Muon Momentum estimation using multiple coulomb scattering in ProtoDUNE

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For the DUNE collaboration

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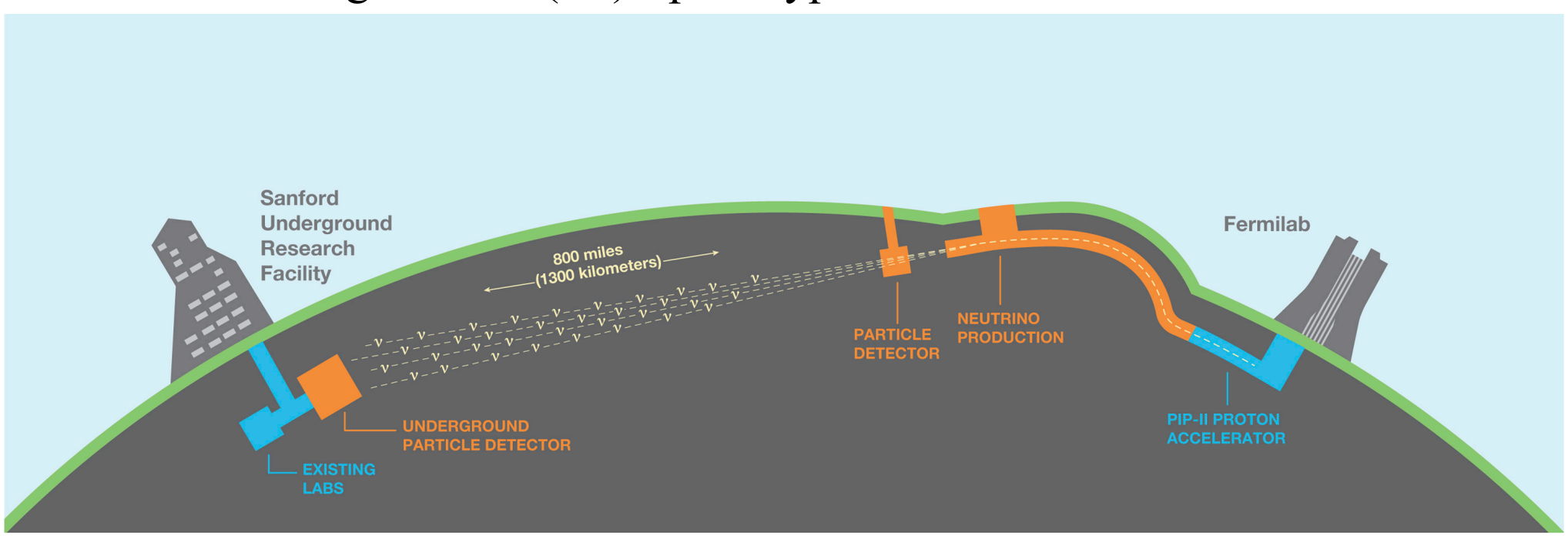
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE Experiment

- Deep Underground Neutrino Experiment (DUNE) is an accelerator-based long-baseline neutrino oscillation experiment.
  - Goals: Determine CP violation, mass hierarchy, precise measurement of oscillation parameters.
- It consists of near detector (ND) situated at Fermilab, and far detector (FD) situated at Sanford Underground Research Facility (SURF).
  - Near detector - constraints on flux and cross-section uncertainties.
  - Far detector - study the neutrino oscillations.
  - ProtoDUNE Single Phase (SP) - prototype for the far detector at CERN.



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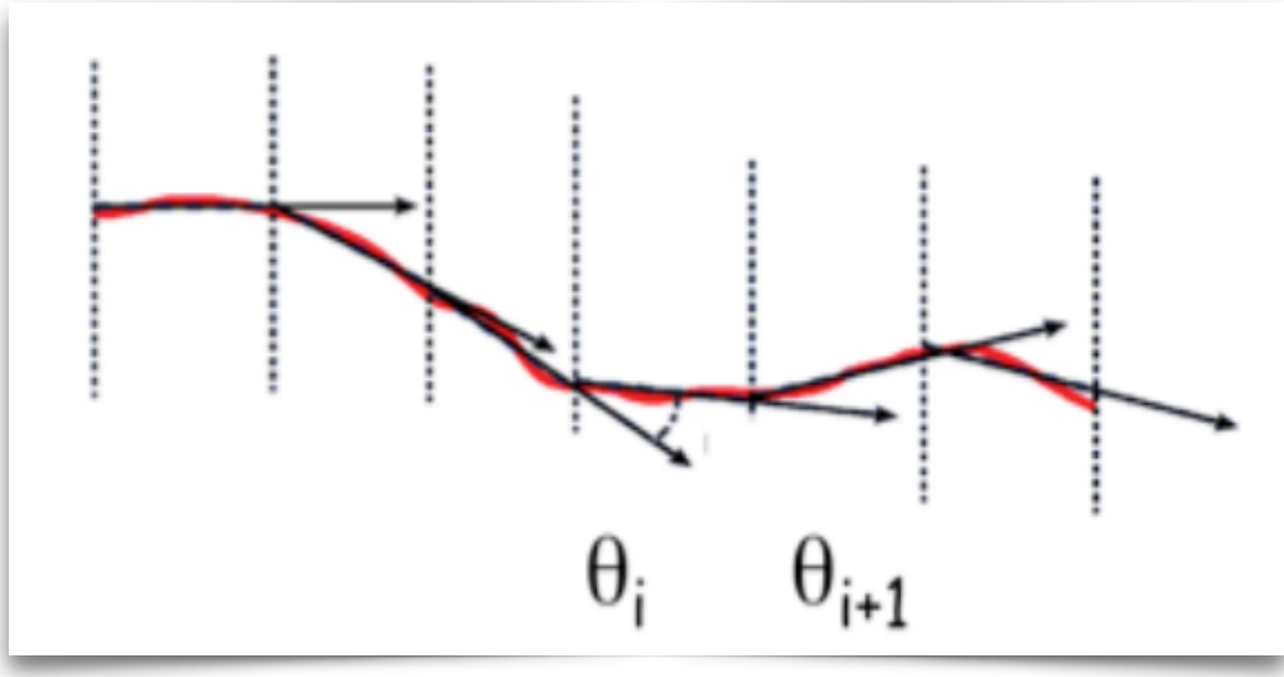
  - Far detector - study the neutrino oscillations.
  - ProtoDUNE Single Phase (SP) - prototype for the far detector at CERN.
- DUNE FD and ProtoDUNE SP uses the Liquid-Argon Time Projection Chamber (LArTPC) technology to identify the particle interactions.
- Momentum estimation of incoming beam particles is essential to understand the detector response and calibration to satisfy the design goals of ProtoDUNE SP as well as for DUNE FD.
  - Multiple Coulomb Scattering (MCS) can be used to estimate the particle momentum.

Multiple Coulomb Scattering (MCS)

- Multiple Coulomb Scattering (MCS) is an electromagnetic scattering of charged particles off atomic nuclei when traversing a medium.
  - Can be used to estimate the momentum of exiting muons in particular.
- This method is based on dividing a track into small segments of characteristic length and measuring the angles between the adjacent segments.
  - For muons in Liquid Argon (LAr), segments are of 14 cm length (radiation length).

Segments are between dashed vertical lines



arXiv:1612.07715

MCS Angle Distributions

- The angle distributions are Gaussian centered at 0 and the width is given by Highland Formula
  - $$\sigma_{HL} = \frac{S_2}{p\beta}\sqrt{\frac{L}{X_0}}\left(1 + \epsilon\ ln\frac{L}{X_0}\right)$$ 1

    where p - muon momentum, L - distance traveled, X_0 - radiation length, ϵ - efficiency, S_2 - parameter MeV/c
- For LAr, this formula is modified by MicroBooNE[a]. For $L \sim X_0$ (which remove ϵ dependency),
  - $$\sigma_{HL} = \frac{\kappa(p)}{p\beta c}, \text{ where } \kappa(p) = \frac{\kappa_a}{p^2} + \kappa_c,$$ 2

    (κ_a, κ_c are fit parameters)

*a - arXiv: 1703.06187

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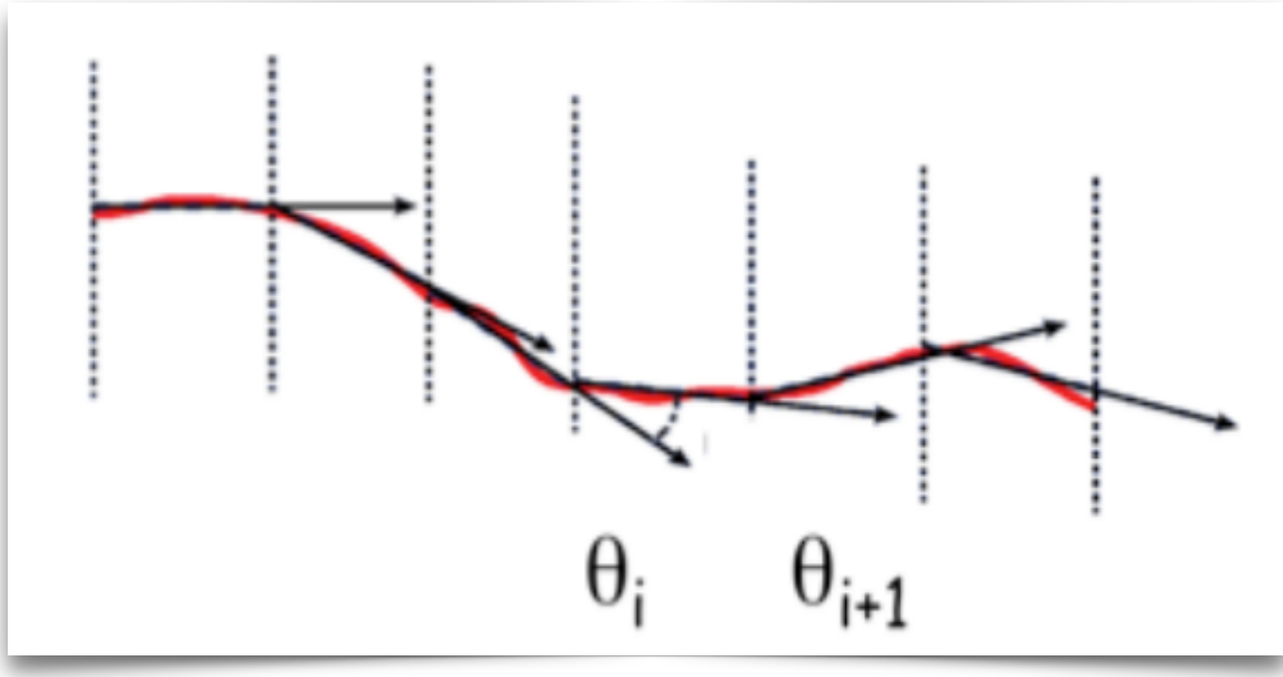
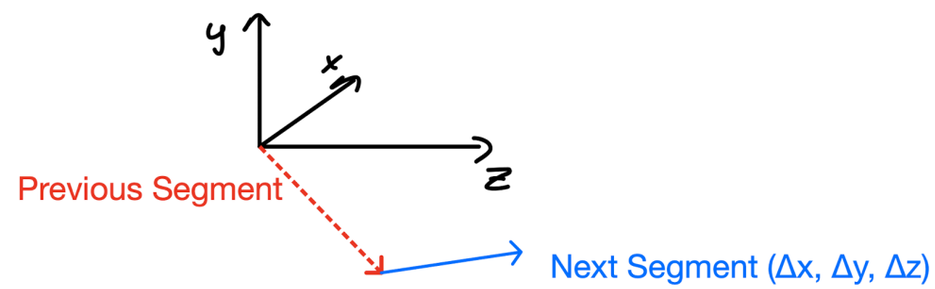


- In addition, a detector inherent resolution term is added in quadrature to σ_{HL}.
  - $$\sigma_{\text{RMS}} = \sqrt{\sigma_{\text{HL}}^2 + \sigma_{\text{RES}}^2}$$ 3

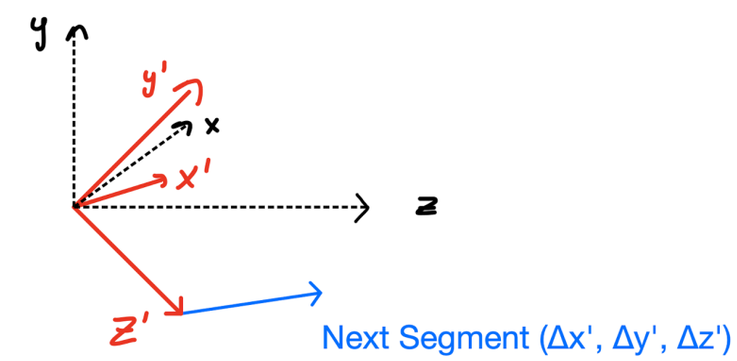
MCS Angle Calculations

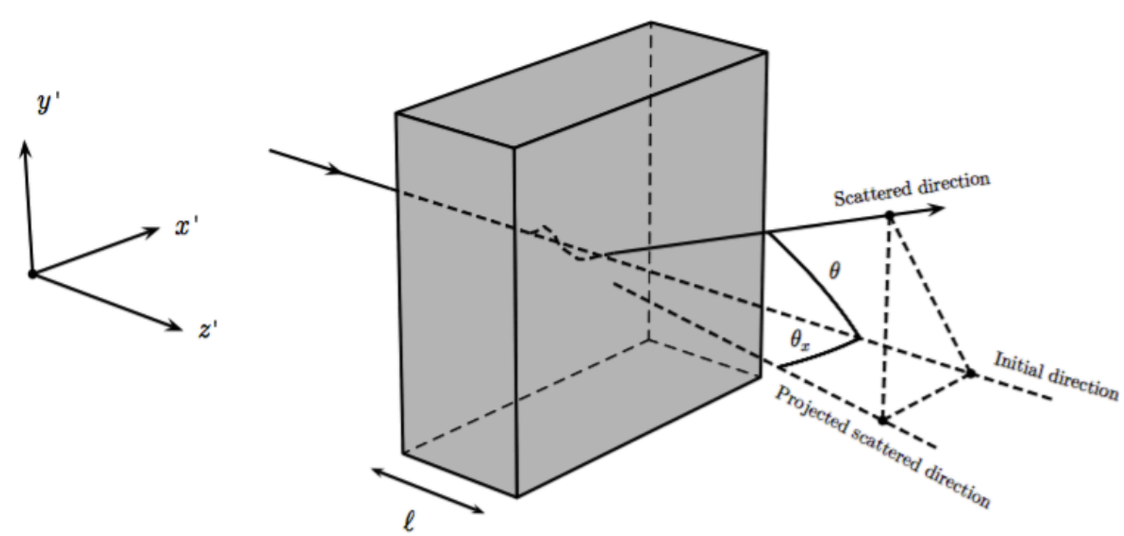
- Segment is a collection of trajectory points within 14 cm length and a vector is defined by the linear fits to those trajectory points.
- For a given segment, the angles are measured following a co-ordinate transformation where the Z axis will lie on the previous segment.
  - $\theta'_{XZ} = \tan^{-1}(\Delta x'/\Delta z')$
  - $\theta'_{YZ} = \tan^{-1}(\Delta y'/\Delta z')$
- The width of the angular distributions as a function of muon momentum are then fitted with σ_{RMS} using Eq. [3] to extract the fit parameters.

Normal Detector Coordinates:



Transformed Coordinate System:





MCS Momentum Estimation

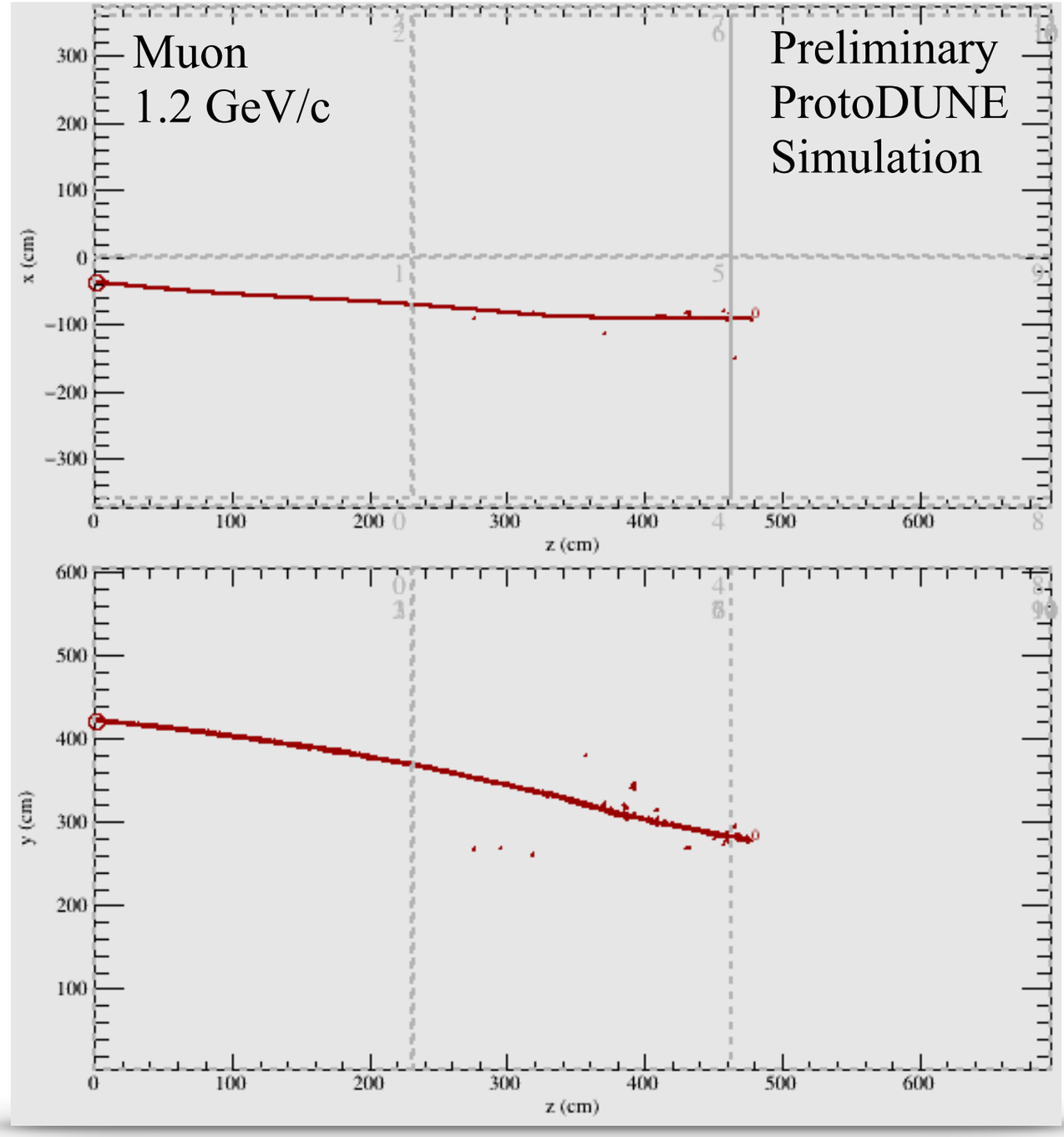
- MCS momentum is estimated using a maximum likelihood method.
- The probability that a scattering angle for a given pair of segments would occur follows a Gaussian distribution.
- Total likelihood is obtained by adding f($\Delta\theta$) in Eq. [4] for all segments along the track.
- The energy loss is considered using Bethe-Block equation.
- The momentum corresponding to the maximum likelihood is the estimated MCS momentum.

$$f(\Delta\theta) = (2\pi\sigma_{\mathrm{RMS}})^{-1/2}\exp\left[-\frac{1}{2}\left(\frac{\Delta\theta}{\sigma_{\mathrm{RMS}}}\right)^2\right] \quad \boxed{4}$$

where σ_{RMS} is from Eq. [3], $\Delta\theta$ is angle

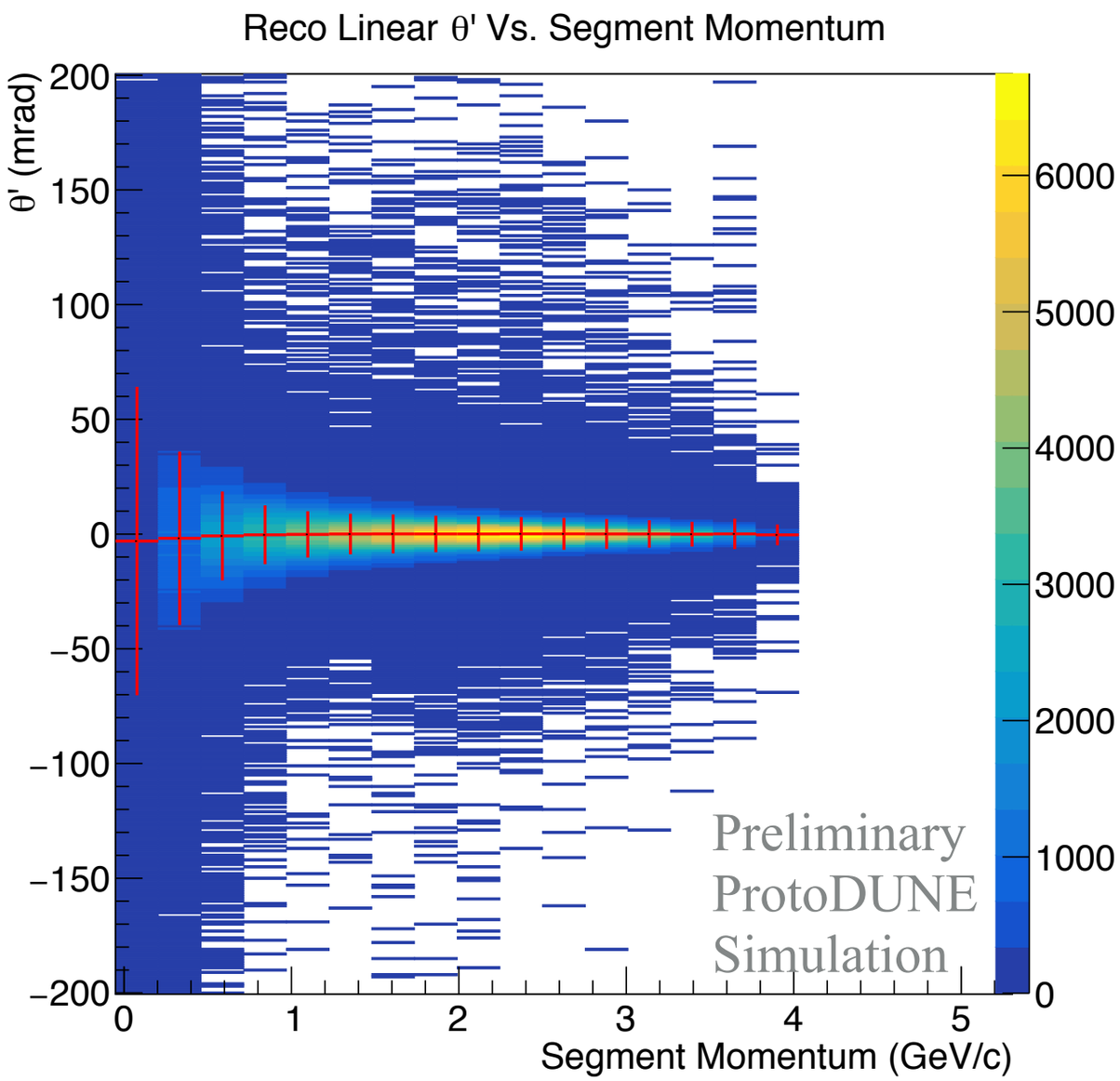
Monte Carlo Samples

- Simulated about 100k single muons with a momentum range between 0.5 - 4.0 GeV/c with uniform distribution.
- Pandora[b] reconstructed tracks are used for this analysis.



*b - https://link.springer.com/article/10.1140/epjc/s10052-015-3659-3

MCS Angles vs Segment Momentum



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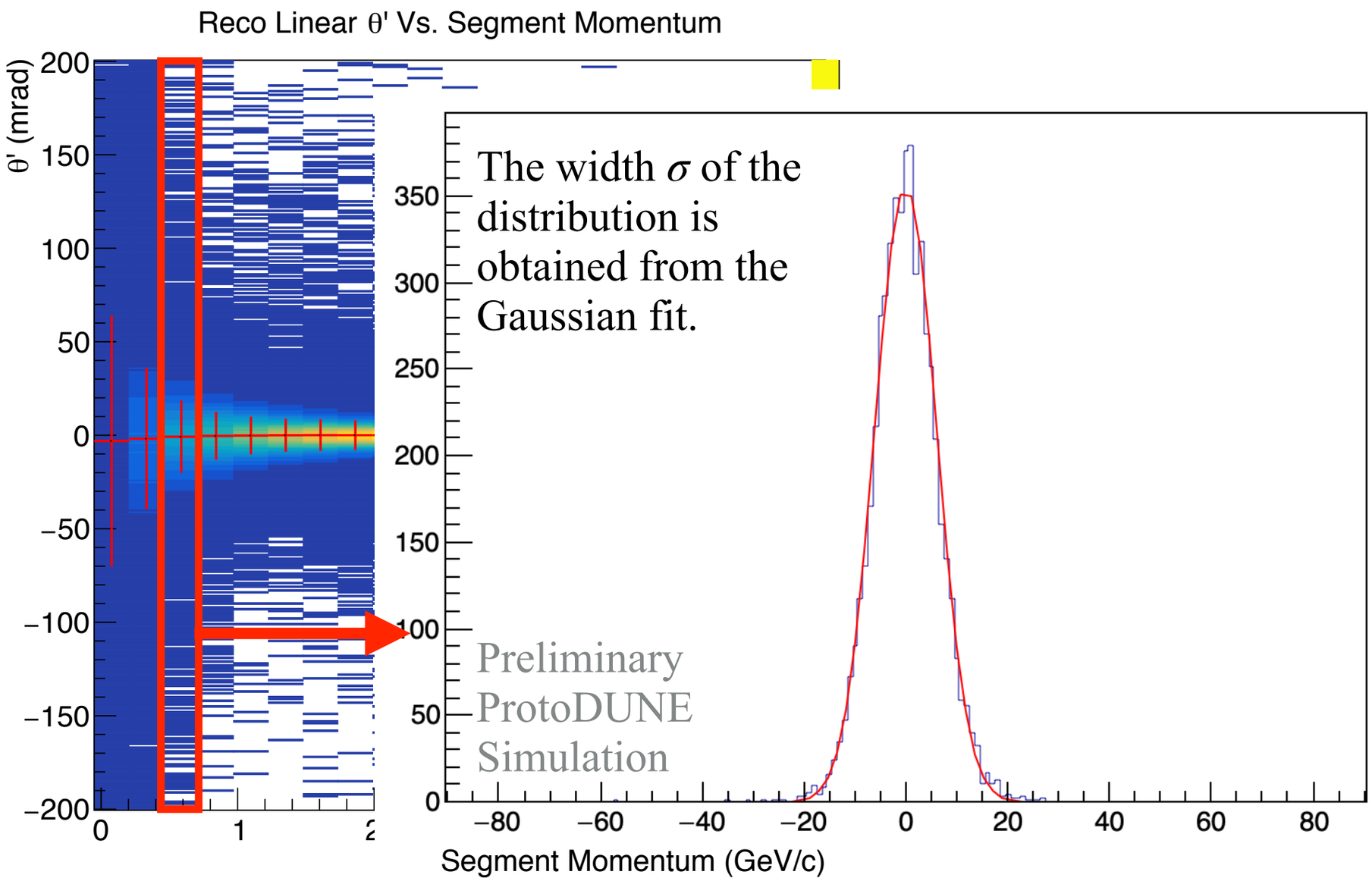

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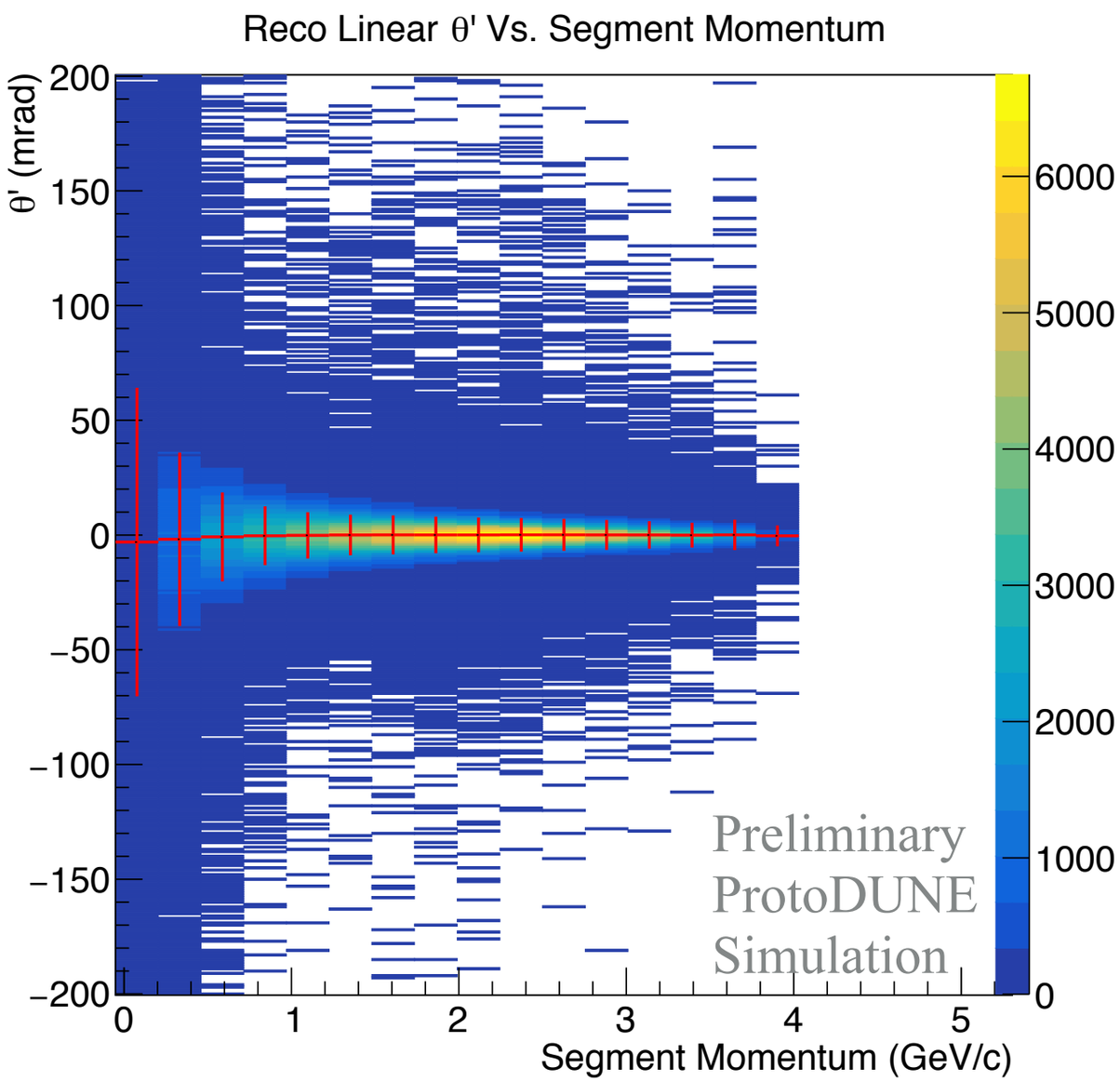
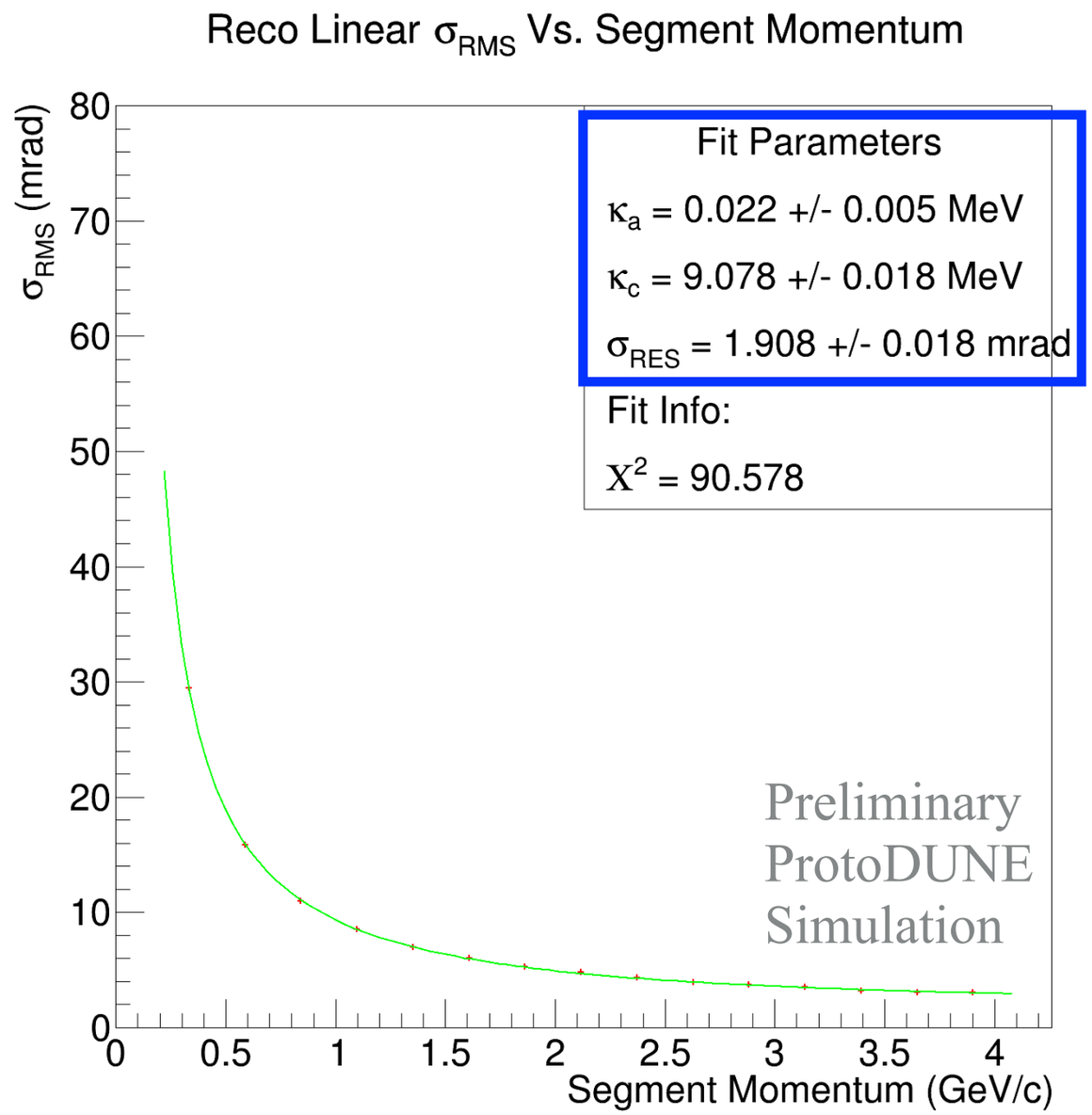
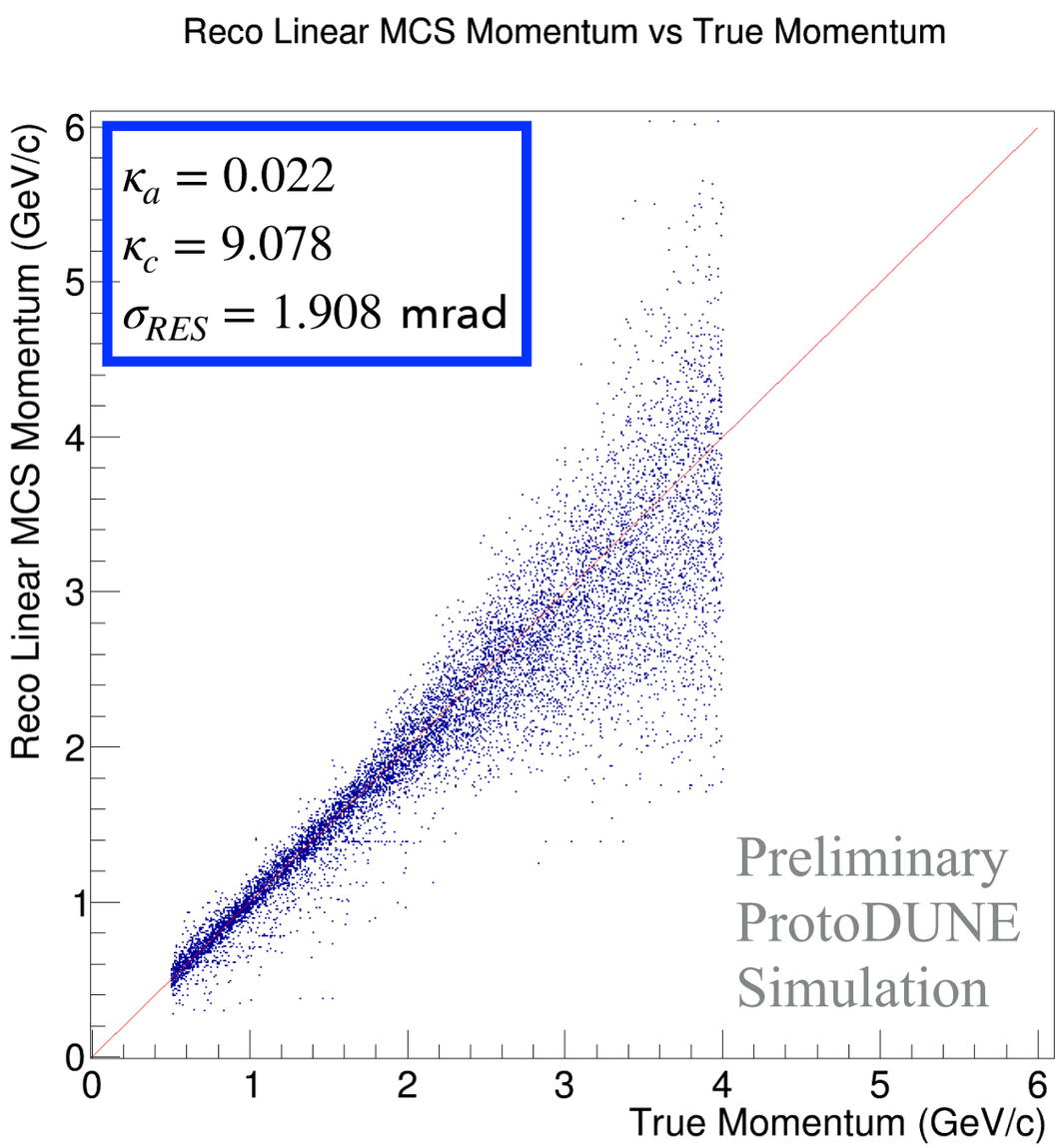
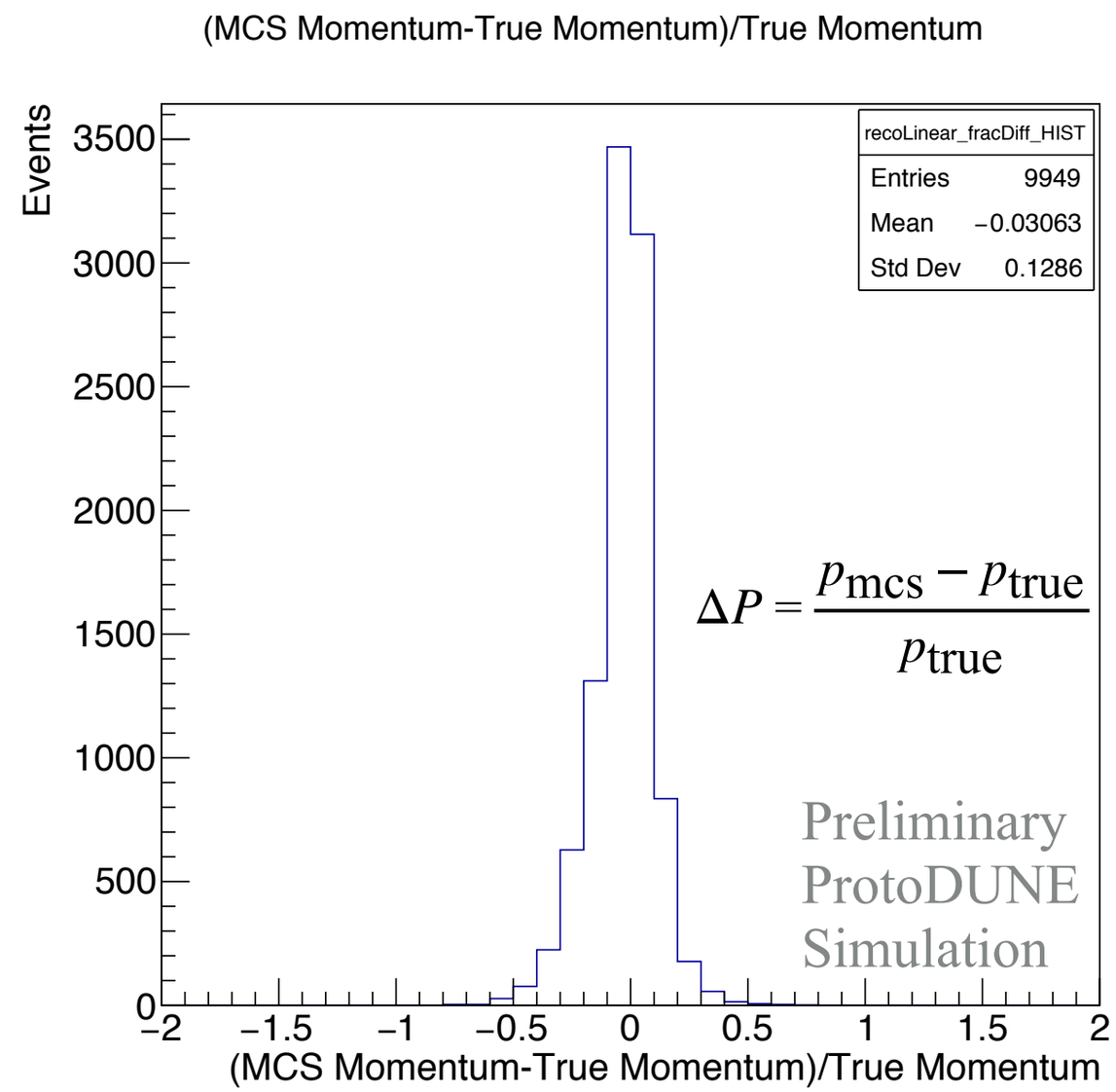




- Sigma of the reconstructed projected angle distributions are fitted with σ_{RMS} (green curve).
- σ_{RMS} fit returns the best-fit values for κ_a, κ_c, σ_{RES} parameters.

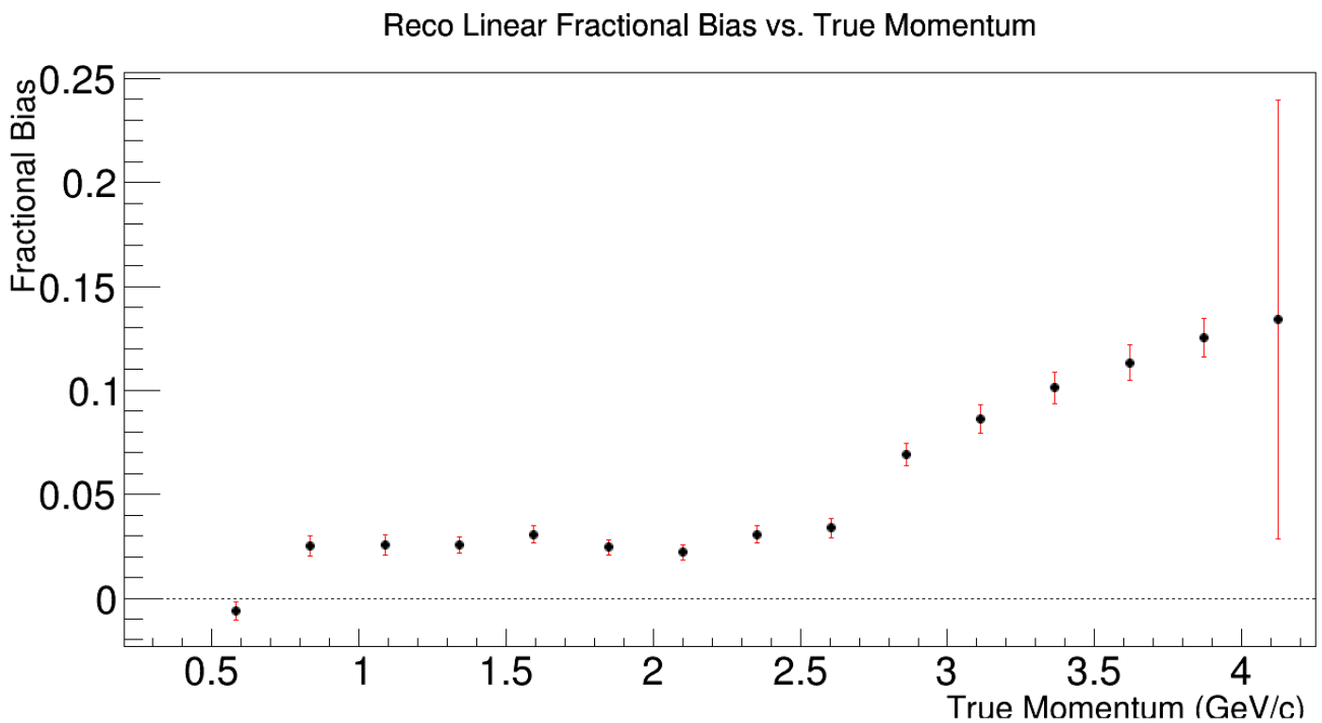
MCS Momentum Estimation

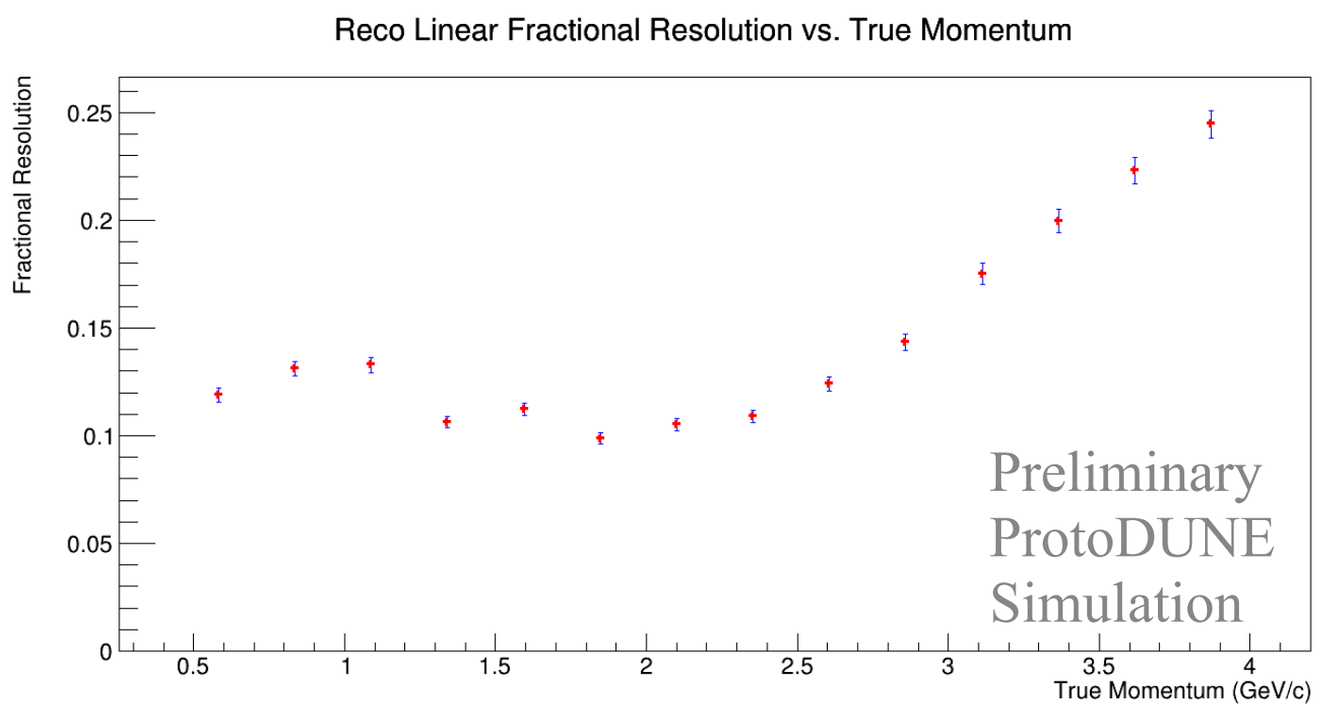




- Momentum estimation uses the fit parameters coming from the σ_{RMS} fit to the angle distributions, using the maximum likelihood method.
- For a given σ_{RMS}, find the momentum at which the likelihood is maximum.

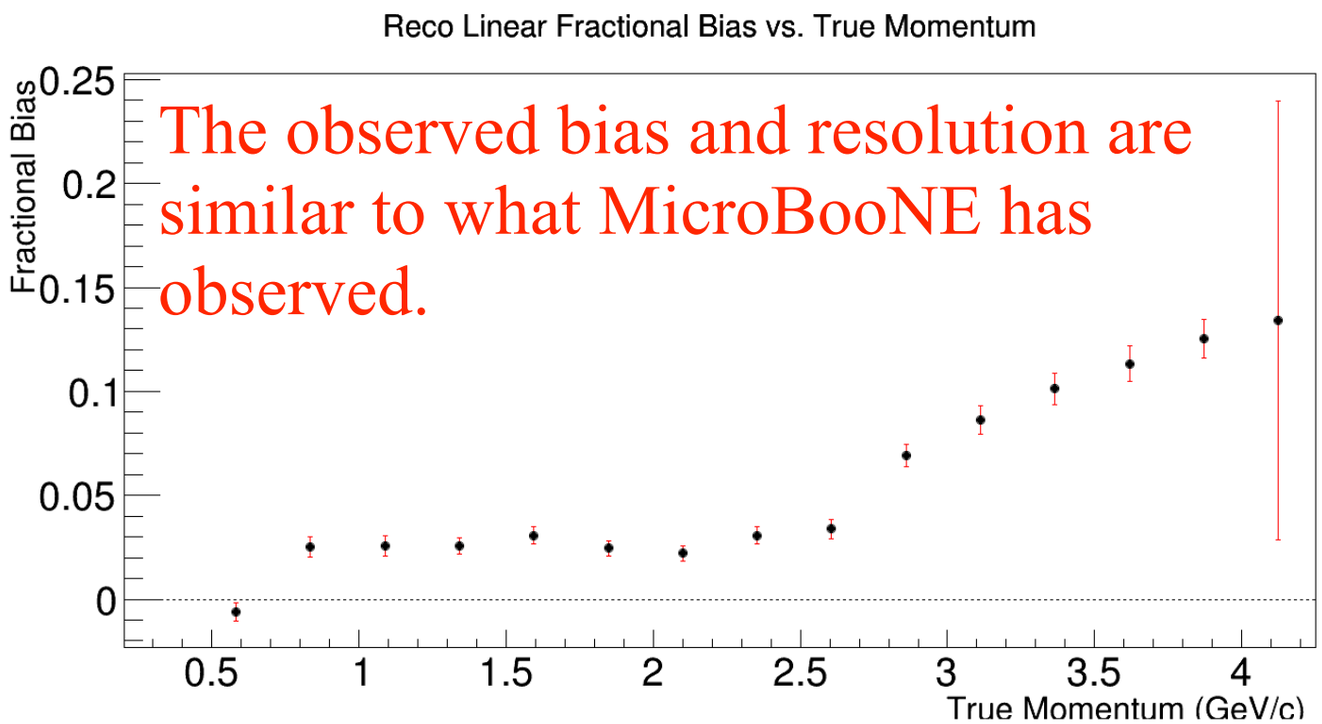
Fractional Bias & Resolution





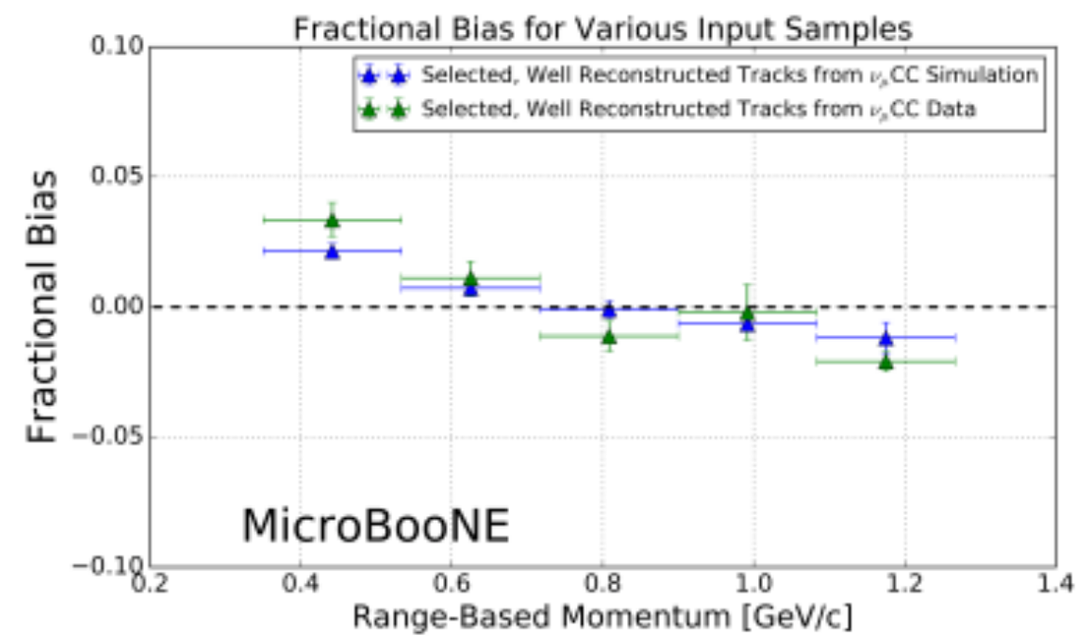
- Fractional Bias is the average of ΔP.
- Fractional Resolution is the spread in ΔP.
- Bias is under 5% and resolution is around 10% for momentum below 2.5 GeV/c
- Muons with momentum above 2 GeV/c are not contained. This may be the reason for the worse performance above 2 GeV/c.

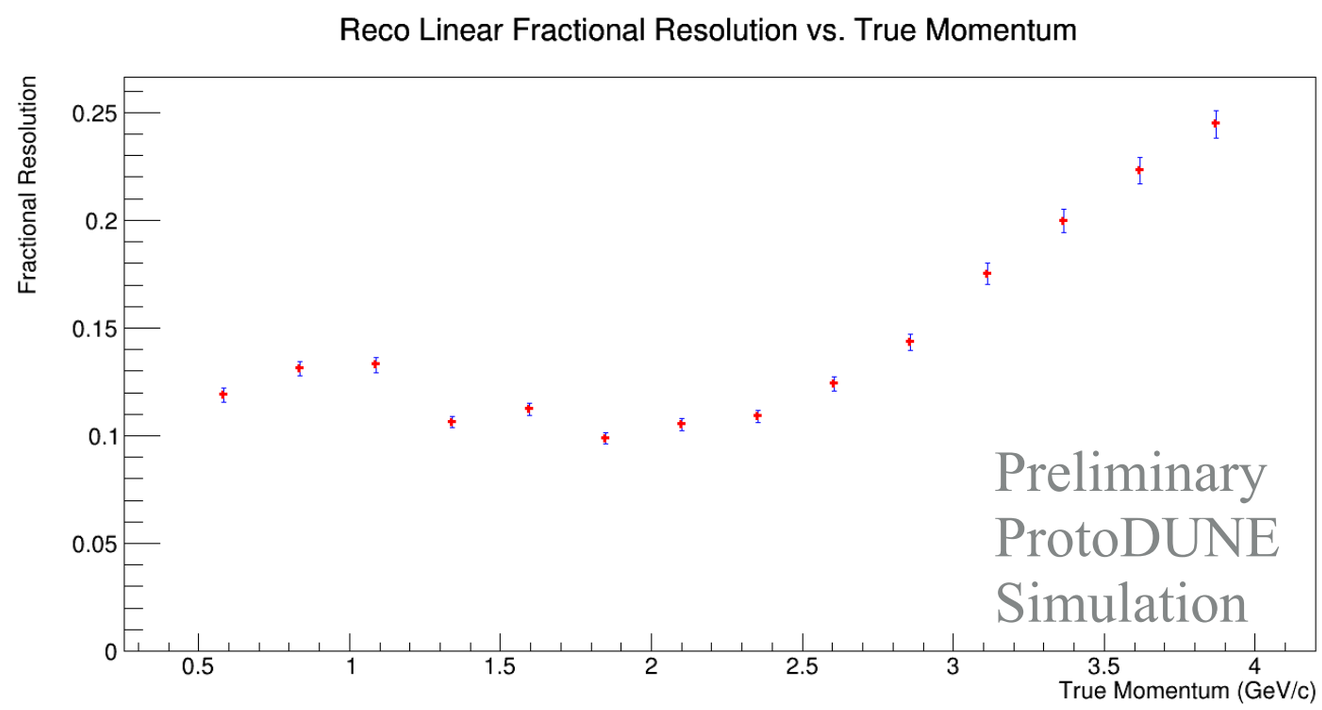
Fractional Bias & Resolution

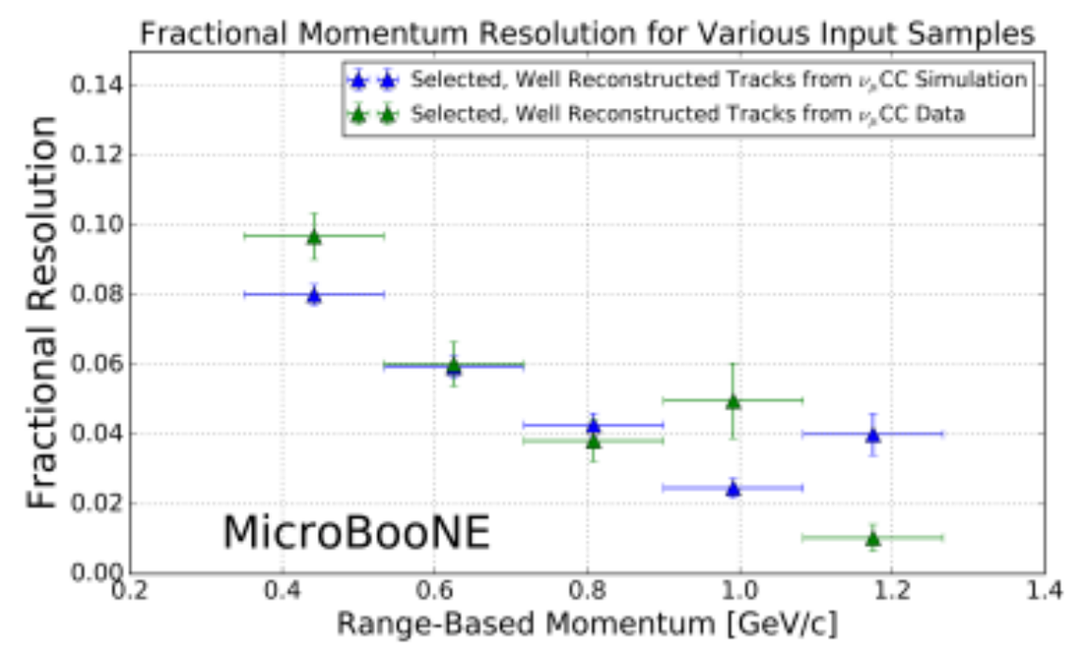


The observed bias and resolution are similar to what MicroBooNE has observed.

MicroBooNE arXiv: 1703.06187







Summary & Next Steps

- Preliminary results on MCS momentum estimation presented for the reconstructed trajectories using single muon sample with momentum range between 0.5 - 4 GeV/c.
- Observed a bias under 5% and resolution around 10% for momentum below 2.5 GeV/c. The initial results obtained are similar to MicroBooNE results.
- Next steps include
  - Run the analysis on ProtoDUNE-SP beam simulation samples.
  - Systematic evaluation.
  - Run over the ProtoDUNE-SP Data.
  - Aim to publish the end of this year.

THANK YOU