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e5 experimentelle physik 5
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Particle propagation for CORSIKA in PROPOSAL

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Technische Universität Dortmund

Introduction

- **PROPOSAL**: Tool to propagate particles through media
  - → MC simulations, multivariate statistics
- **Requirements:** Accuracy, performance
- **Processes:** Energy losses, scattering, decays
- C++ library with Python bindings
- GitHub, UnitTests (Travis CI), ...

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

MMC	JAVA
↓	
PROPOSAL v1	C++
↓	
PROPOSAL v2	modern C++ , Polymorphism, ...

PROPOSAL code structure

```
Propagator(const ParticleDef&,
           const std::vector<Sector::Definition>&,
           const Geometry&,
           const InterpolationDef&)
```

- `Propagator` as base class to propagate a particle
- Objects owns all information necessary for propagation

```
Propagator(const ParticleDef&,
           const std::vector<Sector::Definition>&,
           const Geometry&,
           const InterpolationDef&)
```

- `ParticleDef` includes static information about particle

→ Wide range of predefined particles available

→ Modular structure: Simple creation of additional particles:

```
ParticleDef new_mu = ParticleDef::Builder().SetMass(1000).build();
```

```
Propagator(const ParticleDef&,
           const std::vector<Sector::Definition>&,
           const Geometry&,
           const InterpolationDef&)
```

- List of `Sector::Defintion` objects

→ *Chain of resposibility*: Propagation of our particle through several sectors

→ Each `Sector` object is responsible for the propagation within its borders

Parameter	Description
`Medium`	Medium of the sector
`EnergyCutsSettings`	Stores e_{cut} and v_{cut}
`Geometry`	Geometry of the sector
`stopping_decay`	Whether to force a final decay of the particle if its energy is $\leq e_{\text{low}}$
`cont_rand`	Whether to use continuous randomization
`exact_time`	Whether to calculate the time exactly out of the tracking integral or to use $v = c$ as an approximation
`scattering_model`	Choice of the multiple scattering model
`particle_location`	Location of the particle
`utility_def`	Definition of cross section parameters

`Sector::Defintion` properties, adapted from arXiv:1809.07740

```
Propagator(const ParticleDef&,
           const std::vector<Sector::Definition>&,
           const Geometry&,
           const InterpolationDef&)
```

- Geometry describing the detector
- Different options for particle infront / inside / below the detector volume

```
Propagator(const ParticleDef&,
           const std::vector<Sector::Definition>&,
           const Geometry&,
           const InterpolationDef&)
```

- `InterpolationDef` as an optional parameter

→ When used, calculated crosssections (and several derived values) are saved in interpolation tables

→ Error of interpolation compared to integration: $\leq 10^{-5}$

→ Performance increased by several orders of magnitude

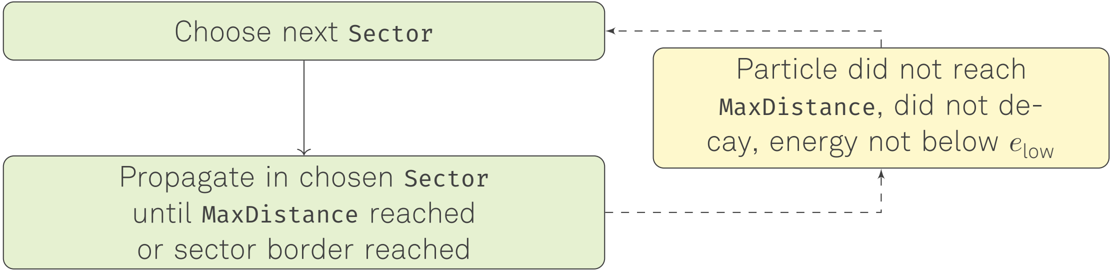
```
Propagator::Propagator(const ParticleDef& particle_def,
                       const std::string& config_file)
```

- Simple usage of a configuration (json) file is possible

```
{
  "global":
  {
    "seed" : 1,
    "continous_loss_output" : false,
    "only_loss_inside_detector" : false,

    "interpolation":
    {
      "do_interpolation" : true,
      "path_to_tables" : ["resources/tables"],
    },

    "exact_time" : true,
    "stopping_decay" : true,
    "scattering" : "Highland",

    "brems" : "BremsAndreevBezrukovBugaev",
    "photo" : "PhotoButkevichMikhailov",
    "lpm" : false,
    "photo_hard_component" : true,
    "photo_shadow" : "ShadowButkevichMikhailov",
  },

  "sectors": [
    {
      "hierarchy": 0,
      "medium": "ice",
      "density_correction": 1,

      "geometry":
      {
        "shape": "sphere",
        "origin": [0, 0, 0],
        "outer_radius": 6374134000000,
        "inner_radius": 0
      },
      ...
```

Propagation algorithm

```
std::vector<DynamicData*> Propagator::Propagate(double MaxDistance_cm)
```



```
double Sector::Propagate(double distance)
```

Remember: Differentiate between continuous losses and stochastic losses !

$v < v_{\text{cut}}$
continuous losses

$v > v_{\text{cut}}$
stochastic losses

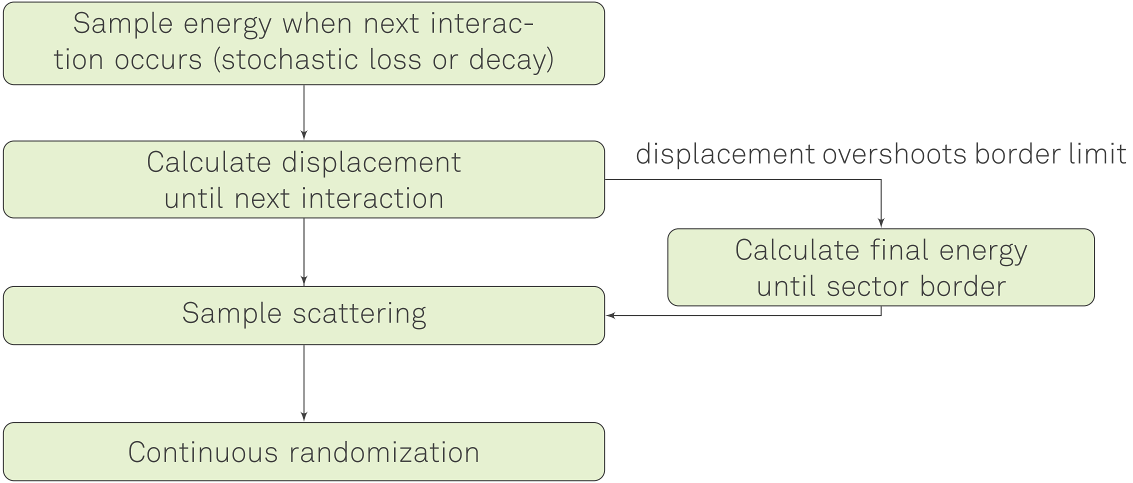
with $v_{\text{cut}} = \min\left[{}^{e_{\text{cut}}}/E, {v'}_{\text{cut}}\right]$

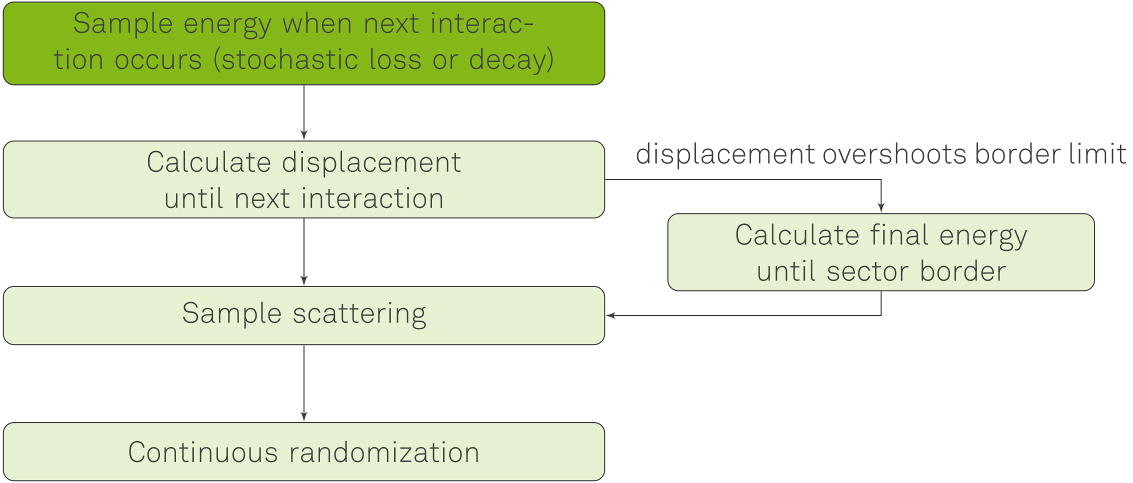
```
double Sector::Propagate(double distance)
```

Remember: Differentiate between continuous losses and stochastic losses !

stoch. stoch. stoch.

$$- - - - - - - \dashrightarrow * \xrightarrow[\text{continuous}]{\hspace{6em}} * \xrightarrow[\text{continuous}]{\hspace{6em}} * - - - - - - - \dashrightarrow$$


Sample energy when next interaction occurs (stochastic loss or decay)
Calculate displacement until next interaction
displacement overshoots border limit
Calculate final energy until sector border
Sample scattering
Continuous randomization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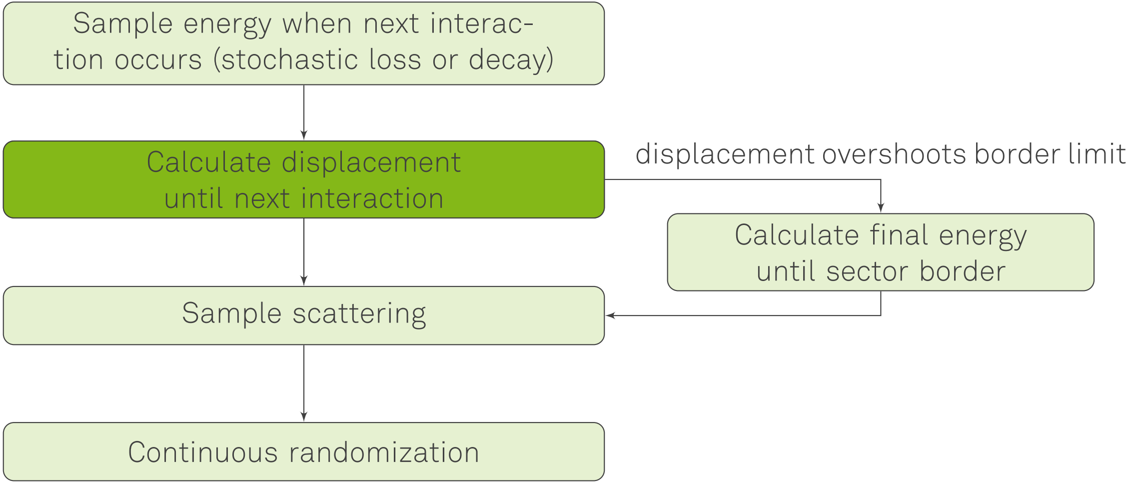
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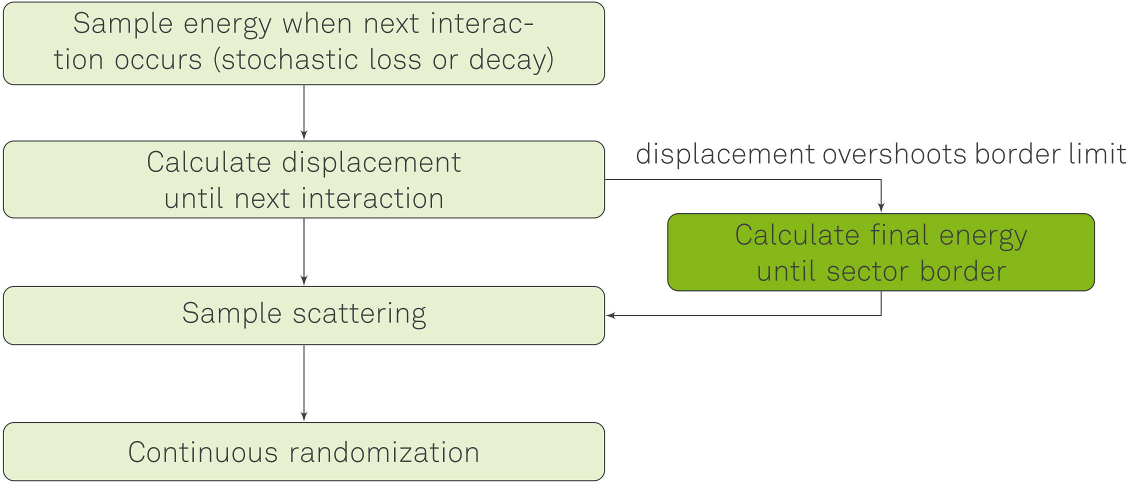
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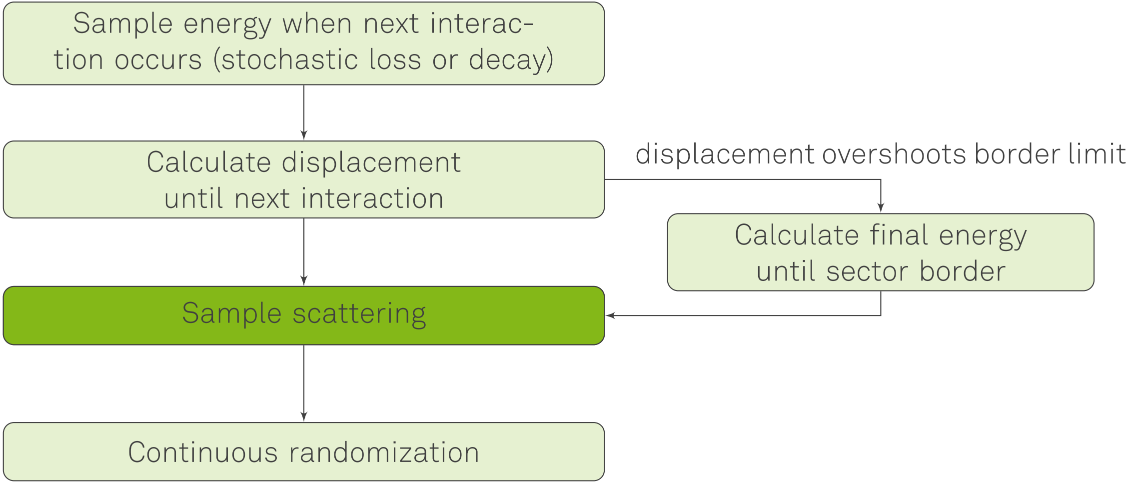
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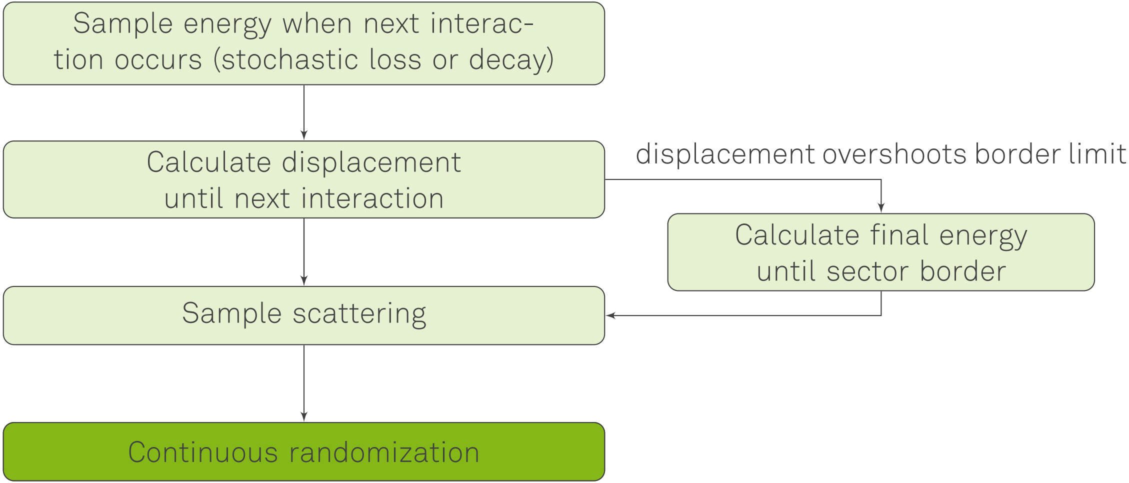
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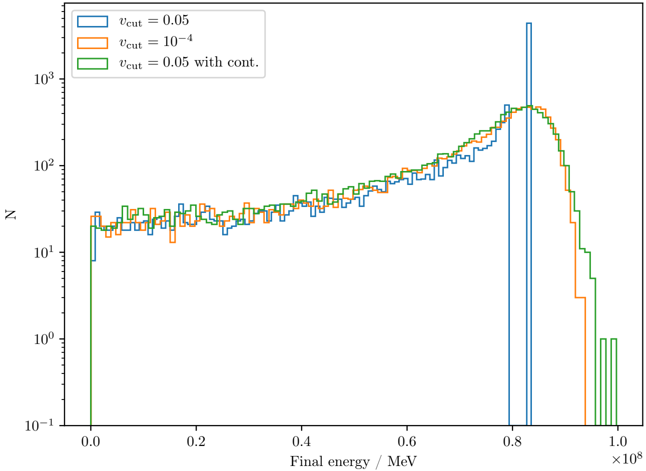


Propagation of 10^4 muons with energy 10^8 MeV through 300 m of standard rock.

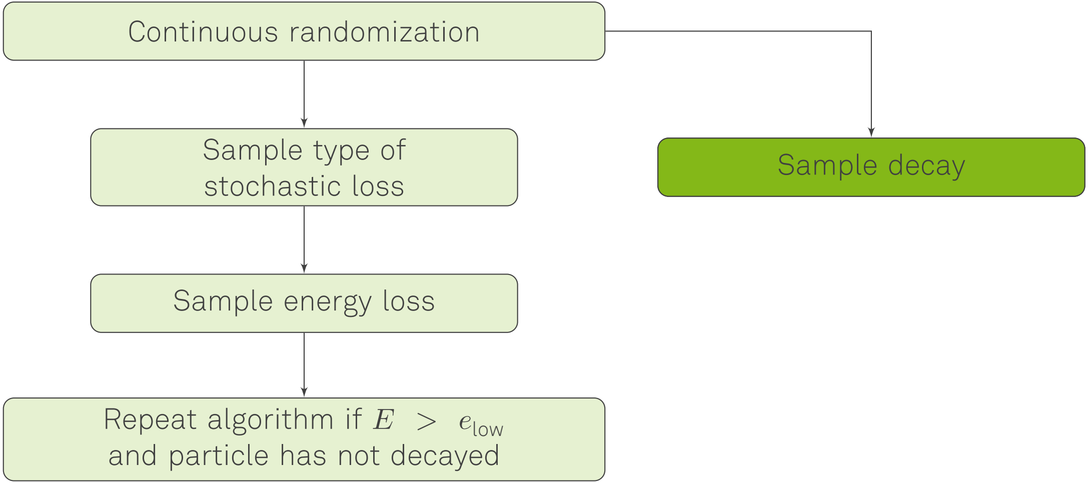
Continuous randomization

Sample type of
stochastic loss

Sample decay

Sample energy loss

Repeat algorithm if $E > e_{\text{low}}$
and particle has not decayed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Sample energy loss
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Continuous randomization

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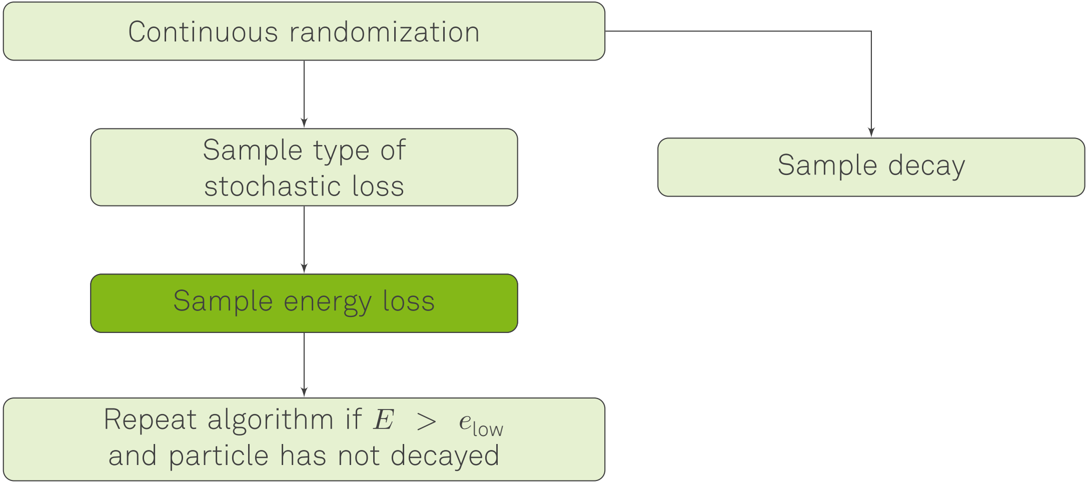
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Sample decay

Continuous randomization

Sample type of stochastic loss

Sample energy loss

Repeat algorithm if $E > e_{\text{low}}$ and particle has not decayed

Sample decay

```
std::vector<DynamicData*> Propagator::Propagate(double MaxDistance_cm);
```

Return value: List of `DynamicData` objects, including

1. Stochastic losses (type, energy, position, time, ...)
2. Decay particles (no redundant static information!)
3. Produced particles (e.g. muon pair)
4. (Continuous losses)

C++ code example

```
Propagator prop(MuMinusDef::Get(), "resources/config.json");
Particle& mu = prop.GetParticle();
Particle mu_backup(mu);

mu_backup.SetEnergy(9e6); //energy in MeV
mu_backup.SetDirection(Vector3D(0, 0, -1));

std::vector<double> ranges;

for (int i = 0; i < 10; i++){
    mu.InjectState(mu_backup);
    prop.Propagate();
    ranges.push_back(mu.GetPropagatedDistance());
}
```

Python code example

```
prop = pp.Propagator(particle_def=pp.particle.MuMinusDef.get(),
                     config_file="path/to/config.json")
mu = prop.particle
mu_backup = pp.particle.Particle(mu)

mu_backup.energy = 9e6 #energy in MeV
mu_backup.direction = pp.Vector3D(0, 0, -1)

ranges = []

for i in range(10):
    mu.inject_state(mu_backup)
    secondaries = prop.propagate()
    ranges.append(prop.particle.propagated_distance)
```

PROPOSAL changes for CORSIKA

Displacement calculation

$$-f(E) = \sum_{\text{crosssec.}} \sum_{\text{comp.}} \frac{\mathrm{d}E}{\mathrm{d}x}$$

Homogeneous medium:

$$-f(E)\,\rho_0 = \frac{\mathrm{d}E}{\mathrm{d}x}$$

$$\mathrm{d}x = -\frac{1}{\rho_0}\frac{\mathrm{d}E}{f(E)}$$

$$x_f = x_i - \frac{1}{\rho_0}\int_{E_i}^{E_f}\frac{\mathrm{d}E}{f(E)}$$

Non-homogeneous medium

$$-f(E)\,\rho(x) = \frac{\mathrm{d}E}{\mathrm{d}x}$$

$$\mathrm{d}x\,\rho(x) = -\frac{\mathrm{d}E}{f(E)}$$

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

solve for x_f

Future work

- Check / include cross sections for electron / positron propagation
- Photon propagation

→ Comparison with EGS4

- Magnetic field deflection

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.

Backup slides

Propagation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} \underbrace{\longrightarrow}_{?} \text{energy losses}$$

Propagation

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

continuous losses

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

stochastic losses

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

Propagation

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:

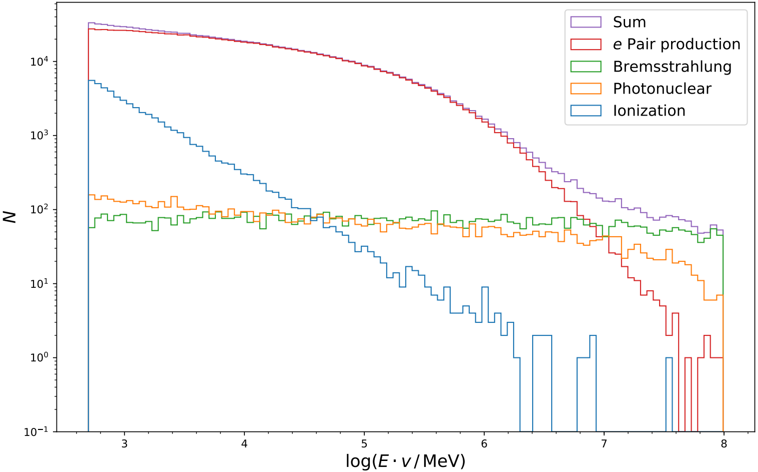
- e pair production
- Bremsstrahlung
- Photonuclear
- Ionization

Rare interactions:

- μ pair production
- Weak interaction

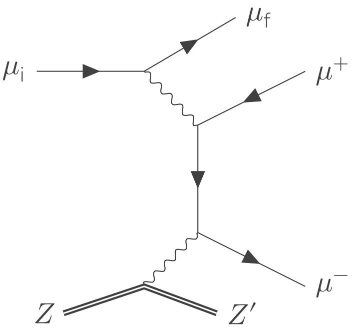
→ Negligible contribution to overall energy loss

→ Observable, interesting signature



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

Direct Production of Muon Pairs



Energy fraction transferred to the muon pair:

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

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]:

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

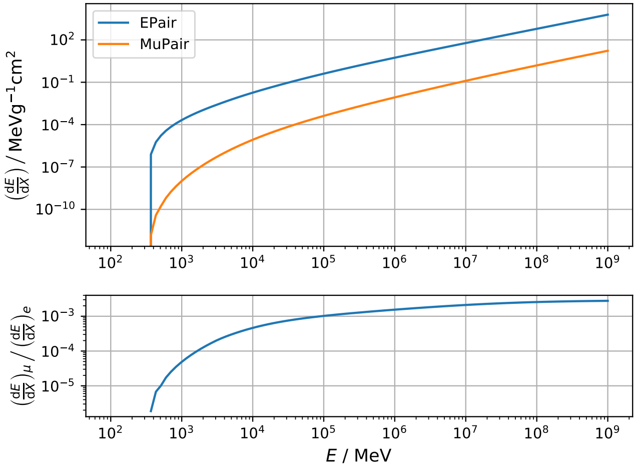
[1] Kelner, Kokoulin, Petrukhin: Phys. of Atomic Nuclei, Vol. 63, No. 9, 2000, pp. 1603-1611
[2] Kokoulin, Petrukhin: Proceedings of 12th ICCR, 1971, p. 2436

Continous energy loss per distance

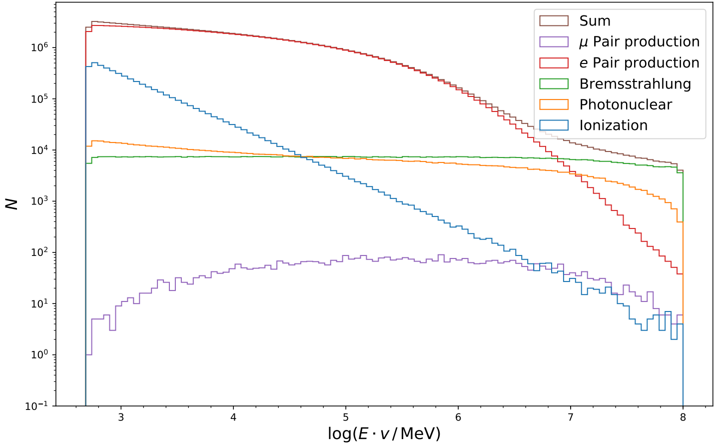
$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = E \frac{N_{\mathrm{A}}}{A} \int_{v_{\mathrm{min}}}^{v_{\mathrm{cut}}} v \frac{\mathrm{d}\sigma}{\mathrm{d}v} \mathrm{d}v$$

with

$$v_{\mathrm{min}} = \frac{2m_\mu}{E},$$
$$v_{\mathrm{max}} = 1 - \frac{m_\mu}{E}.$$

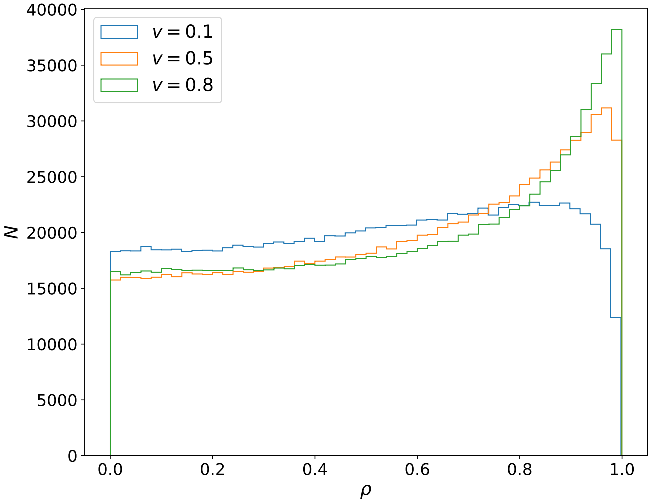


Comparion of e-pair and μ-pair production, only continous losses (i.e. $v_{\mathrm{cut}} = v_{\mathrm{max}}$).



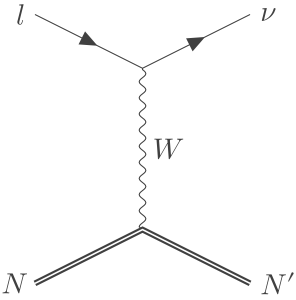
process	$N\,/\,N_{\mathrm{ges}}$	$E\,/\,E_{\mathrm{ges}}$
e pairp.	0,94	0,94
Ioniz.	$4 \cdot 10^{-2}$	$5 \cdot 10^{-2}$
Brems.	$1 \cdot 10^{-2}$	$7 \cdot 10^{-3}$
Photon.	$8 \cdot 10^{-3}$	$6 \cdot 10^{-3}$
μ pairp.	$6 \cdot 10^{-5}$	$5 \cdot 10^{-5}$

Stochastic losses, standard rock, 10^6 muons with $E = 10^8$ MeV, $e_{\mathrm{cut}} = 500$ MeV, $v_{\mathrm{cut}} = 5 \cdot 10^{-2}$.



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]:

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

[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

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