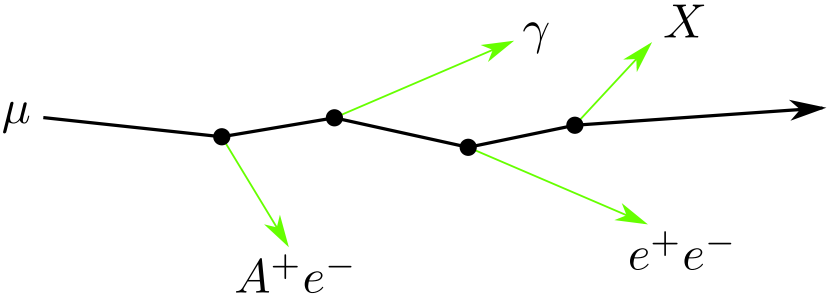
technische universität dortmund

HELMHOLTZ GEMEINSCHAFT Allianz für Astroteilchenphysik

DFG

SFB 876 Providing Information by Resource-Constrained Data Analysis

lehrstuhl physik e5



Recent improvements to the lepton propagator PROPOSAL

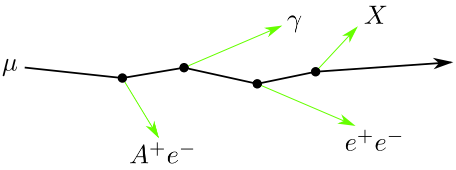
Mario Dunsch, Jan Soedingrekso, **Alexander Sandrock**, Maximilian Meier, Thorben Menne, Wolfgang Rhode

IRN Terascale@Annecy, May 21, 2019

Technische Universität Dortmund

PROPOSAL

- Monte Carlo tool for charged lepton propagation through media
- Written in C++
- Used in the simulation chain of IceCube
- **PR**opagator with **O**ptimal **P**recision and **O**ptimized **S**peed for **A**ll **L**eptons
  - Calculate energy losses
  - Passes interaction points and decay/interaction products to further simulation programs



Energy cuts

- Distinguish between **continous** and **stochastic** energy losses
- Cut between continuous and stochastic loss:

$$\text{cut} = \min(e_{\text{cut}}, v_{\text{cut}} \cdot E), \qquad v := \text{relative energy loss}$$

- Set energy cuts before, inside and behind the detector

Energy cuts in IceCube

- before: $v_{\text{cut}} = 0.05$
- inside: $e_{\text{cut}} = 500\,\text{MeV}$
- behind: $v_{\text{cut}} = v_{\text{max}}$

Continuous loss

Describes energy loss in the range $v \in [v_{\text{min}}, v_{\text{cut}}]$

$$f(E) := \sum_{\text{processes}} \frac{\mathrm{d}E_\sigma}{\mathrm{d}x}$$

$$= E \cdot \sum_{\text{process}} \sum_{\substack{\text{atom}\\ \text{in medium}}} \frac{N_i}{A_i} \int_{v_{\text{min}}}^{v_{\text{cut}}} v \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}v$$

Stochastic loss

Described by the interaction probability $v \in [v_{\text{cut}}, v_{\text{max}}]$

$$dP(E) = \sigma(E)\mathrm{d}x$$

$$\sigma(E) = \sum_{\text{processes}} \sum_{\substack{\text{atom}\\ \text{in medium}}} \frac{N_i}{A_i} \int_{v_{\text{cut}}}^{v_{\text{max}}} \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}v$$

Summary of the algorithm

Basic loop

Do:

Calculate the energy E_f until the next stochastic loss

$\downarrow$

Advance the particle according to E_f

$\downarrow$

Calculate the stochastic loss

Until: The particle decays **or** the max. propagation length is reached

Specific Features

- **Interpolation tables**
- Continuous Randomization
- Multiple parametrizations of cross sections for systematic studies
- Further parameters for the trade-off between performance and precision (e.g. stop propagating the particle, if the energy is below a threshold)

Use of Interpolation tables

e.g. sampling of energy until next stochastic loss E_f

$$\int_{E_i}^{\mathbf{E_f}} \frac{\sum \frac{N_i}{A_i} \int\limits_{v_\text{cut}}^{v_\text{max}} \frac{\mathrm{d}\sigma_j}{\mathrm{d}v} \mathrm{d}v}{E \sum \frac{N_i}{A_i} \int\limits_{v_\text{cut}}^{v_\text{max}} v \frac{\mathrm{d}\sigma_j}{\mathrm{d}v} \mathrm{d}v} \mathrm{d}E = -\ln(\xi)$$

$$\text{where } \sigma_\text{pair}(v) = \int \frac{\mathrm{d}\sigma}{\mathrm{d}v\mathrm{d}\rho} \mathrm{d}v\mathrm{d}\rho$$

$\Longrightarrow$ Calculation of many integrals

- Instead use 1D Interpolation $\rightarrow$ huge performance gain

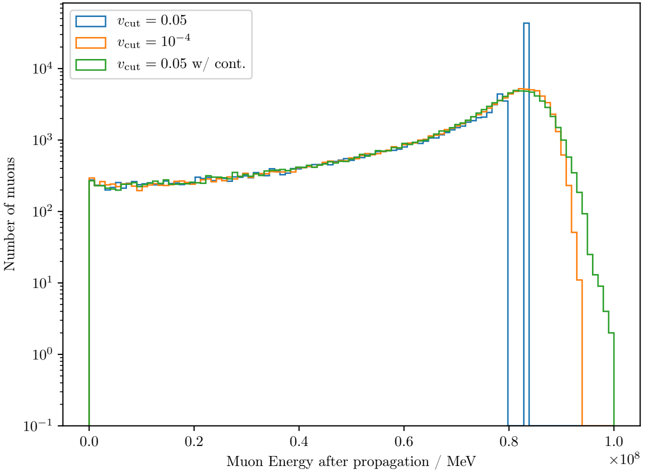
Continuous Randomization

Problem with energy cut:

- low: high precision, but slow and many (unnessesary) secondaries
- high: fast, but less precision and artifacts in muon flux
- muons without a stochastic loss are all treated the same

$\Longrightarrow$ continuous randomization of the muon energy till next stochastic loss E_f

$$\langle(\Delta(\Delta E))\rangle \approx \int_{e_0}^{e_{\text{cut}}} \frac{\mathrm{d}E}{-f(E)} \left(\int_0^{e_{\text{cut}}} e^2 \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}e \right)$$



Cross section parametrizations for systematic studies

Bremsstrahlung

Parametrizations

- KelnerKokoulinPetrukhin
- AndreevBezrukovBugaev
- PetrukhinShestakov
- CompleteScreening
- SandrockSoedingreksoRhode

also consider LPM and TM Effect

e^+e^- Pair Production

Parametrizations

- KelnerKokoulinPetrukhin
- SandrockSoedingreksoRhode

and LPM Effect

Nuclear inelastic Interaction

- Vector meson dominance
  - Kokoulin
  - Rhode
  - BezrukovBugaev
  - Zeus

  with hard and soft component
- Regge Theory
  - AbramowiczLevinLevyMaor91
  - AbramowiczLevinLevyMaor97
  - ButkevichMikheyev
  - RenoSarcevicSu (spin 0)

  with shadowing parametrizations of
  - ButkevichMikheyev
  - DuttaRenoSarcevicSeckel

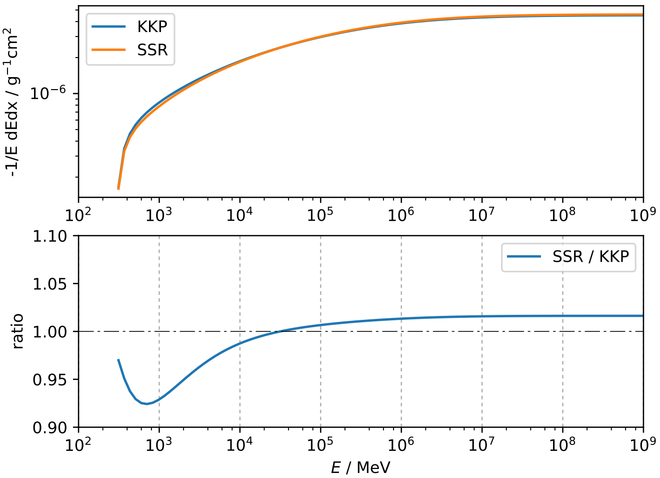
Improvements in the newest version

- New parametrizations of interaction processes
  - Bremsstrahlung
  - Pair production
  - Nuclear inelastic Interaction
  - Multiple Scattering
- Improved hadronic and leptonic decay calculations
- Restructuring of the code (more polymorphism)
  - faster
  - easier to maintain
  - easily extendable
- Python interface using pybind11

New Cross Sections

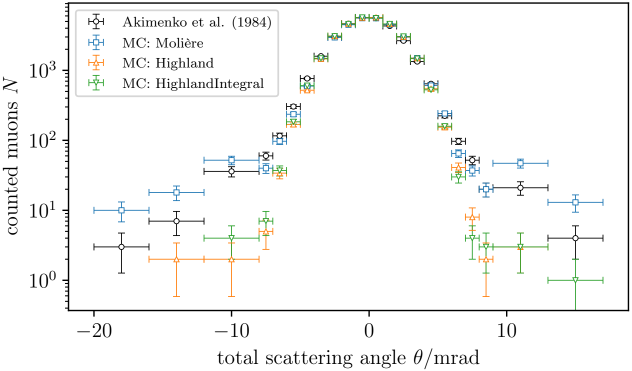
- improved atomic screening functions for
  - bremsstrahlung
  - pair production
- radiative corrections for bremsstrahlung

$\Longrightarrow$ corrections of several percent



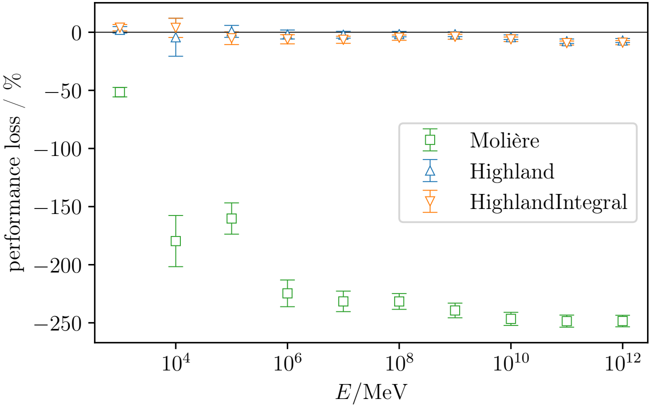
Multiple Scattering

- Molière
  - precise description
  - slow, especially for many components in medium
- Highland parametrization
  - Gaussian approximation to Molière's theory
  - two types available: one including continuous losses and one without
- no scattering



Multiple Scattering

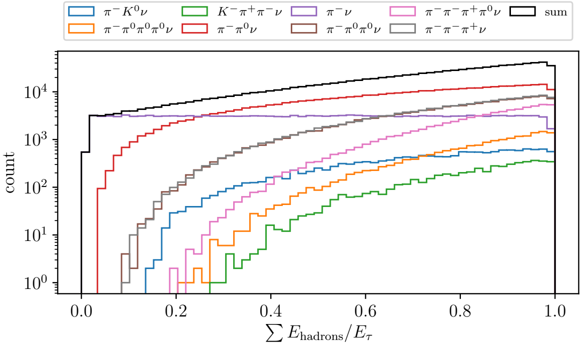
- Molière
  - precise description
  - slow, especially for many components in medium
- Highland parametrization
  - Gaussian approximation to Molière's theory
  - two types available: one including continuous losses and one without
- no scattering



Hadronic Decay

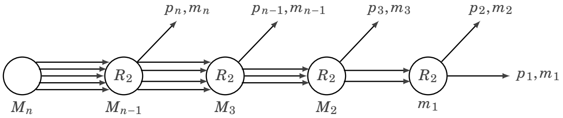
- Before: two-body decay
- Calculate N-body decay phase space
- Constant matrix element

$$\Gamma = \frac{(2\pi)^4}{2M} \underbrace{\int \prod_{i=1}^{n} \frac{d^3 p_i}{2E_i} \delta^4 \left(p - \sum_{i=1}^{n} p_i\right)}_{N\text{-body phase space}} \overbrace{|\langle M(\mathbf{p}_i)\rangle|^2}^{\text{set to 1}}$$



Raubold-Lynch algorithm

- Iterative integration over intermediate two-body phase spaces
- Exactly calculable



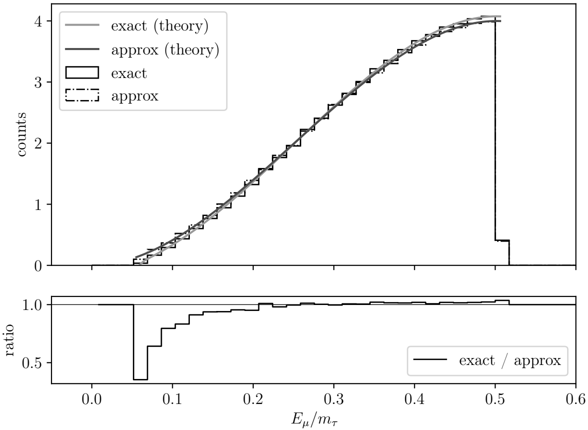
Leptonic Decay

- Muon decay and electronic tau decay ($m_l^2/M^2 \approx 0$)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = \frac{G_\mathrm{F}^2 M^5}{192\pi^3}(3-2x)x^2, \quad x = \frac{E_l}{E_\mathrm{max}}$$

- muonic tau decay ($m_\mu/m_\tau \approx 1/17$)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = \frac{G_\mathrm{F}^2}{12\pi^3} E_\mathrm{max} \sqrt{E_l^2 - m_l^2} \times \left[M E_l (3M - 4E_l) + m_l^2 (3E_l - 2M)\right]$$



Creating custom particle

- use pre-defined particles
  - electrons
  - muons
  - taus
  - sTaus, etc.
- or create new particle with properties
  - lifetime
  - mass
  - charge
  - decay channels
- combination of both

```python
import pyPROPOSAL as pp
mu_def_builder = pp.particle.ParticleDefBuilder()
mu_def_builder.SetParticleDef(
    pp.particle.MuMinusDef.get())
mu_def_builder.SetLow(1e3) # MeV
mu_def_builder.SetName('new_mu')
mu_def_builder.SetMass(1e4) # MeV
mu_def_builder.SetLifetime(1e-5) # sec
mu_def_builder.SetCharge(2)
# create Leptonic decay table
decay_table = pp.decay.DecayTable()
products = [pp.particle.EMinusDef.get(),
            pp.particle.NuMuDef.get(),
            pp.particle.NuEBarDef.get()]
ldec = pp.decay.LeptonicDecayChannel(*products)
decay_table.add_channel(1, ldec)
mu_def_builder.SetDecayTable(decay_table)

particle_def = mu_def_builder.build()
```

Usage of new Structure

- Initialization of a Propagator
  - a Configuration file (json)
  - and a Particle Definition

  The Interpolation files are build
- Propagation through different sectors consisting of a geometry and a medium

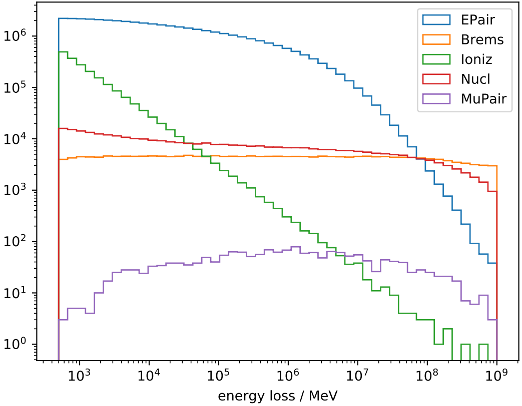
```
prop = pp.Propagator(particle_def,
                     config_file)
mu = prop.particle
mu.position = pp.Vector3D(0, 0, 0)
mu.direction = pp.Vector3D(0, 0, 1)
mu.energy = 1e10 # MeV
max_distance = 1e5 # cm
secondaries = prop.propagate(max_distance)
```

```
"global":
{
        "interpolation":
        {
                "do_interpolation" : true,
                "path_to_tables" : ["resources/tables"],
                "do_binary_tables" : false
        },
        "stopping_decay" : true,
        "scattering" : "Highland",
        "brems" : "BremsAndreevBezrukovBugaev",
        "photo" : "PhotoBezrukovBugaev",
        "lpm" : false,
        "photo_shadow" : "ShadowDuttaRenoSarcevicSeckel"
},
"sectors": [
        {
                "hierarchy" : 0,
                "medium" : "ice",
                "density_correction" : 1,
                "geometry" :
                {
                        "shape" : "sphere",
                        "origin" : [0, 0, 0],
                        "outer_radius" : 6374134000000,
                        "inner_radius" : 0
                },
        }
```

Rare Processes

Implementation of rare processes, but with different sigature in detector

- Muon pair production: Creation of muon bundles originating by a single muon
- Weak interaction: disappearance of a muon in a cascade



Outlook

- medium of sector independent of density (for atmosphere)
- Magnetic field deflection
- further electron/positron processes: Annihilation, Bhabha and Møller scattering

https://github.com/tudo-astroparticlephysics/PROPOSAL

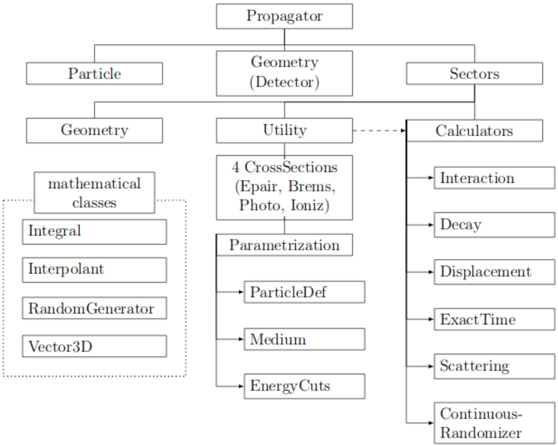
https://arxiv.org/abs/1809.07740

PROPOSAL may be modified and distrubuted under terms of a modified LGPL license.
More information on our GitHub page.

References

- Dunsch, M. et al. (2019). “Recent Improvements for the Lepton Propagator PROPOSAL”. In: *Comput. Phys. Commun.* in press. arXiv: 1809.07740 [hep-ph].
- Koehne, J.-H. et al. (2013). “PROPOSAL: A tool for propagation of charged leptons”. In: *Comput. Phys. Commun.* 184, pp. 2070–2090.
- Sandrock, A., S. R. Kelner, and W. Rhode (2018). “Radiative corrections to the average bremsstrahlung energy loss of high-energy muons”. In: *Phys. Lett. B* 776, p. 350.
- Sandrock, Alexander (2018). “Higher-order corrections to the energy-loss cross sections of high-energy muons”. PhD thesis. Technische Universität Dortmund. URL: http://dx.doi.org/10.17877/DE290R-19810.

Schematic of the main class structure



Runtime improvement

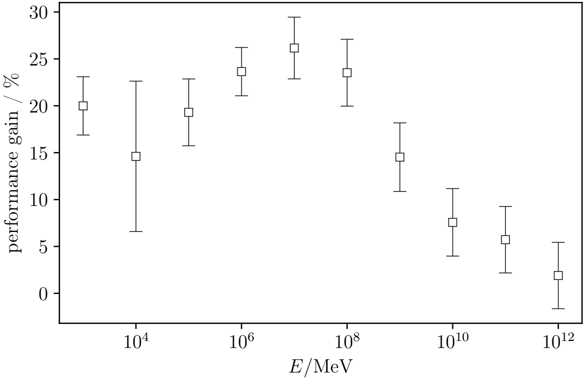


Figure: Runtime improvement $(t_{\text{old}} - t_{\text{new}})/t_{\text{old}}$ of the new version compared to the previous version. Multiple scattering is disabled. Per energy range 1000 muons were propagated through ice until they lost their energy.