High-energy lepton and photon propagation with the simulation framework PROPOSAL

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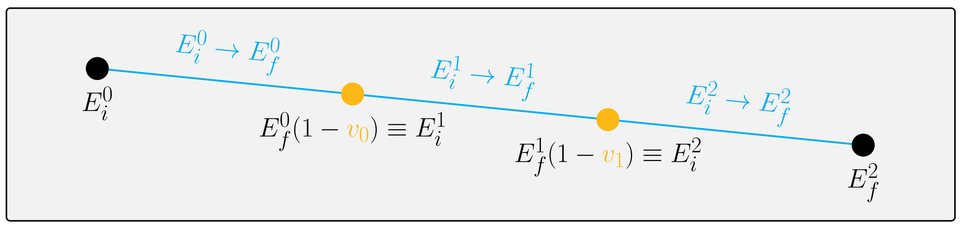
Introduction

- PROPOSAL is a C++/Python 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
- High-performance and high-precision simulations, optimized for large-scale particle propagation

Basic propagation algorithm of PROPOSAL:

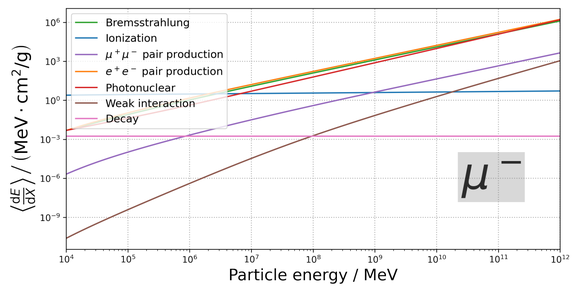
$v < v_{\text{cut}}$ continuous losses | $v > v_{\text{cut}}$ stochastic losses | with $v_{\text{cut}} = \min\left[e_{\text{cut}}/E, v'_{\text{cut}}\right]$

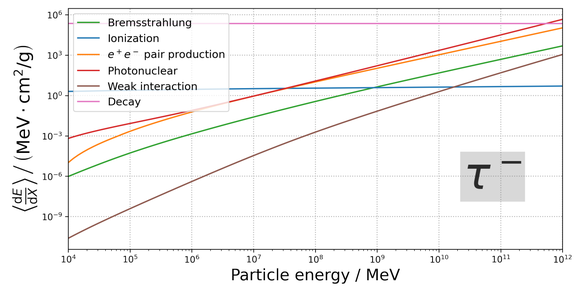
→ Separate relative energy losses v into hard and soft losses

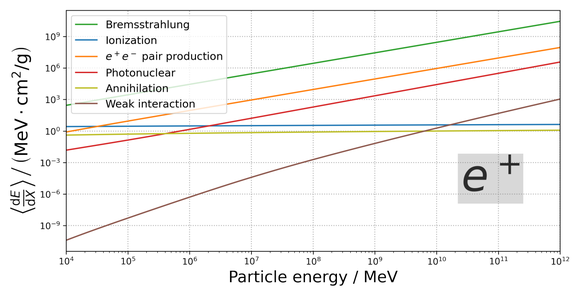


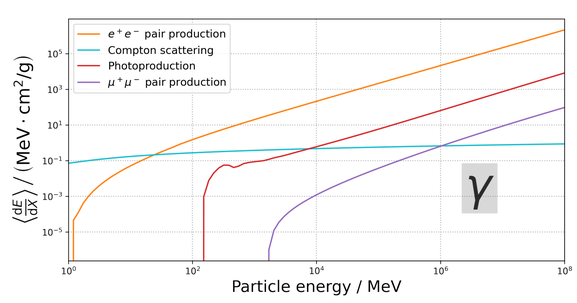
$$\int_{E_i}^{E_f} \frac{\sigma(E)}{-f(E)} \mathrm{d}E = -\log(\xi_{\text{rnd}}) \quad \text{with} \quad f(E) = \left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\text{cont.}}$$

→ Continuous propagation steps take energy losses into account, which allows for larger steplengths







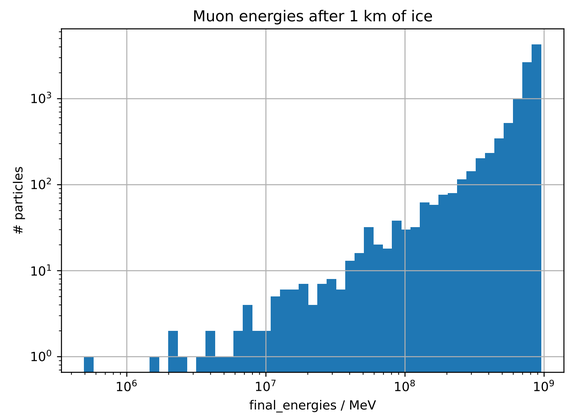


Average energy losses of particles inside PROPOSAL

How to use PROPOSAL

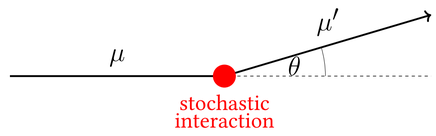
- PROPOSAL can be used as a C++ or a Python library
  - → Simple Python installation with `pip install proposal`
  - → C++ installation using the package manager Conan and CMake
- Information about the configuration environment can be read using a JSON file

```python
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)
```



Recent updates of PROPOSAL

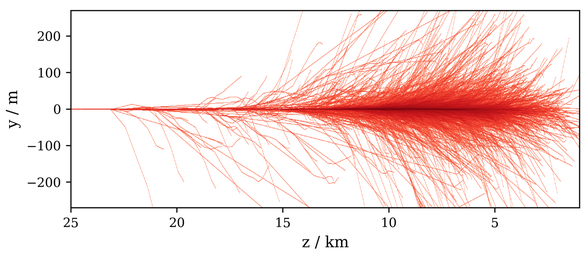
- Simulation of particle deflections in stochastic losses (stochastic deflections)
  - → Muon deflections (multiple scattering and stochastic deflections) might be a source of uncertainty for directional reconstructions [3]



- Improvements in the simulation of photons by including ...
  - → Photoproduction ($\gamma \to$ Hadron): Important for high energies
  - → Photoeffect: Important for low energies
  - → Muon pair production ($\gamma \to \mu^+\mu^-$): Important for the muon number in EM showers
- Improved output of the Propagator class
  - → Repropagate simulated particles to an arbitrary energy/distance
- Code restructuring and modularization
  - → Usage of PROPOSAL as a complete 3D Monte Carlo simulation
  - → Usage of PROPOSAL as a framework, where individual modules are provided

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 [4]
- PROPOSAL is used to simulate the electromagnetic and muonic shower component
  - → PROPOSAL provides individual modules, where each module solves specific physical tasks [5]
  - → 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 [6]

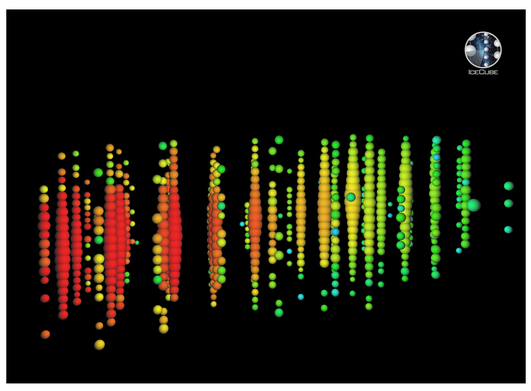


1 TeV e^- shower simulated with CORSIKA 8

→ More about CORSIKA 8 in the talk by A. Sandrock (Thursday, 5:30 PM, Parallel 1)

Application: Neutrino telescopes

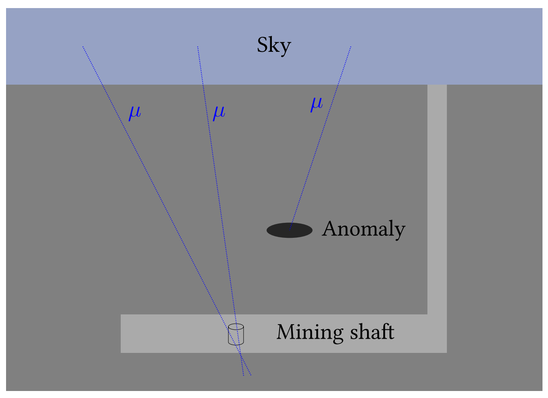
- PROPOSAL is used by neutrino telescopes, for example in the IceCube Neutrino observatory or in RNO-G
- Simulation of muon and tau energy losses in ice
  - → Precise simulations and an accurate description of cross sections are crucial
- Other tools process the energy losses provided by PROPOSAL to simulate Cherenkov photons



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 to explore density anomalies

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

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

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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] P. Gutjahr et al. *Simulation of Deflection Uncertainties on Directional Reconstructions of Muons Using PROPOSAL.* (in prep.) [4] 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* 3.1 (Dec. 2018), p. 2. ISSN: 2510-2044. DOI: 10.1007/s41781-018-0013-0. [5] 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. [6] J.-M. Alameddine et al. *Electromagnetic Shower Simulation for CORSIKA 8.* In: *PoS* ICRC2021 (2021), p. 428. DOI: 10.22323/1.395.0428.

Acknowledgements

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