π^+-Ar inclusive cross-section measurement on ProtoDUNE-SP

Yinrui Liu on behalf of the DUNE collaboration

University of Chicago

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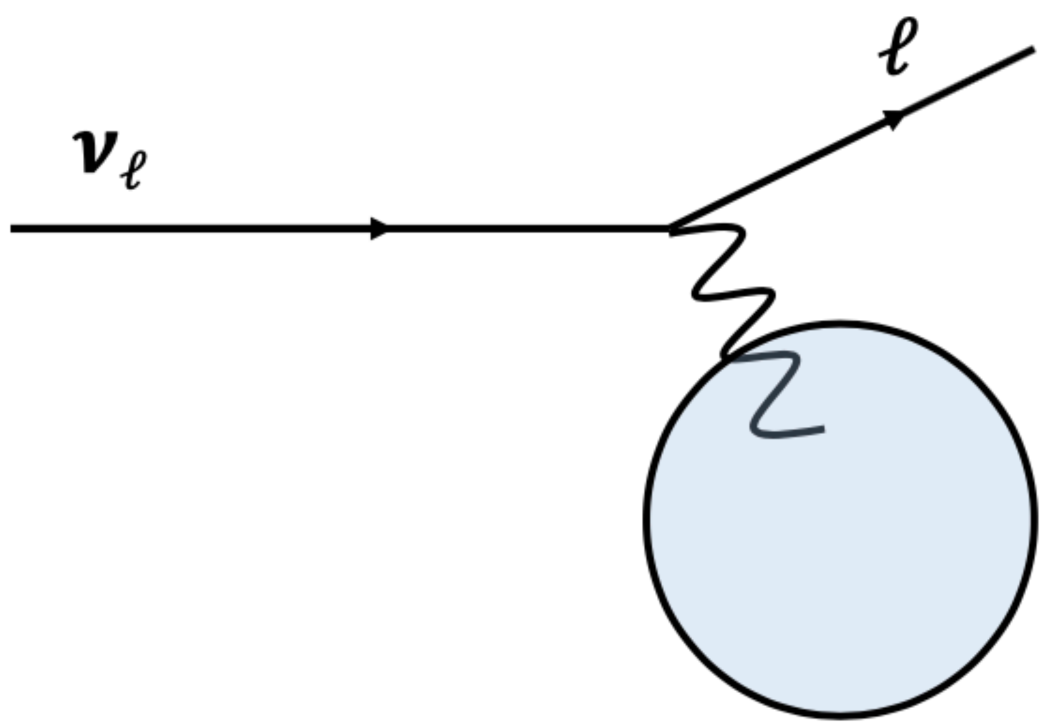
Introduction

- In modern neutrino experiments such as DUNE, we detect neutrino by its interaction with atoms.
- The initially produced hadrons can also interact within the nucleus, which will change the kinematics of particles emitted from the atom. This is called the hadronic final state interaction (FSI) effect.



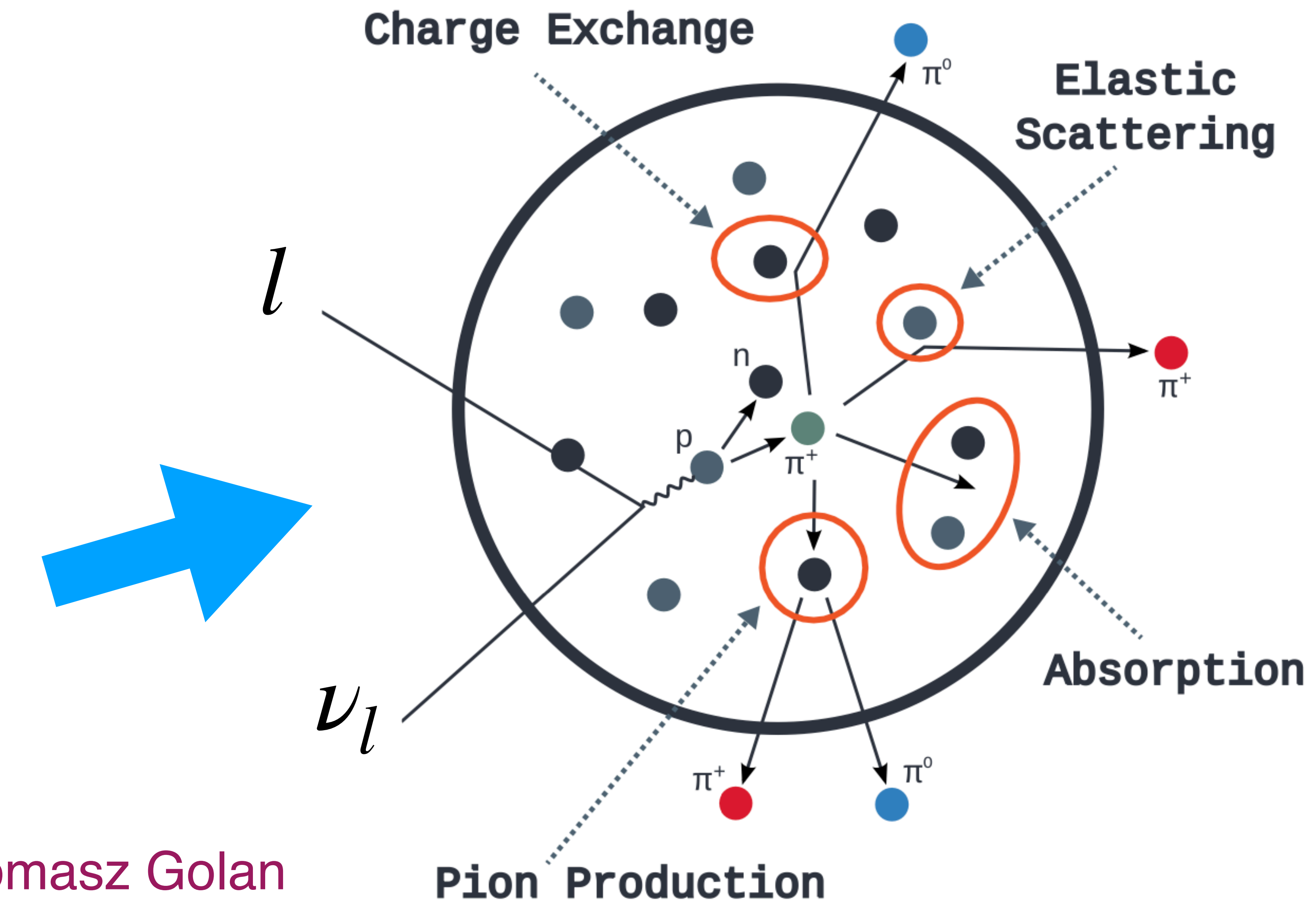


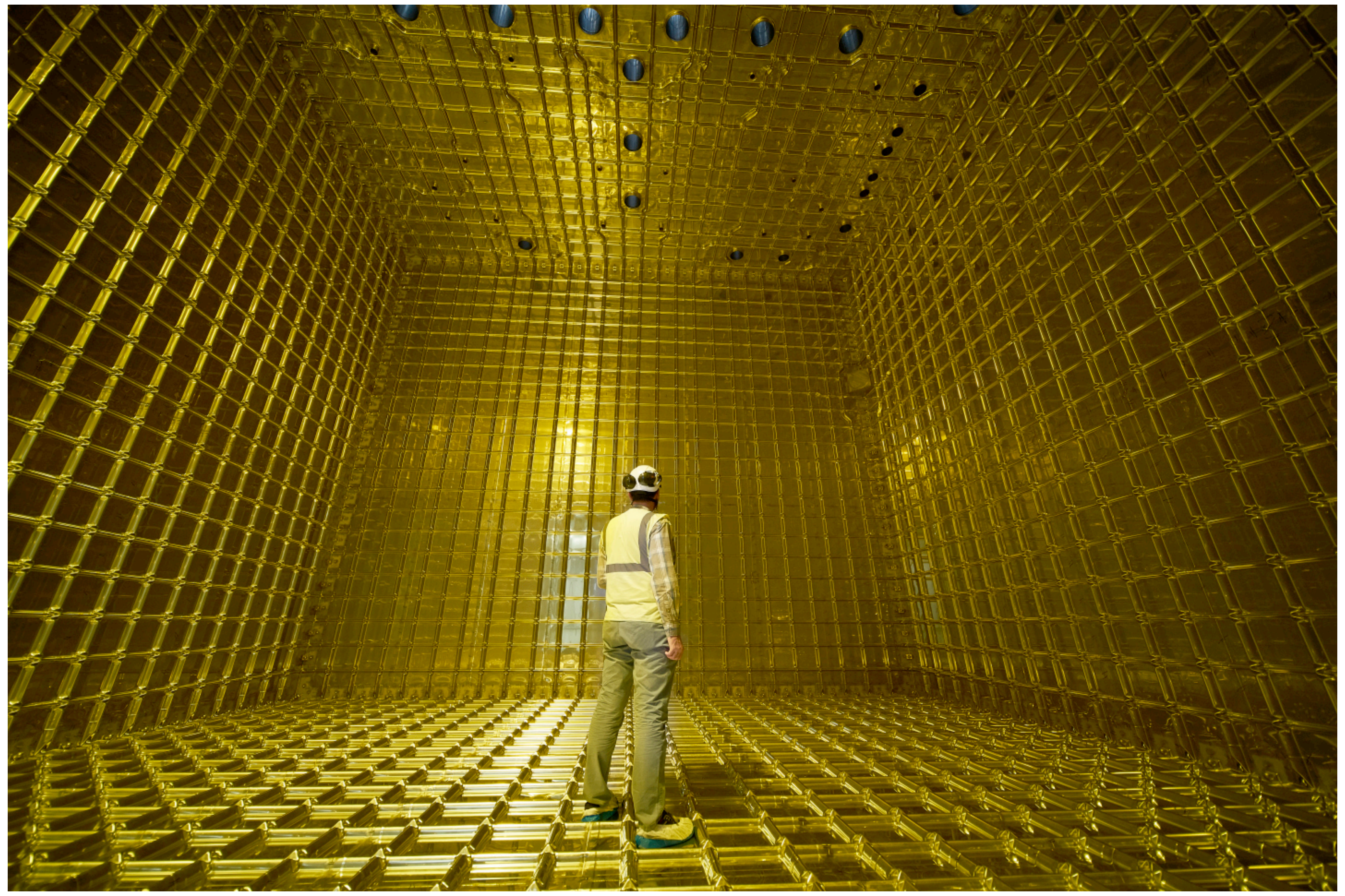
Figure credit: Tomasz Golan

- The FSI accounts for a major source of systematic uncertainty in oscillation analyses.

ProtoDUNE-SP

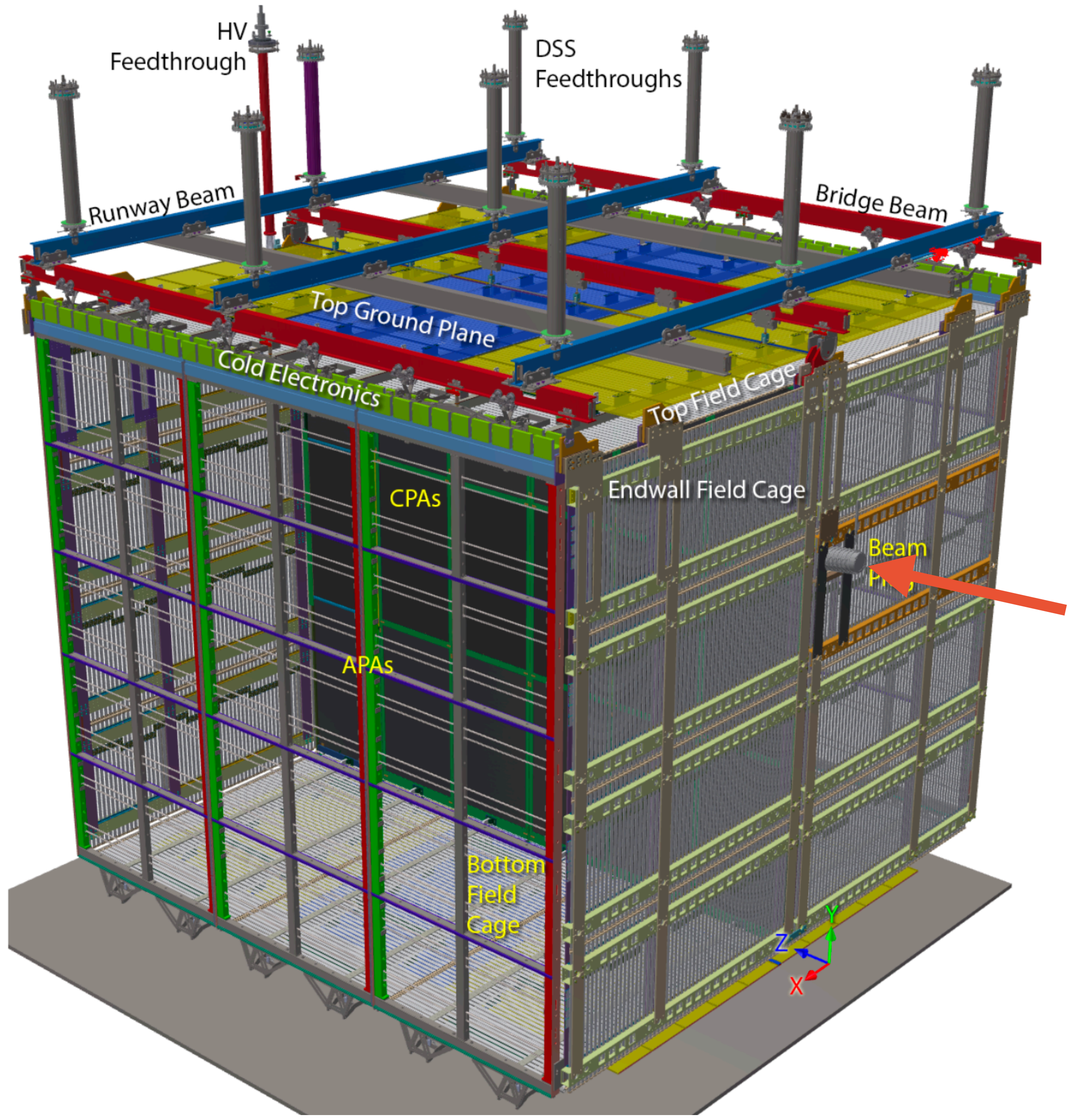
First results published in 2020 (https://iopscience.iop.org/article/10.1088/1748-0221/15/12/P12004)

- ProtoDUNE-SP is a single-phase LArTPC which contains 770 ton LAr, which is a prototype for DUNE far detectors (17 kton LAr × 4).



A person inside the ProtoDUNE-SP cryostat, which will later be filled with 770 t LAr

The active volume is 7.2×6.1×7.0 m³ (x*y*z)



A view of the active volume of ProtoDUNE-SP

- Charged particles (π^+, K^+, p, μ^+ and e^+) with various momentum modes (0.3, 0.5, 1, 2, 3, 6, 7 GeV) are delivered into the TPC through a **beam plug**, which is suitable to measure hadron-argon XS.

Cross-section (XS) measurement

- Currently, pion-argon XS is mainly predicted by interpolating data from lighter and heavier nuclei. Only LADS (1999) and LArIAT (2021) have performed such measurements.

- To measure the XS between a type of particle with an atom, people usually have the particle beam shoot at a thin target made of the atom, and detect its survival rate.

$$\sigma = \frac{M_{\text{atom}}}{\rho t N_A} \ln\left(\frac{N_{\text{inc}}}{N_{\text{sur}}}\right)$$

- M_{atom} is the molar mass of atom
- N_A is the Avogadro constant
- t is the thickness of the target
- ρ is the density of the target material
- N_{inc} is the number of incident particles
- N_{sur} is the number of survived particles

- However, a detector filled with LAr is not a thin target in terms of pions.

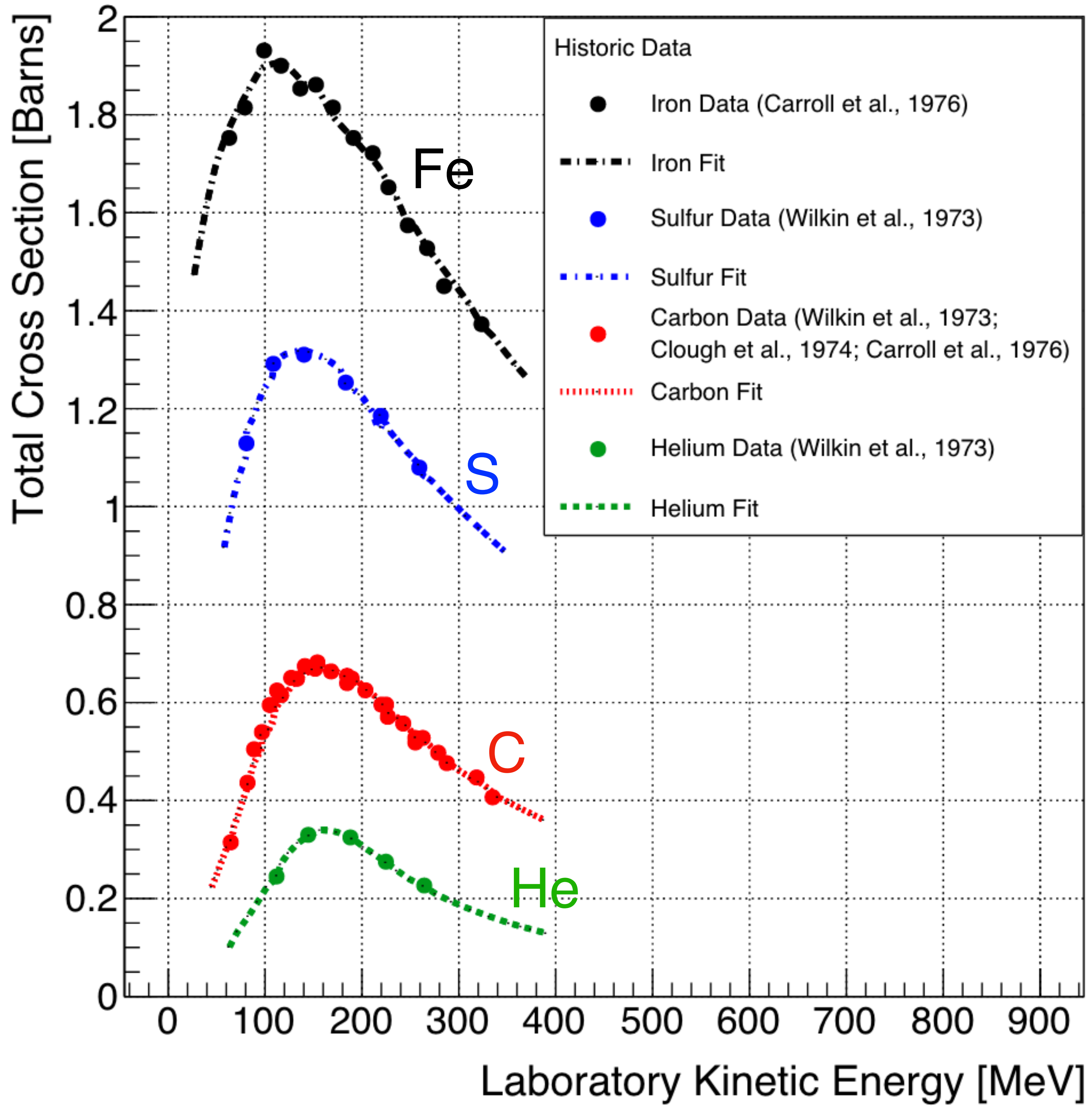
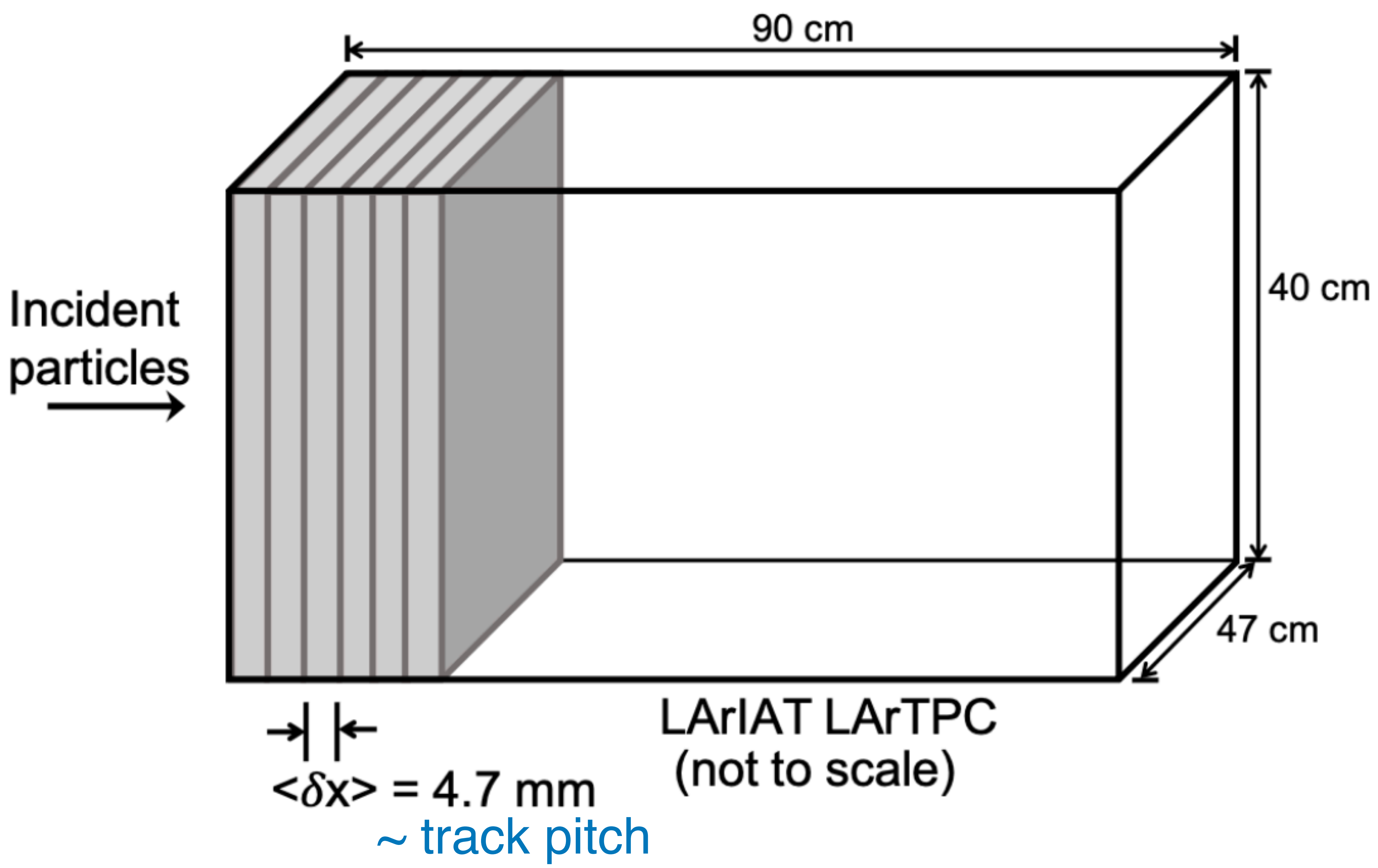


Figure from arXiv:2108.00040

Slicing method

- LArIAT (Liquid Argon In A Testbeam) collaboration proposes the thin-slice method, where they divide the detector into several slices, and each slice can be treated as a thin target to measure pion-argon cross-section.



Thin-slice method

Figure from arXiv:2108.00040

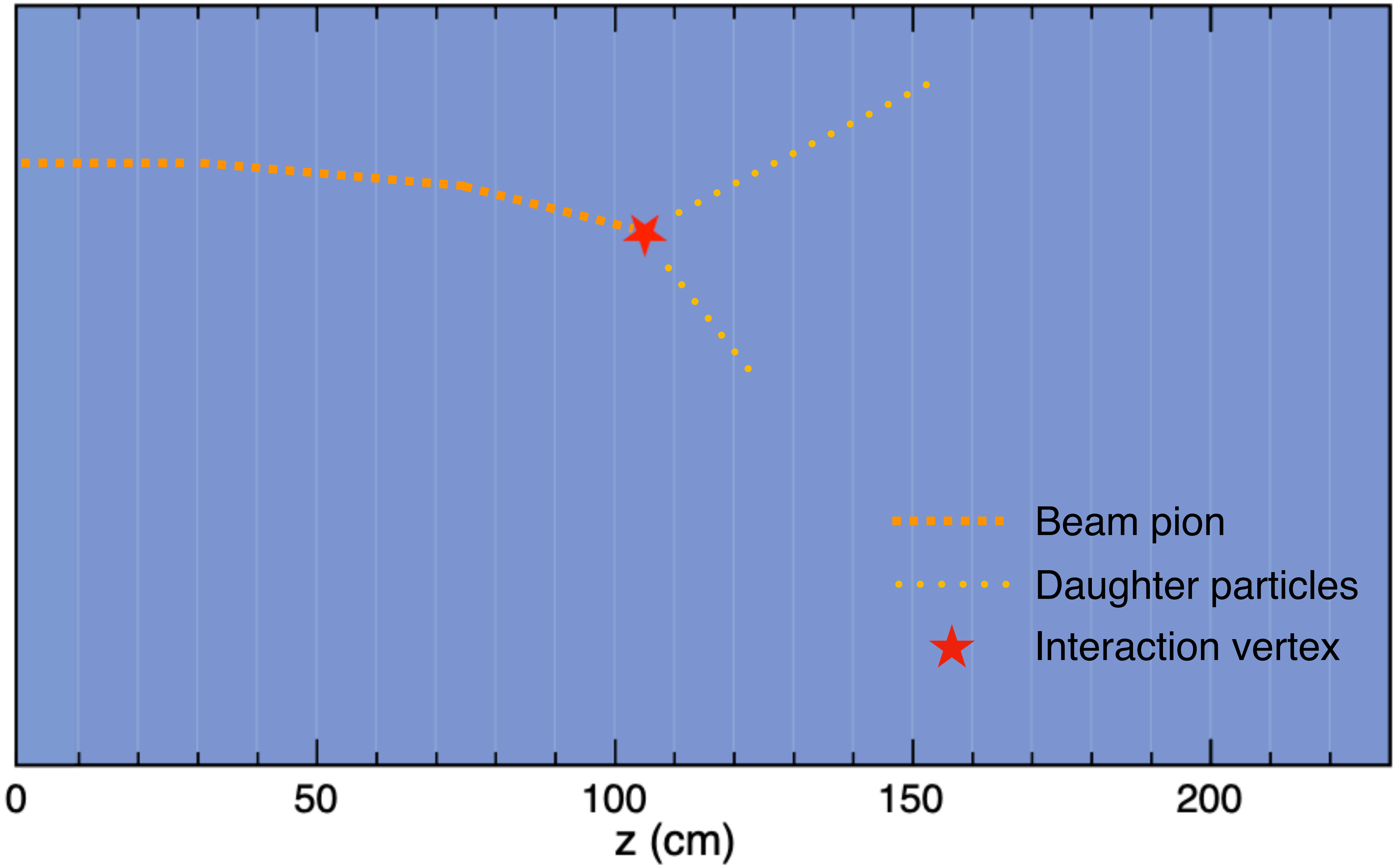
$$\sigma = \frac{M_{\mathrm{Ar}}}{\rho \delta x N_A} \ln\left(\frac{N_{\mathrm{inc}}}{N_{\mathrm{inc}} - N_{\mathrm{int}}}\right)$$

- M_{Ar} is the mass of an 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 interaction in a slice

Energy-slicing method

- For a large-scale TPC like ProtoDUNE-SP, it is subject to space charge effect.
- Based on the thin-slice method, we propose the energy-slicing method, which slices the track by the beam particle kinetic energy (KE)
  - Predefined energy bin edges

[0, 350, 450, 500, 550, 600, 650, 700, 750, 800, 850, 950, ∞) MeV



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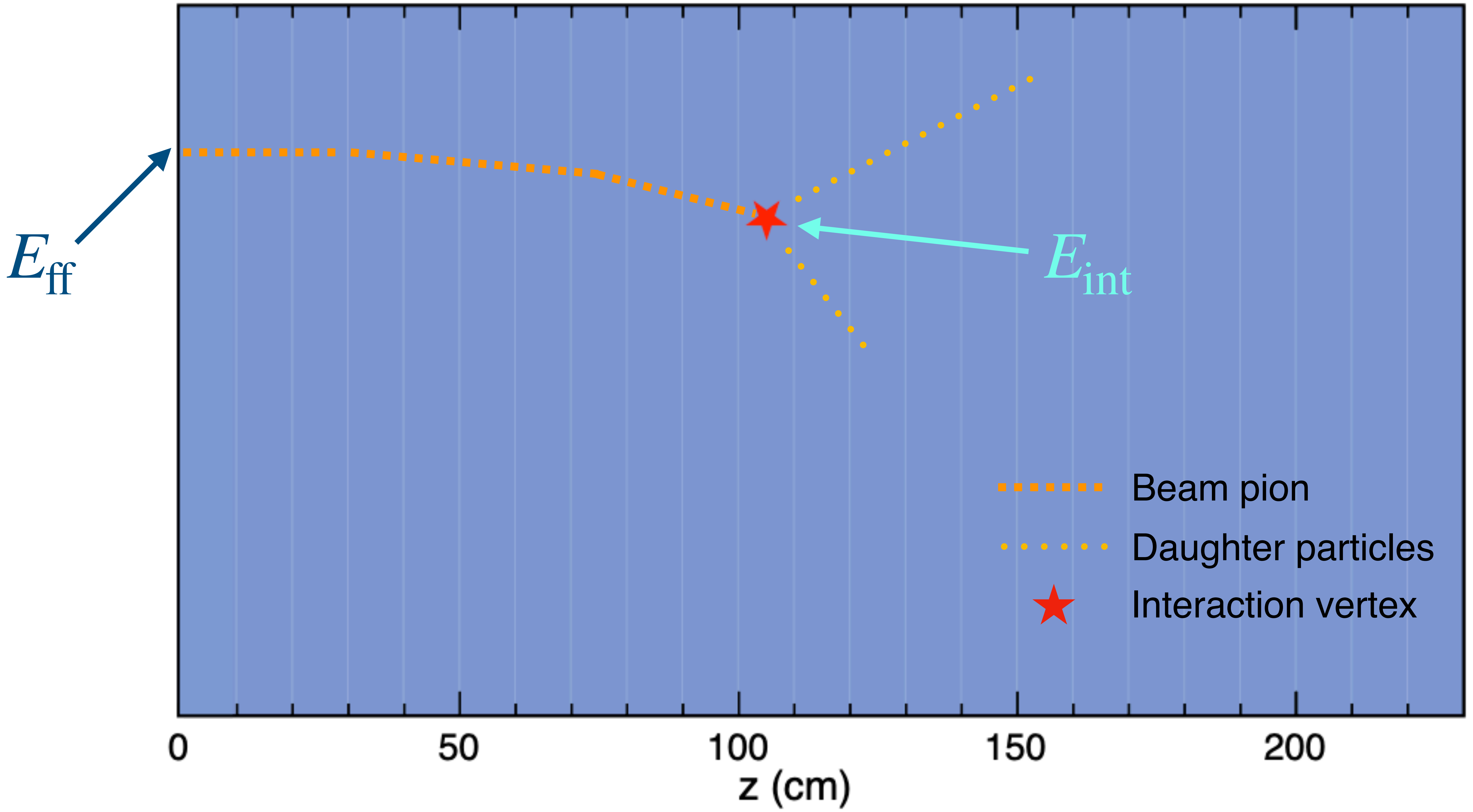
For each beam pion track:

- E_{ff} : the particle KE at the front-face of the TPC
- E_{int} : the particle KE at the interaction vertex



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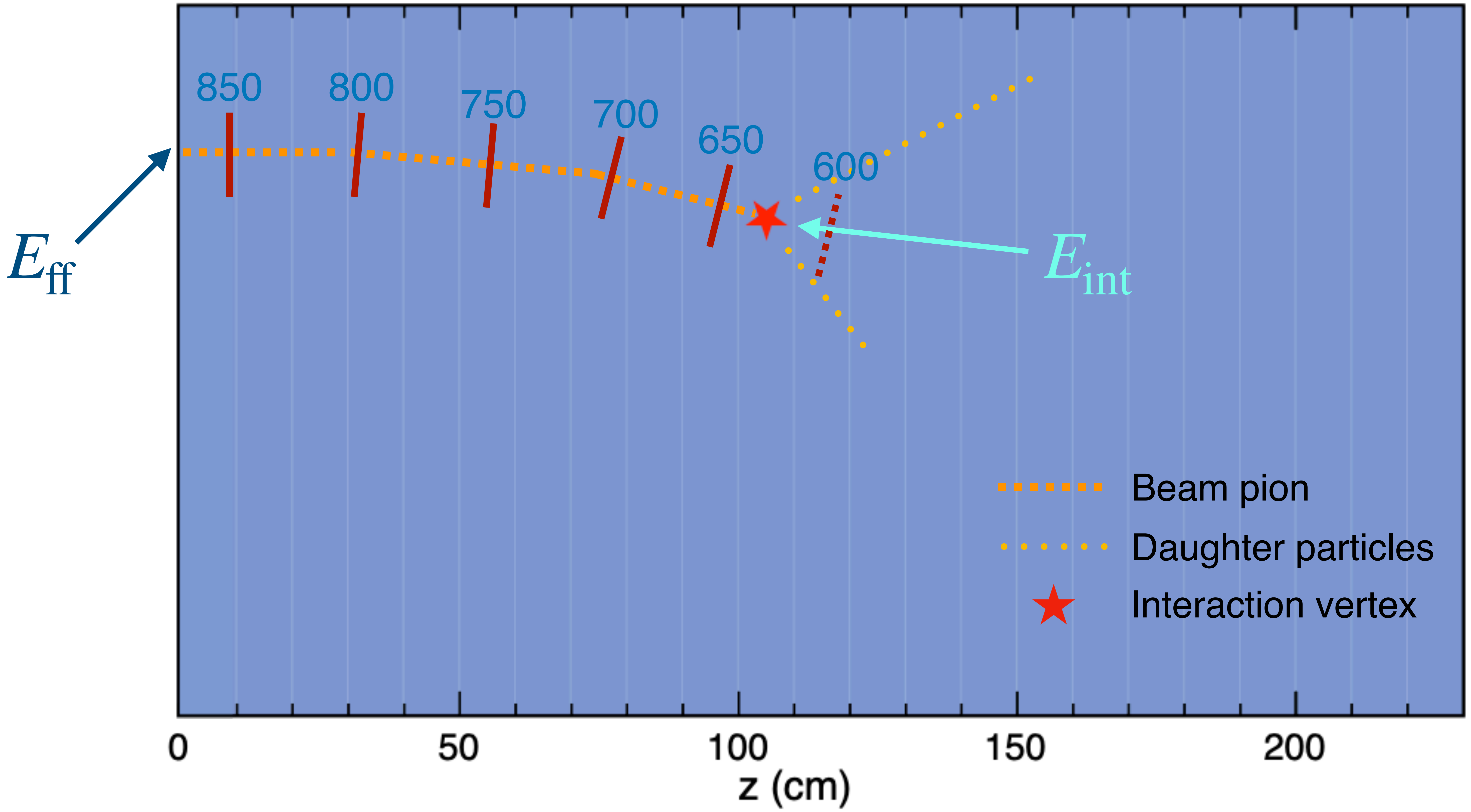

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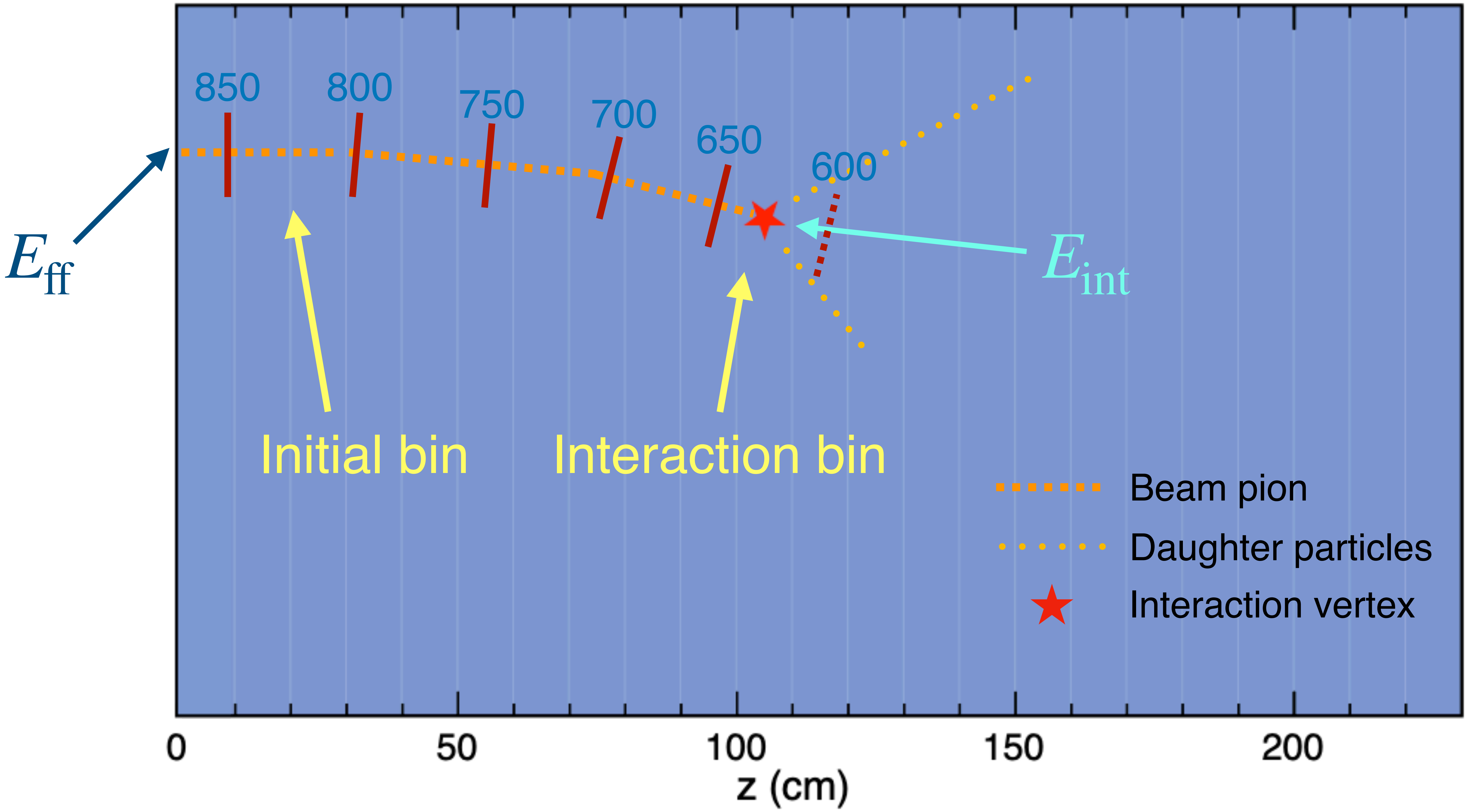
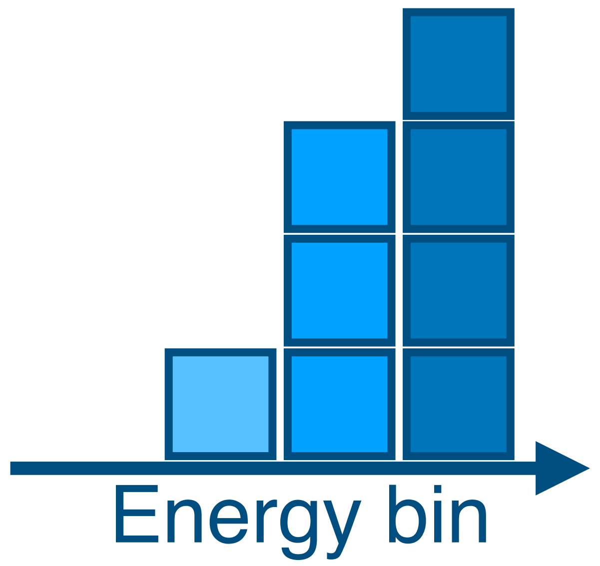


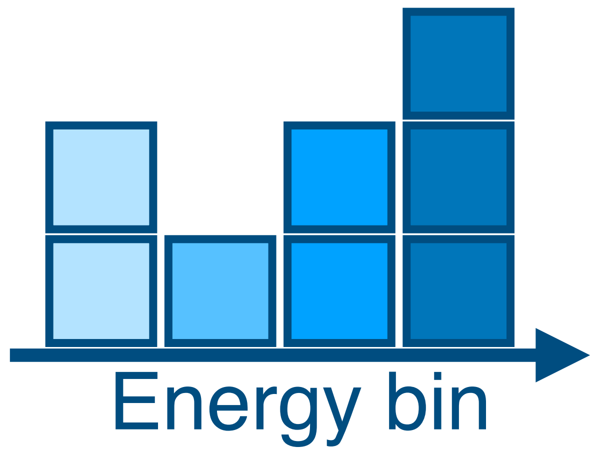
Energy-slicing method

N_{initial}



- The number of events that enter the TPC in each energy bin.

$N_{\text{interaction}}$



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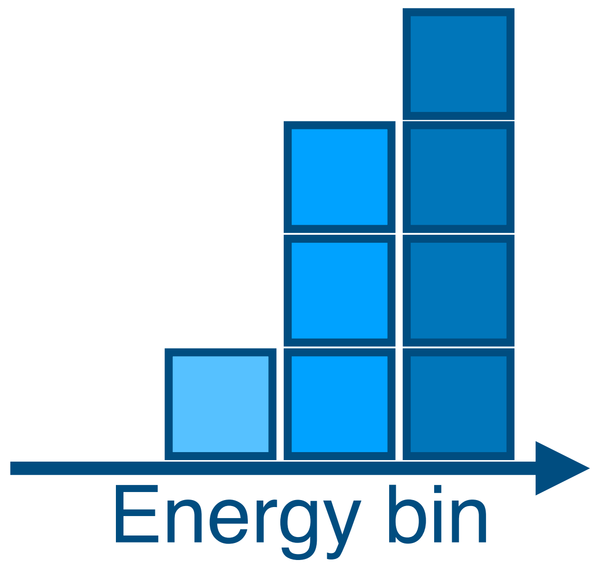

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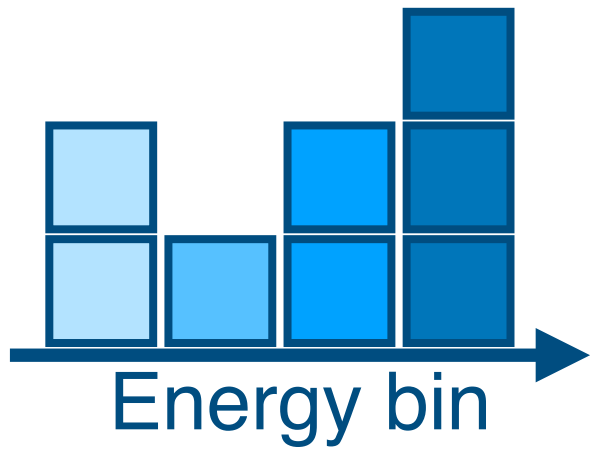

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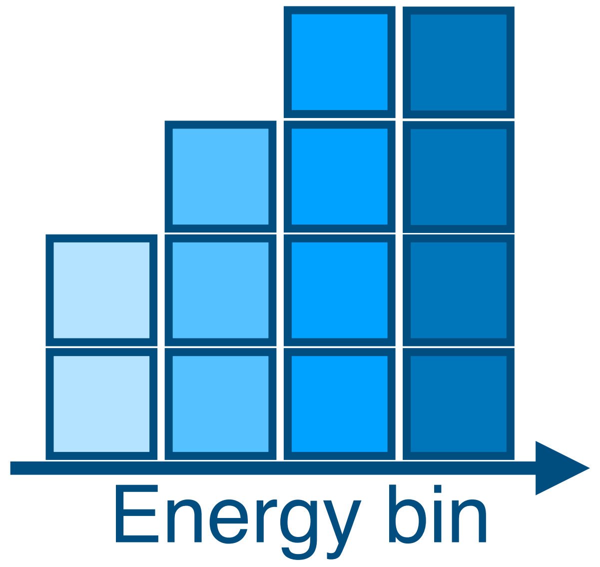

- The number of incident events in each energy bin.
- Given by

$$N_{\text{inc}}(i) = \sum_{j=i}^{N} N_{\text{int}}(j) - \sum_{j=i+1}^{N} N_{\text{ini}}(j)$$

Energy-slicing method

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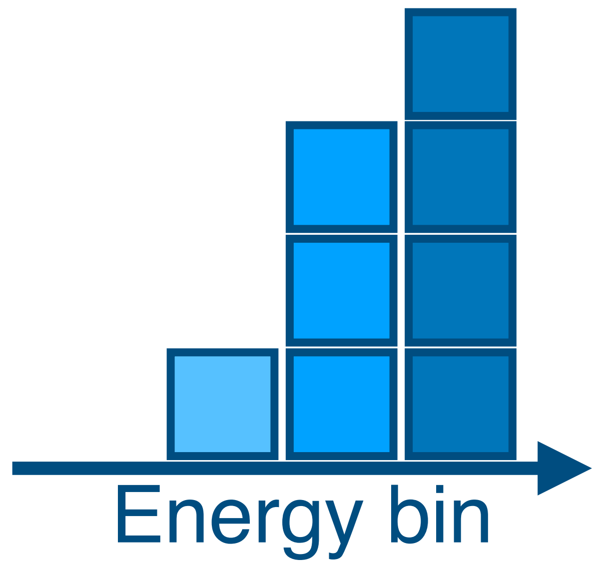

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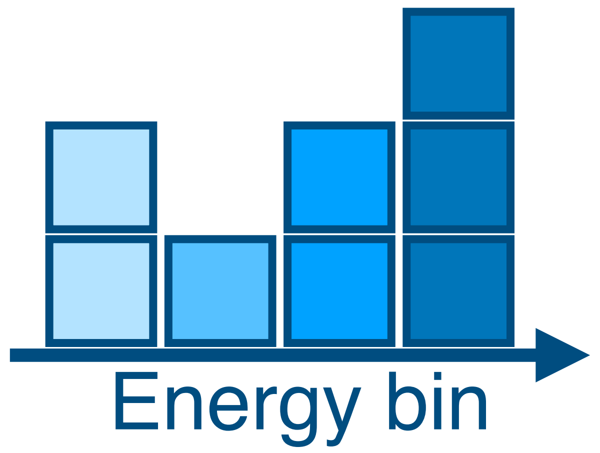

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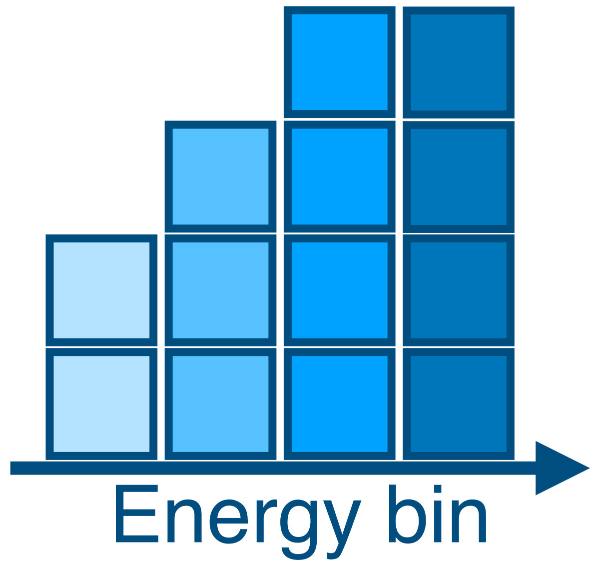

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$$\sigma(E) = \frac{M_{\text{Ar}}}{\rho N_A \Delta E} \frac{dE}{dx}(E) \ln\left(\frac{N_{\text{inc}}(E)}{N_{\text{inc}}(E) - N_{\text{int}}(E)}\right)$$

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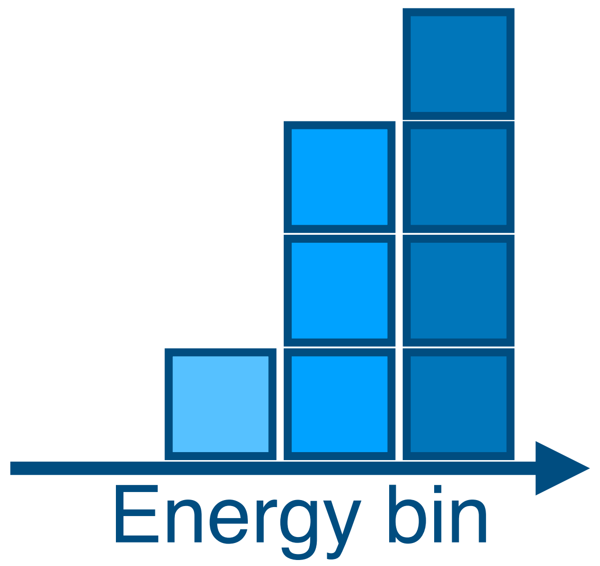

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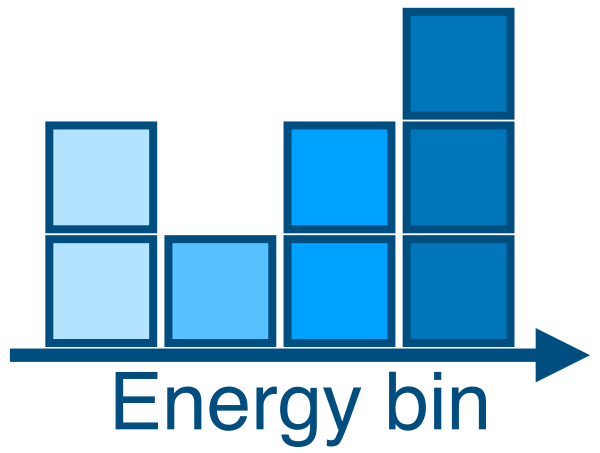

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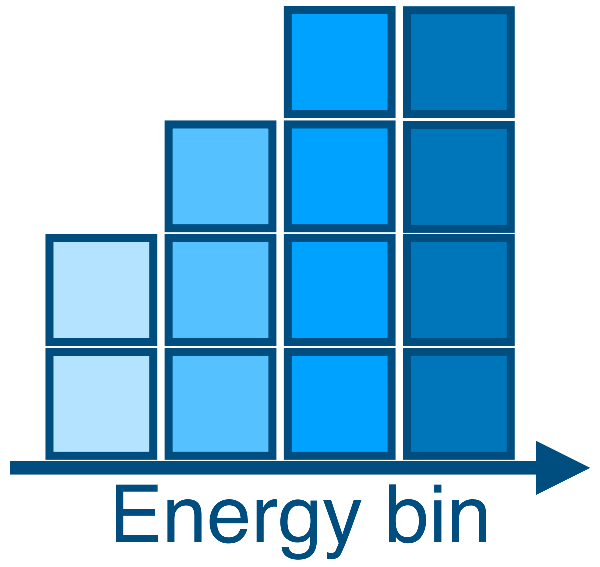

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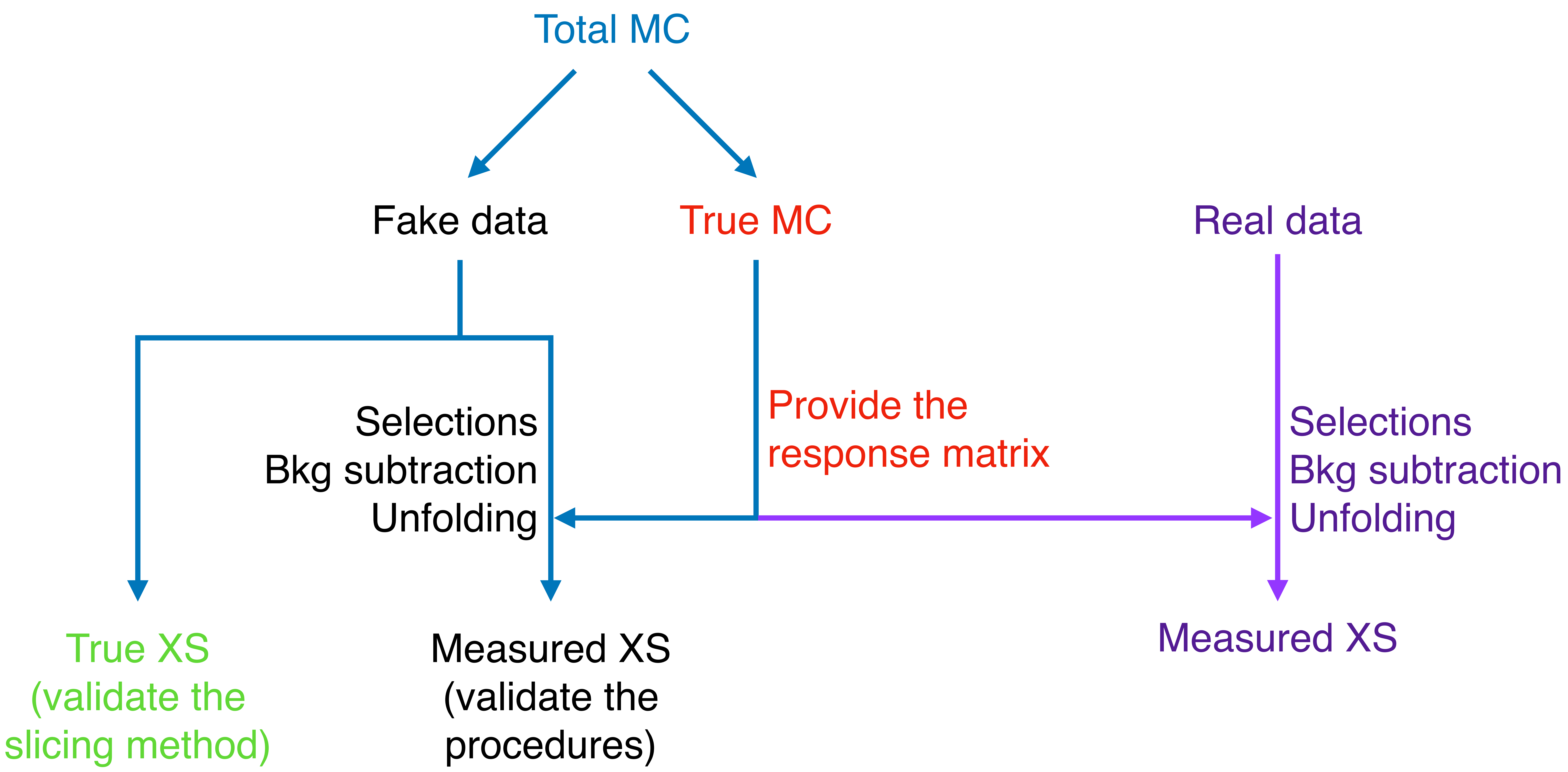
Analysis flow

XS: cross-section



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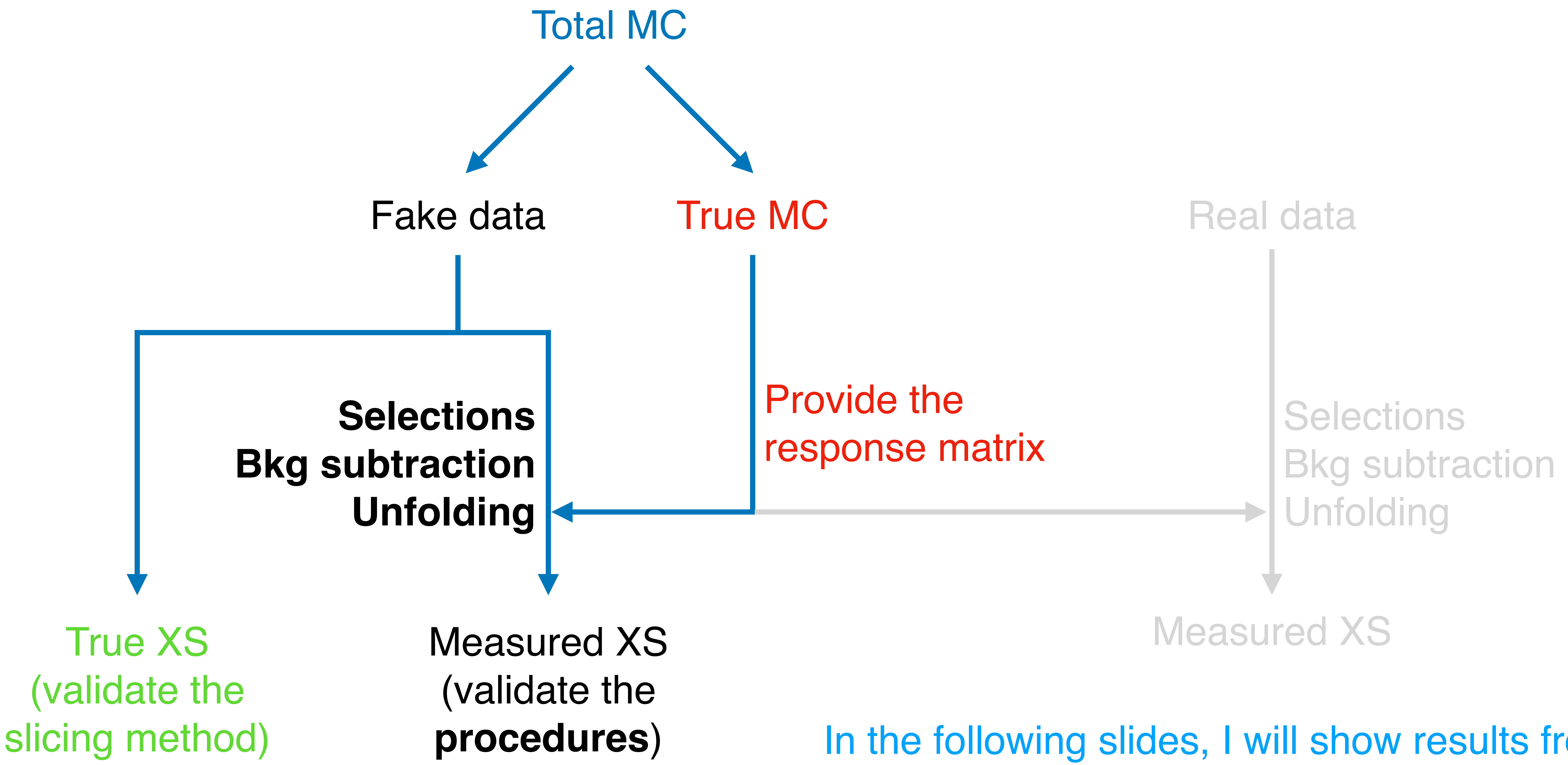
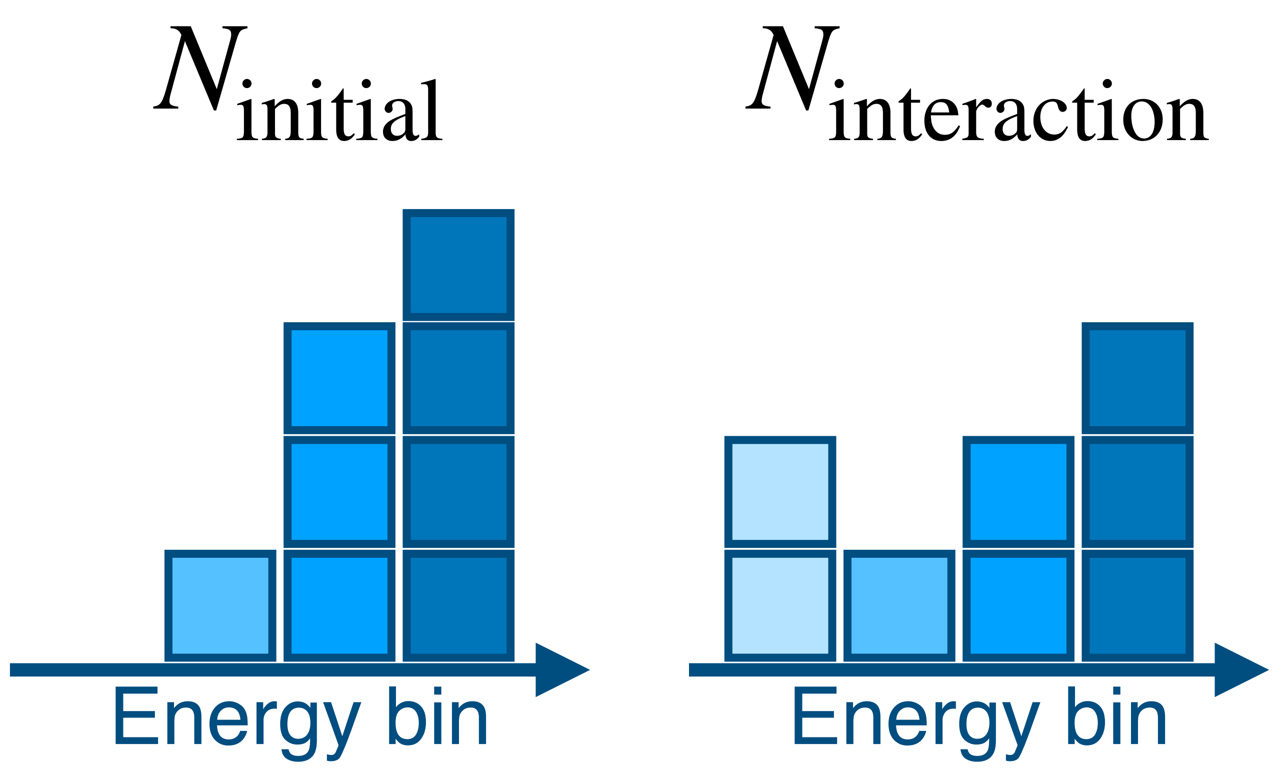


In the following slides, I will show results from **1 GeV fake data** sample as an example.

Analysis flow



Original sample

↓ Selections

N_{reco} (N_{initial} or $N_{\text{interaction}}$)

↓ Background constraints

$$N_{\text{reco}}^{\text{sig}} = N_{\text{reco}} \cdot \left(1 - f_{\text{bkg}}\right)$$

↓ Unfolding

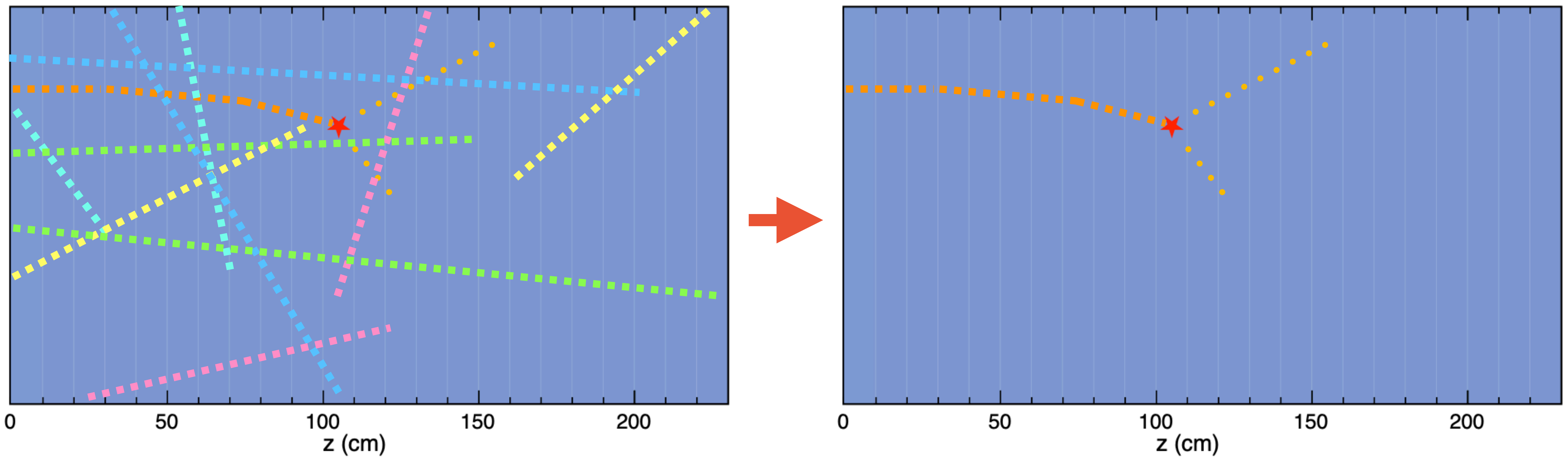
$$N_{\text{true}}^{\text{sig}} = M_{\text{unfolding}} \cdot N_{\text{reco}}^{\text{sig}}$$

Selections

- For inclusive cross-section measurement, we need to select **pion beam events** (regardless of what daughter particles are).

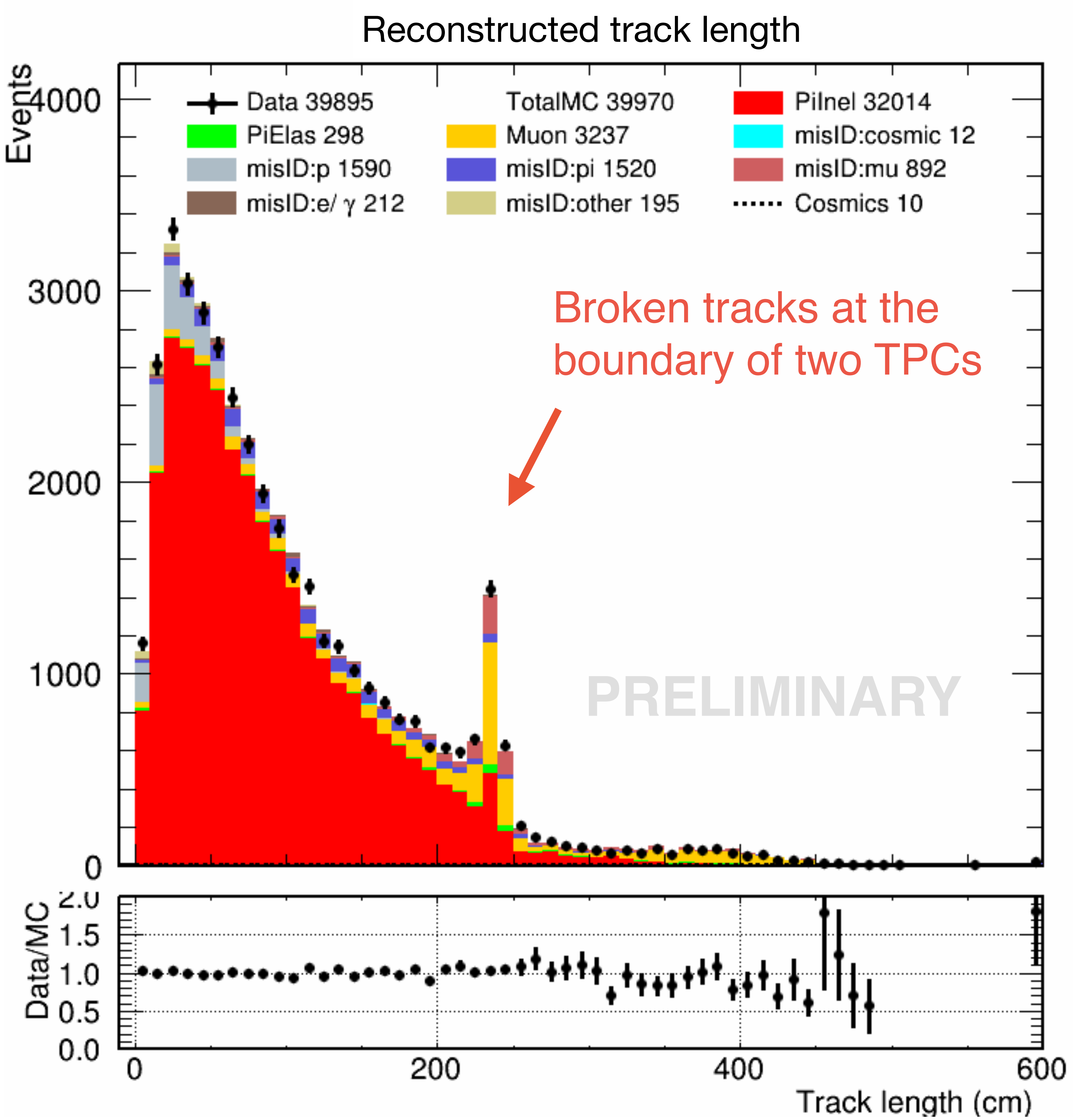
  - Pandora identification
  - Precuts
  - Beam quality cut
  - Proton cut
  - Michel score cut

Details in back-ups



Original event **Pandora identified beam (pion) track**

After full selections (fake data)



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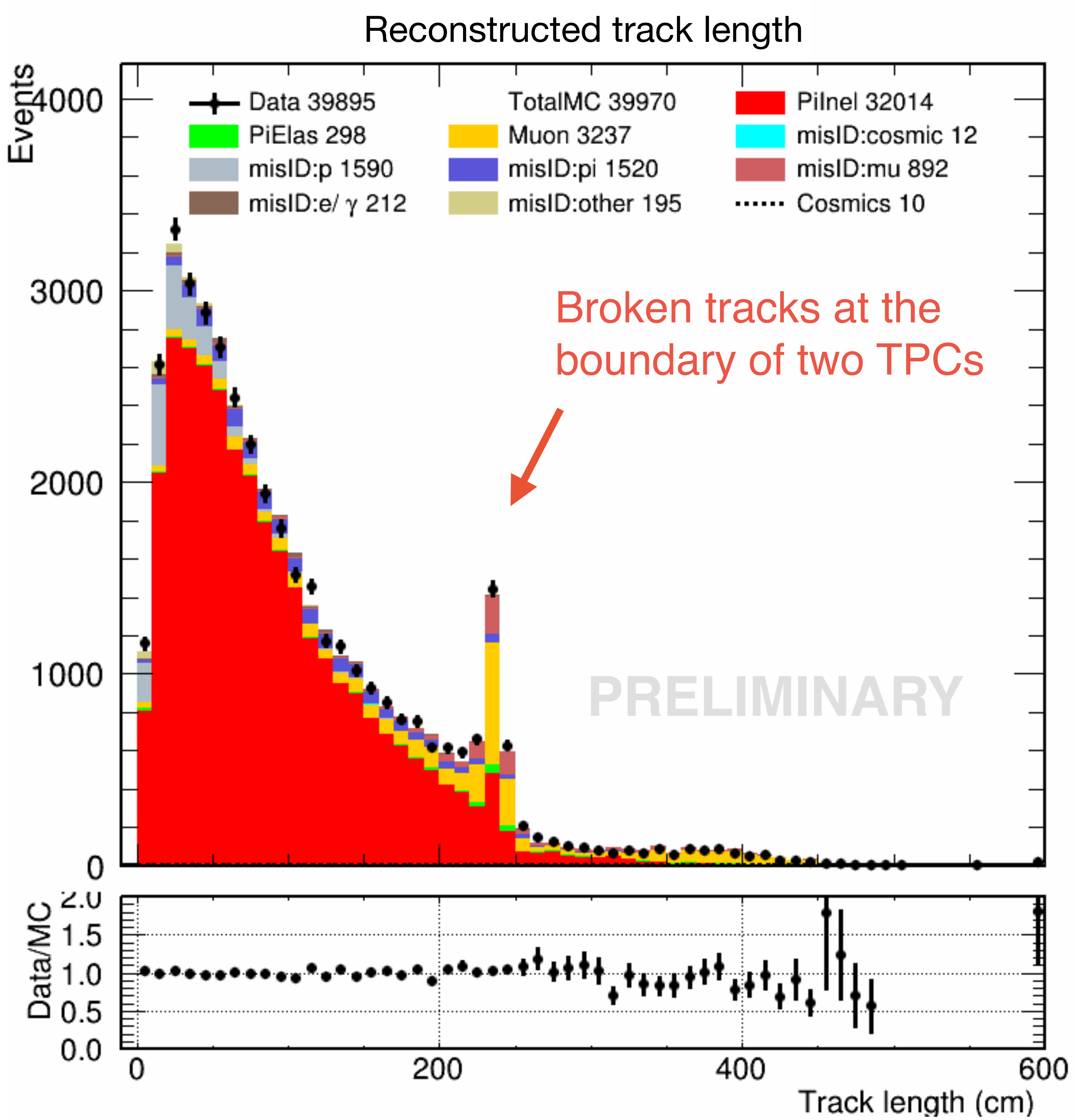
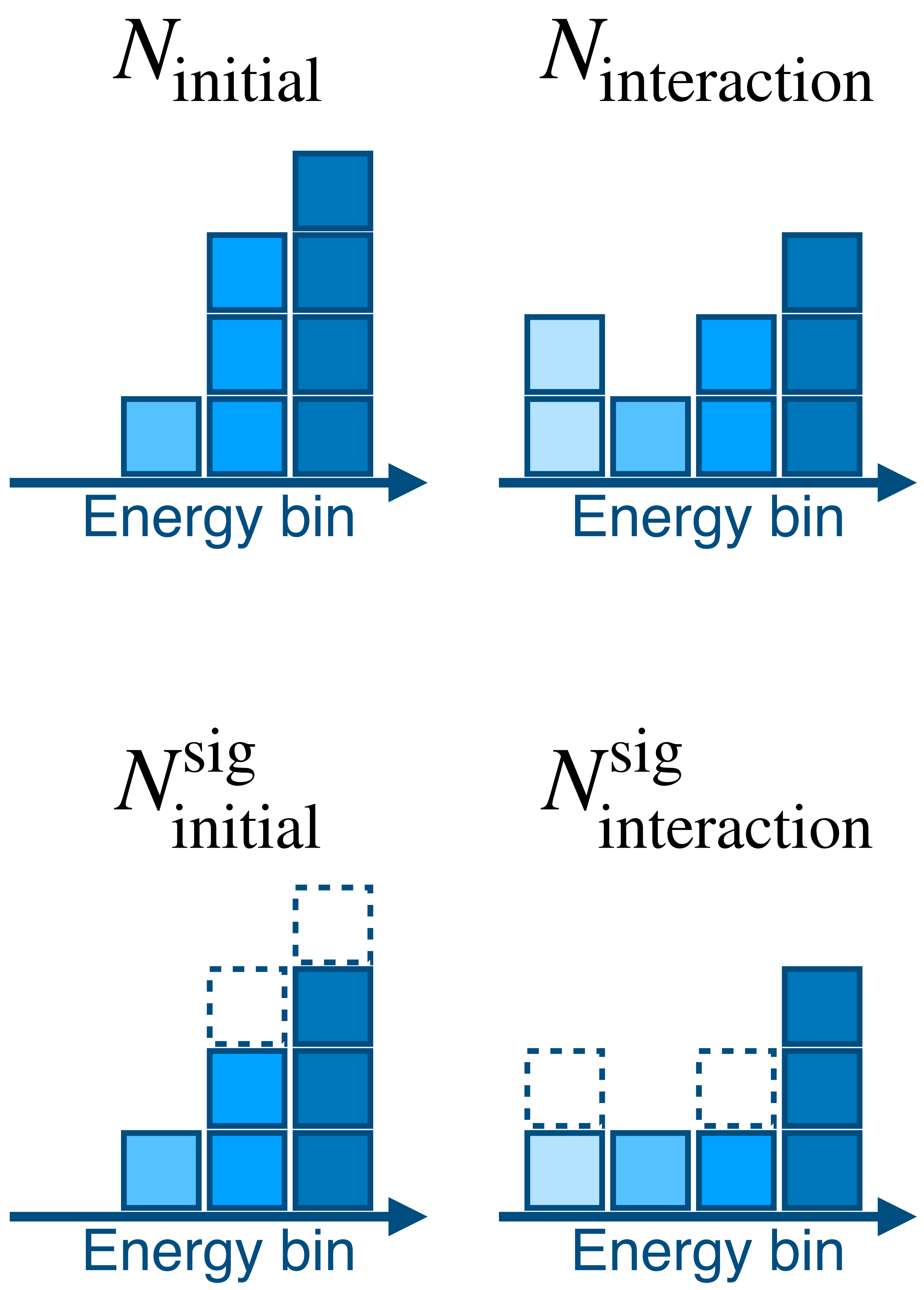


Estimated using true MC sample

- ~ 80.1% pion inelastic (signal)
- ~ 8.1% beam muons
- ~ 4.0% secondary protons
- ~ 3.8% secondary pions
- ~ 2.2% secondary muons
- All the other backgrounds are less than 1%

Secondary particle: daughter of beam particle, which is misidentified as beam particle.

Analysis flow



Orignal sample

↓ Selections

N_{reco} (N_{initial} or $N_{\text{interaction}}$)

↓ Background constraints

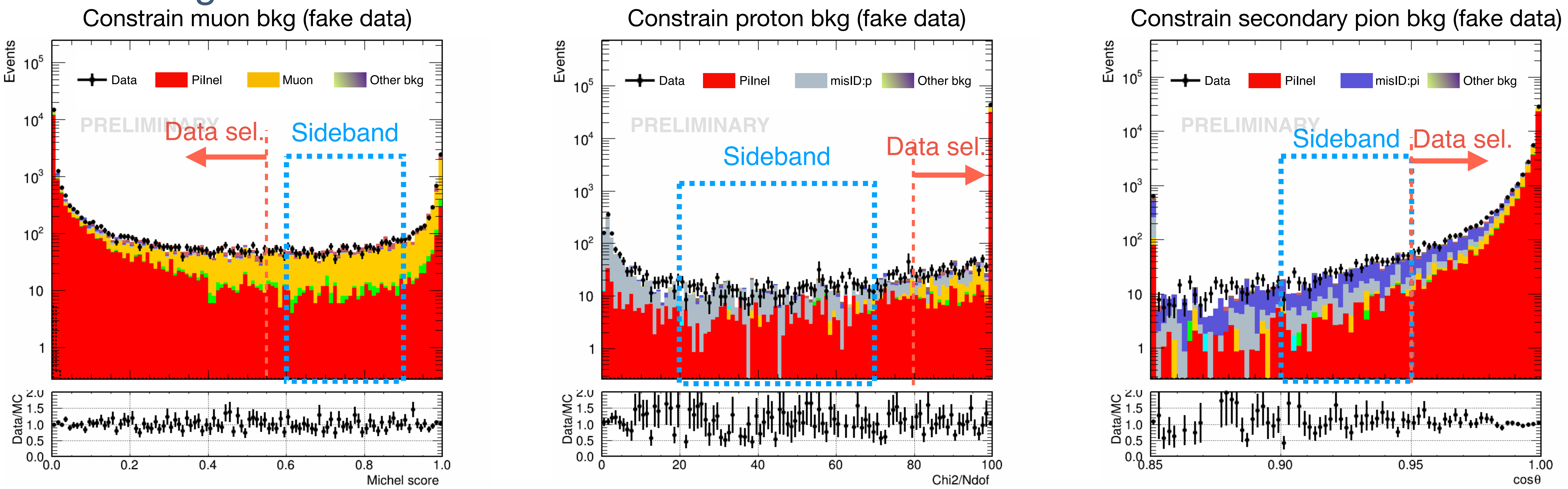
$$N^{\text{sig}}_{\text{reco}} = N_{\text{reco}} \cdot \left(1 - f_{\text{bkg}}\right)$$

↓ Unfolding

$$N^{\text{sig}}_{\text{true}} = M_{\text{unfolding}} \cdot N^{\text{sig}}_{\text{reco}}$$

Background constraints

- A data-driven method is used to account for difference of background fractions in data and MC
    - $$N_{\text{reco}}^{\text{sig}} = N_{\text{reco}} \cdot \left(1 - \sum_i f_i^{\text{data}}\right) = N_{\text{reco}} \cdot \left(1 - \sum_i f_i^{\text{MC}} \cdot \alpha_i\right)$$
- α_i is the scale factor for background i, which is fitted in the sideband of a variable distribution where background i dominates.



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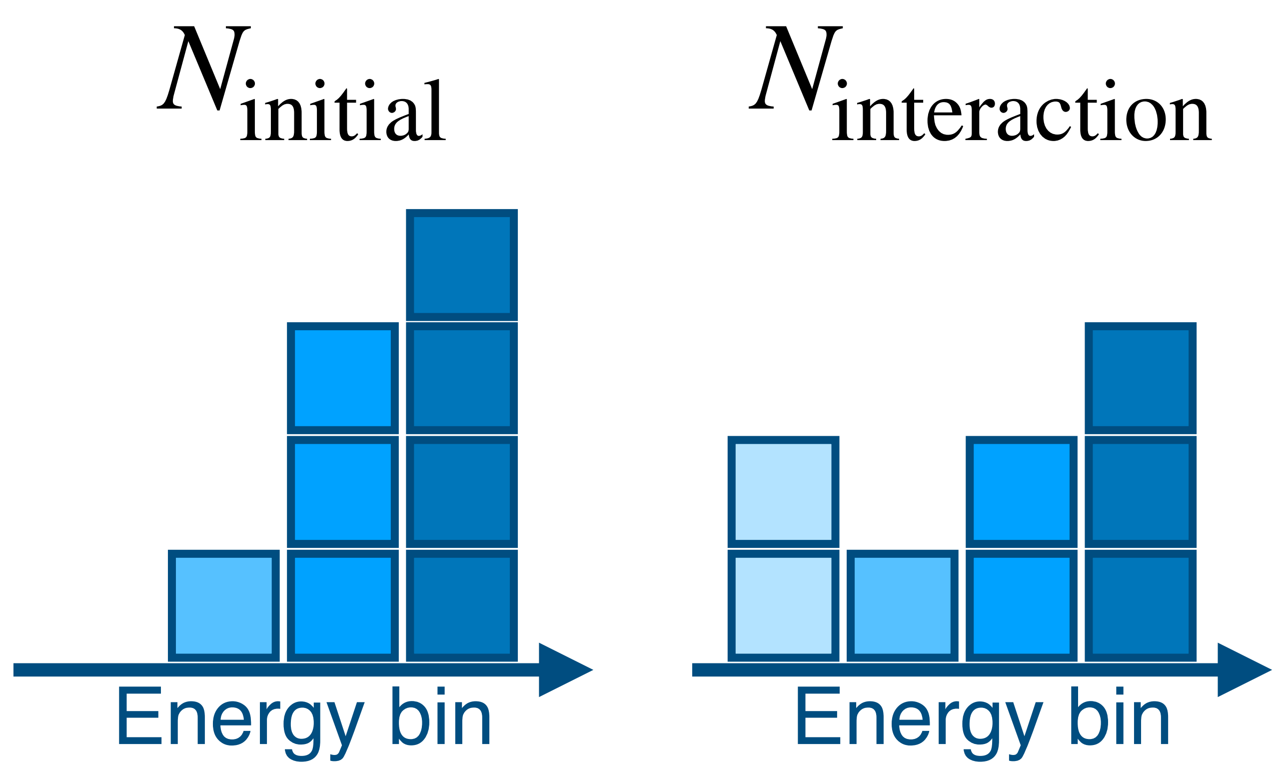

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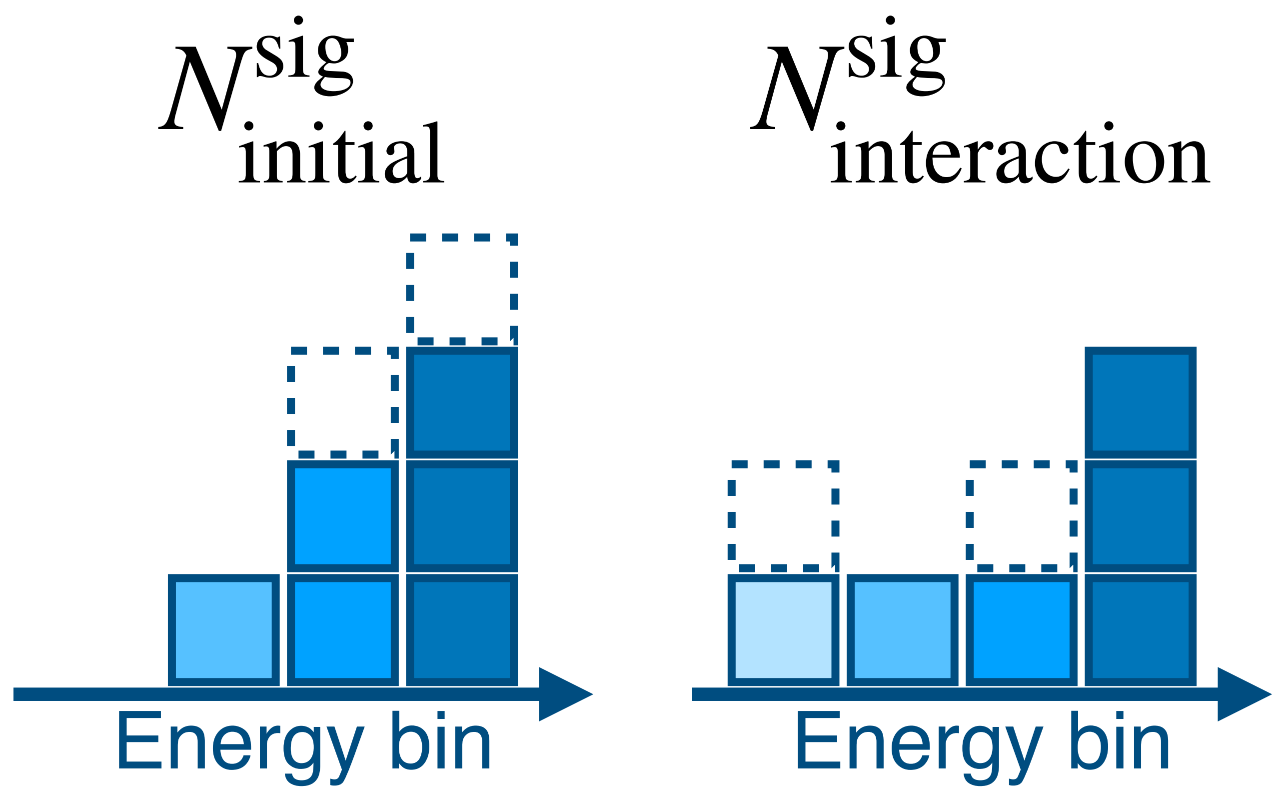

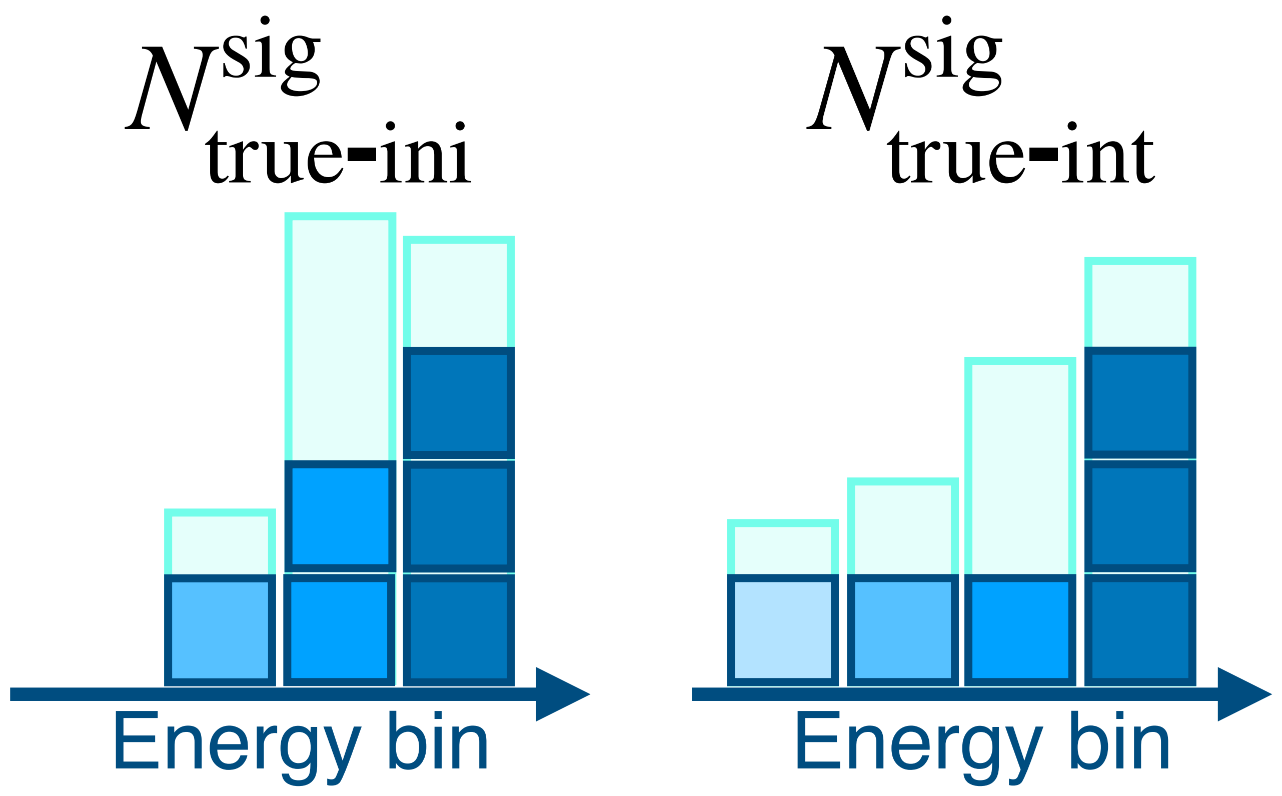

Unfolding

- Unfolding accounts for detector resolution and inefficiency.
- The response matrix $R_{ij} = P(x \in \text{reco bin } i \,|\, y \in \text{true bin } j)$ is derived by **true pion MC**
- The d'Agostini (iterative Bayesian) method is used to model the unfolding matrix.
  https://inspirehep.net/literature/374574
- To take into account the correlations between the histograms, we combine $(N_{\text{initial}}, N_{\text{interaction}})$ as one variable, and unfold them together. (Multi-dimensional unfolding)

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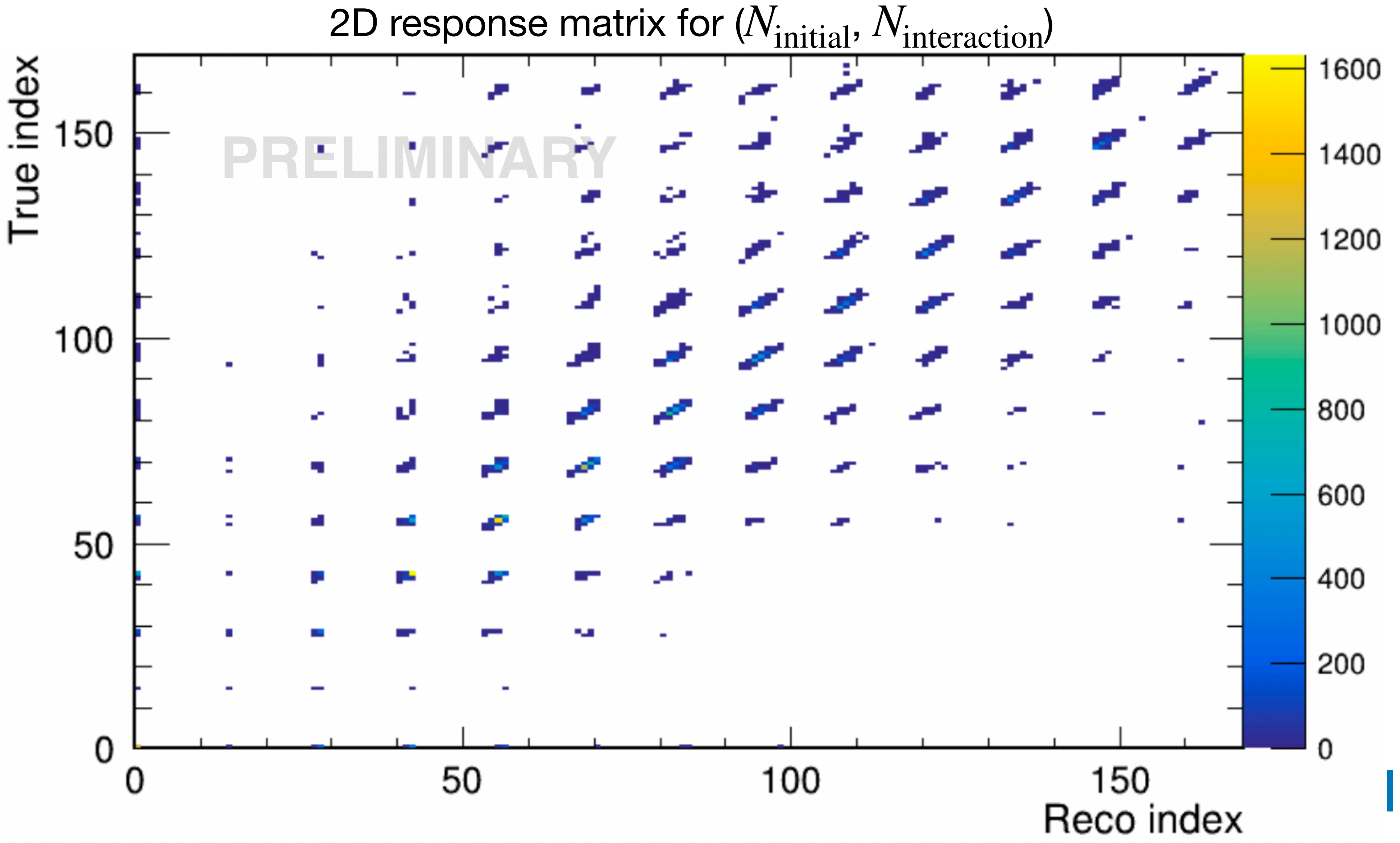
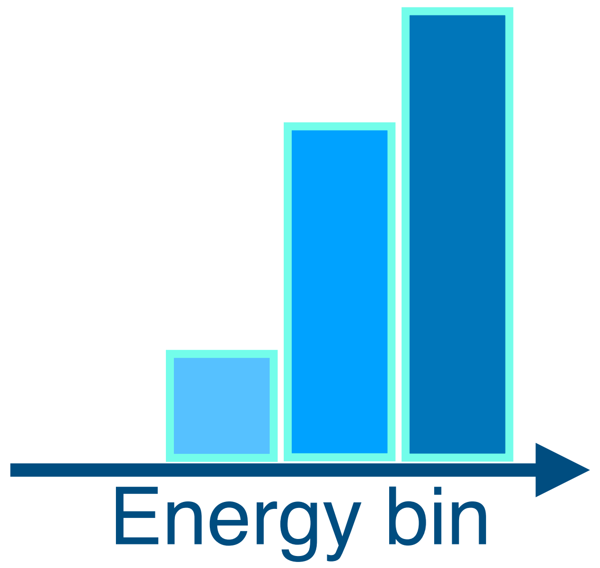


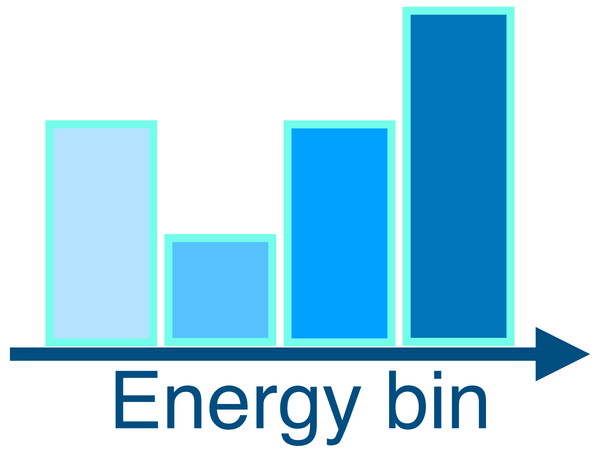
Index = 13*(Initial Bin ID) + Interaction Bin ID

Measured histograms (fake data)

N_{initial}



$N_{\text{interaction}}$



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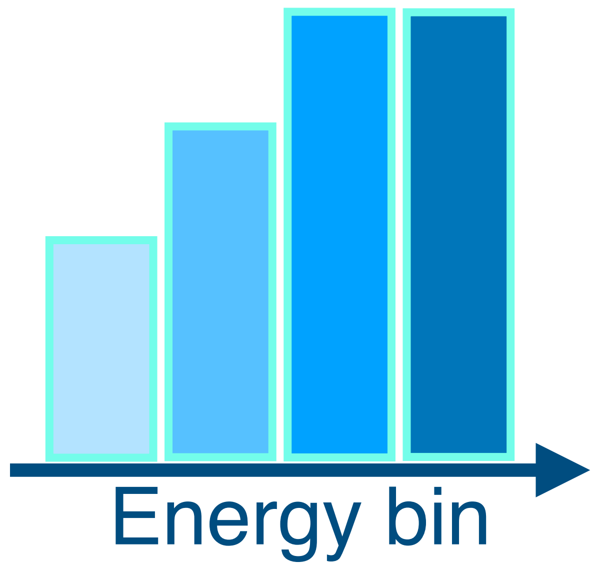
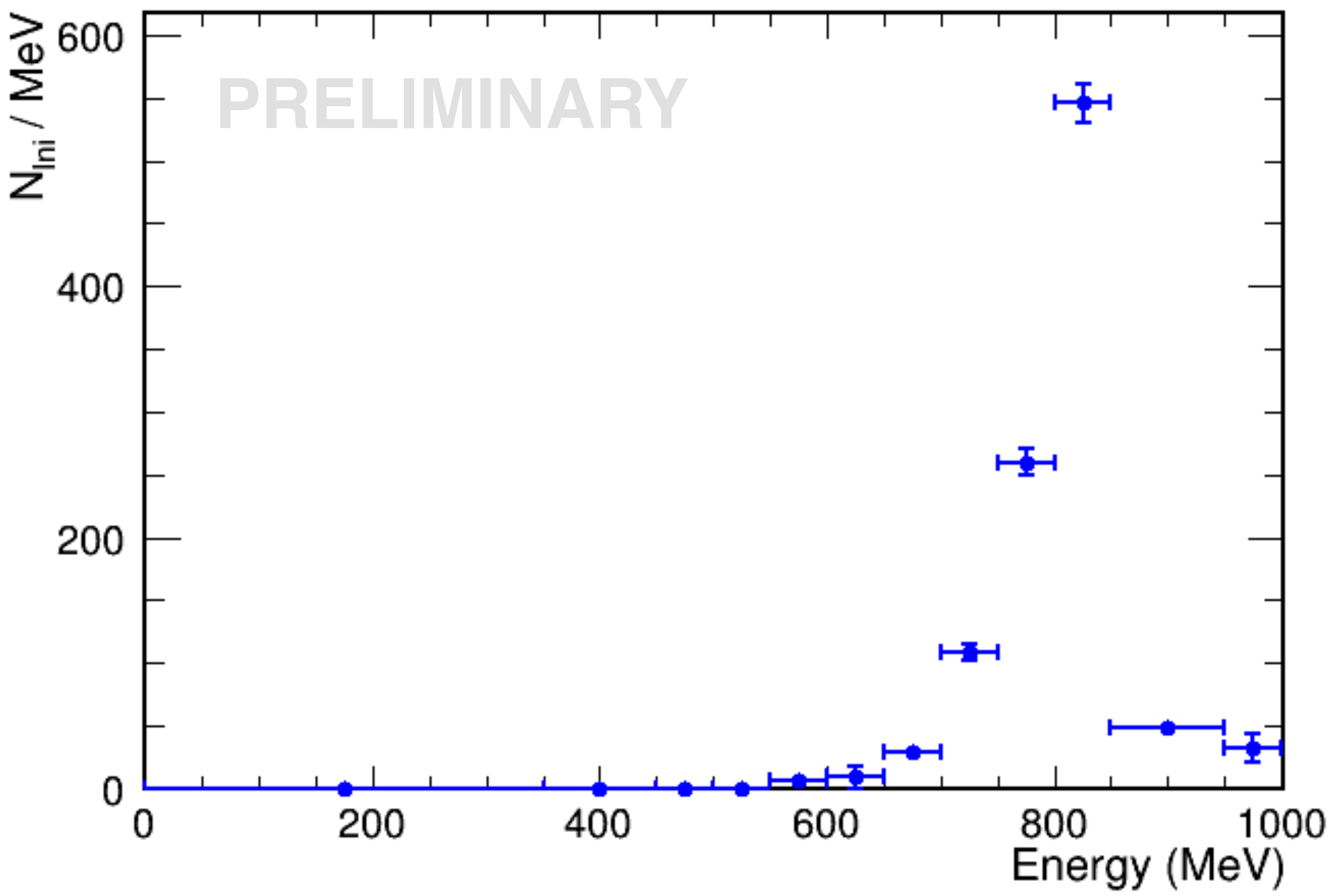
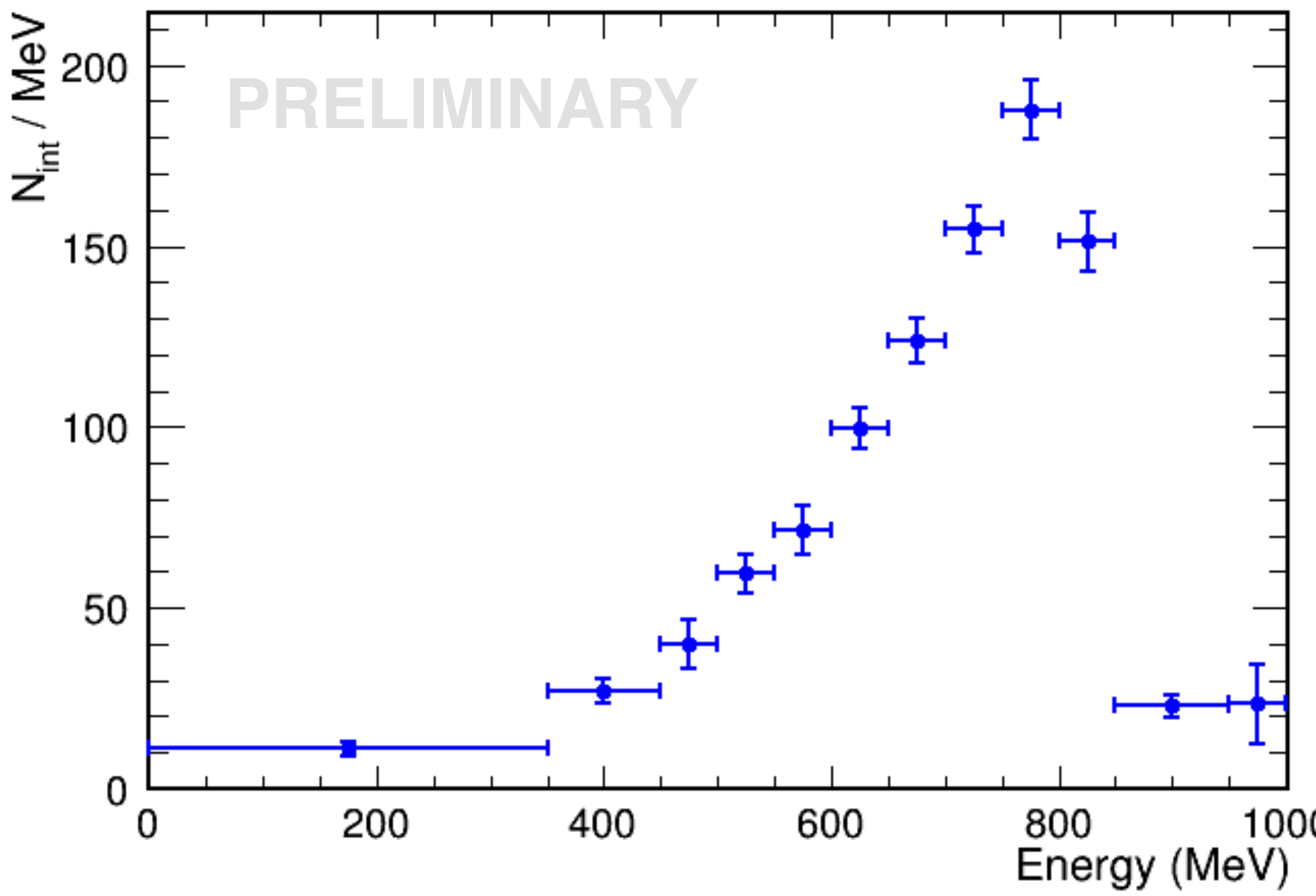
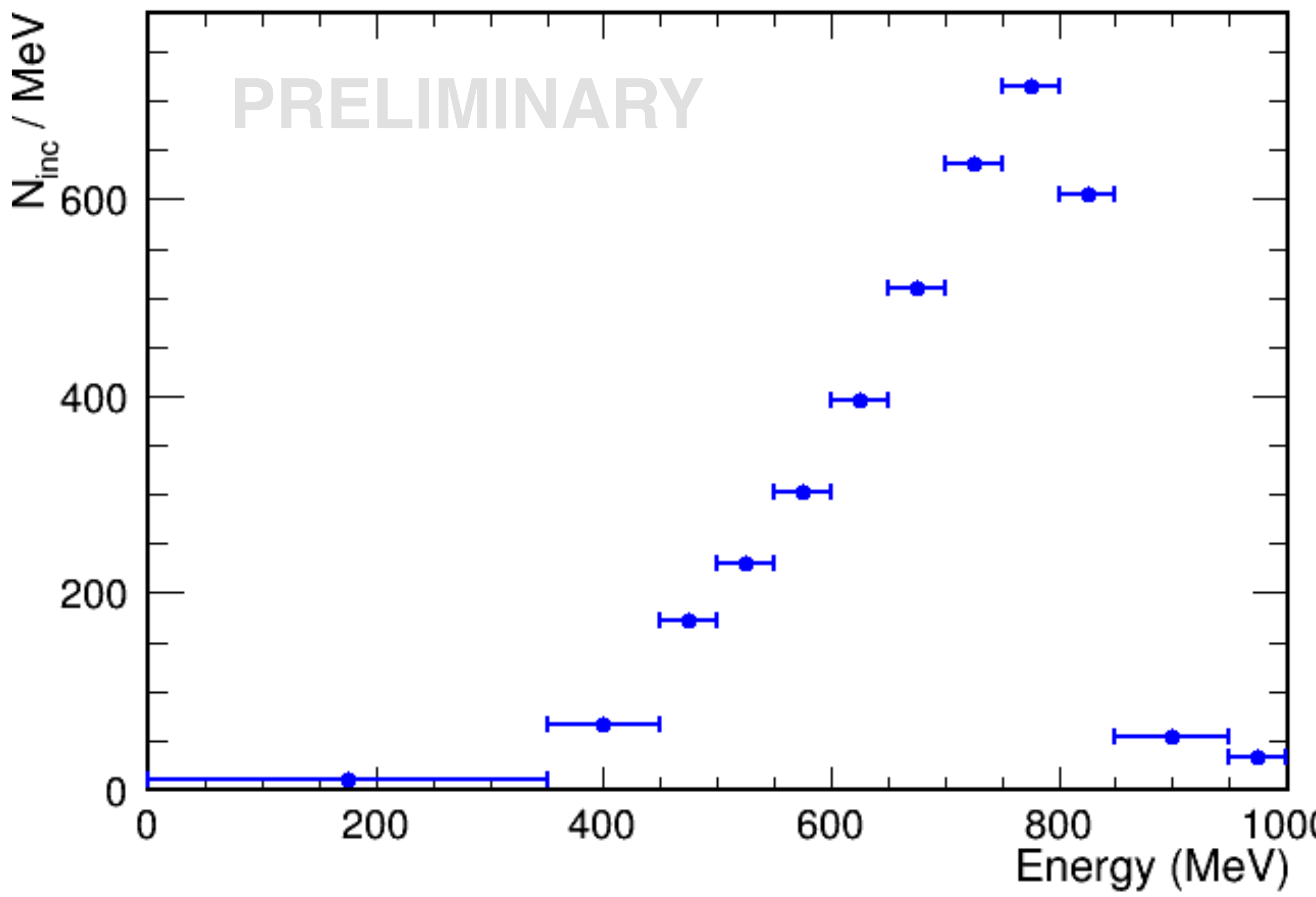


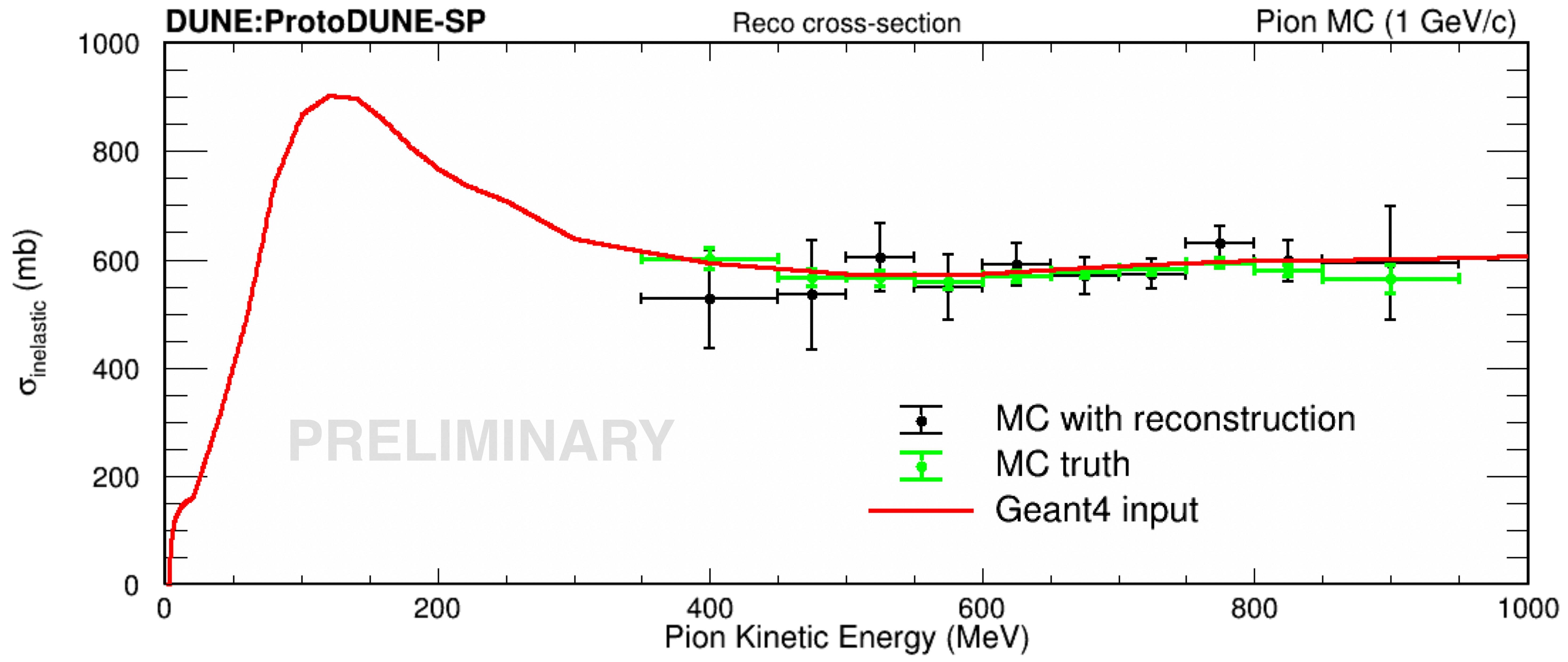


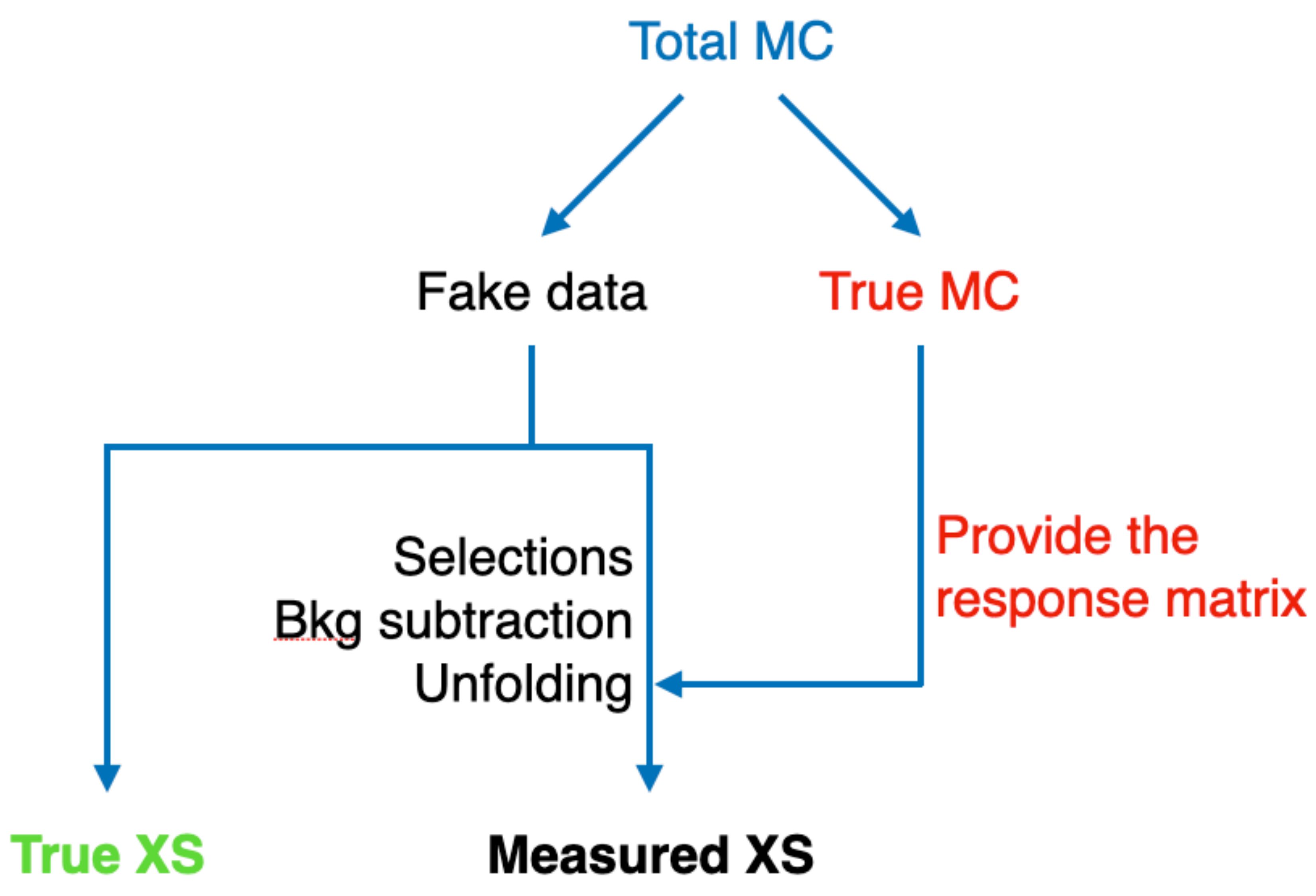




Nominal result (fake data)

$$\sigma(E) = \frac{M_{\text{Ar}}}{\rho N_A \Delta E} \frac{dE}{dx}(E) \ln\left(\frac{N_{\text{inc}}(E)}{N_{\text{inc}}(E) - N_{\text{int}}(E)}\right)$$





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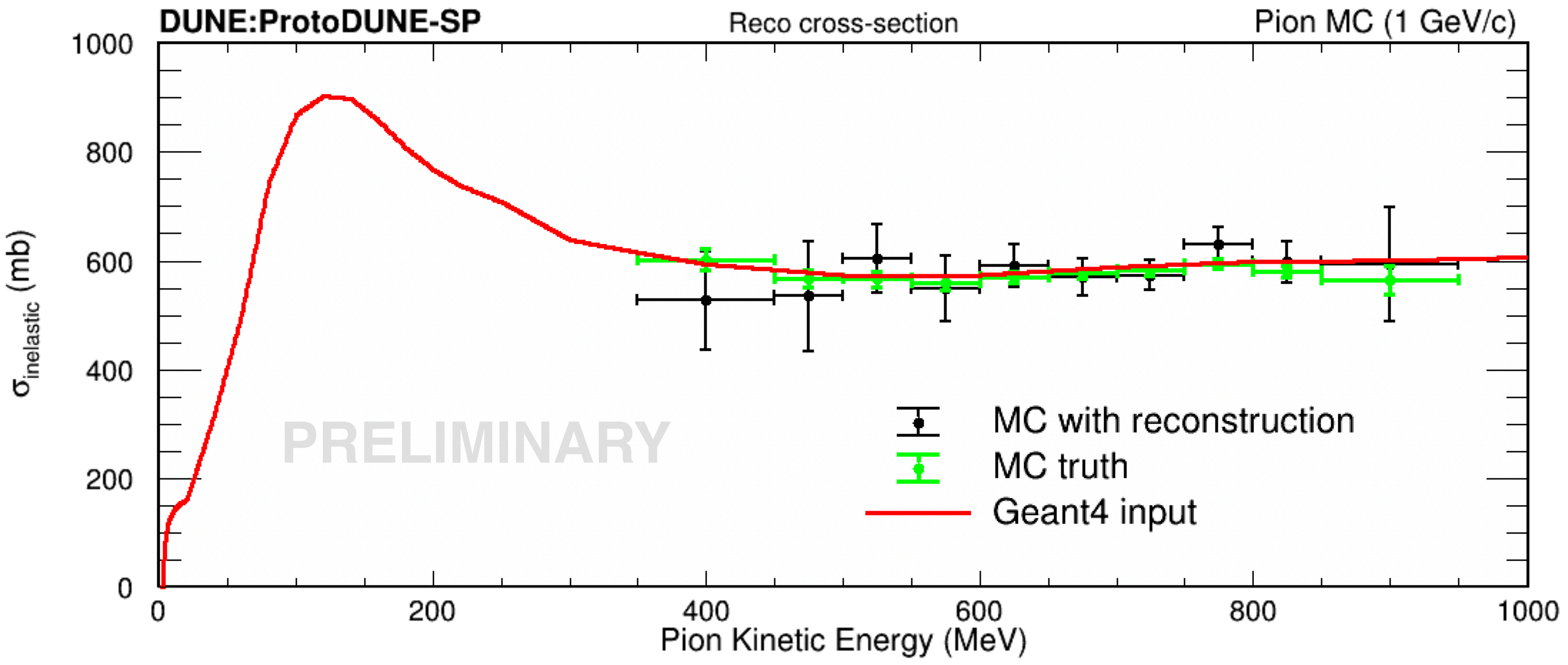

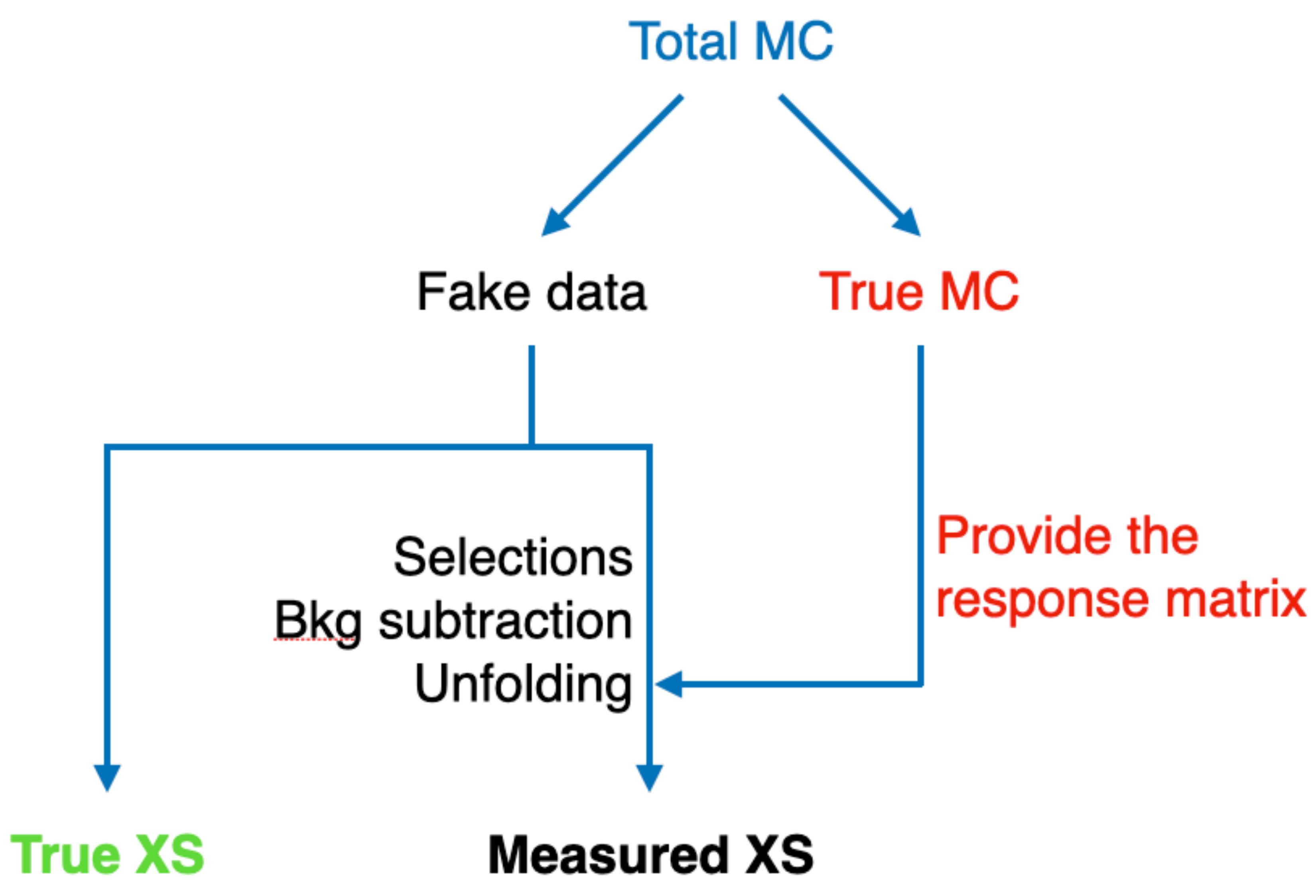

Both true XS and measured XS are consistent with the Geant4 input.

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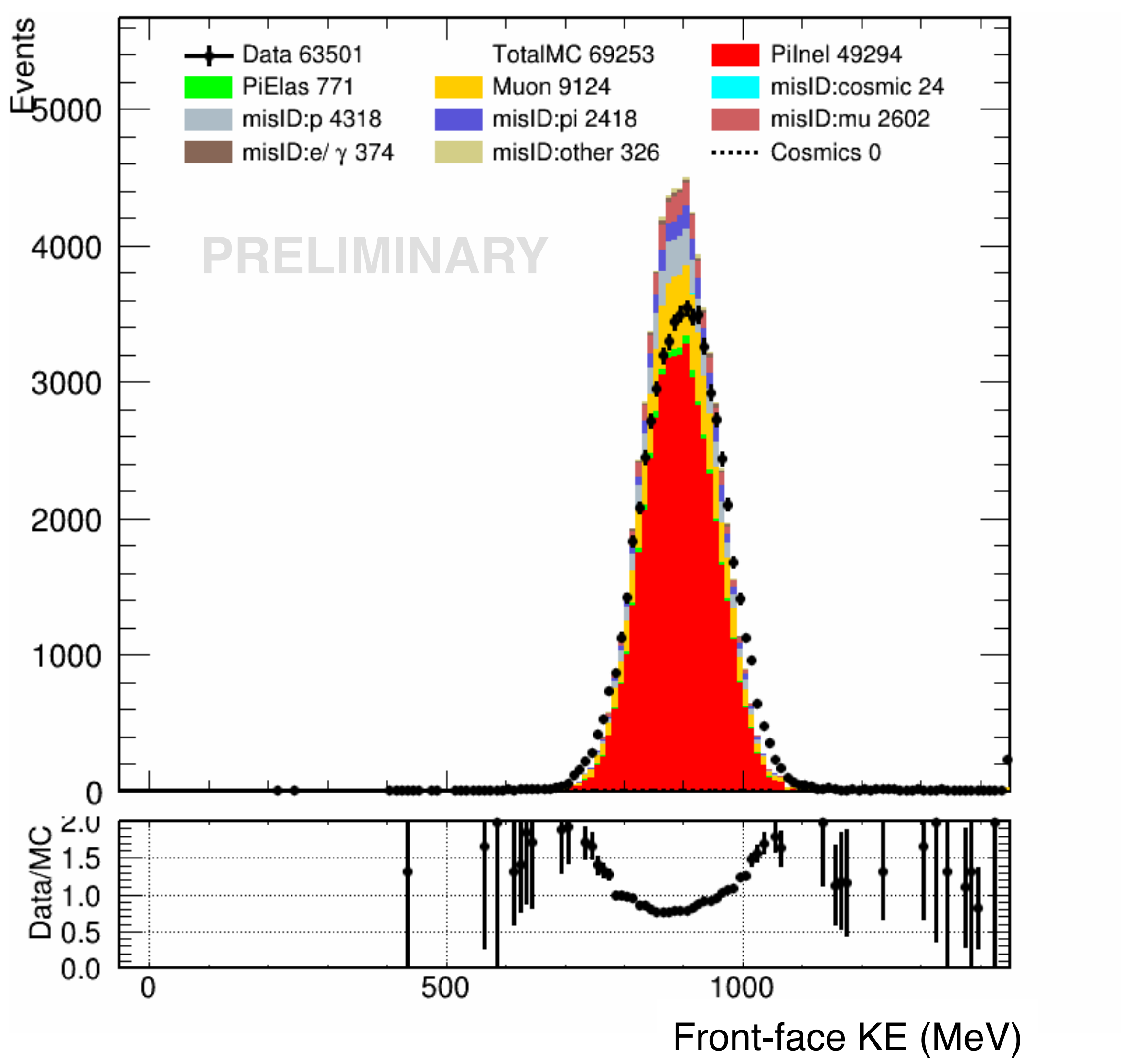
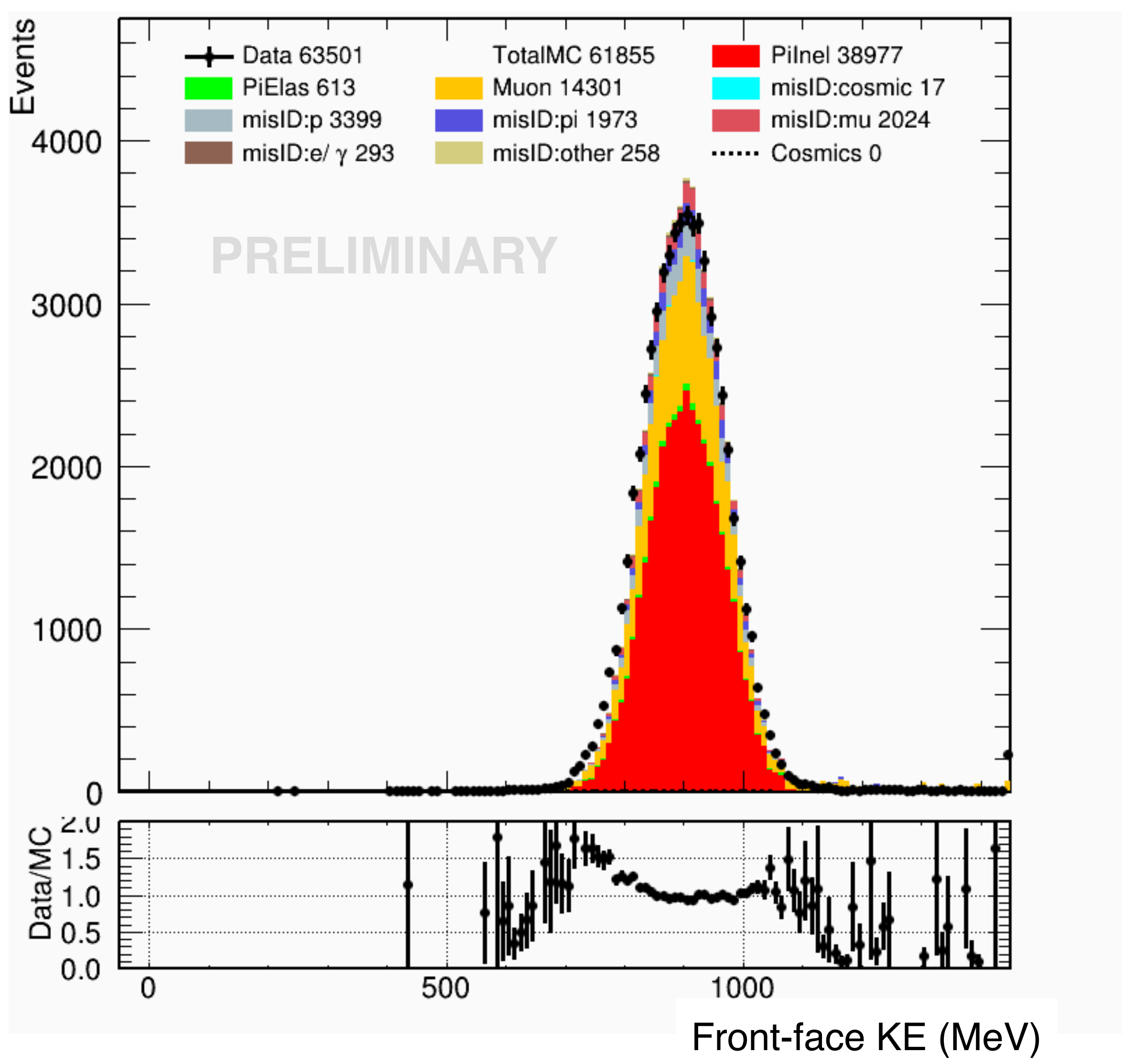
Towards measuring real data

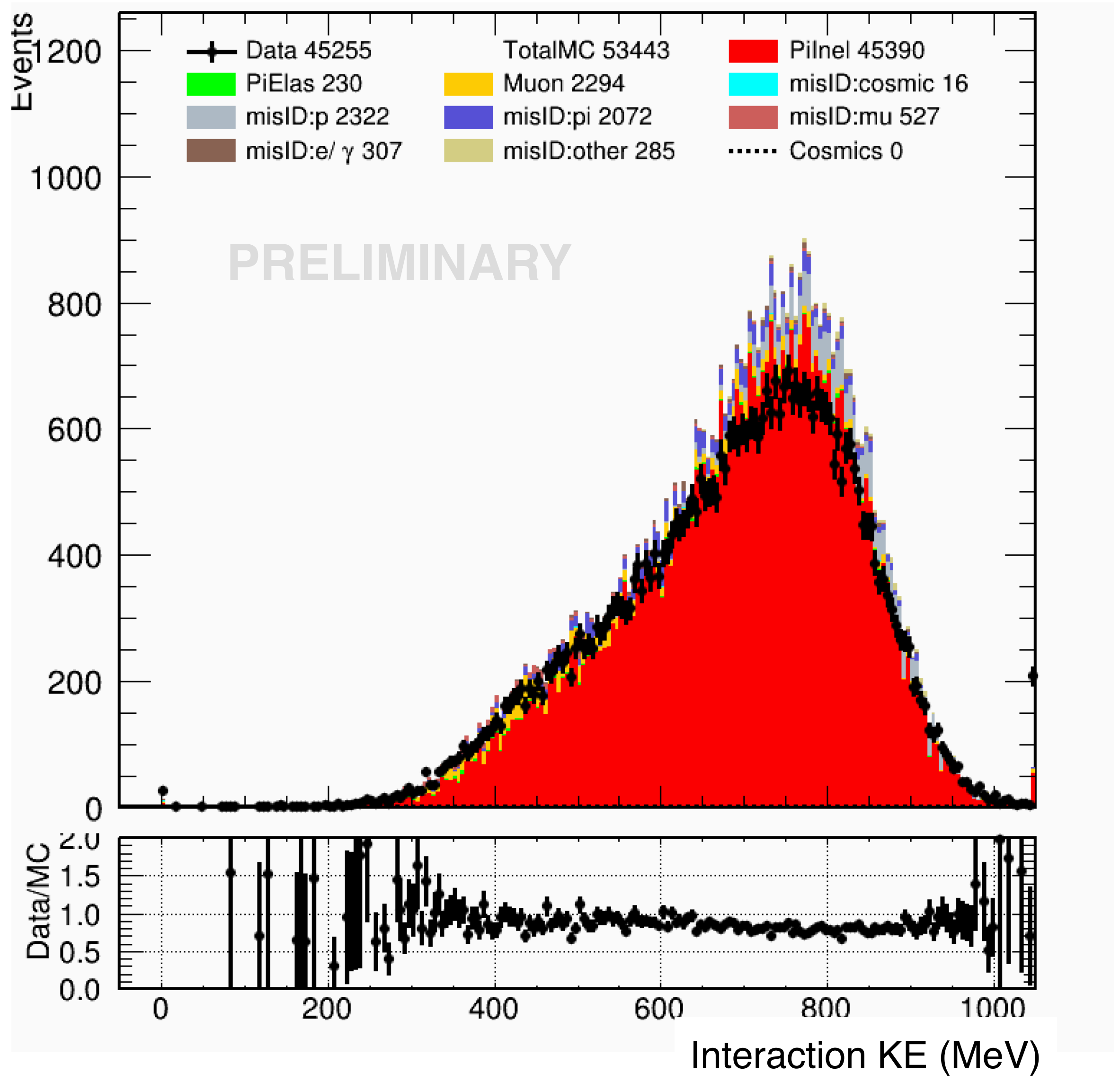
- Preliminary results suggest some mis-modeling of MC.
- We select stopping muon sample to reweight MC according to data distributions, and then apply the reweighting factors when measuring pion XS. Details in back-ups

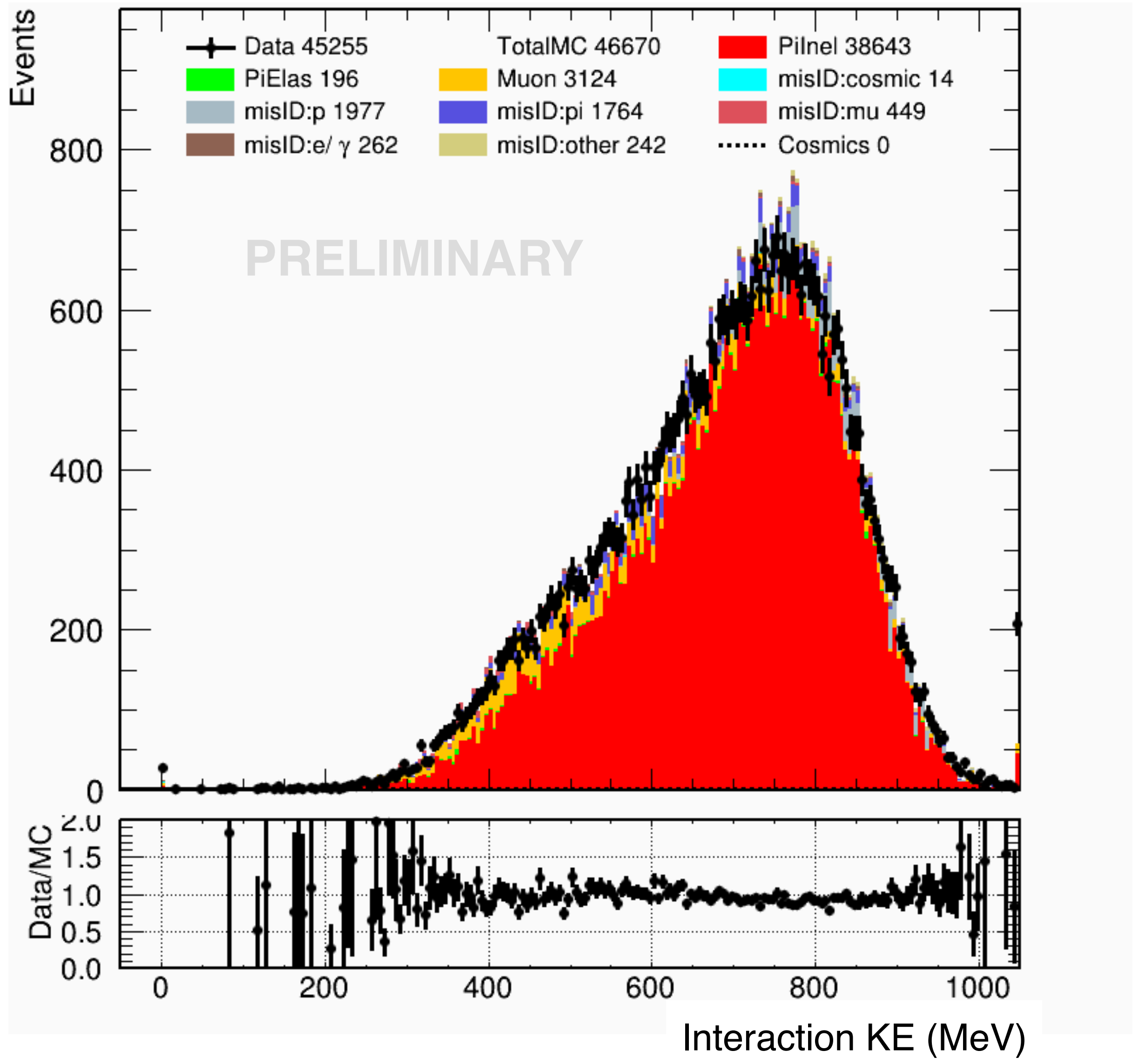
  - Beam momentum reweighting





  - Muon background reweighting

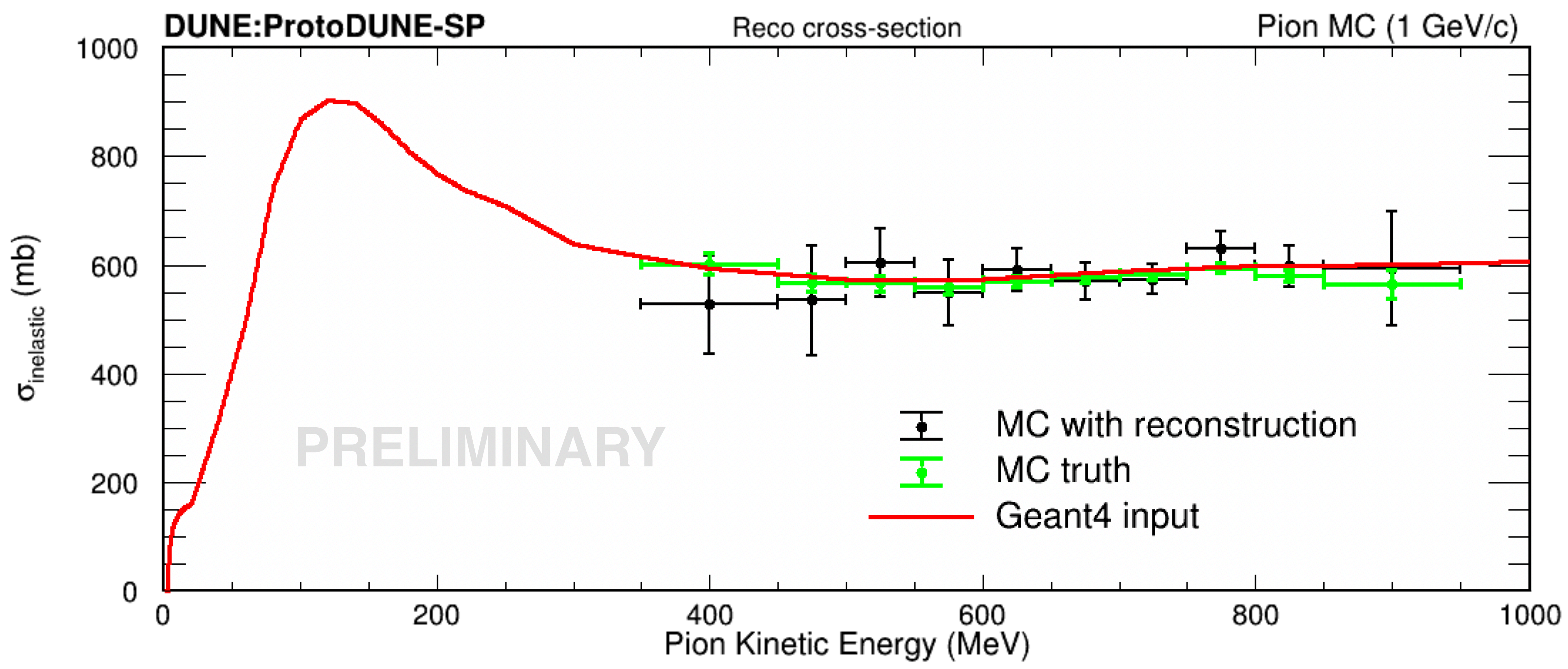




THE UNIVERSITY OF CHICAGO DUNE

Summary

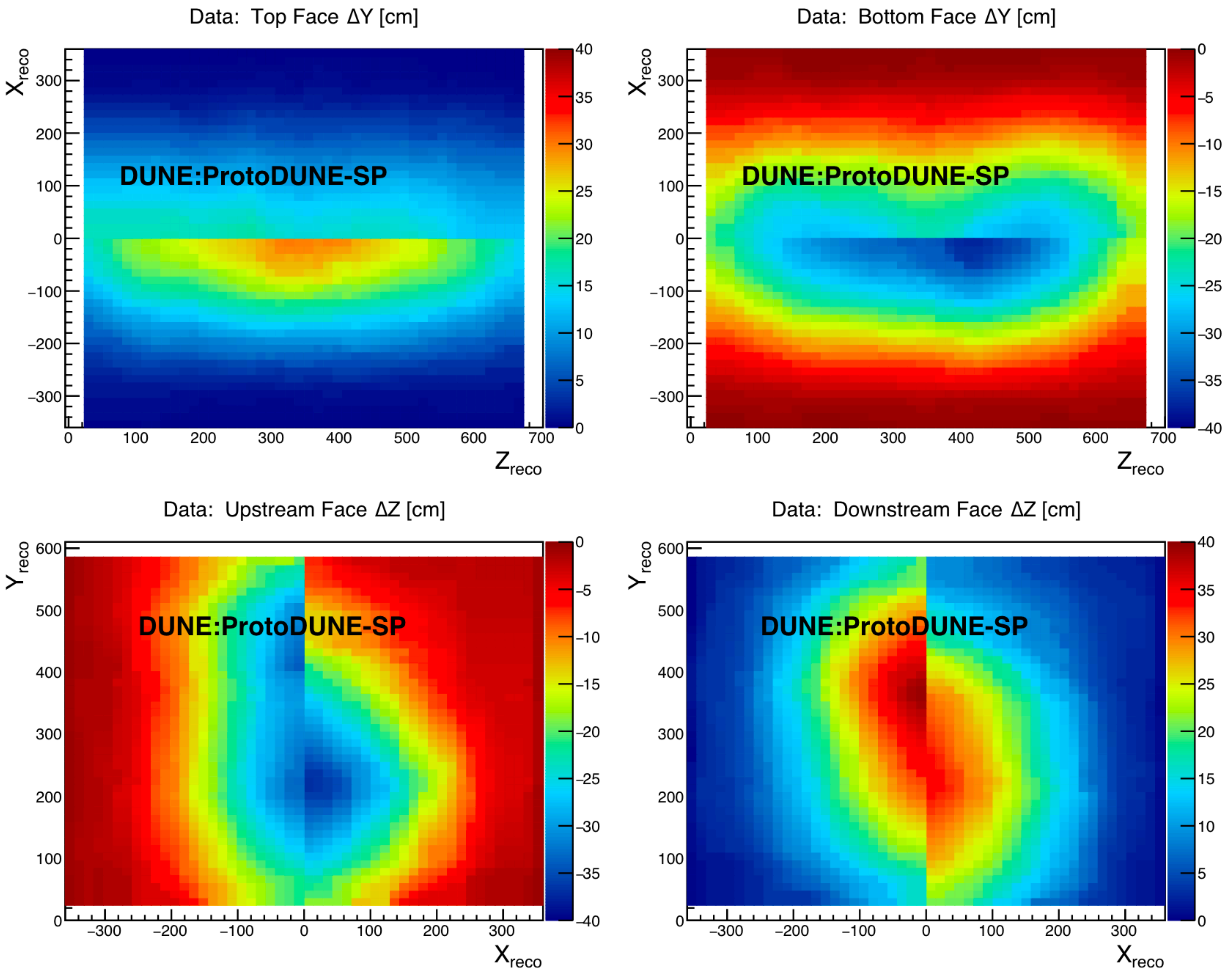
- We have shown validations of the cross-section measurements using 1 GeV fake data.
- Differences between data and MC are being studied, before opening the box for real data.
- The procedures will also be applied to measuring datasets of other momentum modes (0.3, 0.5, 1, 2, 3, 6, 7 GeV).
- ProtoDUNE Run 2 with a slightly different detector configuration is currently being assembled and will offer opportunities to measure XS in low KE region, which is especially interesting to DUNE.
- Thanks for your attention!!



Back-ups

Space charge effect (SCE)

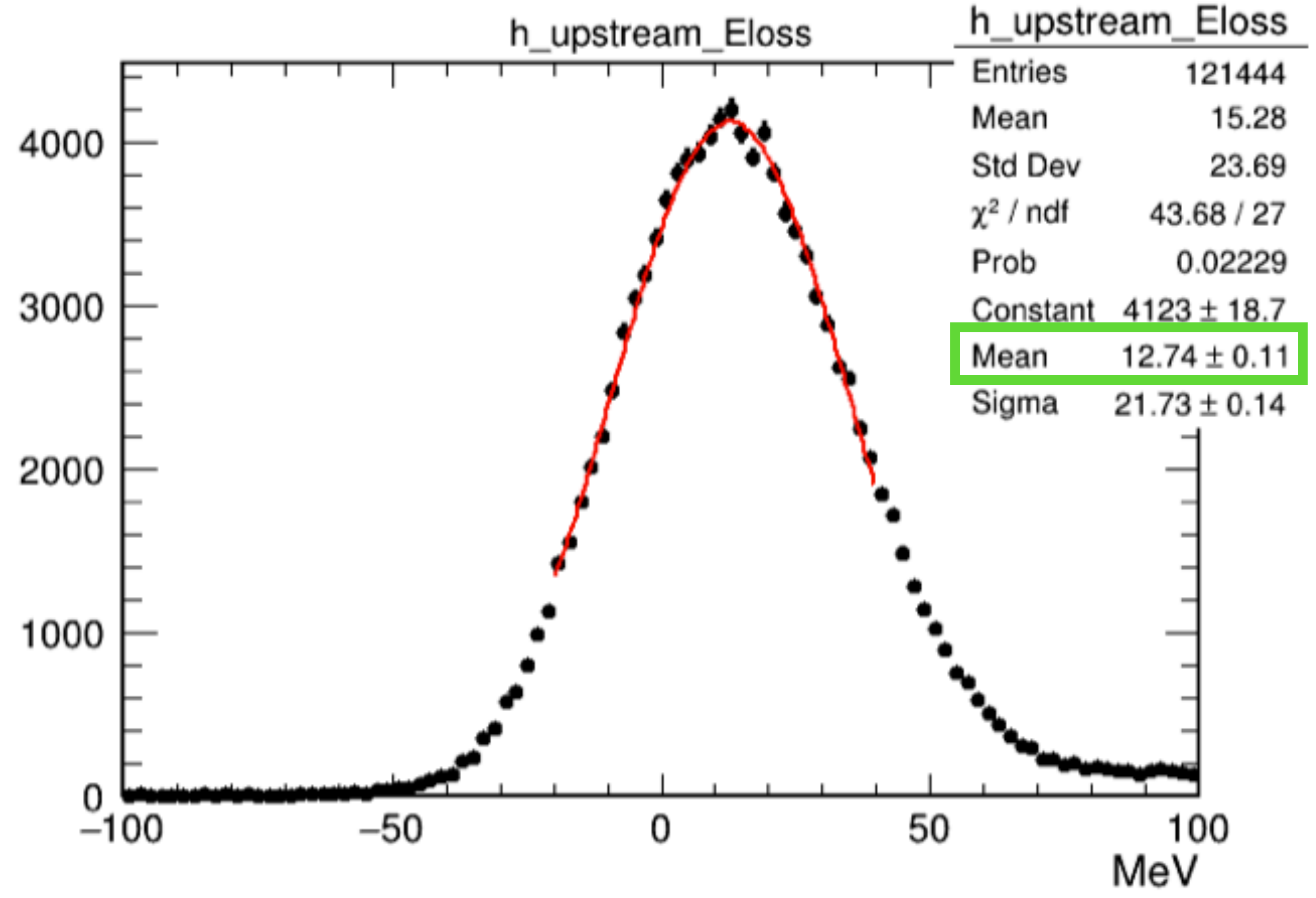
- ProtoDUNE-SP experiences a large flux of cosmic rays which results in a substantial amount of argon ions.
- The argon ions drift slowly (~mm/s at 500 V/cm in LAr), so they build up and cause a considerable amount of positive space charge in the detector.
- SCE distorts the electric field, and biases reconstructed particle energies and trajectories.
- SCE should be carefully characterized at any large LArTPC detector operating at or near the surface.

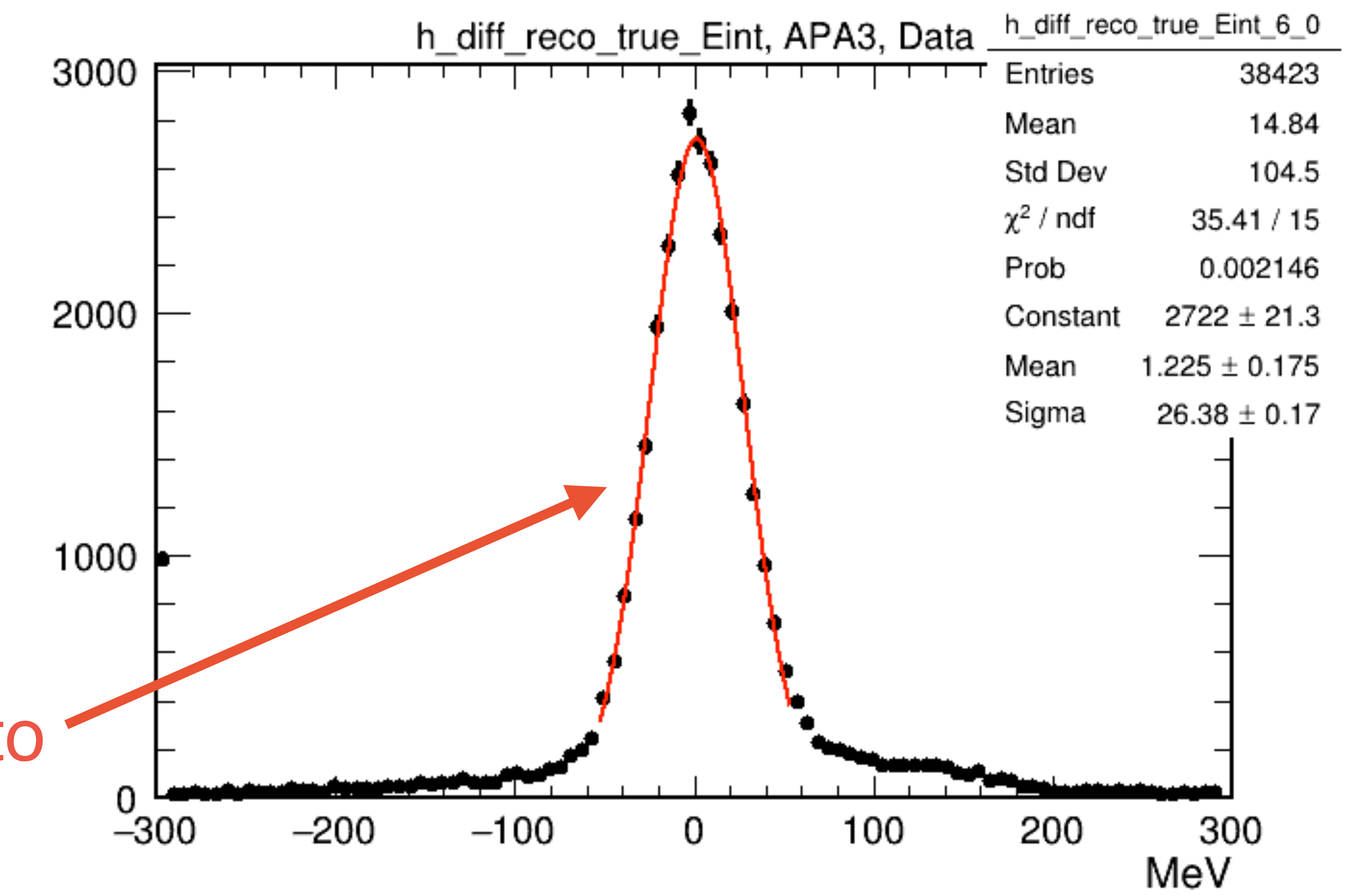


Spatial distortions normal to the top detector face (upper left), bottom detector face (upper right), upstream detector face (lower left), and downstream detector face (lower right) in ProtoDUNE-SP data.

Energy reconstruction

- E_{ff} is calculated by $E_{\mathrm{inst}} - \Delta E_{\mathrm{upstream}}$
  - E_{inst} is the beam kinetic energy measured by beam line instrumentations
  - $\Delta E_{\mathrm{upstream}}$ is the upstream energy loss, estimated as a constant by true pion MC
- E_{int} is calculated by $E_{\mathrm{ff}} - \int \frac{dE}{dx} dx_{\mathrm{reco}}$
- Compare to true E_{int} (after full selections)

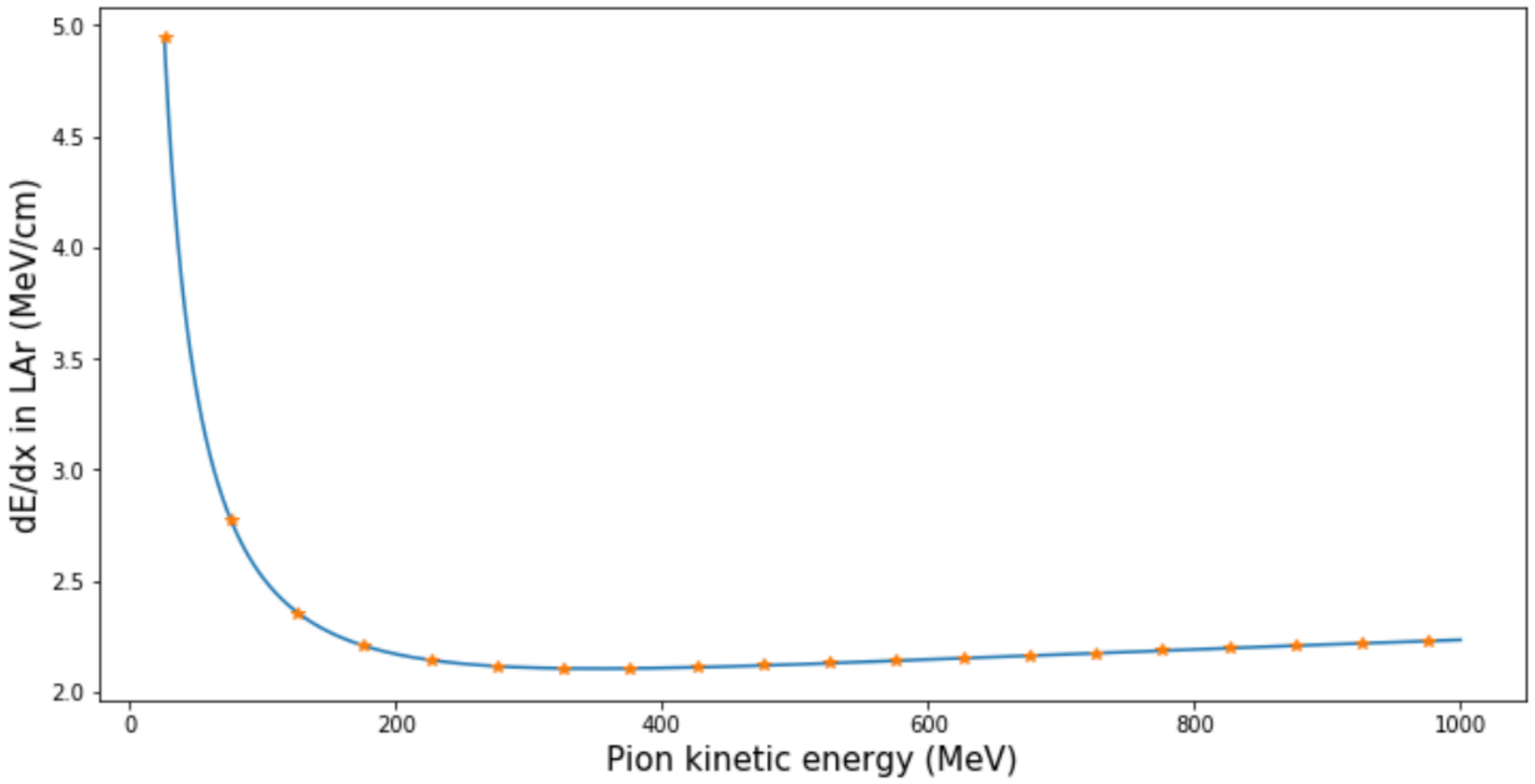


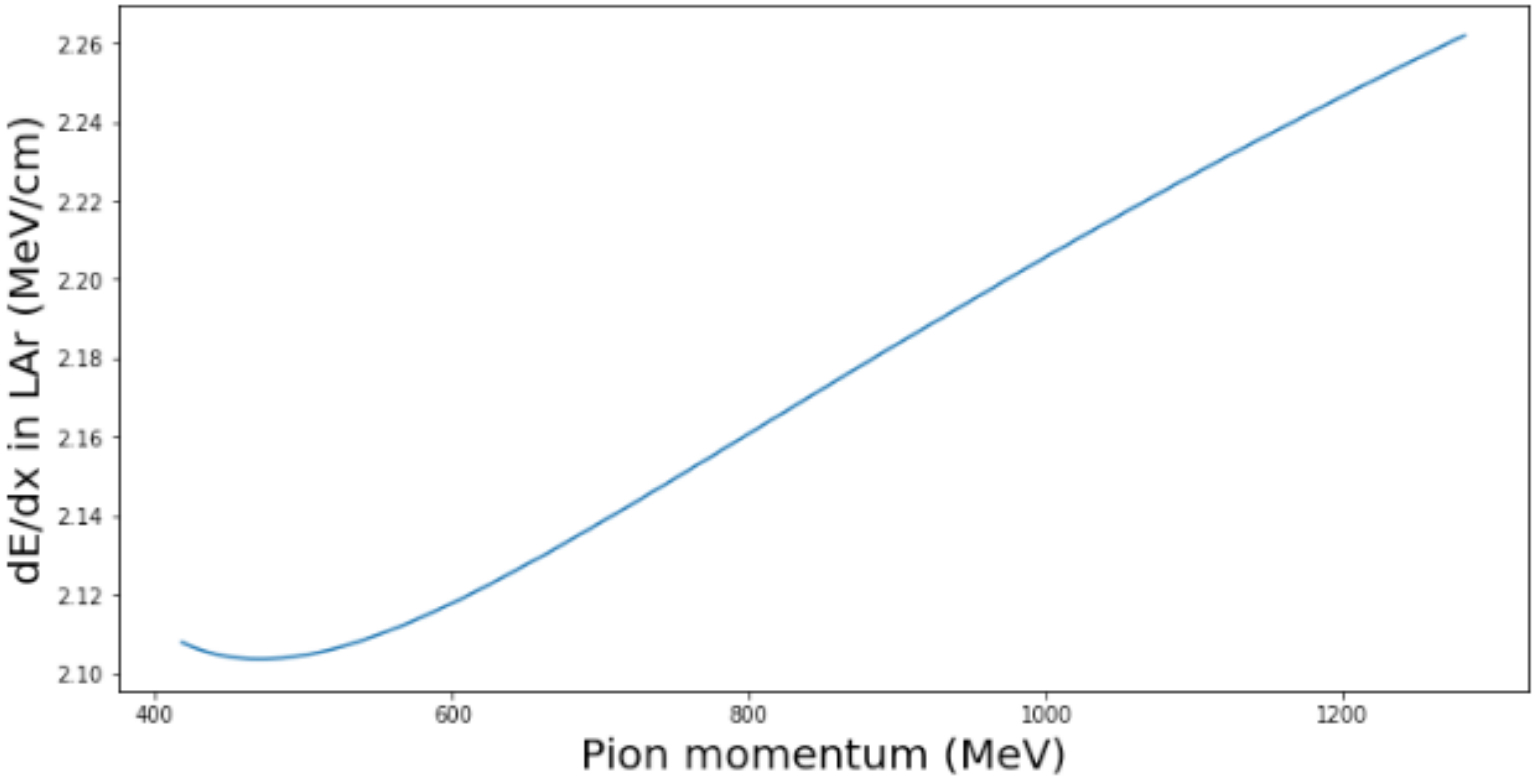


The width of the peak suggests it is proper to choose the energy interval at least 50 MeV.

dE/dx curve of pion in LAr

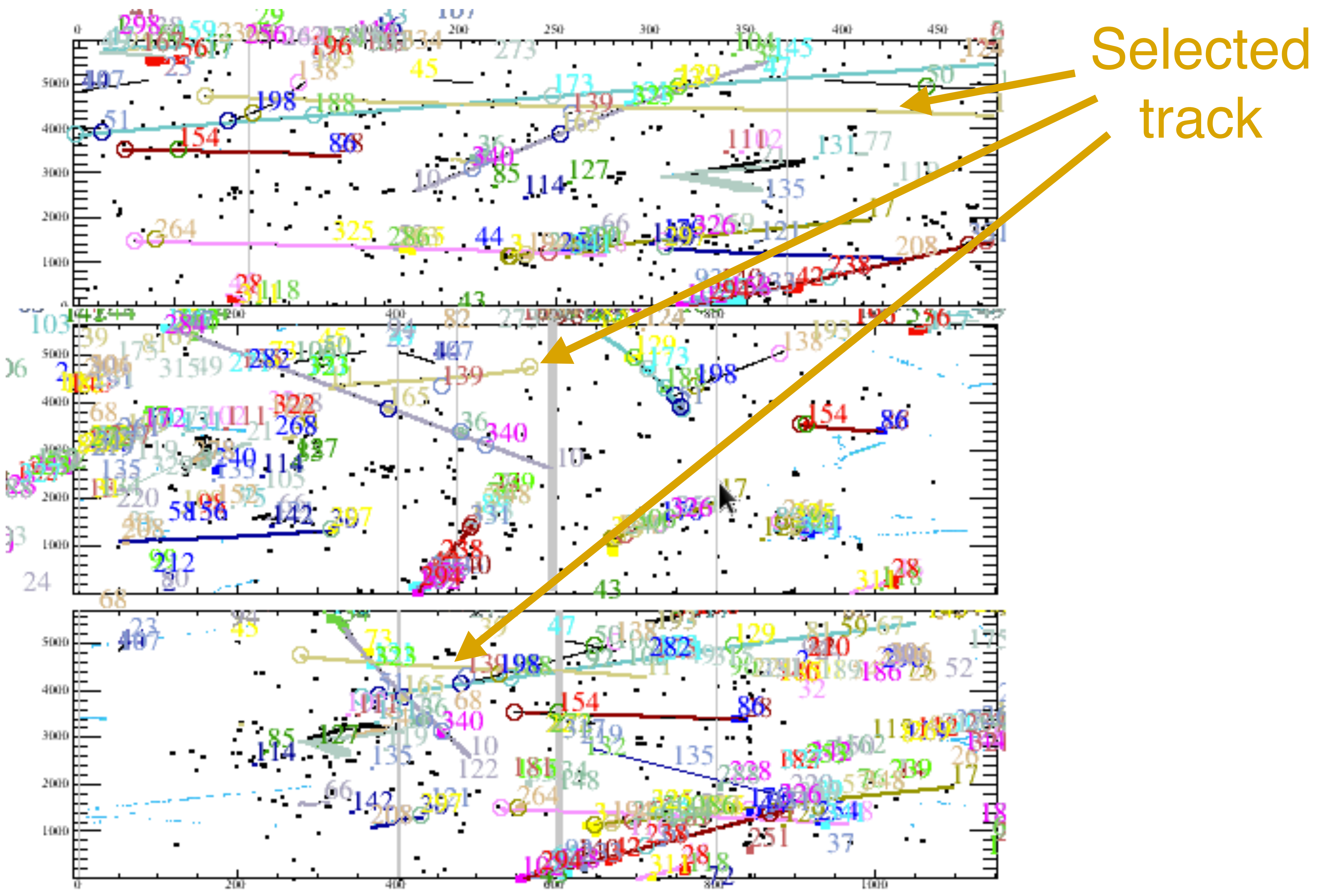
- In $\sigma(E) = \frac{M_{\text{Ar}}}{\rho N_A \Delta E} \frac{dE}{dx}(E) \ln\left(\frac{N_{\text{inc}}(E)}{N_{\text{inc}}(E) - N_{\text{int}}(E)}\right)$, $\frac{dE}{dx}(E)$ is derived according to the Bethe-Bloch formula.



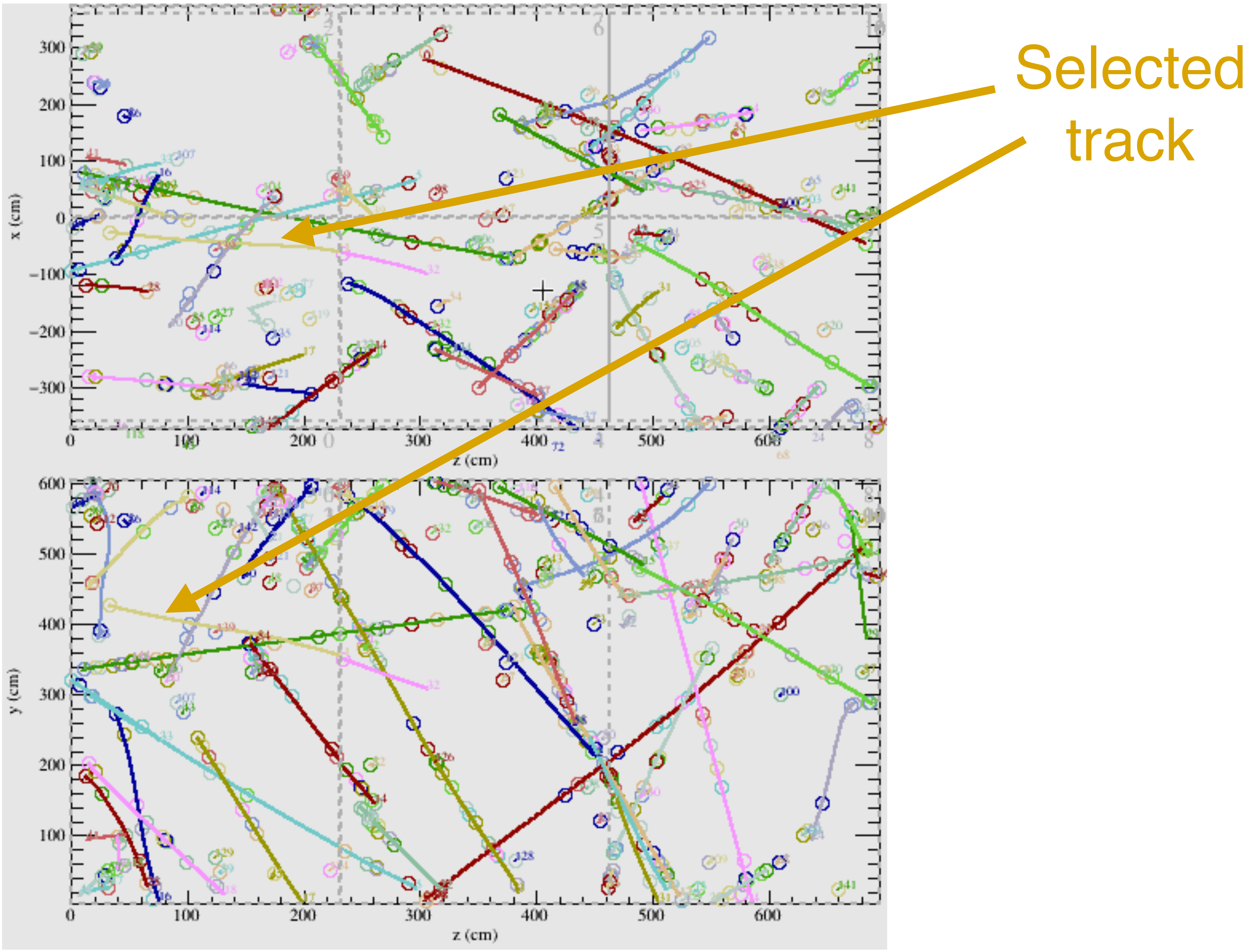


Pandora identification

- In each event, one track is selected as beam track by Pandora based on boosted decision tree (BDT) algorithm.



Wire view (from top to bottom: plane Y; U; V)



Ortho3D view (top: XZ view; bottom: YZ view)

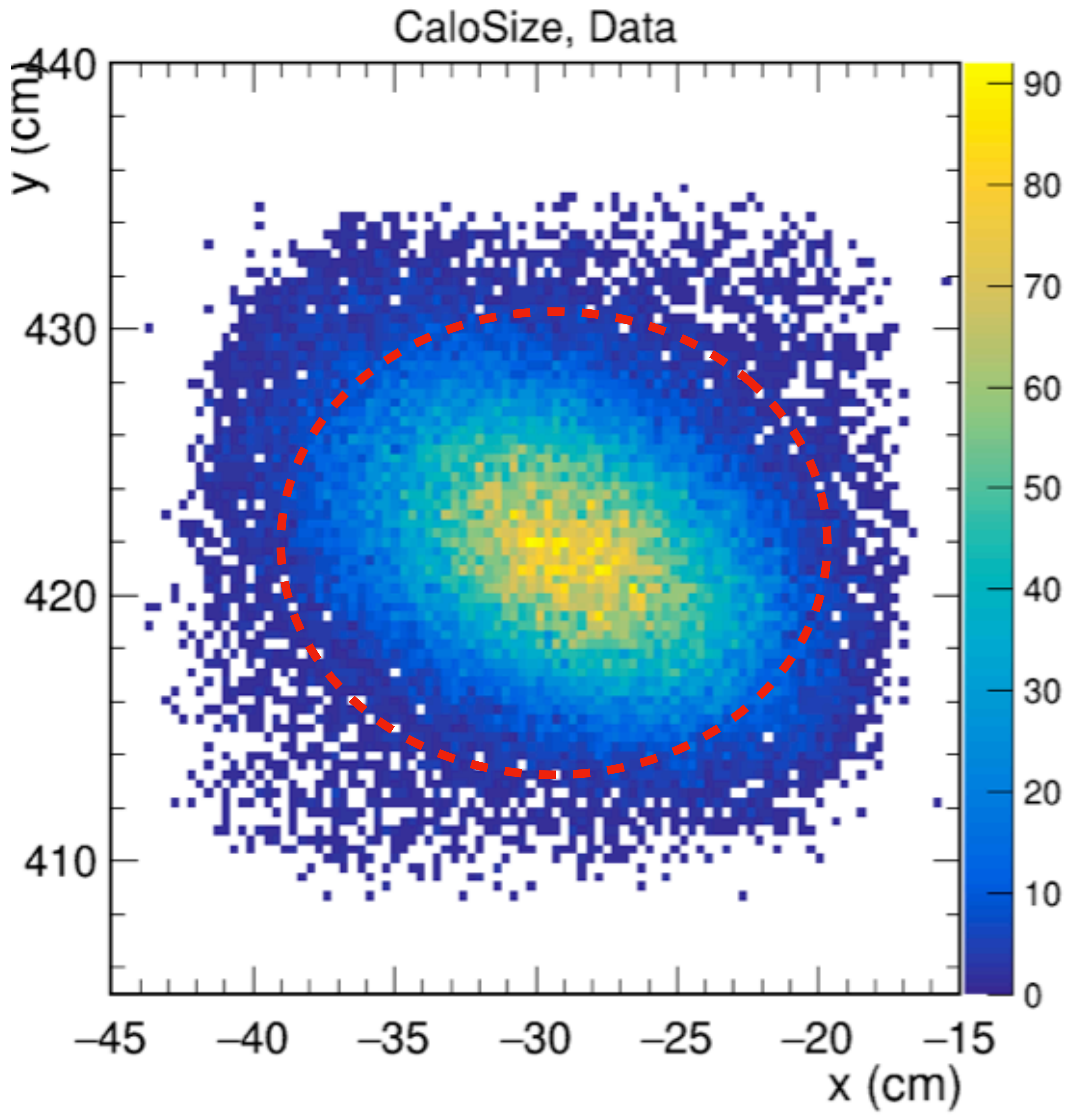
Precut

- Some technical cuts to ensure the beam track can be used.
  - **Upstream beam type selection**
    - MC true_beam_PDG == -13 or 211
    - Data beam_inst_trigger != 8
      beam_inst_nMomenta == 1 && evt.beam_inst_nTracks == 1
      beam_inst_PDG_candidates == -13 or 211
  - **Empty events removal** reco_reconstructable_beam_event != 0
  - **Pandora Slice Cut** to ensure it is a track. reco_beam_type == 13
  - **Calo Size Cut** require hit detected on collection plane. ! (reco_beam_calo_wire->empty( ))

Variable definitions: https://wiki.dunescience.org/wiki/PDSPAnalyzer

Beam Quality Cut

- It consists of two parts. First, cuts on the position of instrumented beam particle projected to the front-face of the TPC.



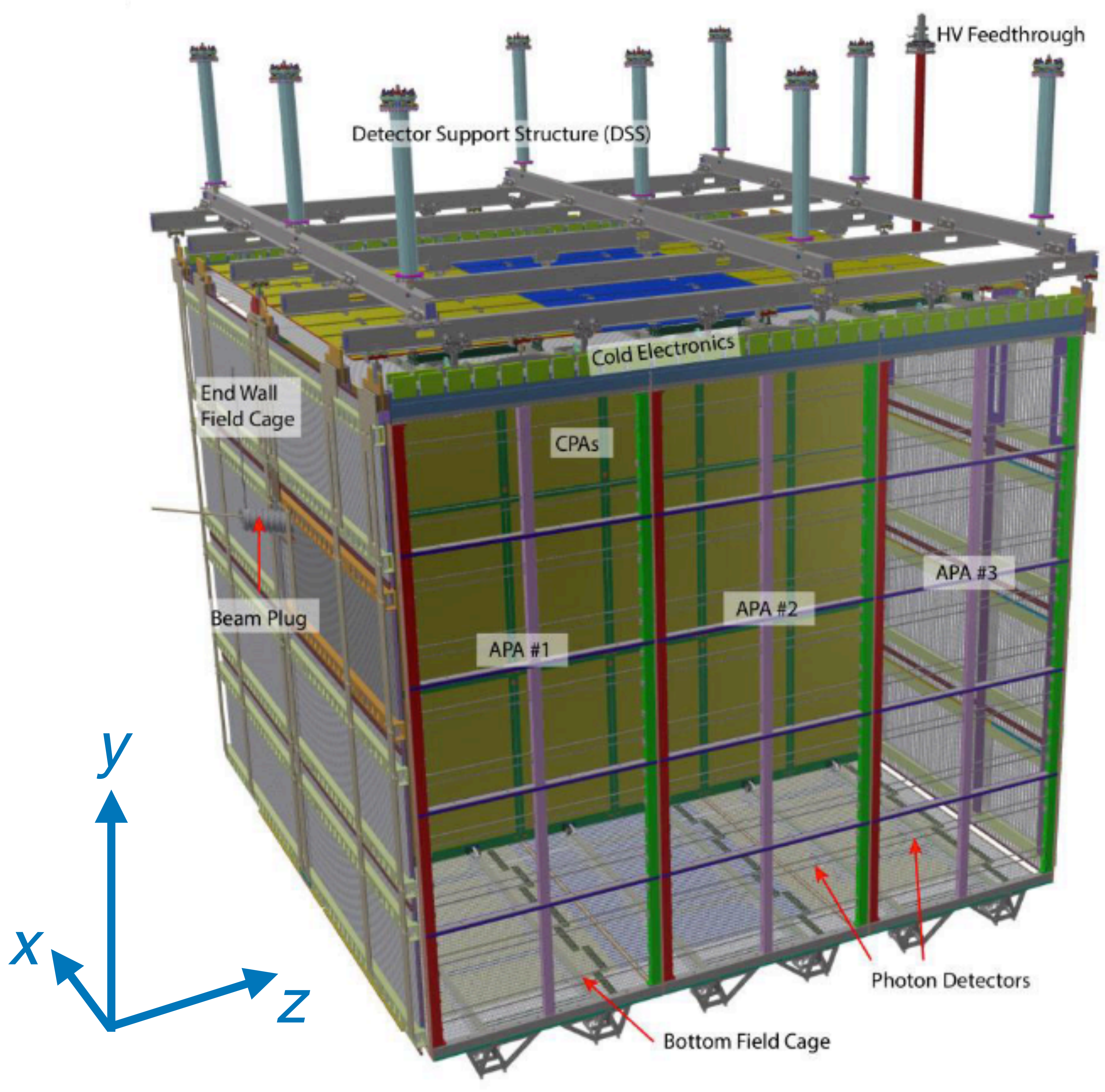
- The events outside of the oval is more likely to be secondary particles produced by upstream interactions.

Selection: sqrt($\Delta x_{\text{inst}}^2 + \Delta y_{\text{inst}}^2$) < 4.5

- Δx_{inst} is $(x_{\text{inst}} - \mu_{x_{\text{inst}}})/\sigma_{x_{\text{inst}}}$
- $\mu_{x_{\text{inst}}}$ and $\sigma_{x_{\text{inst}}}$ are derived before beam quality cut

Beam Quality Cut

- Second, cuts on beam entrance position and beam angle.
  - Entrance point on *xy* plane sqrt($\Delta x^2 + \Delta y^2$) < 3
  - Start *z* position $|\Delta z| < 3$
  - Beam angle $\cos\theta > 0.95$
    - Δx is $(x - \mu_x)/\sigma_x$, where μ_x and σ_x are derived before beam quality cut. Δy and Δz are similar.
    - θ is the angle between the track and the mean direction μ_θ, derived before beam quality cut.

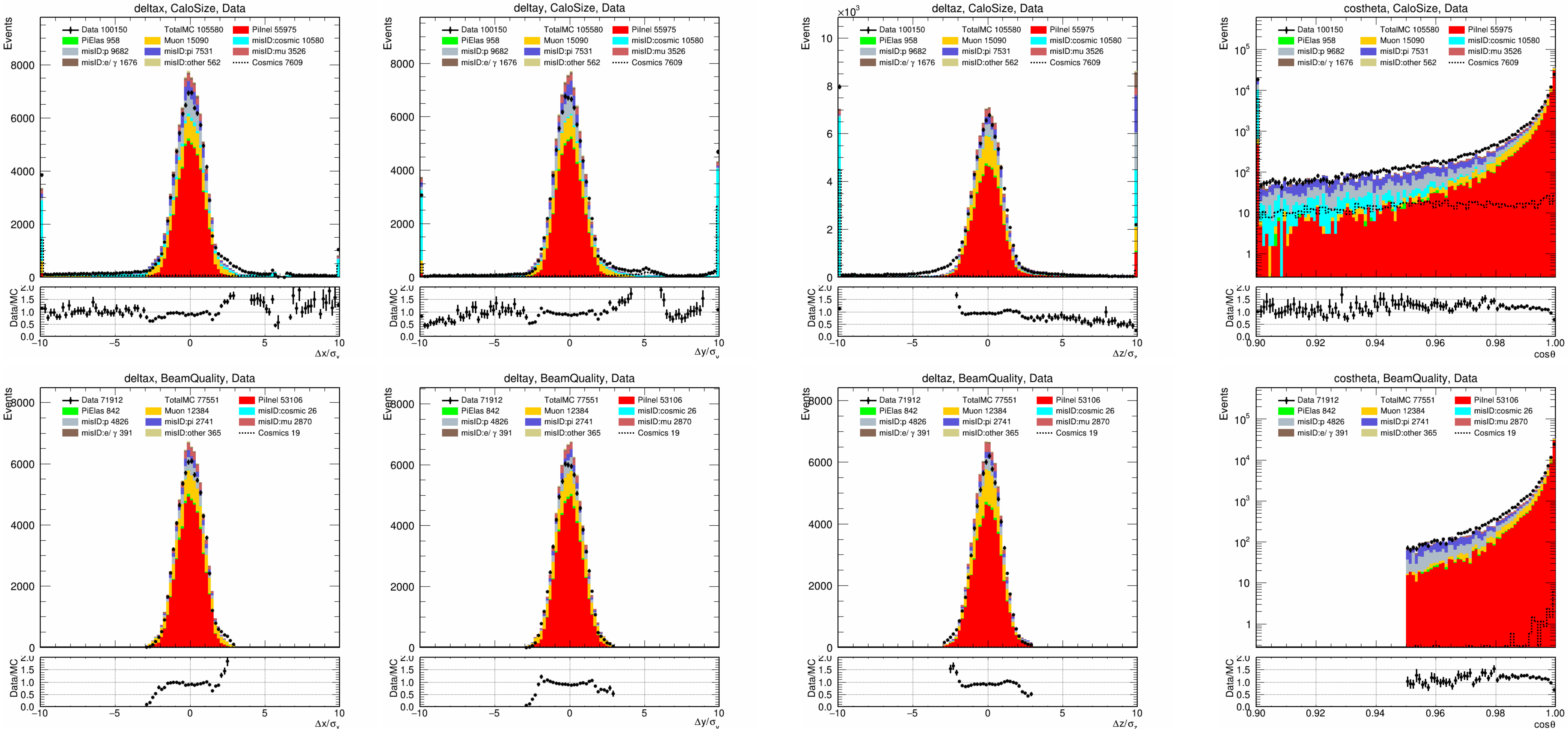


A view of ProtoDUNE-SP detector. The beam plug indicates the direction of beam track

Beam Quality Cut

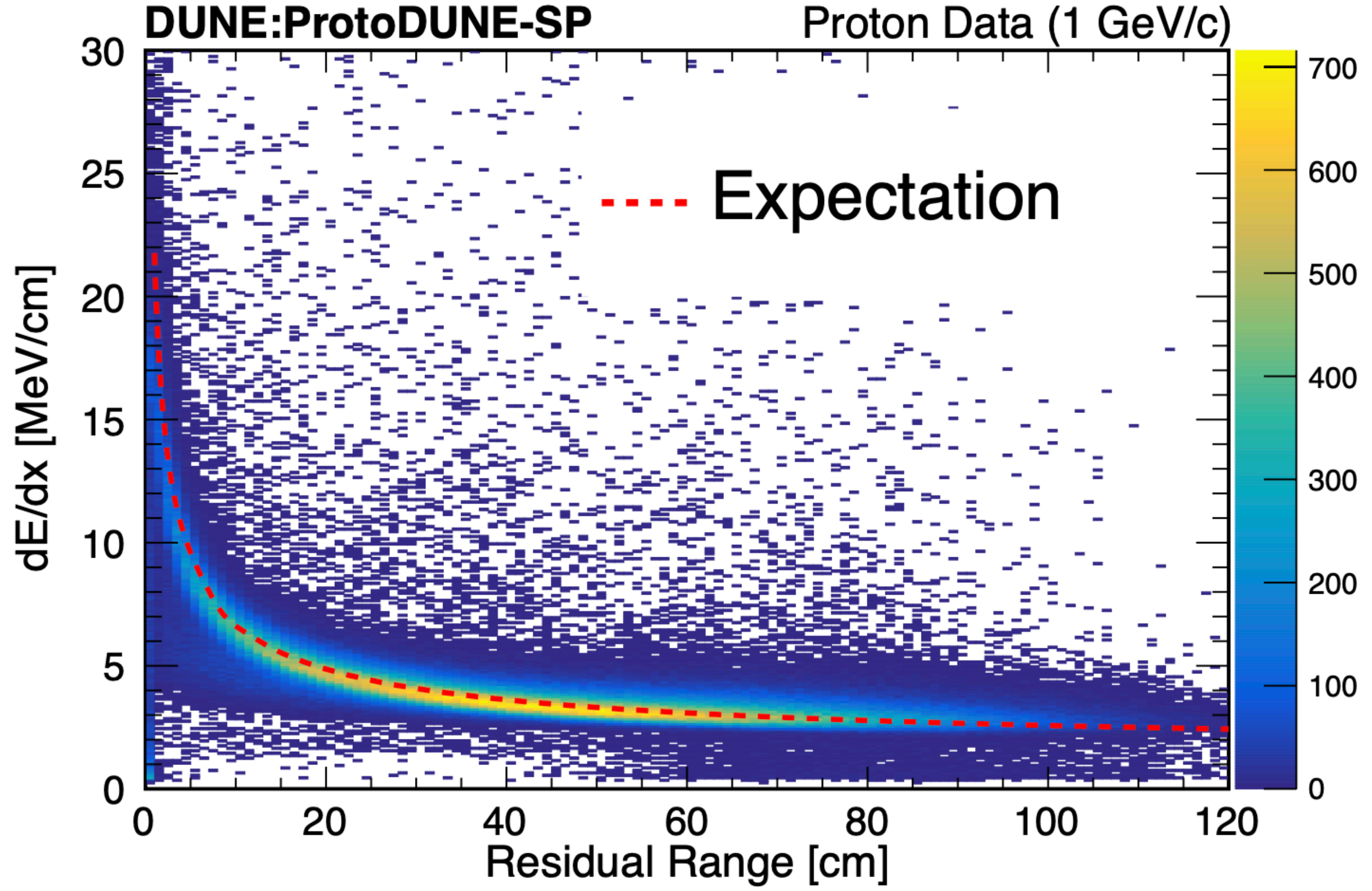
$\mathrm{sqrt}(\Delta x^2+\Delta y^2) < 3$ | $|\Delta z| < 3$ | $\cos\theta > 0.95$

After cut

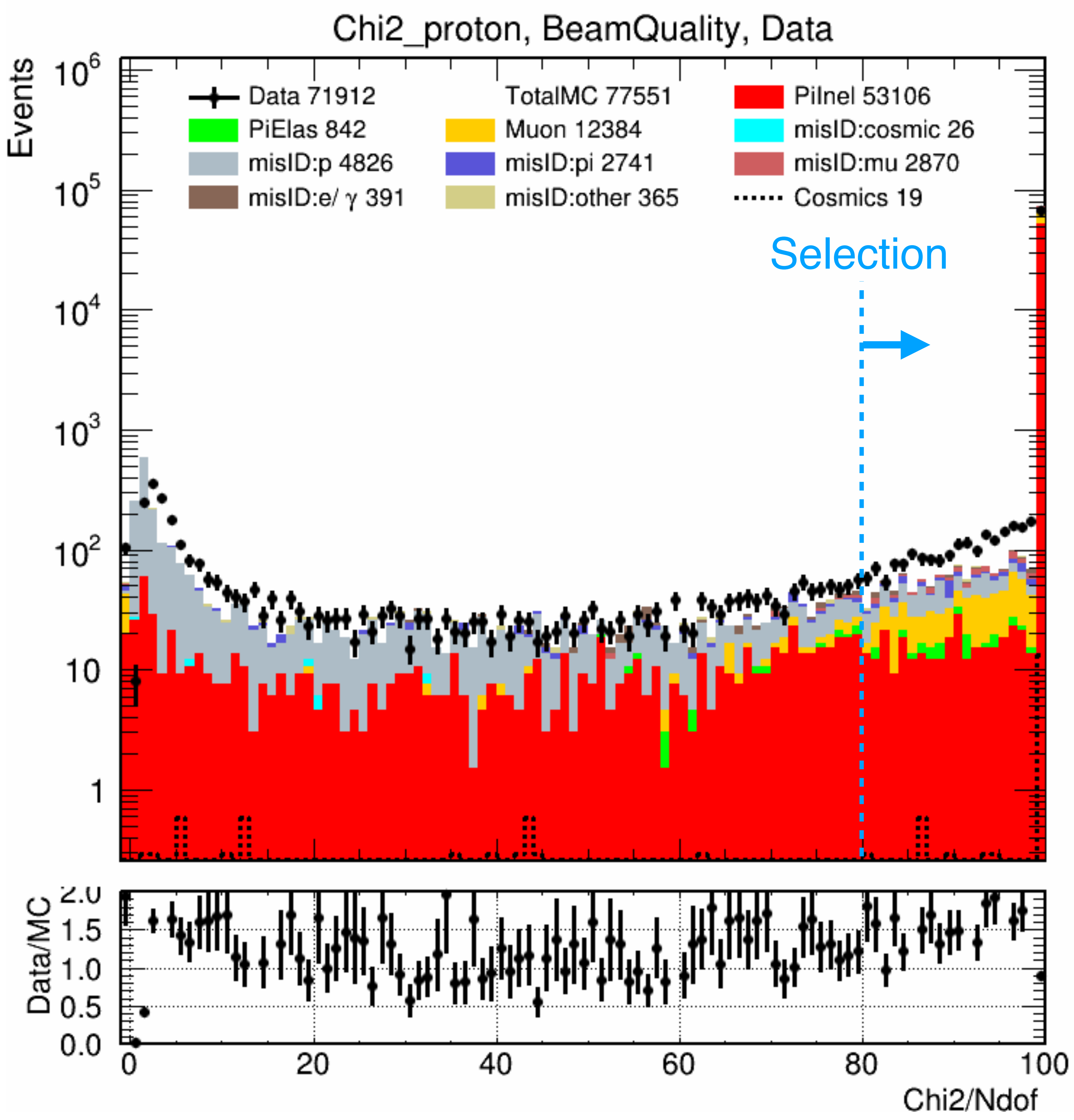


Proton Cut

- We use **Chi2_p/Ndof** to cut proton.
  - Assume it is a stopping proton, then fit dE/dx vs residue range to expectation.

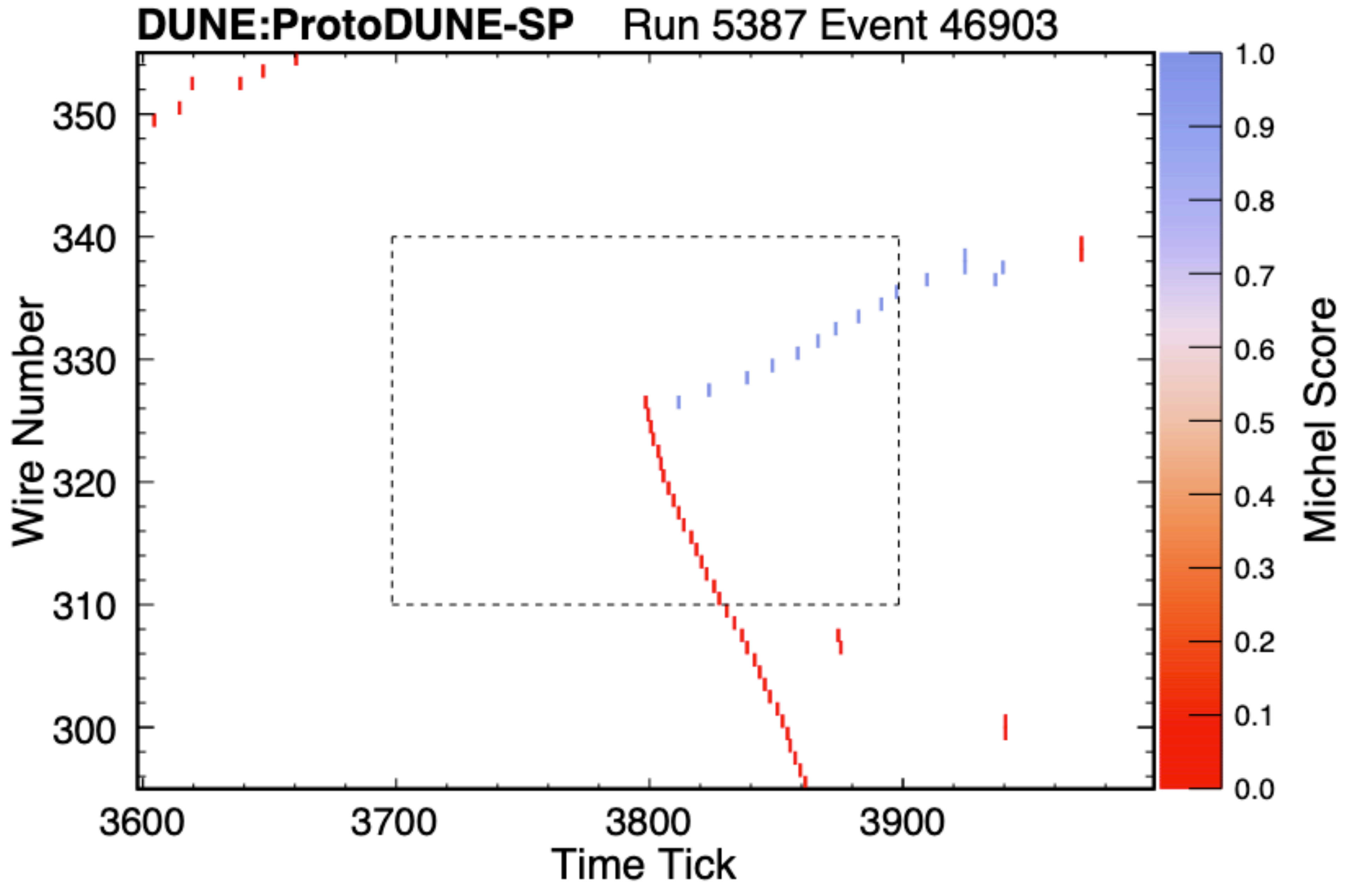


https://doi.org/10.1088/1748-0221/15/12/P12004

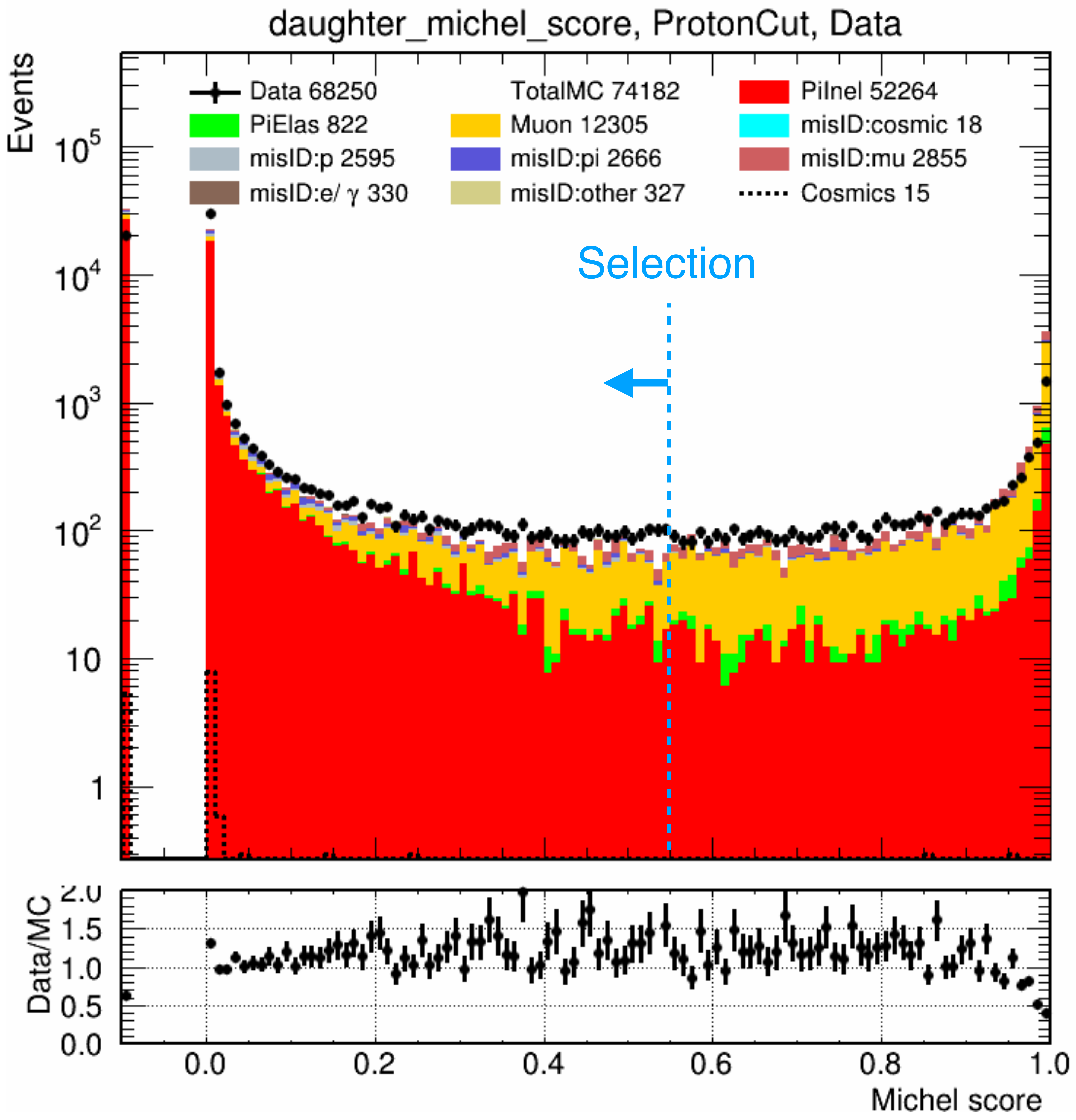


Michel Score Cut

- Michel electron shows some features which can be detected by pattern recognition, thus can be used to cut muon.



A Michel candidate
https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=23125

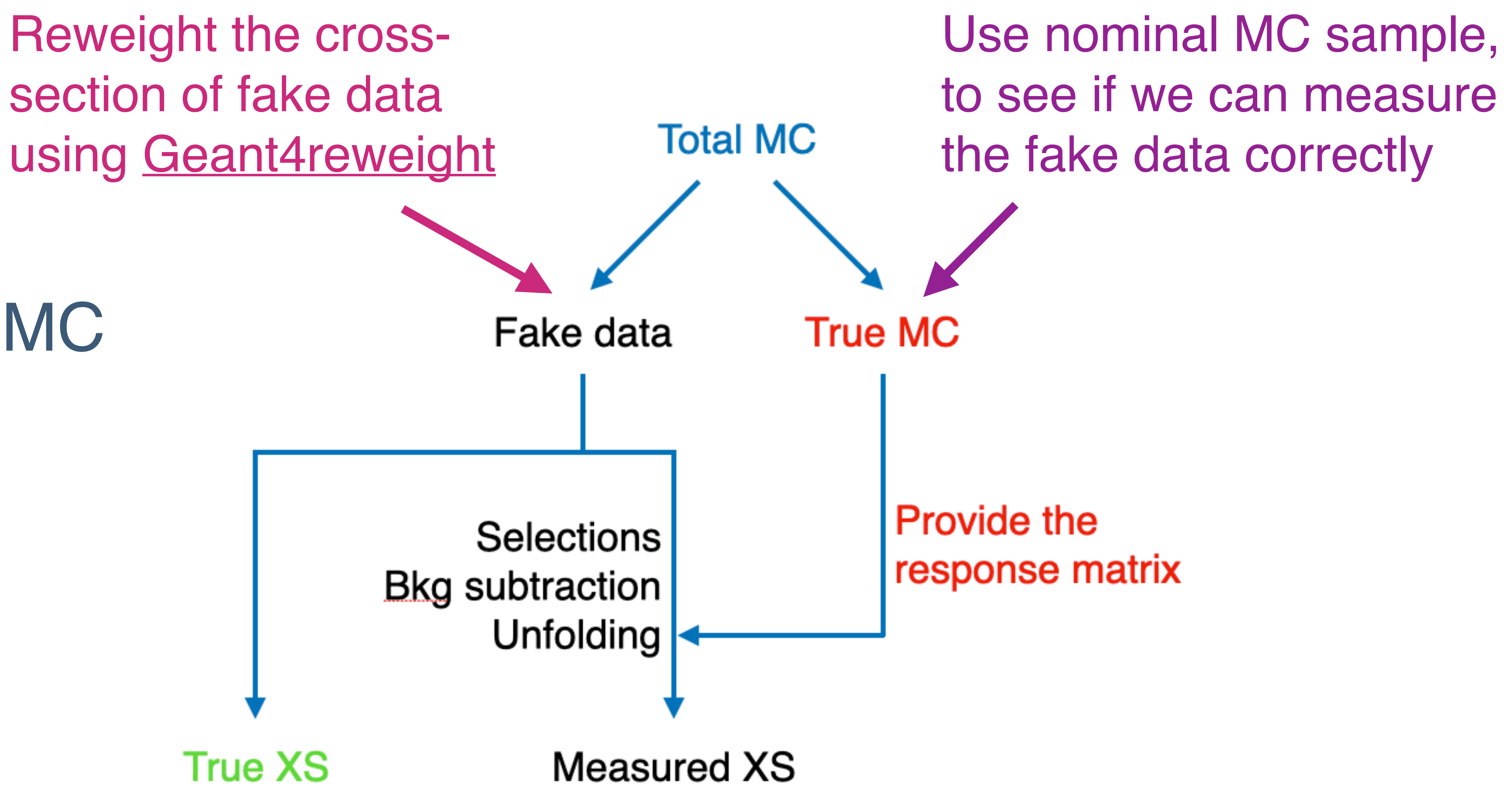


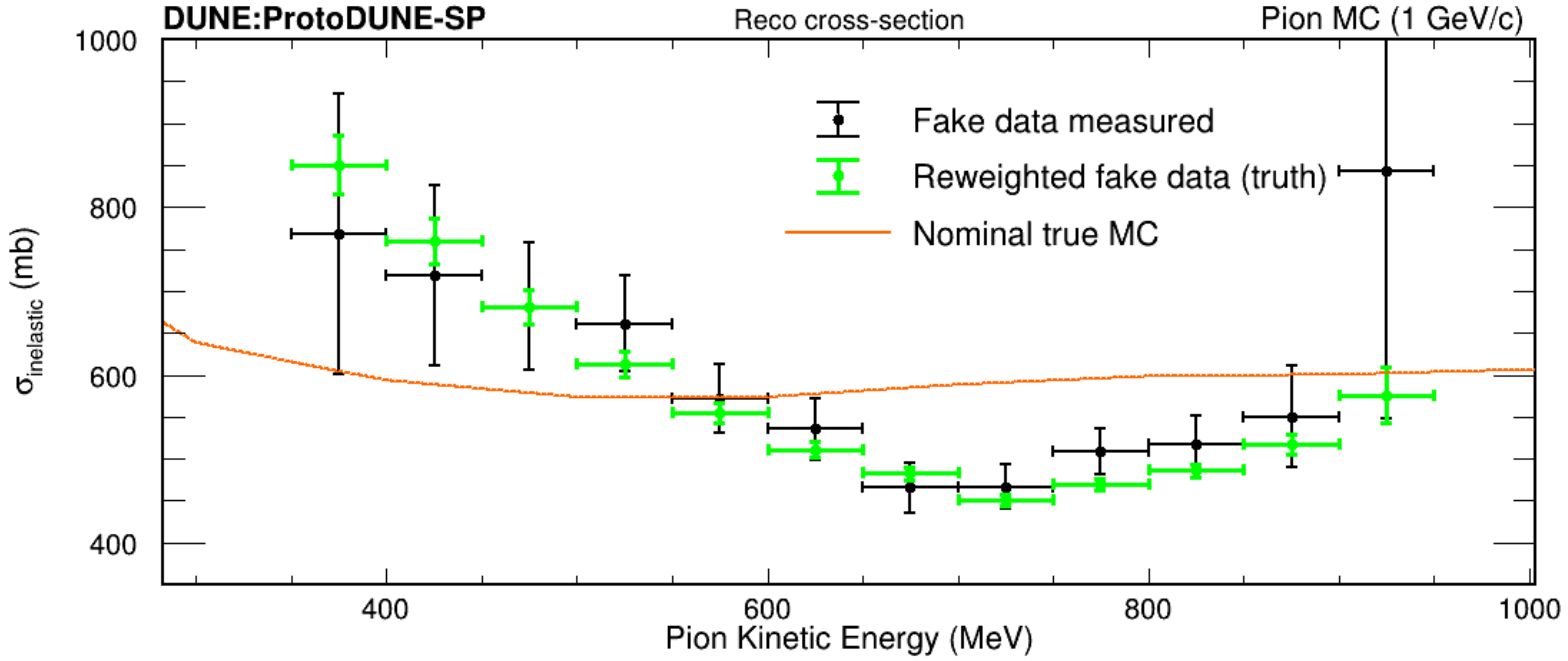
D’Agostini (iterative Bayesian) unfolding

- We use the d’Agostini (iterative Bayesian) method for 20 iterations by default.
  - The response matrix is derived by true pion MC
    $R_{ij} = P(x \in \text{reco bin } i \,|\, y \in \text{true bin } j)$
  - Based on the Bayes’ theorem, the unfolding matrix is estimated as
    $$\widetilde{R}_{ij} = \frac{R_{ij} \cdot P(y \in \text{true bin } j)}{\sum_j R_{ij} \cdot P(y \in \text{true bin } j)}$$
  - To measure real data, $P_{\text{data}}(y \in \text{true bin } j) = \sum_i \widetilde{R}_{ij} \cdot P_{\text{data}}(x \in \text{reco bin } i)$
  - $P(y \in \text{true bin } j)$ is iteratively replaced by the measured result.

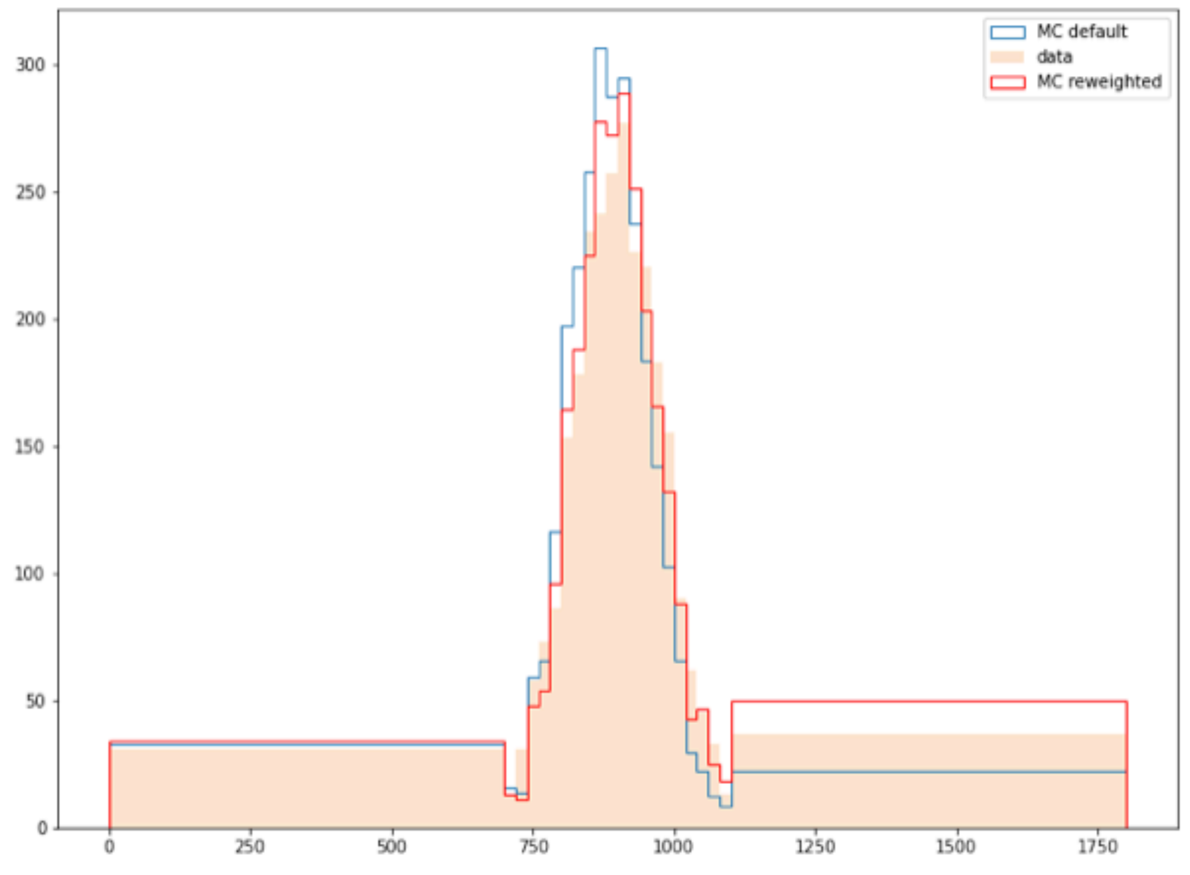
Mock-data test

- Consider differences between fake data and true MC

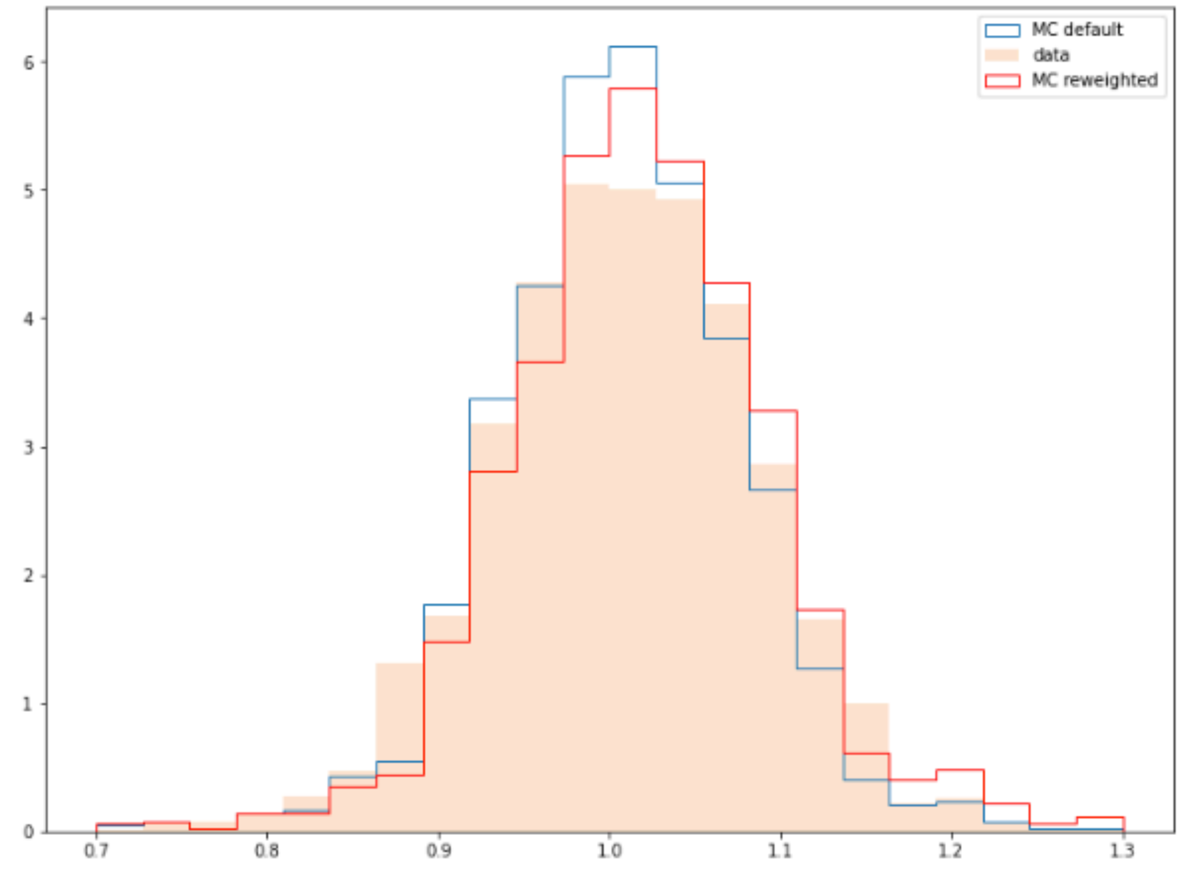




Momentum reweighting



Reconstructed front-face KE (MeV)



Beam instrumented momentum (GeV)

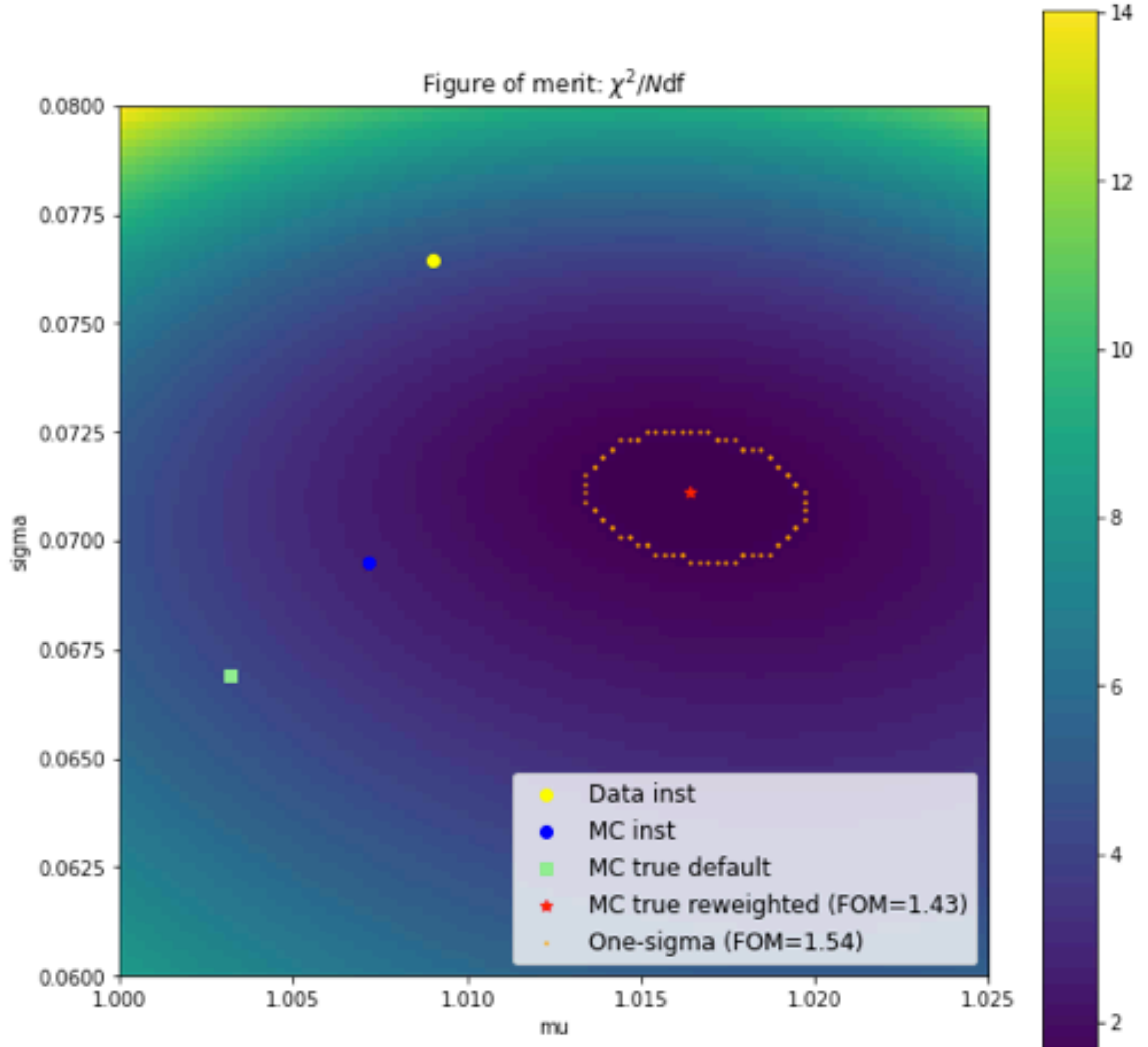
- We use stopping muon tracks to perform momentum reweighting study.

- A weight to each MC event

$$\frac{e^{-\frac{(p-\mu)^2}{2\sigma^2}}}{e^{-\frac{(p-\mu_0)^2}{2\sigma_0^2}}}$$

- p is the true momentum in each MC event
- μ_0 and σ_0 are fit to MC true momentum
- μ and σ are two **fit parameters**

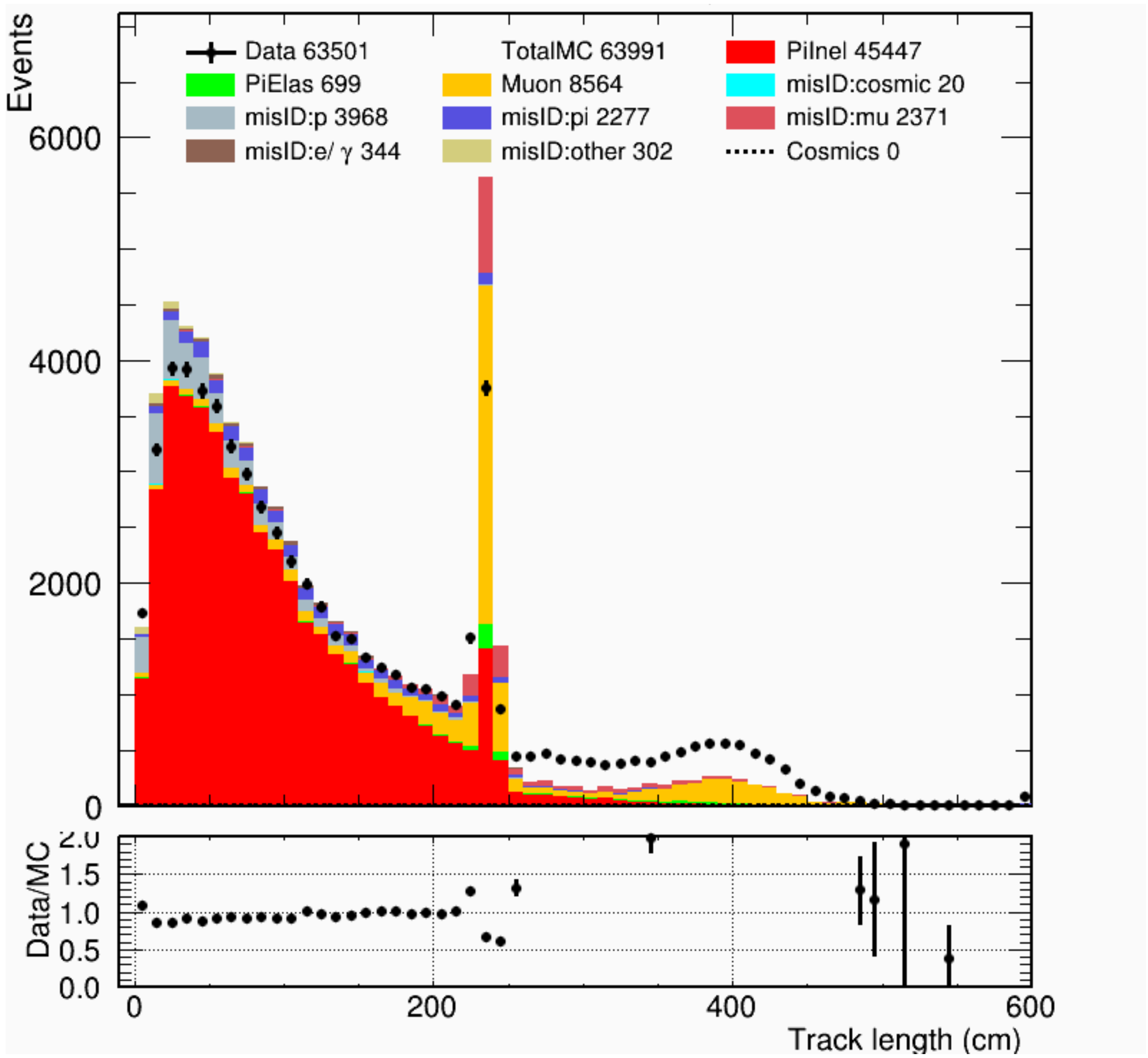
- χ² fit is performed for the best agreement on the reconstructed front-face KE between data and MC.



χ²/Ndf on 2D meshgrid of (μ, σ)

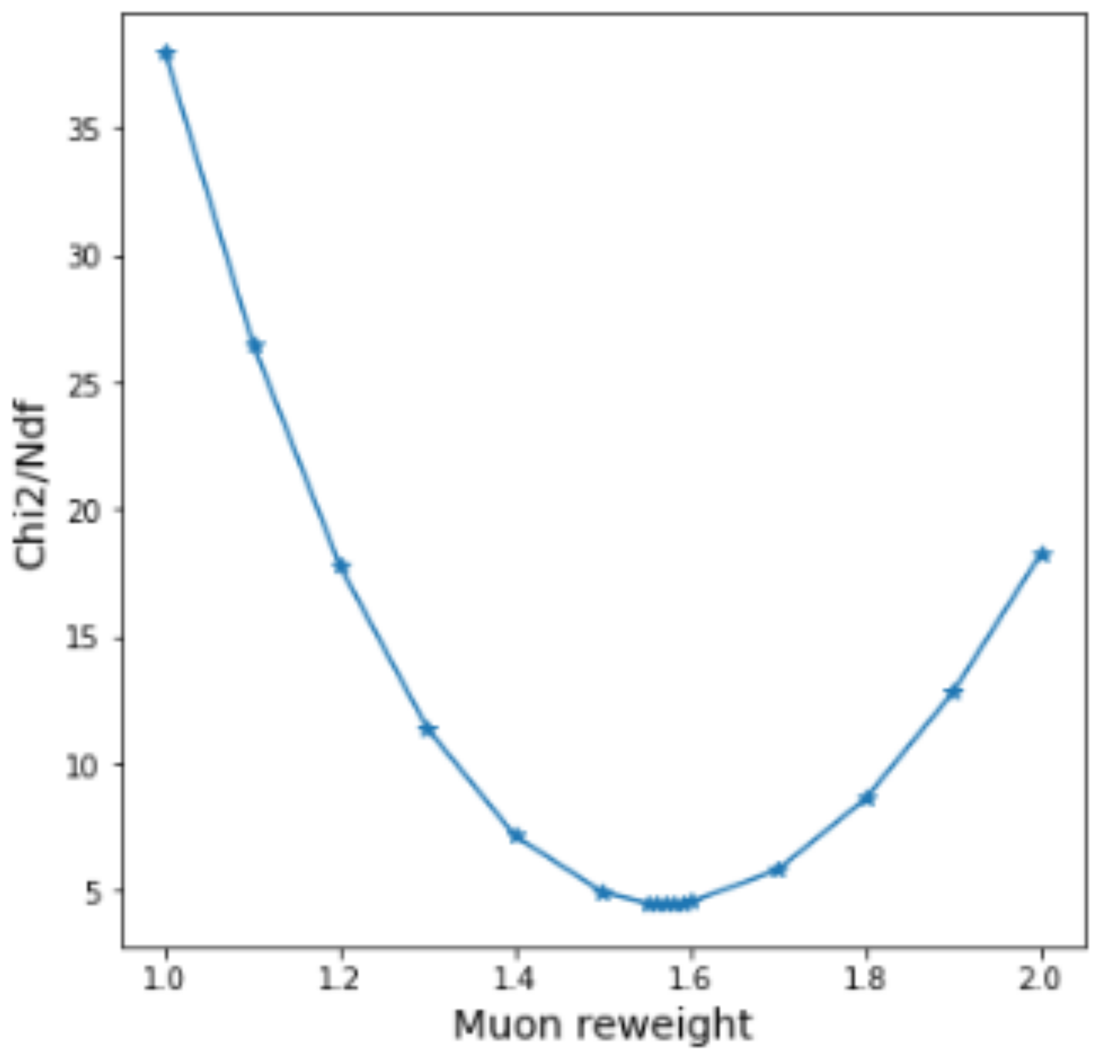
Muon reweighting

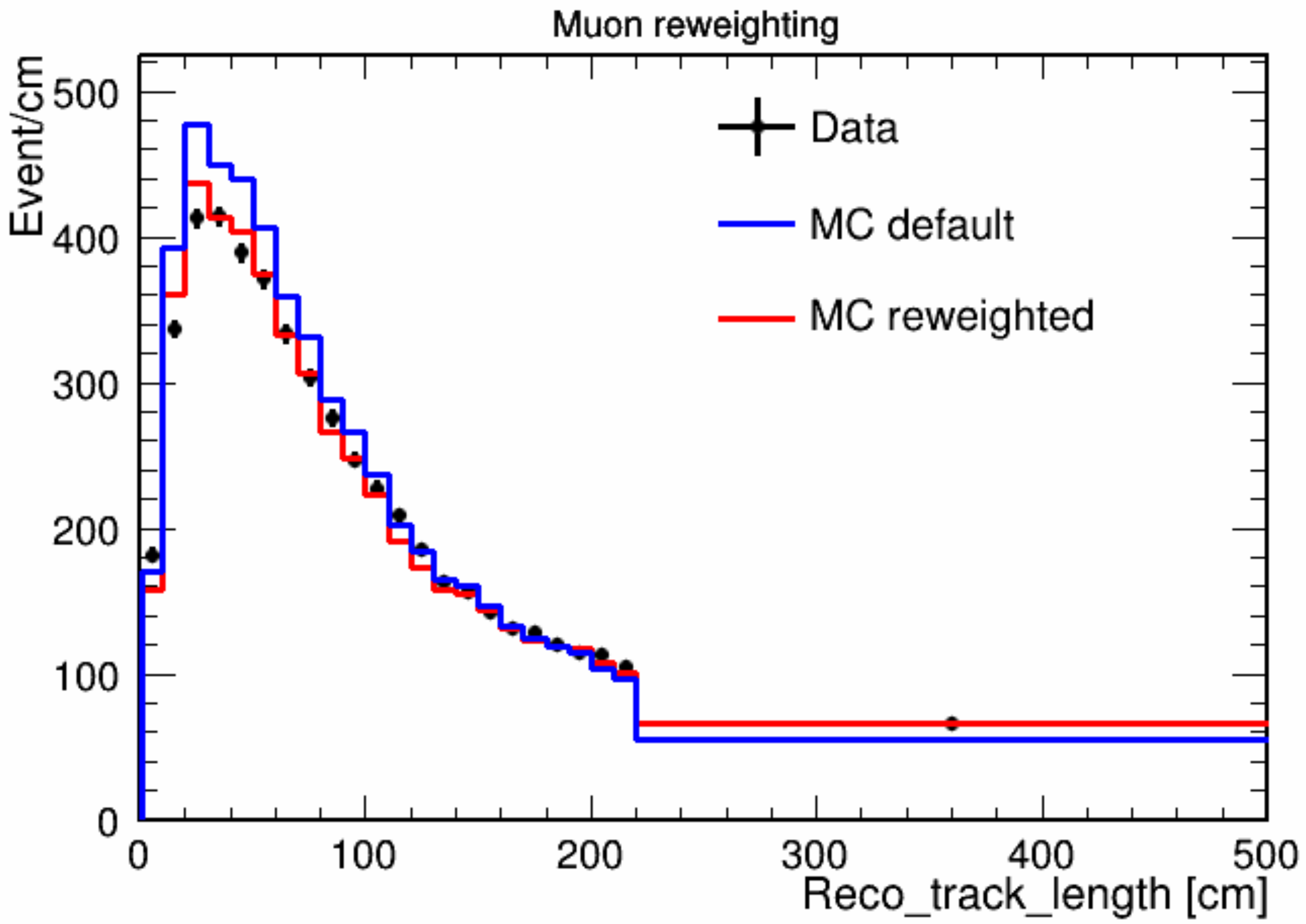
- We notice MC seems to underestimate the fraction of muon components.



Distribution of reco track length

Thus we reweight muon, and perform χ^2 fit on the left plot.





The fitted MC muon weight for is 1.58 (χ^2/Ndf = 4.48).