Charge Exchange Inclusive Differential Cross Section Measurement

EM Shower Group Meeting

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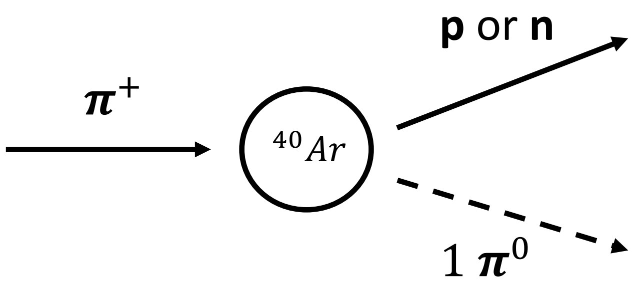
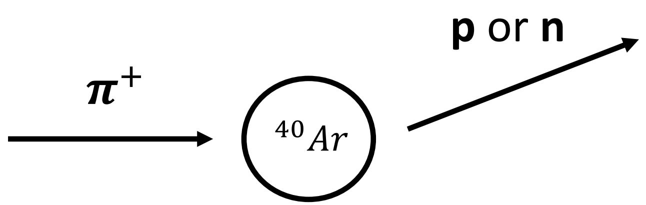
Signal Topology

- 1GeV π^+ beam events in ProtoDUNE-SP.

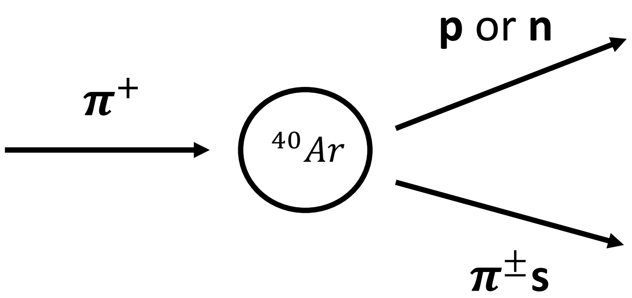
Pion Charge Exchange



Pion Absorption (background)

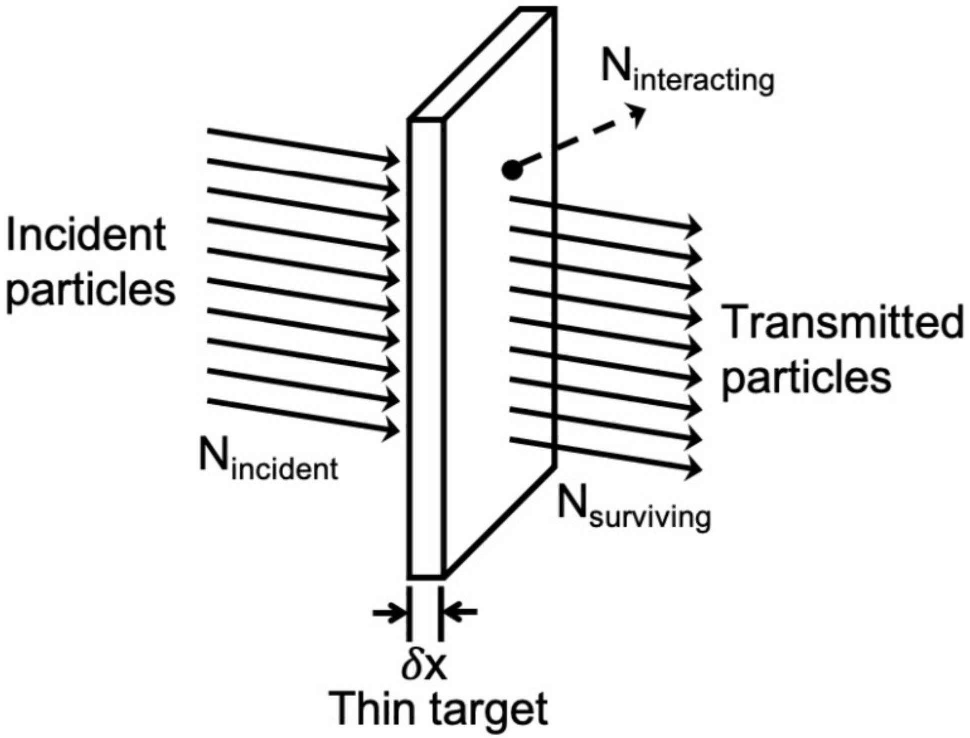


Pion Inelastic (background)

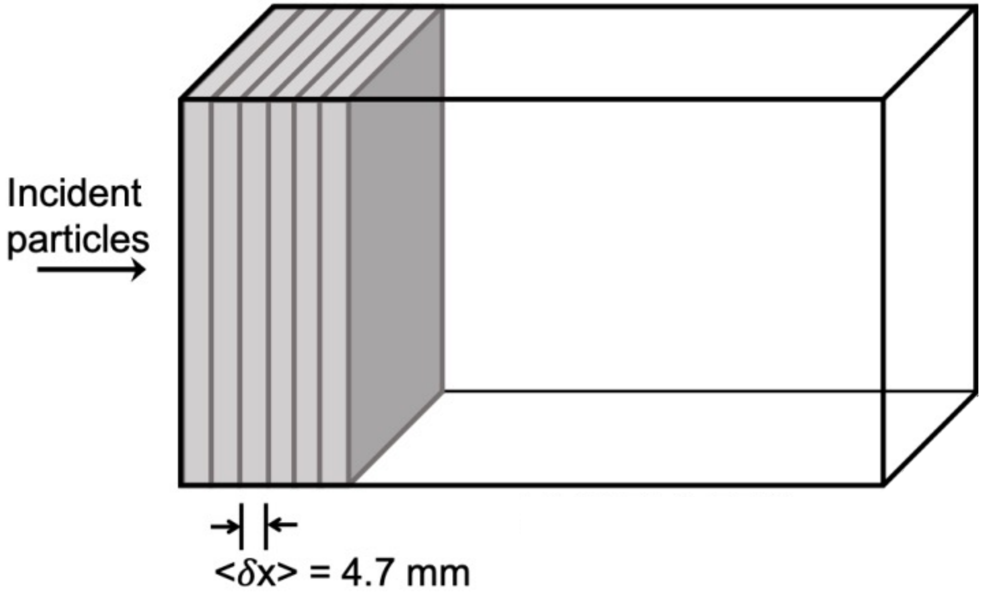


Topology	$\pi^{\pm}$	π^0	proton or neutron
Pion Charge Exchange	No	Yes (only 1 π^0)	Yes
Pion Absorption (background)	No	No	Yes
Pion Inelastic (background)	Yes	No	Yes
Single Pi0 (background)	Yes	Yes (only 1 π^0)	Yes
Multi Pi0 (background)	-	Yes (> 1 π^0)	Yes

Thin-Slice Method

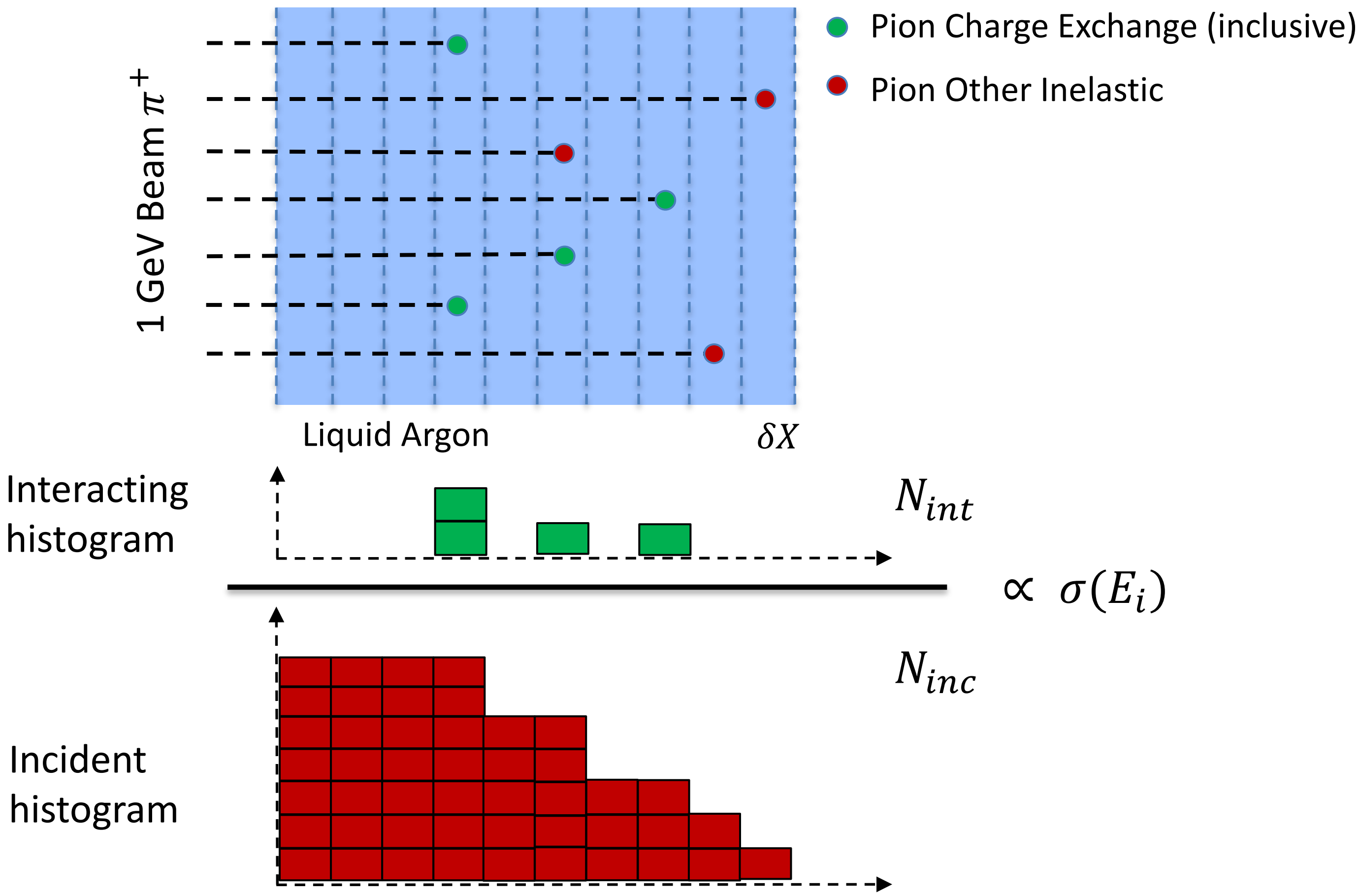


arXiv:2108.00040v1



- Interaction probability $\frac{N_{int}}{N_{inc}} = P_{Int} = 1 - \ e^{-\sigma_{Tot}\, n\, \delta X}$, $n = \frac{\rho N_A}{m_{Ar}}$ is the density of the target.
- The interaction length of pions in liquid argon is of the order of $\sim$ 50 cm.
- Treat the argon volume as a sequence of many adjacent thin targets.

Thin-Slice Method



$$\sigma = \frac{m_{Ar}}{\rho \delta X N_A} \ln\left(\frac{N_{inc}}{N_{inc} - N_{int}}\right)$$

- m_{Ar} is the mass of argon atom
- N_A is the Avogadro constant
- ρ is the density of liquid argon
- δX is the thickness of the slice
- N_{inc} is the number of incident beam pions in a slice
- N_{int} is the number of beam pions which have interactions in a slice

Francesca's thesis

Method Validation in Truth Level

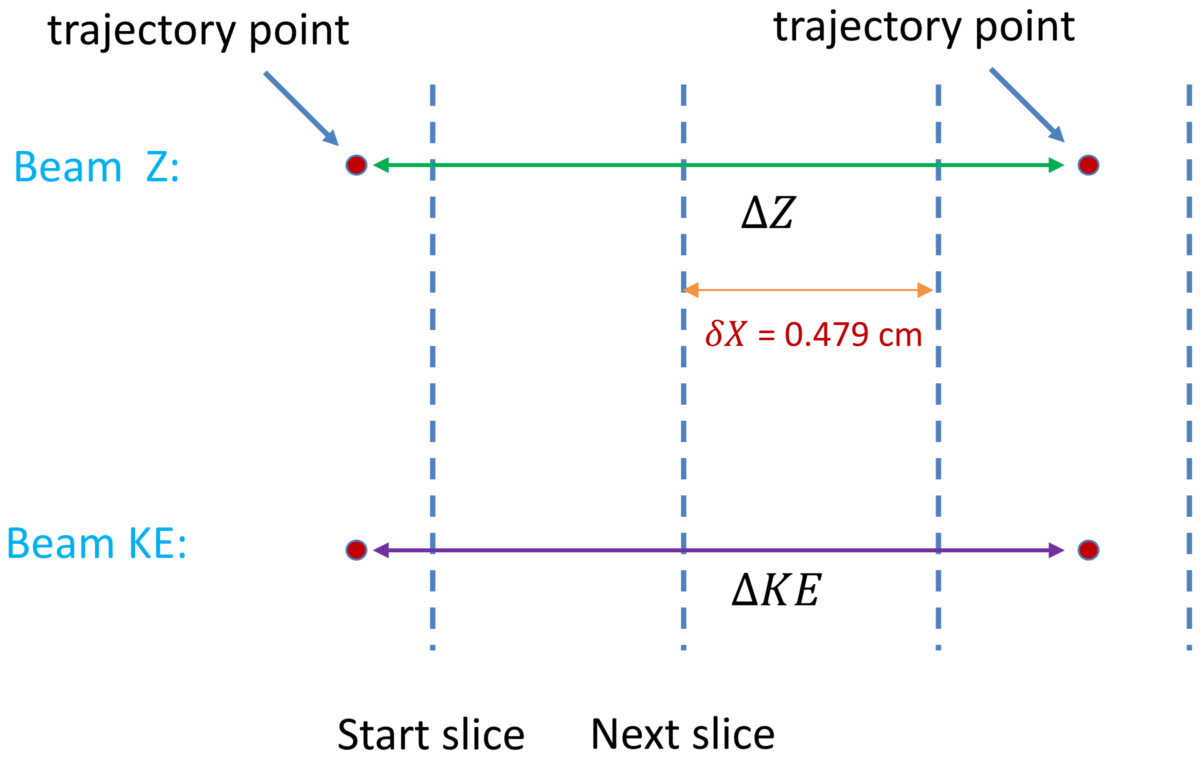
- N_{inc} and N_{int} are two 1D histogram in terms of beam pion kinetic energy (KE).

- Two PDSP Analyzer variables are used to fill the histograms:
  - true_beam_traj_Z (true beam trajectory points - z coordinates)
  - true_beam_traj_KE (true beam trajectory points – kinetic energy)

- Spatial slicing δX = 0.479 cm - wire spacing/pitch.

- Each histogram has a range of 0 – 1000 MeV with a bin width of 50 MeV

Method Validation in Truth Level

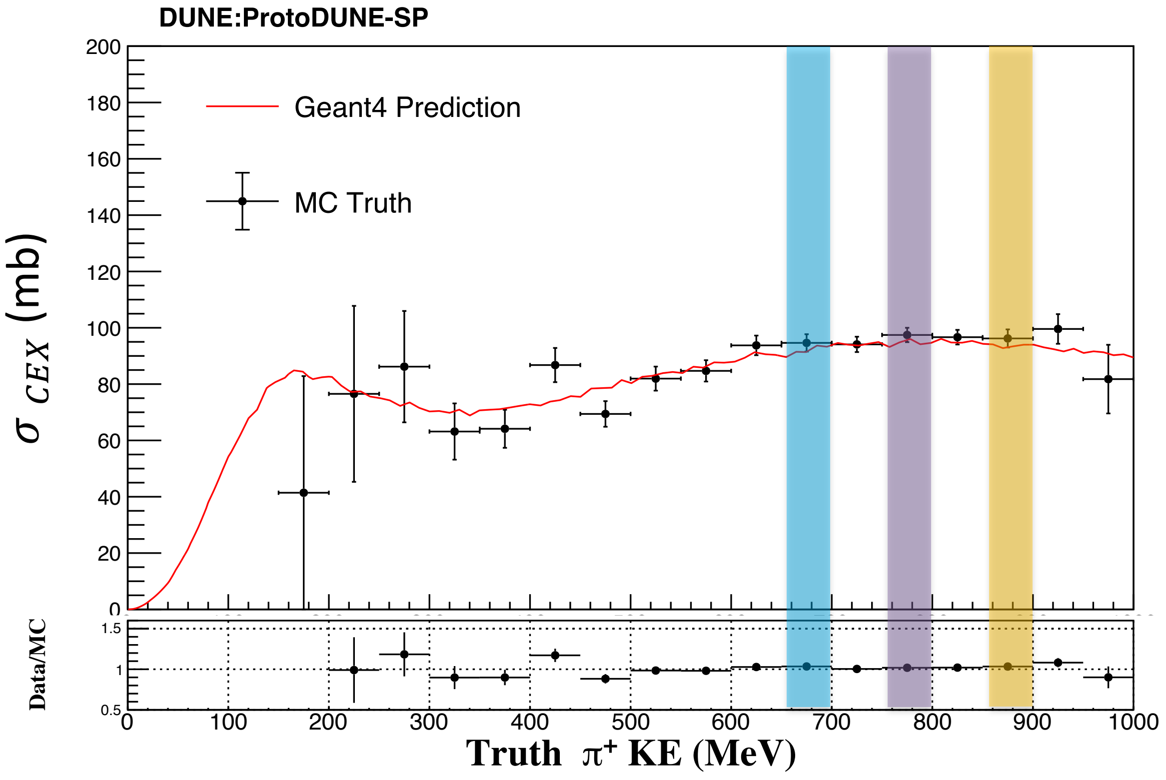


- Only include trajectory points starting in the active volume
- Only include trajectory points less than slice 464 (the end of APA3)
- Loop over all trajectory points
- Calculate ΔZ and ΔKE between adjacent points
- Use $\frac{\delta X}{\Delta Z} = \frac{\delta E}{\Delta KE}$ to get energy slices

- Obtain a new beam KE vector with wire pitch (0.479 cm) slicing
- If the last trajectory point ends within the APA3, the beam interacting energy is assigned.

Total Truth Cross Section σ_{CEX}

- If beam PDG is 211, then loop over the new KE vector and fill N_{inc} histogram.
- If beam end process is "pi+Inelastic" and with charge exchange topology, then fill N_{int} histogram with the last element of the new KE vector .
- For each bin i, the cross section is calculated as:
- $\sigma_i = \frac{m_{Ar}}{\rho \delta X N_A} \ln\left(\frac{N_{inc}}{N_{inc} - N_{int}}\right)_i$
- m_{Ar}= 39.95 g/mol, ρ = 1.39 g/cm^3
- N_A = 6.02 *10^23 1/mol, δX = 0.479 cm



Differential Cross Section Formula

$$\sigma_i \approx \frac{m_{Ar}}{\rho \delta X N_A} \frac{N_{int}^{i}}{N_{inc}^{i}}$$

- Calculate the differential cross section as,

$$\left(\frac{d\sigma}{dE_{\pi^0}}\right)_{ij} = \frac{m_{Ar}}{\rho \delta X N_A} \frac{1}{(\Delta E_{\pi^0})} \frac{N_{int}^{ij}}{N_{inc}^{i}} \quad \text{(Eq. 1)}$$

ΔE_{π^0} is the bin width of π^0 KE

Index i : beam E_{π^+} bin,

Index j : daughter E_{π^0} bin

- Thin slice total CEX cross section is,

$$\sigma_i = \frac{m_{Ar}}{\rho \delta X N_A} \frac{N_{int}^{i}}{N_{inc}^{i}} \quad \text{(Eq. 2)}$$

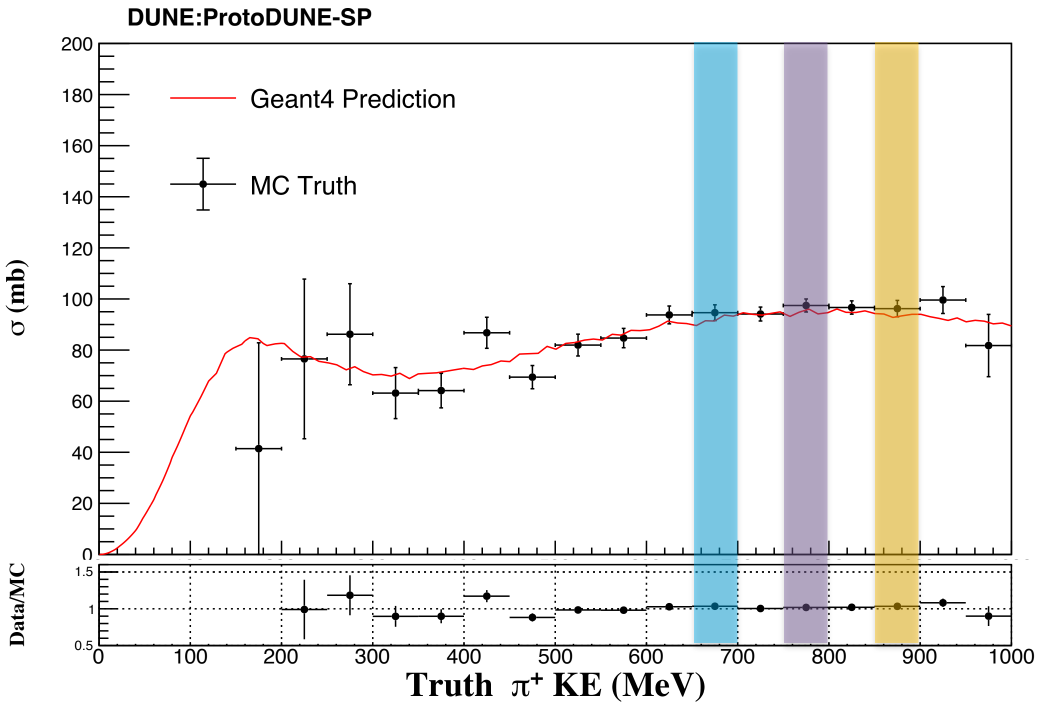
- Then the differential cross section formula is (Sub. Eq. 2 into Eq. 1),

$$\left(\frac{d\sigma}{dE_{\pi^0}}\right)_{ij} = \frac{1}{(\Delta E_{\pi^0})} \frac{N_{int}^{ij}}{N_{int}^{i}} \sigma_i$$

Thank you Jonathon Sensenig for useful discussions!

GEANT4 and Truth dσ Calculation

- The Geant4Rewight package is used to extract the differential cross section, $\frac{d\sigma}{dE}$
- Measure differential XS at each bin i (for a given pion KE).

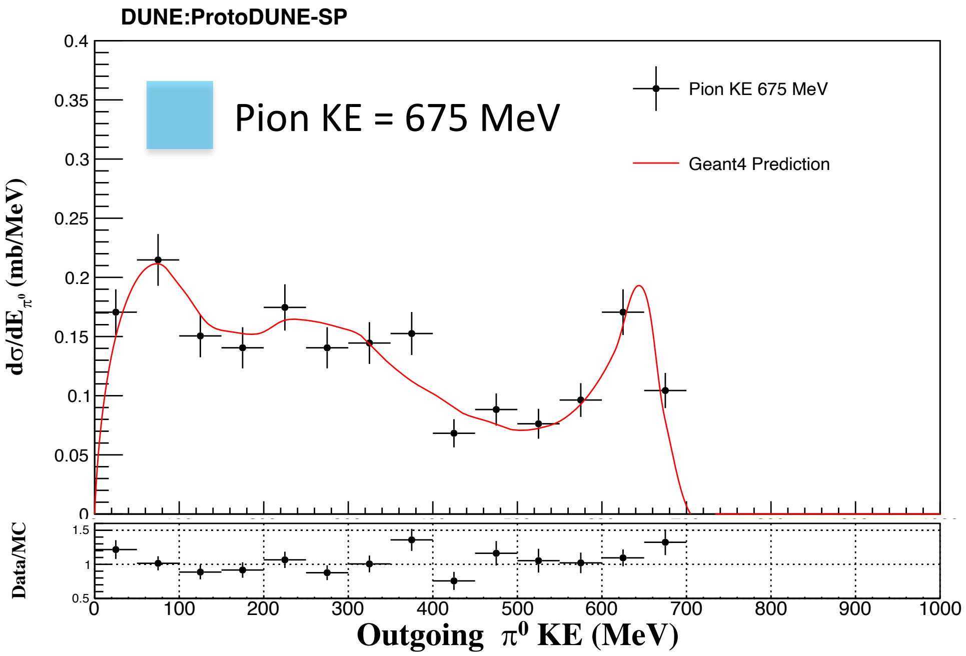


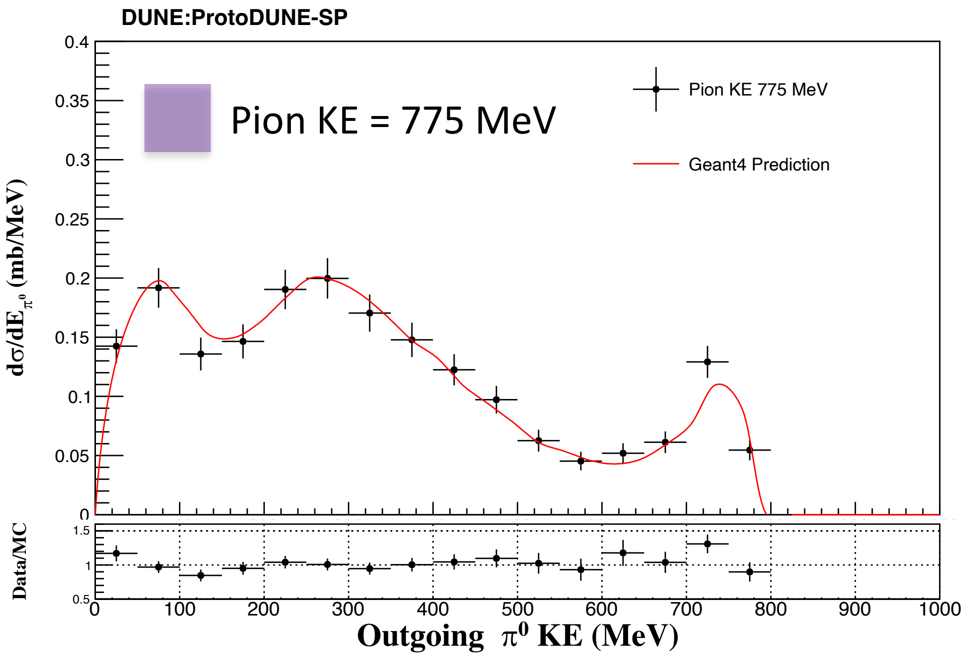
- ➢ Pion KE = 675 MeV → Evaluate $\sigma_{KE=675\ MeV}$
- ➢ Pion KE = 775 MeV → Evaluate $\sigma_{KE=775\ MeV}$
- ➢ Pion KE = 875 MeV → Evaluate $\sigma_{KE=875\ MeV}$

- Differential XS for bin j (daughter E_{π^0} bin) is,

$$\left(\frac{d\sigma}{dE_{\pi^0}}\right)_j = \frac{1}{(\Delta E_{\pi^0})}\frac{N_{int}^j}{N_{int}}\sigma_{KE=775\ MeV}$$

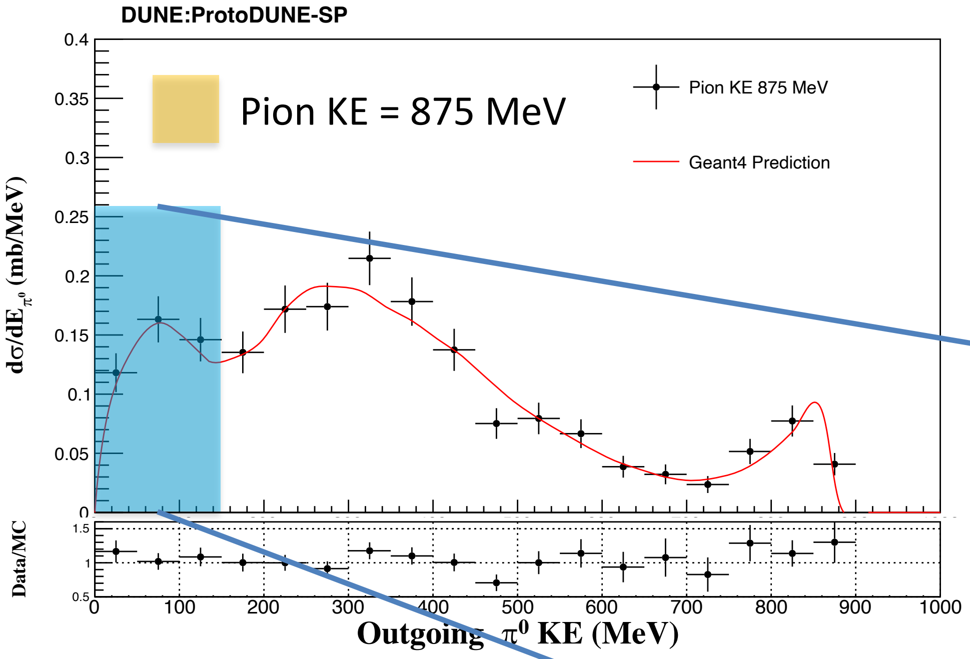
dσ Validation in Truth Level



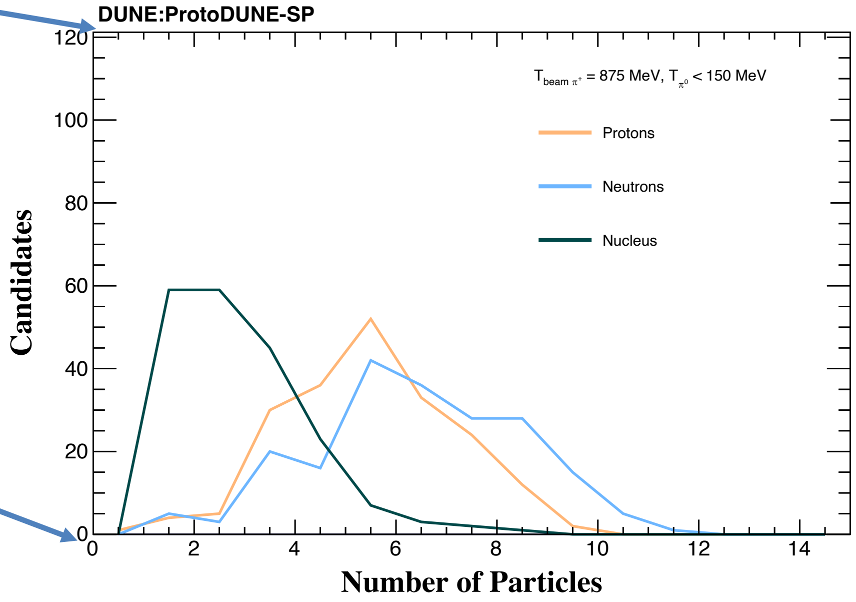


- The differential cross section formula works well in truth level.
- There are three peaks in the differential cross section distribution.

Low E_{π^0} Region

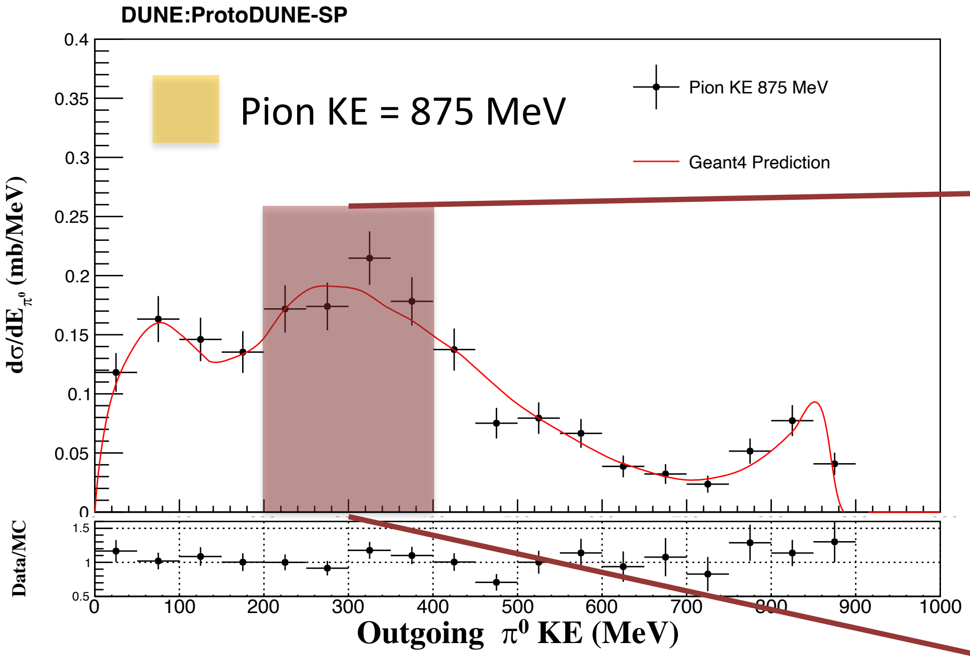


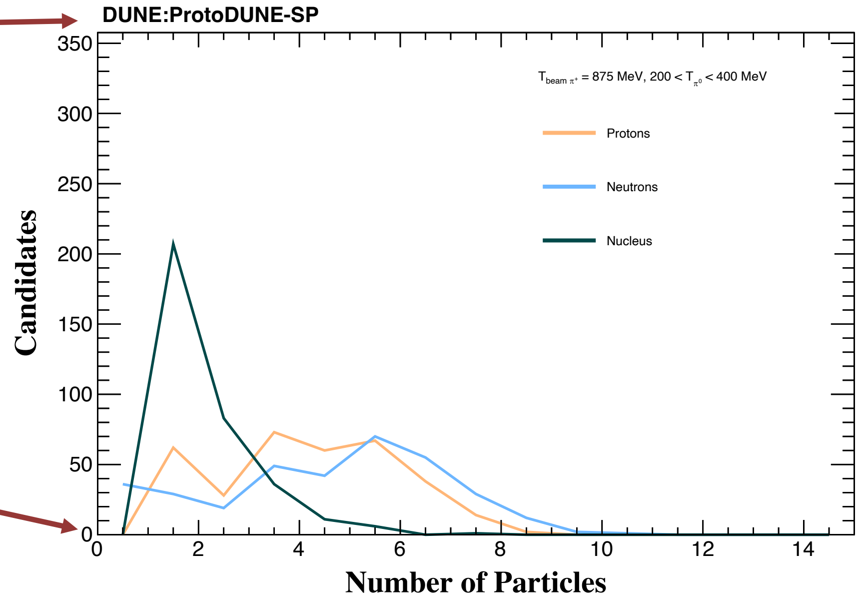
- Nucleus is defined as PDG > 2212, such as a Δ baryon.
- Many daughter nucleons.
- The direction of π^0 is arbitrary.



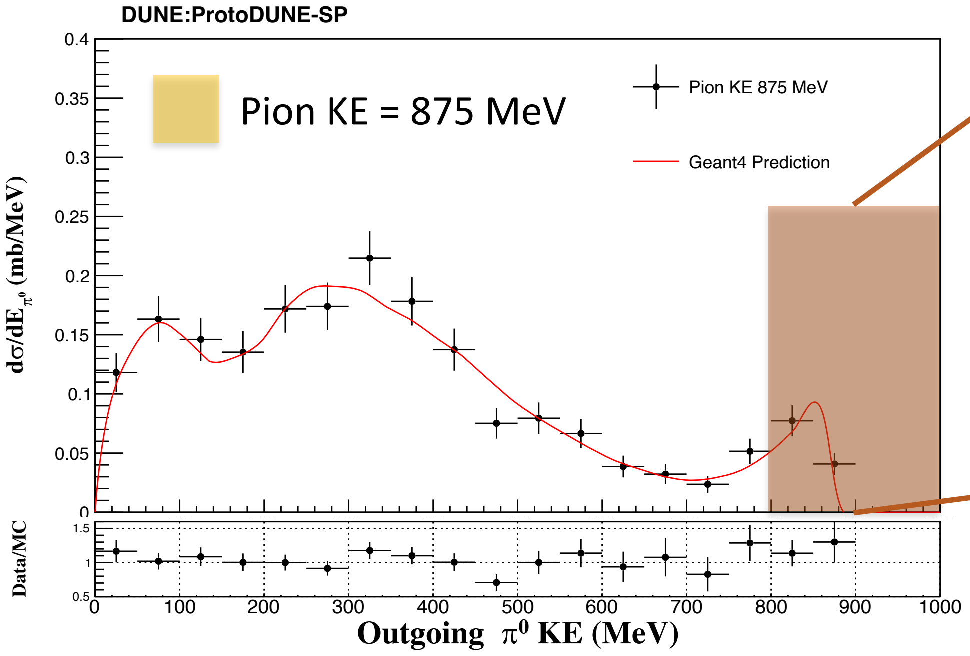
Middle E_{π^0} Region

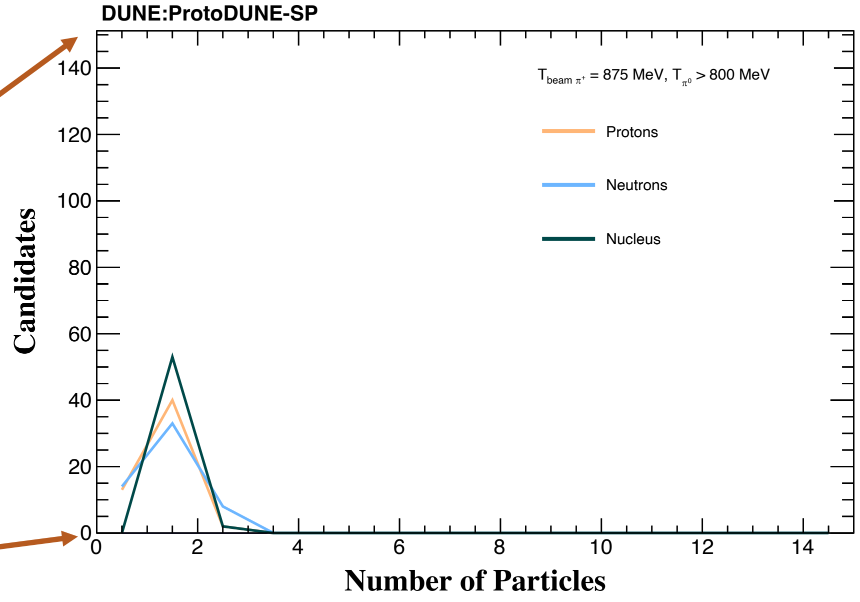
- Less Δ baryons are produced.





High E_{π^0} Region





- Only one Δ baryon is produced.
- Decays into a nucleon and a π^0.
- The direction of π^0 is forward.

Fake Data Test

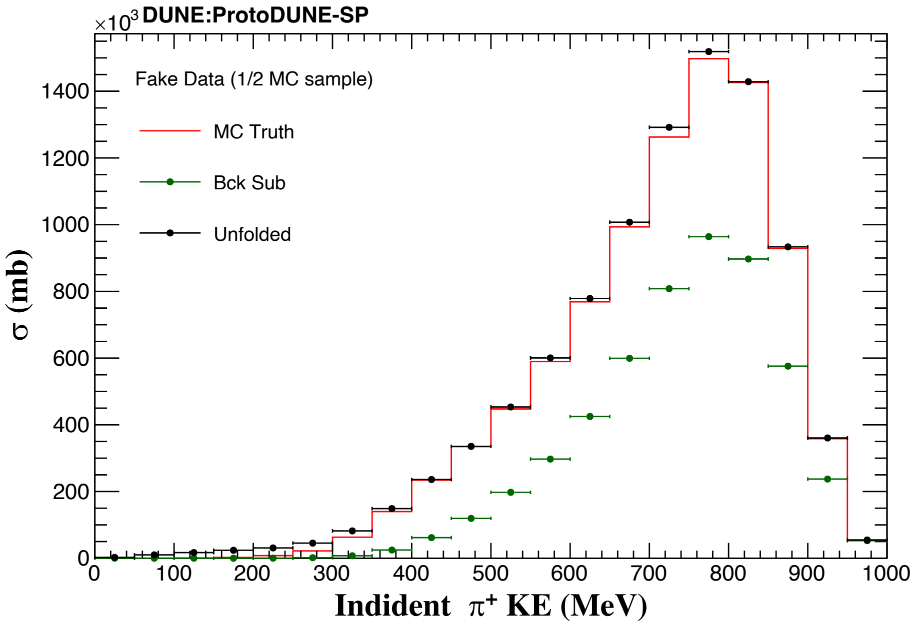
Fake Data

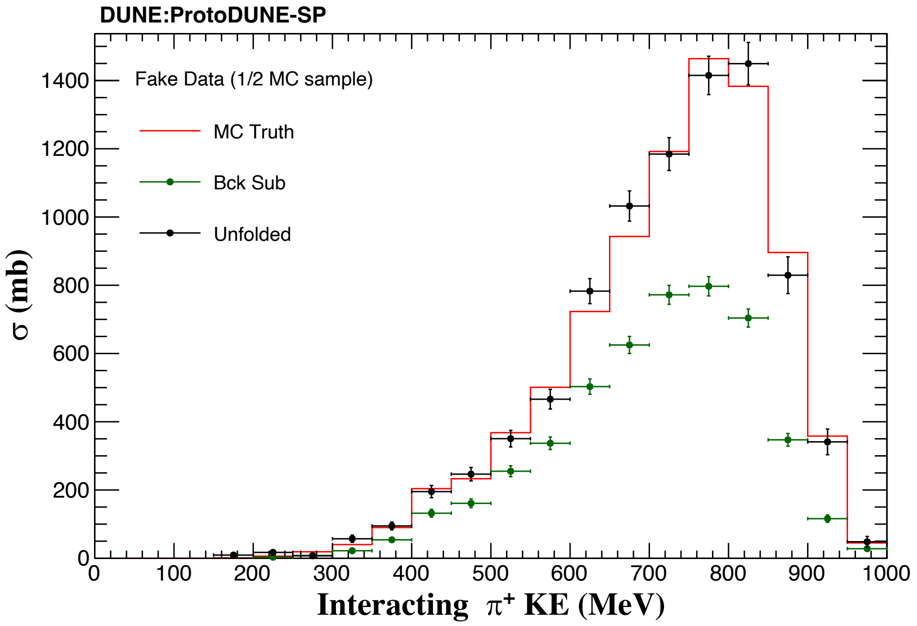
- Full 1GeV Pion MC sample is divided into 2 sub-samples.
  1. Fake Data
  2. MC
- MC sample is used to train the mapping response matrix for unfolding.

- Fake Data is used to validate the cross section extraction procedures.

- The unfolding is done using RooUnfold package (iterative Bayesian method, 4 iterations)

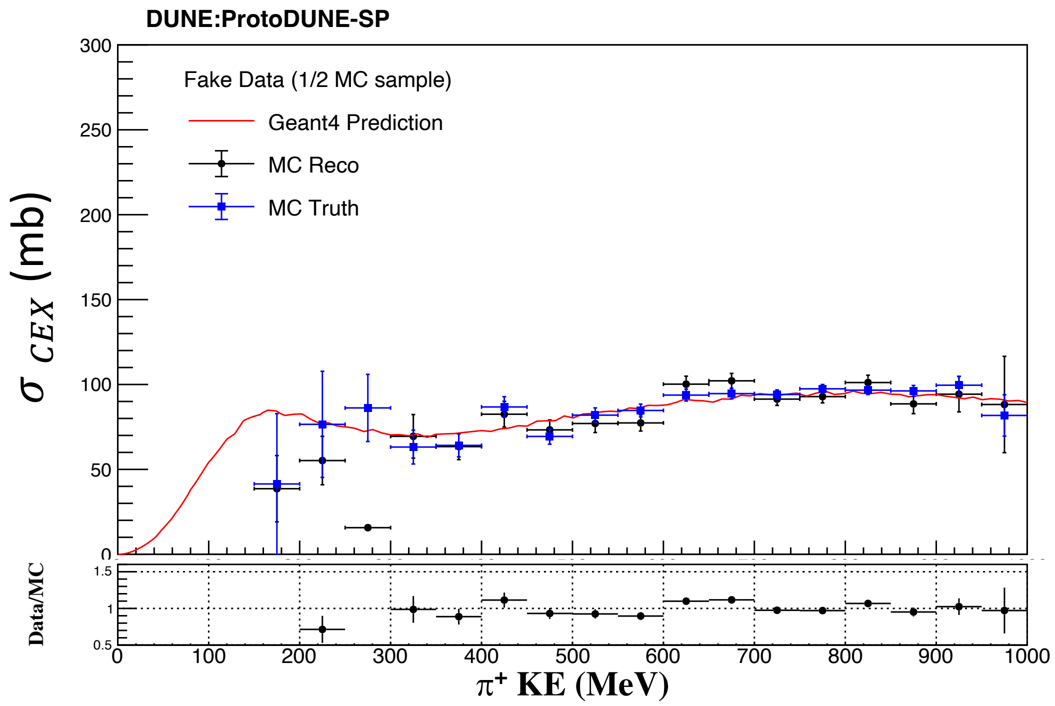
Background Subtraction & Unfolding





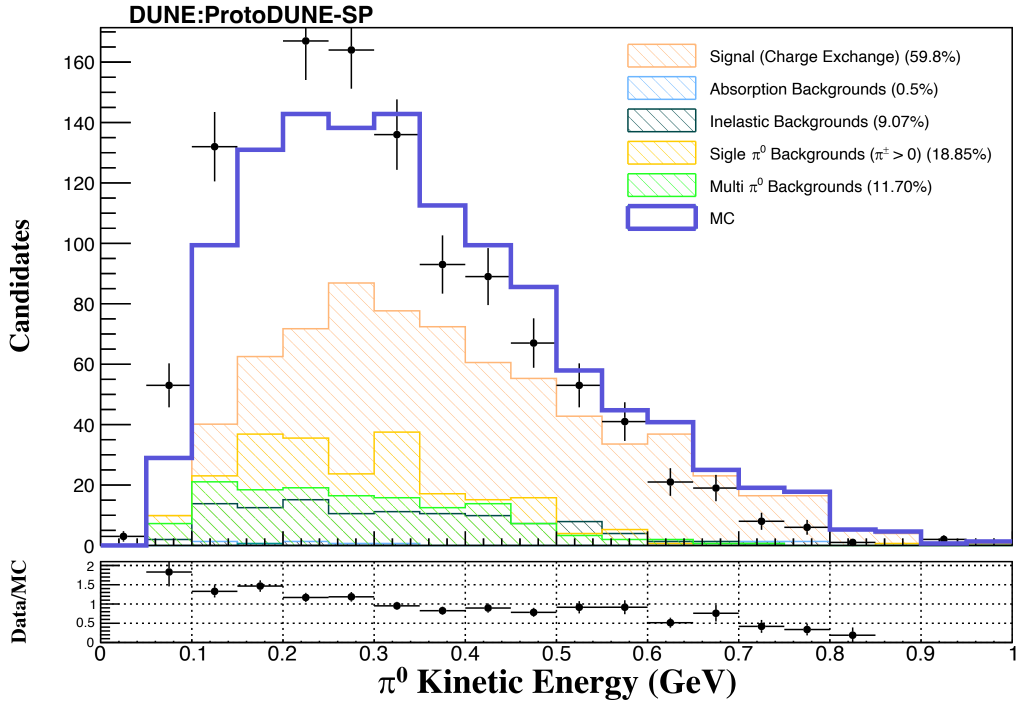
- Mapping response matrix is trained using half of the total MC.
- The other half of the MC is used to test the unfolding procedures.
- The red histogram is computed using the truth information of the fake data sample.

Total Cross Section σ_{CEX} Measurement



- MC Reco is the fake data sample after background subtraction and unfolding.
- MC Truth is derived using the truth information of the fake data sample.
- Above 300 MeV, both Reco and Truth agree with the Gean4 predication well.

π^0 Kinematic Energy Reconstruction



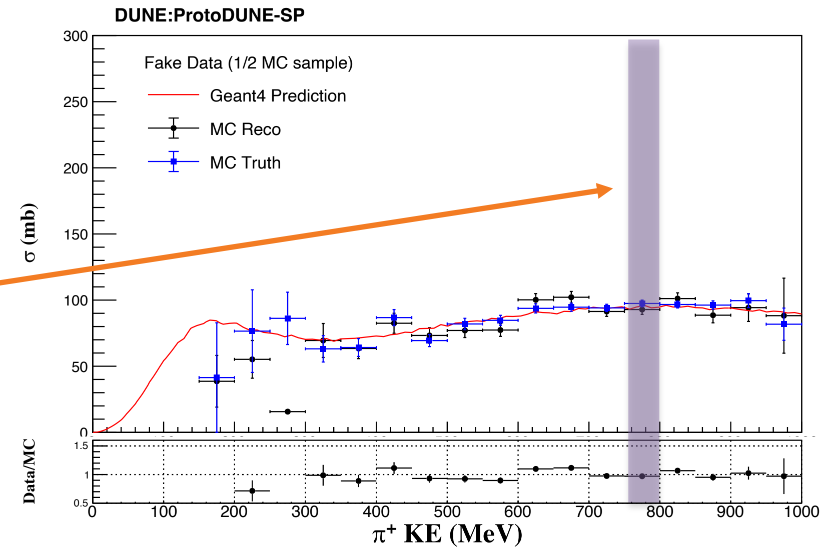
! All Reco Pion Beam Sample !

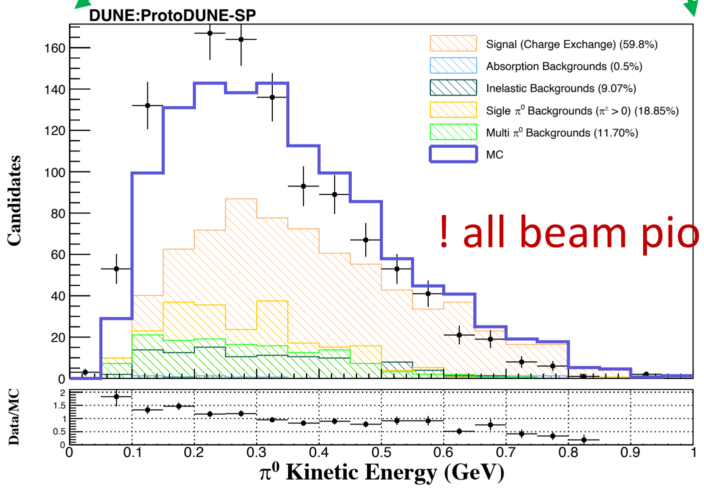
- Reconstructed π^0 kinetic energy distribution from my previous π^0 analysis.
- Event topology definitions can be found in page 2.
- Signal (charge exchange) is around 60%.
- The largest background is single π^0 events but with $\pi^{+/-} > 0$ (19%)
- No phase space cut on daughter $\pi^{+/-}$ (cannot detect pion with mom. < 150 MeV/c)

Towards dσ Measurement

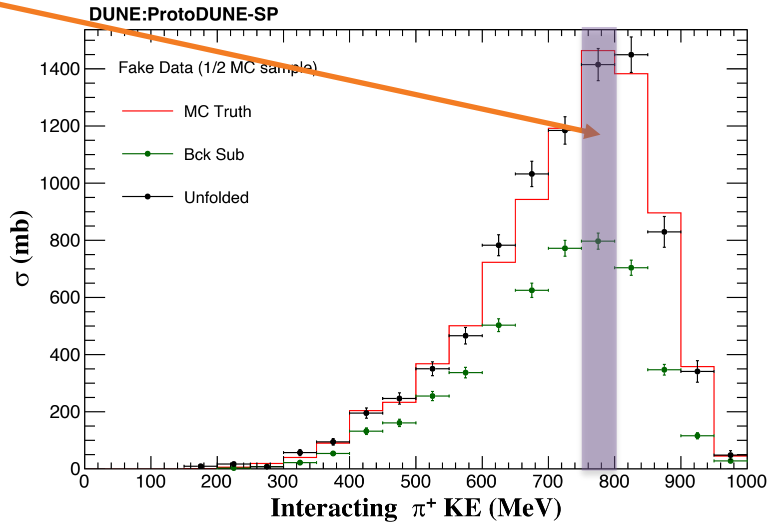
- Differential XS for bin j (daughter E_{π^0} bin) is,

$$\left(\frac{d\sigma}{dE_{\pi^0}}\right)_j = \frac{1}{(\Delta E_{\pi^0})}\frac{N_{int}^j}{N_{int}}\sigma_{KE=775\ MeV}$$





! all beam pion sample !



Summary

- The formula for computing the differential cross section is discussed.
- Truth-level validation is performed and shows good agreement with Geant4 input.
- Fake data sample (1/2 of MC sample) is used to perform the charge exchange cross section measurement.
- After unfolding, both MC Reco and Truth of the fake data sample agree well with the prediction.
- Obtained all the ingredients for differential cross section measurements using fake data.