PROCEEDINGS OF SCIENCE

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

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Current challenges in astroparticle physics like the muon puzzle in air shower physics or the upcoming launch of next-generation neutrino and gamma observatories require modern tools for the simulation of particle propagation, both from a technical and a physical standpoint.

For those purposes, PROPOSAL is a simulation framework that provides 3D Monte Carlo simulations of charged leptons and high-energy photons. PROPOSAL, which is usable in both C++ and Python, provides a high level of customizability, allowing the user to customize both the propagation environment and the underlying physical parametrizations, where up-to-date energy loss cross sections are available.

In this contribution, we present PROPOSAL as a framework, as well as current applications where PROPOSAL is used. This includes the usage of PROPOSAL as an electromagnetic model for the shower simulation framework CORSIKA 8, as well as the usage of PROPOSAL for underground measurements of muon numbers, for example in the context of muography.

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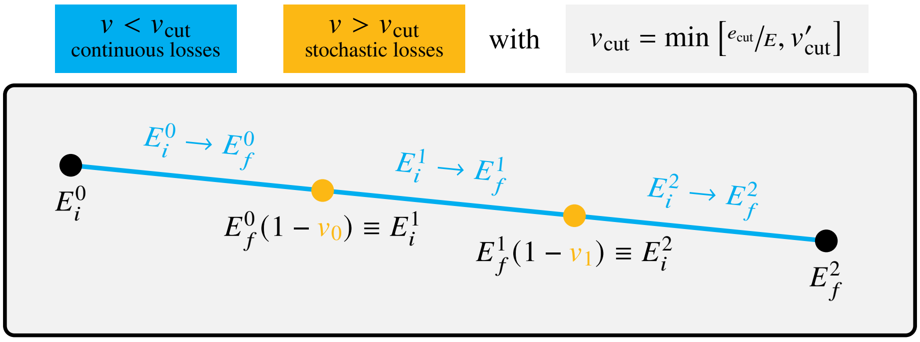

Figure 1: Propagation algorithm visualized.

1. Introduction and propagation

To train the underlying statistical models that are used for data analysis of modern experiments in astroparticle physics, large amounts of high-quality simulated data are required. This can include everything from the simulation of the injected signal or background to the simulation of the actual detector response. These simulations are expected to be as accurate as possible, but also reproducible, robust, and efficient.

PROPOSAL is a simulation framework that provides three-dimensional Monte Carlo simulations of high-energy electrons, positrons, photons, muons, and taus [1, 2]. While at its core, PROPOSAL is written in C++, it is also accessible from Python via a code wrapper.

Given the state of an initial particle, a definition of the propagation environment (e.g. containing information about the medium), and optionally a break condition, PROPOSAL provides the final state of the particle after propagation as well as detailed information about the energy losses.

A visualization of the underlying propagation algorithm is shown in Figure 1. To improve the performance as well as to handle the divergence of small energy losses due to bremsstrahlung, PROPOSAL separates energy losses into continuous energy losses and stochastic energy losses, where the threshold is defined by a total energy cut e_{cut} and/or a relative energy cut v'_{cut}. These cut settings can be chosen by the user, and can also vary for different regions of the propagation environment, which can be used to precisely steer and optimize the balance between performance and accuracy for each individual simulation.

Given an initial particle energy E_i^0, PROPOSAL samples the energy E_f^0 at which the next stochastic interaction, i.e. an energy loss with $v > v_{\text{cut}}$ will occur, by solving the integral equation

$$\int_{E_i}^{E_f} \frac{\sigma(E)}{-f(E)} \, \mathrm{d}E = -\log(\xi_{\text{rnd}}), \tag{1}$$

where $\sigma(E)$ describes the stochastic part of the total cross section, $f(E)$ the continuous energy losses per distance, and ξ_{rnd} a random number (see [1] for a more detailed description and derivation). This sampling method also considers continuous losses, including the change of cross sections with energy during a continuous propagation step. Furthermore, multiple scattering during a continuous propagation step is taken into account, using Molière theory or a Gaussian approximation of it. Afterward, the type and size v_0 of the following stochastic energy loss are sampled, leading to a new particle energy E_i^1. This process is repeated until a breaking condition has been reached.

While the entire propagation algorithm can be used in a closed form, each calculation is written as a self-contained module and can be used individually [3], which makes it possible to use PROPOSAL as a framework for specific simulation tasks.

The settings for the underlying physics used in PROPOSAL are customizable, which means that the user can decide both which effects to take into account, and which physics parametrizations to use. In this context, many up-to-date parametrizations, especially for muon energy losses [4], are provided.

At present, the most recent version of PROPOSAL is 7.4.2 [1].

2. Recent updates of PROPOSAL

2.1 Stochastic deflections

PROPOSAL takes into account multiple scattering of charged particles during continuous propagation steps. However, particles can also change their direction during individual, stochastic energy losses, especially if an energy loss is relatively large. These effects may become important when a high accuracy of the directional information is necessary, for example in muon tomography or for neutrino observatories. Especially for future neutrino observatories, scattering effects of muons can have an impact on directional reconstructions [5]. Therefore, PROPOSAL now considers the deflection of muons in stochastic interactions.

2.2 Interactions of photons

While PROPOSAL has originally been developed to propagate muons and taus, the propagation of electrons, positrons, and high-energy photons has been added with the introduction of version 6.0.0. To further improve the accuracy of photon propagation, especially for very-high and lower energies, photoproduction ($\gamma \to$ Hadrons), muon pair production ($\gamma \to \mu^+\mu^-$), and the photoeffect have recently been implemented as new effects. An overview of the current photon cross sections available in PROPOSAL is shown in Figure 2.

While the process of electron-positron pair production is the dominant photon interaction for high energies, its cross section is suppressed at very-high energies and/or high matter densities due to the Landau-Pomeranchuk-Migdal effect. Therefore, photoproduction becomes the dominant interaction type and needs to be considered. Several parametrizations for photoproduction are available in PROPOSAL [1].

At small energies, the photoeffect becomes the dominant photon interaction. Therefore, a description of the photoeffect in Born approximation [6] has been implemented. This parametrization provides a good agreement for photon energies that are not close to atomic absorption edges.

While the production of muons pairs by photons ($\gamma \to \mu^+\mu^-$) is suppressed by a factor of $\sim (m_e/m_\mu)^2$ compared to electron-positron production, this process provides (next to photoproduction) an additional contribution of muons in electromagnetic showers. It has therefore been implemented to PROPOSAL and can optionally be activated.

[1] https://github.com/tudo-astroparticlephysics/PROPOSAL

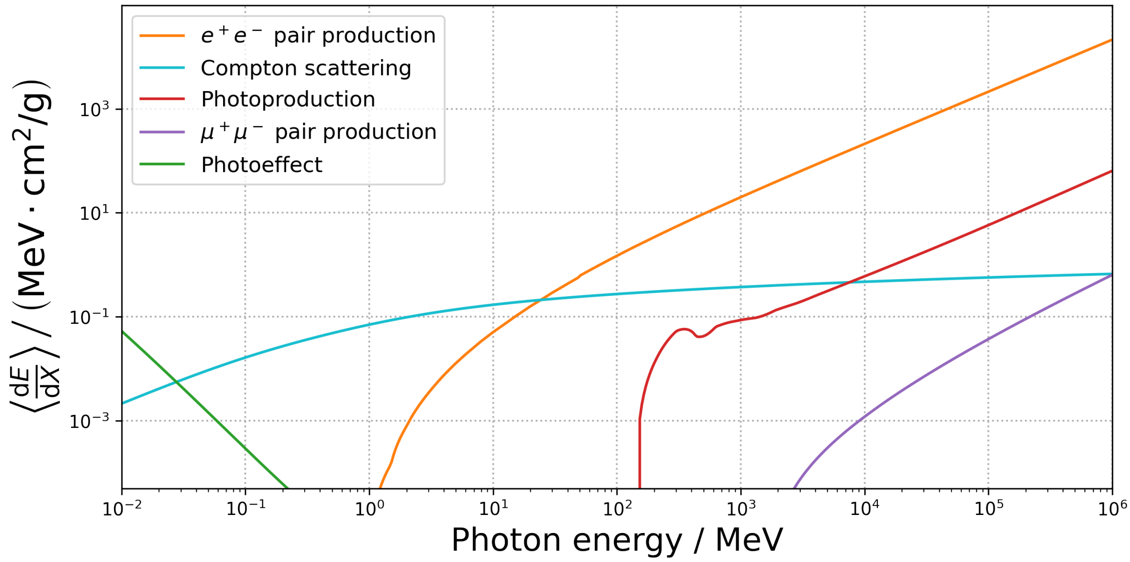

Figure 2: Contribution of the implemented photon interactions to the average energy loss in air.

3. Applications of PROPOSAL

In this section, a selection of current applications of PROPOSAL is presented. This includes its usage as an electromagnetic and muonic interaction module in the shower simulation framework CORSIKA 8, its usage in simulations for neutrino telescopes, here in the context of IceCube and the simulation package NuRadioMC, as well as its usage for studies in the field of muography.

3.1 Electromagnetic shower simulations for CORSIKA 8

For several decades, the Fortran software CORSIKA has been the go-to tool for simulations of extensive air showers, which are crucial for almost all experiments in astroparticle physics [7].

CORSIKA 8 is a complete rewrite of CORSIKA in modern C++, which has been developed since 2018. Its main focus is to overcome limitations of older CORSIKA versions with a focus on flexibility, modularity, efficiency, and reliability [8, 9].

For CORSIKA 8, PROPOSAL is used as a module to describe the electromagnetic and muonic component of extensive particle showers. In this context, the corresponding PROPOSAL modules are used to calculate interaction lengths, continuous energy losses, multiple scattering, and the production of secondary particles.

Figure 3 shows the comparison of electromagnetic showers simulated with an early version of CORSIKA 8, compared to other shower simulation tools. It can be seen that the comparisons already show a good agreement. Further verifications and improvements, especially regarding the optimization of runtimes, are ongoing.

3.2 Muon and tau simulations for neutrino telescopes

PROPOSAL is used in the simulation chain of the IceCube Neutrino Observatory [11] to propagate atmospheric muons from the ice surface to the detector, as well as to simulate the energy

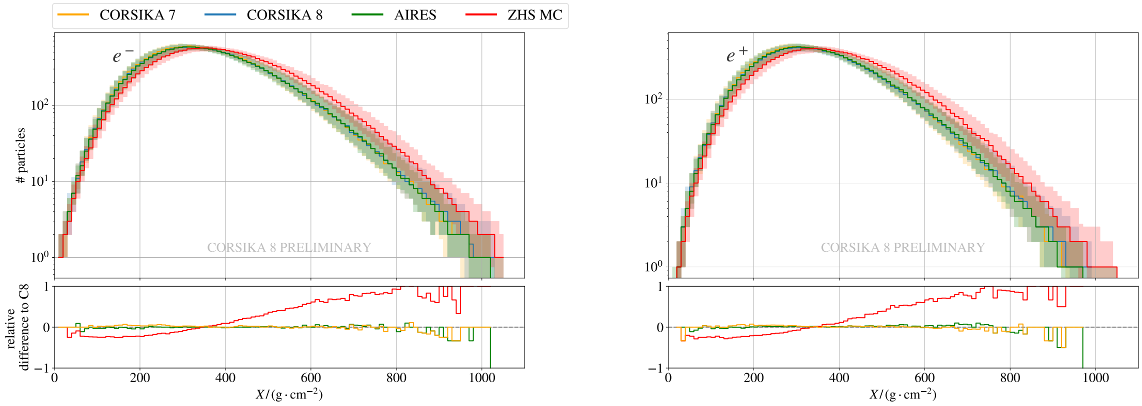

Figure 3: Longitudinal profiles of 1 TeV electron-induced showers in air, compared between CORSIKA 8 (version icrc-2021), CORSIKA 7 (version 7.7410), AIRES (version 19.04.00) and ZHS. [10]

losses of neutrino-induced muons and taus inside the detector. An accurate description of these energy losses is crucial for the reconstruction of the lepton properties such as energy and direction. Furthermore, energy losses in veto regions of the detector can be used to reject events. Due to the stochastic behavior of muon energy losses, their accurate description is important for a correct background estimation.

Another application of PROPOSAL can be found in the Monte Carlo framework NuRadioMC [12], which provides simulations for radio neutrino observatories, including a description of neutrino interactions, radio propagation, and detector responses. Within NuRadioMC, PROPOSAL has been used to investigate the contribution of in-ice showers resulting from energy losses of secondary muons and taus [13]. Next to the radio emission from the primary neutrino interaction, these contributions can be measured in the detector, which means that their estimation is crucial for the calculation of detector sensitivities. Furthermore, the background from atmospheric muons has been estimated and calculated to be a relevant factor for radio neutrino detectors, where the contribution depends on the distance of the antennas to the surface.

3.3 Muography

Atmospheric muons from extensive air showers are abundant and can propagate large distances through media. These properties make it possible to use them for a noninvasive imaging technique called muography. Since the average range of muons depends on the traversed matter density, tracing the number of muons along a specific direction can give information about density distributions. This principle can be used, for example, to explore density anomalies, as depicted in Figure 4.

Since PROPOSAL provides an efficient way to simulate the propagation of muons through large volumes, its usage is convenient for analyses in the context of muography. One example, which is currently under investigation, is the usage of muography to monitor the water level in old mining shafts. In contrast to conventional methods, muography has the advantage that the observation of large areas with a limited amount of detectors is possible, given a sufficient muon rate and directional resolution of the detector.

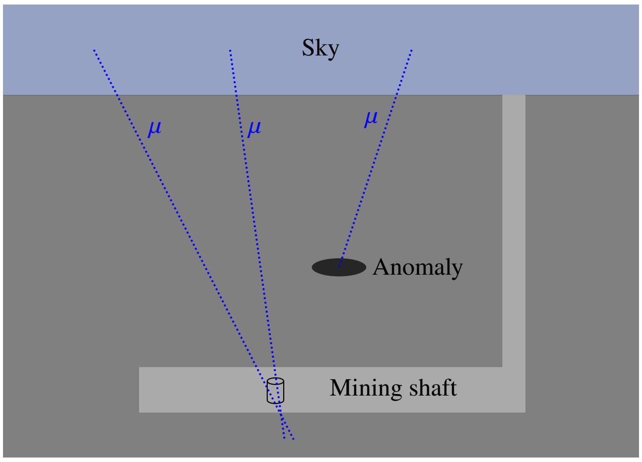

Figure 4: Visualization of the muography technique to explore density anomalies

4. Summary and outlook

PROPOSAL is a modern C++ framework to simulate the propagation of charged leptons and high-energy photons through media. It is currently used for different applications, for example to describe the electromagnetic and muonic air shower component in CORSIKA 8, or to simulate energy losses of high-energy muons and taus for neutrino observatories like IceCube or RNO-G.

PROPOSAL is actively maintained and under continuous development. In a future update, a description of the Landau-Pomeranchuk-Migdal effect, valid in inhomogeneous media, is going to be implemented. While a parametrization for homogeneous media is already available and is for example used in the simulation of high-energy muons for IceCube, a description in inhomogeneous media will be important to correctly describe the electromagnetic component for very-high energy air showers. Furthermore, the implementation of only-stochastic propagation, i.e. propagations without continuous losses, is planned. This will allow the usage of PROPOSAL to propagate neutrinos as well.

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