International MUON Collider Collaboration

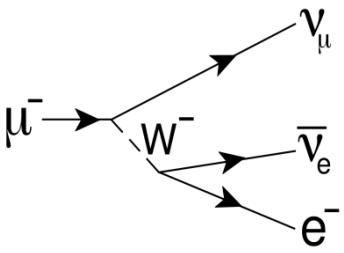
CERN

FLUKA simulations of neutrino-induced dose

G. Lerner, D. Calzolari, A. Lechner, C. Ahdida

Accelerator Design Meeting
31st January 2022

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

Strong dependence on muon energy

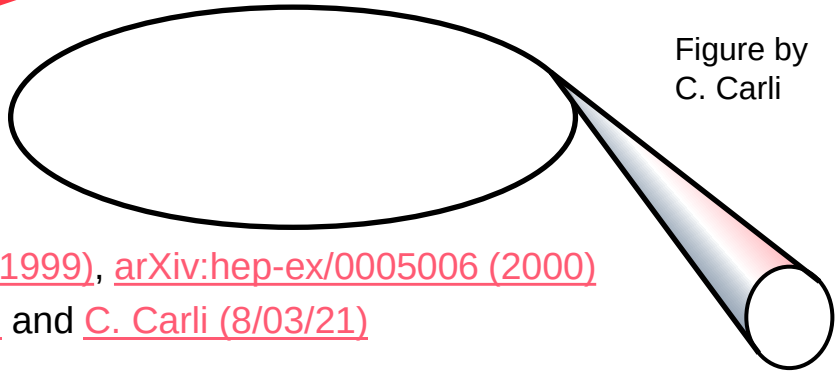


Figure by C. Carli

- Previous work:
  - Calculations by B.J. King:, arXiv:physics/9908017 (1999), arXiv:hep-ex/0005006 (2000)
  - 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

FOCUS OF THIS TALK (for 5-TeV muon beam)

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 the real-world geometry to obtain a realistic **DOSE SURFACE MAP** using dedicated tools (e.g., GeoProfiler)

FLUKA simulation workflow

- 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)

Neutrino cross sections on nucleons in FLUKA /1

- 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 →

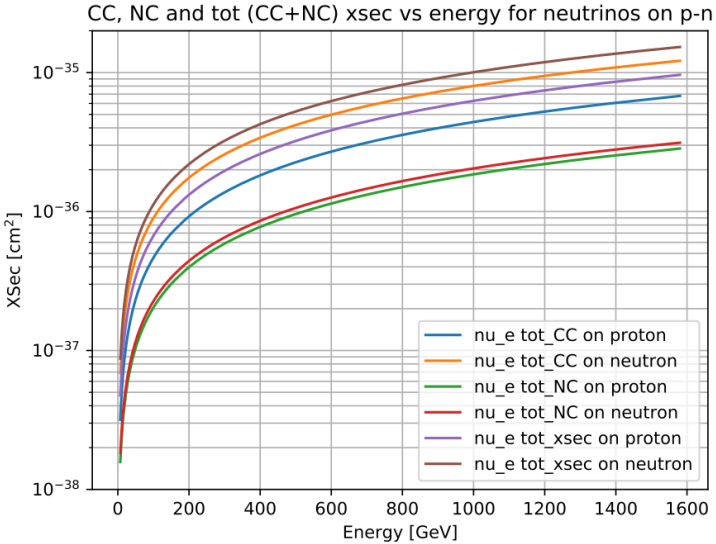
B.J. King neutrino cross sections
from arXiv:physics/9908017 (1999)

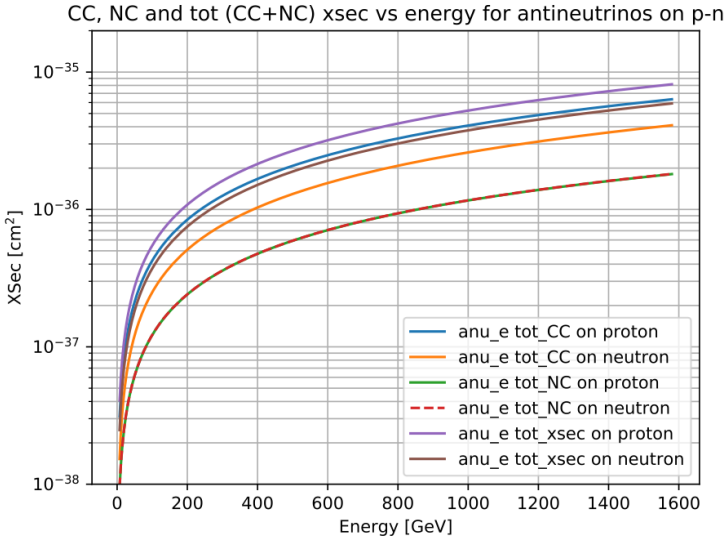
Table 1: Contributions to the radiation dose from the different types of neutrino interactions. The reduced cross-secttion, σ_R^i, is specified for 100 GeV neutrinos and using a simple model for the nucleon in which the cross-section ratio for neutrinos to anti-neutrinos was assumed to be 2:1 and ignoring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

int., i	σ_R^i	k^i	$< x^2 >^i$	$\sigma_R^i \cdot k^i \cdot < x^2 >^i$
$\nu_\mu - CC$	0.722	0.458	0.533	0.176
$\nu_\mu - NC$	0.226	0.458	0.533	0.055
$\nu_e - CC$	0.722	1.000	0.400	0.289
$\nu_e - NC$	0.226	0.458	0.400	0.041
$\overline{\nu_\mu} - CC$	0.375	0.292	0.533	0.058
$\overline{\nu_\mu} - NC$	0.131	0.292	0.533	0.020
$\overline{\nu_e} - CC$	0.375	1.000	0.400	0.150
$\overline{\nu_e} - NC$	0.131	0.292	0.400	0.015
SUM				0.804

Neutrino cross sections on nucleons in FLUKA /2

- 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 Σ**, i.e., the probability of a neutrino interaction per unit distance travelled
- Our approach: compute it for the material (or compound) of interest as:

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

Number density of protons and neutrons in the material (compound)

Neutrino cross section on protons and neutrons

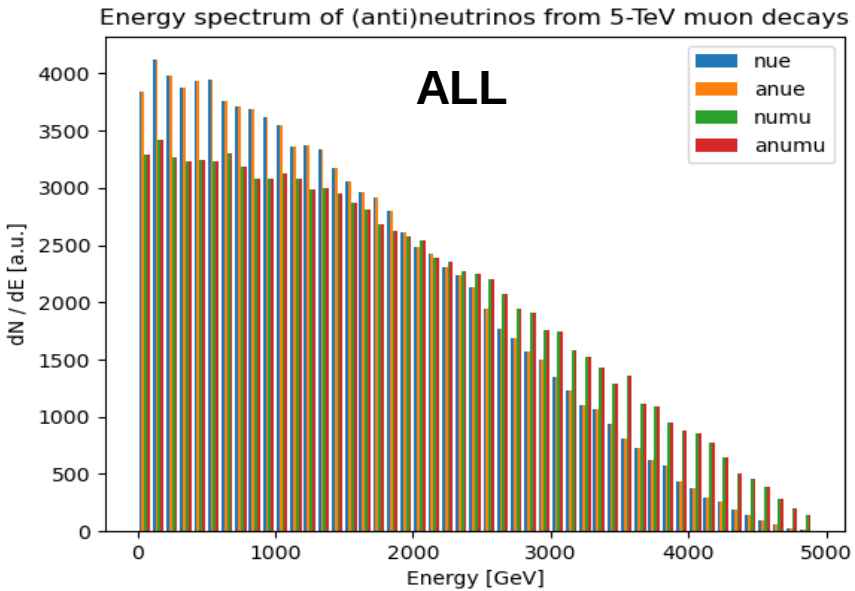
- This approach considers the exact density of protons/neutrons (including breakdown of isotopes)
- Neglected: Fermi motion (changing effective E), Pauli exclusion principle

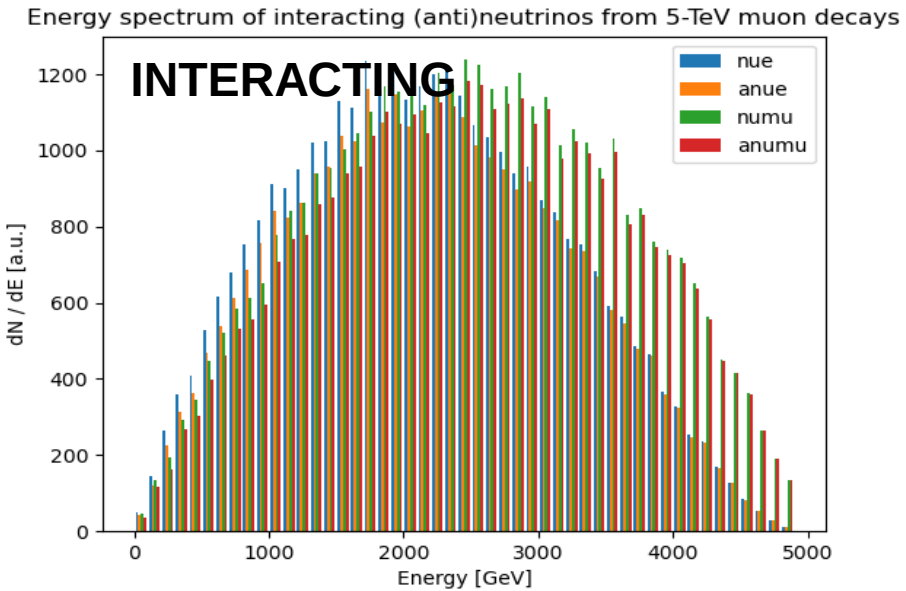
FLUKA simulation: 1st step (muon decay)

- 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)
  → example: for 5-TeV muons, a neutrino with energy X < 5TeV is retained with probability Σ_X / Σ_{5TeV}
- 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

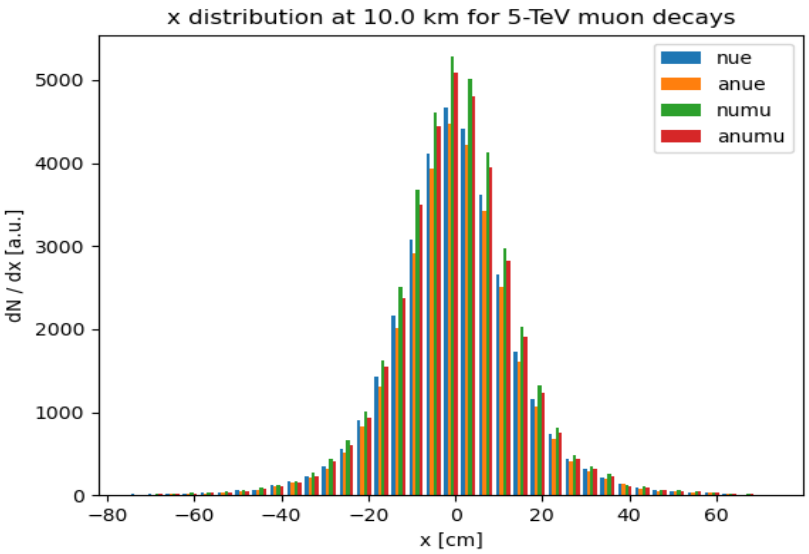
- (anti)neutrino energy spectra before (all) and after (interacting) xsec filtering
- The spectrum of interacting neutrinos peaks at around half the muon energy
- Muon (anti)neutrinos are relatively more energetic than the electron ones

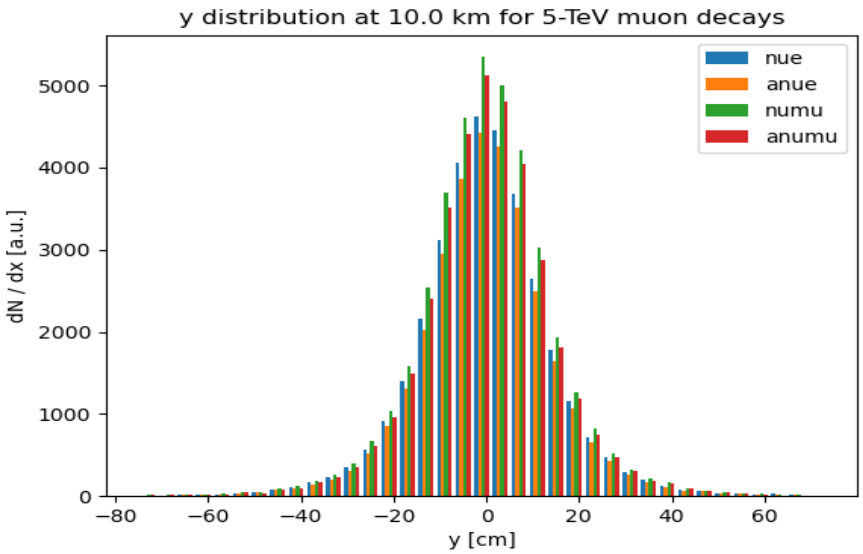




Width of neutrino cone at 10km

- 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

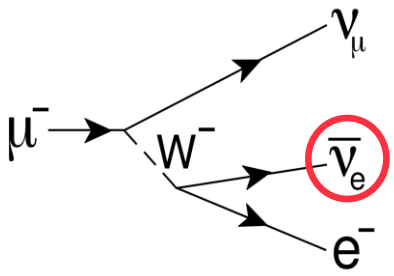


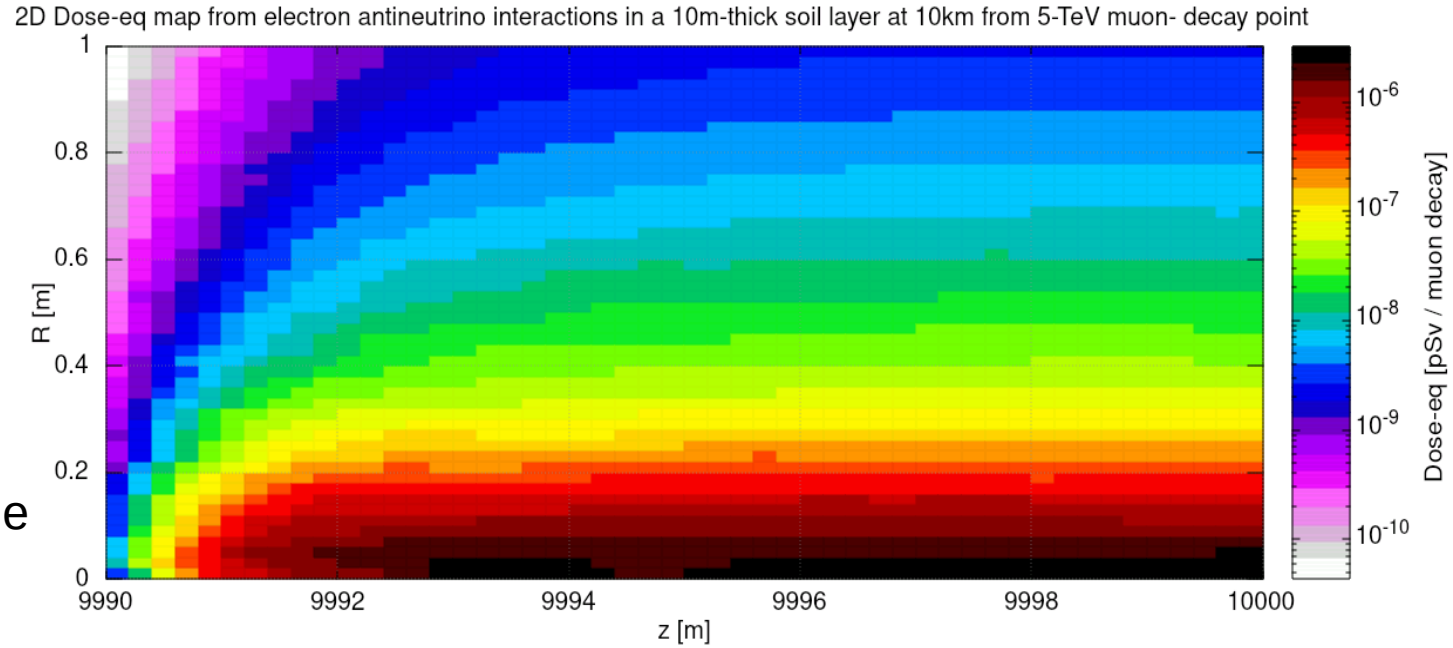


FLUKA simulation: 2nd step (neutrino interactions)

- The 2nd step simulation uses as source the interaction of the neutrinos written in the output file of the 1st step, **sampling the longitudinal position L of the interactions in a user-selected [L_{min},L_{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)
- *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)*

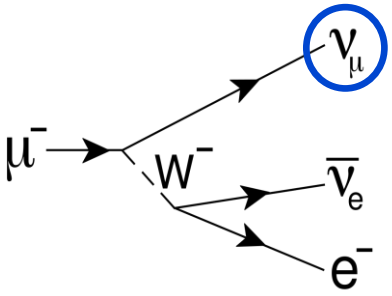
Dose-eq build-up over 10m in soil: antineutrino-e interactions

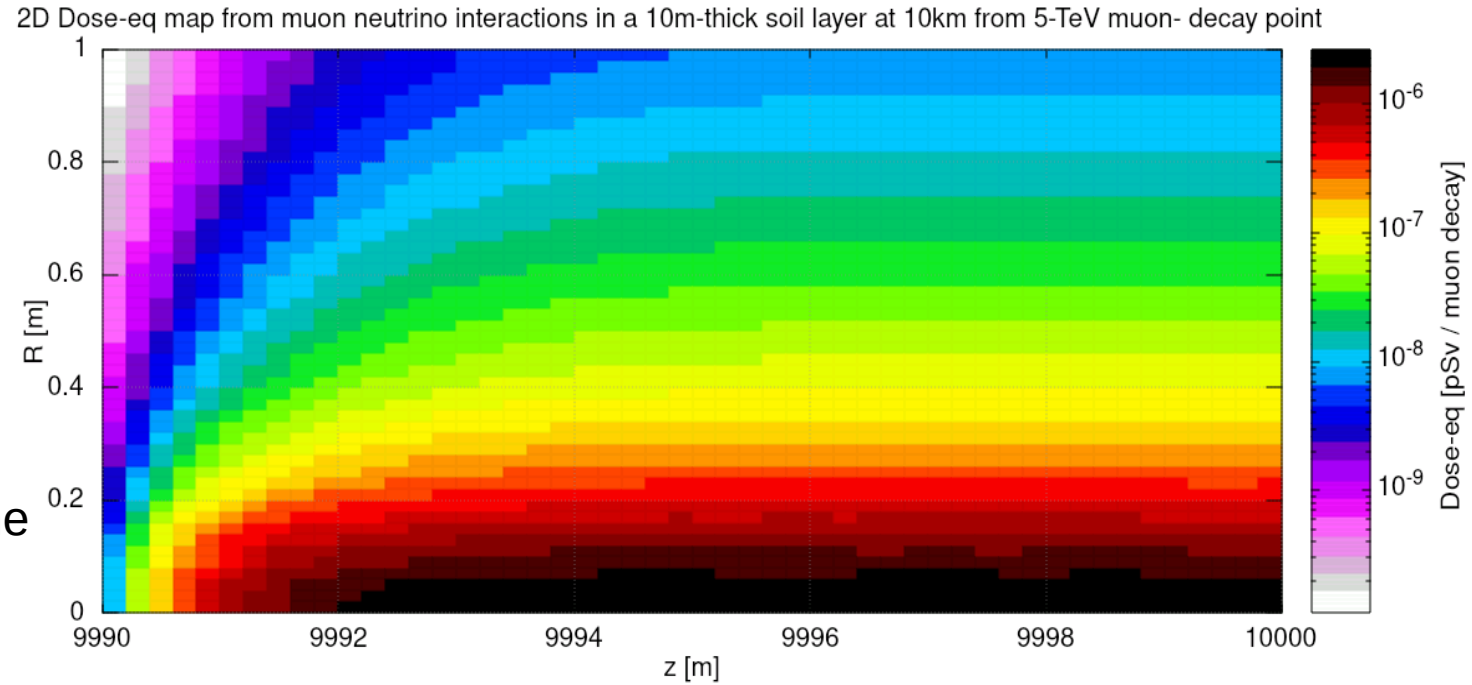




- Forcing neutrino interactions in [9990,10000]m range
- The majority of the dose-eq build-up occurs over few metres

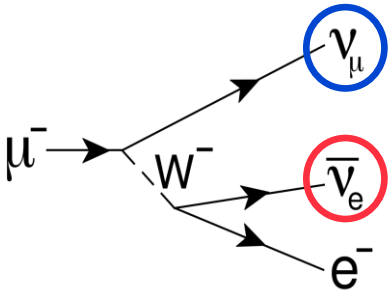
Dose-eq build-up over 10m in soil: neutrino-mu interactions



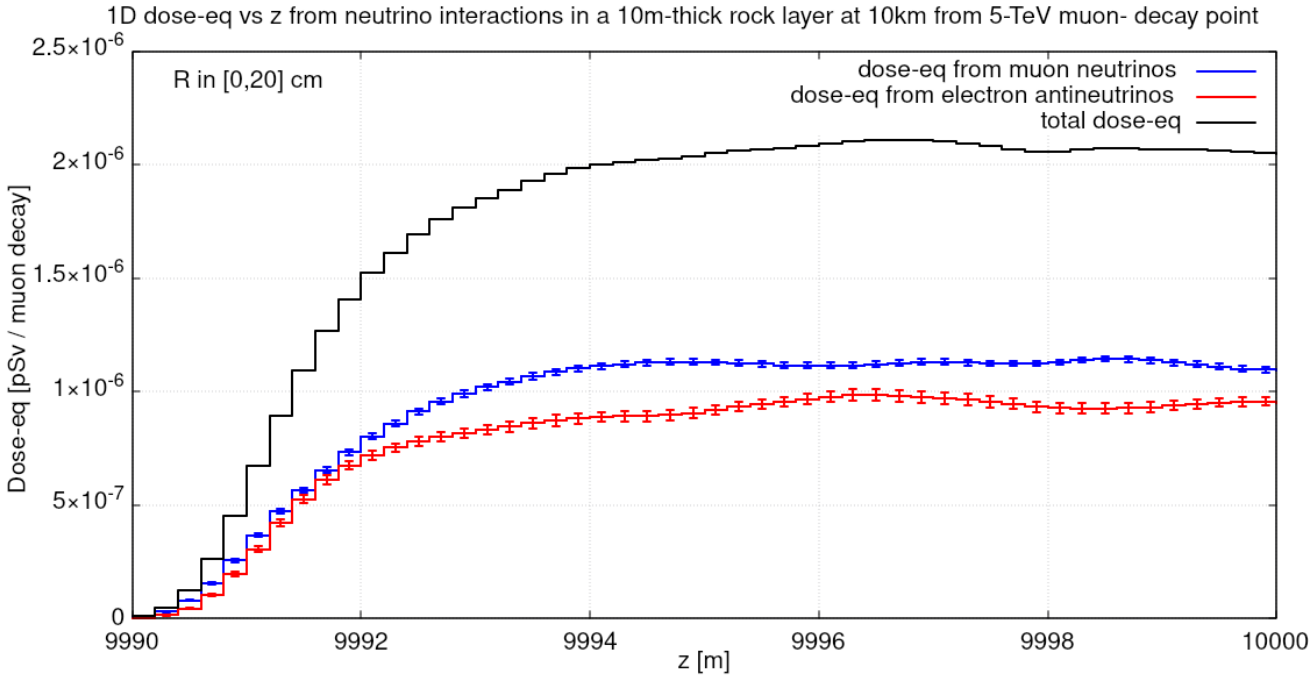


- Forcing neutrino interactions in [9990,10000]m range
- Again, most of the dose-eq build-up occurs over few metres

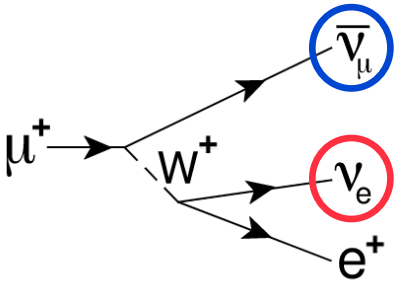
Dose-eq build-up over 10m in soil: 1D projections vs z

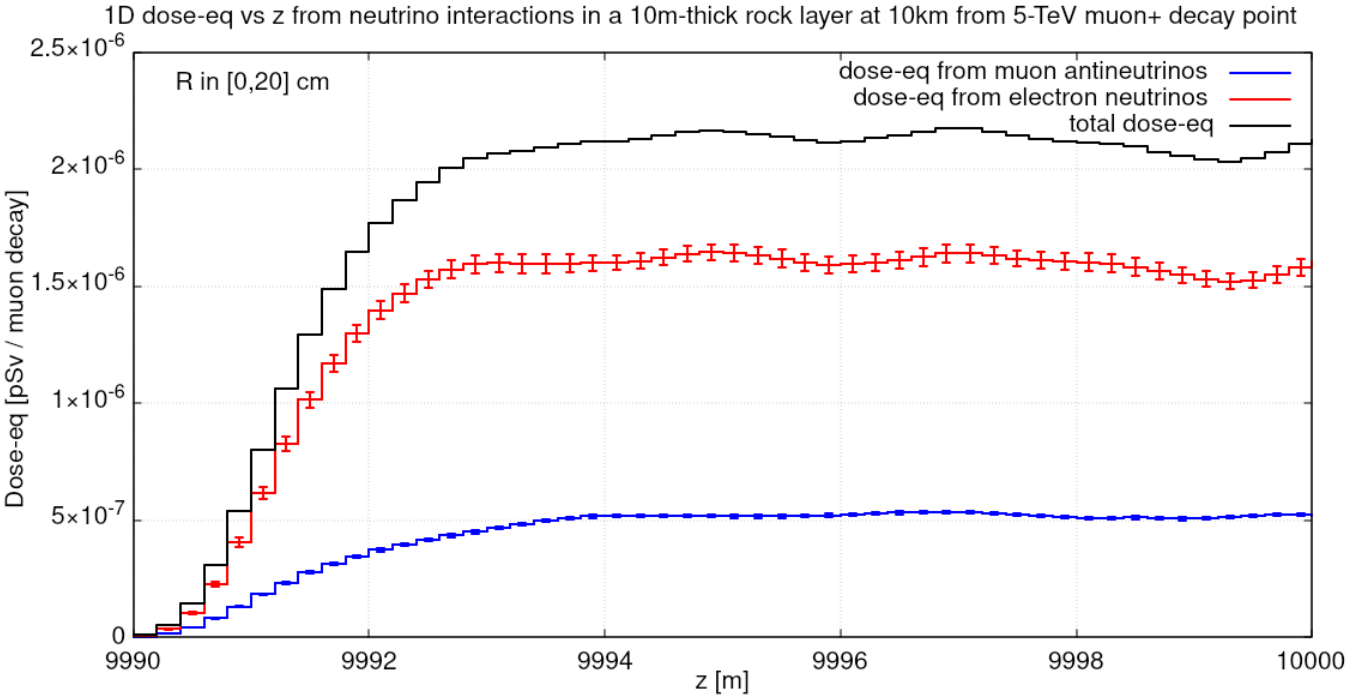


- Ignoring statistical fluctuations and minor effects, after around ~5m in soil the dose-eq reaches plateau conditions



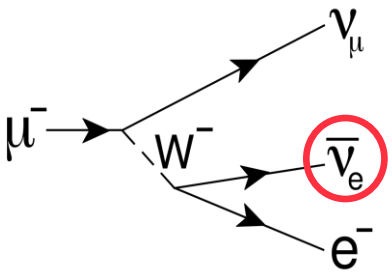
Dose-eq build-up over 10m in soil: 1D projections vs z

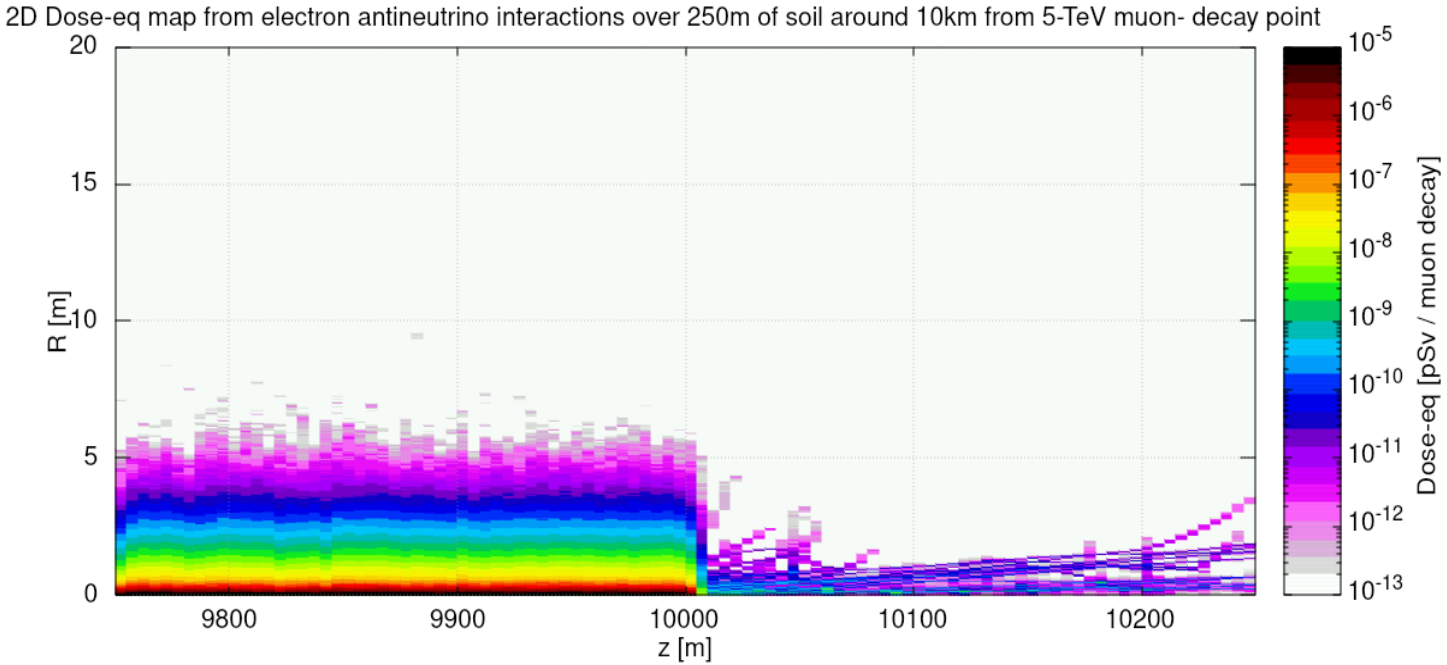




- In the case of the muon+ decay, the dose-eq at the plateau is dominated by the electron neutrino component, but the total is similar

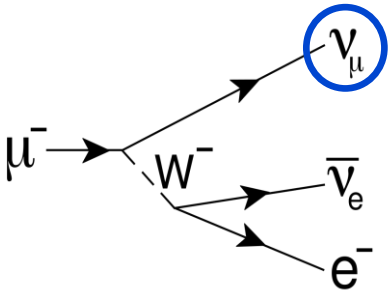
Broader shower in soil: antineutrino-e int. (dose-eq)

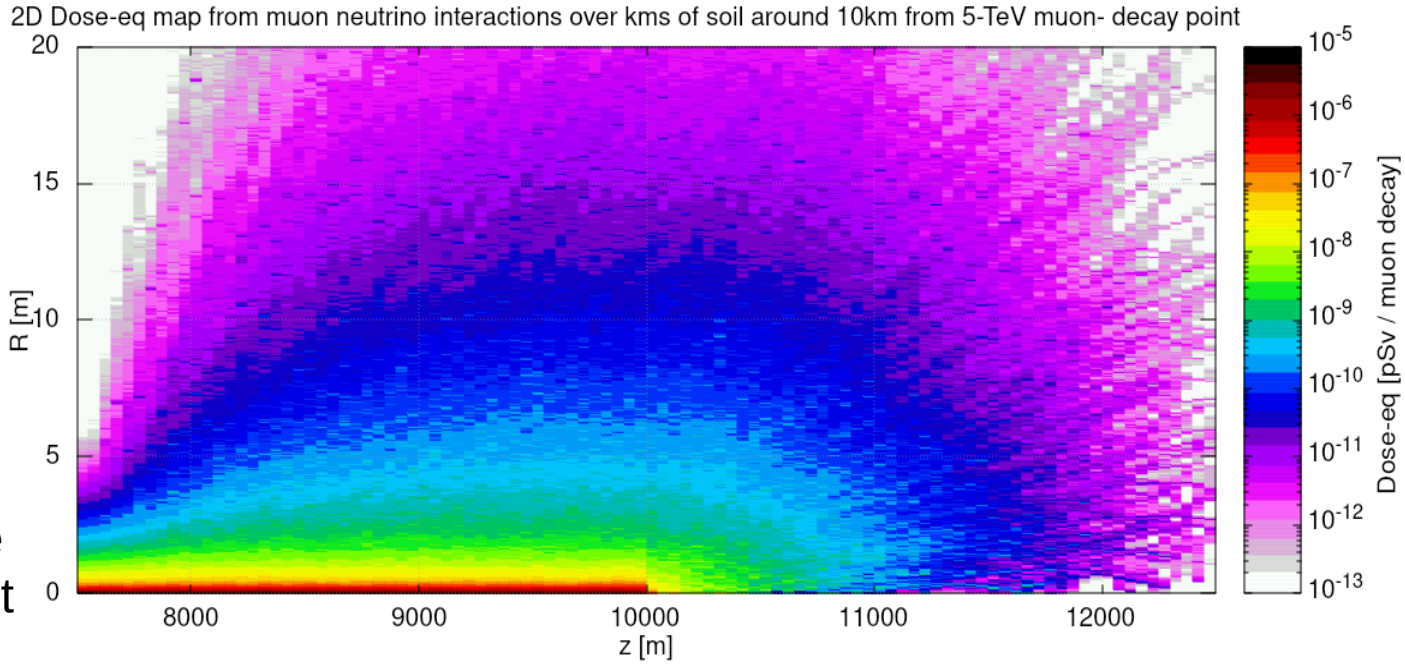




- Forcing neutrino interactions in [9750,10000]m range
- Relatively narrow shower, only few low-E muons leaking

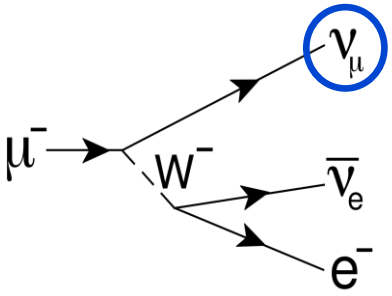
Broader shower in soil: neutrino-mu int. (dose-eq)



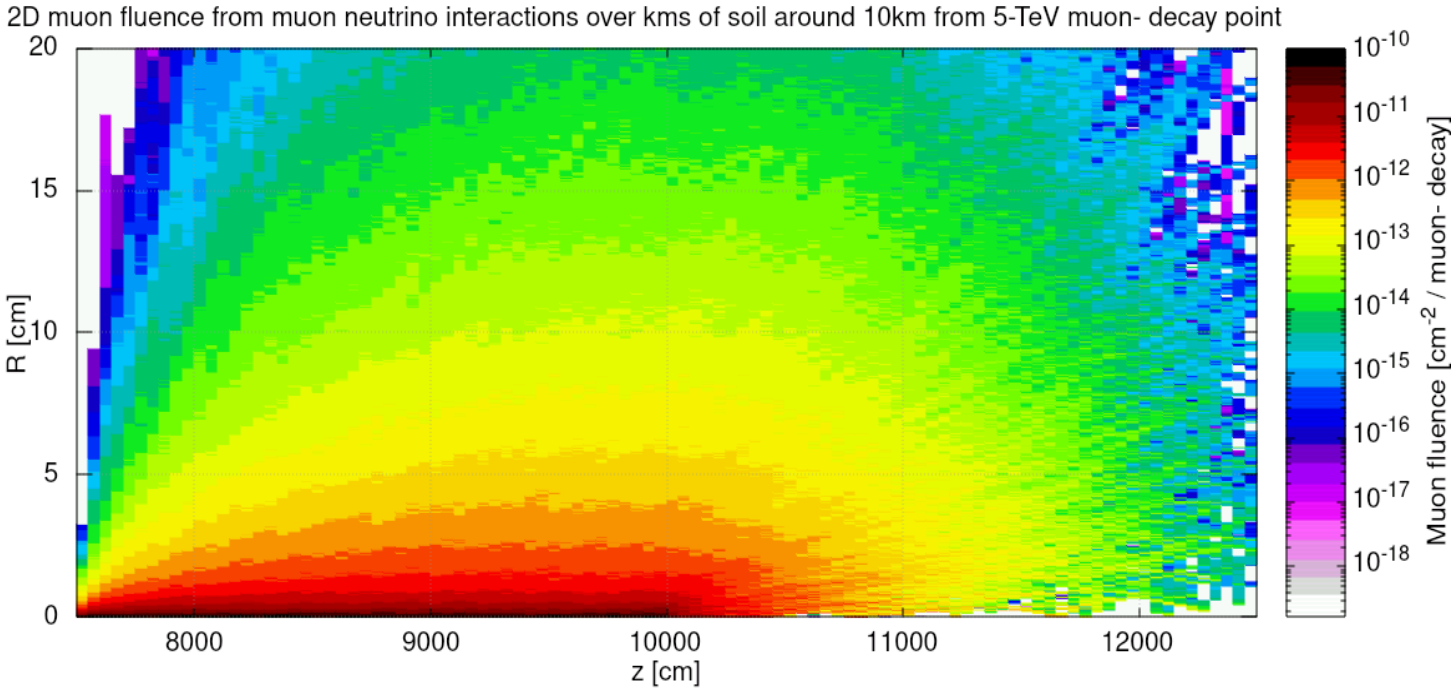


- Forcing neutrino interactions in [9750,10000]m range
- Broader shower due to high-E muons, but dose-eq peak still at low R

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

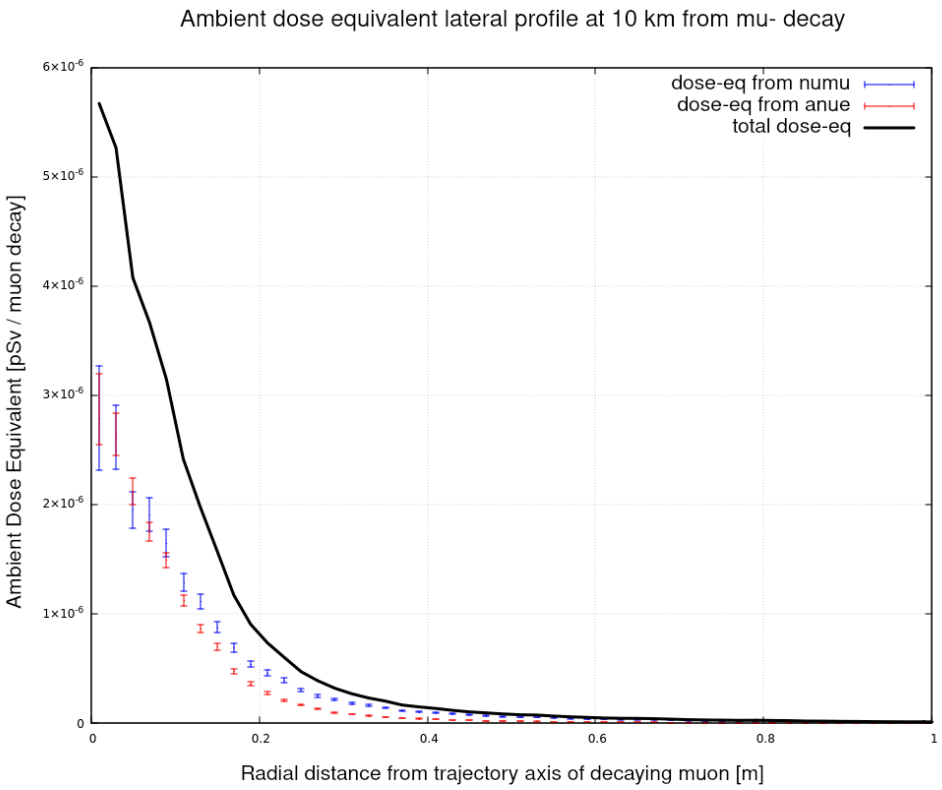


Key dose kernel quantity: dose-eq vs R at plateau

- 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**

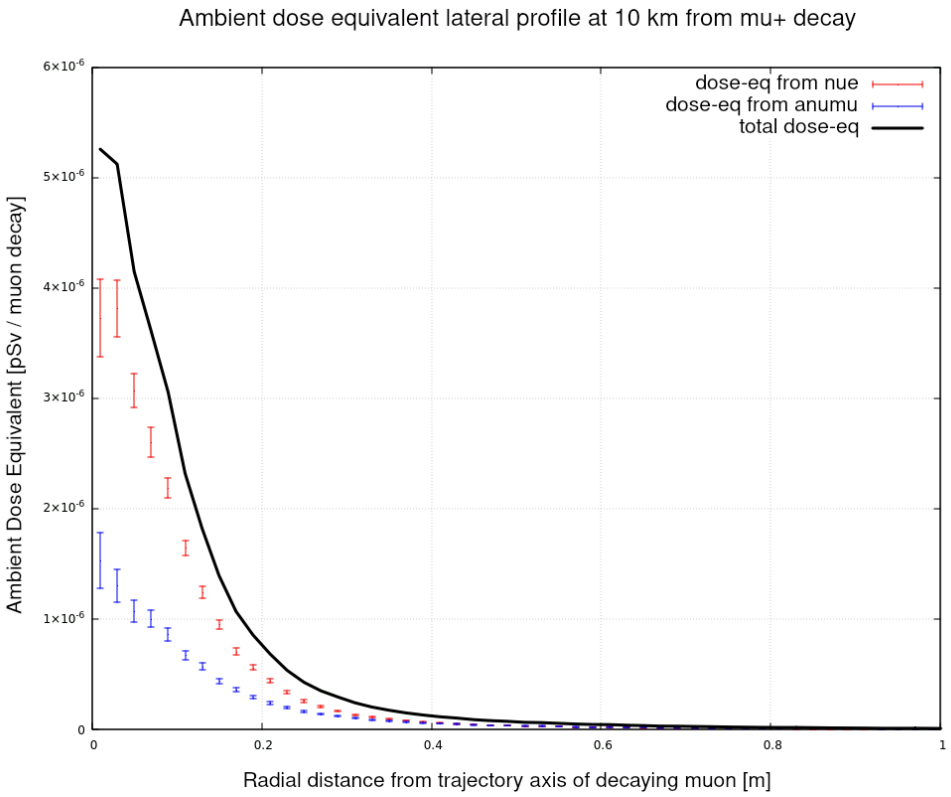
Example/1: dose-eq vs R at plateau from muon- at 10km

- 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



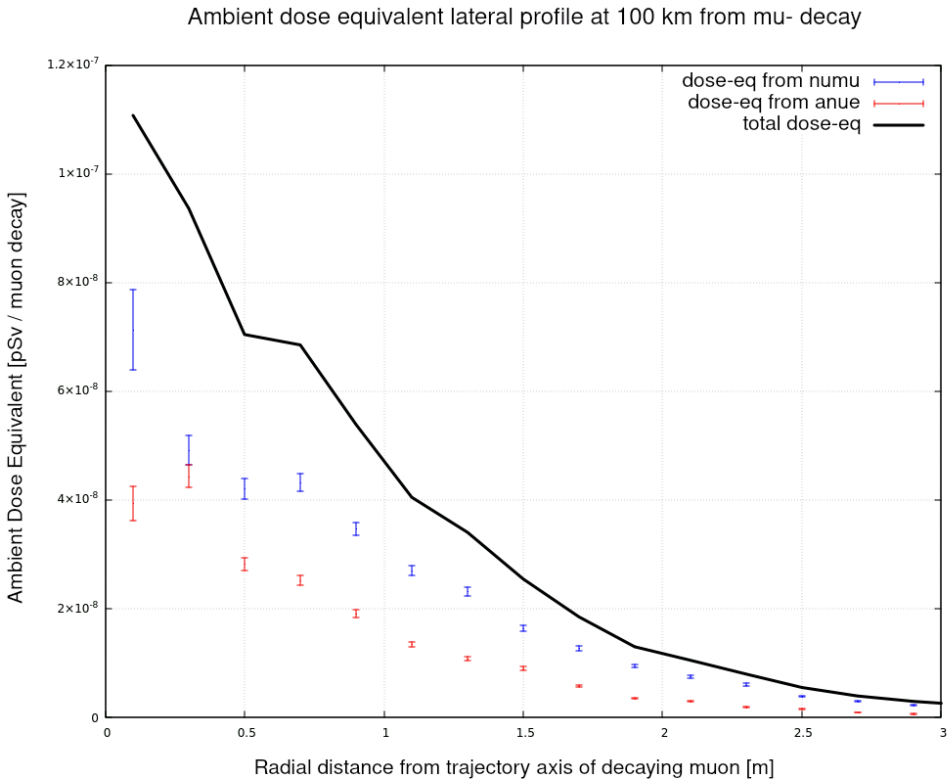
Example/1: dose-eq vs R at plateau from muon+ at 10km

- 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.



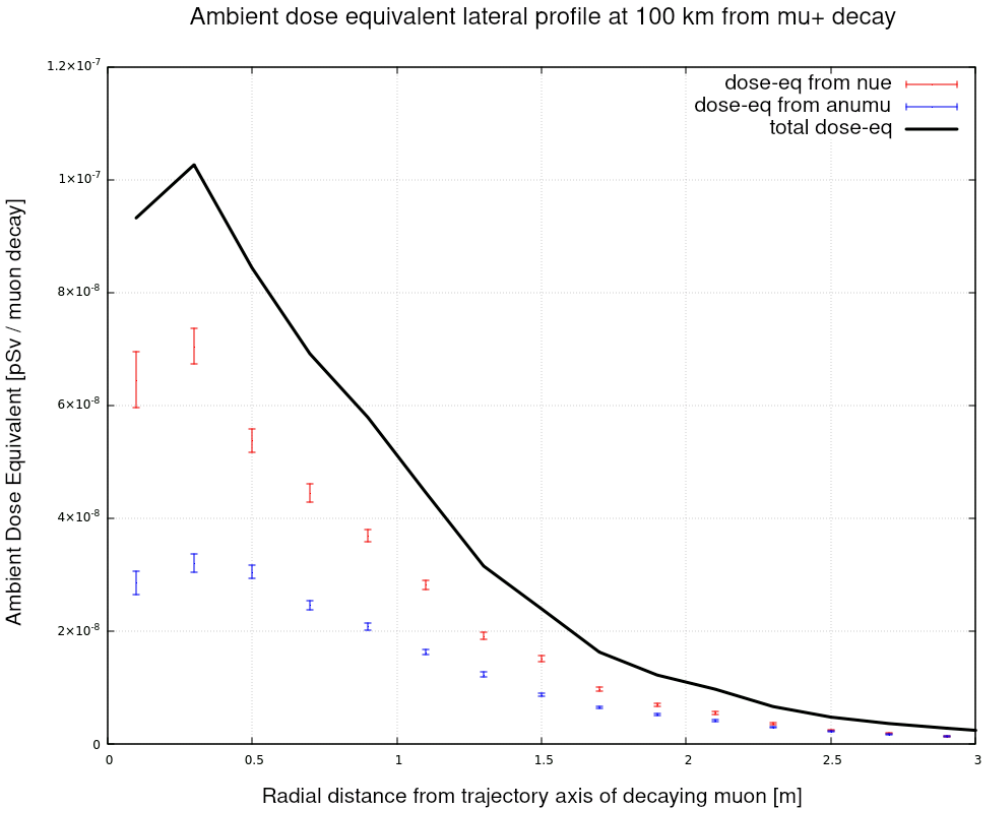
Example/2: dose-eq vs R at plateau from muon- at 100km

- 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



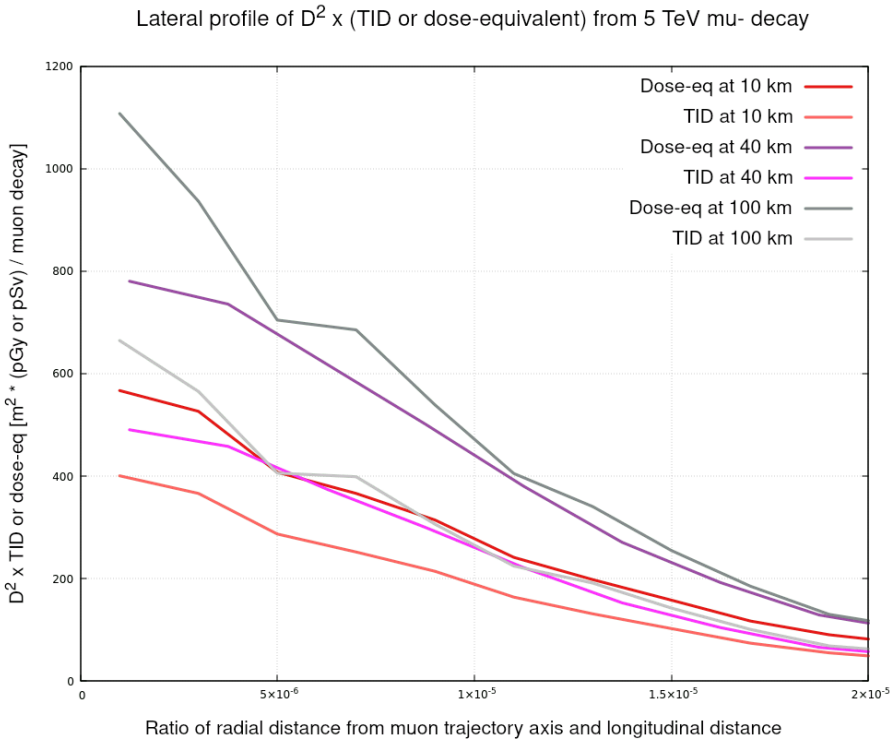
Example/2: dose-eq vs R at plateau from muon+ at 100km

- 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



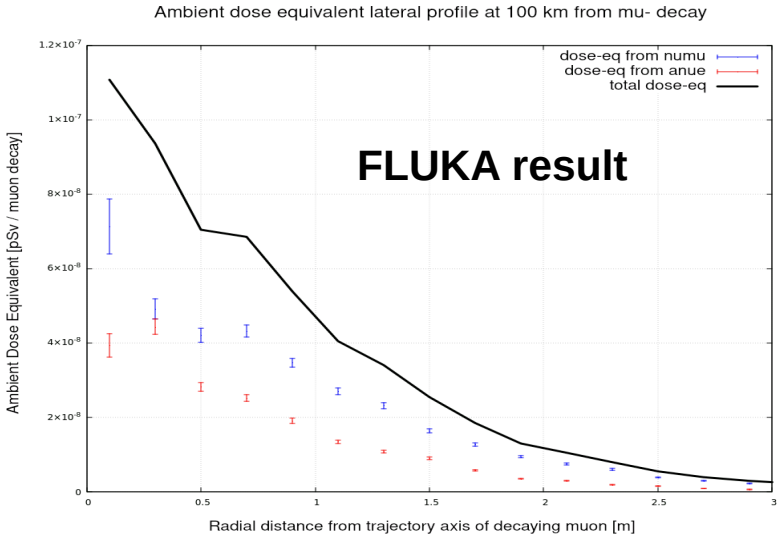
Dose vs dose-eq

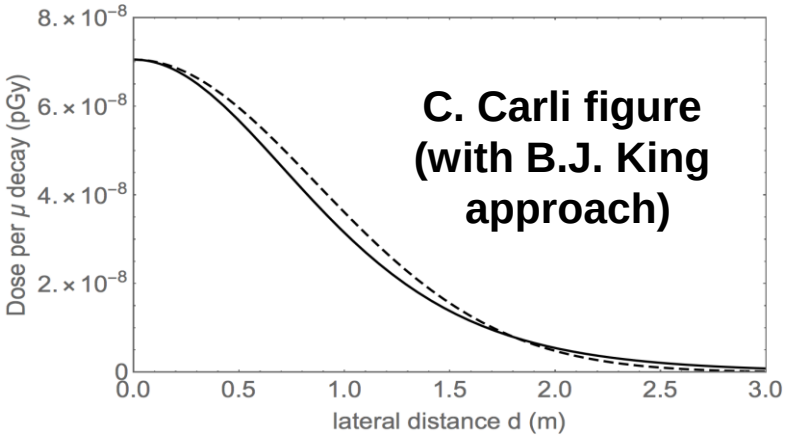
- To benchmark the FLUKA results with previous calculations, we need to compare the scoring of **dose-equivalent** (shown so far) with the **absorbed dose**, simply defined as energy per unit mass (in units of Gy = J/kg)
- Note that the plot is showing L^2*D vs R/L to better compare different distances
- **The dose-eq (expressed in Sv) is about 50% higher**



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

- The FLUKA dose-eq peak is **~1.1·10^{-7} pSv/muon**
- C. Carli's calculation yields a peak of **~7·10^{-8} pGy/muon**, i.e., ~50% less, consistently with the expected difference due to TID vs dose-eq
  → **excellent agreement!**

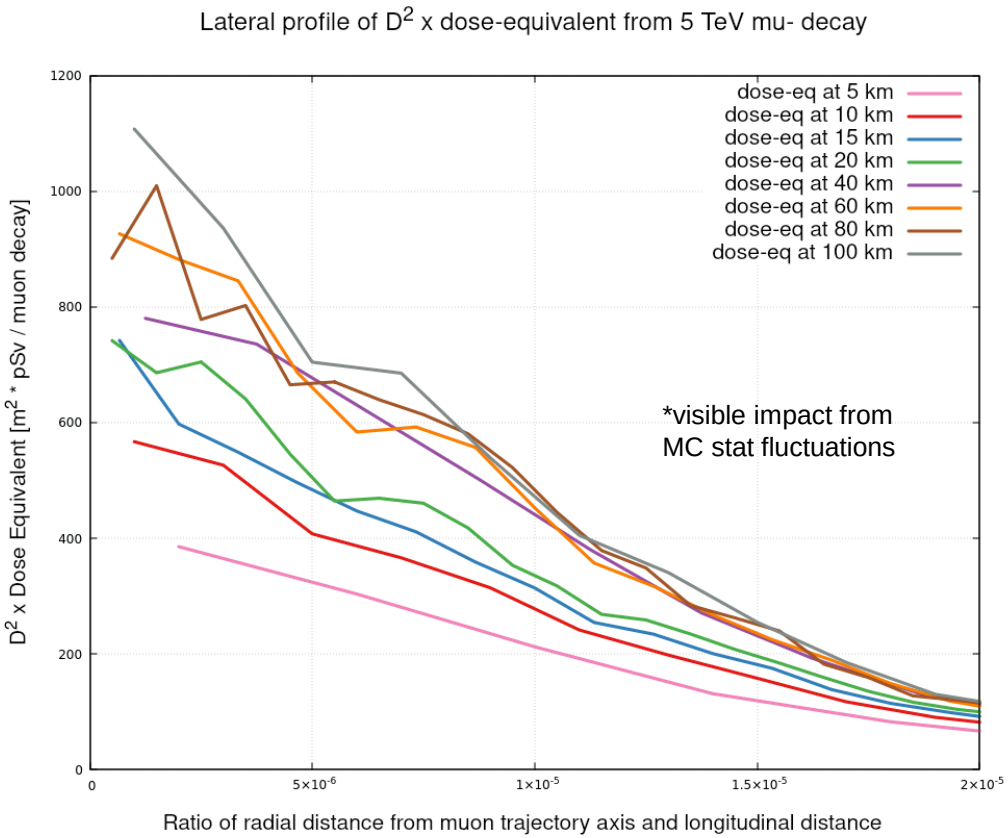




10 TeV c.o.m. energy, L_s = 100 km

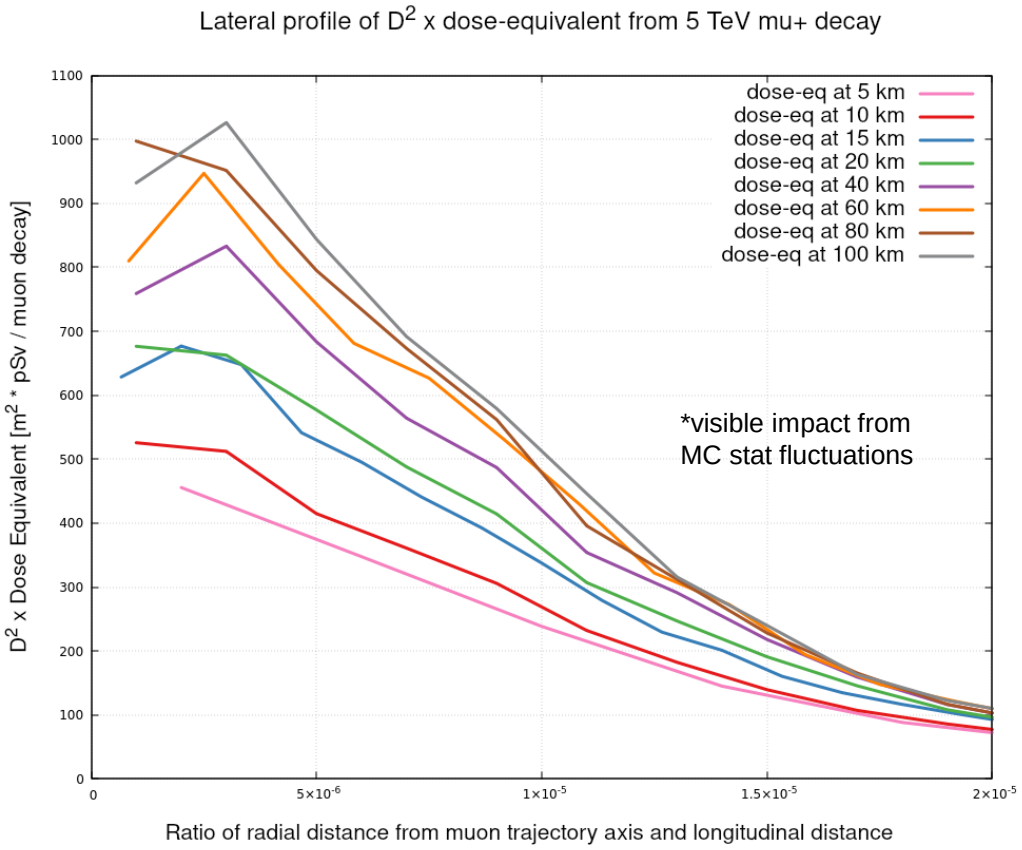
Summary: dose-eq vs R at plateau from muon-

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



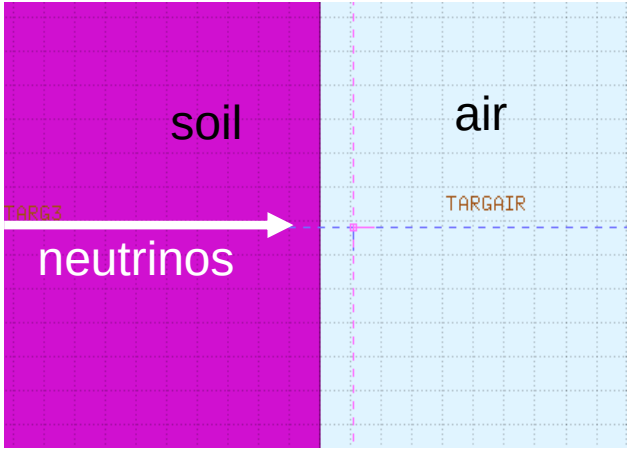
Summary: dose-eq vs R at plateau from muon+

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



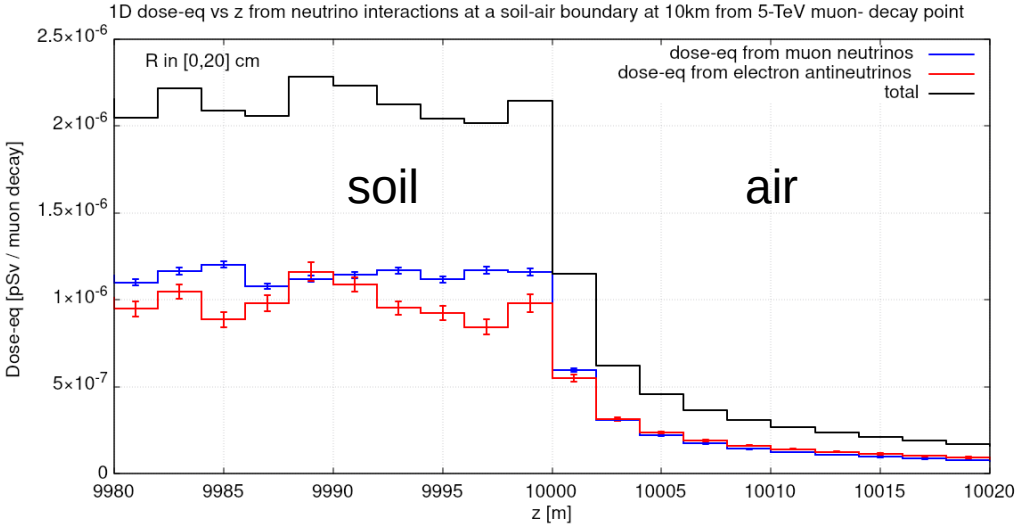
Extra: neutrino-induced dose-eq at soil-air boundary

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



*in realistic scenarios small angles should be considered, but this first calculation can already yield interesting insights

- 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



Summary and Outlook

- I presented the results of FLUKA simulations of neutrino-induced radiation from point-like decays of 5-TeV muons, without angular divergence
- The **dose-eq 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-eq and TID
- The build-up of the dose-eq in soil and the dose-eq 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-eq breakdown in individual particle types (e.g., electrons, hadrons..)
  - boost the Monte Carlo statistics as much as possible