U.S. DEPARTMENT OF ENERGY | Office of Science

Measurement of pion cross-section in ProtoDUNE SP detector at CERN

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NuFact2021

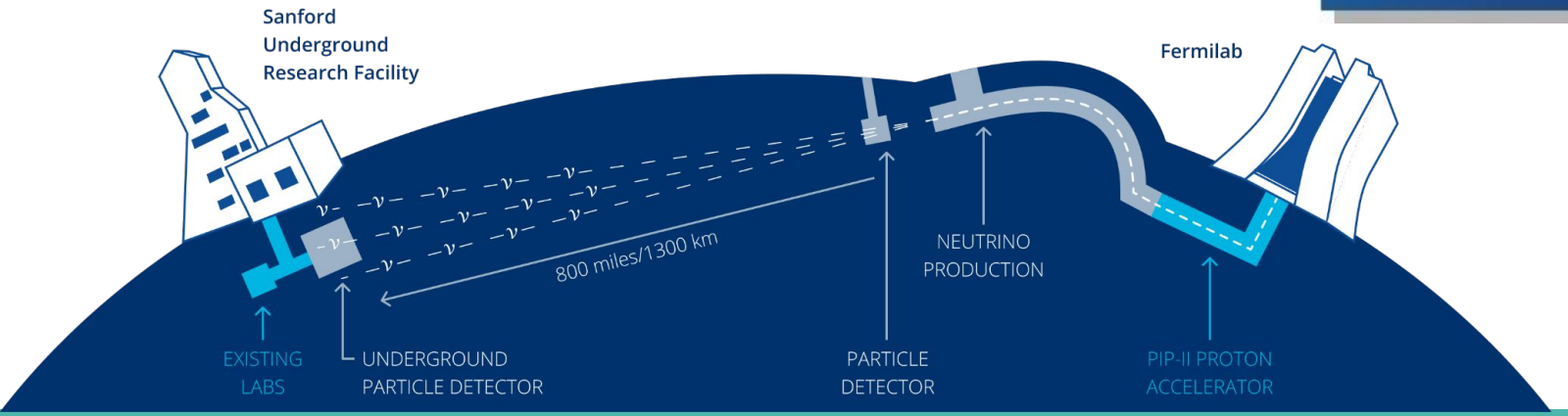
VIRGINIA TECH™

Outline

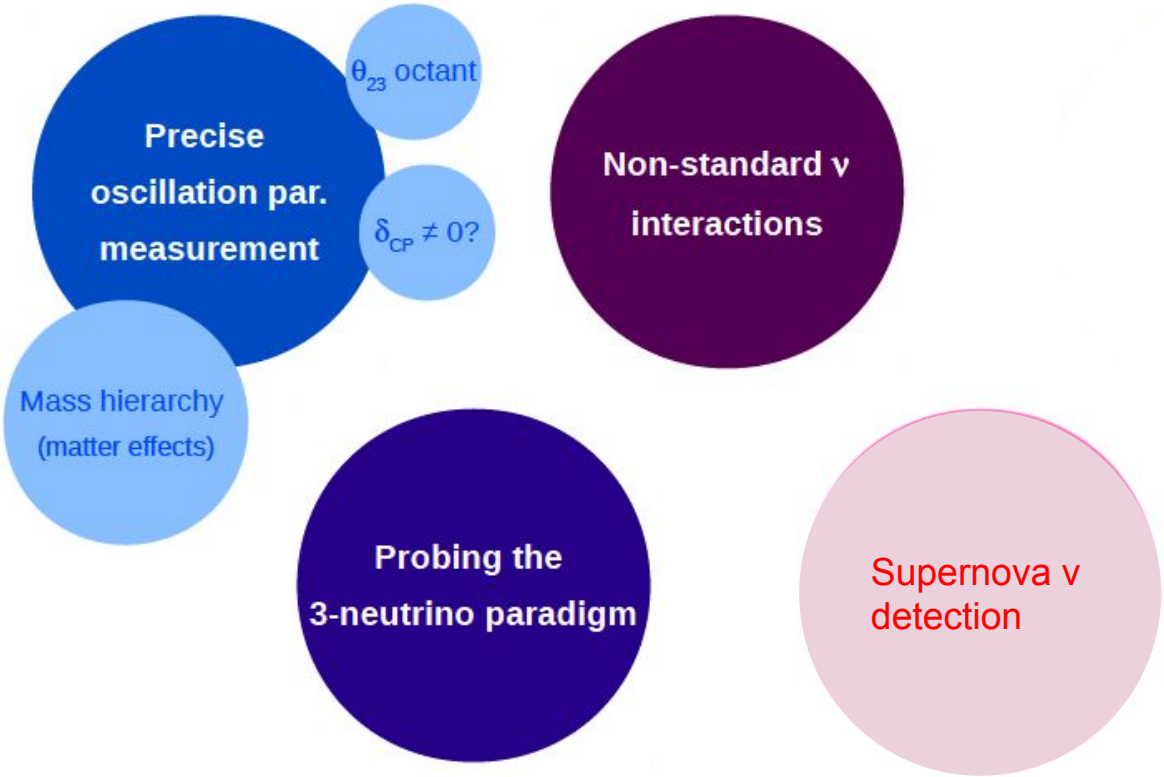
- Deep Underground Neutrino Experiment (DUNE)
- ProtoDUNE
- ProtoDUNE cross section measurements:
  - Motivations & Strategies
  - Particle Identification
  - Slicing method for cross section measurement
  - Analysis status and future
- Summary

Deep Underground Neutrino Experiment - DUNE

- DUNE is a future long-baseline **neutrino oscillation** experiment
- 1300 km baseline, new broadband (0.5-7 GeV) megawatt scale beam ν_μ/anti-ν_μ from Fermilab to SURF
  - High power proton beam : 1.2 MW (2026) up to 2.4 MW (2032)
  - Deep underground (4850 m.w.e) far detector modules
- Large international collaboration: 1100+ physicists, 178+ institutions, 32+ countries

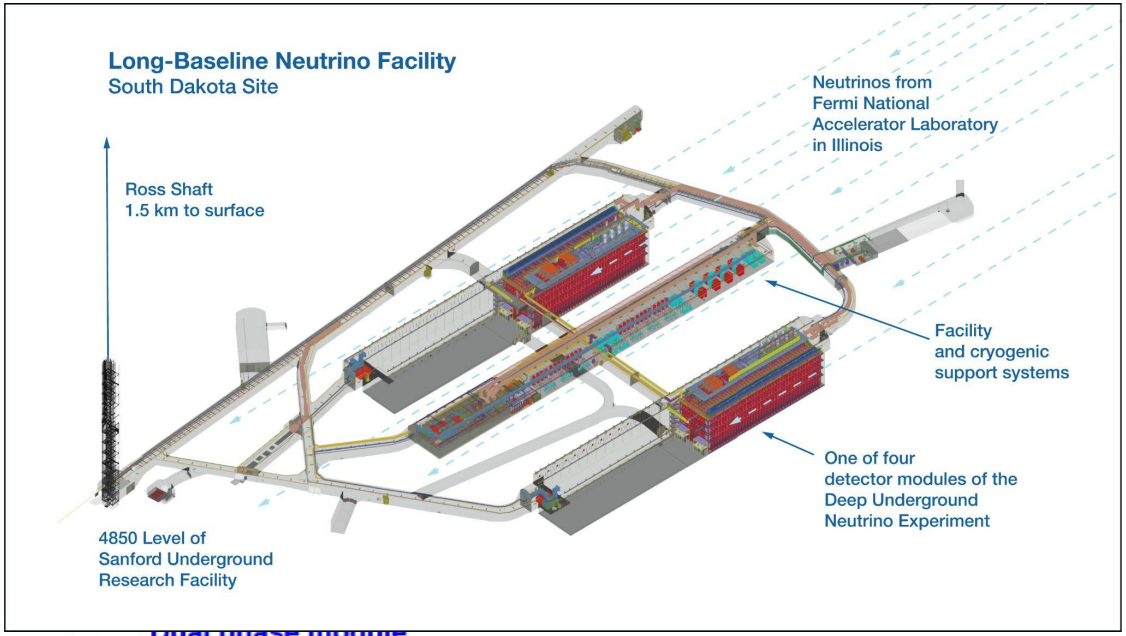


DUNE Goals - Flagship of Neutrino Physics in the US

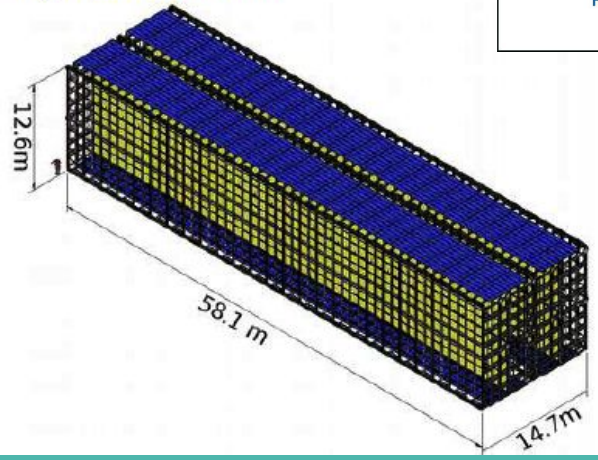


DUNE - Far Detector

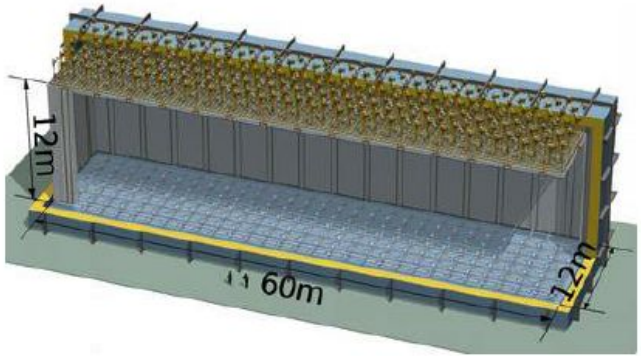
- Deep Underground - 1.5 km
  - Excavation started in 2017
  - Progressing well
- 4 x 17 kton modules
  - Horizontal and vertical drift LArTPC



Single phase module



Dual phase module



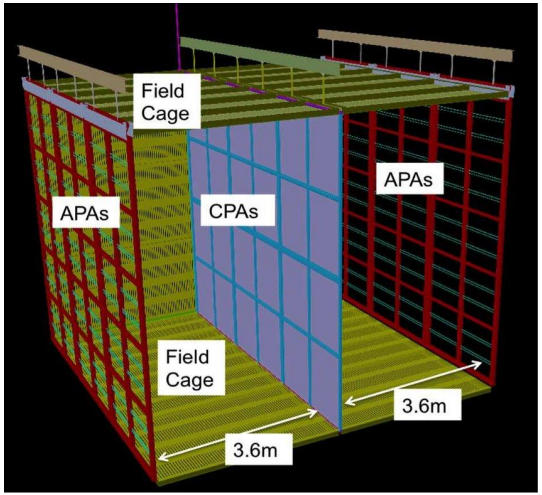
DUNE is a challenge

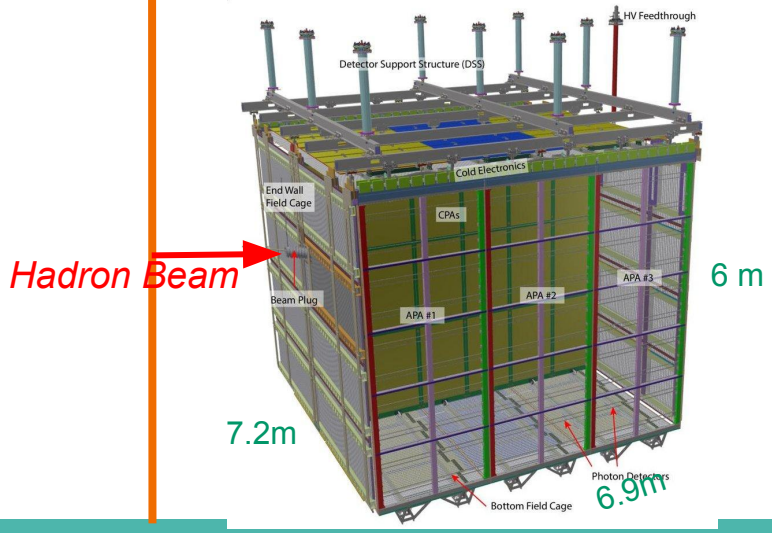
- Working in a cryogenic environment is not trivial! When things cool down, they shrink……
  - Must carefully design every element to avoid stress/breaking components
  - Must carefully select materials, similar shrinking rates if possible
- Liquid argon must be as pure as possible
  - Need a good cryogenic system with recirculation and filters
  - Need to prevent adding contaminants to the LAr
- DUNE is a large underground detector
  - Traditional dewars/cryostats cannot be scaled up
  - How to build such a detector with limited space and access?
- Need to have a good understanding of detector response and calibration

Need R&D and prototypes !!!

protoDUNE - Single Phase

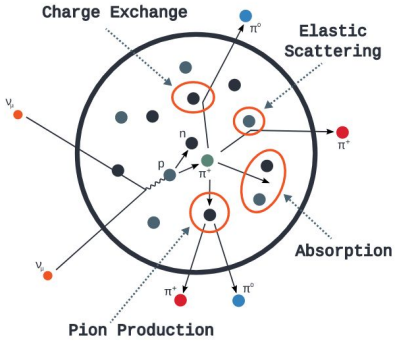
- **Prototype of DUNE far detector**
- Membrane cryostat + cryogenic system
- The TPC component are 1:1 scale with respect to DUNE's Single Phase Far Detector
  - 2 drift volumes divided by cathode (made of 3 CPAs)
  - Wire planes divided into 2x3 APAs
  - Integrated FE cold-electronics
  - Photon detectors for triggering and calorimetry
- 60 photon detector modules
  - 10 per APA





protoDUNE Scientific Goals

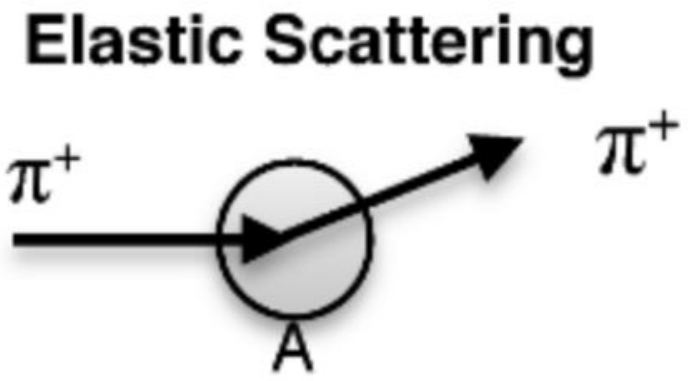
- Prototype the production and installation procedures for DUNE's SP far detector
- Validate the design in terms of basic detector performance
- Accumulate test-beam data to understand calibration of the detector response
  - Improve LArTPC reconstruction -> optimize particle identification, in particular e/γ separation
- Demonstrate the long-term operational stability
- **Physics : Hadron - Argon Scattering**
  - Study the behavior of different hadrons in LArTPC
  - Final state interaction in neutrino nucleus scattering



Credit: T. Golan

Hadronic Scattering - Pion Nucleus Interaction

- Total - calculated from attenuation of initial beam
- **Elastic Scattering**
  - **Nucleus stays intact**
- Inelastic Scattering
  - Nucleus in excited state /broken
  - Charge Exchange
    - Single Charge Exchange ($\pi^+ \rightarrow \pi^0$)
    - Double Charge Exchange ($\pi^+ \rightarrow \pi^-$) - Need to distinguish π^+ and π^- - difficult for LArTPC
  - Absorption
    - No pions in the final state - need to distinguish pions from nucleons
    - Subtraction of other processes



Dominant pion-nucleus interactions in sub-GeV region (Ref: arxiv 1611.05612)

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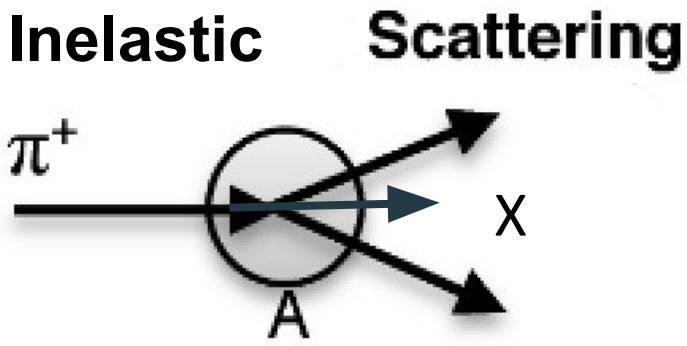

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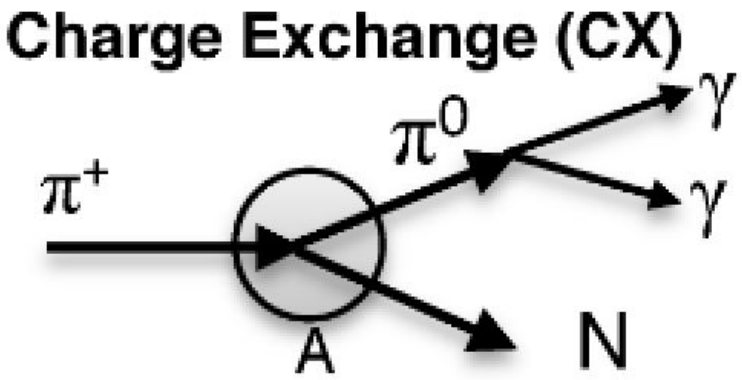

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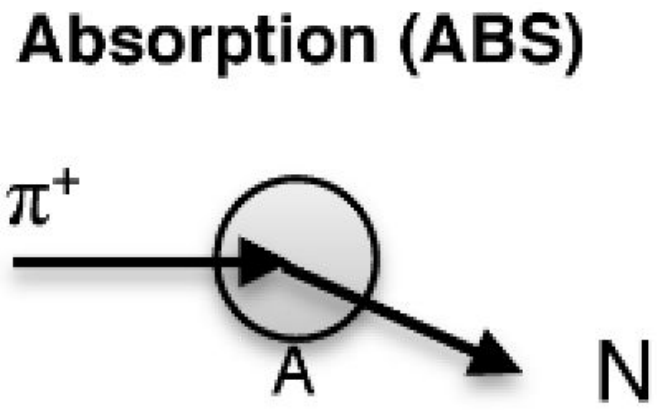

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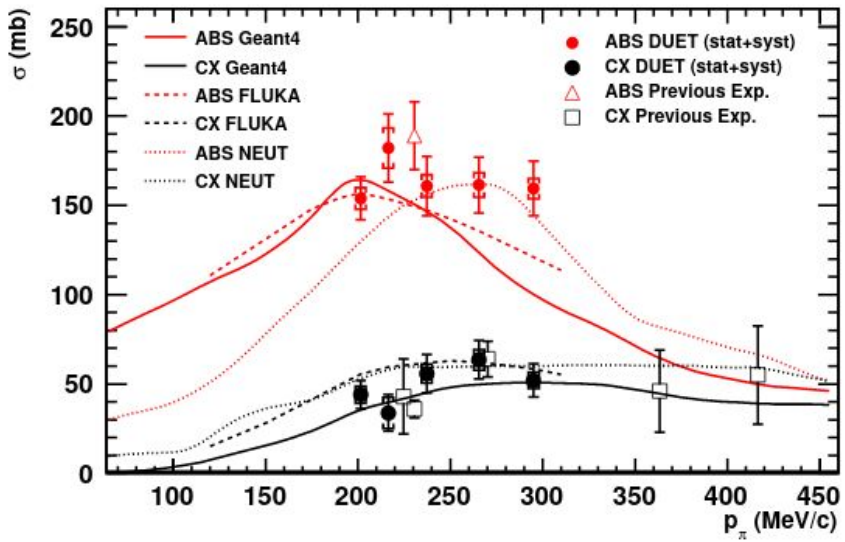
Previous Experimental Results

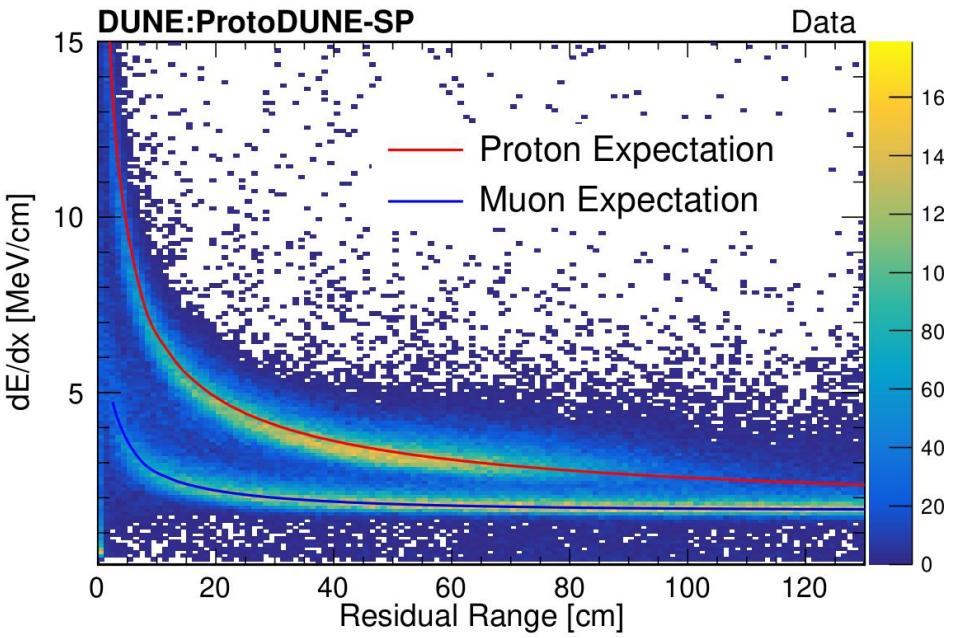


Ref: arXiv: 1611.05612

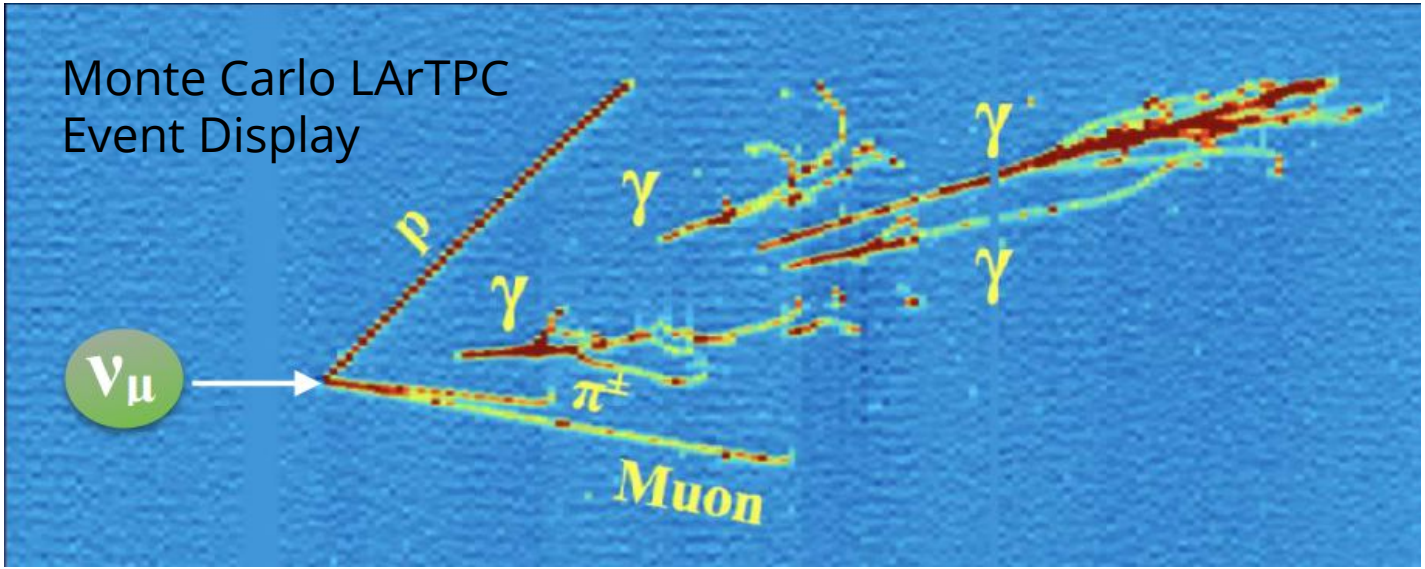
- Charge Exchange and Absorption process cross sections shown on the left with statistical and systematic error bars
- DUET vs previous experimental result
  - 265 MeV pi+ on oxygen Asheryat.al (*Phys. Rev. C, 30(3):946 (1984)*)
- NEUT v5.3.5 cascade model
- GEANT4 v9.04.04: Bertini cascade model
- FLUKA: cascade model
- **No more pion absorption experimental data above 400 MeV**
  - **ProtoDUNE can do it !!!**

Particle Identification

- dE/dx is predicted by Bethe-Bloch formula
- Residual Range: distance from a reconstructed deposit (hit) to the stop point of a reconstructed track
- Particle identification is based on energy deposition per unit of length (dE/dx)



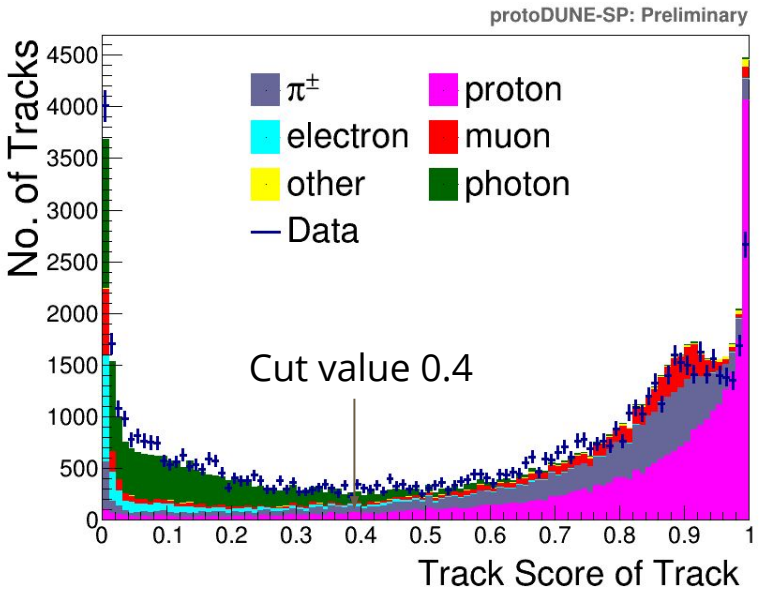
Event Display in LArTPC

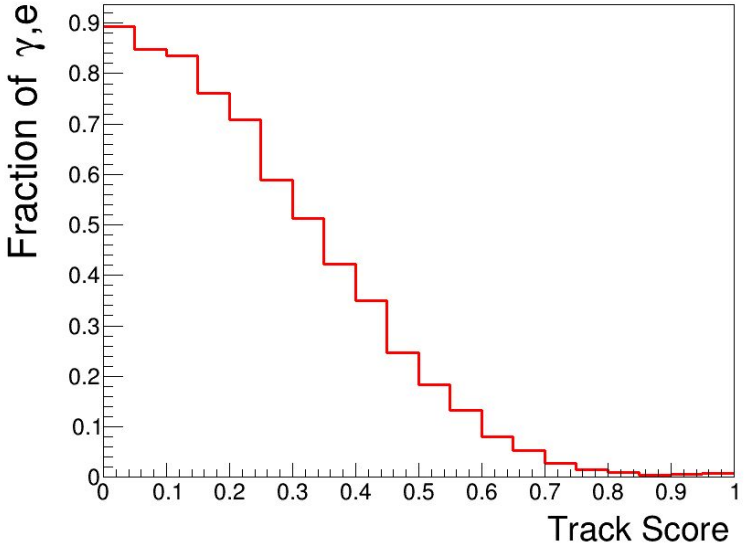


- Tracks: Proton, muon, pion and so on
- Showers: EM activities including electron, photon and photon from π^0

Shower Identification

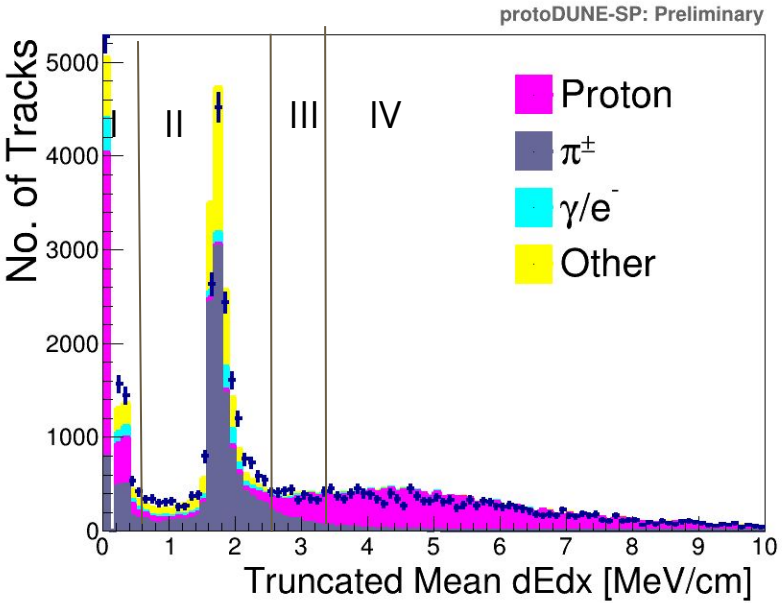
- A cut value = 0.4 is performed in order to identify EM activities - showers

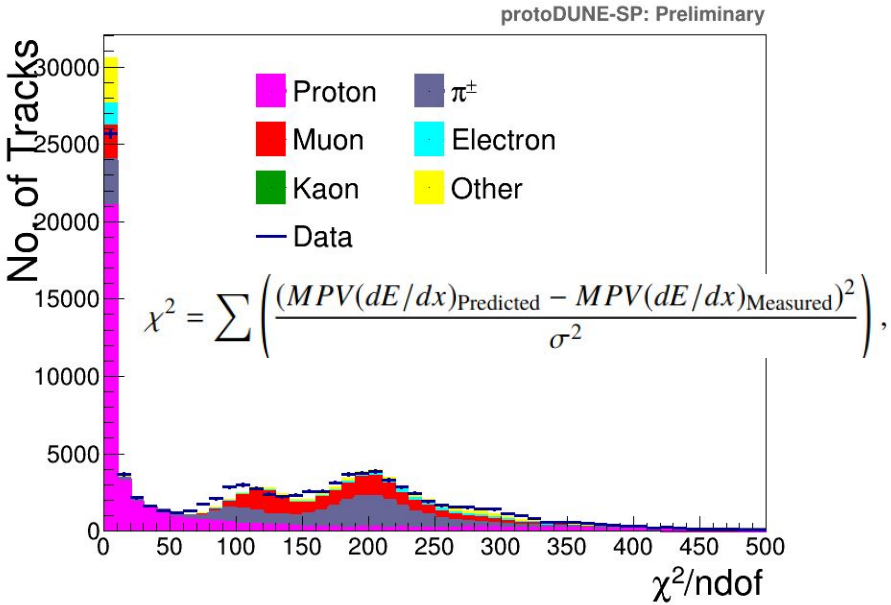




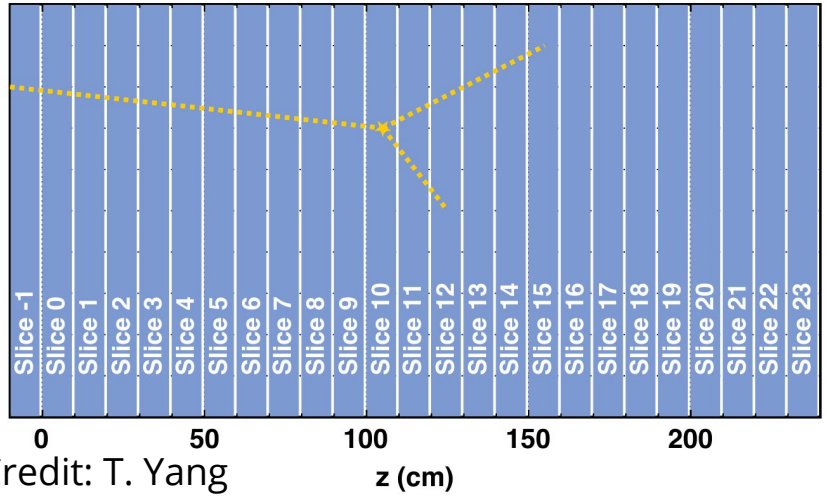
Particle Identification

- Combination of Truncated Mean dE/dx and χ^2/ndof is used for particle (proton identification)
  - Truncated Mean dE/dx was divided into 3 regions
    - I and III transition region, II: Pion region(0.6, 2.6); IV: Proton region(>3.4)
  - χ^2/ndof is only required for the transition region (>70 for proton)



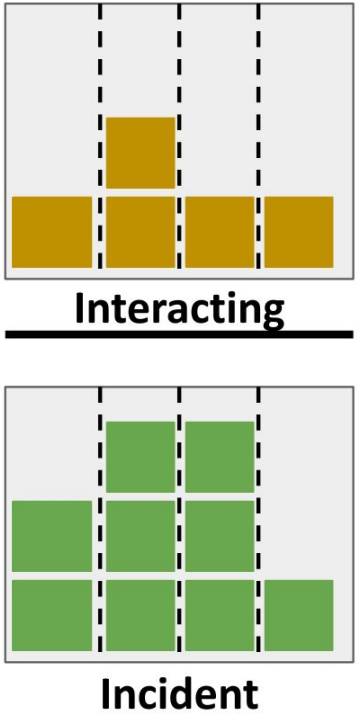


The Slicing Method



Credit: T. Yang

$\sigma \sim$

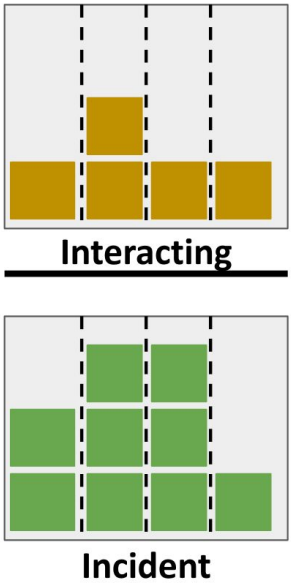


Credit: Jake Calcutt

- First TPC was divided into thin slices (each slice width = 10cm)
- Slice ID is defined based on endz position(truth or reco after SCE correction)
  - Each event has a reco slice ID and true slice ID
- Slice ID=-1 is kept in calculation due to the upstream event

The Slicing Method

$\sigma \sim$



Pion Absorptions

Incidents of all pion

Credit: Jake Calcutt

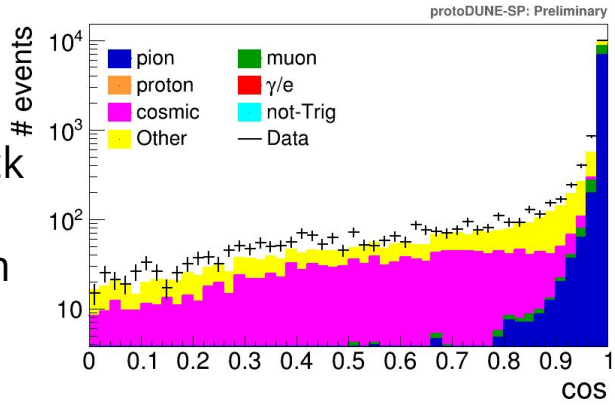
$$\sigma = \frac{M_{Ar}}{\rho t N_A} log\left(\frac{N_{inc}}{N_{inc} - N_{int}}\right)$$

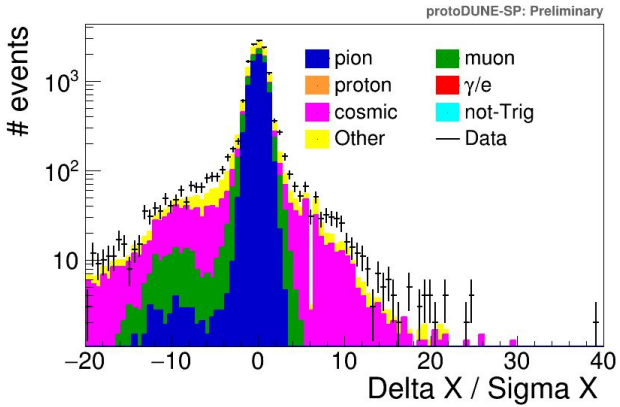
M_{Ar} -- Mass of Ar
t -- Thickness of slice
ρ -- Density of Ar

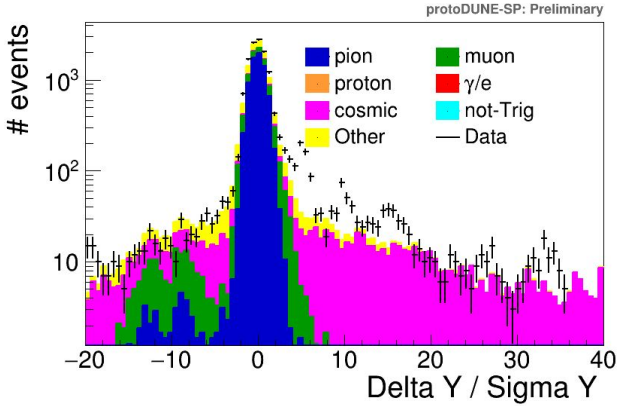
- **M_{Ar} , N_A are constants**
- **Thickness:** 10/0.95983081[cm].
  Angle correction.
- **Number of interactions**
  - Pion Absorption in each slice
- **Number of Incidents** (pions)
  - Calculated from the number of *all the pion interactions* in each slice
  - *Convert Pion interactions to incidents*

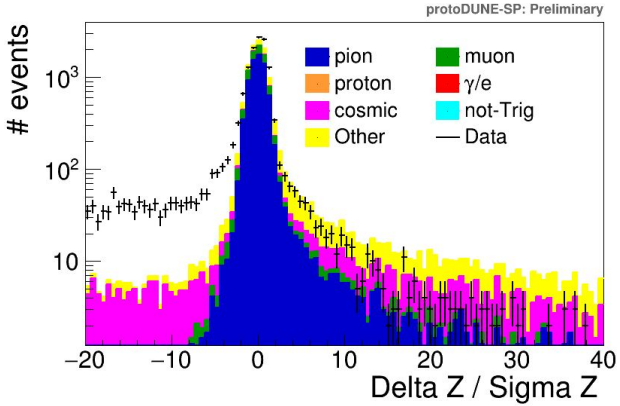
Pre-selection : Beam Quality

- Delta X/Y/Z measure the distance of the reconstructed beam track start from the true track/measured by beam instruments, and the cosine measures the angle between the two
- Distributions are shifted to 0 and normalized by the RMS
- Cuts are +/- 3σ for the X/Y/Z and cos>0.95

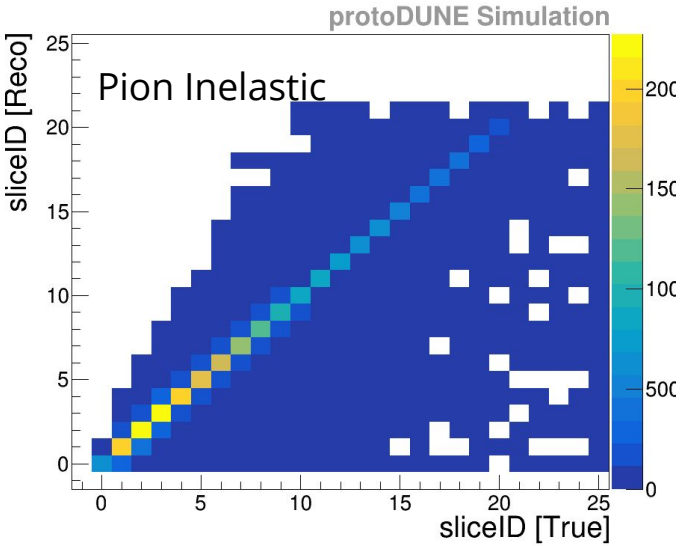


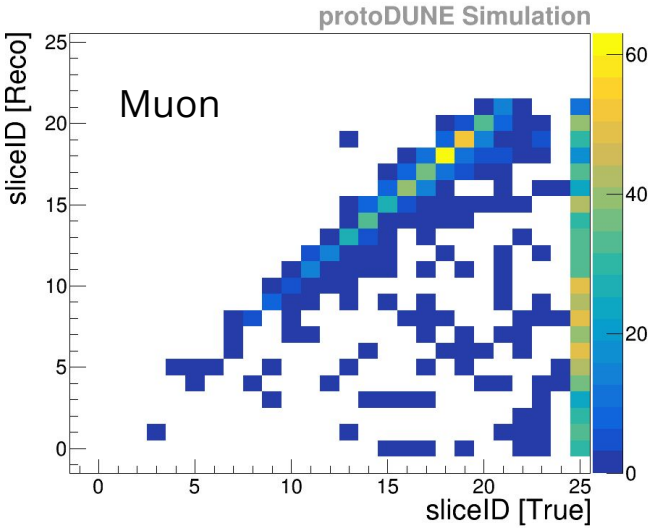






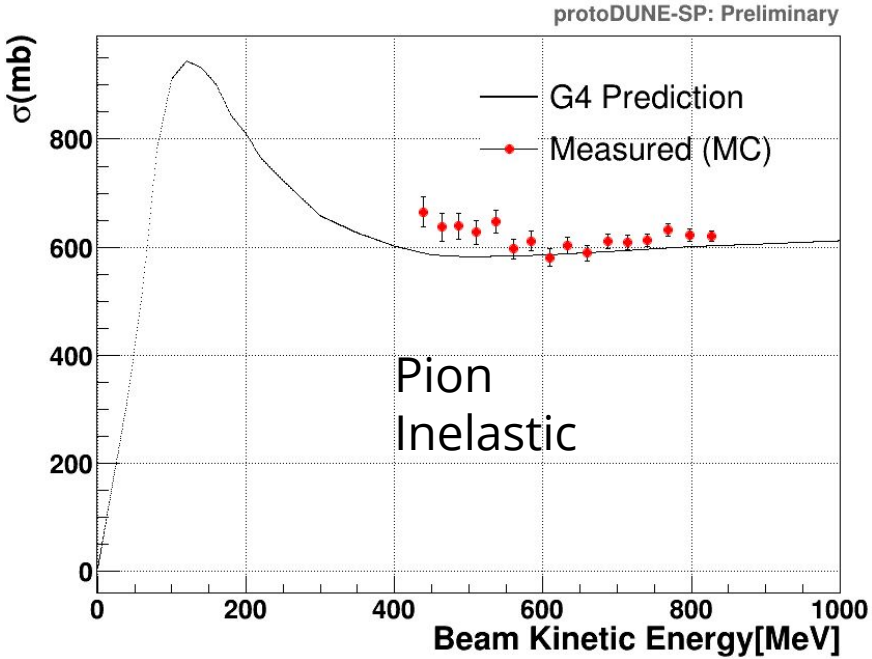
Migration Matrix

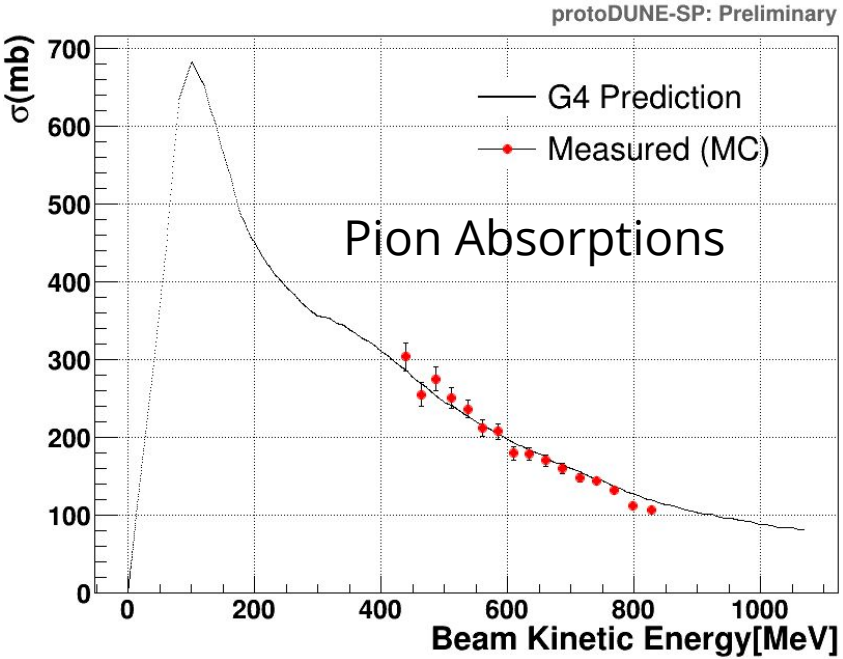




- Selected mostly pion inelastic interactions with a small fraction of muon events
- For both muon and pion beam track reconstruction is pretty good

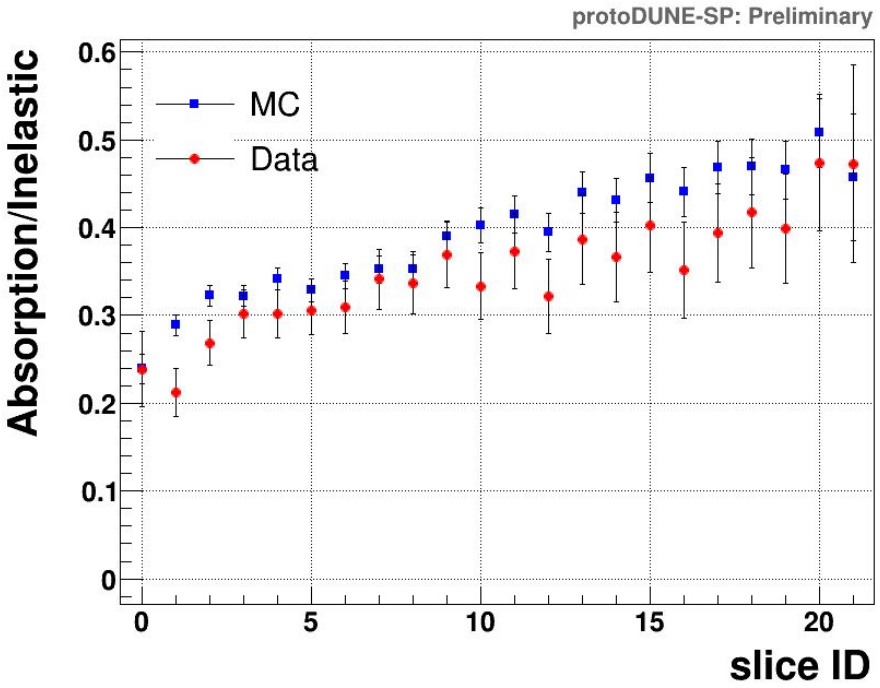
Cross Sections





Absorption/Inelastic

- Same strategy of pion absorption selection performed to protoDUNE data and MC
- Compared to protoDUNE data, pion absorptions are slightly overestimated

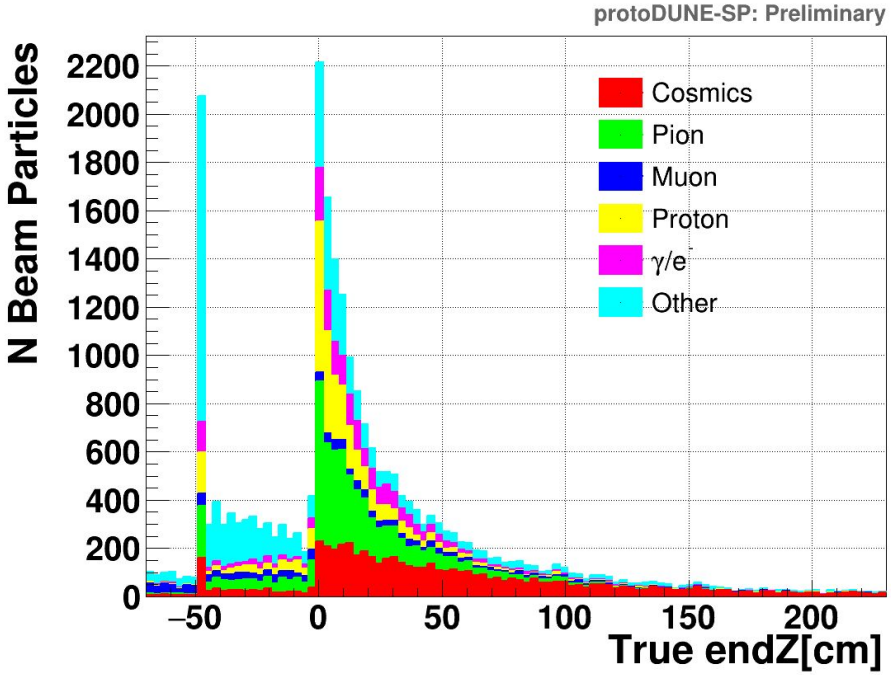


Summary

- A large amount of Hadron-Argon scattering data from protoDUNE has been collected and ready for analysis
- A sophisticated algorithm for particle identification and event selection for pion absorption has been developed and validated.
- Slicing method and RooUnfold were first used for the cross section measurement of pion absorption; validated with MC sample
- Next
  - Add systematics uncertainties
  - Move to real data to further test the method

Pre-selections

- Pass Pandora Slice Cut
  - Track-like beam particle
- Pass **Beam Quality Cut (Owen)**
  - Removen on-beam (misidentified) background
- Pass APA3 Cut
  - reco_beam_calo_endZ< 226
  - remove muons
- Pass Calo Size Cut
  - Require vector size of calorimetric information on collection plane greater than 0
- Pass **Truncated Mean dEdx Cut**
  - Remove background from mis-identified events



RooUnfold Method

RooUnfold: a framework for testing and using different binned unfolding methods:

- Resource: https://gitlab.cern.ch/RooUnfold/RooUnfold
- Iterative Bayes method was implemented for RooUnfold
  - Based on D'Agostini (1995), with corrected error calculation
  - This method seems to be used by the majority of RooUnfold users
- Other Methods Dynamically Stabilized (IDS) unfolding, Singular Value Decomposition (SVD) method
- Techniques: Matrix inversion, iteration, in-by-bin correction factors, with no inter-bin migration

Cross Section of Pion Absorptions