Using Multiple Coulomb Scattering for Particle Identification in Neutrino Experiments

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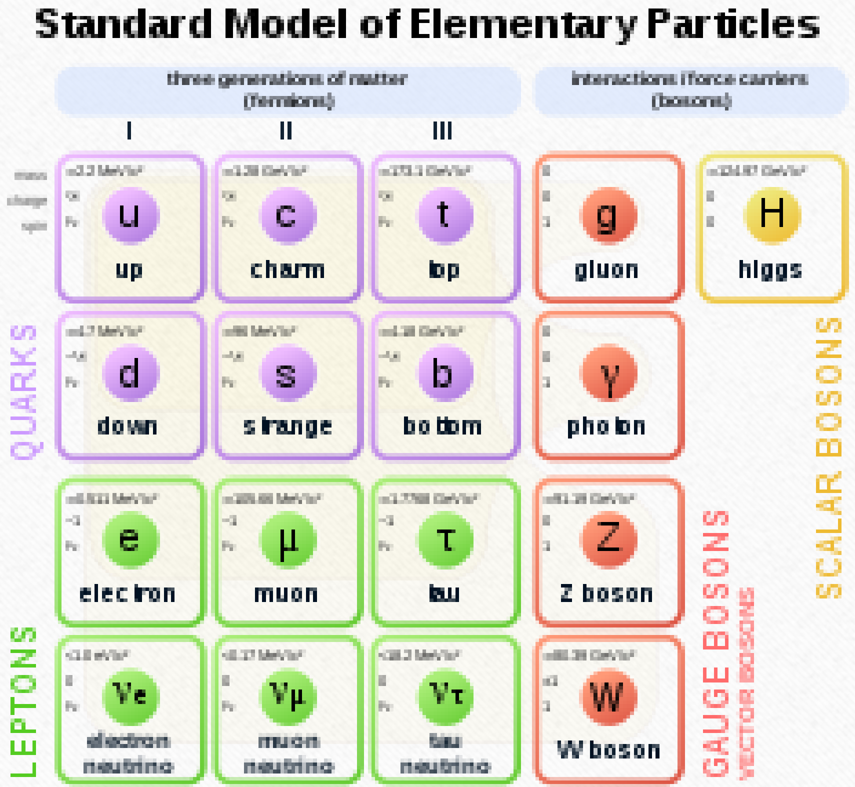
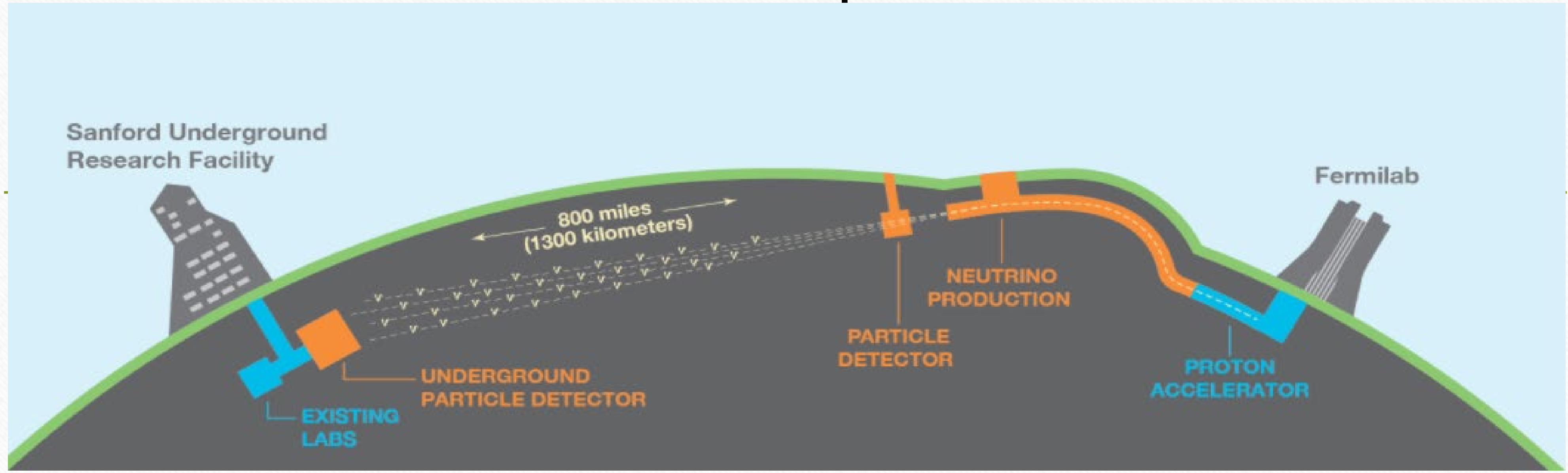
Neutrinos

- Elementary particles
- No charge, tiny mass
- Rarely interact with matter

Studying neutrinos may lead to new physics!



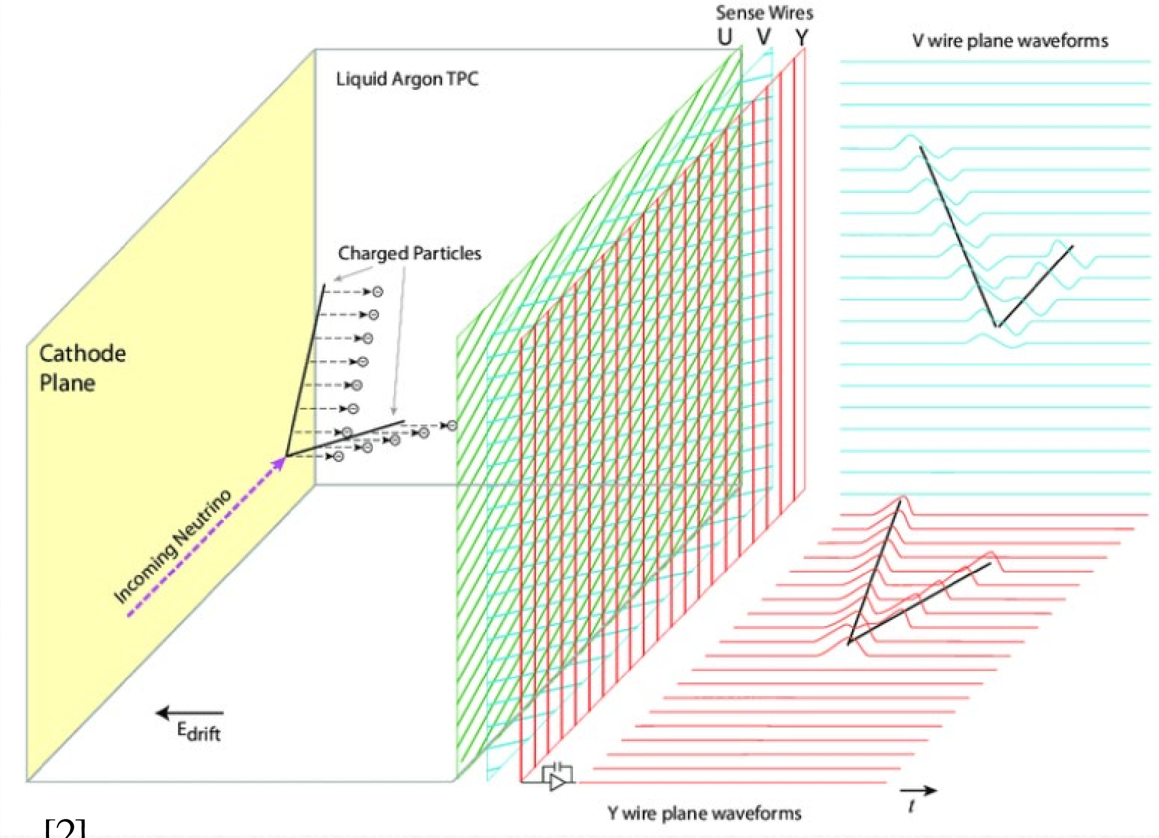
Neutrino Experiments



[1]

- Neutrinos are being studied in experiments like DUNE and MicroBooNE
- Beams of trillions of neutrinos are sent into large tanks of liquid argon to study interactions

Neutrino Experiments

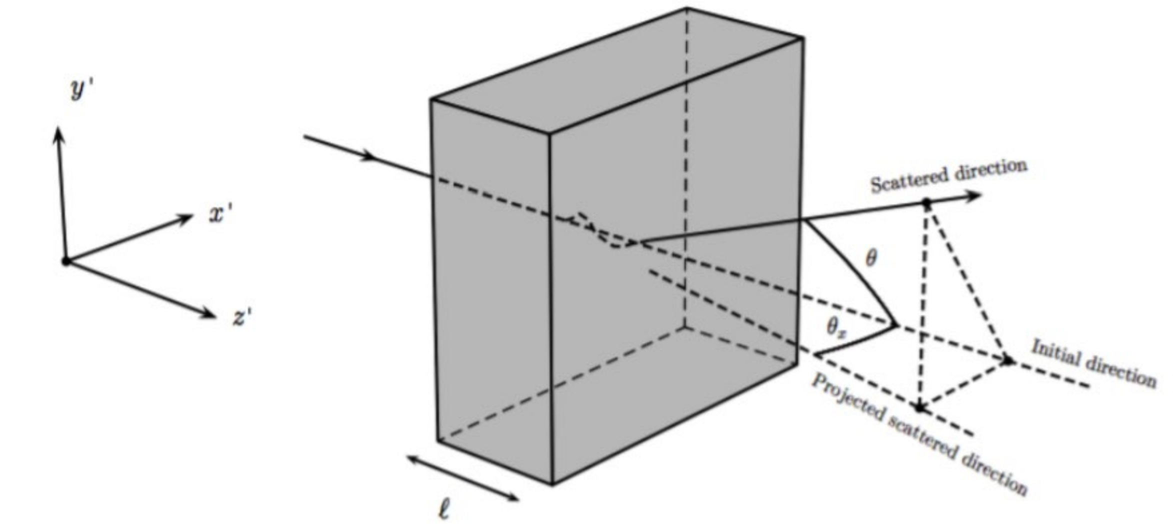


[2]

- Neutrino collisions eject charged particles
- Charged particles knock electrons loose
- To learn more about neutrinos, we need to identify the particle ejected during the collision
- Particle identification is also important in isolating neutrino collisions

Multiple Coulomb Scattering (MCS)

- Charged particles undergo electromagnetic scattering
- Tracks broken into segments of length ℓ
- Best fit lines for each segment are calculated
- Projected angles between segments are modelled by a Gaussian centered at 0



$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0} \right) \right],$$

[5]

Why Use MCS?

Momentum and identity of particles can be more accurately reconstructed using range-based momentum methods

- Range-based methods use measured energy deposits over a particle's track to determine momentum
- These energy deposits can be used to distinguish protons from muons

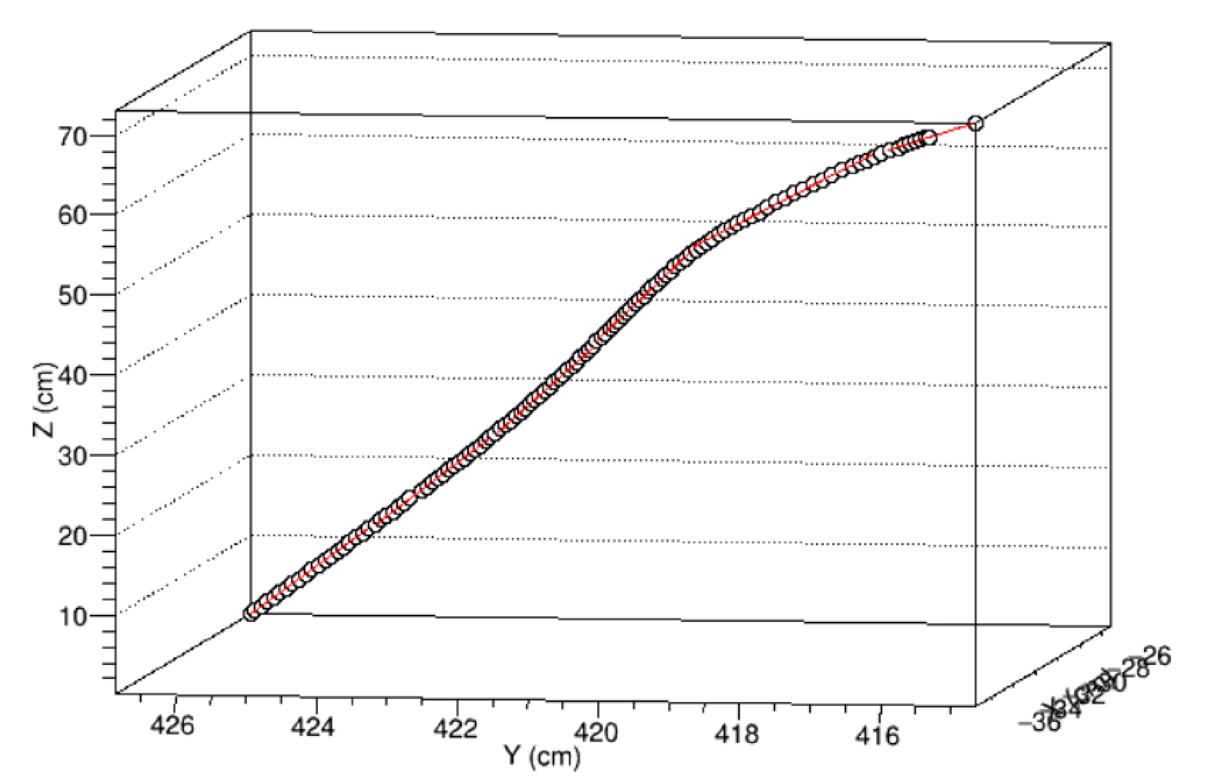
However, MCS can be used on exiting particle tracks.

Track Segmentation & Selection

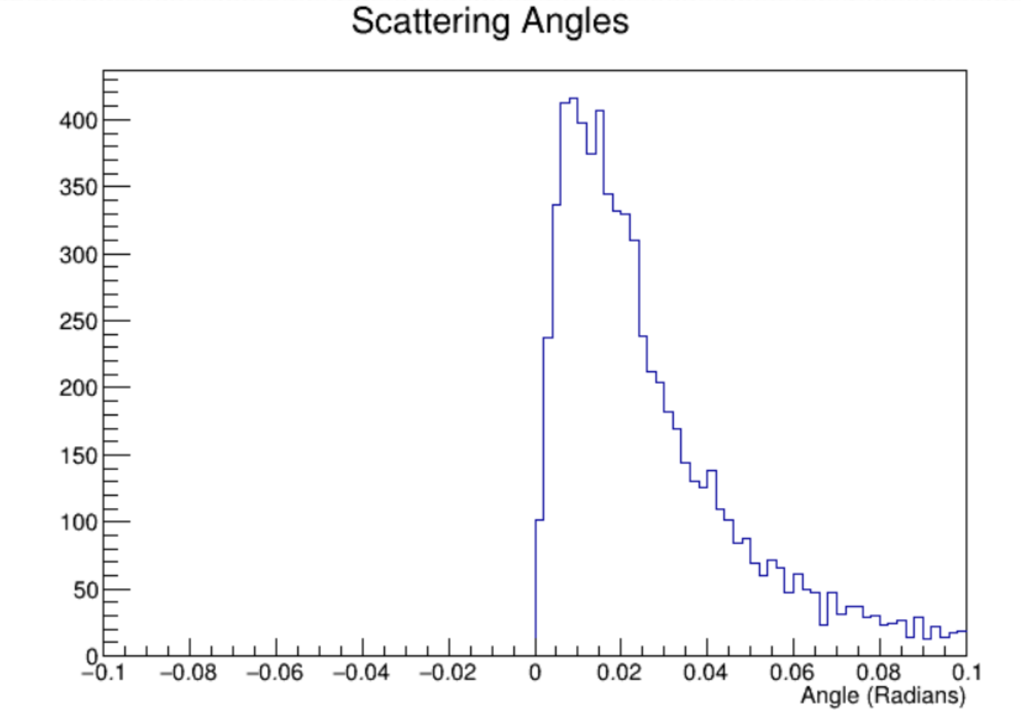
Using segment length of 14 cm

Selection Criteria:

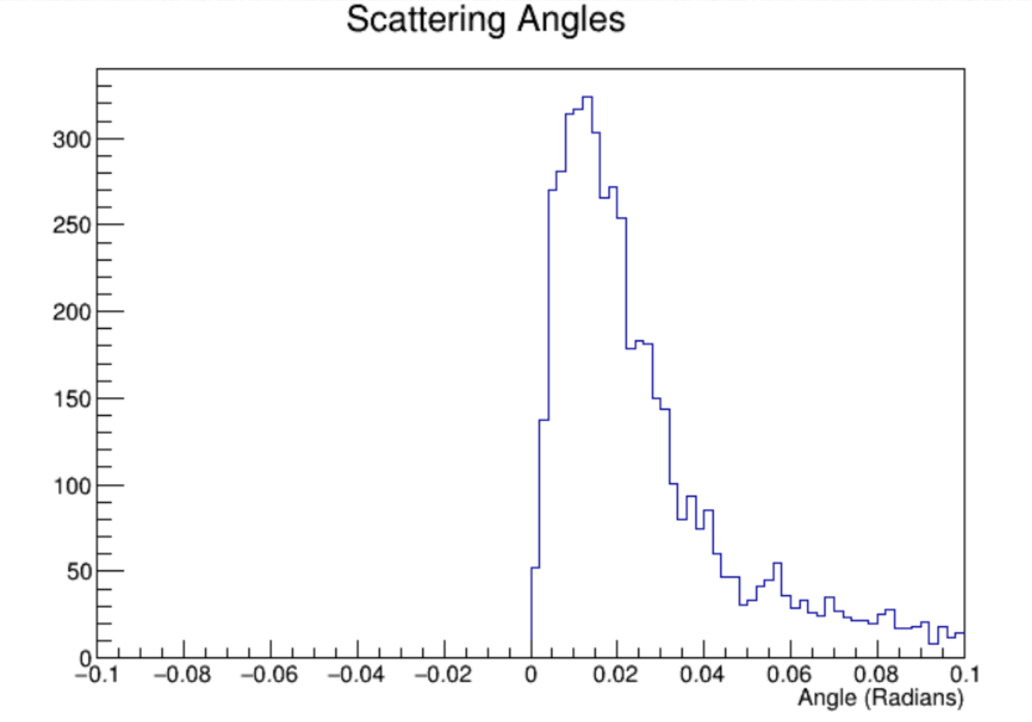
1. Tracks must contain at least 6 segments for protons, 12 segments for muons
2. Only the first 6 segments for protons, or first 12 segments for muons, are used
3. A track with a break of 5 cm or more is thrown out



Protons



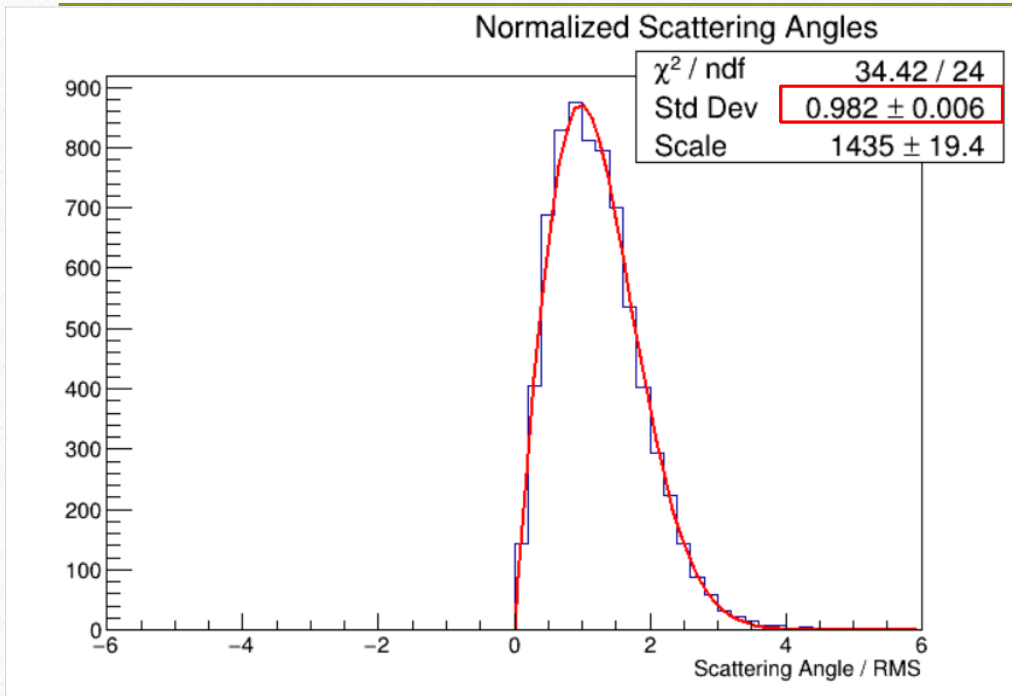
Muons



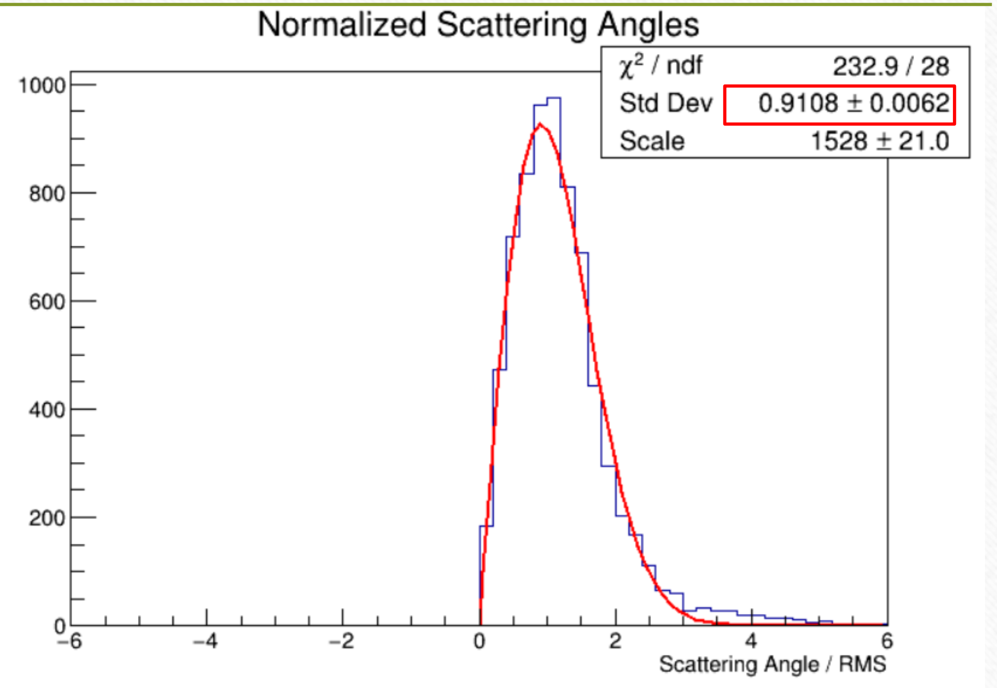
Note: These are 3D scattering angles, so instead of being modelled by a gaussian f(x), the 3D angles are modelled by f(x) * x.

MCS Validation

Muons



Protons



$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right)\right],$$

Momentum Reconstruction

To find momentum using multiple coulomb scattering, we use a maximum likelihood method:

- A momentum scan range and increment is set
  - 0 - 2000 MeV/c, step size of 10 MeV/c
- For a given initial momentum, find expected energy losses over each segment
- Use energy losses to find starting momentum of each segment in the track
- Use measured scattering angles and calculated RMS angle to find likelihood
- Pick momentum with highest likelihood

Momentum Reconstruction

Segment	Momentum (MeV/c)	-dE/dx (MeV/cm)	Final Energy (MeV)
1	1000	-2.0	977
2	971	-2.1	943
3	937	-2.3	912
…	…	…	…

Energy losses:

- Starting with an initial momentum guess
- Use Bethe-Bloch to find energy losses over segments
- Use energy losses to find momentum at each segment

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$ [2]

Momentum Reconstruction

Segment	Momentum (MeV/c)	RMS
1	1000	0.0115
2	971	0.0119
3	937	0.0123
…	…	…

RMS angle:

- Using calculated momentums from Bethe-Bloch energy loss
- Find expected scattering angle from Highland formula

$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right)\right],$$ [5]

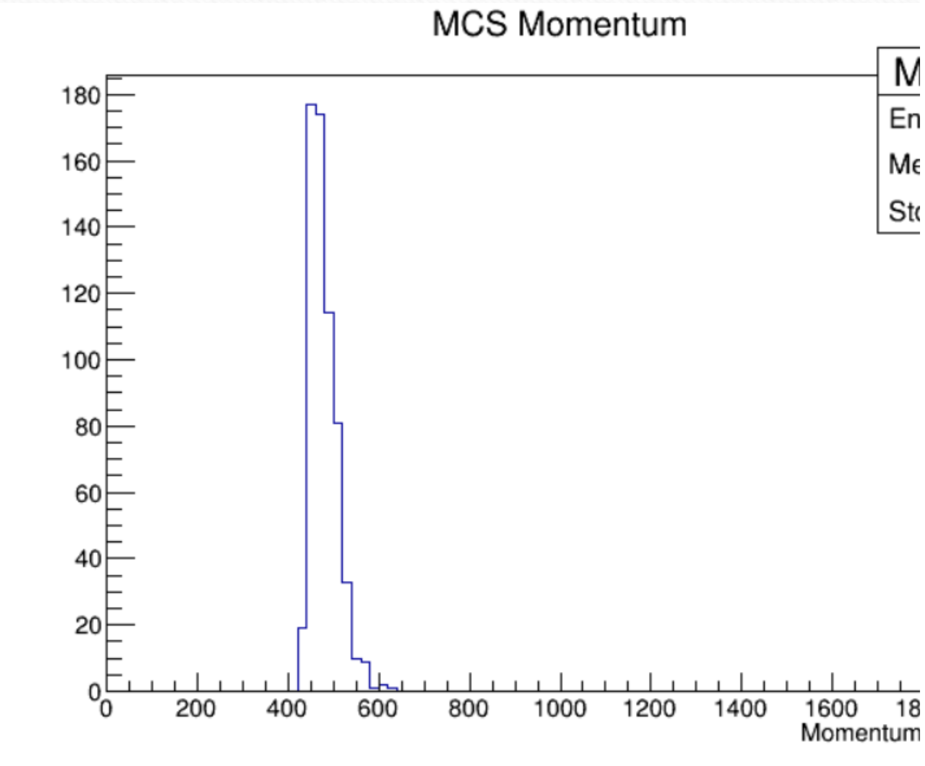
Momentum Reconstruction

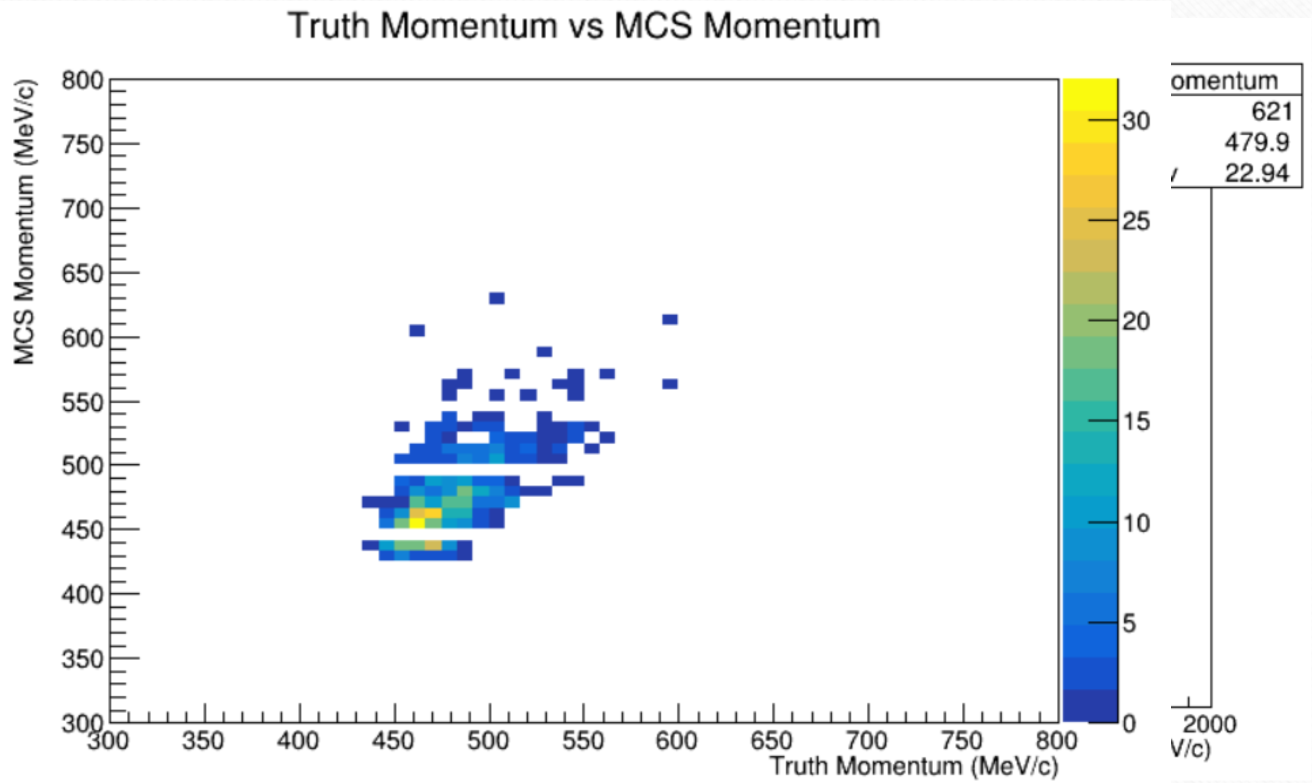
Segment	Δθ	RMS
1	0.025	0.0115
2	0.018	0.0119
3	0.031	0.0123
…	…	…

Pick initial momentum guess with maximum likelihood:

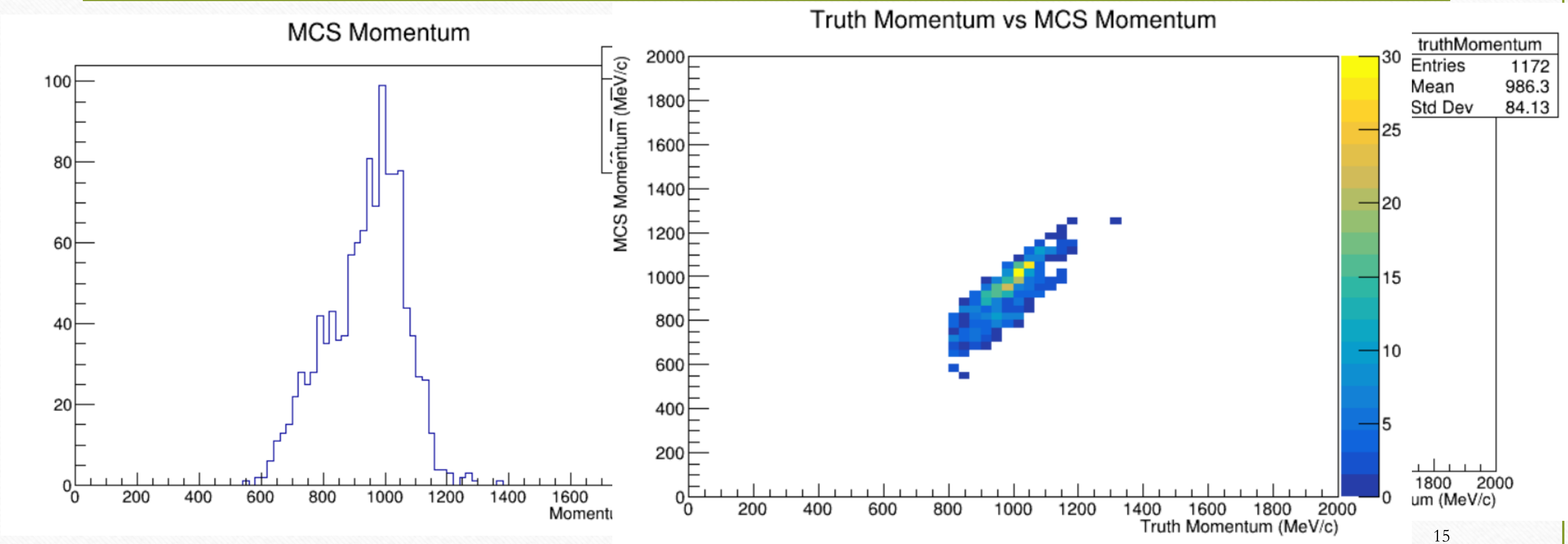
$$f_X(\Delta\theta) = (2\pi\sigma_o^2)^{-\frac{1}{2}} \exp\left[-\frac{1}{2}\left(\frac{\Delta\theta}{\sigma_o}\right)^2\right]$$ [5]

Low Energy Muon Momentum Reconstruction

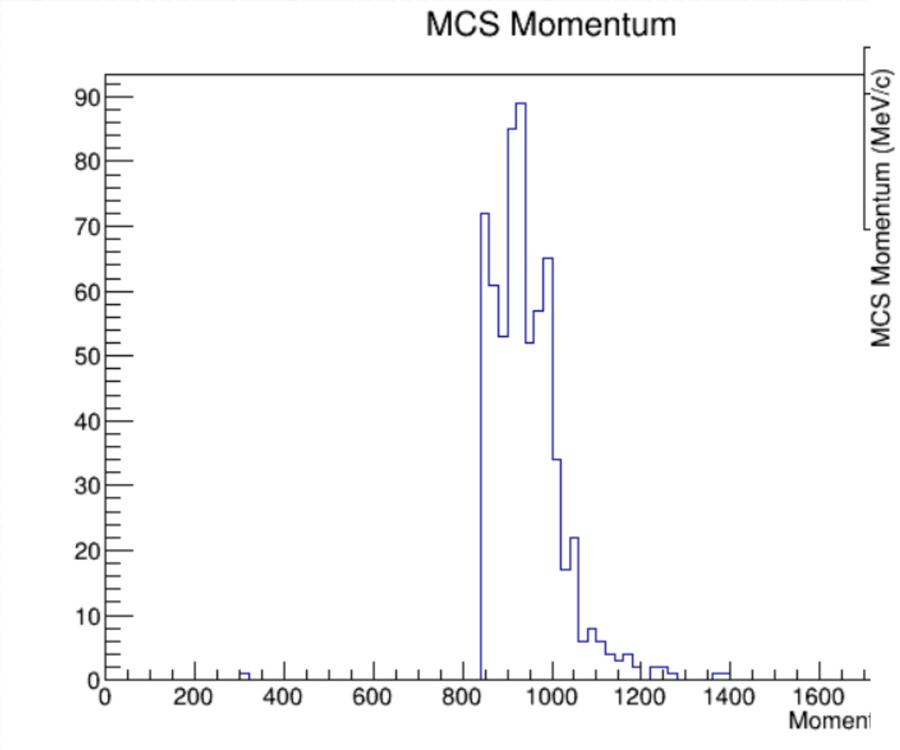


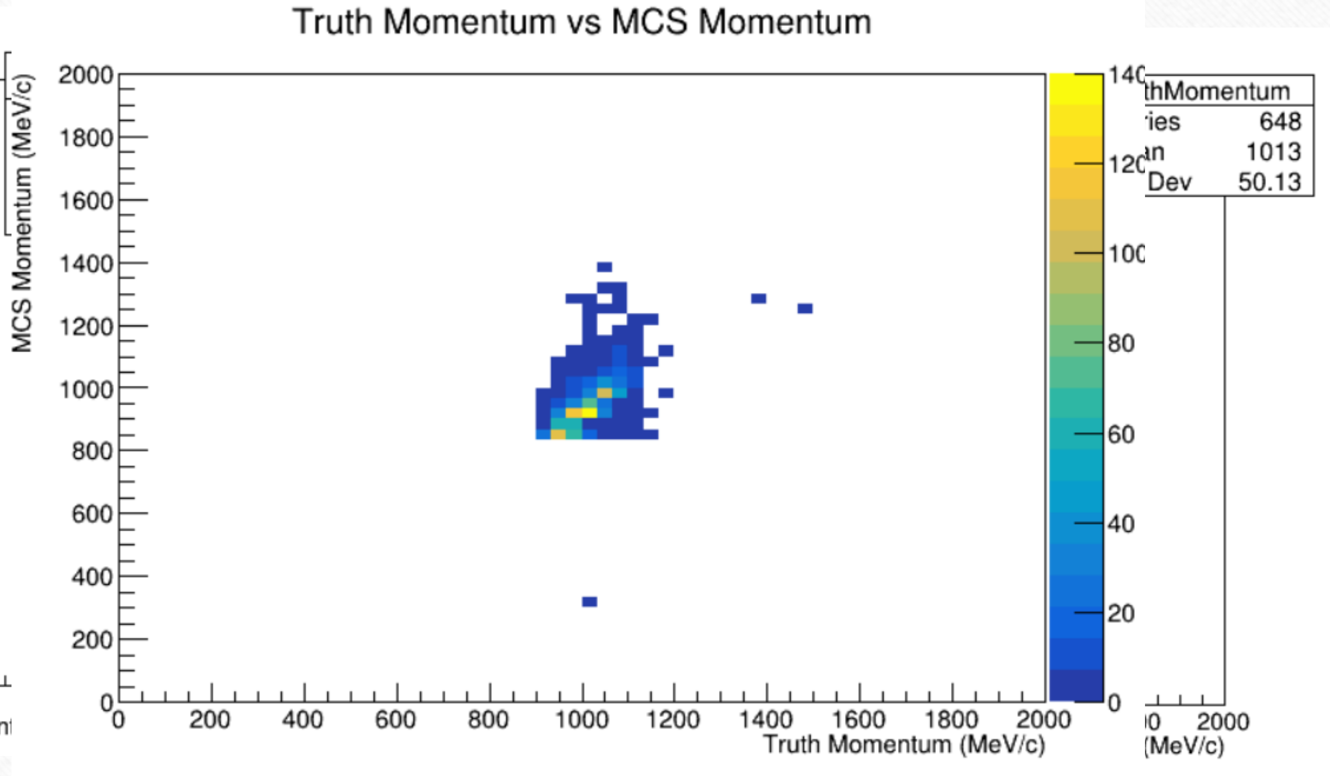


High Energy Muon Momentum Reconstruction



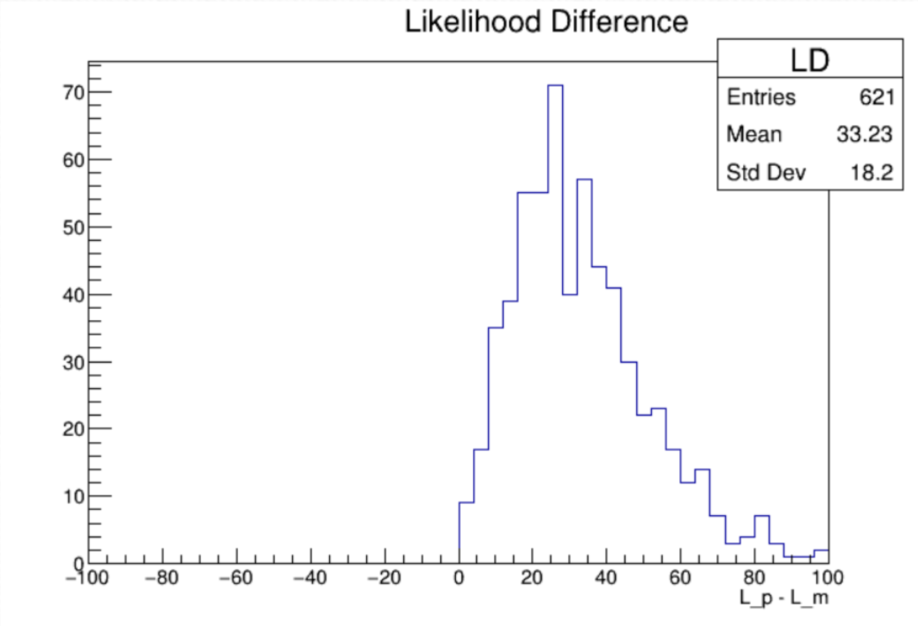
Proton Momentum Reconstruction



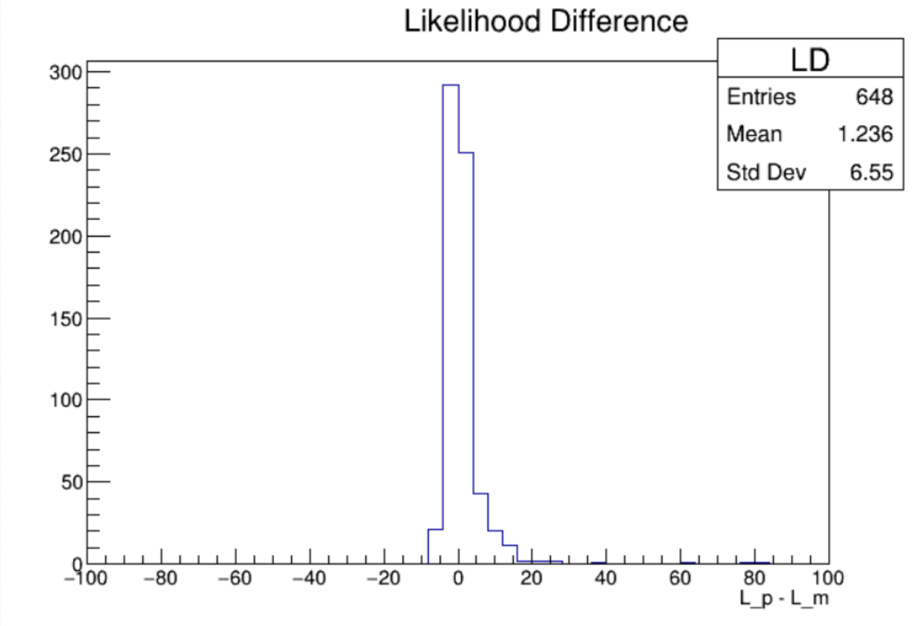


Particle Identification

True Muons (~400 MeV/c)



True Protons (~1000 MeV/c)



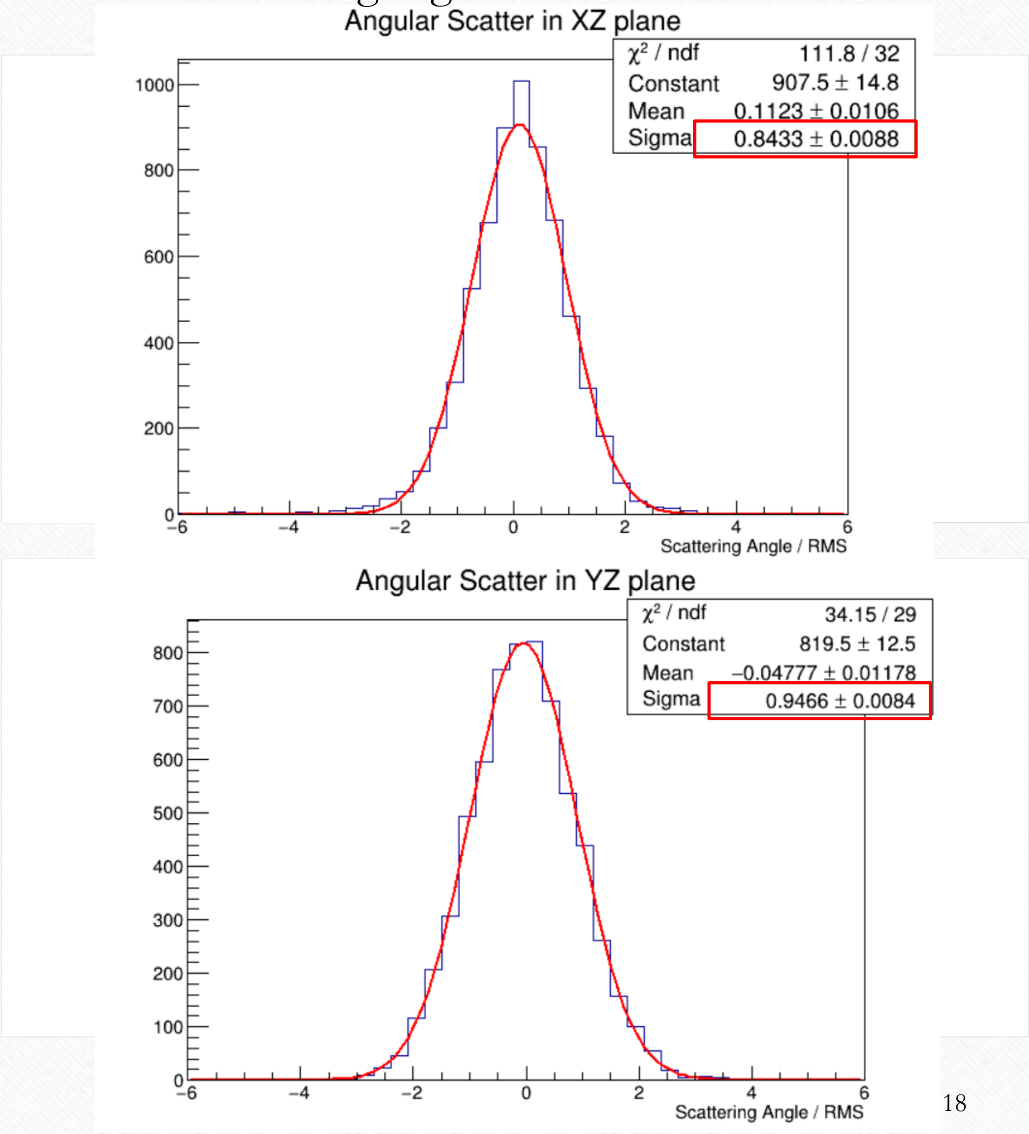
$$-l(\sigma_{o,1}, \ldots, \sigma_{o,n}; \Delta\theta_1, \ldots, \Delta\theta_n) = -\ln(L) = \frac{n}{2}\ln(2\pi) + \sum_{j=1}^{n} \ln(\sigma_{o,j}) + \frac{1}{2}\sum_{j=1}^{n}\left(\frac{\Delta\theta_j}{\sigma_{o,j}}\right)^2.$$

Findings

- All data so far used true position data (Monte Carlo)
- Reconstructed position data reveals anisotropic detector effects

Using truth data

Using reconstructed data



Conclusion

Multiple coulomb scattering allows exiting proton and muon tracks to be analyzed for accurate momentum estimation. Using truth position data, muons can be successfully identified nearly all the time, while protons require a closer look due to inelastic scattering.

Before using MCS for particle identification in neutrino experiments, detector effects on reconstructed position data must be resolved.

Future work:

- Successfully implement MCS on reconstructed track data
- Use MCS to detect inelastic proton scattering
- Distinguish exiting protons and muons in neutrino experiments

Acknowledgements

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Questions?

References

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- [2] M. Tanabashiet al.[Particle Data Group] Passage of Particles Through Matter, Phys. Rev. D98, 030001 (2018).
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- [5] [2] P. Abratenko et al [MicroBooNE collaboration] Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb scattering 2017 JINST 12 P10010.