

High-energy lepton and photon simulations with the framework PROPOSAL

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Introduction to PROPOSAL

- Monte Carlo simulations are crucial to train machine learning algorithms
 - The underlying tools need to be both precise and performant
- PROPOSAL is a simulation framework, providing 3D Monte Carlo simulations of high-energy electrons, positrons, muons, taus and photons [1, 2]
- Different parametrizations of physical processes, including up-to-date parametrizations, are available
- High-performance and high-precision simulations, optimized for large-scale particle propagation
- PROPOSAL is actively maintained. Recent updates include:
 - Improvements in the simulation of photons by including photoproduction, photoeffect, and muon pair production (relevant for low-energy and very-high-energy photons)
 - Code restructuring and modularization, so PROPOSAL can be used as a framework by providing individual modules

Find the PROPOSAL repository under:
github.com/tudo-astroparticlephysics/PROPOSAL



How to use PROPOSAL

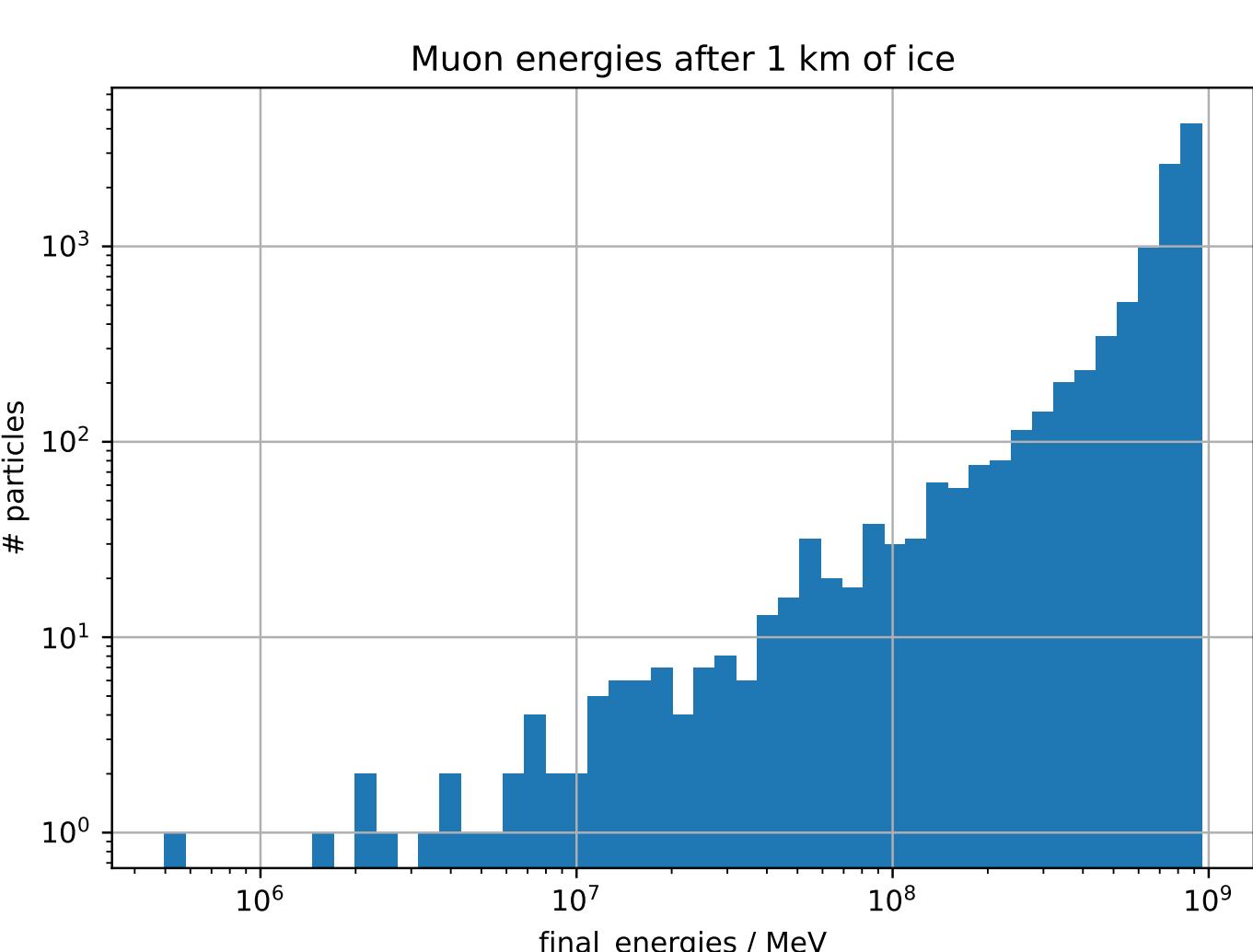
- PROPOSAL can be used as a C++ or a Python library
 - Simple Python installation with [pip install proposal](#)
 - C++ installation using the package manager Conan and CMake
- Information about the configuration environment can be read using a JSON file

```
import proposal as pp

# read properties from config file
particle = pp.particle.MuMinusDef()
prop = pp.Propagator(particle, "config.json")

# define initial particle state
init_state = pp.particle.ParticleState()
init_state.position = pp.Cartesian3D(0, 0, 0)
init_state.direction = pp.Cartesian3D(0, 0, 1)
init_state.energy = 1e9 # MeV

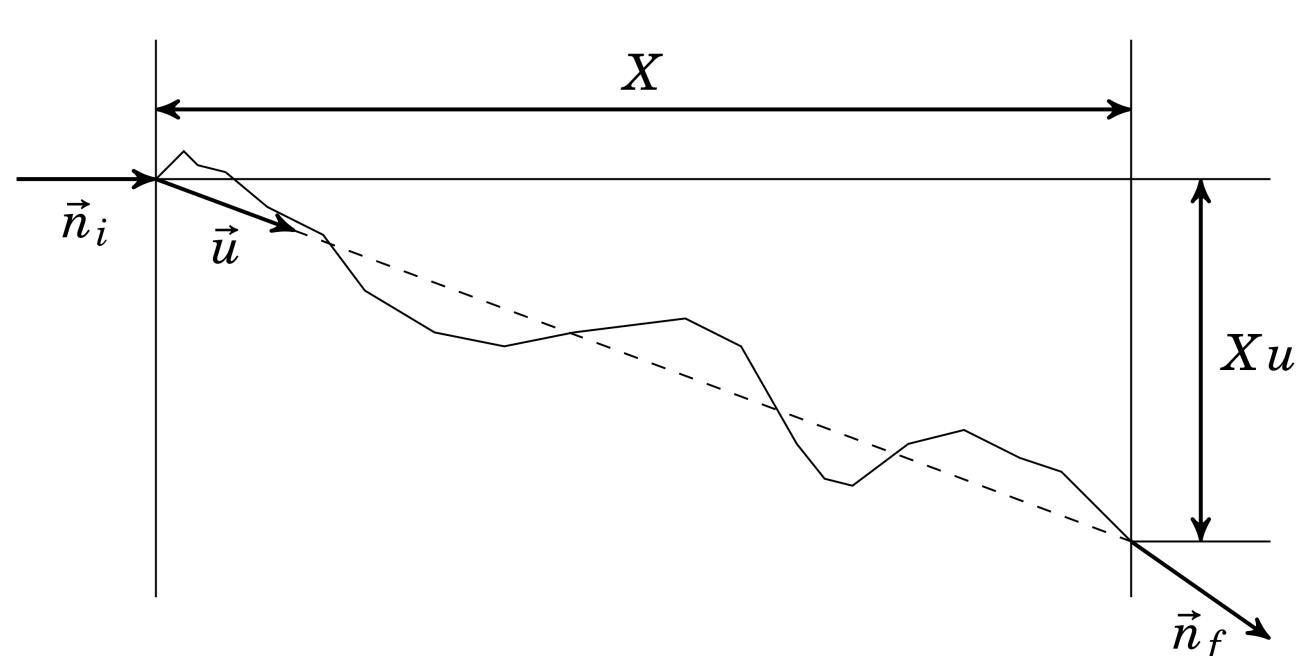
# propagation
final_energies = []
for i in range(10000):
    output = prop.propagate(init_state,
                            max_distance = 1e5) # cm
    E_f = output.final_state().energy
    final_energies.append(E_f)
```



Simulation of Deflection Uncertainties on Direction Reconstructions of Muons Using PROPOSAL

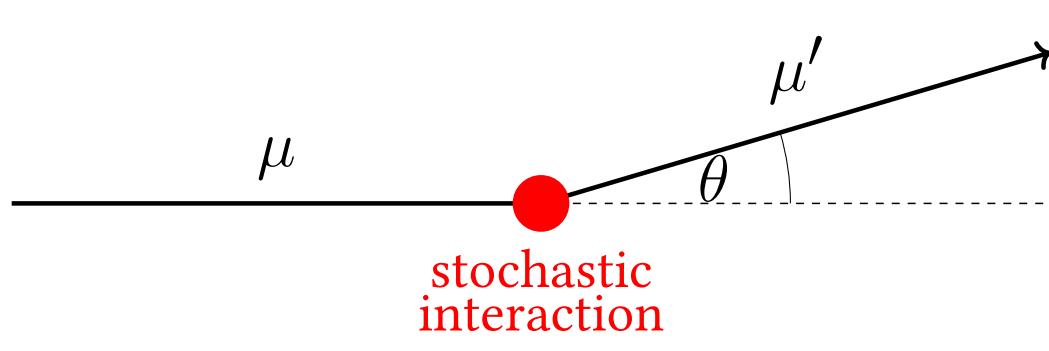
There are two types of scattering interactions for muon propagation:

1. Multiple scattering: (figure adapted from [3])



- Described by Molière theory or a Gaussian approximation
- Relevant contribution, especially at low energies

2. Stochastic deflections:

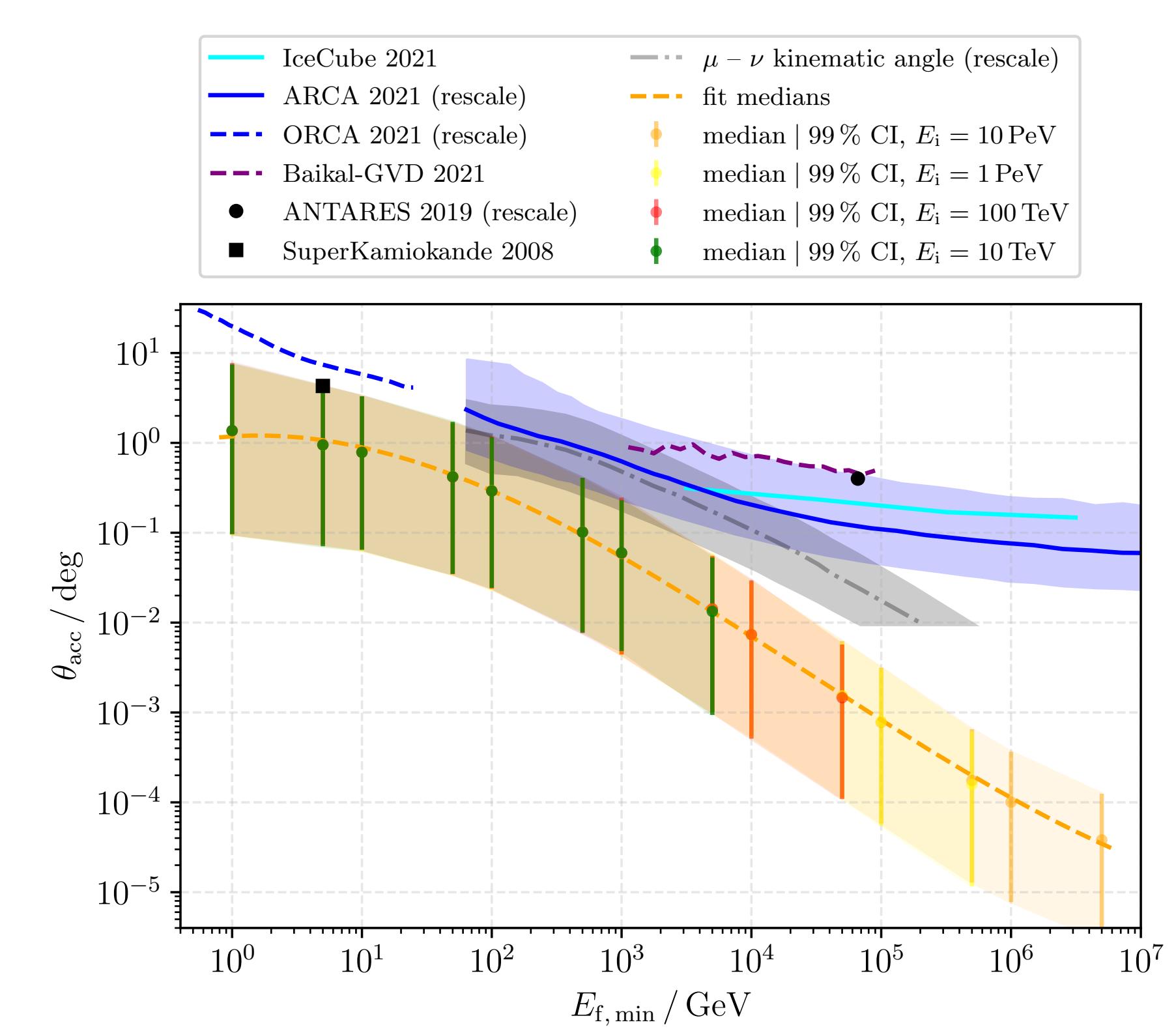


- Deflection of initial particle in individual interaction
- Might be a contribution for highly stochastic energy losses

Results from [arXiv:2208.11902] ([4]):

- Motivation: Directional reconstruction of muons is essential for applications such as neutrino astronomy or muon tomography
- In this paper, we have analyzed muon deflections based on simulations with PROPOSAL
- Comparisons of PROPOSAL simulations with GEANT4, MUSIC, and experimental measurements show a good agreement
- We performed simulations of muons with identical initial energies, and plotted the accumulated muon deflections for different final energies (see Figure on the right)

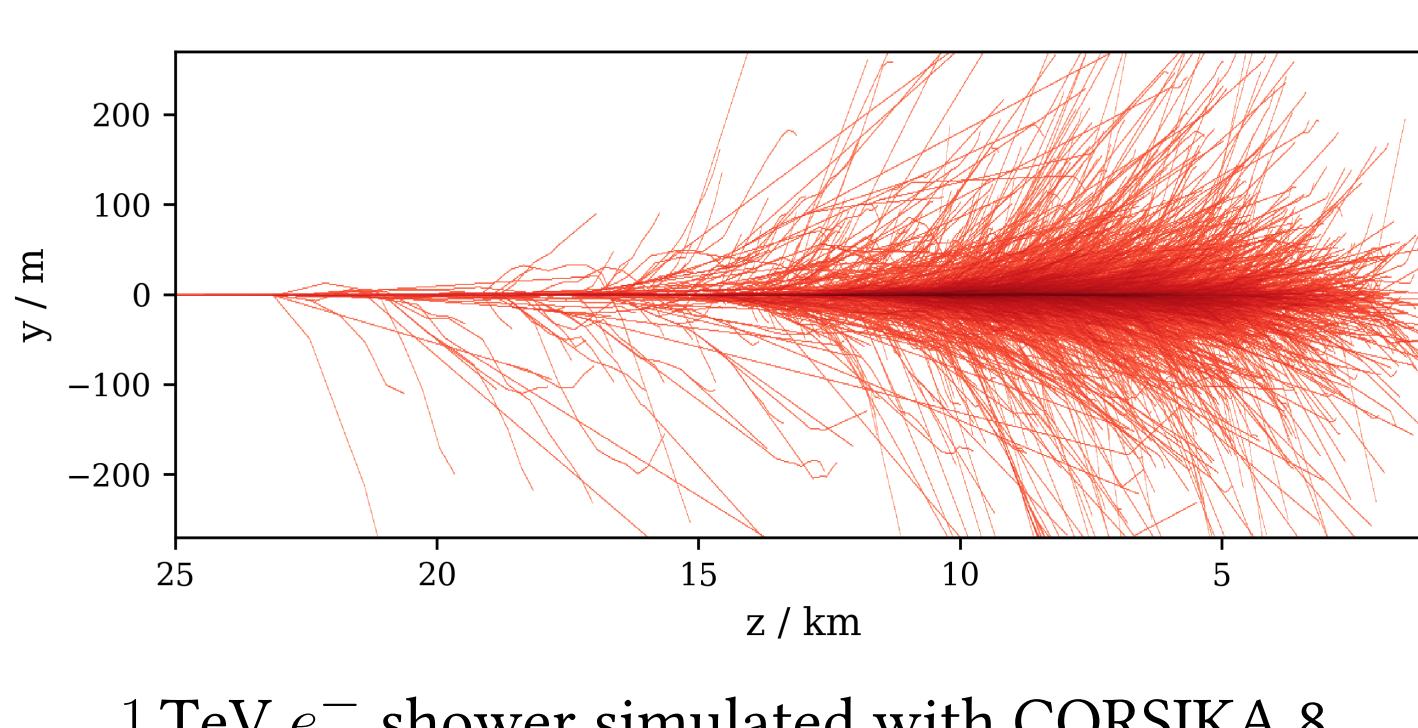
- The accumulated deflection primarily depends on the final muon energy and is independent of the initial energy
- Compared to the angular resolutions of current and future neutrino telescopes, we can see a potential impact of muon deflections on the angular resolution of KM3NeT at energies $E_f \leq 1$ TeV



Median of the accumulated deflection θ_{acc} with a 99 % central interval for four different initial muon energies E_i . Simulations in ice.

Application: CORSIKA 8

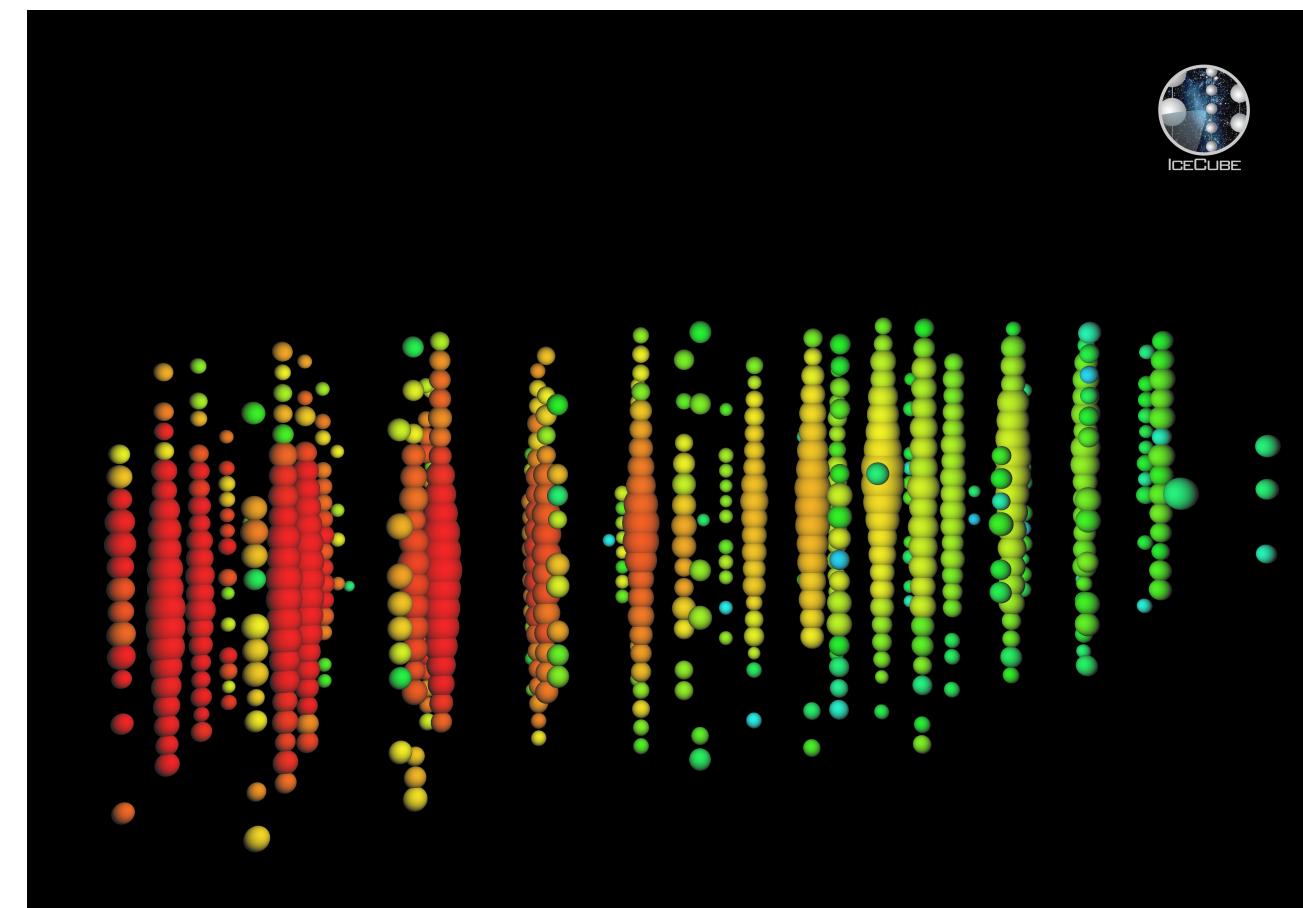
- New version of the air shower simulation framework CORSIKA
 - Entirely new code structure, based on modern C++
 - Focus on flexibility, modularity, efficiency and reliability [5]
- PROPOSAL is used to simulate the electromagnetic and muonic shower component
 - PROPOSAL provides individual modules, where each module solves specific physical tasks [6]
 - CORSIKA 8 uses these modules to calculate interaction lengths, energy losses, multiple scattering and secondary particles
- First comparisons of CORSIKA 8 and CORSIKA 7: Good agreement for simulations of electromagnetic showers [7]



1 TeV e^- shower simulated with CORSIKA 8

Application: Neutrino telescopes

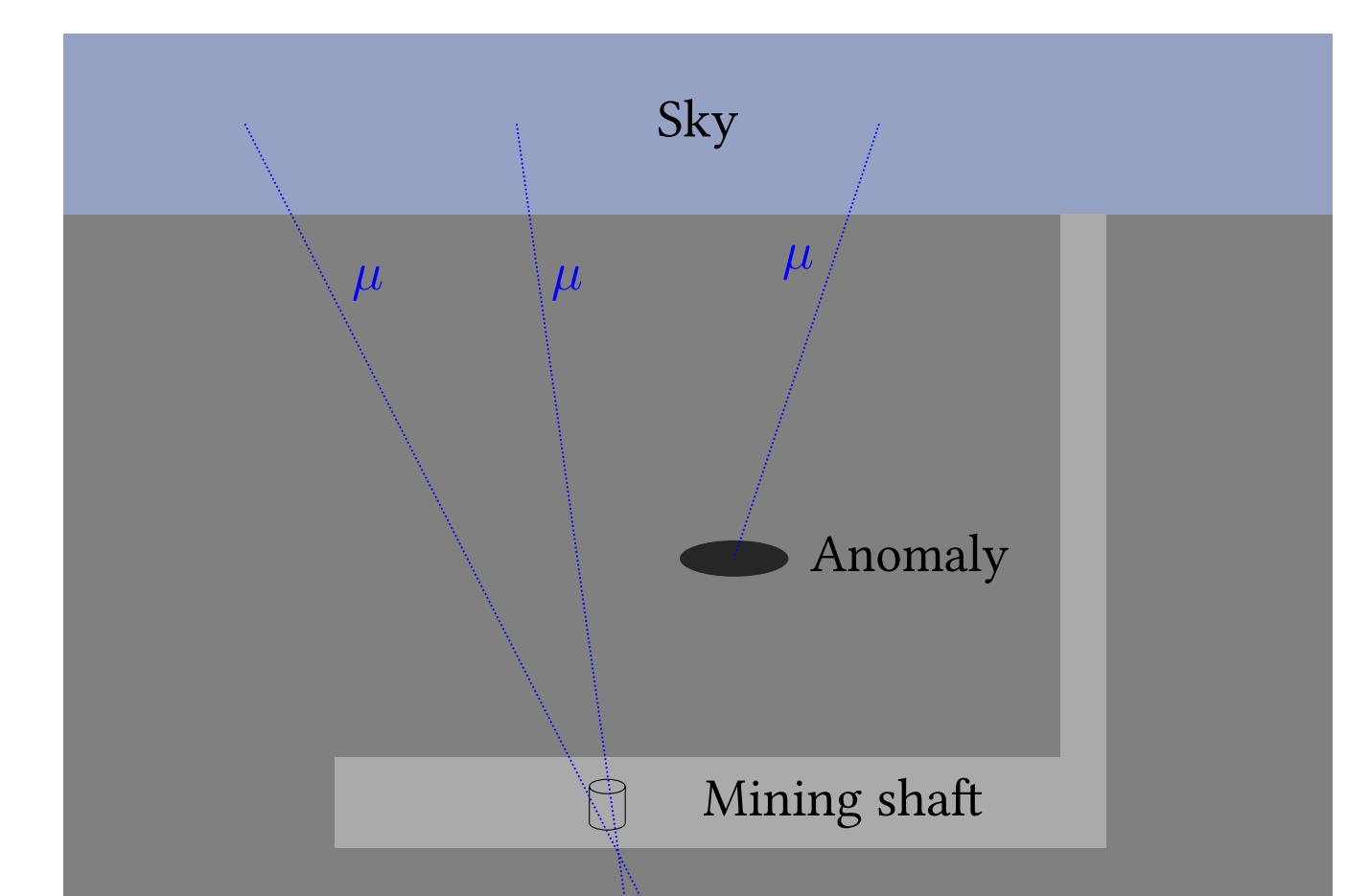
- PROPOSAL is used by neutrino telescopes, for example in the IceCube Neutrino observatory or in the software framework NuRadioMC
- Simulation of muon and tau energy losses in ice
 - Precise simulations and an accurate description of cross sections are crucial



Muon track in the IceCube detector
(Source: IceCube Collaboration)

Application: Muography

- Non-invasive imaging technique using Cosmic Ray muons
- Tracing muon number along trajectories: Provides information, for example on density anomalies
- PROPOSAL is a well-suited tool to provide the necessary muon simulations
 - Currently analyzing the possibilities to use muography in mining with PROPOSAL simulations



Visualization of the muography technique

Outlook

- Implementation of the LPM effect for inhomogeneous media
 - Important for very-high-energy air showers
- Implementation of only-stochastic propagation
 - Allows for neutrino propagation with PROPOSAL

References

- [1] J.-H. Koehne et al. PROPOSAL: A tool for propagation of charged leptons. In: *Comput. Phys. Commun.* 184.9 (2013), pp. 2070–2090. doi: 10.1016/j.cpc.2013.04.001. [2] M. Dunsch et al. Recent Improvements for the Lepton Propagator PROPOSAL. In: *Comput. Phys. Commun.* 242 (2019), pp. 132–144. doi: 10.1016/j.cpc.2019.03.021. arXiv: 1809.07740 [hep-ph]. [3] Mario Dunsch. Make PROPOSAL great again. MA thesis. TU Dortmund 3.1 (Dec. 2018), p. 2. issn: 2510-2044. doi: 10.1007/s41781-018-0013-0.

- [4] Pascal Gutjahr et al. Simulation of Deflection Uncertainties on Directional Reconstructions of Muons Using PROPOSAL. (submitted to EPJ C). arXiv: 2208.11902 [astro-ph.IM]. [5] R. Engel et al. Towards A Next Generation of CORSIKA: A Framework for the Simulation of Particle Cascades in Astroparticle Physics. In: *Computing and Software for Big Science* [6] J.-M. Alameddine et al. PROPOSAL: A library to propagate leptons and high energy photons. In: *J. Phys. Conf. Ser.* 1690.1 (Dec. 2020), p. 012021. doi: 10.1088/1742-6596/1690/1/012021. [7] J.-M. Alameddine et al. Electromagnetic Shower Simulation for CORSIKA 8. In: *PoS ICRC2021* (2021), p. 428. doi: 10.22323/1.395.0428.

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