# High-energy lepton and photon simulations with the framework PROPOSAL


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## Introduction to PROPOSAL

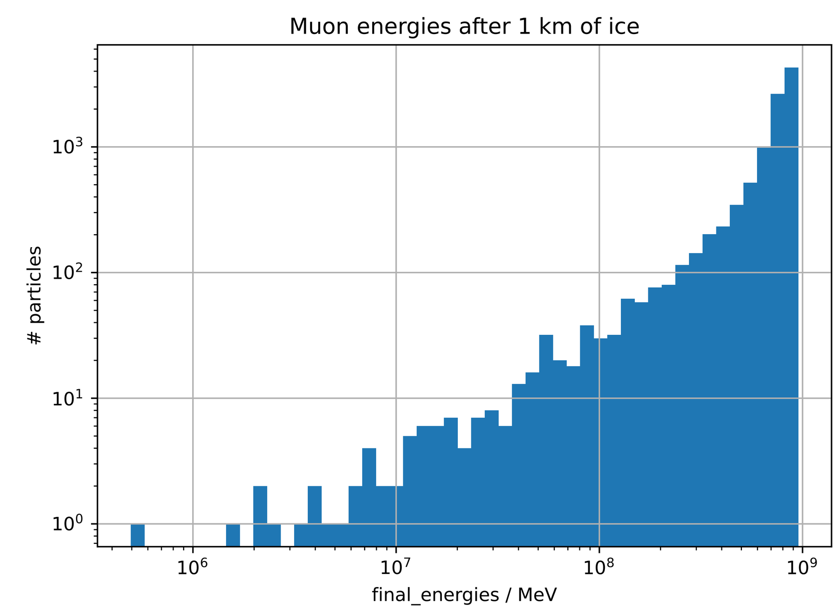
- Monte Carlo simulations are crucial to train machine learning algorithms
  - → The underlying tools need to be both precise and performant
- PROPOSAL is a simulation framework, providing 3D Monte Carlo simulations of high-energy electrons, positrons, muons, taus and photons [1, 2]
- Different parametrizations 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

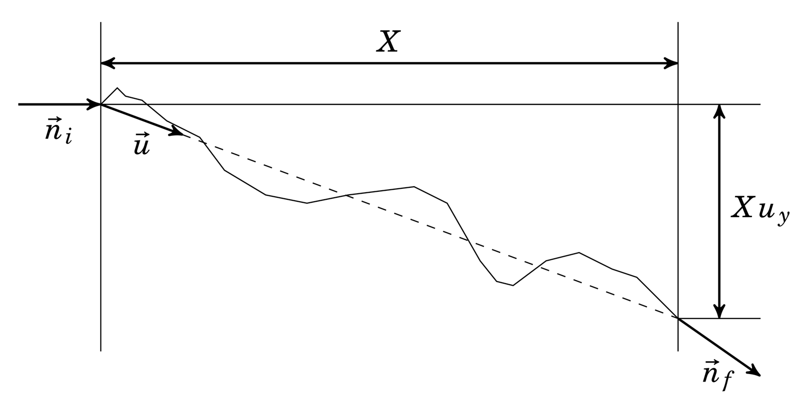
```
import proposal as pp

# 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

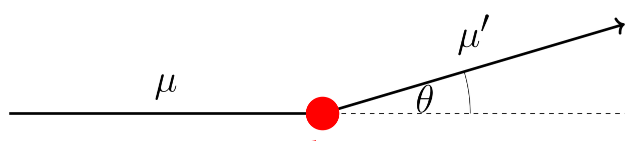
There are two types of scattering interactions for muon propagation:

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




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

**2. Stochastic deflections:**



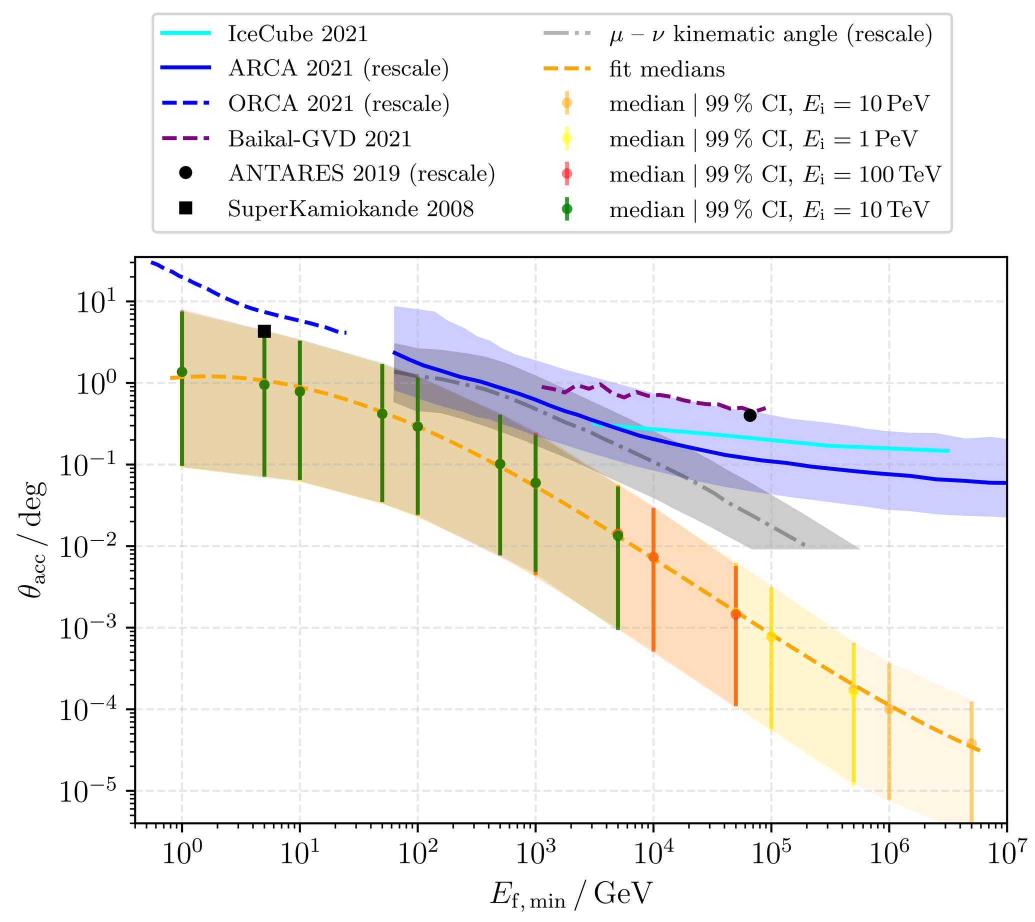

- → Deflection of initial particle in individual interaction
- → Might be a contribution for highly stochastic energy losses

**Summary of 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

**Methods:**
- As a cross check, comparisons of PROPOSAL simulations with Geant4, MUSIC, and experimental measurements were performed
  - → They show a good agreement
- We performed simulations of muons with idential initial energies, and plotted the accumulated muon deflections for different final energies (see Figure on the right)

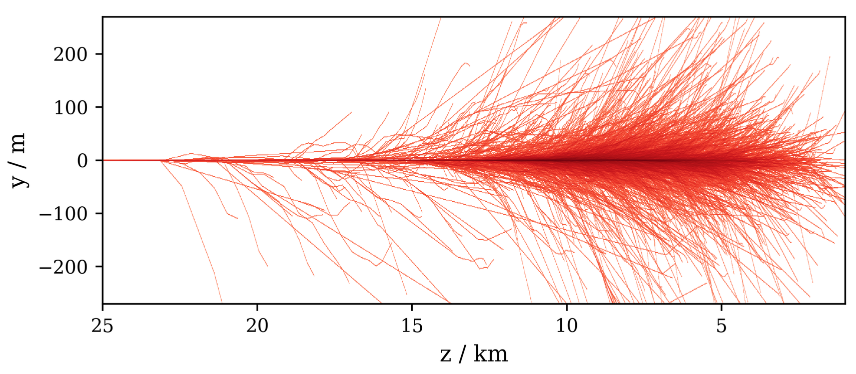
**Results:**
- The accumulated deflection primarily depends in the final muon energy and is independent of the initial energy
- Compared to the angular resolutions of current and future neutrino telescopes, we can see a potential impact of muon deflections on the angular resolution of KM3NeT at energies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




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

## Application: CORSIKA 8

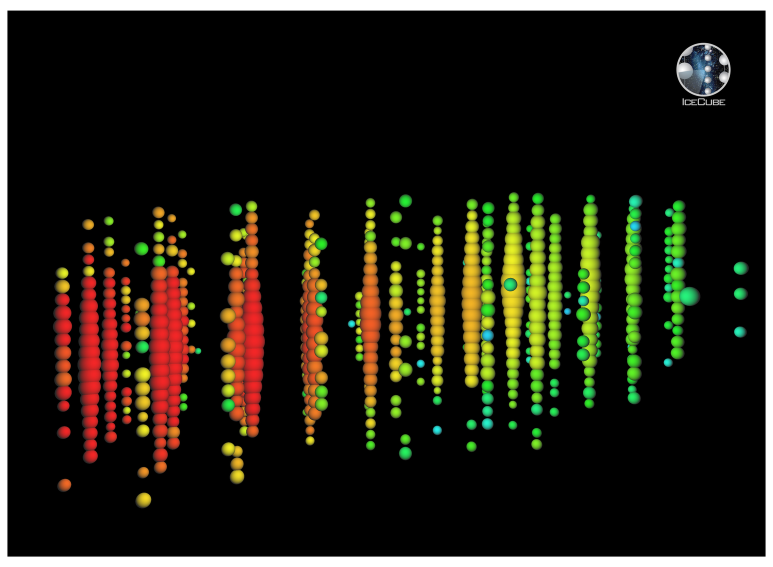
- New version of the air shower simulation framework CORSIKA
  - → Entirely new code structure, based on modern C++
  - → Focus on flexibility, modularity, efficiency and reliability [5]
- PROPOSAL is used to simulate the electromagnetic and muonic shower component
  - → PROPOSAL provides individual 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

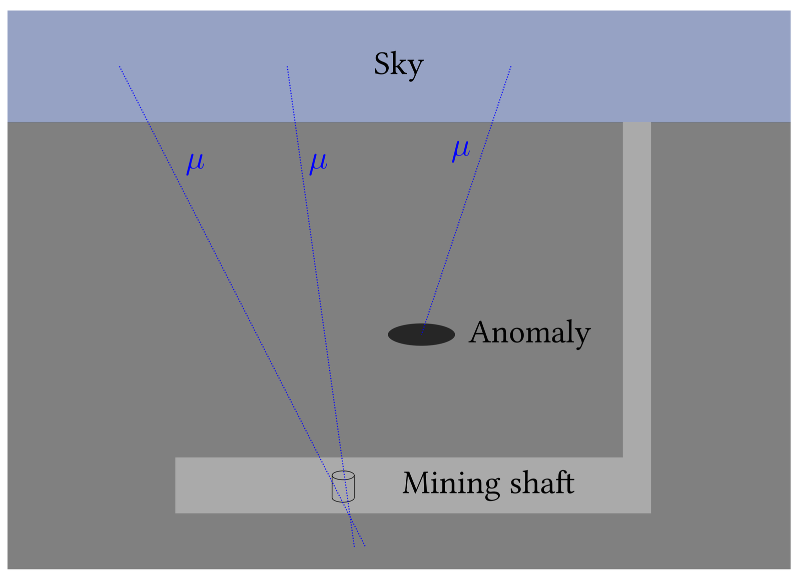
- PROPOSAL is used by neutrino telescopes, for example in the IceCube Neutrino observatory or in the software framework NuRadioMC
- Simulation of muon and tau energy losses in ice
  - → Precise simulations and an accurate description of cross sections are crucial



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

## Contact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References

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