FLUKA simulations of neutrino-induced dose

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Context

- Neutrinos from muon± decays can lead to non-negligible dose levels

- Main features:
  - No benefit from shielding (possibly detrimental)
  - Highly collimated radiation cone (width ~ 1/γ) emerging on the earth surface
  - Neutrino cross sections dominated by Deep Inelastic Scattering and approximately proportional to energy

- Previous work:
  - More recent presentations by D. Schulte (18/01/21) and C. Carli (8/03/21)
Requirements for a full dose assessment in real scenarios

1. **DOSE KERNEL**: dose (or dose-equivalent) in a reference material vs longitudinal and lateral distance from fixed-point decay of monoenergetic and mono-directional muons, per unit muon decay.

2. Folding with **BEAM PARAMETERS** taking into account space distribution of muon decays (e.g., along arc or straight sections), angular divergence (due to optics) and beam intensity.

3. Merging the real-world geometry to obtain a realistic **DOSE SURFACE MAP** using dedicated tools (e.g., GeoProfiler).
A FLUKA simulation framework was set up to calculate the dose kernel

Two-step approach:

1. MUON DECAY SIMULATION
   - Yields as output a list of emitted neutrinos with their flavour, energy and angle (in the lab frame)
   - Allows to ‘filter’ the list of neutrinos according to the macroscopic cross section in a reference material (e.g. soil) to obtain distributions of interacting neutrinos

2. NEUTRINO INTERACTION SIMULATION
   - Takes as input the list of interacting neutrinos obtained in the 1st step (i.e. with cross section filter)
   - Samples uniformly the distance of the neutrino interaction with respect to the muon decay point, within a user-defined range
   - Computes the x-y-z position of the neutrino interaction from the sampled distance and the angular direction read from the input
   - Scores 3D distribution of any relevant quantity supported by FLUKA (e.g., absorbed dose, dose-equivalent, or more)
FLUKA employs internally-computed (NUNDIS) cross sections on nucleons

- **4 processes** (resonant, quasi-elastic, Deep Inelastic Scattering, charm production) with total values driven by DIS at high energy

- Individual cross sections for:
  - **Neutrino flavours** (e-μ-τ) yielding negligible differences (especially at high energy)
  - **Neutrino vs antineutrino**, with antineutrino cross sections generally lower (around a factor 2)
  - **Target nucleon** (proton vs neutron)

Values to be compared with B. J. King’s

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**Table 1: Contributions to the radiation dose from the different types of neutrino interactions.** The reduced cross-section, $\sigma_{IR}^i$, is specified for 100 GeV neutrinos and using a simple model for the nucleon in which the cross-section ratio for neutrinos to anti-neutrinos was assumed to be 2:1 and ignoring the small differences between the average hadronic fractions for NC and CC interactions. The reduced cross-section and product are in units of $10^{-35}$ cm$^2$/TeV.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{IR}^i$</th>
<th>$k^i$</th>
<th>$&lt;x^2&gt;^i$</th>
<th>$\sigma_{IR}^i \cdot k^i \cdot &lt;x^2&gt;^i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu - CC$</td>
<td>0.722</td>
<td>0.458</td>
<td>0.533</td>
<td>0.176</td>
</tr>
<tr>
<td>$\nu_\mu - NC$</td>
<td>0.226</td>
<td>0.458</td>
<td>0.533</td>
<td>0.055</td>
</tr>
<tr>
<td>$\nu_\tau - CC$</td>
<td>0.722</td>
<td>1.000</td>
<td>0.400</td>
<td>0.289</td>
</tr>
<tr>
<td>$\nu_\tau - NC$</td>
<td>0.226</td>
<td>0.458</td>
<td>0.400</td>
<td>0.041</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu - CC$</td>
<td>0.375</td>
<td>0.292</td>
<td>0.533</td>
<td>0.058</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu - NC$</td>
<td>0.131</td>
<td>0.292</td>
<td>0.533</td>
<td>0.020</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau - CC$</td>
<td>0.375</td>
<td>1.000</td>
<td>0.400</td>
<td>0.150</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau - NC$</td>
<td>0.131</td>
<td>0.292</td>
<td>0.400</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td></td>
<td></td>
<td></td>
<td>0.804</td>
</tr>
</tbody>
</table>
Cross sections vs energy for electron neutrinos and antineutrinos

Comparison with B. J. King’s table (using numbers at 1TeV): generally similar, but individual values can deviate, and differences such as neutron vs proton targets are not considered by B. J. King
Macroscopic neutrino cross sections

- The key normalization parameter of the simulations is the macroscopic cross section $\Sigma$, i.e., the probability of a neutrino interaction per unit distance travelled.
- Our approach: compute it for the material (or compound) of interest as:

$$\Sigma(E) = n_p \cdot \sigma_p(E) + n_n \cdot \sigma_n(E)$$

- This approach considers the exact density of protons/neutrons (including breakdown of isotopes).
- Neglected: Fermi motion (changing effective $E$), Pauli exclusion principle.
FLUKA simulation: 1\textsuperscript{st} step (muon decay)

- Muons with fixed energy (5 TeV for the examples presented in this talk) moving along z are forced to decay at (x, y, z) = (0, 0, 0).

- The neutrino info (id, energy, angle cosines) is written in dump files with probability proportional to the energy-dependent macroscopic cross section in a user-selected material relative to ‘max-E’ neutrinos (i.e. neutrinos with the energy of the decaying muons).

  \[ \text{example: for 5-TeV muons, a neutrino with energy } X < 5\text{TeV is retained with probability } \frac{\Sigma_X}{\Sigma_{5\text{TeV}}} \]

- The above cross sections are calculated automatically in the routine for any material or compound, using the formula in slide 7.
Energy distribution of total and interacting neutrinos

- (anti)neutrino energy spectra before (all) and after (interacting) xsec filtering
- The spectrum of interacting neutrinos peaks at around half the muon energy
- Muon (anti)neutrinos are relatively more energetic than the electron ones

![Energy spectrum of (anti)neutrinos from 5-TeV muon decays](image1)

**ALL**

![Energy spectrum of interacting (anti)neutrinos from 5-TeV muon decays](image2)

**INTERACTING**

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Width of neutrino cone at 10km

- At 10km from the muon decay point, the neutrino beam width is of the order of few tens of cm (i.e., the angular aperture is of the order of the $10^{-5}$ rad)
  → in practice, a narrow cone shall be expected at any distance
The 2\textsuperscript{nd} step simulation uses as source the interaction of the neutrinos written in the output file of the 1\textsuperscript{st} step, \textit{sampling the longitudinal position $L$ of the interactions in a user-selected $[L_{\text{min}}, L_{\text{max}}]$ interval}.

With this method the neutrino interactions are correctly sampled proportionally to the energy-dependent cross sections, and the correlation between energy and angles is kept.

The exact position of each interaction positions is a function of the sampled $L$ and of the angle cosines written in the output file: $(x,y,z) = R^* (tx,ty,tz)$.

\textbf{Our example:}

- neutrino interactions forced in soil (standard FLUKA ‘earth’ compound used for many other applications)
- Scoring of dose-equivalent (in pSv) with EDWORST coefficients (as advised by C. Ahdida)
Dose-eq build-up over 10m in soil: antineutrino-e interactions

- Forcing neutrino interactions in [9990,10000]m range
- The majority of the dose-eq build-up occurs over few metres

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Forcing neutrino interactions in $[9990, 10000]$m range

Again, most of the dose-eq build-up occurs over few metres
Ignoring statistical fluctuations and minor effects, after around ∼5m in soil the dose-eq reaches plateau conditions.
Dose-eq build-up over 10m in soil: 1D projections vs z

- In the case of the muon+ decay, the dose-eq at the plateau is dominated by the electron neutrino component, but the total is similar.
Broader shower in soil: antineutrino-e int. (dose-eq)

- Forcing neutrino interactions in [9750,10000]m range
- Relatively narrow shower, only few low-E muons leaking

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Broader shower in soil: \textit{neutrino-mu} int. (dose-eq)

- Forcing neutrino interactions in \([9750,10000]\)m range
- Broader shower due to high-E muons, but dose-eq peak still at low \(R\)
Broader shower in soil: neutrino-mu int. (muon fluence)

- 2D map of muon fluence, confirming that the dose-eq at high distance from neutrino interactions is due to long-range muons

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Key dose kernel quantity: dose-eq vs R at plateau

- We have seen that the dose-equivalent begins to ‘plateau’ already after few metres of soil.

- Other quantities, such as the muon fluence, take longer distances to plateau (due to the longer muon range) but they yield a relatively small contribution to the dose-eq.

- To obtain the dose kernel we compute the profile vs R of the dose-equivalent at different distances from the muon decay point, taking the ‘plateau’ values as reference.
Example 1: dose-eq vs R at plateau from muon- at 10km

- Very narrow dose-eq peak, as expected from the highly collimated neutrino beam
- Wider dose-eq shape for muon neutrinos compared from electron antineutrinos, with similar contribution at the peak
- Note: the 1D projections vs z in slides 14-15 were showing average dose-eq between R=0 and R=20cm
Example 1: dose-eq vs R at plateau from muon+ at 10km

- Similar lateral width also for the muon+ decays
- In this case the dose peak is dominated by the electron neutrinos, as already seen in slide 15.
Example/2: dose-eq vs R at plateau from muon- at 100km

- More statistical fluctuations at 100km
- The profile is wider, as expected (notice the different R range in the figure)
- The contribution to the dose-eq from muon neutrinos is slightly larger, but electron antineutrinos aren’t negligible, especially at R=0
Example/2: dose-eq vs R at plateau from muon+ at 100km

- Similar dose-eq profile at 100km from muon+ decays too

- In this case, most of the dose-eq near R=0 comes from electron neutrino interactions
To benchmark the FLUKA results with previous calculations, we need to compare the scoring of dose-equivalent (shown so far) with the absorbed dose, simply defined as energy per unit mass (in units of Gy = J/kg).

Note that the plot is showing $L^2 \times D$ vs $R/L$ to better compare different distances.

The dose-eq (expressed in Sv) is about 50% higher.
The FLUKA dose-eq peak is $\sim 1.1 \times 10^{-7}$ pSv/muon.

C. Carli’s calculation yields a peak of $\sim 7 \times 10^{-8}$ pGy/muon, i.e., $\sim 50\%$ less, consistently with the expected difference due to TID vs dose-eq.

→ excellent agreement!

Comparing FLUKA and B. J. King / C. Carli calculations

10 TeV c.o.m. energy, $L_s = 100$ km
Summary: dose-eq vs R at plateau from muon-

- Summary figure of dose-equivalent vs R at different distances from the muon-decay point

- Showing again $L^2D$ vs R/L to better compare different distances

Lateral profile of $D^2$ x dose-equivalent from 5 TeV mu- decay

*visible impact from MC stat fluctuations
Summary: dose-eq vs R at plateau from muon+

- Summary figure of dose-equivalent vs R at different distances from the muon+ decay point
- Showing again $L^2D$ vs $R/L$ to better compare different distances

Lateral profile of $D^2 \times$ dose-equivalent from 5 TeV mu+ decay

*visible impact from MC stat fluctuations
Extra: neutrino-induced dose-eq at soil-air boundary

- Simplified geometry: neutrino beam exiting orthogonally* a soil-air surface

- Study the dose-eq in air from the neutrino interactions in soil only (neglecting the few neutrino interactions in air)

- In the first few metres of air the dose-eq is still relatively high, as expected

*in realistic scenarios small angles should be considered, but this first calculation can already yield interesting insights
I presented the results of FLUKA simulations of neutrino-induced radiation from point-like decays of 5-TeV muons, without angular divergence.

The dose-equivalent vs R maps shall serve as dose kernels for full dose predictions, requiring a convolution with machine parameters (arc/LSS lengths, intensity) and considering the geography of the region.

Good agreement is found with previous calculations by B. J. King and C. Carli, after taking into account a ~50% difference between dose-equivalent and TID.

The build-up of the dose-equivalent in soil and the dose-equivalent decay in air occur within ~few metres (neglecting neutrino interactions upstream and in air respectively).

Next steps:
- simulate more cases (e.g., more muon energies) and quantities
- study the dose-equivalent breakdown in individual particle types (e.g., electrons, hadrons..)
- boost the Monte Carlo statistics as much as possible