Liquid Argon under investigation: first results from the LArIAT experiment.

Elena Gramellini - Yale University

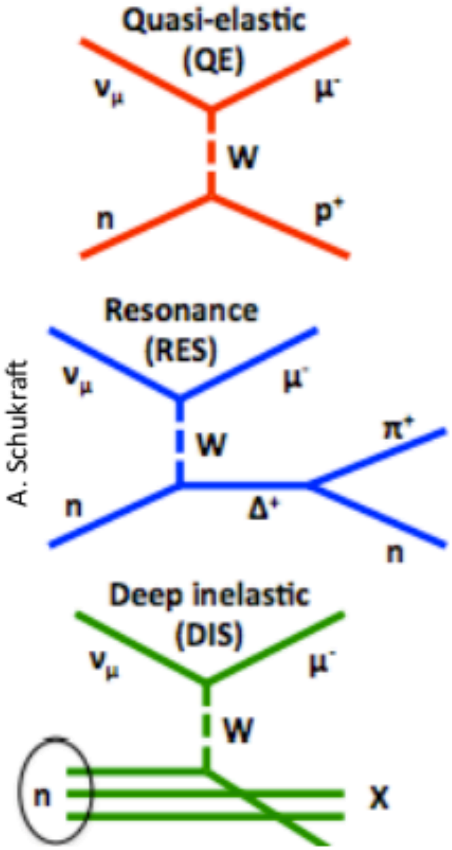
On behalf of the LArIAT collaboration

High Energy Physics Group Seminar
Imperial College London
Nov 1st 2017

What's your picture of a ν interaction?

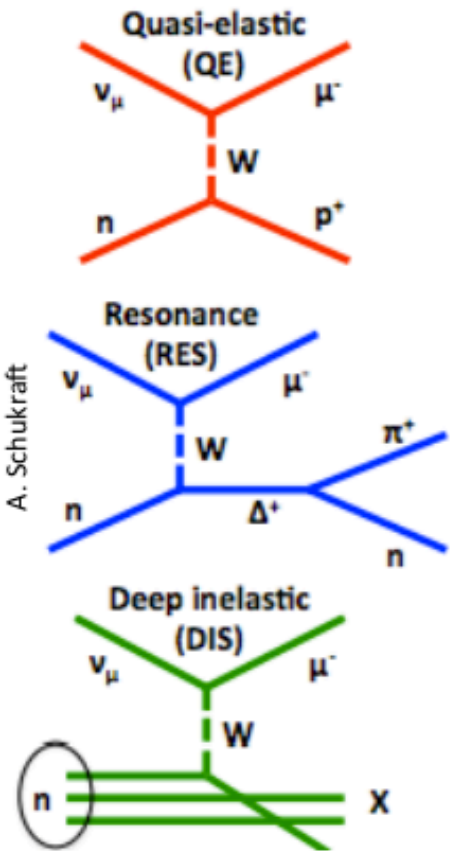
Different points of view

Theorists

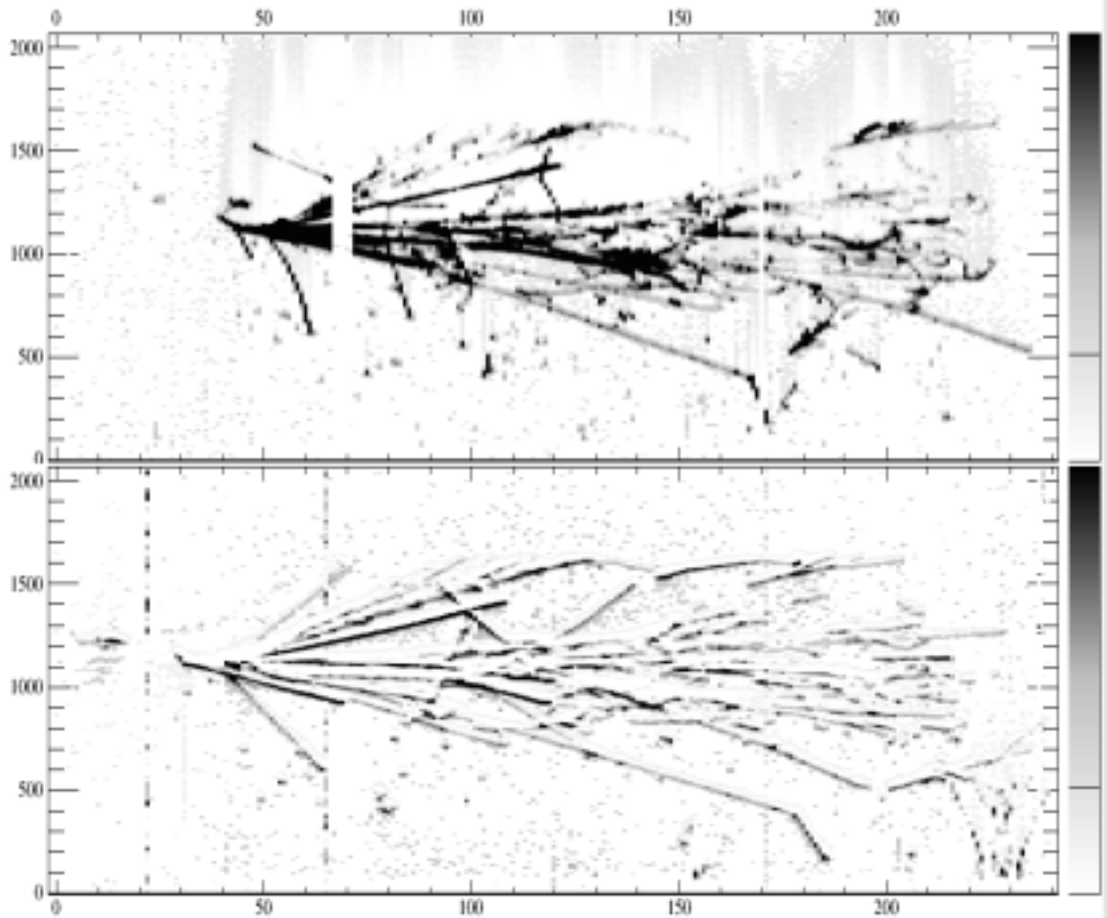


Different points of view

Theorists

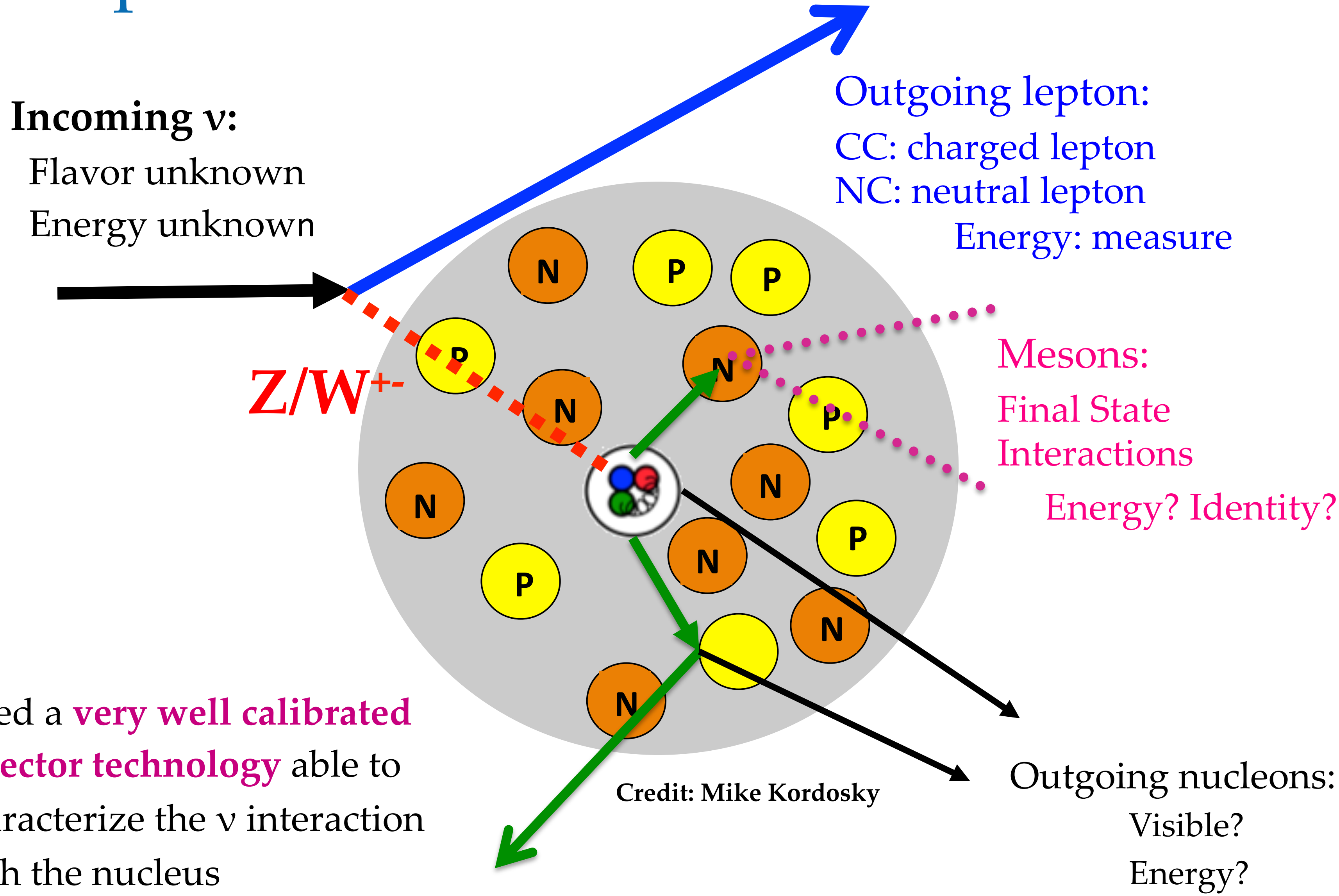


Experimentalists



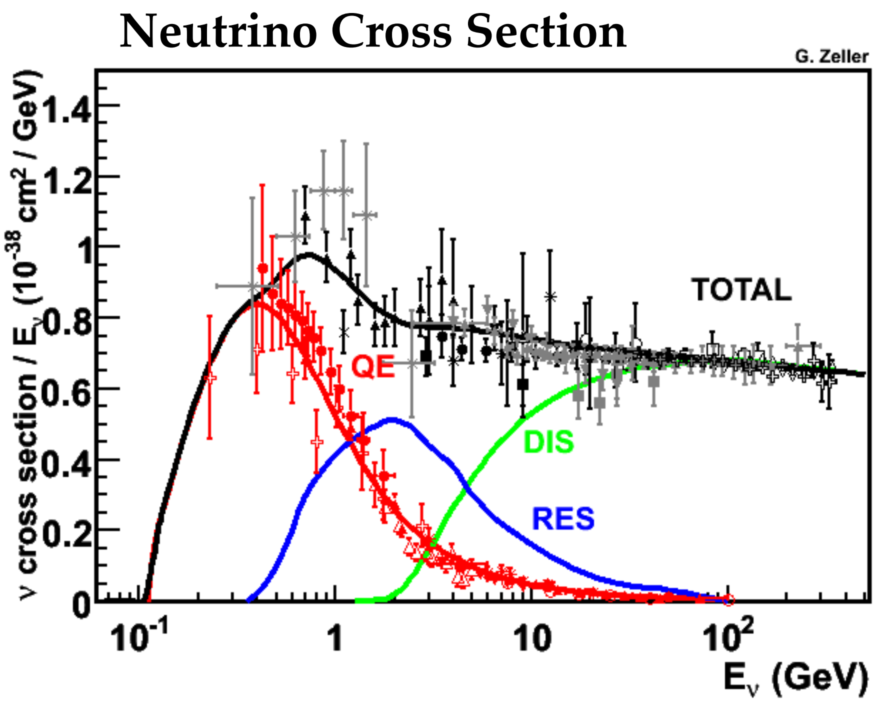
DIS as seen by the ArgoNeuT Detector

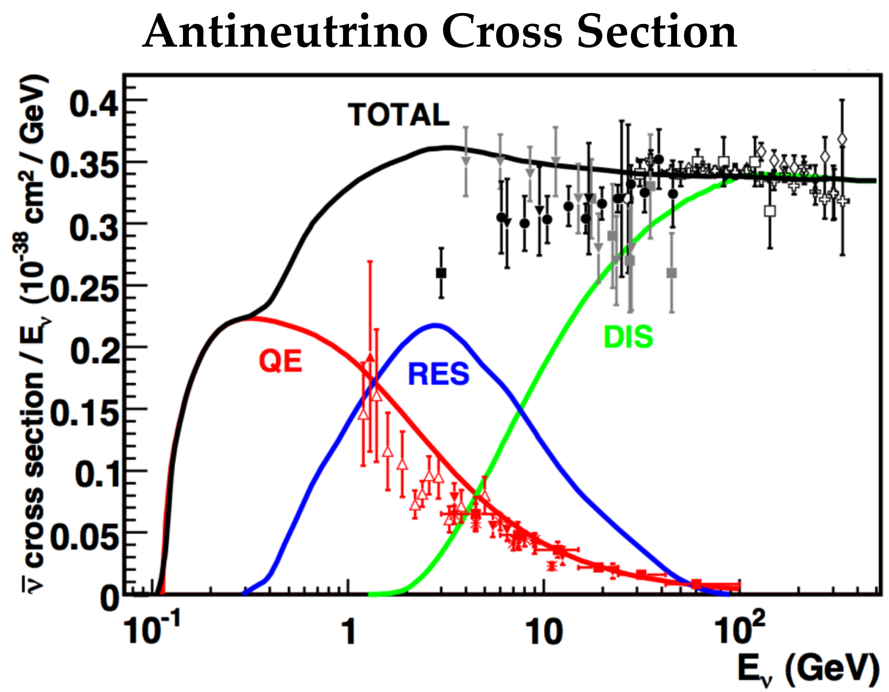
Simplified view of ν interaction



Need a **very well calibrated detector technology** able to characterize the ν interaction with the nucleus

ν Interaction Cross Section





Rev. Mod. Phys. 84, 1307

Neutrinos Cross Section ARE SMALL

What about **low energy** finals state particles in ν interactions?

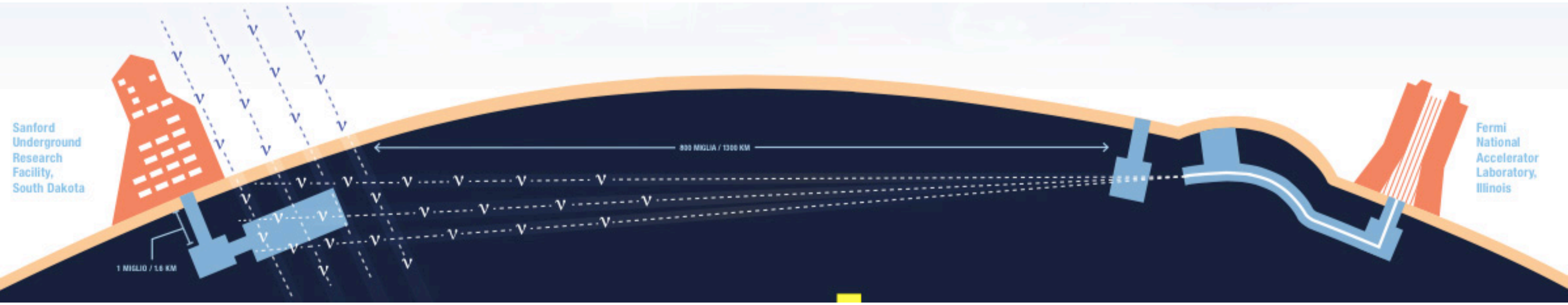
Wish list for your next ν detector

- New big and dense detectors!
- A detector technology able to perform calorimetry and particle ID with a low energy threshold
- An excellent calibration of that technology

Wish list for your next ν detector

- **New big and dense detectors!**
- A detector technology able to perform calorimetry and particle ID with a low energy threshold
- An excellent calibration of that technology

DUNE: the next big thing in ν physics

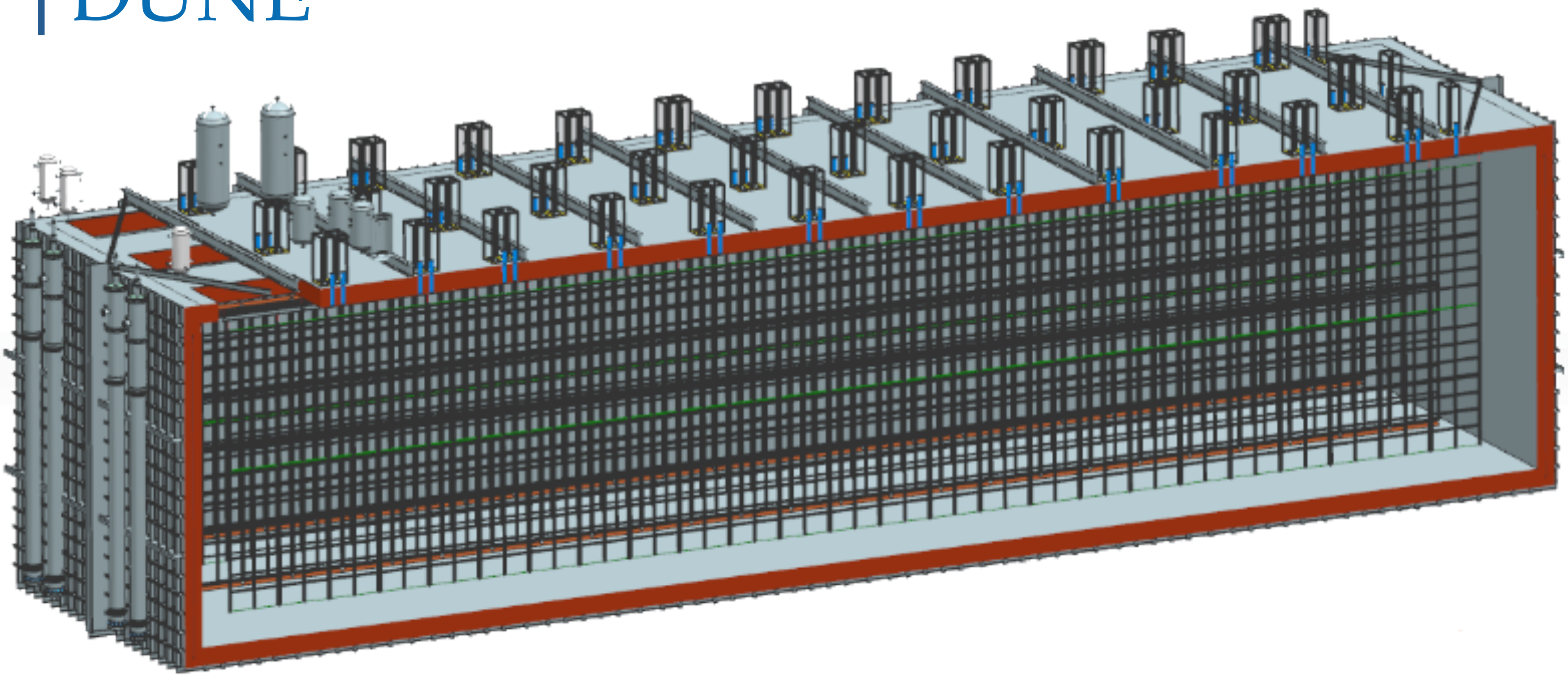


International flagship project in the HEP panorama:

- Explore CP violation in neutrino sector
- Precision Measurements of Neutrino Mixing
- Neutrino Mass Hierarchy
- Rare BSM processes: proton decay, nnbar oscillation

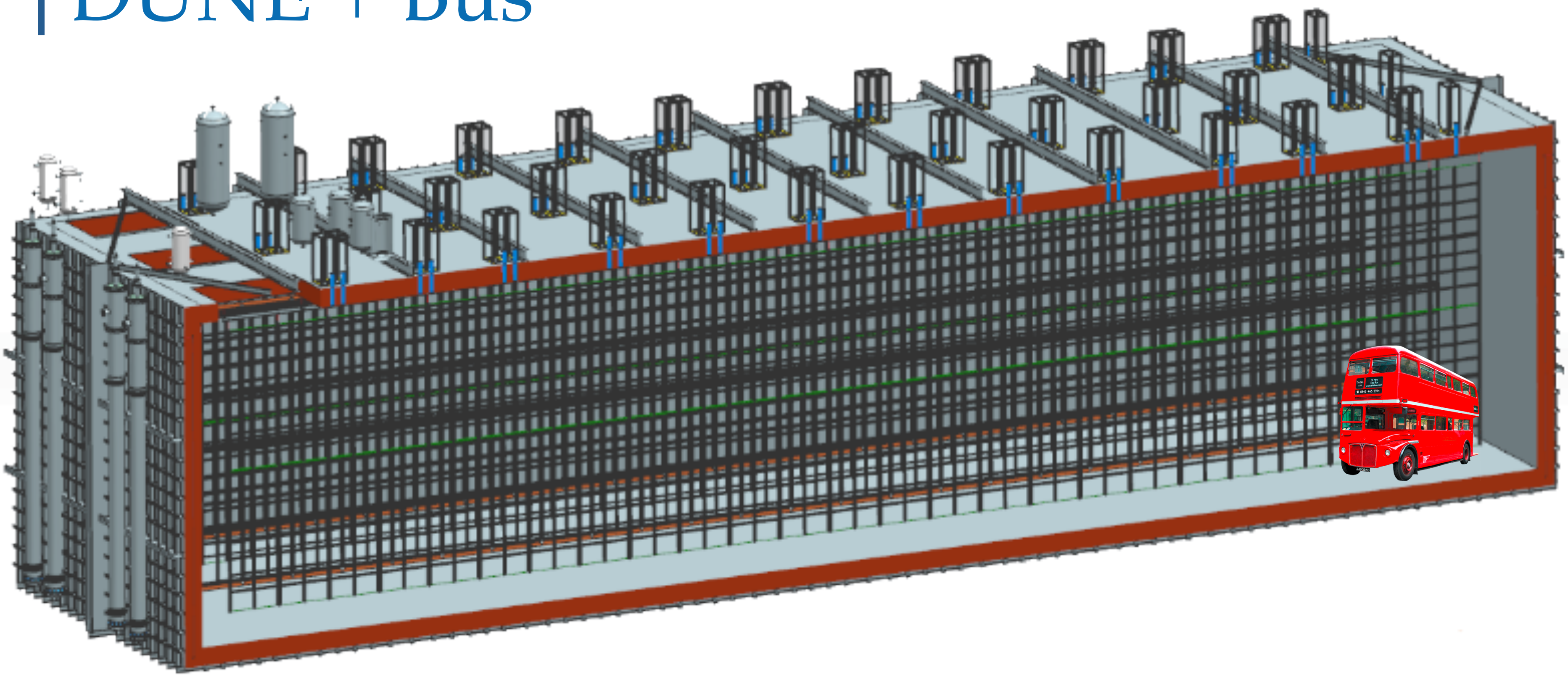
4 gigantic LArTPCs (40 kTon total) located 1.6 km underground

DUNE



One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)

DUNE + Bus



The Routemaster bus (2.4 m x 4.4 m x 9.1 m)

Wish list for your next ν detector

- New big and dense detectors!
- **A detector technology able to perform calorimetry and particle ID with a low energy threshold**
- An excellent calibration of that technology

Liquid Argon ~~Fun~~ Facts

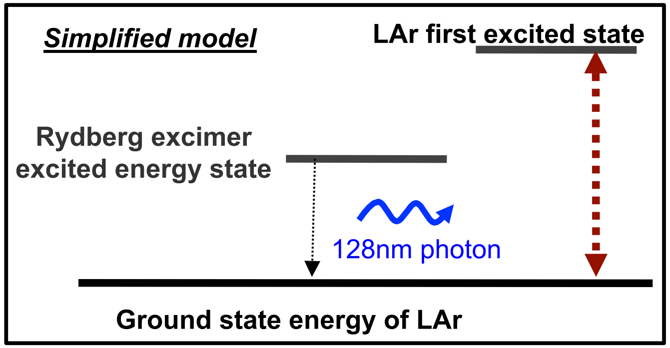
Dense *40% more dense than water*

Abundant *1% of the atmosphere*

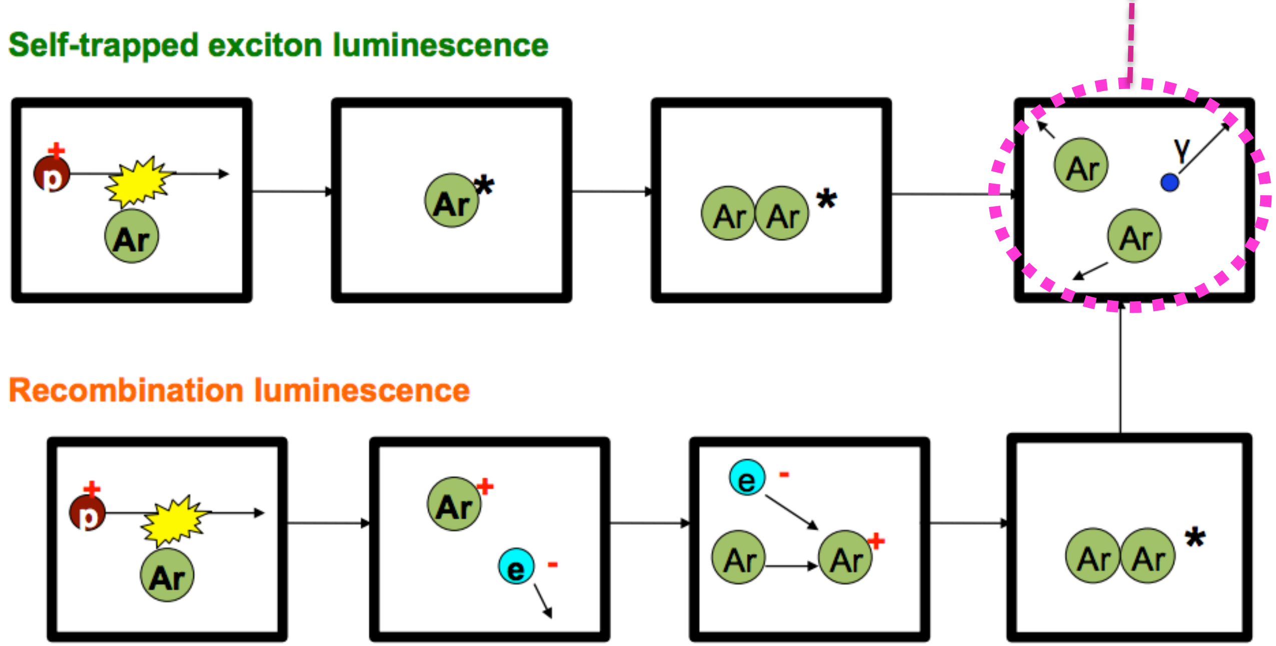
Ionizes easily *55,000 electrons / cm*

High e$^-$ lifetime

Lots of scintillation light *Transparent to light produced*

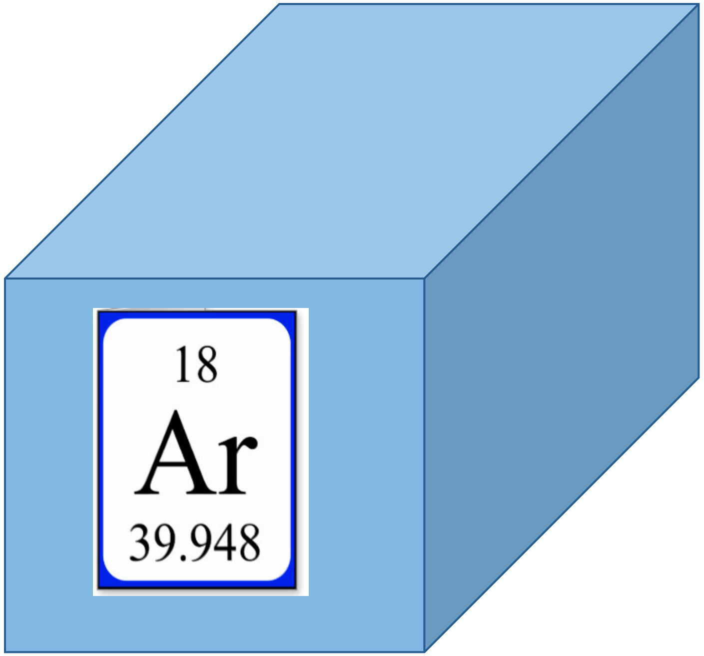


J. Asaadi

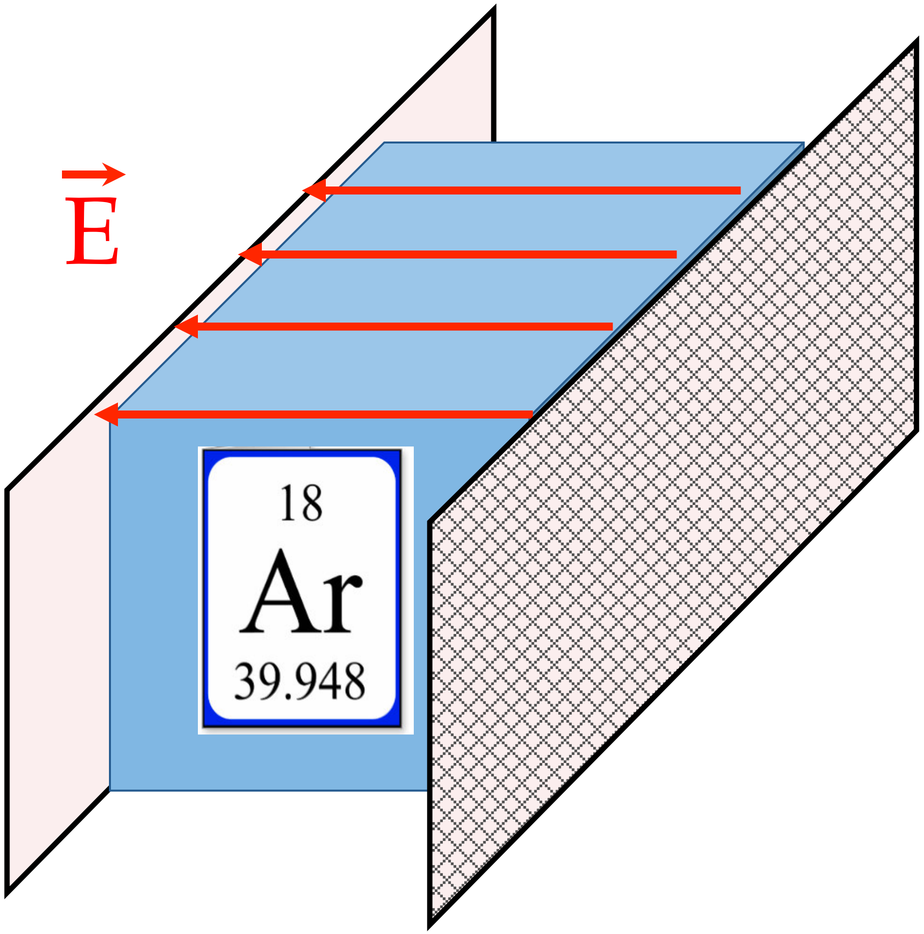


B. Jones

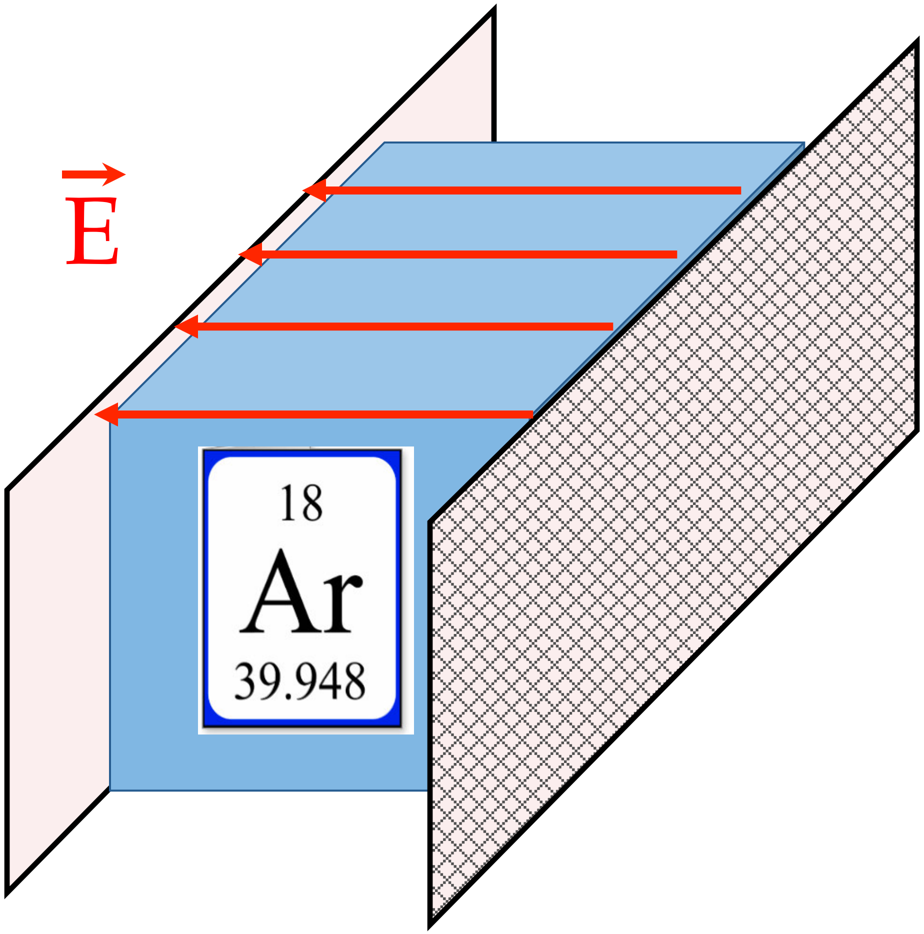
Liquid Argon Time Projection Chamber 101



Liquid Argon Time Projection Chamber 101



Liquid Argon Time Projection Chamber 101



LArTPC working principles

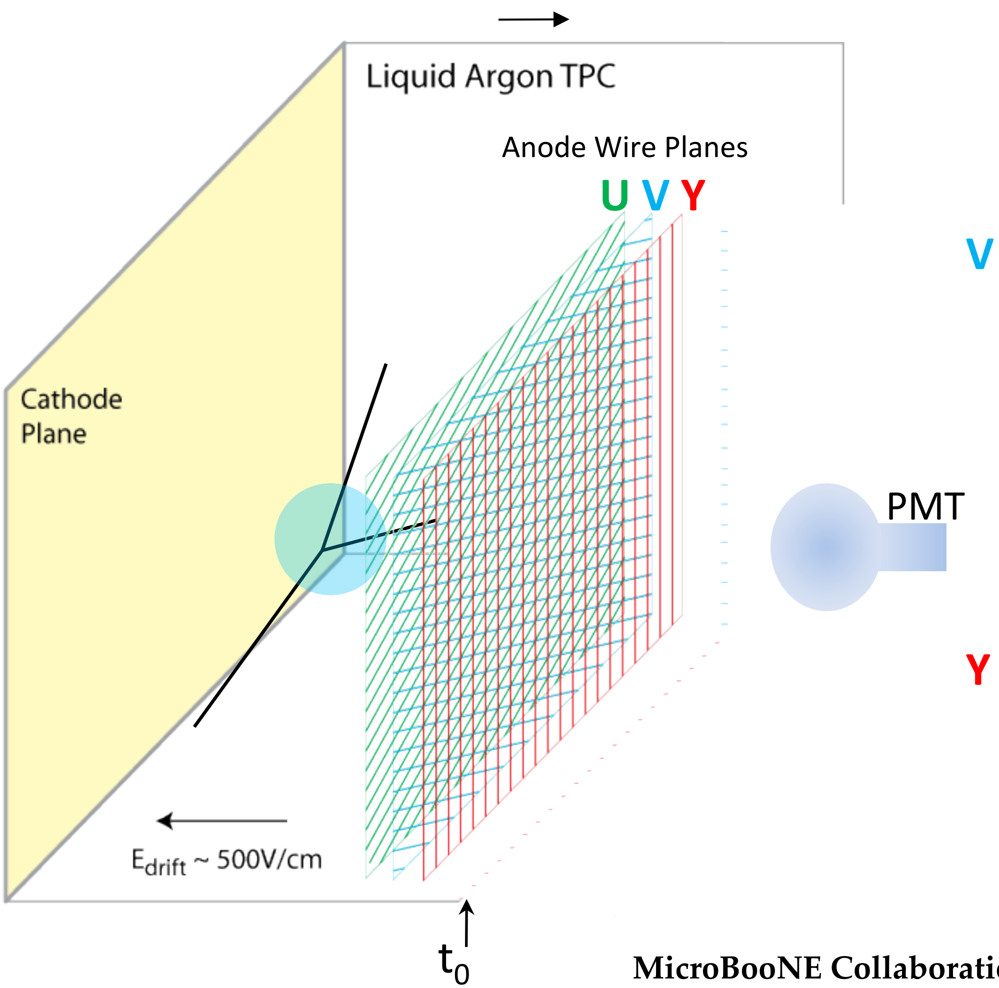
1. Energy loss by charged particles:
   Ionization and
   Excitation of Ar

2. Prompt light emission by Ar_2^+ starts clock

3. Electrons drift to anode
   (Ar^+ ions drift to cathode)

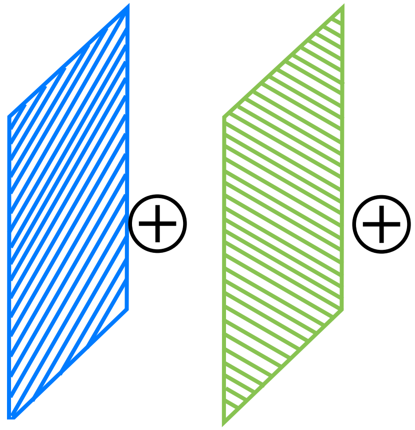
4. Moving electrons induce currents on wires

5. Tracks are reconstructed from wire signals

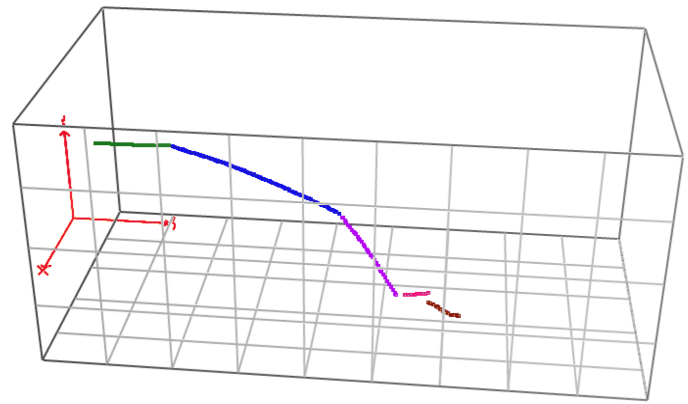


MicroBooNE Collaboration

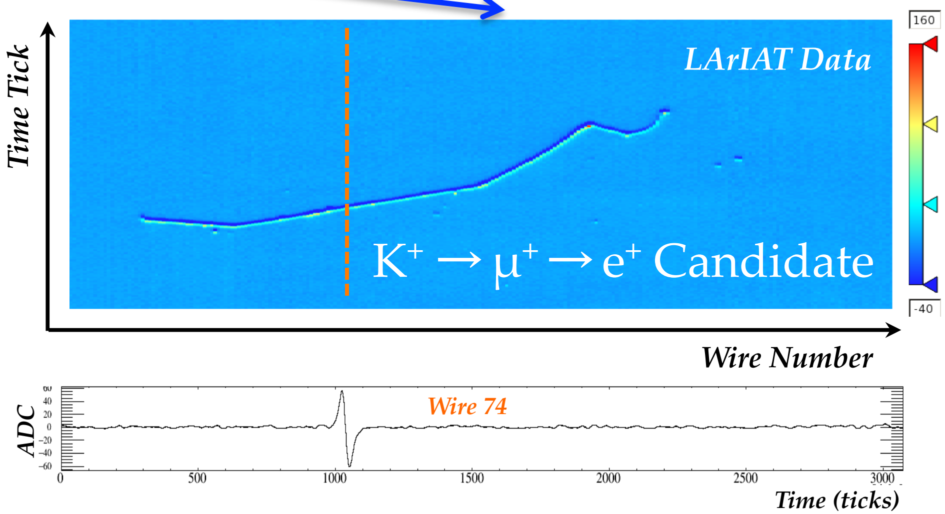
LArTPC Key Features

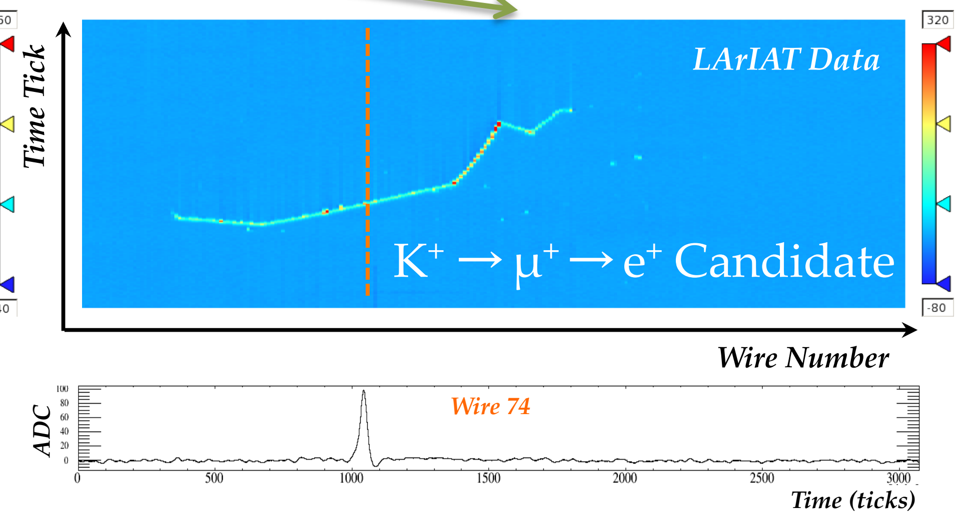


Drift time =

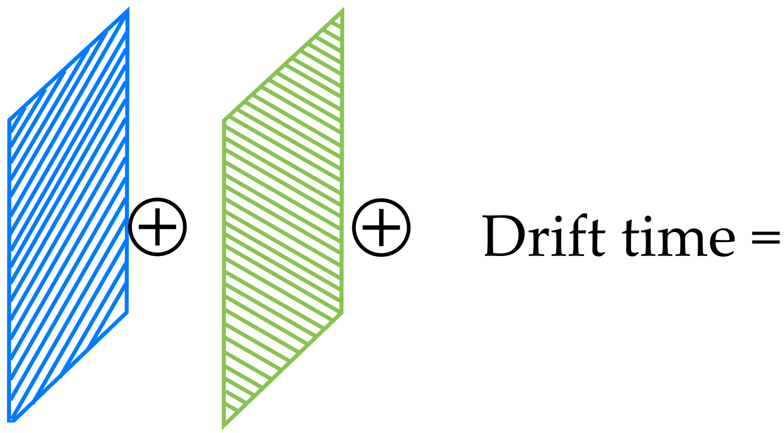


Induction plane **Collection plane**



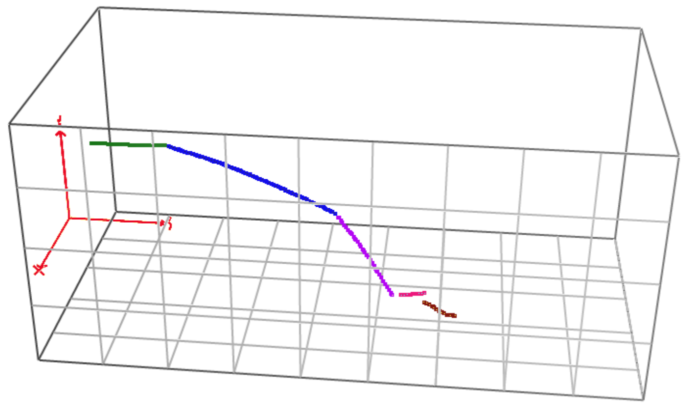


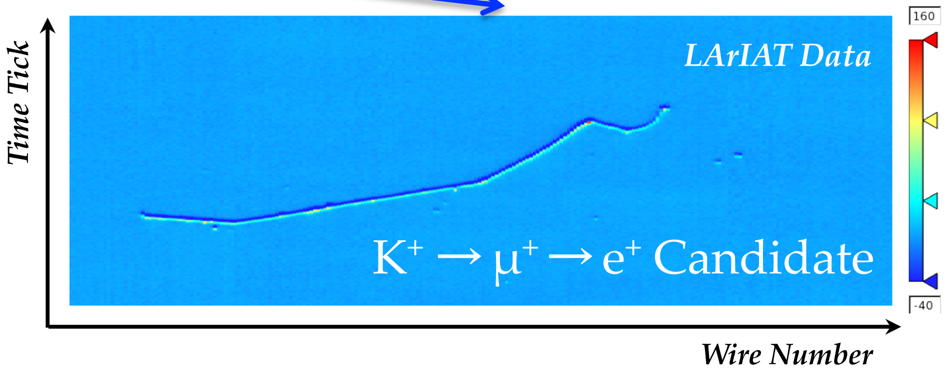
LArTPC Key Features

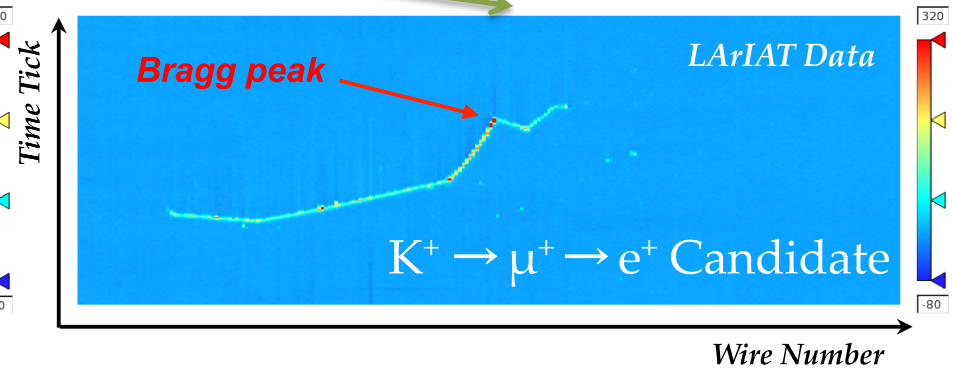


Induction plane

Collection plane







3D imaging with mm space resolution

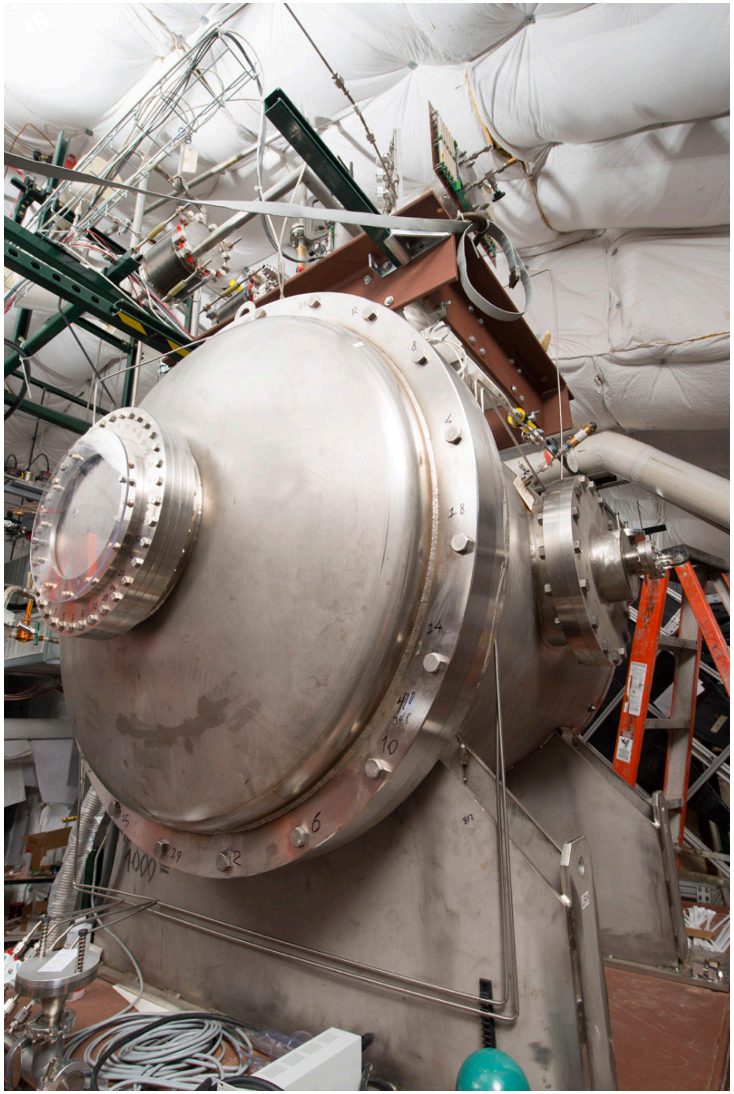
Calorimetry information

PID capabilities

Wish list for your next ν detector

- New big and dense detectors!
- A detector technology able to perform calorimetry and particle ID with a low energy threshold
- **An excellent calibration of that technology**

What's LArIAT? (and why ν experiments need us)



Liquid Argon In A Testbeam

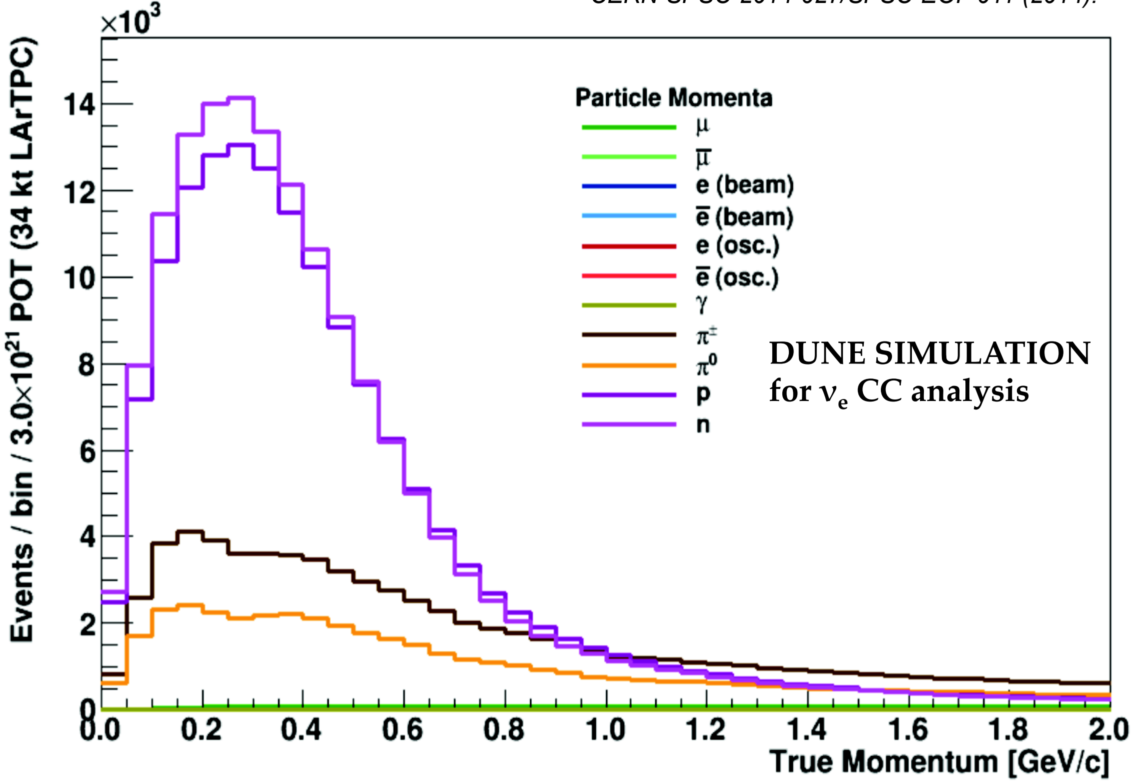
LArIAT is a 170 liters LArTPC deployed in a beam of known charged particles

We want to execute a comprehensive program designed to characterize LArTPC performance in the energy range relevant to the forthcoming neutrino experiments

What's LArIAT? (and why ν experiments need us)

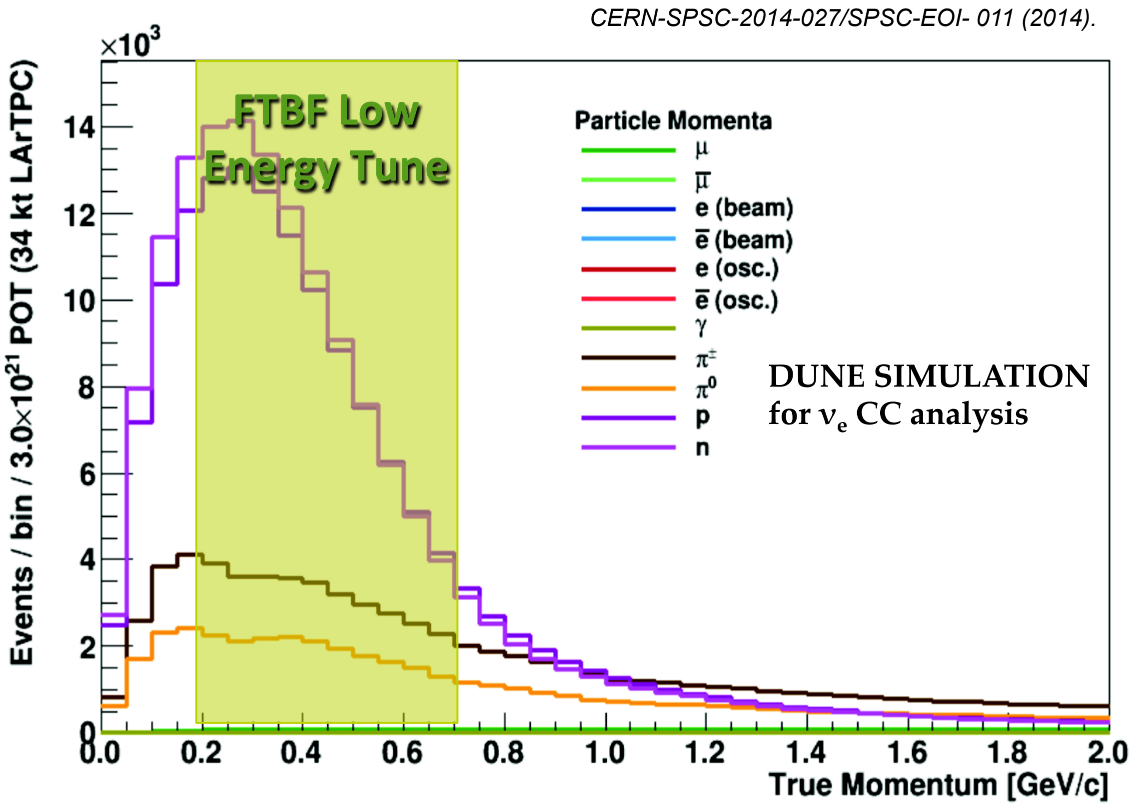
A LArTPC in the Fermilab Test Beam Facility is well suited to study charged particles in the **energy range** relevant to both the **Short-Baseline** (MicroBooNE, SBND, ICARUS) and **Long-Baseline** (DUNE) experiments

CERN-SPSC-2014-027/SPSC-EOI- 011 (2014).



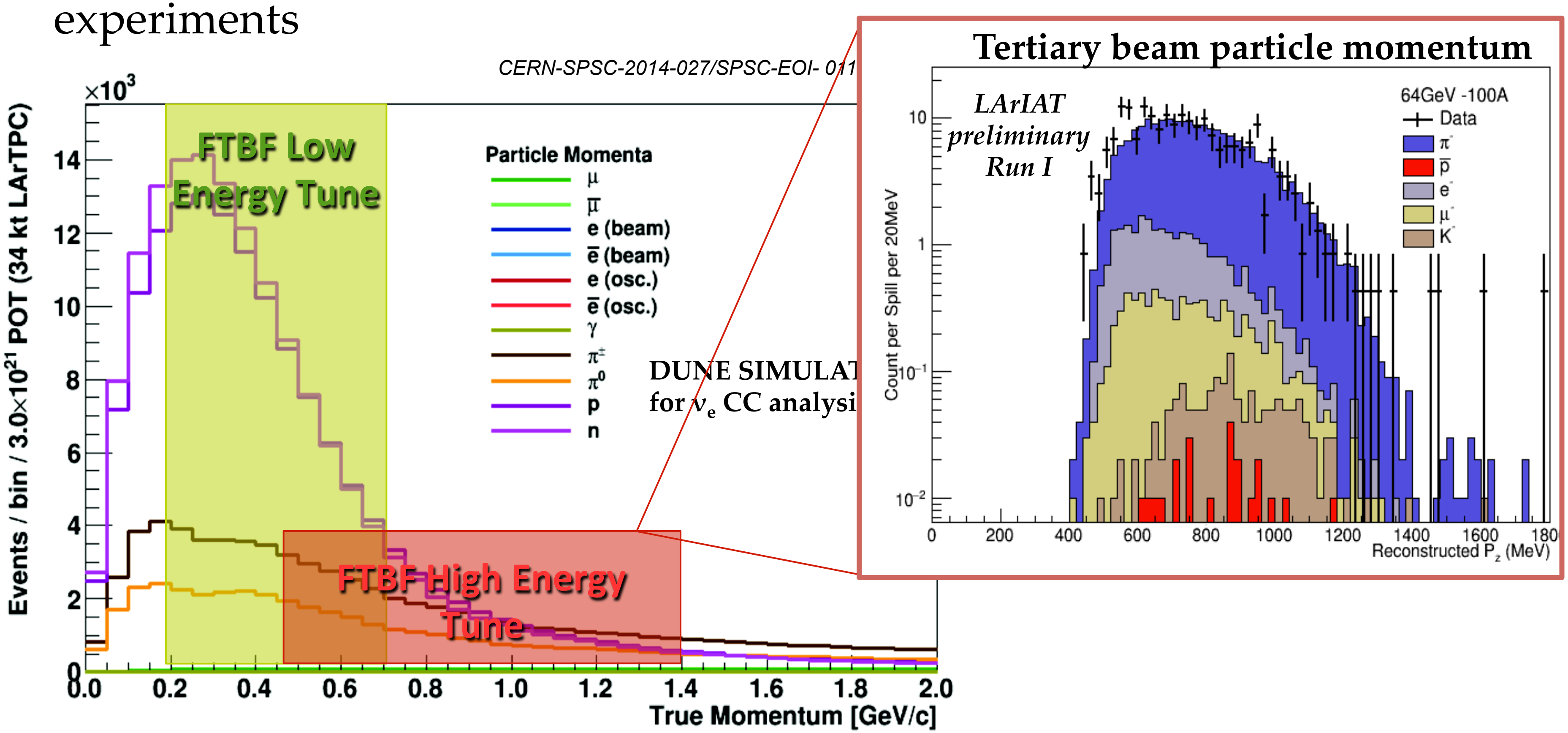
What's LArIAT? (and why ν experiments need us)

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** (MicroBooNE, SBND, ICARUS) and **Long-Baseline** (DUNE) experiments



What's LArIAT? (and why ν experiments need us)

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** (MicroBooNE, SBND, ICARUS) and **Long-Baseline** (DUNE) experiments



Vast physics program

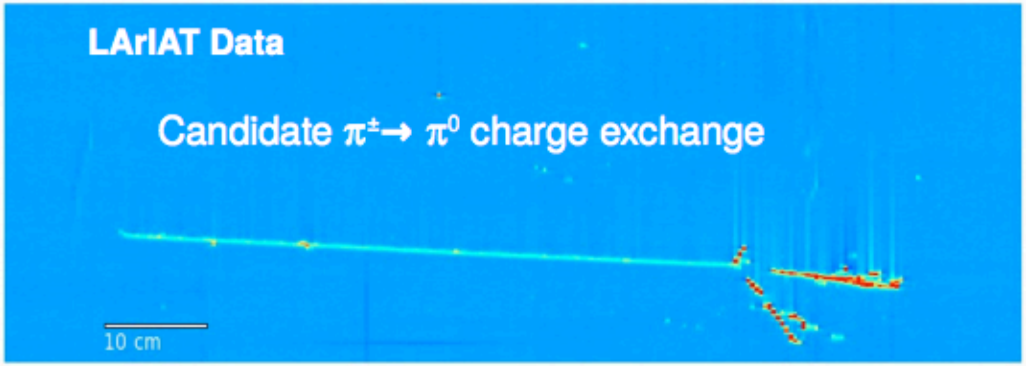
Physics Goals

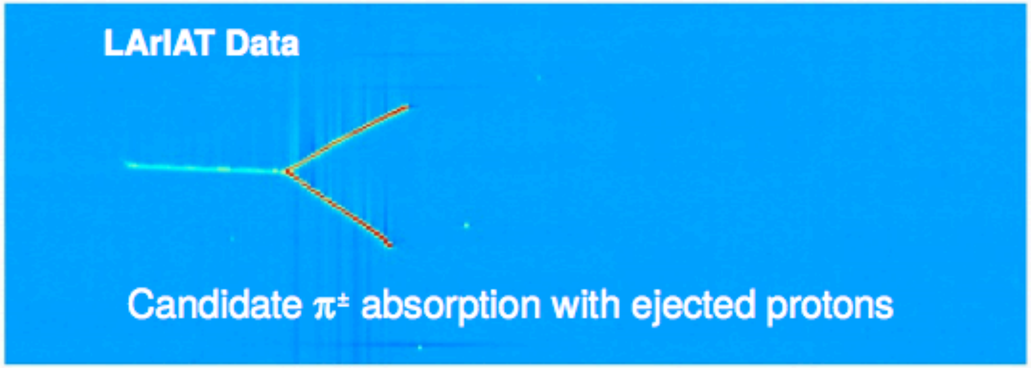
Hadron-Ar interaction cross sections:
π-Ar

Test nuclear structure models

Abundant π production in ν interaction for ν energies of few GeV. π-Ar XS affects the possibility of detecting and measuring π in the interaction: systematics in ν experiments

Pion-Ar Cross Section





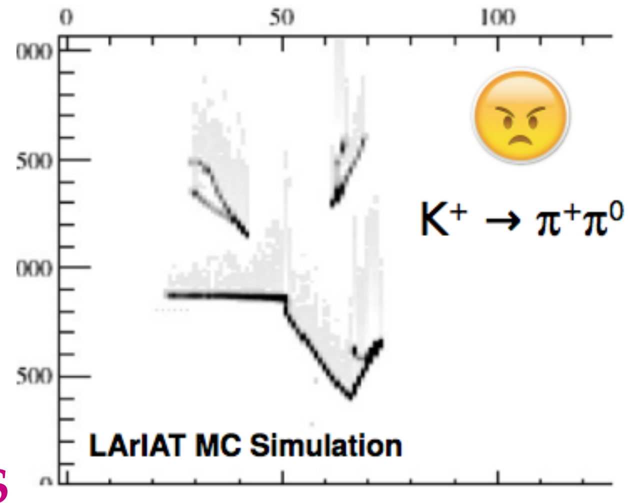
Vast physics program

Physics Goals

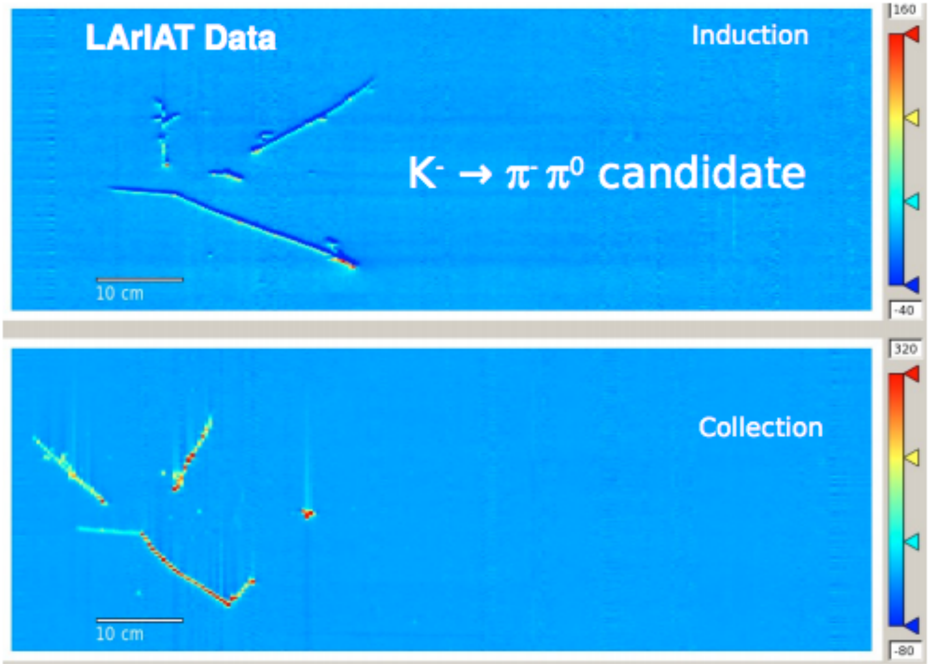
Hadron-Ar interaction cross sections:
K-Ar

Test nuclear structure models

Physics beyond SM
Proton decay modes:
p -> $e^+\pi^0$
water Cherenkov
golden channel
p -> $K^+\bar{\nu}$
LArTPC golden channel



K-Ar XS



Vast physics program

Physics Goals

Hadron-Ar interaction cross sections

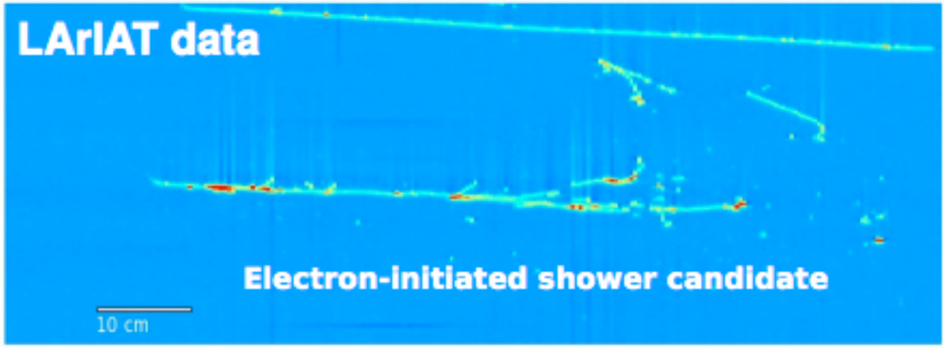
e/γ shower identification

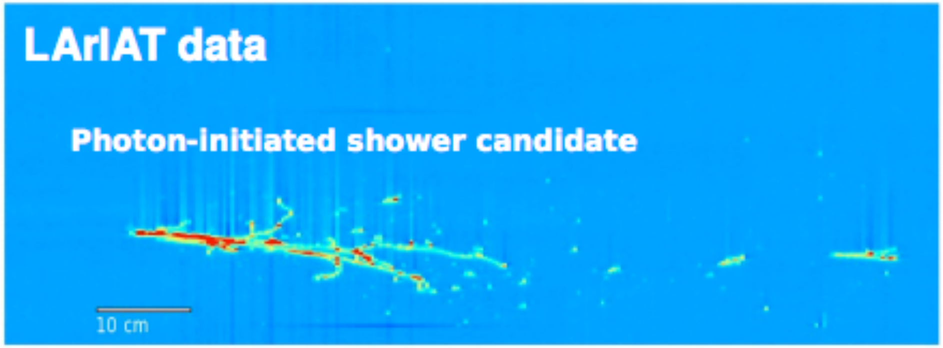
μ sign determination in the absence of a magnetic field, using topology e.g. decay vs capture

Geant4 validation

R&D!

electron photon separation





Vast physics program

Physics Goals

Hadron-Ar interaction cross sections

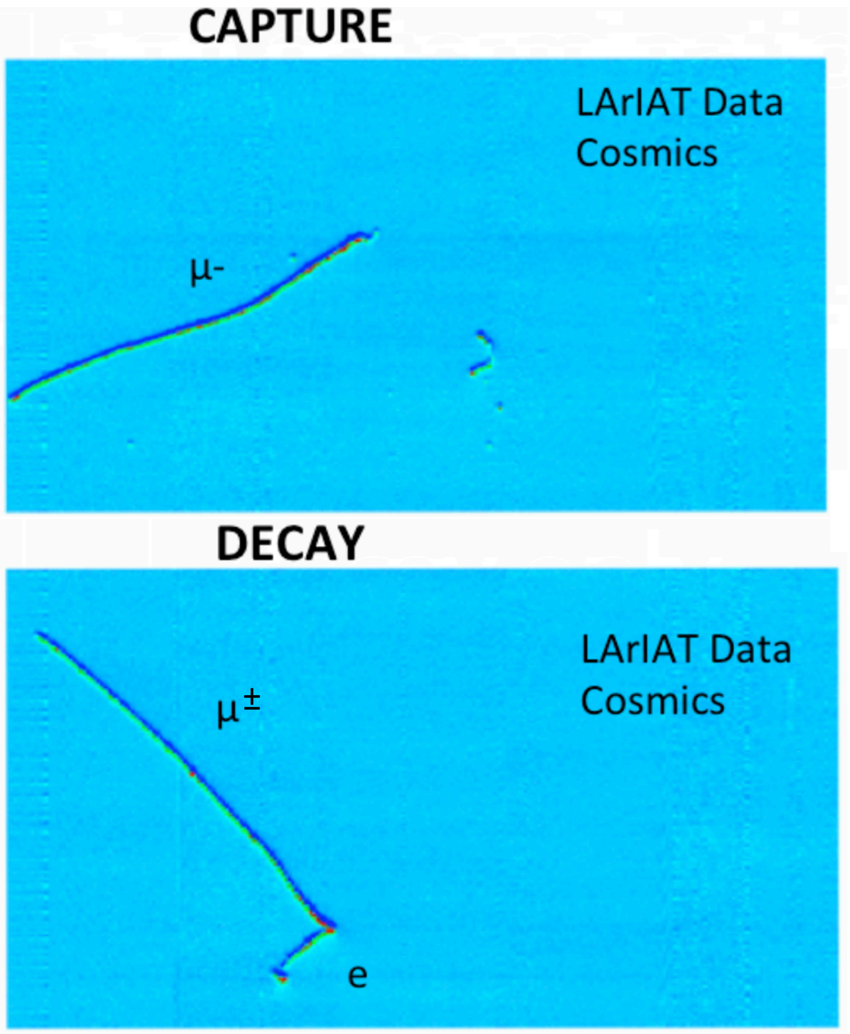
e/γ shower identification

μ sign determination in the absence of a magnetic field, using topology e.g. decay vs capture

Geant4 validation

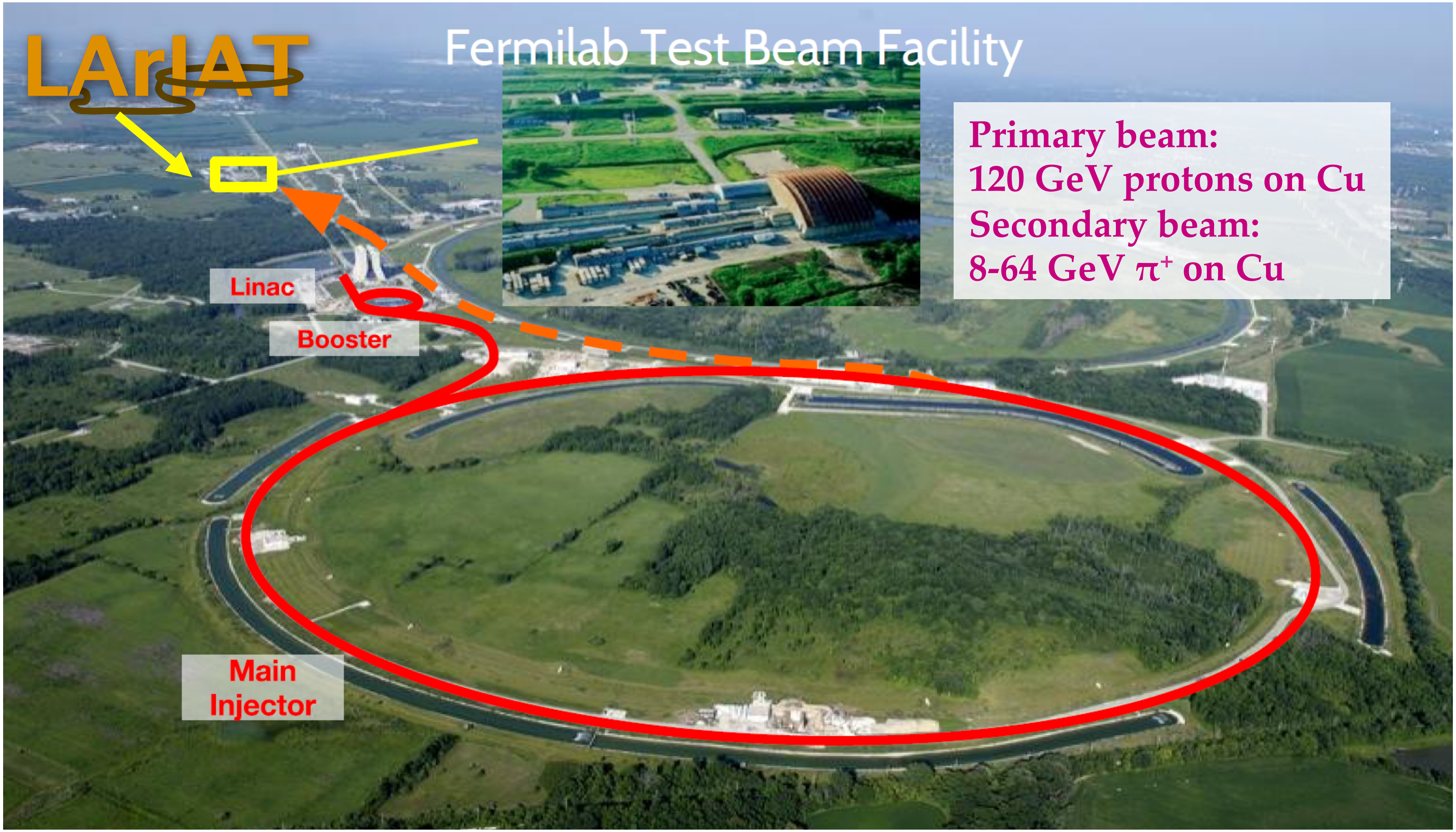
R&D!

μ sign identification, no B field



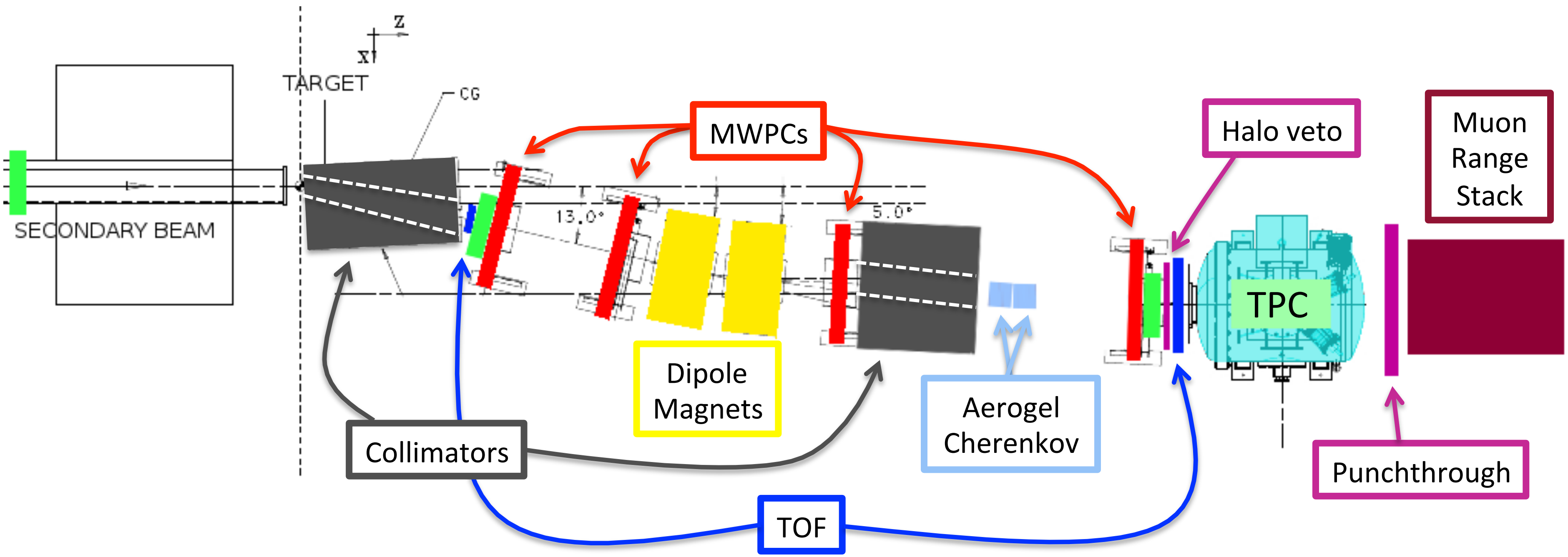
Experiment overview

The proton path



Primary beam:
120 GeV protons on Cu
Secondary beam:
8-64 GeV π^+ on Cu

Bird's eye view of the tertiary beamline



LArIAT Data Taking

2015, Run I:

9 weeks of beam data:

~5.5 weeks at high energy
~3.5 weeks at low energy

2016, Run II:

22 weeks of beam data:

~11 weeks at high energy
~8 weeks at low energy
~3 weeks at very low energy (e^- collection)
~2 weeks rest (filter regeneration)

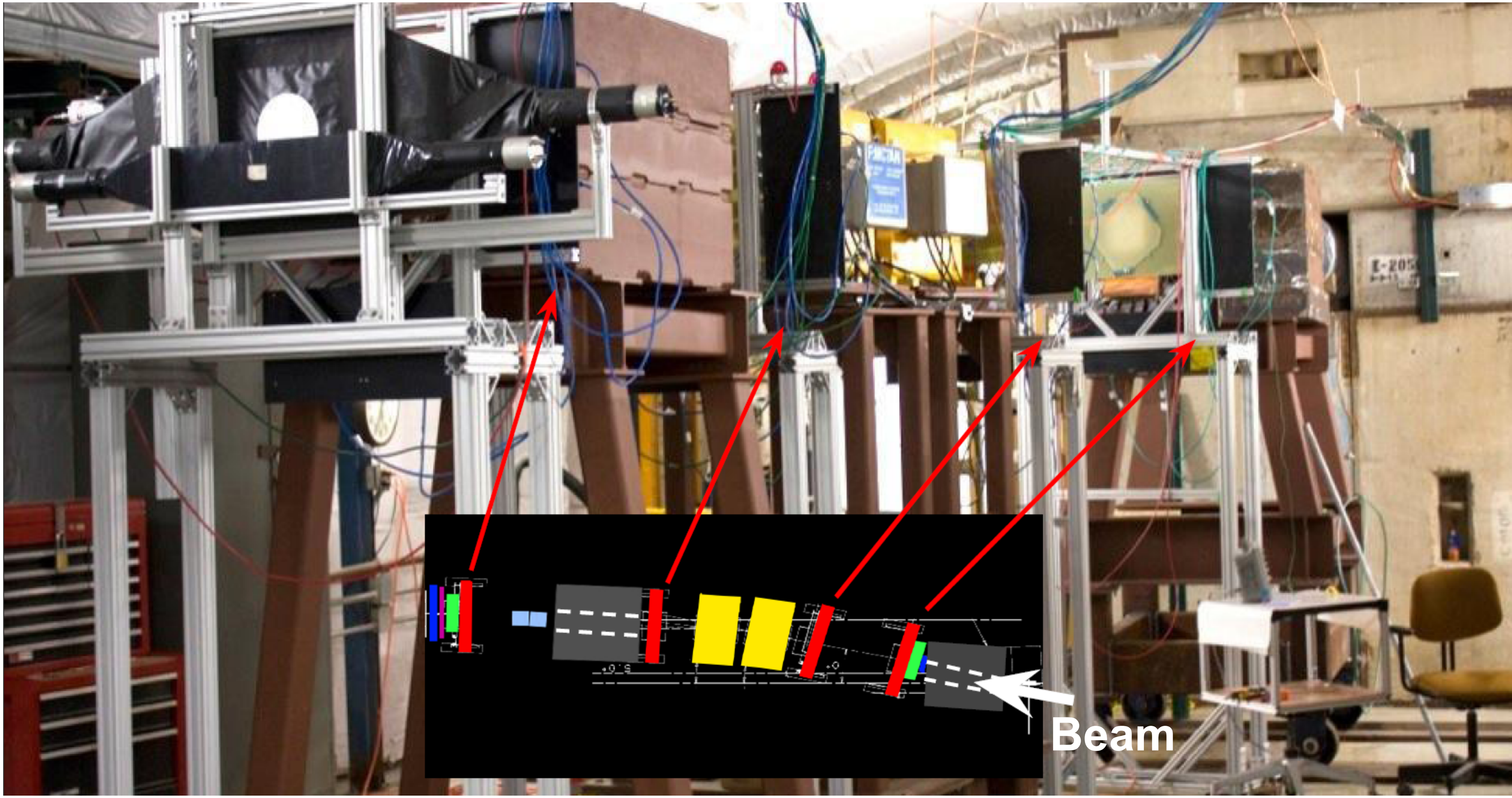
2017, Run III

11 weeks of beam data:

~ 9 weeks at 5 mm TPC wire pitch
~ 2 weeks at 3 mm wire pitch

PixLAr: Coming soon to the best LAr beamline test facility

MWPC and bending magnets



MWPC and bending magnets

Goal: momentum reconstruction

2 upstream Multi-Wire Proportional Chambers

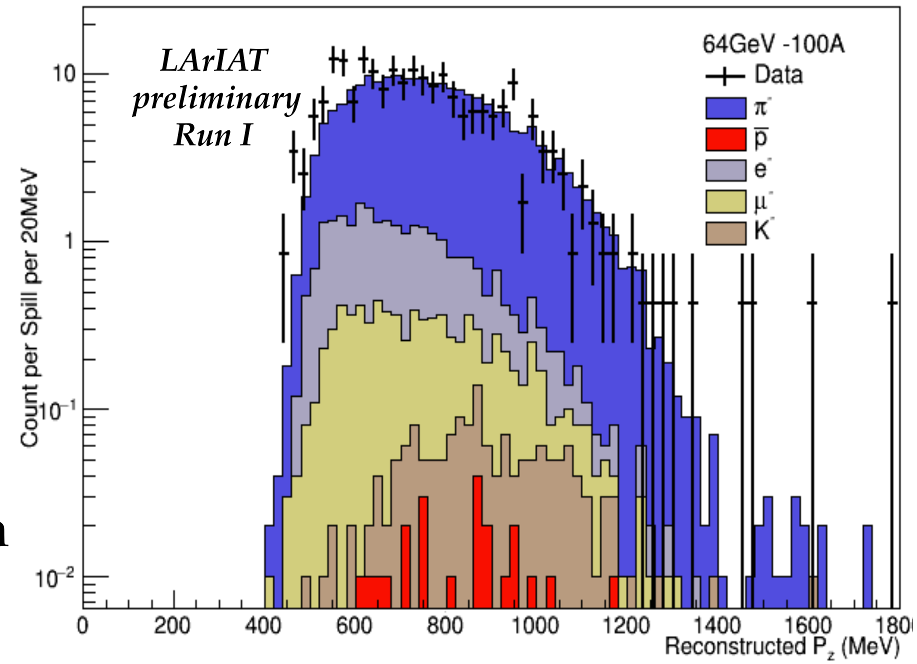
↓

Bending Magnets

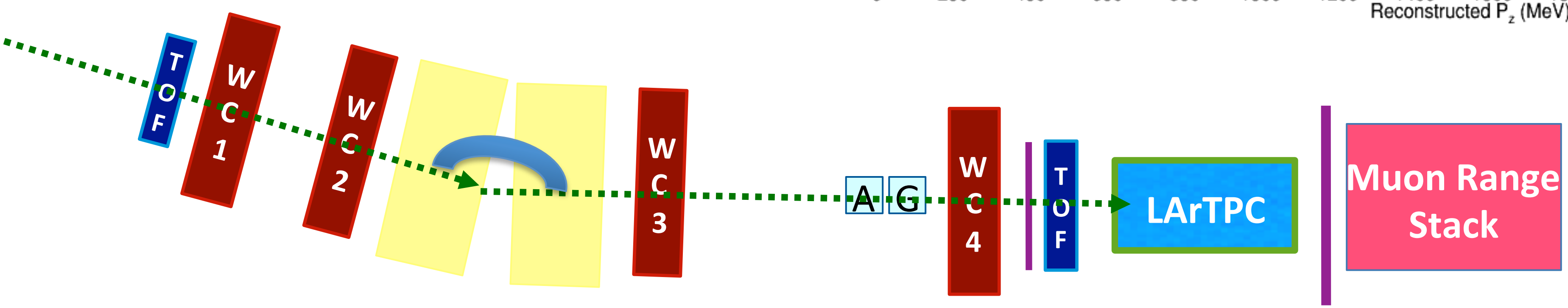
↓

2 downstream Multi-Wire Proportional Chambers

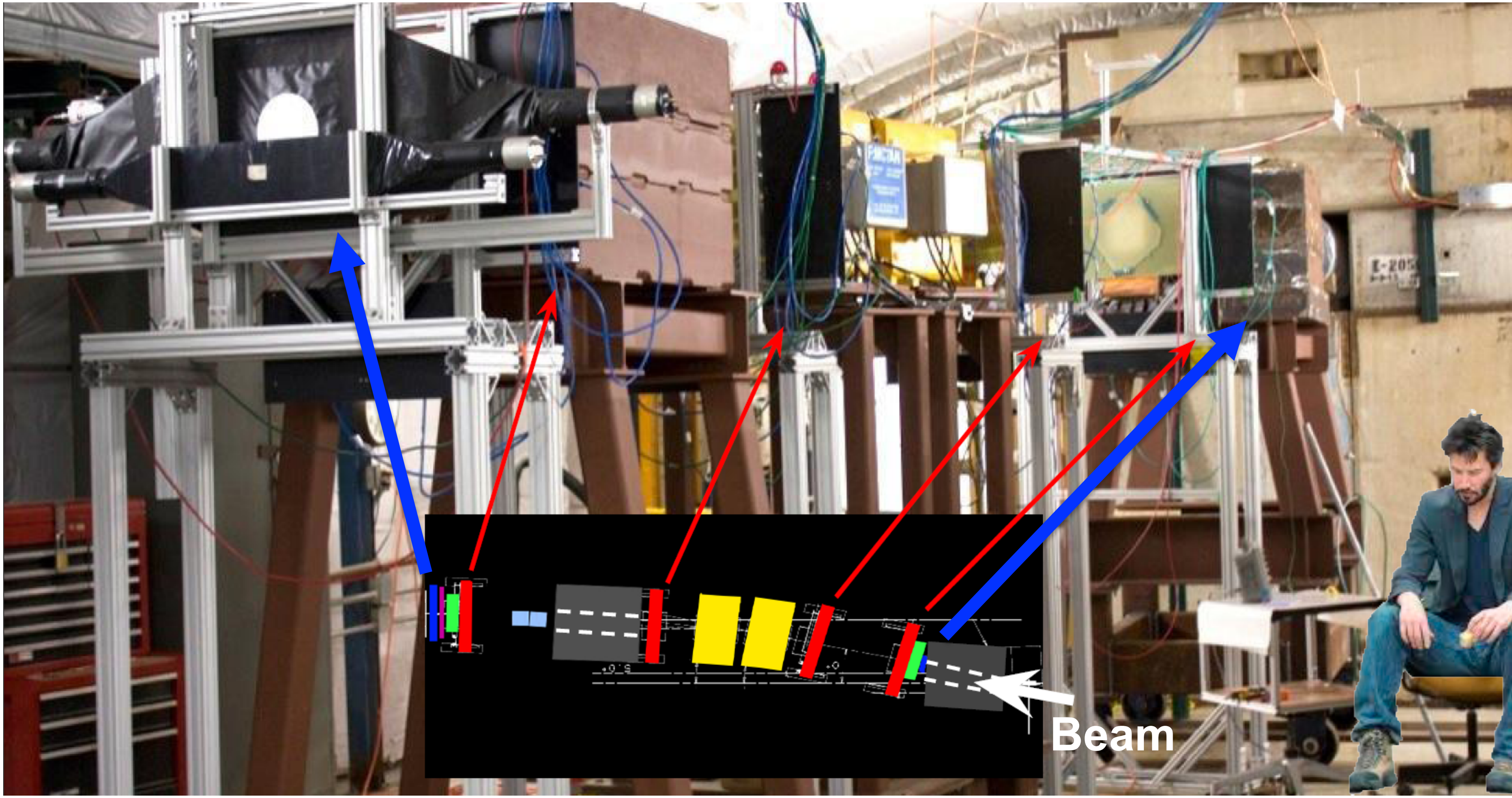
Tertiary beam particle momentum



Difference in angle between tracks determines the momentum reconstruction. Charged particle beam ~200 - 1400 MeV/c



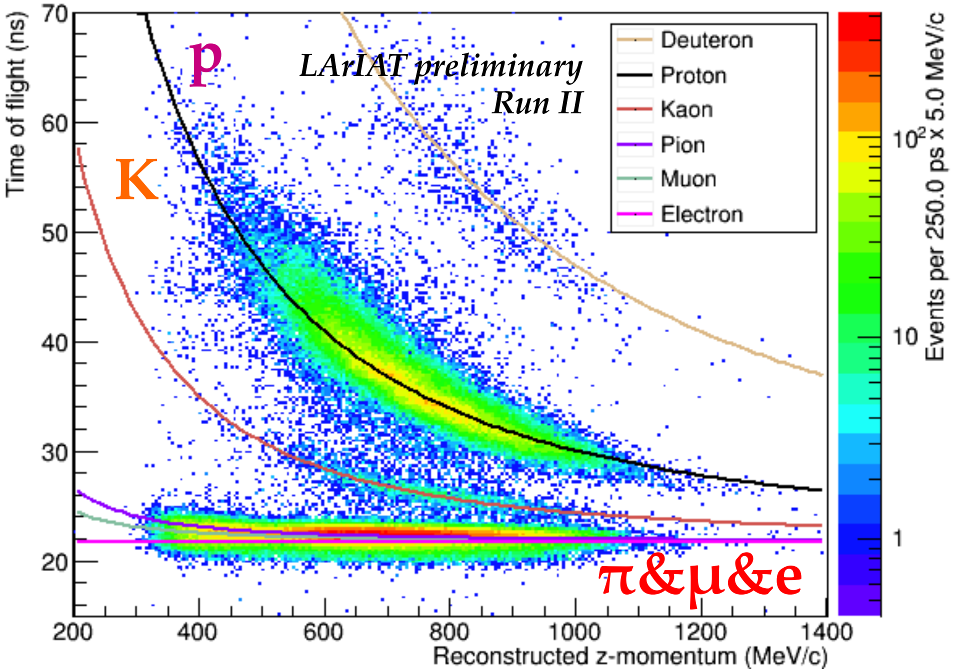
Time Of Flight

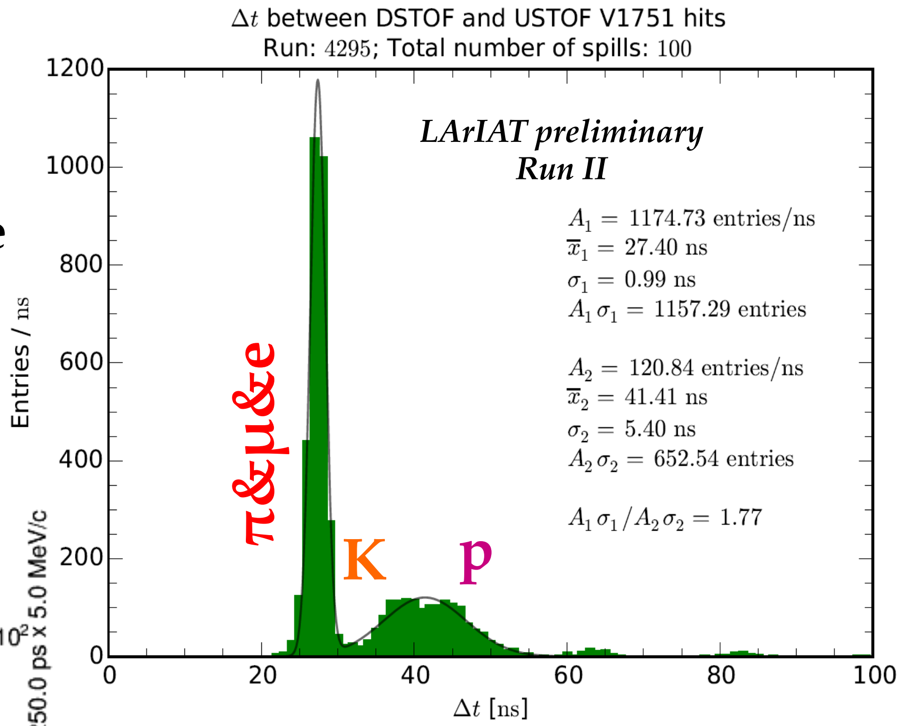


Time Of Flight

2 scintillators counters
Given the timing of the readout of the
TOF + MWPC's
p/K/π&μ&e discrimination

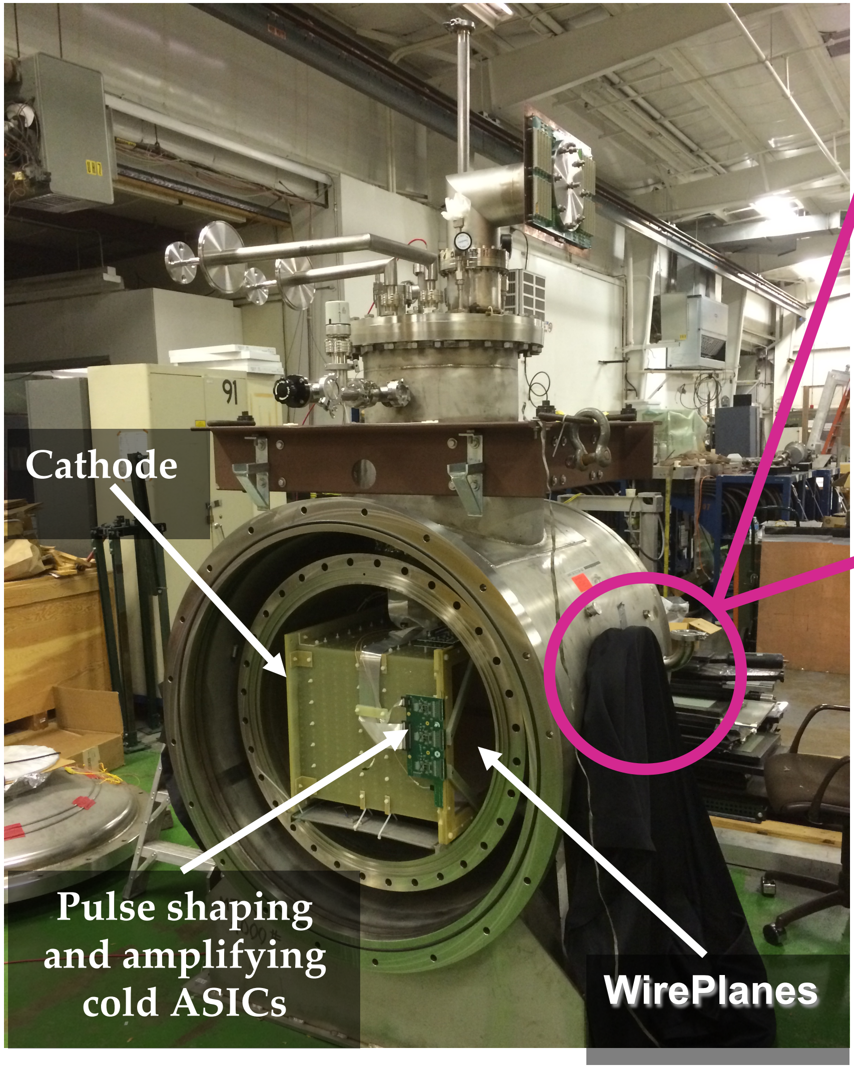
TOF vs reconstructed momentum





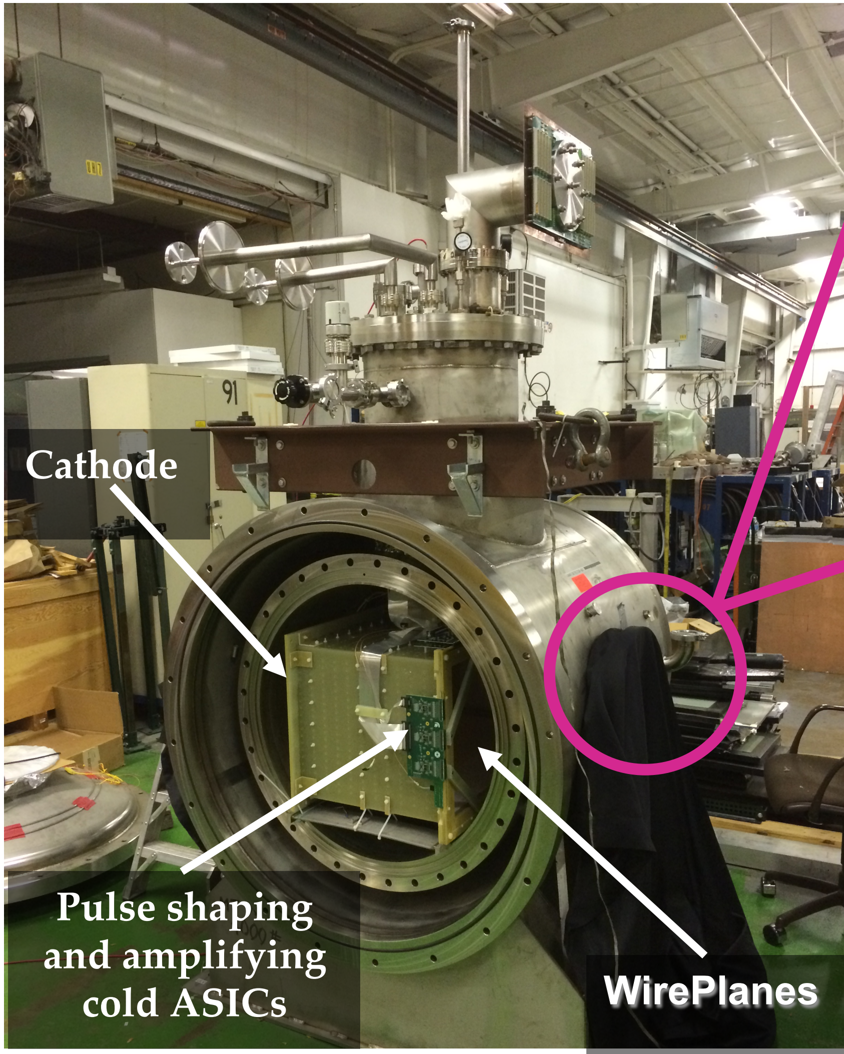
Particle ID and **momentum determination** are performed **before** the particle enters **TPC**!

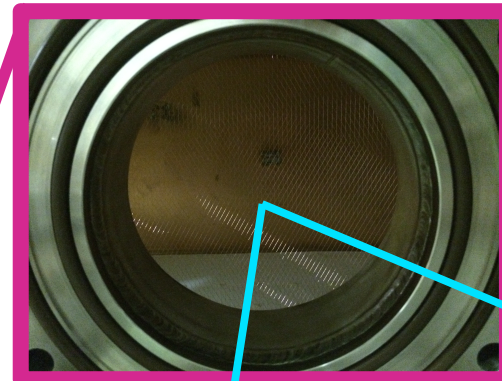
In the Cryostat: TPC & Light Coll System

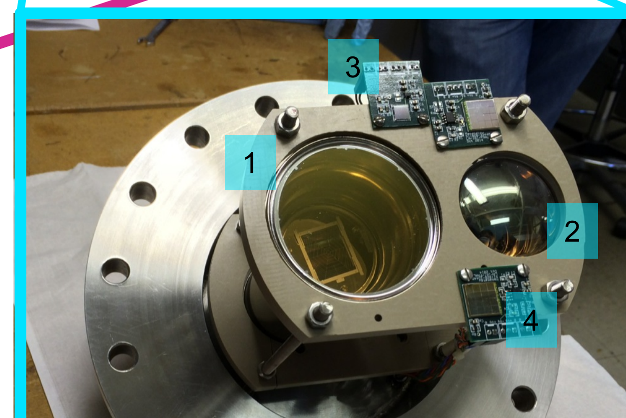


Light Collection System port

In the Cryostat: TPC & Light Coll 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)

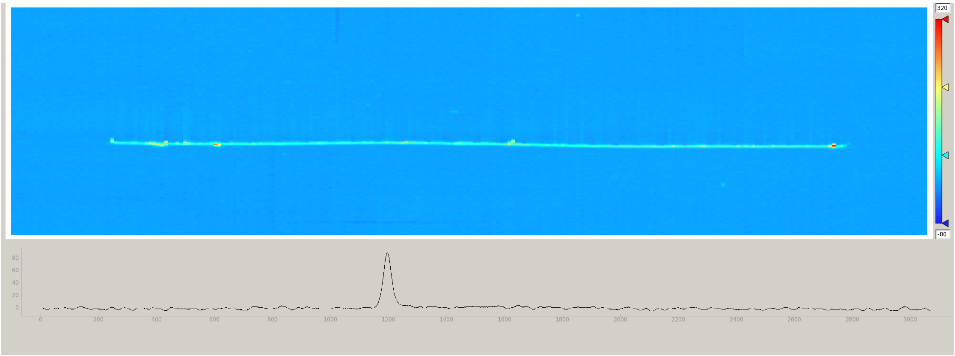
Time Projection Chamber

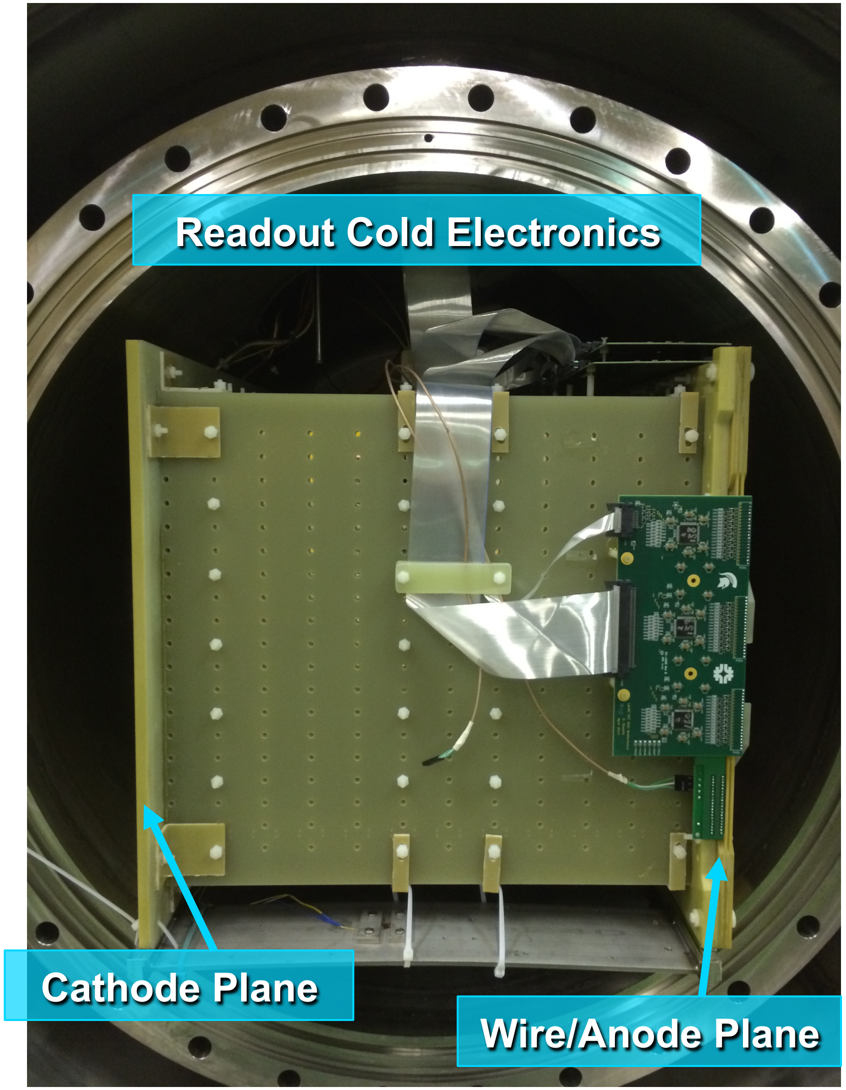
LArIAT uses the refurbished ArgoNeuT TPC

- 2 Readout planes
- 240 wires / plane +/- 60°, 4mm pitch
- Drift field ~500 V/cm

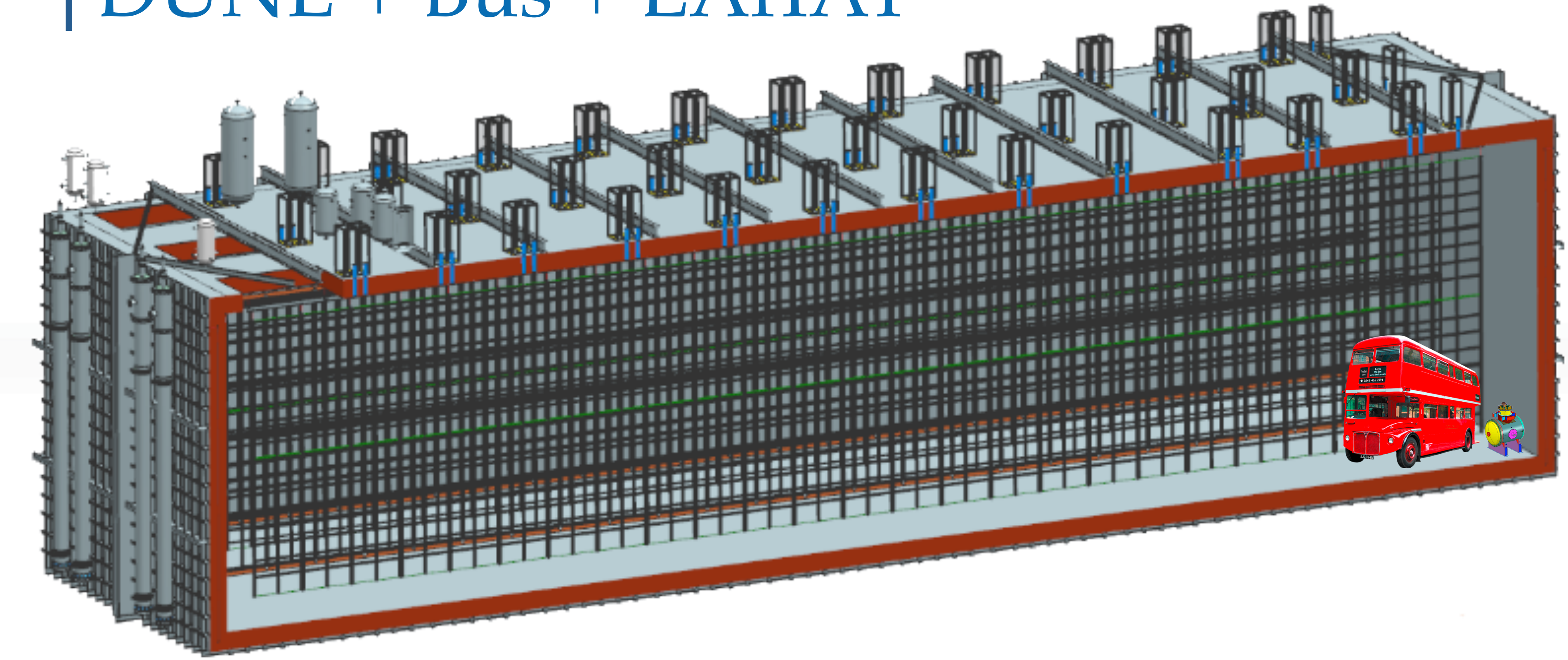
LArIAT uses MicroBooNE preamplifying ASICs on custom motherboards

- Signal-to-noise (MIP pulse height compared to the pedestal RMS)
  - Run-1: ~50:1 (ArgoNeuT ~15:1)
  - Run-2: ~70:1



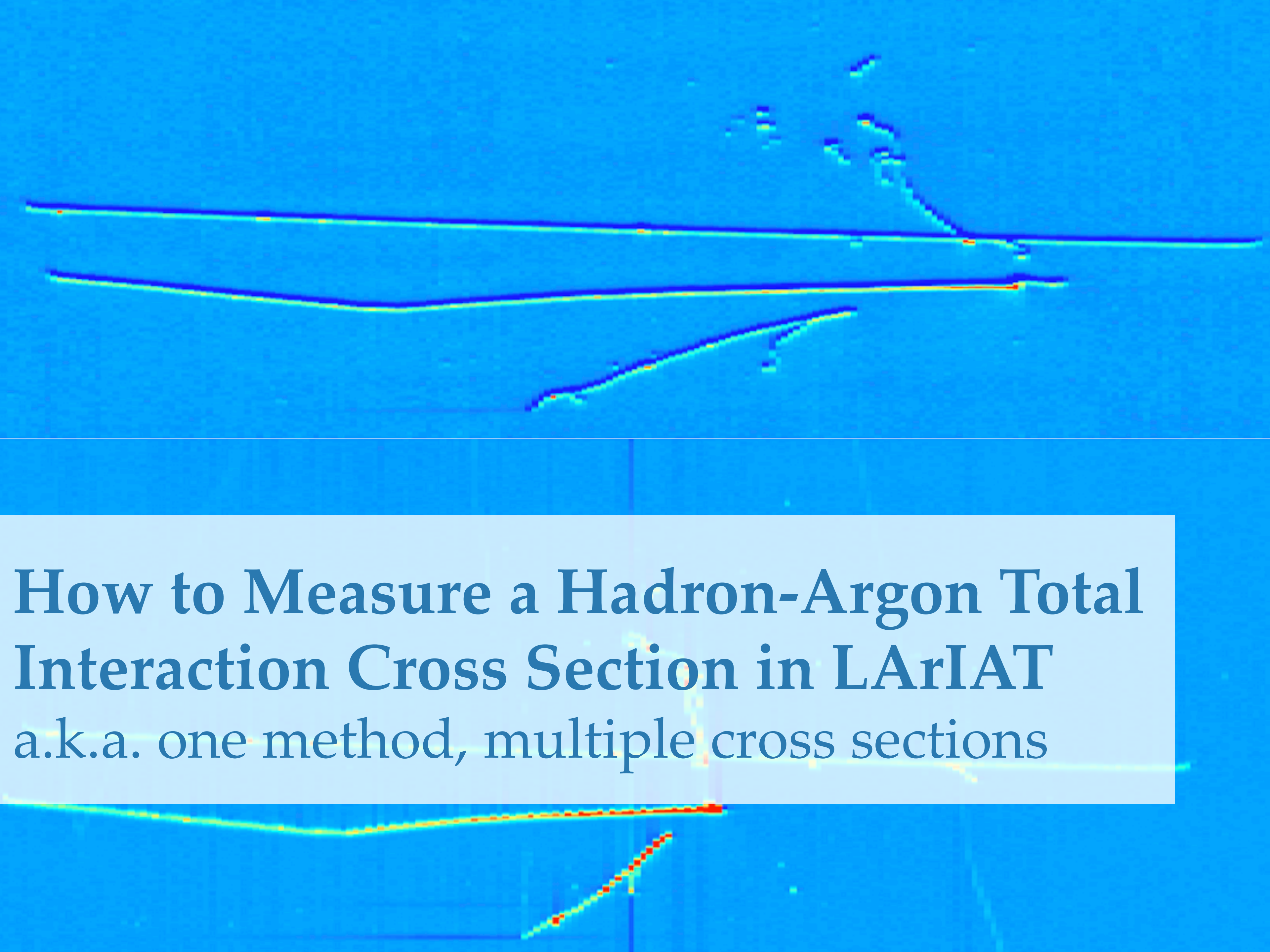


DUNE + Bus + LArIAT



The LArIAT Cryostat (0.42 m x 0.47 m x 0.9 m)

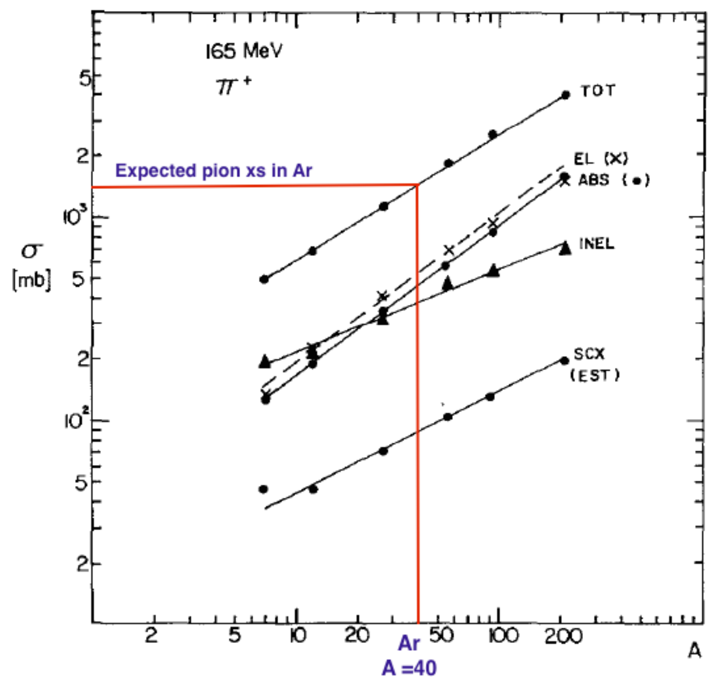
- Yes, we are small.



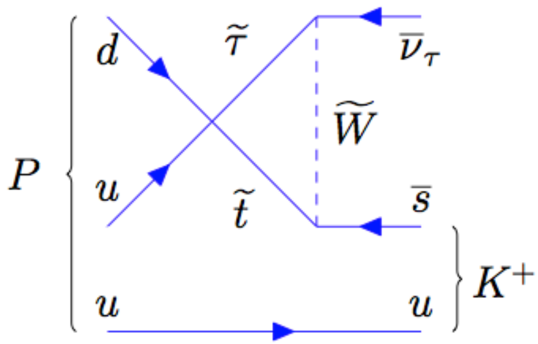
How to Measure a Hadron-Argon Total Interaction Cross Section in LArIAT

a.k.a. one method, multiple cross sections

Hadron-Ar cross section



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



PhysRevD.90.072005

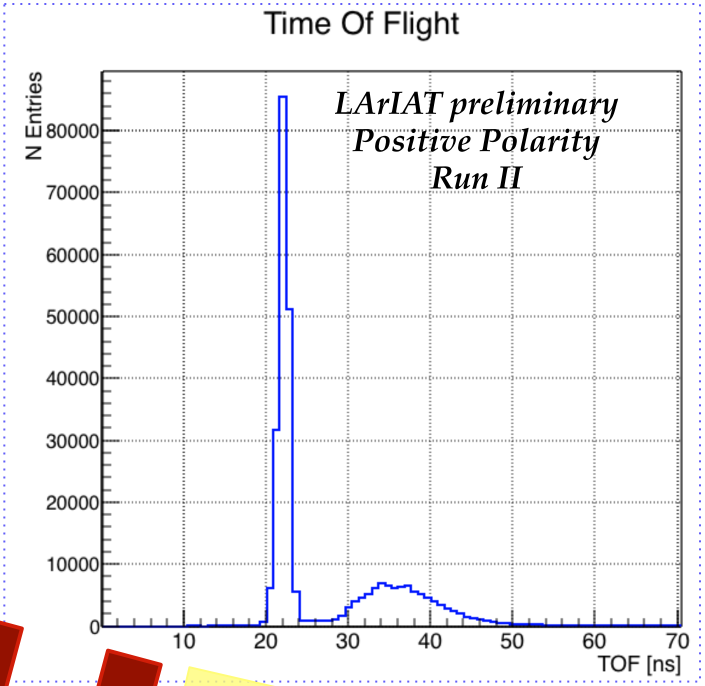
No measurement for Argon: predictions come from interpolation between lighter and heavier nuclei.

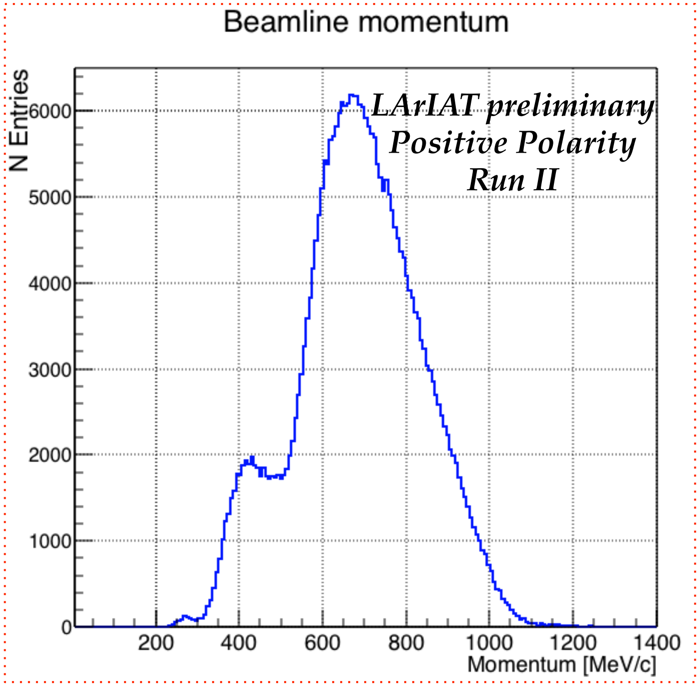
Pion Cross section:
In the energy range of **100-500 MeV**, pion interactions are dominated by **Δ resonances**, and the π-Ar cross section is boosted… the topology of ν events gets complicated!

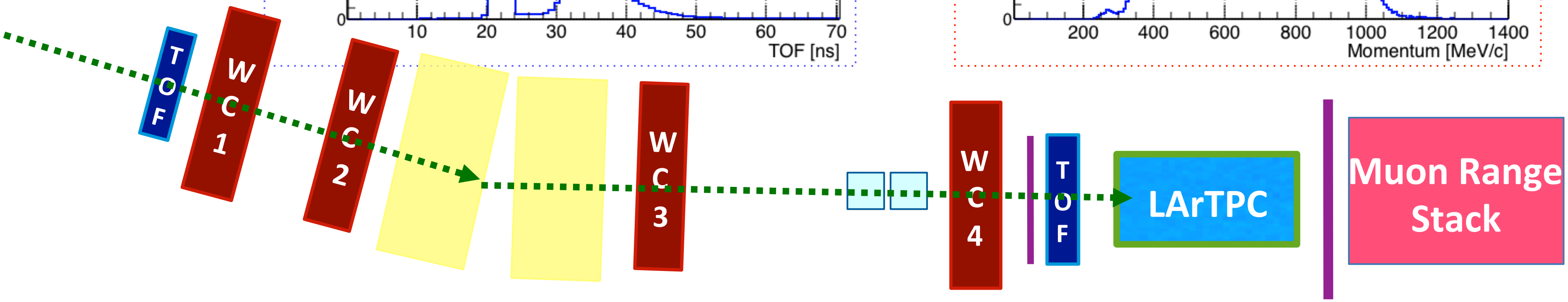
Kaon Cross section:
A clear prediction for Kaon topologies in LAr is fundamental to **efficiently reconstruct rare** proton decay **events**.

Event Selection: Beamline

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







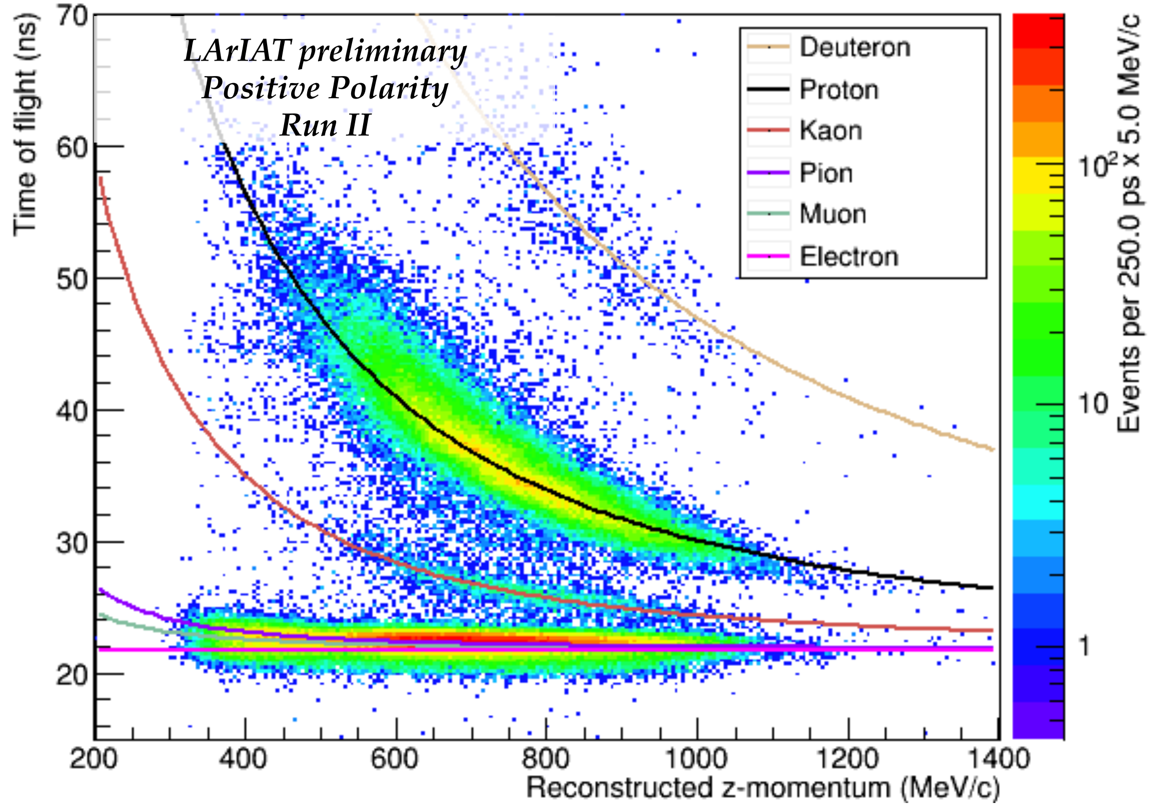
Event Selection: Particle Species

Reconstruct the **invariant mass** with this formula:

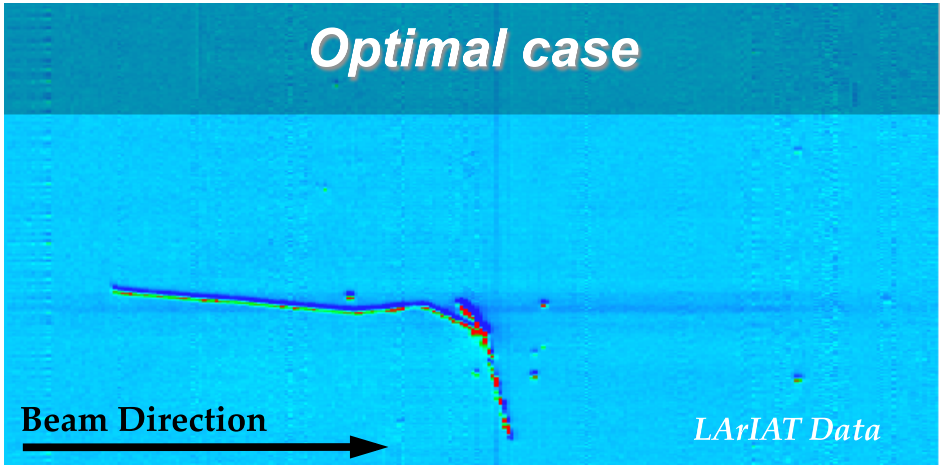
$$m = \frac{p}{c}\sqrt{(\frac{c * TOF}{\ell})^2 - 1}$$

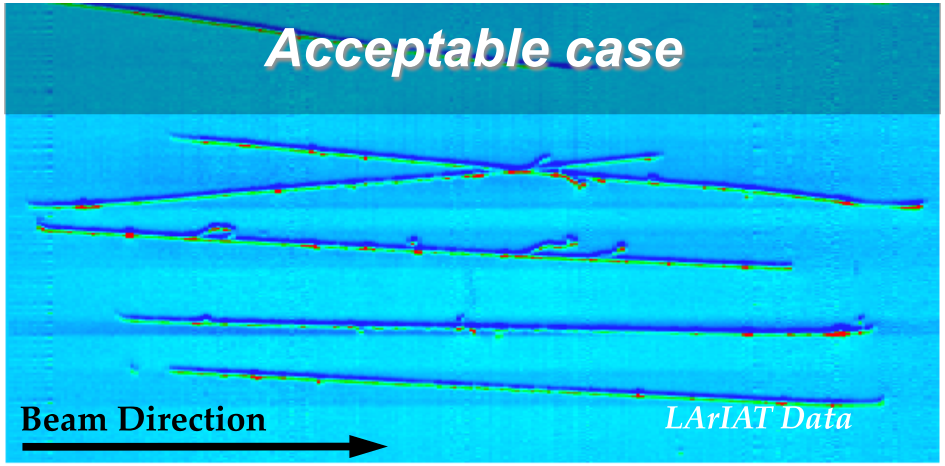
using beamline information, reconstructed **TOF** and **Wire Chambers** momentum.

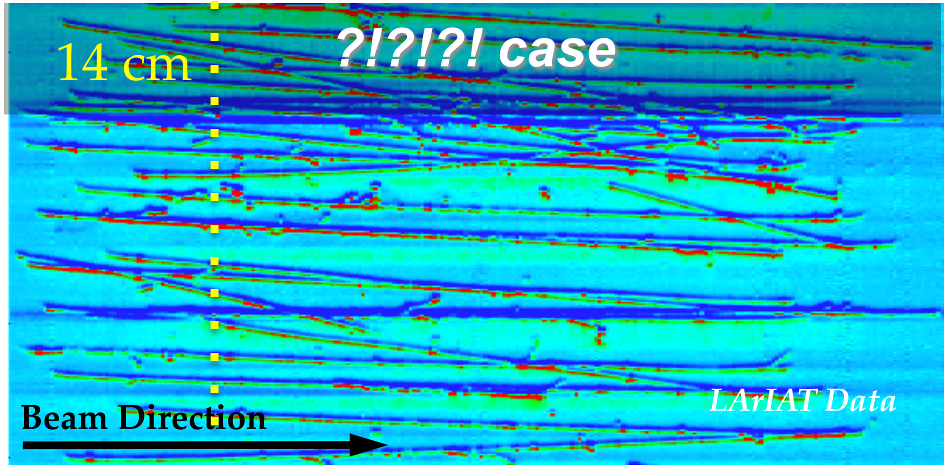
TOF vs reconstructed momentum



Event Selection: avoid high occupancy



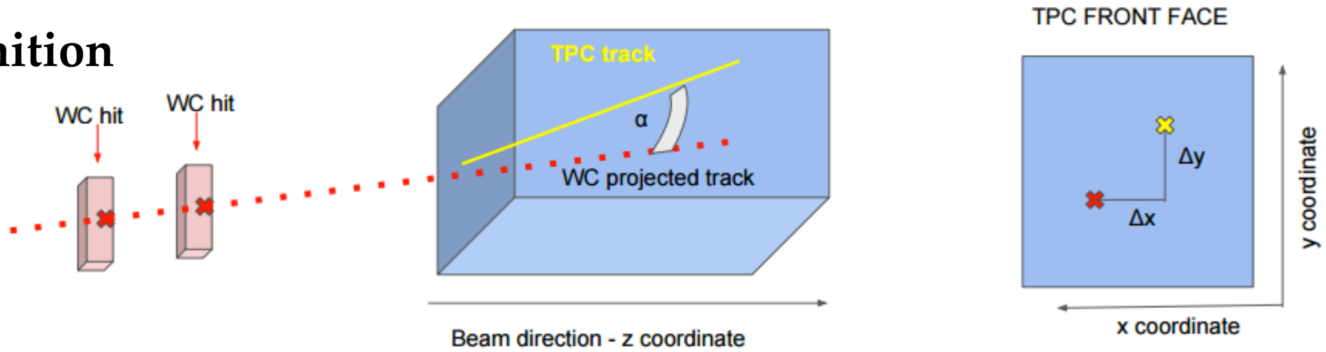


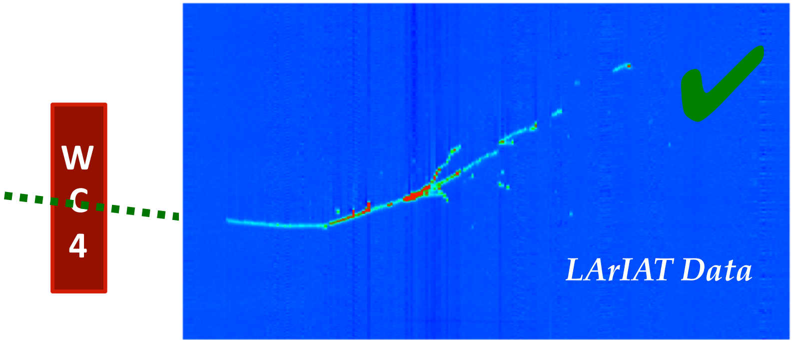


We reject events with more than 4 tracks in the first 14 cm of the TPC to minimize reconstruction issues and beamline-TPC ambiguous matches.

Event Selection: WC to TPC match

Match definition

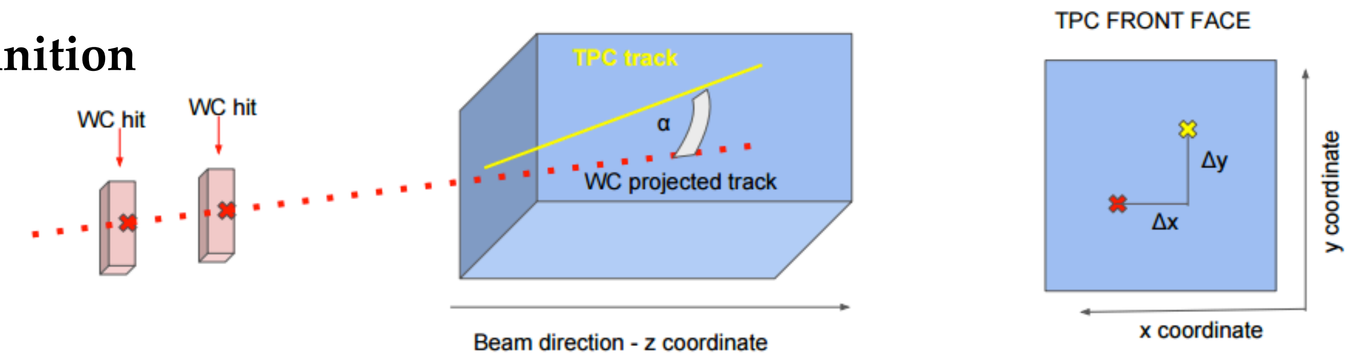


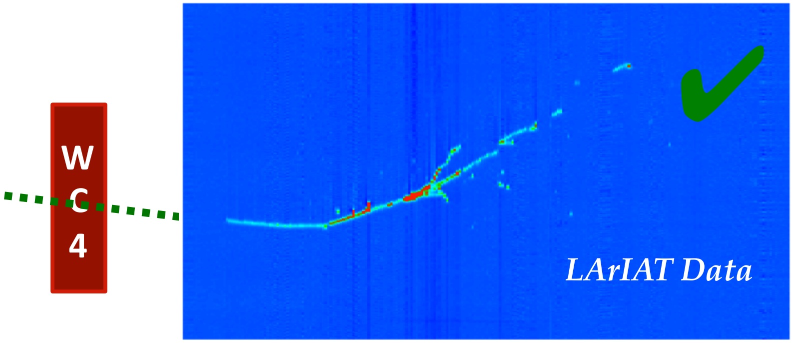


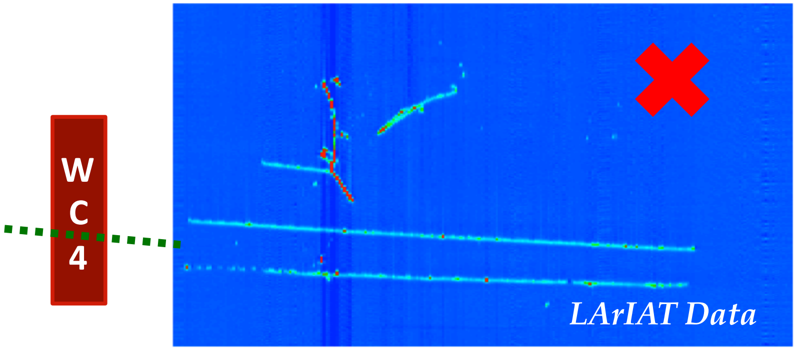
We keep only events with a beamline and TPC match

Event Selection: WC to TPC match

Match definition





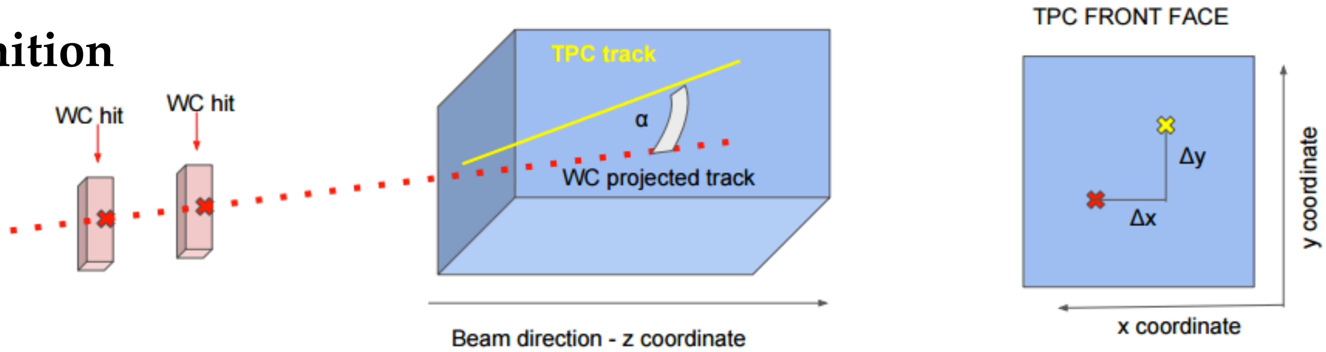


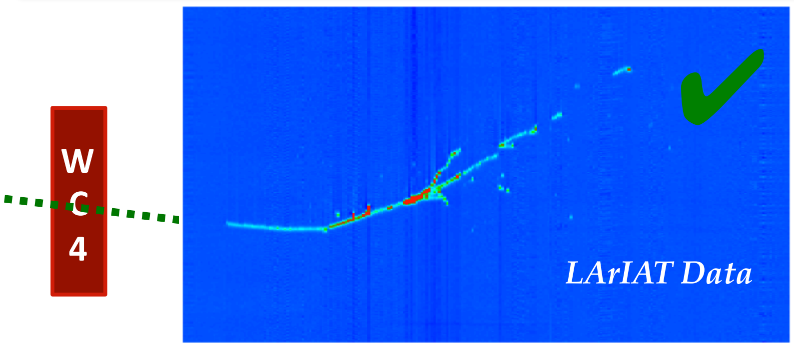
We keep only events with a beamline and TPC match

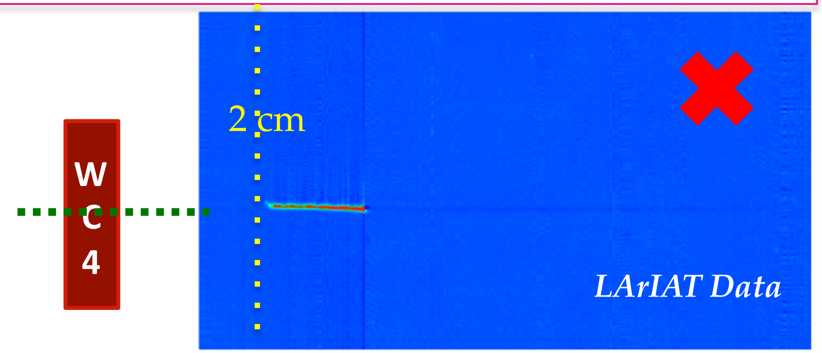
If more than 1 TPC track matches the WC track, we keep the best matched event

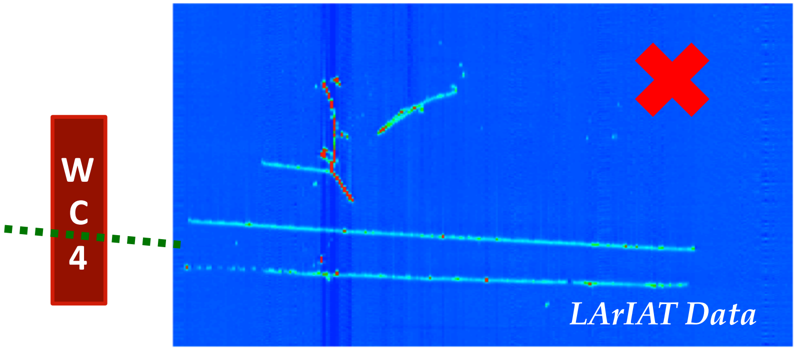
Event Selection: WC to TPC match

Match definition





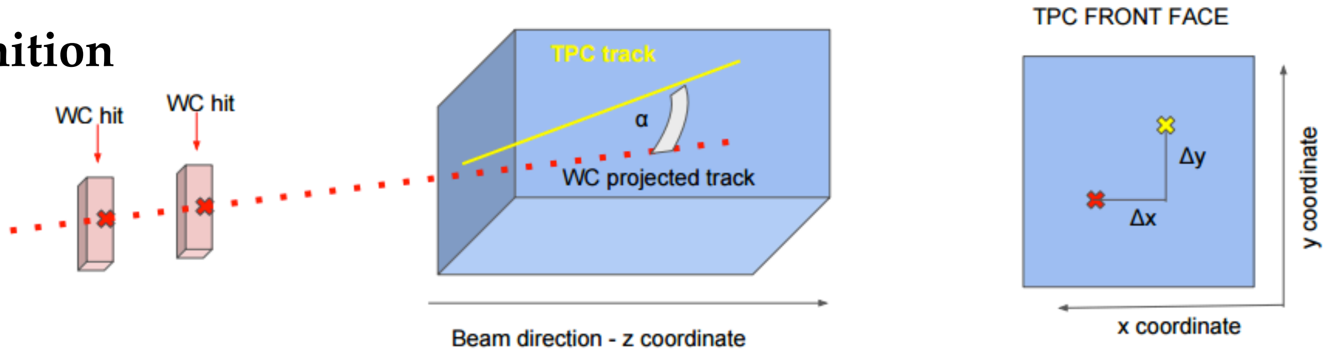


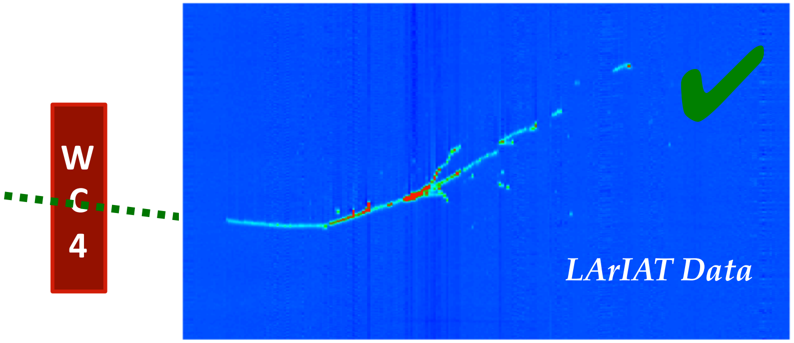


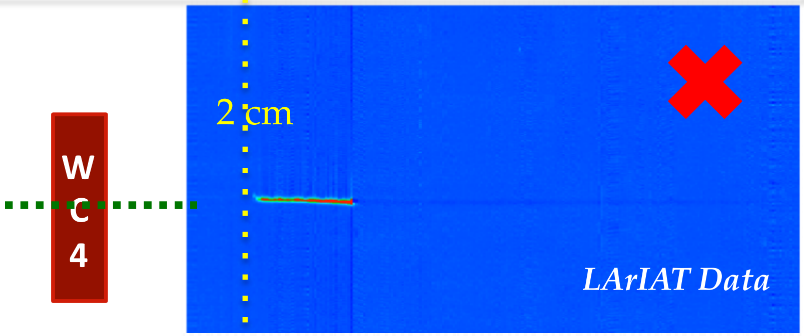
Events are also rejected if the TPC track starts more than 2 cm from the front face of the TPC...

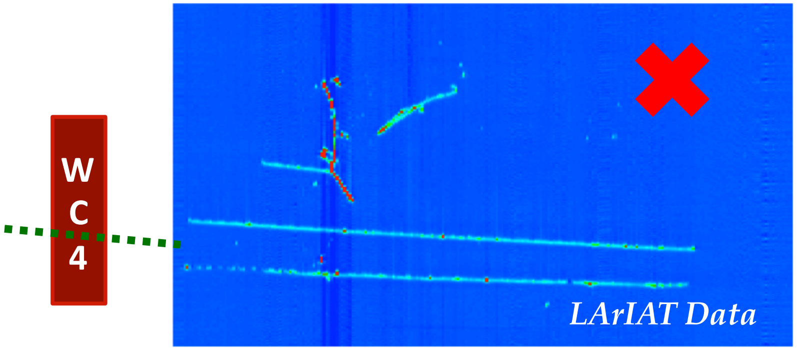
Event Selection: WC to TPC match

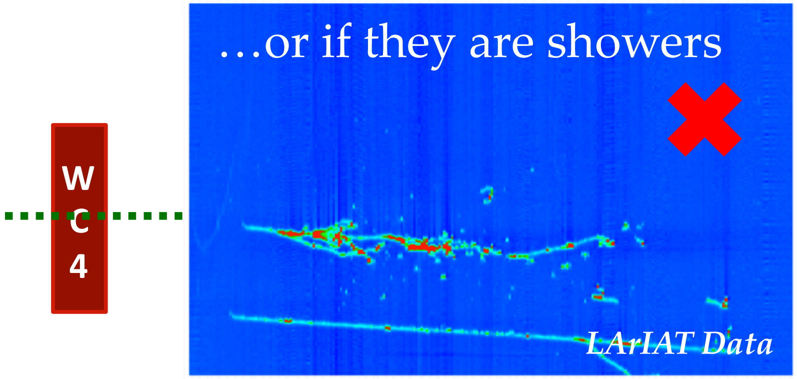
Match definition



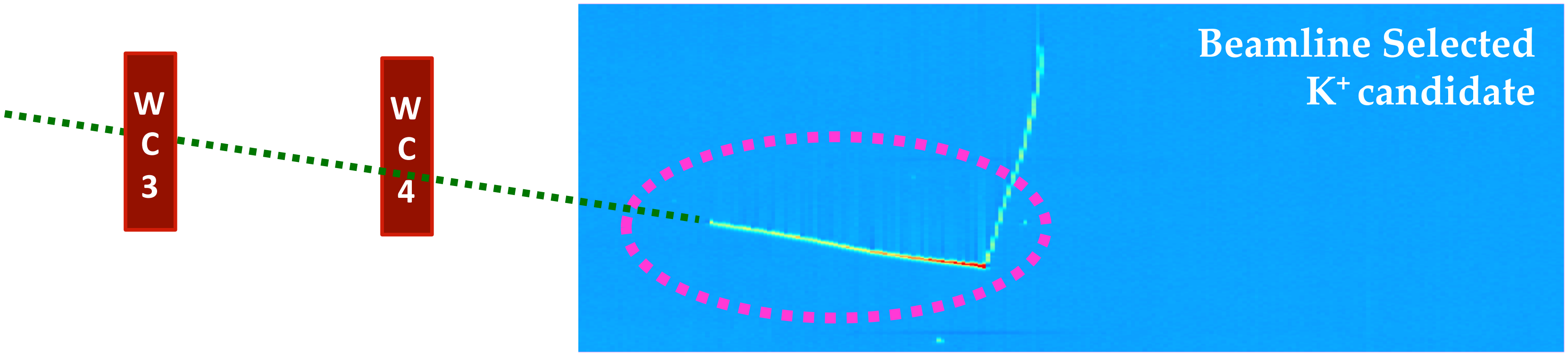








From candidates to Interaction Probability

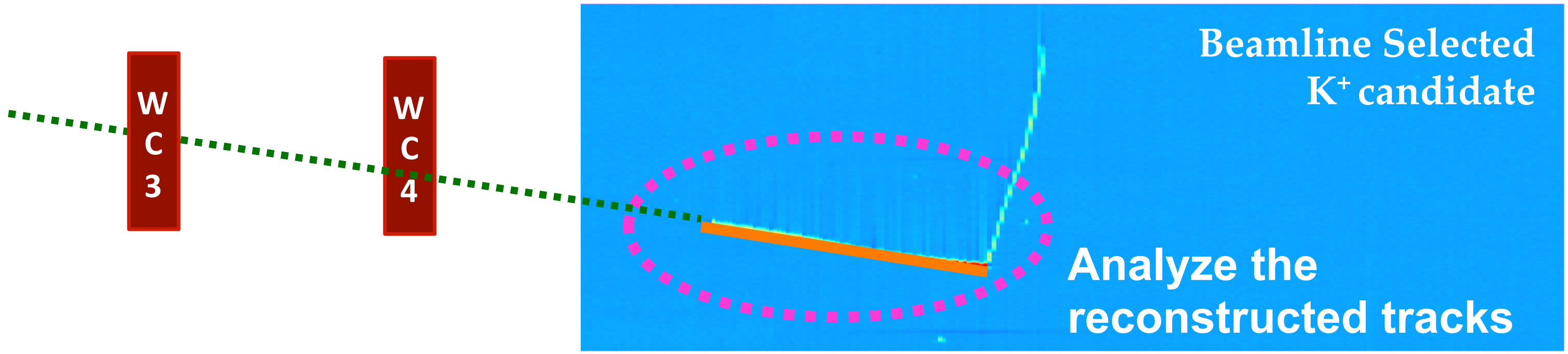


We use the **momentum measured by the WC** to calculate the candidate's initial kinetic energy as

$$KE_I = \sqrt{p^2 + m^2} - m \quad - E_{Flat}$$

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

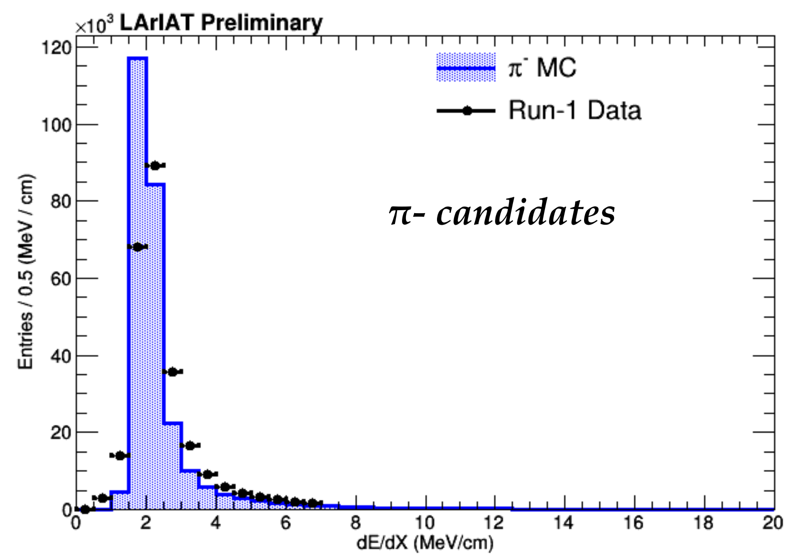
From candidates to Interaction Probability



The **K.E.** at **each point** of the TPC track is calculated by subtracting the **track deposited energy** from the K.E. at the TPC front face.

$$KE_n = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$

This key point of our measurement is enabled by the extraordinary tracking and calorimetry features of LArTPCs



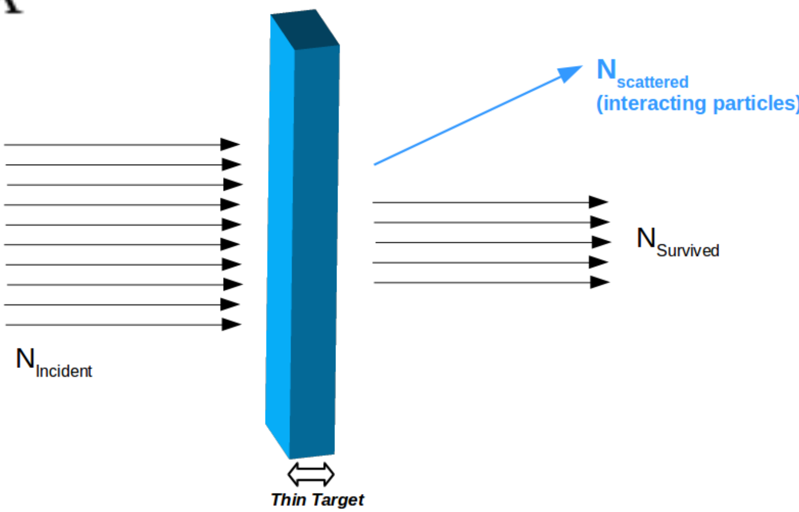
dE/dX constant for the pitch length

Thin-slice method

The **survival probability** of a particle through a **thin slab** of argon is:

$$P_{Survival} = e^{-\sigma_{Tot} n \delta X}$$

σ_{Tot} = cross section per nucleon,
δX = depth of the slab,
n = the density



The **interaction probability** in a thin slab is the **ratio** of the number of **interacting particles** to the number of **incident particles.**

$$\frac{N_{Interacting}}{N_{Incident}} = P_{Interacting} = 1 - P_{Survival} = 1 - e^{-\sigma_{Tot} n \delta X}$$

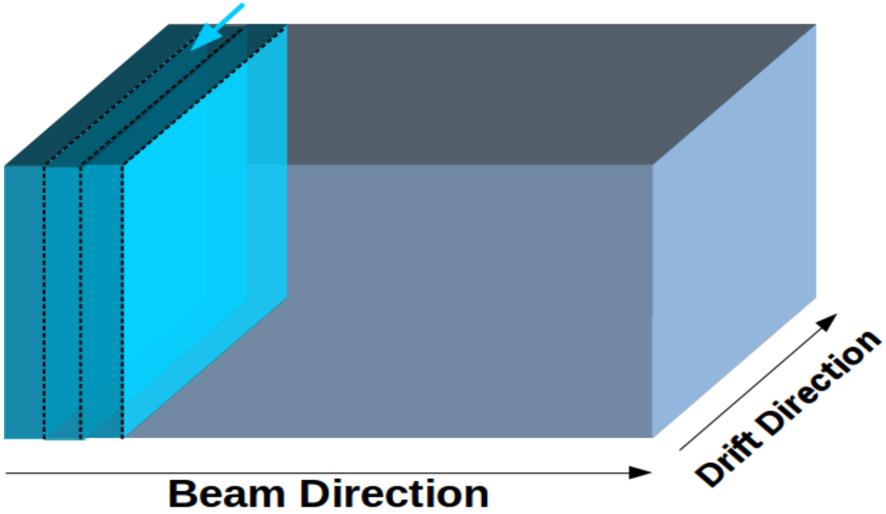
Thin-slice method

Since the slice is thin, we can Taylor expand and solve for the **cross-section**.

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

$$\sigma_{Tot}(E) \sim \frac{1}{n\delta X} P_{Interacting} = \frac{1}{n\delta X} \frac{N_{Interacting}}{N_{Incident}}$$

Using the **granularity** of the LArTPC, we can treat the **wire-to-wire spacing** as a **series of "thin-slab"** targets, as we know the energy of the particle incident to each slice.



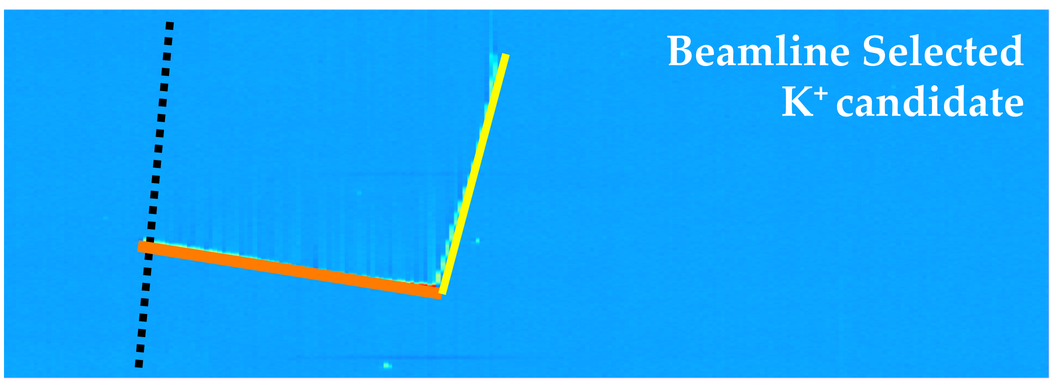
N Incident , N Interacting calculation

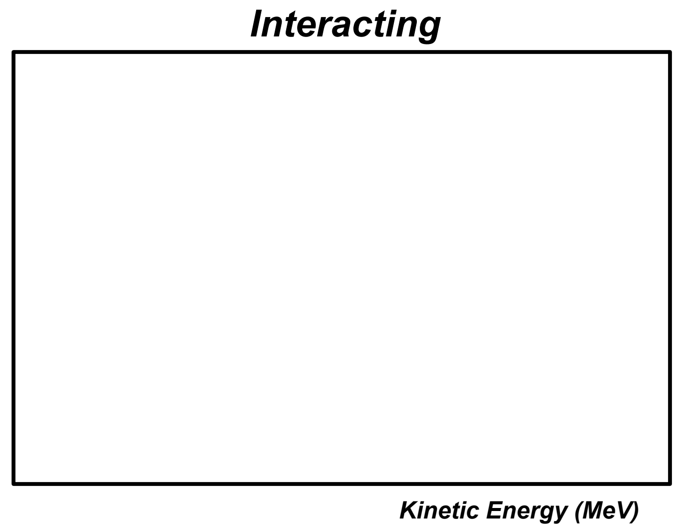
We follow the TPC track slice by slice

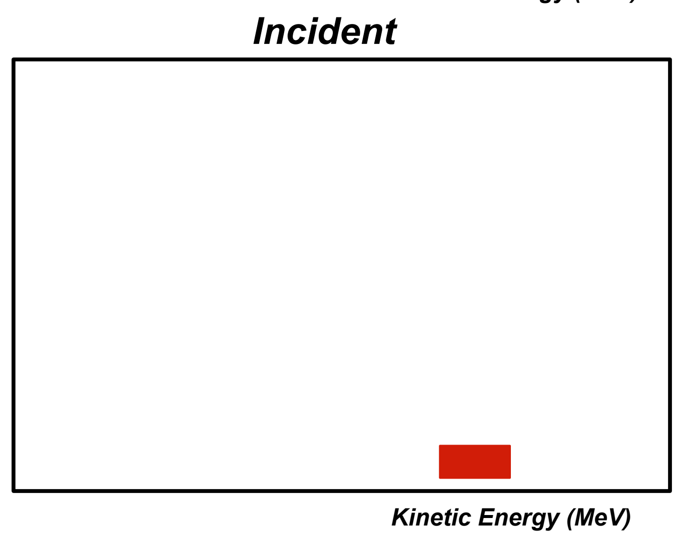
- The slice represents the distance between each 3D point in the track
- For each slice we ask:
  "Is this **the end** of the track?"

  NO: Calculate the kinetic energy at this point and fill the "incident" histogram

$$KE_{Slab} = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$







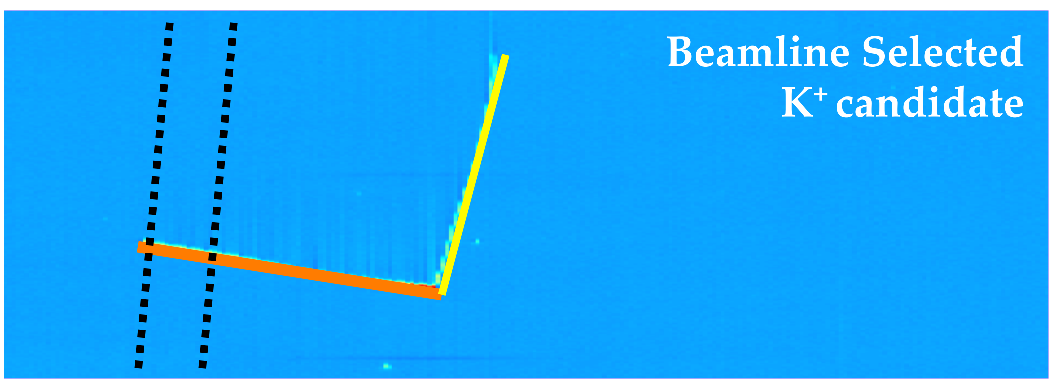
N $_{\text{Incident}}$, N $_{\text{Interacting}}$ calculation

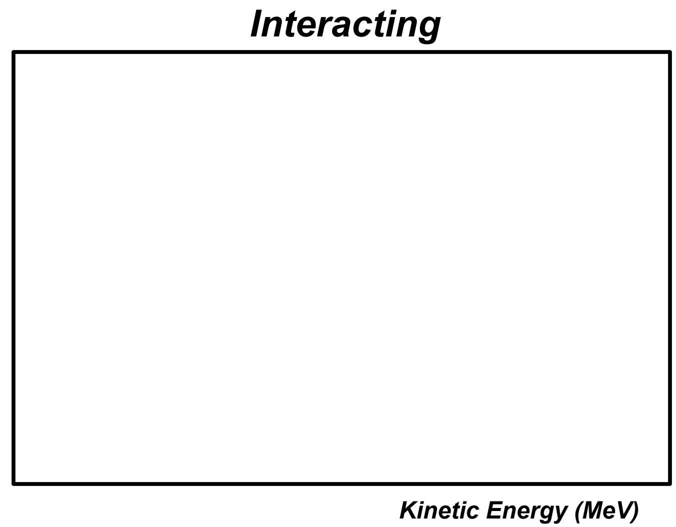
We follow the TPC track slice by slice

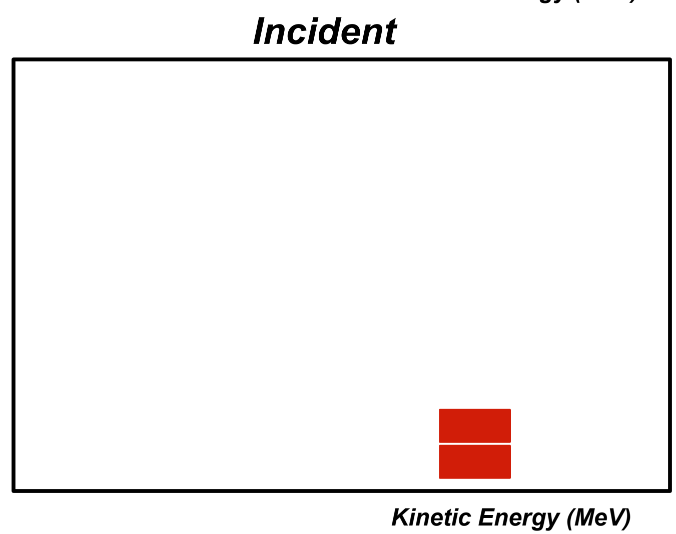
- The slice represents the distance between each 3D point in the track
- For each slice we ask:
  "Is this **the end** of the track?"

NO: Calculate the kinetic energy at this point and fill the "incident" histogram

$$KE_{Slab} = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$







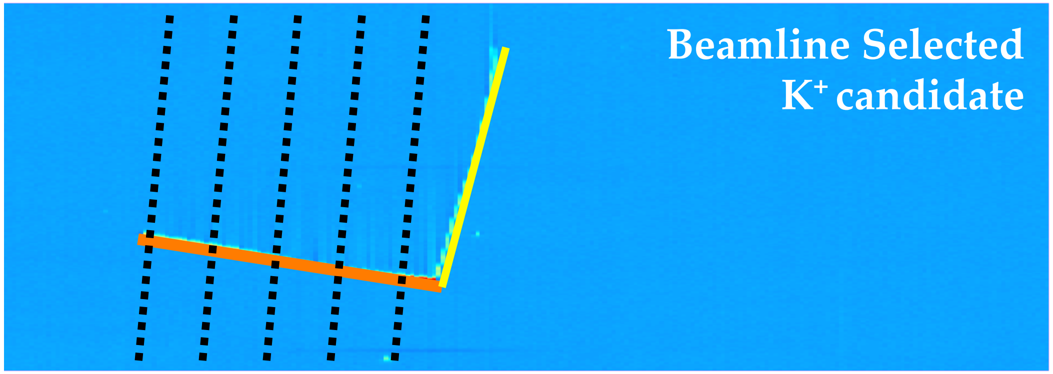
$N_{Incident}$, $N_{Interacting}$ calculation

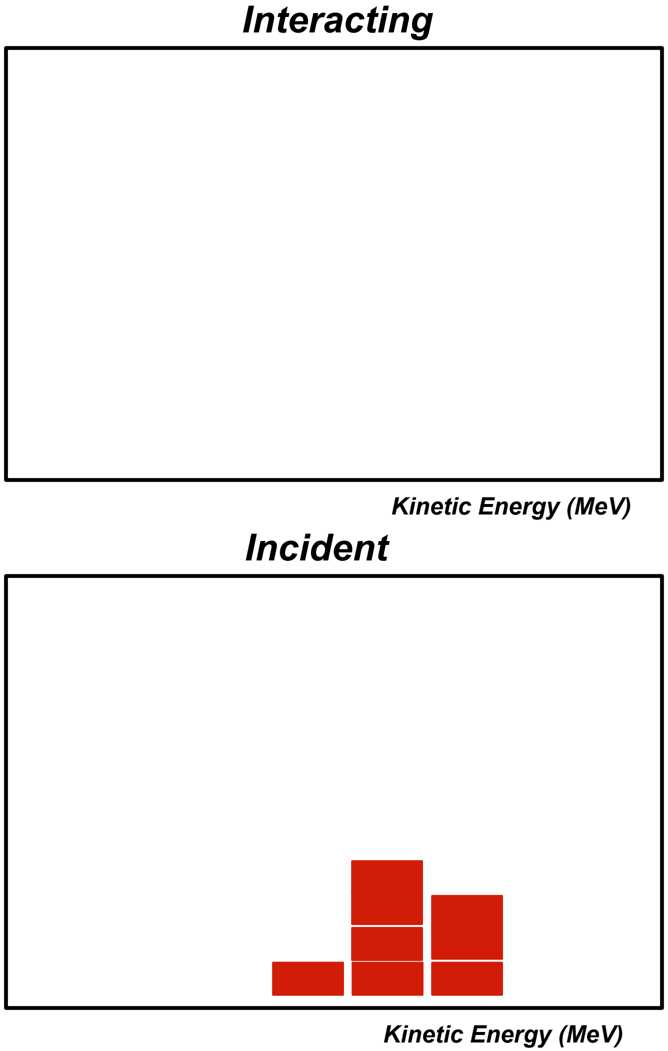
We follow the TPC track slice by slice

- 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 fill the "incident" histogram

$$KE_{Slab} = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$





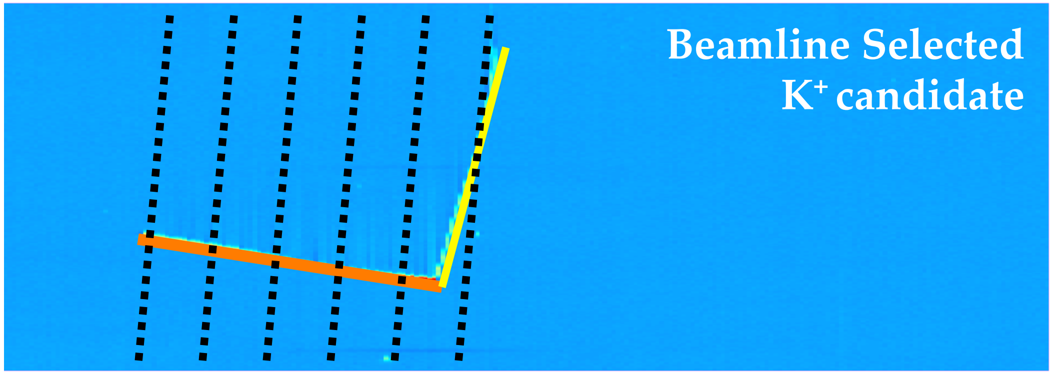
$N_{Incident}$, $N_{Interacting}$ calculation

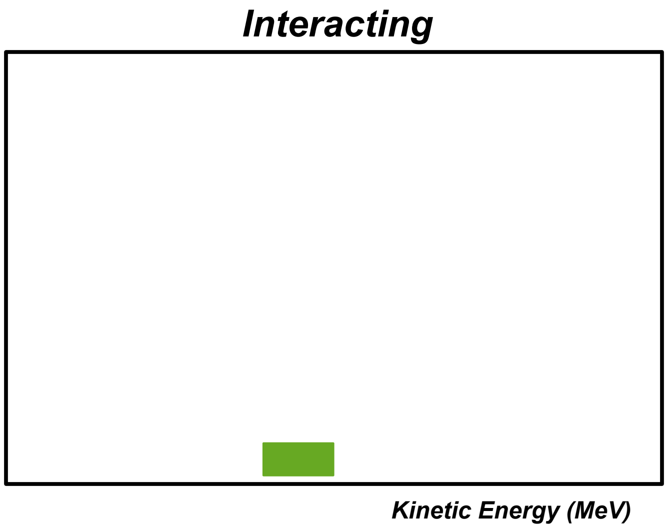
We follow the TPC track slice by slice

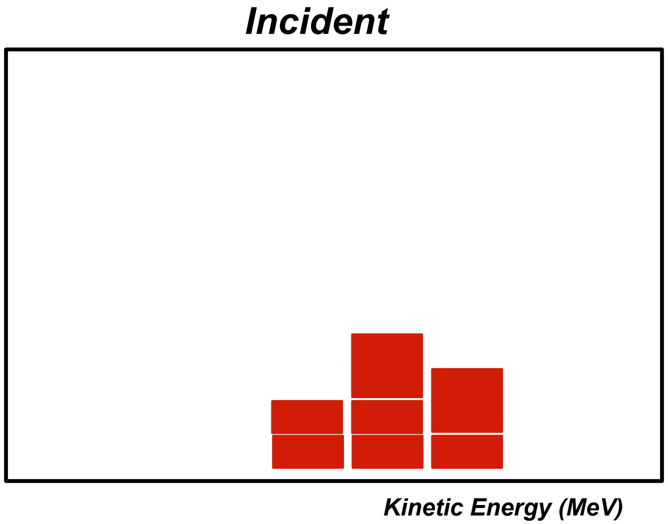
- The slice represents the distance between each 3D point in the track
- For each slice we ask:
  "Is this **the end** of the track?"

YES! Calculate the KE at this point and fill both the "**interacting**" and "**incident**" histograms

$$KE_{Slab} = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$







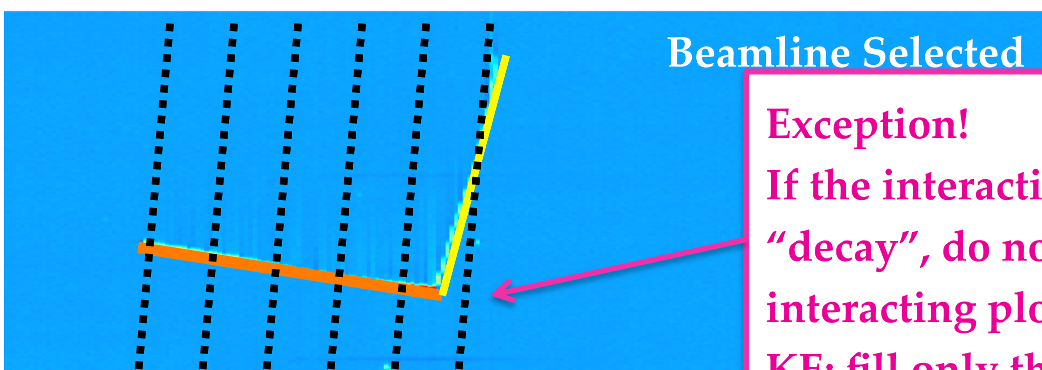
$N_{Incident}$, $N_{Interacting}$ calculation

We follow the TPC track slice by slice

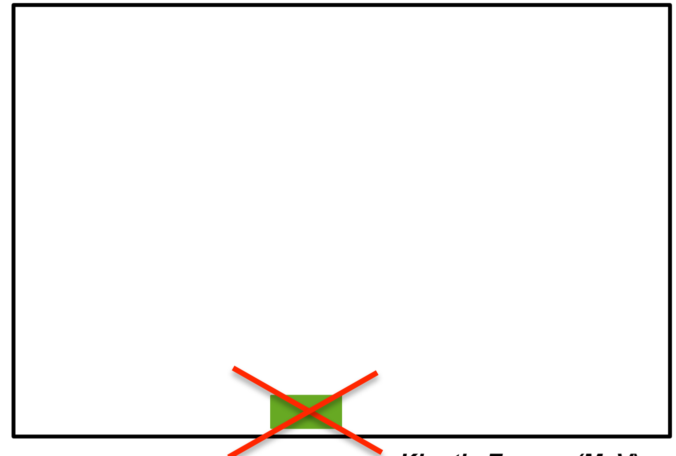
- The slice represents the distance between each 3D point in the track
- For each slice we ask:
  "Is this **the end** of the track?"

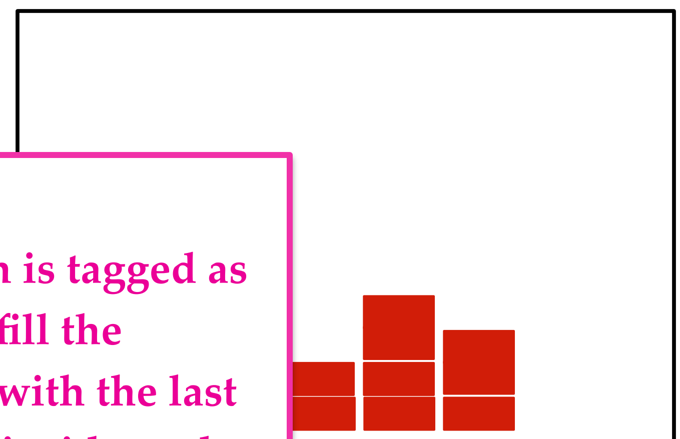
YES! Calculate the KE at this point and fill both the "**interacting**" and "**incident**" histograms

$$KE_{Slab} = KE_I - \sum_{i=0}^{n} \left(\frac{dE}{dX}\right)_i \times \delta X_i$$



Exception!
If the interaction is tagged as "decay", do not fill the interacting plot with the last KE: fill only the incident plot.

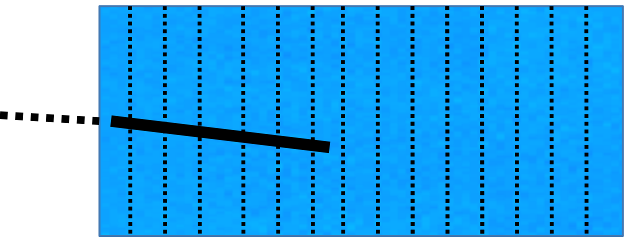




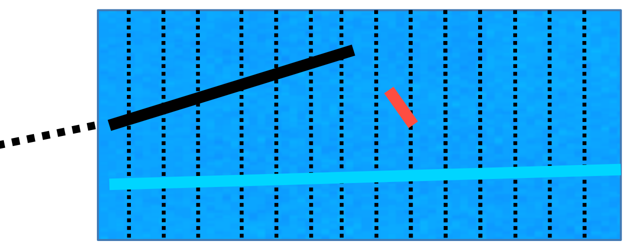
$N_{Incident}$, $N_{Interacting}$ calculation

Repeat for each WC to TPC matched track

- We disregard any other activity occurring in the detector

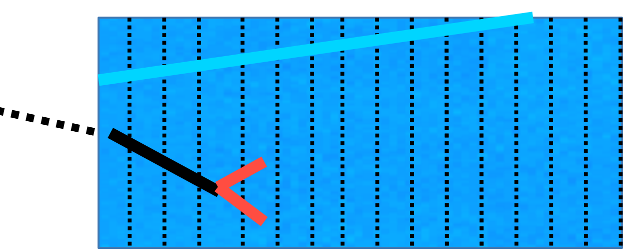


✔ The black track is followed

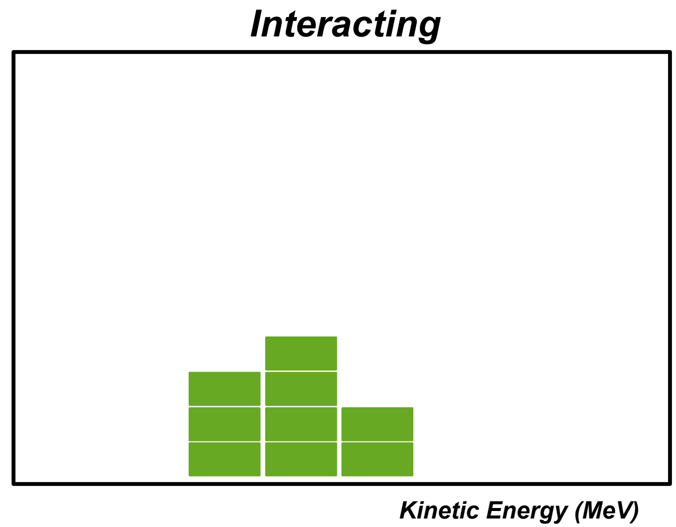


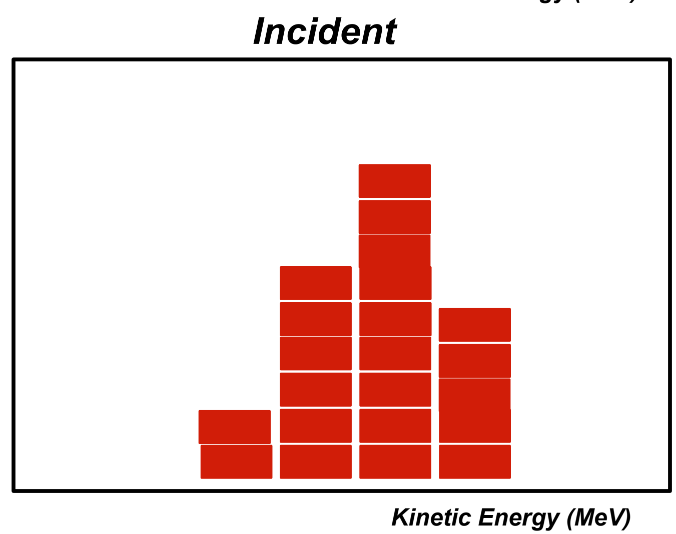
✖ The light blue track is not matched to WC

✖ The red stub is ignored



✖ The red tracks do not belong to the original track



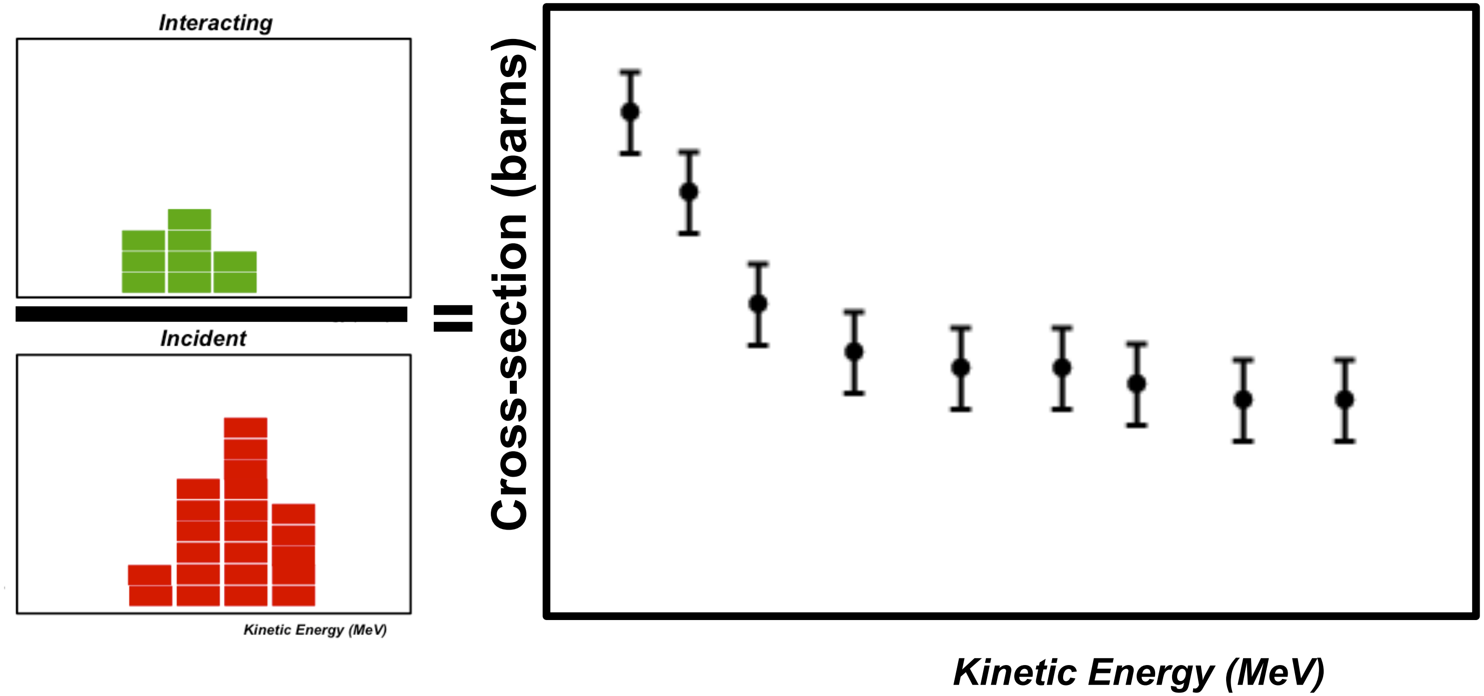


From Probability to Cross Section

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

$$\sigma_{Tot}(E) \sim \frac{1}{n\delta X} P_{Interacting} = \frac{1}{n\delta X} \frac{N_{Interacting}}{N_{Incident}}$$

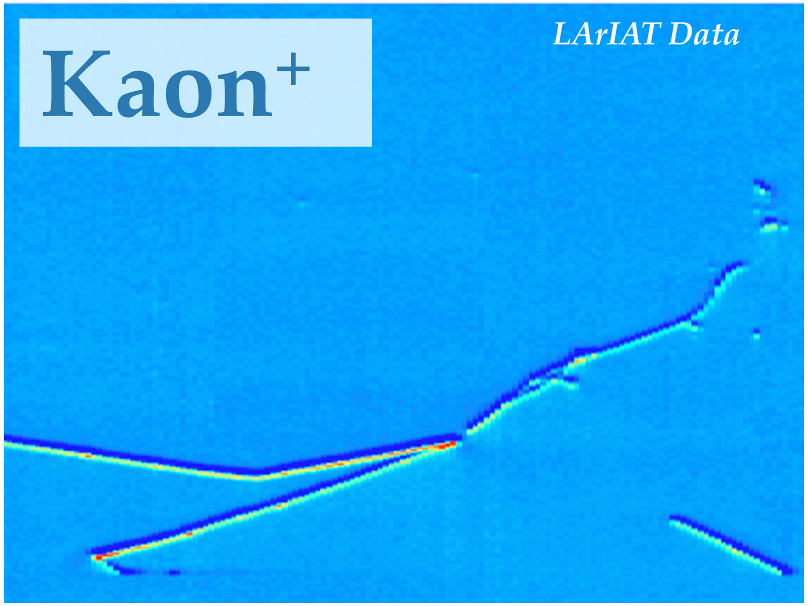
$$\frac{1}{n\delta X}$$

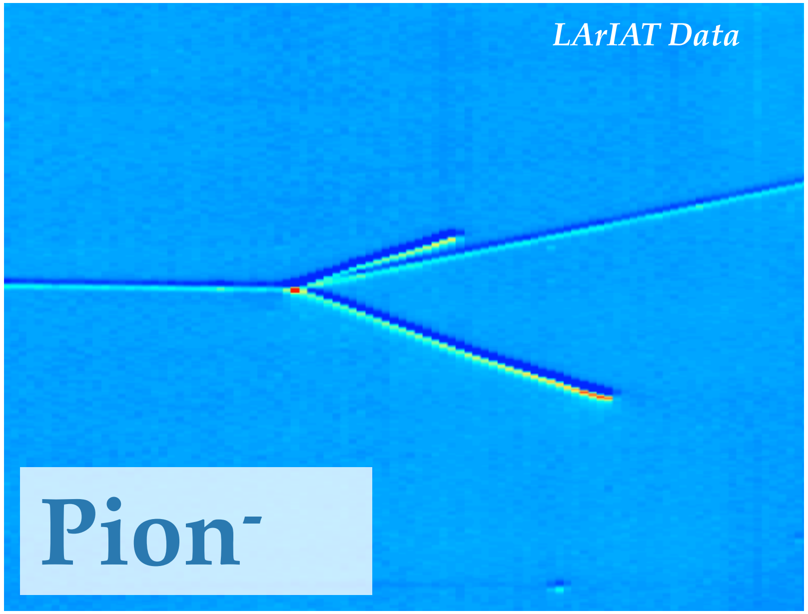


Currently in the pipeline

The technique to measure interaction cross section can be applied to all the hadron we are able to identify in tertiary beam (π, K, p).

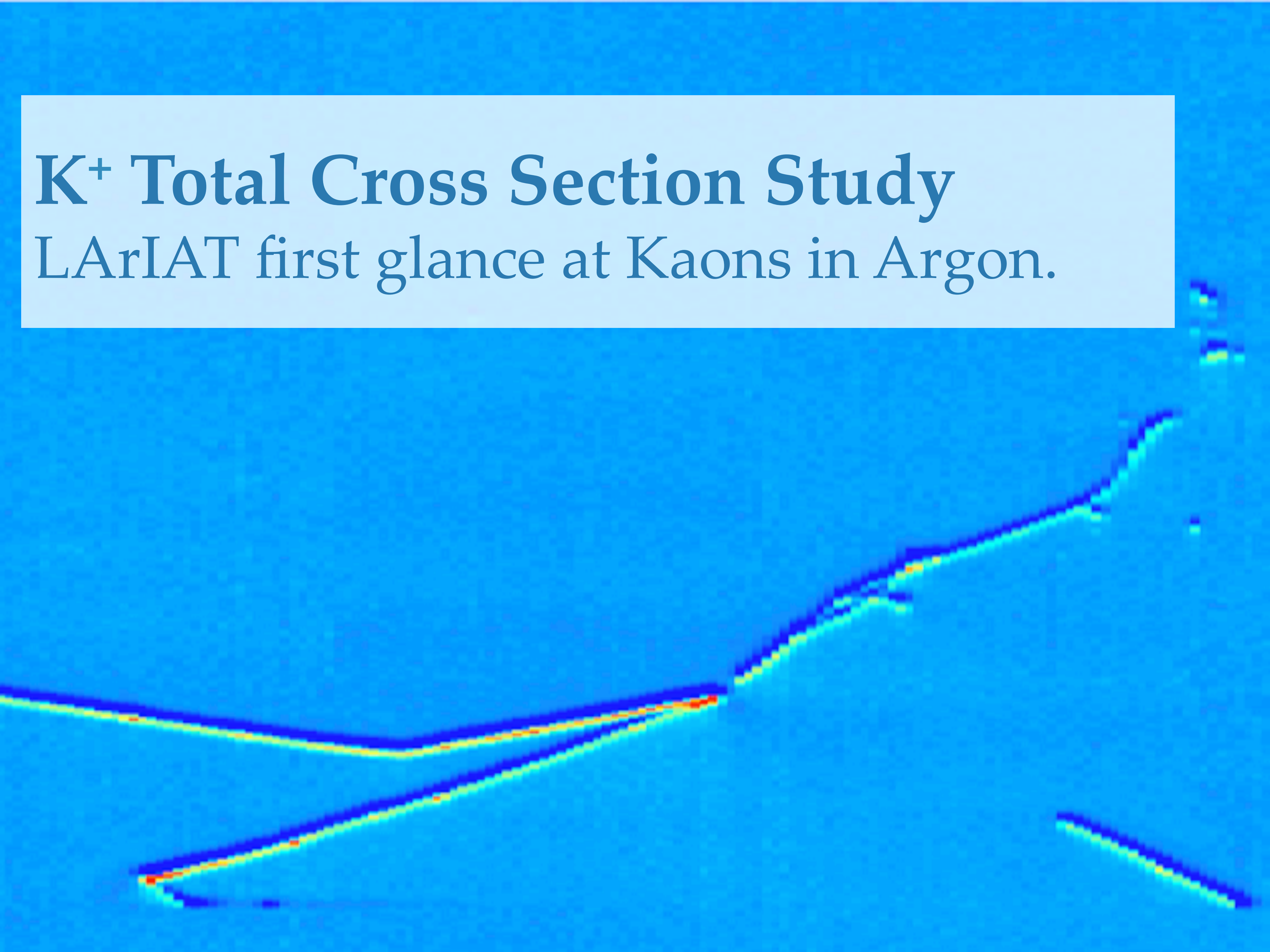
At the moment, the collaboration produced a first result on the **negative π total cross** section in Run I&II and an in depth study of the **positive kaon total cross section** in the Run II dataset.





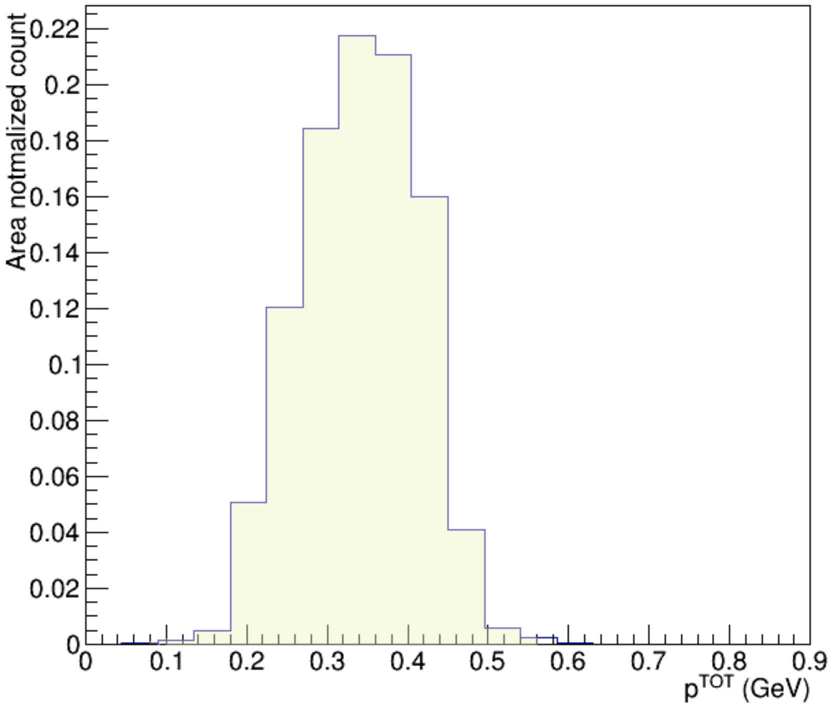
K$^+$ Total Cross Section Study

LArIAT first glance at Kaons in Argon.

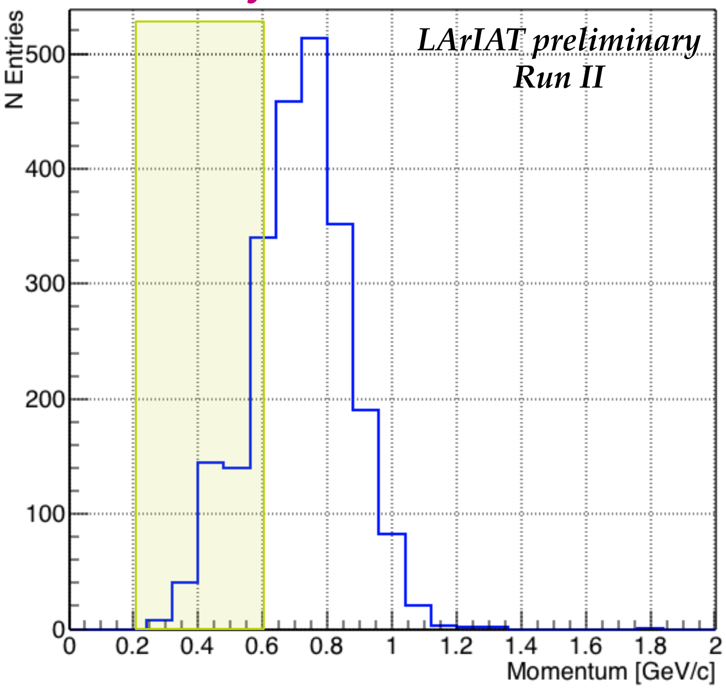


Why LArIAT is the best (place to study kaons)

GENIE simulation of p_K for proton decay event



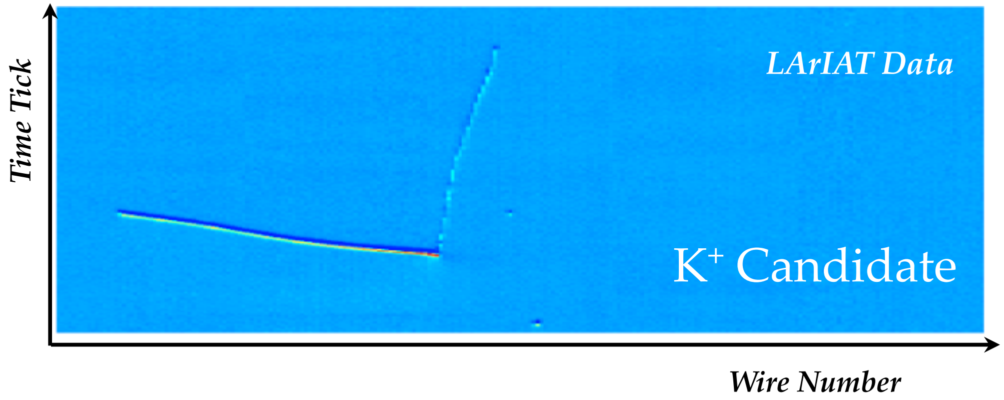
Kaon momentum in LArIAT tertiary beam at last WC



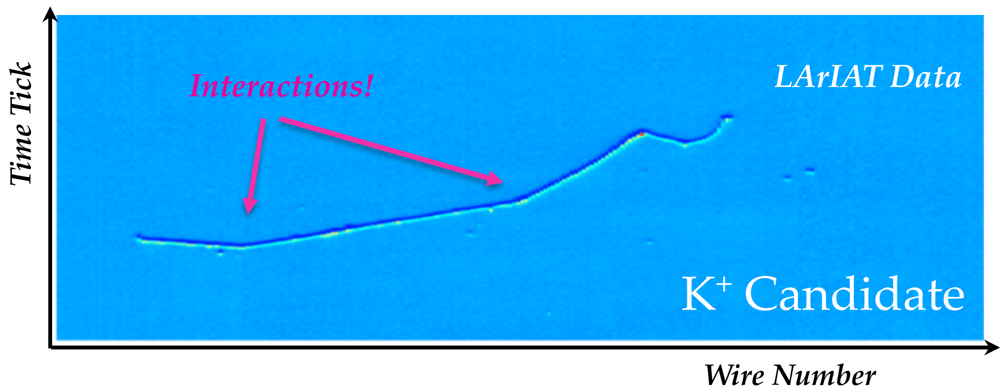
The momentum distribution for kaons in the LArIAT tertiary beamline **overlaps** completely with the momentum spectrum expected for the kaon on a proton decay event.

Why LArIAT is the best (place to study Kaons)

We currently have the biggest sample of identified kaons in LAr: **~ 2000 events**.

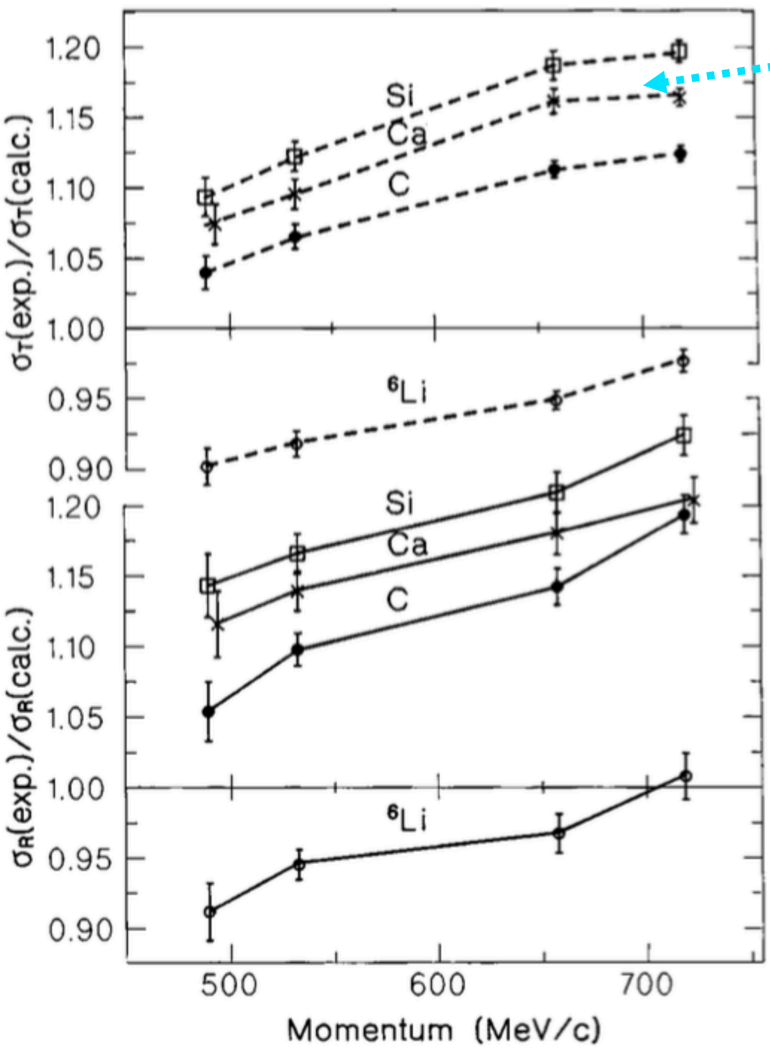


Develop kaon identification algorithms on LAr real DATA



Improve K simulation in Ar used for proton decay signal simulation thanks to the **inclusive hadronic XS measurement**.

Review of (Very Little) Literature on K



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

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

Kaon cross section has been never measured on argon before, and **scarcely measured on other nuclei**.

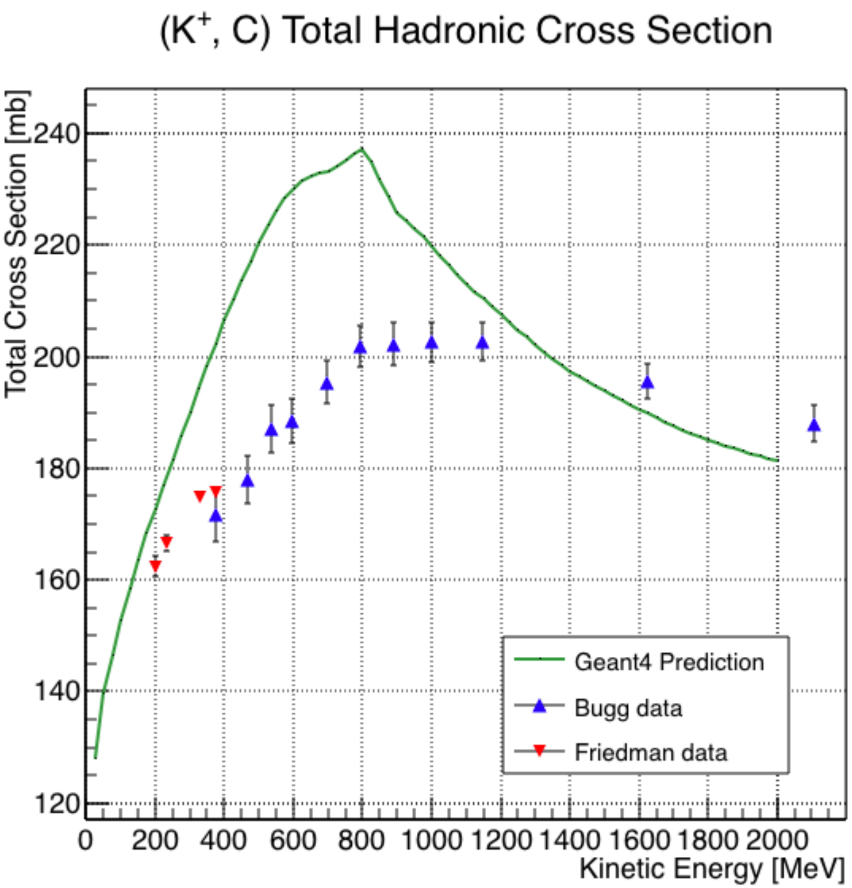
The intrinsic value of this measurement lays in the exploration of the interaction between nuclei and strange light mesons.

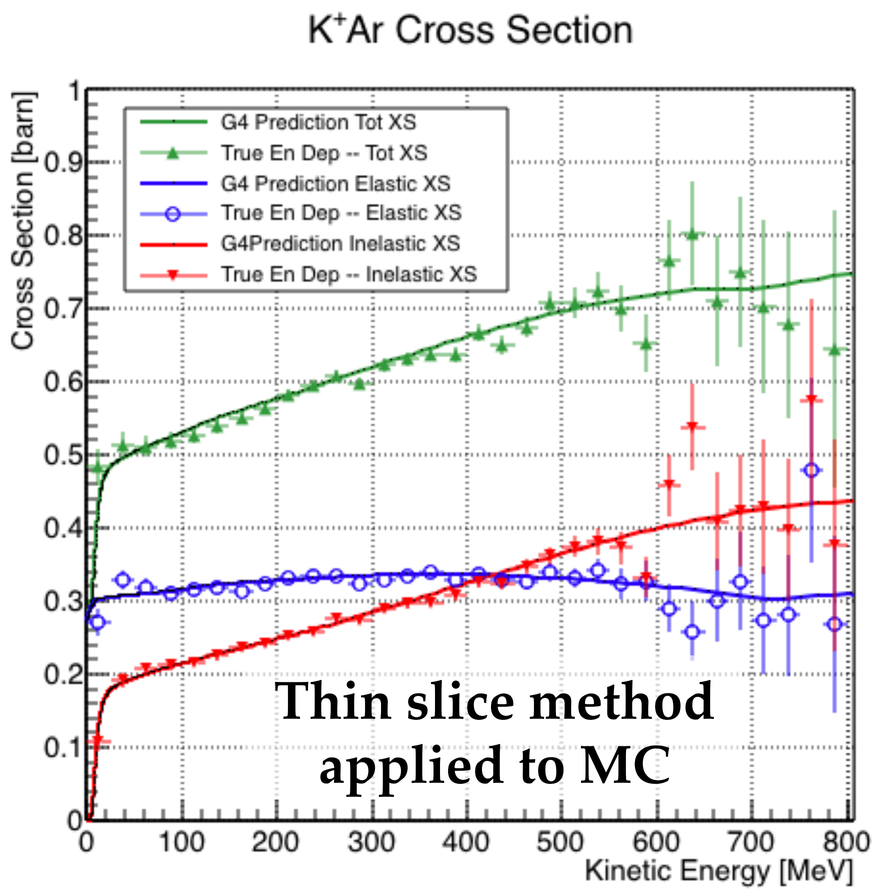
The first LArIAT study concentrates on K^+ cross section, given its relevance to proton decay searches in DUNE.

$p \to K^+ \bar{\nu}$ Golden channel for pdk in LAr.

Status of the Geant4 Process Simulation

Kaon Cross Section in Geant4: no experimental data for Ar.

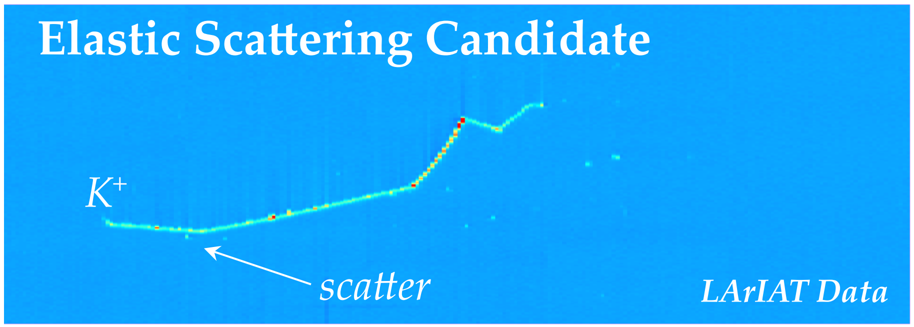


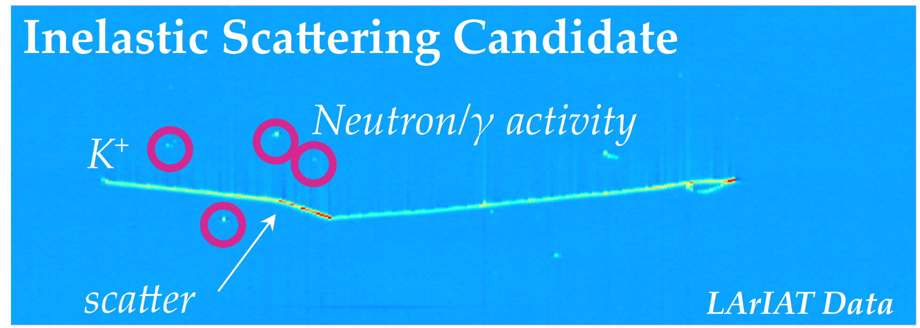


Signal and Background topologies

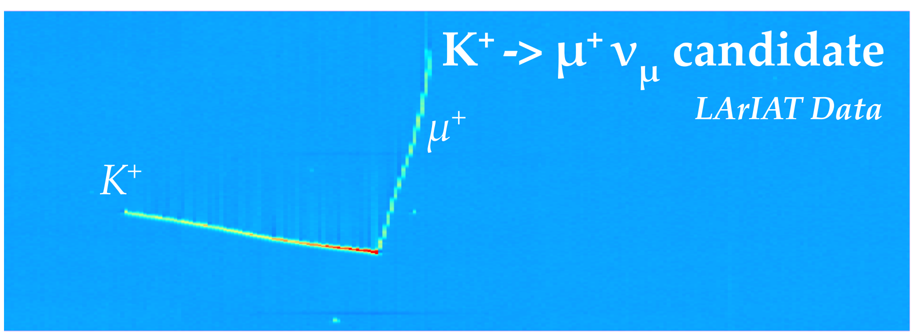
Signal: **All Hadronic Interactions**

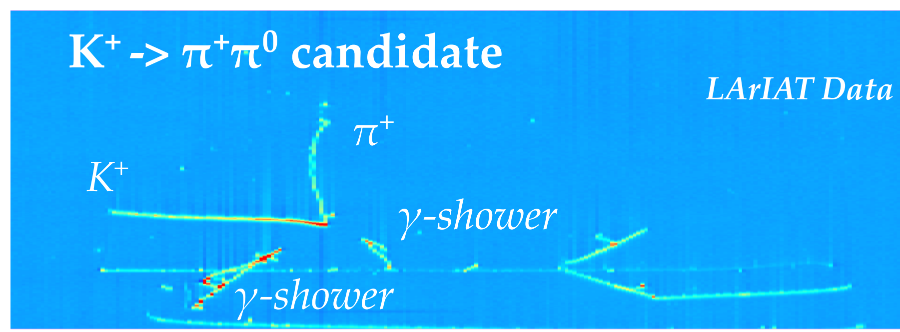
$$\sigma_{Tot} = \sigma_{Elastic} + \sigma_{Reaction}$$





Backgrounds: **Kaon Decay ; Coulomb Scattering**

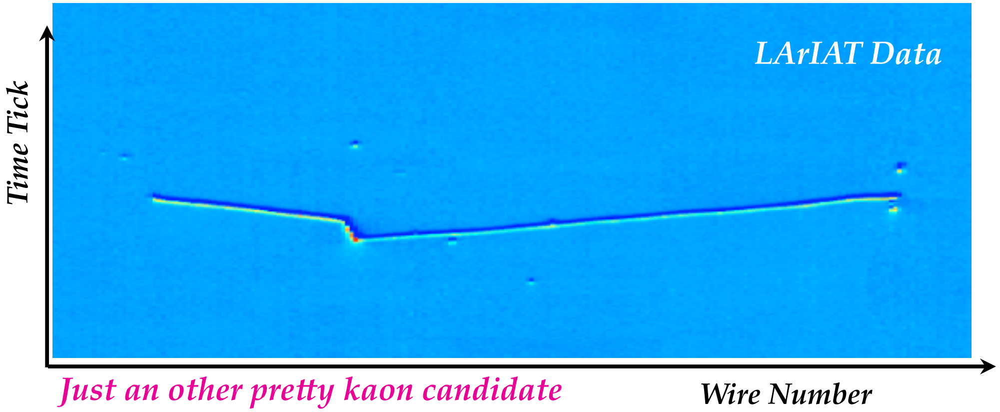




Key elements for the K^+-Ar XS

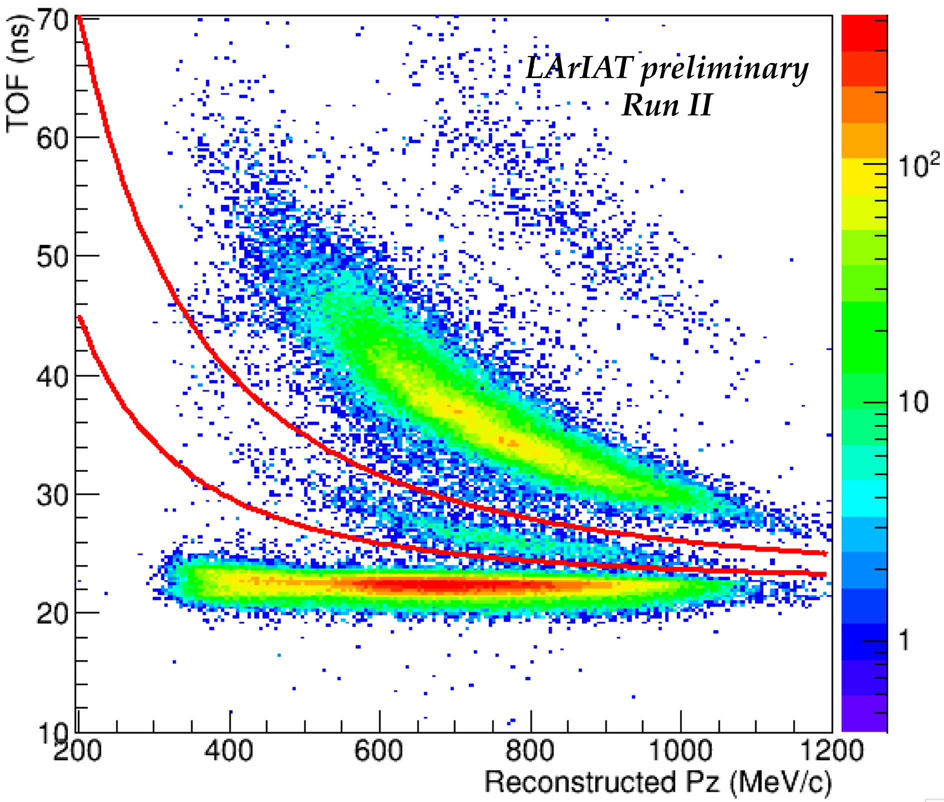
In order to measure the **Kaon Cross Section**, we need to :

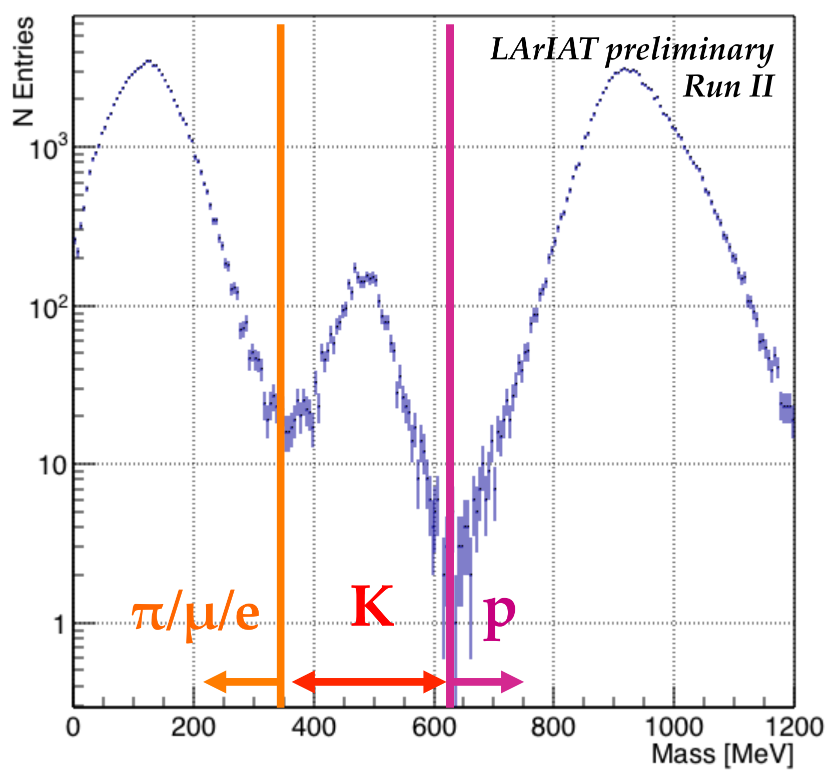
- Identify kaons in the beamline
- Study the contamination in the kaon sample
- Study the loss in dead material between beamline and TPC
- Assess basic reconstruction:
  Tracking & Calorimetry
- Tag kaon decay slices
- Identify signal
  interactions



Just an other pretty kaon candidate

Find Kaons in the beamline!





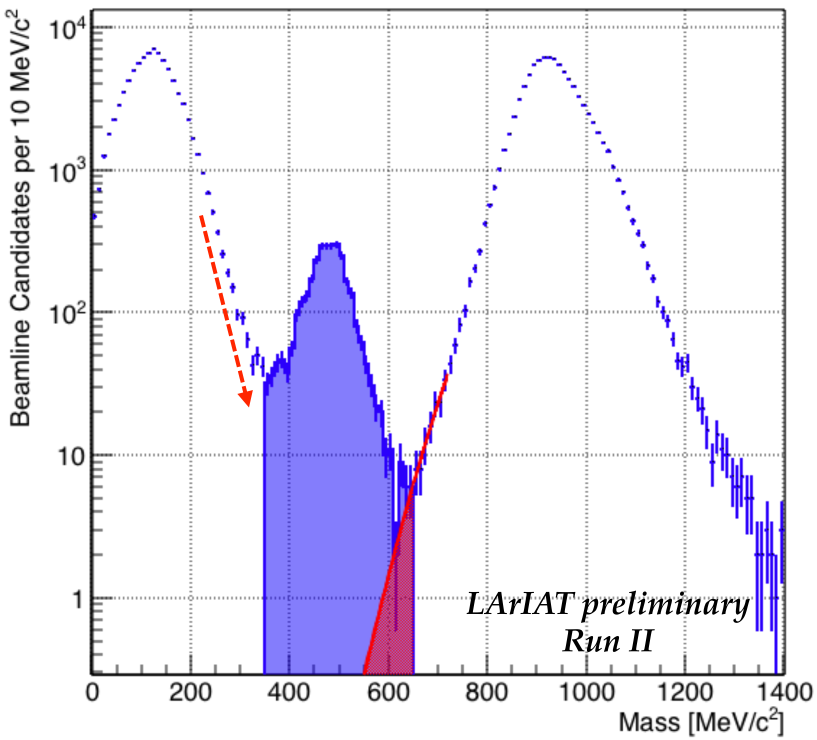
$$m = \frac{p}{c}\sqrt{(\frac{c * TOF}{\ell})^2 - 1}$$

Keep

350 MeV/c² < Mass < 650 MeV/c²

Contamination

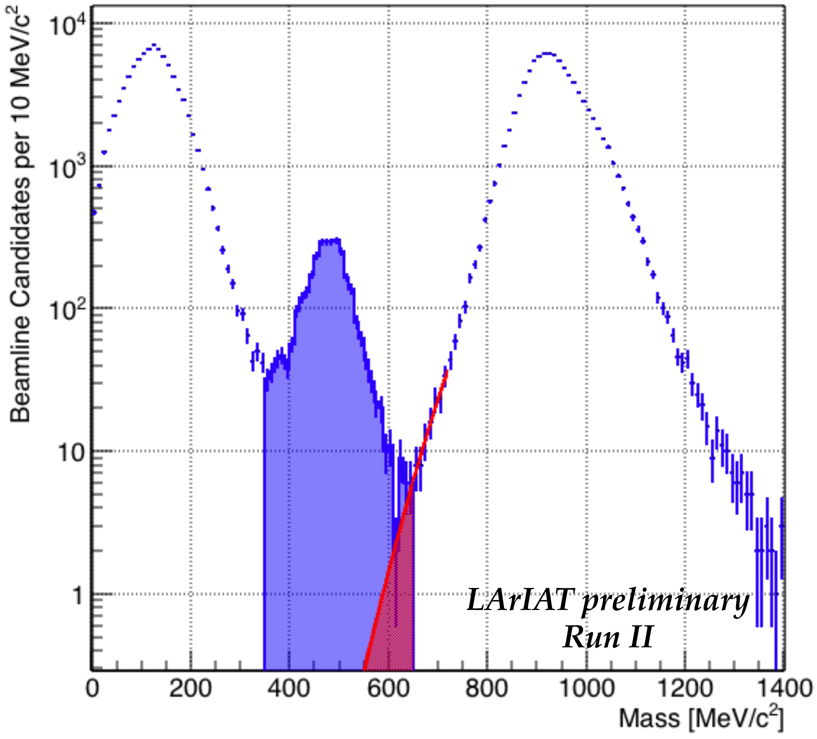
Data Driven method from beamline mass distribution.
The basic idea is to **estimate the bleed over** from high and low mass peaks under the kaon peak.
The catch is that we **don't know** the **shape** of those tails!



1) Choose one in a range of reasonable functions
2) Fit in tail range
3) Extend the fit function under the kaon peak
4) Integrate the between 350-650 MeV/c^2
5) Integrate the mass histogram in the same range
6) Take the ratio between the 2 integrals
7) Repeat for several fit shapes and tail ranges

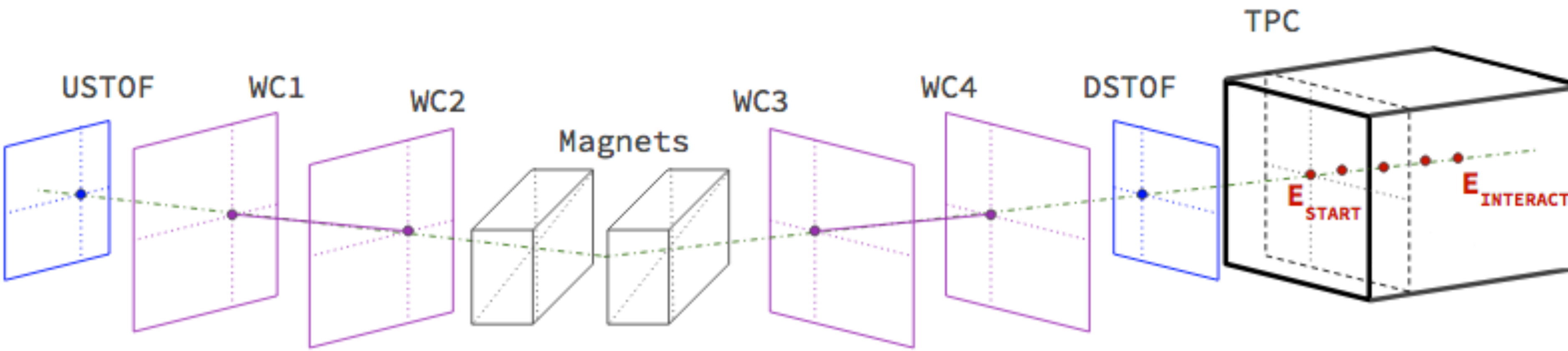
Contamination

Data Driven method from beamline mass distribution.
The basic idea is to **estimate the bleed over** from high and low mass peaks under the kaon peak.
The catch is that we **don't know** the **shape** of those tails!



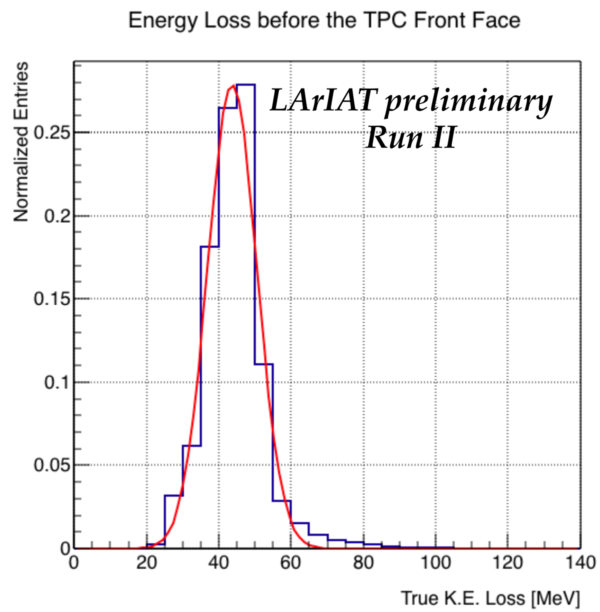
With 12 iterations of this method we find:
High Mass Contamination = 0.2 ± 0.5 %
Low Mass Contamination = 5 ± 2 %

Loss Before TPC



Truth study:
Average energy loss before the TPC Front Face = 44 ± 7 MeV.

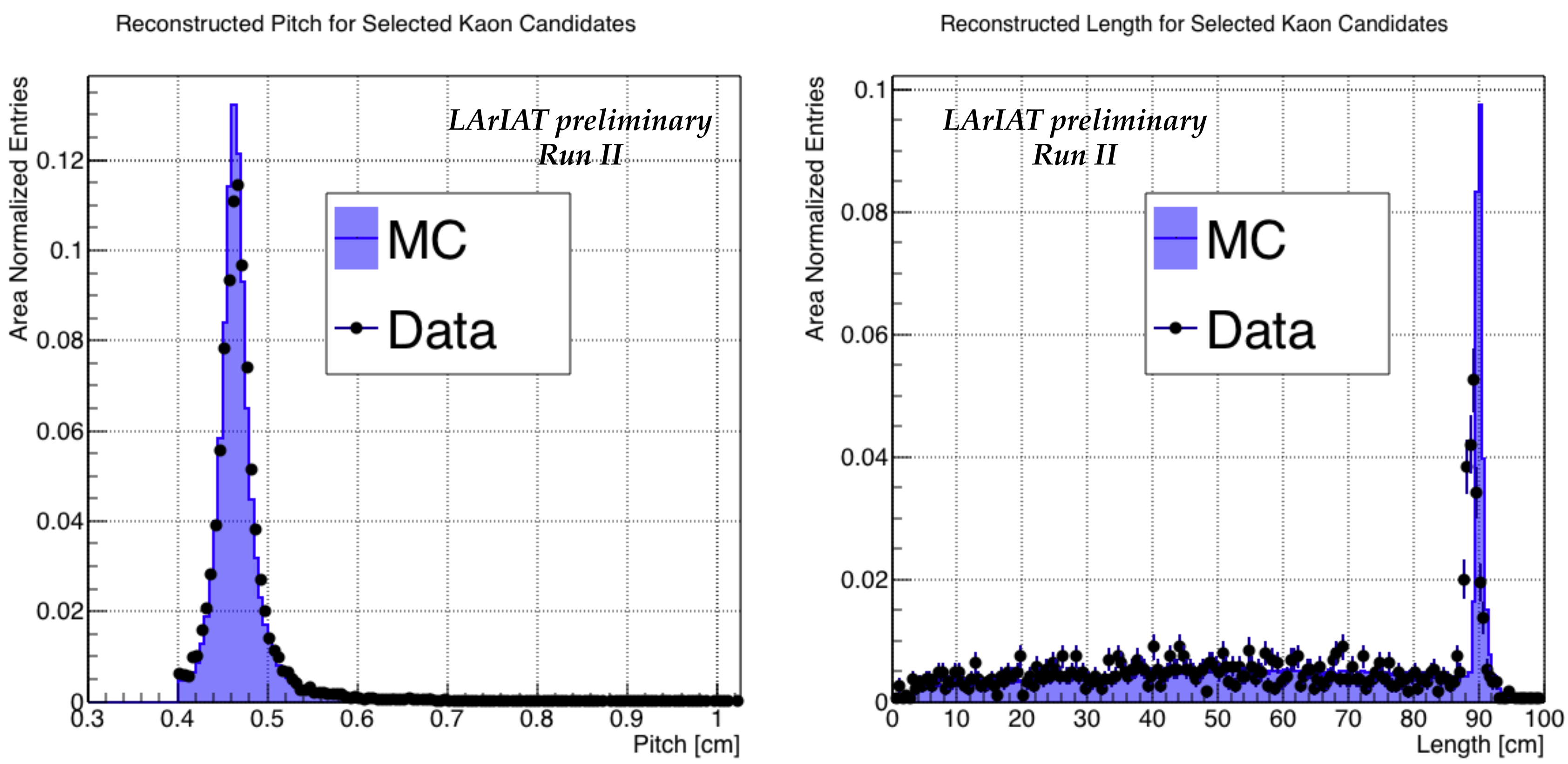
33 % of Kaons in the beamline interact or decay before getting to TPC.



Basic Reconstruction: Tracking

Track Pitch and Track Length.

Data and MC comparison, area normalized.

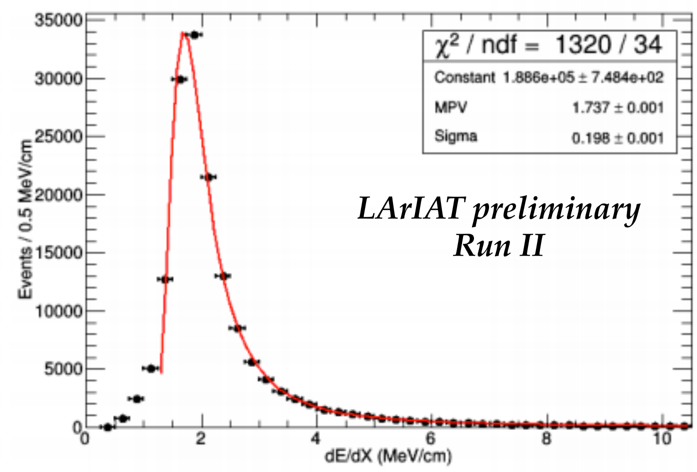


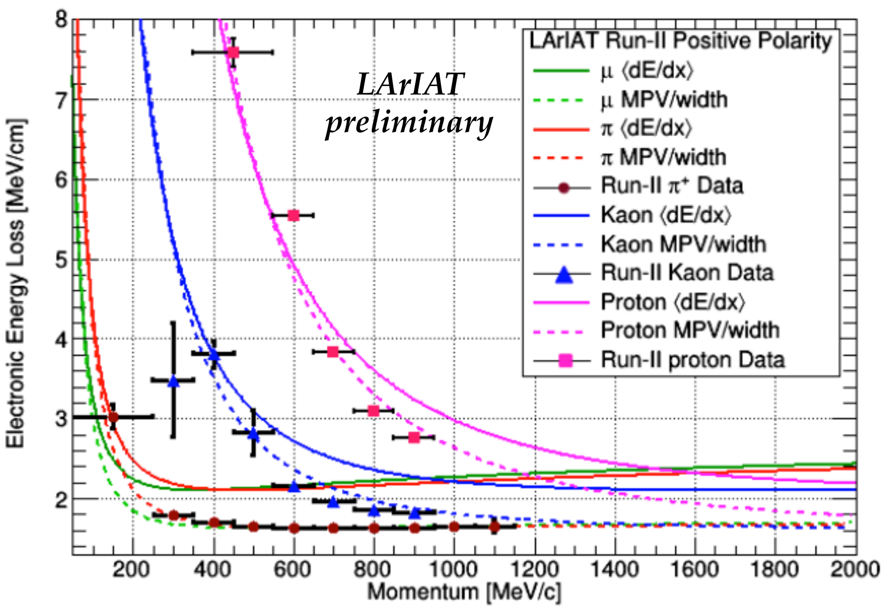
Basic Reconstruction: Calorimetry

Calorimetry calibration technique.

1. Select pions from the beamline
2. Match them to the TPC
3. Use the WC measurement to determine the momentum bin
4. Fit dE/dx plot per momentum bin
5. Plot the MPV against the Bethe-Bloch prediction to calibrate the calorimetry.

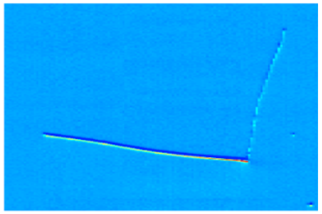
After calibrating calorimetry using a π+ sample, apply the same calibration constants to the kaon and proton samples.

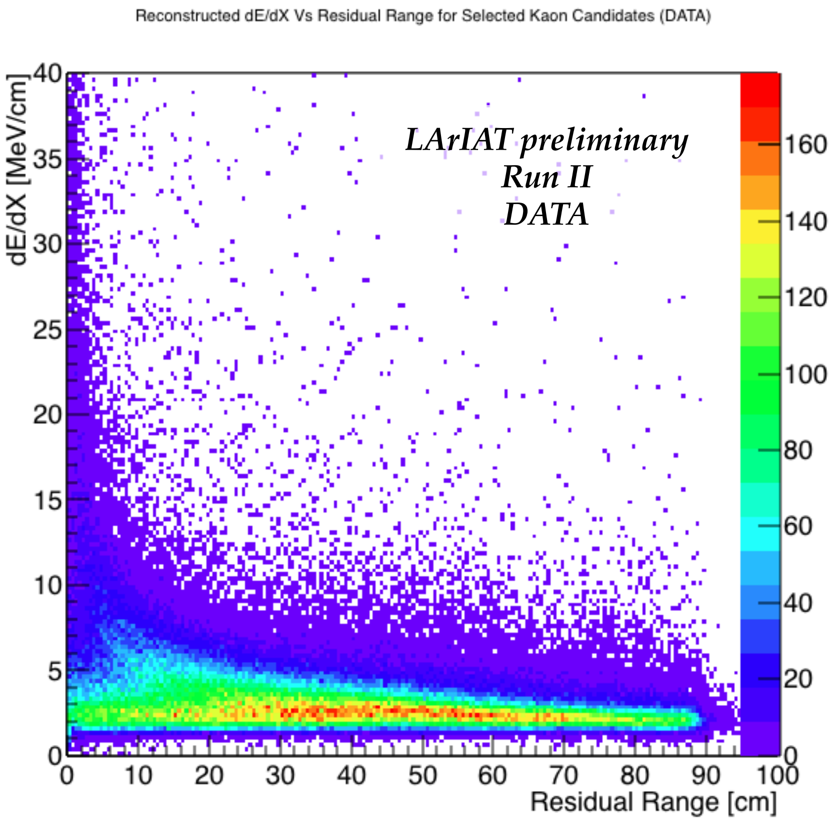


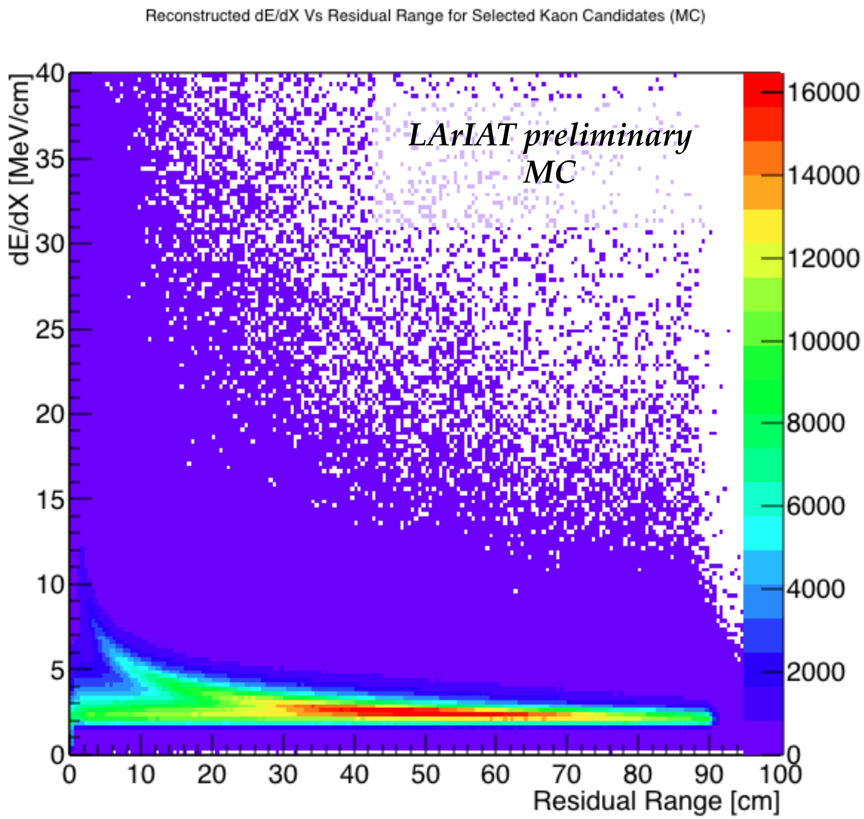


Basic Reconstruction: Calorimetry

dE/dX Vs Residual Range. Data and MC.
Improvement of noise simulation is ongoing.

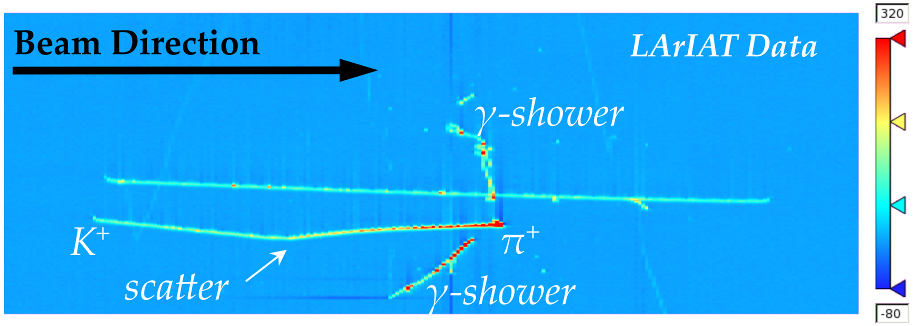




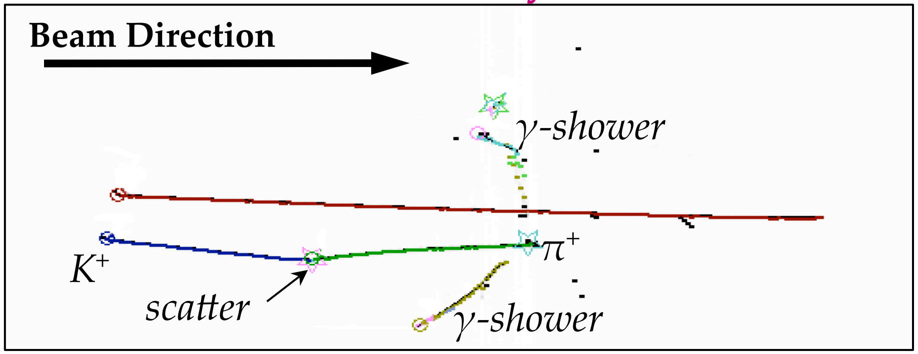


Key element: Identify Signal Interaction

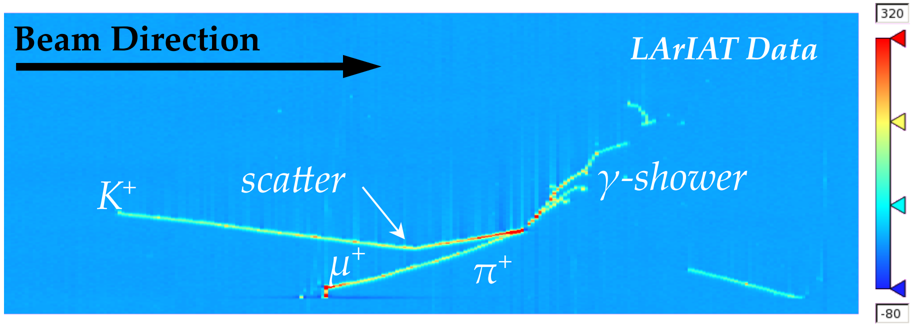
LArIAT Data Preliminary K+ Candidate



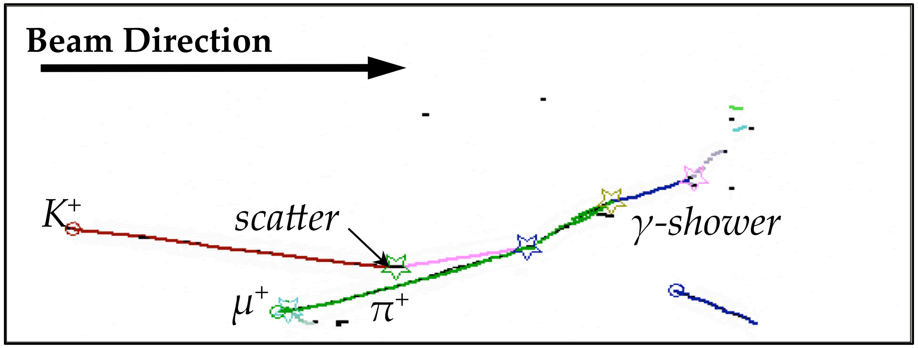
LArIAT Data Preliminary Reconstruction



LArIAT Data Preliminary K+ Candidate



LArIAT Data Preliminary Reconstruction

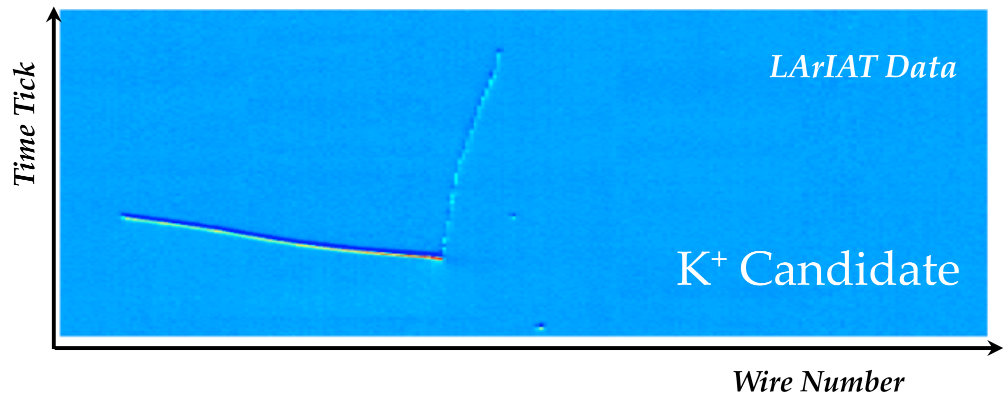


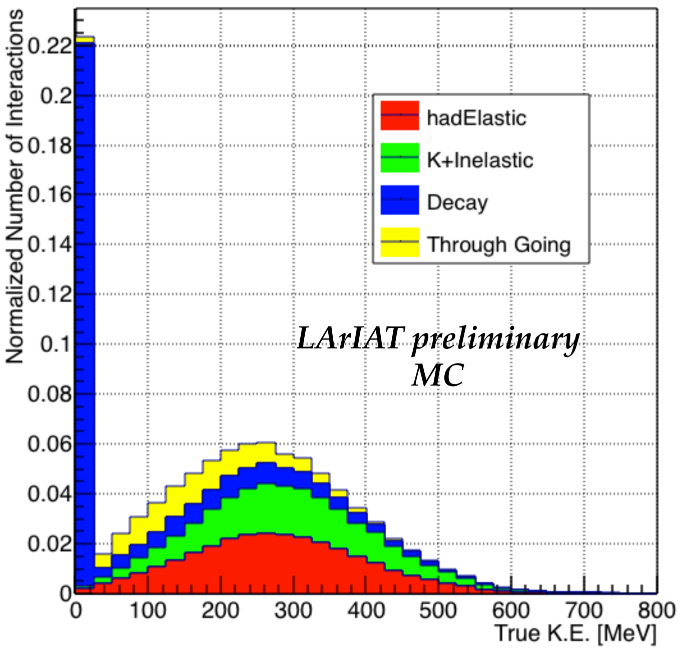
Key element: Tag K Decay Slices

Kaon decay proceeds by the **weak interaction**.

The endpoint of a decaying kaon could be **misidentified as a single strong interaction**.

For kaon **decay at rest**, we can use the presence of a **Bragg peak** to tag the end point as non-interacting and simply cut off the lowest energy bin.
The development of the tools to tag **kaon decay in flight** is ongoing.





Event reduction table

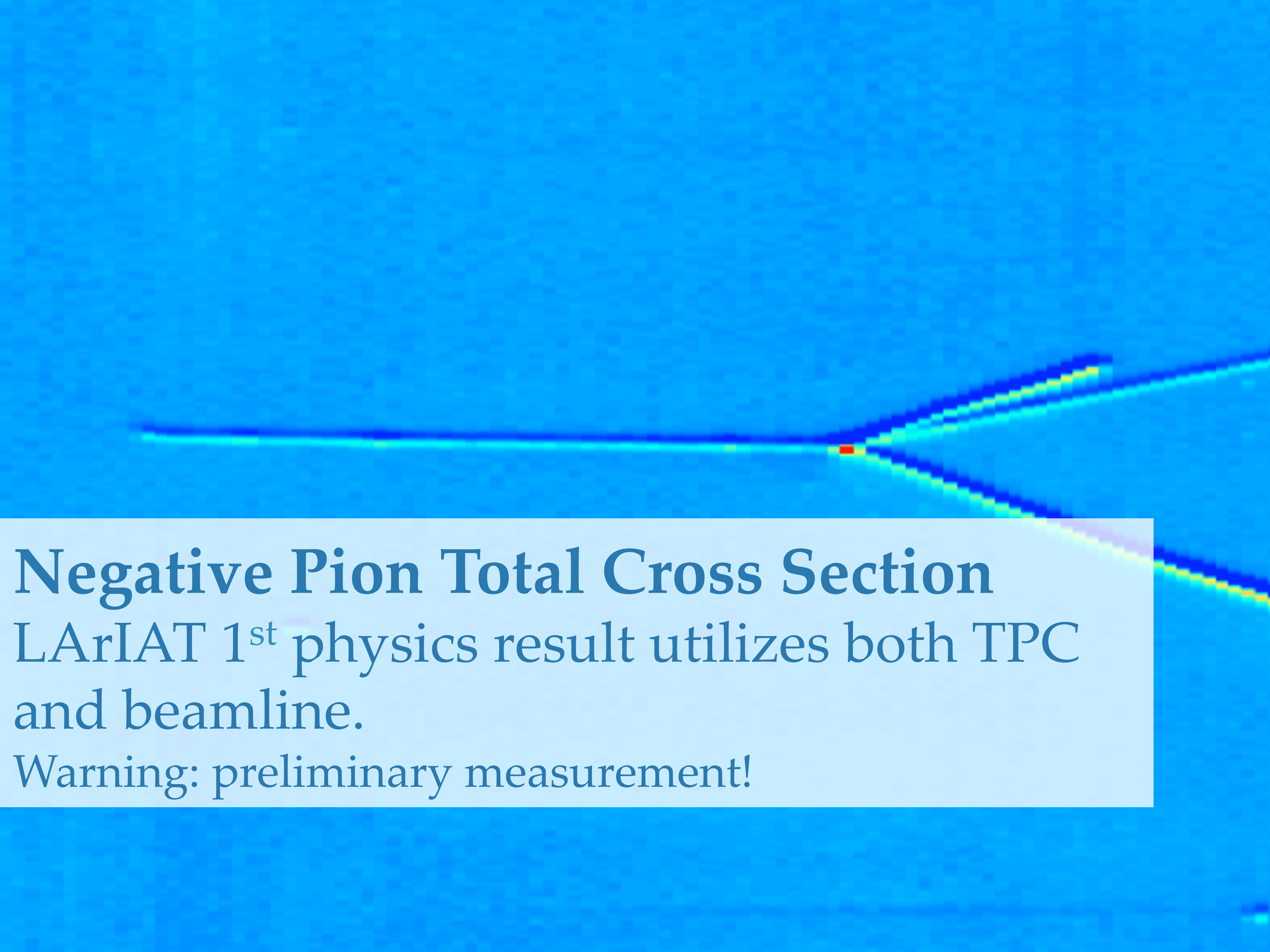
Stage	Number of Events
Run II Positive Polarity Data	~4000000
Cosmic Removal	1555402
Beamline Reconstruction	188060
Mass Filter	4289
WC to TPC match	1986

Effects we want to address

(before we make the XS public) :

- Tracking fine tuning & interaction tagging efficiency
- Decay MisID rate
- WC Momentum Uncertainty

K⁺Ar Cross Section



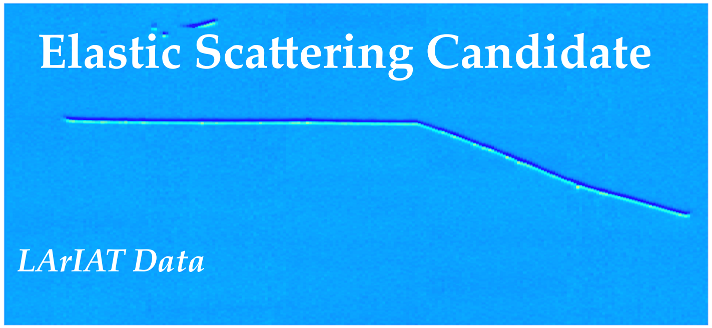
Negative Pion Total Cross Section

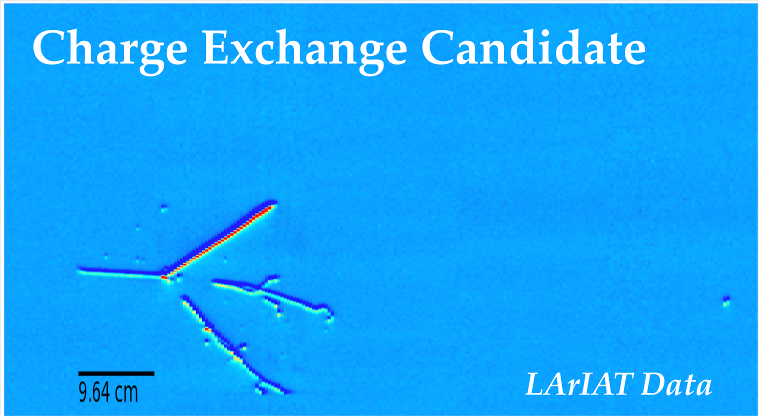
LArIAT 1st physics result utilizes both TPC and beamline.

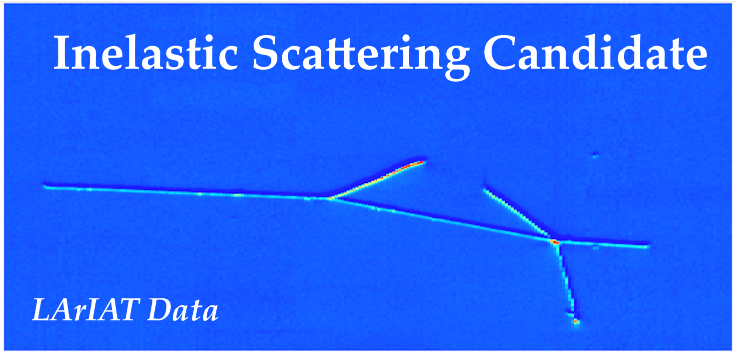
Warning: preliminary measurement!

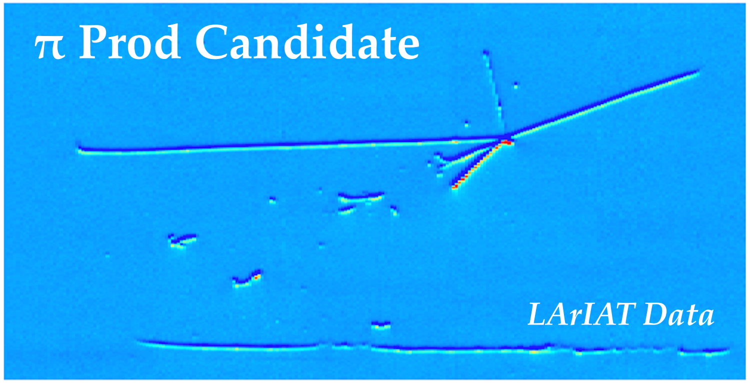
Signal topologies

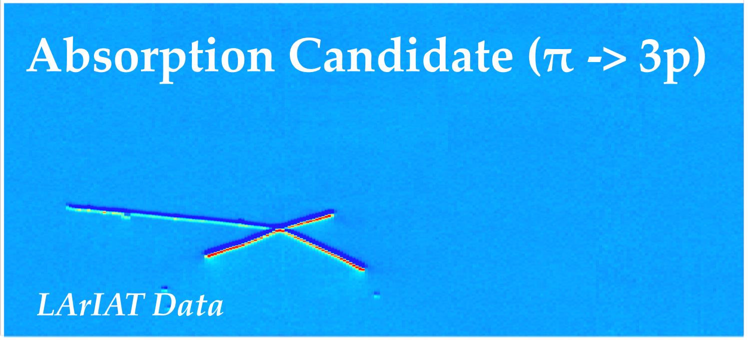
$$\sigma_{Tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{abs} + \sigma_{charge\ XC} + \sigma_{\pi\text{-prod}}$$







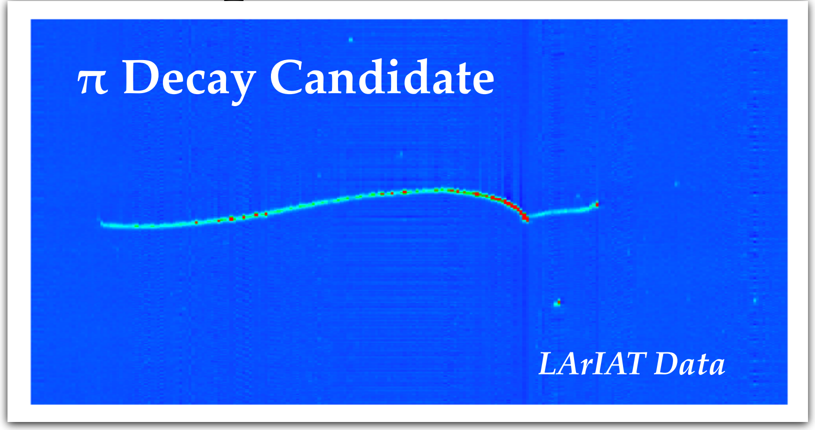


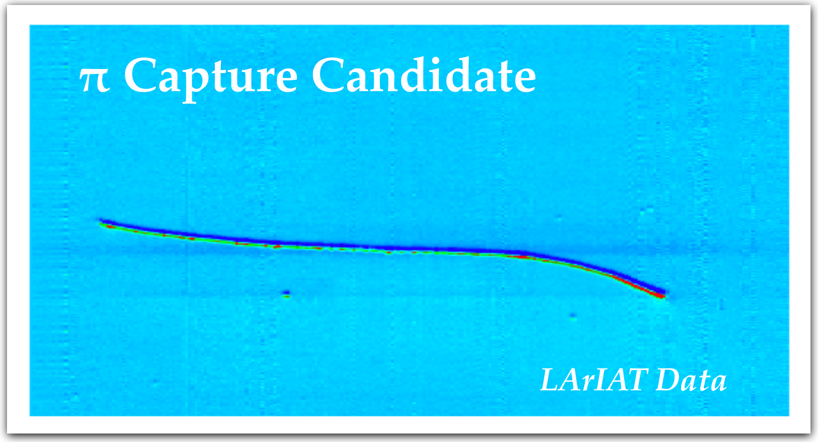


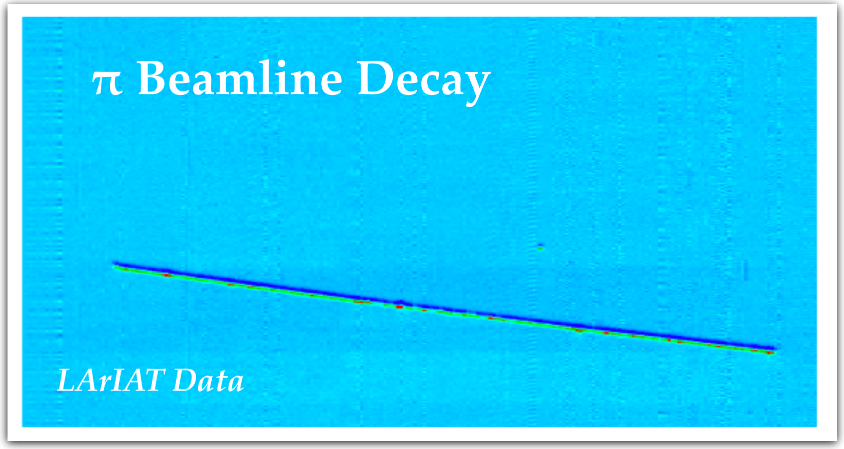
Background topologies

Currently included in the analysis

These processes will be estimated and removed





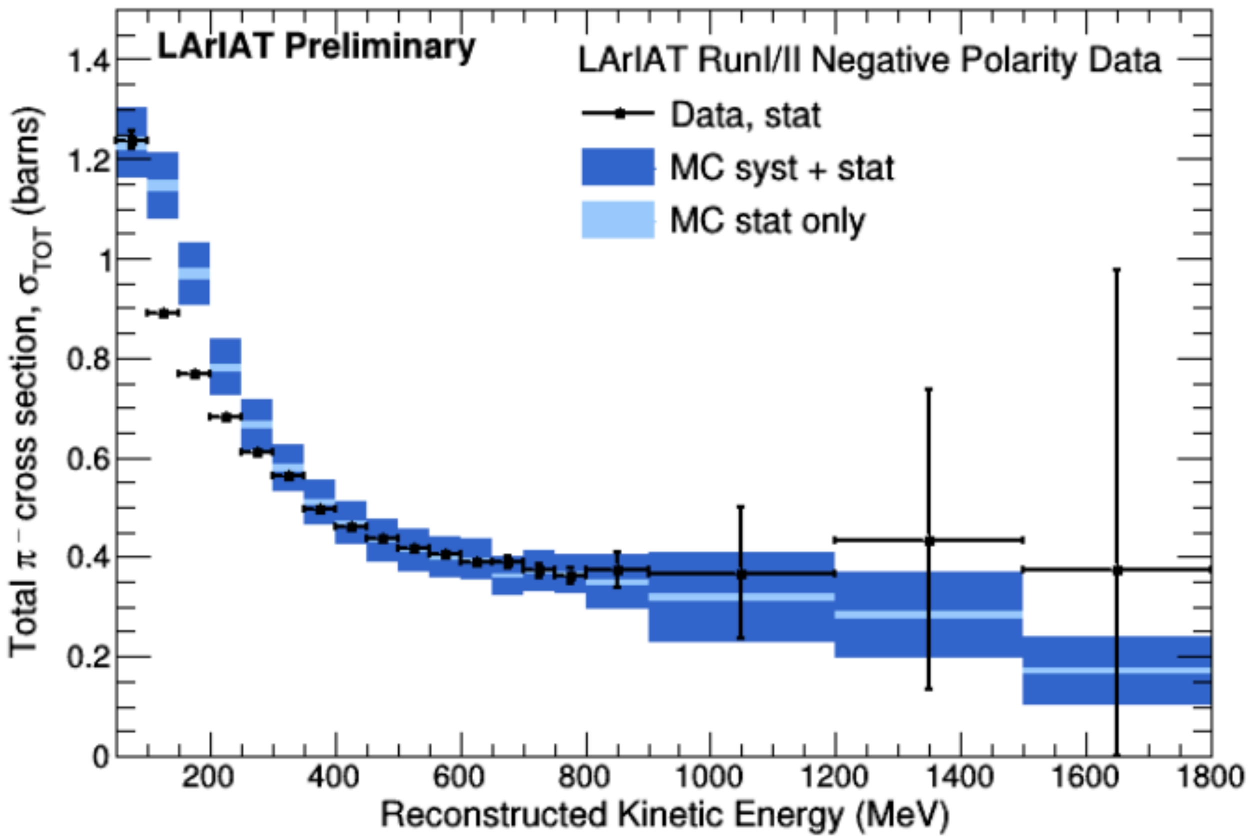


Event Selection: reduction table

Event Selection	Run-I Negative Polarity	Run-II Negative Polarity	Combined
Total Number of Beam Events	113,336	1,585,598	1,698,934
π, μ, e Mass Selection	20,653	493,455	514,108
20 ns <TOF<27	20,577	485,159	505,736
Requiring an upstream TPC Track within $z < 2$cm	18,882	403,561	422,443
< 4 tracks in the first $z < 14$cm	12,910	316,451	329,361
Electromagnetic shower rejection	9,824	232,510	242,334
Unique match between WC/TPC Track	5,500	120,956	126,456

	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%

Pion-Ar Cross Section



<u>Systematics Considered Here</u>

dE/dX Calibration: 3%

Energy Loss Prior to the TPC: 3.5%

Through Going μ: 3%

WC Momentum Uncertainty: 3%

Hadron-Ar Cross Section: Summary

First analysis from LArIAT Run I and II

- Total Pion and Kaon XS on argon never before measured
- Demonstrated the capability to identify Pion and Kaon hadronic interactions in LAr
- Demonstrated the ability to automatically reconstruct Pion and Kaon events in beamline and TPC

Next steps:

K) Assessment of systematic uncertainties

K) Measure the total cross section!

π) Treatment of pion capture and decay processes

π) Improvement of the energy corrections

What's next? Other Analyses

Analyses to come from LArIAT

Cross section analyses

- Exclusive negative π-Ar absorption and charge exchange channels as well as elastic and inelastic scattering are all underway
- All of the above for positive π as well
- Kaons
- Protons

e/γ separation, muon sign determination, scintillation light studies, antiproton annihilation.

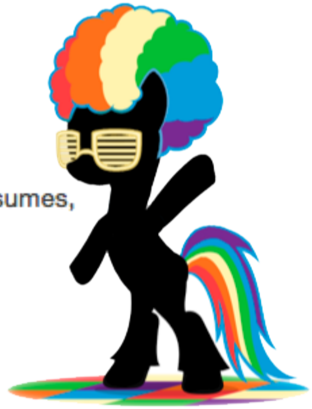
Run I and Run II collected wonderful datasets for physics analyses, Run III & PixLAr are hard core R&D:

3 mm vs 5 mm wireplane pitch, big pixel TPC, new light collection detectors, more precise TOF detectors and much more.

The LArIAT Collaboration

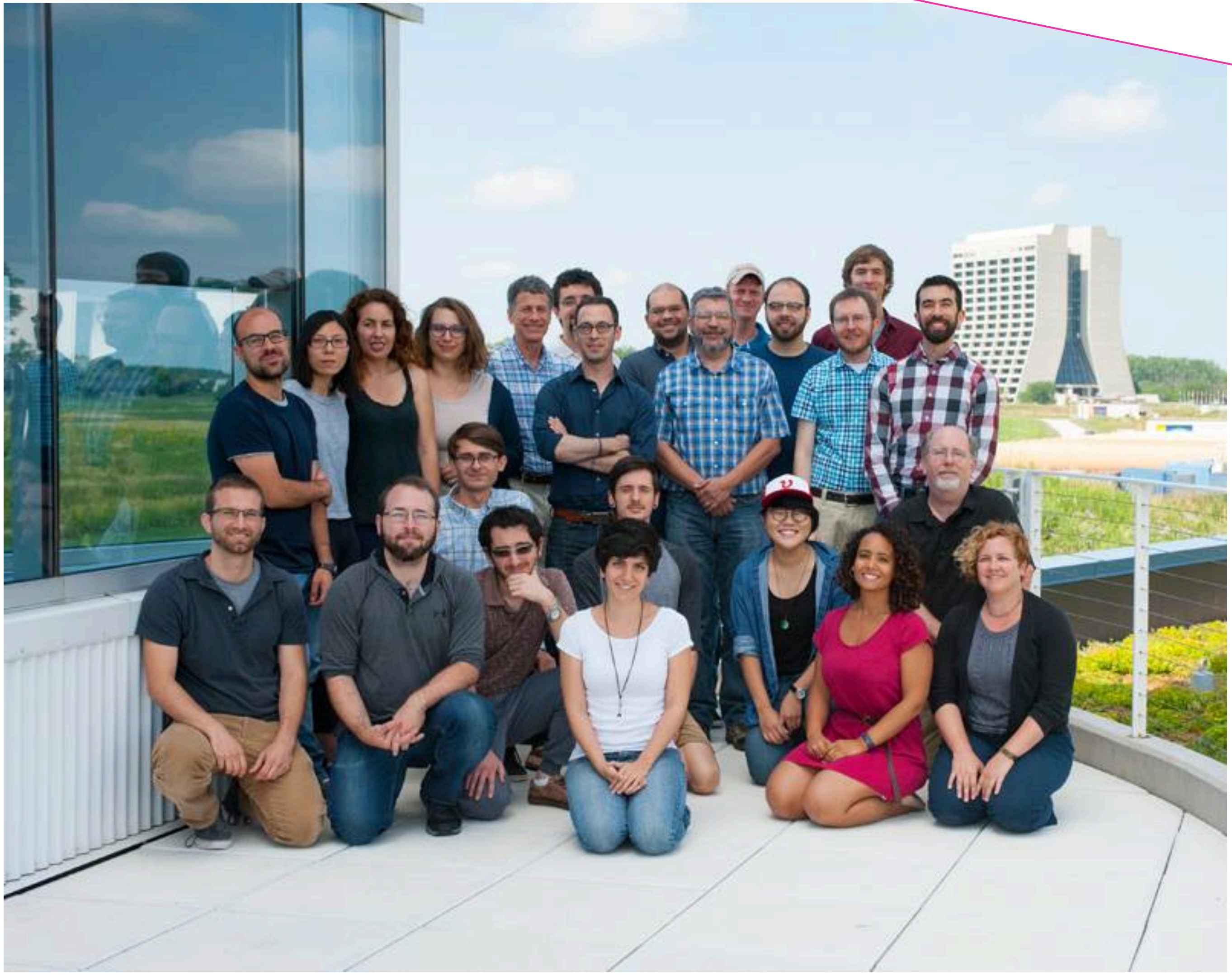
THANKS!!!!

- **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, Rob Carey, Bruno Gelli, Marina Guzzo, Dan Gastler, Ed Kearns, Ryan Linehan, Daniel Smith, Silvia Zhang
- **U. Campinas, Brazil (UNICAMP)** Carlos Escobar, Ernesto Kemp, Ana Amelia B. Machado, Mônica Nunes, Lucas Mendes 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, Mark Ross-Lonergan (also Durham U), Michelle Stancari, Tingjun Yang, Sam Zeller, James Zhu (also UC Berkeley)
- **Federal University of Goiás, Brazil (UFG)** Tapasi Ghosh, Ricardo A. Gomes, Ohana Rodrigues
- **Istituto Nazionale di Fisica Nucleare, Italy (INFN)** Flavio Cavanna (also Fermilab), Ornella Palamara (also Fermilab)
- **KEK** Eito Iwai, Takasumi Maruyama
- **Louisiana State University** Justin Hugon, William Metcalf, Andrew Olivier, Martin Tzanov
- **U. Manchester, UK** Justin Evans, Diego Garcia-Gamez, Pawel Guzowski, Colton Hill, Andrzej Szelc
- **Michigan State University** Carl Bromberg, Dan Edmunds, Dean Shooltz
- **U. Minnesota, Duluth** Rik Gran, Alec Habig, Miranda Elkins
- **National Centre for Nuclear Research (NCBJ), Poland** Robert Sulej, Dorota Stefan
- **Syracuse University** Jessica Esquivel, Pip Hamilton, Greg Pulliam, Mitch Soderberg
- **U. Texas, Arlington** Jonathan Asaadi[†], Animesh Chatterjee, Andrea Falcone, Amir Farbin, Ilker Parmaksiz, Dalton Sessumes, Sepideh Shahsavarani, Zachary Williams, 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** Corey Adams, Bonnie Fleming, Elena Gramellini, Xiao Luo



The LArIAT Collaboration

THANKS!!!!



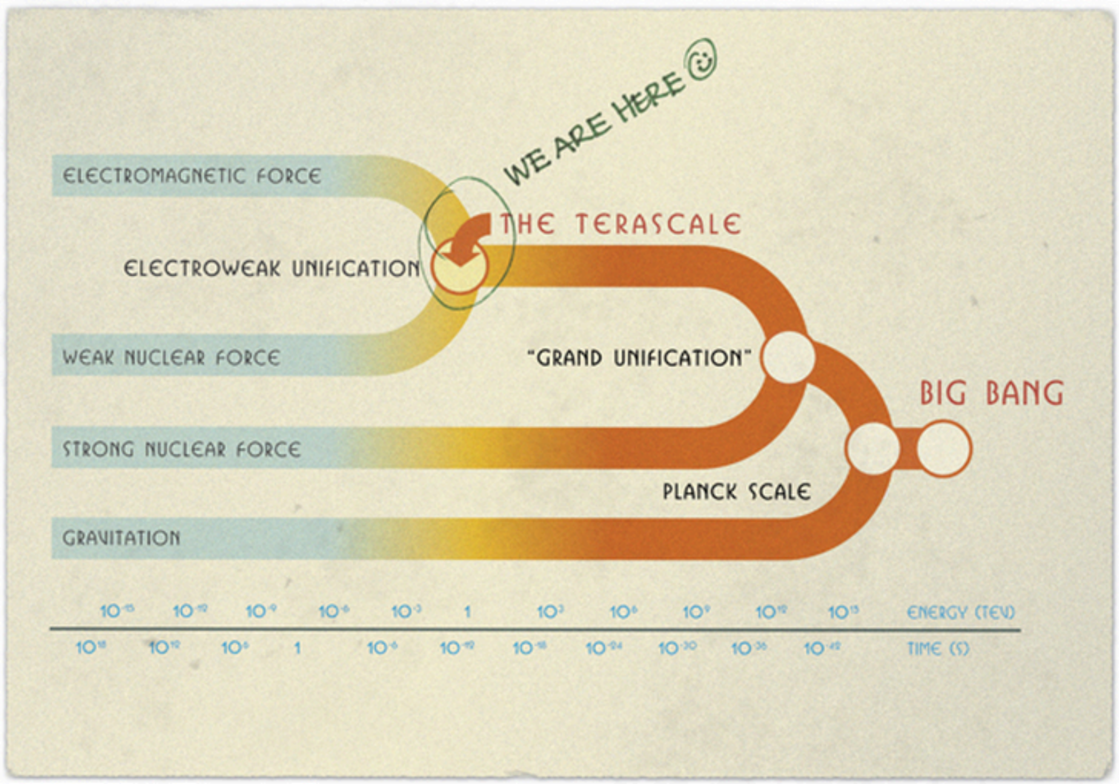

"A small detector with a big heart"

Nucleon Decay Searches

The detection of even one nucleon decay event would be a **direct evidence** of **physics BSM**, opening a window on GUTs exploration.

Every interaction in the **SM conserves baryon number**.

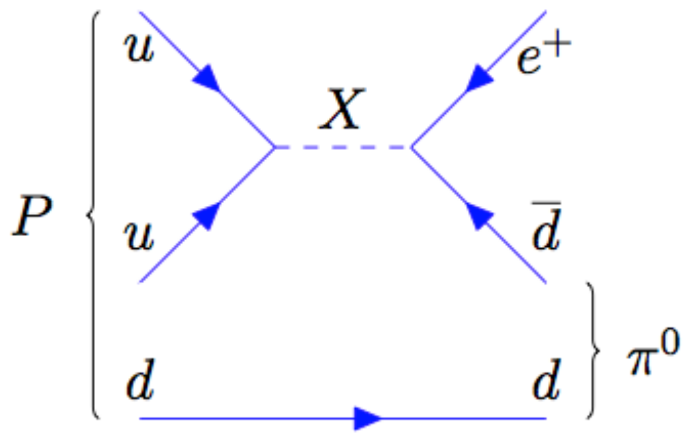
Proton (or bound neutron) **decay** can occur only as a **violation of baryon number** and it's predicted by almost every GUT.



Golden Modes

$p \rightarrow e^+\pi^0$

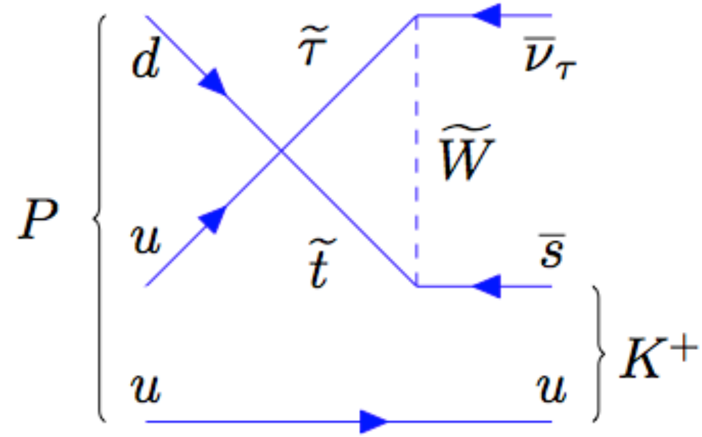
$\tau/B_{p\rightarrow e\pi 0} > 1.6 \times 10^{34}$ yr



Water Cherenkov

$p \rightarrow K^+\,\bar{\nu}$

$\tau/B_{p\rightarrow K+\nu} > 5.9 \times 10^{33}$ yr



Liquid Argon

arXiv:1307.7335 PhysRevD.95.012004 PhysRevD.90.072005

Ingredients for Nucleon Decay Detection

Lots of nucleons

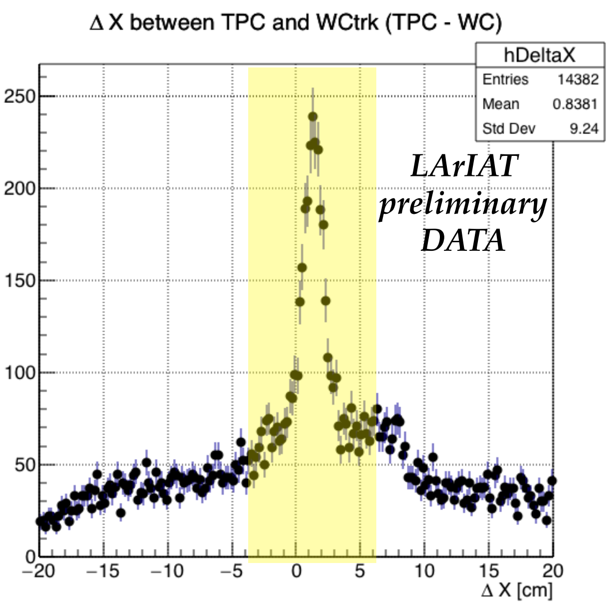
Lots of time

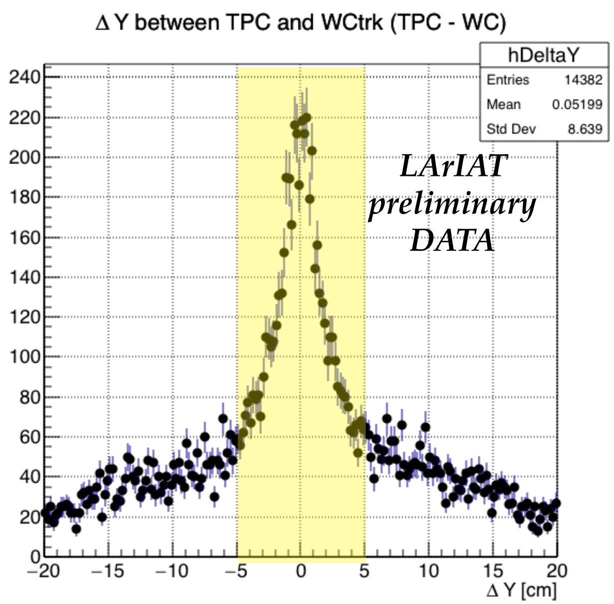
Low background

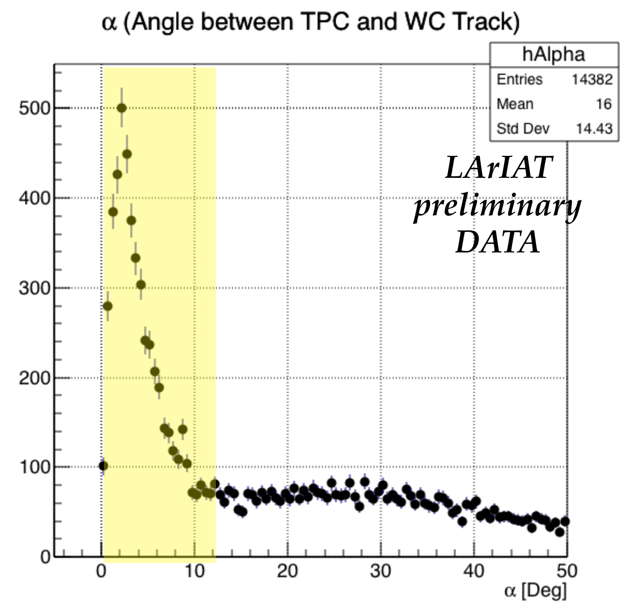
Excellent signal efficiency

1. Find Kaons: WC2TPC Δx, Δy and α

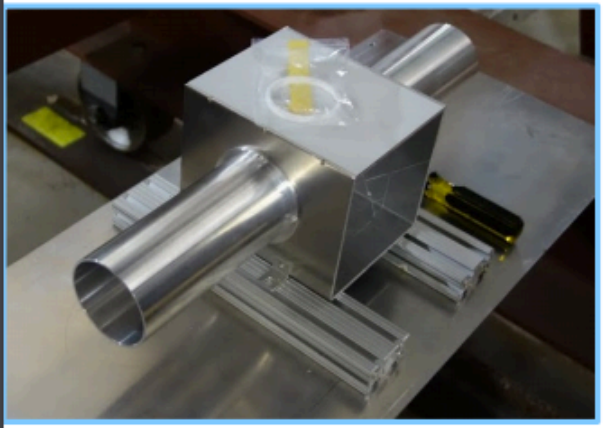
Plot the distribution of WC2TPC match before the cuts are applied.
Selection:
Δx and Δy within ± 5 cm from the peak
$\alpha < 10^o$

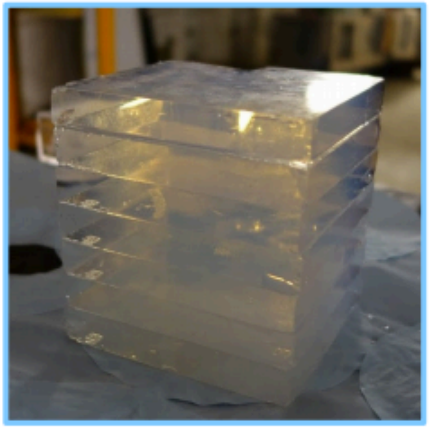






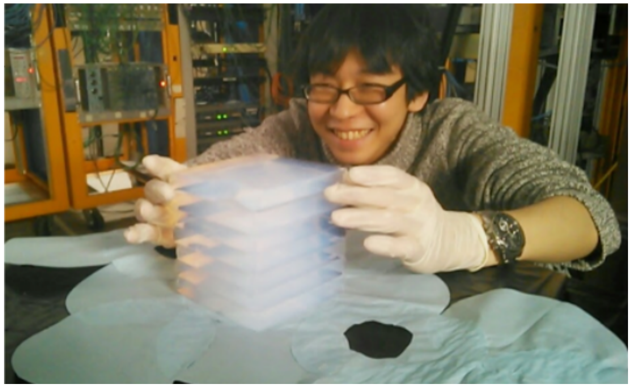
Aerogel Cherenkov detectors

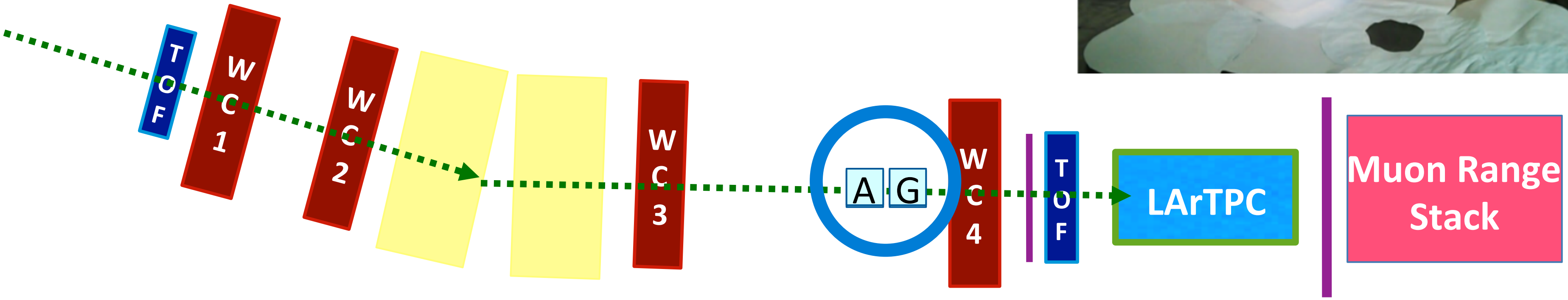




	n=1.11 Aerogel	n=1.057 Aerogel
200-300 MeV/c	μ π	μ π
300-400 MeV/c	μ π	μ π

Improve Particle ID for
μ π K/p
currently under investigation

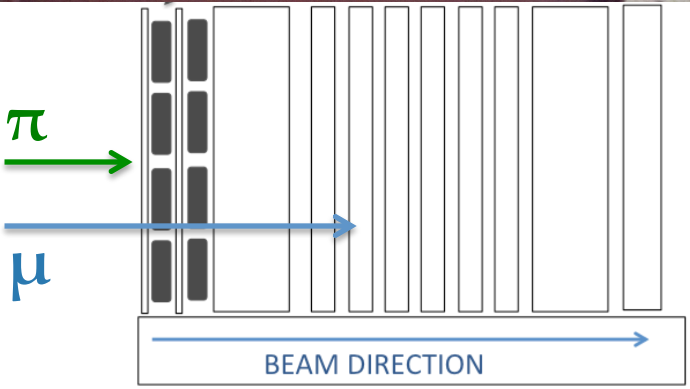


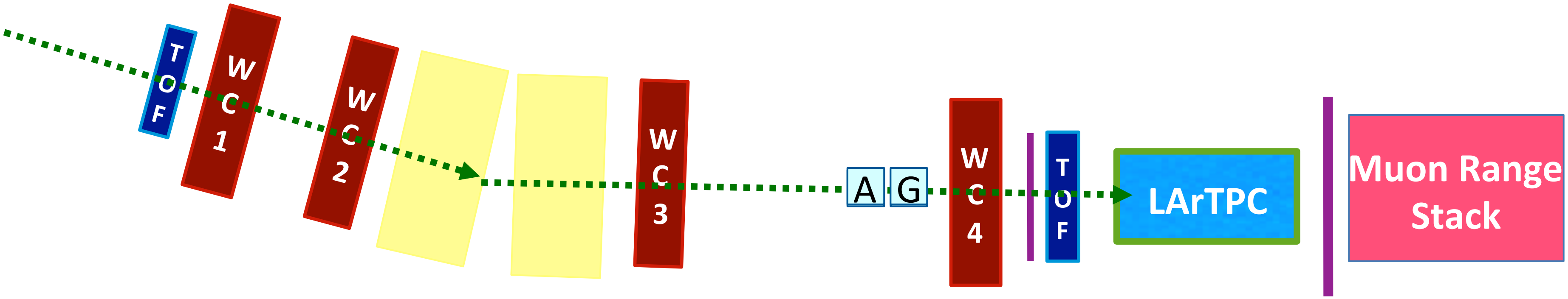


Muon Range Stack

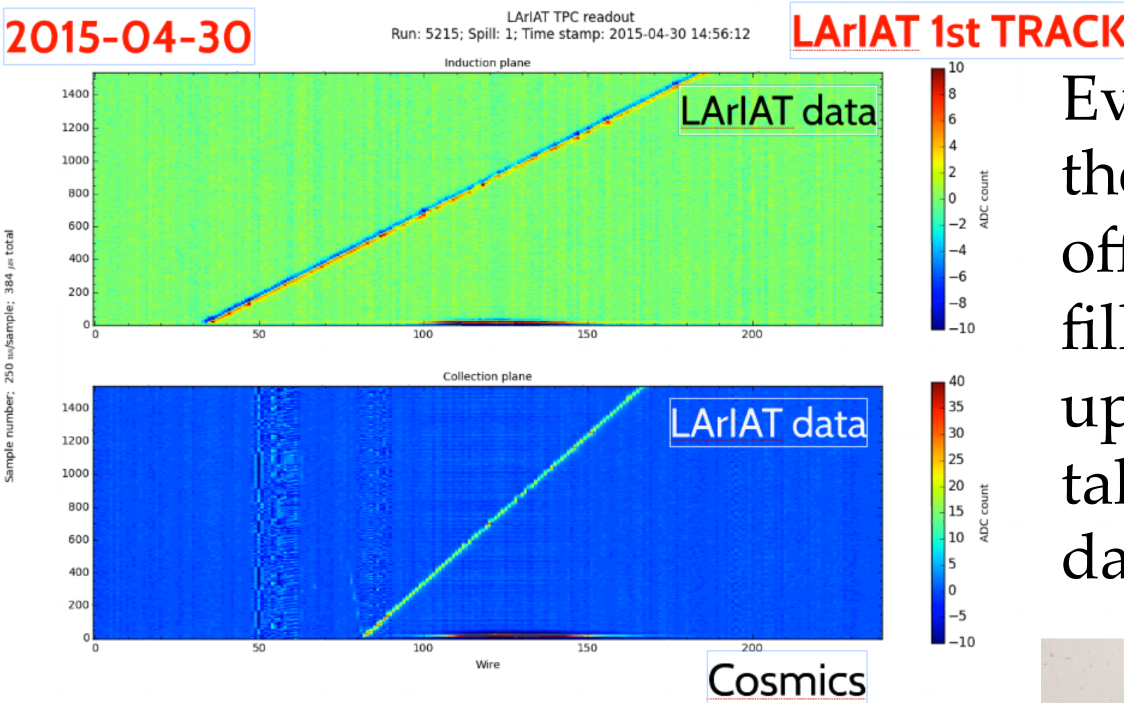
Essentially a segmented block of (pink) steel with scintillator bars and PMTs

Improve Particle ID for through going μ/π **momentum > 450 MeV/c** currently under investigation

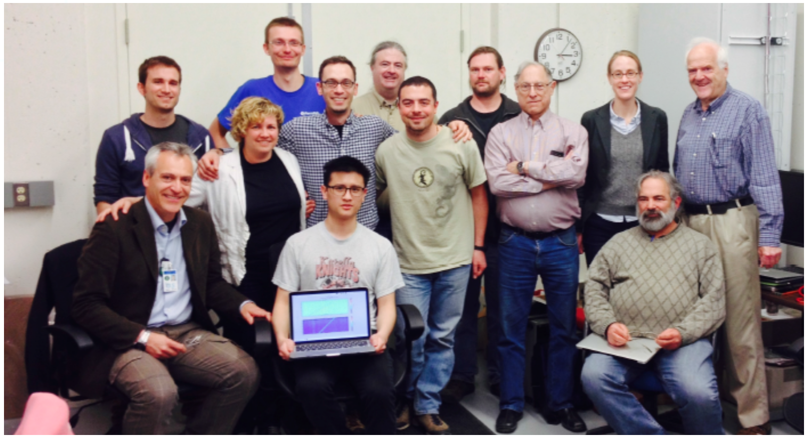




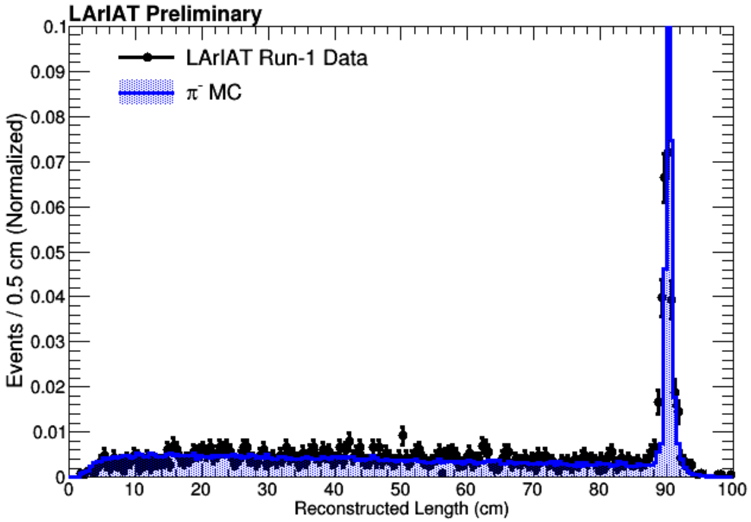
DATA! LArIAT first event

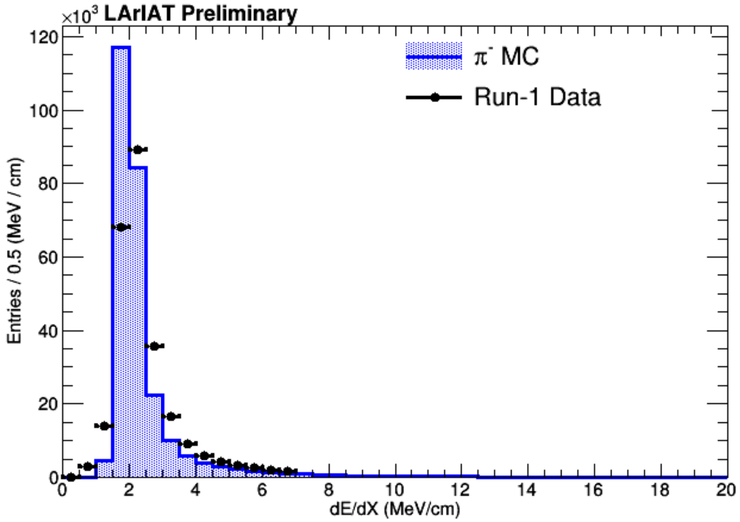


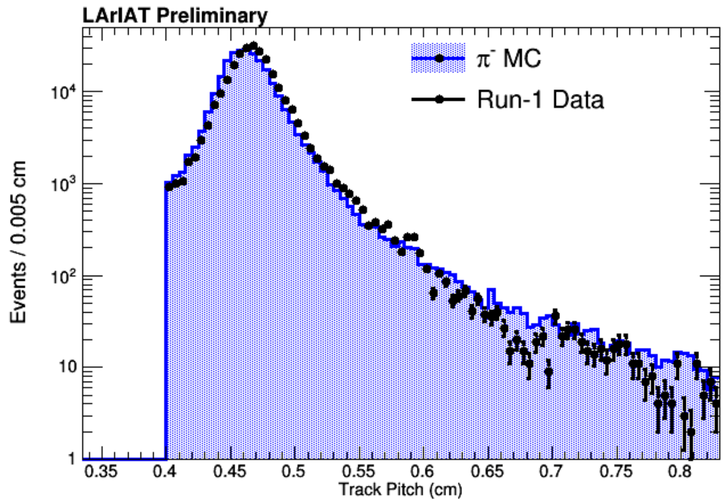
Every component inside the cryostat worked right off the bat: we purged and filled the cryostat, ramped up the HV, and began taking data in less than 1 day (April 30th 2015)

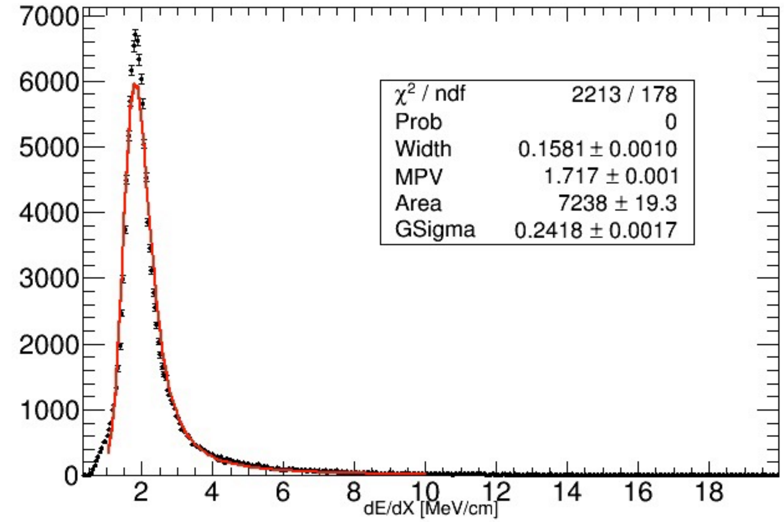


A glance at systematics

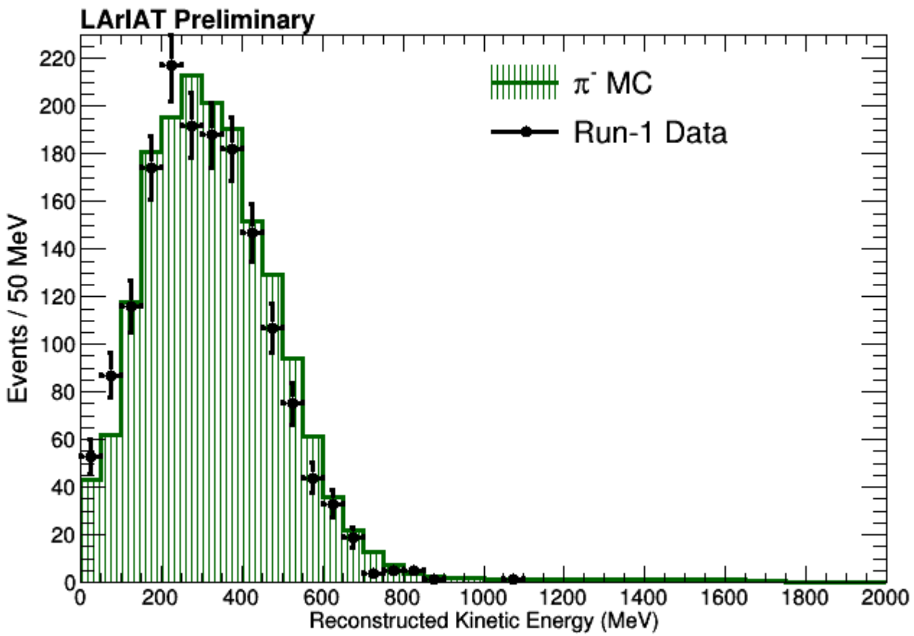


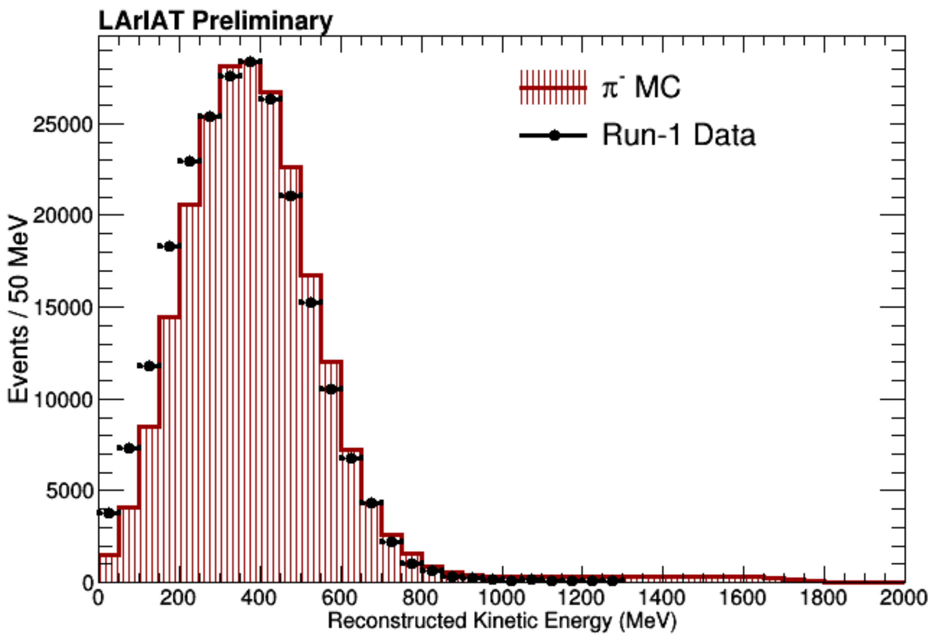






$N_{Incident}$, $N_{Interacting}$



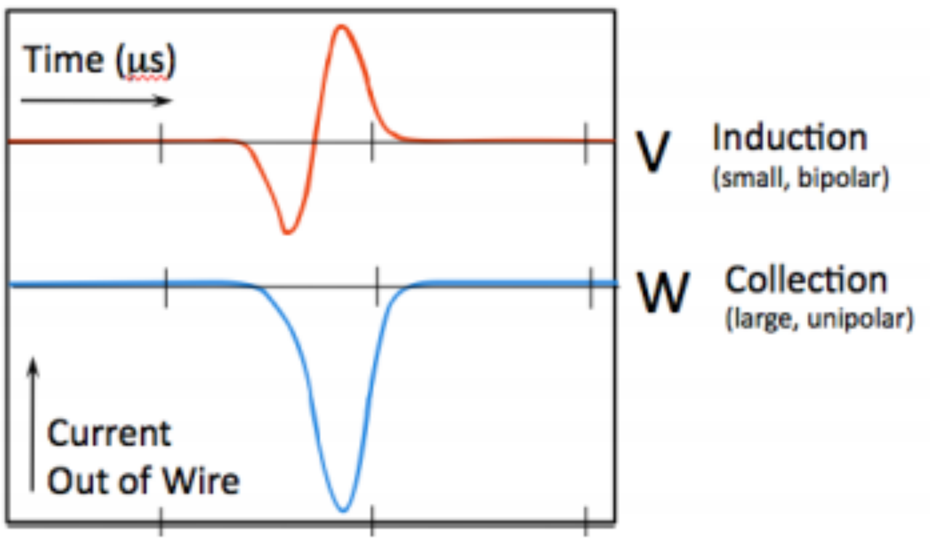


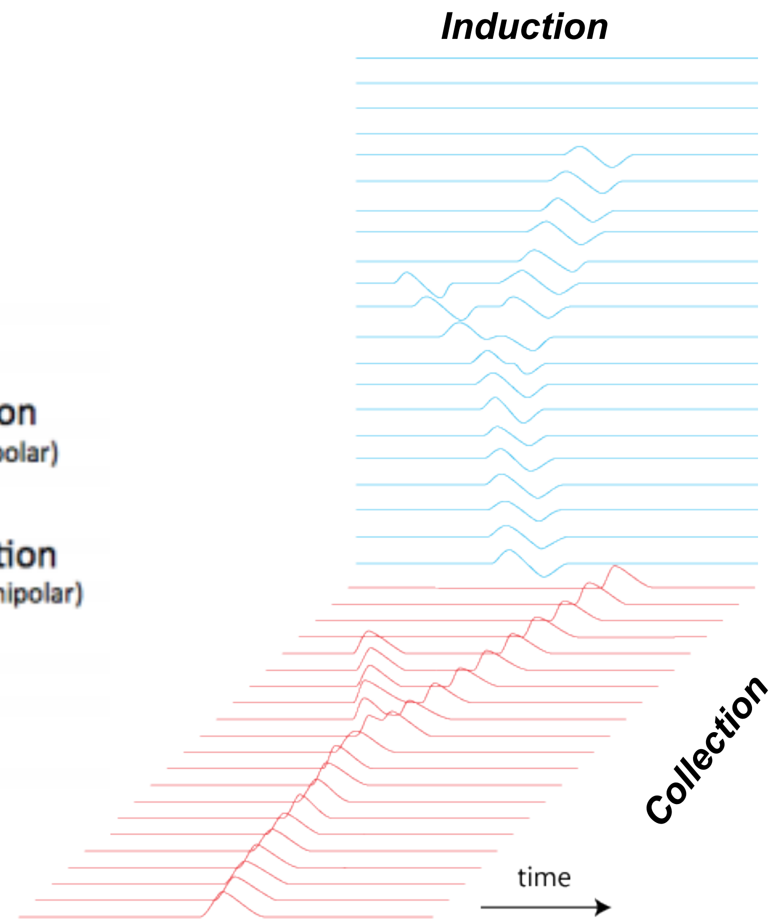
Noble gases comparison

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm^3]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Tracking and calorimetry reconstruction

1. Start with raw way forms on your wires and apply noise filter!

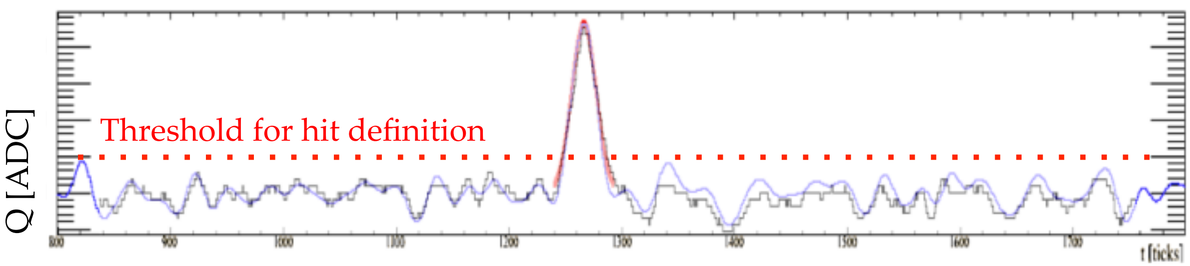




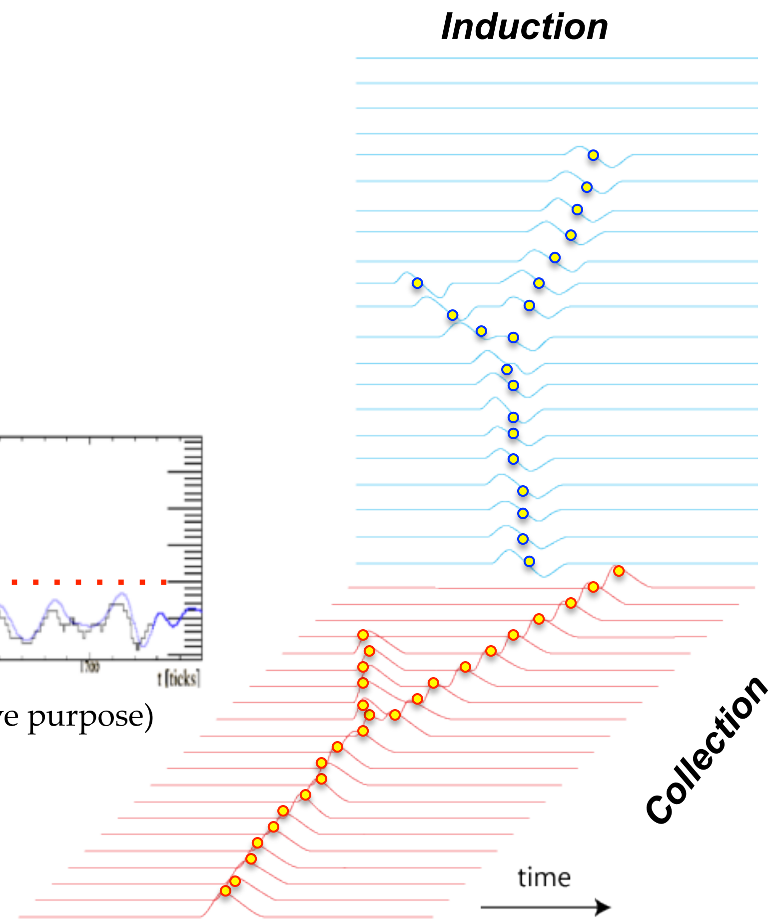
Tracking and calorimetry reconstruction

1. Start with raw way forms on your wires and apply noise filter!

2. Hit reconstruction and identification



(Only collection shown for illustrative purpose)



Gaussian Fit of a hits –> Determination of :

- Wire number
- Time tick
- Hit Amplitude
- Hit Width

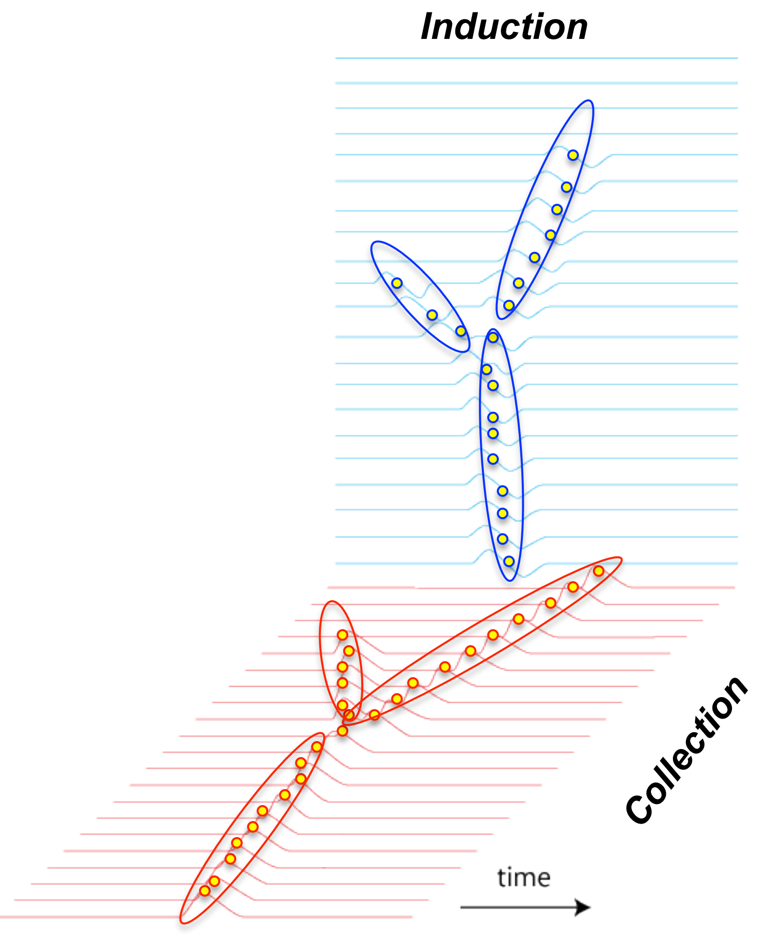
Tracking and calorimetry reconstruction

1. Start with raw way forms on your wires and apply noise filter!

2. Hit reconstruction and identification

3. Clustering of proximal hits

   A density-based Spatial Clustering algorithm clusters close and dense hits together



Tracking and calorimetry reconstruction

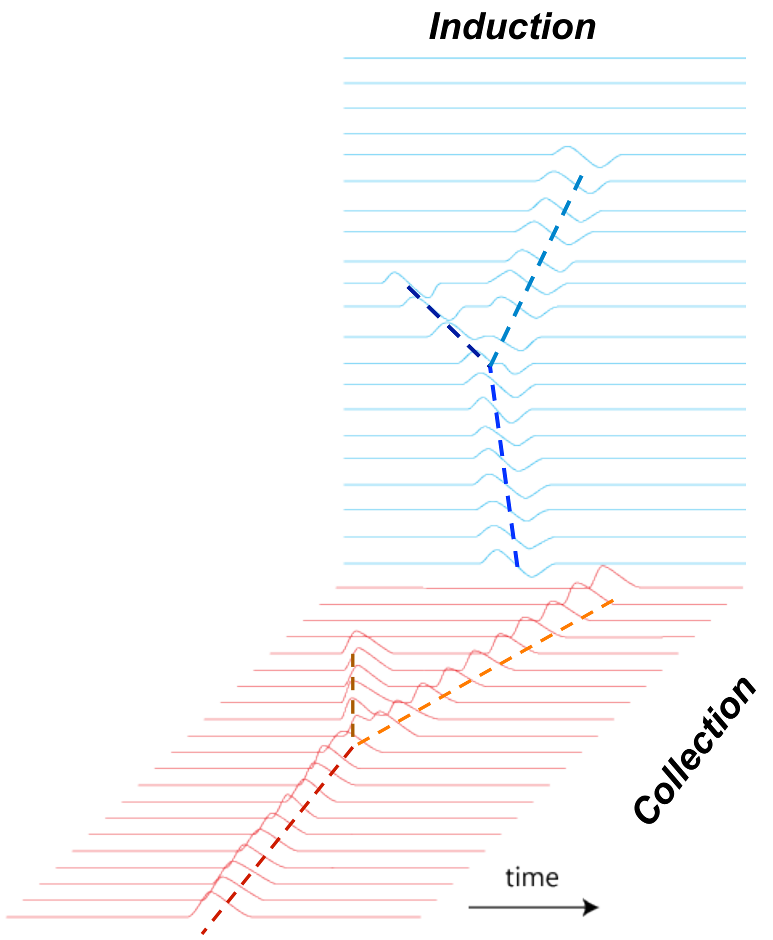
1. Start with raw way forms on your wires and apply noise filter!

2. Hit reconstruction and identification

3. Clustering of proximal hits

4. 2D line reconstruction

   Fit straight lines using the hits (wire, time) within a cluster



Tracking and calorimetry reconstruction

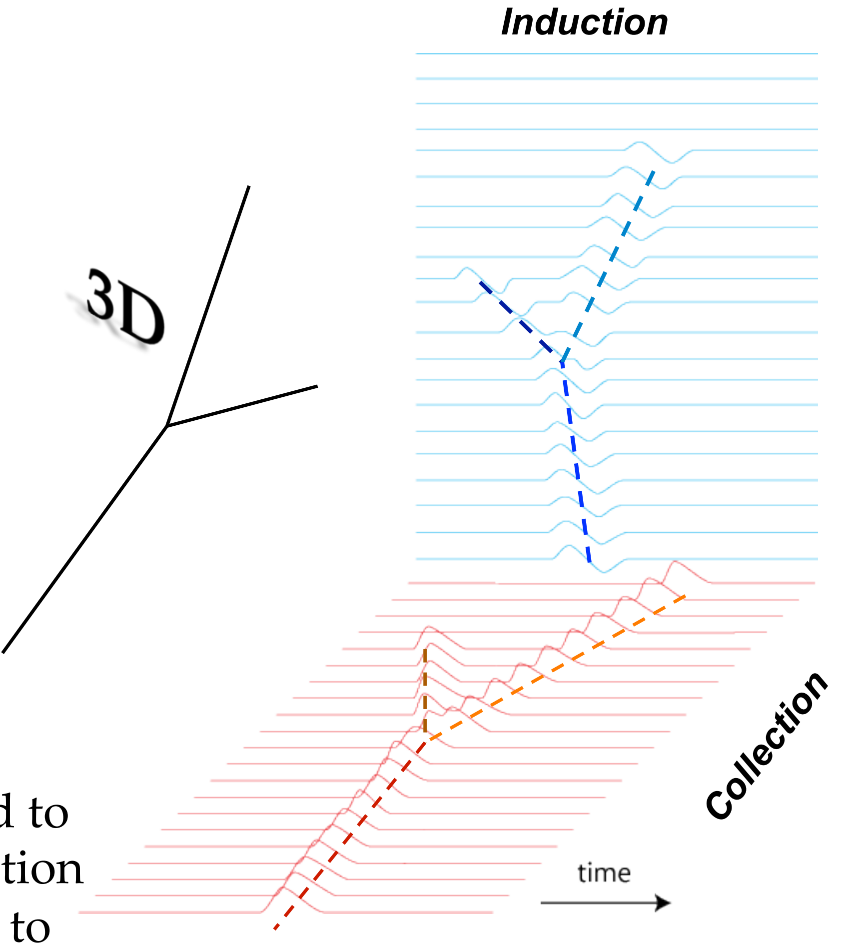
1. Start with raw way forms on your wires and apply noise filter!

2. Hit reconstruction and identification

3. Clustering of proximal hits

4. 2D line reconstruction

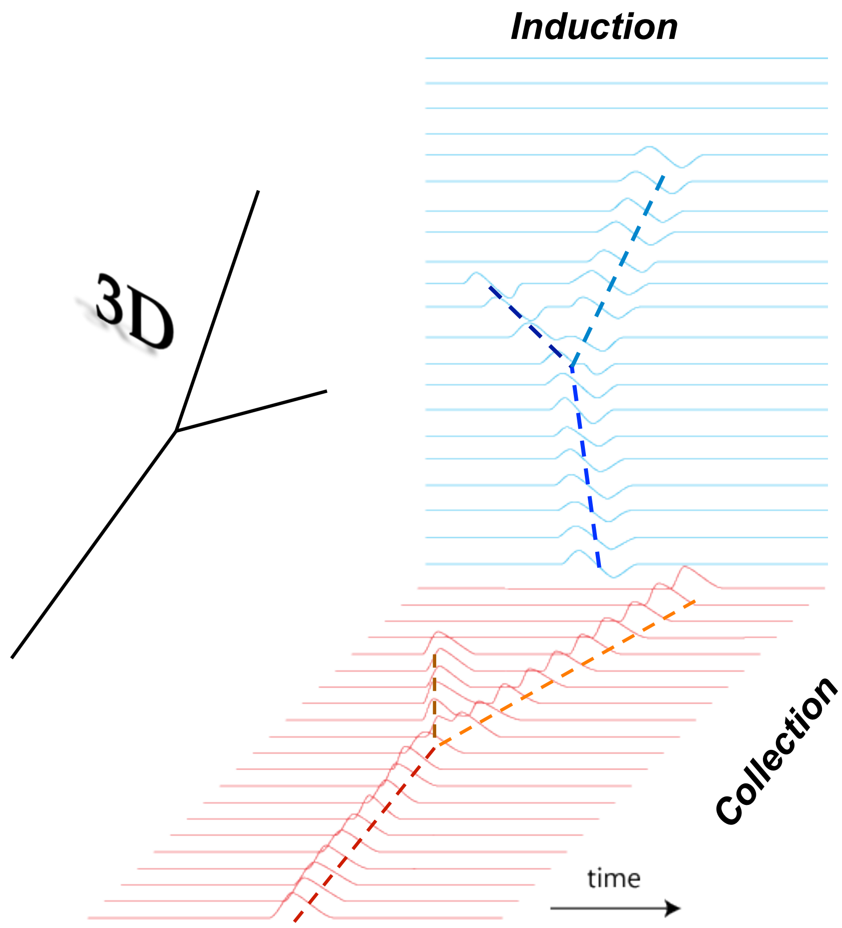
5. 3D track reconstruction



2D lines in the 2 views are combined to form a 3D track. A hit-by-hit association from the 2 planes is then performed to ensure 3D fine granularity. Fundamental step for calorimetry

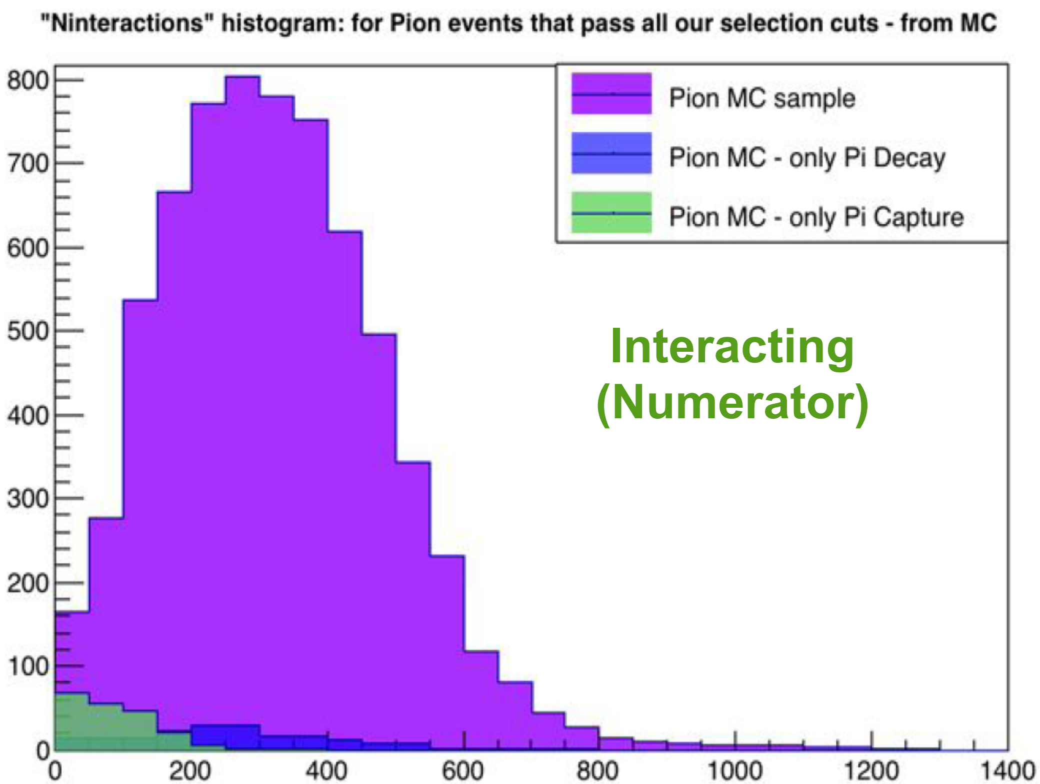
Tracking and calorimetry reconstruction

1. Start with raw way forms on your wires and apply noise filter!
2. Hit reconstruction and identification
3. Clustering of proximal hits
4. 2D line reconstruction
5. 3D track reconstruction
6. Calorimetry reconstruction of deposited energy



The hits amplitude on the Collection plane, the hit time and the track pitch δX are the fundamental quantities for calorimetry reconstruction

Background contamination



Reconstructed Kinetic Energy [MeV]

Approximately **9% π-capture** and **2% π-decay** in the interacting sample

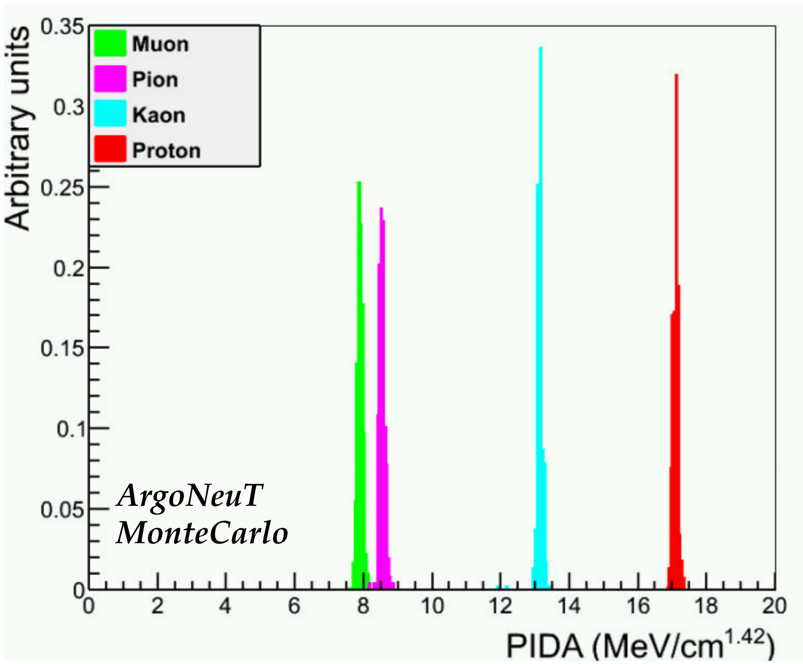
34% crossing particles (π/μ) and 66% interacting particles in the TPC

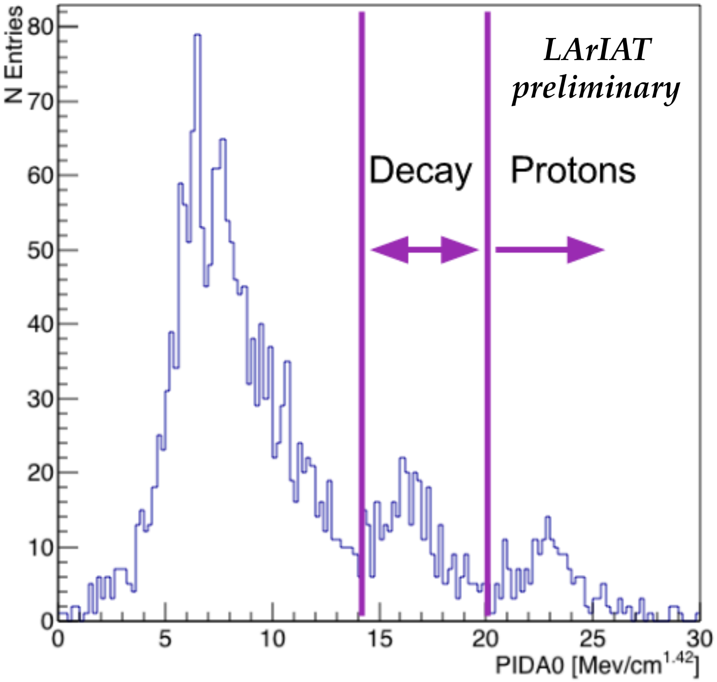
~10% muon contamination uniformly distributed (not shown here)

Decay tag with PIDA

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 **dE/dx**, exploiting the characteristic Bragg peak unique for each particle.

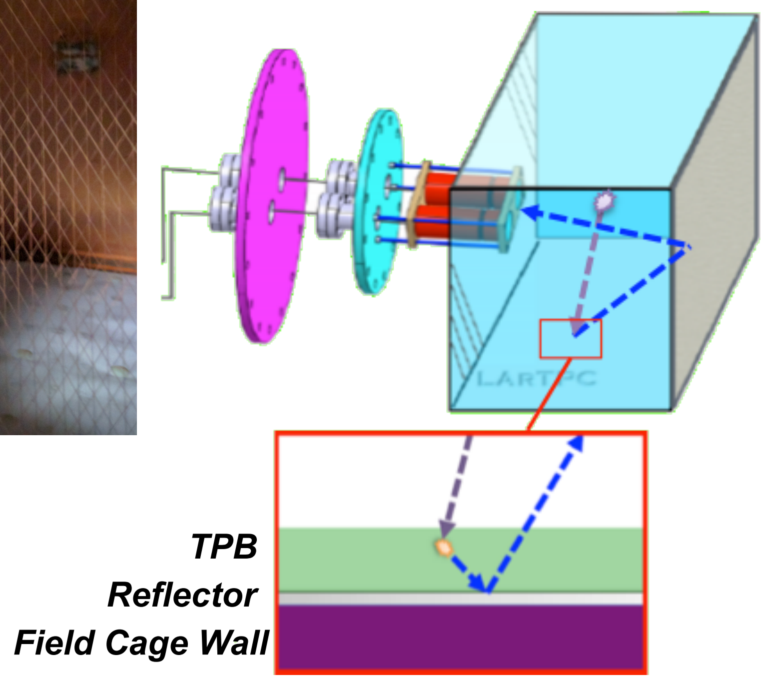


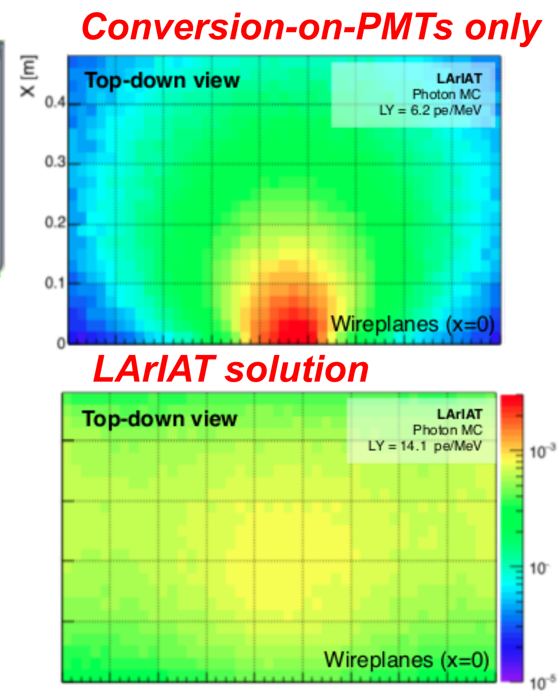


Light Collection System

Wavelength shifting (evaporated) **reflector foils** to shift the scintillation light into the visible spectrum
R&D for ν experiments, technique borrow from **dark matter** experiments

Higher and **more uniform** light yield





Light Collection System: ARAPUCA

Mônica Nunes Slides