Improvements in the high-energy lepton propagator PROPOSAL

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E5b

Introduction

- **PROPOSAL**: Tool to propagate charged leptons
    - $\rightarrow$ MC simulations, multivariate statistics
- **Requirements:** Accuracy, performance
- **Processes:** Energy losses, scattering, decays
- Possibility to use **different parametrizations** $\rightarrow$ Study **systematic uncertainties**
- C++ library with Python bindings

Propagation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} \underset{?}{\Longrightarrow} \text{energy losses}$$

Propagation

$$v < v_{\text{cut}} \qquad v > \qquad v_{\text{cut}}$$

continuous losses   stochastic losses

$$\text{with } v_{\text{cut}} = \min\left[e_{\text{cut}}/E, v'_{\text{cut}}\right]$$

Propagation

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┌─────────────────────────────┐          ┌ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┐
│  Calculate energy at which  │ ◁ ─ ─ ─ ─                           ┆
│  a stochastic loss occurs   │                                     ┆
└─────────────────────────────┘                                     ┆
              │                                                      ┆
              ▼                                                      ┆
┌─────────────────────────────┐      ┌──────────────────────────────┐
│ Calculate type of stochastic│      │  Repeat until $E < e_0$ or    │
│             loss            │      │ particle reaches section border│
└─────────────────────────────┘      └──────────────────────────────┘
              │                                     ▲
              ▼                                     ┆
┌─────────────────────────────┐                     ┆
│ Sample the stochastic energy│ ─ ─ ─ ─ ─ ─ ─ ─ ─ ─ ┘
│          loss via:          │
│                             │
└─────────────────────────────┘
```

Calculate energy at which a stochastic loss occurs

Calculate type of stochastic loss

Sample the stochastic energy loss via:

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

Repeat until $E < e_0$ or particle reaches section border
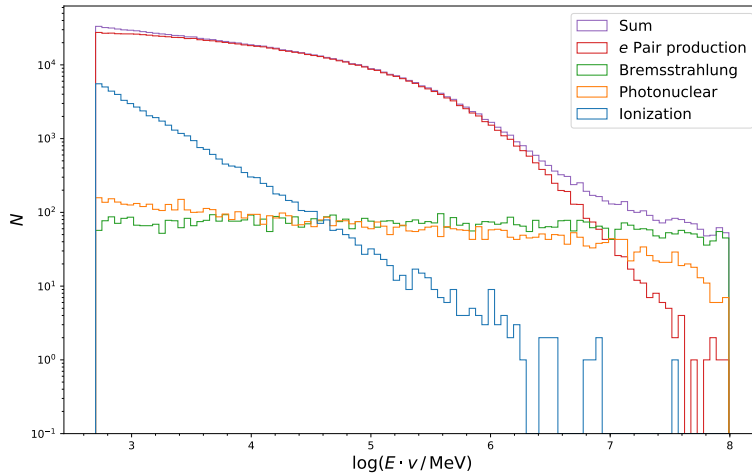
Standard interactions:

- e pair production
- Bremsstrahlung
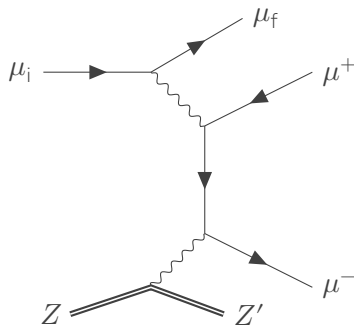- Photonuclear
- Ionization

Rare interactions:

- μ pair production
- Weak interaction
- → Negligible contribution to overall energy loss
- → Observable, interesting signature

Propagation of 10^4 muons with energy 10^8 MeV through 100 m of standard rock.

Direct Production of Muon Pairs

With the energy fraction transferred to the muon pair:

$$v = \frac{(\epsilon_+ + \epsilon_-)}{E}$$

With the asymmetry parameter:

$$\rho = \frac{(\epsilon_+ - \epsilon_-)}{(\epsilon_+ + \epsilon_-)}$$

E: Initial energy of the incoming muon μ_i
$\epsilon_\pm$: Energy of the produced (anti)muon

Double-differential cross section

For production of muon pairs [1]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v\mathrm{d}\rho} = \frac{2}{3\pi}(Z\alpha r_\mu)^2\frac{1-v}{v}\Phi(v,\rho)\ln(X)$$

For production of electron positron pairs [2]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v\mathrm{d}\rho} = \frac{2}{3\pi}Z(Z+\xi)(\alpha r_e)^2\frac{1-v}{v}\left(\Phi_e + \frac{m_e^2}{m_\mu^2}\Phi_\mu\right)$$

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[1] Kelner, Kokoulin, Petrukhin: Phys. of Atomic Nuclei, Vol. 63, No. 9, 2000, pp. 1603-1611
[2] Kokoulin, Petrukhin: Proceedings of 12th ICCR, 1971, p. 2436

Continous energy loss per distance

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = E \frac{N_A}{A} \int_{v_{\min}}^{v_{\mathrm{cut}}} v \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}v$$

with

$$v_{\min} = \frac{2m_\mu}{E},$$

$$v_{\max} = 1 - \frac{m_\mu}{E}.$$
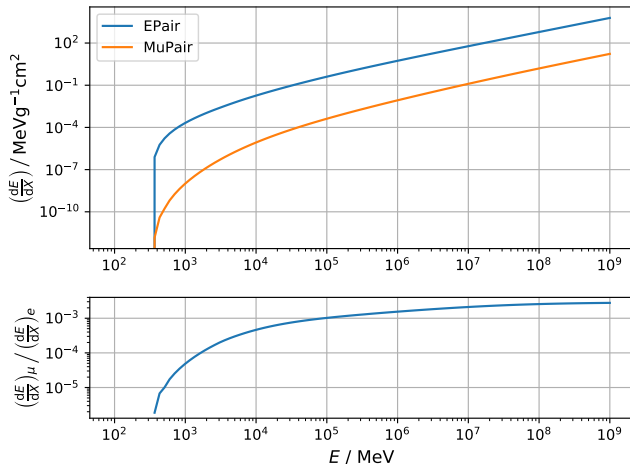
Comparison of e-pair and μ-pair production, only continous losses (i.e. $v_{\mathrm{cut}} = v_{\max}$).
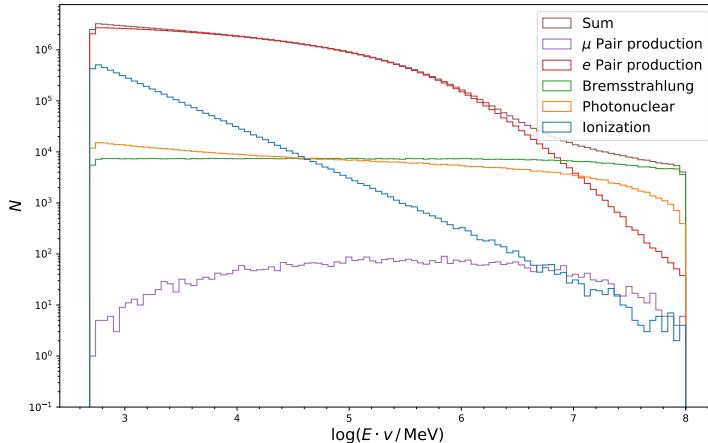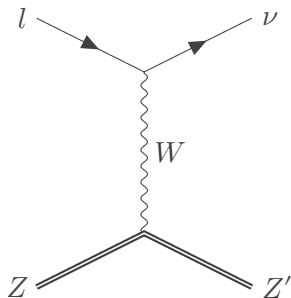
process	N / N_{ges}	E / E_{ges}
e pairp.	0,94	0,94
Ioniz.	$4 \cdot 10^{-2}$	$5 \cdot 10^{-2}$
Brems.	$1 \cdot 10^{-2}$	$7 \cdot 10^{-3}$
Photon.	$8 \cdot 10^{-3}$	$6 \cdot 10^{-3}$
μ pairp.	$6 \cdot 10^{-5}$	$5 \cdot 10^{-5}$

Stochastic losses in standard rock of 10^6 muons with $E = 10^8$ MeV, $e_{\text{cut}} = 500$ MeV, $v_{\text{cut}} = 5 \cdot 10^{-2}$.
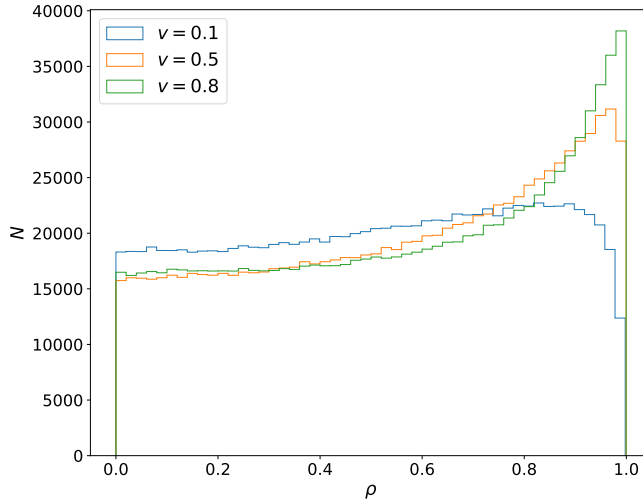
Sampling of ρ for muons with $E = 1 \cdot 10^6$ MeV and different v in standard rock.

Weak interaction

- Highly suppressed process
- Similarities with "lollipop" signature in τ-events
- Crossing symmetry [3]:

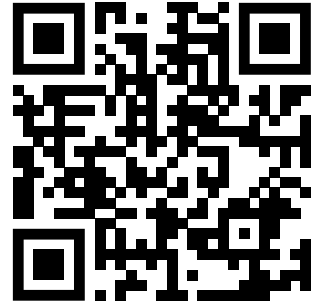$$\mathrm{d}\sigma\left(\mu Z \to \nu_\mu Z\right) = \frac{1}{2}\mathrm{d}\sigma\left(\nu_\mu Z \to \mu Z\right)$$

[3]Sandrock, Alexander: Higher-order corrections to the energy loss cross sections of high-energy muons, 2018, pp. 38-40

Future: Physical improvements in PROPOSAL

- Improvement of electron propagation
- Propagation of high-energy photons
- Deflection of particles in magnetic fields
- Propagation through media with non-homogenous density

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

https://arxiv.org/abs/1809.07740