Evaluating the Performance of Multiple Coulomb Scattering-Based Momentum Reconstruction with MicroBooNE Data

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The MicroBooNE Experiment

• Goals: investigate the excess of low energy events seen by LSND/MiniBooNE (maybe due to oscillations), study neutrino-argon cross-sections, LArTPC R&D…

• Neutrino oscillation for the two neutrino case:

\[ P_{\alpha \rightarrow \beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \]

\( P \) = probability of a neutrino of flavor \( \alpha \) later being measured to have flavor \( \beta \)
\( \theta \) = mixing angle
\( \Delta m^2 \) = neutrino mass squared difference
\( L \) = distance from neutrino source to detector
\( E \) = energy of neutrino
The MicroBooNE Experiment

- For $\nu_\mu$ CC events (used in cross-section/oscillation measurements), neutrino-induced muons are used to reconstruct neutrino energy.
- However, in MicroBooNE, ~50% of the time, these muon tracks are not fully contained in the TPC!
- It’s not possible to use range or calorimetric methods to compute momentum; we must use Multiple Coulomb Scattering (MCS).
Multiple Coulomb Scattering

• When a charged particle passes through some material, it undergoes EM collisions with atomic nuclei
• After each collision, the particle's trajectory is deflected from its initial direction

What is Multiple Coulomb Scattering (MCS)?
Charged particle passes through material, undergoes EM collisions with atomic nuclei (Coulomb scattering)
Trajectory is deflected from particle's initial direction
Multiple Coulomb Scattering

• The collection of these small deflections is distributed like a Gaussian, with a mean at 0 and RMS given by the tuned Highland formula:

\[
\sigma^\text{HL}_0 = \frac{S_2}{p} \beta c z \sqrt{\frac{l}{X_0}} \left[ 1 + \epsilon \times \ln\left( \frac{l}{X_0} \right) \right]
\]

- \( p \) = particle momentum
- \( \beta \) = ratio of particle velocity to \( c \)
- \( l \) = distance travelled inside medium
- \( X_0 \) = radiation length of argon
- \( z \) = magnitude of charge of particle
- \( S_2, \epsilon \) = fit parameters

• We can determine the momentum of the particle if we know the angular deflections

*MCS is the only way to reconstruct the energy of exiting muon tracks in MicroBooNE!*
Multiple Coulomb Scattering Algorithm Overview

• We determine these angular deflections by splitting the particle’s track into segments and then computing the angle between adjacent segments
• We use the Maximum Likelihood Method to calculate the momentum of a given muon
  • Input angular deflections
  • Raster likelihood scan from 1 MeV to 7.5 GeV
  • Momentum and RMS updated through use of energy-range relation
• Conditions:
  • Nominal segment length of 14 cm
  • Tracks must be above 100 cm in length
MCS Performance on Contained Data Tracks
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• Beam neutrino induced NumuCC data

Selected, Well Reconstructed Tracks from $\nu_\mu$ CC Data

MicroBooNE Data

MicroBooNE collaboration, JINST 12 P10010 (2017)
MCS Performance on Contained Data Tracks

- MCS bias vs. range momentum for both simulation and data

![Fractional Bias for Various Input Samples](image)

MCS Performance on Contained Data Tracks

- MCS resolution vs. range for both simulation and data

**Figure 8.** Inverse momentum difference (as defined in the text) fractional bias (top) and resolution (bottom) for automatically selected contained $\nu_e$-induced muons from full simulated BNB events with cosmic overlay where the track matches with the true muon track (blue), and automatically selected and hand-scanned (see text) contained $\nu_e$-induced muons from MicroBooNE data (green).

MCS Performance on Exiting Data Tracks
MCS Performance on Exiting Data Tracks

• MCS will ultimately be used to determine the momentum of exiting muons in data, so it's very important to quantify this!

• But how would we measure this?
  • Doesn't make sense to compare to momentum from range!

• Introduce "pseudo-exiting" tracks:
  • Take a fully contained track, cut it off somewhere along its length
  • We choose cutoff lengths of 2, 4, 6 segments exiting the fiducial volume (corresponding to 28 cm, 56 cm, 84 cm, respectively)
    • Note that we are limited in segment removal because we are dealing with contained tracks
MCS Performance on Exiting Data Tracks

• First, we compared these pseudo-exiting tracks with real exiting tracks (all simulation)

• To do this, we placed a cut on length outside the TPC for real exiting tracks

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In order to validate the method, pseudo-exiting tracks with 4 segments removed are first compared to true exiting tracks in simulation. For this comparison, exiting tracks are required to match a simulated muon track which exits the detector with momentum $0.22 \text{ GeV}$, corresponding to the momentum at the end of a pseudo-exiting track with 4 segments removed. As shown in Fig. 5, the agreement in bias and resolution for true exiting and pseudo-exiting tracks is rather good; there may be a small systematic difference in the resolution (Fig. 5b), but we consider this a minor effect and thus the method as validated. Similar tests are also performed for 2 and 6 segments removed, with similar conclusions.

![Figure 5: Comparison of MCS momentum bias (a) and resolution (b) vs. truth momentum for pseudo-exiting tracks with 4 segments removed and exiting tracks with $0.22 \text{ GeV}$.](image)

We then compare pseudo-exiting tracks in data to simulation, where bias and resolution of pseudo-exiting tracks are parametrized in terms of $p_{\text{Range}}$. As shown in Fig. 6, for 2, 4, and 6 segments removed the expected bias in simulation shows little variation, while the resolution degrades with a larger number of removed segments. The bias and resolution values observed in data for 2, 4, and 6 segments removed demonstrate a very good agreement with simulation (Fig. 7), thus validating in data the MCS momentum measurement for exiting tracks presented in ref. [7].
MCS Performance on Exiting Data Tracks

- Comparison of pseudo-exiting tracks for 2, 4, 6 segments removed
  - MCS bias and resolution versus range

**Figure 6:** Comparison of MCS momentum bias (a) and resolution (b) vs. range-based momentum for pseudo-exiting tracks with 2, 4, 6 segments removed. The bias is similar for all numbers of removed segments, while the resolution degrades with larger number of removed segments.
MCS Performance on Exiting Data Tracks

• Comparison of pseudo-exiting tracks and data (2 segments removed)
  • MCS bias and resolution versus range

Figure 7: MCS momentum performance for pseudo-exiting tracks in data compared to simulation:
  (a) bias for 2 segments removed and (b) resolution for 2, 4, and 6 segments removed.
MCS Performance on Exiting Data Tracks

- Comparison of pseudo-exiting tracks and data resolution vs range
  - 4, 6 segments removed

Figure 7: MCS momentum performance for pseudo-exiting tracks in data compared to simulation: bias for 2 segments removed (a) and resolution for 2 (b), 4 (c), and 6 (d) segments removed.
Conclusion

- Performance of MCS for contained tracks was shown to be within 5-10% in MicroBooNE data
  - Comparable to the performance of MCS on contained simulated tracks
- Performance of MCS for exiting tracks in data has been shown to be within 5% bias and under 20% resolution for 2 segments removed
  - Under 30% for 4, 6 segments removed
  - Comparable to results from simulation

MicroBooNE is able to reconstruct the momentum of TPC-exiting muons using MCS at a resolution of under 20-30%
Backup
The MicroBooNE Experiment

- Part of the Short Baseline Neutrino (SBN) program at Fermilab
- Detector located 470 m from Booster Neutrino Beam (BNB) target
- Liquid Argon Time Projection Chamber (LArTPC) technology
  - 90 tons active LAr in TPC (170 tons total in cryostat)
  - Current largest TPC in the U.S. actively taking data

Dimensions: 2.3 m x 2.6 m x 10.4 m
Example distribution of fractional inverse momentum difference with the fit used to compute the bias (mean) and resolution (width) of the MCS method.
Figure 48: Highland validation figures analogous to Figure 17 for various segment lengths, taken from the sample of well reconstructed neutrino-induced truth-selected muons in simulation. The gaussian nature of this plot breaks down for segment lengths that are too short.
Why did we choose a length of 100 cm?

Leonidas initially set a lower limit of 20 cm for the track length, but we increased it to 100 cm and ran over the same sample. The plot below shows the momentum resolution as a function of track length for contained tracks only. We can see that the resolution worsens significantly with track lengths smaller than 100 cm, so we kept this length cut.