International
MUON Collider
Collaboration

Muon Collider Neutrino-Induced Hazard and its Mitigation

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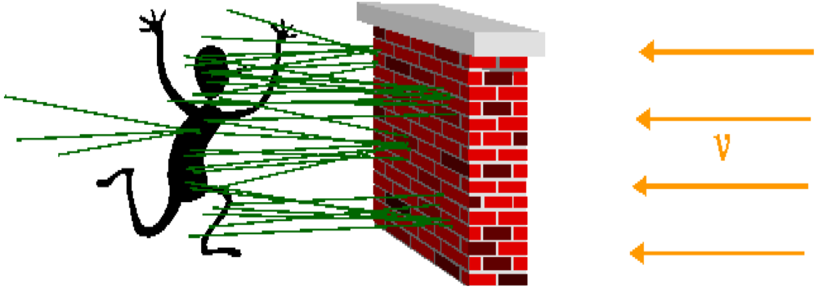

Nikolai Mokhov, Fermilab, May 20, 2021

Outline

- Neutrino-Induced Radiation at Muon Colliders (MC)
- “Neutrino” Dose to a Human Body *vs* Distance
- Neutrino-Induced Radiation around MC Ring and downstream of Field-Free Regions
- Four Ways to Mitigate Neutrino-Induced Hazard

Neutrino-Induced Radiation at MC (1)

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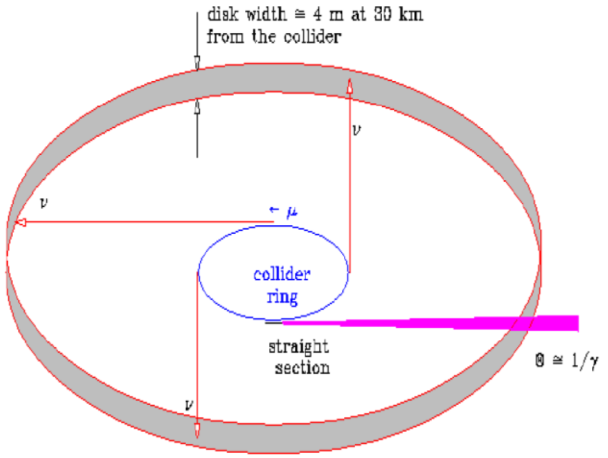
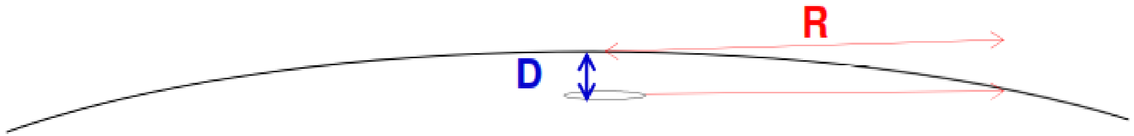
Intense highly collimated neutrino beams, created from muon decays in the ring and various straight sections of high-energy $\mu^+\mu^-$ colliders (MC), can cause – to the surprise of many - radiation problems even at very large distances from the machine.





$$R = \sqrt{2R_{earth}D}$$

The more energetic decay neutrinos emanate radially outward from the collider ring at angles with respect to the muon direction of order

$$\theta_\nu = 1/\gamma_\mu = m_\mu/E_\mu \simeq 10^{-4}\ /E_\mu[\mathrm{TeV}]$$

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Neutrino-Induced Radiation at MC (2)

Dose per neutrino at a given location from muon colliders (MC) grows with muon energy – keeping all other MC parameters the same - roughly as $\boldsymbol{E_\mu^3}$ due to (each responsible for a factor of E_μ):

1. Increase with energy of the neutrino cross section
2. Grows of total energy deposited
3. Collimation of the decay neutrinos

It becomes clear that ν-radiation will impact strongly on siting issues and cost of a high energy muon collider and therefore needs to be taken very seriously. Care must be taken in evaluating long-term averaged neutrino dose.

Developed by NM & AVG in 1996 a weighted neutrino interaction generator for the MARS Monte Carlo code permitted detailed simulations of the interactions with matter of neutrinos and of their progeny in and around MC capable to modeling neutrinos in the energy range from 10 MeV to 10 TeV.

Neutrino-Interaction Model in MARS15

The model serves to represent energy and angle of the particles emanating from a simulated interaction. These particles, along with the showers initiated by them, are then further processed by the MARS code which calculates, e.g., energy deposition and dose as a function of location in a user specified geometry model.

Muon and electron neutrinos and their antiparticles are included and distinguished throughout, which are represented in the decays from MC in roughly equal amounts. The model identifies the following types of interactions: charged and neutral current deep inelastic, neutrino-nucleon elastic and quasi-elastic scattering, interactions with atomic electrons and coherent elastic scattering.

”Neutrino Dose around Muon Colliders

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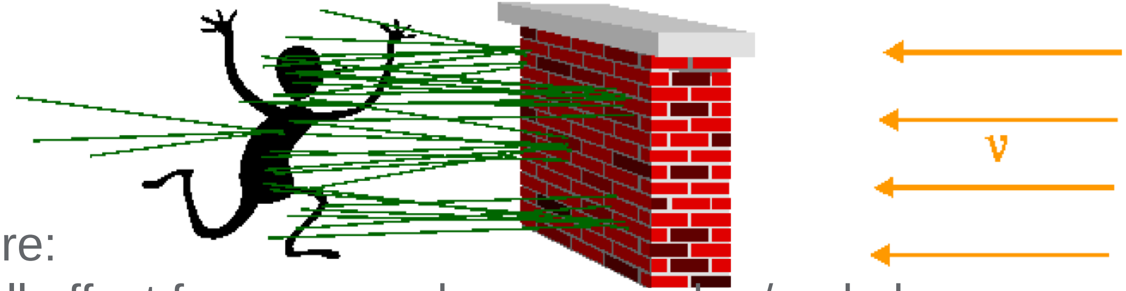
Extremely low interaction and scattering probabilities mean that neutrinos travel essentially in a straight line and survive over enormous distances. Much like neutrons and gammas, neutrinos by themselves cause little or no biological damage but instead create charged particles which in turn deposit their energy in tissue to be interpreted as dose “due to neutrinos”. “Neutrino” dose is by charged particles generated by neutrinos upstream a human.

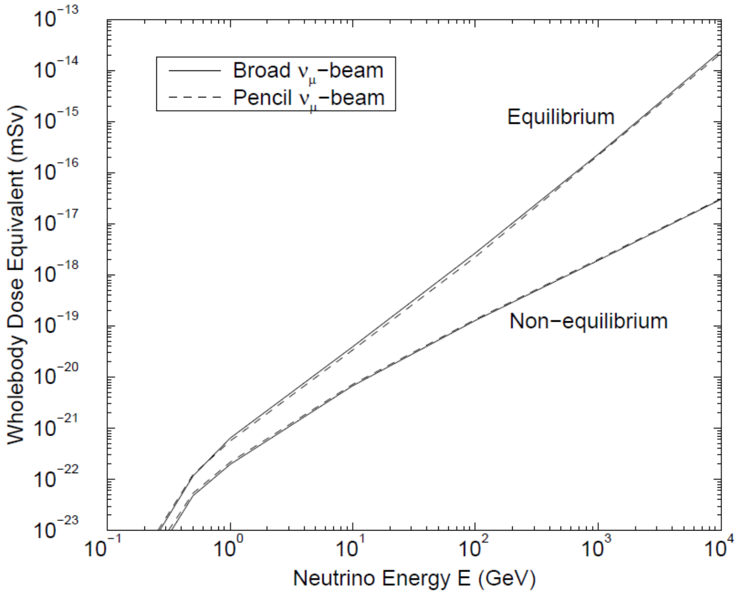


Therefore:

- Small effect for anyone above ground or/and above ground building
- Noticeable effect inside a “basement swimming pool”
- Unacceptably high effect, e.g., for a person lying in a basement room for extended period

Dose to a Human Body *vs* Neutrino Energy

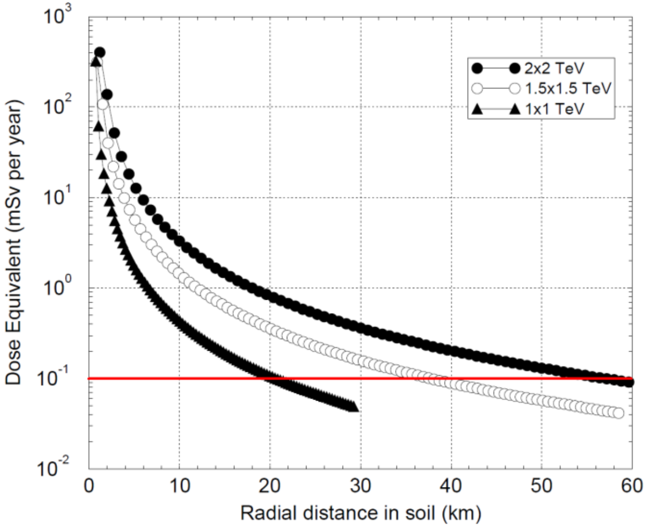
- Total whole-body effective dose in a bare seated person (**non-equilibrium**) and in one embedded in infinite soil (**equilibrium**).
- The whole-body dose is a factor of 2 lower than the maximum dose.
- The equilibrium dose is achieved after 3-4 m of soil or concrete at all neutrino energies considered here.
- Instead of providing shielding, the presence of soil/concrete upstream enhances the dose by up to a factor of 1000 in the TeV region as compared to the case with no shielding.



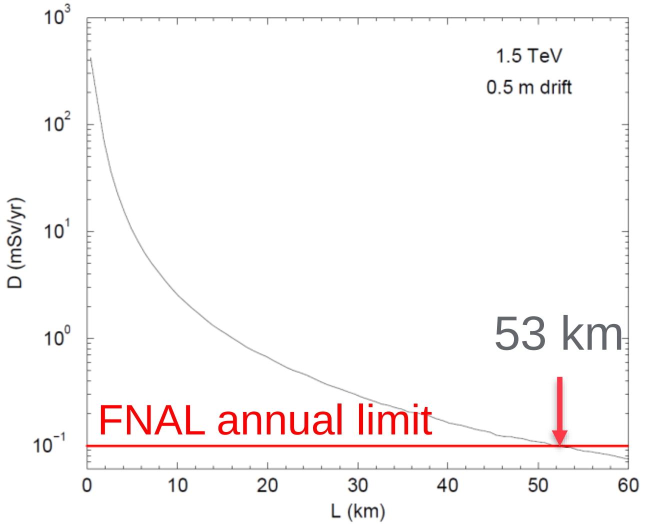
<u>Annual off-site limits:</u>

DOE	1 mSv = 100 mrem
FNAL	0.1 mSv = 10 mrem

Maximum Equilibrium Dose vs Distance in Soil



Around the 2, 3 and 4 TeV rings in orbit plane with 1.2×10^{21} decays/yr *vs* distance in soil from ring center



1.5-TeV muon beam with 2.6×10^{16} decays/yr in a 0.5-m drift *vs* distance in soil downstream the drift

ν-radiation from field-free regions (drifts, straight sections, etc.) becomes a most serious radiation problem at high-energy muon colliders even over very short regions: at E_μ = 10 TeV, 0.1-m drift and10^{16} decays/yr → L=380 km

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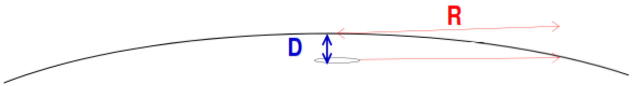
Mitigation of ν Hazard (1): Place Collider Deep Underground



$$R = \sqrt{2R_{earth}D}$$

	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N \times 10^{21}$	0.2	0.2	1.2	1.2	1.2
1 mSv	R (km)	0.4	1.1	6.5	12	18
	d (m)	≤ 1	≤ 1	3.3	11	25
0.1 mSv	R (km)	1.2	3.2	21	37	57
	d (m)	≤ 1	≤ 1	34	107	254

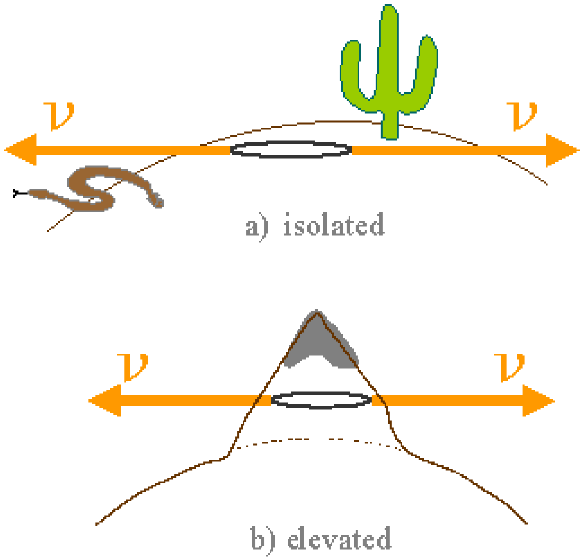
- Assuming suppressed contribution from field-free regions
- The Earth's curvature prevents this from being a generic solution
- There is also the regulatory question whether delivering an off-site dose above the limit at any depth underground or height above it is permissible

MARS-calculated depth D to reduce ν-induced long-term maximum dose at surface (at radial distance R from collider ring center) to DOE and Fermilab annual off-site limits at N decays/yr.

Note that useful simplified expressions derived by B. King in 1996-1998 give noticeably more conservative results compared to those from MARS sophisticated Monte Carlo. For example, for the 3-TeV case, depth to stay within 1% of the DOE limit is 300 m (MARS) compared to the analytical 500 m (Ankenbrandt et al , 2018).

Mitigation of ν Hazard (2): Isolated Site for multi-TeV MC

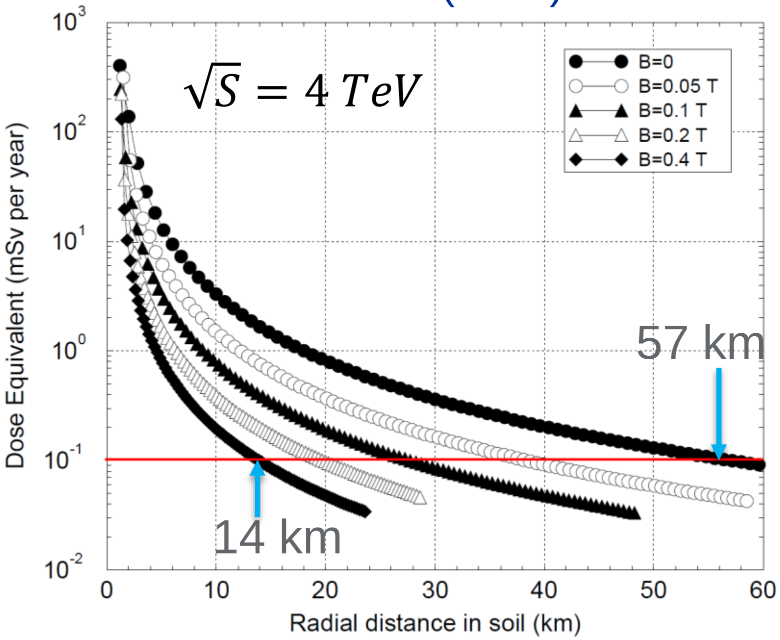
- Desert
- Mountain region
- Remote island



Mitigation of ν Hazard (3): Minimize Field-Free Regions

- Presence of a field of even a fraction of 1 T is enough to reduce the dose to a below-limit level
- The application of such a field over all RF and other components seems possible
- Straight sections could be shortened by using continuous combined function magnets
- Beam wobbling by vertical wave field weekly shifting the orbit longitudinally, CJ & NM (1997)

MARS15 (1997)



Mitigation of ν Hazard (4): Reduce Muon Beam Intensity

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- Better cooling, *e.g.*, optical stochastic cooling, might reduce the emittances by several orders of magnitude, thus greatly reducing the required muon beam currents keeping luminosity the same
- Better focussing: its strength could be increased by the use of plasma or other exotic focusing method at IP

Thank you for attention

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