ProtoDUNE Pion Cross Sections Likelihood Fitting

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Introduction

ProtoDUNE-SP provides pion data which can inform both hadron interaction models (Geant4) and FSI models in neutrino event generators

See previous work by T2K[1] using DUET data[2] for NEUT tuning

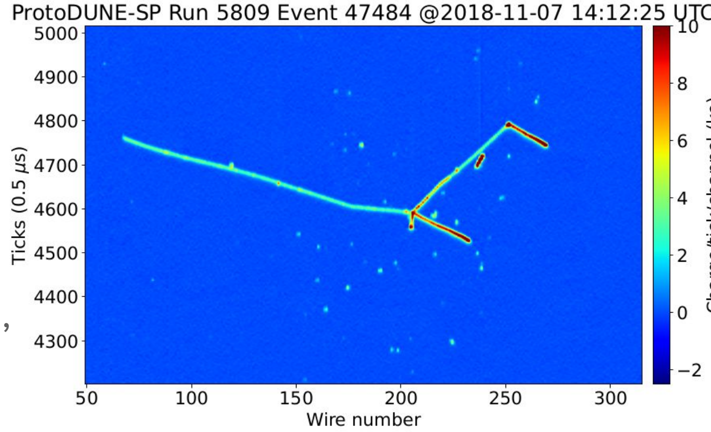
Heavily informed by cross section measurements on T2K

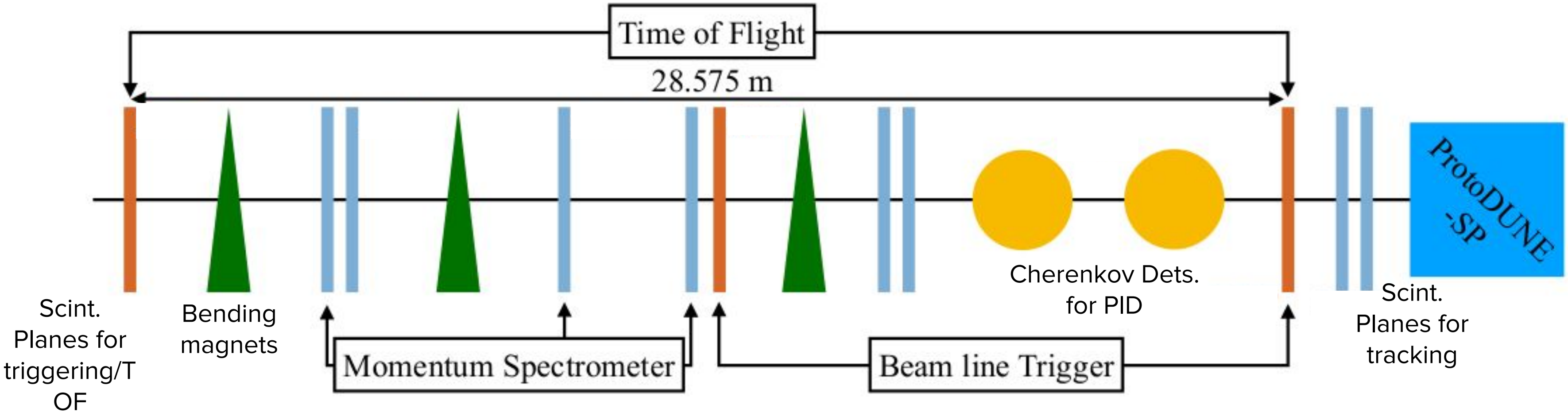
1. PhysRevD.99.052007
2. PhysRevC.95.045203

Experiment Overview

ProtoDUNE-SP: LArTPC situated in charged particle test beam

Beam line instrumentation allowed for momentum reco., tracking, PID





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

Use a likelihood fit to unfold from various reconstructed variables (combination of reconstructed energy at interaction point and depth into detector) 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

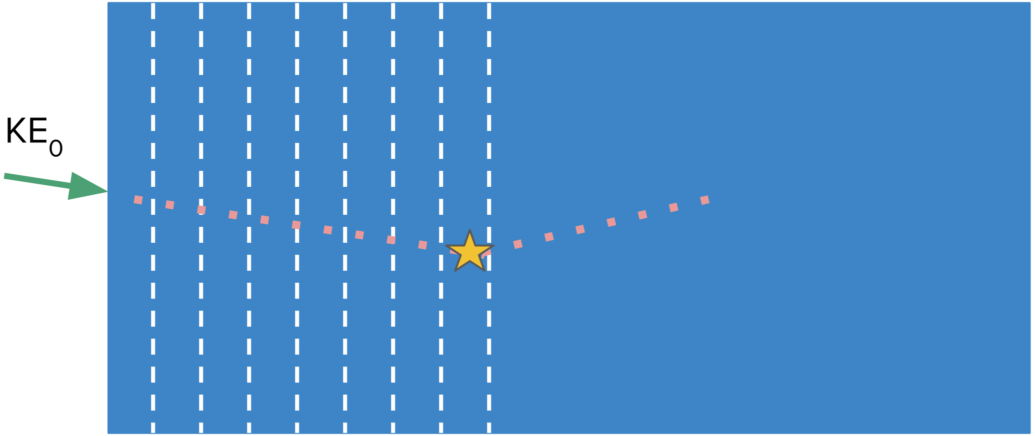
To calculate the cross section, ‘slice’ up the path of the simulated pion to create a sequence of thin target scattering experiments.

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

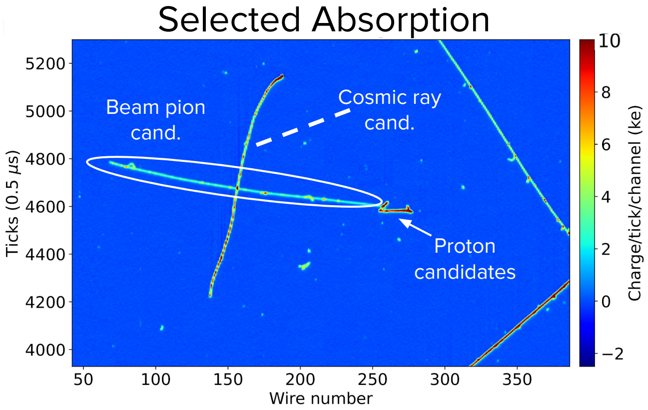
Also: Ch. Exch. can contain any number of pi-zeros

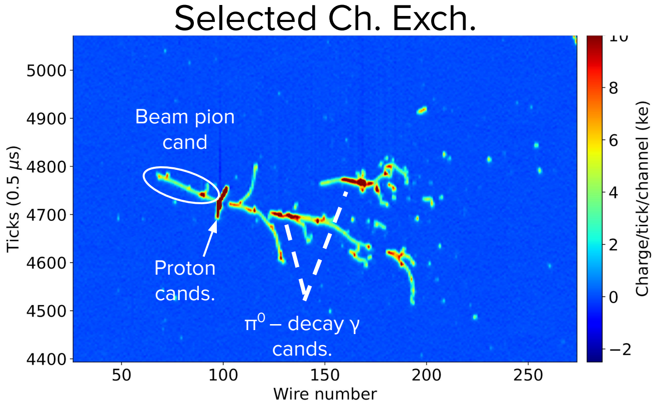
Event Selection

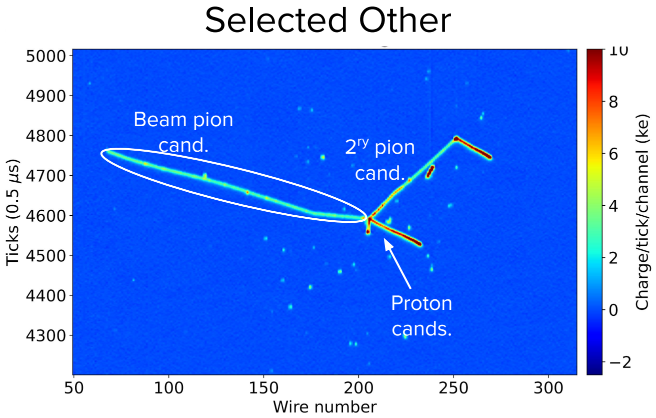
Consider every π/μ candidate event

- Reject events:
  - Without a reconstructed TPC track
  - With a reco. TPC track that was inconsistent with the beam
- Bin the remainder:
  - Events in which the TPC track extended past the Fiducial Volume (FV)
  - In-FV events with Michel-like vertex activity
  - Candidate interactions, separated by associated reco. interaction products:
    - Absorption: no charged-π-like track, no π^0-like showers
    - Charge Exchange: no charged-π-like track, at least 1 π^0-like shower
    - Other Interactions: at least 1 charged-π-like track

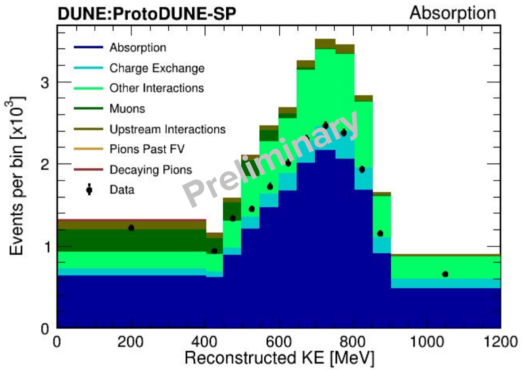
Selected Event Displays

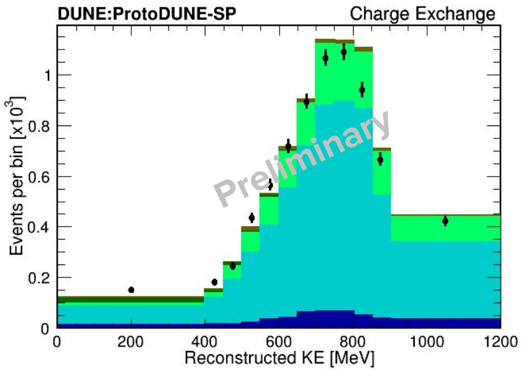


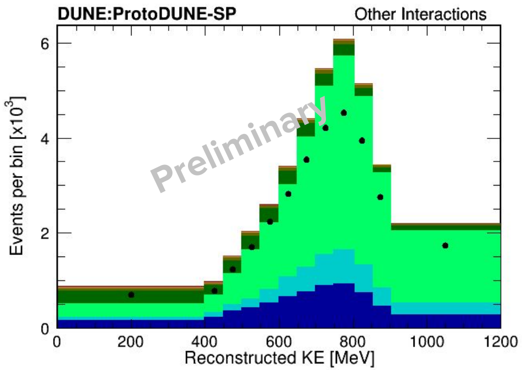


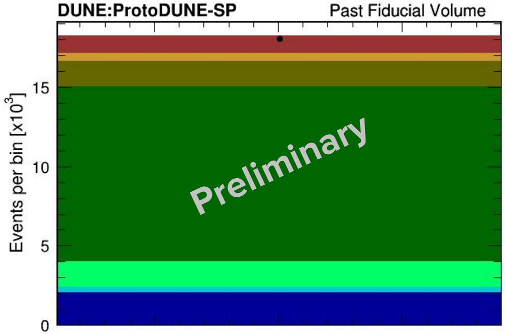


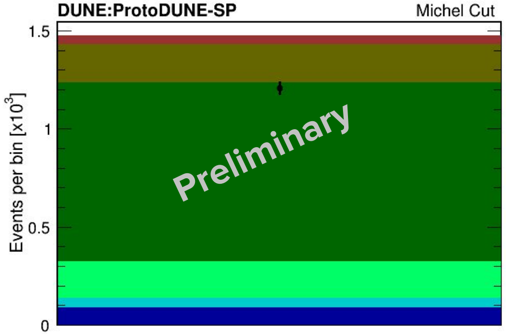
Event Distributions











Fit Statistic

λ ➔ Likelihood ratio

Statistical term (w/ Barlow Beeston scale factors β_j for MC stats)

Systematic term

$$-2\ln\lambda = 2\sum_j\left(\beta_j y_j - n_j + n_j \ln\frac{n_j}{\beta_j y_j} + \frac{(\beta_j-1)^2}{2\sigma_j^2}\right) + \sum_{i,j}(p_i-q_i)V^{-1}_{\mathrm{Cov}}(p_j-q_j)$$

Data

MC

Loop over reco bins

Nominal systematic parameter values

Input systematic covariance matrix

Loop over all covariance bins

Varied systematic parameter values

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 & 900 MeV, <500 MeV, >900 MeV

Signal-like parameters

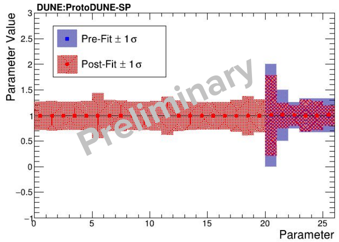
- Number of primary muons
- Number of interactions upstream of TPC

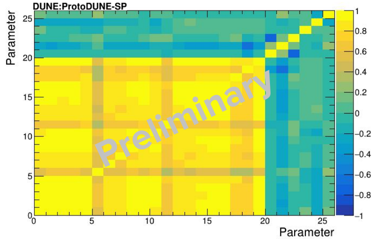
Systematic parameters (constrained by some input covariance)

Uncertainty Propagation

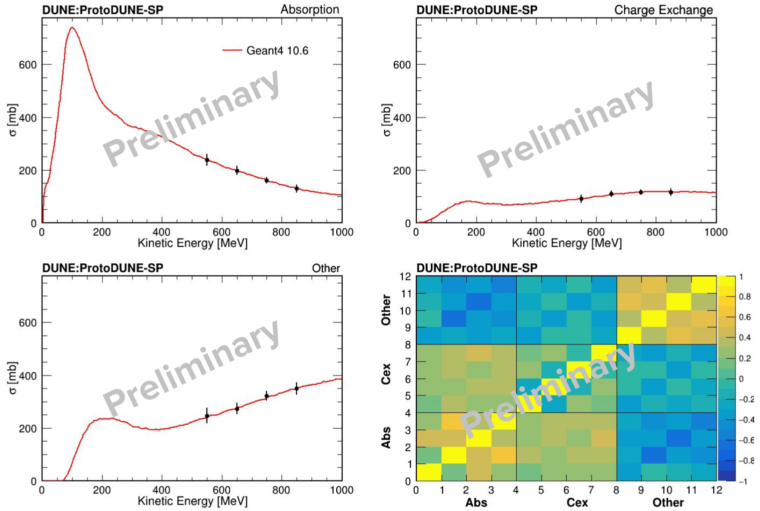
Throw to the post-fit covariance matrix are performed to create MC ensembles representing the likelihood surface near the best-fit point

The cross sections are extracted from each of these and the covariance between each cross section bin is found





Example:
[Asimov Fit]

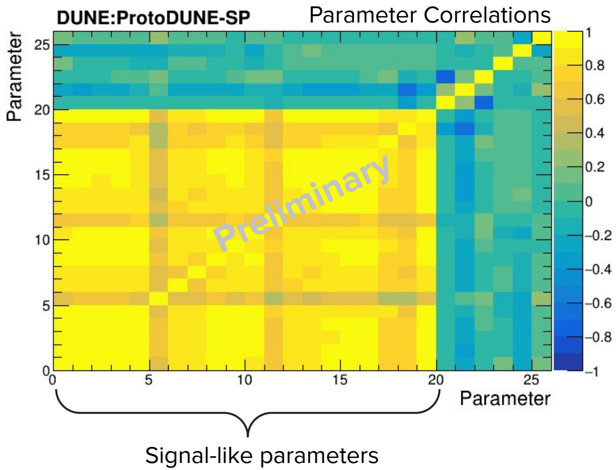


Challenges & Complications

Beam Constraint

Test beam experiment differs to neutrino cross section:

- We ‘know’ how many particles we shot into the detector (events)
  - Constrain the number of total beam particles
  - Renormalize events each step of fit
    - Effectively change the *fraction* of events of a given category
    - I.e. Signal interactions vs Muons vs Upstream Interactions

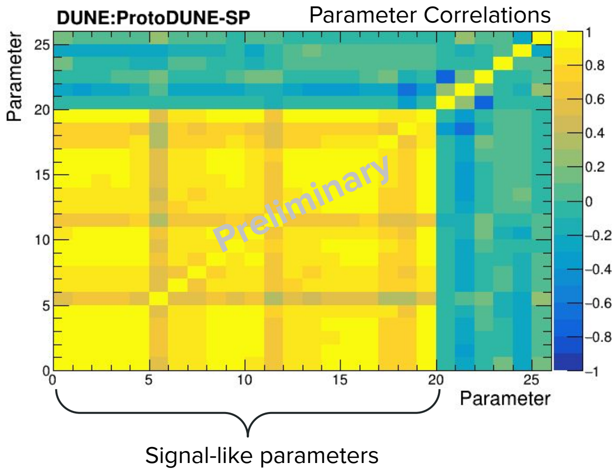


Leads to a nearly-determined fit and thus high correlations in the signal-like parameters

Beam Constraint

Because of this, the likelihood surface can be highly non-parabolic

- Minuit needs to force the Hessian matrix (2nd derivative of likelihood surface) positive-definite before inverting into the parameter covariance

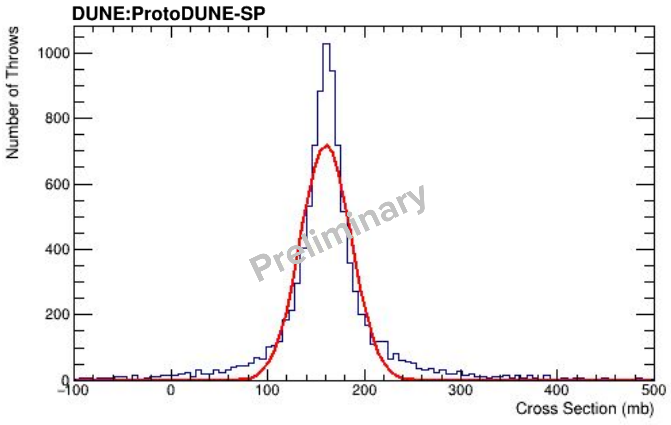


Thrown Cross Section Distributions

Because of non-linearity in calculating cross section: $\sigma \propto \ln\left(1 - \frac{N_{\mathrm{Int}}}{\Phi}\right) \approx 1 - \left(1 - 2\frac{N_{\mathrm{Int}}}{\Phi}\right)^{\frac{1}{2}}$

Parameter covariance is Gaussian (by definition) but not necessarily so for the cross sections values

- Approximately?

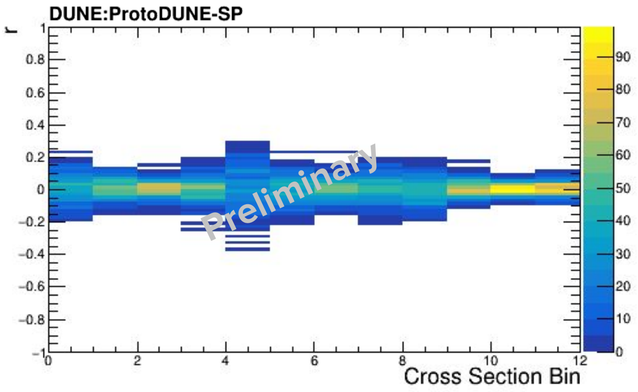


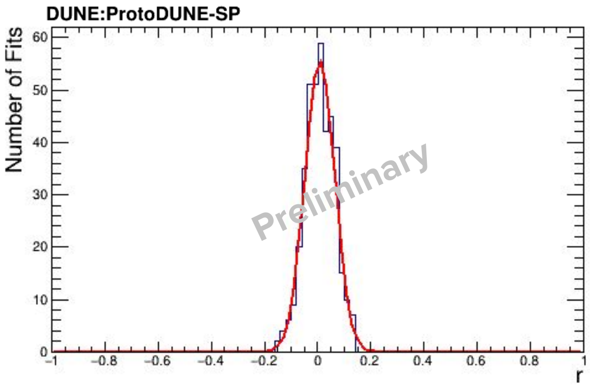
Distribution of cross section values in one bin from post-fit throws from fit to data

‘Alternative’ Error Prop: Confidence Intervals

Instead of throwing to the post-fit covariance matrix: run fits to ensemble of representative MC with statistical fluctuations

- Mean & covariance of best-fit cross sections gives the 1σ confidence intervals
- Below: differences to truth each cross section bin (nominal Geant4 cross sections)
  - Fraction Residual: $r = (xsec_{Best\ Fit} - xsec_{Fake})/xsec_{Fake}$





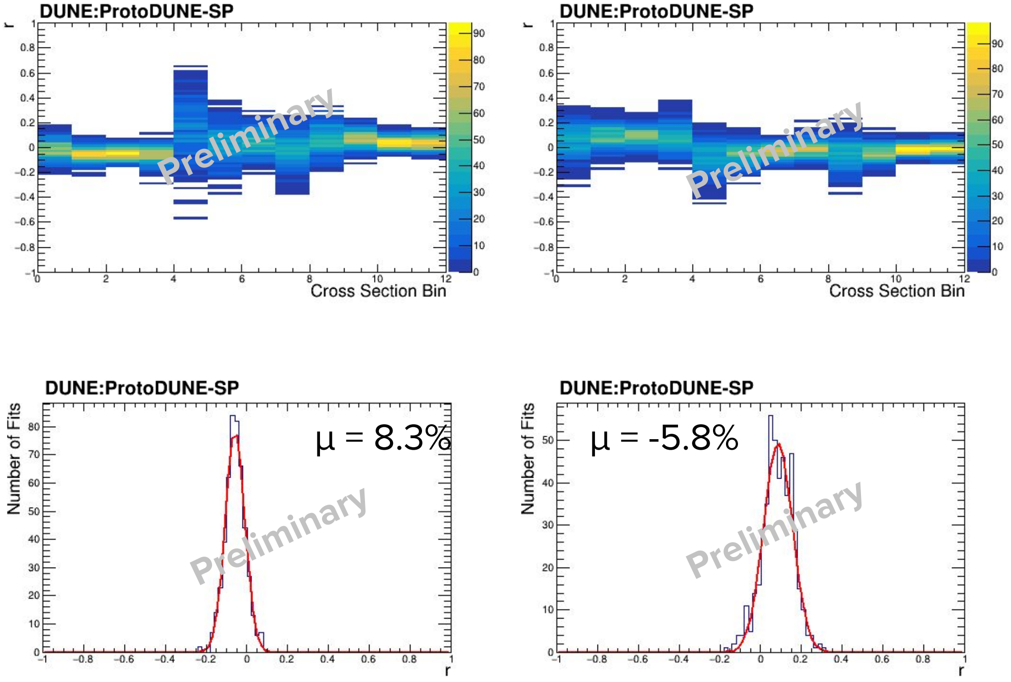
'Alternative' Error Prop: Confidence Intervals

Fit to fake datasets with varied MC signal model (Geant4) + stat. Fluc.

- Left: Abs x 1.44, Ch. Exch x 0.69, Other x 1.00
- Right: Abs x 0.69, Ch. Exch x 1.44, Other x 1.00

Observe biases O(5 – 10%)

- Example dists. from bin 1
- Further investigation necessary



Preliminary Data Results

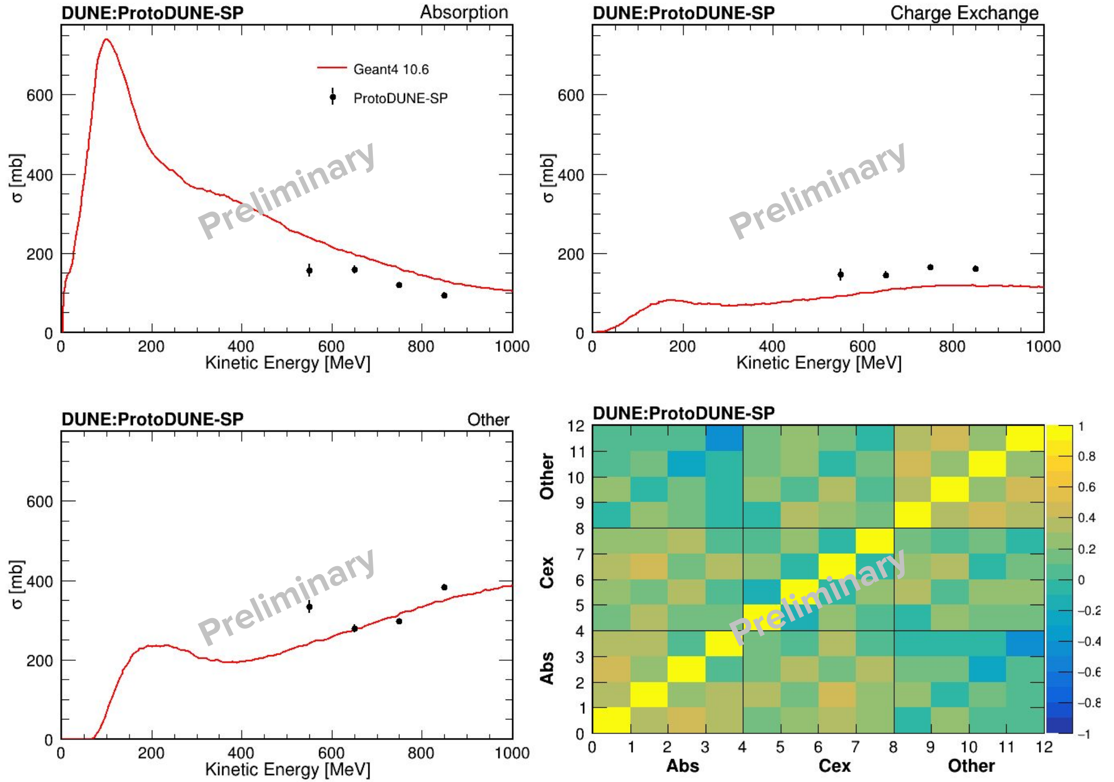
Preliminary results on data

- Statistical error shown only

Systematic error propagation will work similar to stats:

- Throw to input systematic covariance to create fake data sets

Need to account for biases shown on previous slide



Conclusions

Presented experience of likelihood-fit-based hadron–Ar cross section extraction using ProtoDUNE-SP data

- This analysis will provide important data to constrain DUNE's Final State and Secondary Interaction modeling

Highlighted challenges in using this method

Showed preliminary results on data

Thanks for Listening

ProtoDUNE-SP Detector

700T LArTPC at CERN

Fine-grained TPC allows tracking and energy reconstruction of charged particles within the argon

Charged particle test beam provided O(160k) pion-like triggers to study pion interactions within the argon