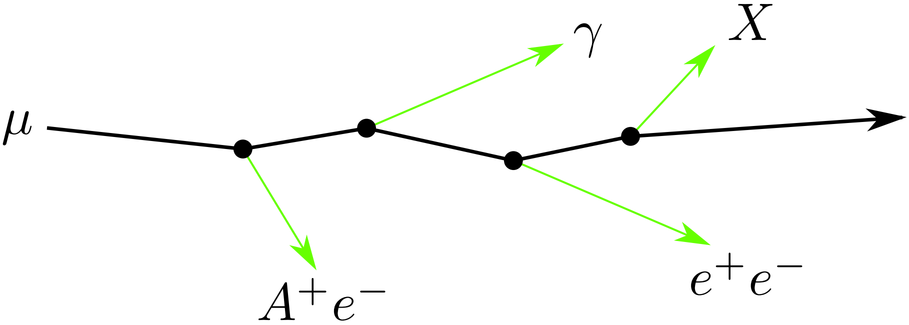
technische universität dortmund

DFG SFB 876 Providing Information by Resource-Constrained Data Analysis

lehrstuhl physik e5



The Leptonpropagator PROPOSAL for CORSIKA

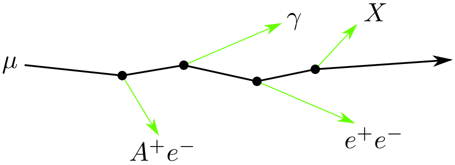
Jan Soedingrekso, Alexander Sandrock
Jean-Marco Alameddine, Maximilian Sackel

CORSIKA Phone Call

05.03.2019

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 $v \in [v_{\text{min}}, v_{\text{cut}}]$

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

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

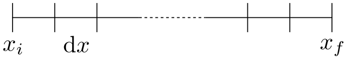
Stochastic loss

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 $\mathrm{d}x$:

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

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

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

↓

Advance the particle according to E_f

↓

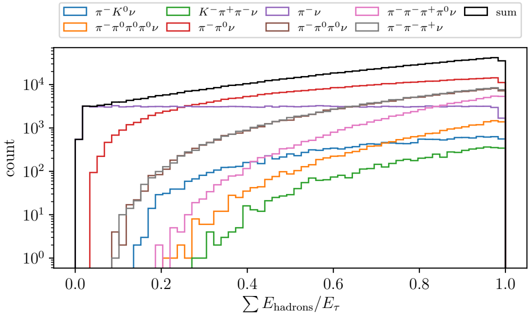
Calculate the amount of the stochastic loss

Until: The particle decays

Hadronic Decay

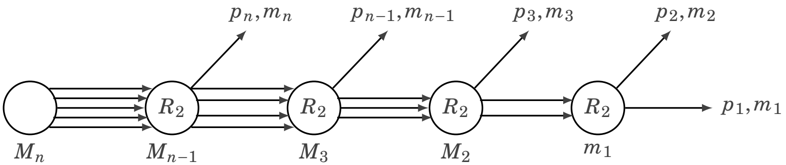
- Calculate N-body decay phase space
- Not consider the matrix element

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



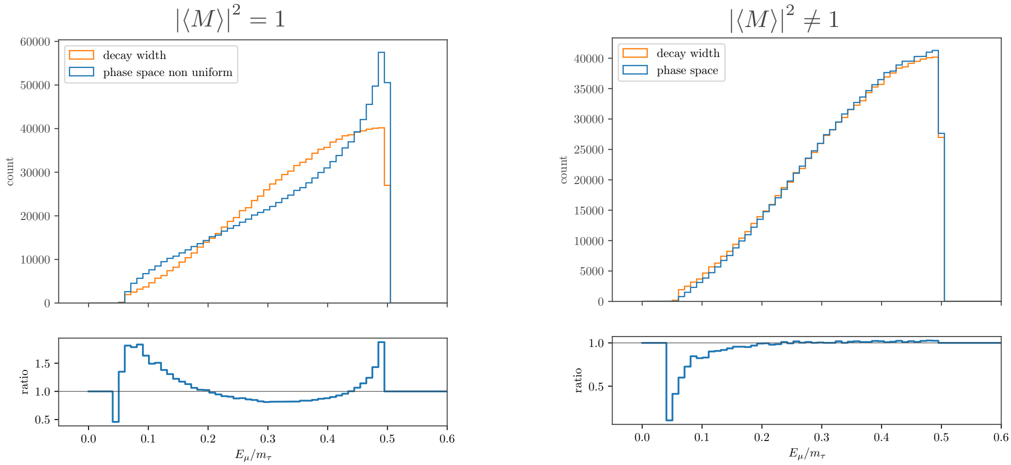
Raubold-Lynch algorithm

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



Effects of constant Matrix Element

Leptonic decay: known decay width and known matrix element



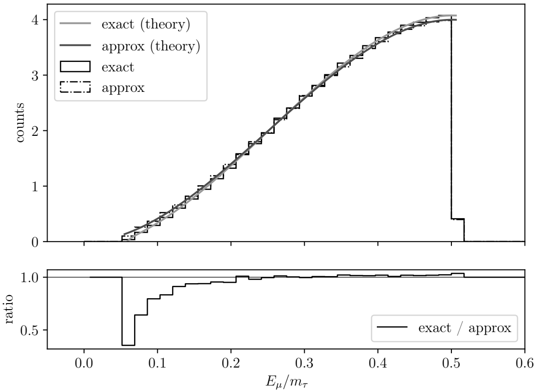
Leptonic Decay

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

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



Outlook: matrix elements for hadronic modes (was not necessary for IceCube, only requiring a smooth spectrum)

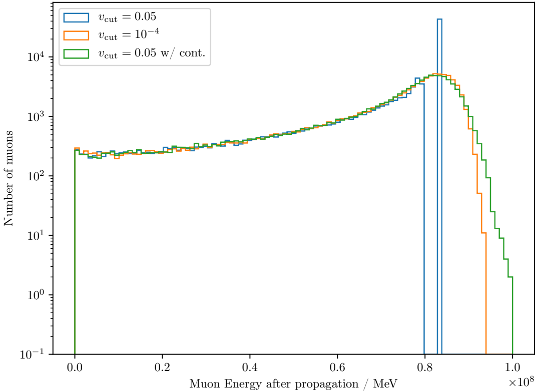
Propagation Improvements

- Continuous Randomization
- Multiple parametrizations for cross sections
- Multiple parametrizations for multiple scattering
- Interpolation tables
- Further parameter for the trade-off between performance and precision

Continuous Randomization of the E_f

- lower energy cut means higher precision, but more calculation time and secondaries to deal with
- higher energy cut results in less precision and artifacts in final muon energy spectrum
- muons without a stochastic loss are all treated the same

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



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

cross section parametrizations

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

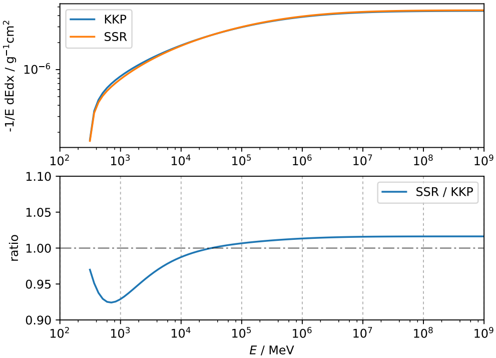
- real photon assumption
  - Kokoulin
  - Rhode
  - BezrukovBugaev
  - Zeus

  with hard and soft component
- Regge Theory
  - AbramowiczLevinLevyMaor91
  - AbramowiczLevinLevyMaor97
  - ButkevichMikheyev
  - RenoSarcevicSu

  with shadowing
  - ButkevichMikheyev
  - DuttaRenoSarcevicSeckel

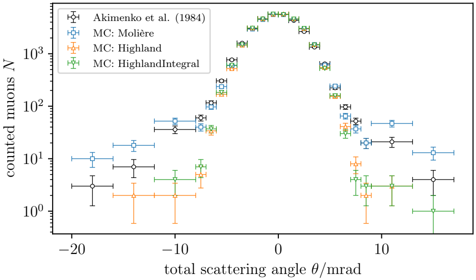
New Cross Sections

- improved tree-level cross sections based on current standard parametrizations for bremsstrahlung and pair production
- radiative corrections for bremsstrahlung
- corrections of several percent
- current used parametrizations are still the default



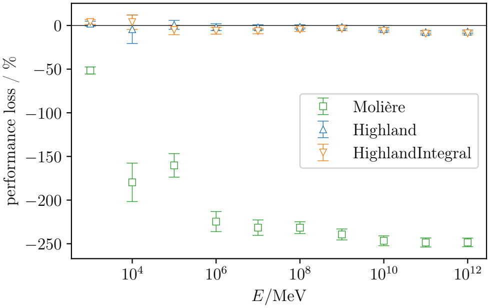
Multiple Scattering

- Molière
  - analytic, precise
  - slow, depending on number of components in medium
- Highland
  - gaussian approximation to Molière
  - two types available: one including continuous losses (default) and one without
- no scattering



Multiple Scattering

- Molière
  - analytic, precise
  - slow, depending on number of components in medium
- Highland
  - gaussian approximation to Molière
  - two types available: one including continuous losses (default) and one without
- no scattering



Desiderata

- Density currently part of medium
  - each medium has its own interpolation tables
  - Maximilian currently investigates how large the non-linear effects of the density are (interpolation)
- Magnetic field deflection
  - We have basically worked out how to implement this
  - Jean-Marco will take care of that
- Propagation of electrons/positrons
  - Was taken care of in IceCube by other MC
  - 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
  - Jan and Alexander have discussed how to do this and will take care of it