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Muon deflection uncertainties on directional reconstructions using PROPOSAL

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Motivation of muon deflection simulation

Why?

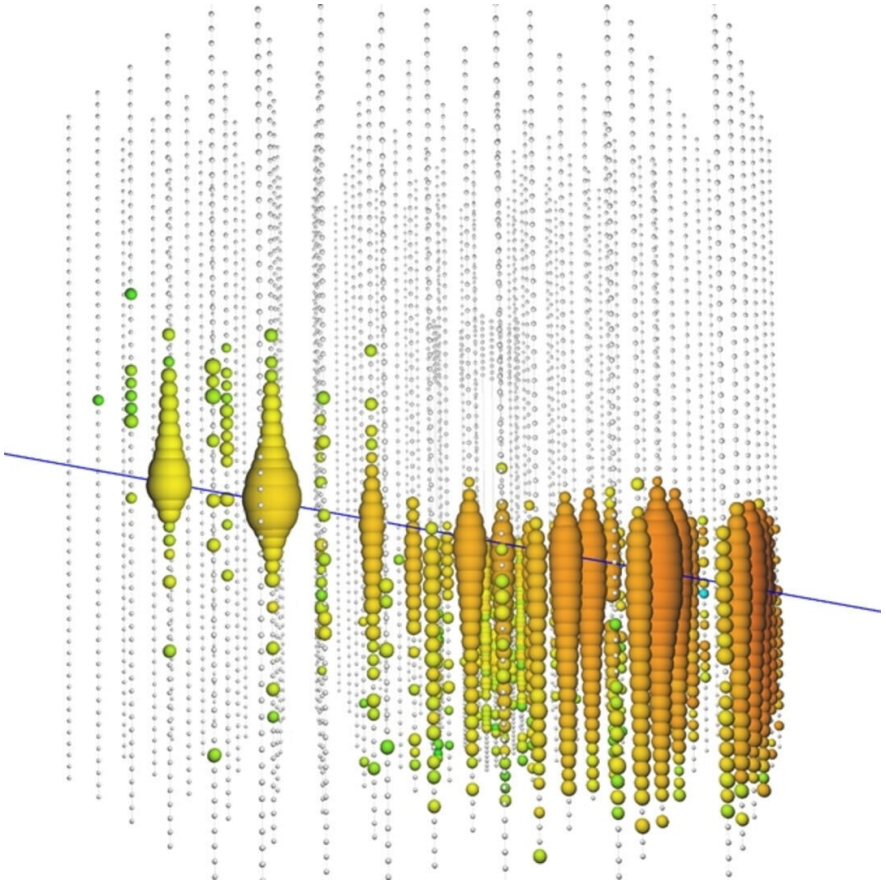
- TeV to PeV muons are strongly forward boosted
  - Single deflection lower than angular resolution of ~0.6°
  - ➢ Assume muon propagation along a straight line

But:

- Muons can propagate up to several km through media
  - ➢ Thousands of interactions
  - ➢ Large energy losses
  - ➢ Deflection in each interaction

What happens if thousands of deflections accumulate?

Is a total deflection on the order of magnitude of current angular resolutions possible?



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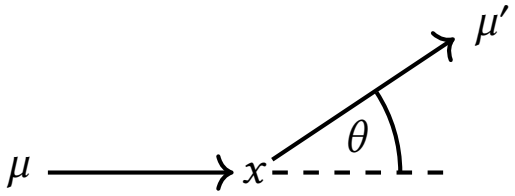

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Overview

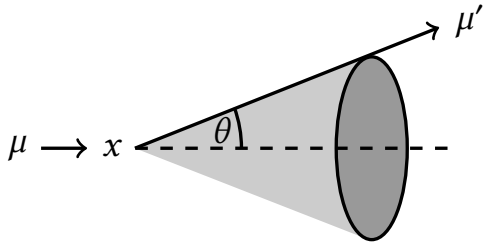
- Motivation of muon deflection simulation
- Simulation tool PROPOSAL
- Muon deflection per interaction
- Comparison with other simulation tools
- Data-MC checks
- Estimate muon deflection uncertainty on angular reconstruction
- Summary & outlook

Simulation tool PROPOSAL

- C++/Python simulation framework for leptons -> muons
- Optimized for large-scale particle propagations
- Up-to-date parametrizations
- Relative and absolute energy cut to speed up propagation process
  - $v_{\text{cut}}, e_{\text{cut}}$
  - Continuous and stochastic processes

- Propagation
  - Initial energy
  - Final energy
  - Energy cuts
  - Medium
  - Distance

- Deflection
  - Multiple scattering
    - Molière
    - Highland
  - Stochastic deflection
    - Bremsstrahlung
    - Photonuclear interaction
    - Electron pair production
    - Ionization
    - Different parametrizations from Van Ginneken[1] and Geant4[2] are available



github.com/tudo-astroparticlephysics/PROPOSAL

github.com/icecube/icetray/tree/main/PROPOSAL

[1] NIM A251 (1986) 21-39
[2] geant4.web.cern.ch

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Muon deflection per interaction

- 1000 muons propagated in ice
- Initial energy 1 PeV
- Final energy 1 TeV
- e_cut = 500 MeV, v_cut = 0.05

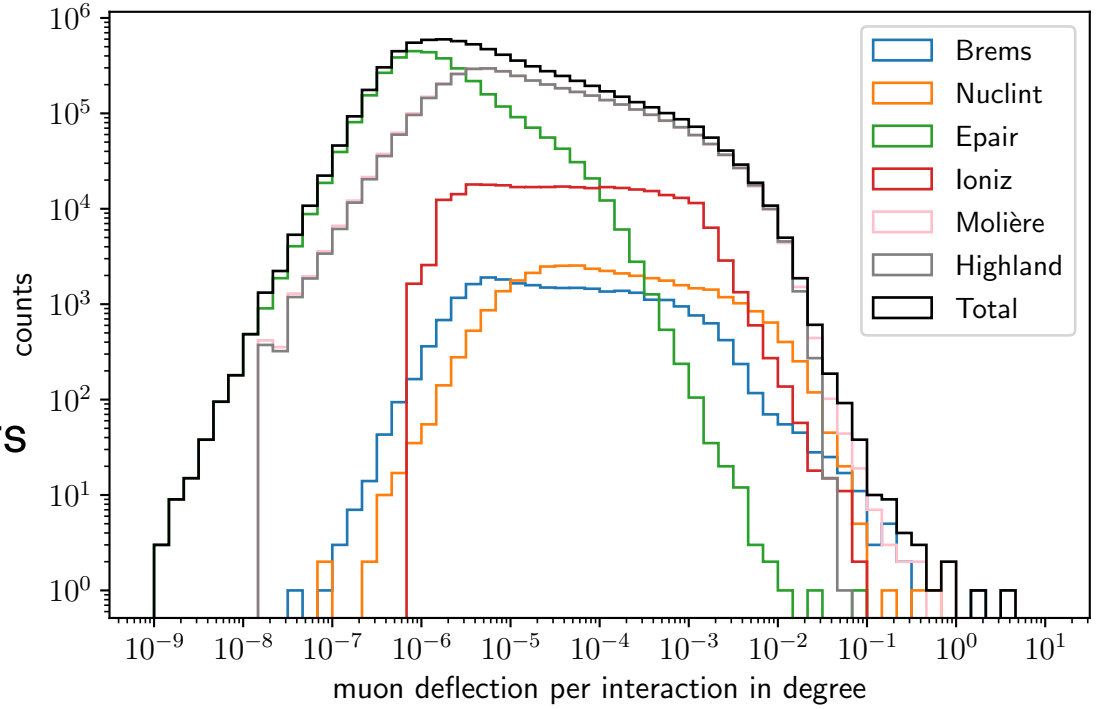
➢ Largest median deflection by photonuclear interaction

➢ Largest outliers by bremsstrahlung

➢ Highland – Gaussian approximation neglects outliers

➢ Deflection dominated by multiple scattering

arXiv:2208.11902



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Accumulated deflection

- Single deflections extend over several order of magnitudes up to a few degrees
- Muons do up to thousands of interactions

Question

Can all deflections along the muon propagation accumulate to a total deflection that impacts our angular resolution?

- First, validate PROPOSAL results with other simulation tools and data

Comparison with other simulation tools

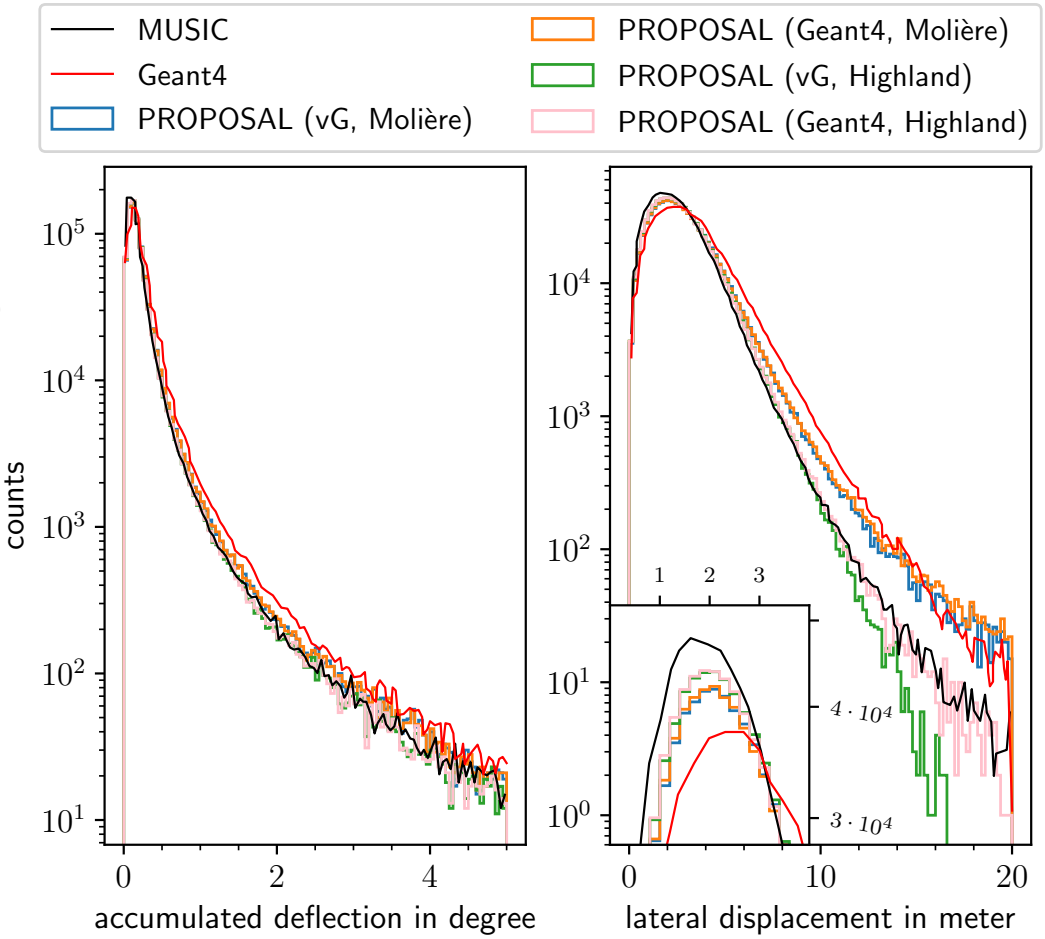
- MUSIC[1]
  - 3D muon simulation code
- Geant4[2]
  - Simulates passage of particles through matter very precisely, but intensive computing
  - Made for simulations in particle detectors

➢ Good agreement in angular deflection

➢ Small deviations in lateral displacement

➢ Highland approximation neglects outliers

arXiv:2208.11902



1 Mio. muons are propagated from 2 TeV over a distance of 3 km in water

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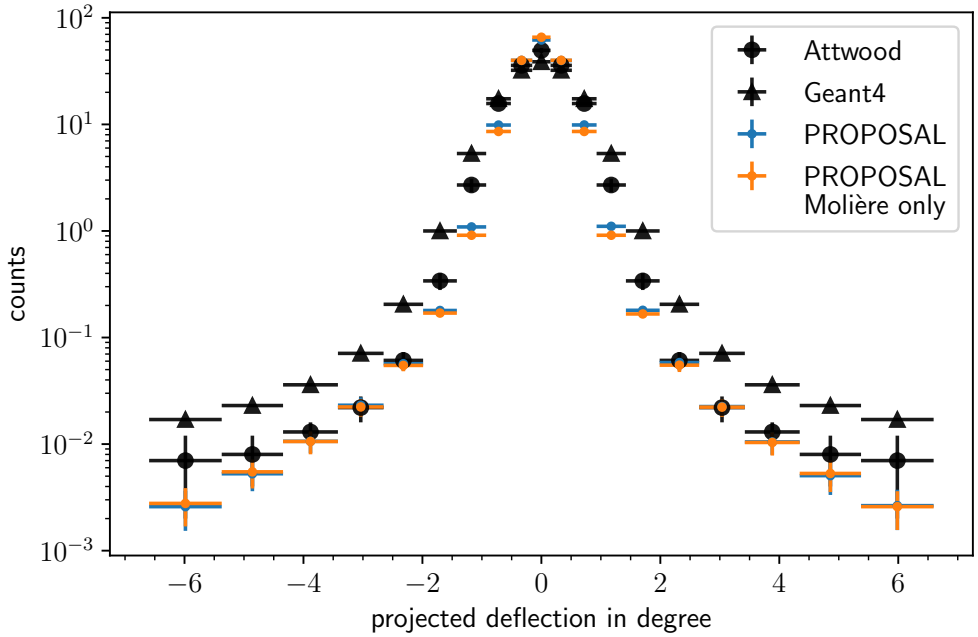
[1] Astropart. Phys. 7.4 (1997) 357-368

[2] geant4.web.cern.ch

Data-MC checks

Attwood[1]

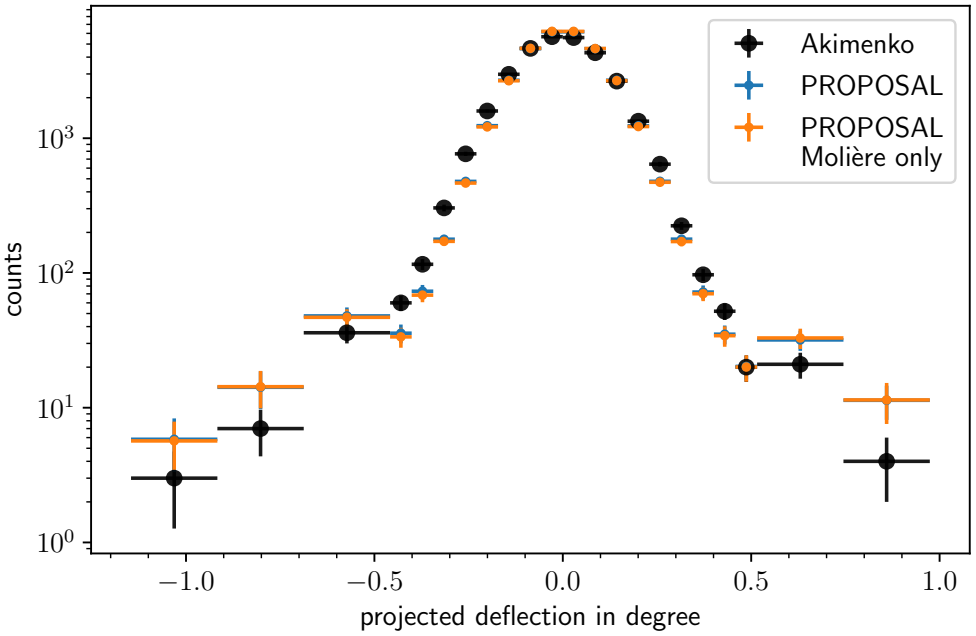
- $E_\mathrm{i} = 199\ \mathrm{MeV}$
- $d = 109\ \mathrm{mm}$
- Liquid hydrogen (low Z)



Akimenko[2]

- $E_\mathrm{i} = 7.3\ \mathrm{GeV}$
- $d = 144\ \mathrm{mm}$
- Copper

arXiv:2208.11902



➢ Good agreement in both measurements

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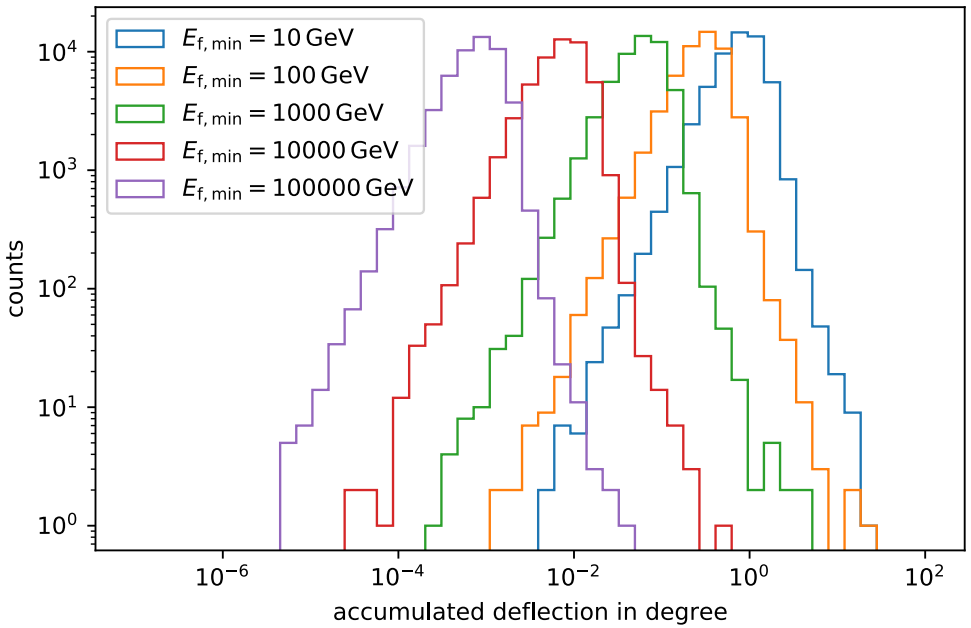
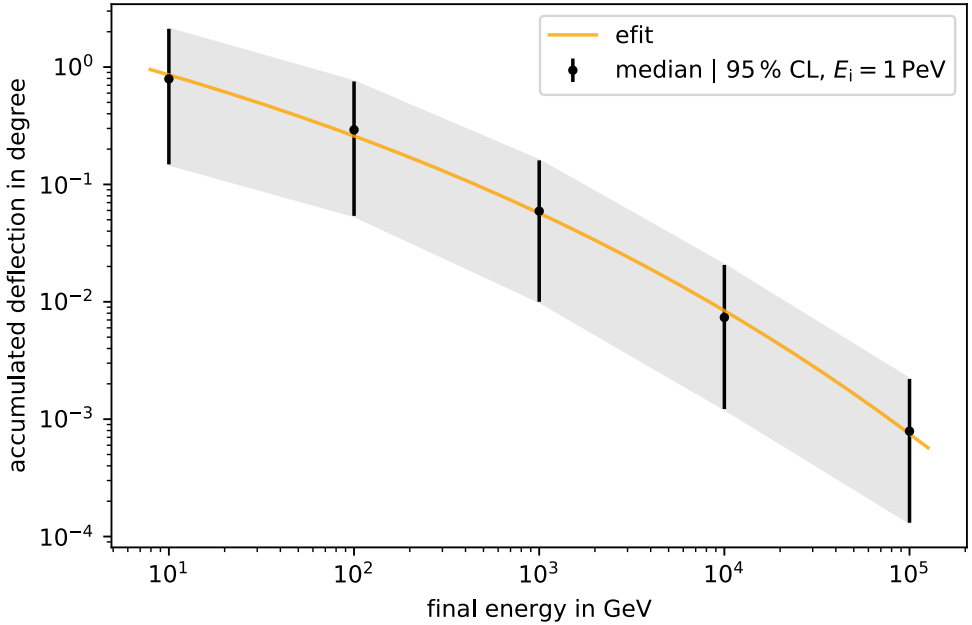
[1] NIMB 251.1 (2006) 41-55
[2] NIMA 243 (1986) 518-522

Accumulated deflection for several final muon energies

- Use fixed initial energy $E_\mathrm{i} = 1\ \mathrm{PeV}$
- Vary final energy



median with 95% content level → exponential fit



➢ Deflection increases as final energy decreases

➢ Check median deflection for different initial energies

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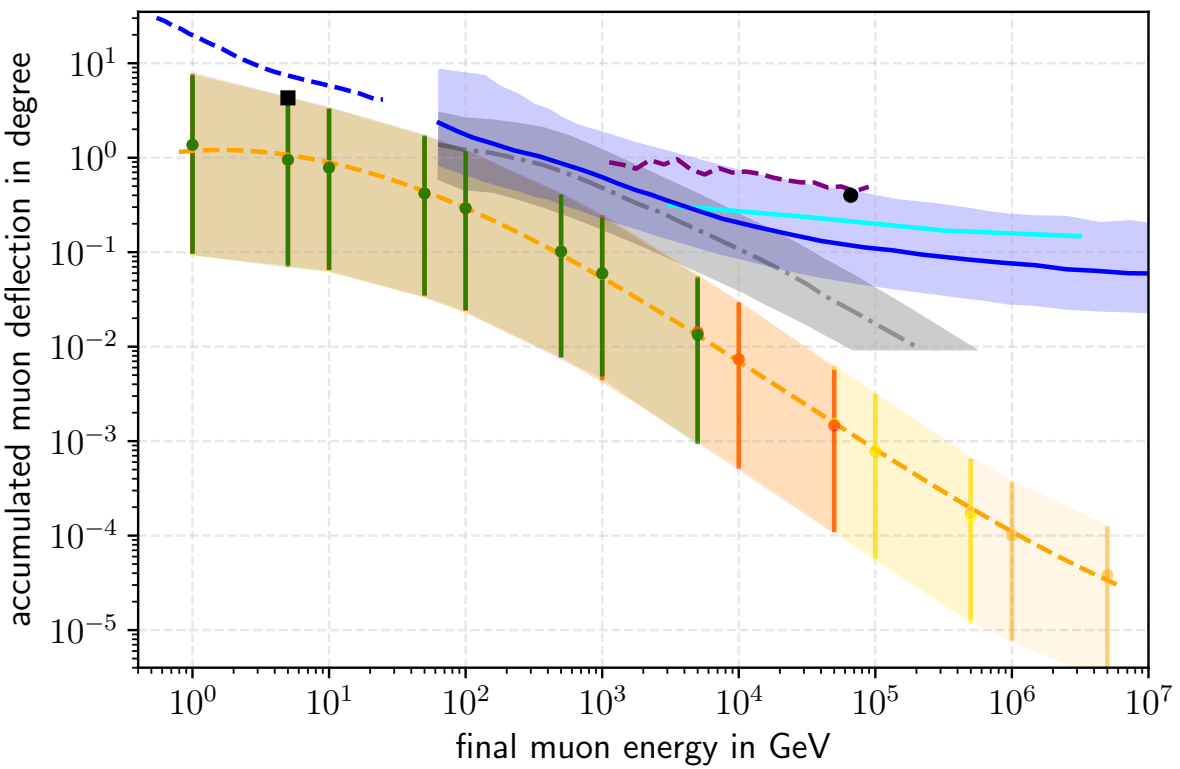
Accumulated deflection impact on angular resolutions

- Check median of accumulated deflections for:
  - $E_\mathrm{i} \in \{10\ \mathrm{PeV},\ 1\ \mathrm{PeV},\ 100\ \mathrm{TeV},\ 10\ \mathrm{TeV}\}$
  - $E_\mathrm{f,min} \in \{10\ \mathrm{GeV}, \ldots, 500\ \mathrm{TeV}\}$
  - number events > 50,000 for each data set



- Median of deflections overlap for different initial energies
  - No strong impact of the initial energy
- Median can be fit by third degree polynomial in log-space

Fit function:
$f(x) = 0.018x^3 - 0.003x^2 + 0.093x + 0.073$
$g(x) = 10^{f(x)}, \qquad x = \log_{10}(E_\mathrm{f}/\mathrm{GeV})$

with $E_\mathrm{f} \in [1\ \mathrm{GeV}, 5\ \mathrm{PeV}]$

- $E \leq 1$ TeV: minimal influence of deflection on angular resolution (KM3NeT)

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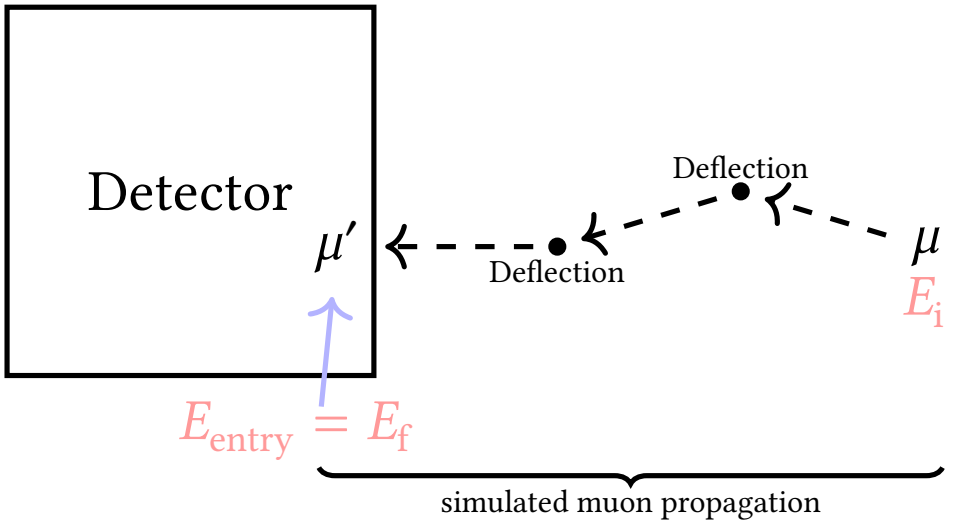
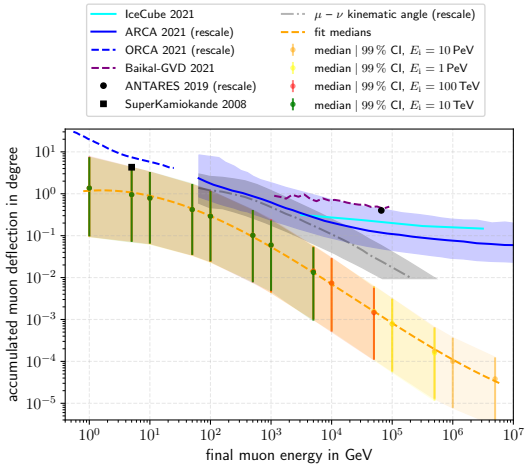
arXiv:2208.11902

Estimate muon deflection uncertainty on angular reconstruction

- No information about the muon before the detector entry
- We can only reconstruct the muon at the detector entry
  - Energy
  - Direction
- Detector entry energy = final muon energy
- Muon deflection depends only on the final muon energy
- Use reconstructed muon energy to estimate the muon deflection before the detector entry

➢ Systematic uncertainty





Fit function:
$f(x) = 0.018x^3 - 0.003x^2 + 0.093x + 0.073$
$g(x) = 10^{f(x)}, \quad x = \log_{10}(E_f/\text{GeV})$

with $E_f \in [1\ \text{GeV}, 5\ \text{PeV}]$

Summary

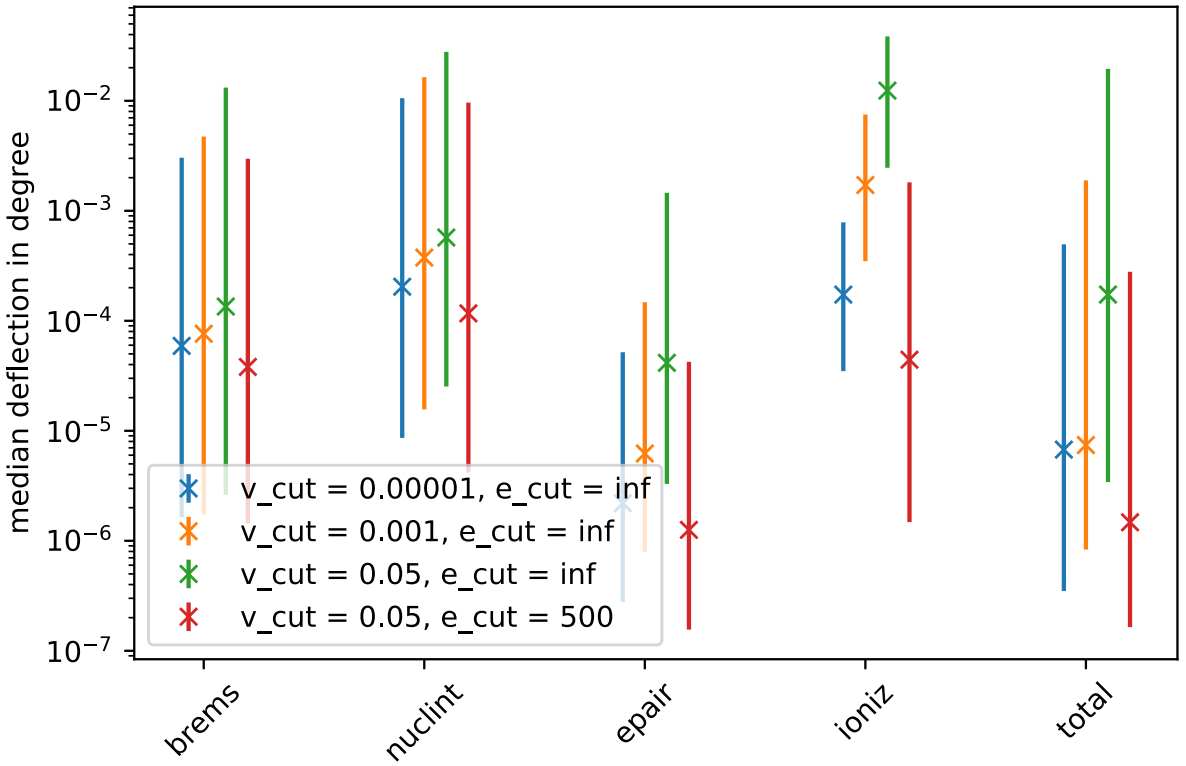
- Good agreement with MUSIC and Geant4 and two muon deflection measurements
- Muon deflection per interaction: $\theta \in [10^{-9}°, 1°]$ for $E_{\mathrm{i}} = 1\ \mathrm{PeV}$, $E_{\mathrm{f,min}} = 1\ \mathrm{TeV}$
- Deflections accumulate along the track
  - Deflections increase as the final muon energy decreases
  - Muon deflection is nearly independent of initial muon energy
  - Median deflections can be parametrized in dependence of final muon energy
- Fit function and reconstructed muon energy at detector entry can be used to estimate the muon deflection before the detector entry
- KM3NeT angular resolution is already impacted at $\leq \mathrm{TeV}$
- IceCube is not yet impacted

Outlook

- Paper submitted to EPJ C
- Use PROPOSAL 7 in IceCube
  - Now: PROPOSAL 6 -> without stochastic deflection
- Measure muon deflections at energies of TeV to PeV
  - Validate simulations at higher energies
  - IceCube Gen-2
- Muon deflection becomes more relevant with further angular reconstruction improvements
  - Especially at energies lower than TeV (IceCube Upgrade)

Appendix – median deflection with different energy cuts

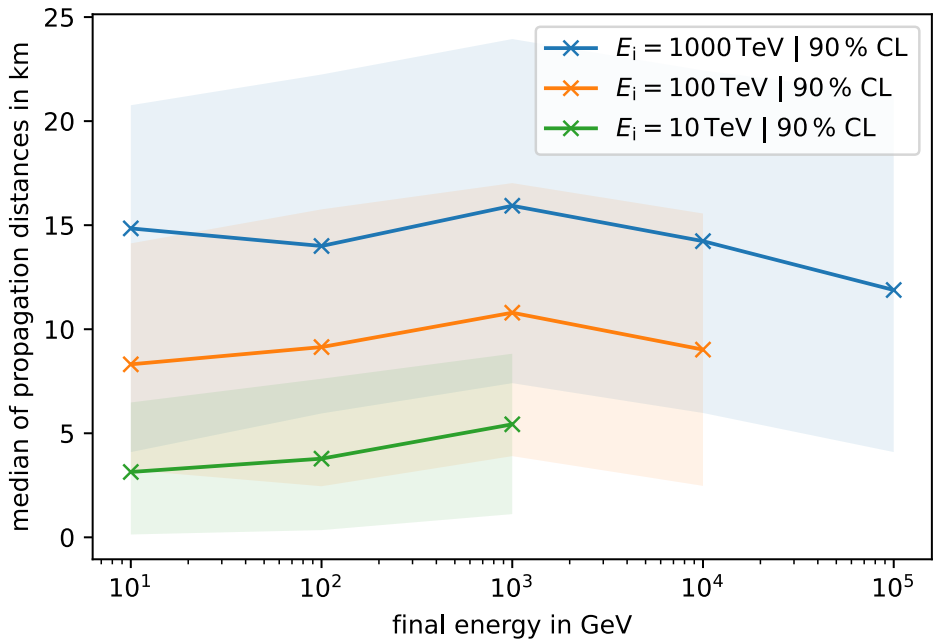
1 PeV to 1 TeV, 1000 events each, Molière, 95% Interval

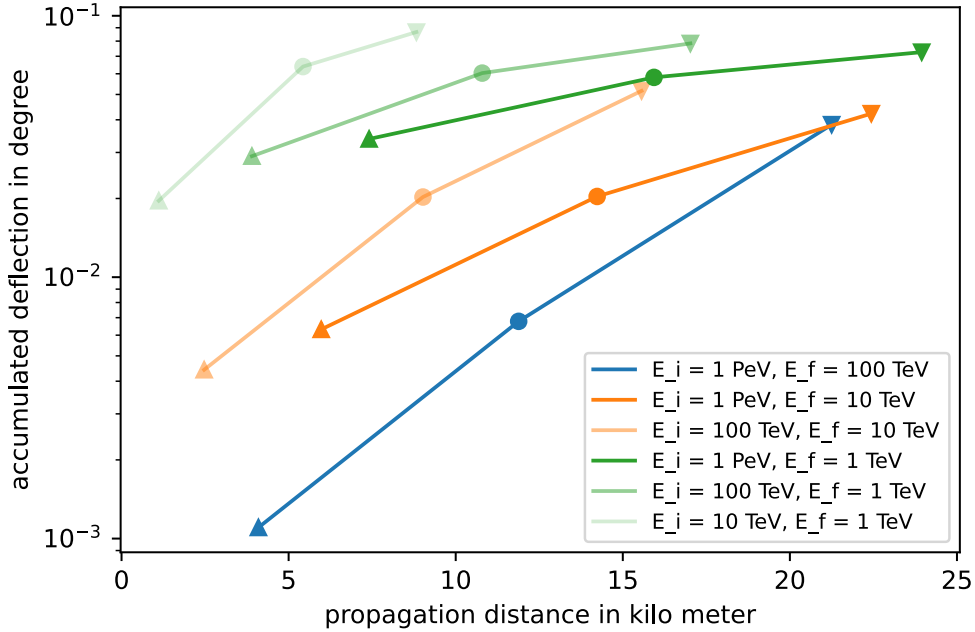


- Low cuts –> more stochastic propagation
  - ➢ Leads to lower deflections
  - ➢ Molière simulates larger deflections at higher energies
    - ➢ See Akimenko

Appendix – check deflection in dependence of propagation distance

- 3 data points per line
  - median ●, lower ▲ and upper ▼ bound 90% CL
- using data within ± 10%



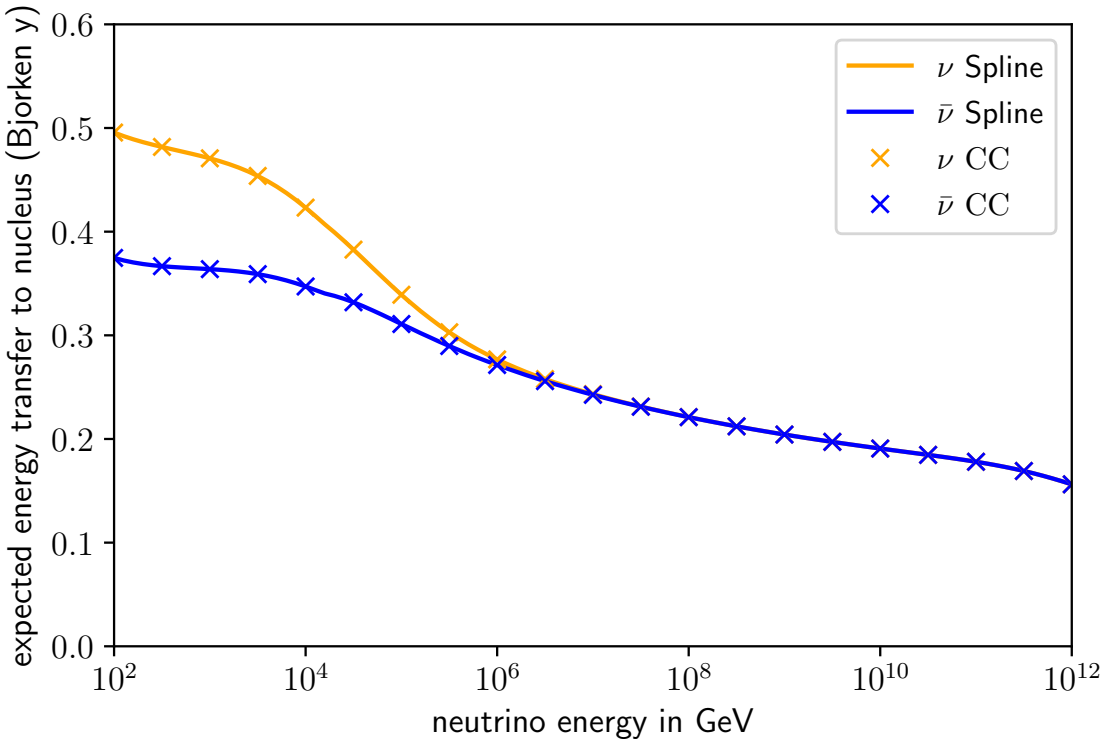


➢ propagation distance depends on initial particle energy

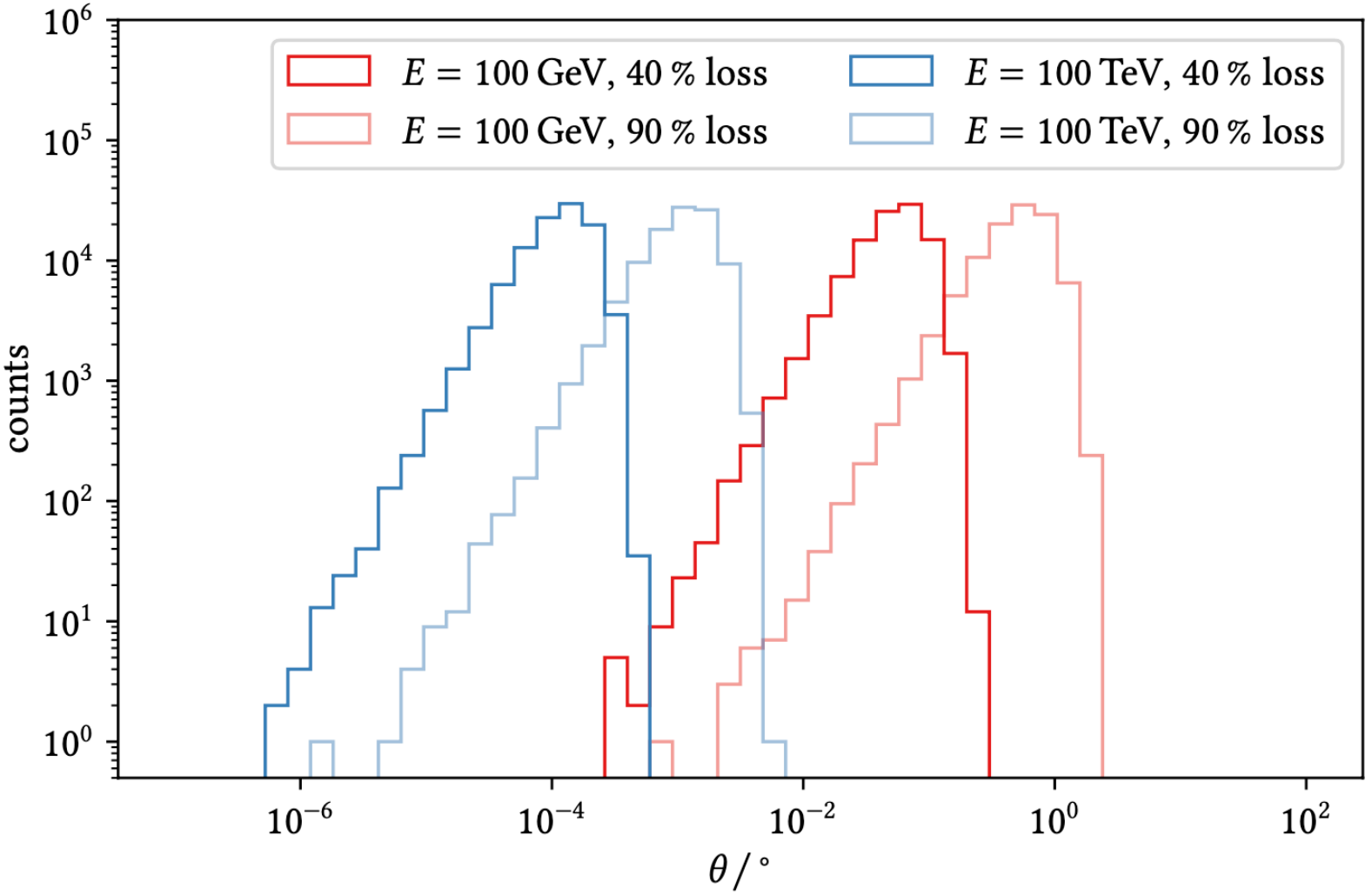
➢ deflection increases with propagation distance

➢ deflection is similar for medians of propagation distance for different initial energies

Appendix – energy rescale to muon energy



Electron pair production – Van Ginneken



- Several orders of magnitude for fixed energy and energy loss