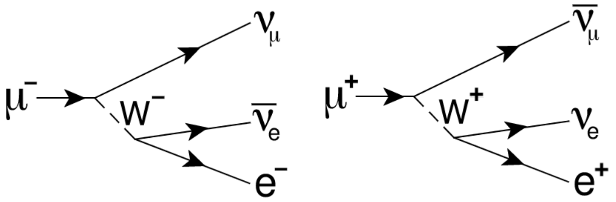
FLUKA dose calculations for neutrinos

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

Muon Collider Collaboration Meeting
13th October 2022

Introduction

- Neutrinos from $\mu^{\pm}$ decays can lead to significant dose levels, as introduced in the talk by C. Ahdida



- Main features:
  - Narrow neutrino cone (width ~ $1/\gamma$) emerging on the earth's surface
  - Neutrino cross sections growing linearly with the energy
  - No benefit from shielding (possibly detrimental)

Strong dependence of the peak dose on the muon energy

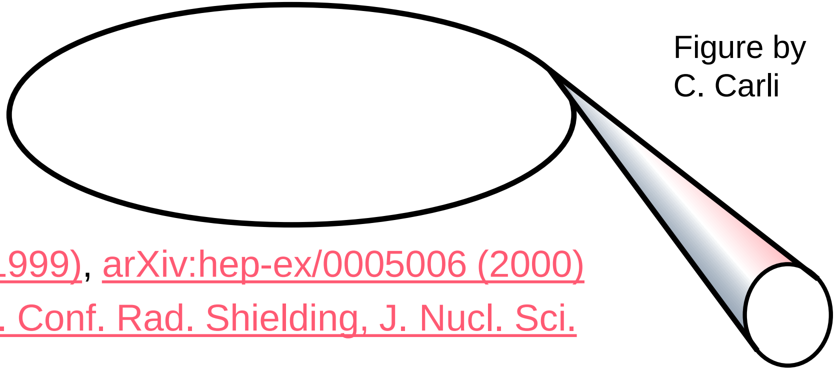


Figure by C. Carli

- Previous work (among others):
  - Calculations by B.J. King: arXiv:physics/9908017 (1999), arXiv:hep-ex/0005006 (2000)
  - Work by N. Mokhov, A. Van Ginneken: Proc. 9th Int. Conf. Rad. Shielding, J. Nucl. Sci. Tech. S1 172 (2000)

Requirements for a full dose assessment in real scenarios

Focus of this talk

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

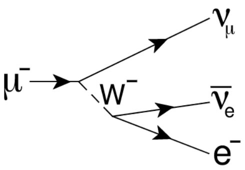
Talk by C. Carli

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

Talk by G. Lacerda

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

Two-step FLUKA simulation of effective dose kernel



1. MUON DECAYS

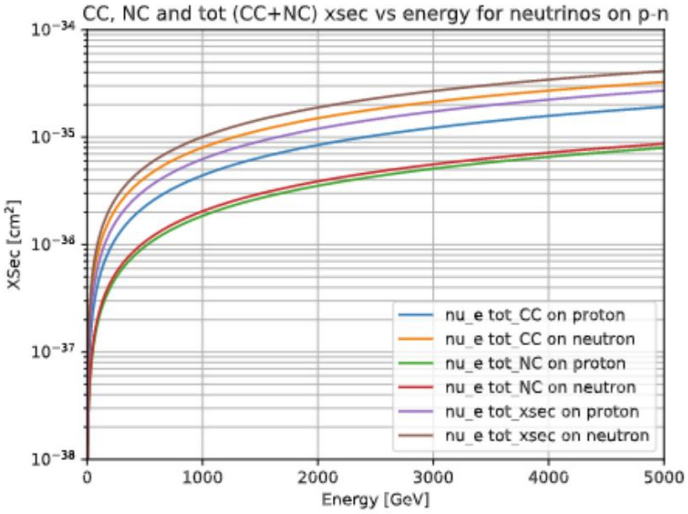
- Samples the muon decay products with a focus on the neutrinos
- Yields (1) a **list of all decay neutrinos** with their flavor, energy, and lab-frame angle
- Yields (2) a **list of interacting neutrinos** by filtering the above list based on the interaction probability in soil (via the macroscopic cross section)

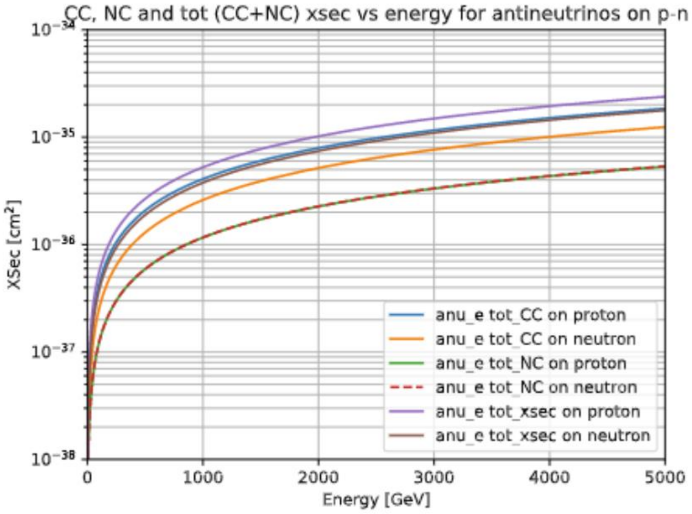
2. NEUTRINO INTERACTIONS IN SOIL

- Input: list of interacting neutrinos from the muon decay
- **Samples linearly the distance of the interaction from the muon decay point** within a user-defined range, obtaining the exact (x-y-z) position of the interaction by combining it with the angular direction from the input
- **Simulates the radiation showers from the neutrino interactions in soil**
- Scores 3D distributions of relevant quantities (e.g., absorbed dose, **effective dose**…)

Neutrino cross sections on nucleons in FLUKA

- Individual curves of neutrino cross section vs energy for:
  - **Target nucleons** (proton vs neutron)
  - **Reaction process** (dominated by Deep Inelastic Scattering, DIS)
  - **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)





Close to the values used by B.J. King in arXiv:physics/9908017 (1999)

Macroscopic neutrino cross sections in soil

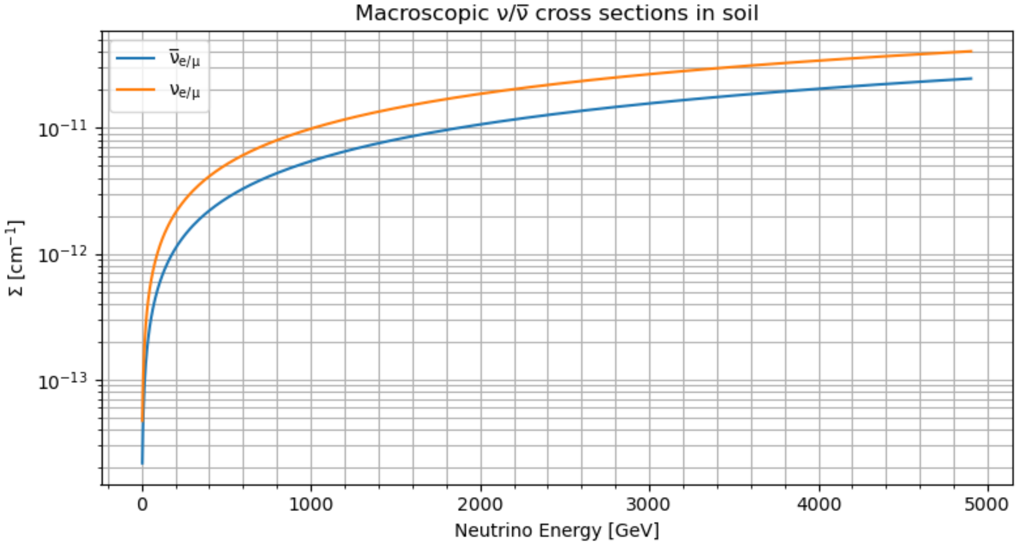
Soil density: 2 g/cm³
Composition in the backup

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

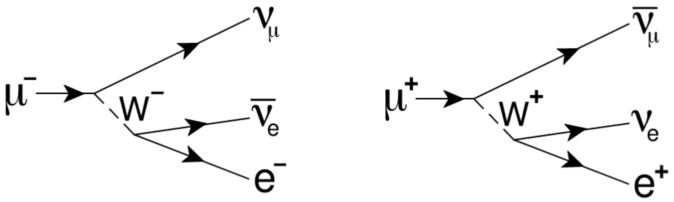
Proton/neutron density in soil

Neutrino cross section on protons/neutrons

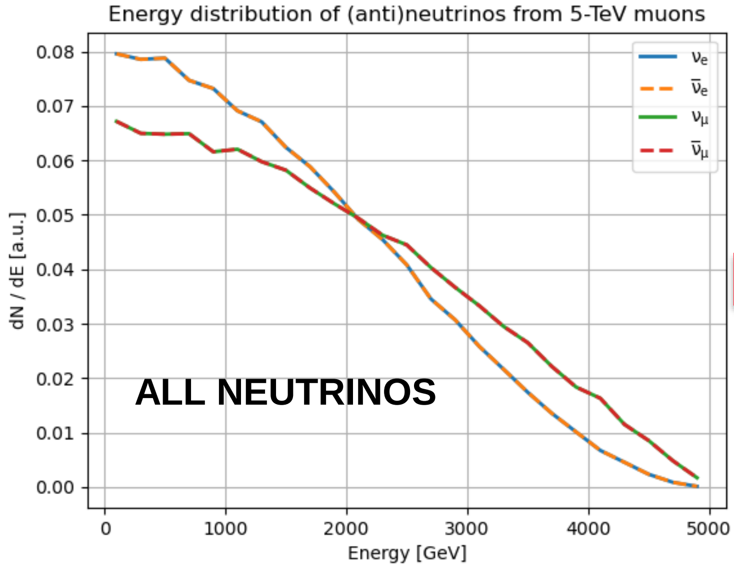
- This **simplified approach** yields a macroscopic cross section vs energy curve in soil
- Neglected: Fermi motion and Pauli exclusion principle, requiring more accurate simulations (verified for a few energies, finding small discrepancies from the above formula)



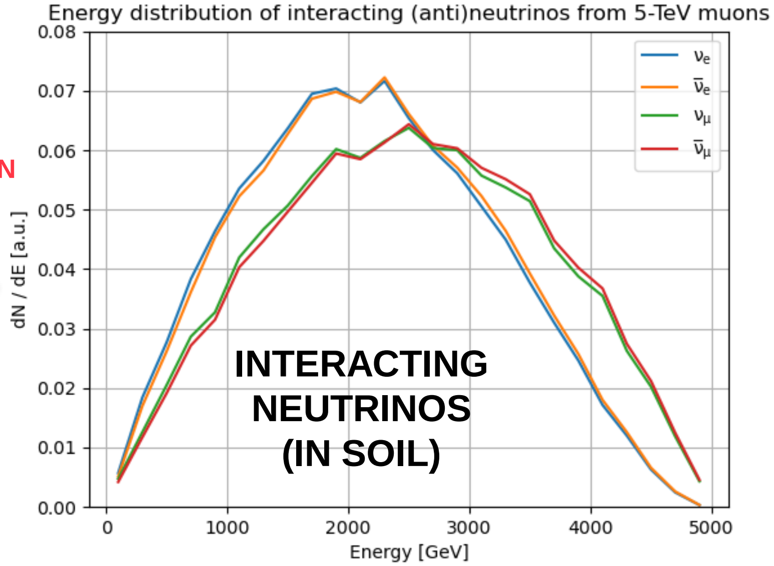
5-TeV muon decay: neutrino energy spectra



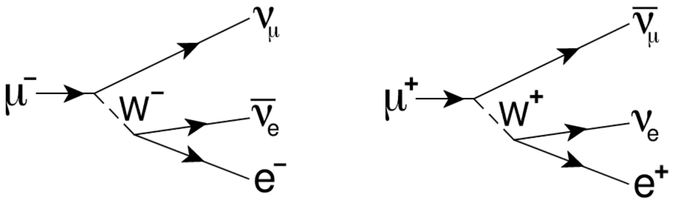
- Energy spectrum of the interacting neutrinos peaking at around half of the muon beam energy



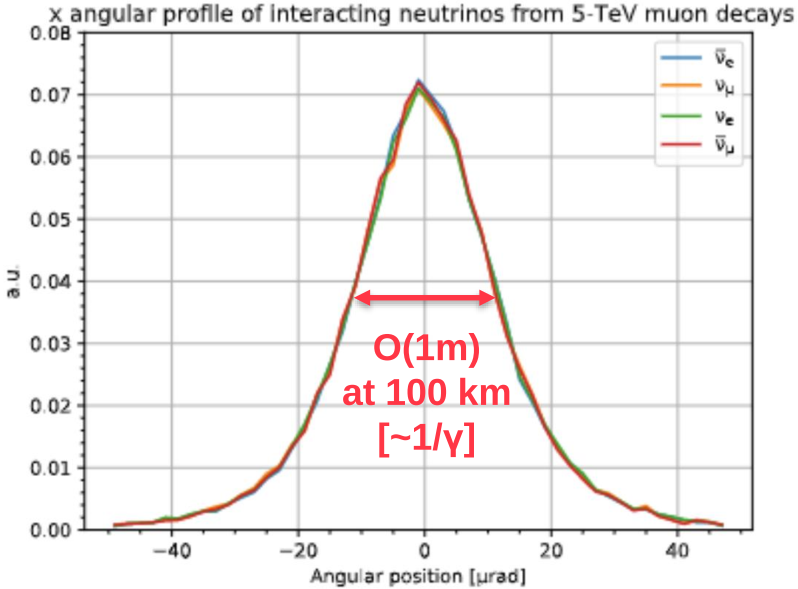
CROSS SECTION FILTERING

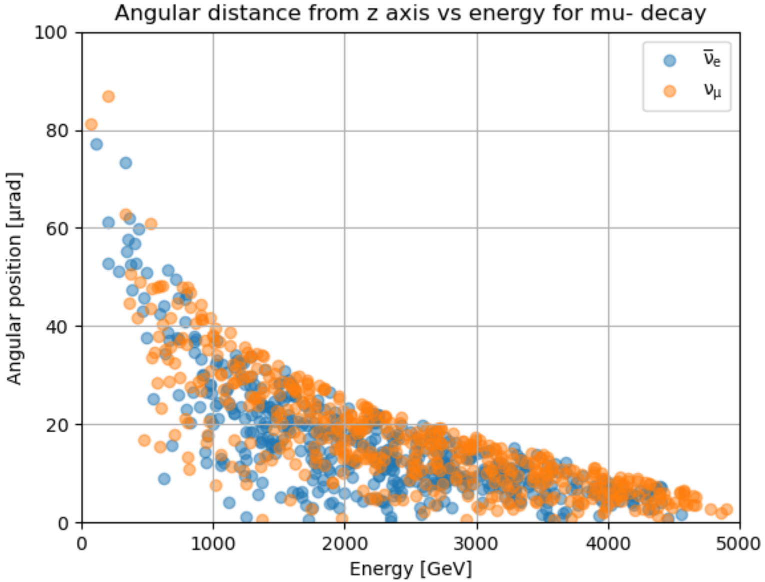


5-TeV muon decay: neutrino angles and energy



- Very narrow neutrino cone, with anti-correlation between neutrino energy and angle





Two-step FLUKA simulation of effective dose kernel

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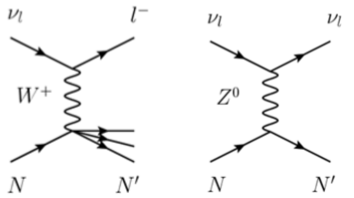

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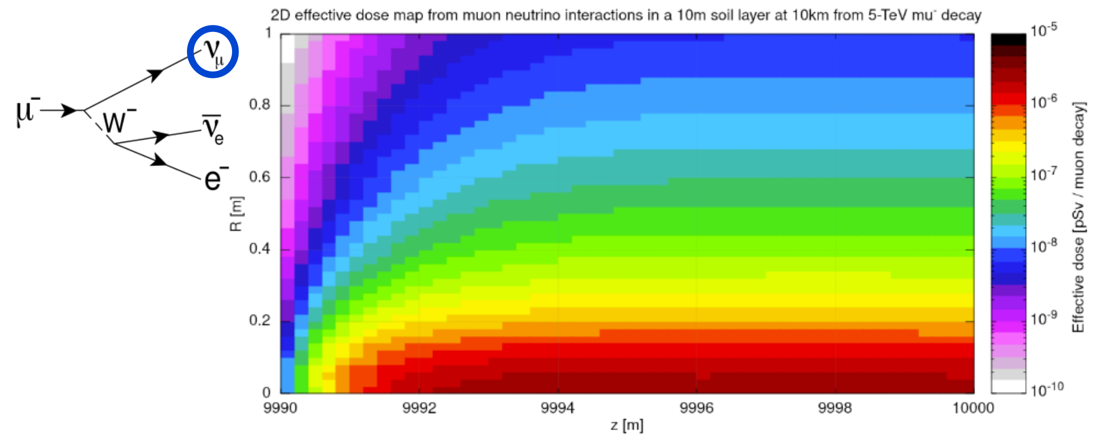
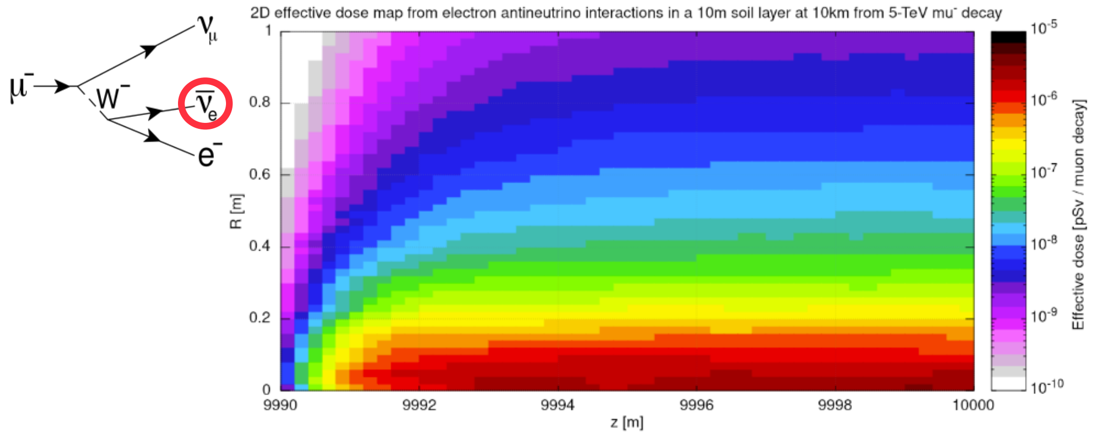
Effective dose build-up in soil for 5-TeV μ^-

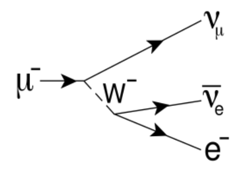


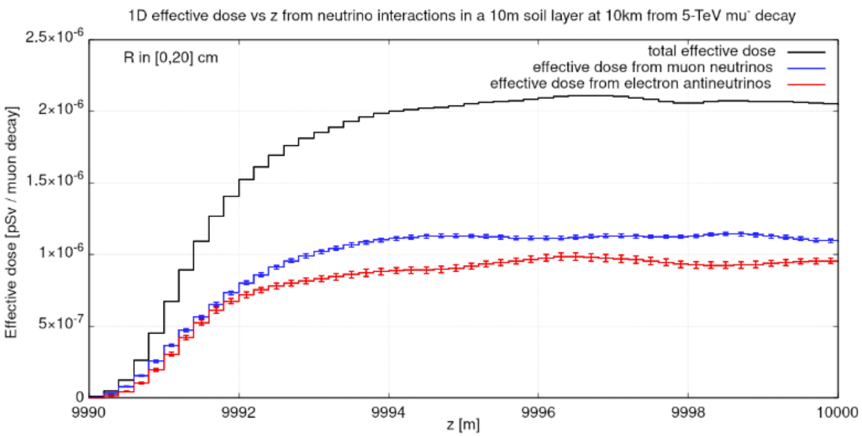


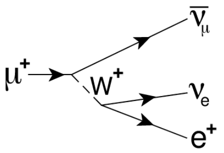
- Sampling the neutrino interactions within a **10m range** at **10km** from the muon decay
- Narrow cone of **effective dose** (see the talk by C. Ahdida) near the neutrino beam axis (i.e., at small R)
- The build-up of the shower occurs within a few meters

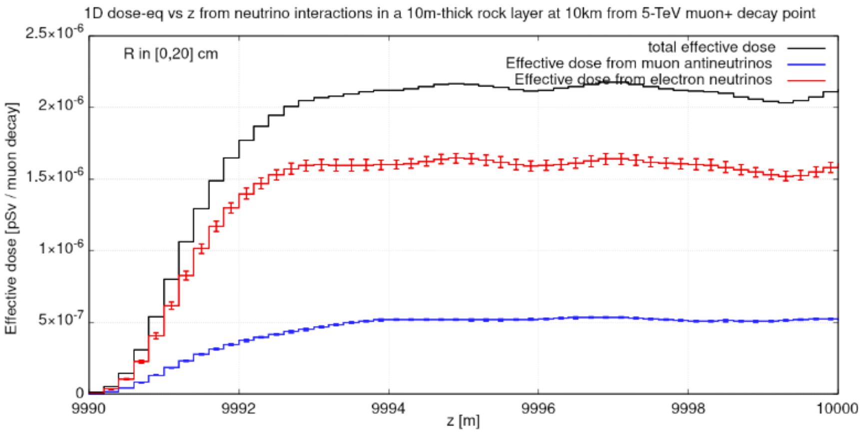
(very similar results for μ^+)

Effective dose build-up in soil for 5-TeV μ^- and μ^+ (1D)



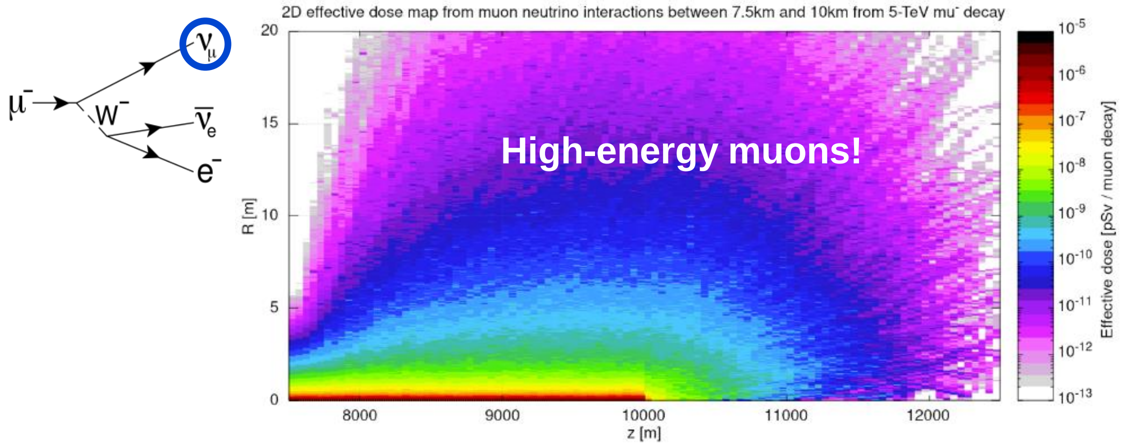


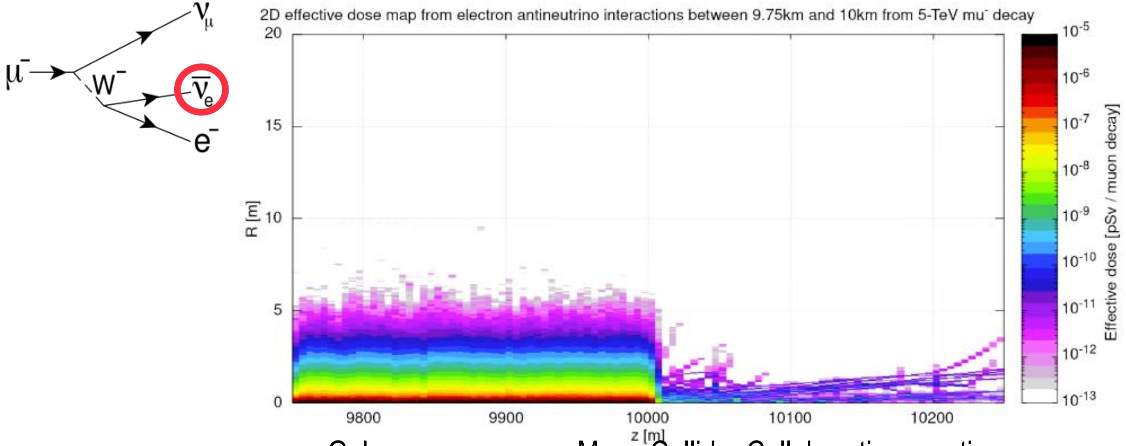




- The 1D projections of the effective dose within 20cm from the neutrino beam axis show that **a plateau of the effective dose is reached after a few meters**
- In μ^- and μ+ decays the contribution of the two neutrinos to the total effective dose is different, but the plateau values of the effective dose are similar

Effective dose build-up in soil for 5-TeV μ^-: large distances



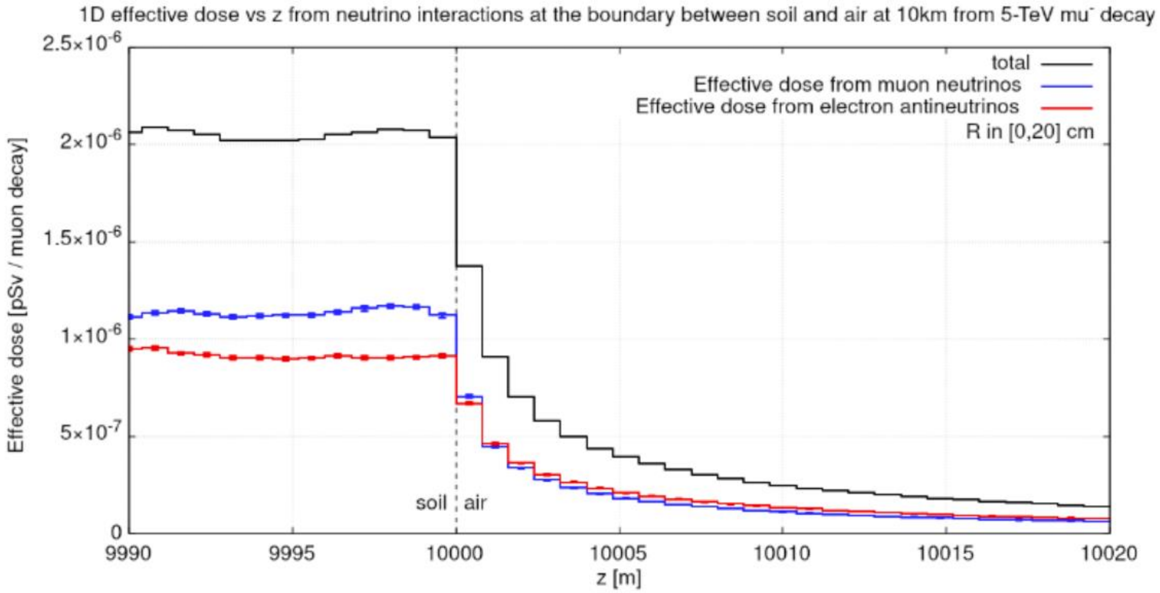


- Due to **high-energy muon production**, the radiation showers induced by muon neutrinos and antineutrinos build up over km-scale distance, and reach larger radial distances
- …but **muons give a small contribution to the effective dose**, so they can be ignored for the dose kernel calculations

(very similar results for μ^+)

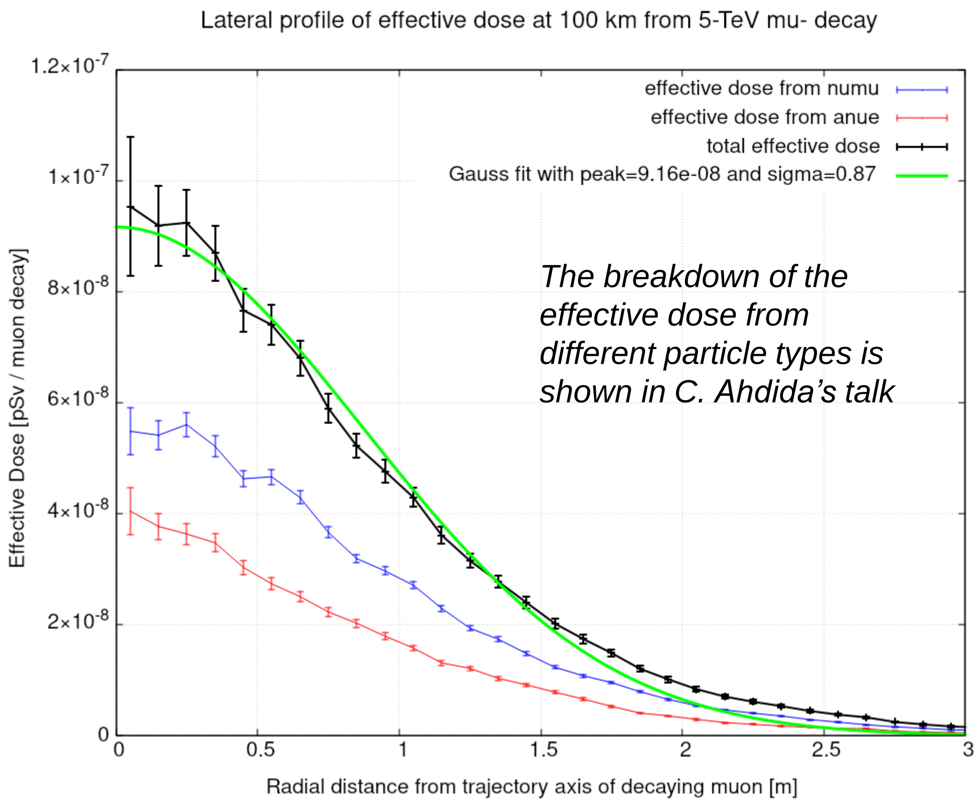
Effective dose from 5-TeV μ⁻: from soil to air

- If we assume that the neutrino beam exits orthogonally from soil to air, the effective dose rapidly drops from the plateau in soil (more than 4x decrease after only 5m)
- In realistic scenarios the angle between the neutrino beam and the earth's surface plays a role, but we can regard the plateau dose in soil as the maximum dose that a person can be exposed to



Effective dose kernel calculation: effective dose vs R

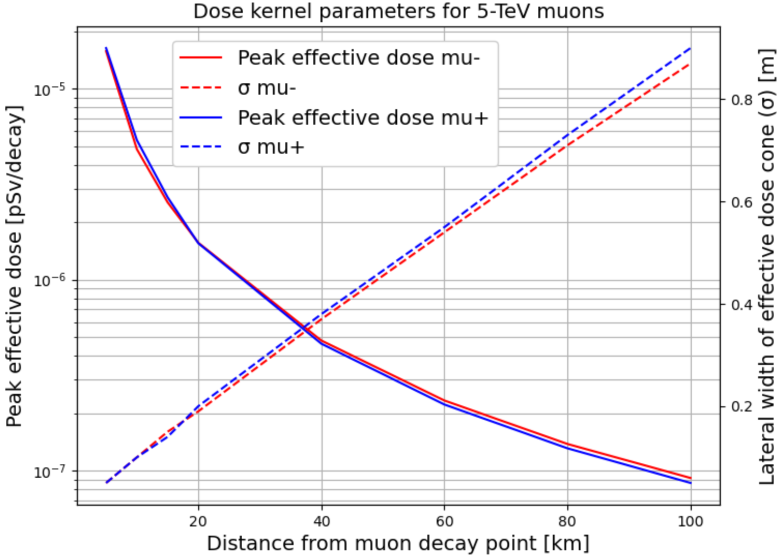
- 1D projection of the effective dose vs R at the plateau in soil
- The profile is modeled by a **Gaussian fit** (not accurate in the tails) yielding:
  - **Peak dose** [pSv / μ decay]
  - **Dose width** [σ, in meters]
- To obtain the **effective dose kernel** we extract these two parameters for different muon signs, energies, and baseline distances from the decay point



The breakdown of the effective dose from different particle types is shown in C. Ahdida's talk

Effective dose kernel results: 5-TeV muon beam

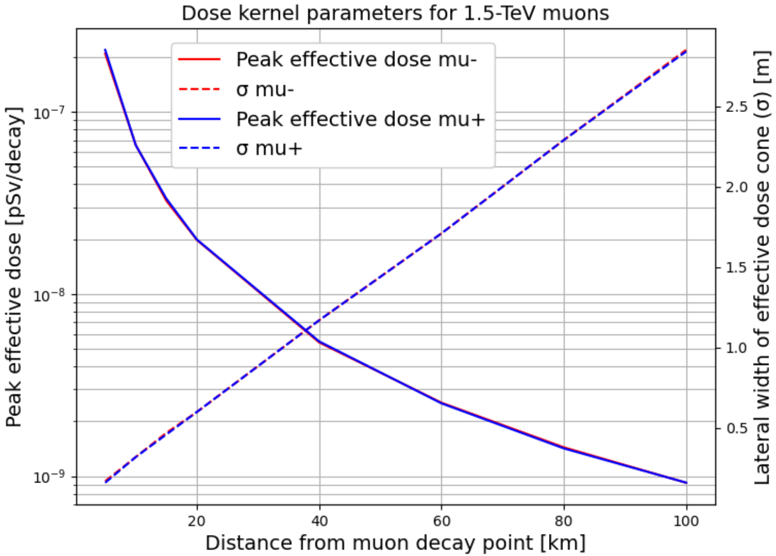
- Very similar effective dose parameters for positive and negative muons
- Peak dose from ~$1.6 \cdot 10^{-5}$ pSv/decay at 5 km to ~$9 \cdot 10^{-8}$ pSv/decay at 100 km
- σ exhibits a linear increase from just 5 cm at 5 km to ~90 cm at 100 km, reflecting the increasing aperture of the neutrino cone



	μ^-		μ^+	
Distance	Peak eff. dose [pSv / decay]	σ [m]	Peak eff. dose [pSv / decay]	σ [m]
5 km	$1.57 \cdot 10^{-5}$	0.05	$1.63 \cdot 10^{-5}$	0.05
10 km	$4.86 \cdot 10^{-6}$	0.10	$5.38 \cdot 10^{-6}$	0.10
15 km	$2.54 \cdot 10^{-6}$	0.15	$2.70 \cdot 10^{-6}$	0.14
20 km	$1.56 \cdot 10^{-6}$	0.19	$1.55 \cdot 10^{-5}$	0.20
40 km	$4.80 \cdot 10^{-7}$	0.37	$4.62 \cdot 10^{-6}$	0.38
60 km	$2.33 \cdot 10^{-7}$	0.54	$2.22 \cdot 10^{-6}$	0.55
80 km	$1.38 \cdot 10^{-7}$	0.71	$1.31 \cdot 10^{-7}$	0.73
100 km	$9.16 \cdot 10^{-8}$	0.87	$8.63 \cdot 10^{-8}$	0.90

Effective dose kernel results: 1.5-TeV muon beam

- Peak dose from ~$2 \cdot 10^{-7}$ pSv/decay at 5 km to ~$9 \cdot 10^{-10}$ pSv/decay at 100 km, i.e., lower by a factor of ~100 compared to the 5-TeV beam
- σ from ~16 cm at 5 km to ~285 cm at 100 km, i.e., ~3x larger than the 5-TeV case, coherently with the 1/γ scaling of the neutrino cone width



	μ^-		μ^+	
Distance	Peak eff. dose [pSv / decay]	σ [m]	Peak eff. dose [pSv / decay]	σ [m]
5 km	$2.09 \cdot 10^{-7}$	0.17	$2.19 \cdot 10^{-7}$	0.16
10 km	$6.57 \cdot 10^{-8}$	0.32	$6.56 \cdot 10^{-8}$	0.32
15 km	$3.28 \cdot 10^{-8}$	0.47	$3.34 \cdot 10^{-8}$	0.46
20 km	$1.98 \cdot 10^{-8}$	0.60	$1.99 \cdot 10^{-8}$	0.60
40 km	$5.42 \cdot 10^{-9}$	1.17	$5.49 \cdot 10^{-9}$	1.17
60 km	$2.53 \cdot 10^{-9}$	1.71	$2.51 \cdot 10^{-9}$	1.71
80 km	$1.44 \cdot 10^{-9}$	2.29	$1.42 \cdot 10^{-9}$	2.29
100 km	$9.20 \cdot 10^{-10}$	2.85	$9.21 \cdot 10^{-10}$	2.84

First look at an (unrealistic) straight section

- Reminder: **the effective dose kernel refers to a single muon trajectory**
- Still, we can combine the kernel with baseline accelerator parameters to compute the effective dose in a hypothetical/simplified straight section of 1m where we neglect the muon beam divergence

- Peak effective dose at 100km:
  - 1.5 TeV → ~40 μSv/y
  - 5 TeV → ~1.4 mSv/y

>>10 μSv/y

	$E_\mu = 1.5$ TeV	$E_\mu = 5$ TeV
Circumference	4.5 km	10 km
Bunch intensity	$2.2 \cdot 10^{12}\ \mu$	$1.8 \cdot 10^{12}\ \mu$
Number of bunches	1	1
Bunch frequency	5 Hz	5 Hz
Days of operation	200/y	200/y
Annual muon decays (total)	$1.9 \cdot 10^{20}$	$1.56 \cdot 10^{20}$
Annual muon decays per meter	$4.2 \cdot 10^{16}$	$1.56 \cdot 10^{16}$

- Important message: the muon divergence and, possibly, mitigation measures are essential to reduce the peak dose in realistic scenarios (see talk by C. Carli)

Summary and Outlook

- The issue of neutrino-induced radiation is critical at muon colliders, as introduced in the talk by C. Ahdida: "Update on RP aspects"
- An **effective dose kernel** is calculated using the FLUKA Monte Carlo code for neutrino-induced radiation
- For muon beam energies of 1.5 TeV and 5 TeV, and for baseline distances ranging from 5 km to 100 km, we provide:
  - Peak dose in soil [pSv / μ decay]
  - Dose cone width [σ, in meters]
- The above parameters serve as a key input for more specific calculations considering the muon collider lattices
  → talk by C. Carli: "Neutrino radiation for a realistic collider"
  → talk by G. Lacerda: "Dose tool development and siting at CERN"

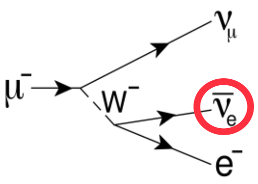
BACKUP

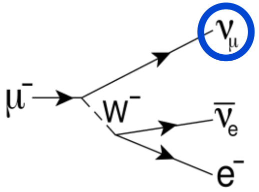
Soil composition and density

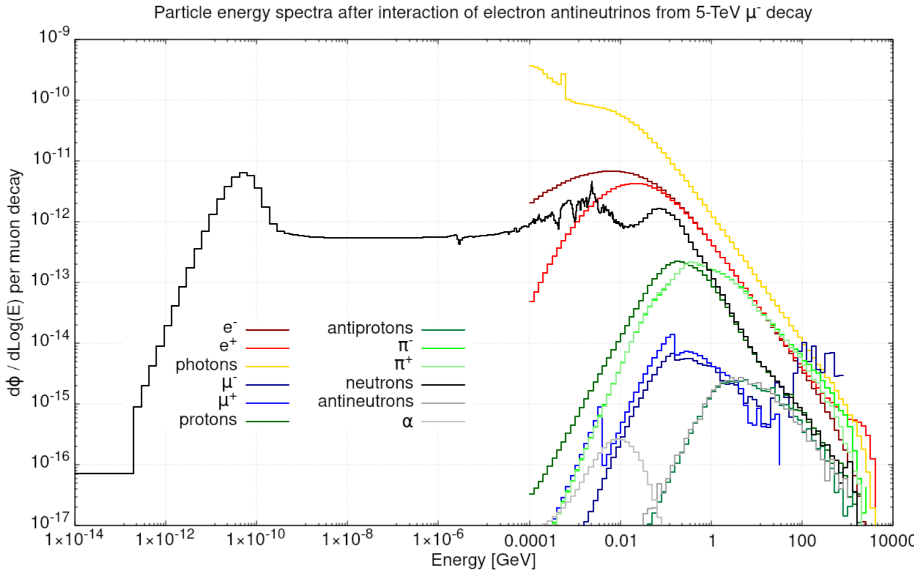
- The soil composition used to obtain the effective dose kernel is shown in the table
- Different calculations must be made for different materials and/or densities
- While no major differences are expected regarding the material composition, a larger density will result in a higher concentration of neutrino interactions, likely resulting in a higher peak dose inside the material

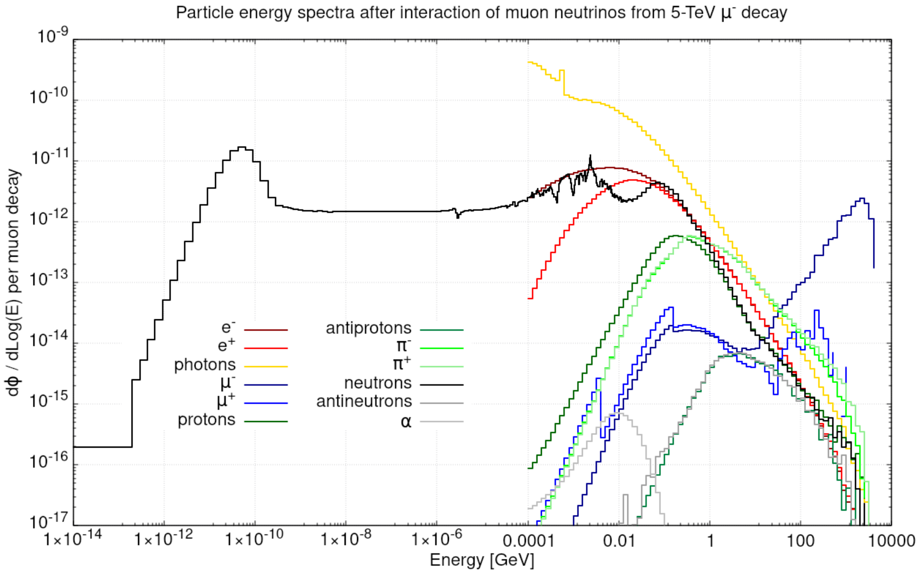
Density:	2 g/cm^2
Material	**Mass fraction**
Oxygen	50%
Silicon	20%
Calcium	19.5%
Carbon	3%
Aluminium	3%
Iron	1.4%
Potassium	1%
Hydrogen	0.6%
Magnesium	0.5%
Sodium	0.01%

Energy spectra: 5-TeV μ⁻ decay

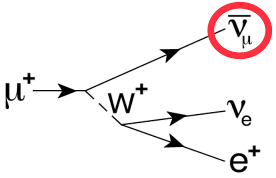


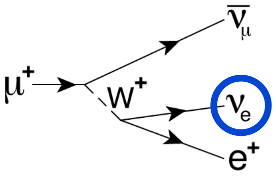




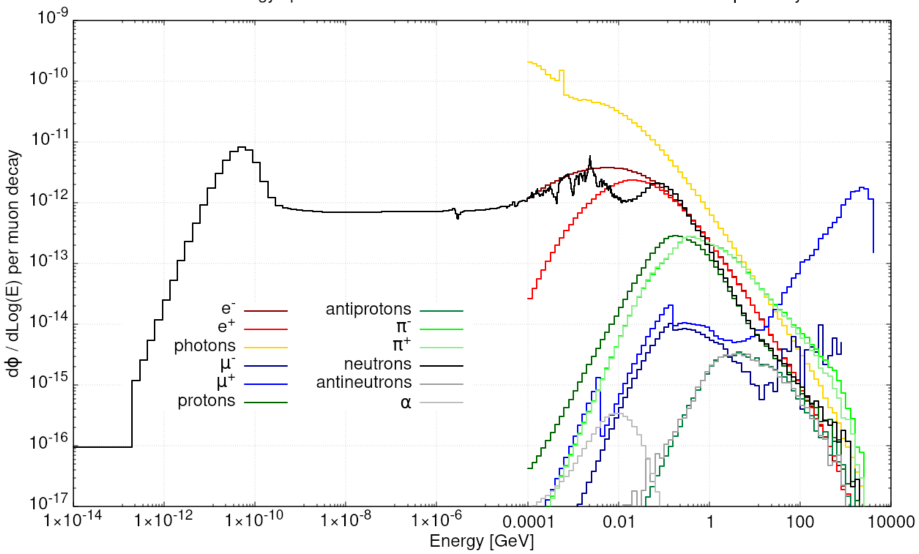


Energy spectra: 5-TeV μ^+ decay





Particle energy spectra after interaction of muon antineutrinos from 5-TeV μ^+ decay



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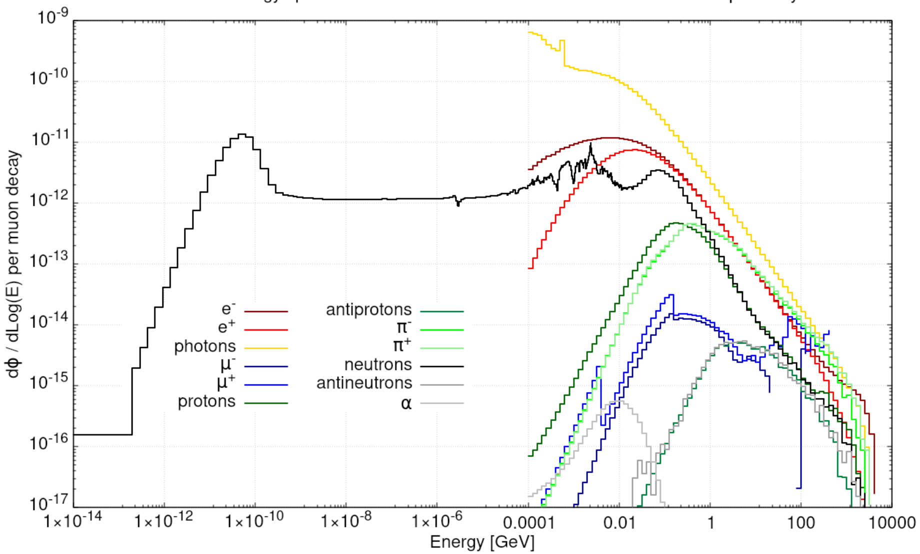
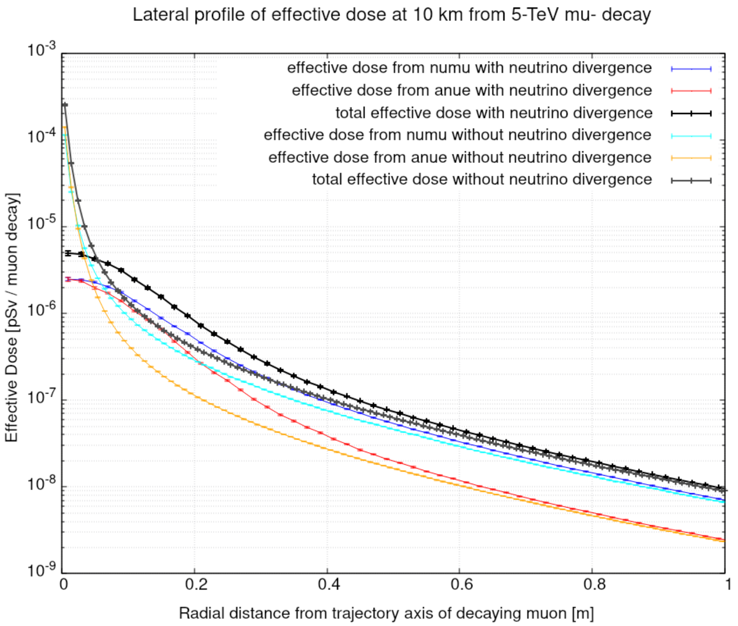
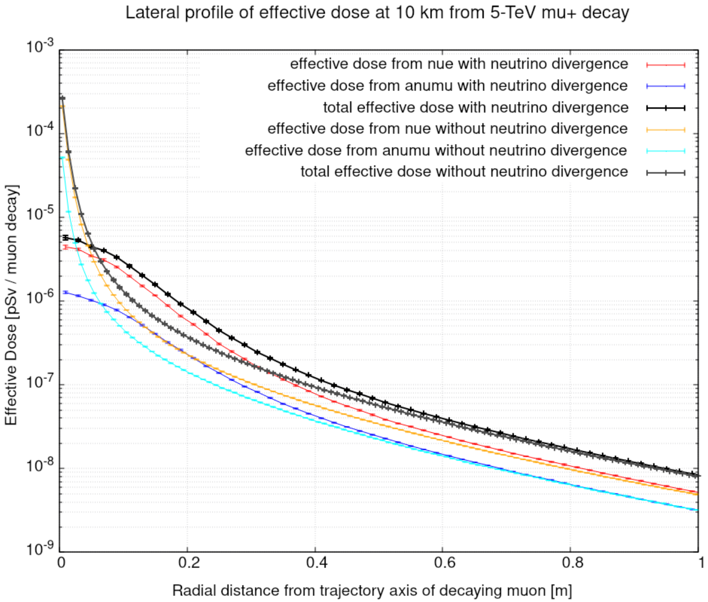


Impact of the angular width of the neutrino beam

- The peak effective dose is driven by the width of the neutrino beam
- Instead, the tails are driven by the width of the radiation shower originating from the neutrino interactions





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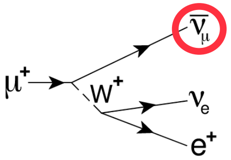

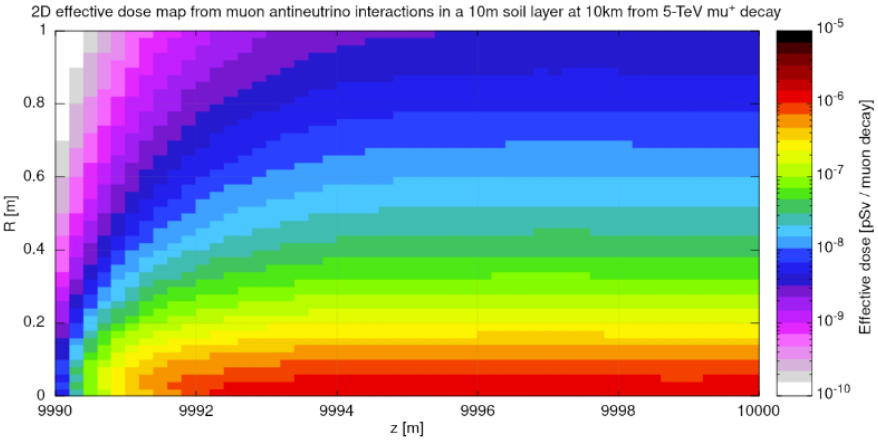

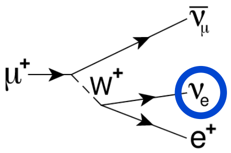

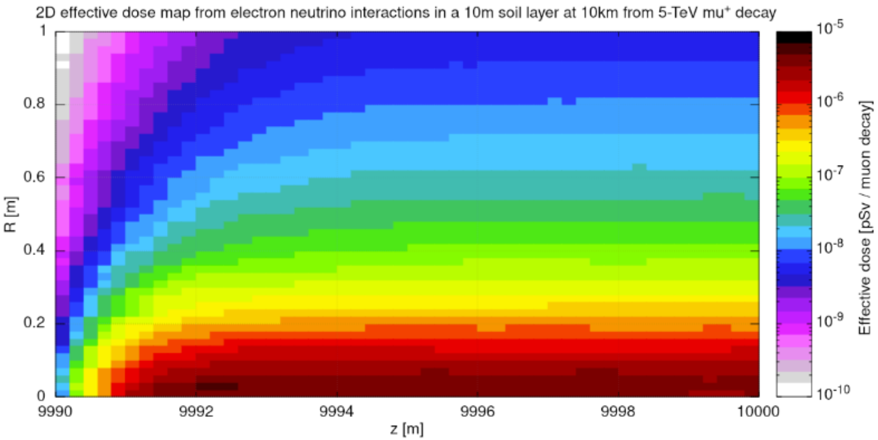

International
MUON Collider
Collaboration

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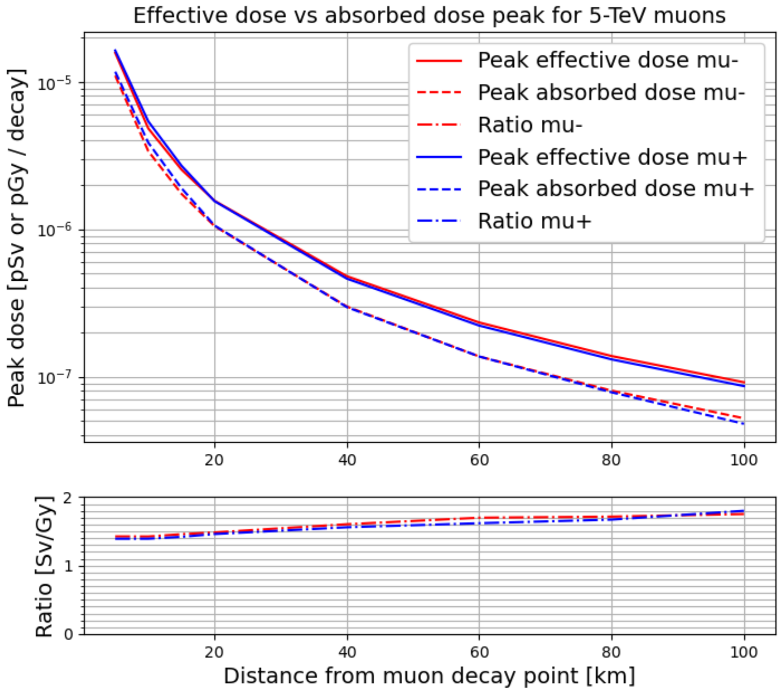
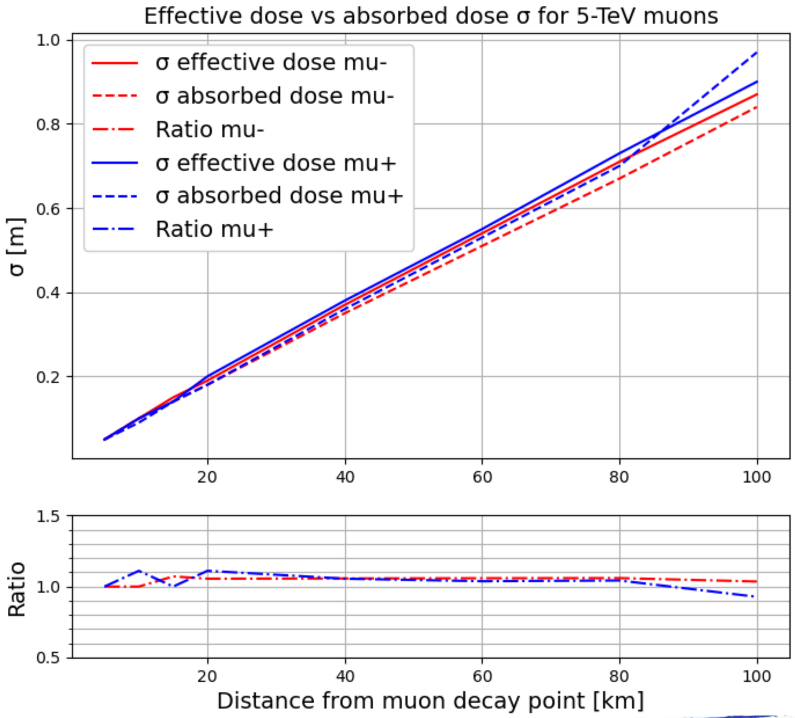
- Narrow cone of **effective dose** (see the talk by C. Ahdida) near the neutrino beam axis (i.e., at small R)
- The build-up of the shower occurs within a few meters

Effective dose vs absorbed dose: 5-TeV μ decay

- The effective dose peak is larger than the absorbed dose by a factor of 1.5-2, while the σ is similar for the two quantities





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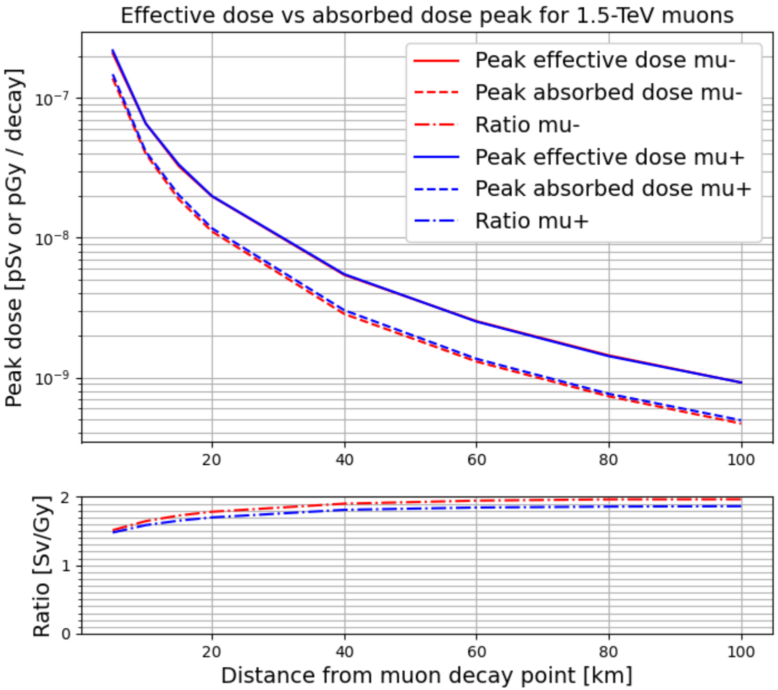
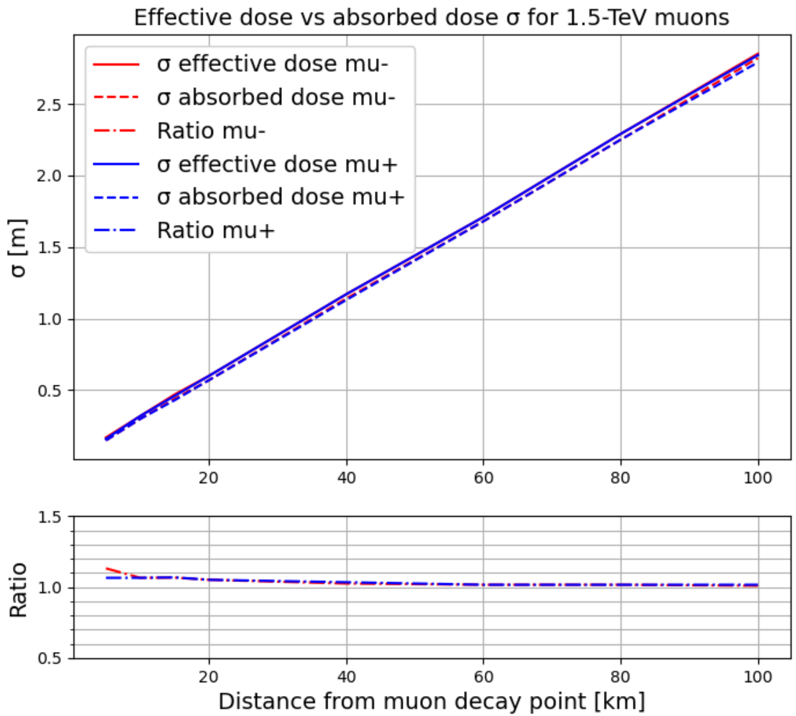
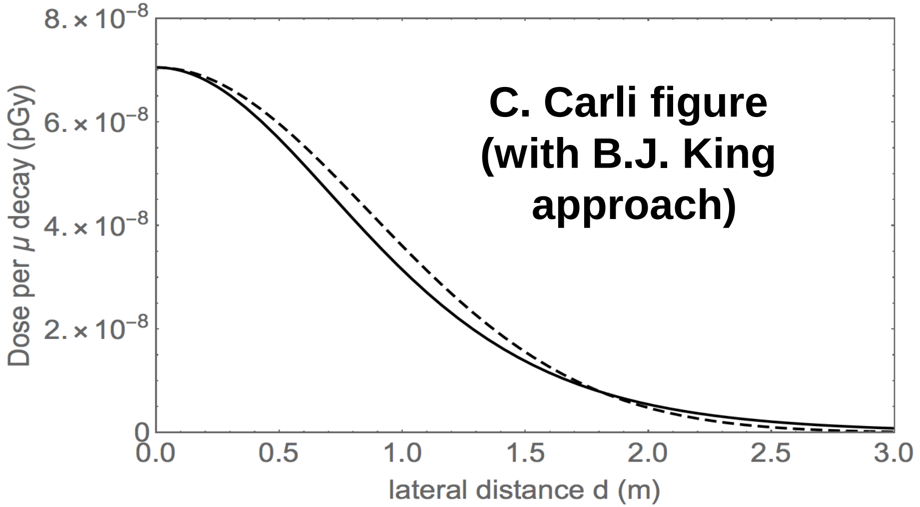




Comparing FLUKA and B. J. King / C. Carli calculations

- Comparison with the absorbed dose profile calculated by C. Carli, which yields a peak of approximately $7 \cdot 10^{-8}$ pGy / μ
- To be compared with a peak effective dose of around $9 \cdot 10^{-8}$ pSv / μ (from the kernel)
- From FLUKA we have seen that the ratio of effective dose and absorbed dose at 100km is around 1.7-1.8 → C. Carli's prediction corresponds to around $1.2 \cdot 10^{-7}$ pSv / μ, i.e., approximately 30% more than the FLUKA-based effective dose kernel



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