Risk mitigation muon spectrometer: physics requirements

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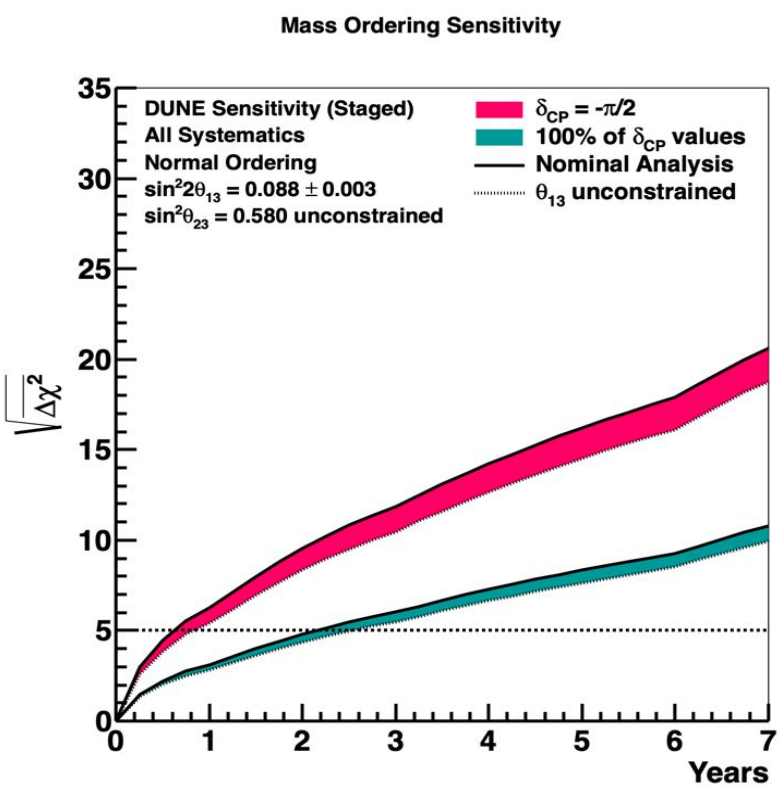
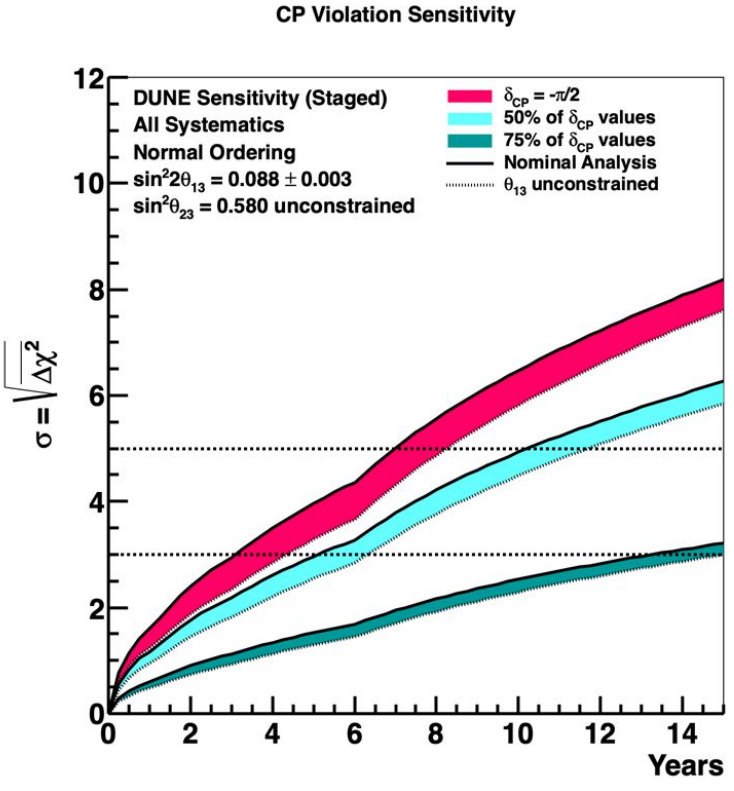
19 February, 2020

Day 1 physics requirements

- Ensure that FD data collected in “Day 1” ND configuration can be used in all future long-baseline oscillation physics analyses
  - Robust beam monitoring, such that flux*XS constraints from full ND can be retroactively applied to early ND data
  - Ability to ensure high data quality
  - In the scenario where we go off-axis with the LAr+RMMS, this is a requirement on SAND
- Allow DUNE to produce oscillation physics results with early ND+FD data

Physics goals in 3 years





- Early sensitivities are FD statistics limited, and sensitive primarily to ν_e rate → can likely be achieved with limited ND
- By 3 years, we can reach 5σ MH determination for any value of δ, and 2σ CPV for 50% of δ, up to 3σ at δ = -π/2
- MH determination is the simplest story for RMMS physics

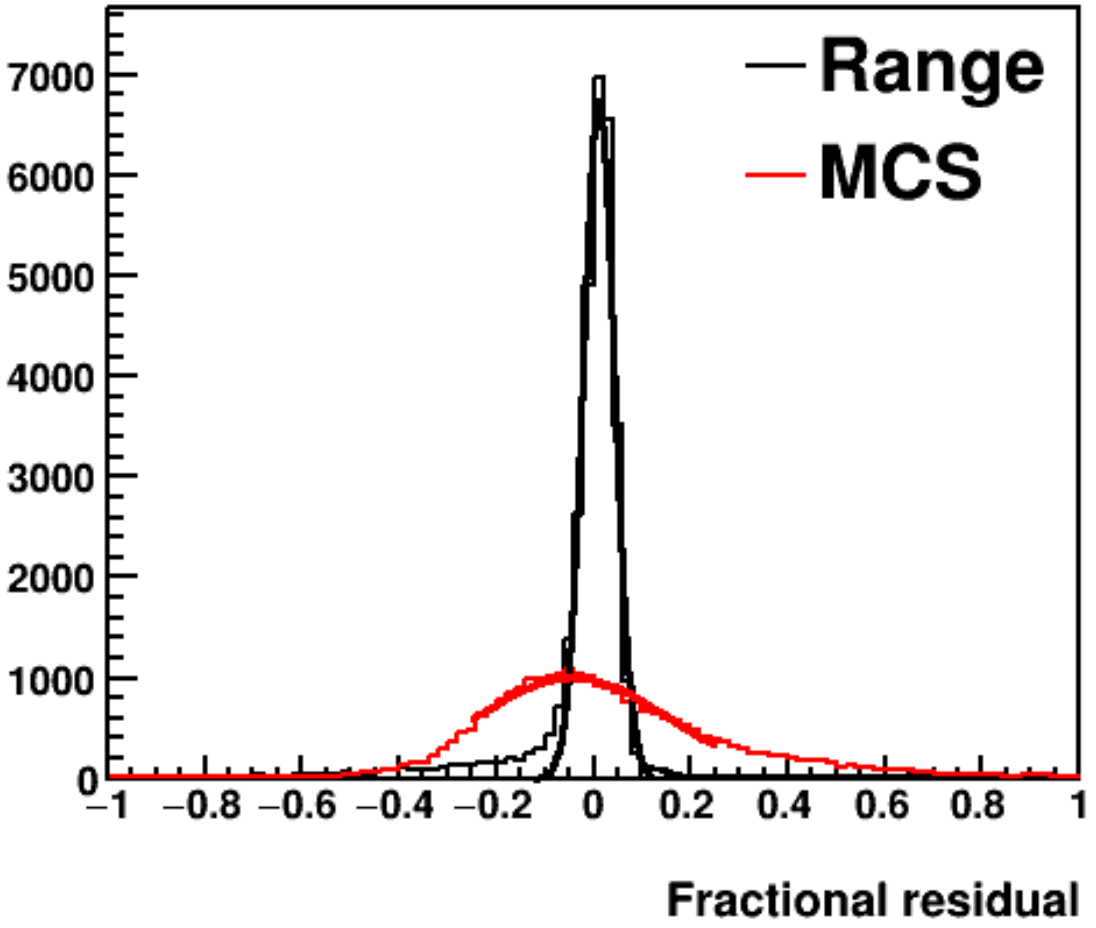
What muon resolution is required?

- Goal: estimate unoscillated ν_μ and ν_e CC event rates at FD, based on ND measurements
- Cannot extrapolate ND spectra to FD unless energy resolution is **at least as good**
- If resolutions are worse at ND, then FD predictions will require an interaction model
- Without full ND suite, it will be difficult to validate this model

FD muon energy resolution

- MCC11 FD full reconstruction
- CAVEAT: “1x2x6” geometry, which is not the full module, so containment is not correct
  - Real module is 54m in beam direction
  - 1x2x6 geometry is 14m in beam direction, so only muons up to ~3 GeV can be contained

$1 < E_{\mu} < 1.5$ GeV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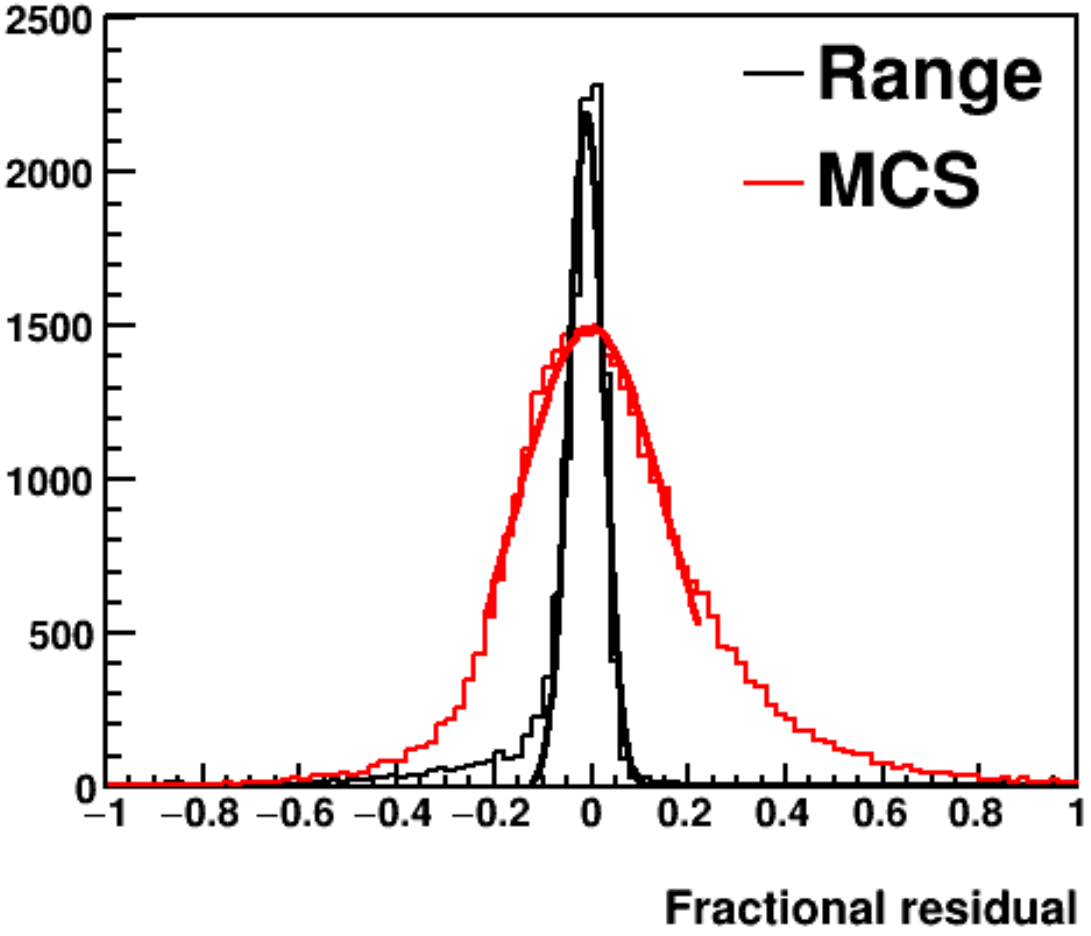
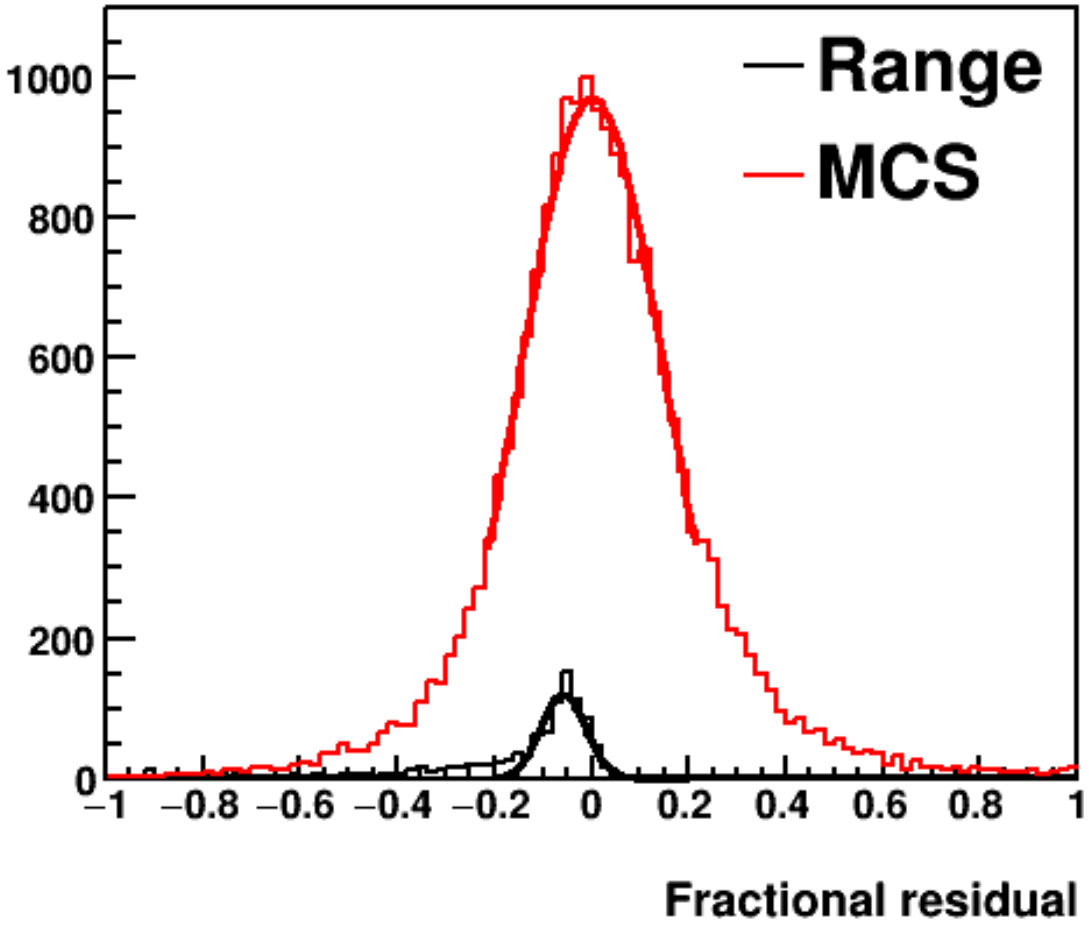
Fractional residual

$2 < E_{\mu} < 2.5$ GeV



$3 < E_{\mu} < 3.5$ GeV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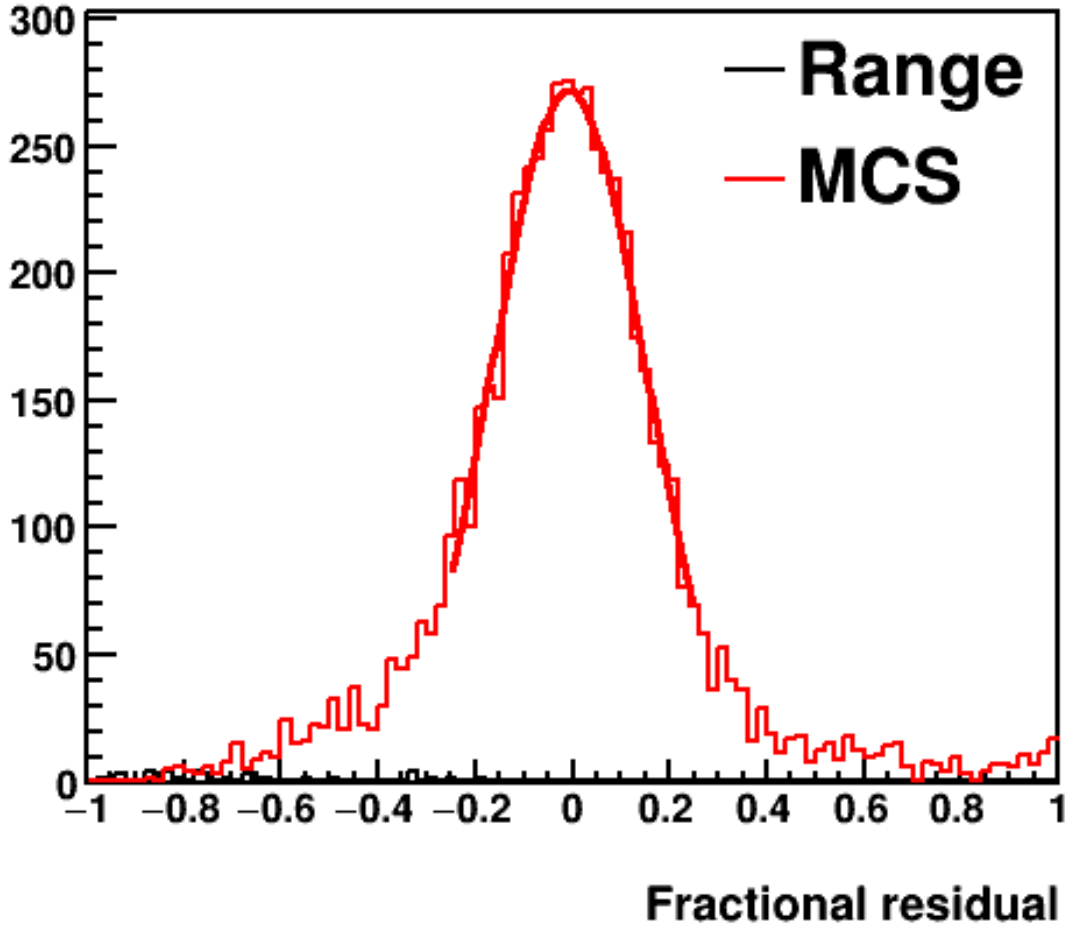
Fractional residual

$4 < E_{\mu} < 4.5$ GeV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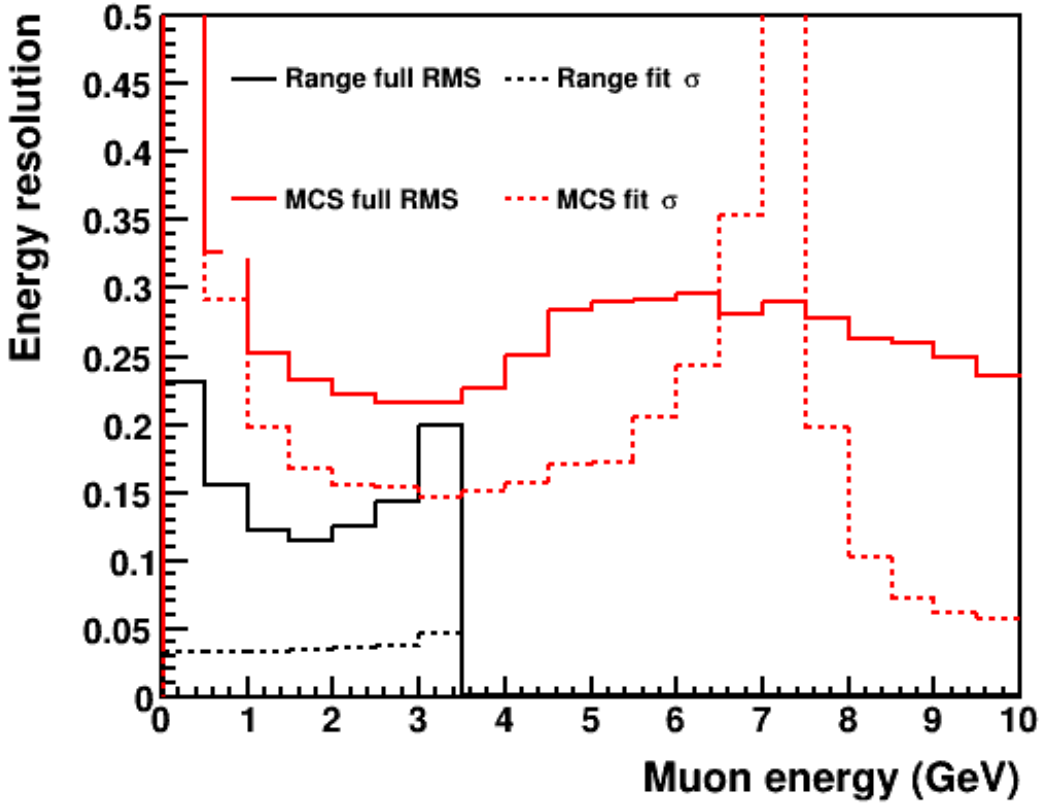
1
Fractional residual

Full RMS and central Gaussian σ

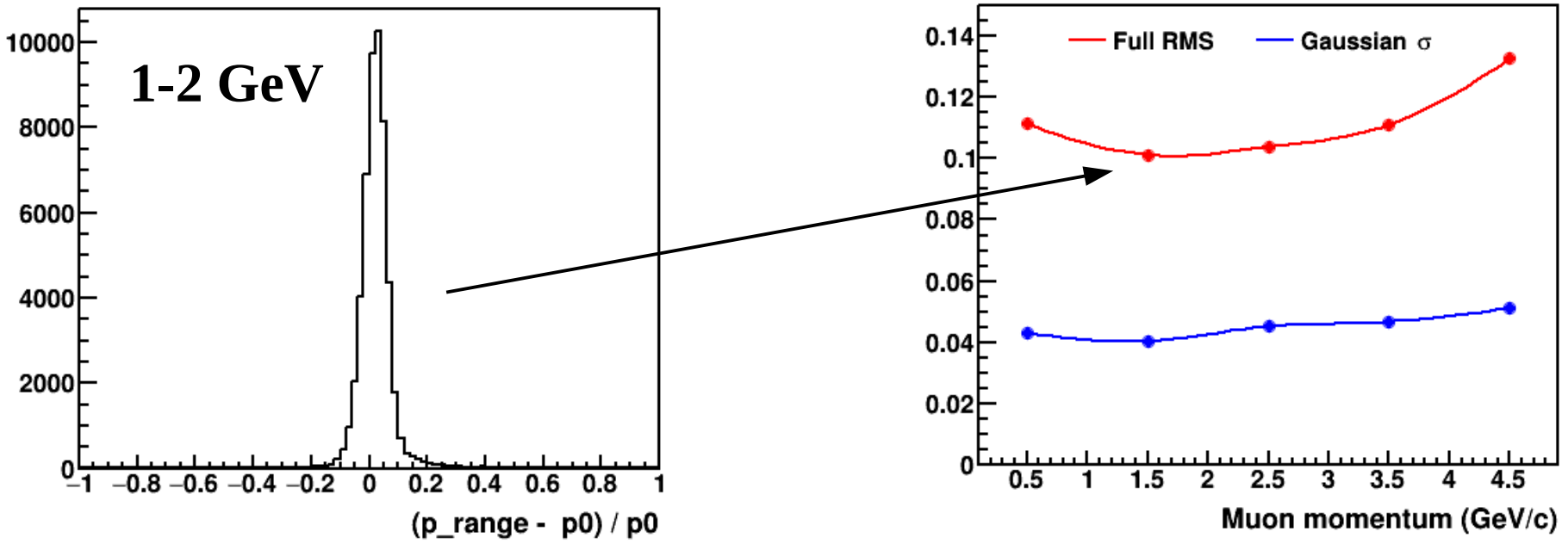


- For contained muons, the central peak σ is 3-4% up to 3 GeV, above which muons are not contained in the ~1/8 size volume that was simulated
- Full RMS in that region is ~10%; at higher energy, it is biased by the fact that "contained" muons are likelier to be broken tracks
- MCS resolution is ~20% as expected
- Something very strange is happening at 5-7 GeV that I don't understand

Implications for RMMS spec

- This is obviously not the optimal performance for the FD in terms of muon resolution, and should not be used as-is to define a spec
- The 10% full RMS and ~4% Gaussian σ in the peak that is observed in MINOS ND for front entering tracks is basically consistent with what we get for the FD by range
- We expect the full FD module to contain ~70% of fiducial muons at 4 GeV and ~50% at 5 GeV
- My opinion: we should design fro the 4%/10% resolution out to 5 GeV

MINOS ND muon resolution



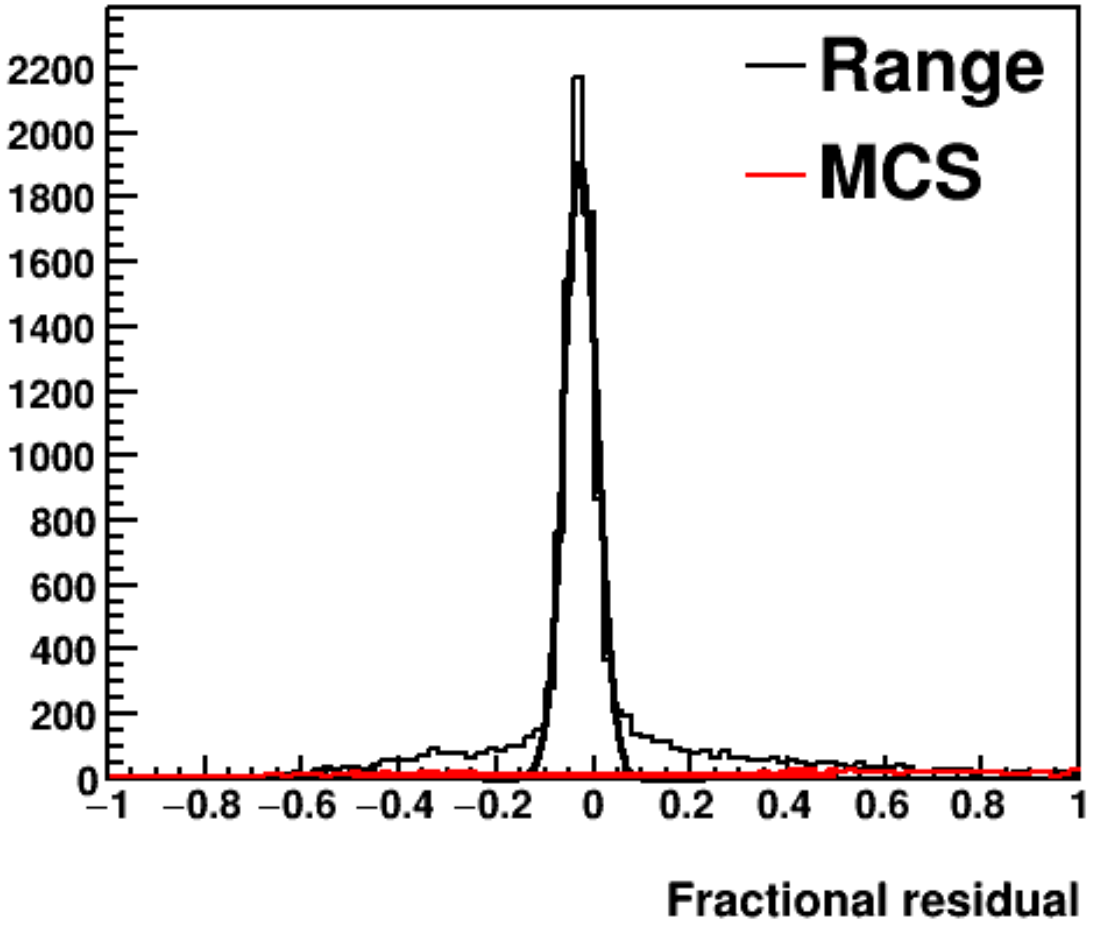
- MINOS ND (2.5cm steel + 1cm scintillator) gives 4% resolution by range, comparable to what is achieved in FD
- Thanks to Trung Le (MINERvA/Tufts) for inputs to these plots

Conclusions

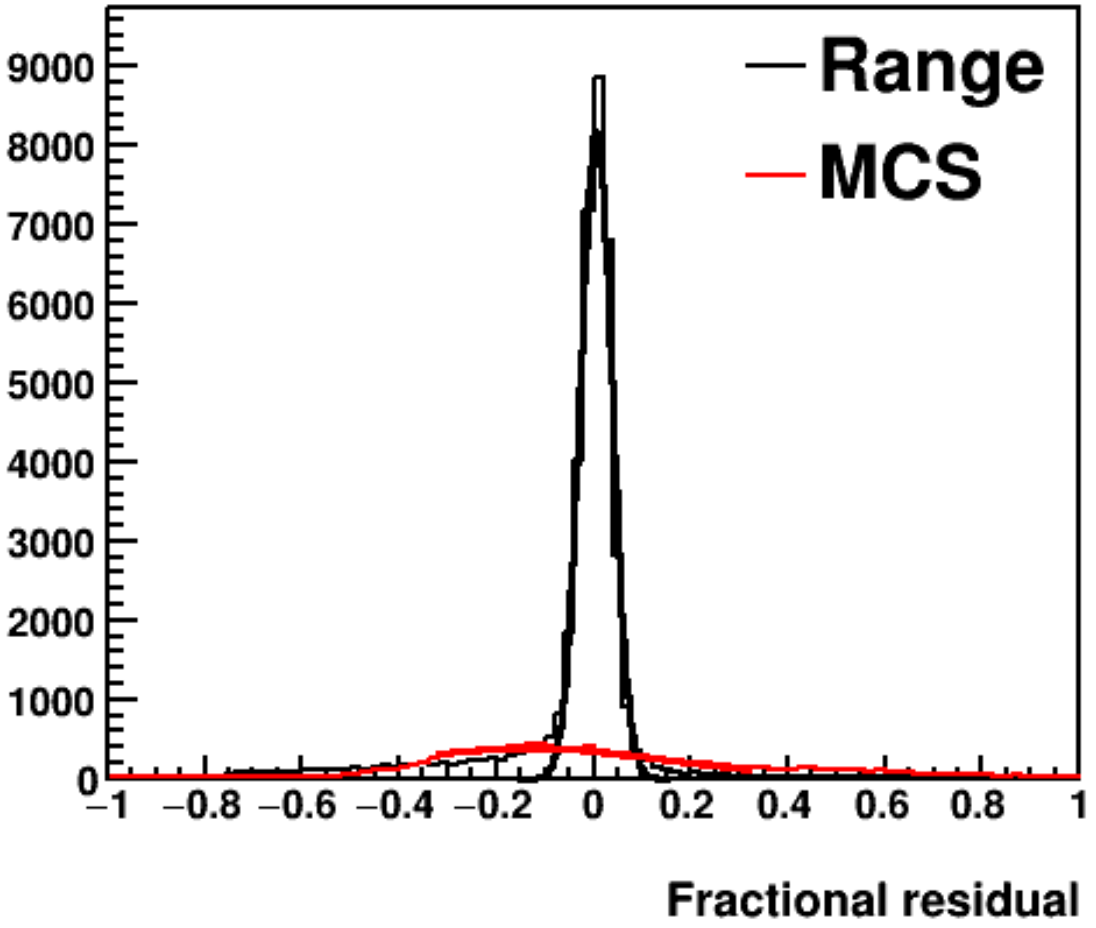
- DUNE FD muon energy resolution is 4% peak σ and 10% full RMS for contained muons
- Full FD module will contain >70% muons out to 5 GeV, so this should be used as the specification
- MINOS ND observed ~4%/10% for front-entering muons in the 1-5 GeV region, meeting the minimum requirement for RMMS

Backups

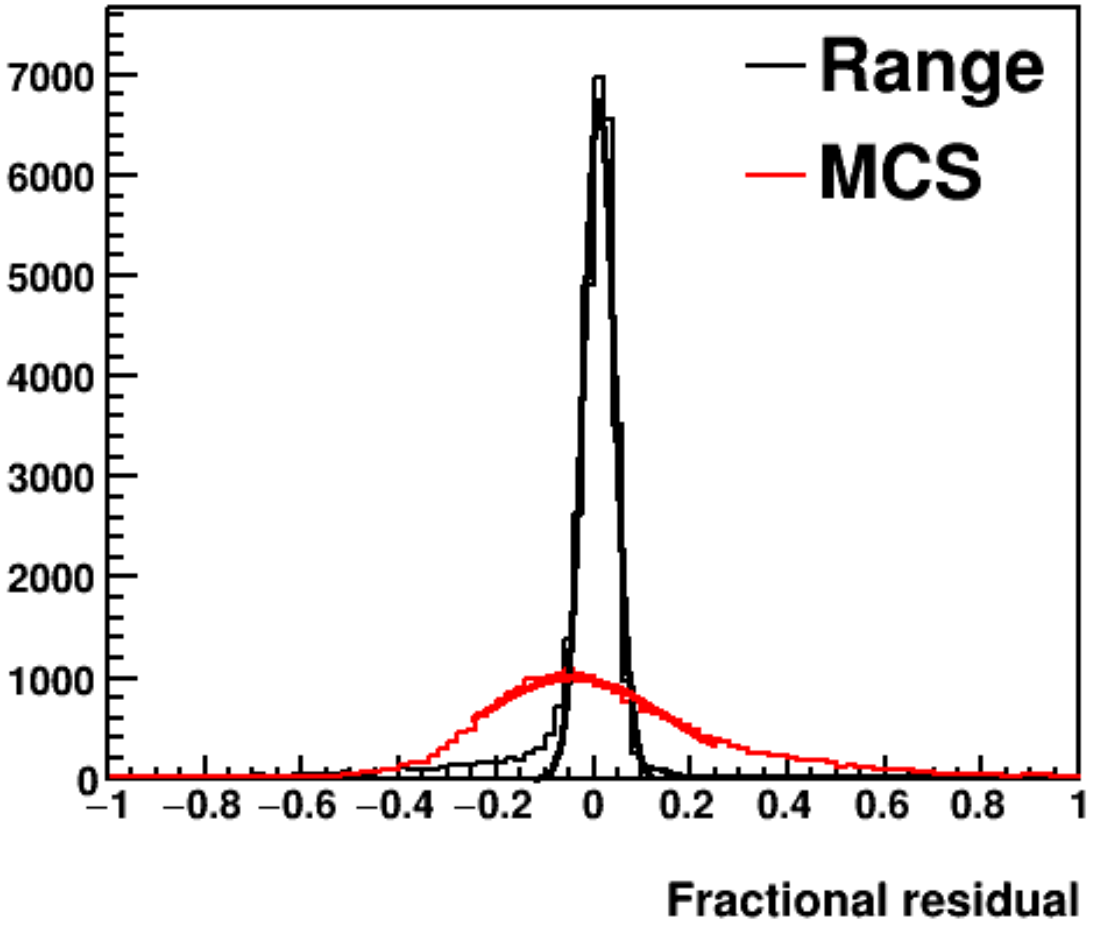
$0 < E_{\mu} < 0.5$ GeV



$0.5 < E_{\mu} < 1$ GeV



$1 < E_{\mu} < 1.5$ GeV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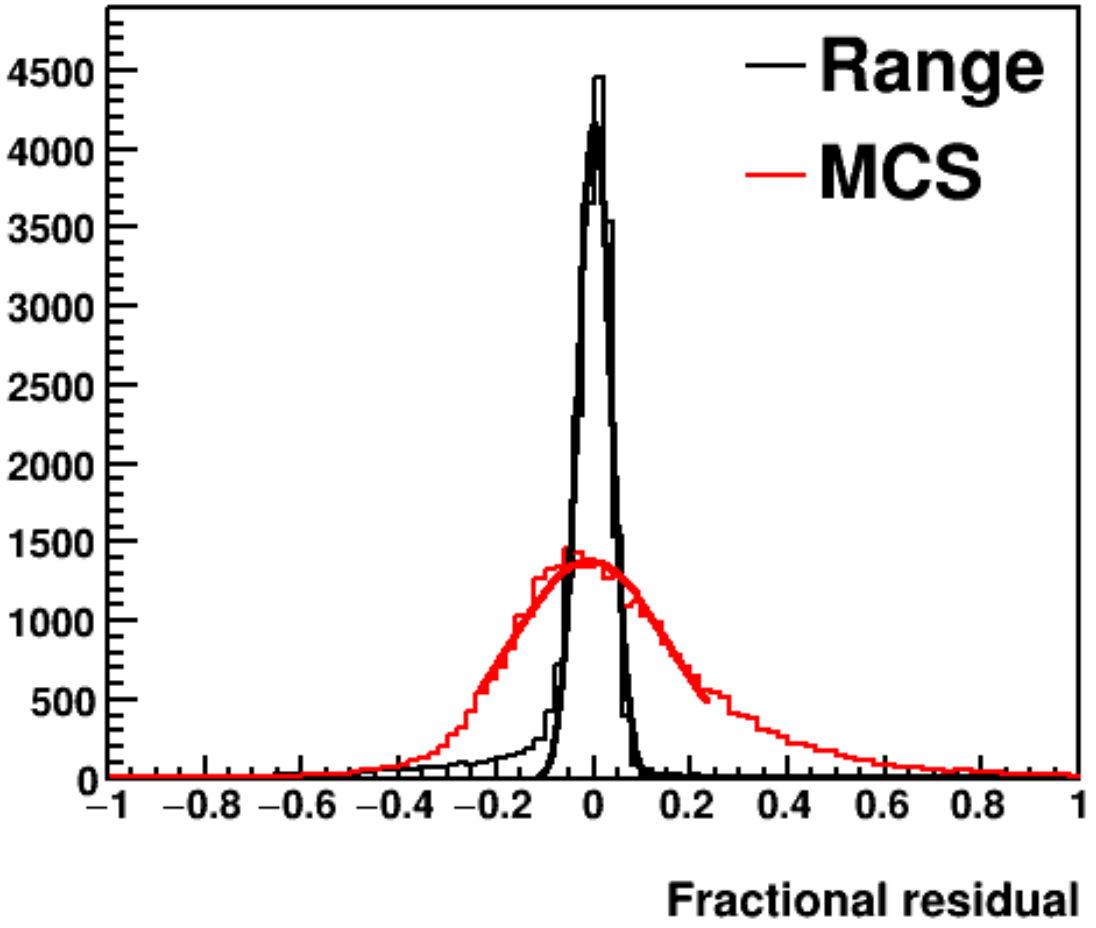
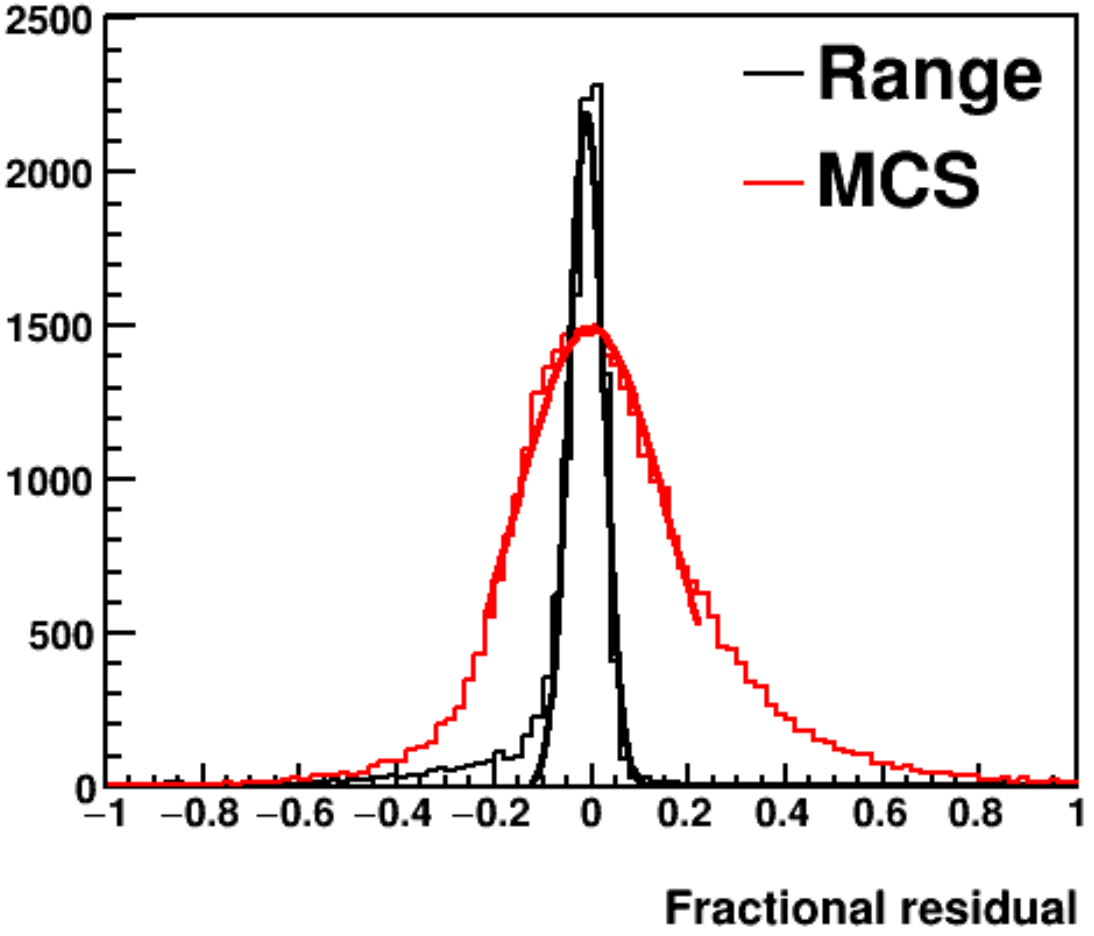
0.2
0.4
0.6
0.8
1
Fractional residual

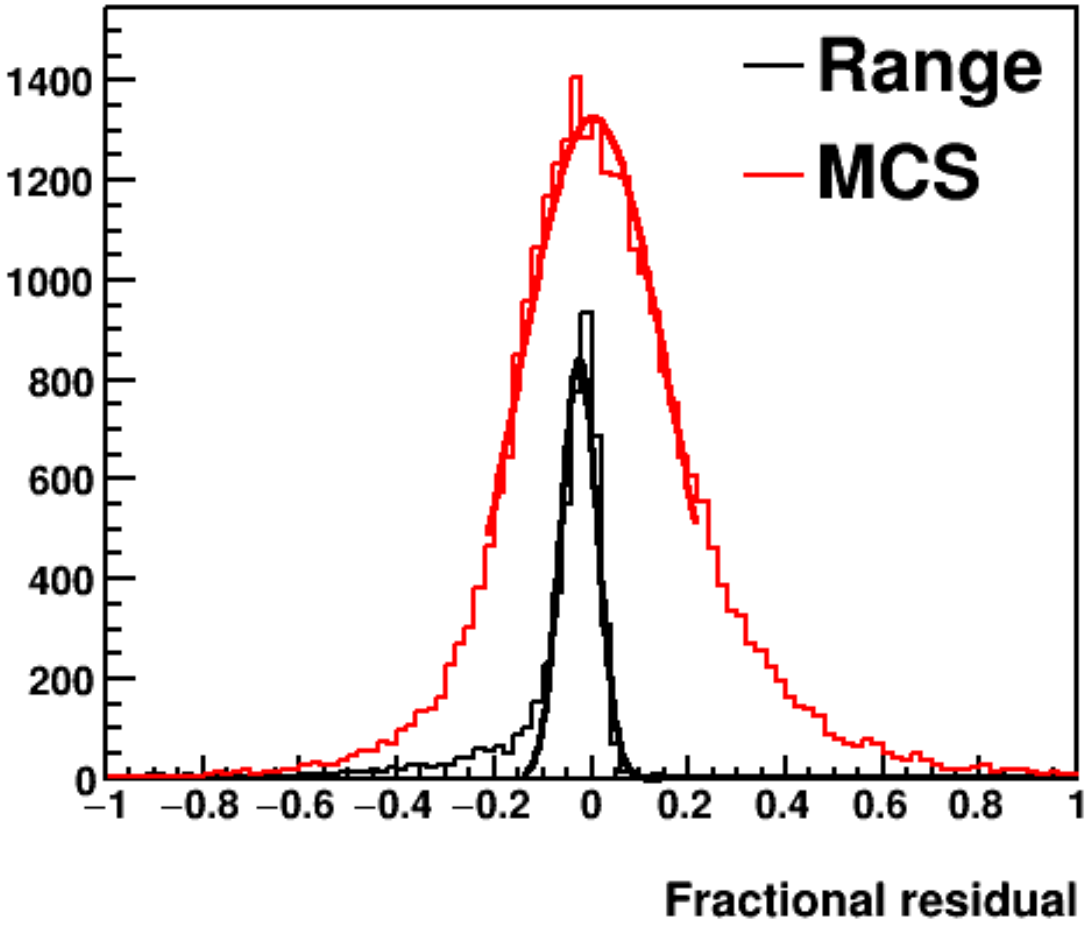
$1.5 < E_{\mu} < 2$ GeV



$2 < E_{\mu} < 2.5$ GeV



$2.5 < E_{\mu} < 3$ GeV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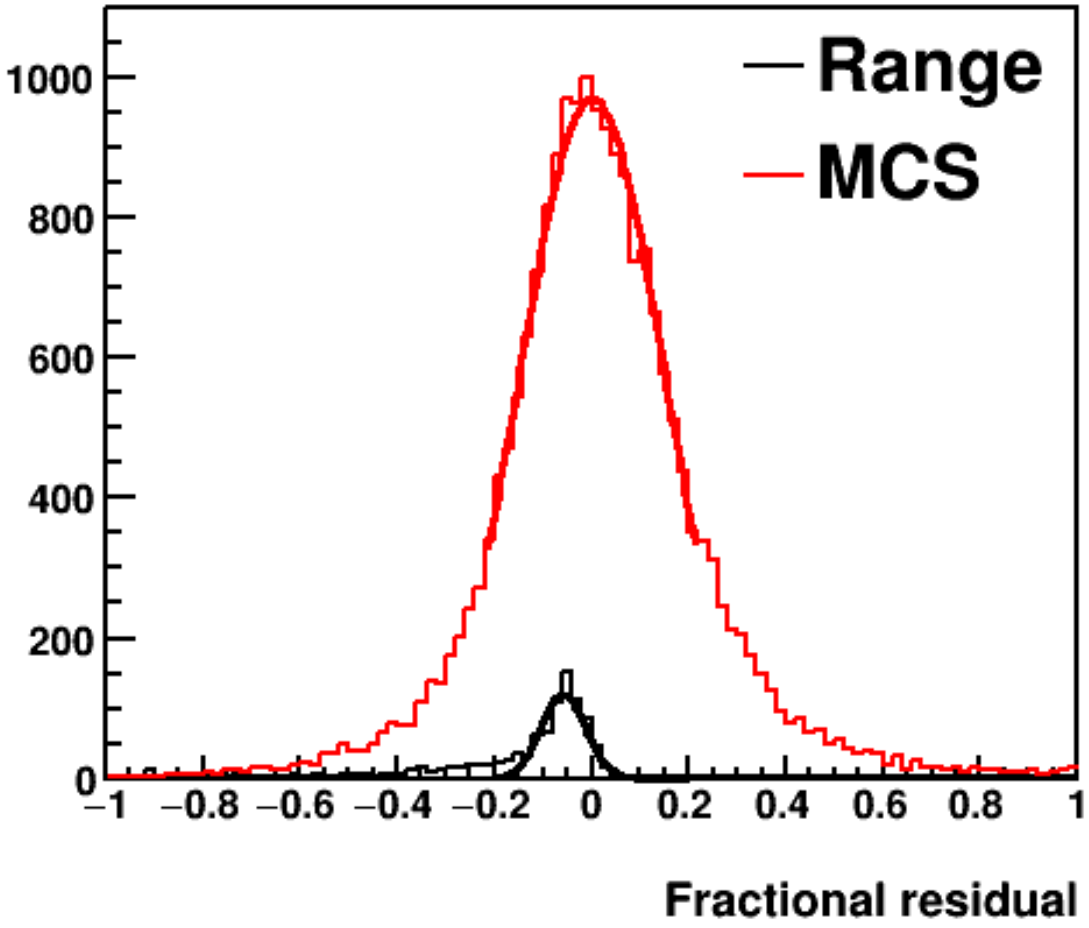
Fractional residual

$3 < E_{\mu} < 3.5$ GeV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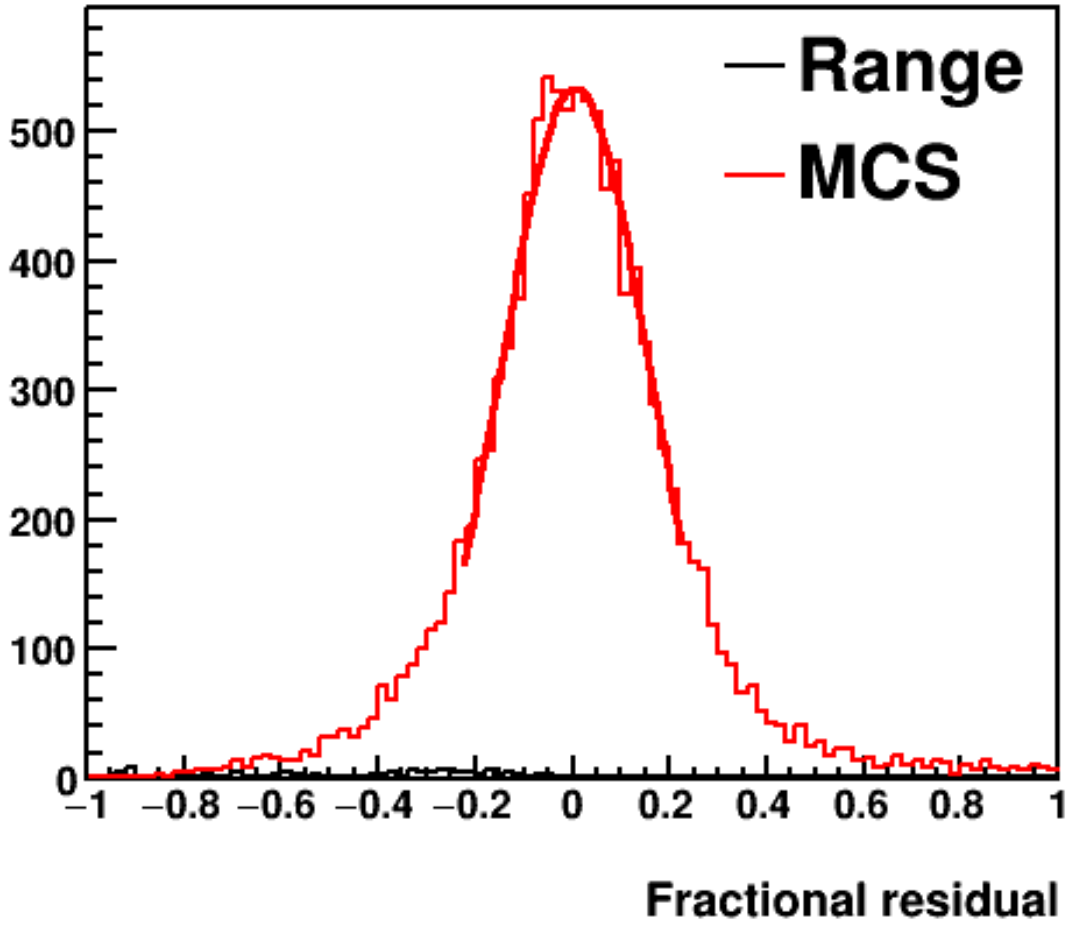
1
Fractional residual

$3.5 < E_{\mu} < 4$ GeV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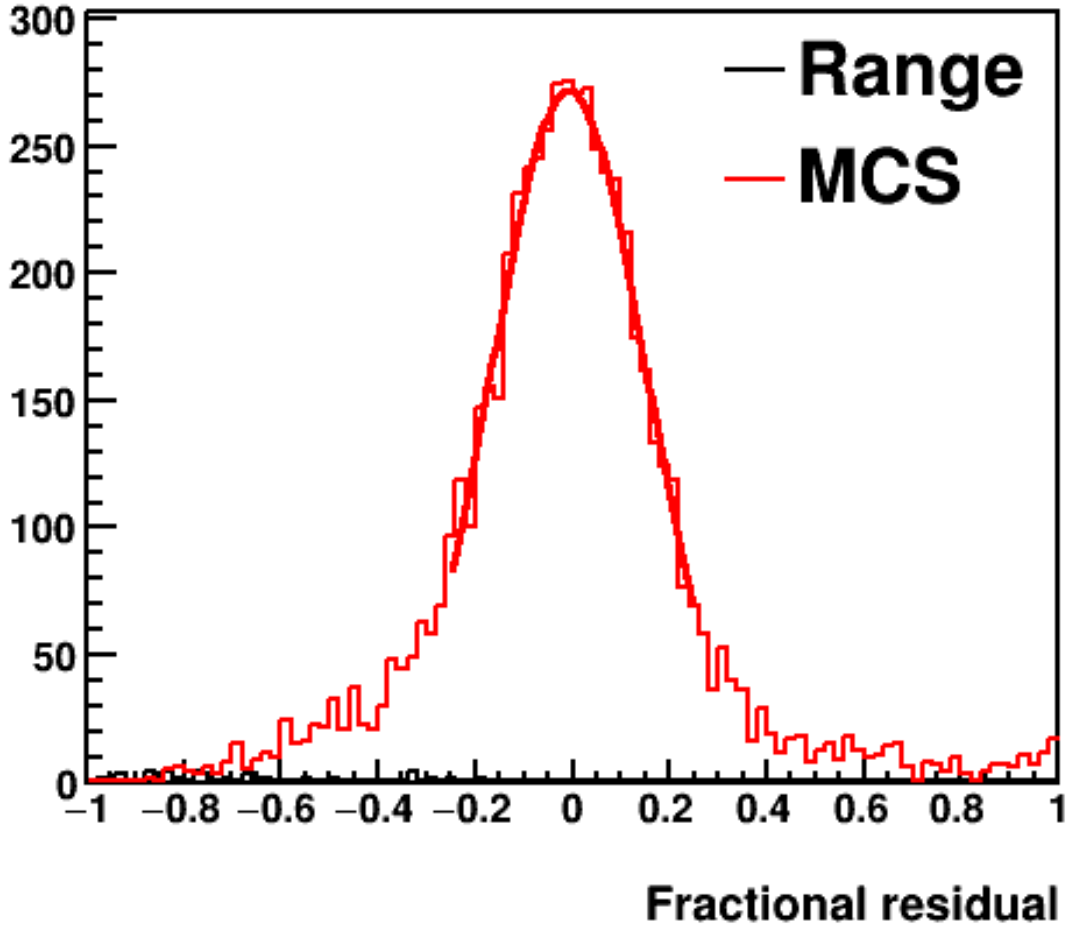
Fractional residual

$4 < E_{\mu} < 4.5$ GeV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0.6
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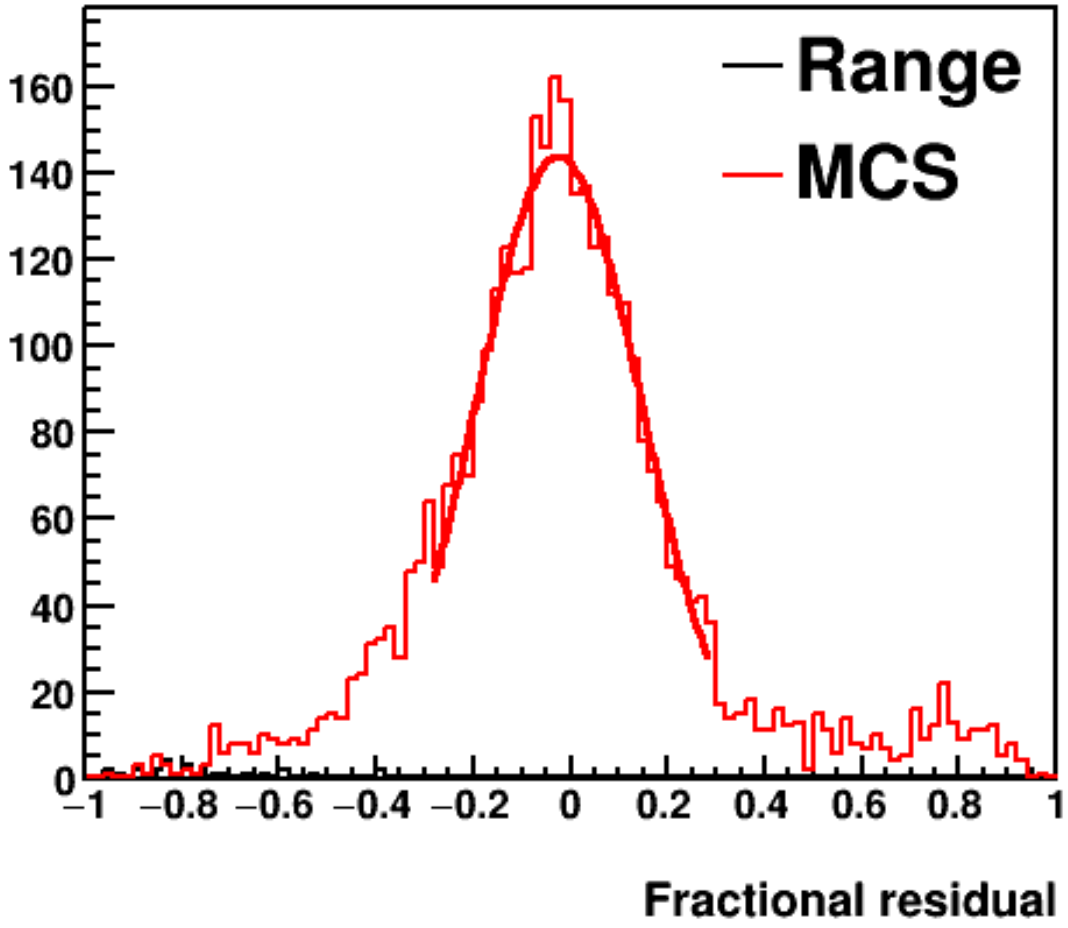
Fractional residual

$4.5 < E_{\mu} < 5$ GeV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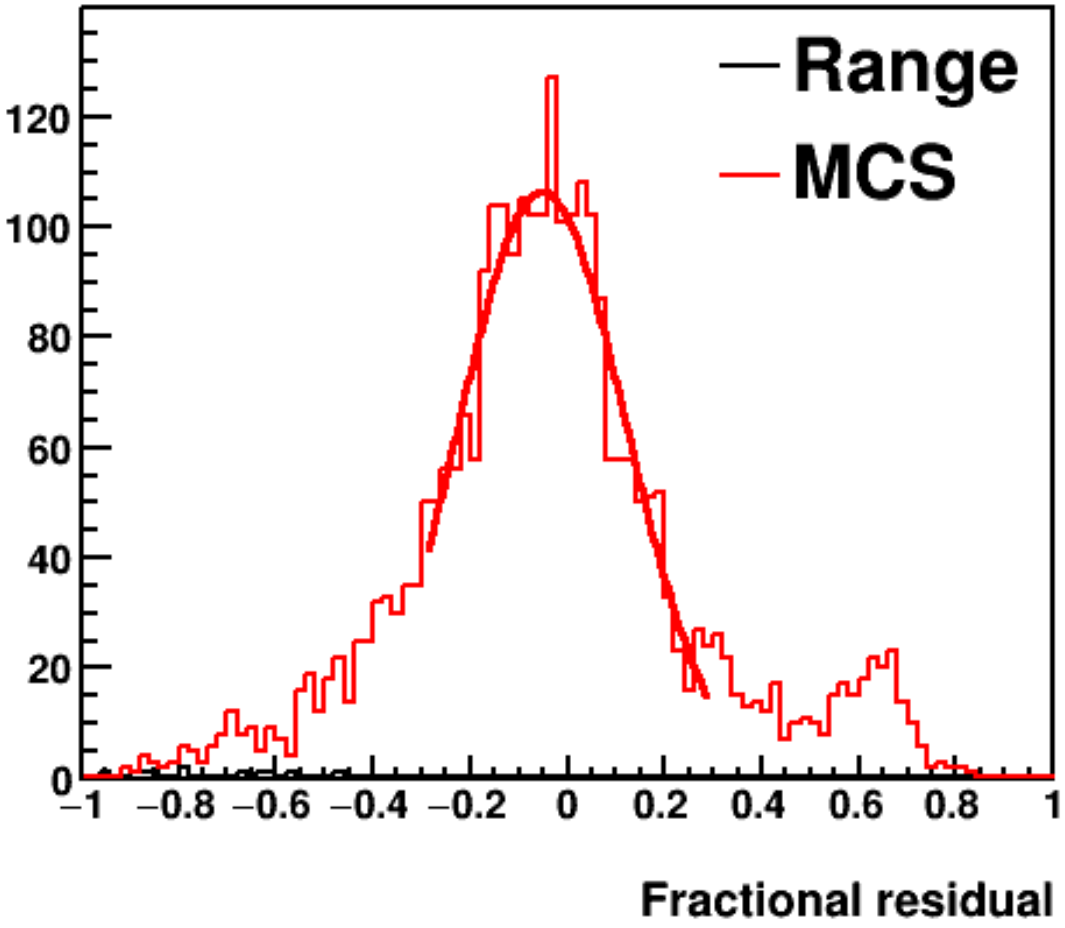
Fractional residual

$5 < E_{\mu} < 5.5$ GeV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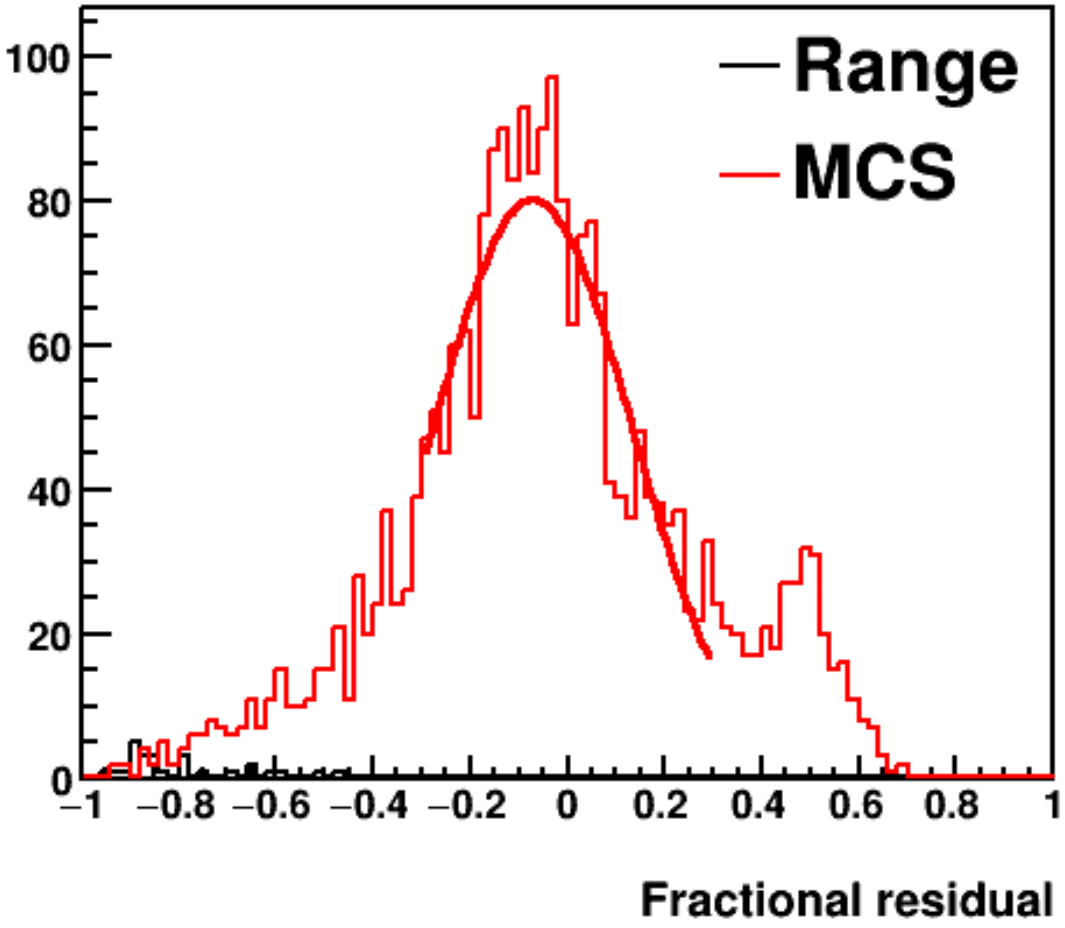
0.6
0.8
1
Fractional residual

$5.5 < E_{\mu} < 6$ GeV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0.8
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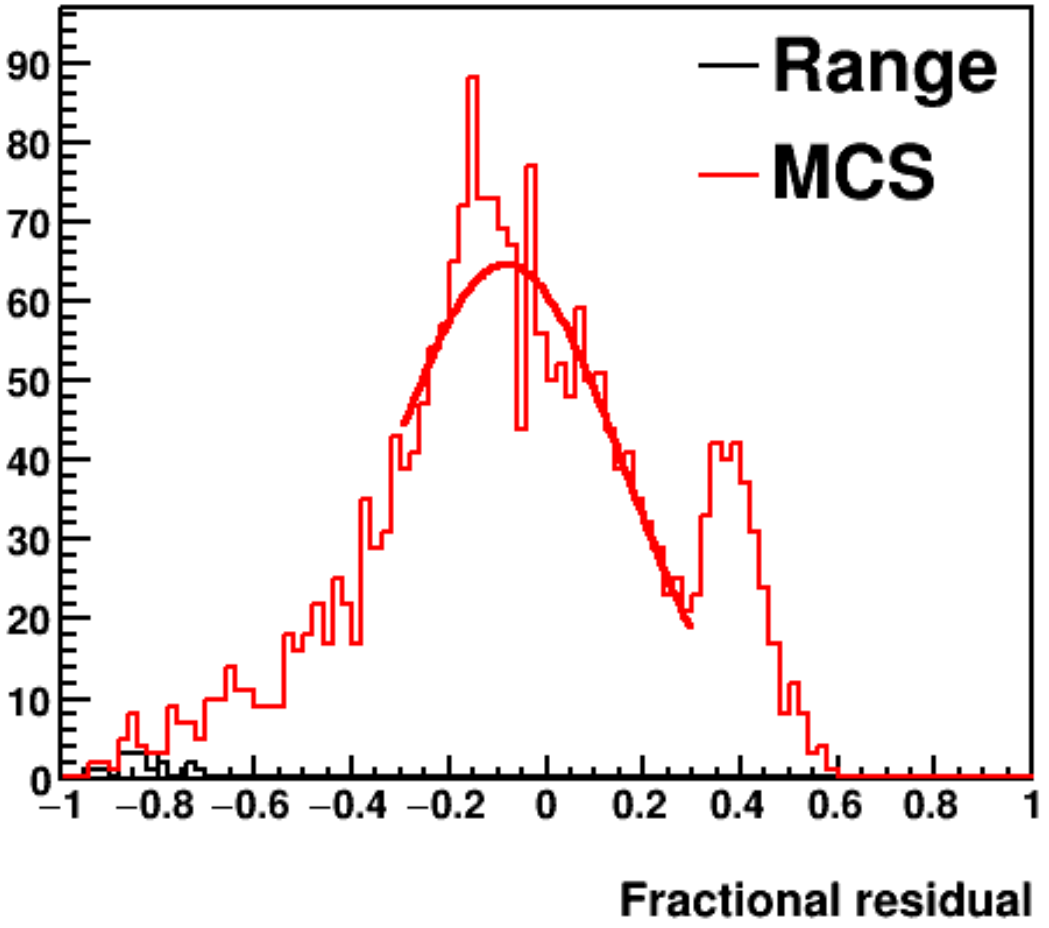
Fractional residual

$6 < E_{\mu} < 6.5$ GeV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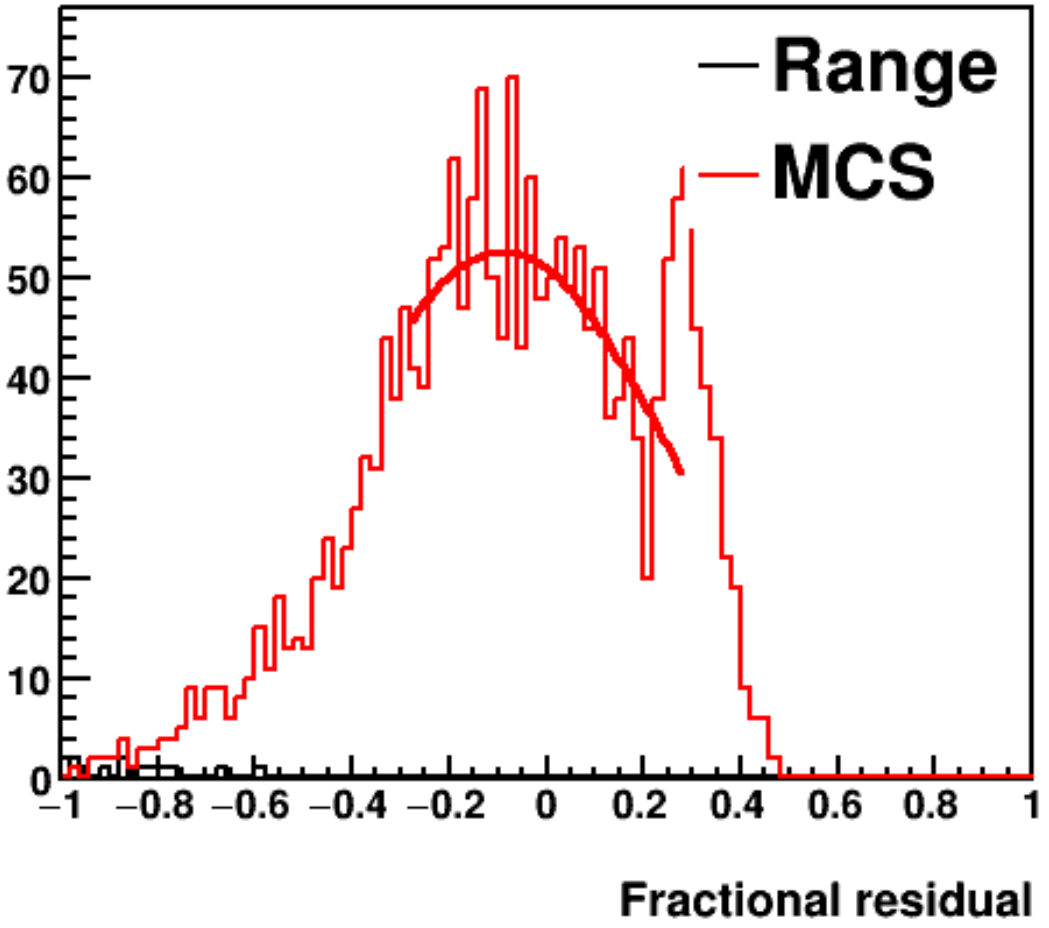
Fractional residual

$6.5 < E_{\mu} < 7$ GeV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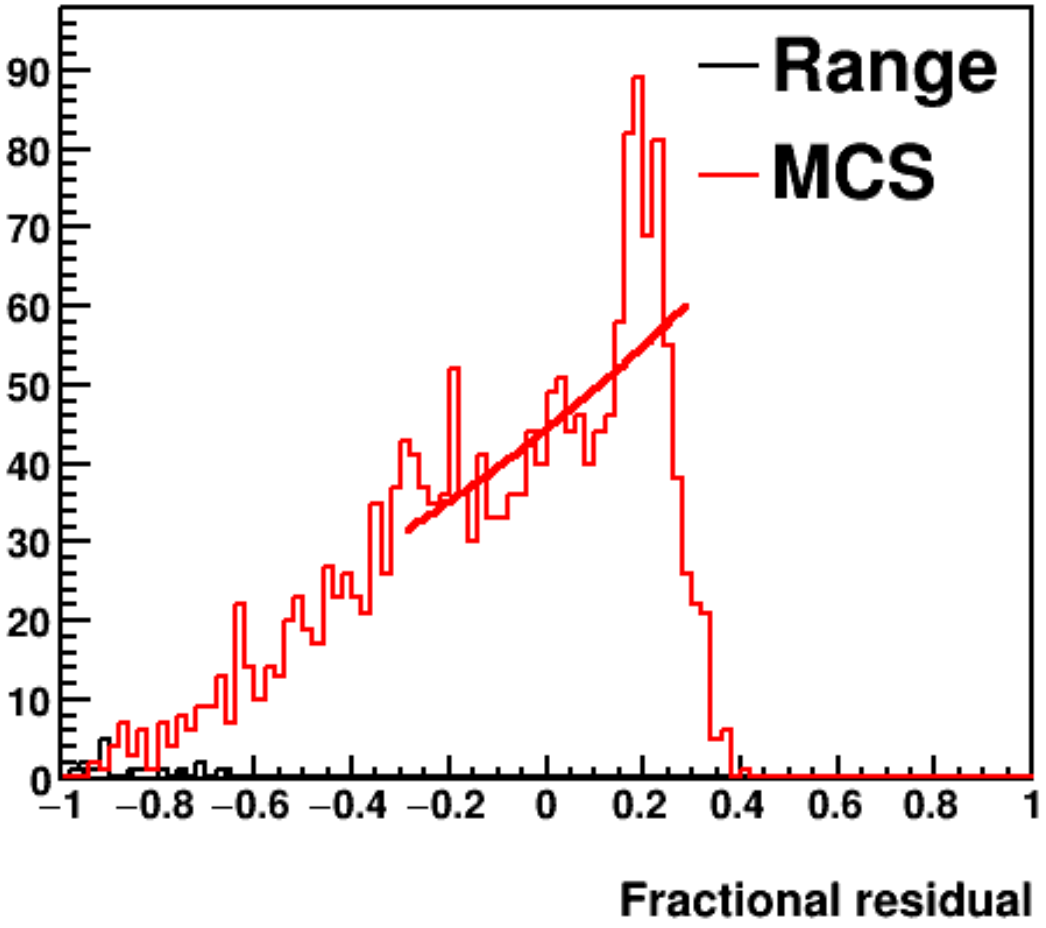
Fractional residual

$7 < E_{\mu} < 7.5$ GeV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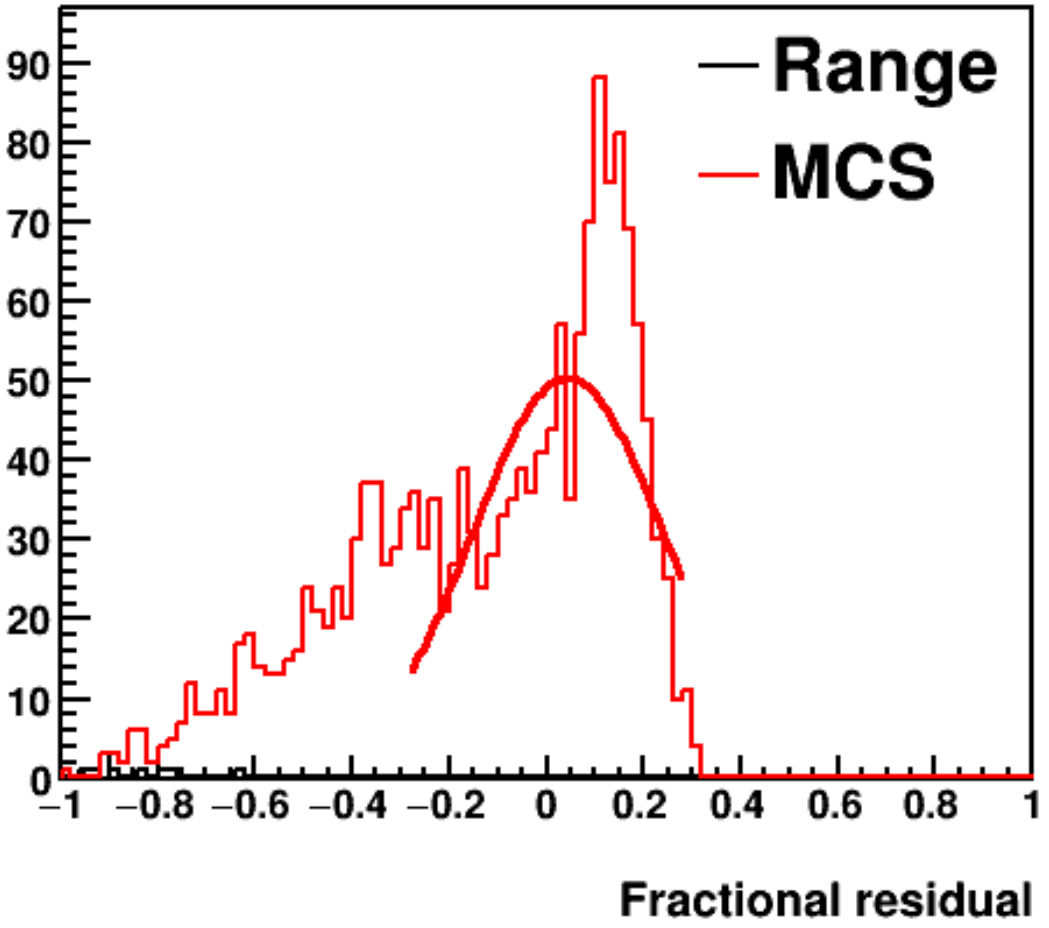
Fractional residual

$7.5 < E_{\mu} < 8$ GeV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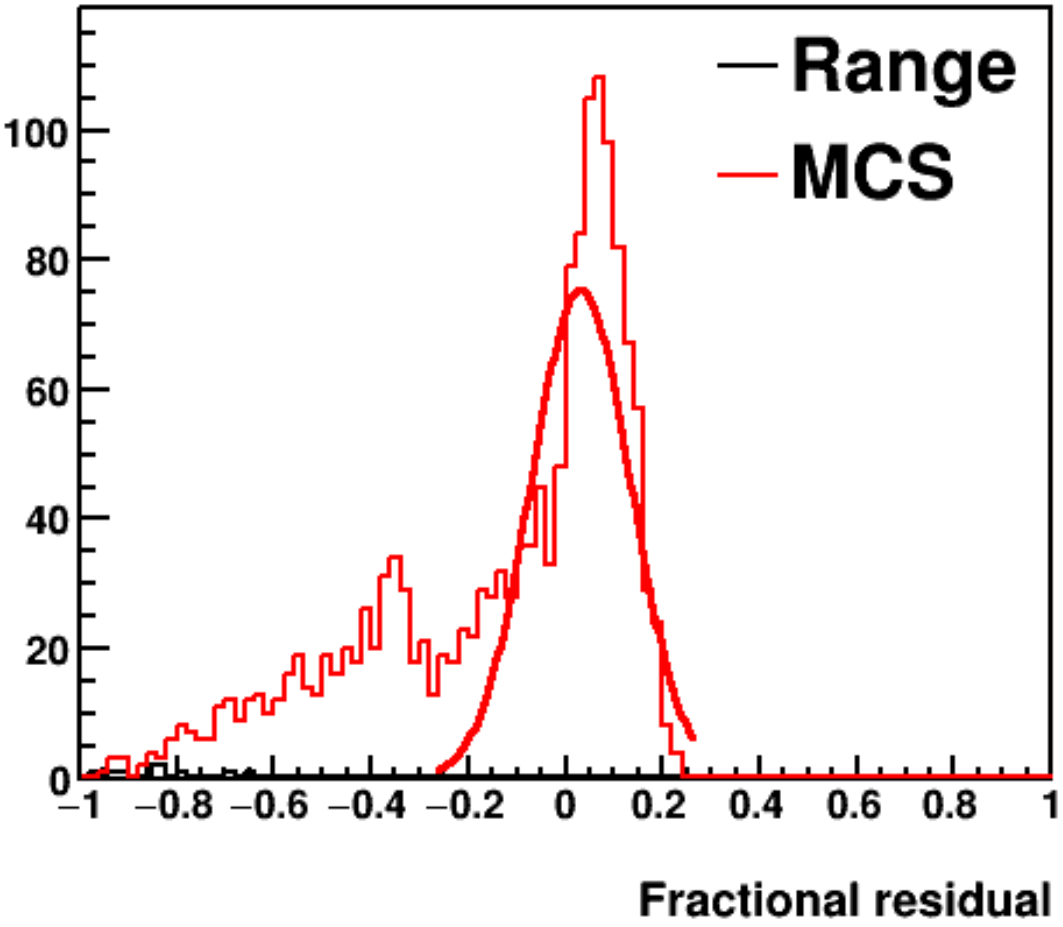
Fractional residual

$8 < E_{\mu} < 8.5$ GeV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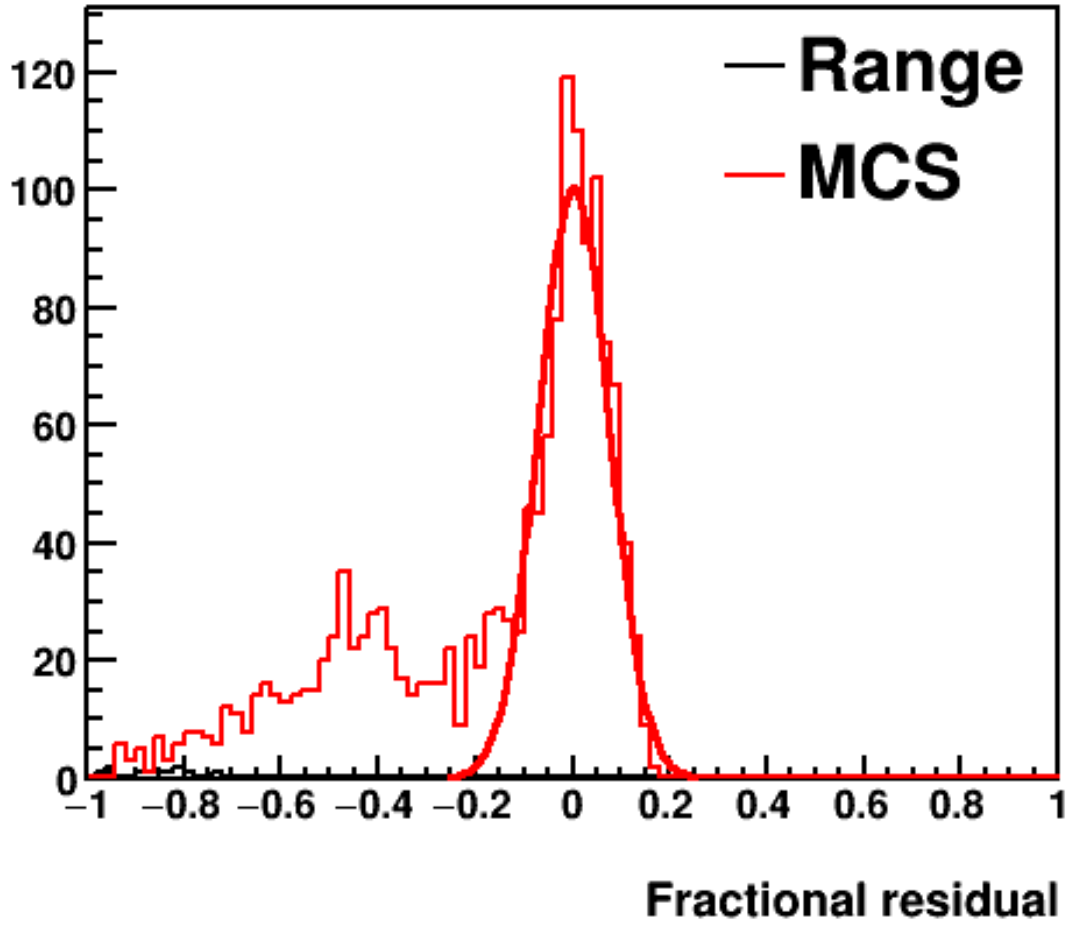
Fractional residual

$8.5 < E_{\mu} < 9$ GeV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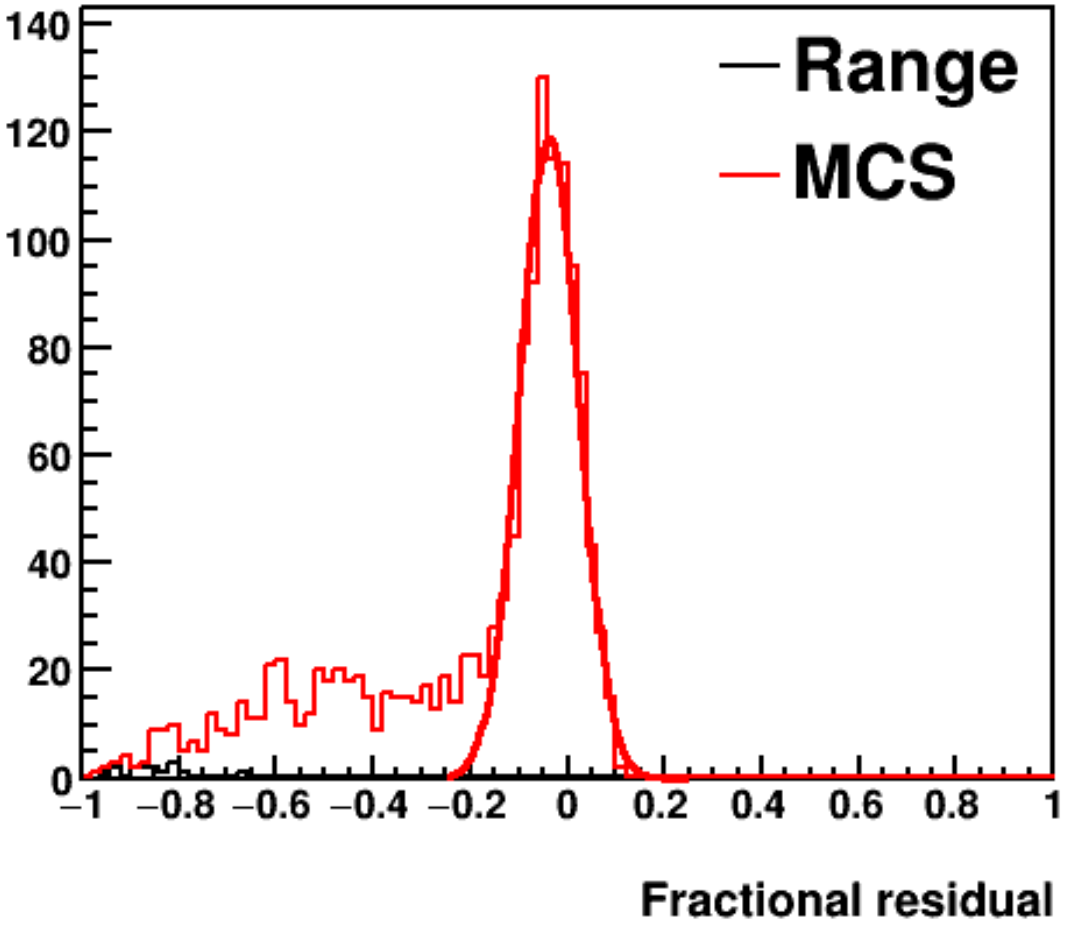
Fractional residual

$9 < E_{\mu} < 9.5$ GeV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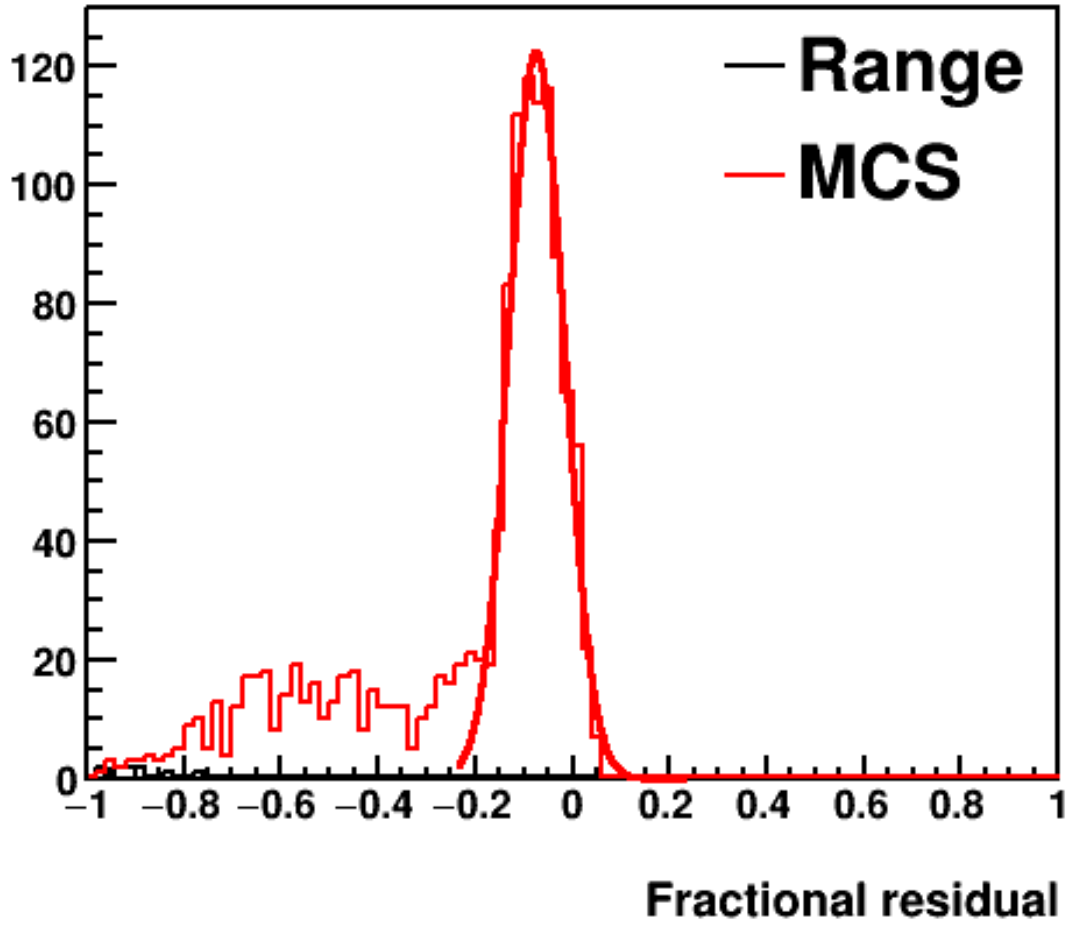
Fractional residual

$9.5 < E_{\mu} < 10$ GeV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Fractional residual