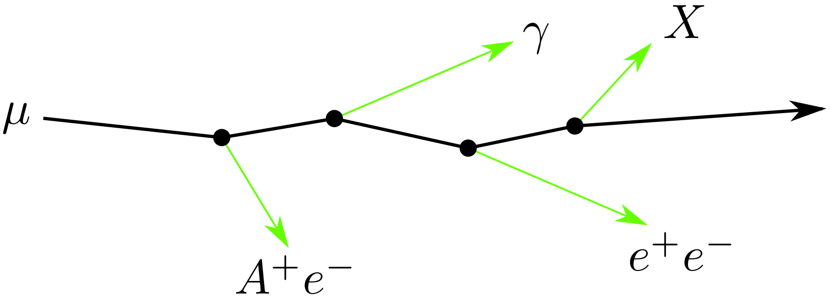
technische universität dortmund

HELMHOLTZ GEMEINSCHAFT Allianz für Astroteilchenphysik

DFG

SFB 876 Providing Information by Resource-Constrained Data Analysis

lehrstuhl physik e5



The lepton propagator PROPOSAL and the air shower simulation code CORSIKA

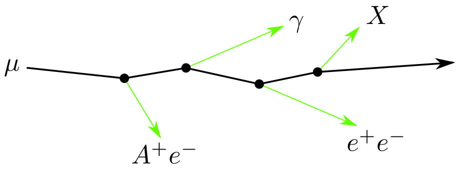
Alexander Sandrock

CORSIKA Cosmic Ray Simulation Workshop Karlsruhe, June 17, 2019

Technische Universität Dortmund

PROPOSAL

- Monte Carlo tool for charged lepton propagation through media.
- 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 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 $v \in [v_{\text{min}}, v_{\text{cut}}]$

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

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

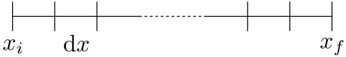
Stochastic loss

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

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

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

Determine the occurrence of a stochastic loss



Probability to have no stochastic loss in (x_i, x_f), but at x_f within $\mathrm{d}x$:

$$
\begin{cases}
\quad (1-\mathrm{d}P(E(x_i)))\cdot\ldots\cdot(1-\mathrm{d}P(E(x_{f-1})))\cdot\mathrm{d}P(E(x_f)) \\
\approx \exp(-\mathrm{d}P(E(x_i)))\cdot\ldots\cdot\exp(-\mathrm{d}P(E(x_{f-1})))\mathrm{d}P(E(x_f)) \\
\approx \exp\left[-\int_{P(E(x_i))}^{P(E(x_f))}\mathrm{d}P(E(x))\right]\cdot\mathrm{d}P(E(x_f)) \\
= \mathrm{d}\left[-\exp(-\int_{E_i}^{E_f}\frac{\sigma(E)}{-f(E)}\mathrm{d}E)\right] =: \mathrm{d}(-\xi)\in(0,1]
\end{cases}
$$

$\Rightarrow$ Sample E_f from $\displaystyle\int_{E_i}^{E_f}\frac{\sigma(E)}{-f(E)}\mathrm{d}E = -\ln(\xi)$

Advance the particle according to E_f

- Calculating the displacement

$$x_f = x_i - \int_{E_i}^{E_f} \frac{\mathrm{d}E}{f(E)}$$

- the elapsed time

$$t_f = t_i - \int_{t_i}^{t_f} \frac{\mathrm{d}x}{v(x)} = t_i - \int_{E_i}^{E_f} \frac{\mathrm{d}E}{f(E)v(E)}$$

- and the deviation from the shower axis (multiple scattering)

$$u_{x,y} = \frac{1}{2}\left(\frac{1}{\sqrt{3}}\xi_{x,y}^{(1)} + \xi_{x,y}^{(2)}\right), \qquad \xi_{x,y}^{(1,2)} \sim \mathcal{N}(0, \theta_0^2)$$

Calculate the stochastic loss

- Calculate the interaction probability for each process

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

- Calculate the amount of stochastic loss for each atom in the medium

$$\frac{1}{\sigma} \int_{v_\text{cut}}^{v(\xi)} \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}v = \xi$$

$$E_\text{stochastic loss} = v(\xi) \cdot E_\text{particle}$$

- Choose the Component, at which the energy loss takes place

Summary of the algorithm

Basic loop

Do:

Calculate the energy until a stochastic loss

$\downarrow$

Advance the particle according to E_f

$\downarrow$

Calculate the amount of the stochastic loss

Until: The particle decays

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

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

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

$\Longrightarrow$ Calculation of many integrals

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

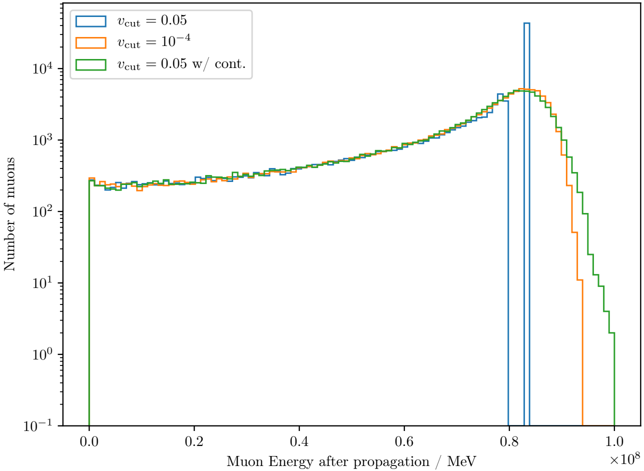
Continuous Randomization

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

Propagation

- propagation through dense media
- requires media of uniform density
- propagation is fast
- adding new particles is relatively simple

Decay

- particles can decay based on lifetime
- final state particles calculated using Raubold-Lynch algorithm

Multiple Scattering

- Coulomb scattering on atoms in the medium
- several algorithms available
  - Molière scattering
  - Highland approximation to Molière scattering

Electromagnetic cascades

- MC-simulation requires propagation of many electrons, positrons and photons
- currently based on EGS4 (Nelson, Hirayama, and Rogers 1985)
- photon cross sections similar to lepton cross sections

Necessary extensions

- Density currently part of medium
  - each medium has its own interpolation tables
- Magnetic field deflection
  - We have basically worked out how to implement this
- Propagation of electrons/positrons
  - Some processes need to be added (Annihilation; Bhabha and Møller scattering compared to μe scattering)
- Propagation of photons
  - in principle similar to propagation of charged particles, but without continuous losses

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.
- Nelson, W. R., H. Hirayama, and D. W. O. Rogers (1985). *The EGS4 Code System*. Tech. rep. Report SLAC-265. Stanford, CA: Stanford Linear Accelerator Center.
- 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`.

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

```
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

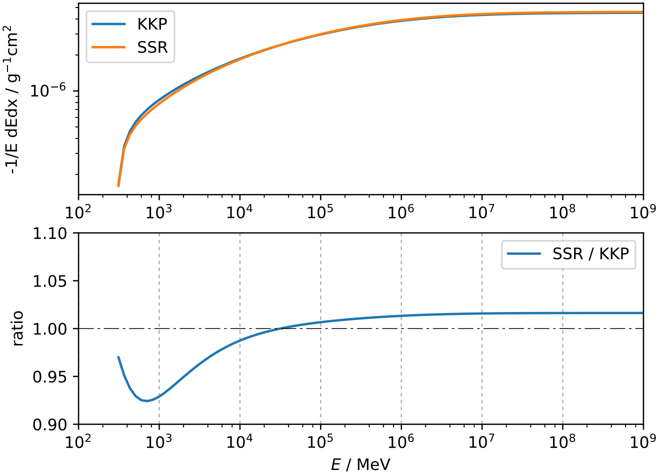
```
prop = pp.Propagator(particle_def,
                     config_file)
mu = prop.particle
mu.position = pp.Vector3D(0, 0, 0)
mu.direction = pp.Vector3D(0, 0, 1)
mu.energy = 1e10 # MeV
max_distance = 1e5 # cm
secondaries = prop.propagate(max_distance)
```

```
"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
                },
        }
```

New Cross Sections

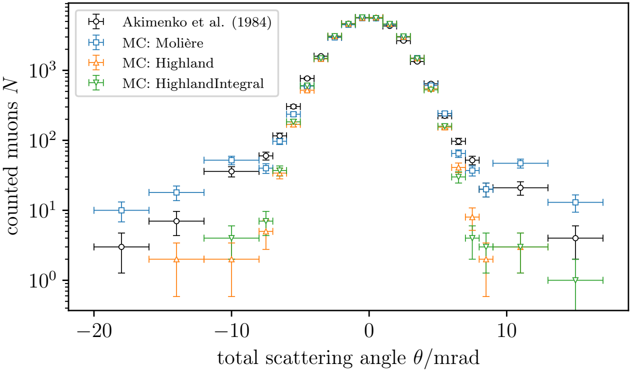
- improved atomic screening functions for
  - bremsstrahlung
  - pair production
- radiative corrections for bremsstrahlung

$\Longrightarrow$ 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



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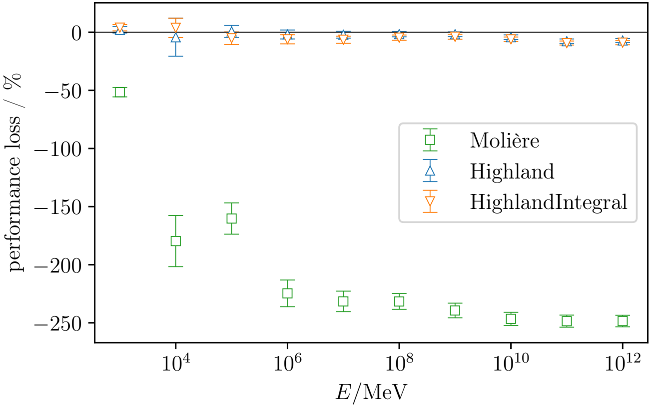
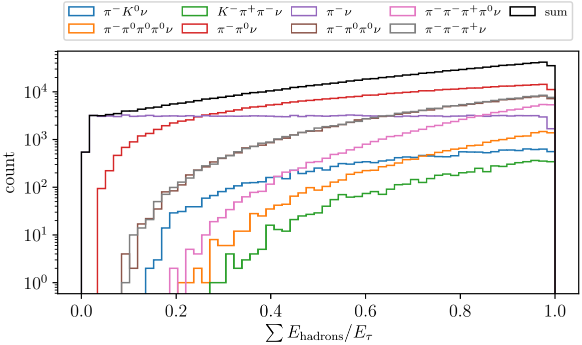


Hadronic Decay

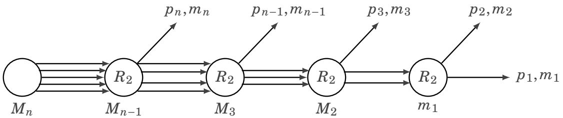
- Before: two-body decay
- Calculate N-body decay phase space
- Constant matrix element

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



Raubold-Lynch algorithm

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



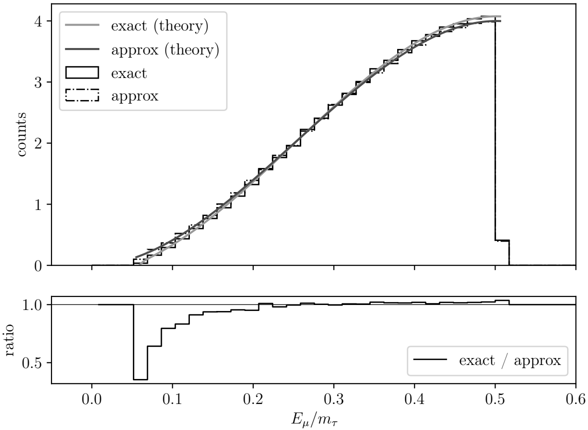
Leptonic Decay

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

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



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