I scream, you scream, we all scream for TESTBEAM!

The What, the Why and the How of Testbeam Experiments for Neutrino Physics.

Elena Gramellini
Fermilab Lederman Fellow

Neutrino Seminar May 2nd 2019

What's a testbeam experiment?

TB Experiments in a Nutshell

``Monte Carlo Truth" + **Your Neutrino Experiment**

Beam of KNOWN charged particles

Baby MINERνA

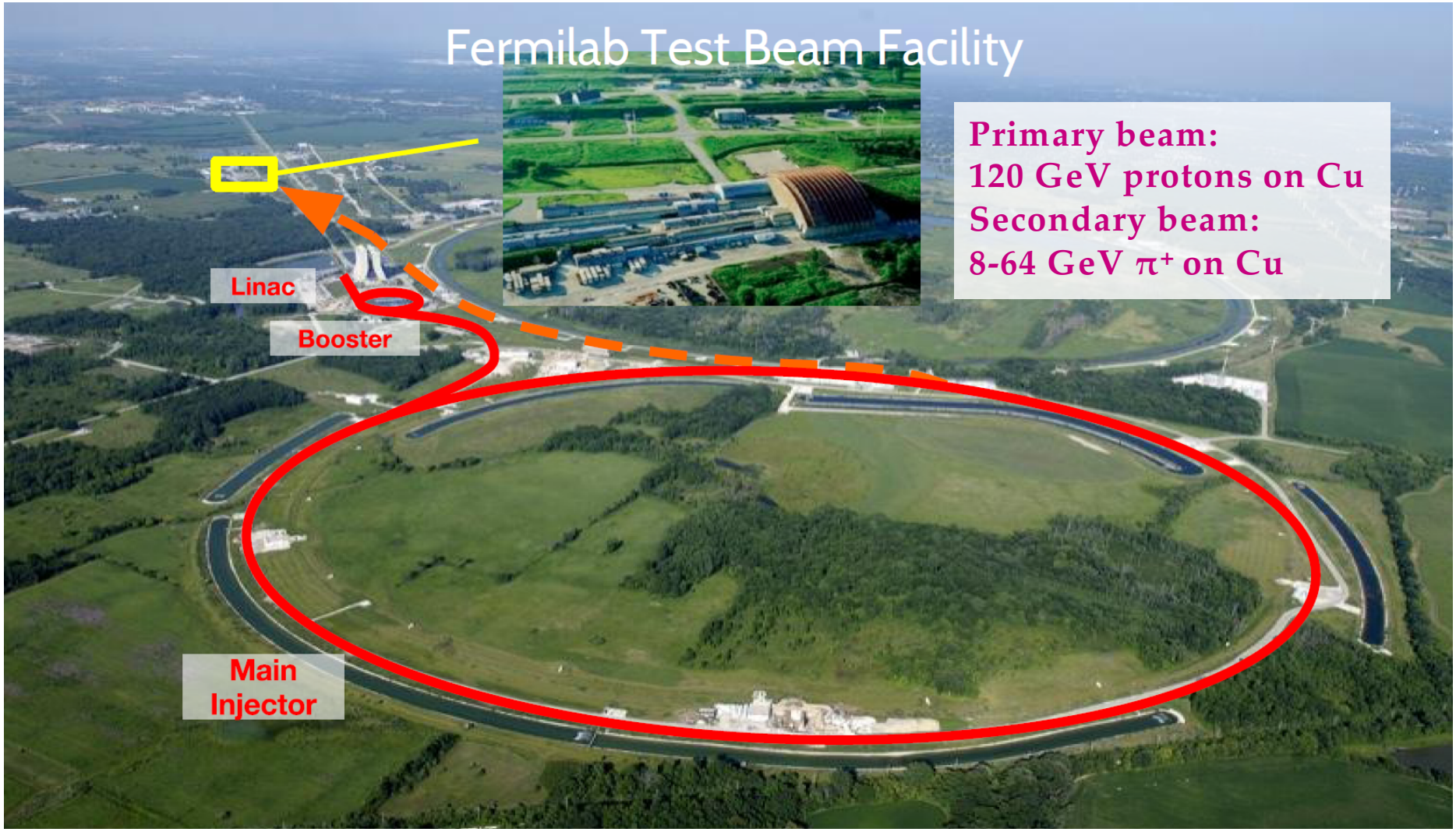
LArIAT

ProtoDUNE

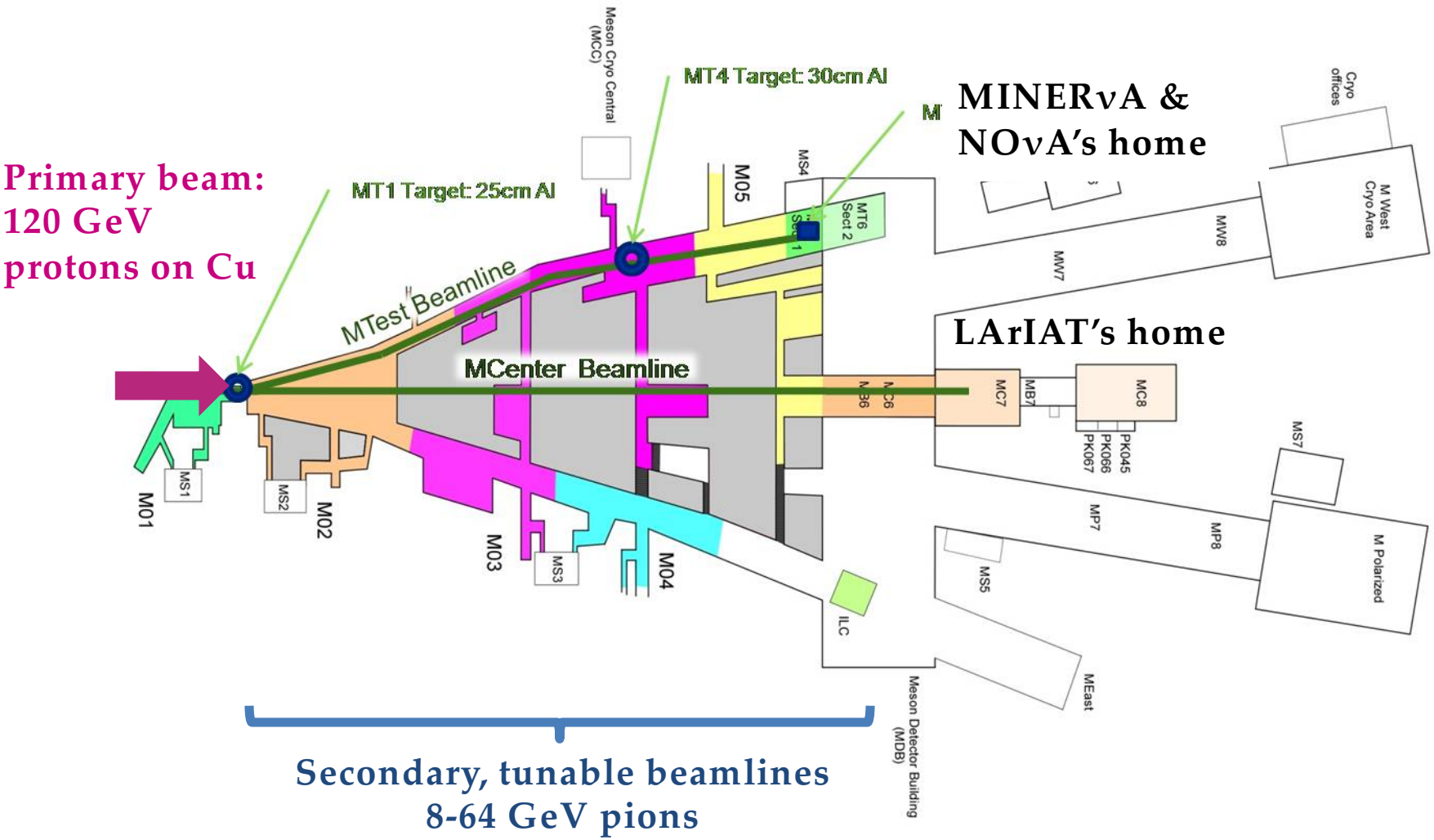
Baby NOνA

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

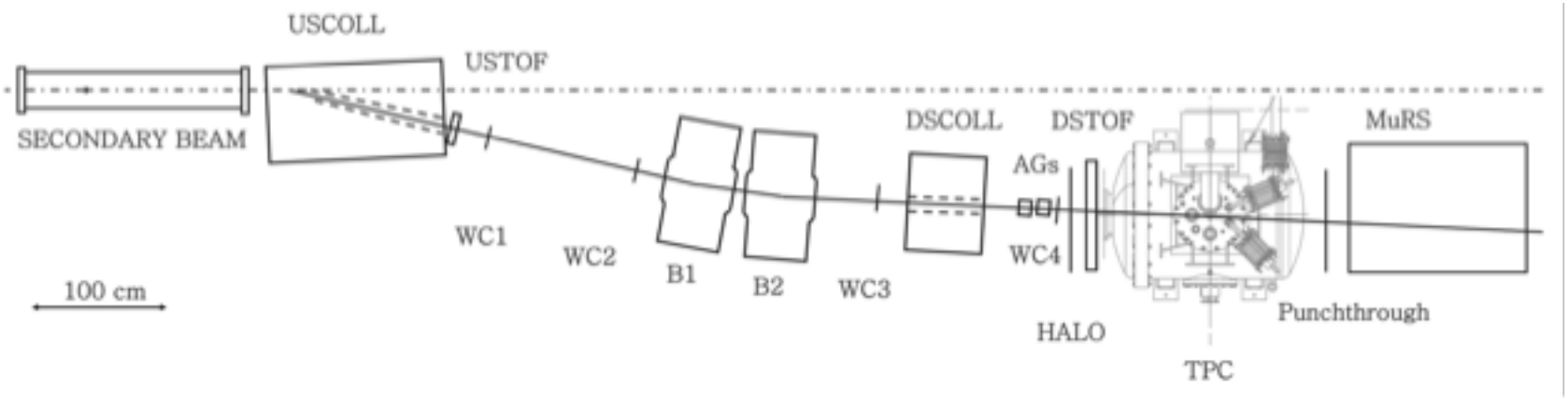
Let's talk about the beam!



Bird's eye view of FTBF



Tertiary Lines



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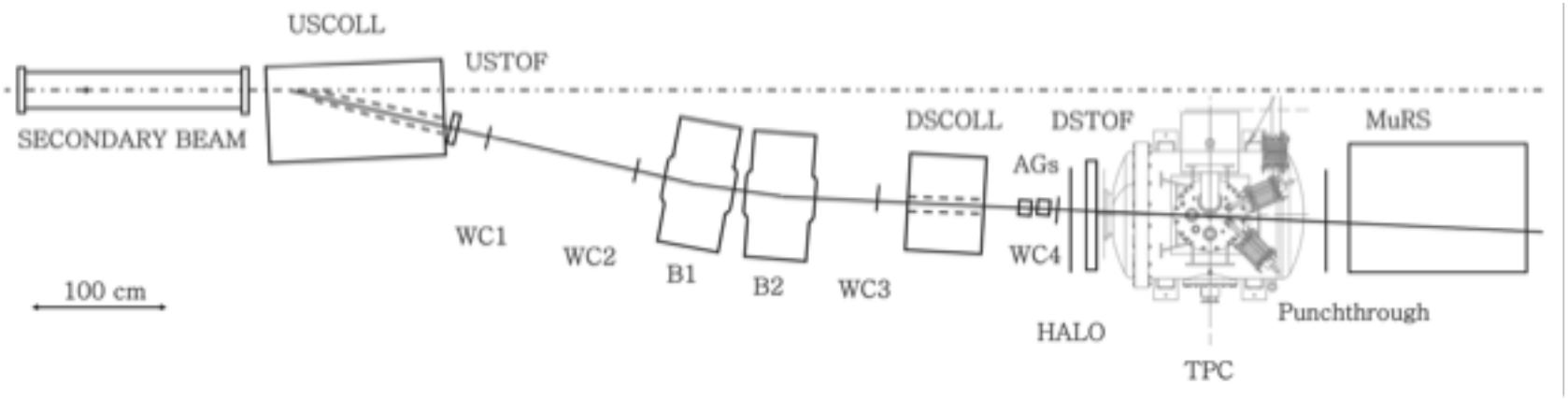
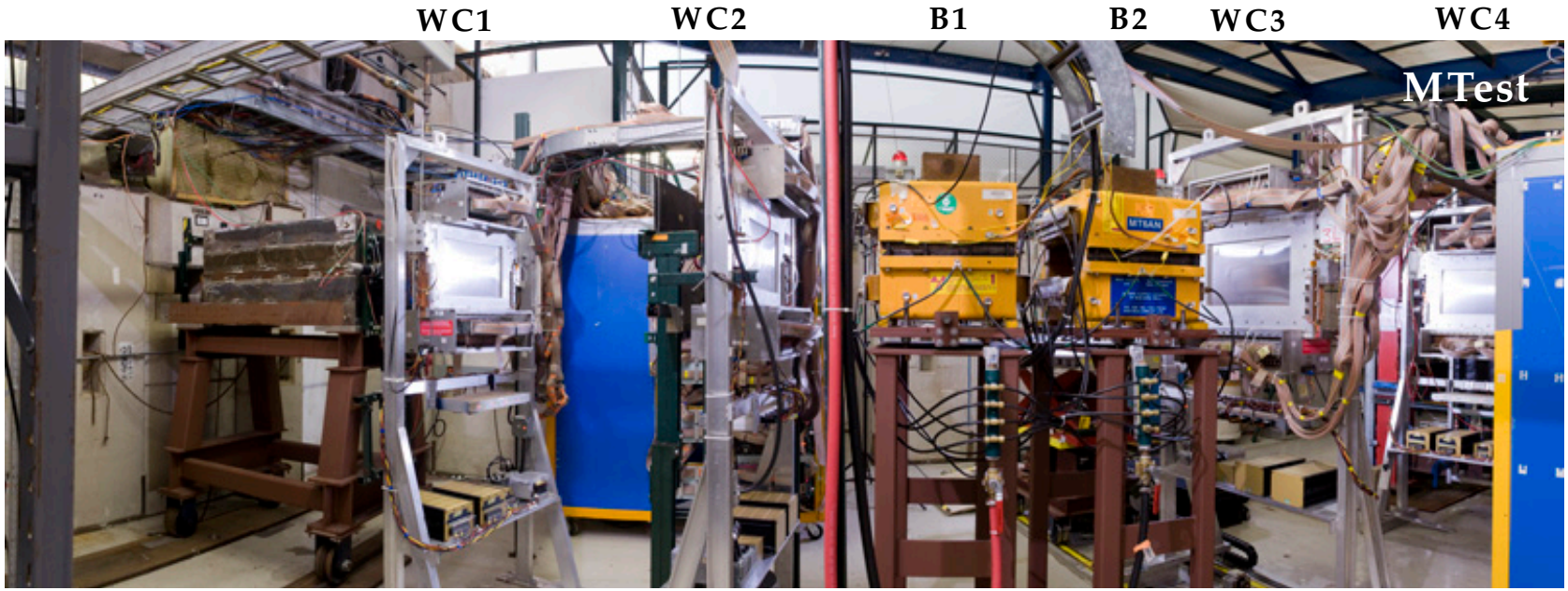
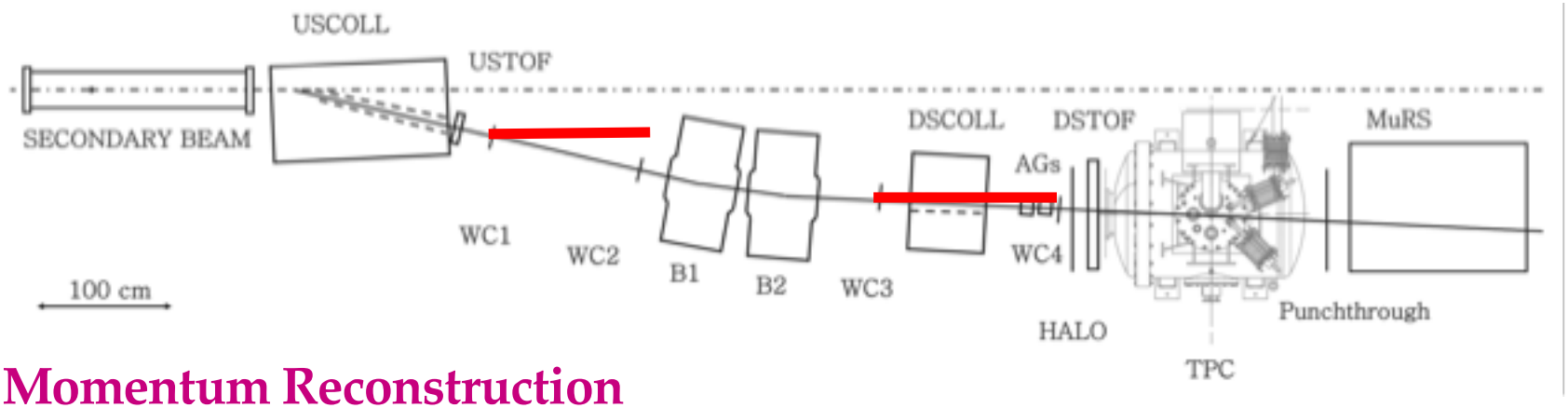




Beamline: **Momentum** & Identity



Momentum Reconstruction

Hit position in 4 Wire Chambers (few mm resolution) + Magnets, in first approximation:

$$P_z = \frac{B_{eff} L_{eff}}{3.3(sin(\theta_{DS}) - sin(\theta_{US}))}$$

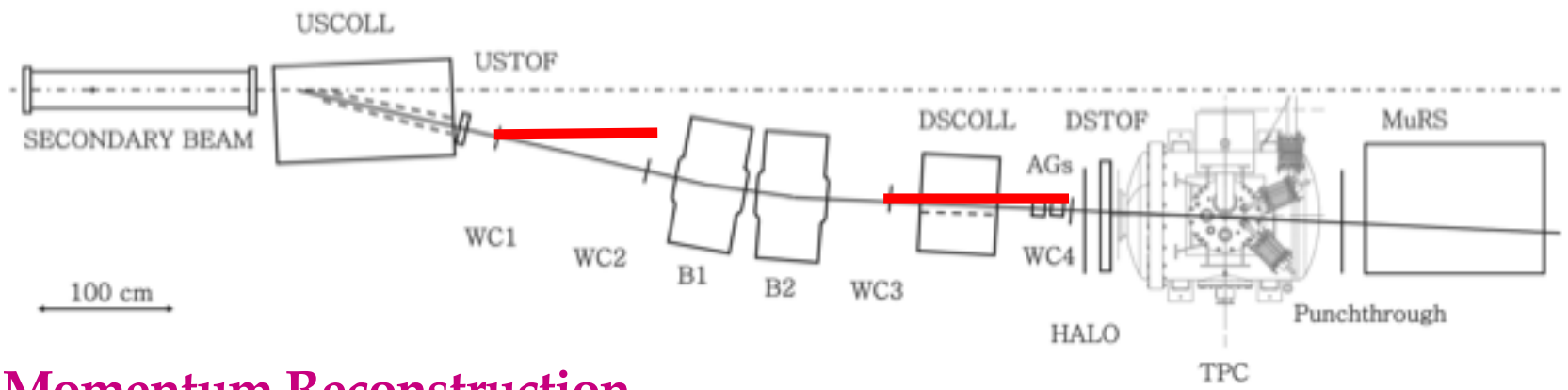
Key ingredients 4 good momentum measurement (~2%):

beamline geometry (survey data)

know your magnetic field

calibrate

Beamline: **Momentum** & Identity



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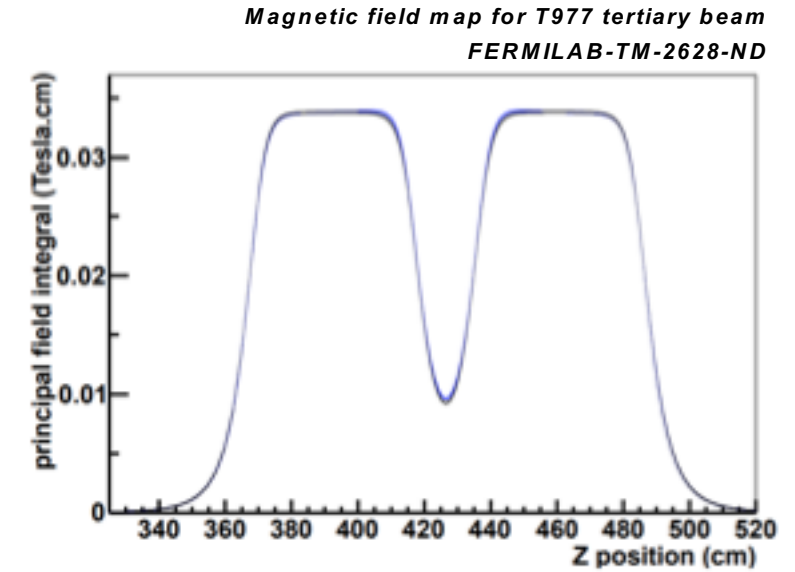

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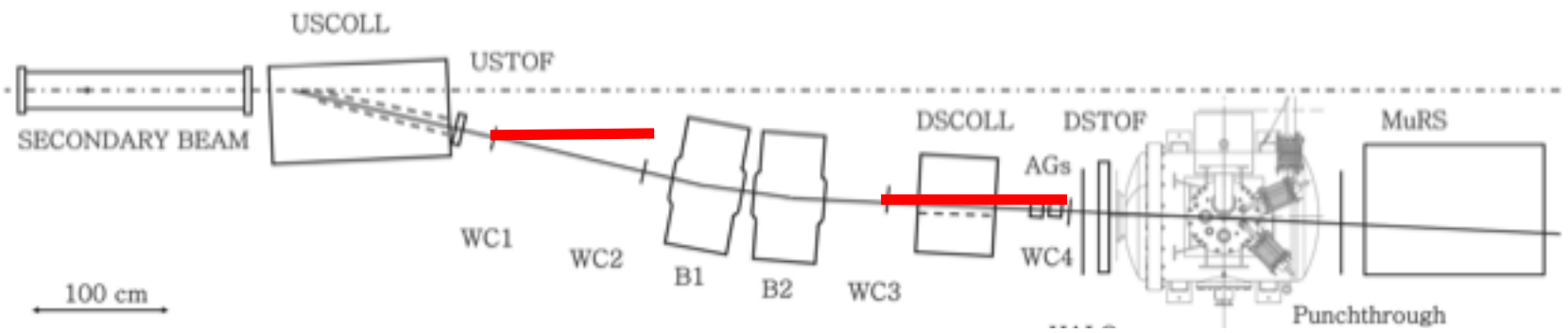

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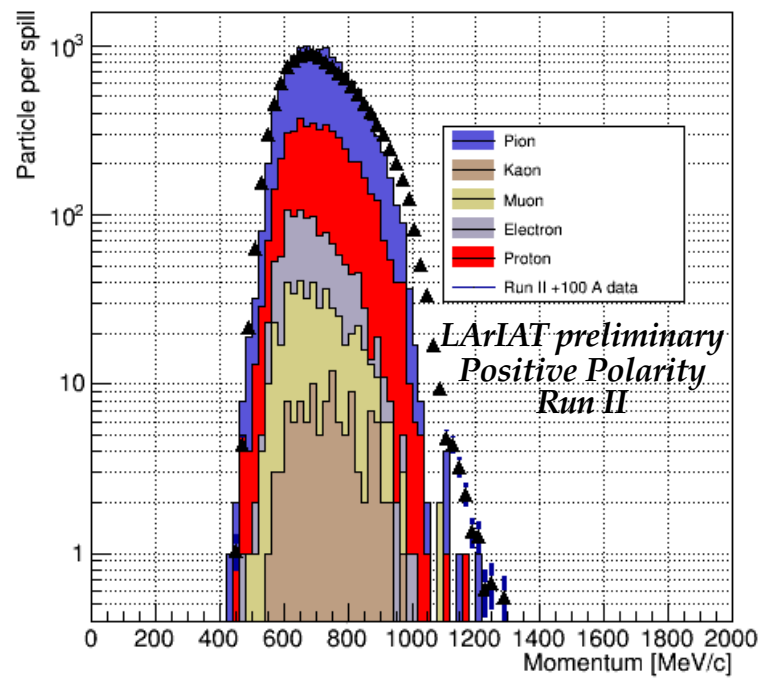
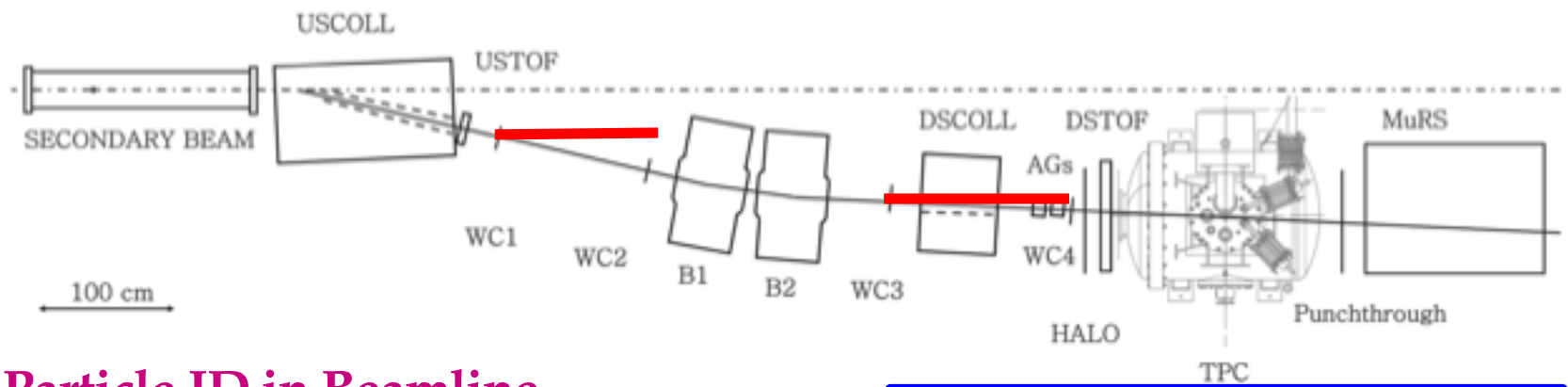
Tertiary beam particle momentum

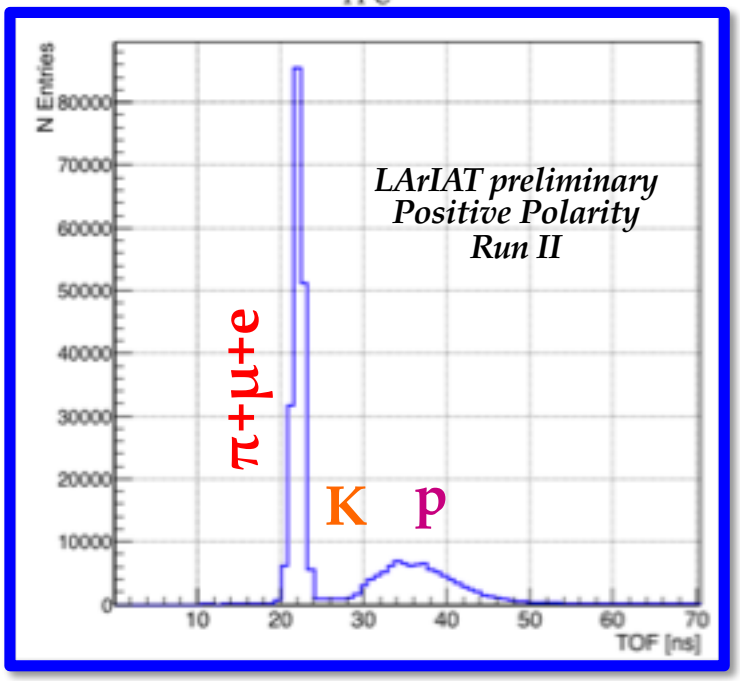


Beamline: Momentum & **Identity**

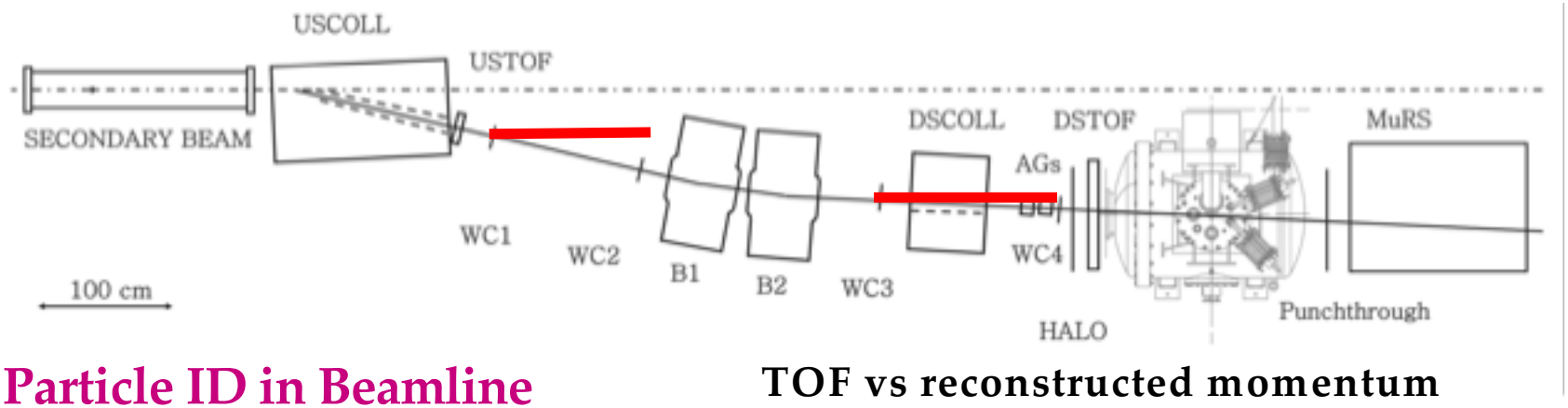


Particle ID in Beamline

TOF
p/K/π&μ&e discrimination



Beamline: **Momentum & Identity**



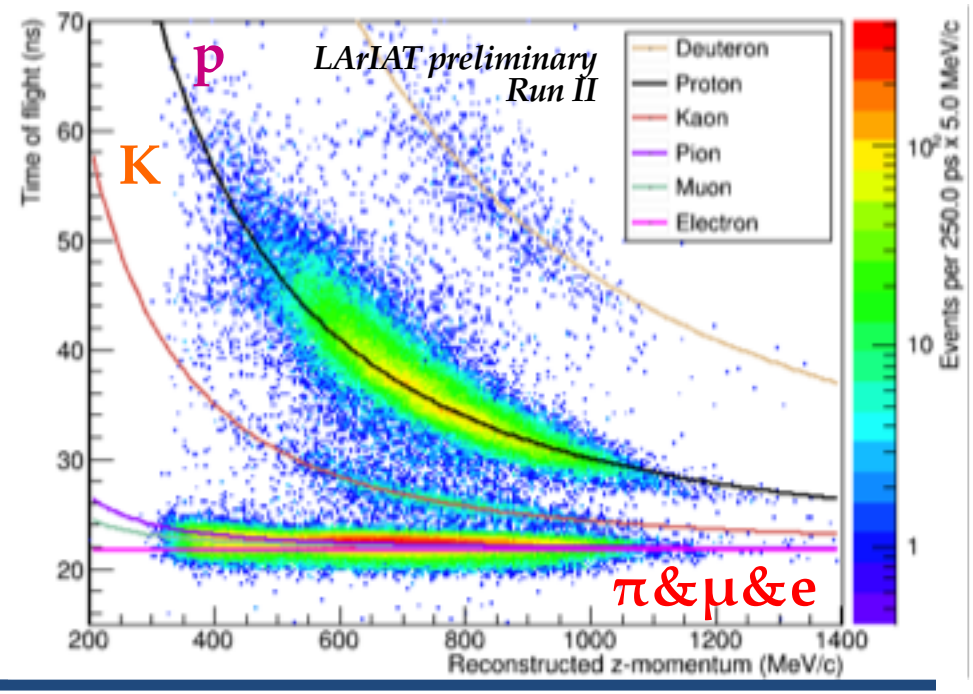
Particle ID in Beamline

TOF + Reco Momentum
p/K/π&μ&e discrimination

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

Depending on particles and beamlines ~1-10% contamination from other species.

TOF vs reconstructed momentum



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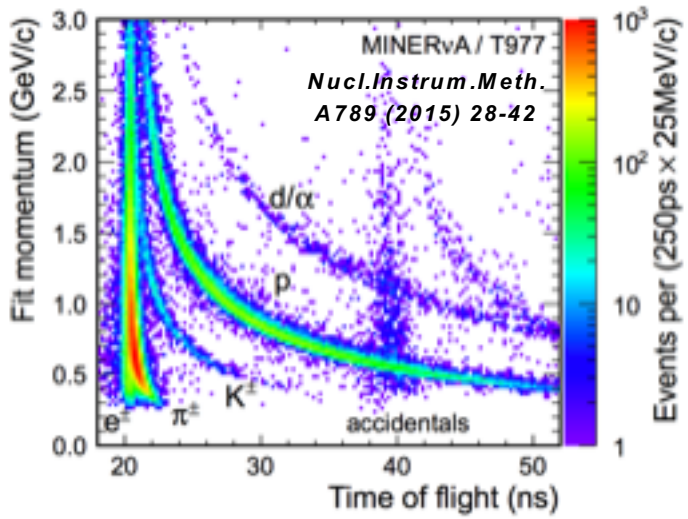
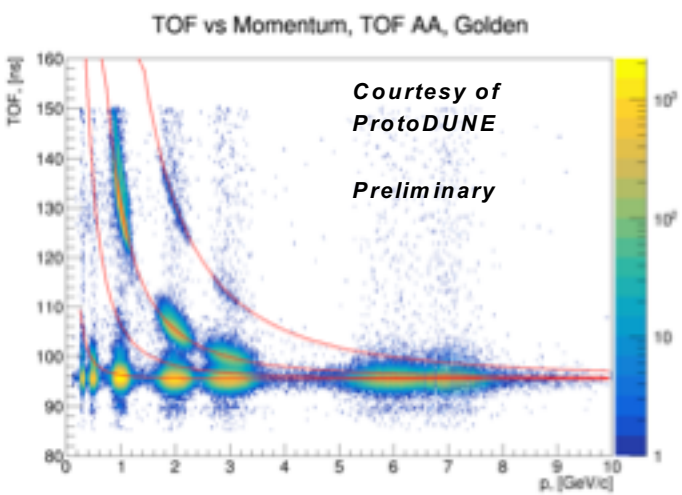
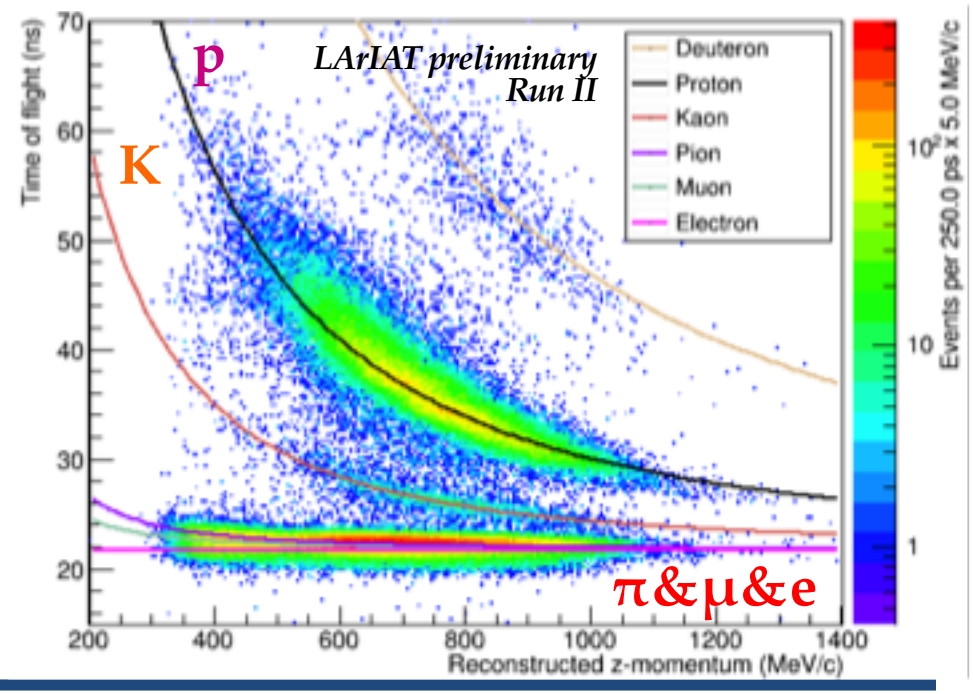


MINERvA, protoDUNE and **LArIAT**



TOF vs reconstructed momentum



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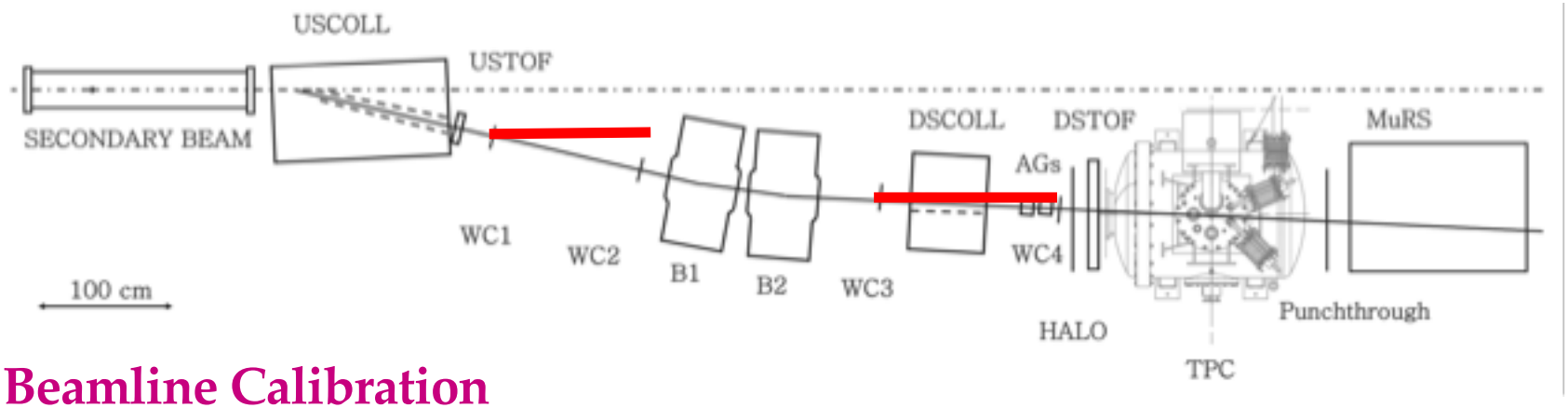
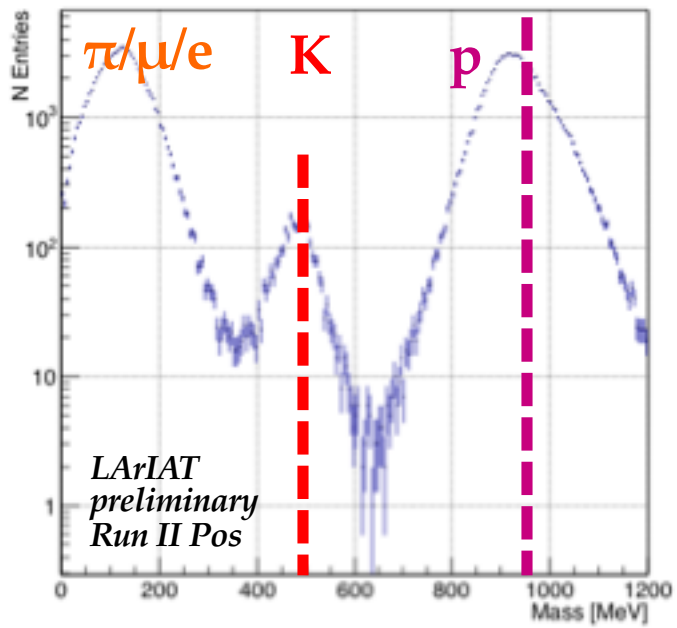


Beamline Calibration



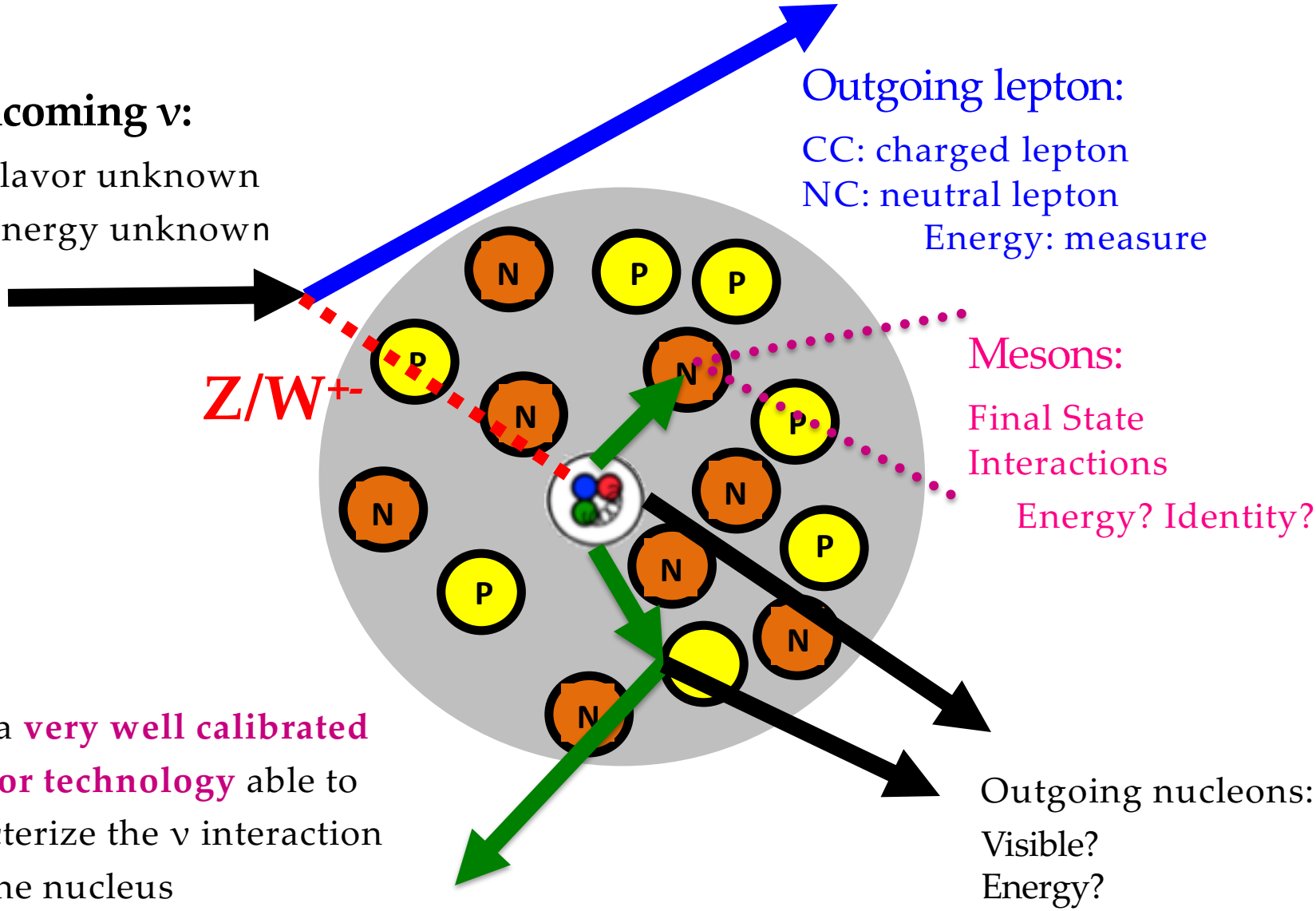
$$m = \frac{p}{c}\sqrt{\left(\frac{c * TOF}{\ell}\right)^2 - 1}$$

Find **Momentum** and **TOF** scale

$$m_{K\&p} = \frac{\alpha p}{c}\sqrt{\left(\frac{c * (TOF - \Delta TOF)}{l}\right)^2 - 1}$$

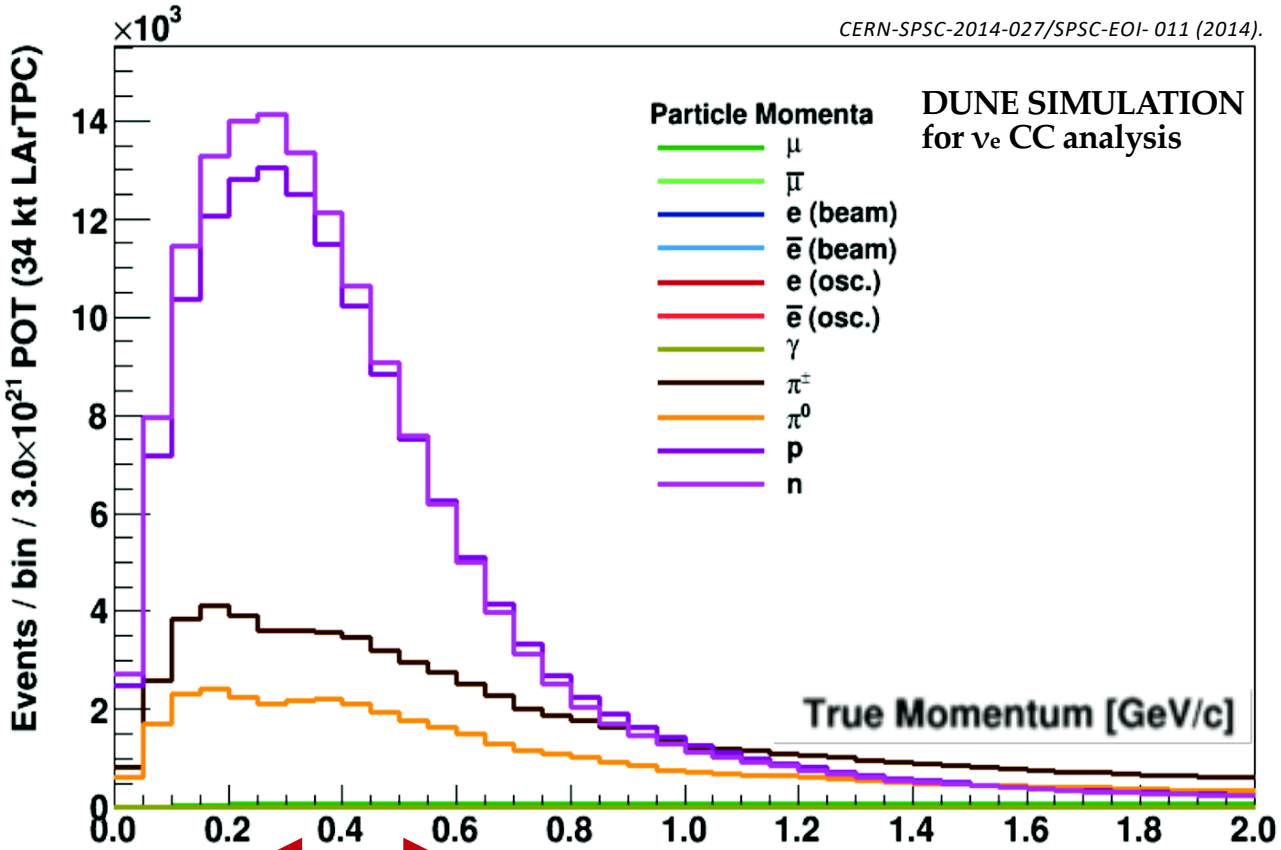
Why do neutrino experiment need one (or multiple) test beam experiments?

Simplified view of ν interaction



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

Neutrinos & Testbeam Overlap



LArIAT Low/High E Tunes

Minerva & Nova TBs

… 3,6,7 GeV/c

ProtoDUNE

How can test beam experiments help?

A.K.A. what do we actually measure?

TB Recent Efforts

MINERvA neutrino detector response measured with test beam data

Abstract

The MINERvA collaboration operated a scaled-down replica of the solid scintillator tracking and sampling calorimeter regions of the MINERvA detector in a hadron test beam at the Fermilab Test Beam Facility. This article reports measurements with samples of protons, pions, and electrons from 0.35 to 2.0 GeV/c momentum. The calorimetric response to protons, pions, and electrons are obtained from these data. A measurement of the parameter in Birks' law and an estimate of the tracking efficiency are extracted from the proton sample. Overall

Nucl.Instrum.Meth. A789 (2015) 28-42

LArIAT

Liquid Argon Time Projection Chambers (LArTPCs) are ideal detectors for precision neutrino physics. These detectors, when located deep underground, can also be used for measurements of proton decay, and astrophysical neutrinos. The technology must be completely developed, up to very large mass scales, and fully mastered to construct and operate these detectors for this physics program. As part of an integrated plan of developing these detectors, accurate measurements in LArTPC of known particle species in the relevant energy ranges are now deemed as necessary. The LArIAT program aims to directly achieve these goals by deploying LArTPC detectors in a dedicated calibration test beam line at Fermilab. The set of measurements envisaged here

FERMILAB-PUB-14-268-E , 2014

ProtoDUNE

1.1 ProtoDUNE-SP in the context of DUNE/LBNF

ProtoDUNE-SP is the single-phase DUNE Far Detector prototype that is under construction and will be operated at the CERN Neutrino Platform (NP) starting in 2018. It was proposed to the CERN SPSC in June 2015 (SPSC-P-351), and following positive recommendations by SPSC and the CERN Research Board in December 2015, was approved at CERN as experiment NP-04 (ProtoDUNE). The Fermilab Director and the CERN Director of Research and Scientific Computing signed a Memorandum of Understanding (MoU) for this experiment in December 2015 that is initially valid until December 2022, and may be extended by mutual agreement.

ProtoDUNE-SP, a crucial part of the DUNE effort towards the construction of the first DUNE 10-kt fiducial mass far detector module (17 kt total LAr mass), is a significant experiment in its own right. With a total liquid argon (LAr) mass of 0.77 kt, it represents the largest monolithic single-phase LArTPC detector to be built to date. It is housed in an extension to the EHN1 hall in the North Area, where the CERN NP is providing a new dedicated charged-particle test beamline. ProtoDUNE-SP aims to take its first beam data before the LHC long shutdown (LS2) at the end of 2018.

ProtoDUNE-SP prototypes the designs of most of the single-phase DUNE far detector module (DUNE-SP) components at a 1:1 scale, with an extrapolation of about 1:20 in total LAr mass. This is similar to the scaling factor adopted by ICARUS; its T600 detector, split into two half-modules of about 375 t total LAr mass each, was preceded by the 14 t "10-m³" prototype.

ProtoDUNE SP tdr

NOvA

- Testbeam program addresses dominant NOvA systematic errors
  - energy scale for muons, hadrons, EM showers
  - relative calibration
  - light/scintillator response model
- Provides real (tagged) data for sophisticated machine learning particle ID algorithms
- Installation begins this summer
  - Data collection starts end of the calendar year

Patricia Vahle. PAC Talk July 2018

TB Recent Efforts

LArIAT

MINERvA neutrino detector response measured with test beam data

Liquid Argon Time Projection Chambers (LArTPCs) are ideal detectors for precision neutrino physics. These detectors, when located deep underground, can also be used for measurements of proton decay, and astrophysical neu-

1) Model the **Detector Response**

2) Perform Detector / Analysis **R&D**

3) Perform Physics Measurements to **Reduce Systematics** Associated to **ν-nucleus Interaction Models**

Patricia Vahle. PAC Talk July 2018

TB Recent Efforts

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   MINERνA Testbeam

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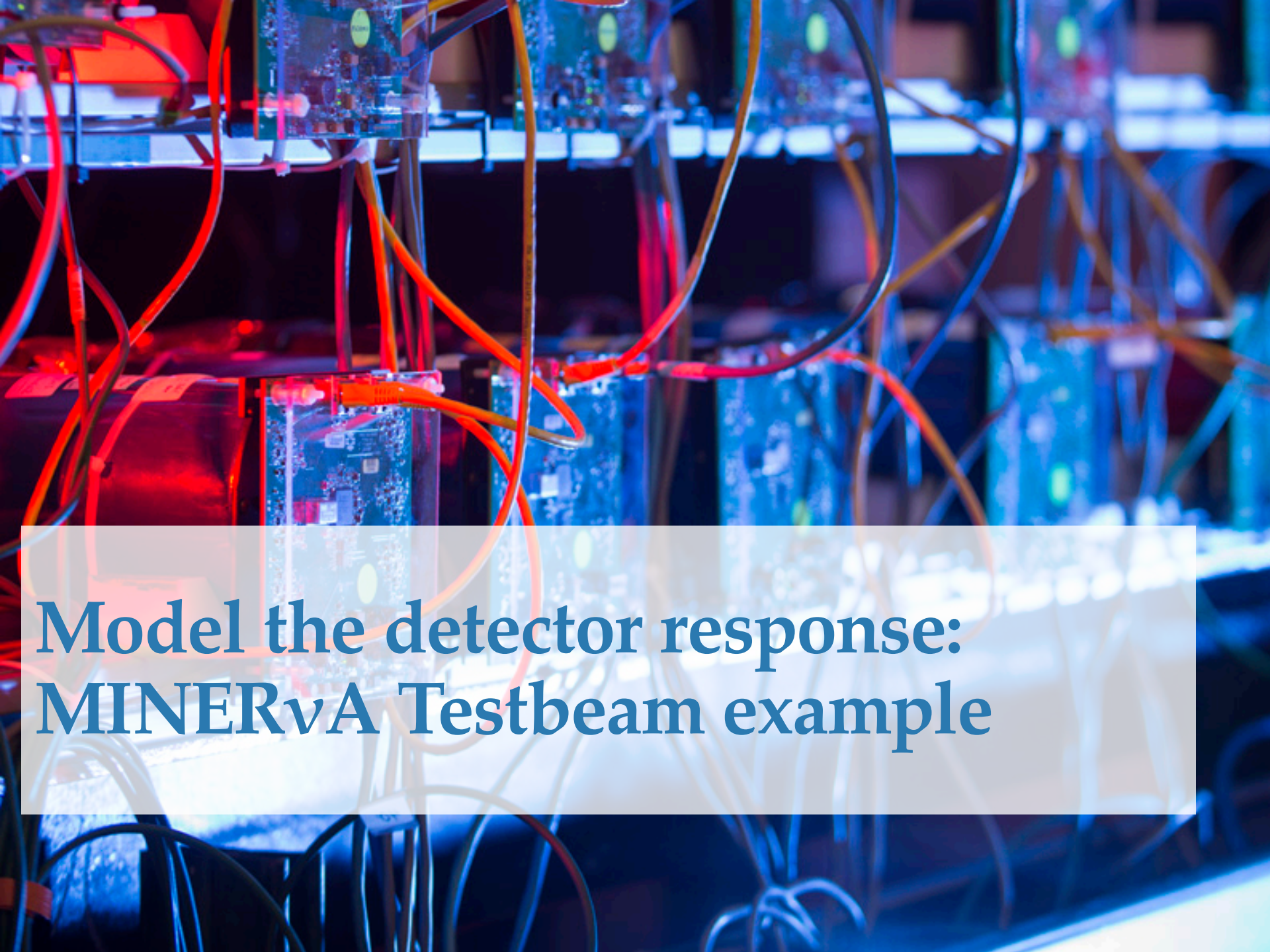
Patricia Vahle: PAC Talk July 2018



Model the detector response: MINERνA Testbeam example

Scope of work

Determining the detector **response** to **protons, pions** & **electrons**

tune the MINERνA **detector simulation,** reduce detector **systematics.**

First MINERνA testbeam effort (low energy):

1) Measurement of **Birk's law parameters.**

2) Compare the **calorimetric response** to **protons, pions** & **electrons** between TB data and MC, assess the **MC accuracy.**

3) Study **tracking efficiency** for protons.

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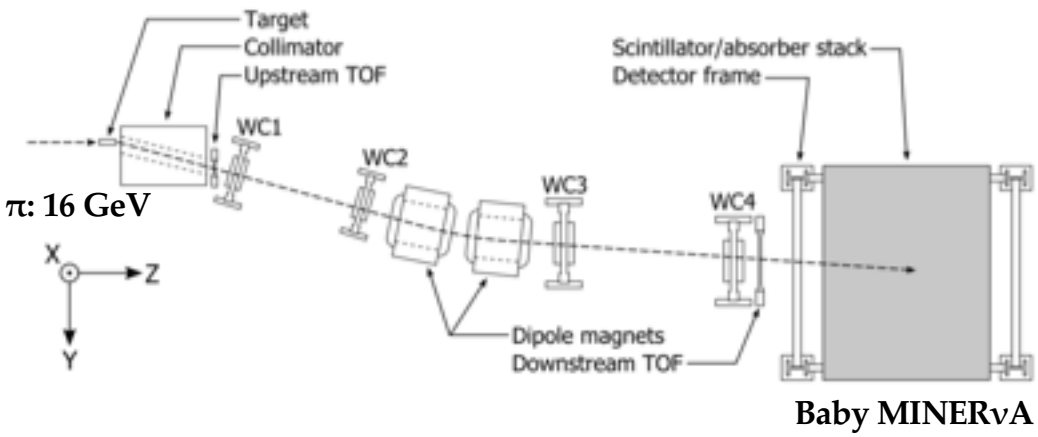
MINERνA TB: Set Up

Beam: Fermilab Test Beam Experiment T977



High Momentum

▼

Small Bent

▼

High Y

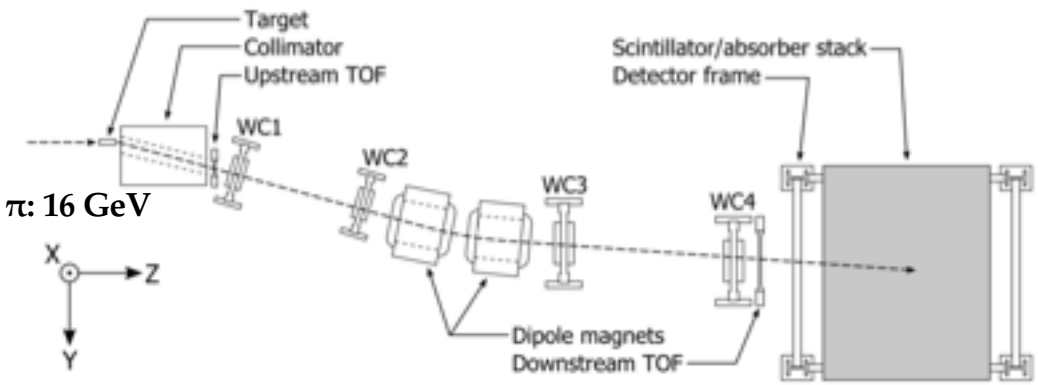
Energy Range: **0.35 GeV** ⟷ **2.0 GeV** **Match low E ν run**

Momentum Accuracy: 1-2% ▶ 3D Hall probe + FEA of the magnets

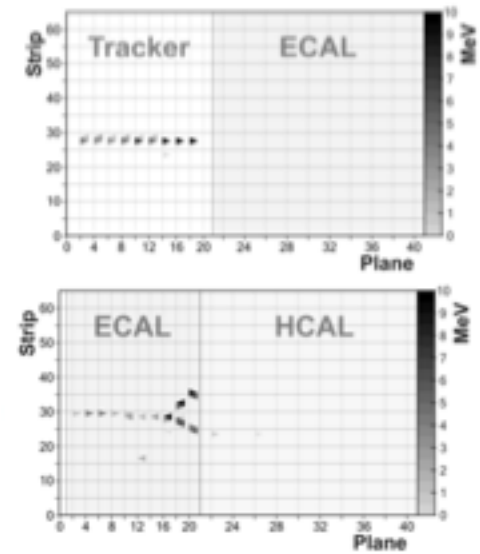
MINERνA TB: Set Up

Two Possible Configurations

Beam: Fermilab Test Beam Experiment T977

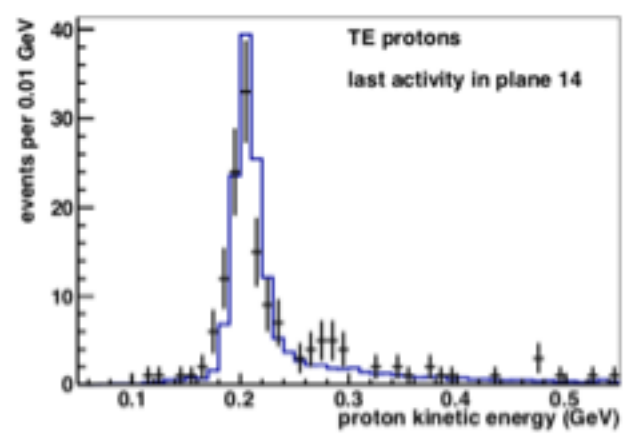


Baby MINERνA



Detector energy scale calibration based on **light yield injection** + **through going μ** tune the peak number of pe to be equivalent between data and sim.

Stopping Proton technique to **cross check beam measurement**



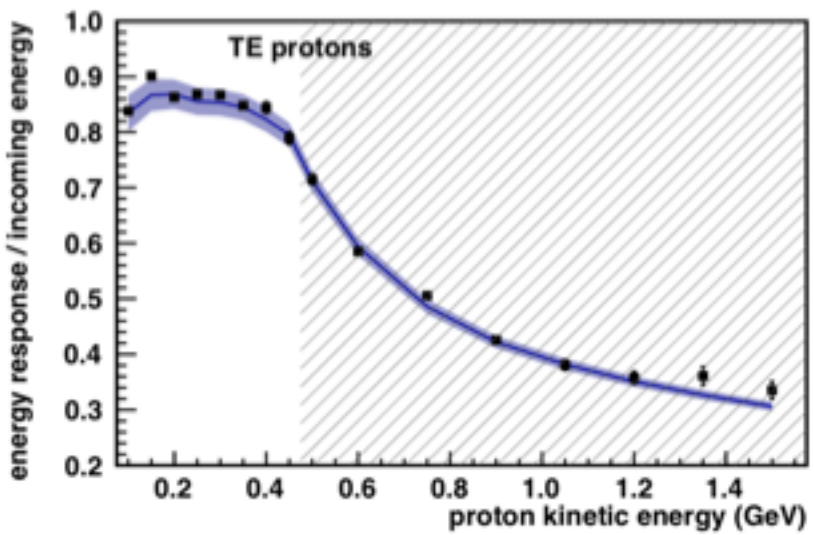
MINERνA TB: Proton Calo Response

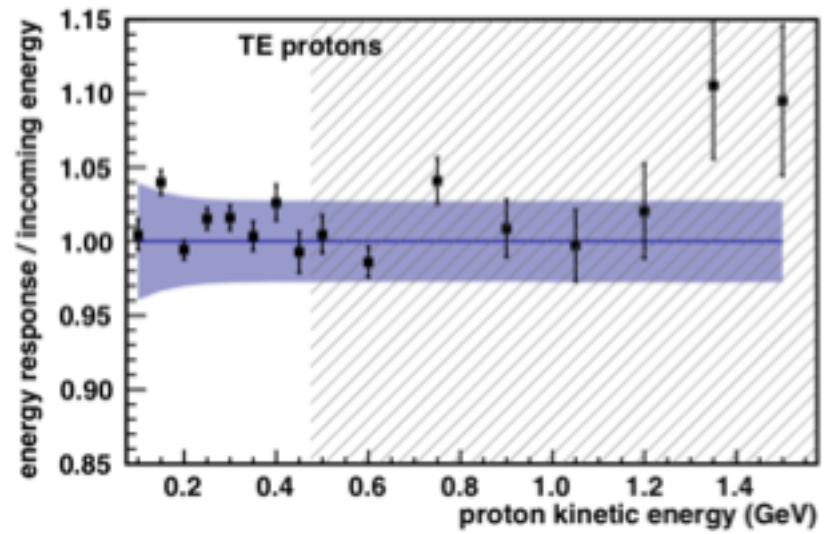
Event Selection: spatial and time coincidence with predicted beam trajectory
ask event the proton peak (± 20% of the true mass)
reject beam-induced activity (spatial selection)

Energy Response: sum all calibrate energy measured in the scintillator within 150 ns
adjusted by a sample calorimetry factor (tracker ≠ ECAL ≠ HCAL)

Incoming Energy : KE measured in the beam

Relative to MC





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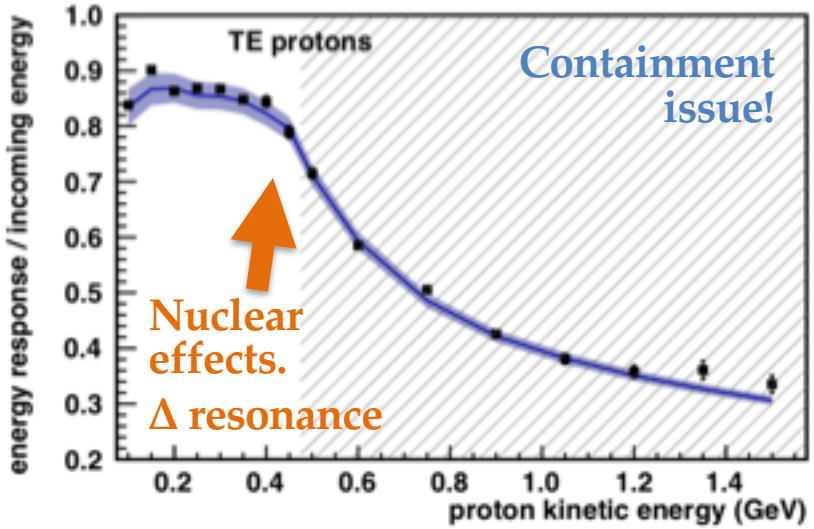
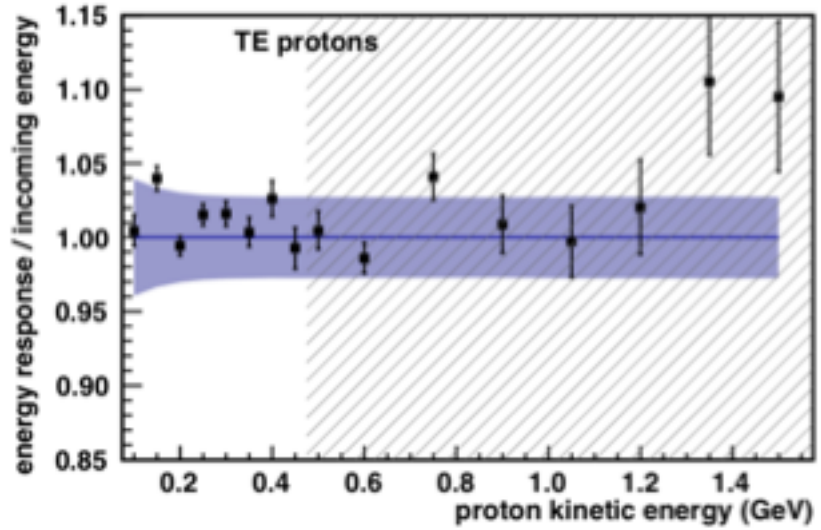


Relative to MC



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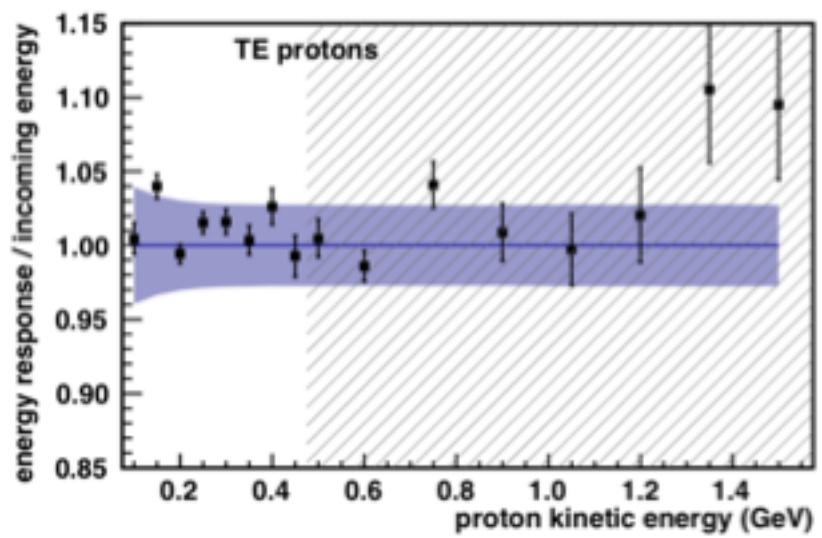
Systematics Budget

Source	TE p	EH p	EH π^+	EH π^-	EH e	TE e
Beam momentum	1.9%	1.9%	1.0 to 2.0%	1.0 to 2.0%	1.0	1.0
Beamline mass model	0.7	0.7	<0.2	<0.2	<0.2	<0.2
Birks' parameter	2.0 to 0.9	2.0 to 1.2	1.0	1.0	0.3	0.3
Correlated late activity	0.3	0.6	1.4	1.4	<0.2	<0.2
Temperature stability	1.0	1.0	1.0	1.0	1.0	1.0
Relative energy scale	0.6	0.6	0.6	0.6	0.6	0.6
PMT nonlinearity	0.7	0.7	0.9	0.9	0.4	0.2
Event selection	<0.2	<0.2	0.7	1.5	1.1	1.1
Crosstalk	0.7	0.9	0.5	0.5	0.5	0.5
Statistical	~1.0	~1.0	~1.0	~1.0	1.7	1.1
Total	3.3 to 2.7%	3.4 to 2.9%	2.6 to 3.4%	2.9 to 3.6%	2.6%	2.3%

Relative to MC



MINERνA TB: Proton Tracking Eff

Tracking Efficiency: the prob that a proton will be reconstructed as a 3D track object

Important for measurements of neutrino differential cross sections with **specific proton and pion final states:** if you can't track the proton, you can't count it!

Efficiency depends on tracking algo.

MINERνA usually requires 9+ planes (long track) for ν physics analyses...

proton	pion short tracker		quasielastic short tracker	
depth	data	mc	data	mc
$\geq$ 9 planes	$99.2^{+0.2}_{-0.3}$ %	99.8±0.1 %	$99.5^{+0.2}_{-0.2}$ %	99.9±0.1 %
8 planes	$96.2^{+1.2}_{-1.6}$ %	97.7±0.6 %	$96.8^{+1.2}_{-1.6}$ %	98.3±0.5 %
6 and 7 planes	$91.1^{+1.5}_{-1.6}$ %	96.5±0.5 %	$93.5^{+1.3}_{-1.4}$ %	98.1±0.4 %

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Short tracks = lower proton energy: **discrepancy** between data and MC.
A data driven correction can be derived.

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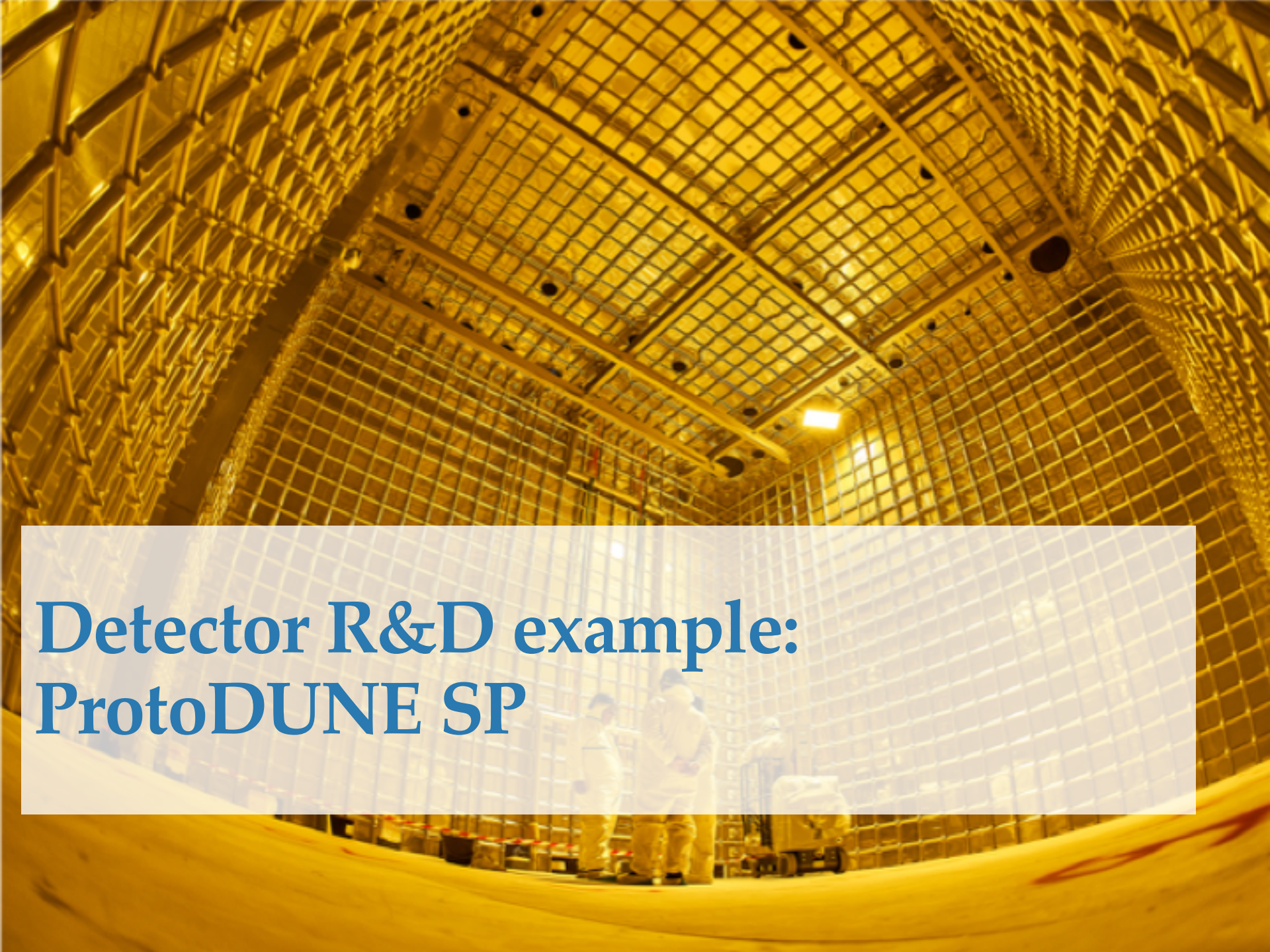
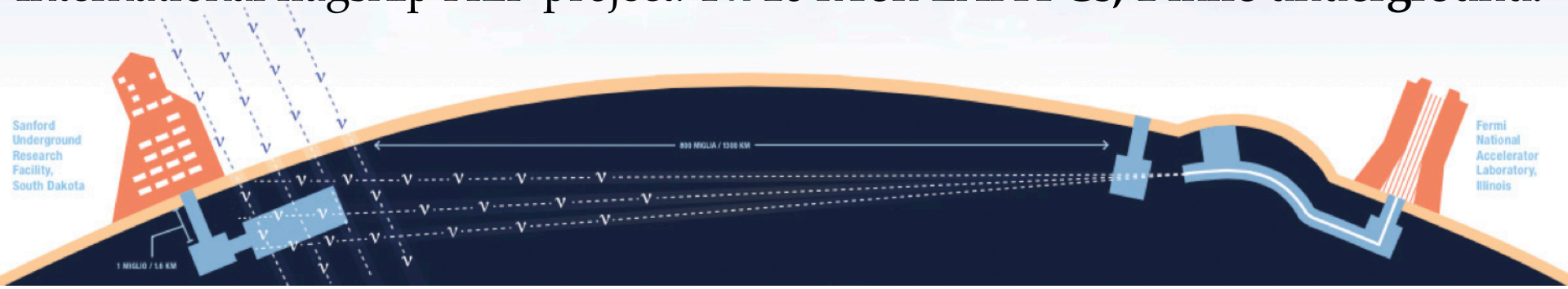
A data driven correct



Detector R&D example: ProtoDUNE SP

DUNE: the next big thing in ν physics

International flagship HEP project: **4 x 10 kTon LArTPCs, 1 mile underground.**



Largest LArTPC operated before 2018 was ICARUS (600 ton).
Moving from 0.6 kton to 4X10 kton requires a jump in size: brand new engineering and technology solutions, careful detector characterization, international partnership à la LHC.

How do we ensure DUNE will be **successful**?
From the technology point of view, we build **big scale prototypes.**

protoDUNE

Prototyping **production** and **installation** procedures for DUNE Far Detector **TDR**.

Validating design from perspective of **basic detector performance.**

Demonstrating long term operational stability of the detector

LArTPC technology development: fine tuning & explore **near/beyond current technological limits.**

Why in a testbeam?

Test-beam data help to **understand & calibrate response of detector** to different particle species.

A calibrated beam provides a stable **benchmark to compare** different detector choices e.g. light collection systems

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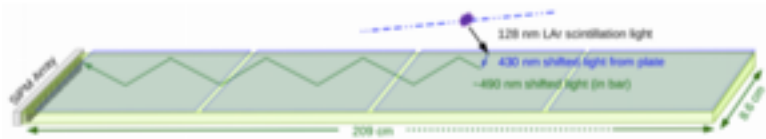
Benchmark Light Collection Systems

3 different detectors on the **same beam:** comparison will provide inputs for **final DUNE light collection system**



Double shift light guide (Indiana University)

Wavelength shifting plates + wavelength shifting light guide. Transport shifted light via total internal reflection to readout.

Dip-coated light guide (MIT and Fermilab)

Acrylic dip-coated with TPB+toluene solution.
Same readout as Indiana light guide

ARAPUCA (Campinas University and Fermilab)

Novel idea: cover large areas maintaining spatial resolution. Trap light in a high internal reflectivity cell via a dichroic optical filter deposited with 2 wavelength shifters (p-Terphenyl on outer surface, TPB inside).

Solutions for a new scale detector

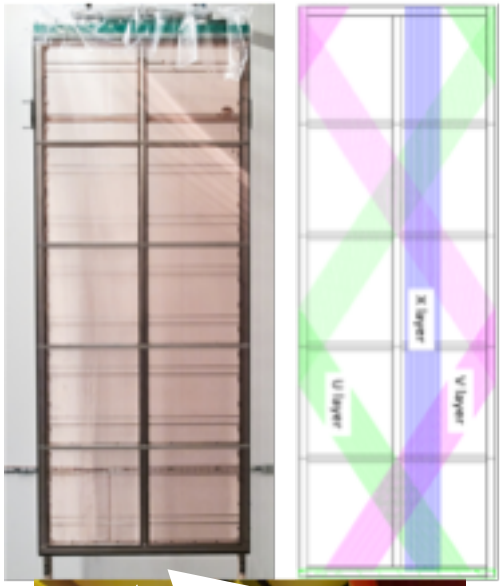
A biased and quick list of my favorites:

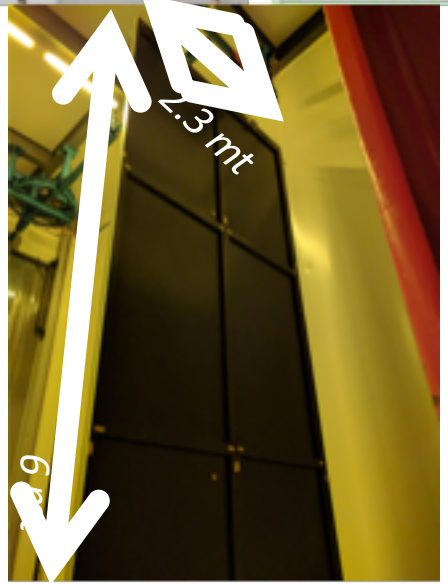
Test " **wrapped**" wires solution on **1:1 scale**
(reduce number of electronic channels and allows all electronics on top reduce dead space on the sides).

APA frame isolated from the cryostat, grounded through power cables (avoid ground loops).
Proposed design change for next pDUNE iteration.

Resistive cathode to better control energy release in case of discharge. 3 CPA positioned in the middle of the cryostat: **180 kV, same as for DUNE**

Field Cages: 12 ground planes with holes for LAr circulation to ensures null field outside active volume, **instrumented** to detect discharges





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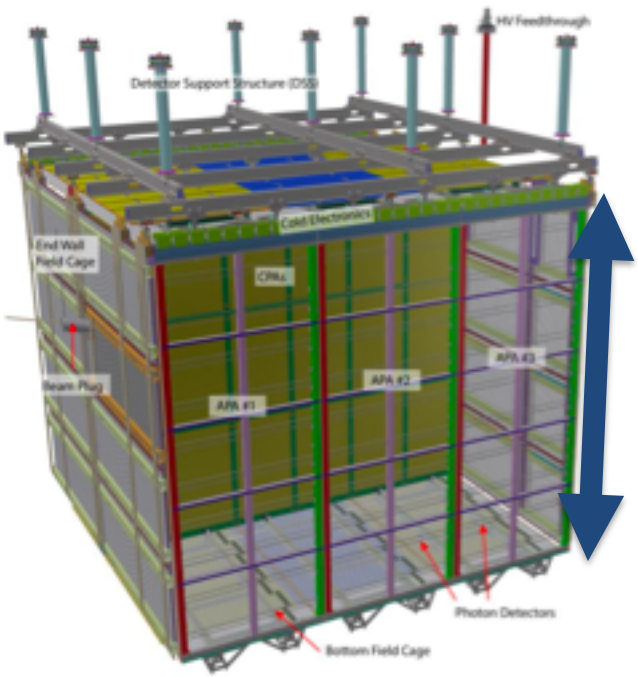
Resistive ca
of discharge
cryostat: **180**

Field Cages:
circulation to
instrumented

Record time. From installation to physics data taking: **2 years** (same as LArIAT)

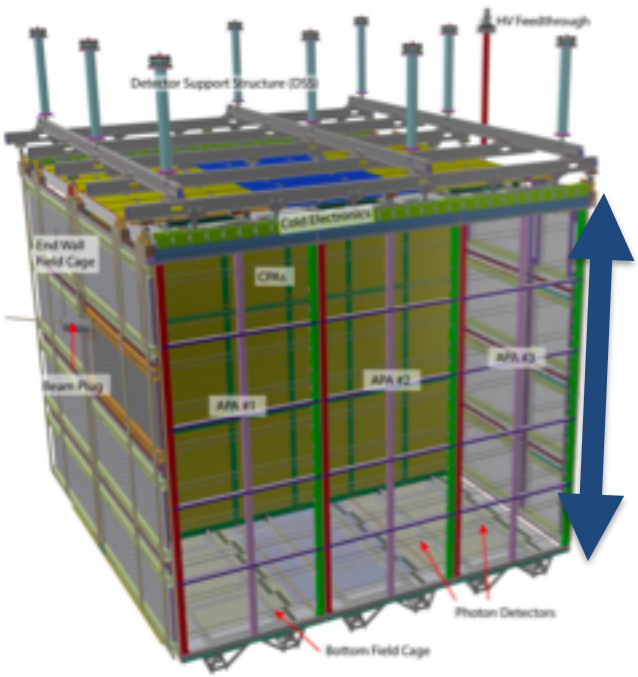
ProtoDUNE & LArIAT: sister programs



11 m
800 ton

~1 m
170 L

ProtoDUNE & LArIAT: sister programs



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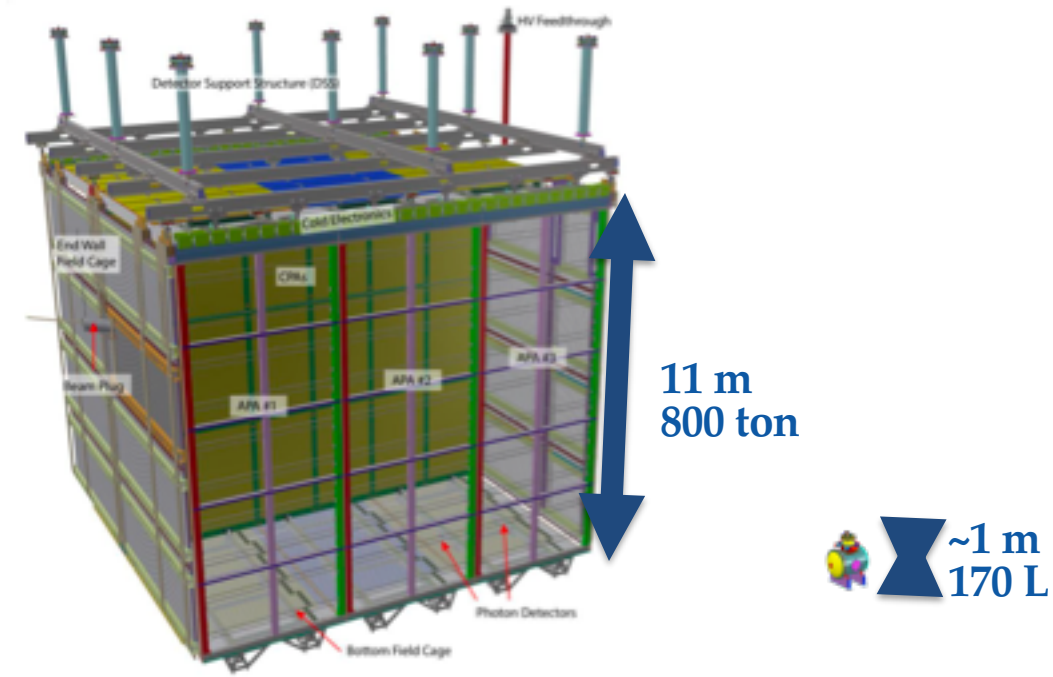
Thanks Rob & Flavio
For the pDUNE material

ProtoDUNE & LArIAT: sister programs



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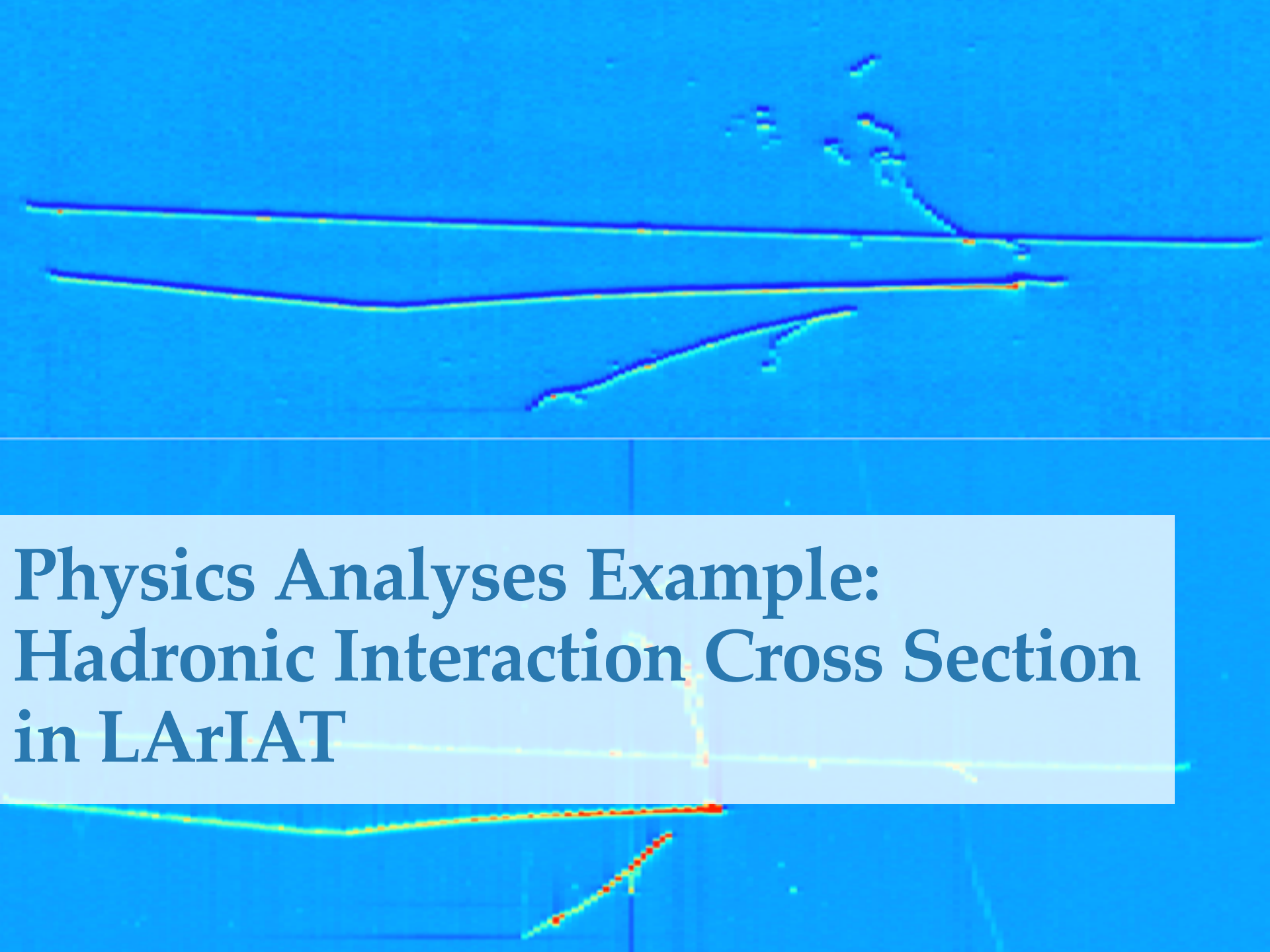
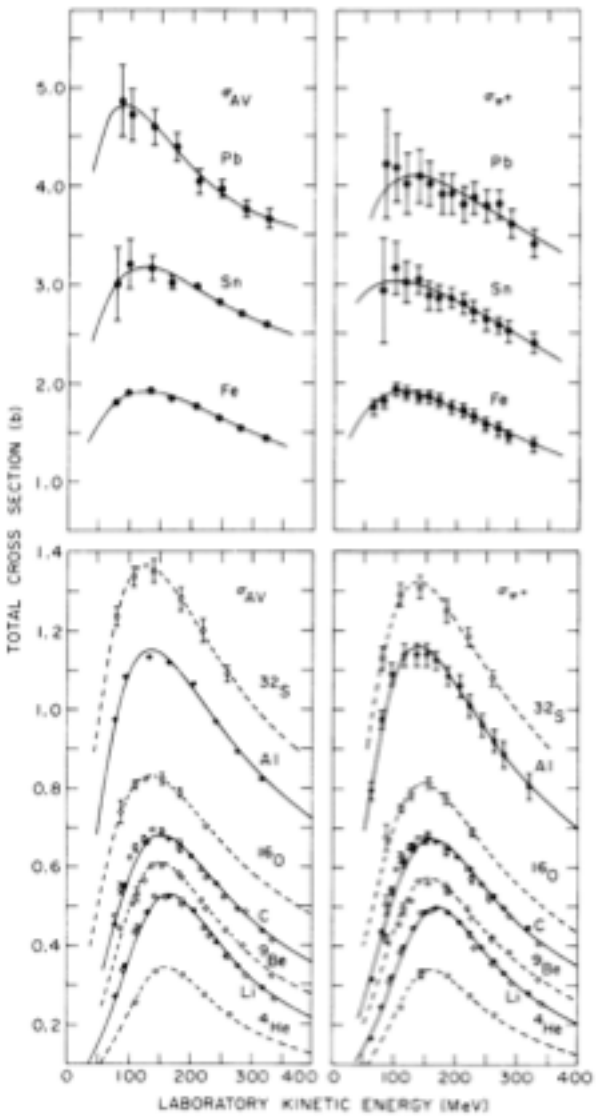
LArIAT & ProtoDUNE Core Physics Goal: Measure Hadronic XS in LAr

LArIAT R&D: a smaller detector comes with more flexibility:
- Mesh cathode
- Light Detection: Reflector foils + sipms/pmts/arapuca
- Positive ion buildup studies
- Different Wire pitch (3 mm vs 4 mm vs 5 mm)



Physics Analyses Example: Hadronic Interaction Cross Section in LArIAT

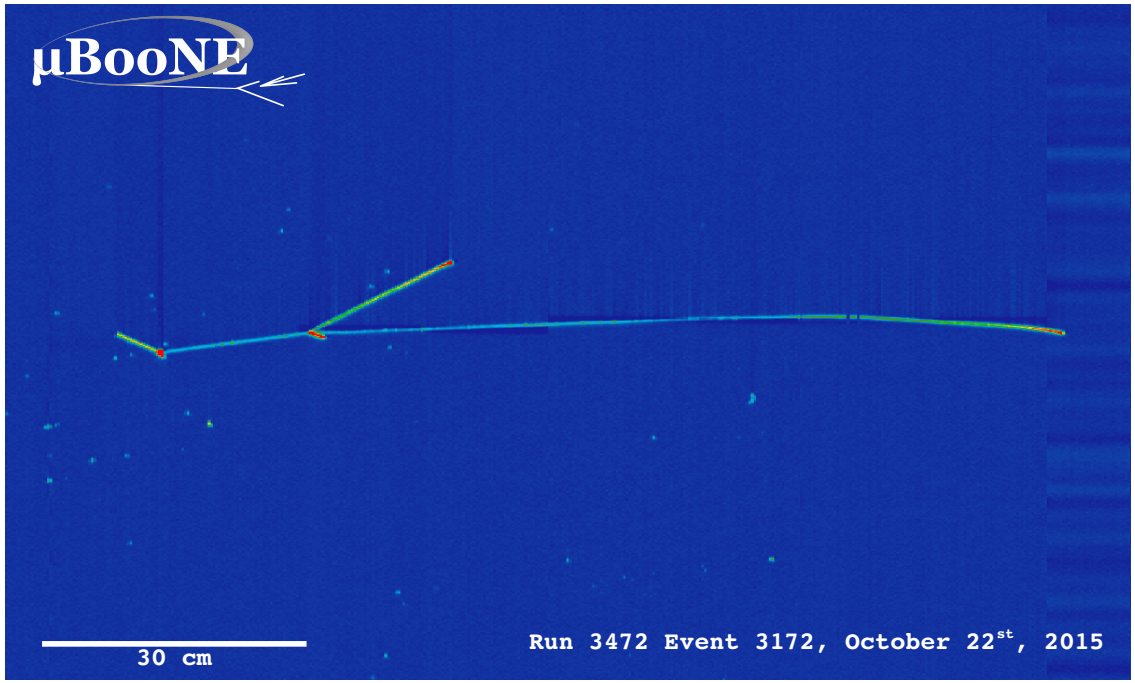
Cross Sections in the Grand Scheme



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

Hadronic XS affect **ν products** both in their **interaction with the nucleus** and in their **propagation** in the detector medium.

Pion XS



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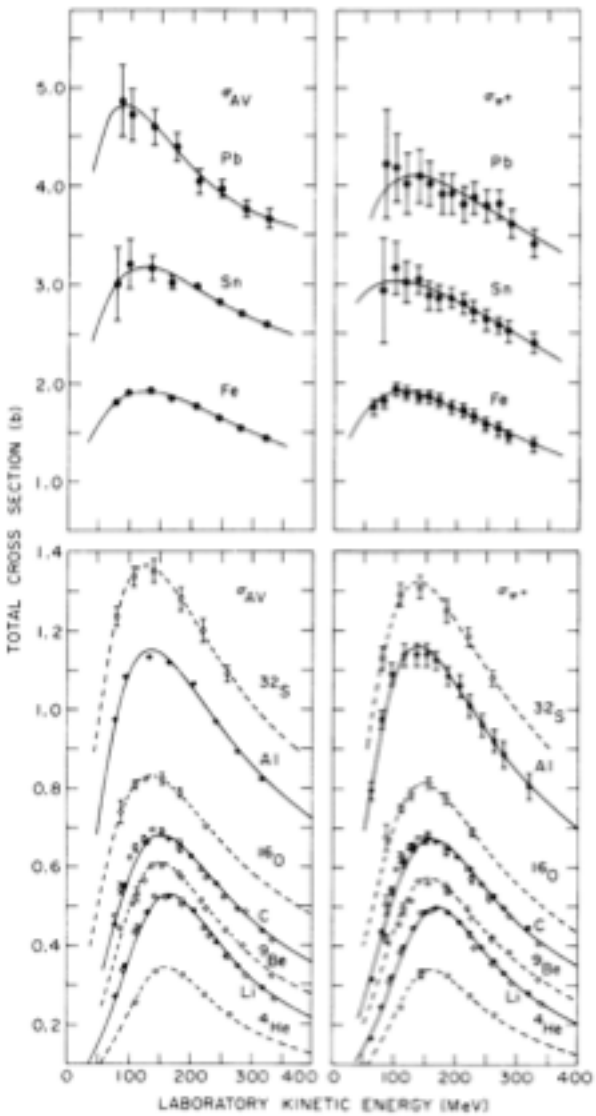

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Hadronic XS affect **ν products** both in their **interaction with the nucleus** and in their **propagation** in the detector medium.

Pion XS:

In the energy range of **100-500 MeV**, pion interactions are dominated by the **Δ resonance**, and the π-Ar cross section is boosted… the topology of ν events gets complicated & so does FSI!

No **Ar data**: Geant4 & ν Event Γenerators use interpolation from lighter-heavier nuclei…

The shape of the delta resonance **changes** as a function of the **mass number**.

LArIAT LArTPC

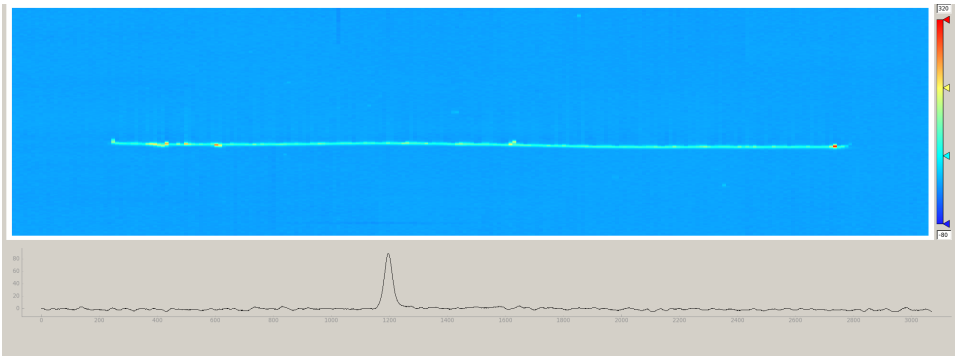
LArIAT TPC: 47x40x90 cm^3

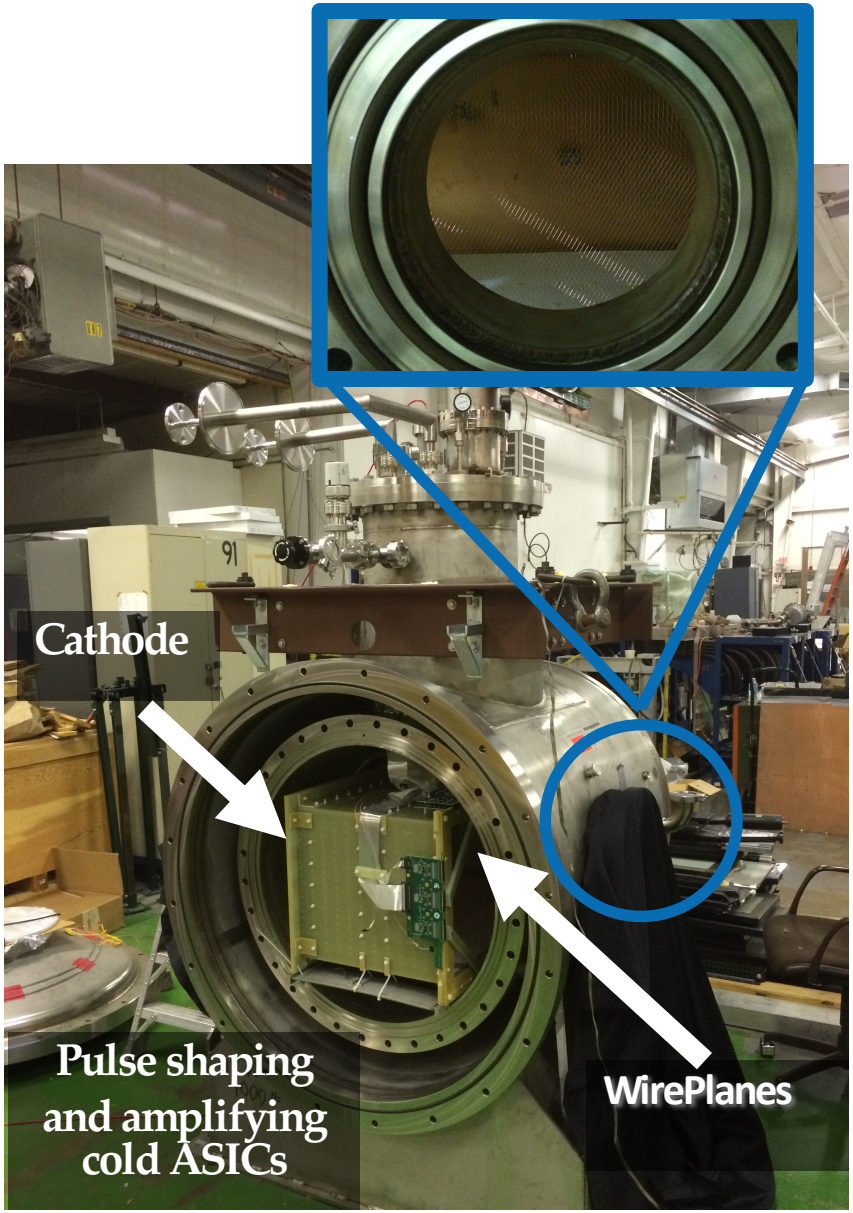
2 Readout planes

240 wires / plane +/- 60º, 4mm pitch
Drift field = 487 ± 21 V/cm

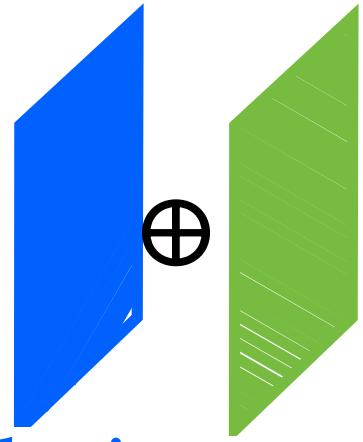
Signal pre-amplification in cold

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

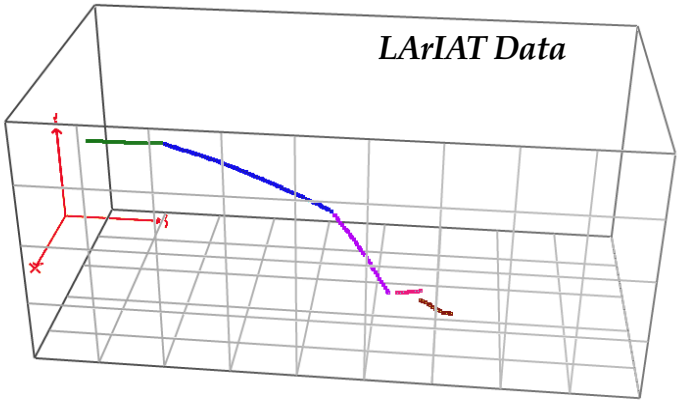




LArTPC Key Features

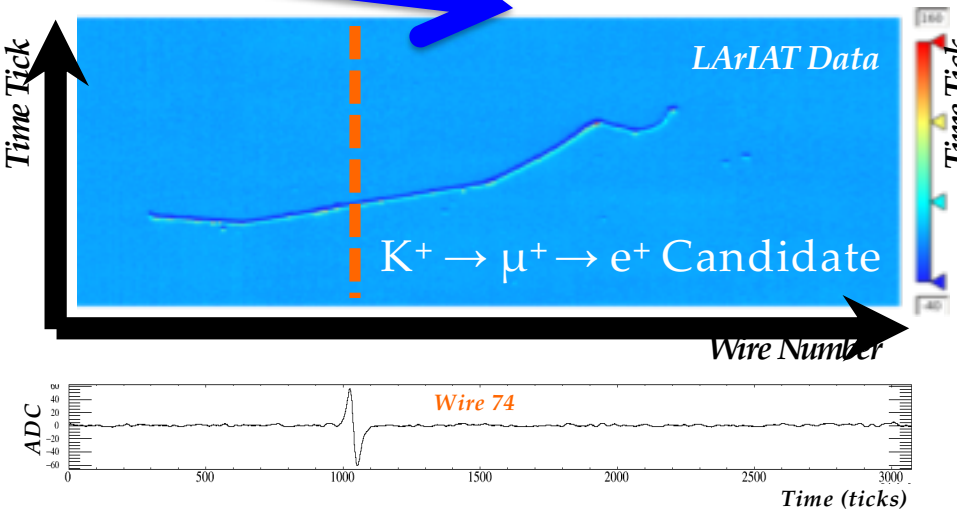


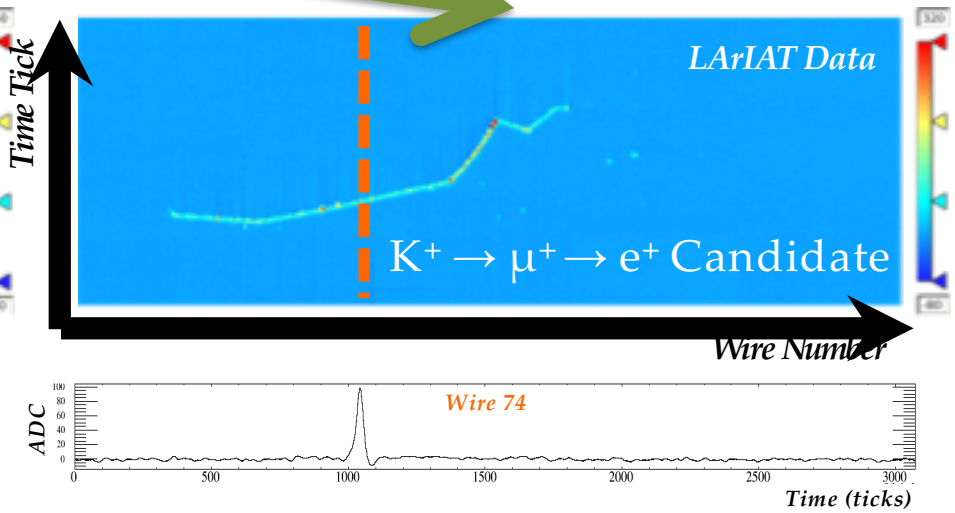
Drift time =



Induction plane

Collection plane





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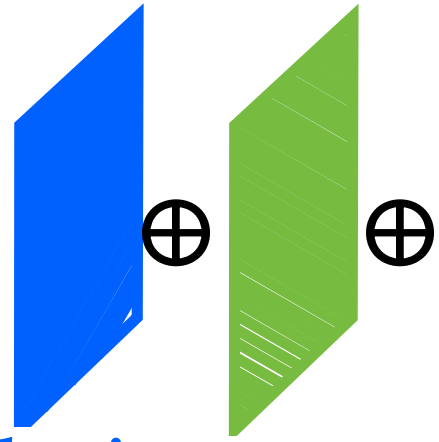

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Collection plane

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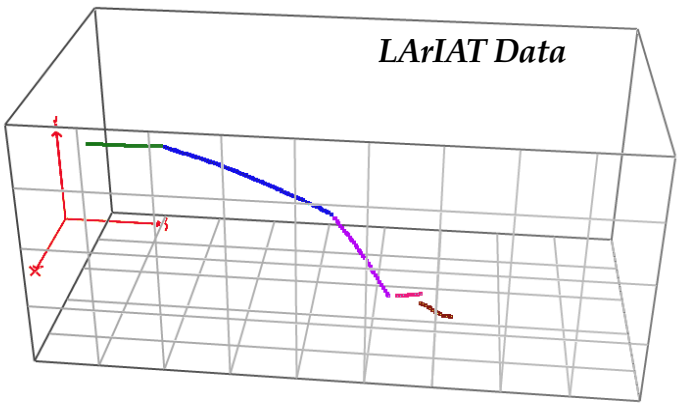
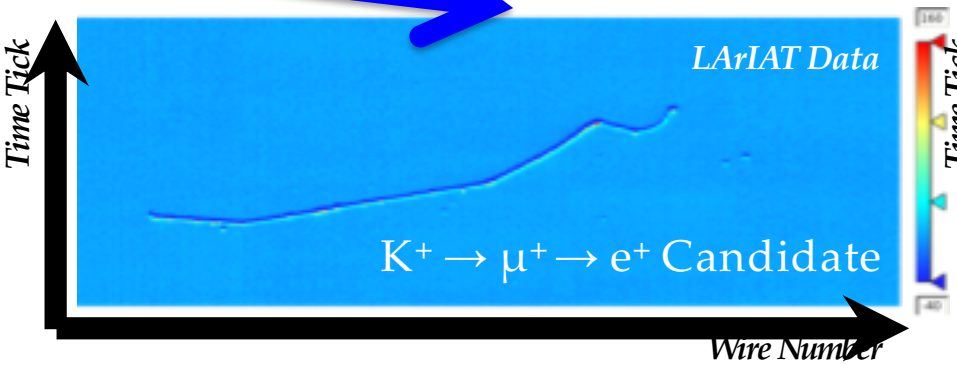
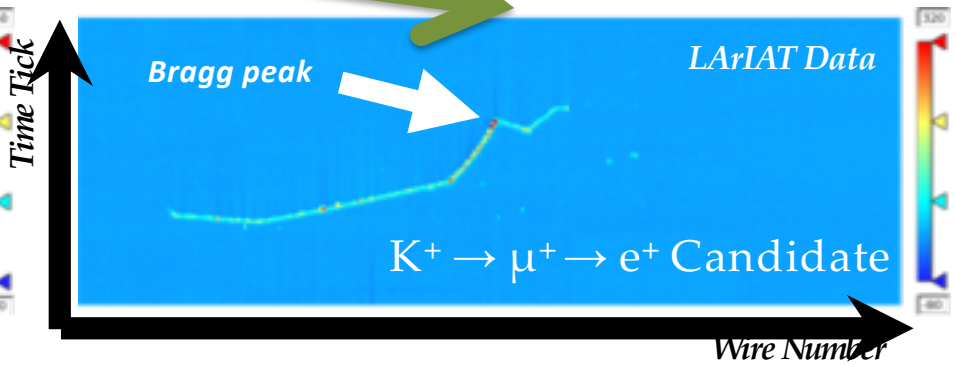






3D imaging with mm space resolution

Calorimetry information

PID capabilities

LArIAT XS analyses in 4 simple steps:

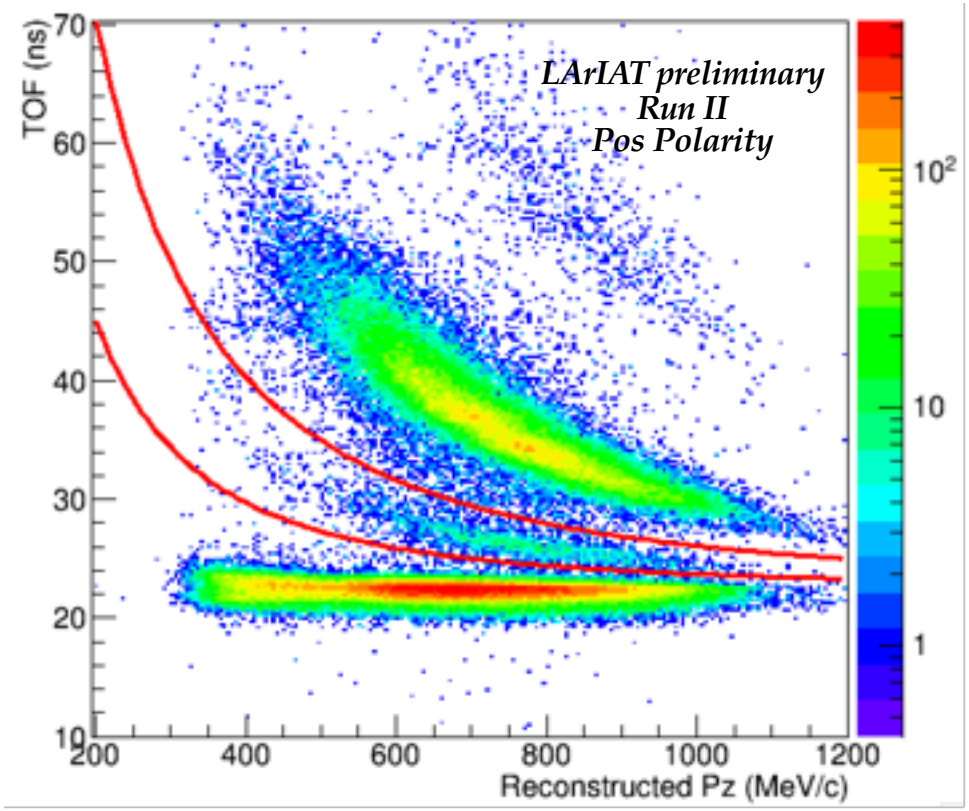
1) Select the right particles in the beamline

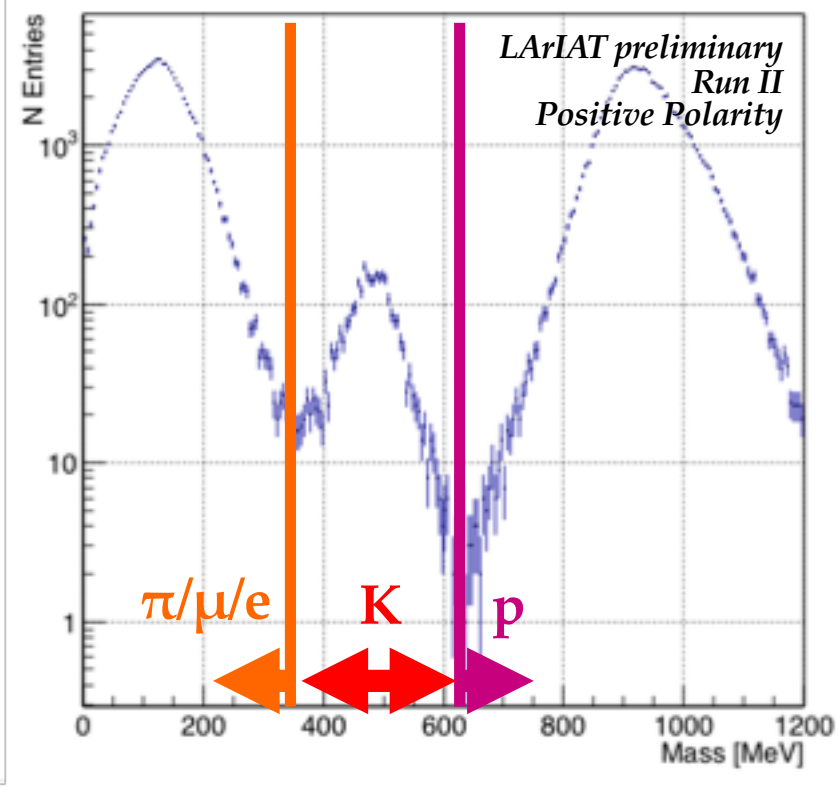
2) Beamline-TPC Handshake

3) Apply the "thin slice method" (TSM)

4) Correct for Backgrounds and Reco effects

1) Select the right particles in beamline





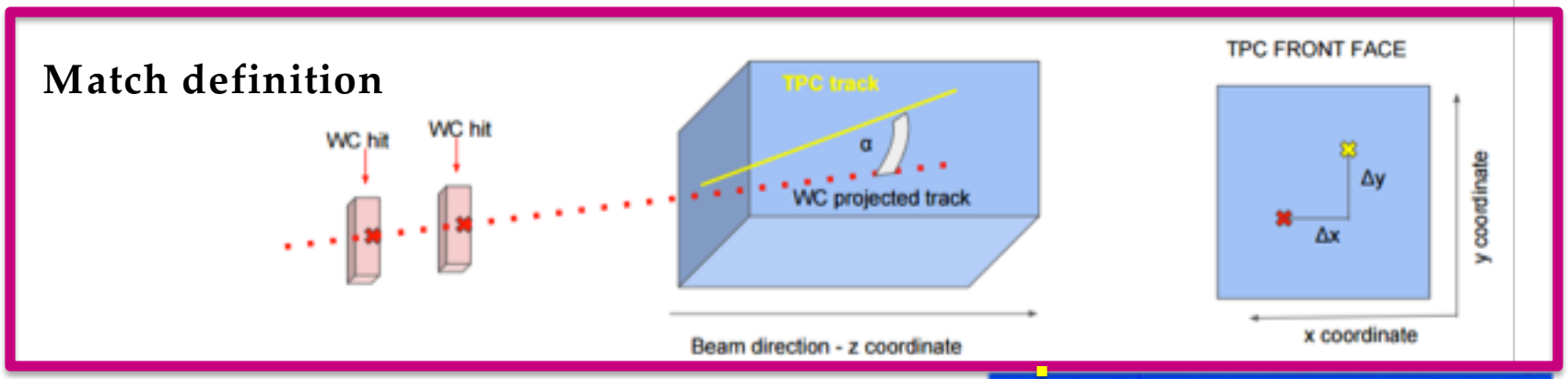
$$m = \frac{p}{c}\sqrt{\left(\frac{c * TOF}{\ell}\right)^2 - 1}$$

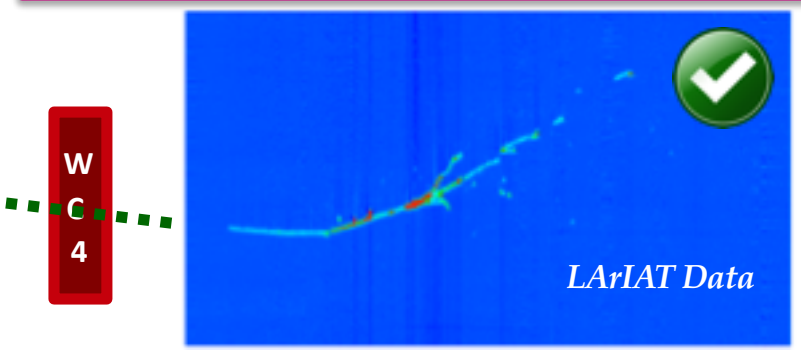
Keep

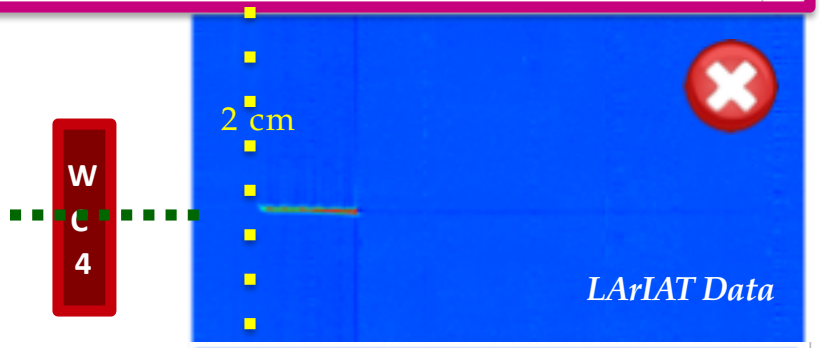
π: Mass < 350 MeV/c^2

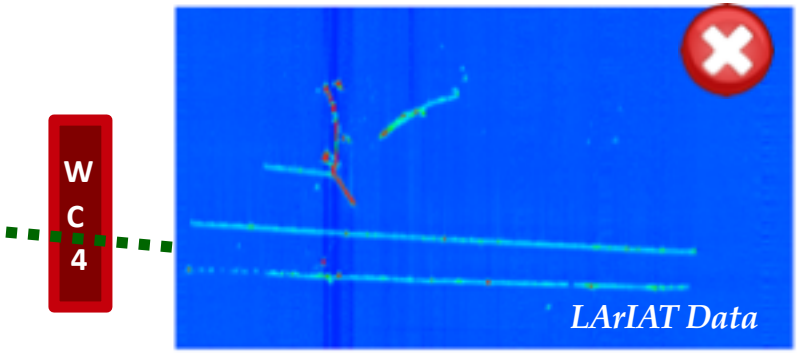
K: 350 MeV/c^2 < Mass < 650 MeV/c^2

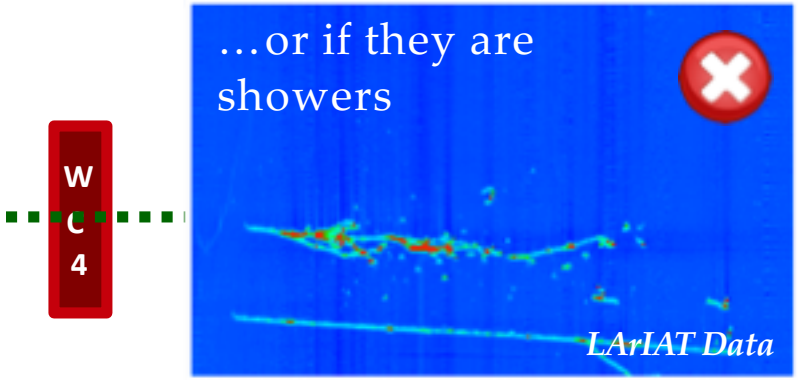
2) Beamline-TPC handshake





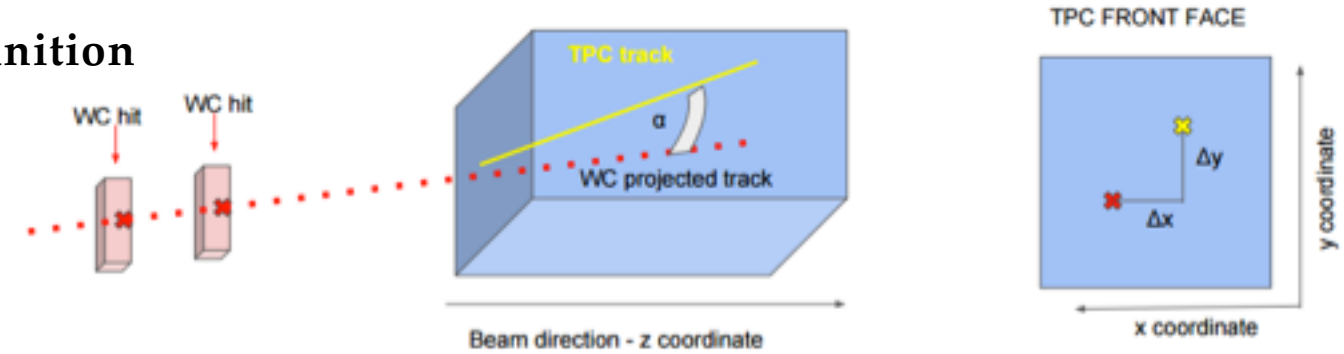






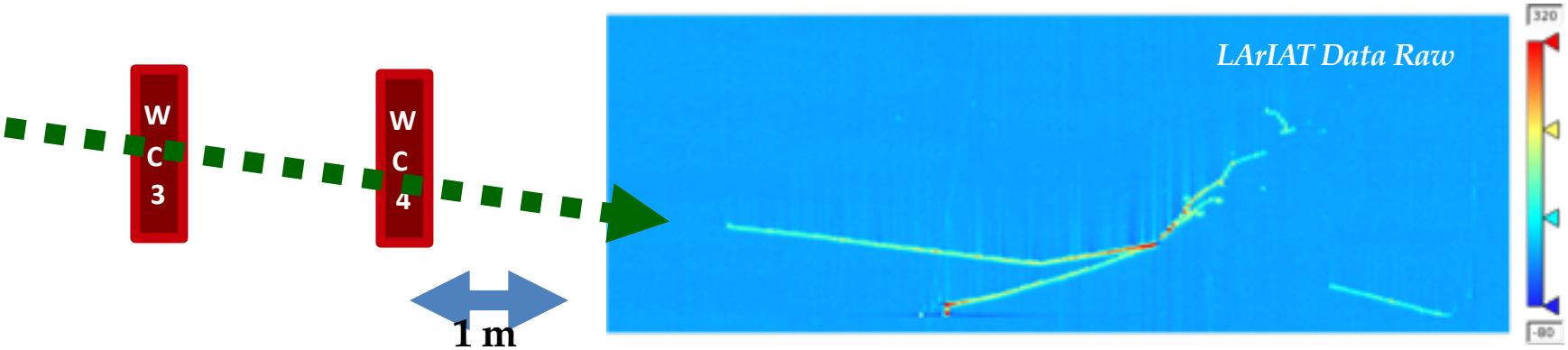
2) Beamline-TPC handshake

Match definition



	Run-II Neg Pol
1. Events Reconstructed in Beamline	158396
2. Events with Plausible Trajectory	147468
3. Beamline $\pi^-/\mu^-/e^-$ Candidate	138481
4. Beamline K^+ Candidate	N.A
5. Events Surviving Pile Up Filter	108929
6. Events with WC2TPC Match	41757
7. Events Surviving Shower Filter	40841
8. Available Events For Cross Section	40841

Beamline candidates: what do we know?

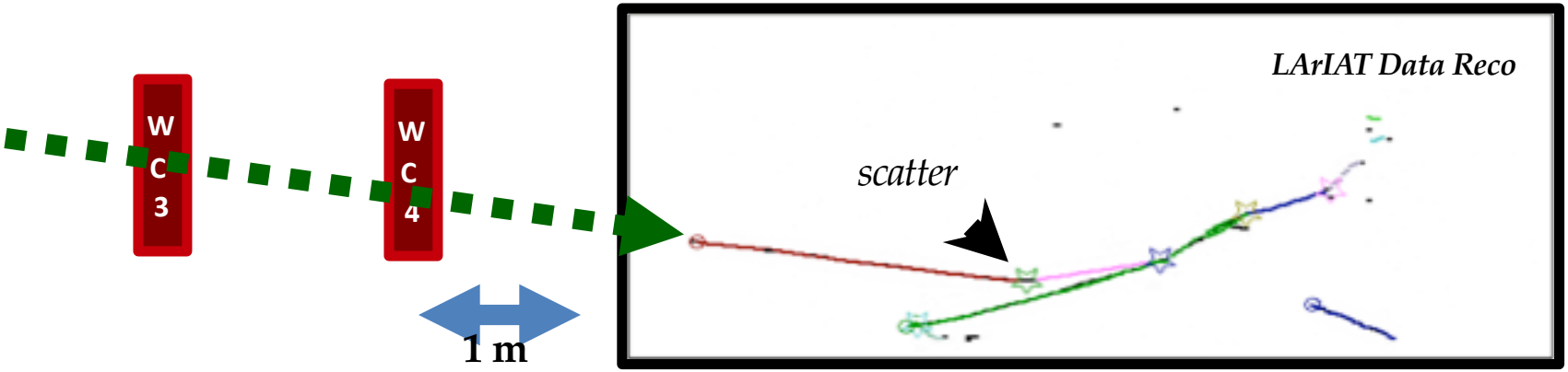


We use the **momentum measured by the WC** to calculate the candidate's initial kinetic energy as

$$E^{\text{kin}}_{\text{Front Face}} = \sqrt{p^2_{Beam} + m^2_{Beam}} - m_{Beam} - E_{Loss}$$

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

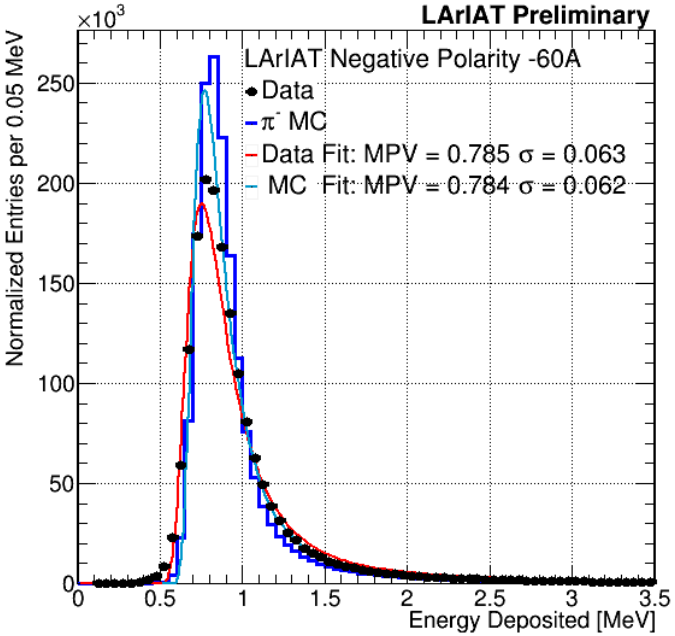
Beamline candidates: what do we know?



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.

$$E_j^{\text{kin}} = E^{\text{kin}}_{\text{Front Face}} - \sum_{j<i} E_{\text{dep i}}$$

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

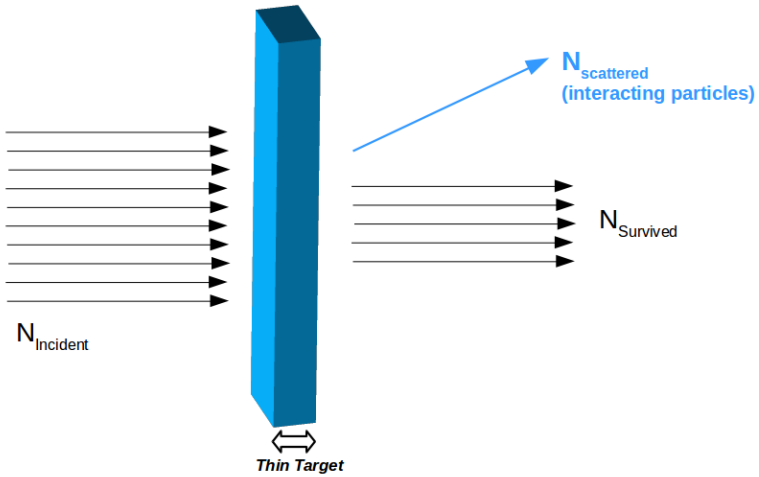


3) TSM: a new spin on an old technique

The particle **interaction probability** through a **thin slice** of Ar

$$P_{\mathrm{Int}} = \frac{N_{\mathrm{Int}}}{N_{\mathrm{Inc}}} = 1 - e^{-\sigma_{\mathrm{TOT}}\, \mathrm{n}\, \delta X}$$

σ_{Tot} = cross section per Ar,
n = Ar number density,
δX = depth of the slice



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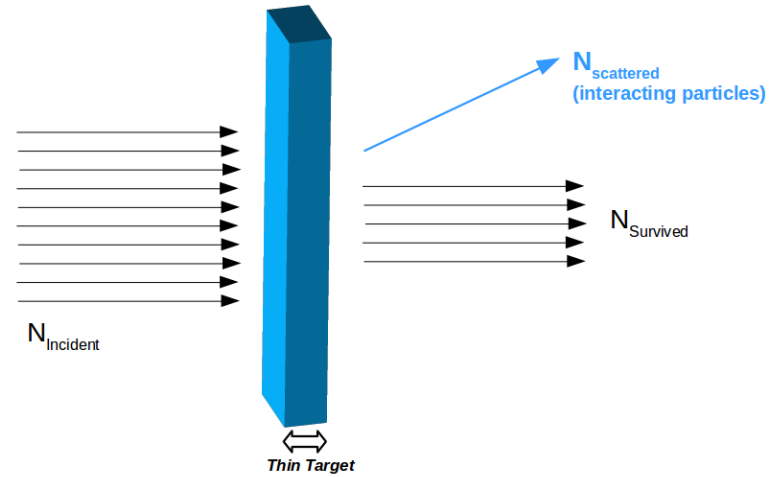
THIN

$$\sigma_{\mathrm{TOT}}(E) \sim \frac{1}{\mathrm{n}\, \delta X} \frac{N_{\mathrm{Int}}}{N_{\mathrm{Inc}}}$$



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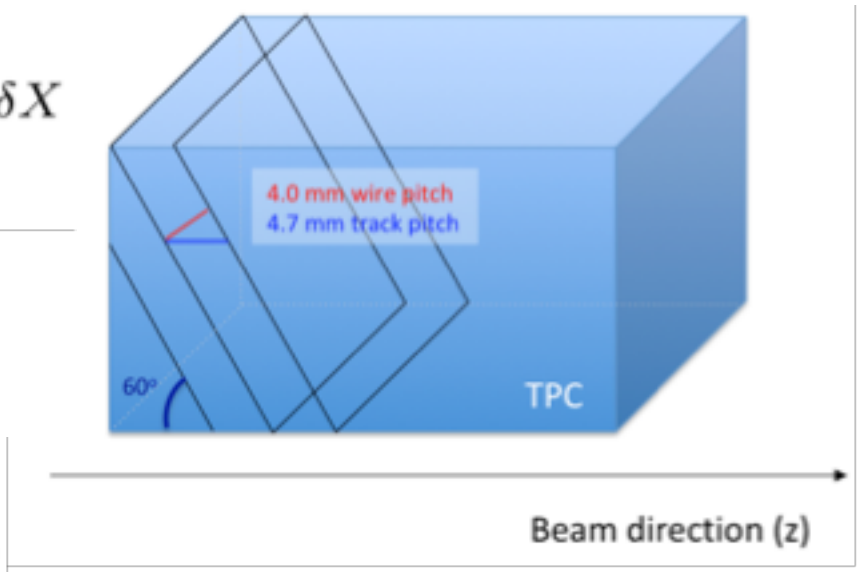


We treat the **wire-to-wire spacing** as a **series of "thin-slice"** targets, since we know the energy of the particle incident to each slice.

Each thin slice is an independent experiment

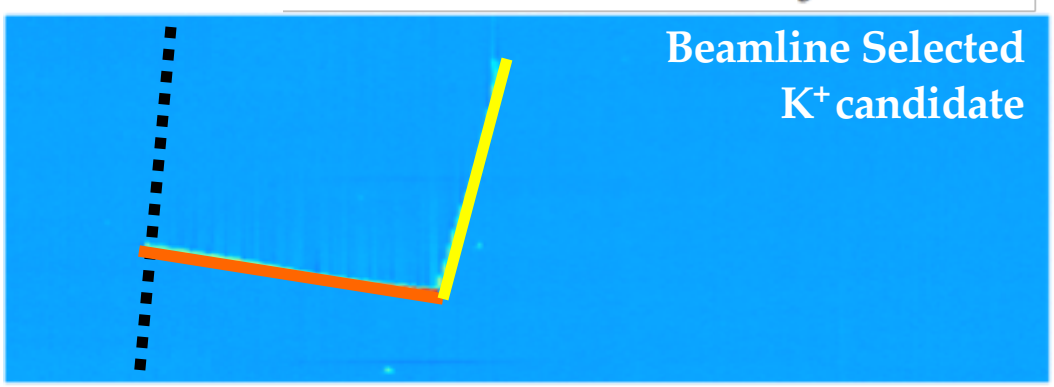
$N_{Incident}$, $N_{Interacting}$ calculation

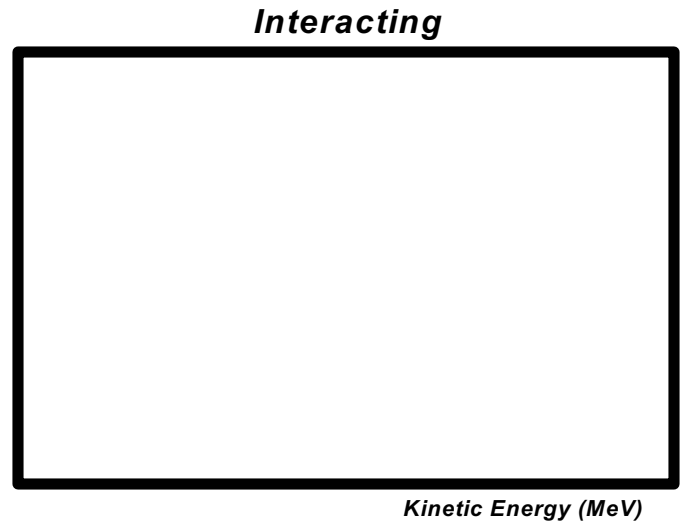
We follow the TPC track slice by slice

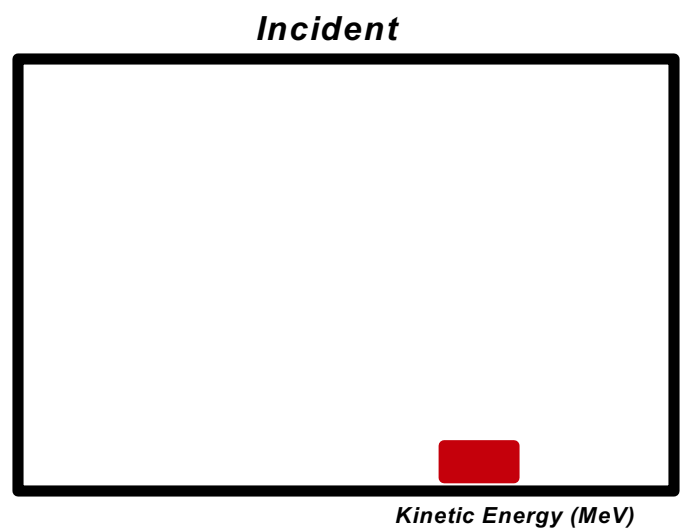
- The slice represents the distance between each 3D point in the track
- For each slice we ask: "Is this **the end** of the track?"

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

$$E_j^{\text{kin}} = E_{\text{Front Face}}^{\text{kin}} - \sum_{j<i} E_{\text{dep i}}$$







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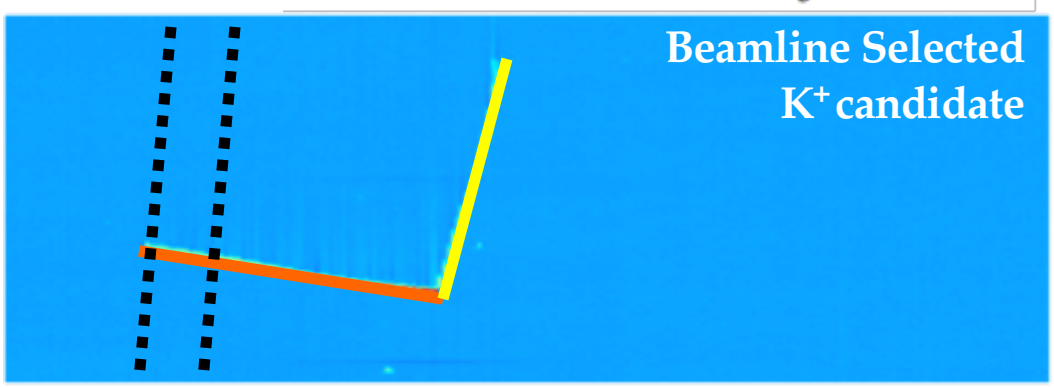

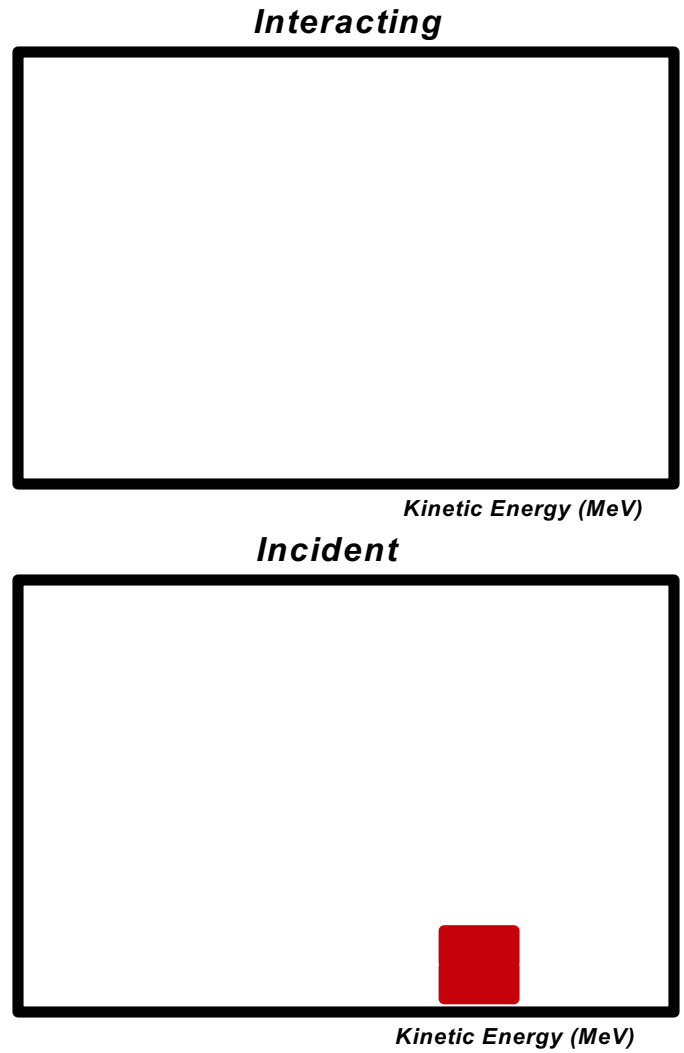

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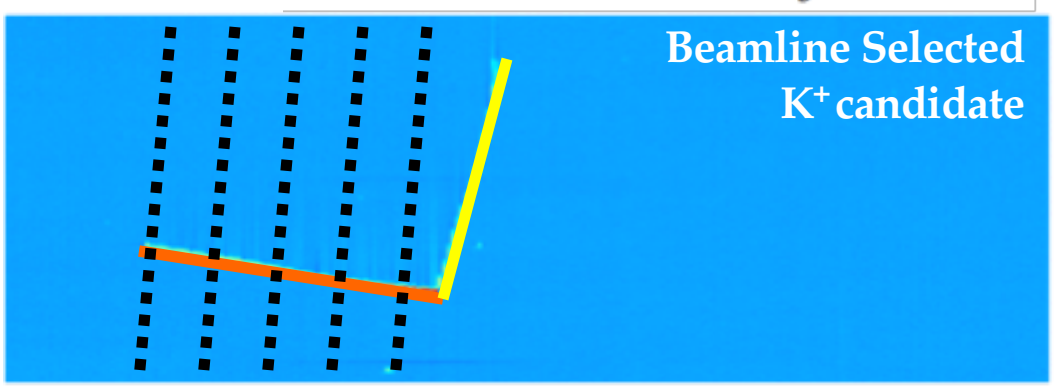
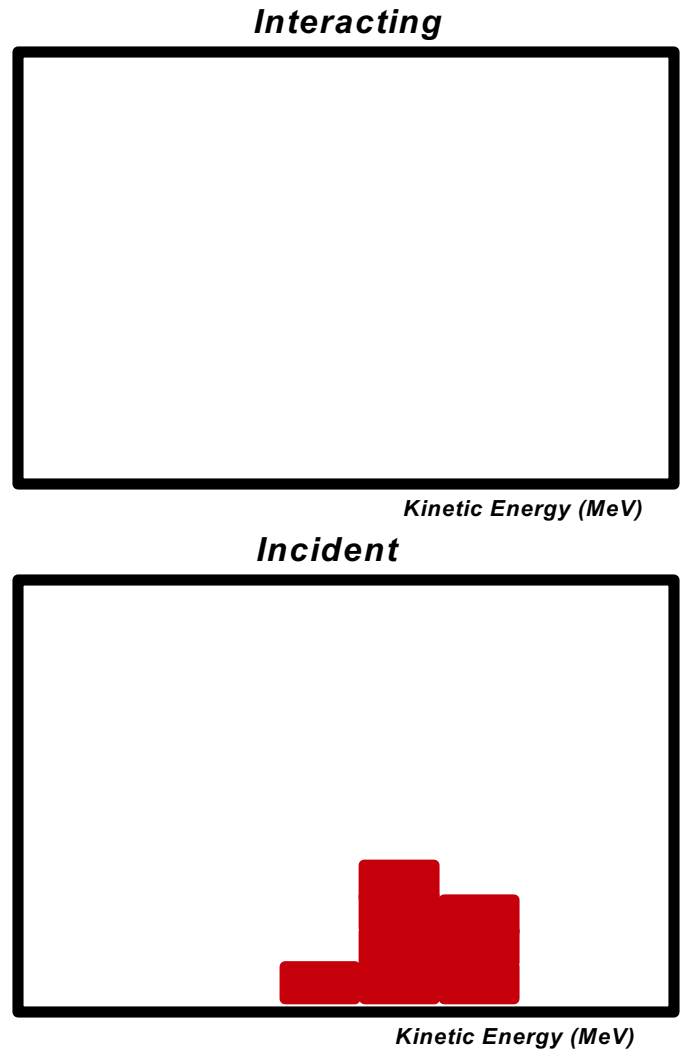




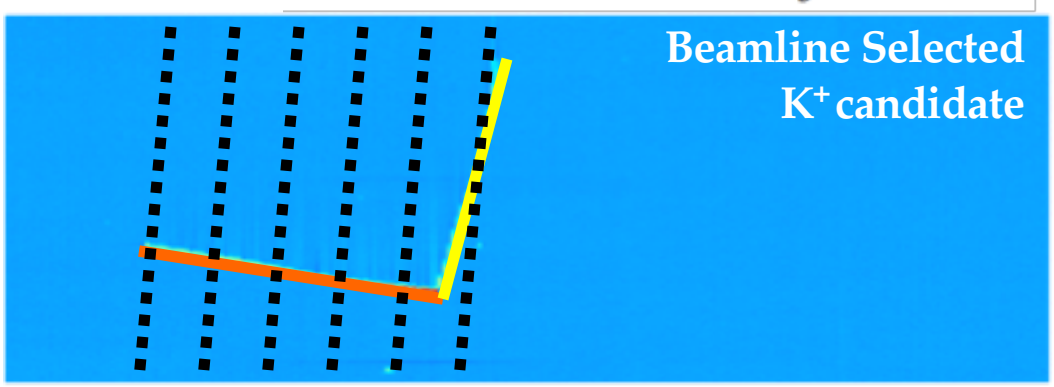
$N_{Incident}$, $N_{Interacting}$ calculation

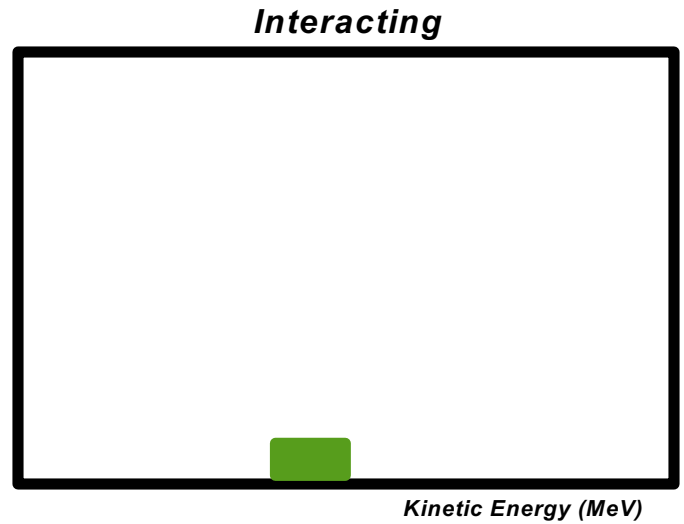
We follow the TPC track slice by slice

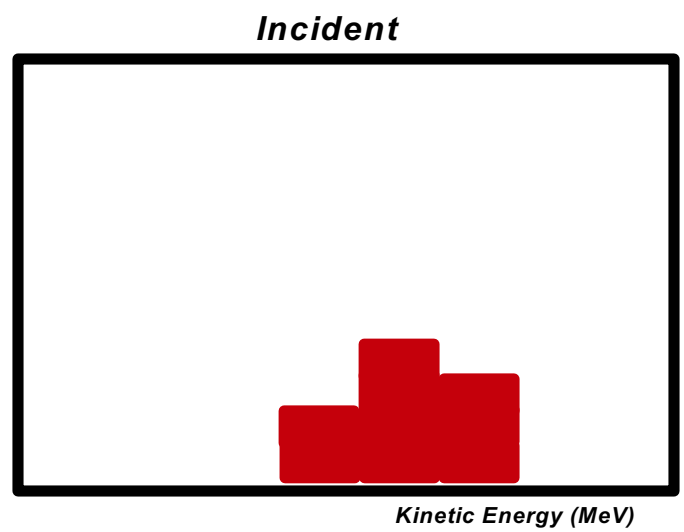
- The slice represents the distance between each 3D point in the track
- For each slice we ask: "Is this **the end** of the track?"

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

$$E_j^{\text{kin}} = E_{\text{Front Face}}^{\text{kin}} - \sum_{j<i} E_{\text{dep i}}$$



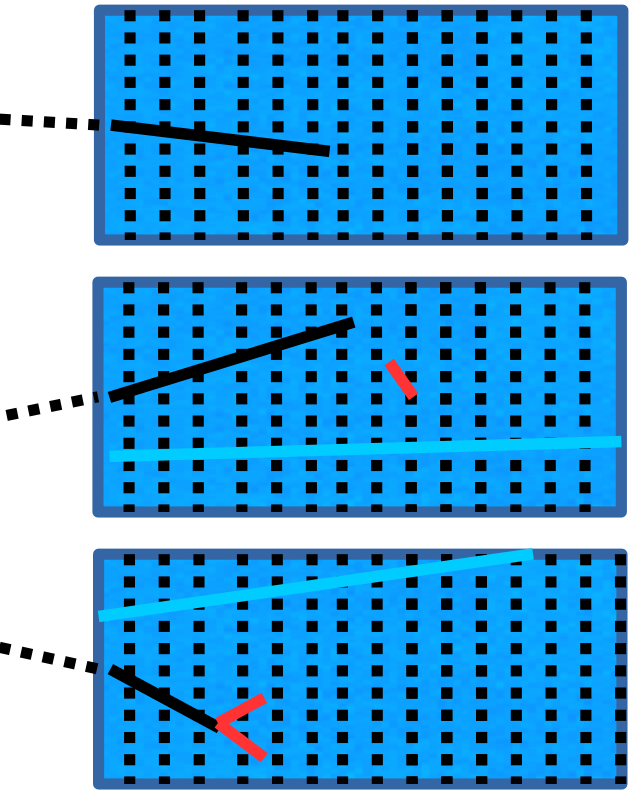




N Incident , N Interacting calculation

Repeat for each WC to TPC matched track

- We disregard any other activity occurring in the detector

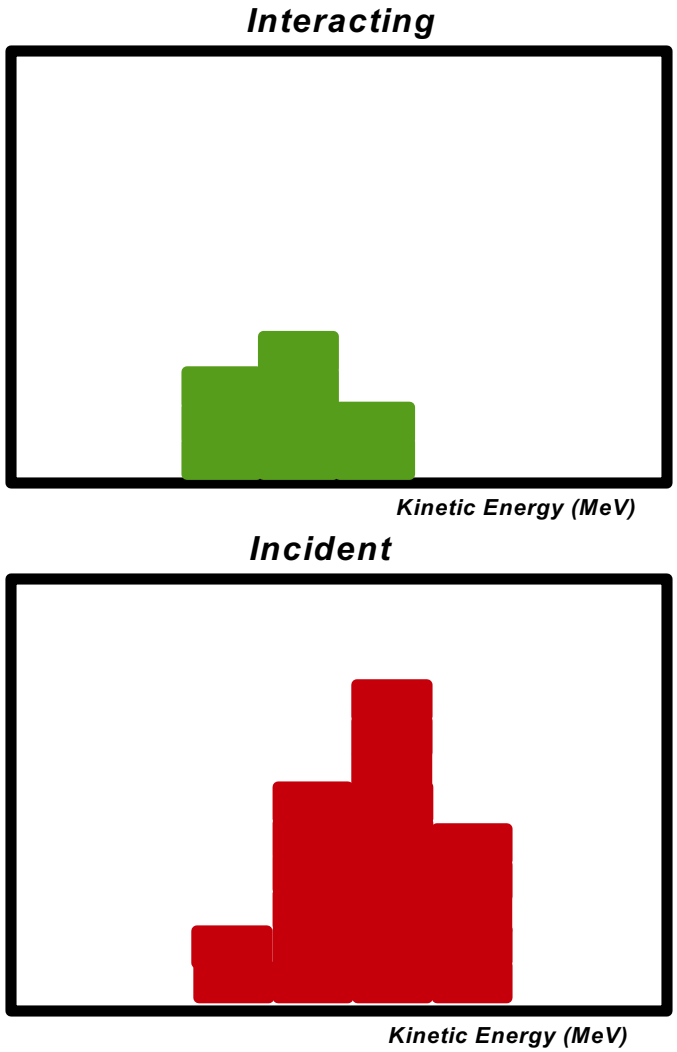


The black track is followed

The light blue track is not matched to WC

The red stub is ignored

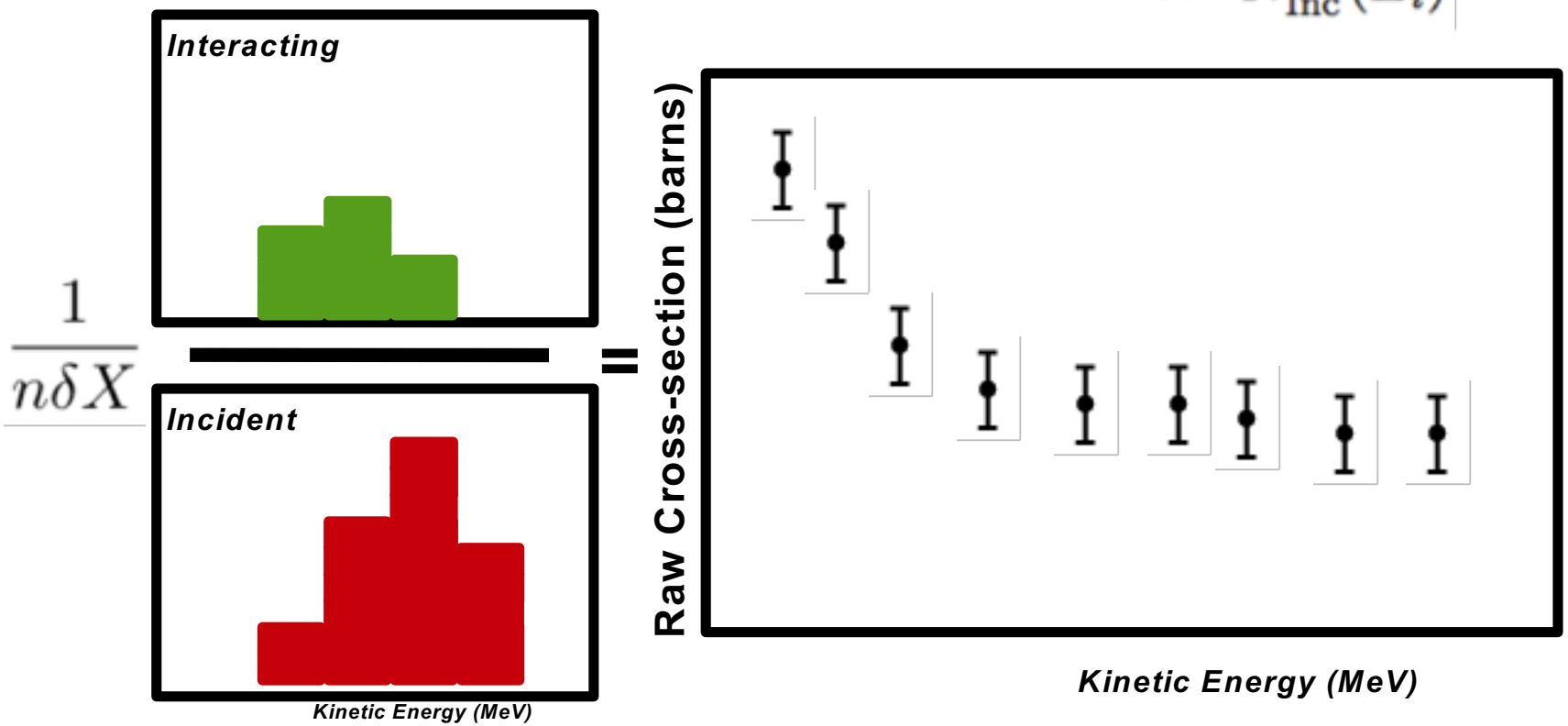
The red tracks do not belong to the original track



3) Thin-slice method

We take **the ratio** of the **two histograms** and calculate the **raw cross section**

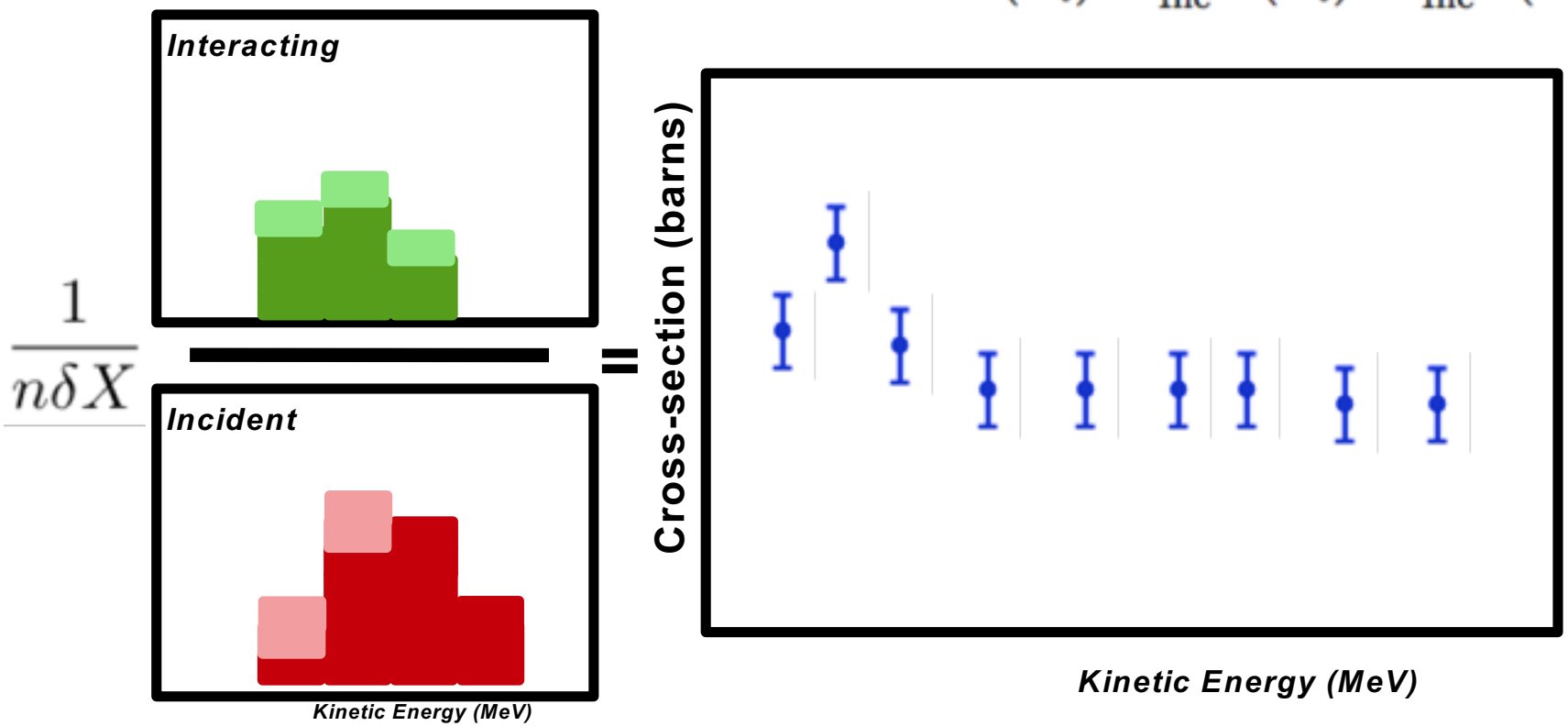
$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\,\delta X}\frac{N^{\pi^-}_{\mathrm{Int}}(E_i)}{N^{\pi^-}_{\mathrm{Inc}}(E_i)}$$



4) Correct for Background and Reco

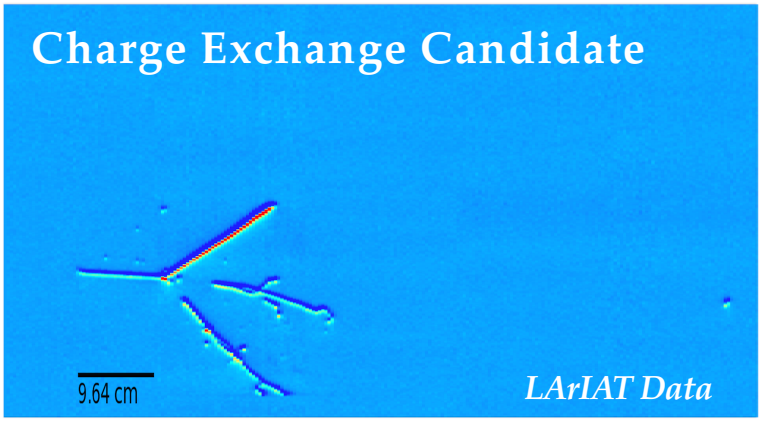
We evaluate the **background** and the **reconstruction** effects on the interacting and incident distributions **separately**

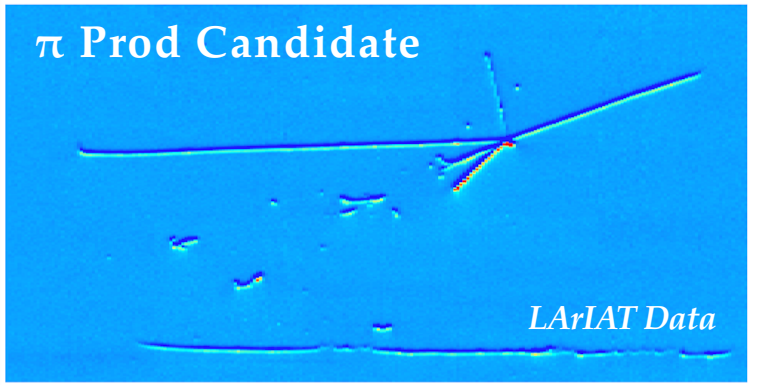
$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X} \frac{\epsilon^{\mathrm{Inc}}(E_i)\ C^{\pi MC}_{\mathrm{Int}}(E_i)\ N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)\ C^{\pi MC}_{\mathrm{Inc}}(E_i)\ N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$

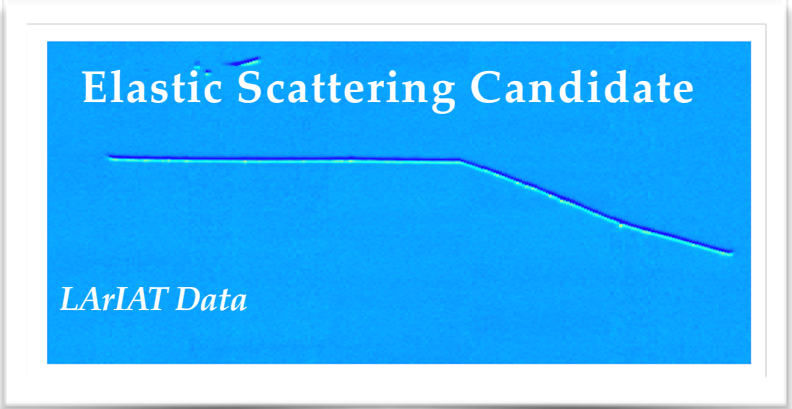


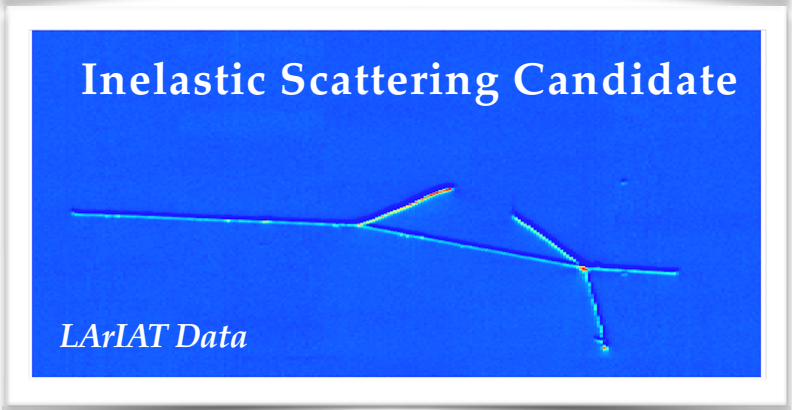
Signal Topologies

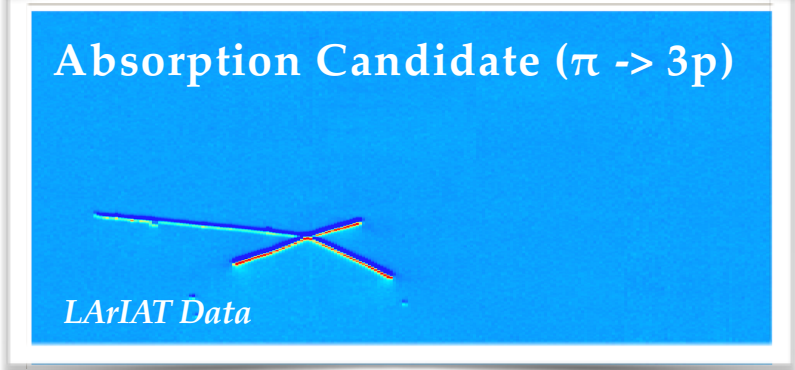
$$\sigma_{Tot} = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{abs} + \sigma_{charge\ xc} + \sigma_{\pi\text{-prod}}$$



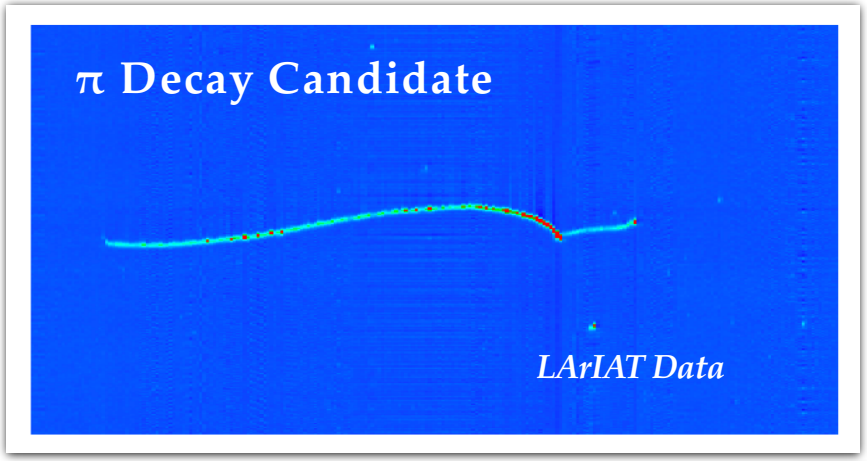


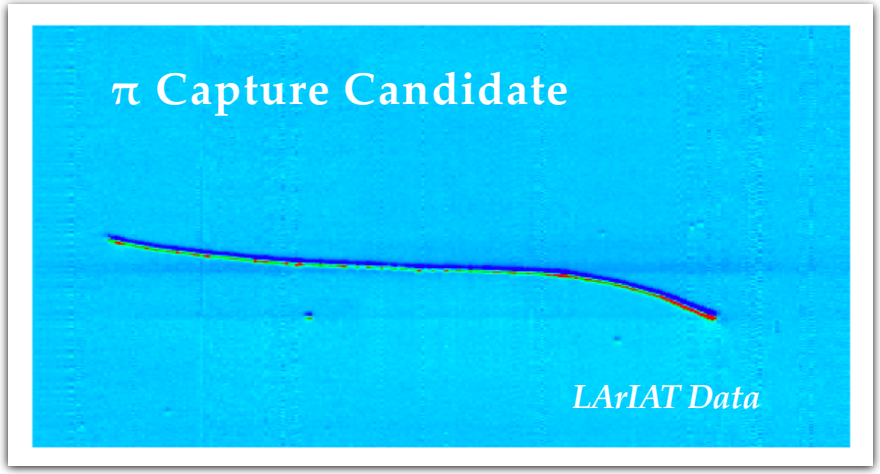






Intrinsic and Beamline Backgrounds



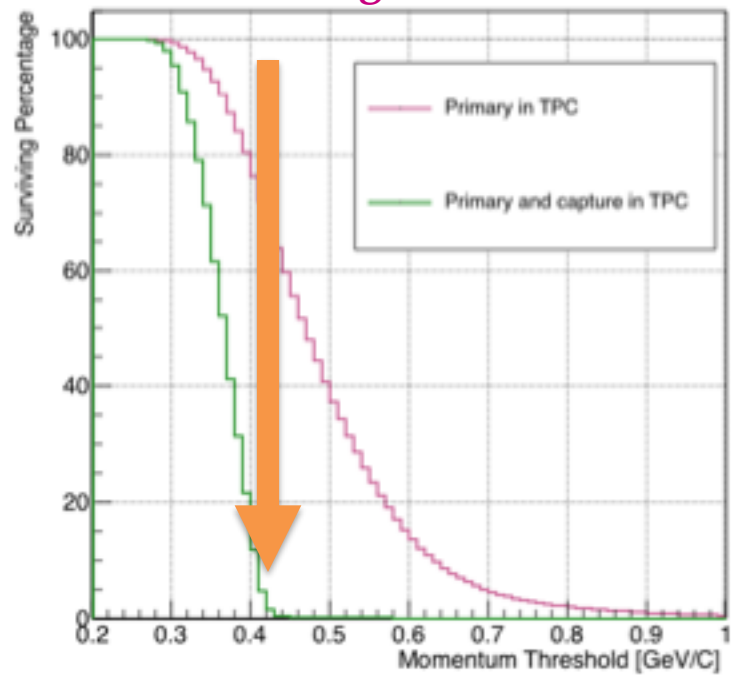


+ residual electrons & muons

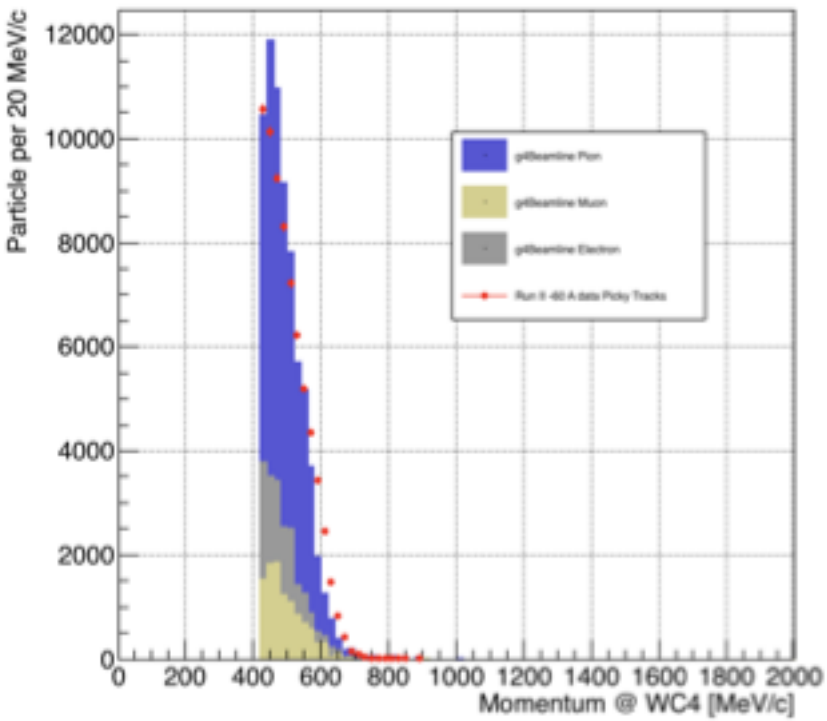
Intrinsic and Beamline Backgrounds

π-Capture and π-Decay occur mainly at rest: select particles with high incoming momentum.

Surviving Event Ratio



Beam Composition: Low Energy



Assess beam composition and simulate contaminants

	Low E Beam	High E Beam
G4Pions	70.9 %	82.3 %
G4Muons	14.6 %	13.5 %
G4Electrons	14.5 %	4.2 %

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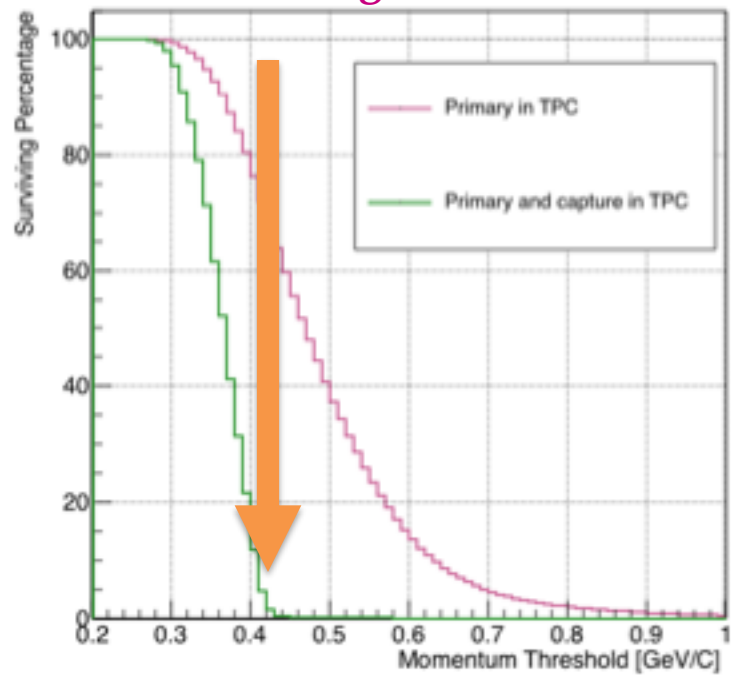
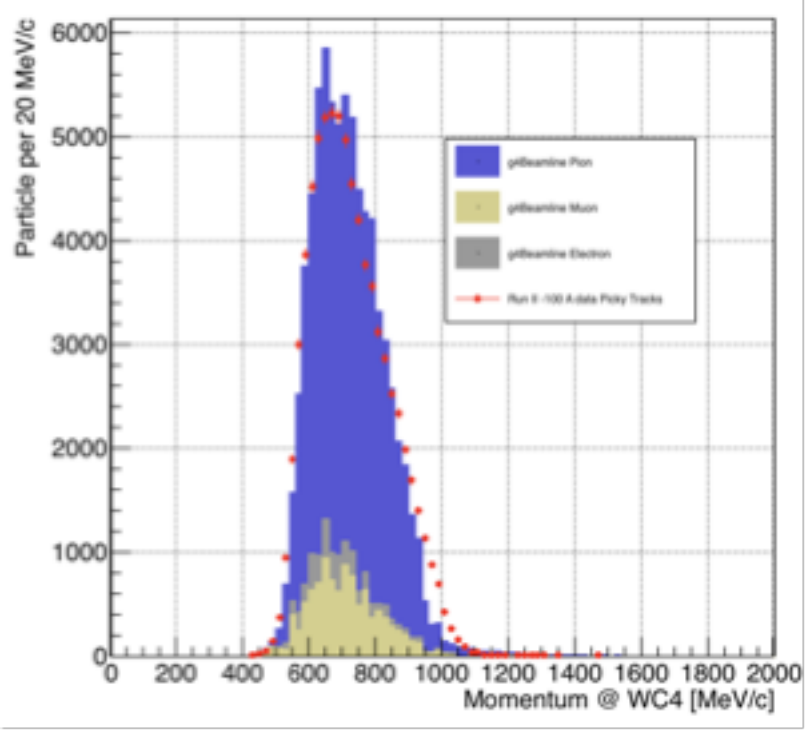


Beam Composition: High Energy



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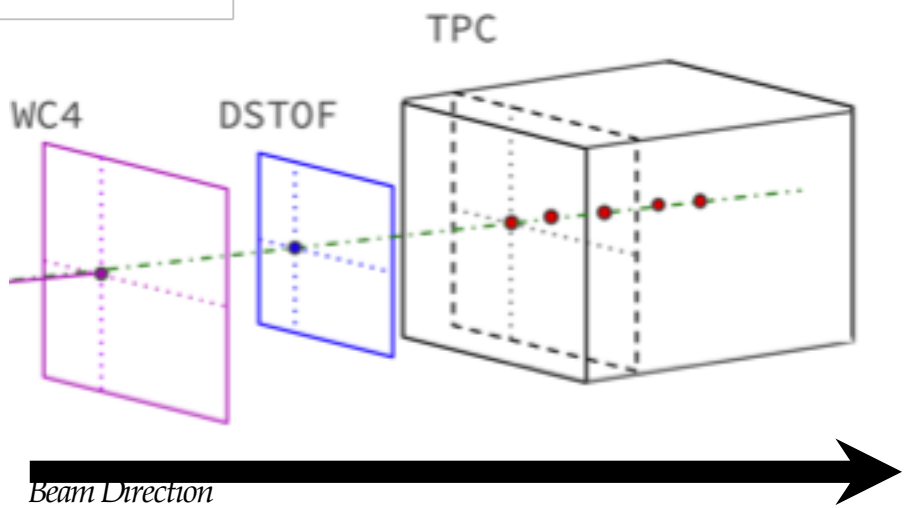
XS Formula: how well do we know E_i ?

$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X} \frac{\epsilon^{\mathrm{Inc}}(E_i)\ C^{\pi MC}_{\mathrm{Int}}(E_i)\ N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)\ C^{\pi MC}_{\mathrm{Inc}}(E_i)\ N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$

$$E_{\text{slice j}} = \sqrt{p^2_{Beam} + m^2_{Beam}} - m_{Beam} - E_{Loss} - E_{\text{dep FF-j}}$$

$$\delta E_{\text{slice j}} = \sqrt{\delta p^2_{Beam} + \delta E^2_{Loss} + \delta E^2_{\text{dep FF-j}}}$$



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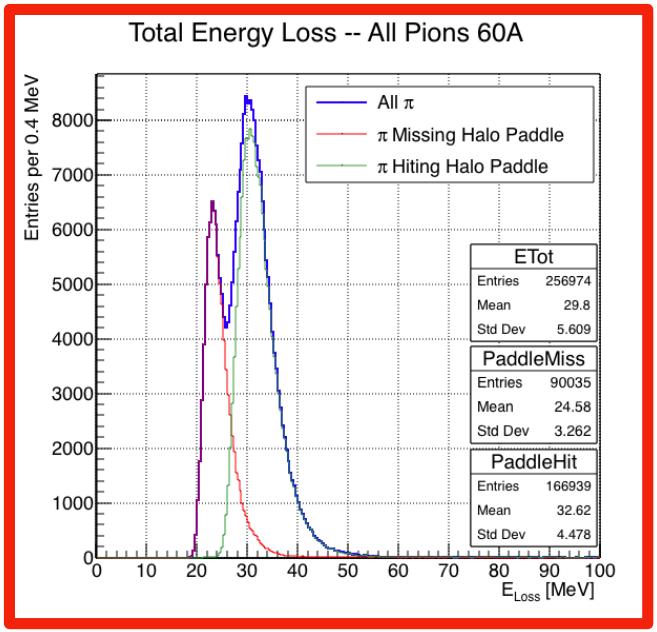
6 MeV

2% p_{Beam}



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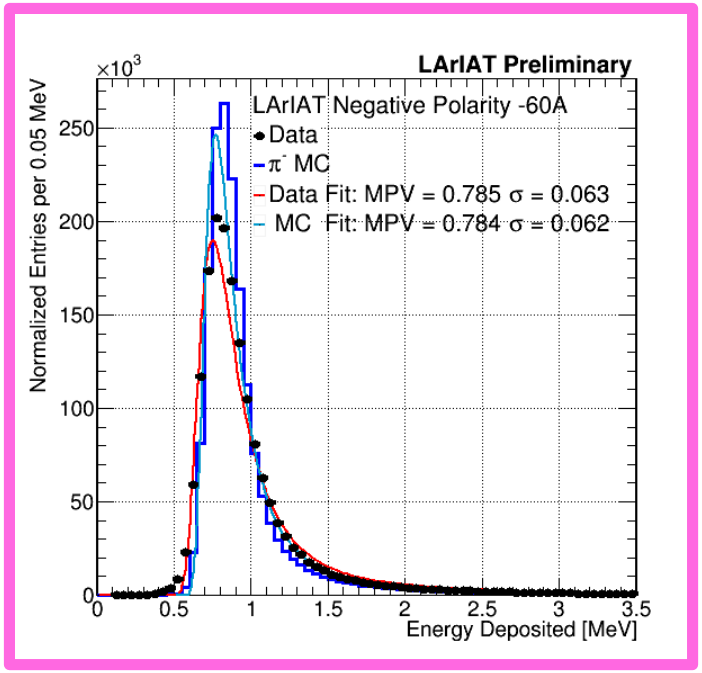
$$E_{\text{dep FF-j}} = \sum_{j<s} E_{\text{dep s}}$$

$$\delta E_{\text{dep FF-j}} = (j-1)\delta E_{\text{dep s}}$$



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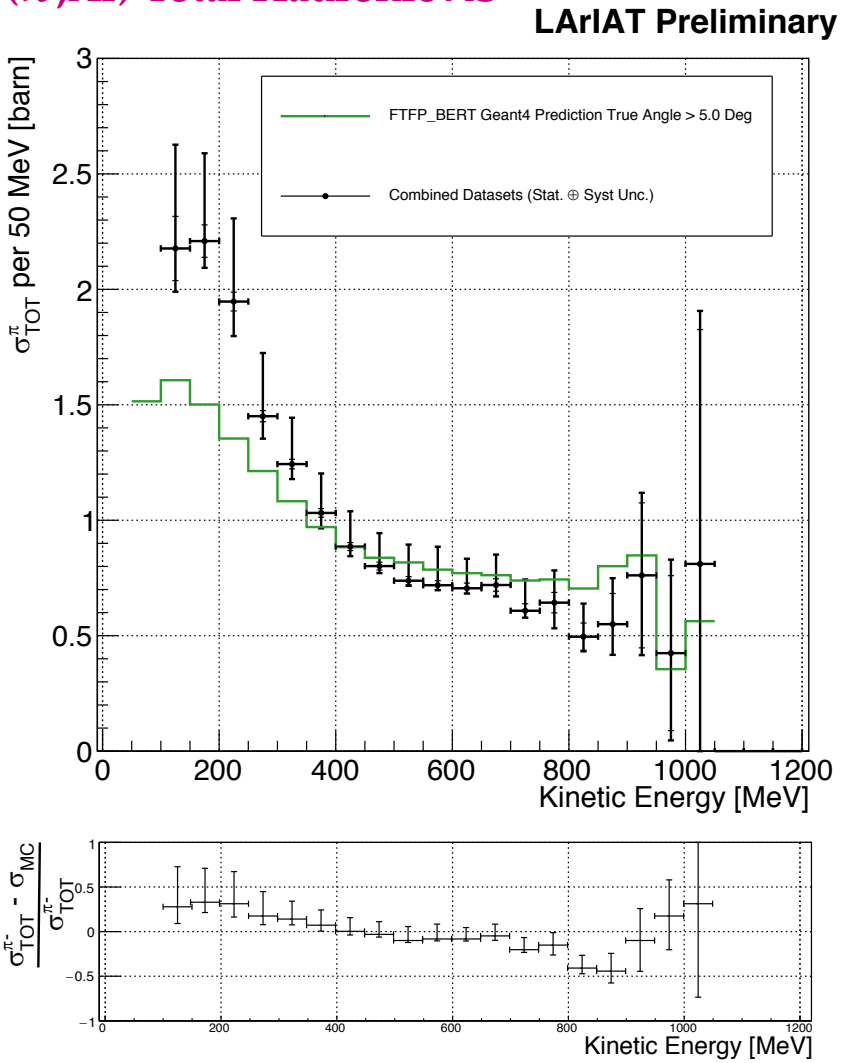
$$\delta E_{\text{slice j}} = \sqrt{\delta p^2_{Beam} + \delta E^2_{Loss} + \delta E^2_{\text{dep FF-j}}}$$

Propagation to the cross section
Calculate Interacting and Incident Plots for 3 cases:

E_i, $E_i + \delta E$, $E_i - \delta E$
take ratio separately: 100% correlation

(π^-,Ar) XS Measurement

(π^-,Ar) Total Hadronic XS



The **π^- total hadronic cross section** has been measured for the **first time on Argon** in the 100-1050 MeV kinetic energy range.

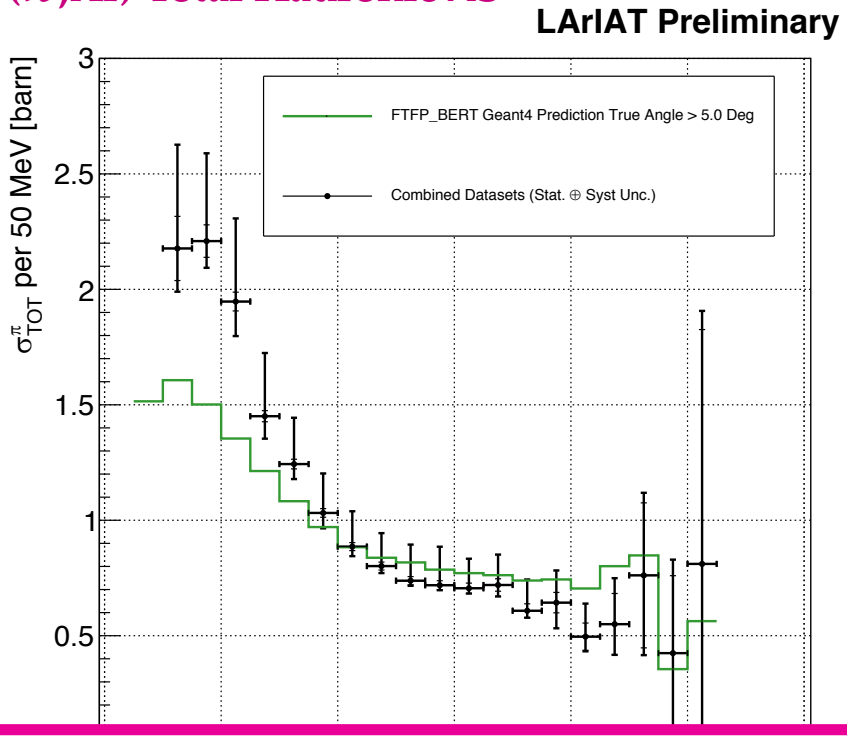
With the exception of the highest KE bins, the uncertainty is mostly dominated by the **systematics**.

Agreement with Geant4 FTFP_BERT predictions outside the Δ peak. Hint to a shape difference, ground for exciting developments.

Current update: data driven E_{loss} measurement, beam recalibration.

(π^-,Ar) XS Measurement

(π^-,Ar) Total Hadronic XS



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Agreement with Geant4 FTFP_BERT predictions outside the Δ peak. Hint to a shape difference, ground

The technique pioneered by LArIAT is also used in protoDUNE for the **(π,Ar), (p,Ar)** and **(K,Ar)** cross section measurements in **inclusive** and **exclusive** channels.

Conclusions

The What? Testbeam experiments for neutrinos are often a small version of your ν detector in a beam of known charged particles.

The Why? Scope of testbeam experiments is abating systematics for ν measurements…

The How? …by characterizing the detector response, by prototyping the feasibility of a project, by benchmarking detector solutions and by performing physics measurements on the neutrino interaction products.

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A tighter integration with ν physics analyses would boost the benefit that the neutrino community can gain from its testbeam experiments.

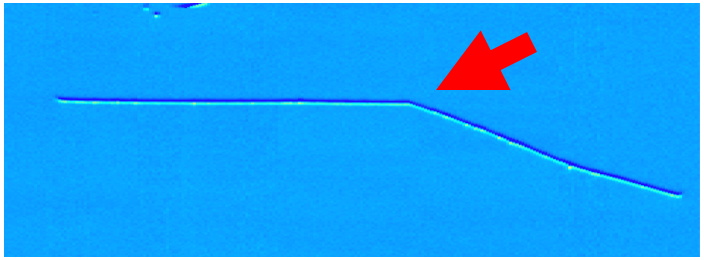
TESTBEAM

Thanks

XS Formula: Reconstruction Effects

$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X} \frac{\epsilon^{\mathrm{Inc}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)} \frac{C^{\pi MC}_{\mathrm{Int}}(E_i)}{C^{\pi MC}_{\mathrm{Inc}}(E_i)} \frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$

Interaction



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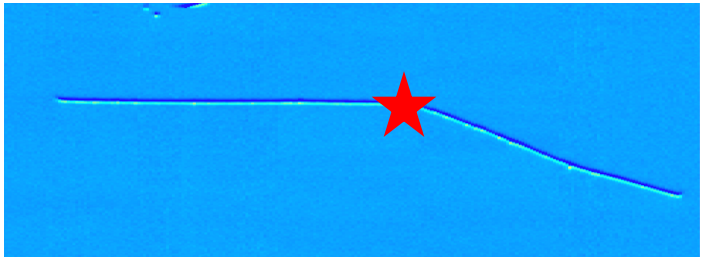
Interaction



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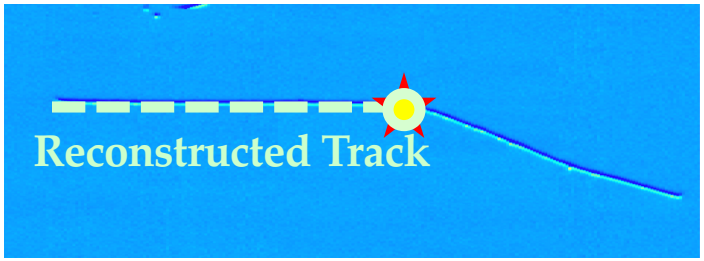
Correct Interaction ID



Missed Interaction

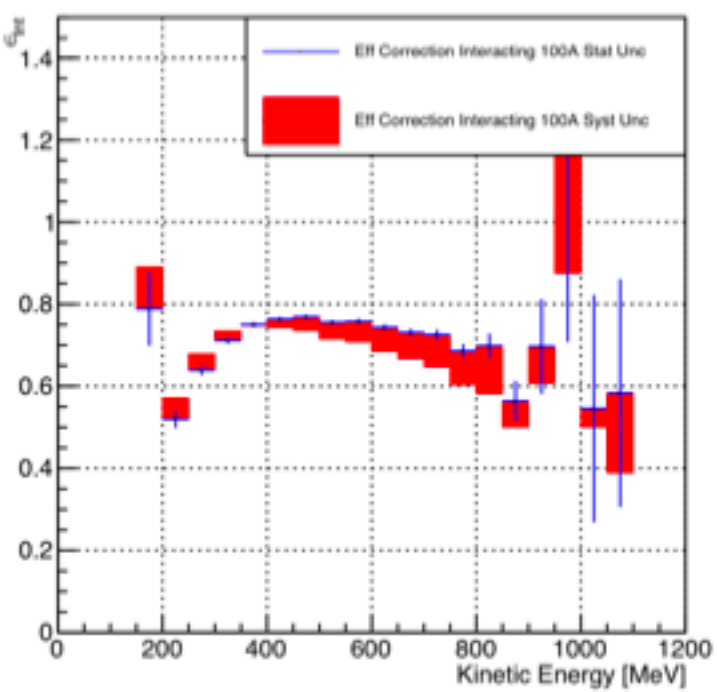
Early Stop

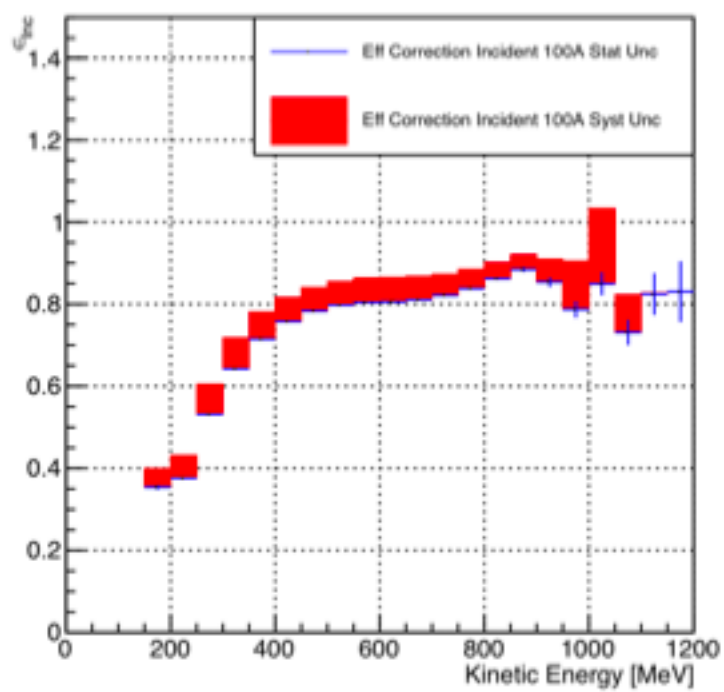
No sensitivity for angles < 5 deg

XS Formula: Reconstruction Effects

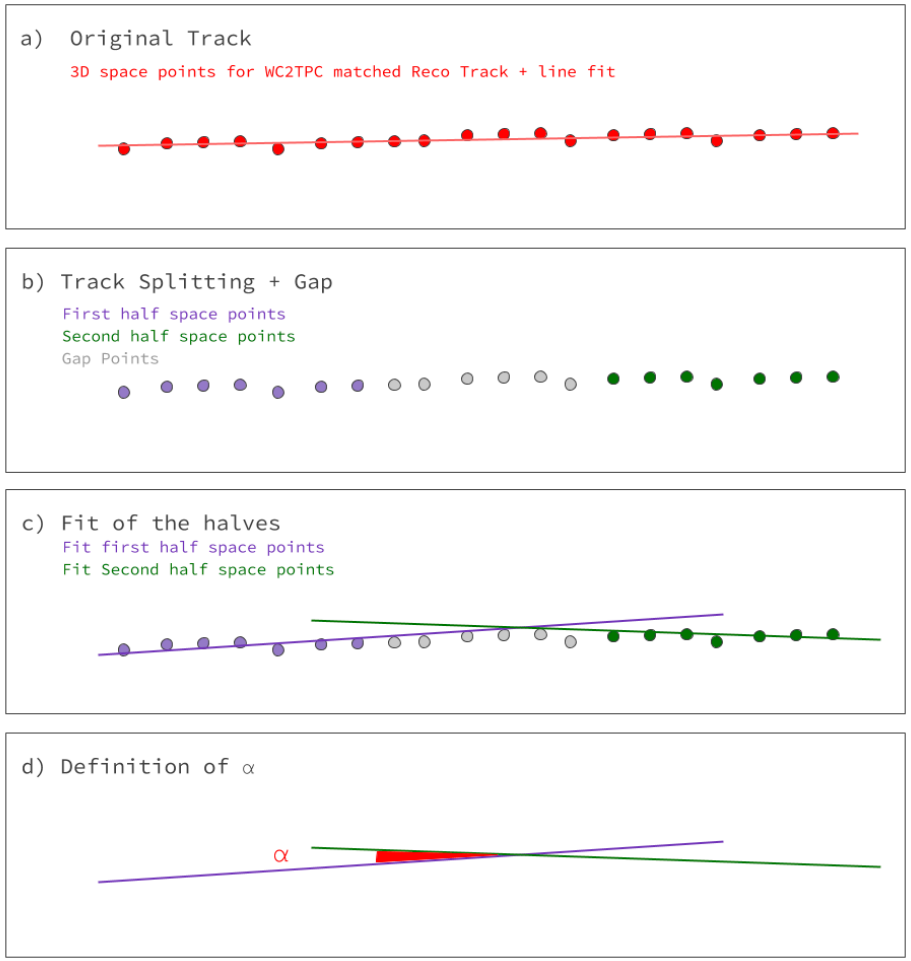
$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X} \frac{\epsilon^{\mathrm{Inc}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)} \frac{C^{\pi MC}_{\mathrm{Int}}(E_i)}{C^{\pi MC}_{\mathrm{Inc}}(E_i)} \frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$

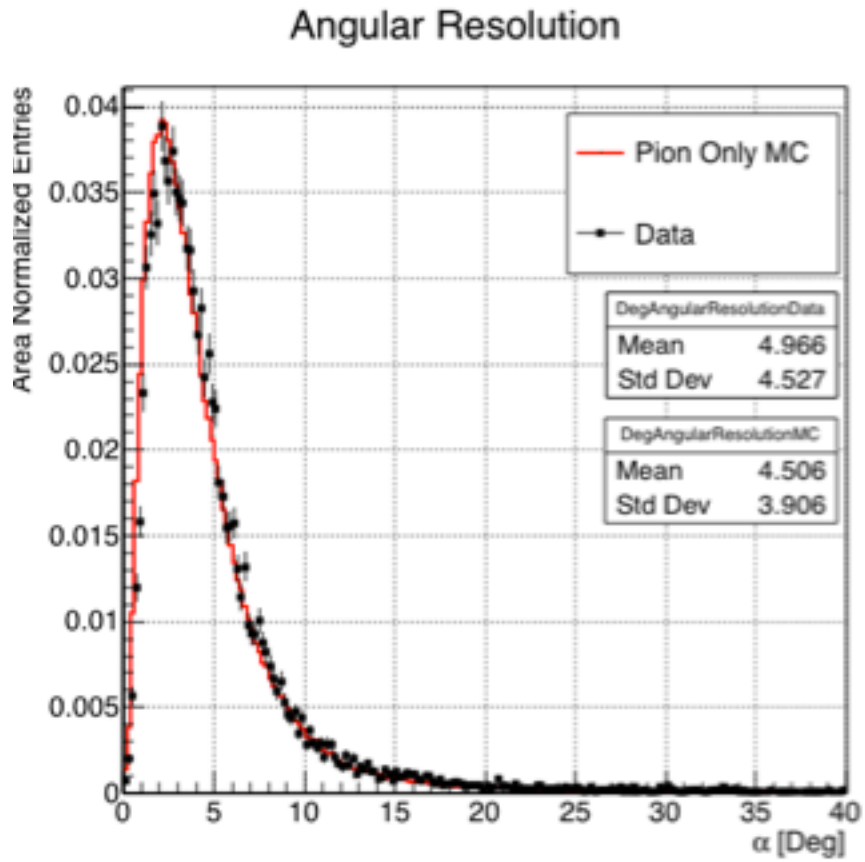
$$\epsilon^{\mathrm{Int}}_i = \frac{N^{\mathrm{Reco\ MC}\ \pi}_{\mathrm{Int,i}}}{N^{\mathrm{True\ MC}\ \pi}_{\mathrm{Int,i}}} \qquad \epsilon^{\mathrm{Inc}}_i = \frac{N^{\mathrm{Reco\ MC}\ \pi}_{\mathrm{Inc,i}}}{N^{\mathrm{True\ MC}\ \pi}_{\mathrm{Inc,i}}}$$





What angles are invisible to us?





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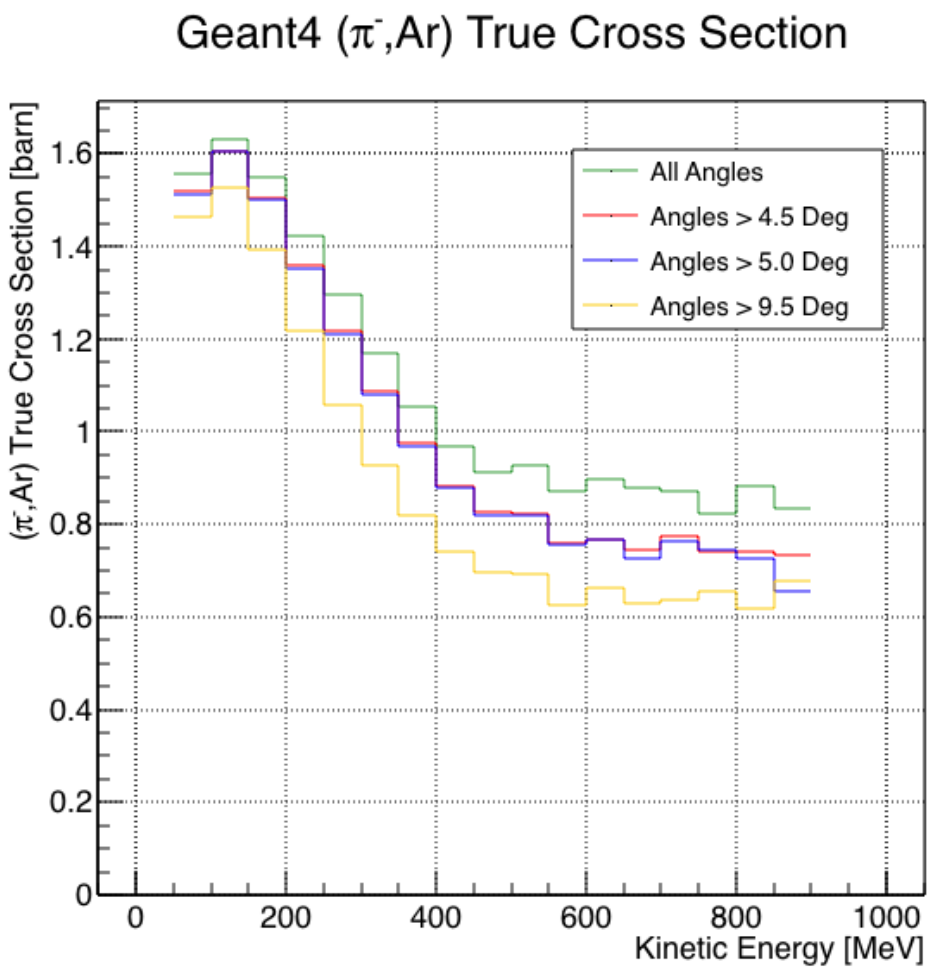

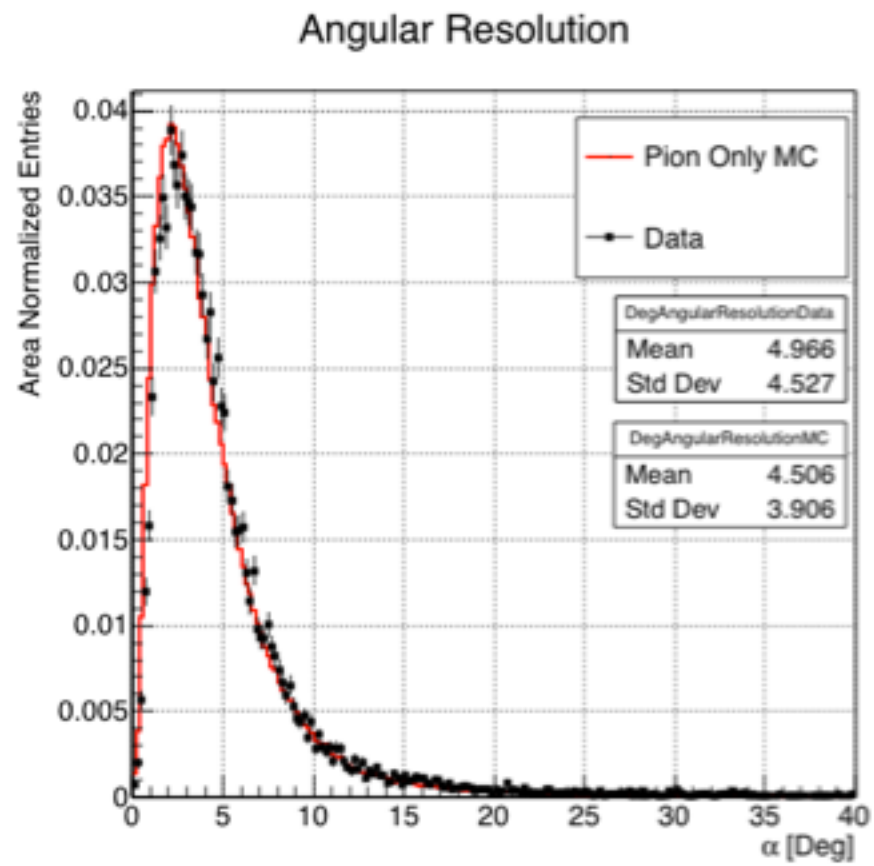

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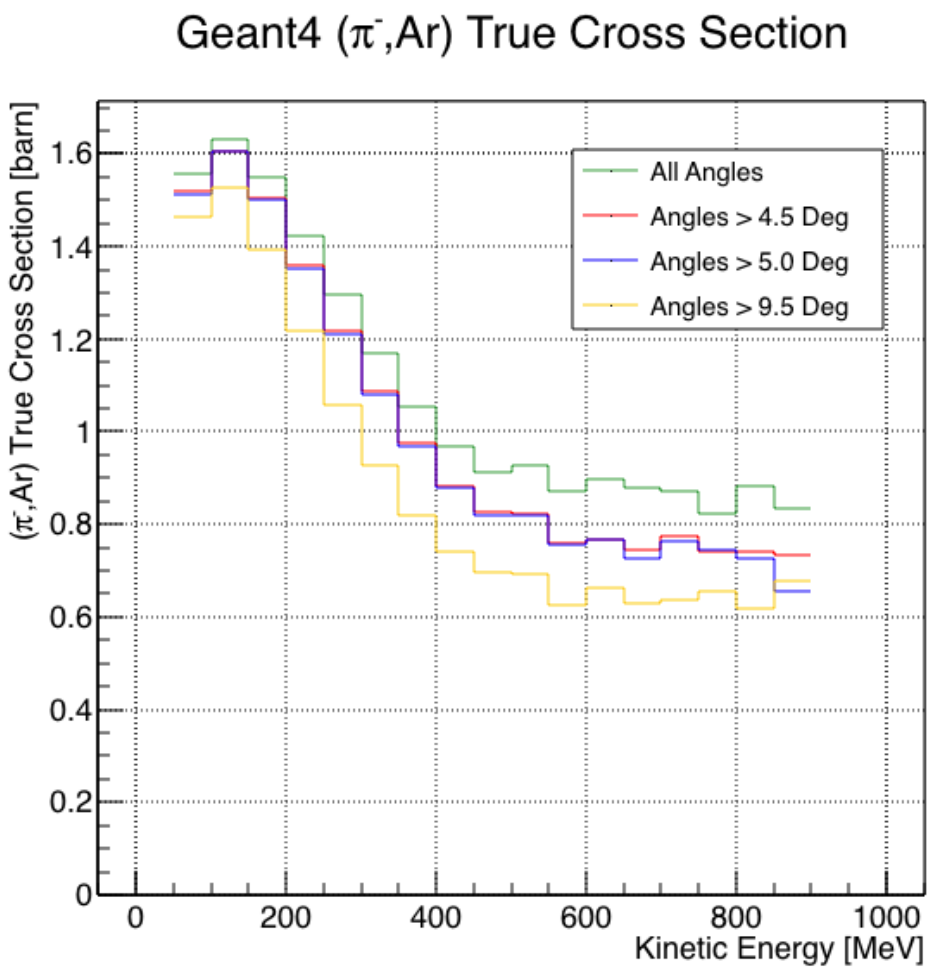
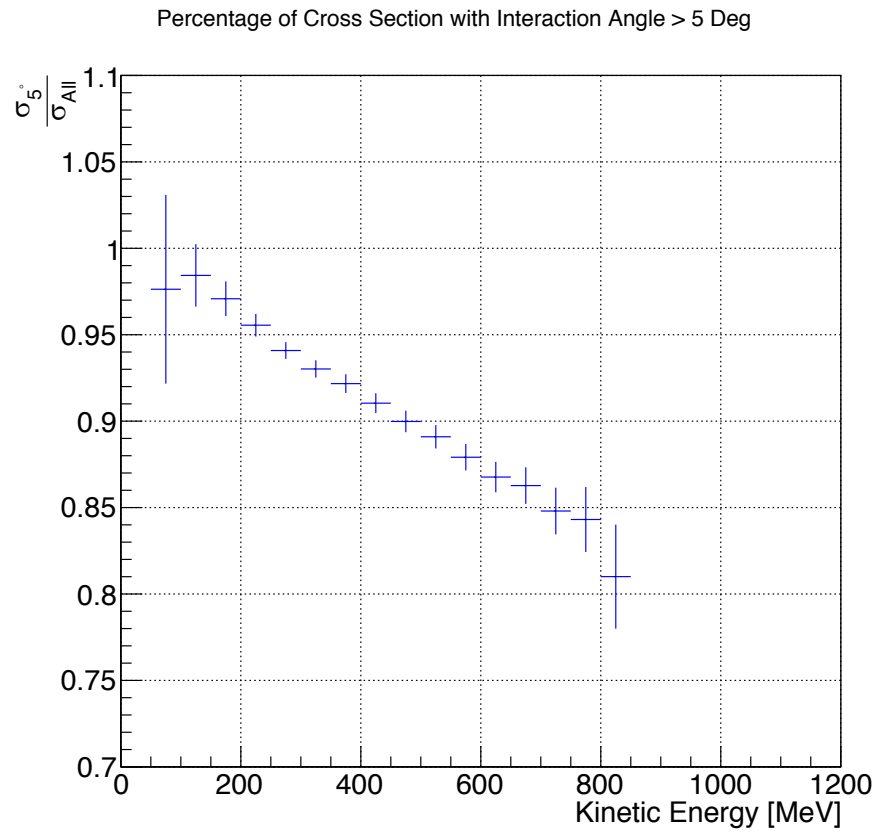
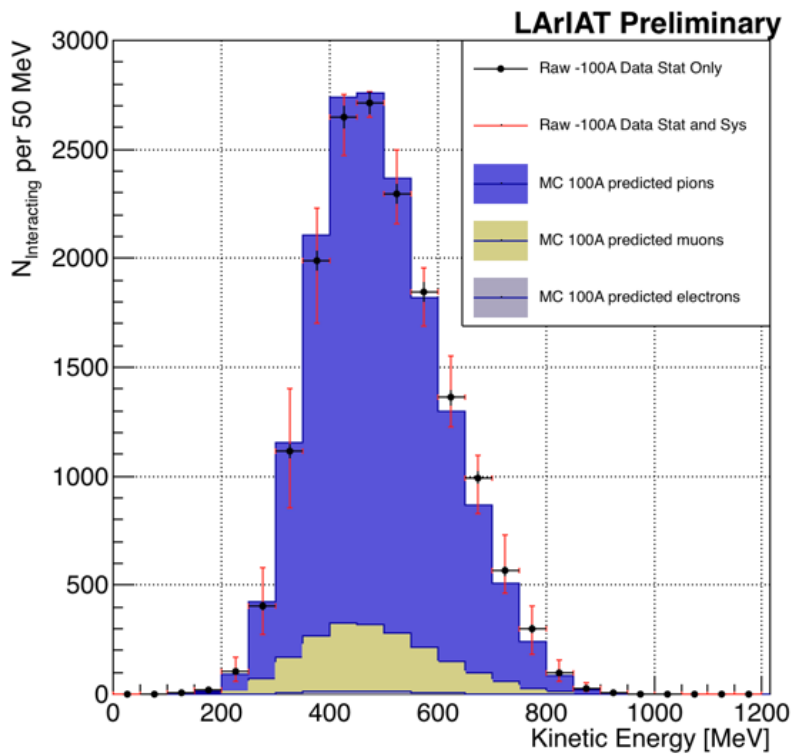
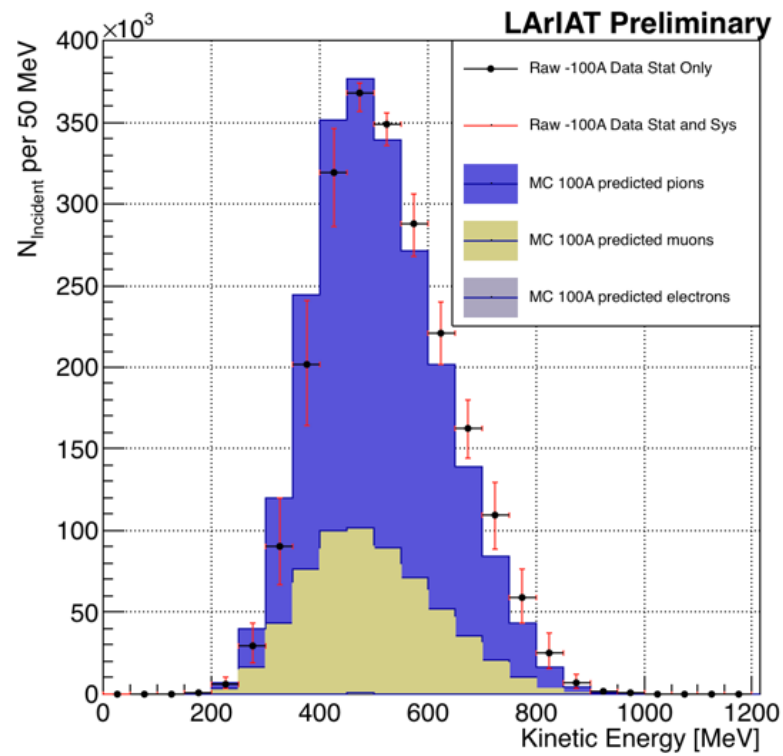




XS Formula: Raw Count

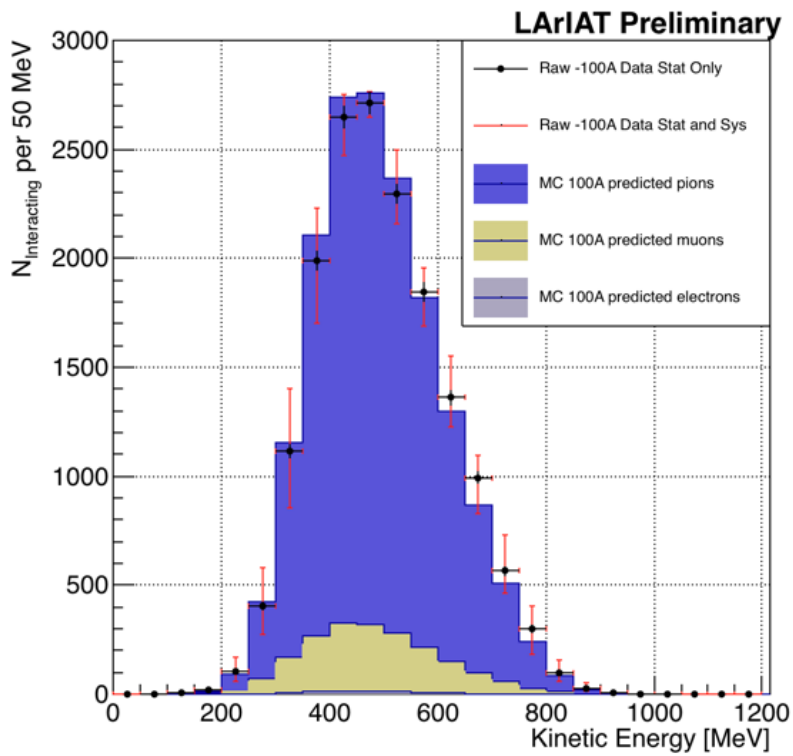
$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X} \frac{\epsilon^{\mathrm{Inc}}(E_i)\ C^{\pi MC}_{\mathrm{Int}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)\ C^{\pi MC}_{\mathrm{Inc}}(E_i)} \frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$





XS Formula: Background Subtraction

$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X}\frac{\epsilon^{\mathrm{Inc}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)}\frac{C^{\pi MC}_{\mathrm{Int}}(E_i)}{C^{\pi MC}_{\mathrm{Inc}}(E_i)}\frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$



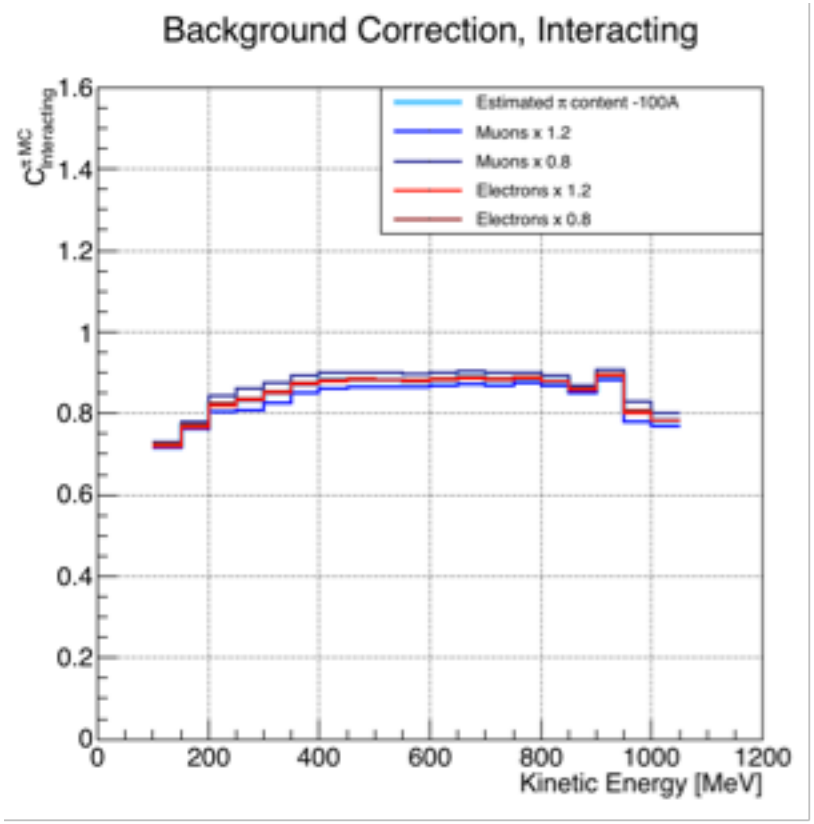
A.k.a. Pion Content

$$C^{\pi\ \mathrm{MC}}_{\mathrm{Int}}(E_i) = \frac{N^{\pi\ \mathrm{MC}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT\ MC}}_{\mathrm{Int}}(E_i)} = \frac{N^{\mathrm{TOT\ MC}}_{\mathrm{Int}}(E_i) - B^{\mathrm{TOT\ MC}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT\ MC}}_{\mathrm{Int}}(E_i)}$$

$$C^{\pi\ \mathrm{MC}}_{\mathrm{Inc}}(E_i) = \frac{N^{\pi\ \mathrm{MC}}_{\mathrm{Inc}}(E_i)}{N^{\mathrm{TOT\ MC}}_{\mathrm{Inc}}(E_i)} = \frac{N^{\mathrm{TOT\ MC}}_{\mathrm{Inc}}(E_i) - B^{\mathrm{TOT\ MC}}_{\mathrm{Inc}}(E_i)}{N^{\mathrm{TOT\ MC}}_{\mathrm{Inc}}(E_i)}$$

XS Formula: Background Subtraction

$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X}\frac{\epsilon^{\mathrm{Inc}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)}\frac{C^{\pi MC}_{\mathrm{Int}}(E_i)}{C^{\pi MC}_{\mathrm{Inc}}(E_i)}\frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$



Beam composition

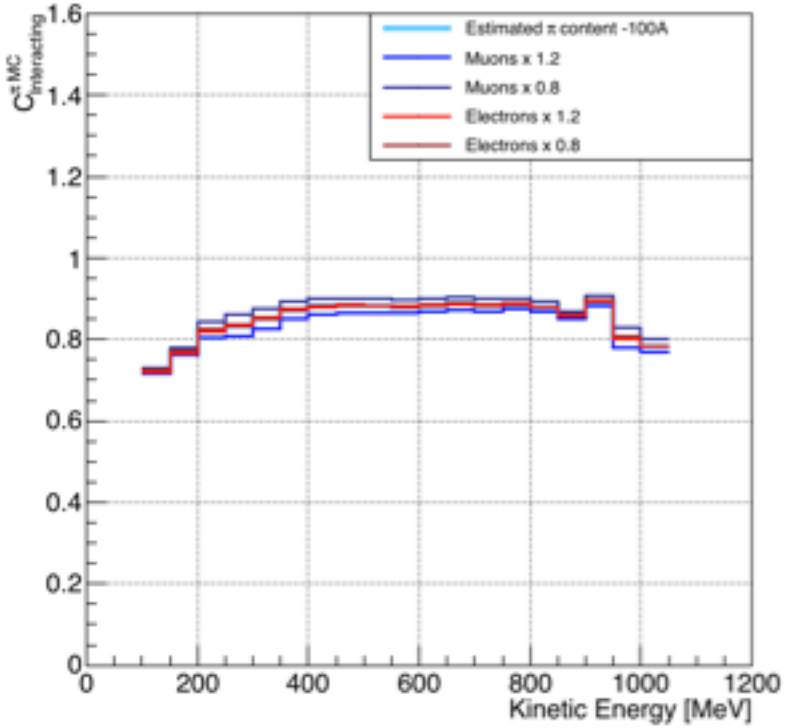
	Low E Beam	High E Beam
G4Pions	70.9 %	82.3 %
G4Muons	14.6 %	13.5 %
G4Electrons	14.5 %	4.2 %

+/-20% variation in electron
+/-20% variation in muon

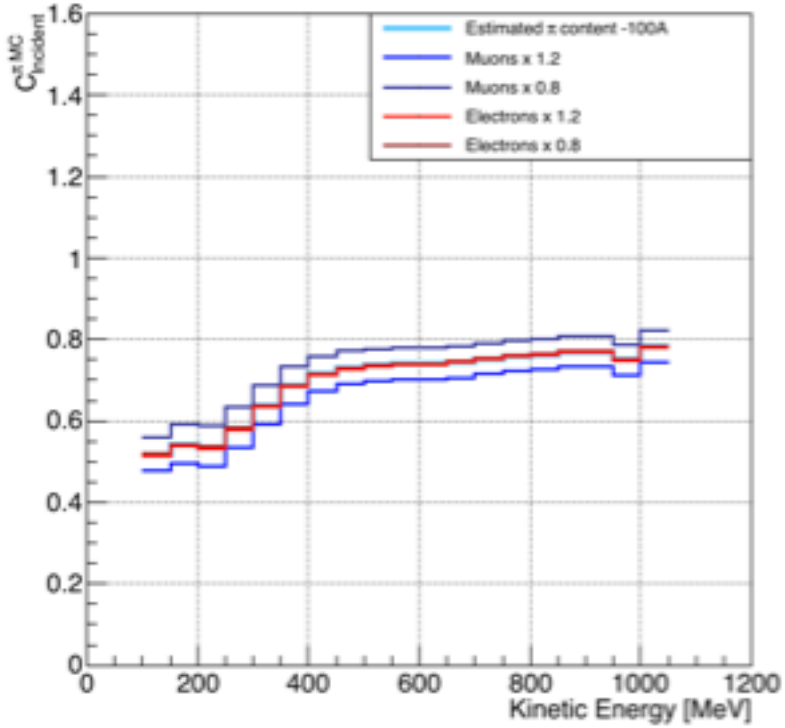
XS Formula: Background Subtraction

$$\sigma^{\pi^-}_{TOT}(E_i) = \frac{1}{n\ \delta X}\frac{\epsilon^{\mathrm{Inc}}(E_i)}{\epsilon^{\mathrm{Int}}(E_i)}\frac{C^{\pi MC}_{\mathrm{Int}}(E_i)}{C^{\pi MC}_{\mathrm{Inc}}(E_i)}\frac{N^{\mathrm{TOT}}_{\mathrm{Int}}(E_i)}{N^{\mathrm{TOT}}_{\mathrm{Inc}}(E_i)}$$

Background Correction, Interacting

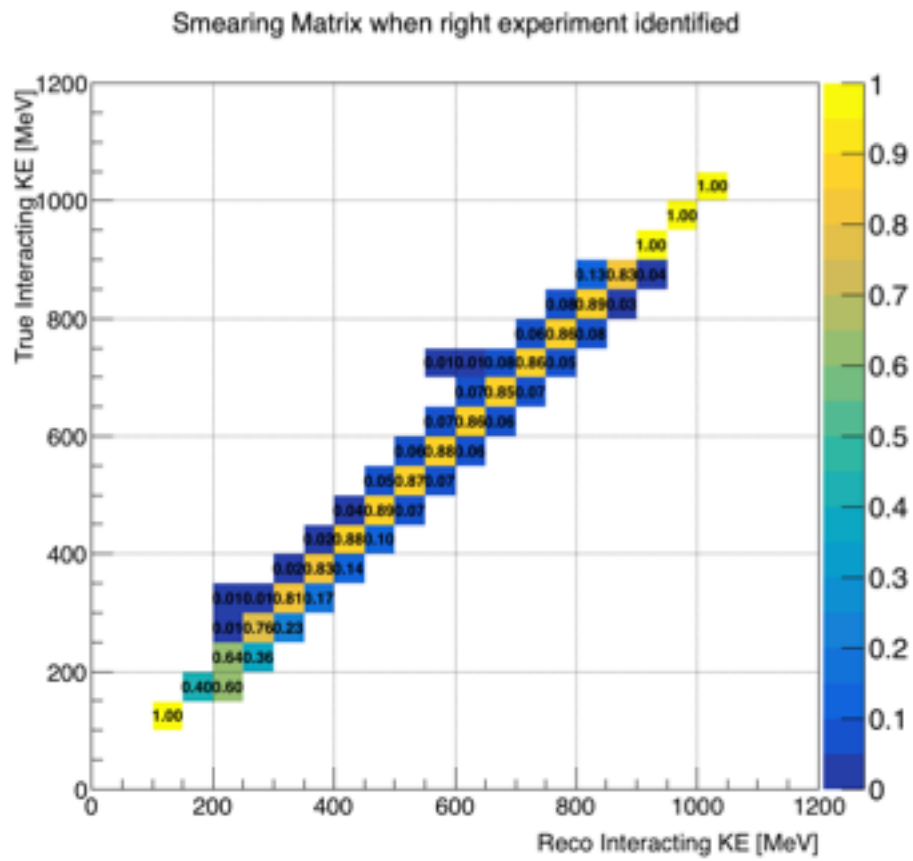


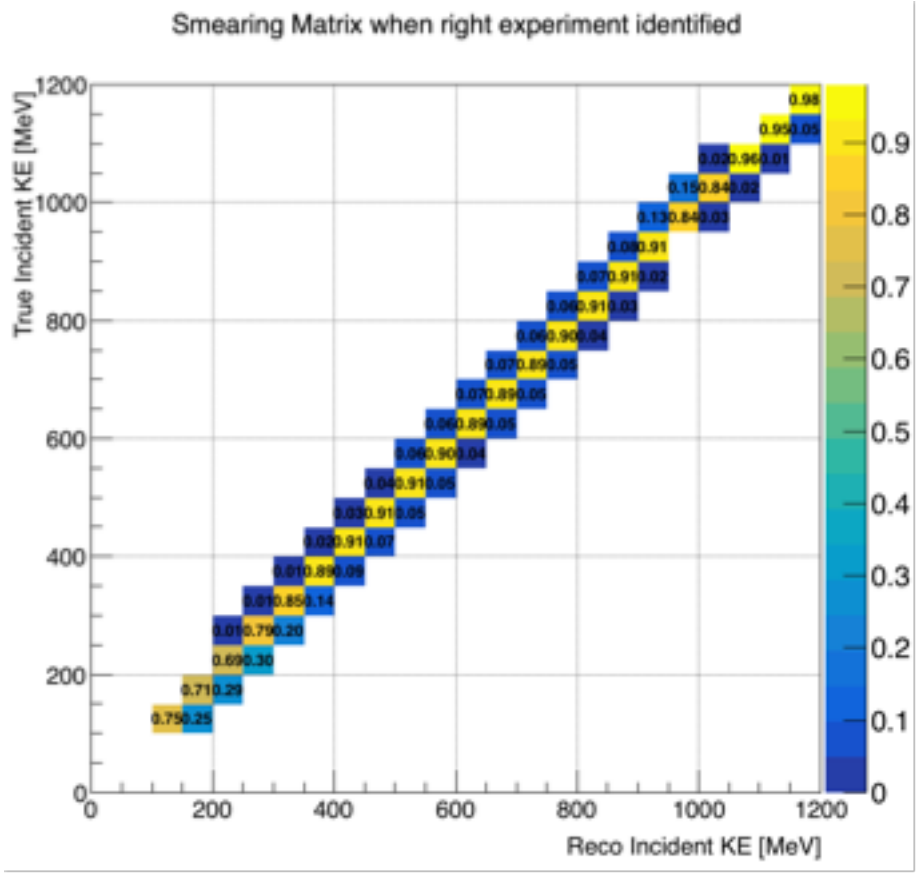
Background Correction, Incident



Pion smearing matrices

High Energy Beam Negative Pion





Kaon Plots
Repeat
Check Transitions