

Study of high-energetic muon deflections

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DPG 2023, Dresden

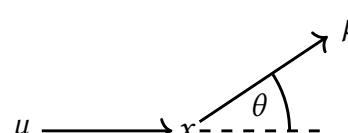


Motivation of muon deflection simulation

- Muons travel up to several kilometers
- PeV – TeV energies → forward boosted
- Muons are assumed to traverse along a straight line

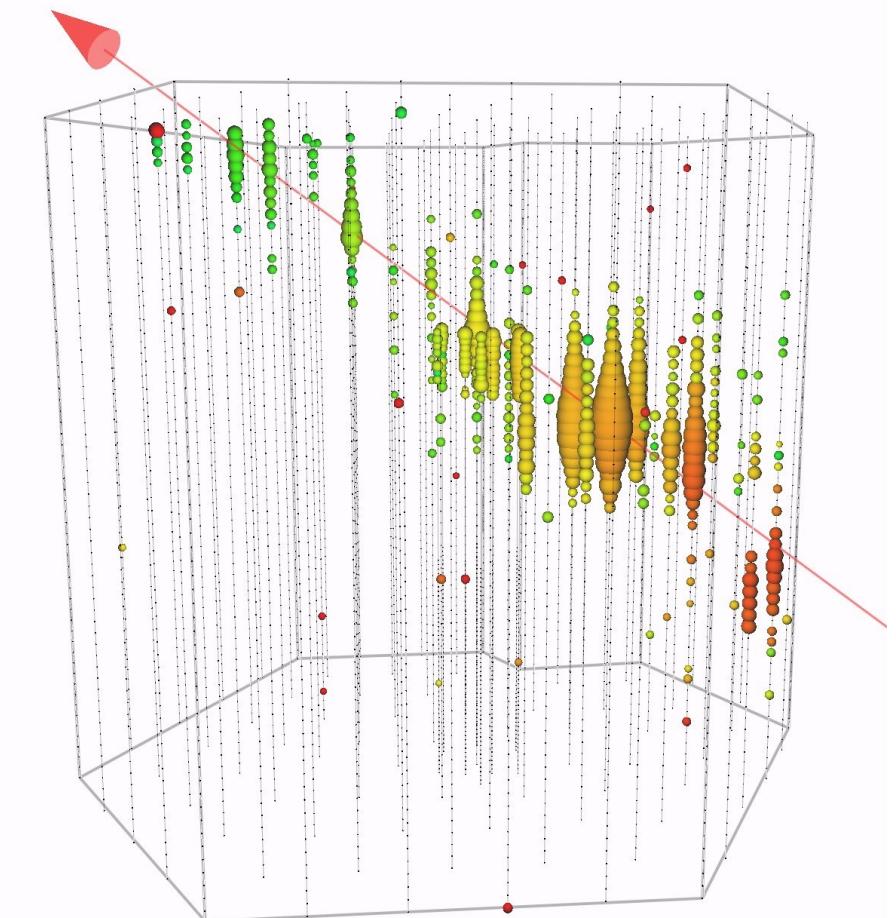
But:

- Thousands of interactions
- Large energy losses
- Deflection in each interaction
- Angular reconstructions are improved ($< 1^\circ$)



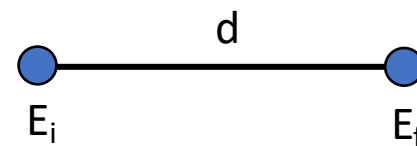
What happens, when thousands of deflections accumulate?

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

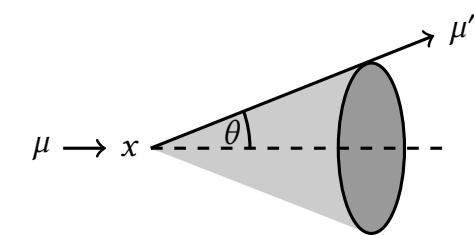


Simulation tool PROPOSAL

- C++/Python simulation framework for leptons
- Optimized for large-scale particle propagations
- 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 Ginneken¹ and Geant4² are available



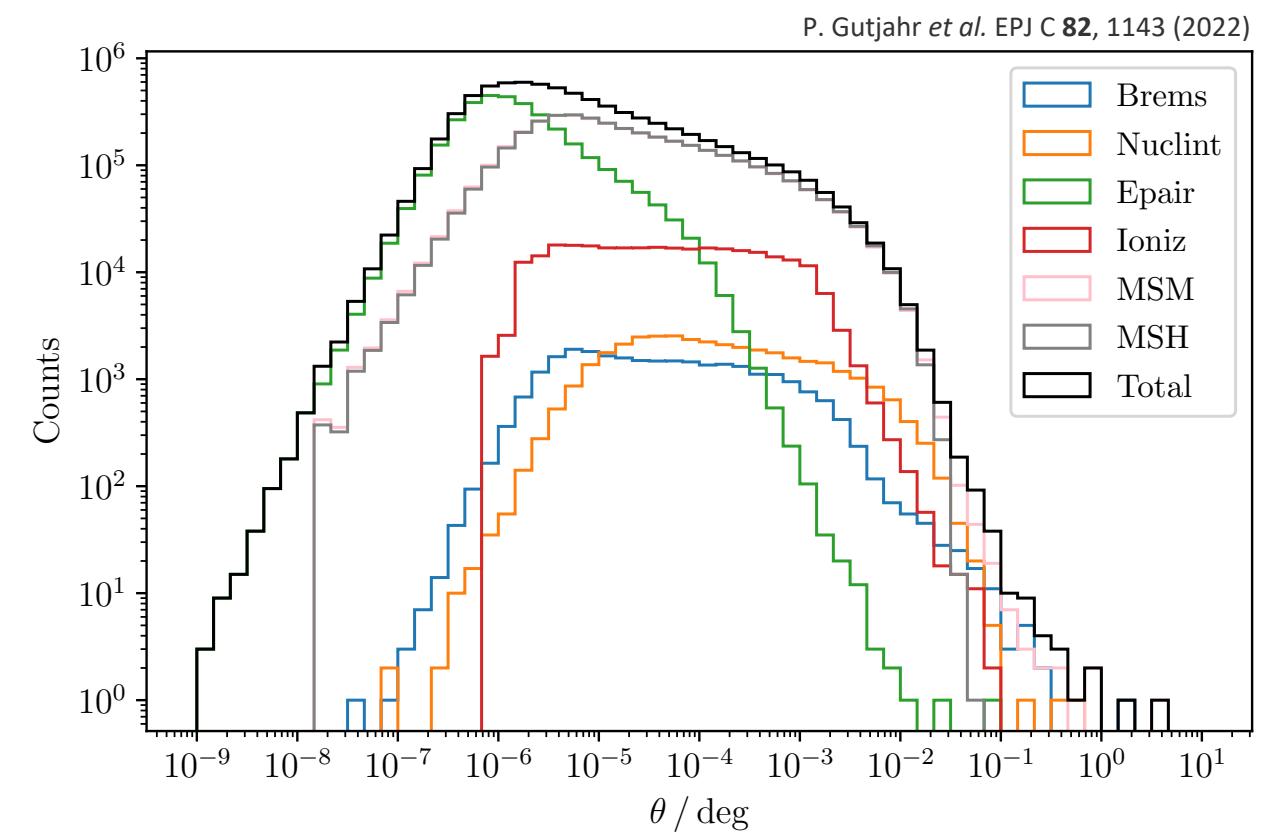
github.com/tudo-astroparticlephysics/PROPOSAL

¹ NIM A251 (1986) 21-39

² geant4.web.cern.ch

Muon deflection per interaction

- 1000 muons propagated in ice
 - Initial energy 1 PeV
 - Final energy 1 TeV
 - $e_{\text{cut}} = 500 \text{ MeV}$, $v_{\text{cut}} = 0.05$
- Largest median deflection by photonuclear interaction
- Largest outliers by bremsstrahlung
- Highland – Gaussian approximation neglects outliers
- Deflection dominated by multiple scattering



MSM: multiple scattering Molière
MSH: multiple scattering Highland

Summary of single deflection

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

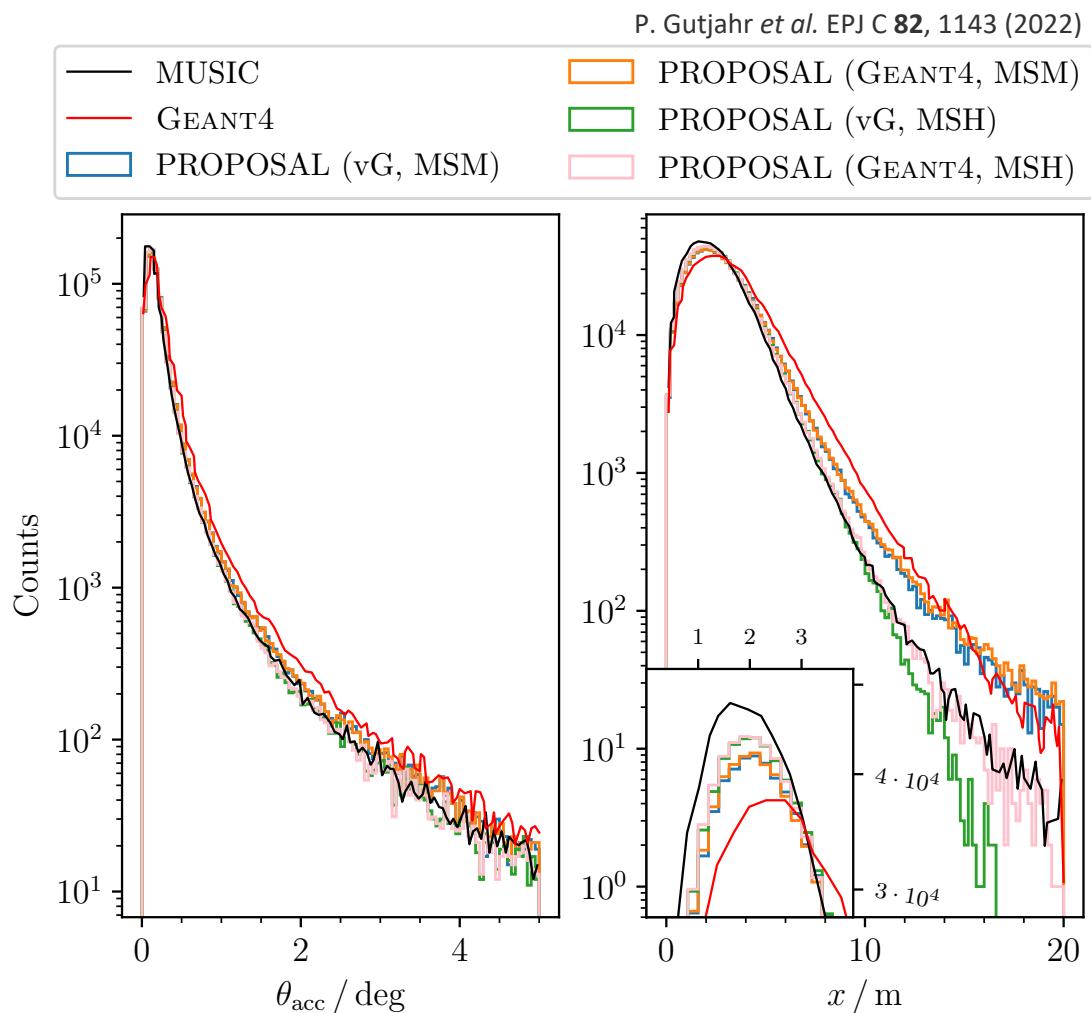
Question

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

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

Comparison to other simulation tools

- MUSIC¹
 - 3D muon simulation code
 - Geant4²
 - 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



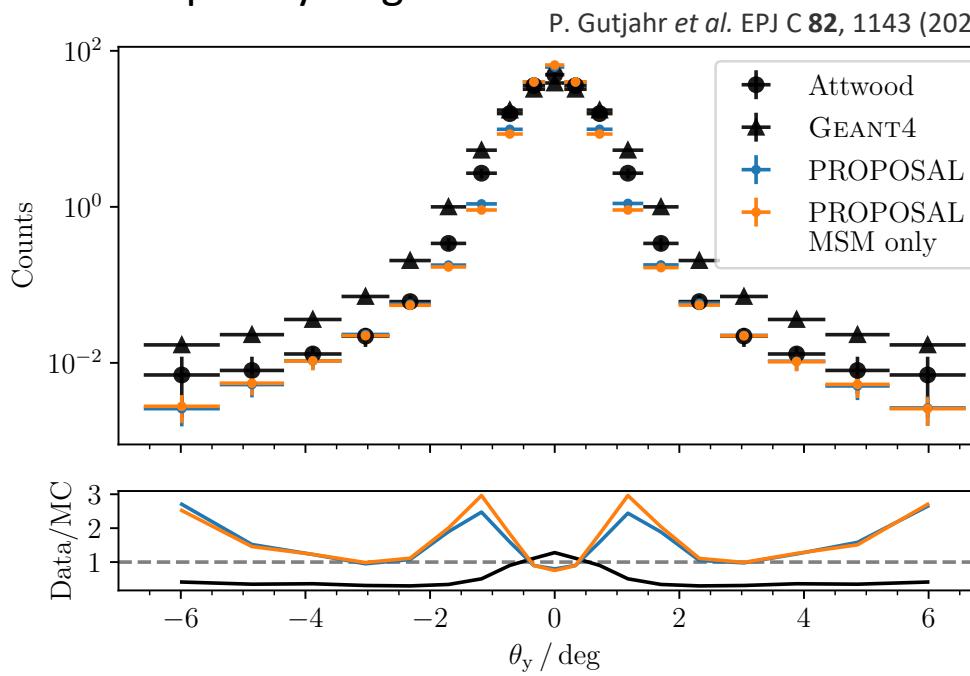
¹ Astropart. Phys. 7.4 (1997) 357-368

² geant4.web.cern.ch

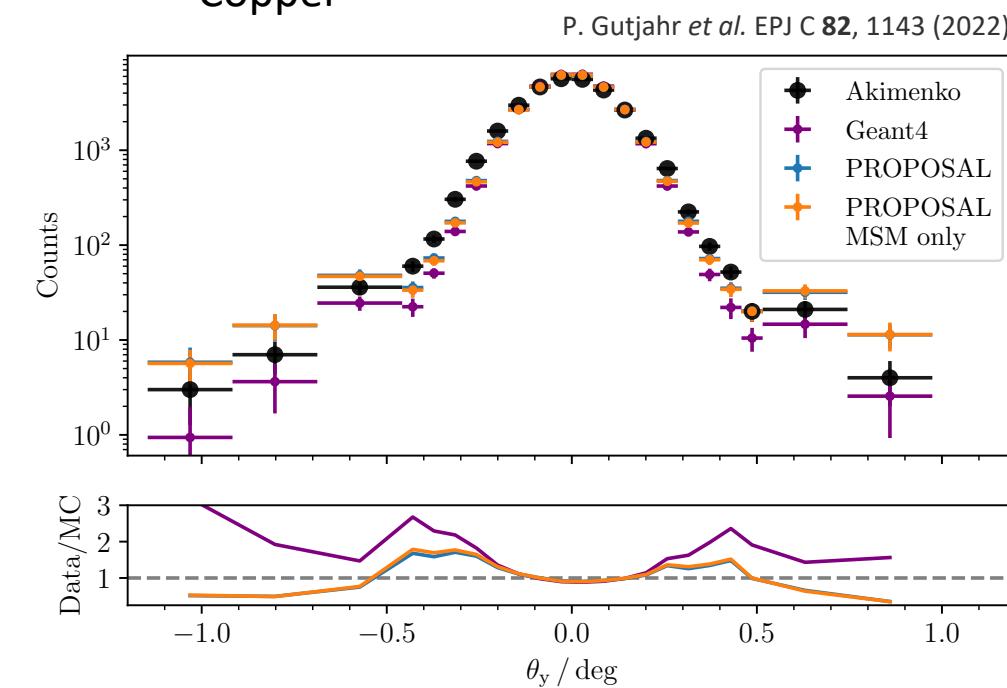
- 1 Mio. muons are propagated from 2 TeV over a distance of 3 km in water

Data-MC checks

- Attwood¹
- $E_i = 199$ MeV
- $d = 109$ mm
- Liquid hydrogen

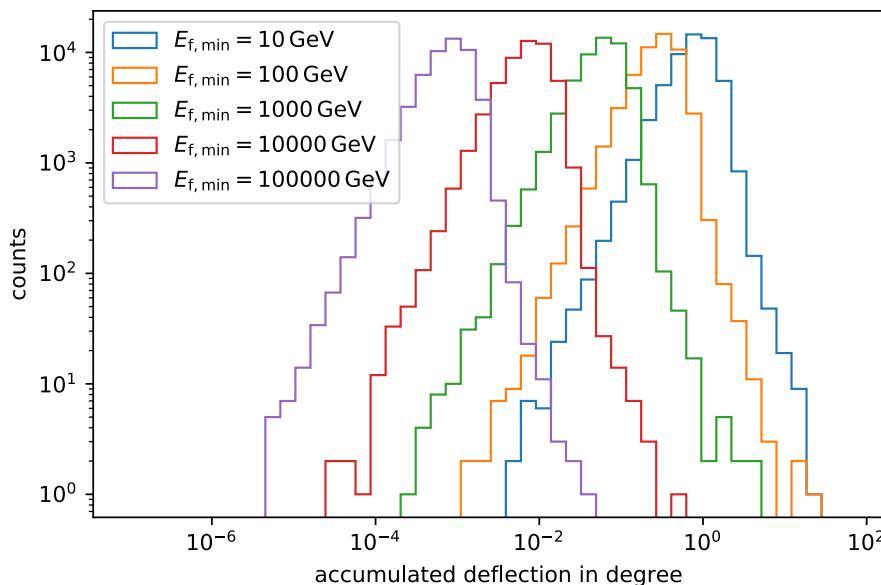


- Akimenko²
- $E_i = 7.3$ GeV
- $d = 144$ mm
- Copper

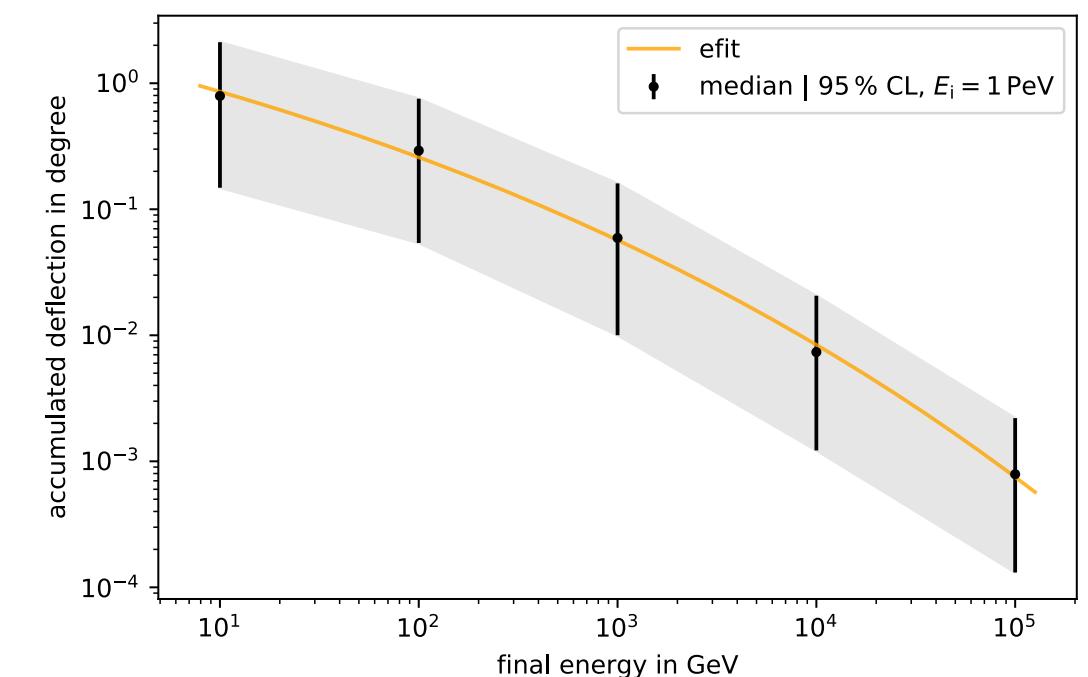


Accumulated deflection for several final muon energies

- Use fixed initial energy $E_i = 1 \text{ PeV}$
- Vary final energy



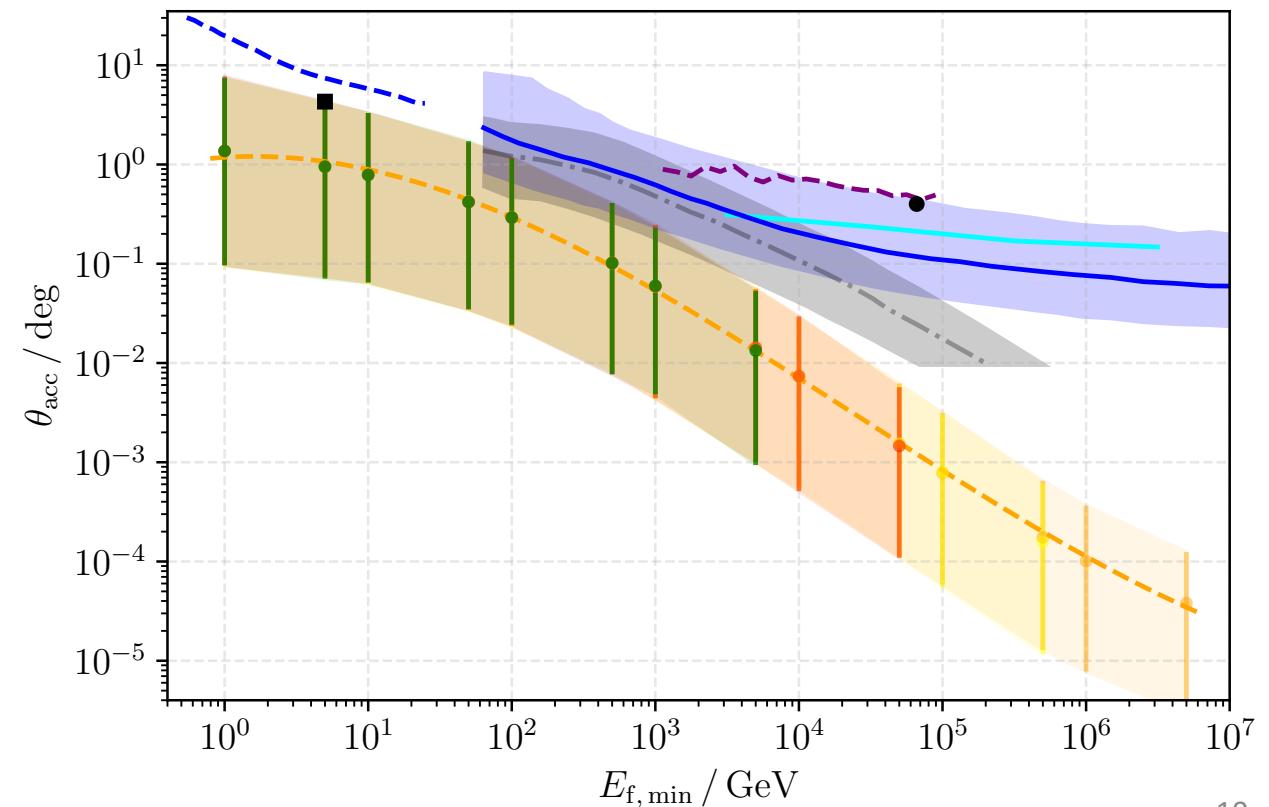
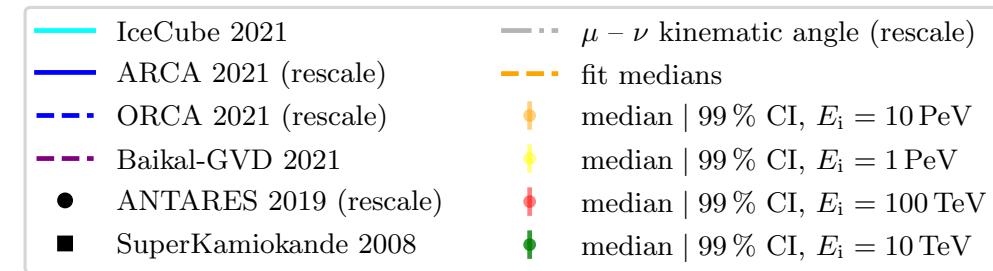
➤ Deflection increases as final energy decreases



➤ Check median deflection for different initial energies

Impact of muon deflection on angular resolutions

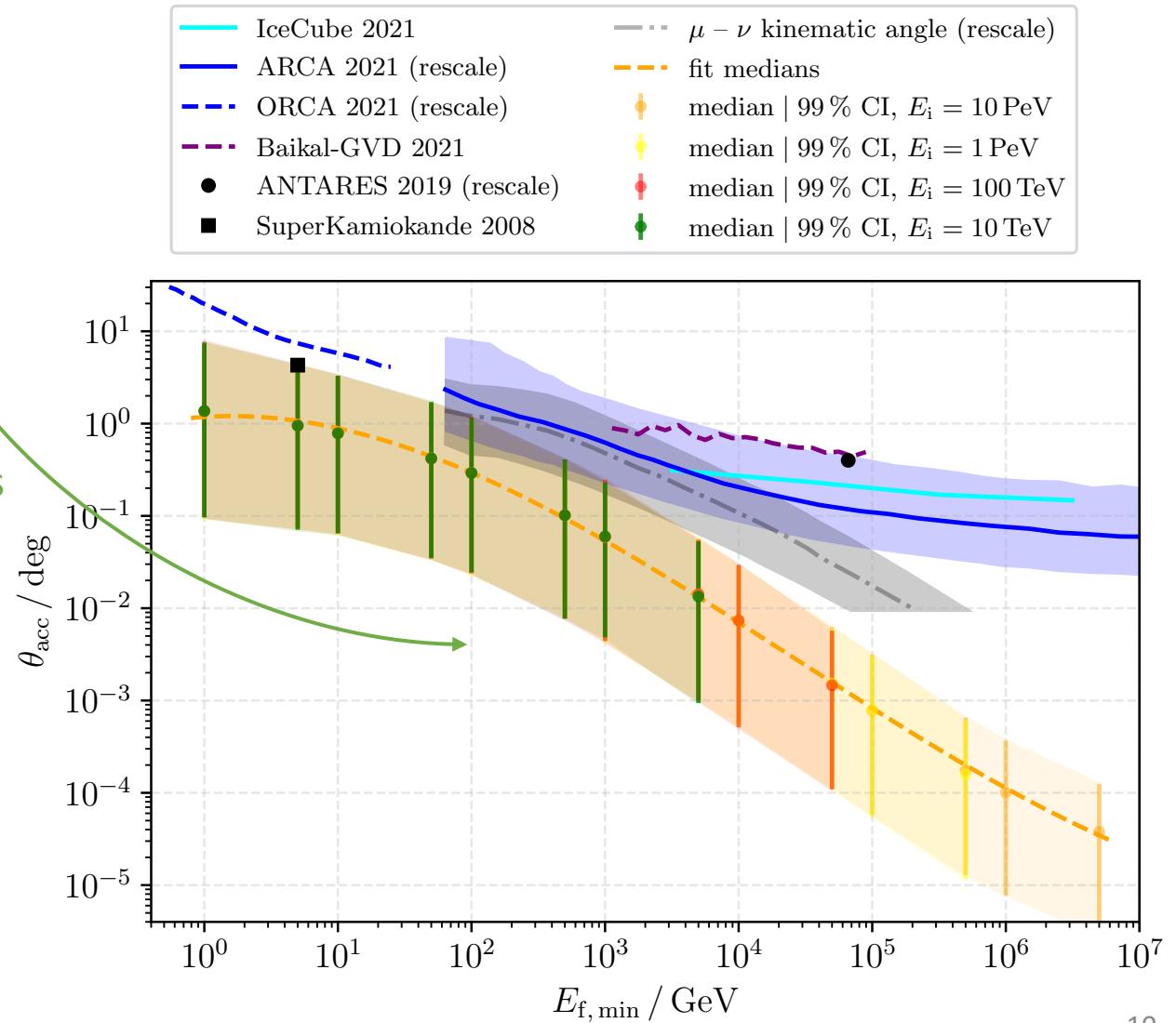
- Check median of accumulated deflections for:
 - $E_i \in \{10 \text{ PeV}, 1 \text{ PeV}, 100 \text{ TeV}, 10 \text{ TeV}\}$
 - $E_{f,\min} \in \{10 \text{ GeV}, \dots, 500 \text{ TeV}\}$
 - number events $> 50,000$ for each data set
- Median of deflections overlap for different initial energies
 - No strong impact of the initial energy
- Median fit by polynomial
- $E \leq 1 \text{ TeV}$: minimal influence of deflection on angular resolution for KM3NeT
- IceCube is not impacted



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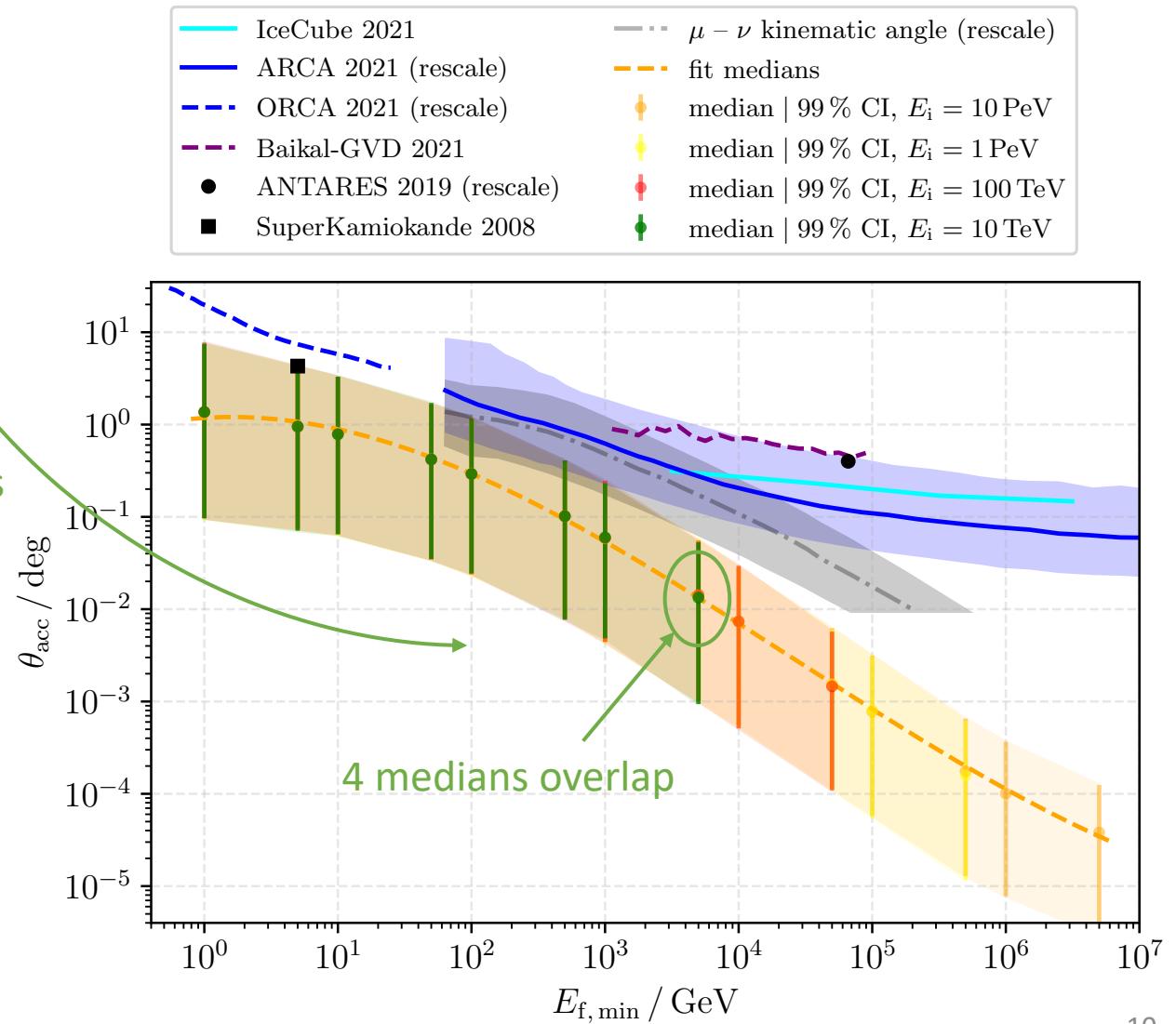
4 colors



Impact of muon deflection on angular resolutions

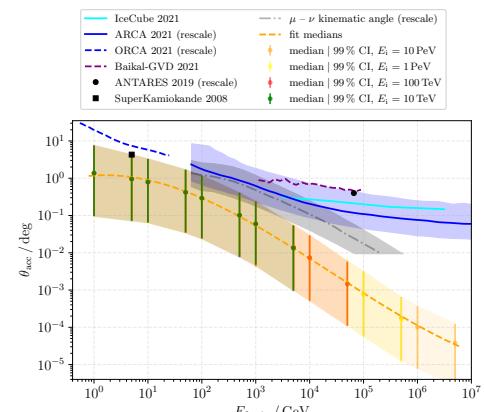
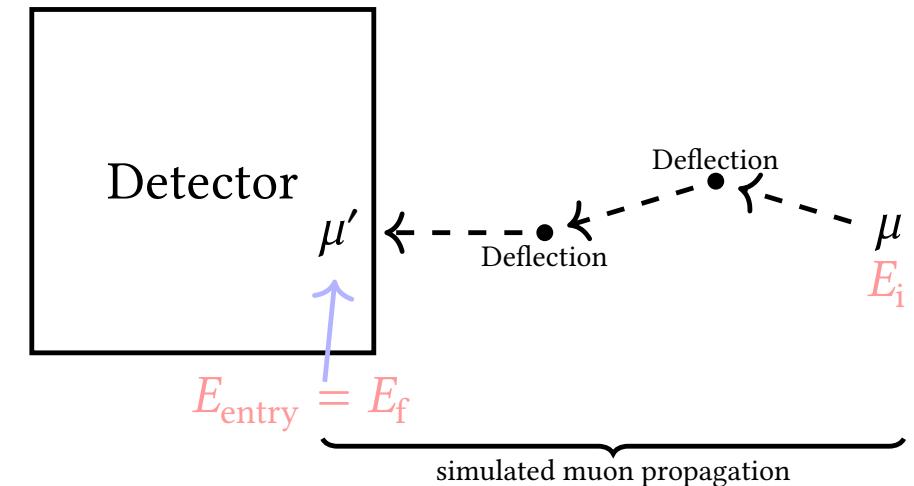
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Estimate muon deflection uncertainty on angular reconstruction

- 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



Summary & Outlook

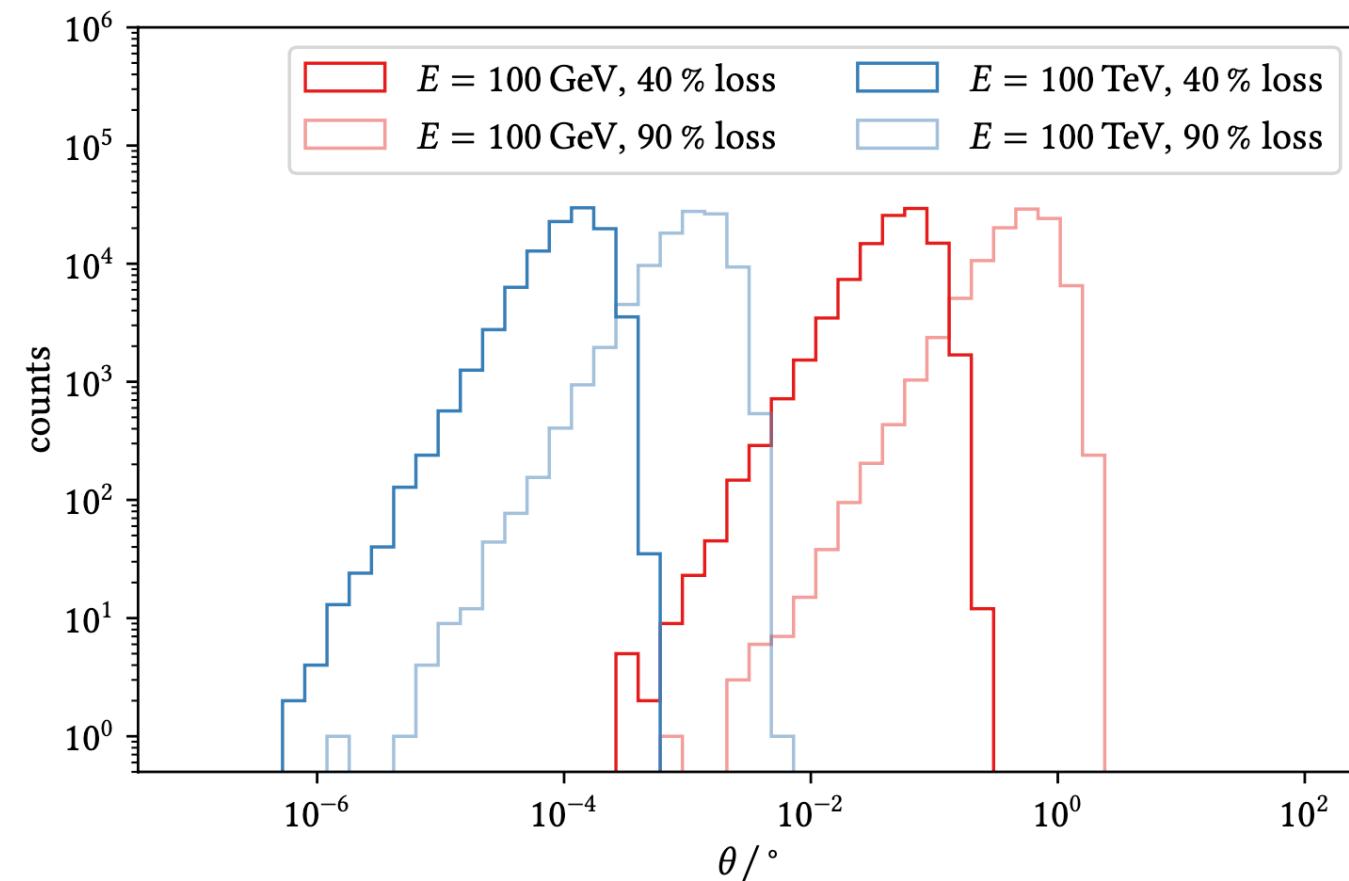
- Good agreement with Geant4, MUSIC and data
- Single deflection: $\theta \in [10^{-9}\text{°}, 1\text{°}]$ for $E_i = 1 \text{ PeV}$, $E_{f,\min} = 1 \text{ TeV}$
- Deflections accumulate along the track
 - Deflections increase as the final muon energy decreases
 - Muon deflection is nearly independent 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 energies $\leq \text{TeV}$
- IceCube is not yet impacted

Outlook

- Measure accumulated muon deflections at higher energies (TeV - PeV) + simulation validation
- Measure single muon deflection → large energy loss and good resolution required
- Consider deflection as systematics in improved angular reconstructions

Backup

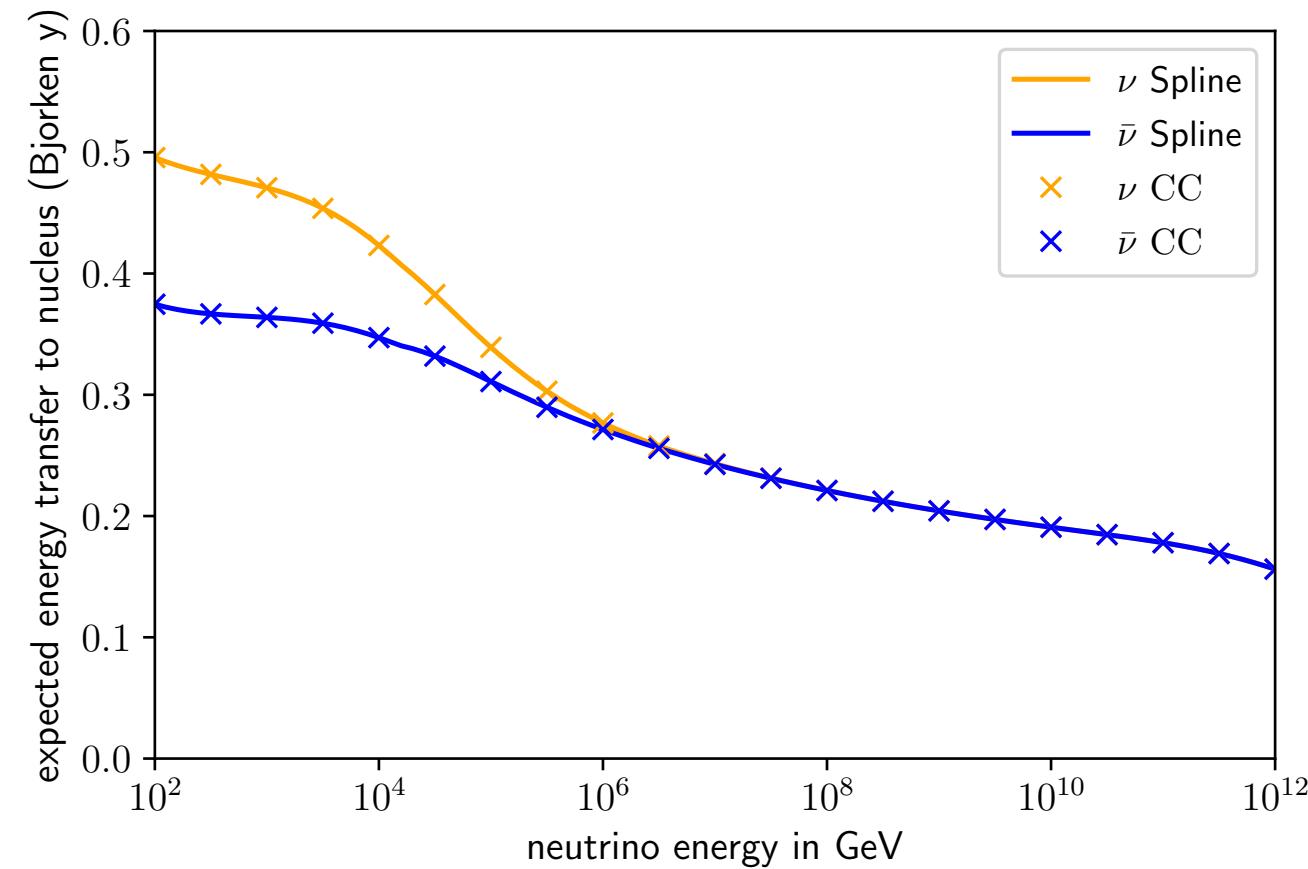
Electron pair production – Van Ginneken



➤ Several orders of magnitude for fixed energy and energy loss

Energy rescale to muon energy

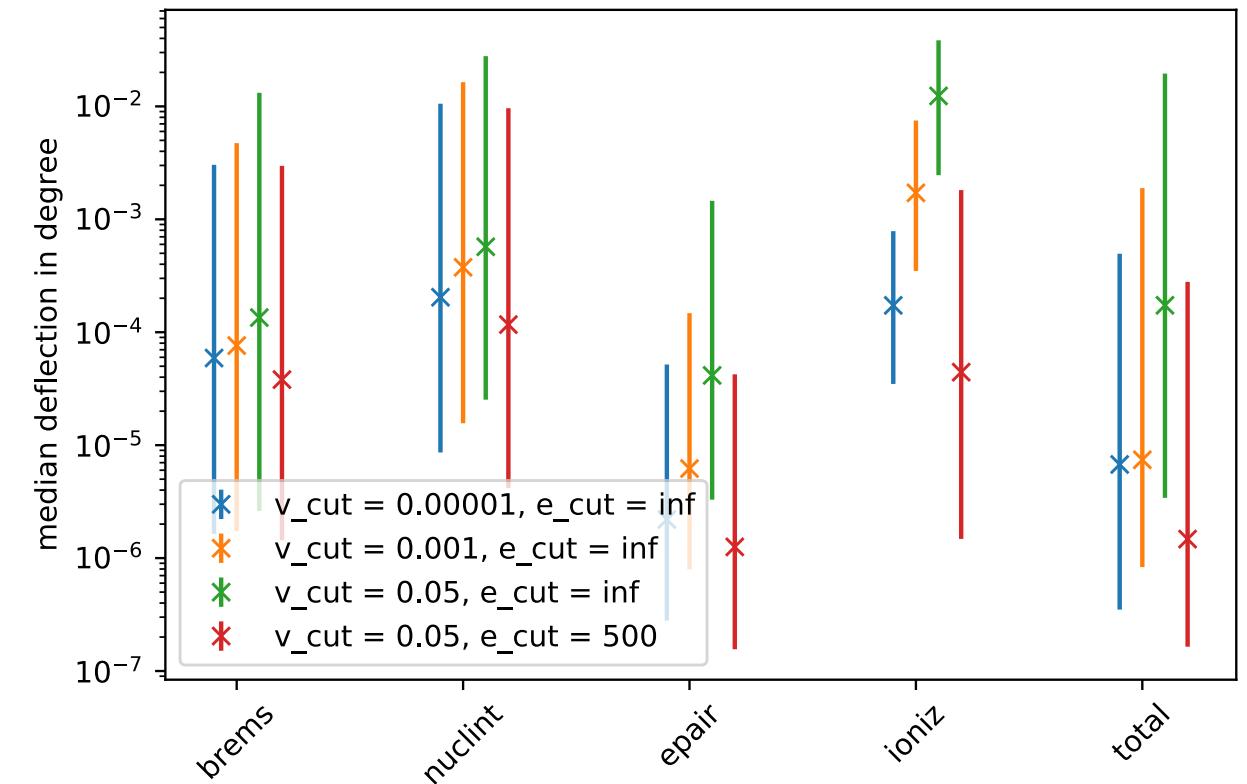
- Bjorken variables are used to transfer neutrino energies to muon energies



Median deflections with different energies cuts

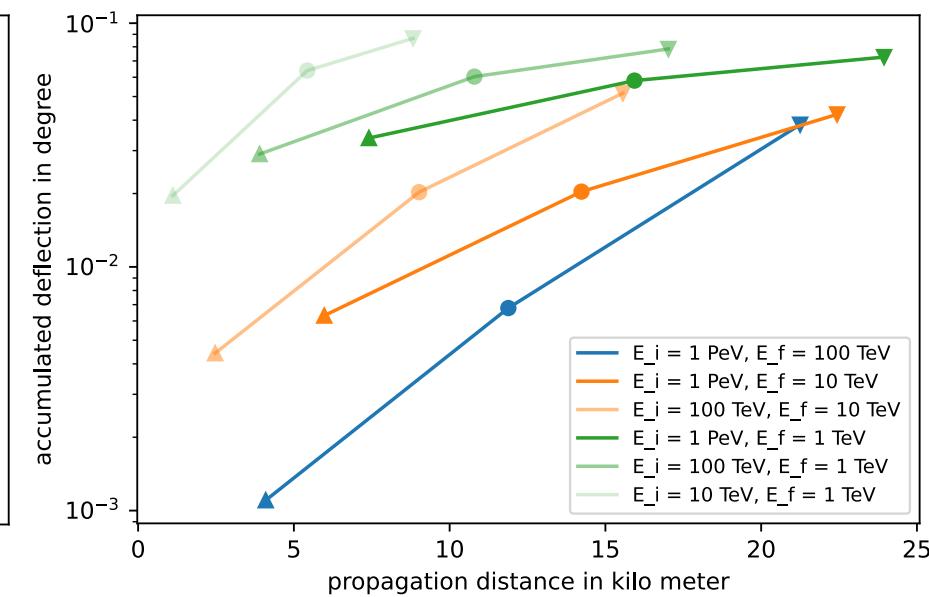
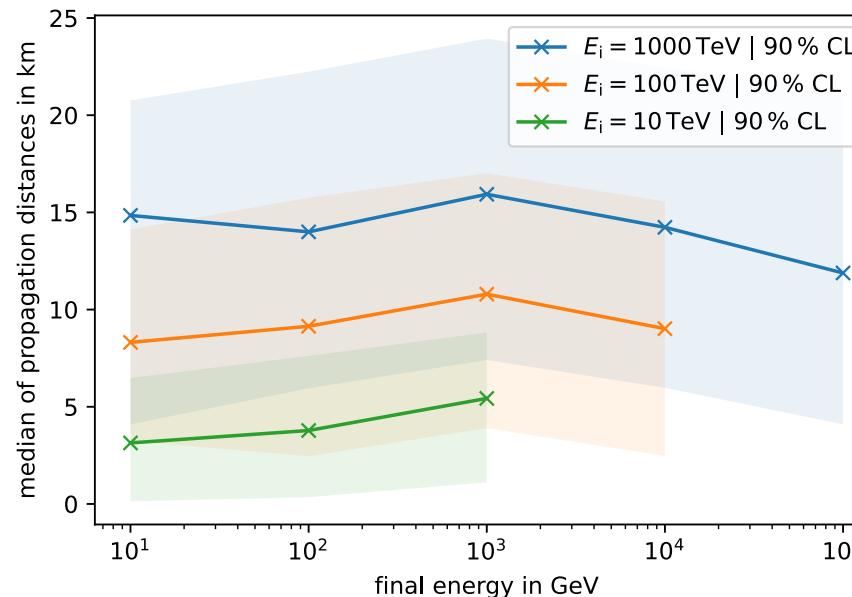
1 PeV to 1 TeV, 1000 events each, Molière, 95% Interval

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



Deflection in dependence of propagation distance

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



➤ propagation distance depends on initial particle energy

- deflection increases with propagation distance
- deflection is similar for medians of propagation distance for different initial energies

Deflection in dependence of propagation distance

- Initial muon energies are sampled from a Gaisser muon flux model
 - No color change along a fixed muon energy column
 - No large impact of propagation distance on the muon deflection

