NPPS Intro Talk

Jake Calcutt
NPPS Group Meeting
Oct. 16, 2024

Introduction

Education

- Michigan State University – B.S. Physics
- Michigan State University – M.S. Physics
- Michigan State University – Ph.D. Physics (2021)
    - Thesis: Measurement of Piplus-Argon Absorption and Charge Exchange Interactions Using ProtoDUNE-SP

Current Position

- Oregon State University – Postdoctoral Scholar (2021 – Present)

Research Interests

Neutrino Physics

- Discovery of CP-violation in neutrino oscillations would be a historic discovery
- Joined T2K in 2015, DUNE in 2016

Low-energy Hadron Physics

- Provide important constraints to detector response (secondary interactions) and nuclear model (final state interactions) in neutrino experiments

Software and Computing for Physics

- Started my undergraduate studies within Computer Science before switching to Physics
- Much of my work has focused on developing algorithms and software to perform physics analysis

Recent Research – Overview

DUNE Computing

ProtoDUNE-HD Offline Coordinator

Geant4Reweight

Pion Cross Section Analysis

DUNE Computing

Started working in DUNE Computing when I started at OSU

Projects:

- Code Management
  - Transitioned DUNE software from redmine to github
  - Refactored software stack
  - Currently working to develop policy/procedures and grow code management team
- Data Management & Production
  - Began converting DUNE Production to use new/state of the art data-handling software (Metacat & Rucio)
  - Assisted in various Data Challenges and Dress Rehearsals
- Wrote NTuple production software for ProtoDUNE analyses
  - Was previously lacking standardized & official analysis ntuples with associated metadata

ProtoDUNE-HD Offline Coordination

Starting in Summer 2022, I was appointed ProtoDUNE-HD (Horizontal Drift) Offline Coordinator

Responsible for overseeing preparation of offline data processing, simulation, and reconstruction for the new iteration of DUNE's HD Far Detector prototype

Geant4Reweight

Developed Geant4Reweight[1] as part of a DOE SCGSR alongside Laura Fields and Kendall Mahn

Provides reweighting of hadron trajectories simulated by GEANT4 under varied cross section models

Has been used by MicroBooNE for systematic uncertainties in several recent analyses[2-8]

Currently being used for several ProtoDUNE analyses for systematic uncertainties and fake data studies

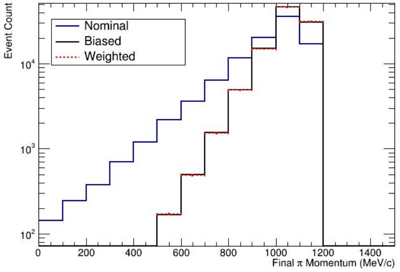
Currently integrating into DUNE’s 2x2 ND Prototype analysis

Example

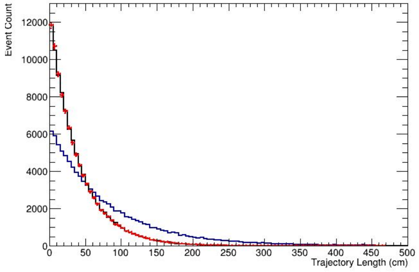
Ran GEANT4 with the nominal pi-Ar cross section as well as one ‘biased’ by a factor of 2 (separate simulation)

Weighted nominal according to that factor of 2 → Matches the ‘biased’ results

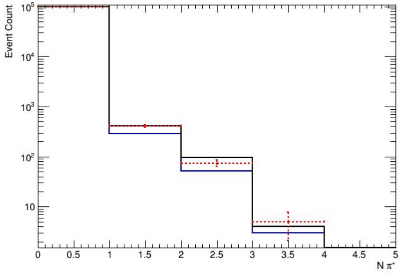
End Momentum



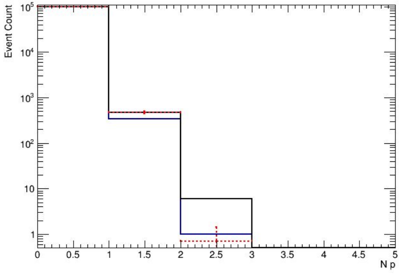
Trajectory Length



Final State pi Multiplicity



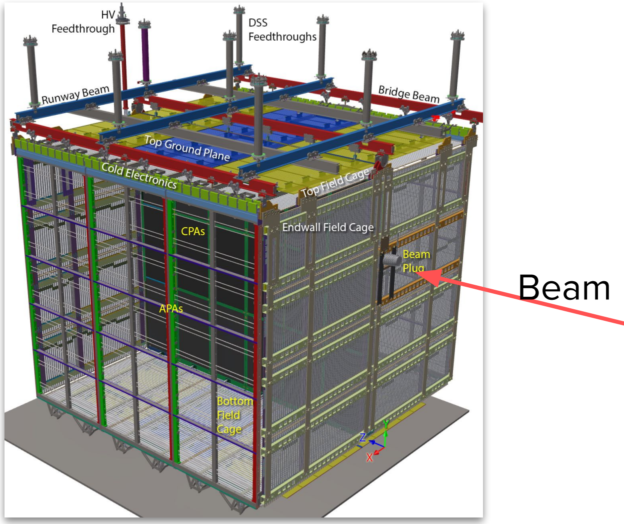
Final State p Multiplicity

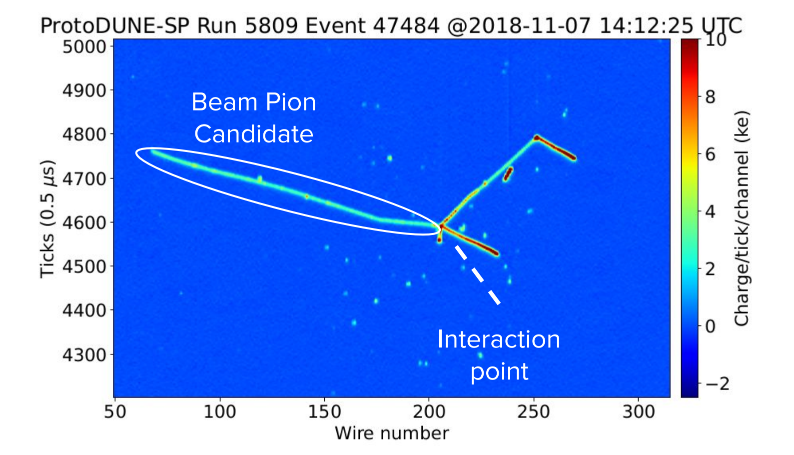


ProtoDUNE-SP Pion Cross Section Analysis

Extended thesis measurement (pion-Ar absorption & charge exchange) to cover entire pion-Ar inelastic cross section (absorption, charge exchange, ‘other’)

Right: Pion interaction candidate used within analysis





Analysis Overview

Study rate of pion interactions in various channels

- Select pion/muon triggers with well-reconstructed beam tracks
- Separate muons from pions
- Select three types of pion interactions
  - Requires separate tracks (π^+, *p*) from showers (π^0 decays) and separating π^+ tracks from *p* tracks

Use a likelihood fit to unfold from various reconstructed variables into the number of true interactions of a given channel at a given energy

Extract cross section from varied MC truth information

Extracting Cross Section from Truth Info

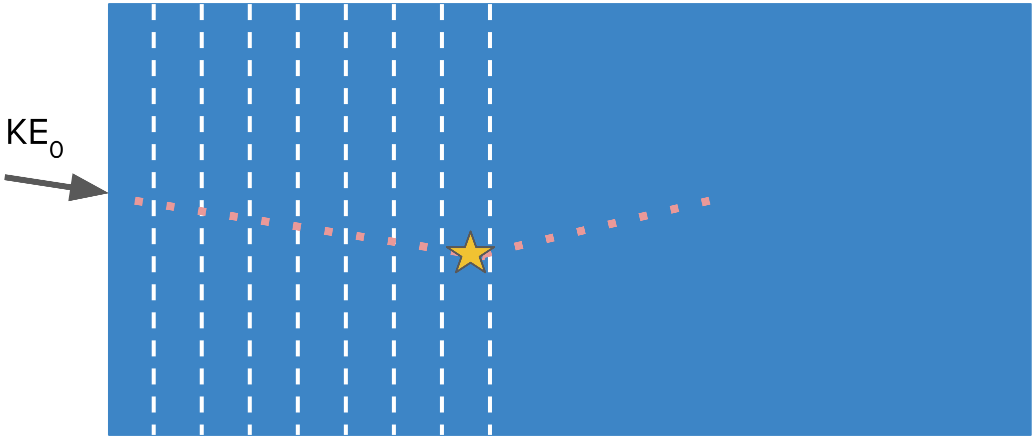
To calculate the cross section, ‘slice’ up the path of the simulated pion to create a sequence of thin target scattering experiments.

Using the true energy at the start of LAr, and the energy of the MC trajectory points: calculate the incident energy in each of the slices (pion loses energy in volume)

Use these to build up a flux (Φ) as in a ‘classic’ thin target experiment

Count number of interactions (N_{Int}) at given energies

Cross sections are functions of N_{Int} and Φ



Signal Definition

Absorption:

$$\pi^+ + \mathrm{Ar} \rightarrow \mathrm{N}' + \mathrm{nucleons}$$

Charge Exchange:

$$\pi^+ + \mathrm{Ar} \rightarrow \mathrm{N}' + \mathrm{nucleons} + n\pi^0$$

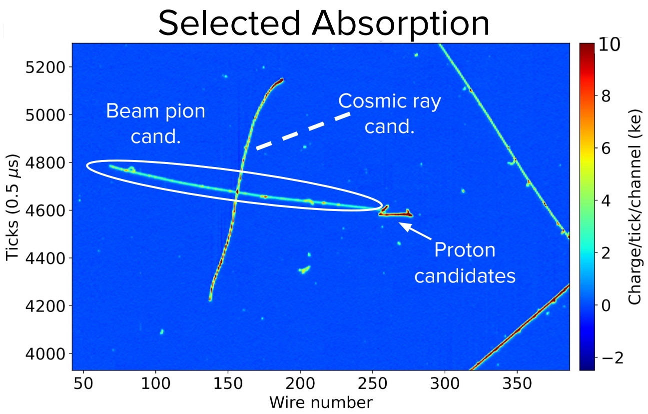
Other:

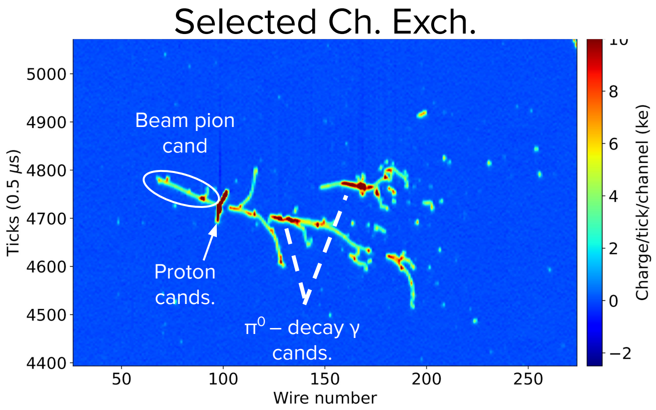
$$\pi^+ + \mathrm{Ar} \rightarrow \mathrm{N}' + \mathrm{nucleons} + \mathrm{charged\ pions}$$

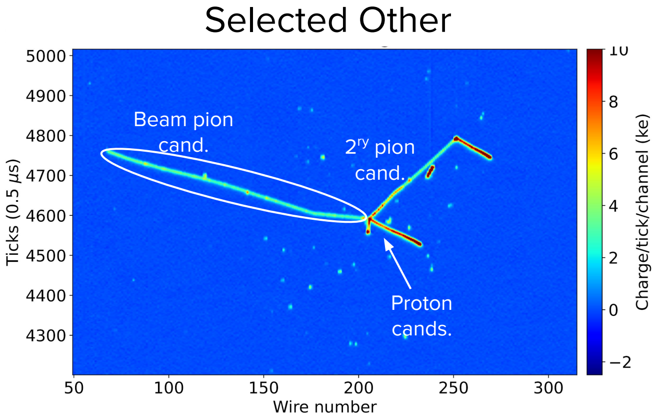
Note: 150 MeV/c threshold on secondary charged pions ➔ Signal Abs. and Ch. Exch. events can contain charged pions < 150 MeV/c

Also: Ch. Exch. can contain any number of pi-zeros

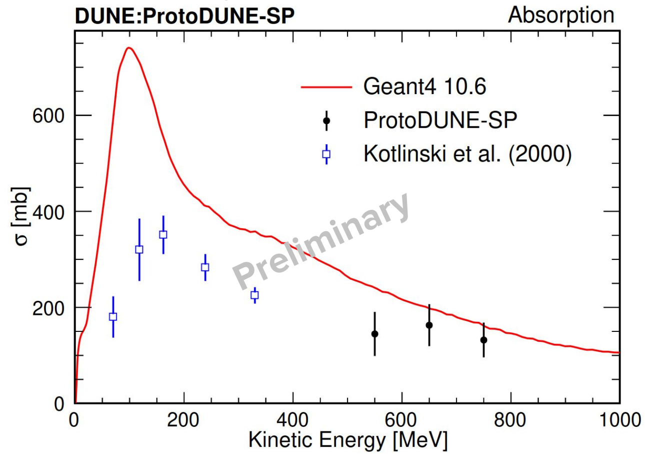
Selected Event Displays

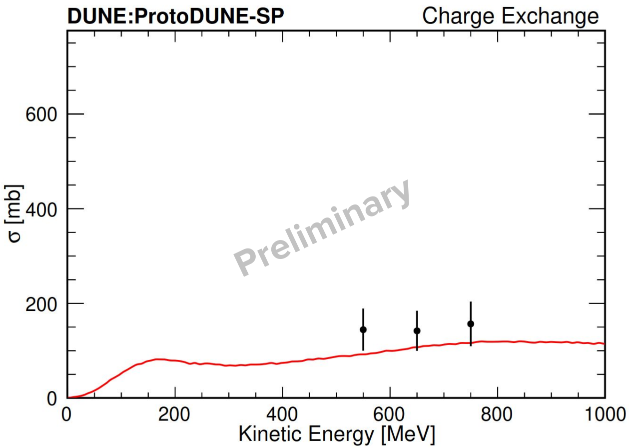


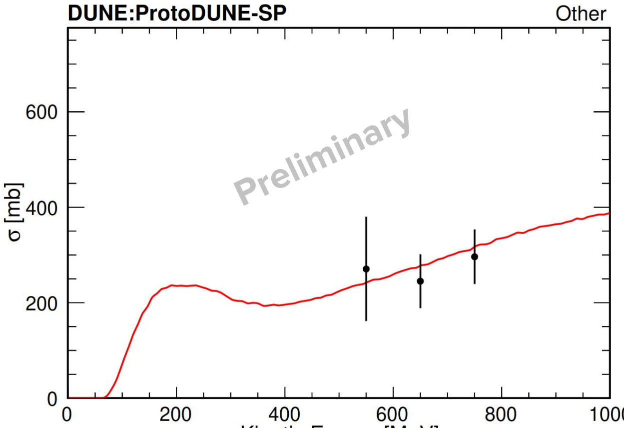


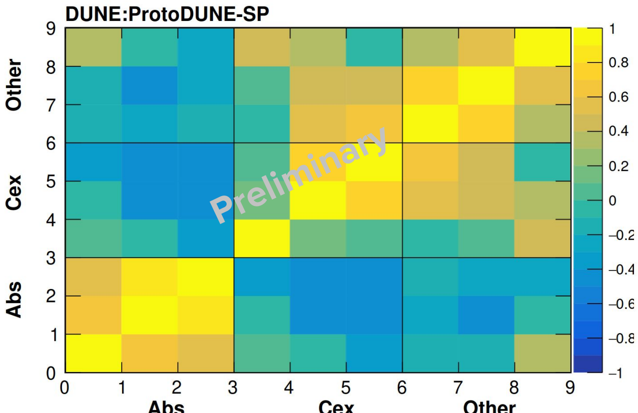


Preliminary Results









Current Work

Prompt Signal Processing

- Enabling use of GPUs in WireCell’s LArTPC signal processing
- Eventually: setting up nearline infrastructure to do this processing near to data to reduce global offline computing needs

Neutrino cross section analysis at MicroBooNE

- Improving final state pion reconstruction
- Combined analysis using data from 2 beams (Booster Neutrino Beam & Neutrinos from the Main Injector)

Current Work – Continued

Continuing ProtoDUNE-HD Offline Coordination

- Organizing processing of taken taken this summer
- Set up and monitored keep-up processing as data was collected

Continuing Development on Geant4Reweight

- Extending variations to full-phase-space reweighting using Particle Flow Networks[11]

Conclusion

I am excited to continue research focusing on computing and software in the context of DUNE

Thank you for the opportunity to give this presentation and share my ideas with you

References

1. J. Calcutt *et al* 2021 “Geant4Reweight: a framework for evaluating and propagating hadronic interaction uncertainties in Geant4” *JINST* **16** P08042
2. P. Abratenko *et al.*, “First Measurement of Quasielastic Λ Baryon Production in Muon Antineutrino Interactions in the MicroBooNE Detector” *Physical Review Letters* **130** 231802 (2023)
3. P. Abratenko *et al.*, “Measurement of neutral current single-π^0 production on argon with the MicroBooNE detector” *Physical Review D* **107** 012004 (2023)
4. P. Abratenko *et al.*, “Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector” *Physical Review D* **106** 092006 (2022)
5. P. Abratenko *et al.*, “Differential cross section measurement of charged current νe interactions without final-state pions in MicroBooNE” *Physical Review D* **106** 051102 (2022)
6. P. Abratenko *et al.*, “Search for an anomalous excess of inclusive charged-current νe interactions in the MicroBooNE experiment using Wire-Cell reconstruction” *Physical Review D* **105** 112005 (2022)
7. P. Abratenko *et al.*, “Search for an anomalous excess of charged-current νe interactions without pions in the final state with the MicroBooNE experiment” *Physical Review D* **105** 112004 (2022)
8. P. Abratenko *et al.*, “Search for an anomalous excess of charged-current quasielastic νe interactions with the MicroBooNE experiment using Deep-Learning-based reconstruction” *Physical Review D* **105** 112003 (2022)
9. A Abed Abud et al. Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network Eur.Phys.J.C **82** (2022) 10, 903

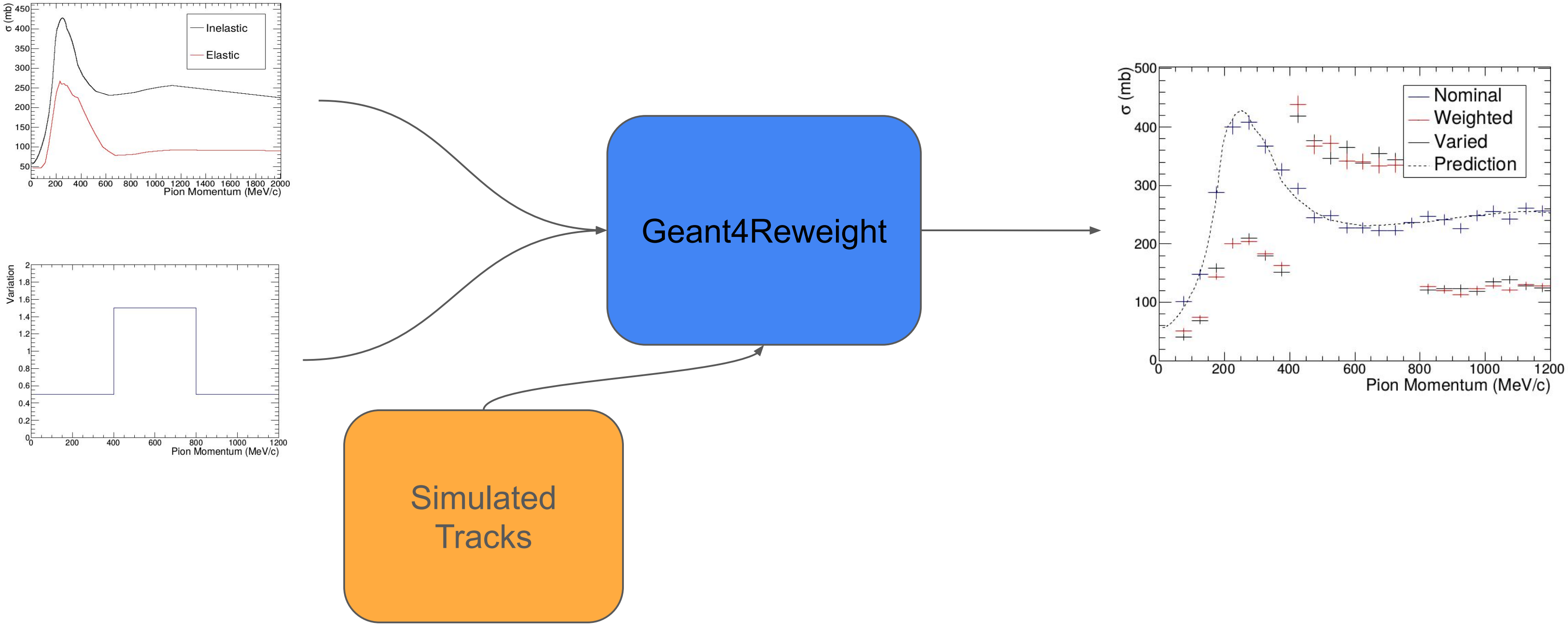
References

10. J. Calcutt et al. “Shower Clustering with Graphs” SLAC Summer Institute 2023 Project Session slides 69-80
11. Andreassen *et al.*, “Neural Networks for Full Phase-space Reweighting and Parameter Tuning” *Physical Review D* **101** 091901 (2020)

Backup Slides

What is Geant4Reweight?

Software that produces weights for simulated particle tracks from



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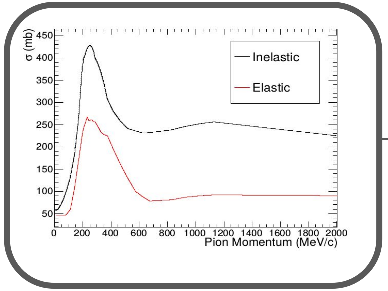
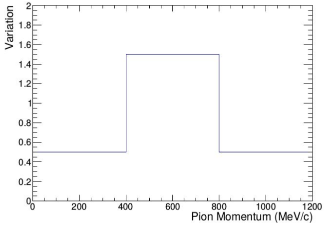
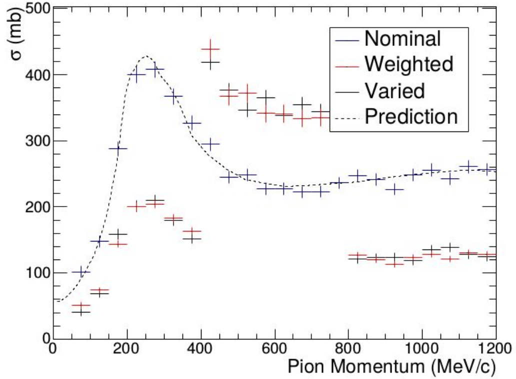
Software that produces weights for simulated particle tracks from





Geant4Reweight

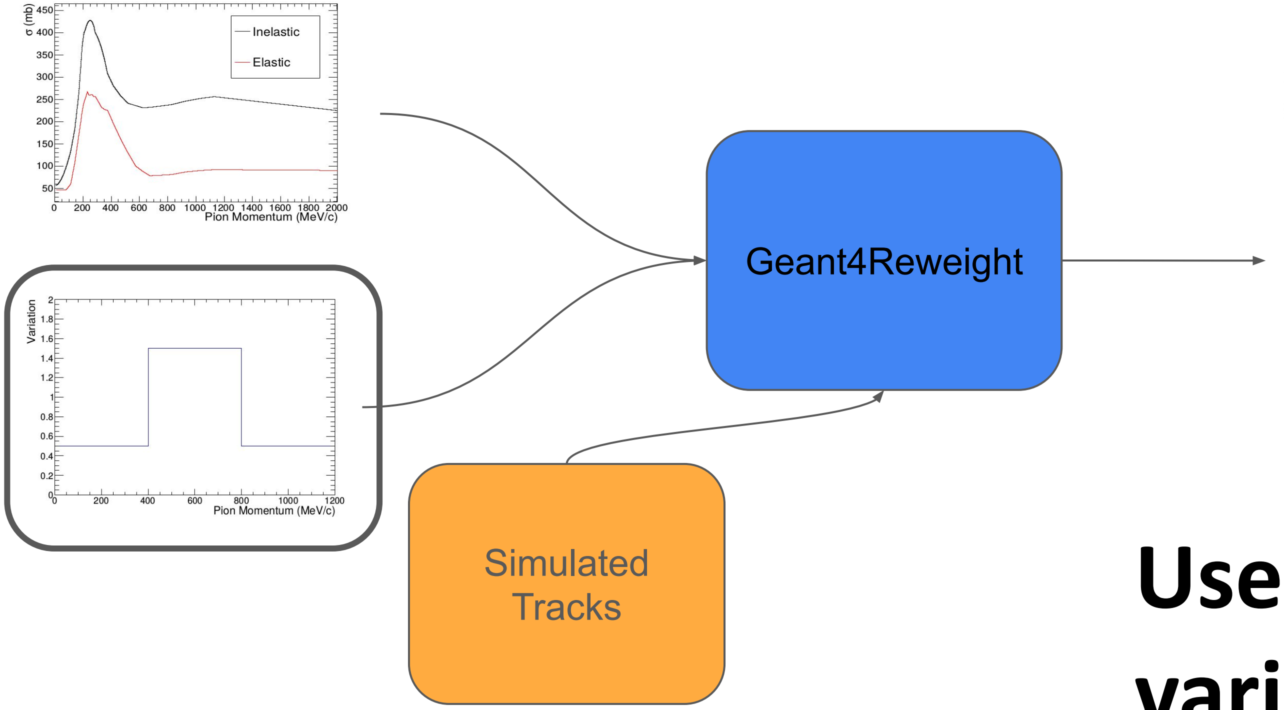
Simulated Tracks

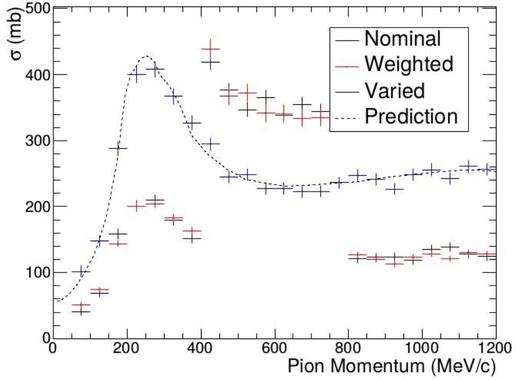


Nominal Predictions

What is Geant4Reweight?

Software that produces weights for simulated particle tracks from

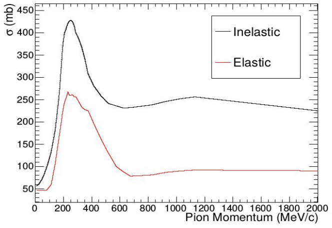


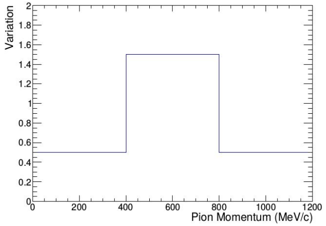


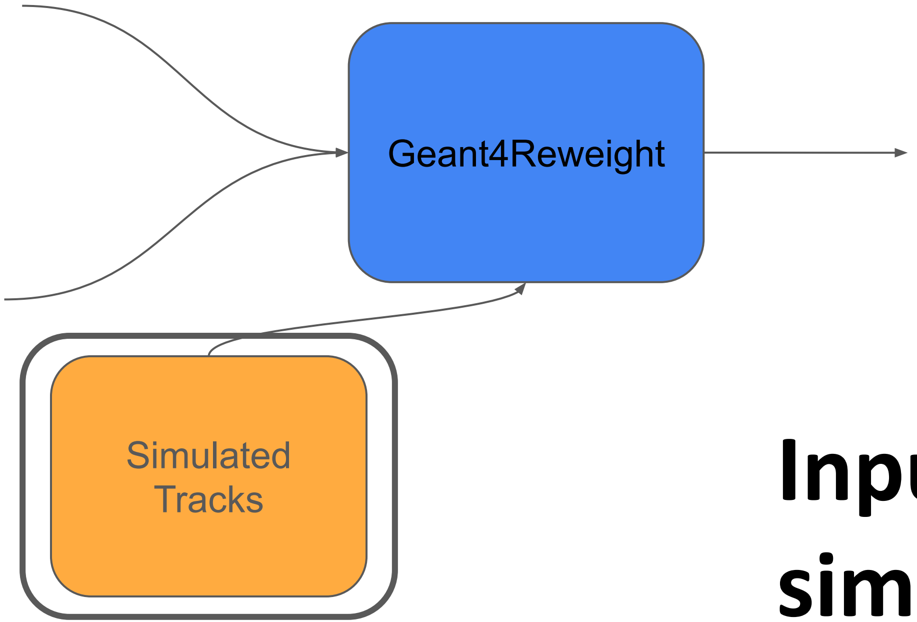
User-defined variations

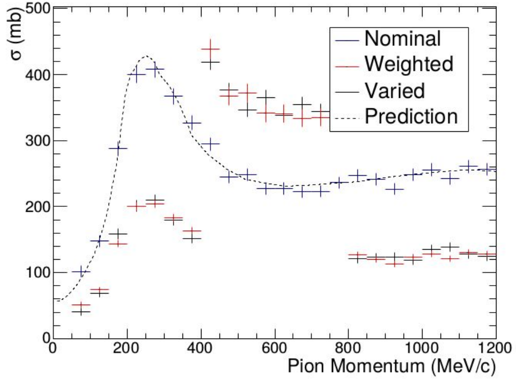
What is Geant4Reweight?

Software that produces weights for simulated particle tracks from





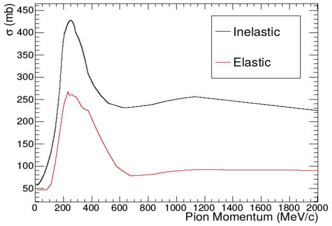


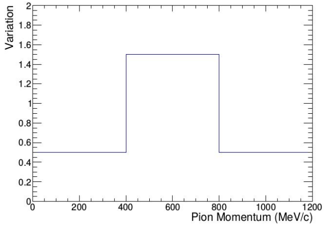


Input simulation

What is Geant4Reweight?

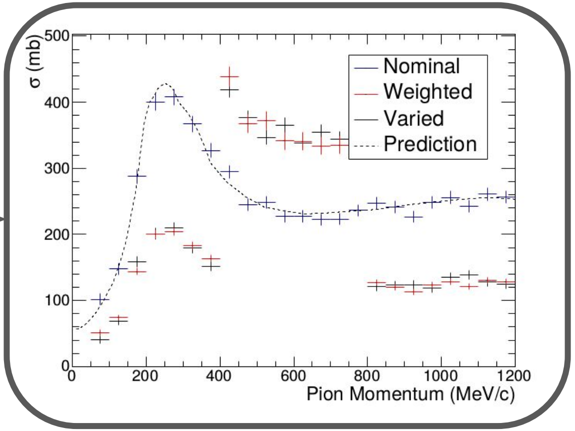
Software that produces weights for simulated particle tracks from





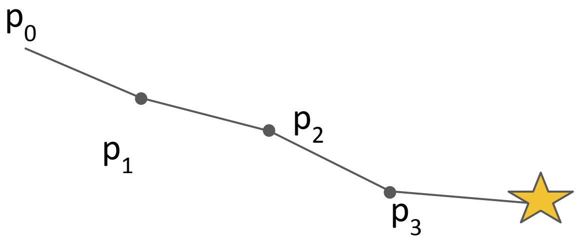
Geant4Reweight

Simulated Tracks

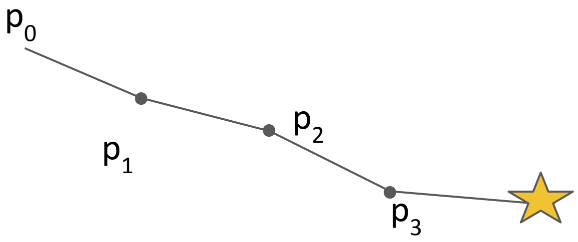


Weighted observables

How Reweighting is Done



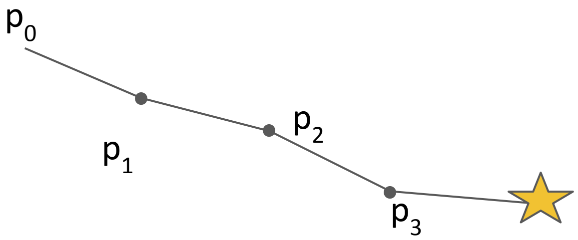
How Reweighting is Done



The hadron takes a set of steps, possibly interacting each time

-- Geant4 samples cross section tables at each step (energy dependent)

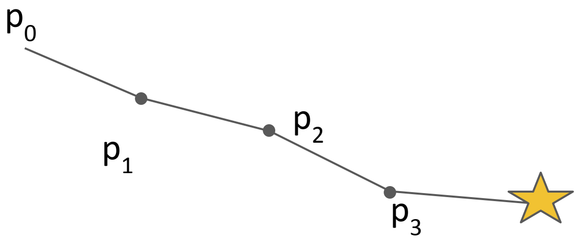
How Reweighting is Done

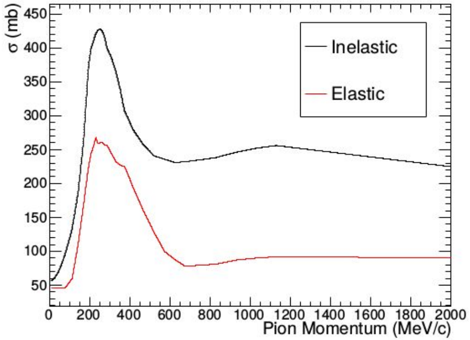


The hadron ends in an interaction

-- Possibly the interaction we want to reweight

How Reweighting is Done





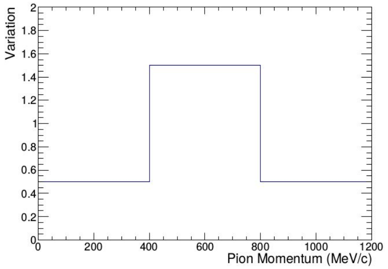
For each step:

-- Find the cross section from G4 table

-- Get the varied cross section from variation input

-- What happened?

Interaction? Stepping? Transportation?



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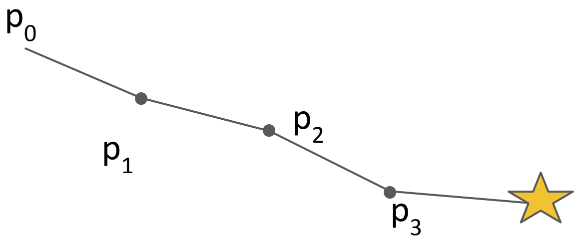
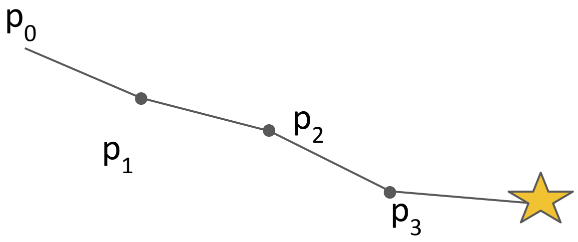


Particle did not interact at end (maybe it stopped, or decayed, or left volume)
-- It gets a ‘survival’ weight

Runs over all steps in trajectory

$$W_{\text{No Int.}} = \prod_{i=0}^{N_{\text{steps}}} \frac{e^{-\sigma'_i L_i}}{e^{-\sigma_i L_i}}$$

How Reweighting is Done



Particle interacted at end
-- It gets an 'interacting' weight

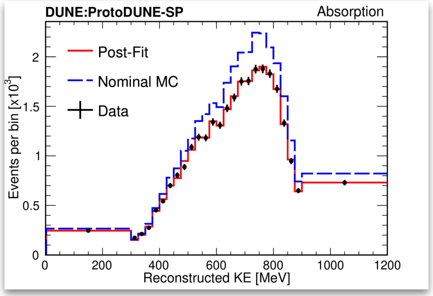
$$W_{\text{Int.}} = f \prod_{i=0}^{N_{\text{steps}}} \frac{e^{-\sigma'_i L_i}}{e^{-\sigma_i L_i}}$$

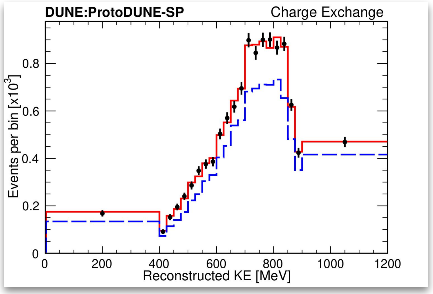
Cross section variation at last step

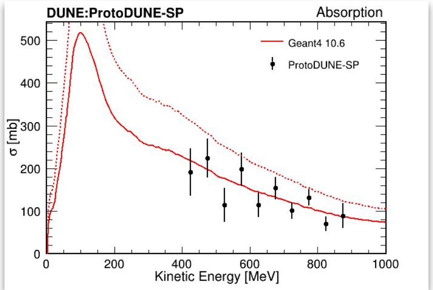
What Can You Use G4RW For?

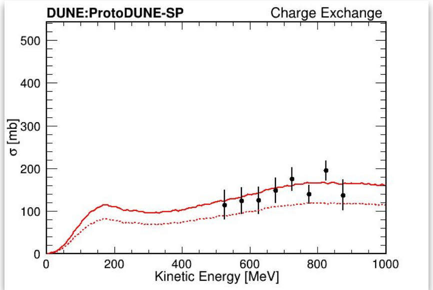
Fake data studies i.e. Below: Pion-Ar Fit to Absorption (Ch. Exch.) scaled by 0.7 (1.4)

Systematic Uncertainties









Future Work: ProtoDUNE-HD

ProtoDUNE-HD has completed its test beam physics run

Will continue to coordinate the offline effort

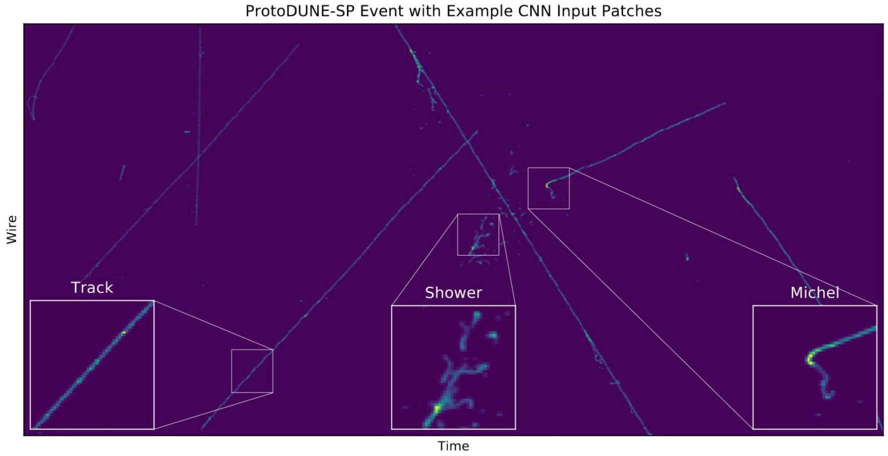
With experience from this analysis, I can provide support for future calibration & physics analyses

- Hopefully we can get lower momentum pion data to explore more relevant physics
- Cross sections as functions final state kinematics would be incredibly useful for nuclear modeling in neutrino event generators

Future Work: PDHD ML Event Selection

ML is currently used within PDSP reconstruction[9]

- CNN applied to patches around each hit in each plane
  - Classify each hit as track-like or shower-like w/ independent Michel-like score
- Used within my analysis event selection: aggregate over each reco. particle associated as an interaction product → Classify as track vs shower



Future Work: PDHD ML Event Selection

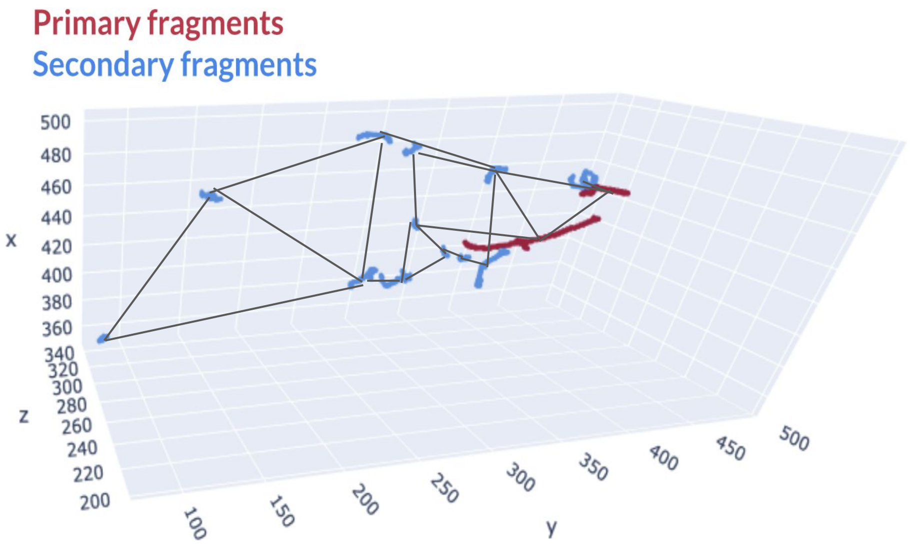
Other ML techniques are well-suited for TPC data

- Sparse information
- 3D information is available after space-point solving
- Graph Neural Nets are well suited for this

Future Work: PDHD ML Event Selection

Completed a shower-clustering project[10] at this year's SLAC Summer Institute using a GNN

Could be tweaked to do event selection or other stages of reconstruction/analysis with PDHD data



Future Work: 2x2 Prototype Analysis

Data from the upcoming 2x2 prototype of DUNE's near detector can be used to measure neutrino cross sections on argon

$CC1\pi^+$ could probe similar physics as my pion analysis

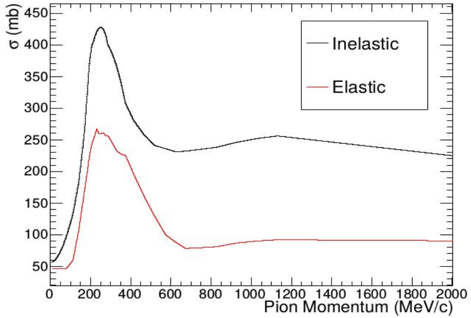
Containment could be an issue

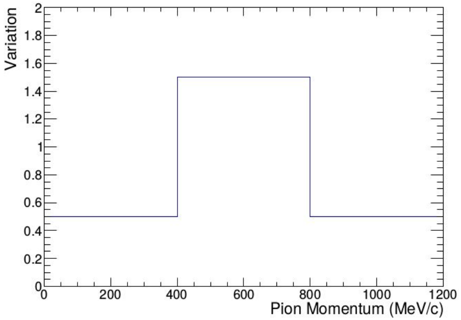
- Need to investigate feasibility more first, but have begun thinking about the analysis

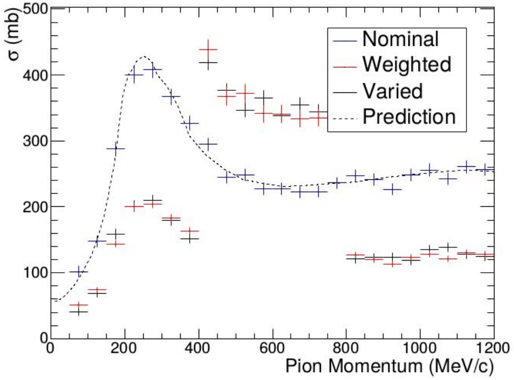
Future Work: Geant4Reweight Extensions

Currently, Geant4Reweight relies on very basic variations applied to a (possibly exclusive) cross section

- No differential reweighting
- How does one choose a set of variations? I.e. what is the physics basis?







Future Work: Geant4Reweight Extensions

My idea for this: use Machine Learning!

Heavily inspired by Andreassen and Nachman[11]

Goal of reweighting: get a weight (*w*) for an event (with features ***x***) to go from simulation 1 → 0 (represented as pdfs)

$$w(\vec{x}) = p_0(\vec{x})/p_1(\vec{x})$$

A neural network (*f*) trained to classify events from (i.e. from sets 0 and 1 as below) approximates this ratio

$$f(\vec{x})/(1 - f(\vec{x})) \approx p_0(\vec{x})/p_1(\vec{x})$$

With the right network *f*, can work with large/arbitrary dimensionality in ***x***

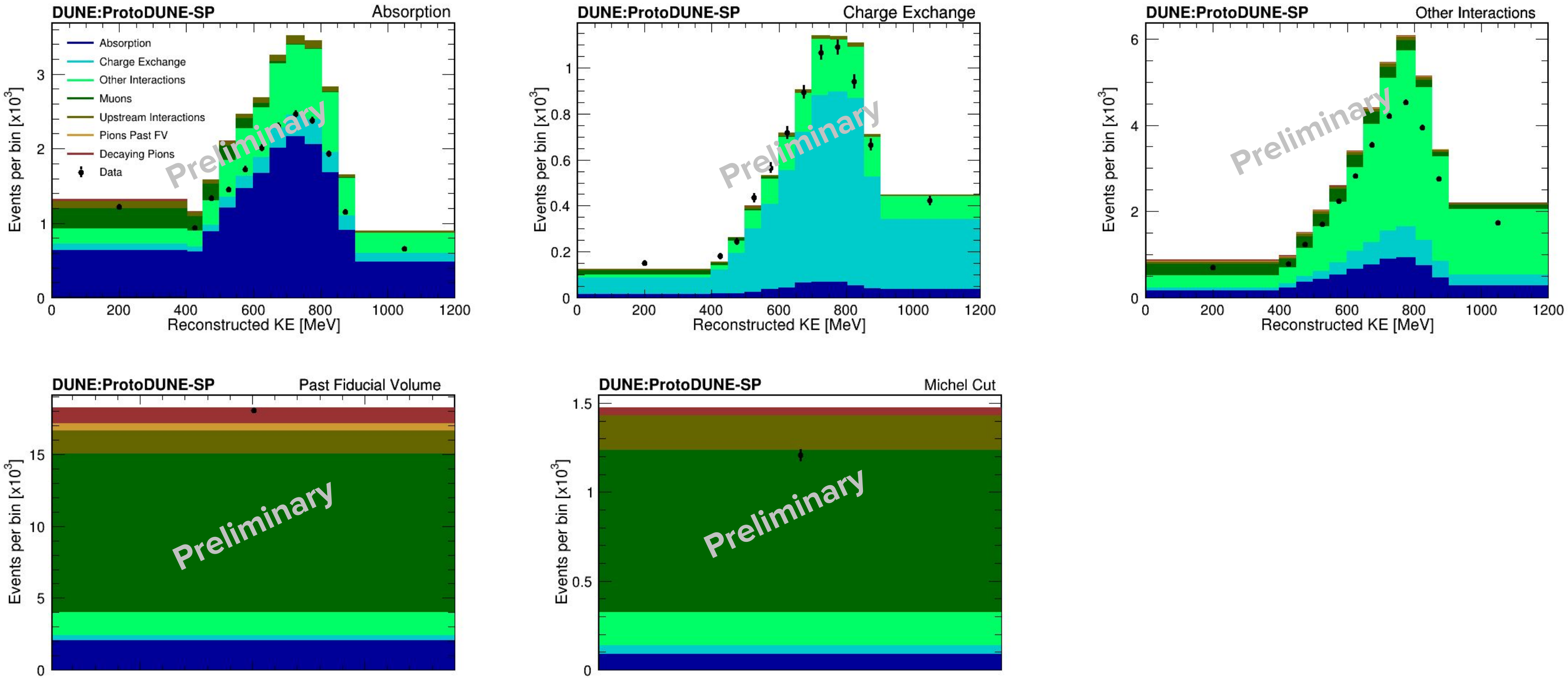
Future Work: Geant4Reweight Extensions

How to fit this into G4RW:

- Separate total cross section reweighting (a.k.a. number of interactions that occur) from differential $(1/\sigma)(d^N\sigma/d\Omega)$ (a.k.a. how those interactions occur)
- Train a network for various values of the available interaction parameters from GEANT4's Bertini Cascade
- Use that as the differential reweighting 'engine'

Will then have a defined set of dials (with physical motivation) and variations will now effect full post-interaction final state

Event Distributions



Parameterization

Signal parameters – Scale number of events of signal interactions (absorption/charge exchange/other) in bins of true kinetic energy at interaction

- 100-MeV-wide bins between 500 & 800 MeV, <500 MeV, >800 MeV

Signal-like parameters

- Number of interactions upstream of TPC

Systematic Uncertainties:

- Physics (input pion/proton cross sections, final state kinematics/multiplicities)
- Experimental apparatus (Calibration, beam energy smearing, space charge effect, reconstruction efficiencies)