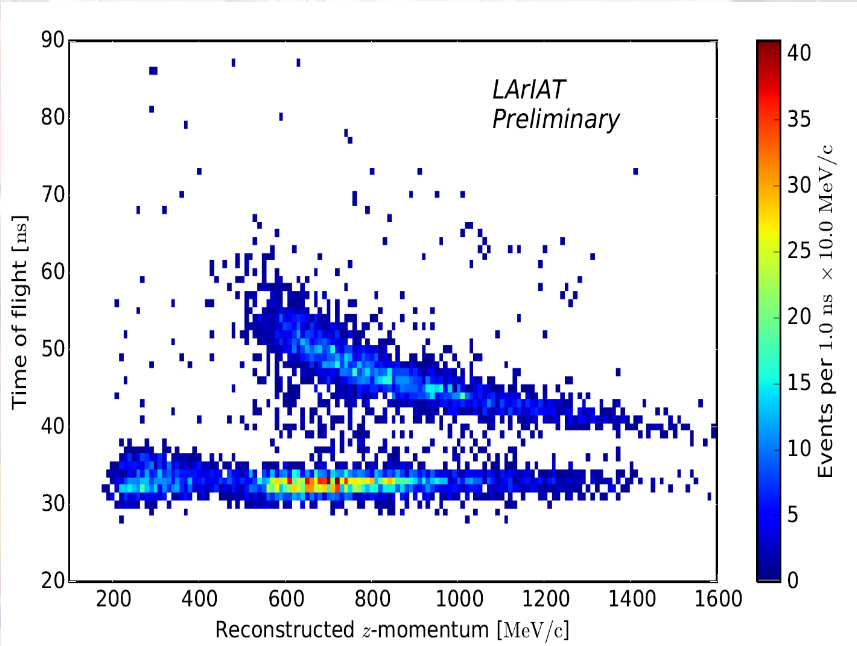




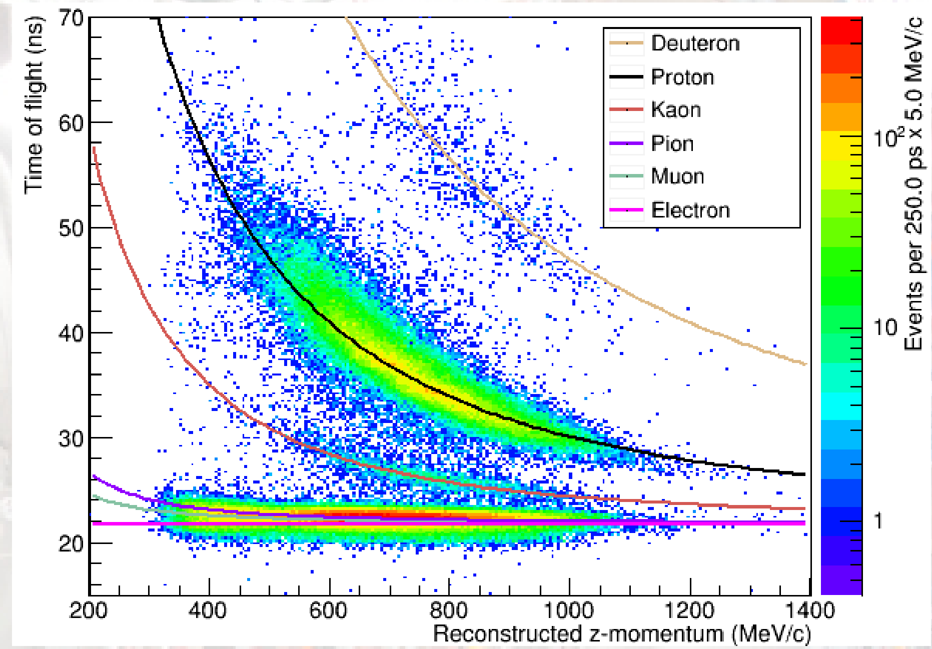
Particle ID and momentum known before it enters the LarTPC!

Improving TOF and particle ID

Last April W&C plot



Today plot

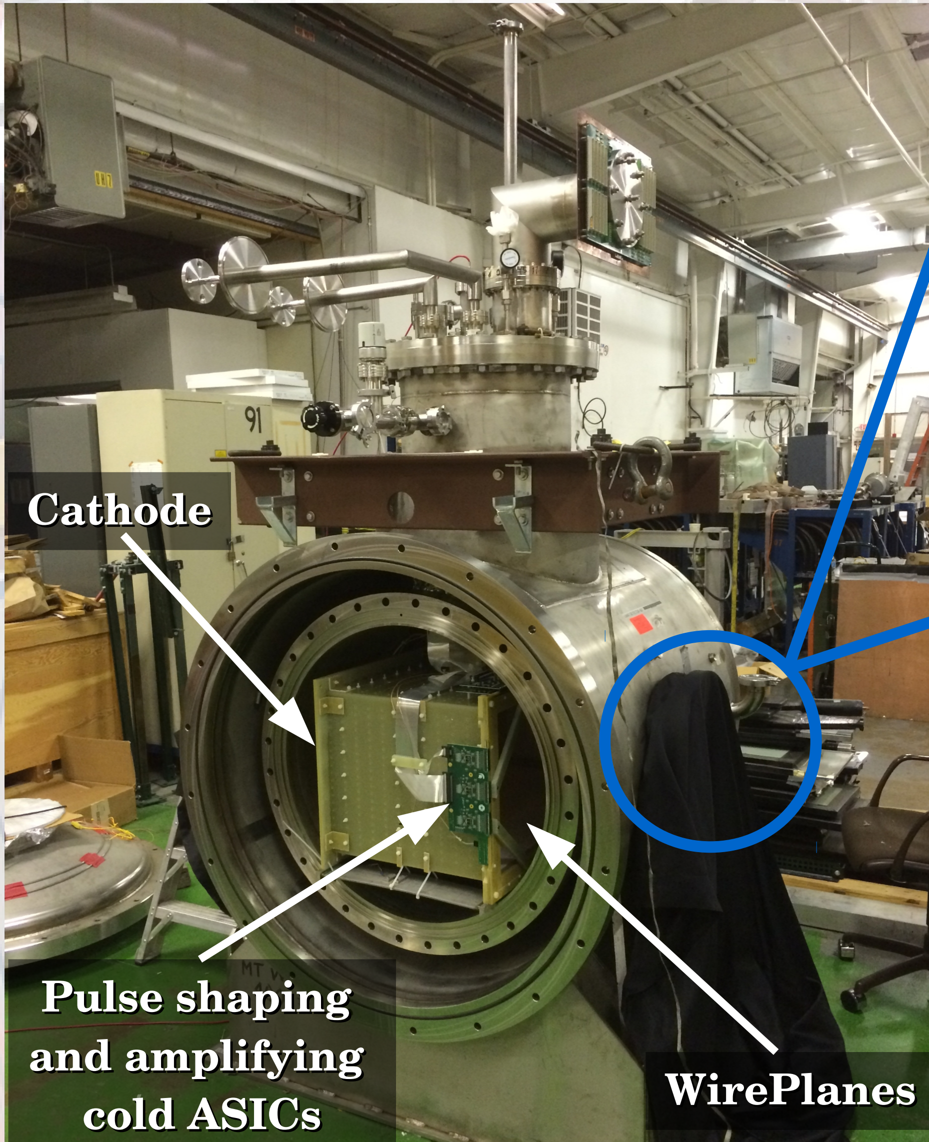


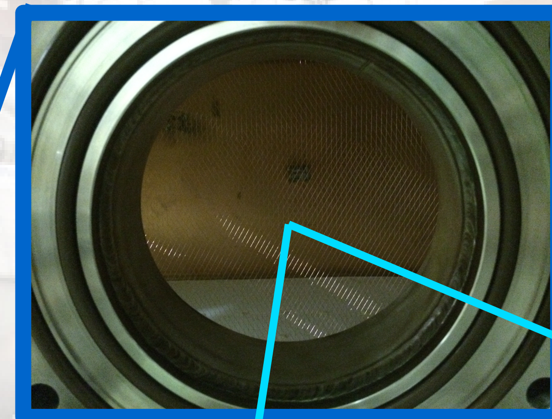
✔ DAQ samples scintillating counters waveform at 1 ns, not enough for our purposes

✔ Work done on hit time determination and hit matching between the two scintillators allowed us to improve the TOF resolution to less than one ns

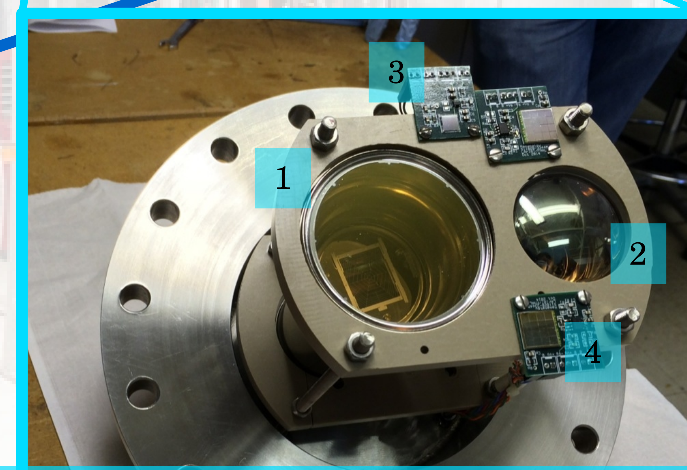
✔ The development of a new pulse fitting algorithm is currently underway, to bring our resolution down to the order of few hundreds of ps

Inside the cryostat: TPC and light collection system



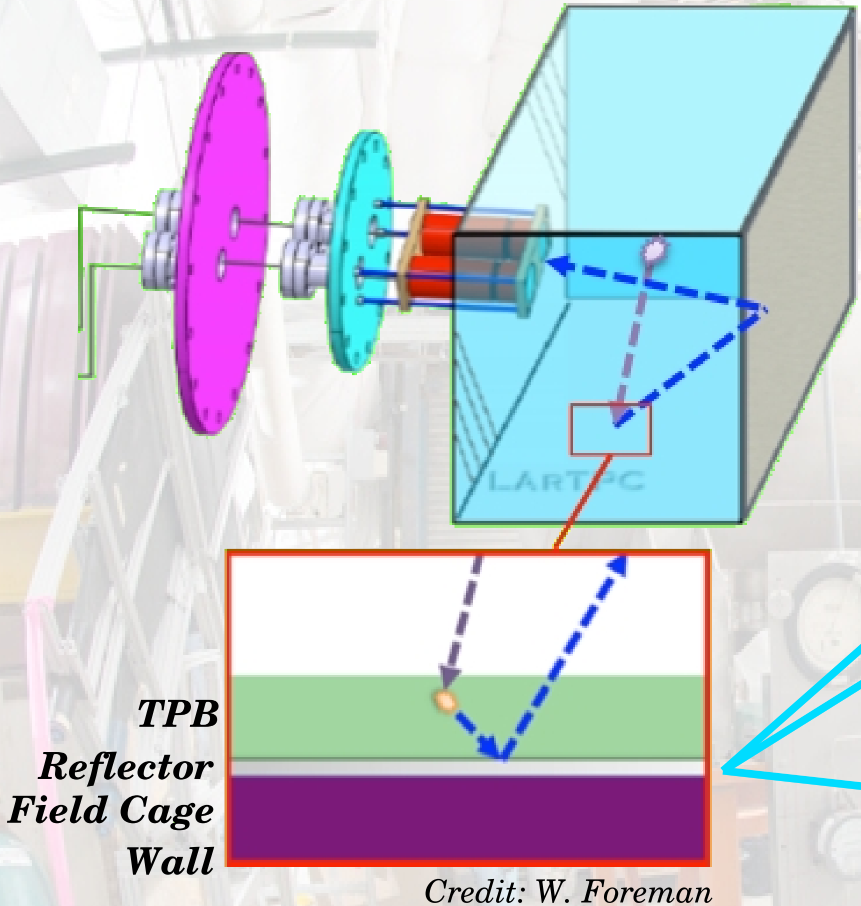


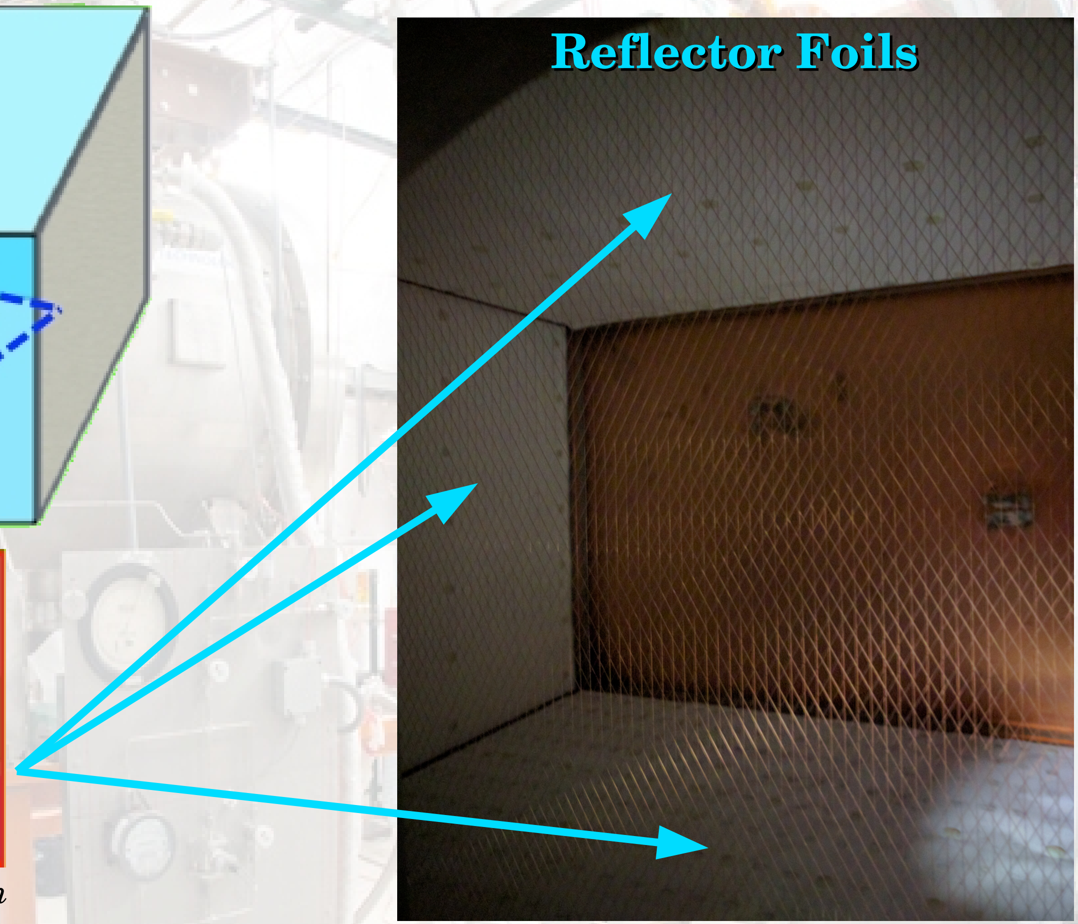
Light Collection System port



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)
SiPM: Hmm. VUV-sensitive (Run II)!

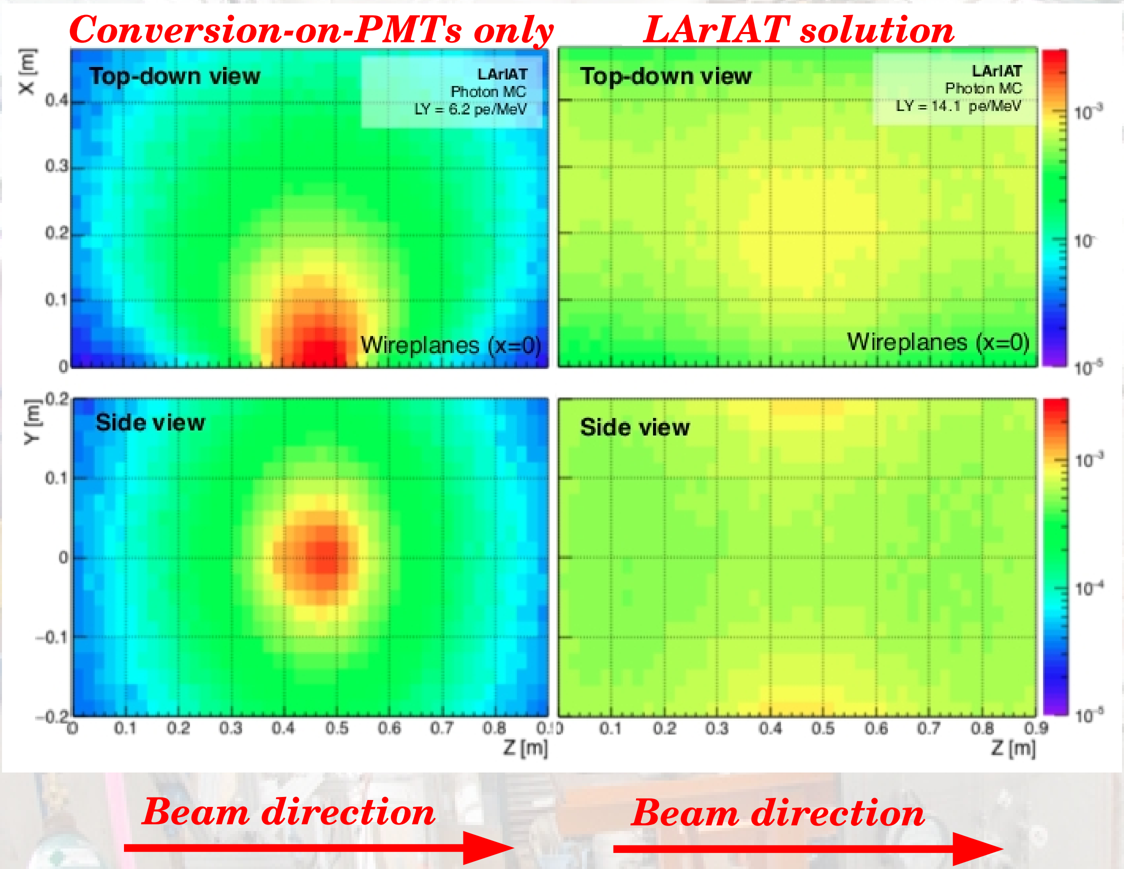
Light Collection System

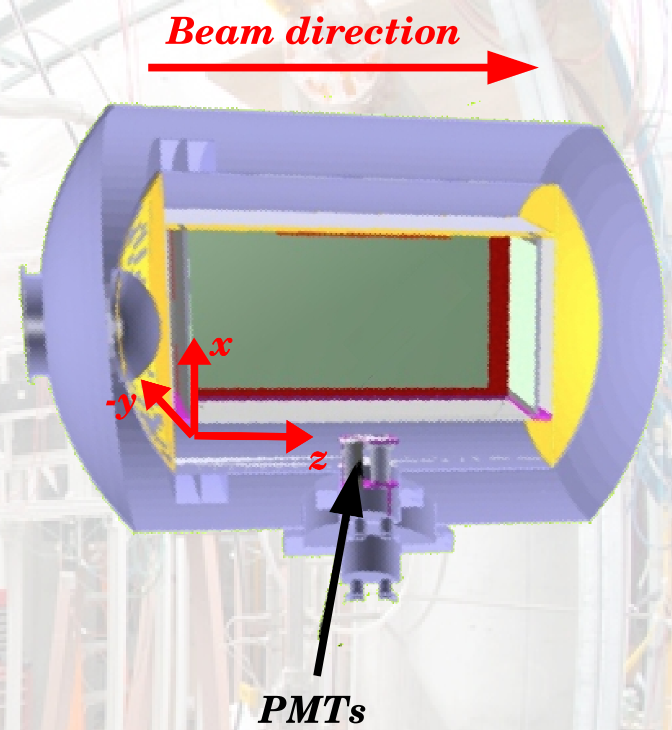




- ✔ Wavelength shifting (evaporated) reflected foils on the four field cage walls to shift scintillation light into visible spectrum
- ✔ Technique borrowed from dark matter experiments

Light Collection System



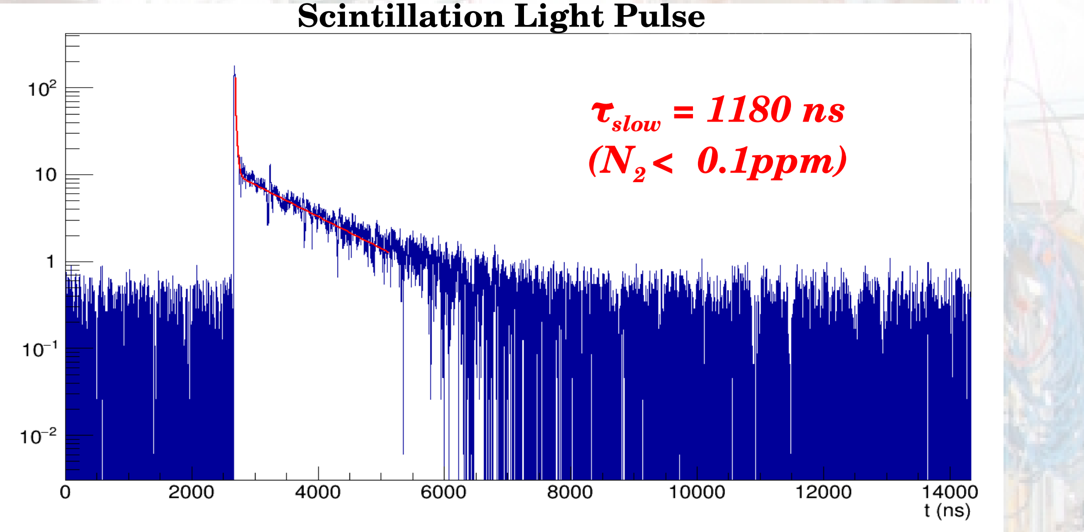


✔ Provides higher (~ 40 pe/MeV at zero field) and more uniform light yield respect to standard conversion-on-PMTs-only light collection systems for neutrino experiments

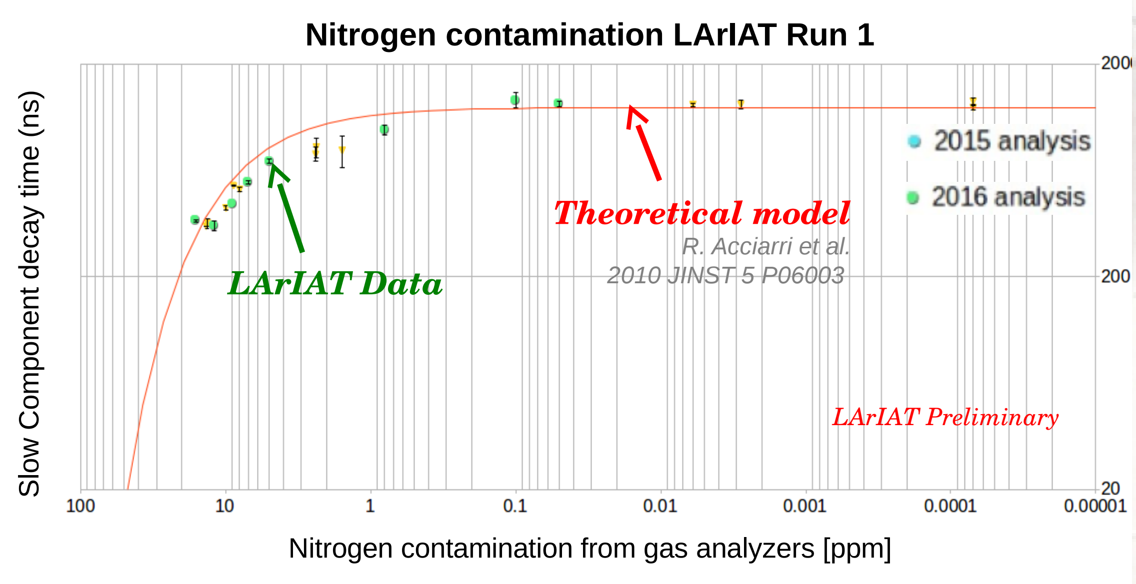
✔ R&D for future neutrino experiments (like SBND) as a way to improve calorimetry and triggering

Measurements with light: N_2 contamination

- N_2 contamination in LAr suppresses scintillation light already for $[N_2]$ as low as few ppm



- N_2 affects mostly the "slow" component of LAr scintillation light (τ=1500 ns), leaving unaffected the "fast" component (τ=7 ns)

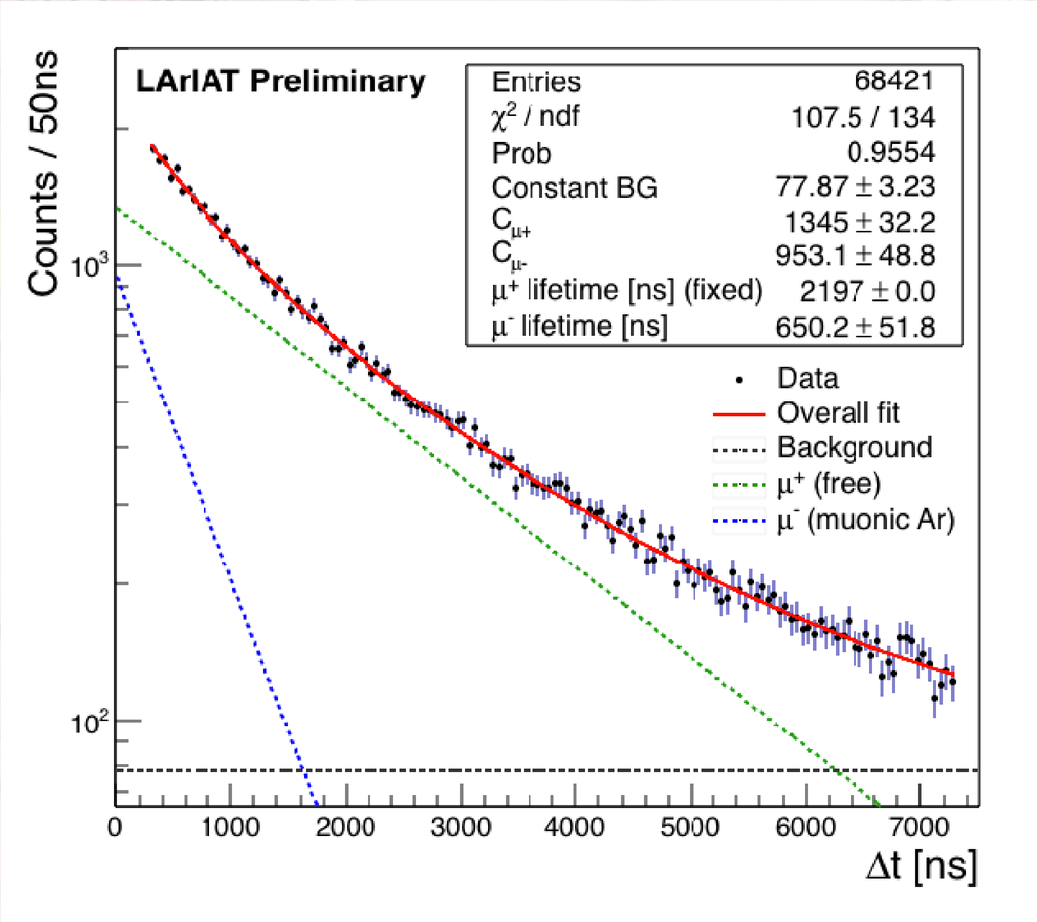


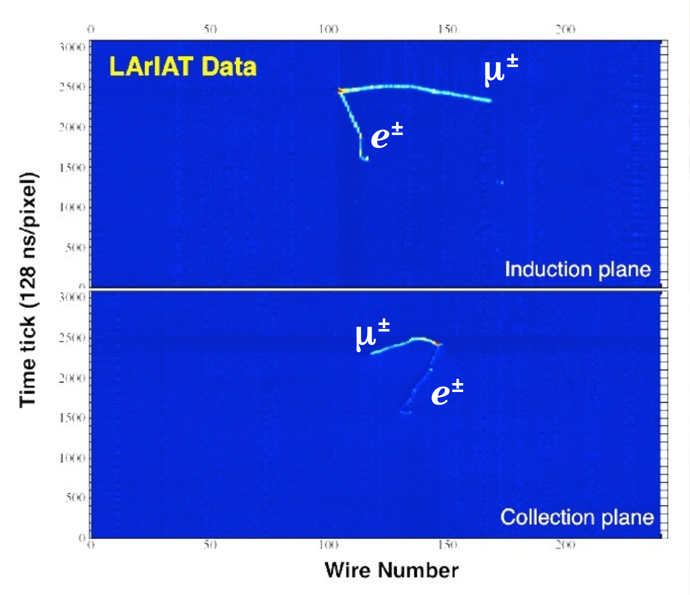
- From a fit of the scintillation light pulse the "slow" light time component can be extracted and the [N2] determined

- Results agree with trend from model

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

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

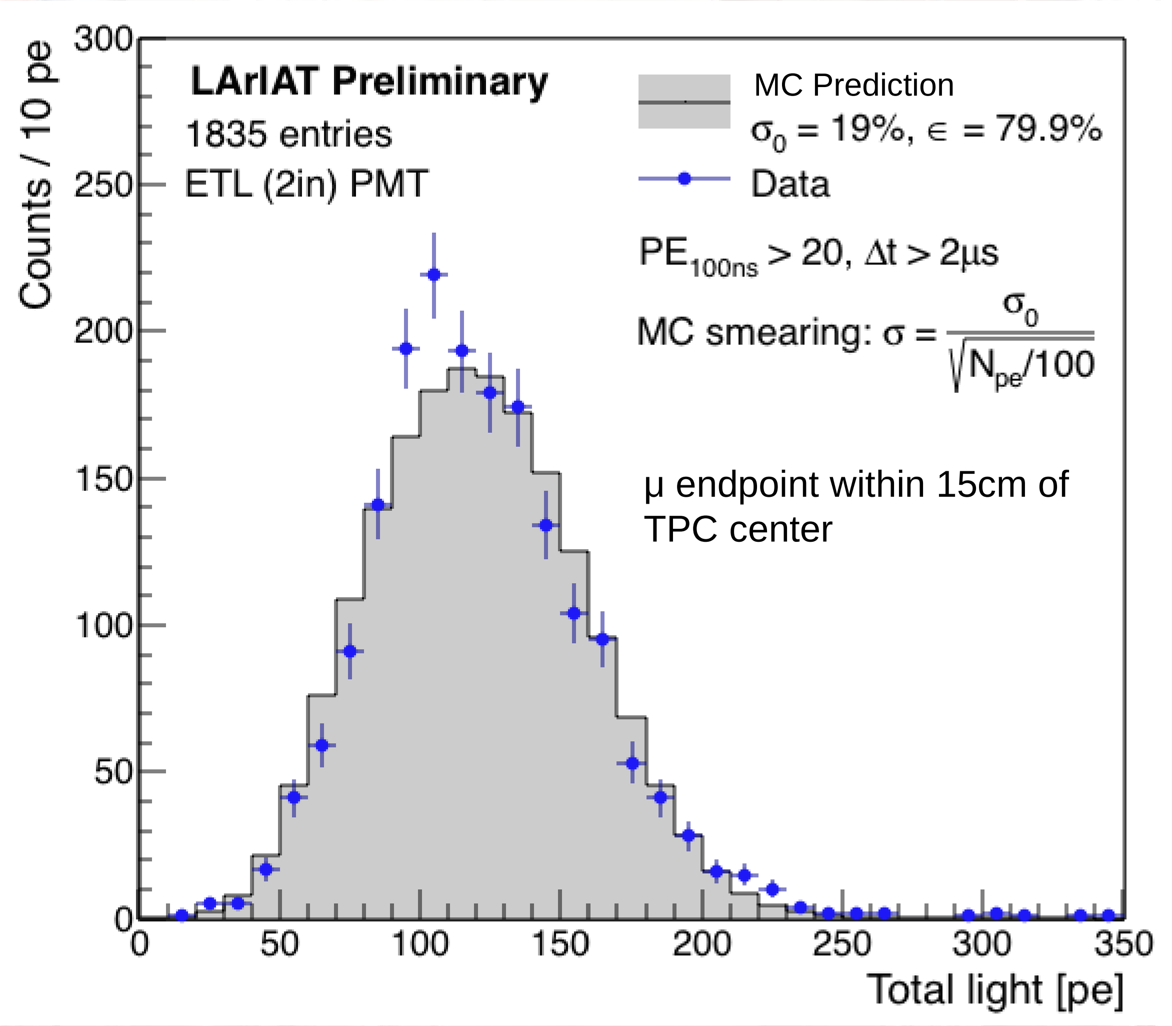
T_{free} = 2197 ns (fixed)

$\tau_{capture}$ = 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)

Measurements with light: Michel electrons



- Michel-candidate signals integrated to get PhotoElectron spectrum from ETL 2" PMT
- PE spectrum compared to toy light propagation MC (point-like events)
- Smearing resolution σ_0 and PMT collection efficiency factor ε tuned to match data via χ^2 minimization

✔ ***Data and MC in approximate agreement***

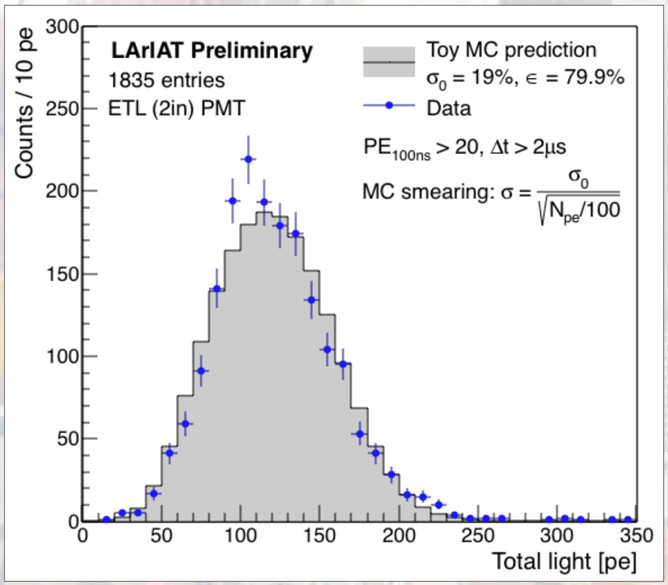
✔ ***Gives confidence in MC predicted Light Yield (2.4 pe/MeV for 2" PMT in Run 1)***

✔ ***Working to adopt a more realistic simulation***

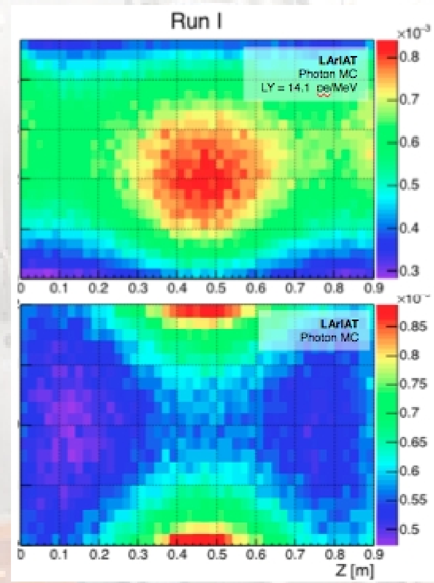
Measurements with light: Michel electrons

Next step: from light (γ) to energy (MeV)

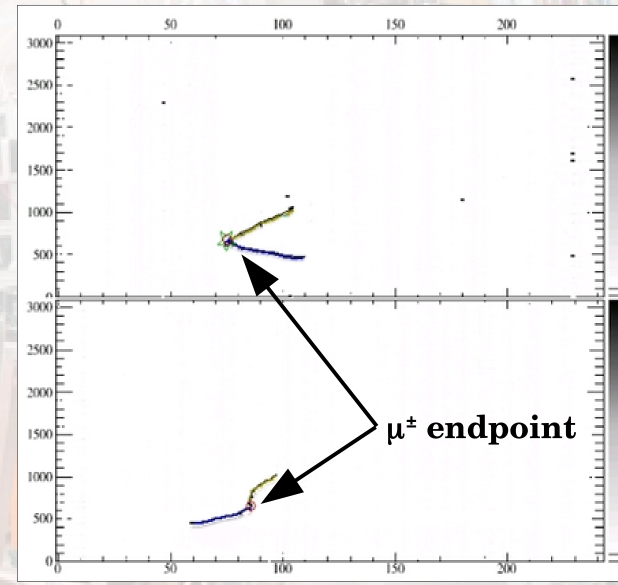
Raw PE spectrum



MC photon visibility and Light Yield

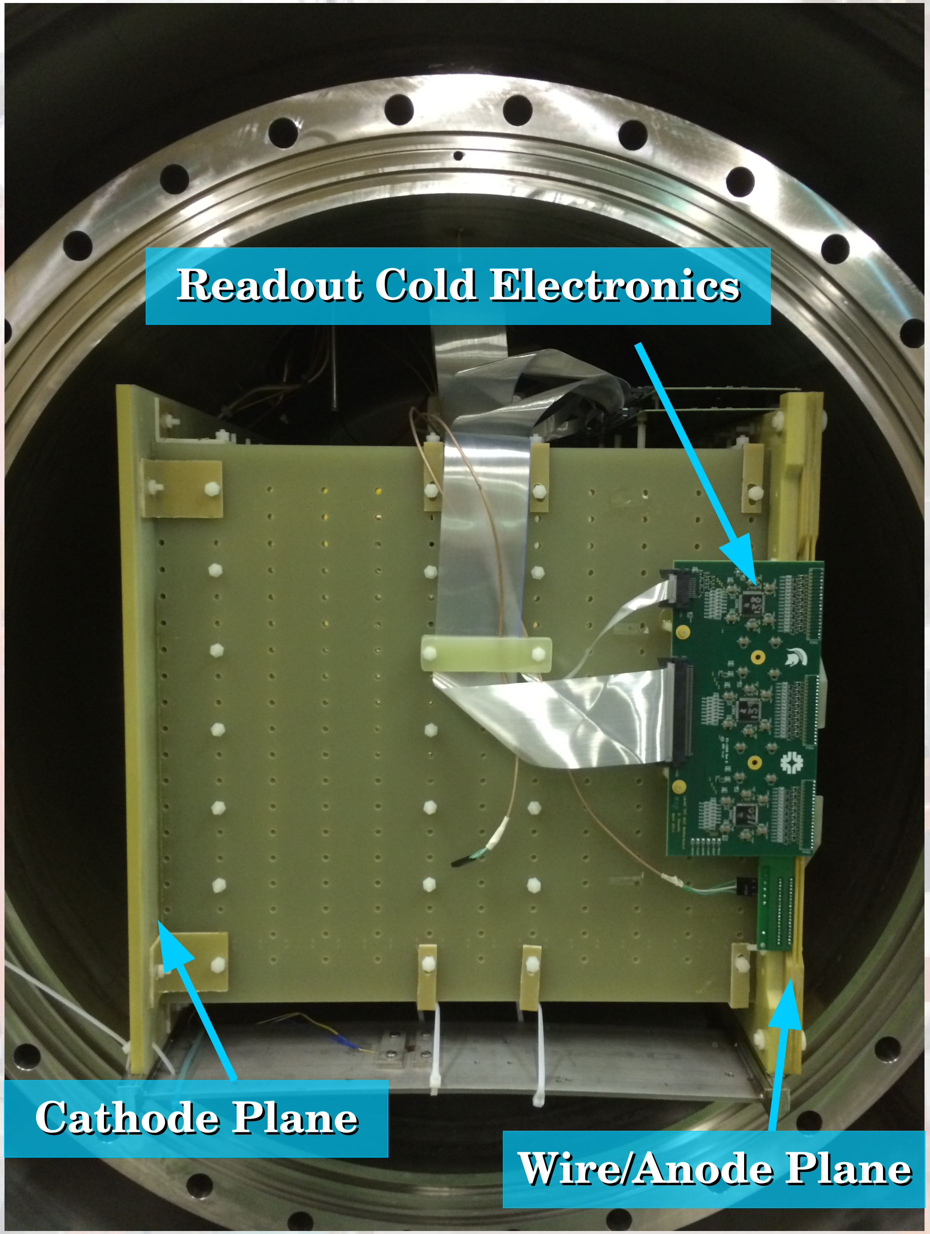


Reconstructed $e^{\pm}$ position

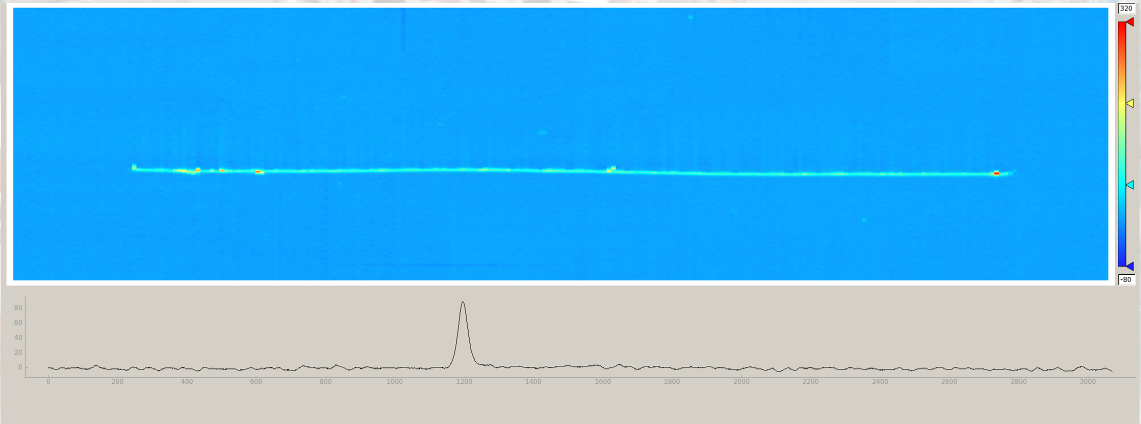


3D track/shower reconstruction actively under development

LArTPC

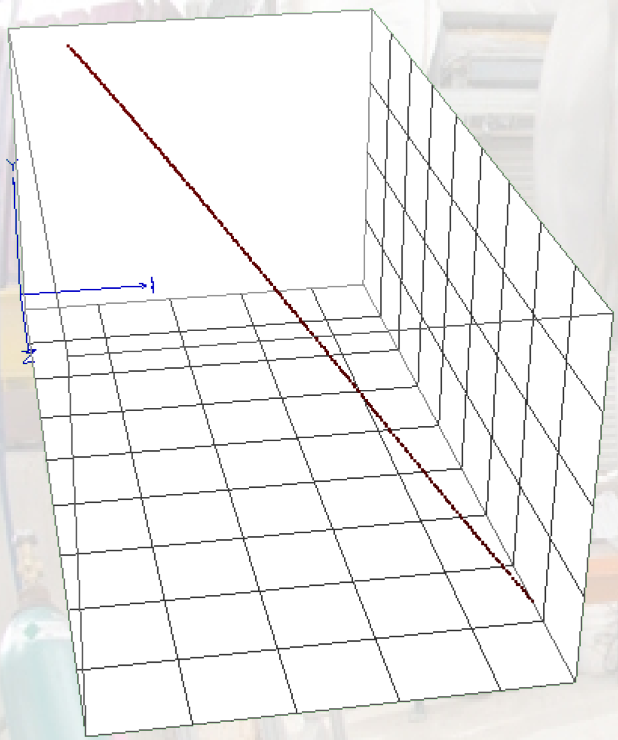


- **Refurbished ArgoNeuT TPC**
  - ✔ 2 Readout planes
  - ✔ 240 wires/plane, ±60° respect to beam, 4 mm pitch
  - ✔ 500 V/cm nominal drift field
- **Cold Electronics: MicroBooNE preamplifying ASICs on custom motherboards**
  - ✔ Signal to Noise ratio (MIP pulse height compared to pedestal RMS)
    - **Run 1** ~50:1 (ArgoNeuT warm electronics ~15:1)
    - **Run 2** ~70:1



April 30th, 2015: LArIAT is on!

Cosmic Ray Paddles

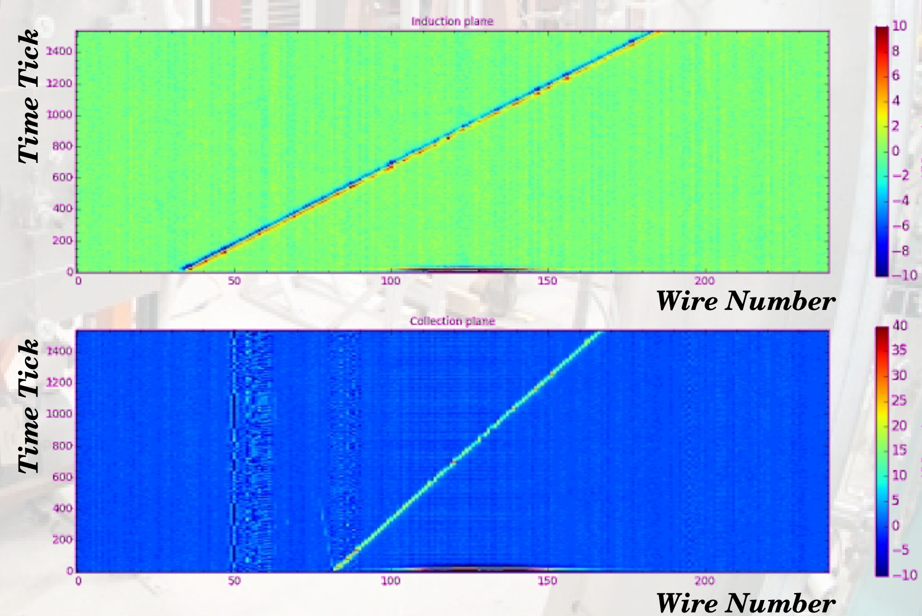


Cosmic Ray Paddles

April 30th, 2015

- LArIAT cryostat is purged, cooled down and filled. Cathode HV is ramped up and we start data taking in that same day

- The first event was recorded a few minutes after turning on the system with a set of scintillating paddles (Cosmic Ray Paddles) triggering on cosmic muons crossing the TPC along its diagonal



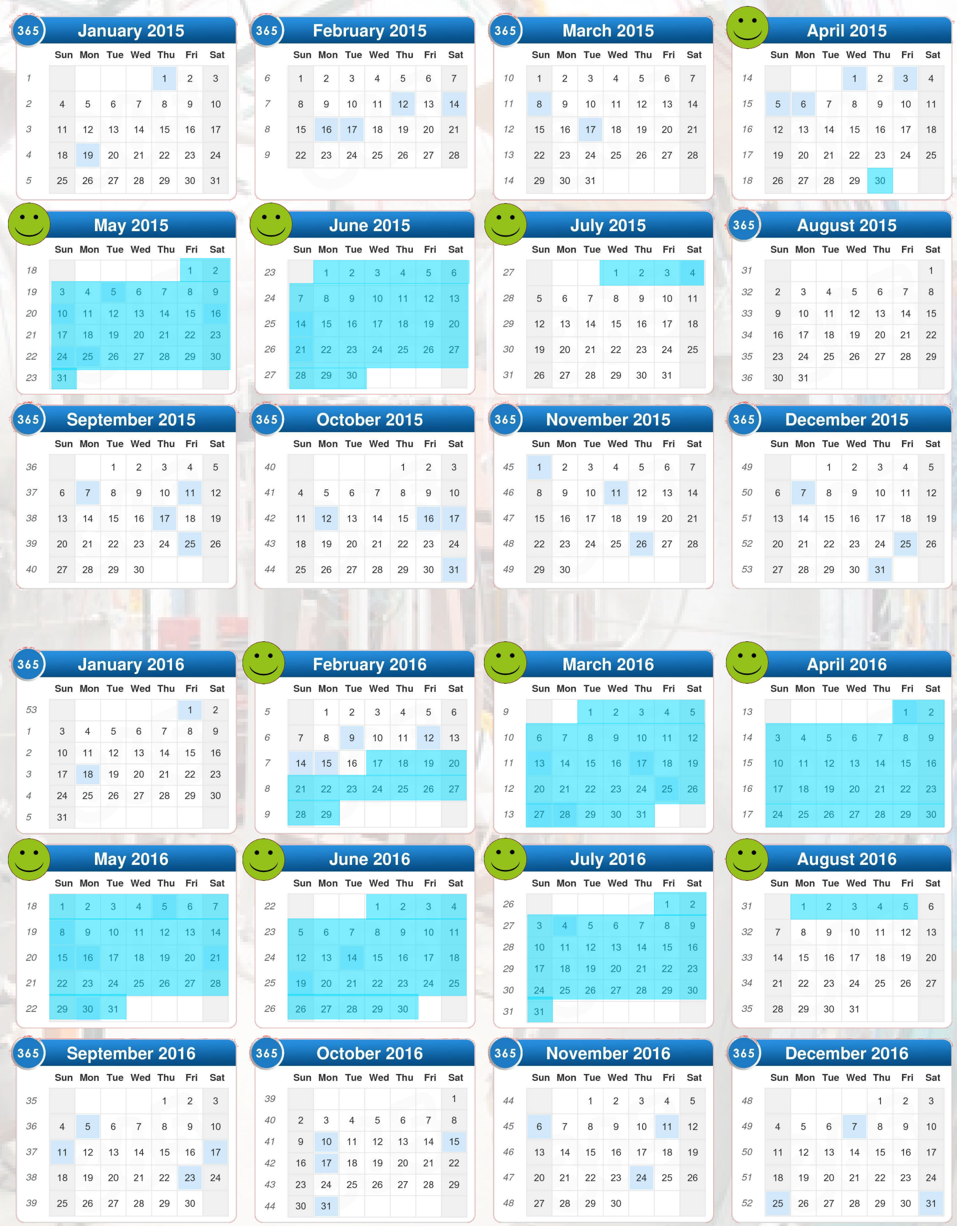
LArIAT runs

Run 1

- ~9 weeks of beam data
- ~5.5 weeks at high energy tune (both positive and negative polarity)
- ~3.5 weeks at low energy energy tune (both positive and negative polarity)

Run 2

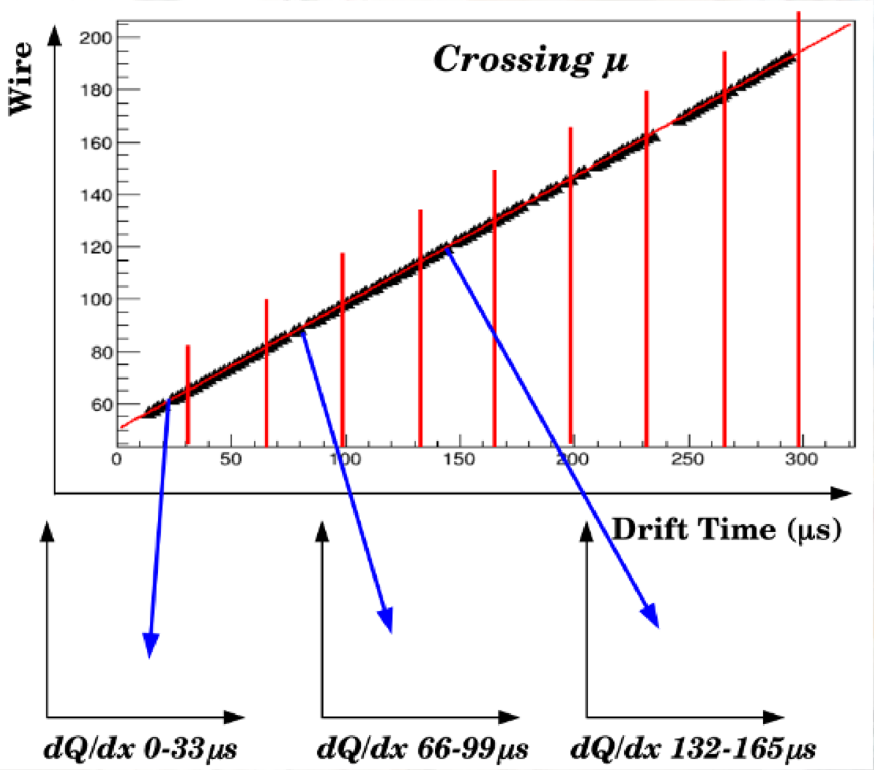
- ~24 weeks of beam data
- ~11 weeks at high energy energy tune (both positive and negative polarity)
- ~8 weeks at low energy tune (both positive and negative polarity)
- ~3 weeks at very low energy tune (negative polarity, e^- collection)
- ~2 weeks rest (a.k.a filter regeneration)



On the path to physics analyses:

Purity measurement

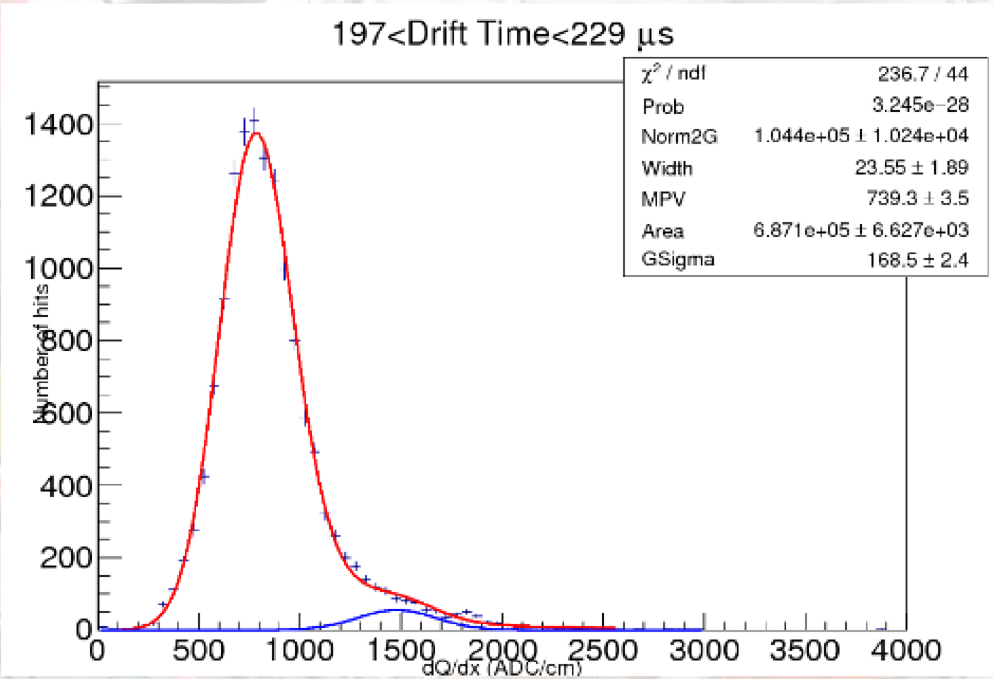
- Electronegative contaminants in the liquid argon (O_2, H_2O) quench the charge produced by interacting particles
- Amount of charge per unit length (dQ/dx) collected at wire planes depends on distance it drifted
- For a given charge deposited in the LAr, the amount of charge collected at the wire planes will exhibit an exponential decay trend as a function of drift time

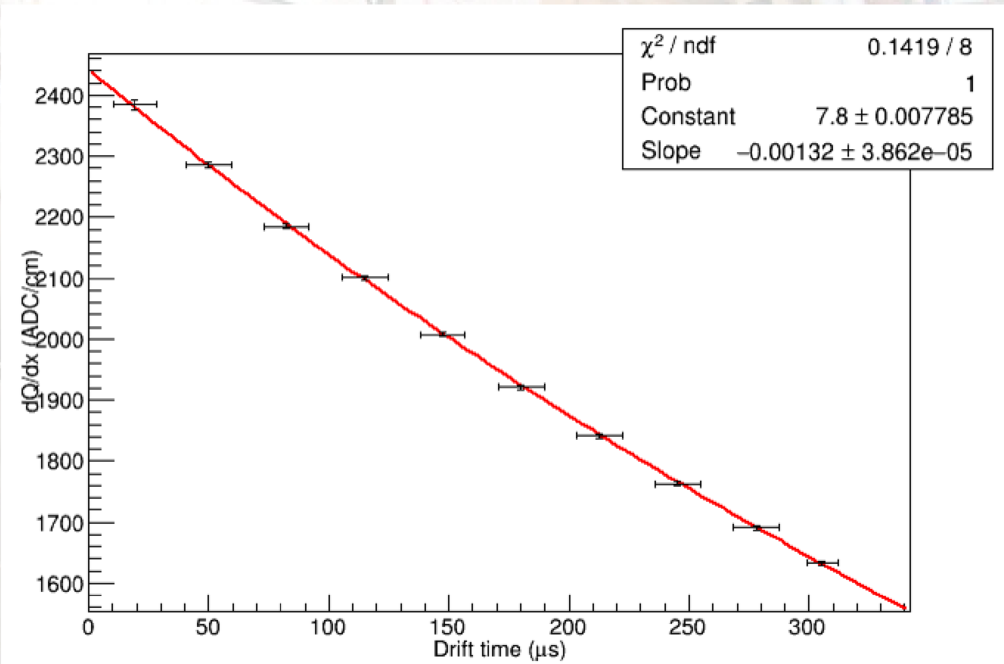


Cosmic muons triggered by the Cosmic Rays Paddles are *mip* particles and cross the entire drift field: they can be used to determine the decay constant of the exponential trend – the *electron lifetime*

On the path to physics analyses:

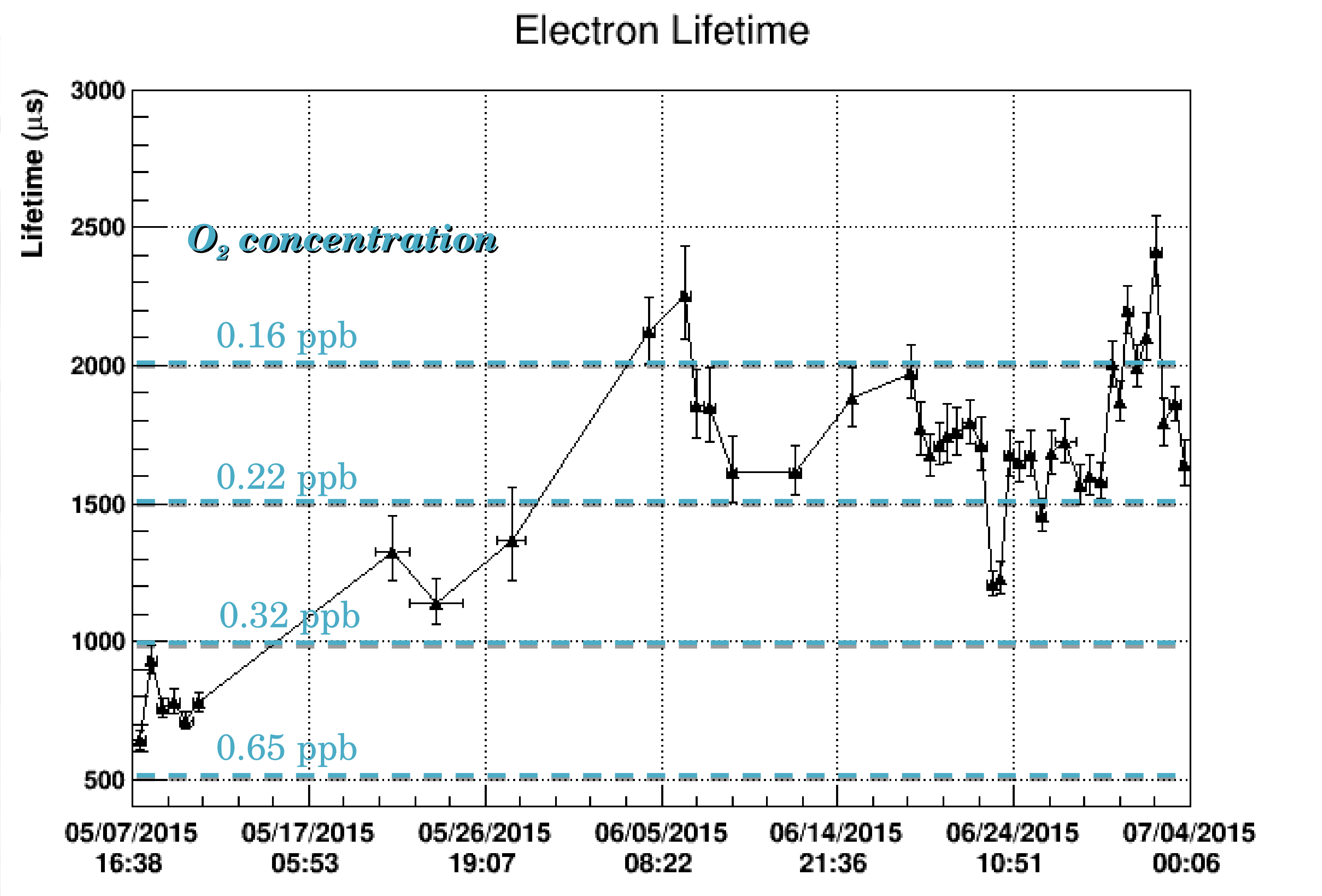
Purity measurement





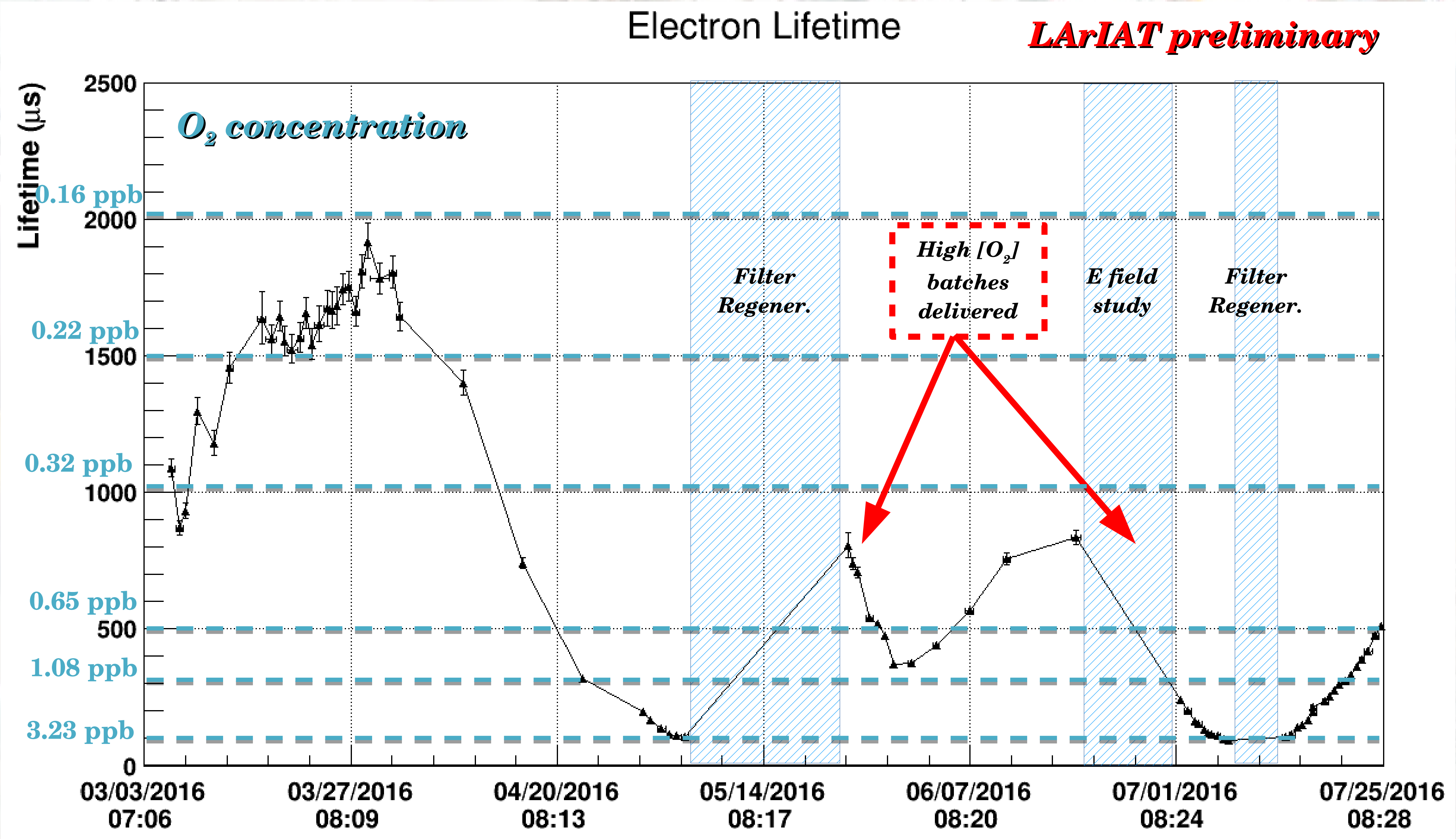
- ✔ ***Each bin in right histogram comes from result of a fit like that on left***
- ✔ ***Exponential fit to right plot gives electron lifetime***

Run 1 Lifetime



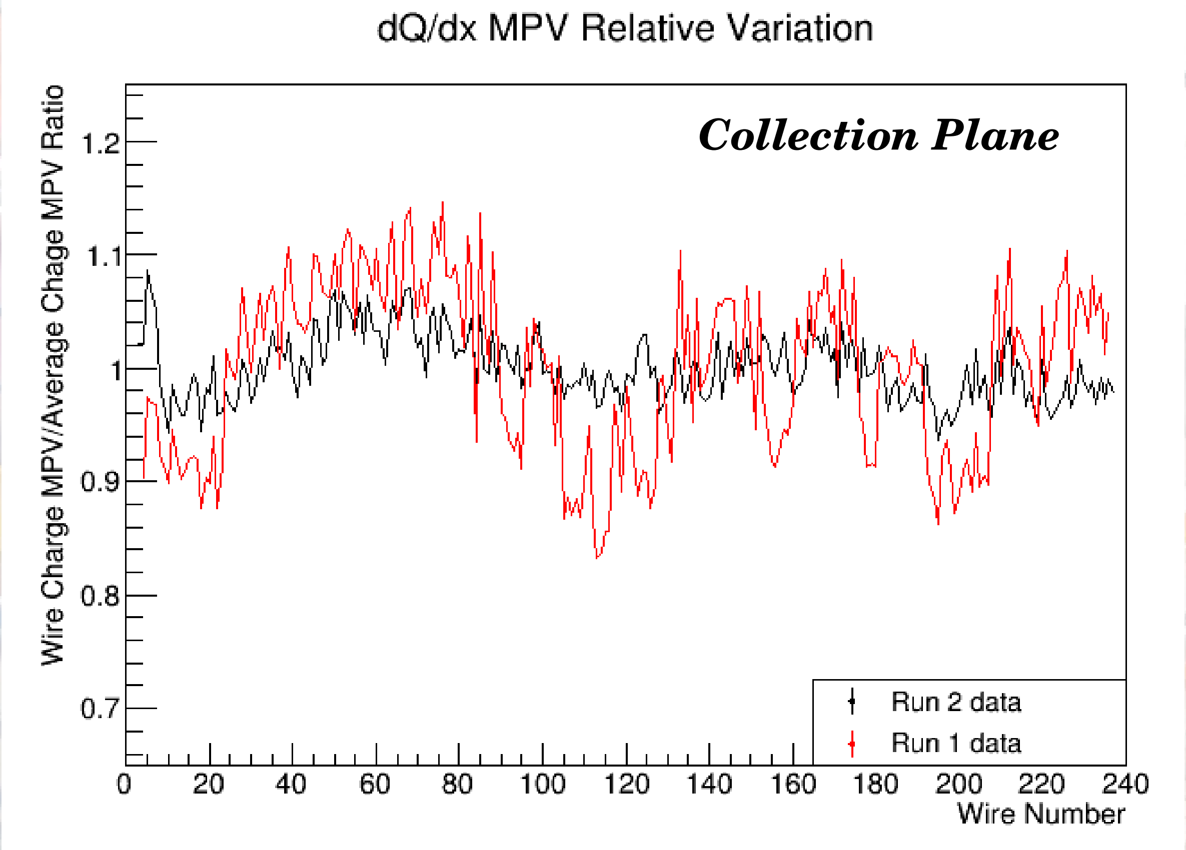
Purity achieved without LAr recirculation

Run 2 Lifetime



Daily measurement of LAr purity as monitoring tool

Wire response to collected charge



- Same cosmic muon data sample can be used to measure the response of each wire to the charge per unit length (dQ/dx) reaching the wire
- >20% variation in the collected charge from wire to wire in Run 1 (red line)
- Performed an extensive set of tests to determine the reason of such variation
- The M.P.O. (Most Probable Offender) has been identified in a 200 MHz noise generated by feedback capacitors of the warm amplifier channels

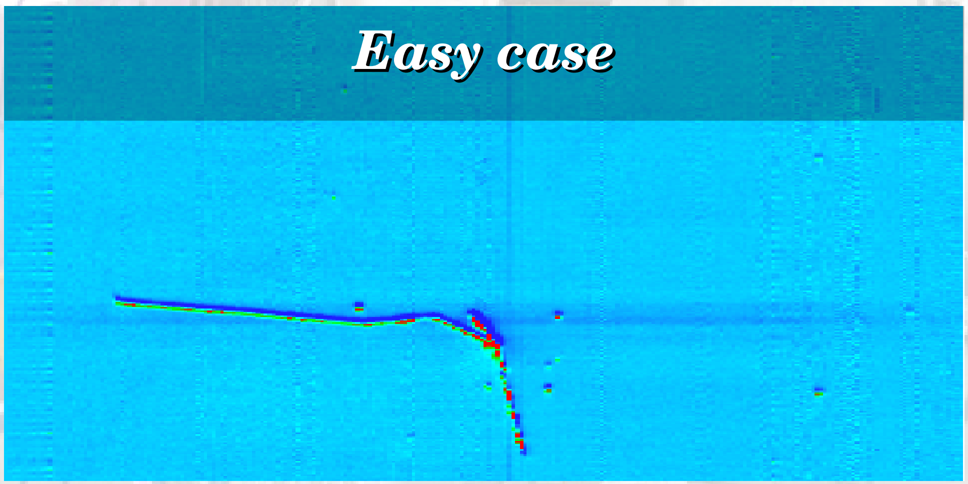
✔ ***The hardware work aimed at noise reduction performed between Run 1 and 2 allowed to lower the variation in wire response to collected charge to a few % level***

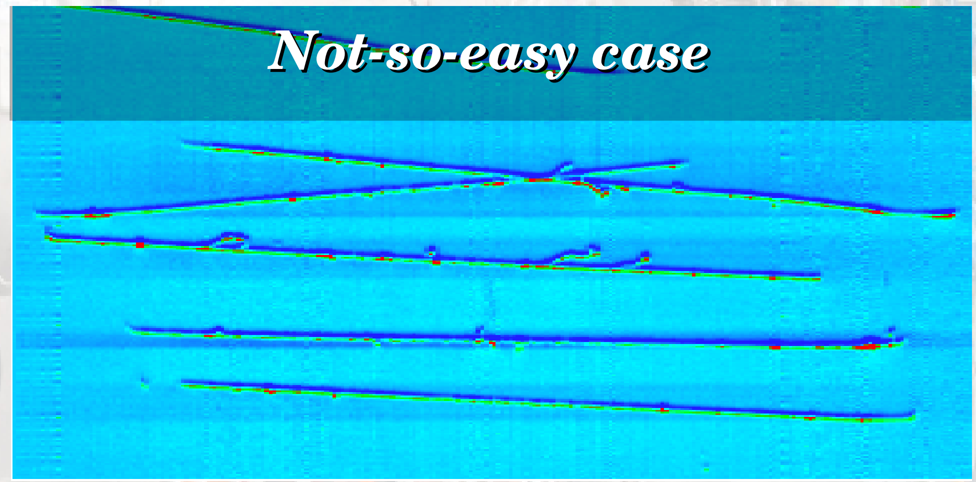
✔ ***Such variations are corrected for in the charge reconstruction independently for Run 1 and 2***

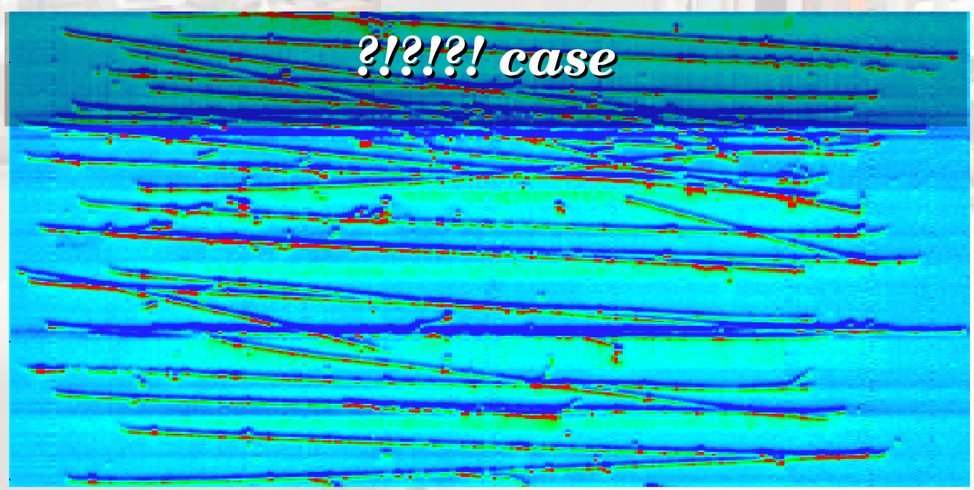
On the path to physics analyses:

Wire Chambers – TPC tracks matching

Which track is associated with the beamline particle?

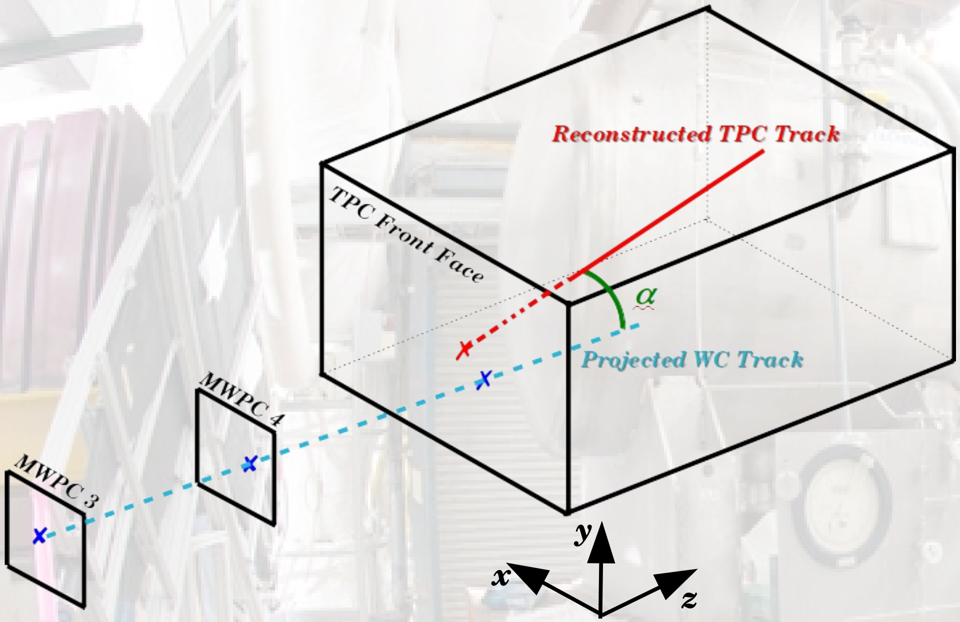


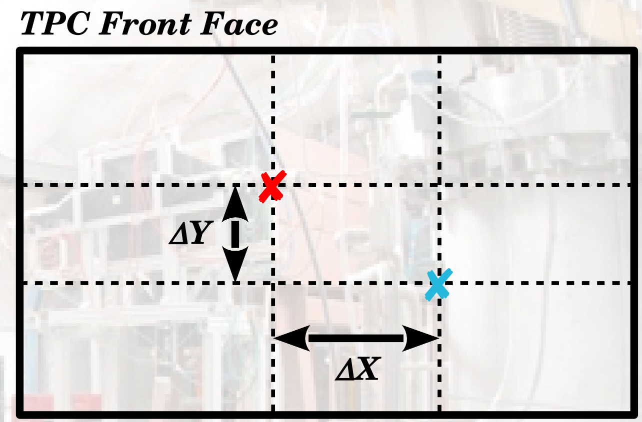




On the path to physics analyses:

Wire Chambers – TPC tracks matching

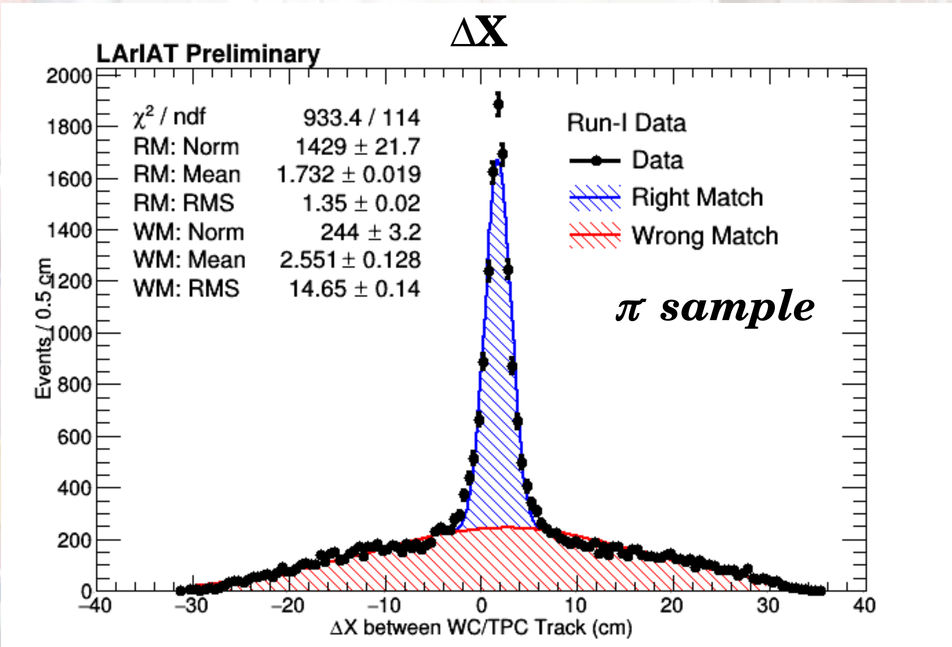


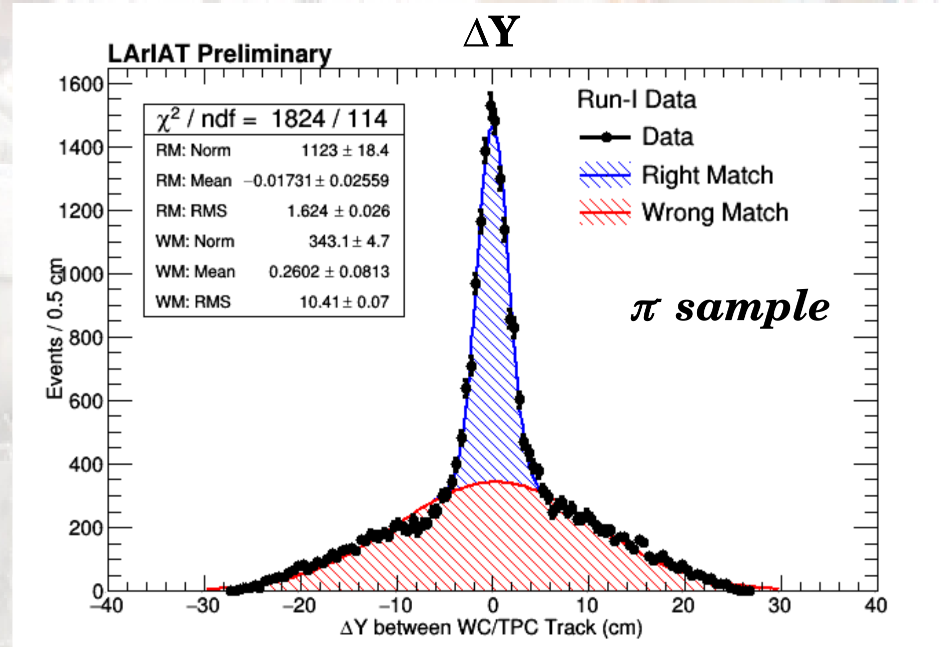


- WC – TPC track matching is essential to associate the right reconstructed track inside the TPC to the particle identified by the beamline detectors
- Both beamline particle trajectory - as determined be the last two MWPCs - and the reconstructed TPC tracks are projected to the TPC front plane
- Matching based on ΔX, ΔY and α

On the path to physics analyses:

Wire Chambers – TPC tracks matching



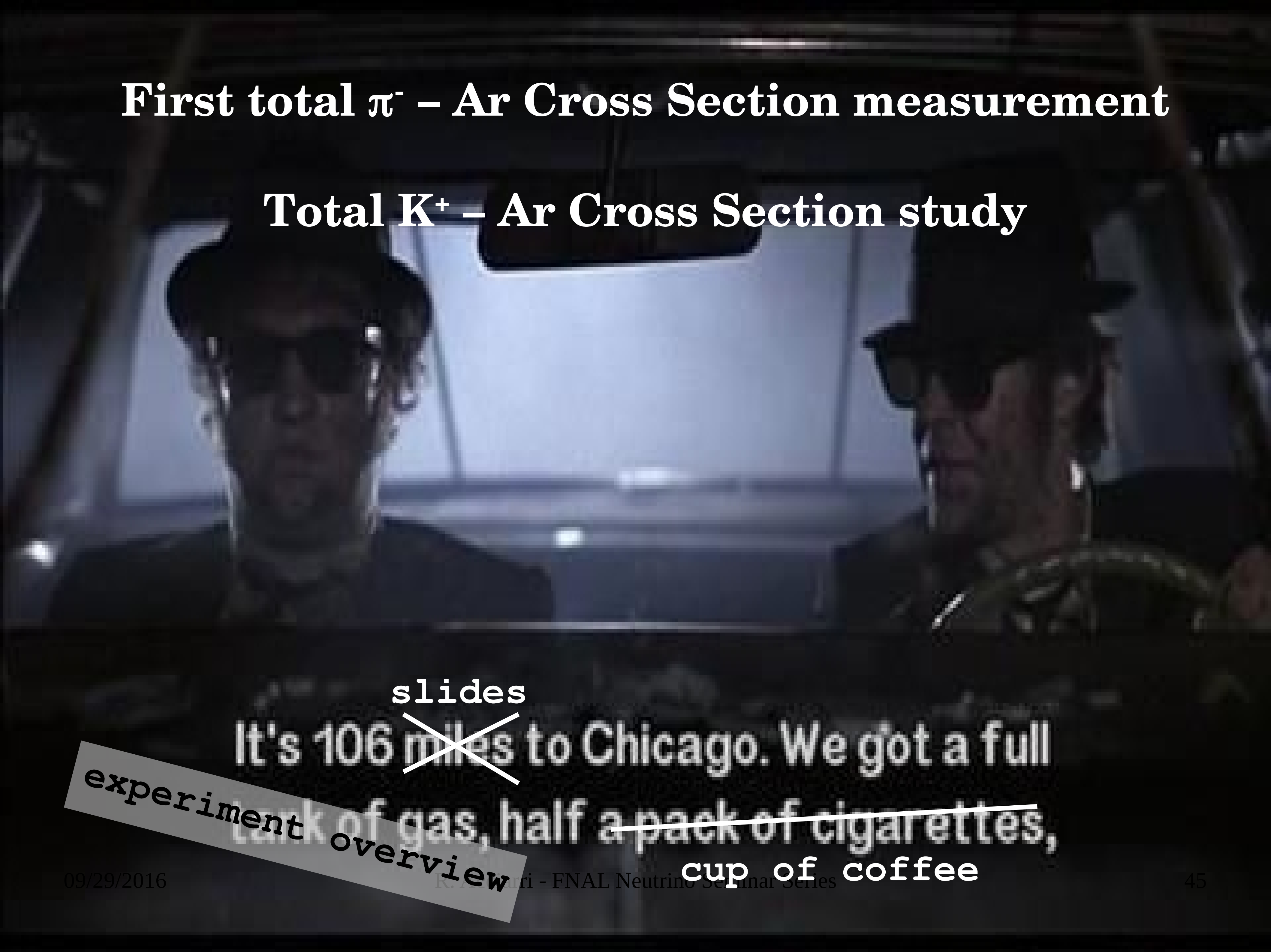


- A successful matching requires only one reconstructed TPC track in the first 2 cm of the TPC length and only one WC – TPC track pair with low ΔX, ΔY and α values

- Asymmetry in ΔX probably due to an accidental displacement of MPWC 4 after position survey

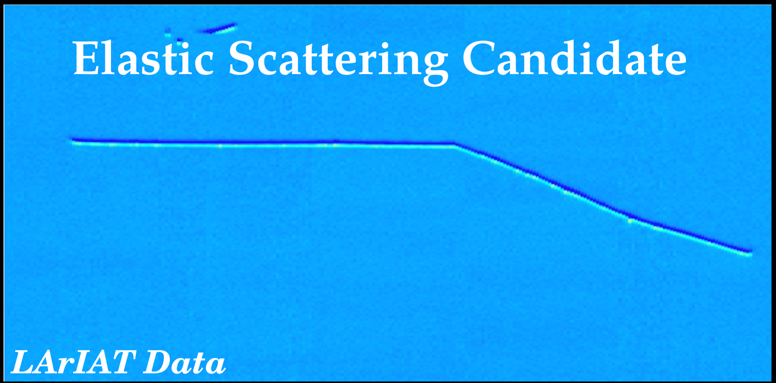
First total π^- – Ar Cross Section measurement

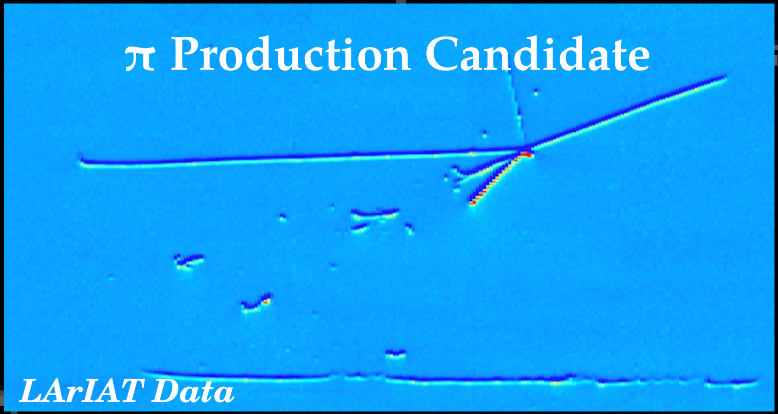
Total K^+ – Ar Cross Section study

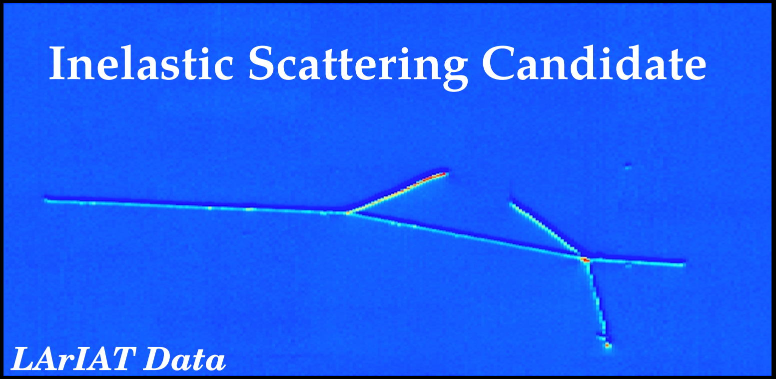


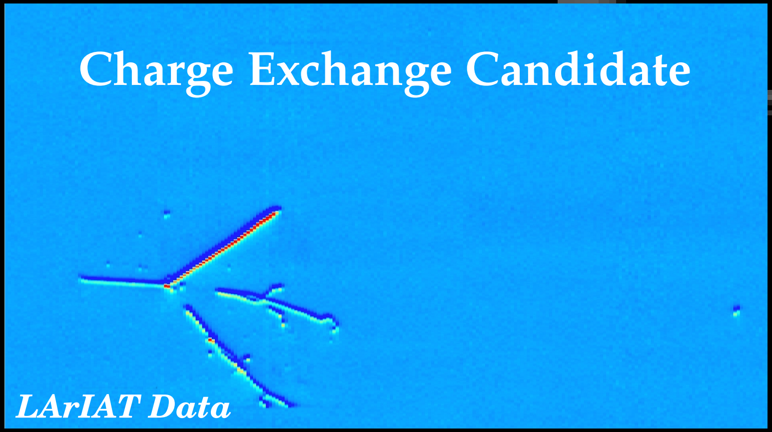
π – Ar cross section: signal topologies

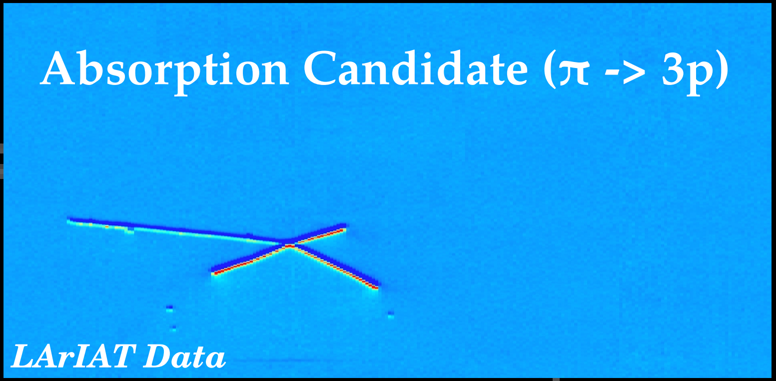
$$\sigma_{Tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{abs} + \sigma_{charge\ XC} + \sigma_{\pi\text{-prod}}$$





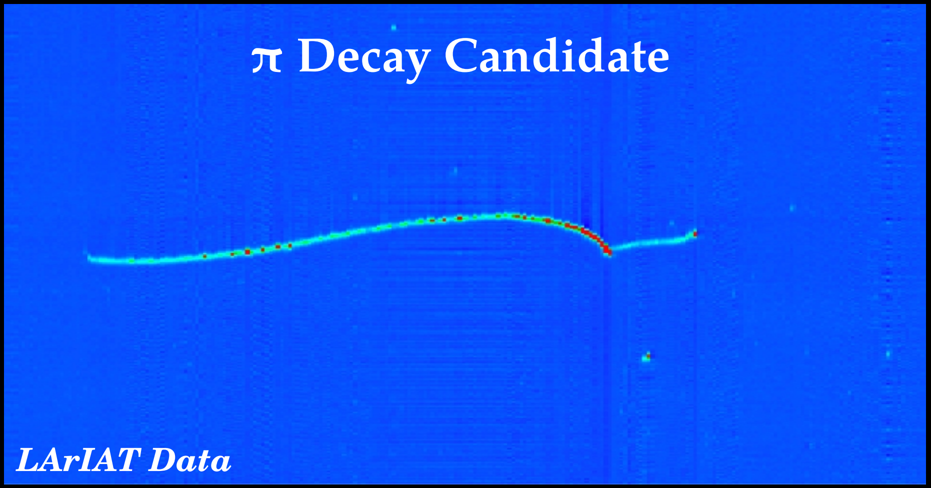


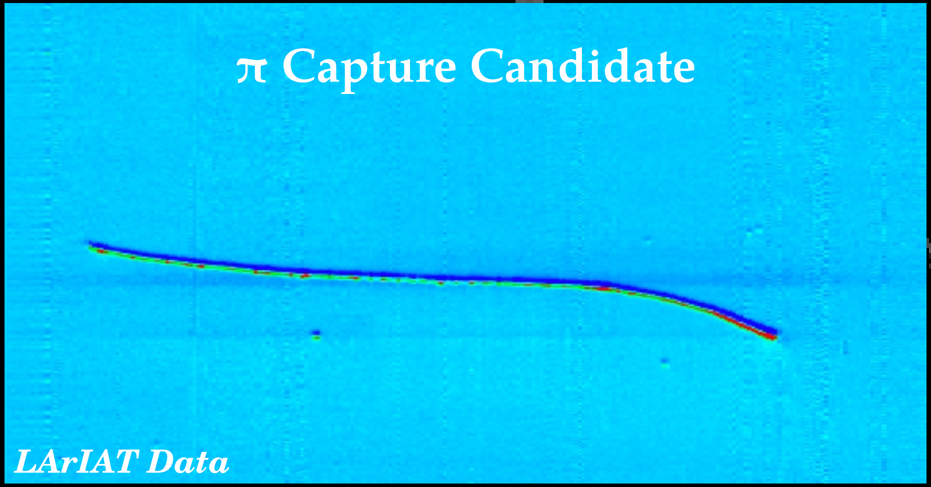


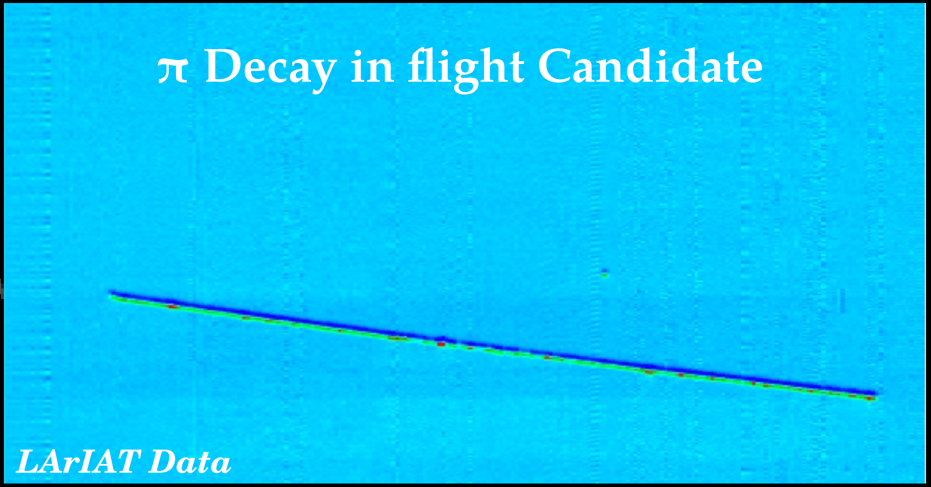


π^- – Ar cross section: background topologies

- Background topologies are currently included in the analysis
- Currently working on estimating these processes and removing them from the data sample

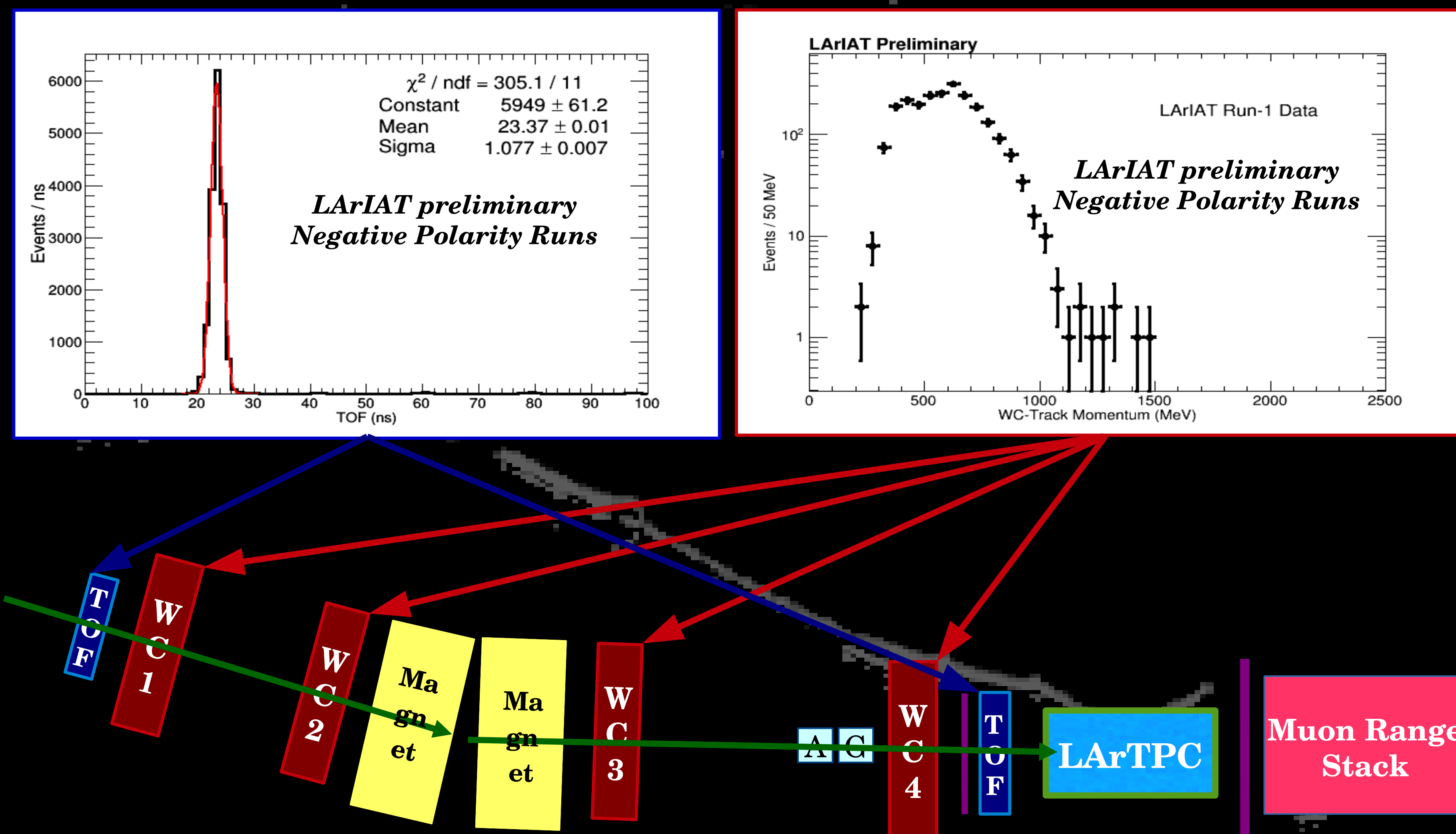




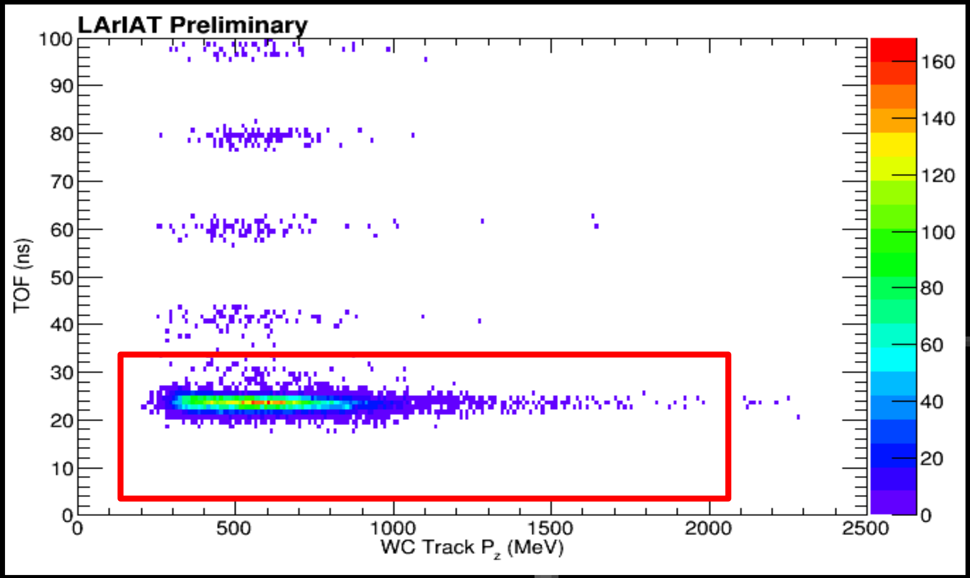


Event selection: beamline

Existence of TOF hits and WC track to ensure PID and initial momentum determination

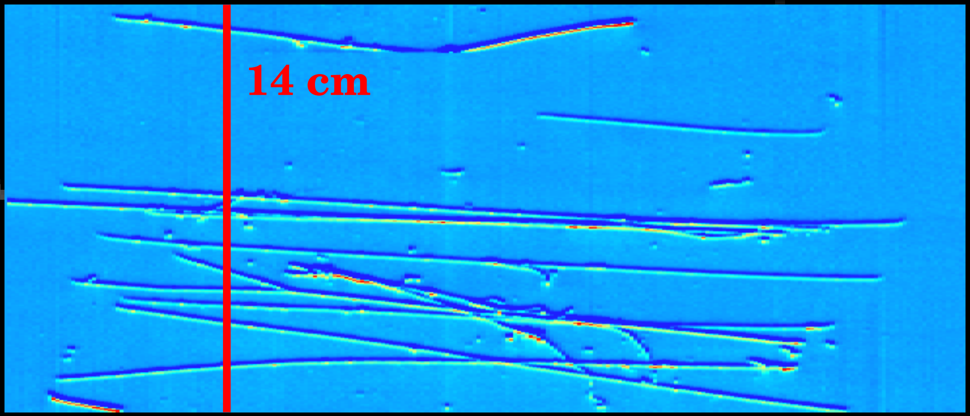


Event selection: PID and pile up

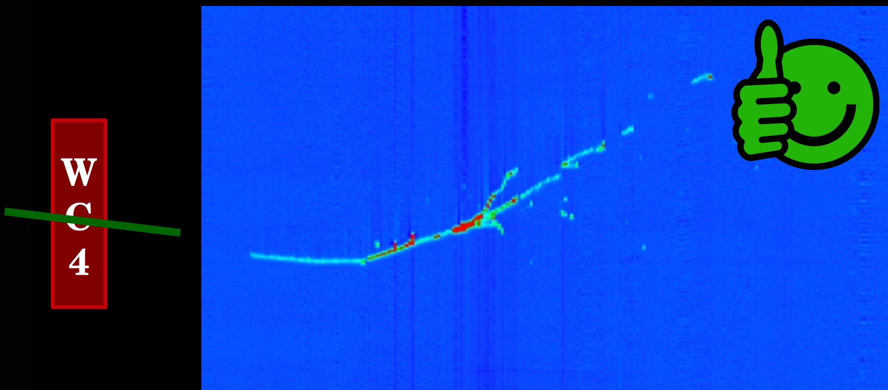


Separation of π/μ/γ from proton and late bunches through the TOF vs momentum measurement

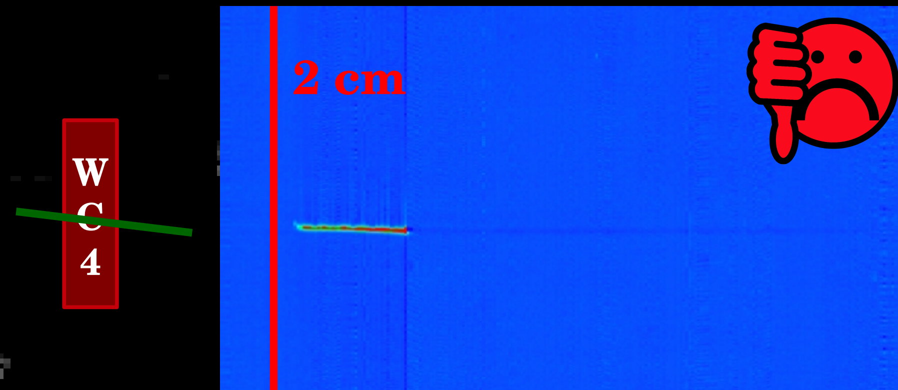
Rejection of events with more than 4 tracks in the upstream portion of the TPC



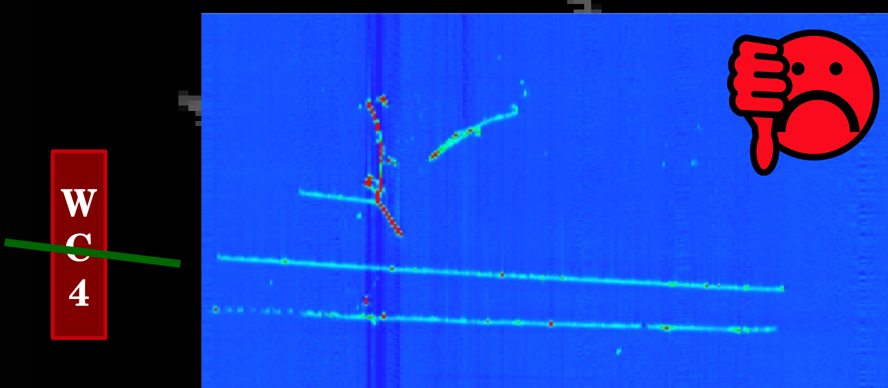
Event selection: WC – TPC match



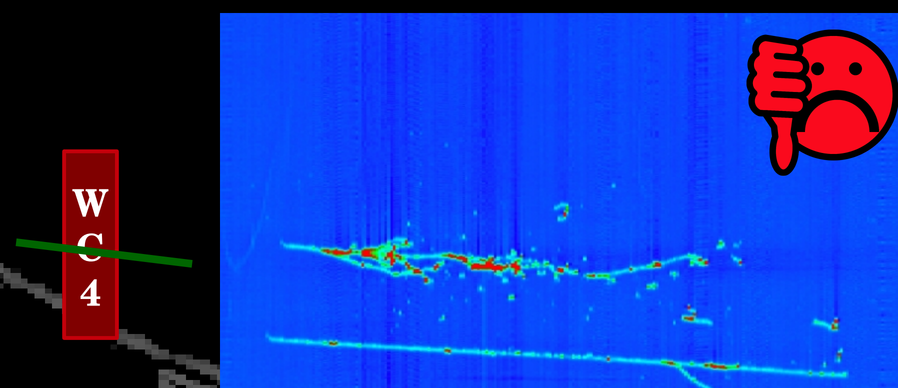
Accepted: one unique WC – TPC track matching



Rejected: more than 2 cm from TPC front face



Rejected: multiple WC – TPC track matching

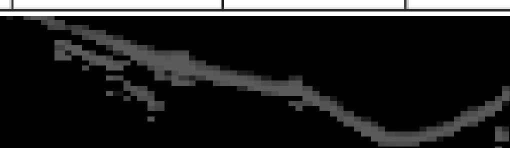


Rejected: shower-like event

Event selection: Reduction table

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^-
Beam Composition Before Cuts	48.4%	40.9%	8.5%	2.2%	0.035%
Selection Efficiency	74.5%	3.6%	0.9%	90.0%	70.6%



Thin-sliced TPC method

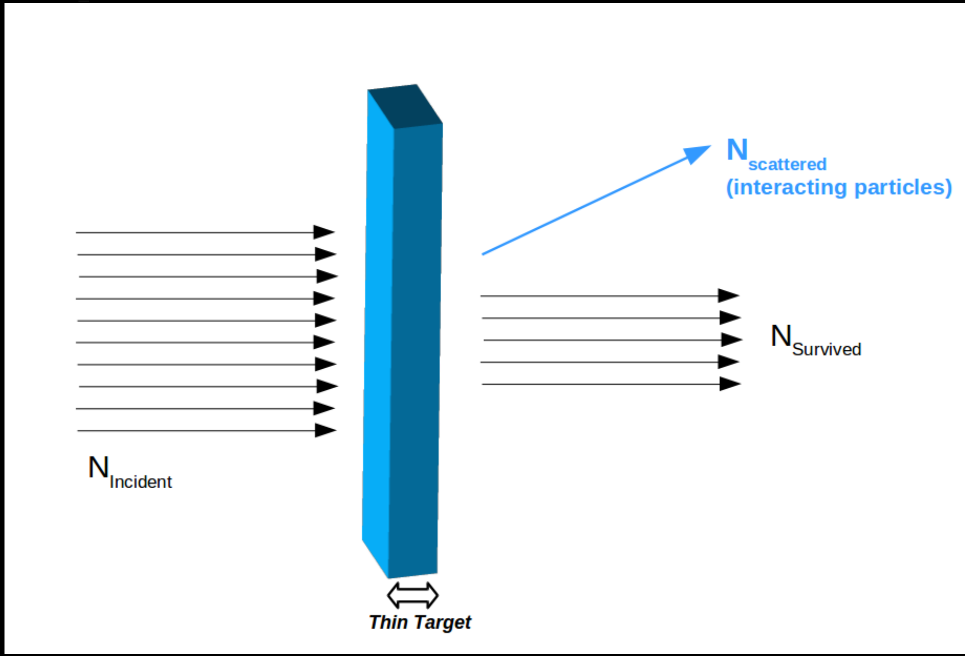
Given a thin slab of argon, the probability of a π interacting is $P_{Interacting} = 1\text{-}P_{survival}$ with

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

σ *cross section per nucleon*

n *density*

z *slab thickness*



The probability of interacting can be measured as the ratio of the number of interacting π to the number of incident ones

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

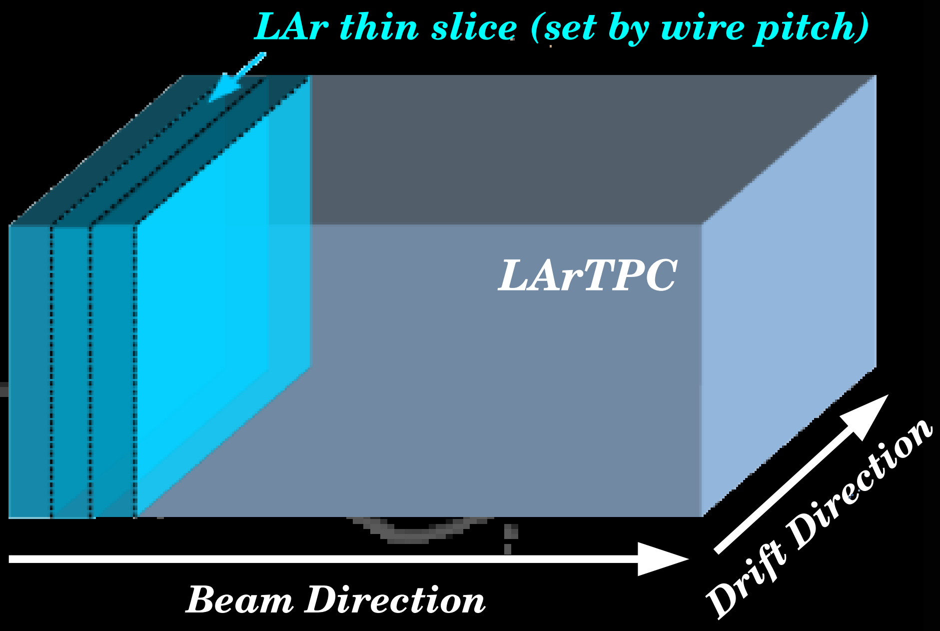
Thin-sliced TPC method

Given the thickness of the slices, we can Taylor expand and solve for the pion cross section:

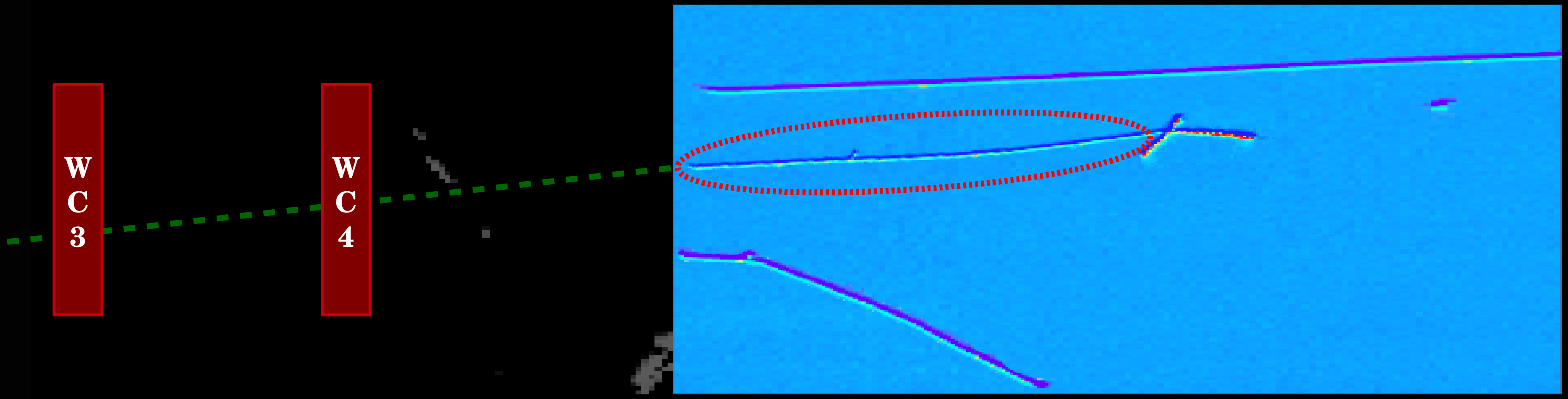
$$P_{Interacting} = 1 - e^{-\sigma n z} = 1 - (1 - \sigma n z + o(\delta X^2))$$

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

Using the granularity of the LArTPC, we can treat the wire-to-wire spacing as a series of "thin--slab" targets, if we can measure the energy of the pion incident to each slice… ***and we can!***



Initial pion Kinetic energy



The momentum measured by the Wire Chambers is used to calculated the π- candidate's initial energy in the TPC:

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

Where E_{Flat} is the energy loss due to material upstream of the TPC (argon, steel, beamline detectors)

Energy, $N_{incident}$, $N_{Interacting}$ calculation

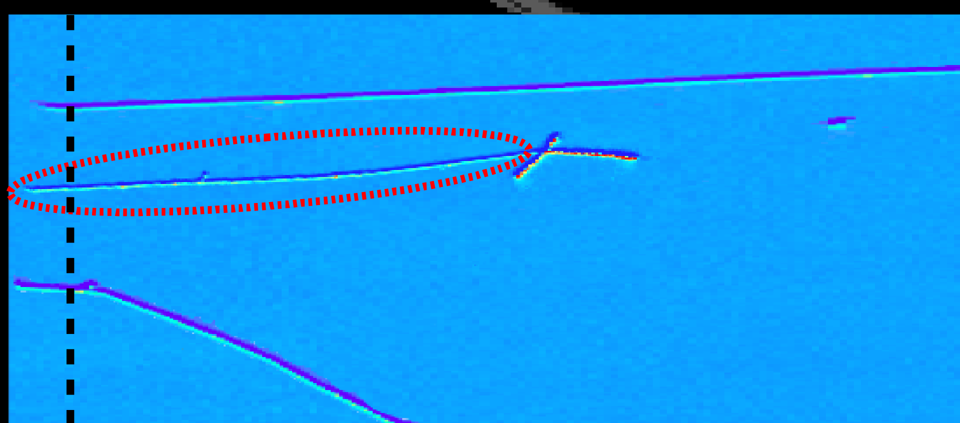
We start follow the TPC track (matched to the Wire Chamber track) in slices:

- the slice represent 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 the **incident** histogram

The kinetic energy at the slice n is calculated by subtracting the track deposited energy in the first n slices from the kinetic energy at the TPC front face

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



Interacting

Kinetic Energy (MeV)

Incident

Kinetic Energy (MeV)

Energy, $N_{incident}$, $N_{Interacting}$ calculation

We start follow the TPC track (matched to the Wire Chamber track) in slices:

- the slice represent the distance between each 3D point in the track
- for each slice we ask: “is this the end of the track?”

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The kinetic energy at the slice n is calculated by subtracting the track deposited energy in the first n slices from the kinetic energy at the TPC front face

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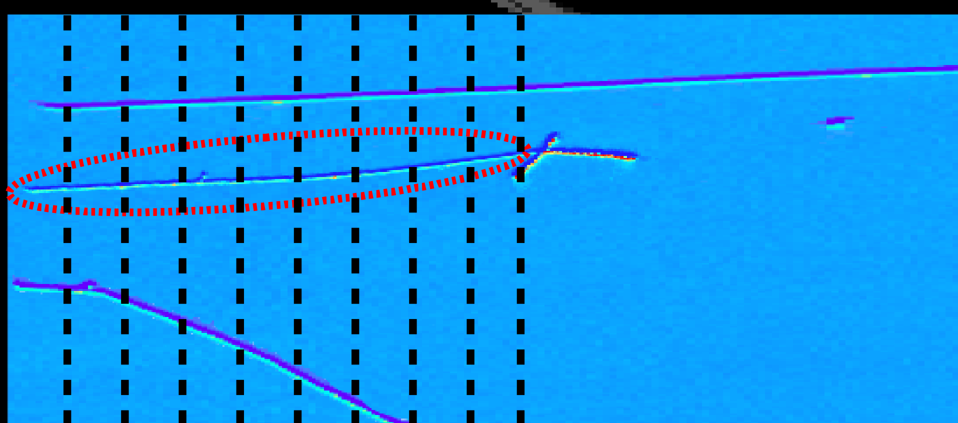
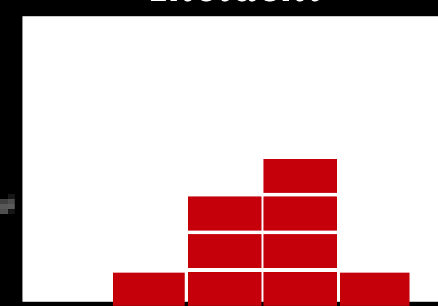




Energy, $N_{incident}$, $N_{Interacting}$ calculation

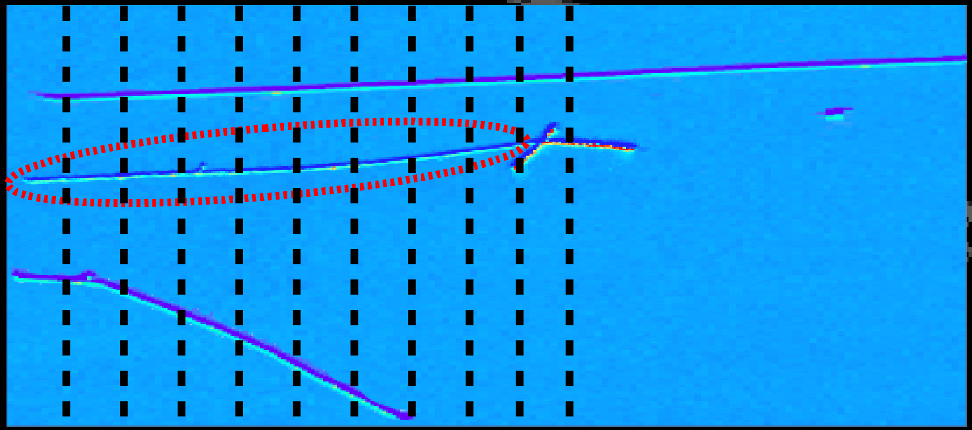
We start follow the TPC track (matched to the Wire Chamber track) in slices:

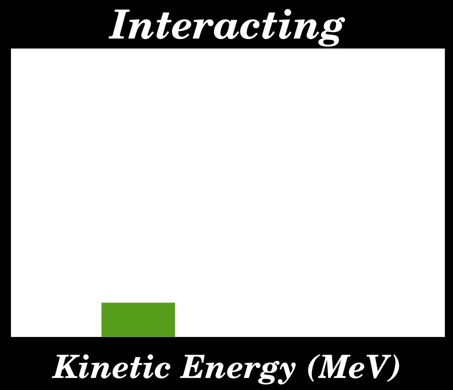
- the slice represent the distance between each 3D point in the track
- for each slice we ask: “is this the end of the track?”

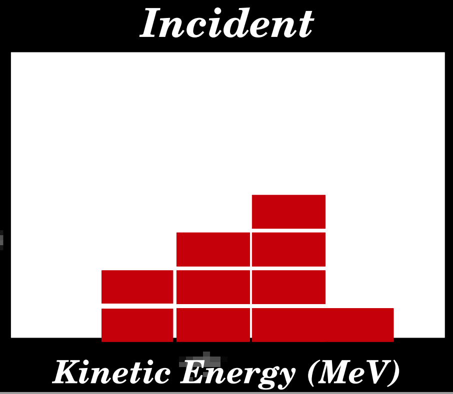
YES: calculate the kinetic energy at this point and put that both in the **interacting** and **incident** histogram

The kinetic energy at the slice n is calculated by subtracting the track deposited energy in the first n slices from the kinetic energy at the TPC front face

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

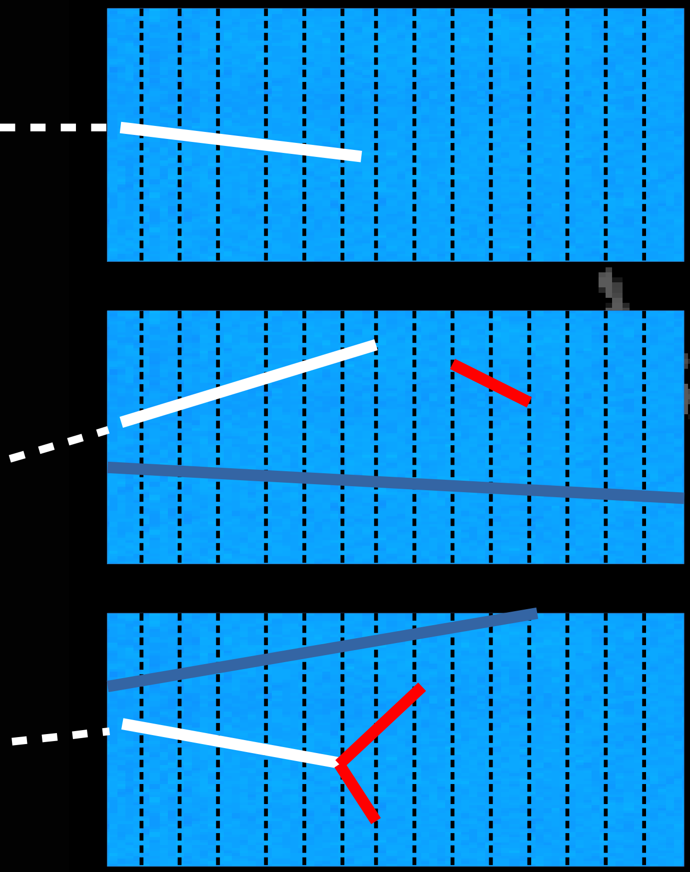


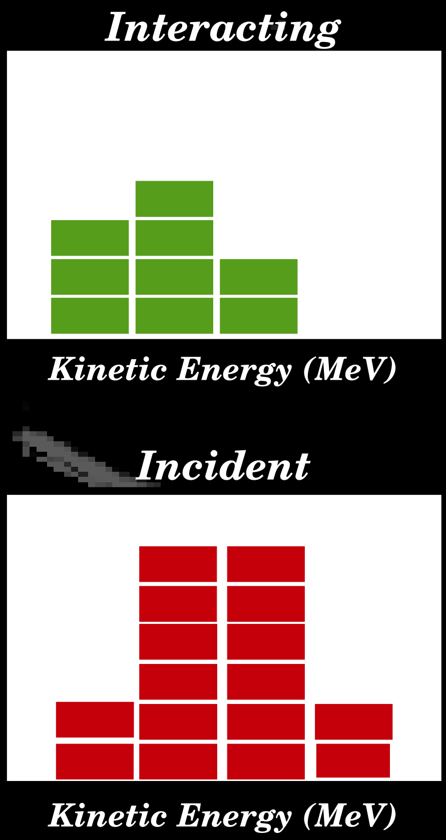


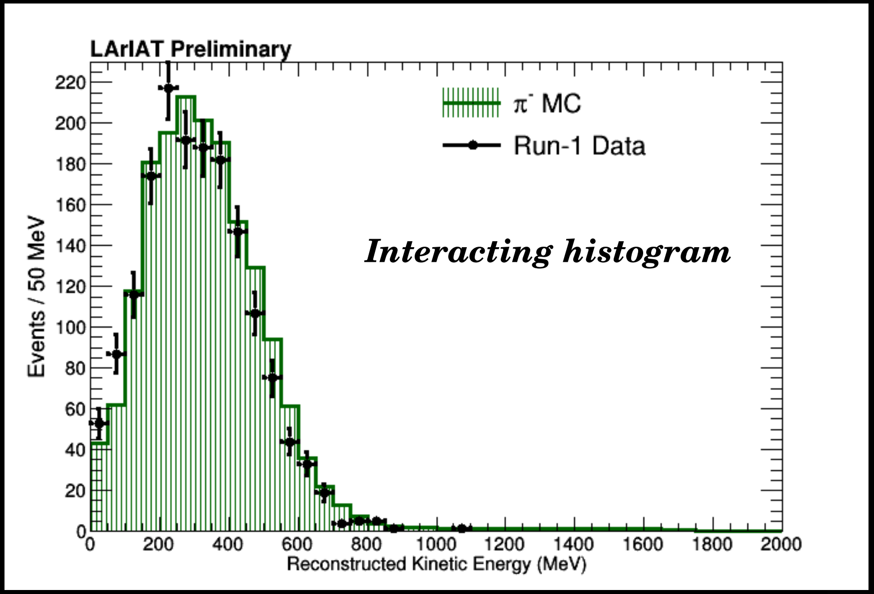


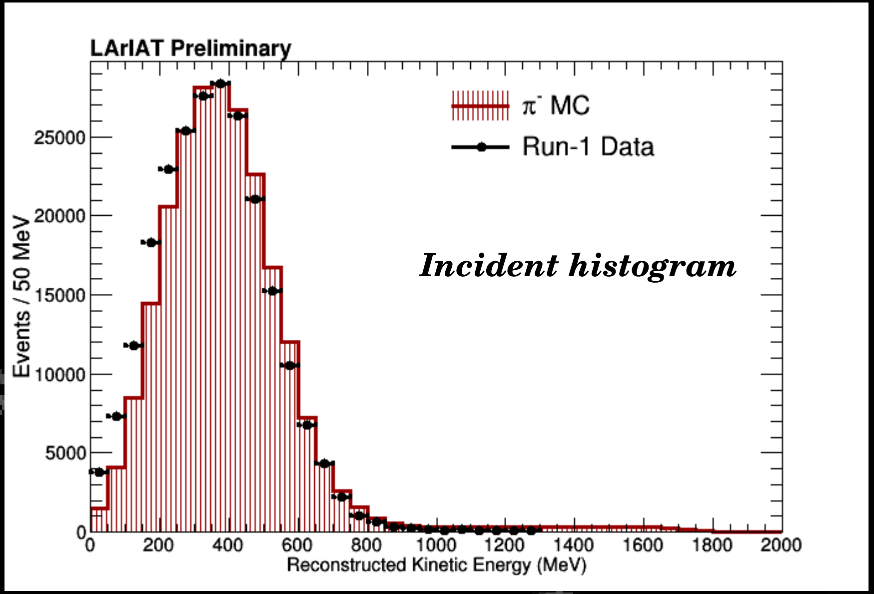
Energy, $N_{incident}$, $N_{Interacting}$ calculation

- The process is repeated for each event in the data sample
- Only WC to TPC matched tracks are considered. Any other activity is disregarded





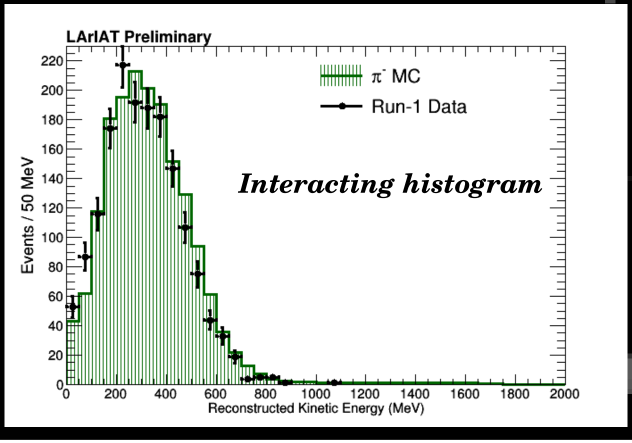


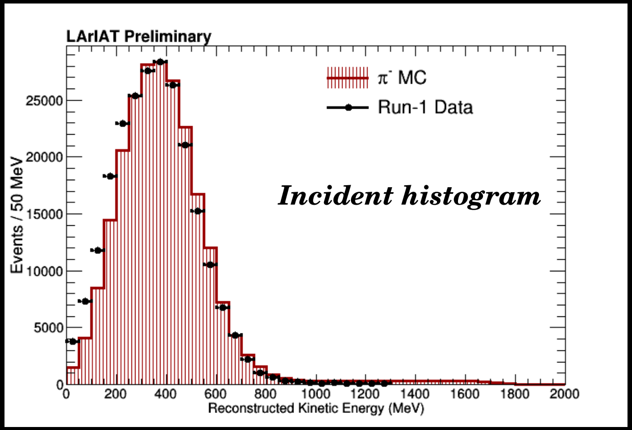


Total π⁻ – Ar cross section

Finally, we take the ratio of the two histograms and calculate the cross section

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





= nz

Cross-section (barns)

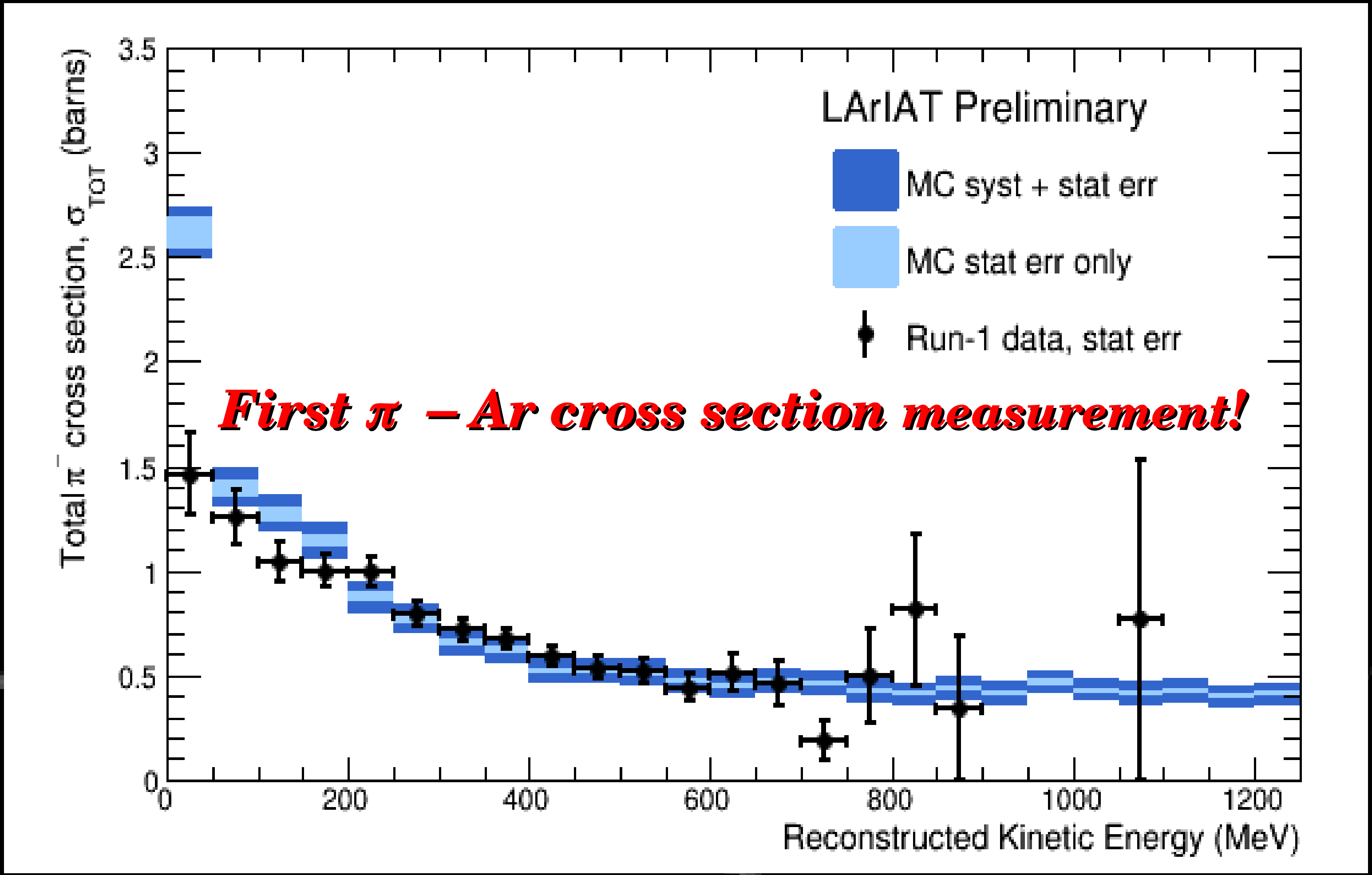
Reminder:

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)

Total π⁻ – Ar 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%

π^- – Ar cross section sum up

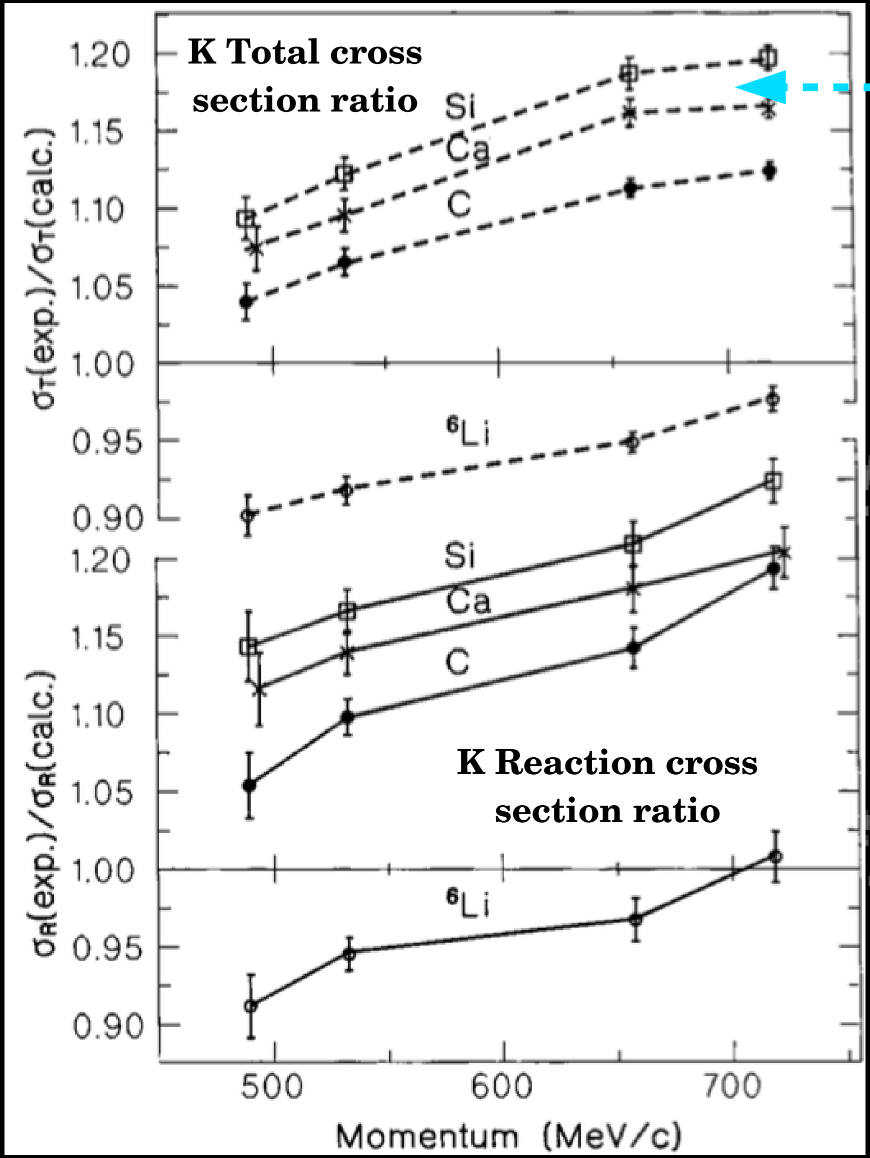
First LArIAT analysis

- Total pion cross section never measured on argon before
- Fully automated reconstruction

Next steps

- Treatment of pion capture and decay processes
- Improvement of the energy corrections by taking into account the dependence on the incident angle
- Investigate Aerogel and Muon Range Stack for through-going muon removal

Towards a K^+ – Ar cross section measurement



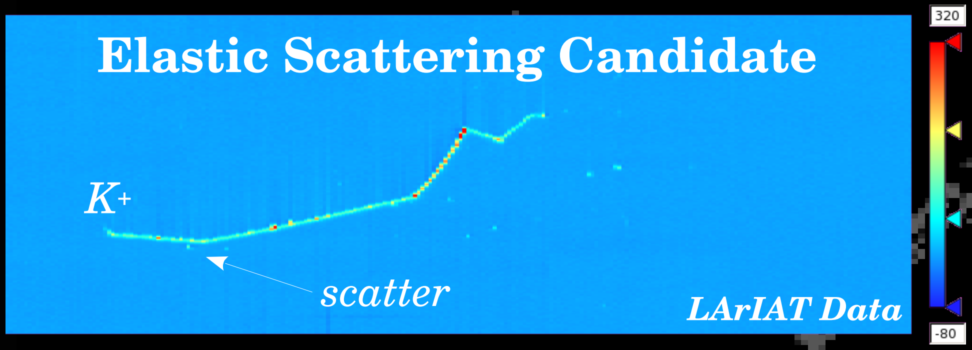
E. Friedman et al. Phys. Rev., C55:1304–1311, 1997

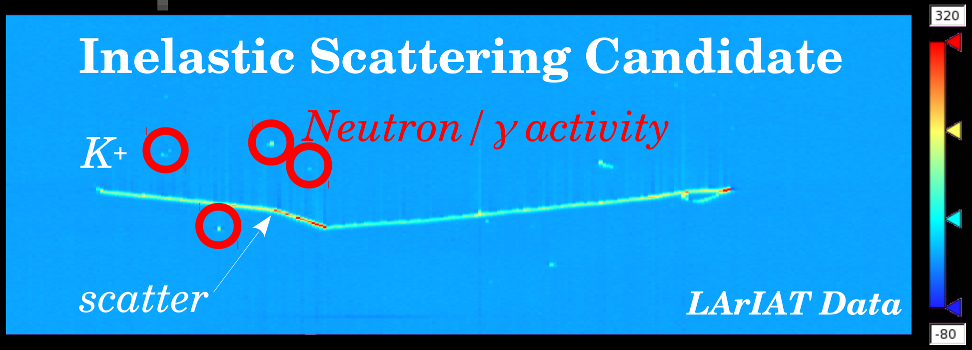
K – Ar cross section expected to lay between Ca and Si ones

- 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 -> $\bar{\upsilon}$ K^+ Golden channel for proton decay in LAr

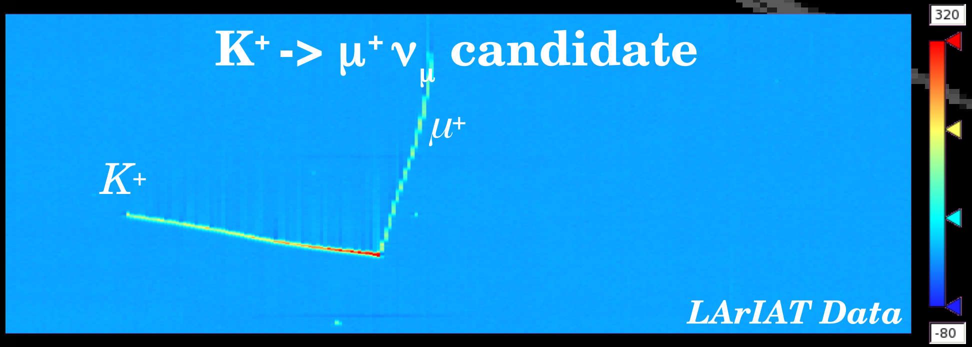
K^+ – Ar cross section: event topologies

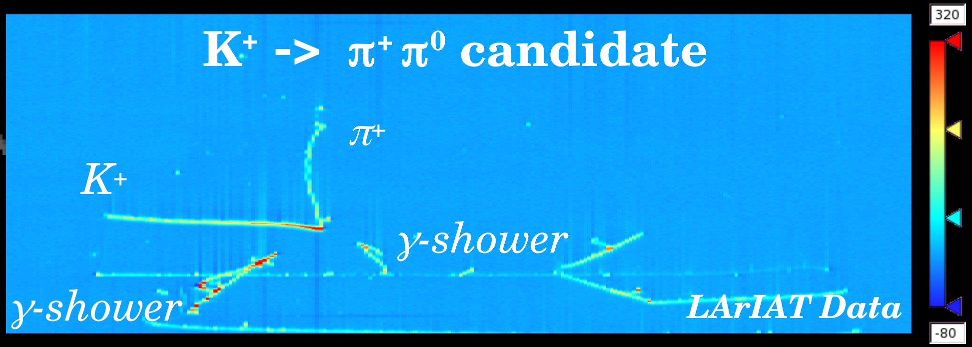
Signal topologies: $\sigma_{Tot} = \sigma_{Elastic} + \sigma_{Reaction}$





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

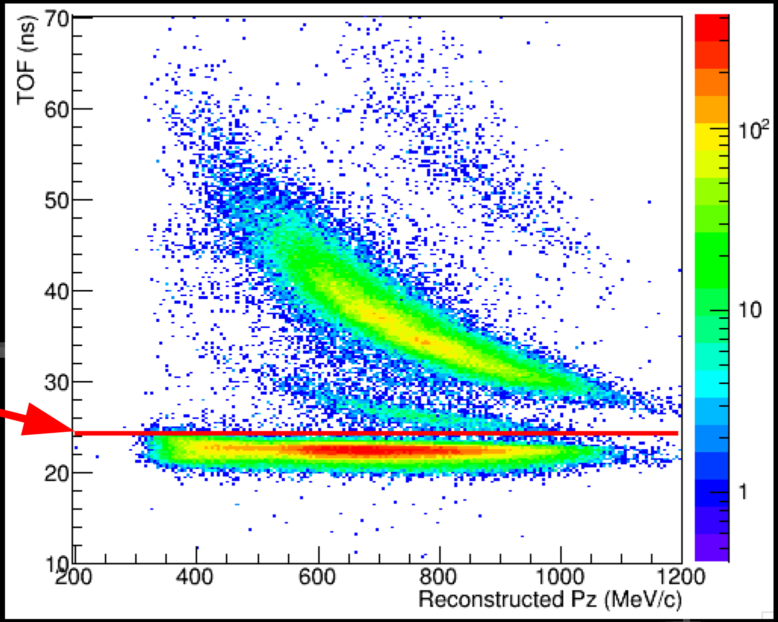




K^+ – Ar cross section: event selection

The first set of cuts is similar to the pion cross section analysis

- A single beamline particle fully reconstructed (TOF+ WC track)
- Less than 5 tracks in the first 14 cm of the TPC length
- At least one track in the first 2 cm of the TPC length
- A unique WC-TPC matching
- TOF > 24.3 ns

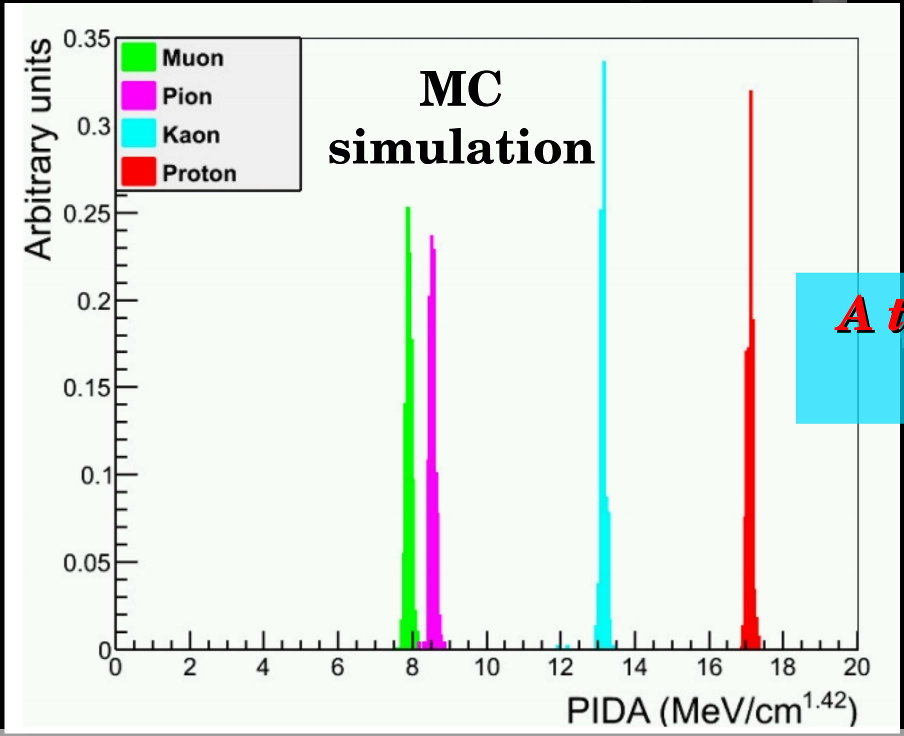


Event selection: PIDA cut

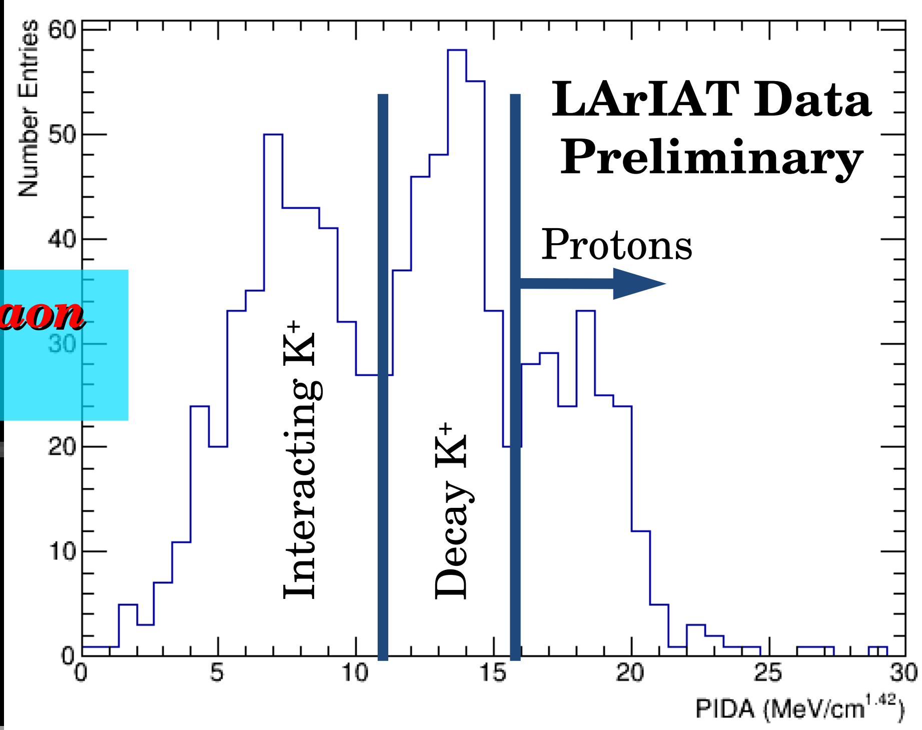
R. Acciarri et al. (ArgoNeuT Collaboration), JINST 8 (2013) P08005

- Particle IDentification Algorithm (PIDA) is a LArTPC based technique developed by ArgoNeuT
- It parameterizes the Bethe-Block energy deposition curve for ***stopping particles*** in terms of the residual range **R** and a parameter **A**, unique for each particle (the PIDA parameter)
- For each given track, A is calculated by averaging the value of dE/dx and R for each reconstructed point *i* of the track

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

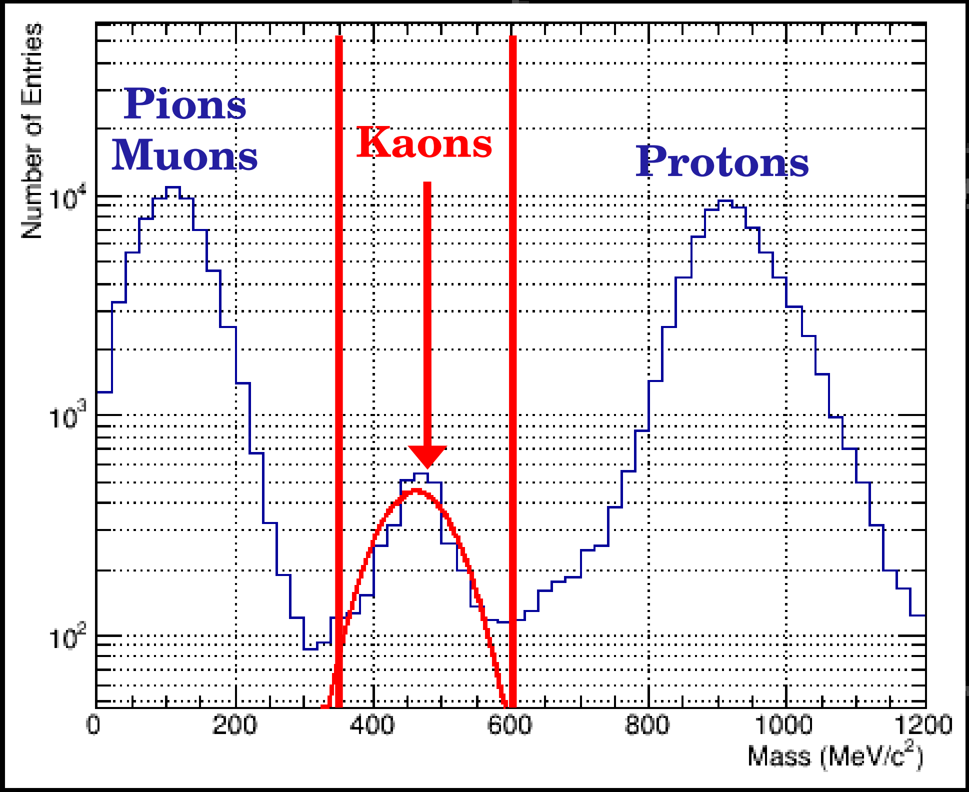


A tag for Kaon decay!



Event selection: Mass cut

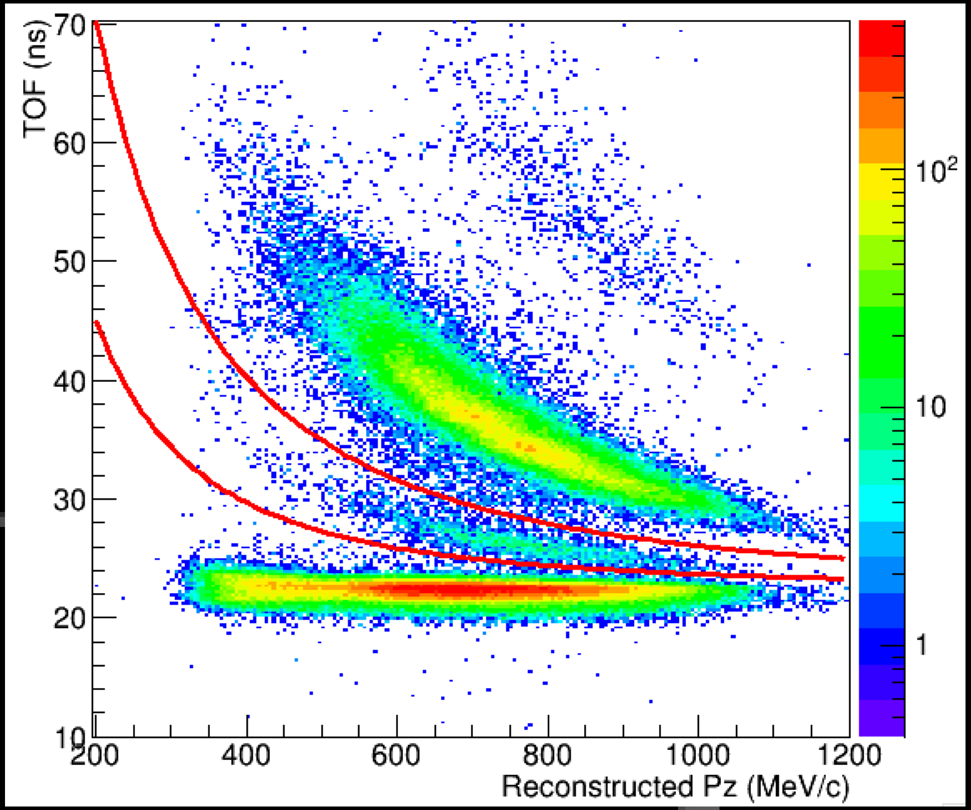
Using the TOF and Wire Chamber information, a cut on the particle's invariant mass is performed



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

l length between TOF paddles (6.7 m)

350 < m < 600 MeV/c²

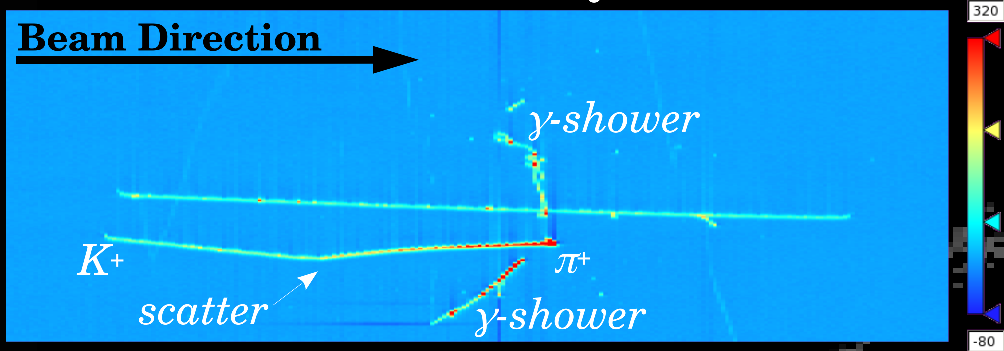


Event selection: reduction table

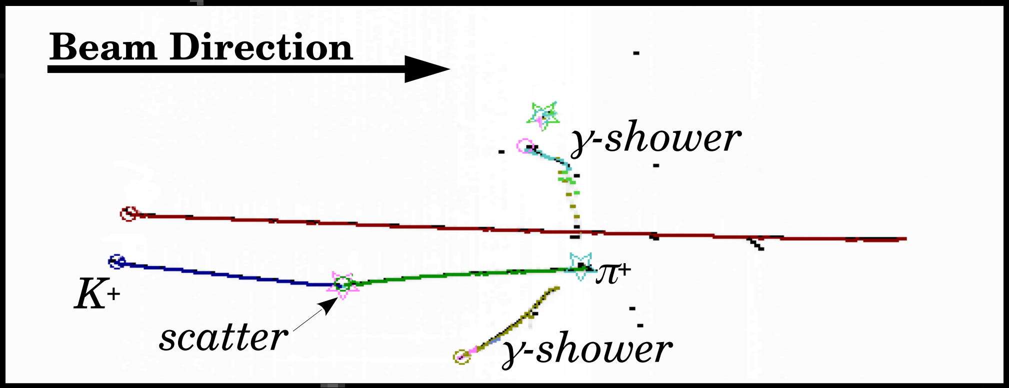
Event Sample	Number of Events
Single beamline particle fully reconstructed	187463
# tracks > 0 in first 2 cm TPC && < 5 in first 14 cm	117710
Unique WC – TPC track matching	70801
TOF cut	28303
PIDA cut	8231
Invariant Mass Cut	**882**

Events from the selected sample

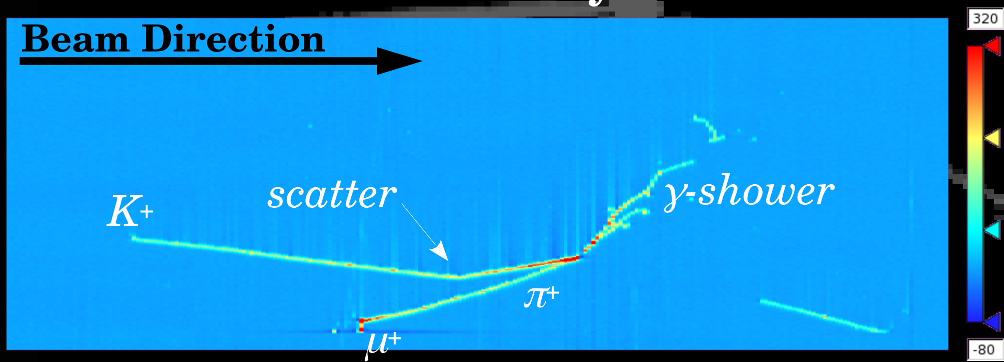
LArIAT Data Preliminary K⁺ Candidate



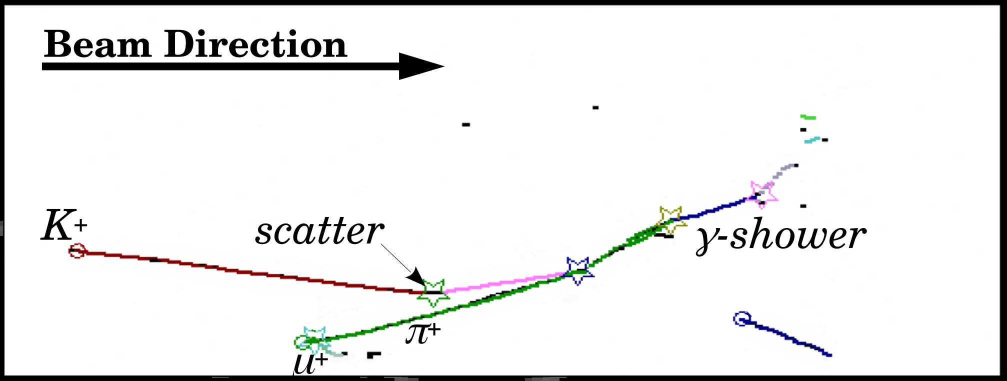
LArIAT Data Preliminary Reconstruction



LArIAT Data Preliminary K⁺ Candidate



LArIAT Data Preliminary Reconstruction



K^+ – Ar cross section study sum up

So far

- Demonstrated the capability to identify Kaon hadronic interactions in LArIAT
- Demonstrated the capability to tag and remove Kaon decay from the sample
- Demonstrated the ability to automatically reconstruct Kaon events

Next steps

- Refine cuts to possibly improve sample statistics and/or purity
- Measure the total cross section!

In conclusion

Run 1 and 2 collected a wonderful dataset

- ✔ Special thank you to the Accelerator Division (beautiful beam), FTBF (for hosting and support), Scientific Computing (support for our DAQ and offline software) and support from PPD and ND (material, engineering, scientific and technical support)!!!

That's just the beginning! More analyses to come...

- ✔ Cross section analyses
  - ➢Kaons are on the way (total, and possibly exclusive channels as well)
  - ➢Exclusive π-Ar absorption and charge exchange channels as well as elastic, inelastic are all underway
  - ➢All of the above for π^+'s as well
  - ➢proton, etc...
- ✔ e/γ, muon sign determination, scintillation light studies

Good things come always in threes!

- ✔ LArIAT Run 3 will start early next year
- ✔ Mainly R&D studies: 3 mm vs 5 mm wireplane pitch, new light collection detectors, etc...

Thank YOU from the 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
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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!!!!

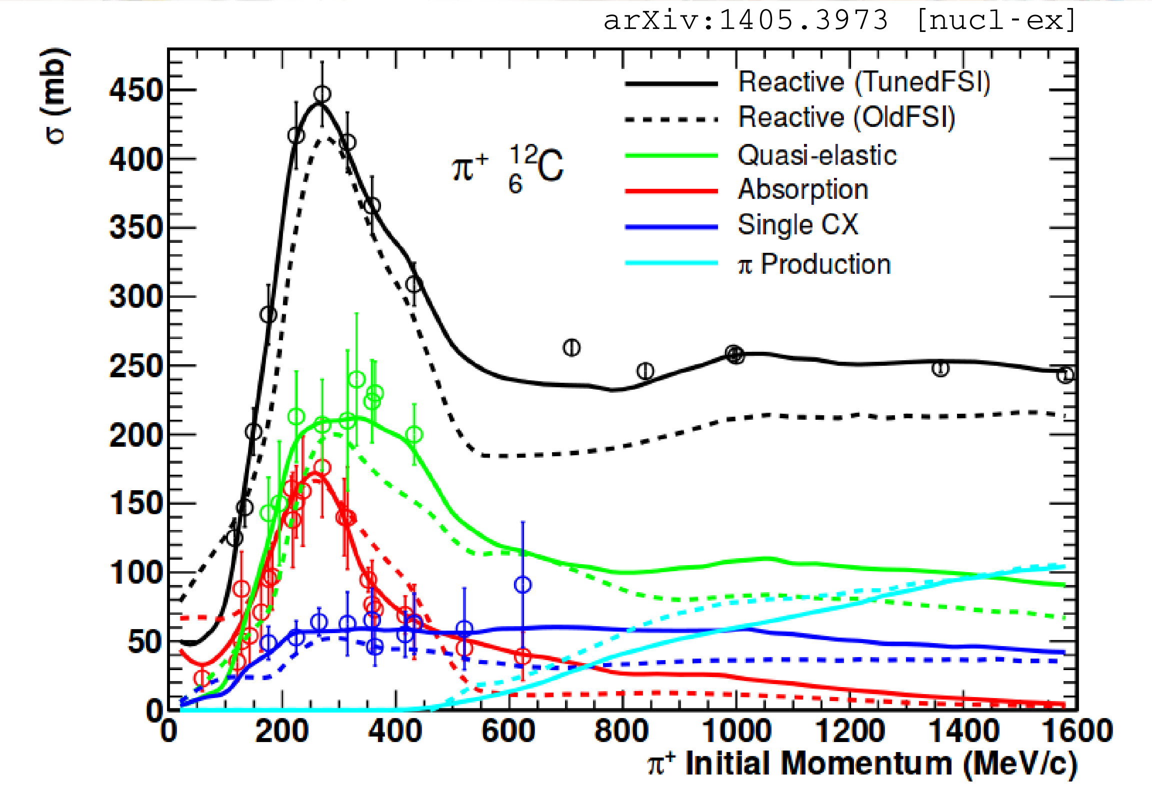
Hadron – Ar interaction cross sections: π – Ar

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

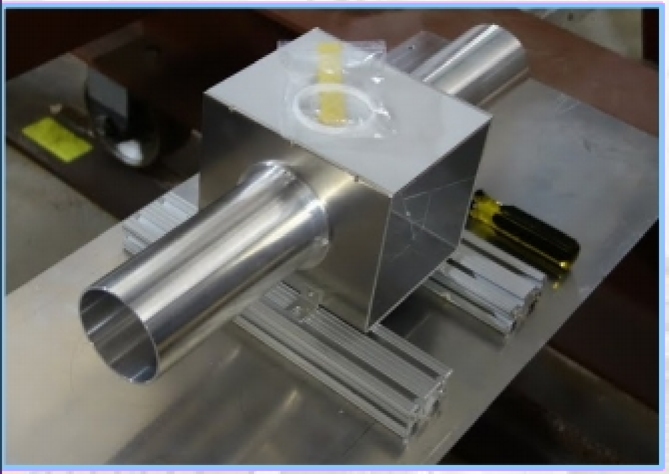
✔ Cross section is boosted in this energy range

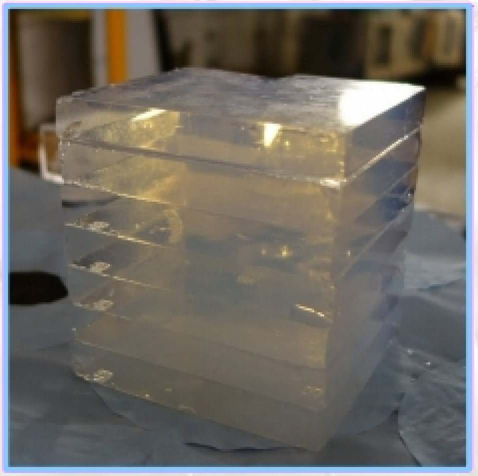
✔ Pion interaction becomes an important systematic in the neutrino cross section

π^+ scattering data on ^{12}C

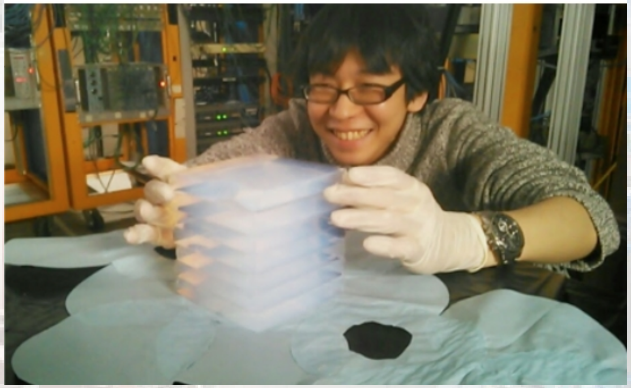


Aerogel counters

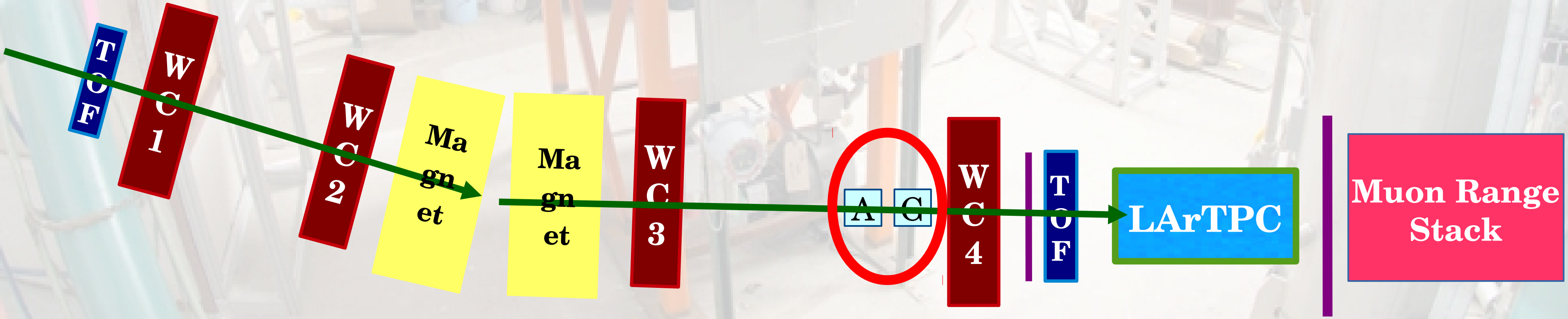




	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

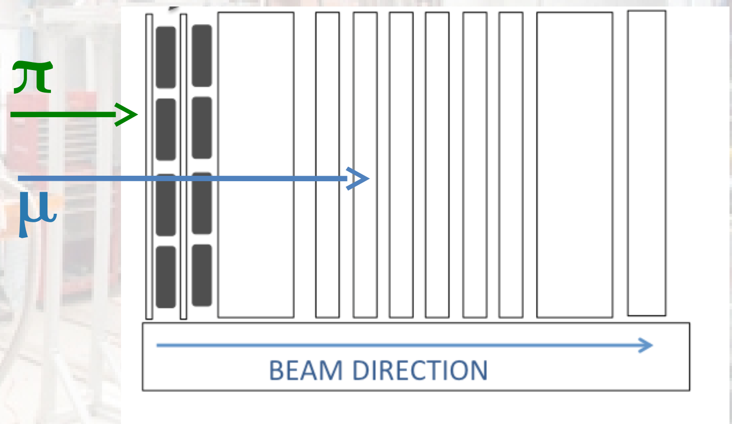


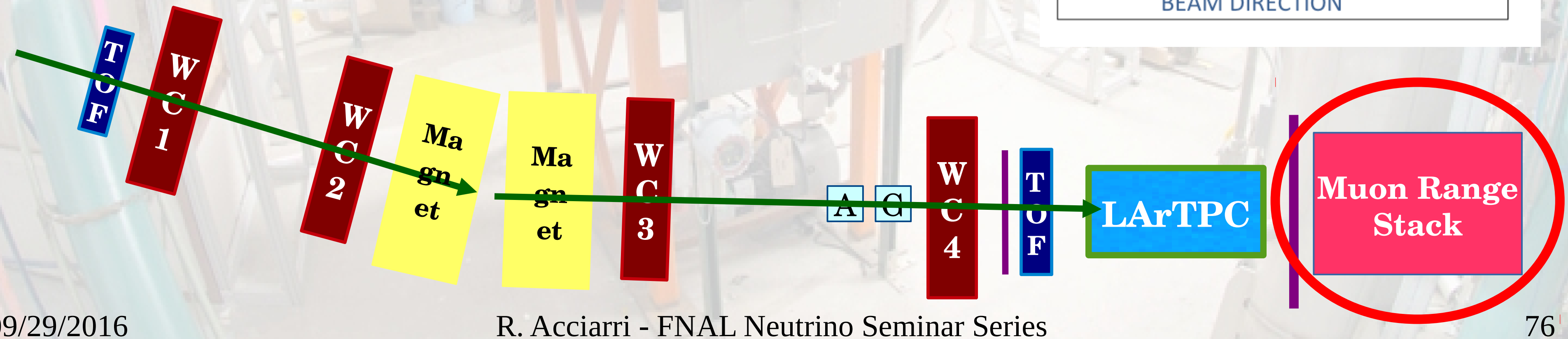
- ✔ Allows to perform π/μ separation over a range of momentum
- ✔ Currently under investigation



Muon Range Stack

- ✔ 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

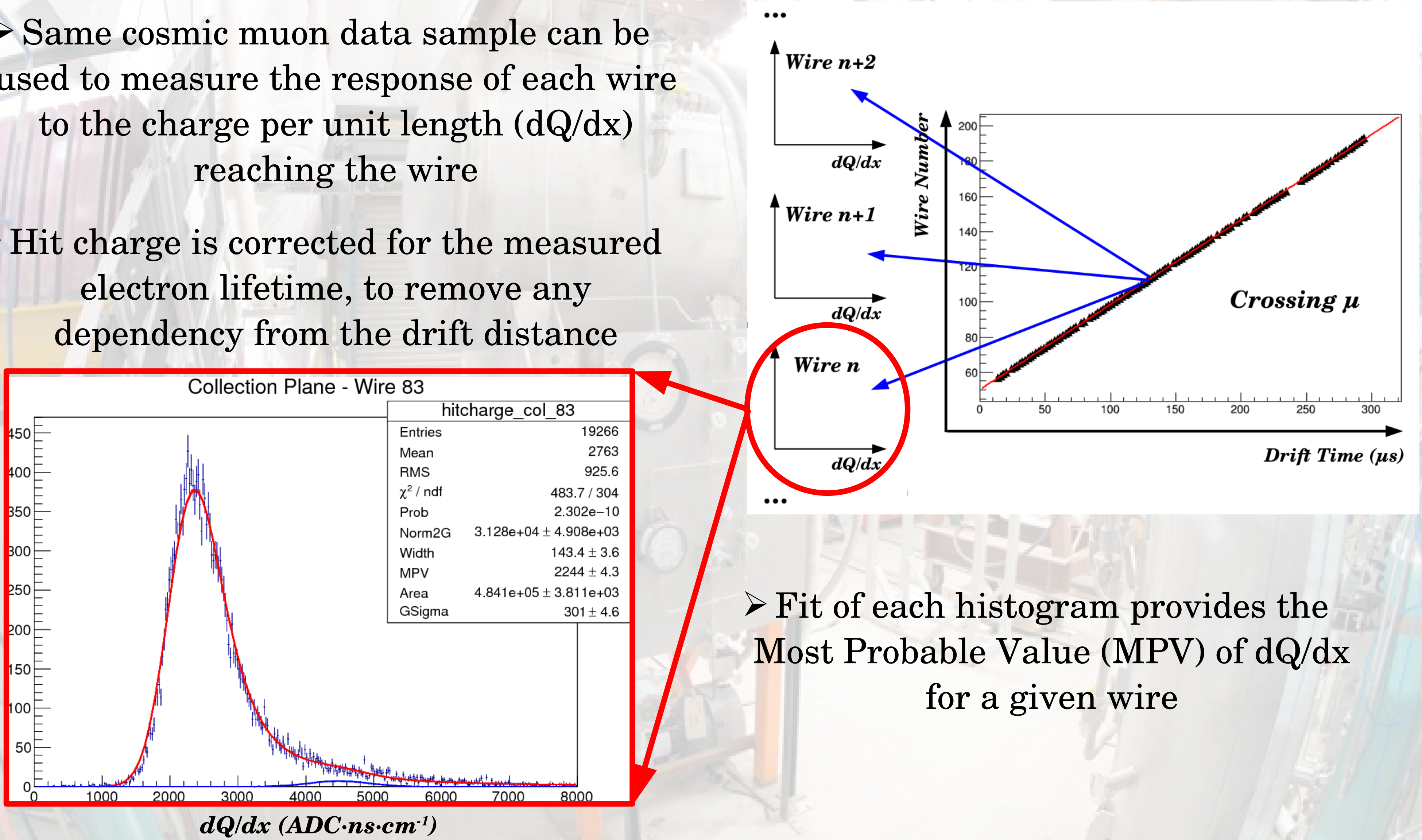




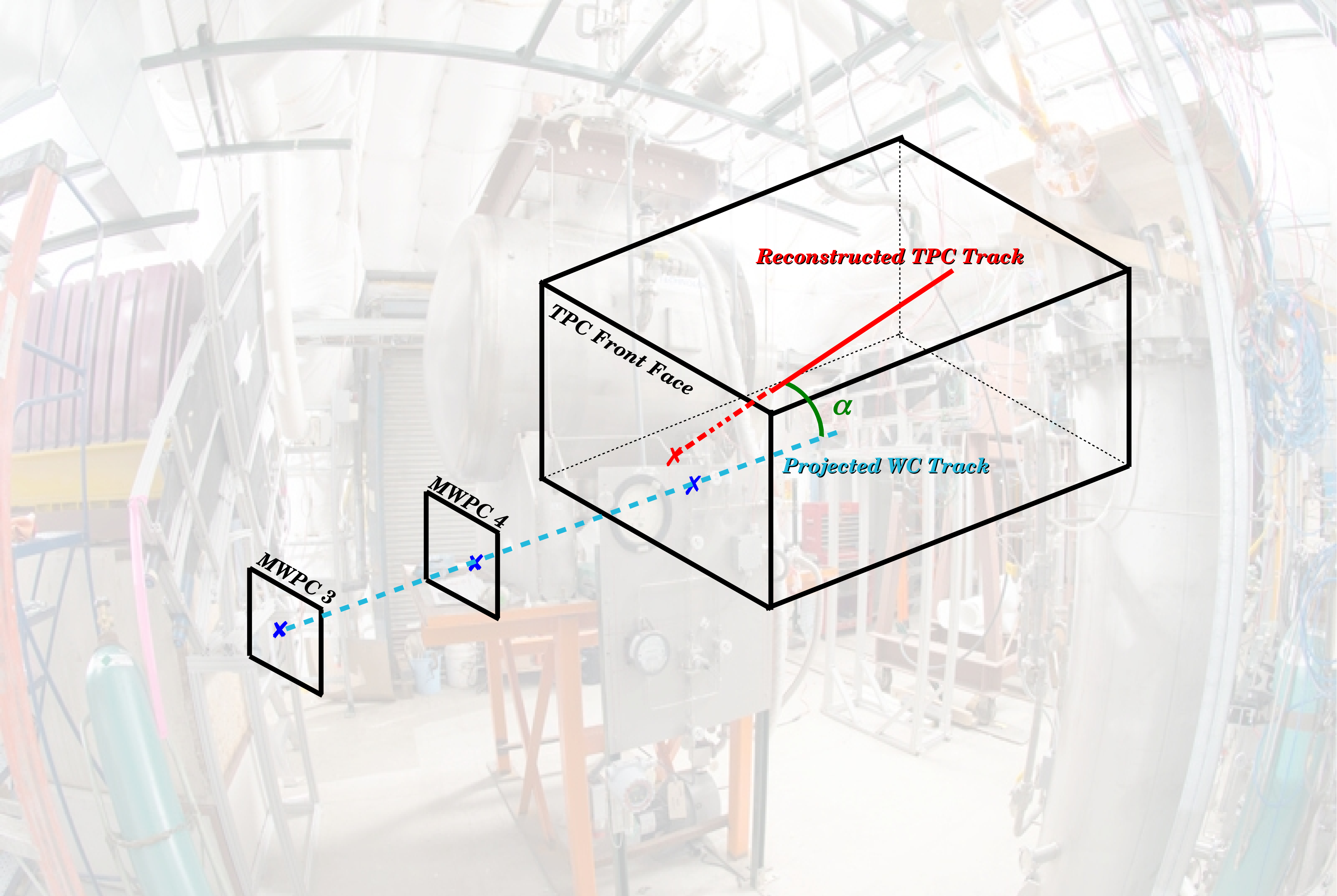
On the path to physics analyses:

Wire response to collected charge

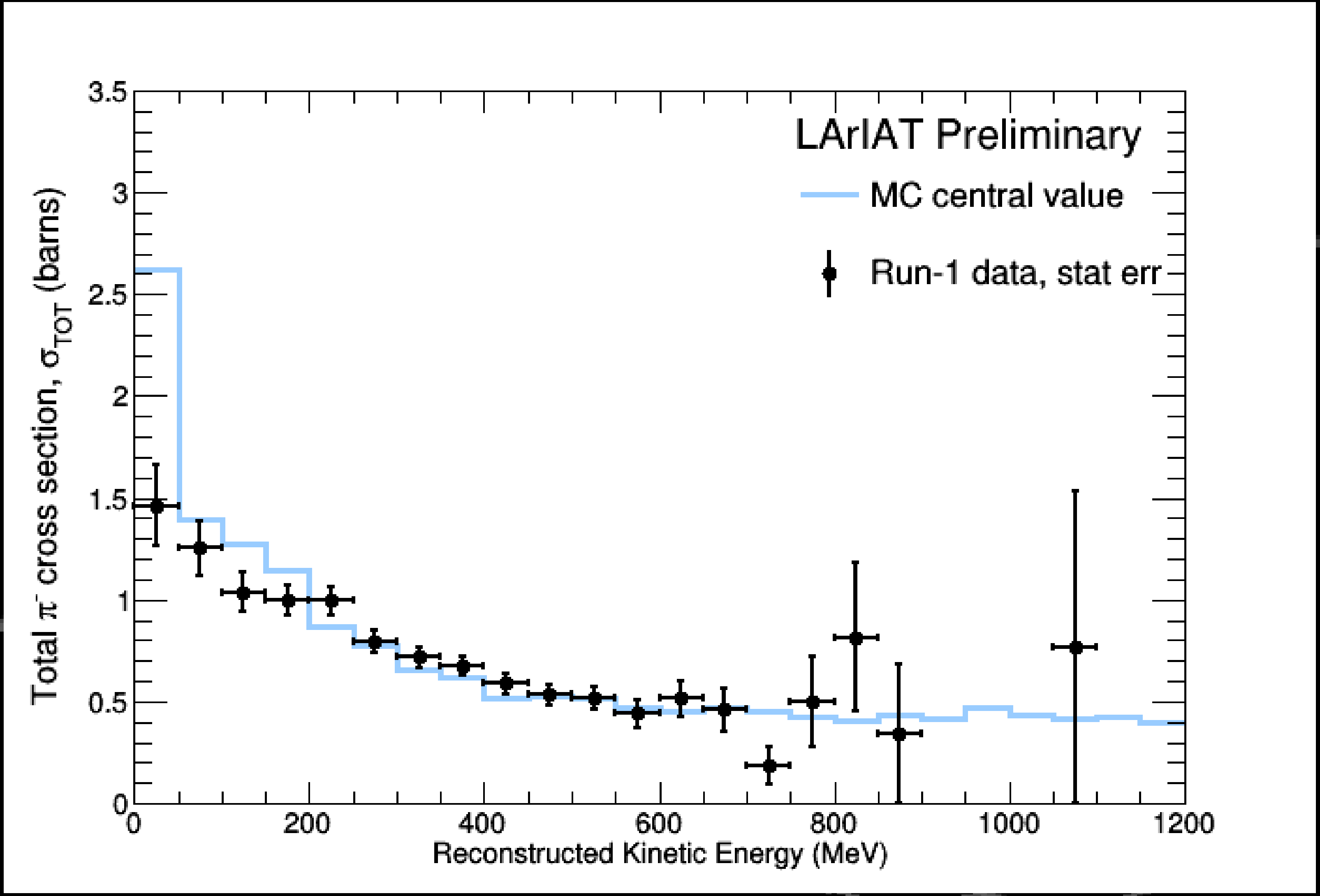
- Same cosmic muon data sample can be used to measure the response of each wire to the charge per unit length (dQ/dx) reaching the wire
- Hit charge is corrected for the measured electron lifetime, to remove any dependency from the drift distance



- Fit of each histogram provides the Most Probable Value (MPV) of dQ/dx for a given wire

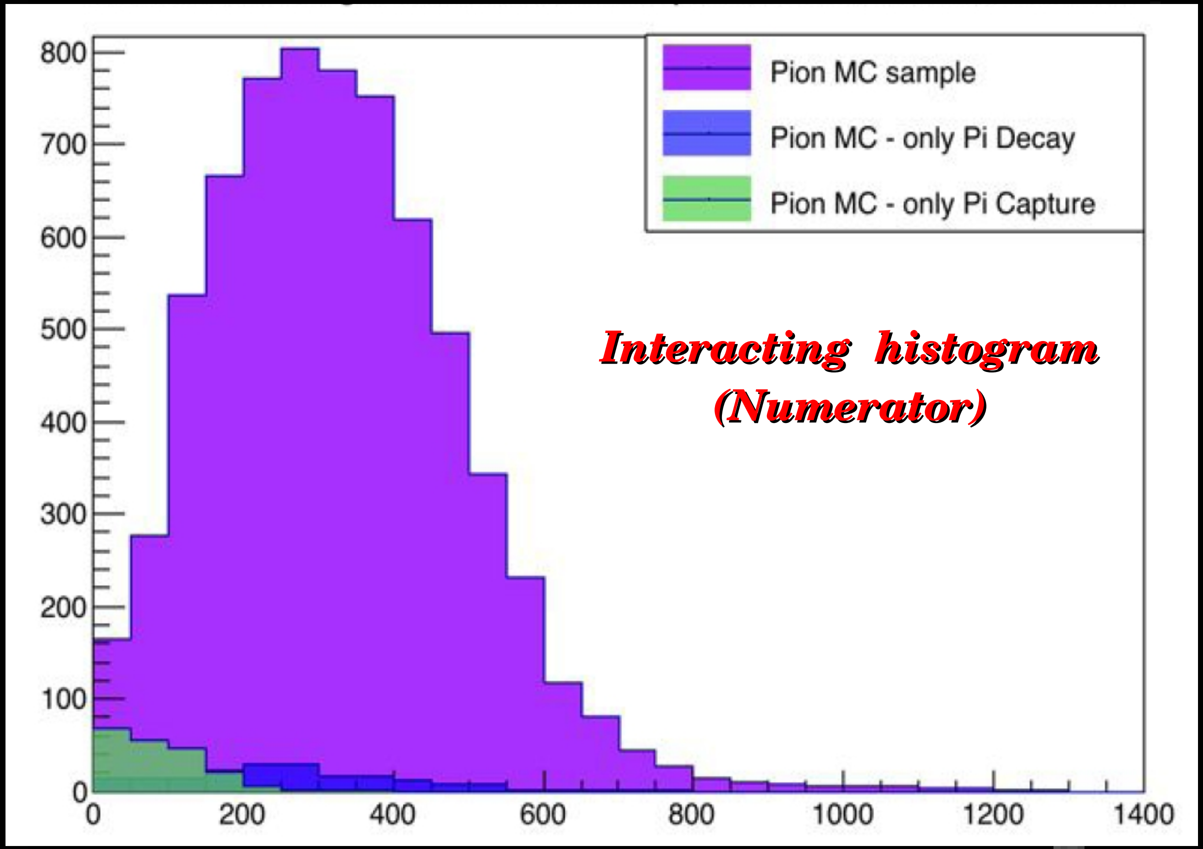

Reconstructed TPC Track
TPC Front Face
α
Projected WC Track
MWPC 4
MWPC 3

Total π⁻ – Ar cross section



First π⁻ – Ar cross section measurement!

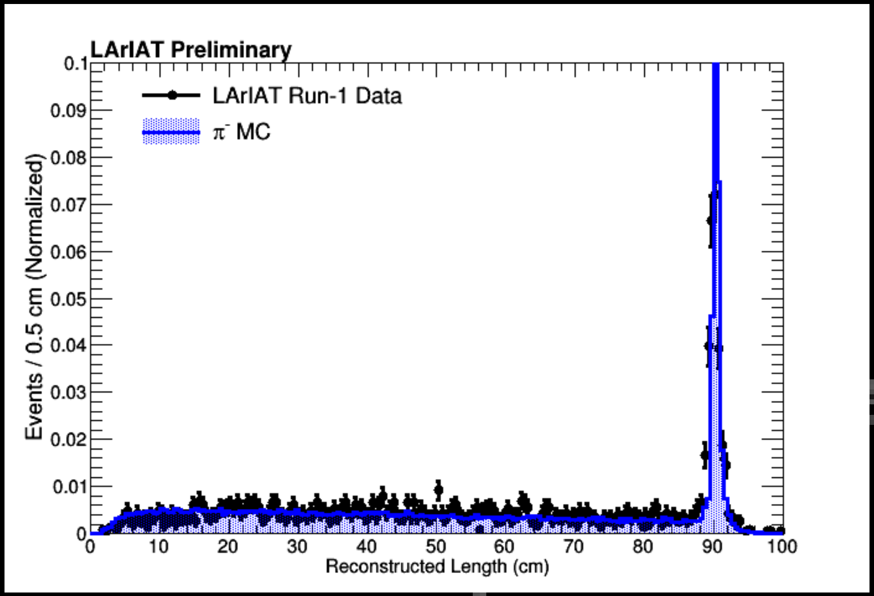
Background contamination

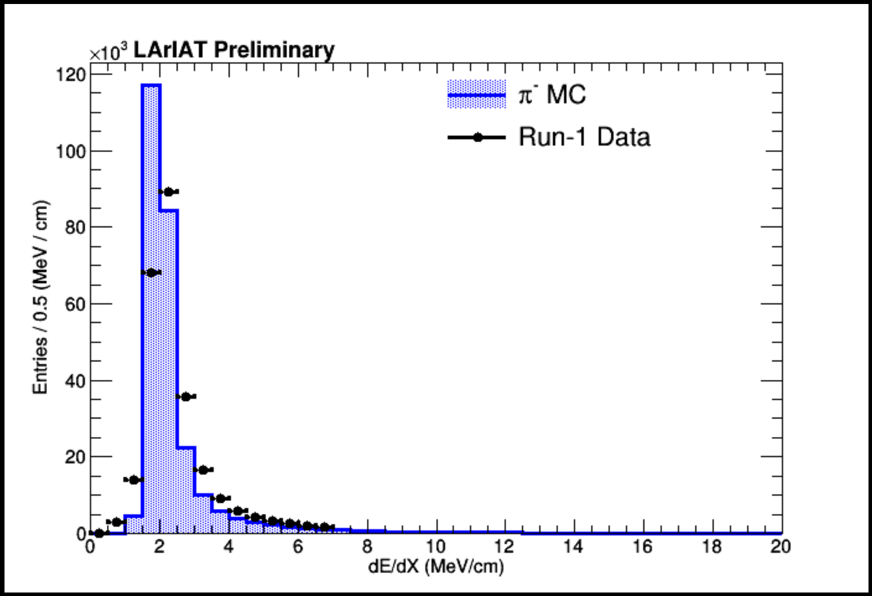


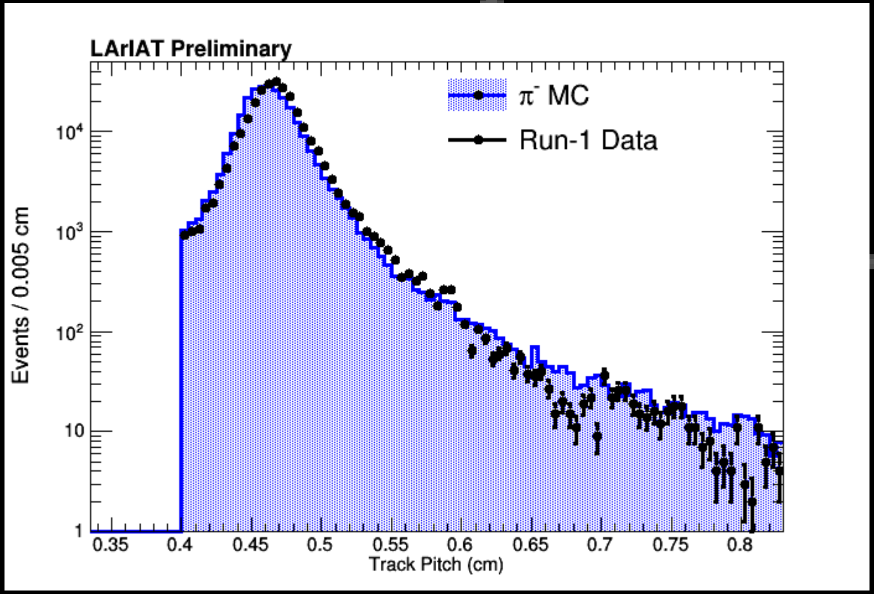
Reconstructed Kinetic Energy (MeV)

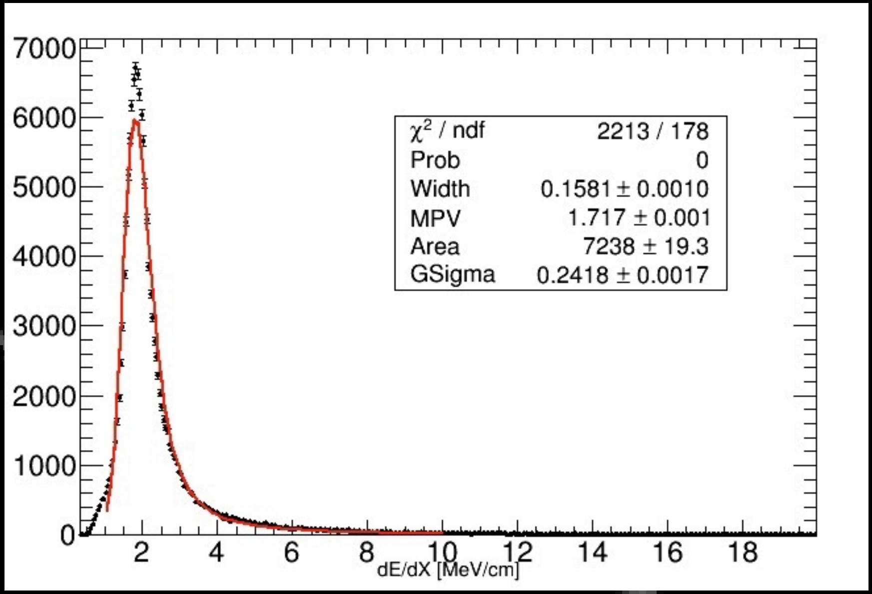
- Approximately 9% π-capture and 2% π-decay in the interacting sample
- 34% crossing particles (π/μ) and 66% interacting particles in the TPC
- ~10% muon contamination uniformly distributed (not shown here)

A look at some variables



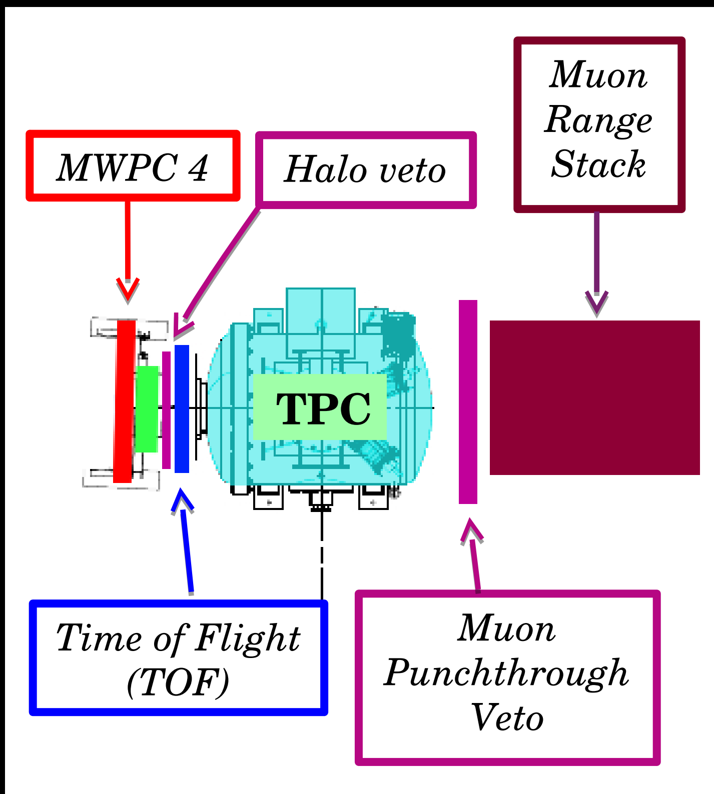


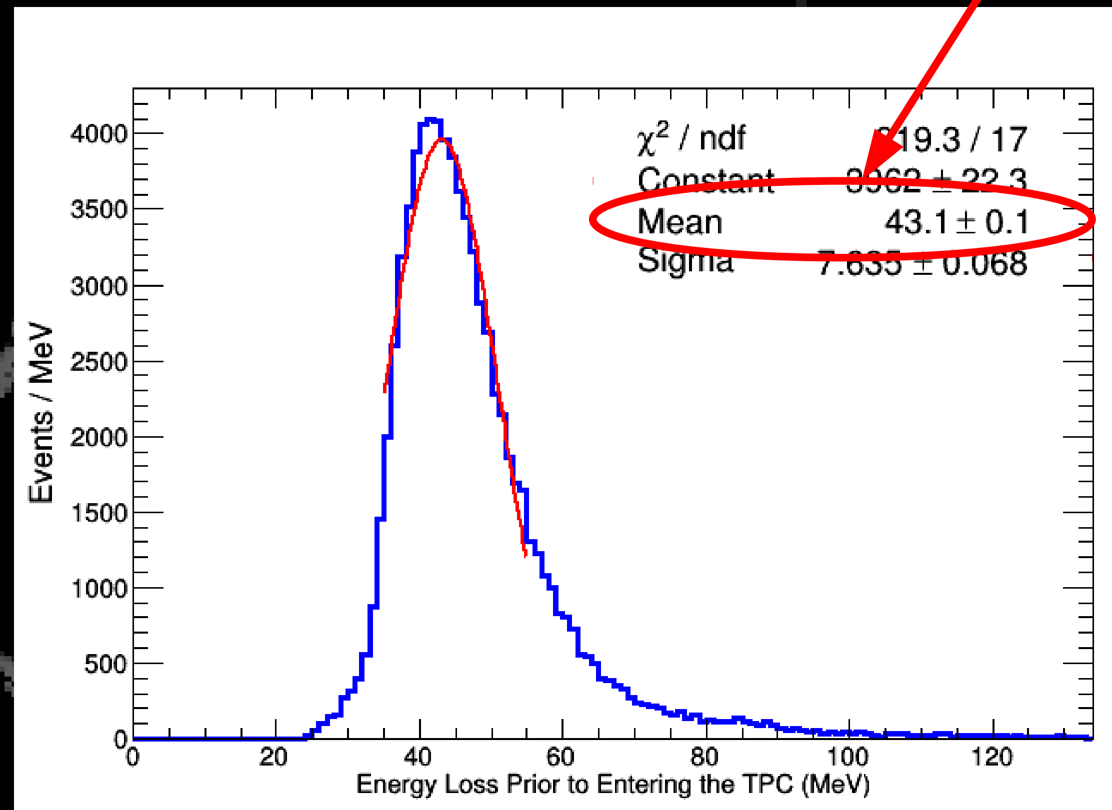




Energy Corrections

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





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