Neutrino hazard

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- Introduction (many of you already know..)

- Scaling laws from full simulations
  - Comparisons with previous results
  - Distributions in space
- Hints for mitigation

Neutrino Hazard

- How is it possible??
- First of all, we are dealing with low doses: Limit is given by limit to population → STAY AT 1/10 →below 0.1mSv/y

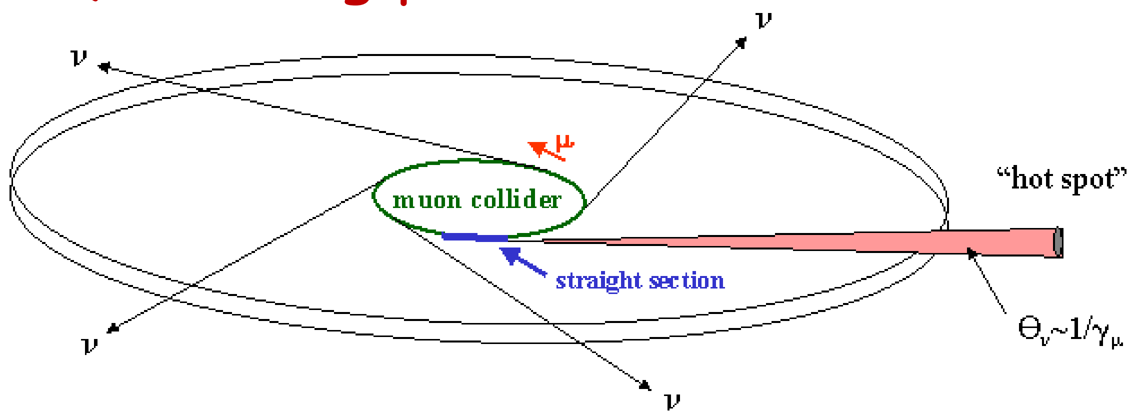
Definition	Limits
Effective dose whole body	1 mSv/an
Equivalent dose for crystalline lens	15 mSv/an
Equivalent dose for the skin	50 mSv/an

Annual exposure limits beyond medicine and natural radioactivity
These annual limits for exposure of the population are those of the public health code. These limits apply to the total effective dose or equivalent received outside of natural radioactivity and medicine, including those resulting from nuclear activities. The maximum permissible dose of 1 mSv per year represents approximately 40% of natural exposure. (For the skin, it is the average dose per cm2 of skin, regardless of the display surface).
©ASN http://www.radioactivity.eu.com/site/pages/Doses_Limits.htm

- Neutrinos from decay of (intense) muon beams are extremely well collimated: Neutrino beam size roughly given by muon $1/\gamma$. At 1 TeV, $1/\gamma \approx 10^{-4}$
- Number of muon decays ~3×10^{13} /s/beam ➔ 6×10^{20} /year/beam (these are not p.o.t!)
- Dose comes from energy released by neutrino interaction products
- Collider is underground: problem is when beam reaches surface

Neutrino Hazard

- Number of muon decays ~3×10^{13} /s/beam ➔ 6×10^{20} /year/beam ($2\times10^{12}\mu$/bunch)
- (Assuming proton driver. Electron driver has 300 times lower current!)



"Ring" dose and "straight section" dose
(plot from B.King, hep-ex/005006)

$\frac{D}{\gamma}$ = 5m !

- Example: 1TeV muons, ring dose at D=50 km:

TeV

- $\Phi_\nu = 2 * \frac{1.2\cdot10^{21}}{2\pi D * \frac{D}{\gamma}} \approx 1.5\cdot10^{11}\nu/cm^2y$ $\quad < \sigma_\nu > \approx 0.5 * 1000 * 10^{-38}cm^2$.

Interactions/kg/y $=\Phi\sigma N_A * 1000 \approx 400$.

At equilibrium, deposited energy=Interactions*energy. Convert TeV to J:

Gy/y $= 4\cdot10^2 * 1.610^{-7} \approx 6\cdot10^{-5}$. ➔ approx 0.06 mSv/y

Neutrino Hazard

- Importance of radiation hazard due to highly collimated intense neutrino beams known since many years
- Already studied in analytical way and with MARS simulations: see for instance
  - Nikolai Mokhov & Andreas Van Ginneken *Neutrino Radiation at Muon Colliders and Storage Rings*, J. of Nuclear Science and Technology, 37:sup1, (2000) 172
  - R. B. Palmer *Muon Colliders* RAST 7 (2014) 137
  - B. J. King *Neutrino Radiation Challenges and Proposed Solutions for Many-TeV Muon Colliders* arXiv:hep-ex/0005006 (2000)

Fluka Simulations

- Full simulation of muon decay along a ring or in a straight section
- Full simulation of the neutrino interactions (along decay direction)
- Full simulation of particle showers
- Calculated: ambient dose equivalent (H*(10)) due to neutrino interaction products: from convolution of particle fluence and conversion coefficients (online in Fluka). This is a conservative estimate routinely used in Radiation Protection
- Idealized earth (round, no mountains)
- Most of the simulations do not include beam divergence
- Simulation at one fixed depth, use depth-exit point relation to recover shallower ring depths :

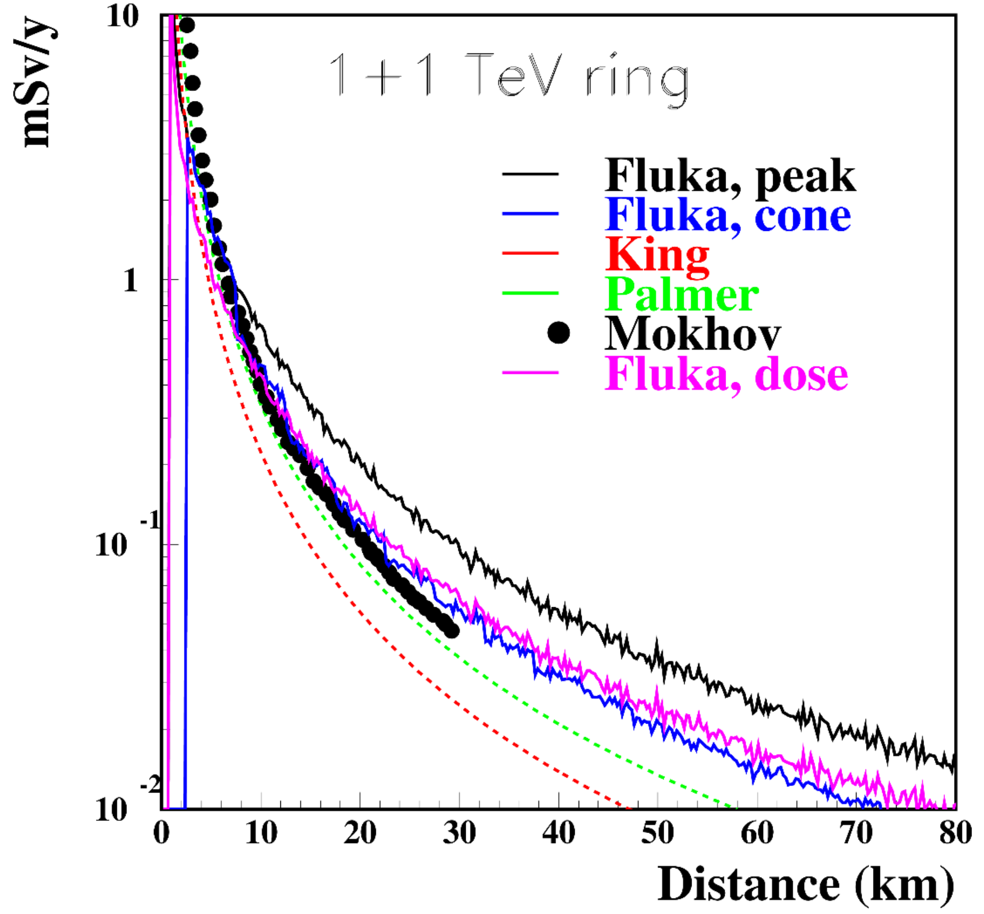
$$\mathrm{L} = \sqrt{(R_{earth} - h)^2 - {R_{earth}}^2} \sim \sqrt{2R_{earth}\, h}$$ (L=exit distance, h=depth)

Comparison with other works: Ring

- Analytical B. King : $$D^{ave}[mSv] \simeq 3.7 \times N_\mu^+[10^{20}] \times \frac{(E_\mu[TeV])^3}{(L[km])^2}.$$
- Where L is the distance from ring to exit point, and N the number of decaying muons of each sign
- Similar for M. Palmer, with 3.7→5.6 (if I have everything right)
- Note the dependence on E^3, from Energy*cross section*1/γ
- Simulated by N. Mokhov et al (MARS)
- For the comparison, assume Nikolai's normalization: 1.2×10^{21} μ/year TOTAL (6×10^{20} each sign). Also consistent with Mark's parameters

Comparison: 1+1 TeV ring

Year dose vs exit distance



Many Fluka lines… what?

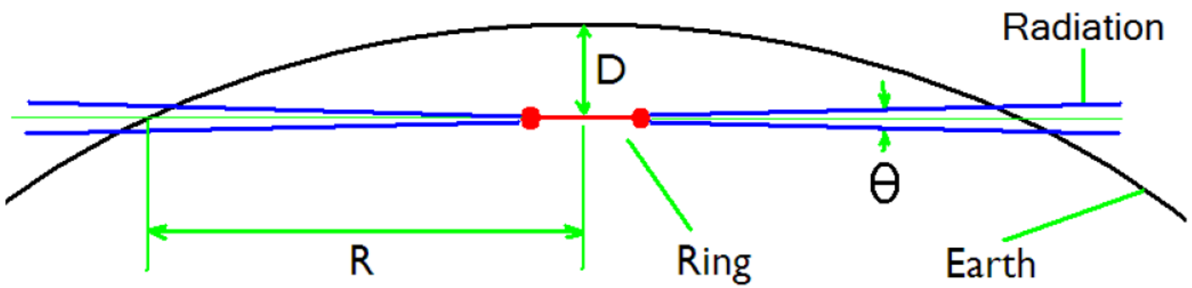
- **Peak** and **cone** refer to the extent of averaging in space: cone is all what is within a $1/\gamma$ cone. Peak is narrower, corresponds to minimum scoring area in the setup . Both H*(10)
- **Dose** is energy/mass (no quality factors). Same as peak in space

Comments:

- King's formula underestimates. Probably because of underestimation of ν_μ contribution
- Agreement Palmer, Mokhov, Fluka-cone : all of them assume uniform neutrino flux within $1/\gamma$
- FlukaPeak higher

➔ let's have a look to distribution in space

Space distribution: Ring

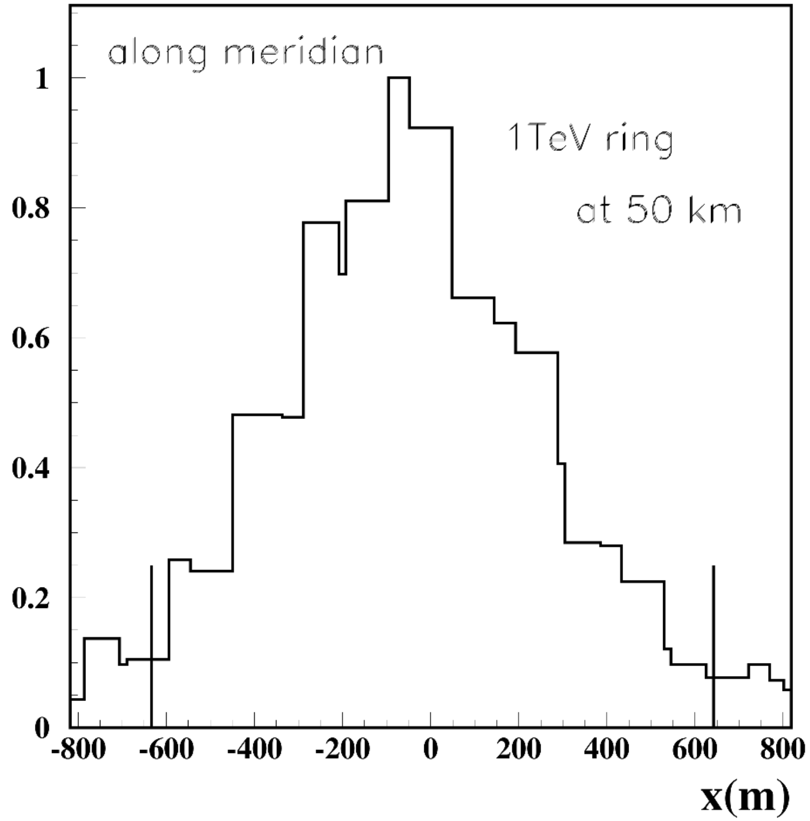


Radiation from ring exits on a phi-symmetric corona. (Plot: M. Palmer)
Due to Earth curvature, linear dimensions along the local "meridian" are stretched with respect to perpendicular

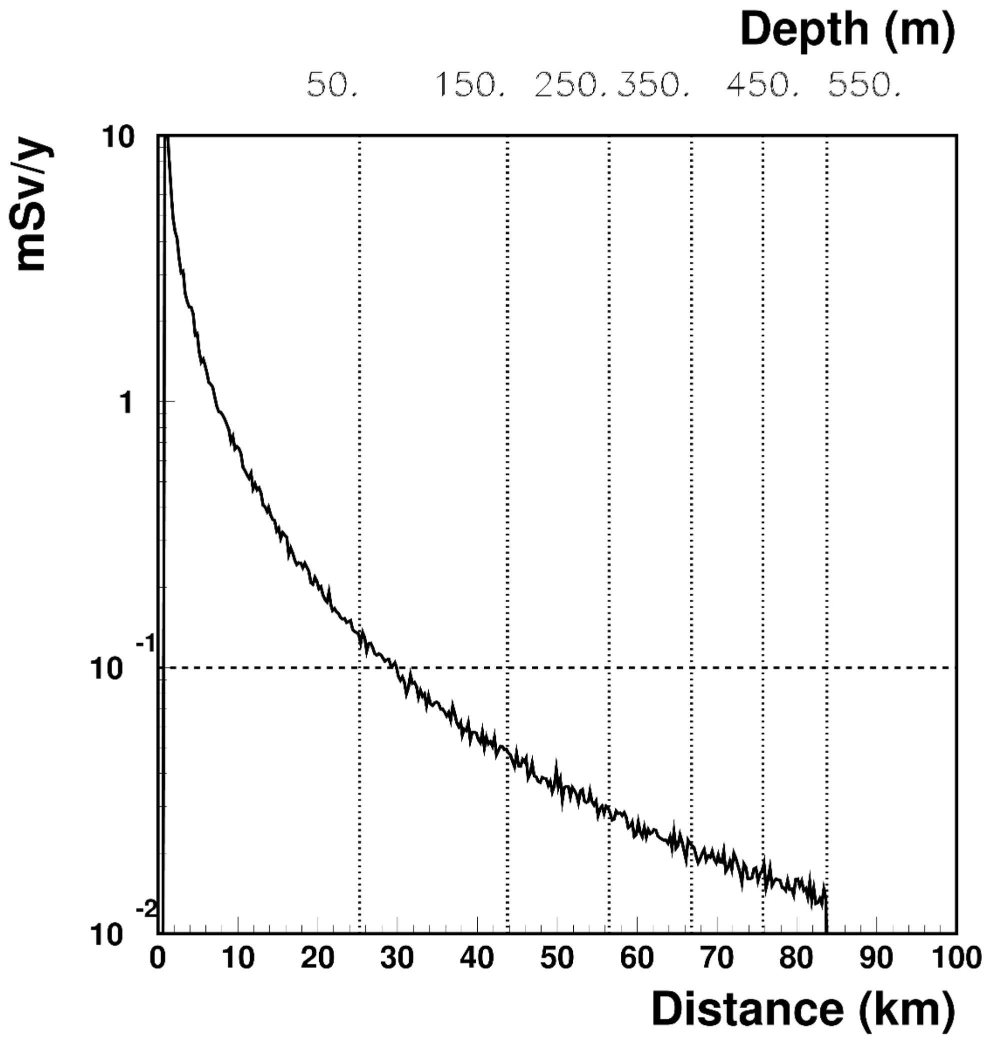
H*(10) profile along the "meridian" for a 1+1 TeV ring, with exit distance of 50 km.
Normalized to maximum (peak) value
Vertical lines are the $1/\gamma$ cone: at 1 TeV it extends up to +-600 meters.

Cone averaging underestimates the dose

Shape independent on exit distance ,
σ [m] $\approx 300/E_{\mu}$[TeV]



1+1 TeV : ring dose, safe



plot stops at 550m==position of ring in MC geo

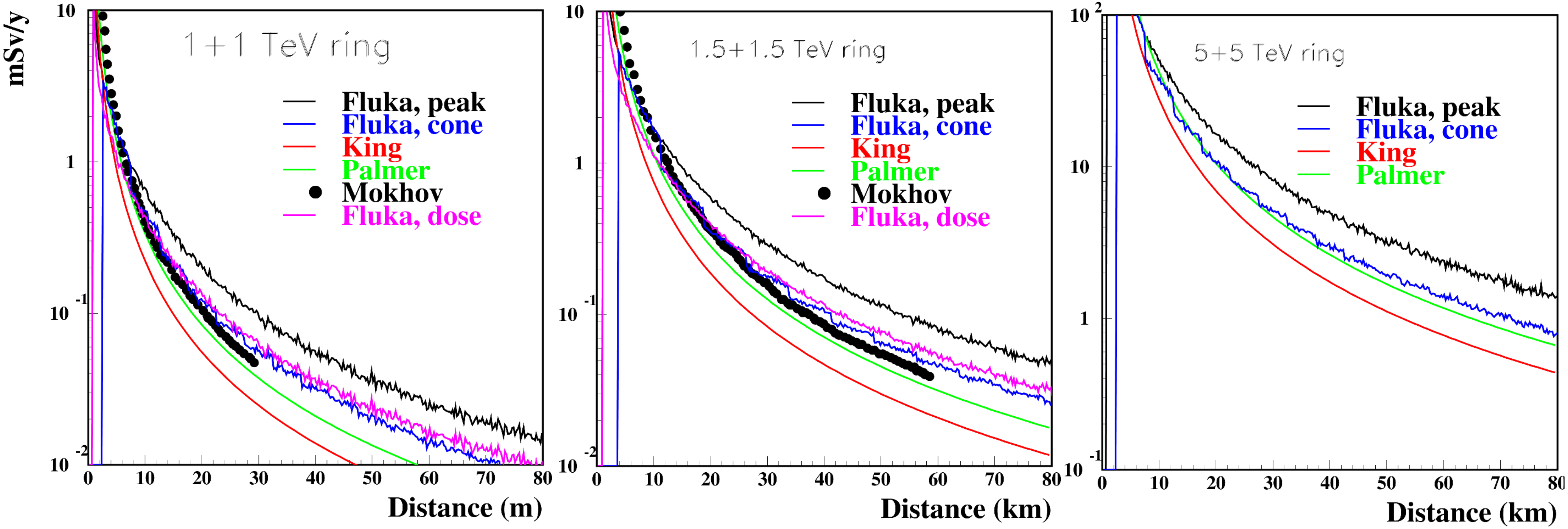
FLUKA results for ambient dose equivalent (H*(10)) as a function of distance from ring, or (top axis), depth of the ring. Averaged over 1m in the vertical plane. Assuming **1.2 10 ^{21}** decays/y (2.10^{12} μ/bunch, 15 Hz, 200 days)

Muon beams with Zero emittance

Warning here : distance/depth relation from spherical earth surface, no mountains

No problem !!

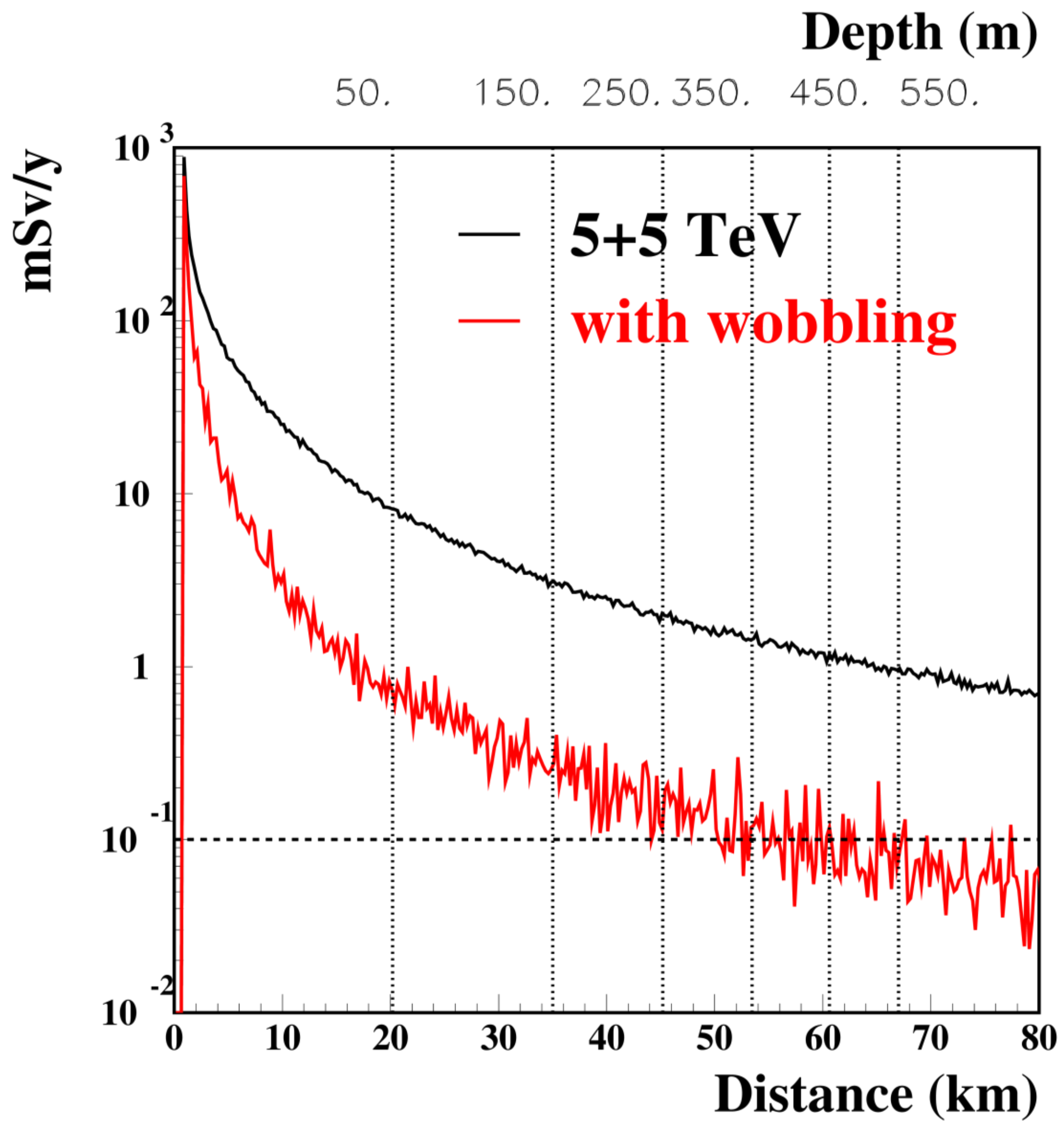
Other energies, ring, all same N_μ



	1.5/1	5/1
E^3	3.4	125
Fluka, peak	3.1	90

E^3 scaling tends to overestimate. At high energies, shower size and muon lateral displacement start to play a role.

Can we go up? Ring solutions



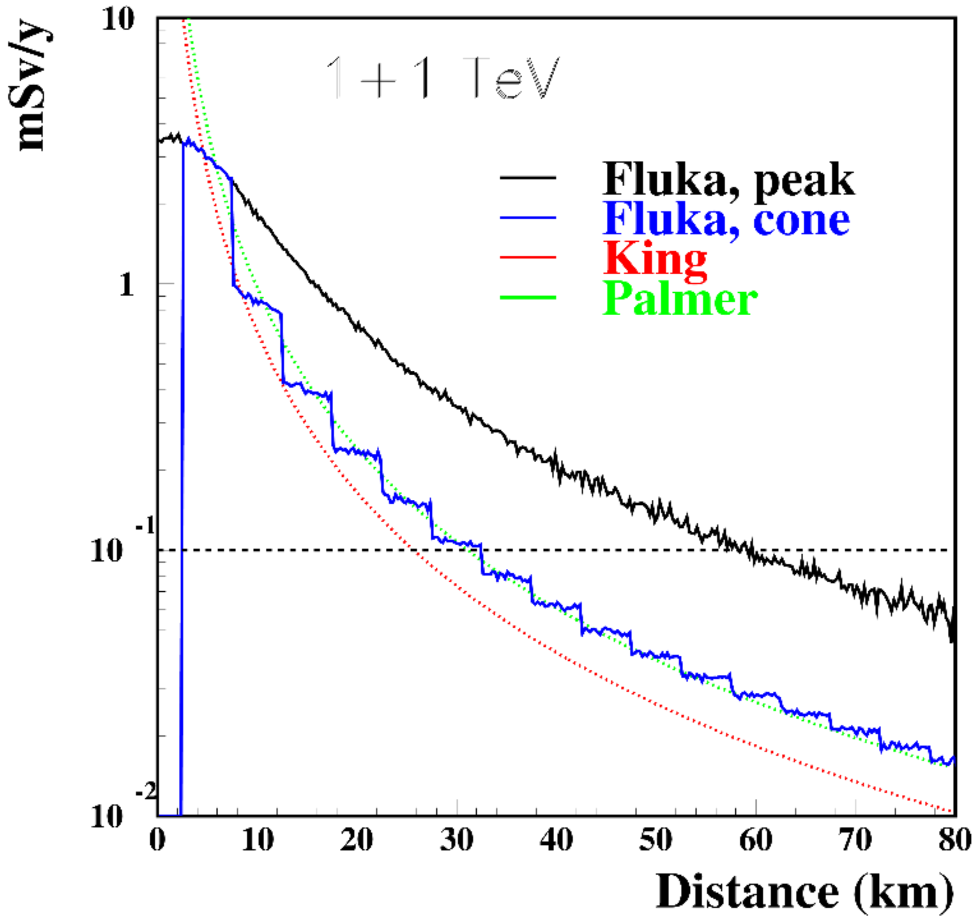
- Wobbling: Vertical periodic deflection of muon beams in the ring (achievable with small tilt of the magnets). Here example with a 200μrad kick: almost OK
- Periodic "bumps", slowly changing during the year . Provided we always stay ~ background (below 1mSv/y)
- Emittance: possibility 20 times more vertical than horizontal ?
- Luminosity?? Do we need the same beam intensity at all energies?
- This plot is with $\frac{1}{2}$ N_μ wrt 1 TeV, corresponds to 3+3TeV assumed intensity in MAP studies (Palmer)

Comparison with other works: Straight sections

- Analytical B. King $$D^{ss}[mSv] = 1.1 \times 10^5 \times N_\mu[10^{20}] \times f^{ss} \times \frac{(E_\mu[TeV])^4}{(L[km])^2},$$
- Where $f^{ss} = \frac{l^{ss}}{C}.$ = length of straight section/ circumference
- Similar for M. Palmer, with 1.1 ➔1.61 (if I have everything right)
- Note the dependence on E^4, from Energy*cross section*1/γ* 1/γ
- For the comparison, assume Nikolai's normalization: $1.2\text{x}10^{21}$ μ/year TOTAL ($6\text{x}10^{20}$ each sign). Also consistent with Mark's parameters

Comparison: 1+1 TeV Straight section

Year dose vs exit distance



$f_{ss} = 1/10000$, $N_{\mu} = 6\ 10^{20}$

Reminder

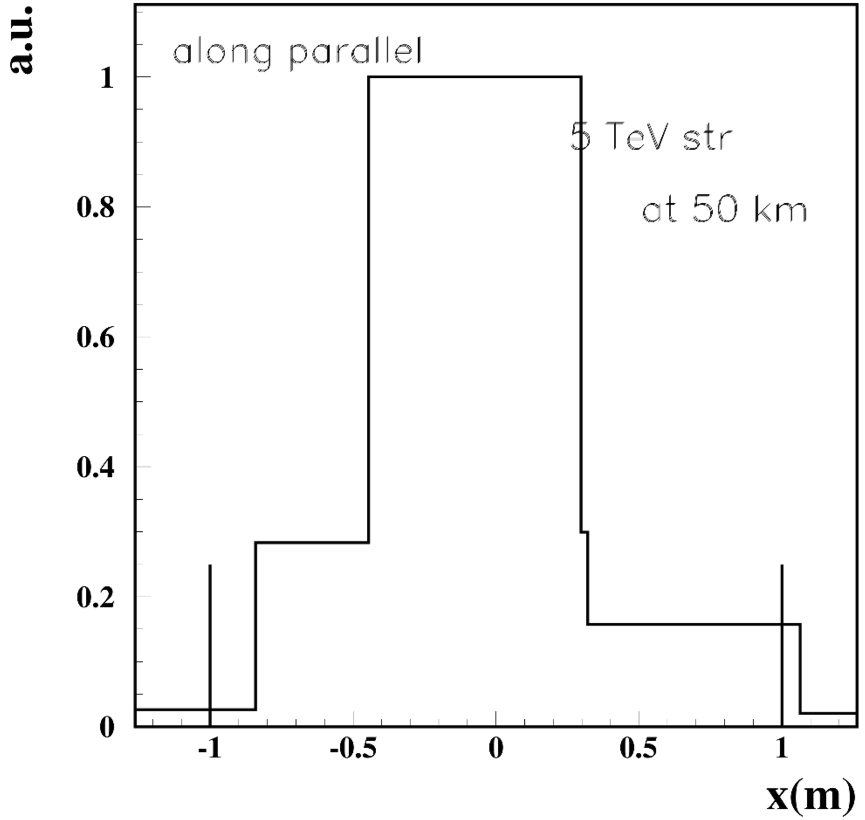
- **Peak** and **cone** refer to the extent of averaging in space: **cone** is all what is within a $1/\gamma$ cone. Peak is narrower, corresponds to minimum scoring area in the setup . Both H*(10)

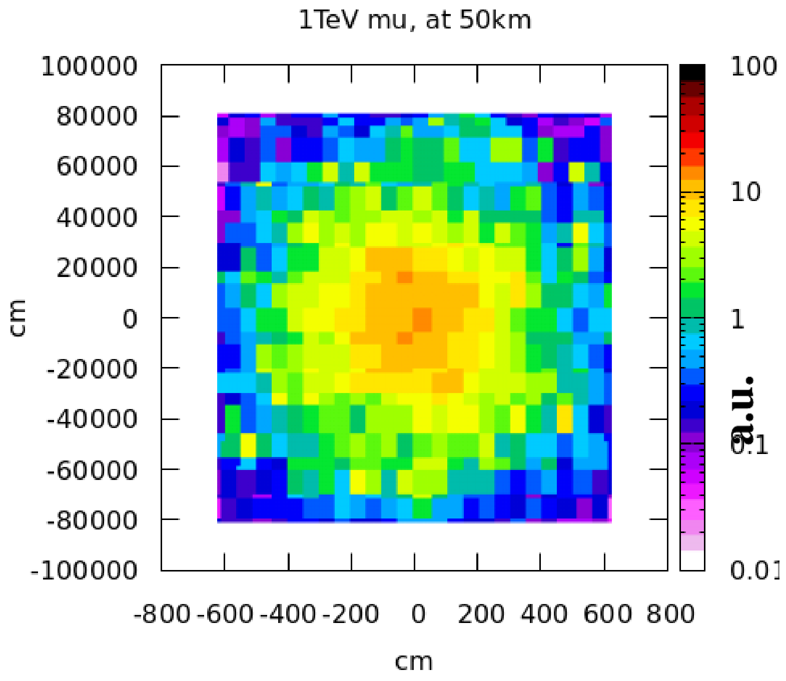
Comments:

- King's formula underestimates. Probably because of underestimation of ν_{μ} contribution
- Agreement Palmer, Fluka-cone : uniform neutrino flux within $1/\gamma$
- FlukaPeak higher

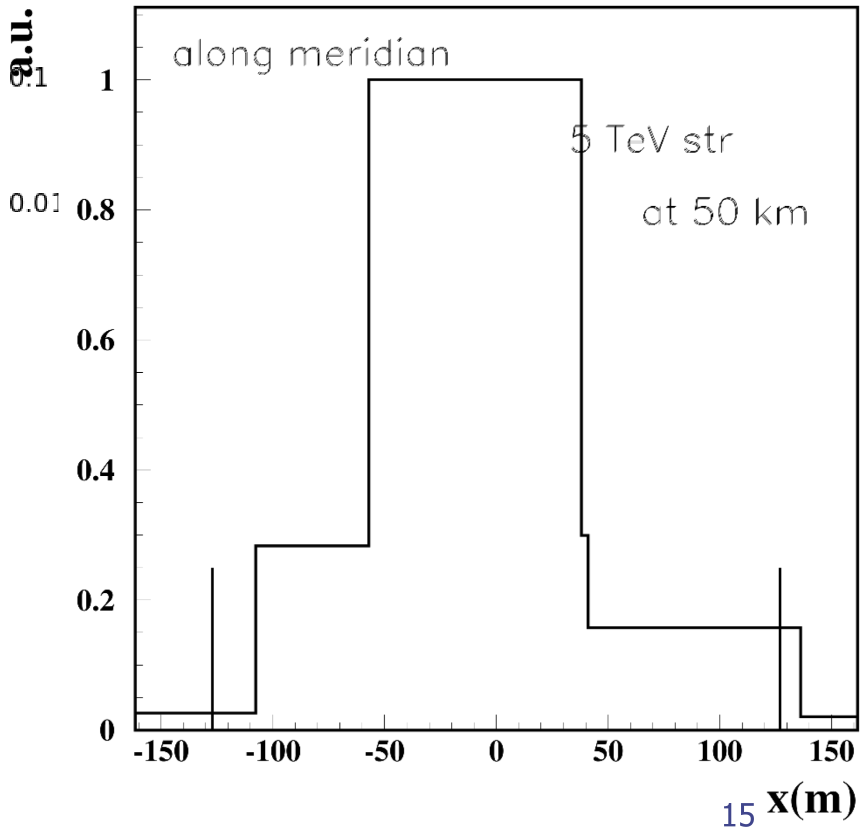
➔ let's have a look to distribution in space

Straight section: spatial distribution



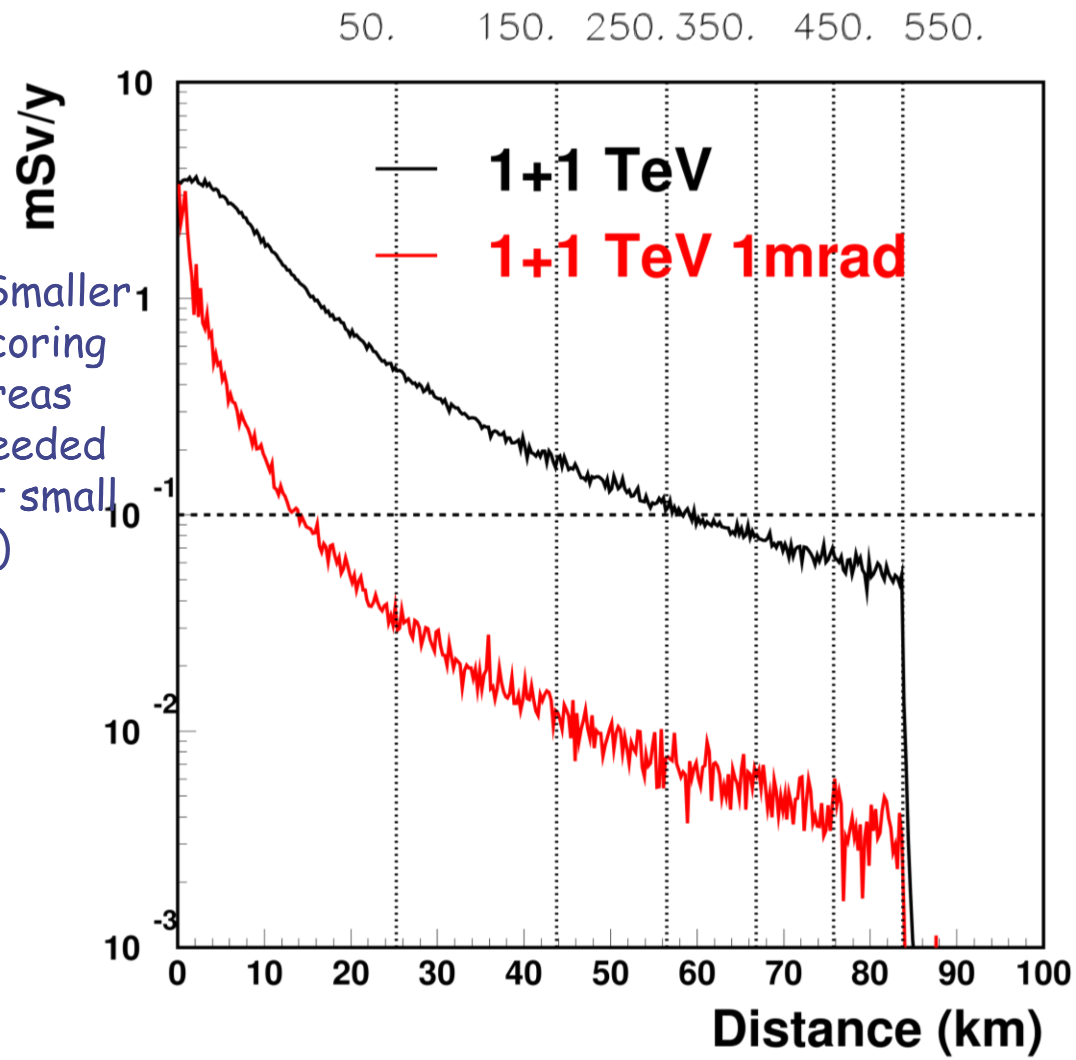


In the "vertical" (along a meridian): Same as ring σ [m] ≈ 300/E[TeV]



In the "horizontal" (along a parallel): Few metres σ[m] ≈ 0.3 *γ * R[m] R=distance to exit point

1+1 TeV : straight sections: possible



(Smaller scoring areas needed at small D)

Dose vs distance from exit, or depth, for a straight section

whose length is 1/10000 of the ring circumference. Which is small, means **that optics must be well studied.**

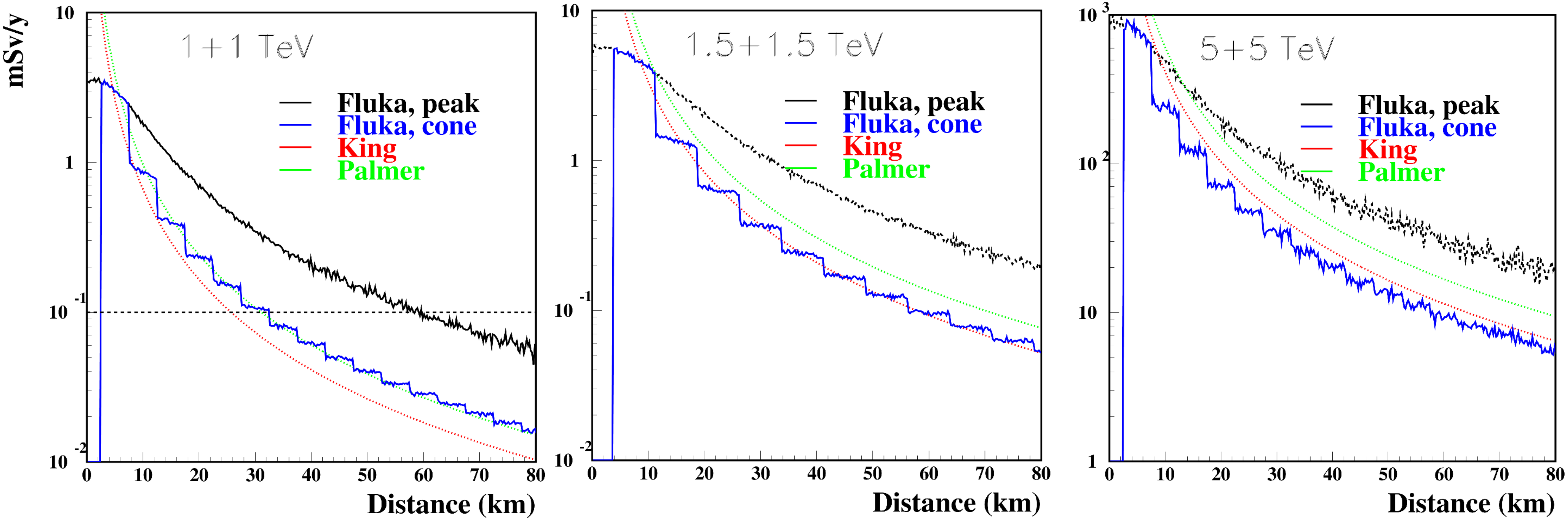
Red: added divergence=1mrad (10 times $1/\gamma$)

Also here no big problem, need care

Need to design new ring with suitable orientations

More difficult for interaction point: must be longer!

Other energies, straight, all same N_μ



	1.5/1	5/1
E^4	5	625
Fluka, peak	3.2	300

E^4 scaling tends to overestimate. At high energies, shower size and muon lateral displacement start to play a role.

Combining arcs+straight sections

1. What is the relative dose from arcs and straight sections?
2. What is the shape and intensity of dose from a "complex" situation: arcs+straight sections?

- 1: combining analytical descriptions both from King and Palmer one gets (L= length of straight section, C=total ring)

$$D_{ss}/ D_r = 3\ 10^4 * E_\mu * L / (C-L)$$

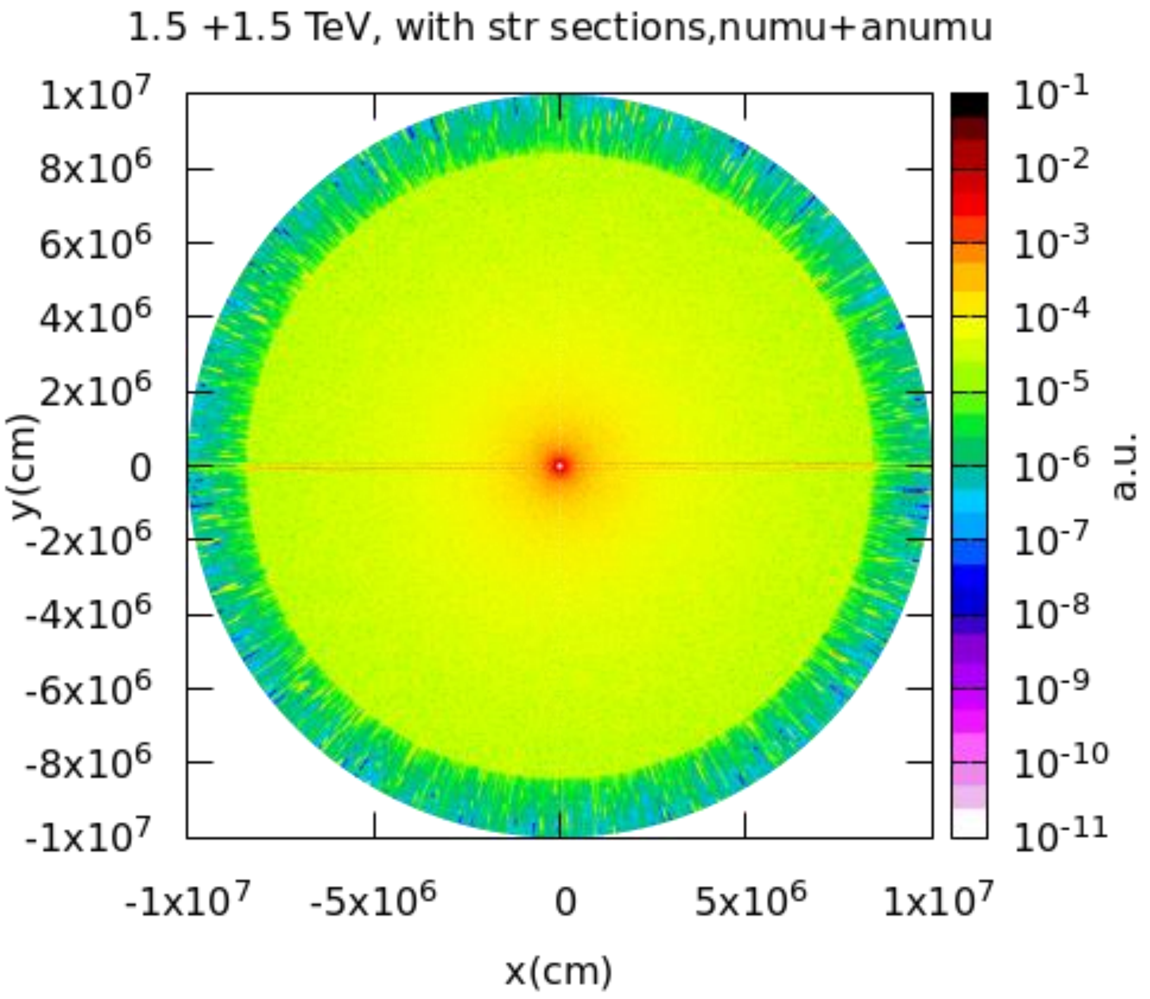
sometimes re-expressed in terms of average B field. In reality, what matters is the relative length == relative number of muon decays

The relation is confirmed by full MC simulation.

➔ The two become comparable for $L/C < 0.3 * E_\mu * 10^4$

Non- uniform ring

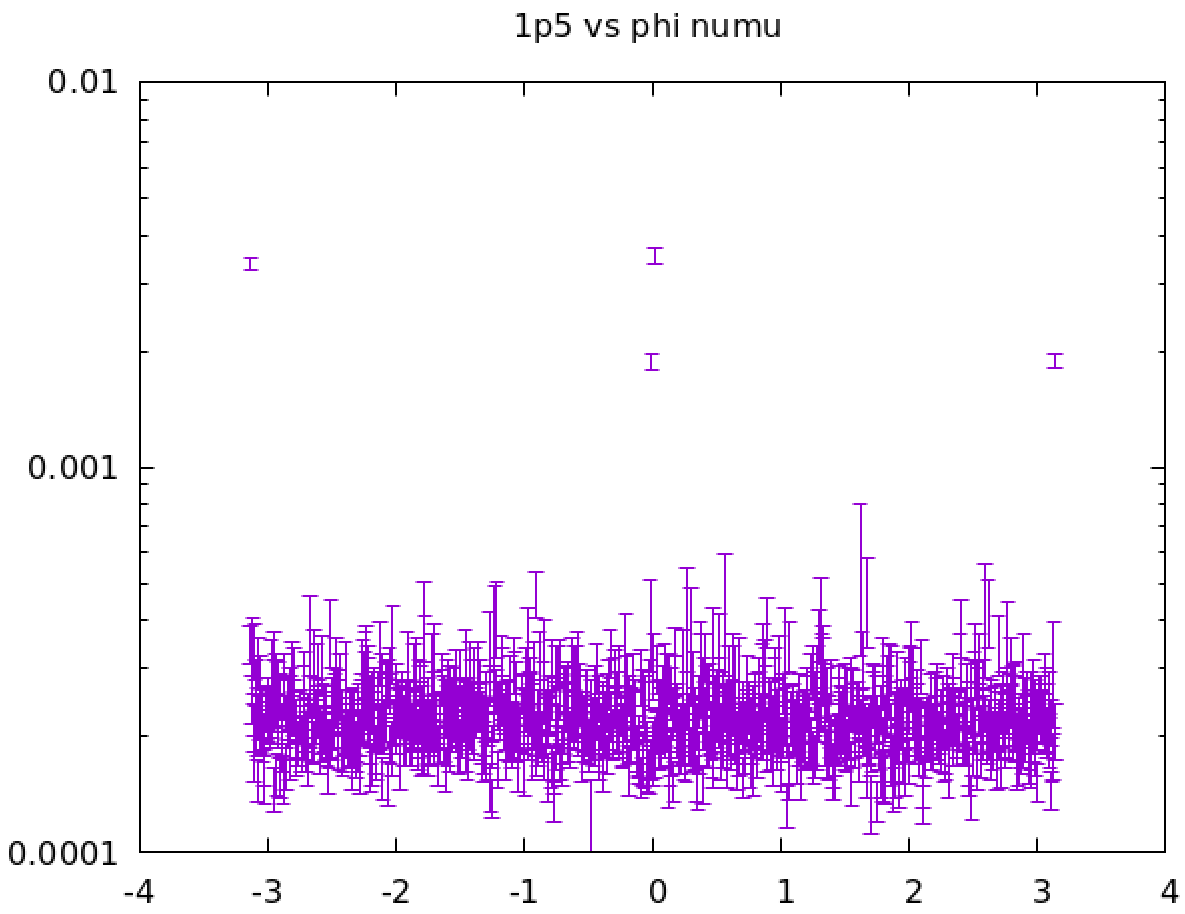
- Does the shape of the ring influence the dose? **NO**.
- Whatever the shape, it will be a closed ring: from far away it will be a point source with intensity proportional to N_μ * (C-L) (here L is total length of all straight sections)
- Plus of course the hot spots, in very limited cones
- Tried with a 5km ring + 2 straight sections 100m each, 1.5+1.5 TeV



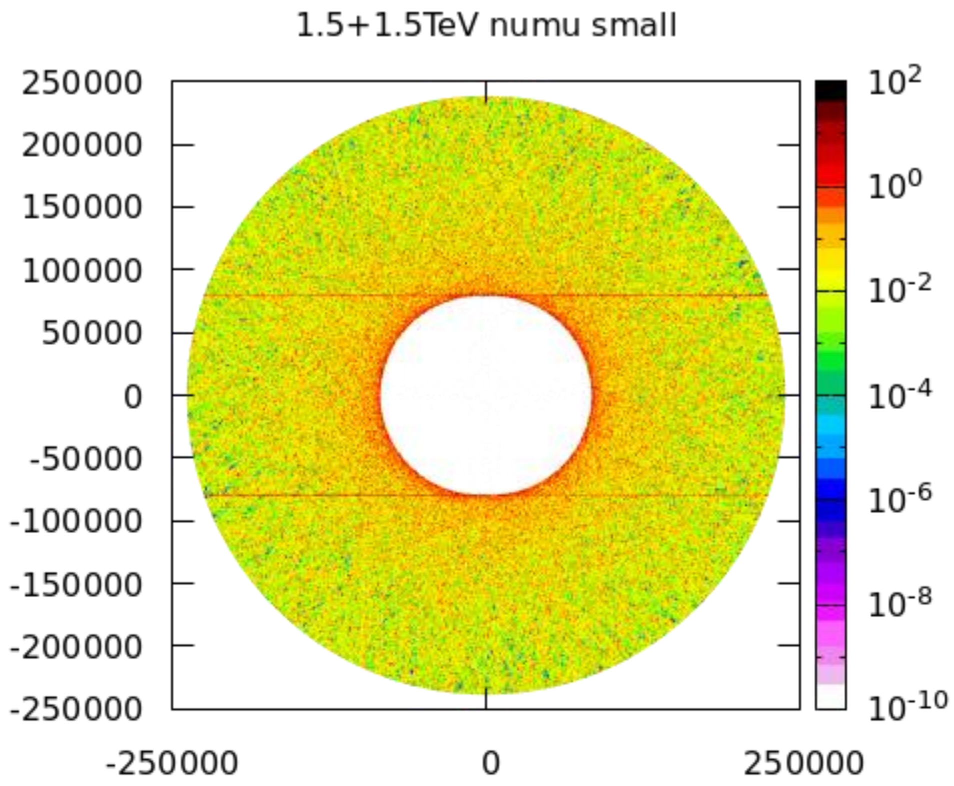
Seen from top. Earth surface at 80km distance

Non uniform ring: more plots

Far from the ring azimuthal distribution



Near to the ring, seen from top



Density?

- All simulation shown here used a uniform soil density = 2.4 g/cm^3
- What is the effect of soil density ?
- None on neutrino flux (interaction probability too small)
- Locally? Neutrino interaction rate scales with density, but Dose is defined as energy/density ➔ no effect at first order
- Lower density: longer distances needed to reach equilibrium
- Lower density: showers spread more ➔ here is the effect
- Tried with extreme: density = 1 g/cm^3

→ Small effect: dose reduces to 82% of original one

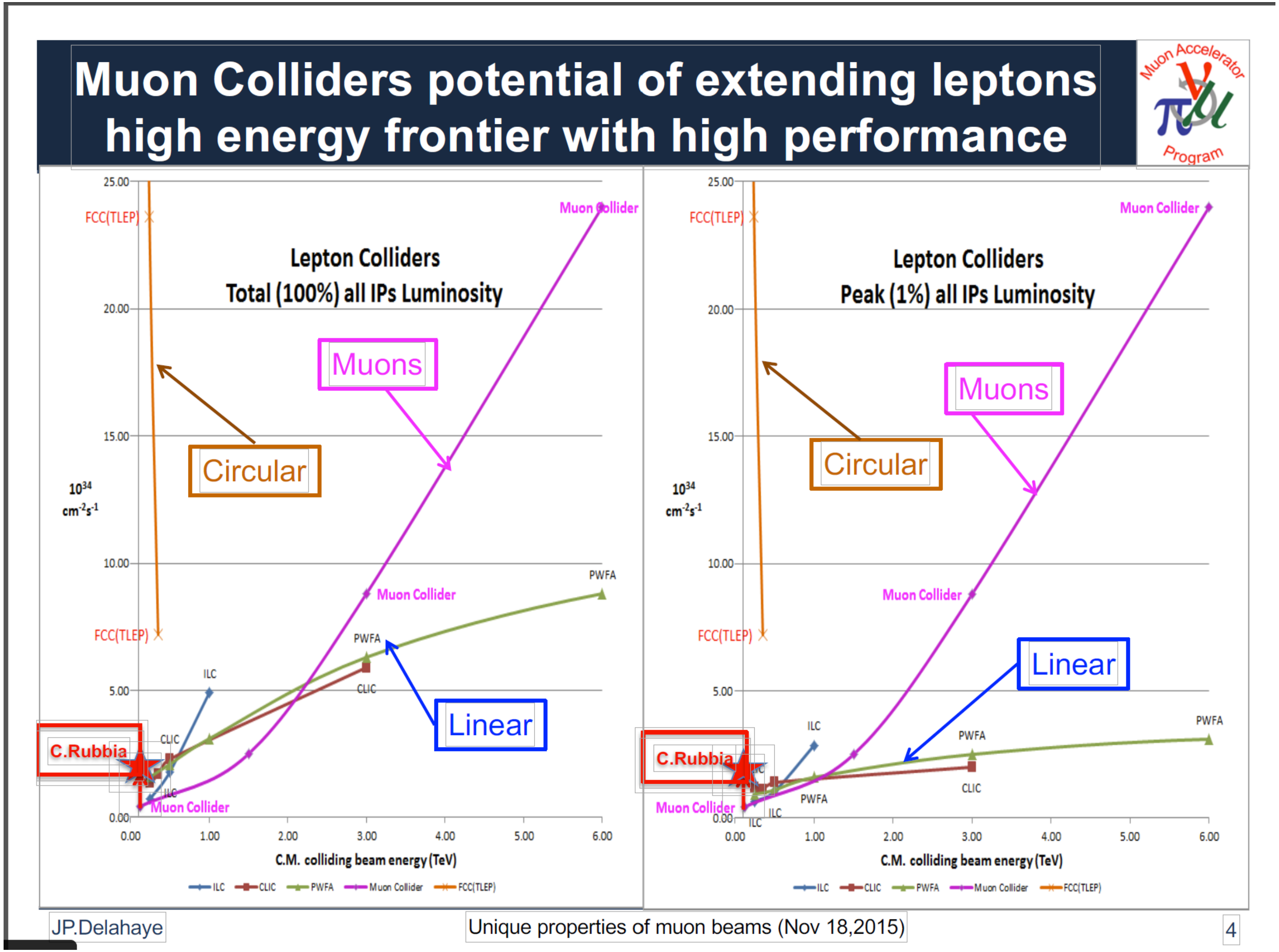
Summary

- Analytical formulae for dose provide good guidance, within factors of a few (generally underestimating)
- Energy dependence not as steep as foreseen
- Dimensions of the spot , or of the corona, scale rougly as
  - σ [m] $\approx$ 300/E[TeV] along the local meridian
  - σ [m] $\approx$ 0.3 *γ * R[m] $\approx$ 0.03* R[m] /E[TeV]   (R=distance to exit)
- Arcs+ straight section numbers can be safely calculated separately and added back
- Soil density plays a very minor role

Conclusions

- Neutrino hazard exists, should and can be managed
- With ease at 1+1 TeV
- With more thinking at higher energies:
  - Try to keep straight sections as small as possible
  - Play with emittance
  - Reduce (a bit) luminosity
  - Play with exit points (especially for interaction region)
  - Incline?
  - Add orbit bumps, wobbling, periodic changes…please, accelerator experts!
- Limits: 1/10 of natural background for whole year exposure,
- Never above natural background (equiv 1mSv/y) for shorter periods

backup



Luminosity

- MuonC design luminosities FAR EXCEED the ones considered for electron-positron colliders.
- Thus there could be room to sacrifice some of the MC luminosity to help deal with the radiation issue
- As already considered by the MAP collaboration

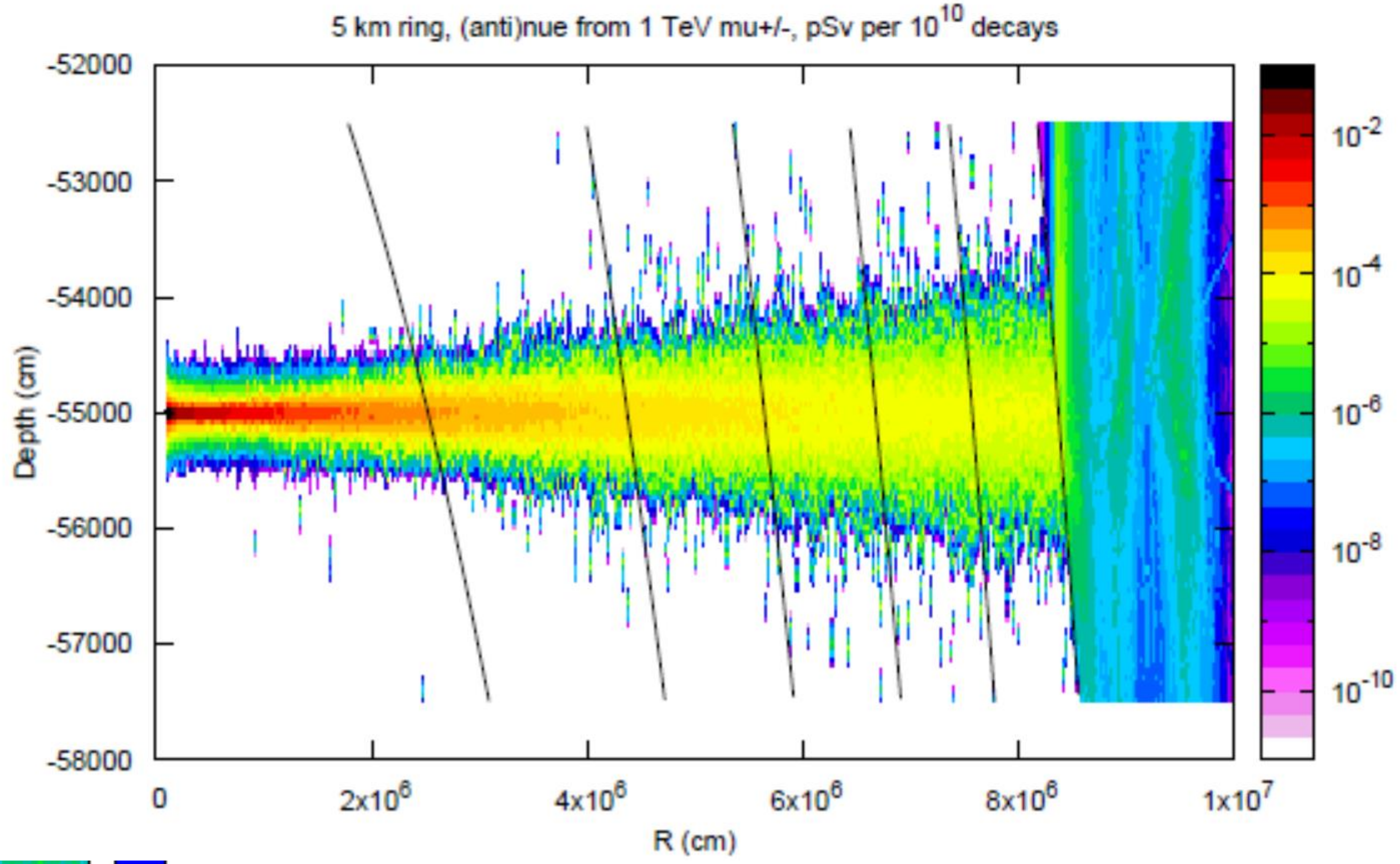
wikipedia

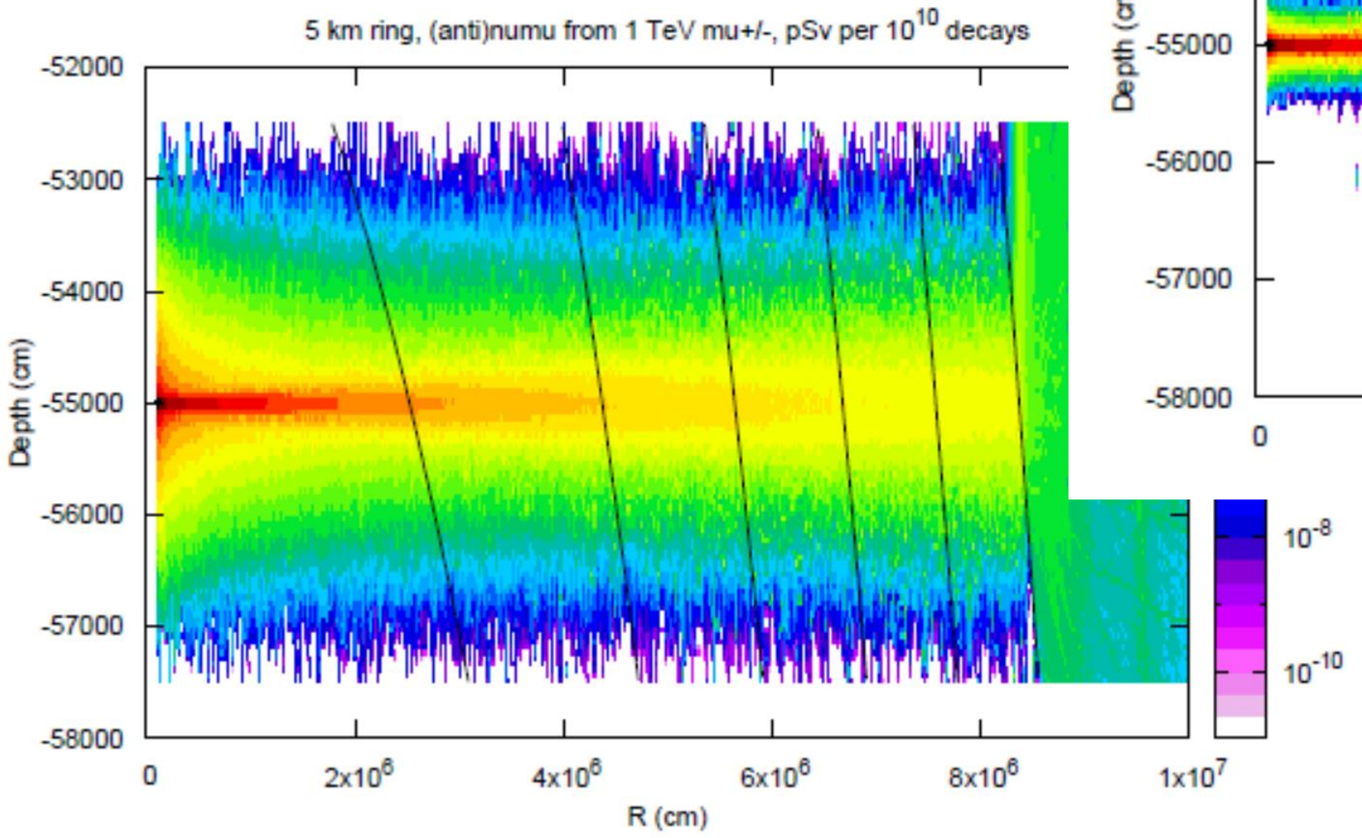
Average annual human exposure to ionizing radiation in millisieverts (mSv) per year

Radiation source	World[2]	US[3]	Japan[4]	Remark
Inhalation of air	1.26	2.28	0.40	mainly from radon, depends on indoor accumulation
Ingestion of food & water	0.29	0.28	0.40	(K-40, C-14, etc.)
Terrestrial radiation from ground	0.48	0.21	0.40	depends on soil and building material
Cosmic radiation from space	0.39	0.33	0.30	depends on altitude
sub total (natural)	2.40	3.10	1.50	sizeable population groups receive 10–20 mSv
Medical	0.60	3.00	2.30	worldwide figure excludes radiotherapy; US figure is mostly CT scans and nuclear medicine.
Consumer items	–	0.13		cigarettes, air travel, building materials, etc.
Atmospheric nuclear testing	0.005	–	0.01	peak of 0.11 mSv in 1963 and declining since; higher near sites
Occupational exposure	0.005	0.005	0.01	worldwide average to workers only is 0.7 mSv, mostly due to radon in mines;[2] US is mostly due to medical and aviation workers.[3]
Chernobyl accident	0.002	–	0.01	peak of 0.04 mSv in 1986 and declining since; higher near site
Nuclear fuel cycle	0.0002		0.001	up to 0.02 mSv near sites; excludes occupational exposure
Other	–	0.003		Industrial, security, medical, educational, and research
sub total (artificial)	0.61	3.14	2.33	
Total	3.01	6.24	3.83	**millisieverts per year**

(anti) muon vs (anti) electron neutrinos

Left: (anti) electron neutrinos
Bottom: (anti) muon ν
Same color scale

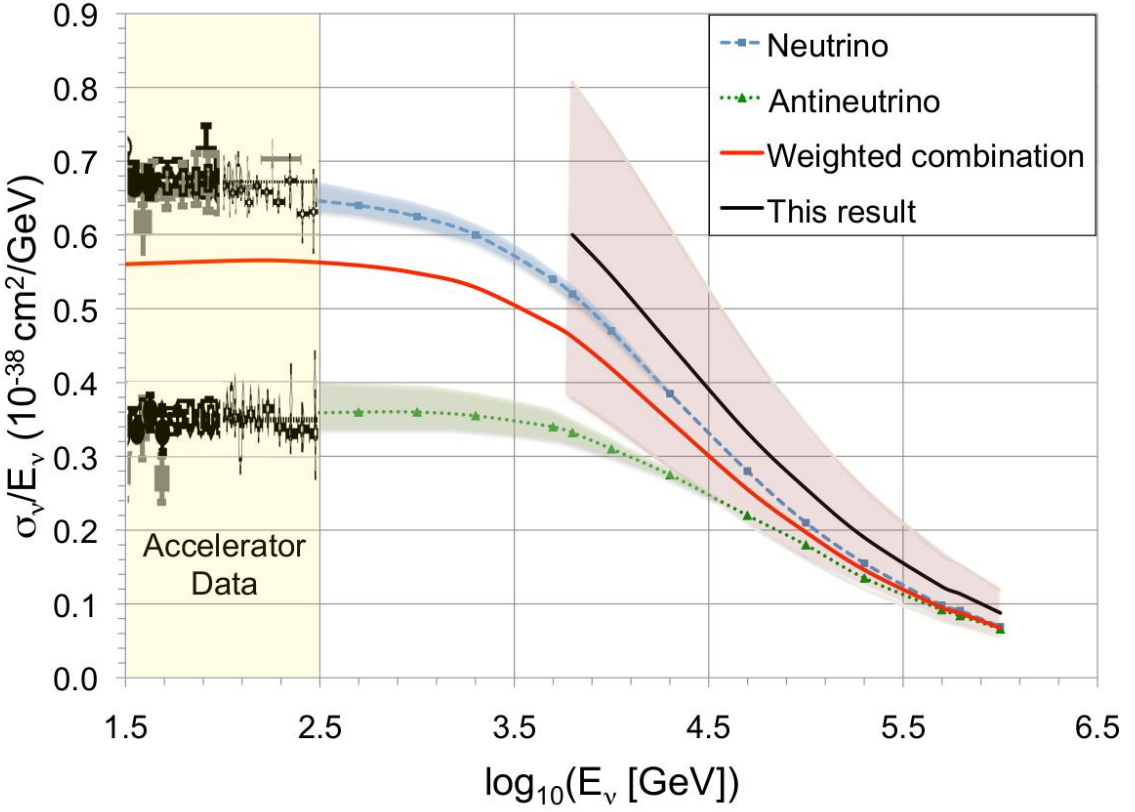




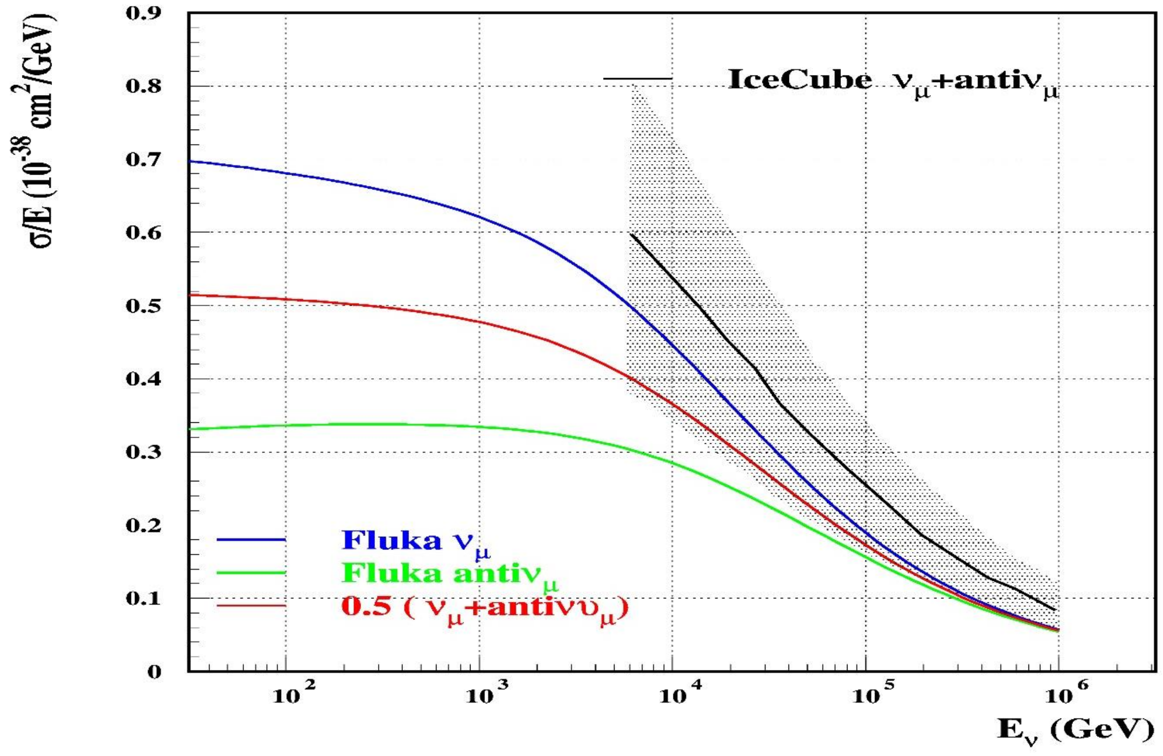
Note different lateral spread,
From different electron/muon
ranges

At higher energies

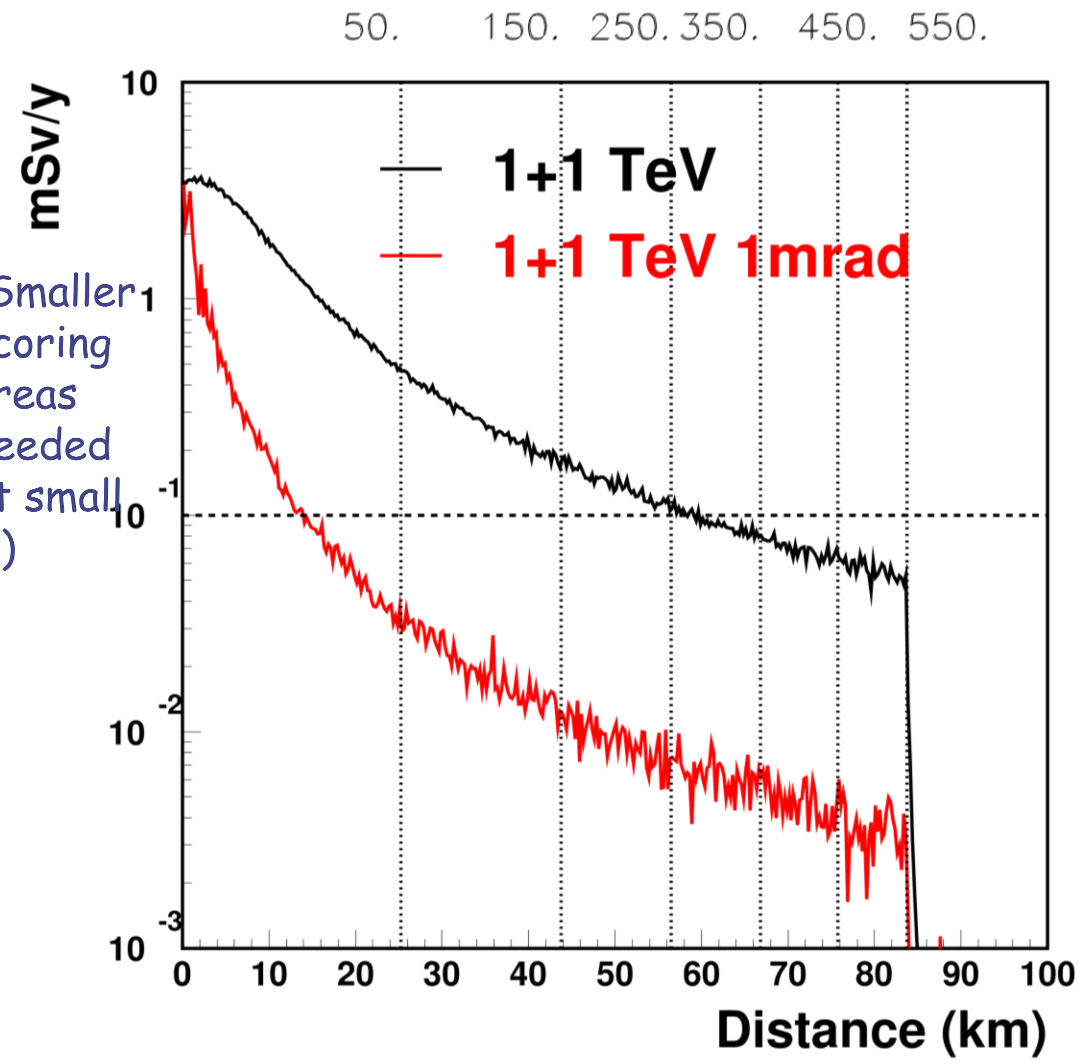
IceCube cross section data, Muon neutrino and antineutrino ,
"weighted combination" ?
arXiv:1711.08119 , *Nature* **51**,596 (2017)
Blue and green: "standard model predictions"



FLUKA results



Let's start at 1+1 TeV : interaction point



(Smaller scoring areas needed at small D)

Plot is the same. But the interaction point will not fit in ~1m..

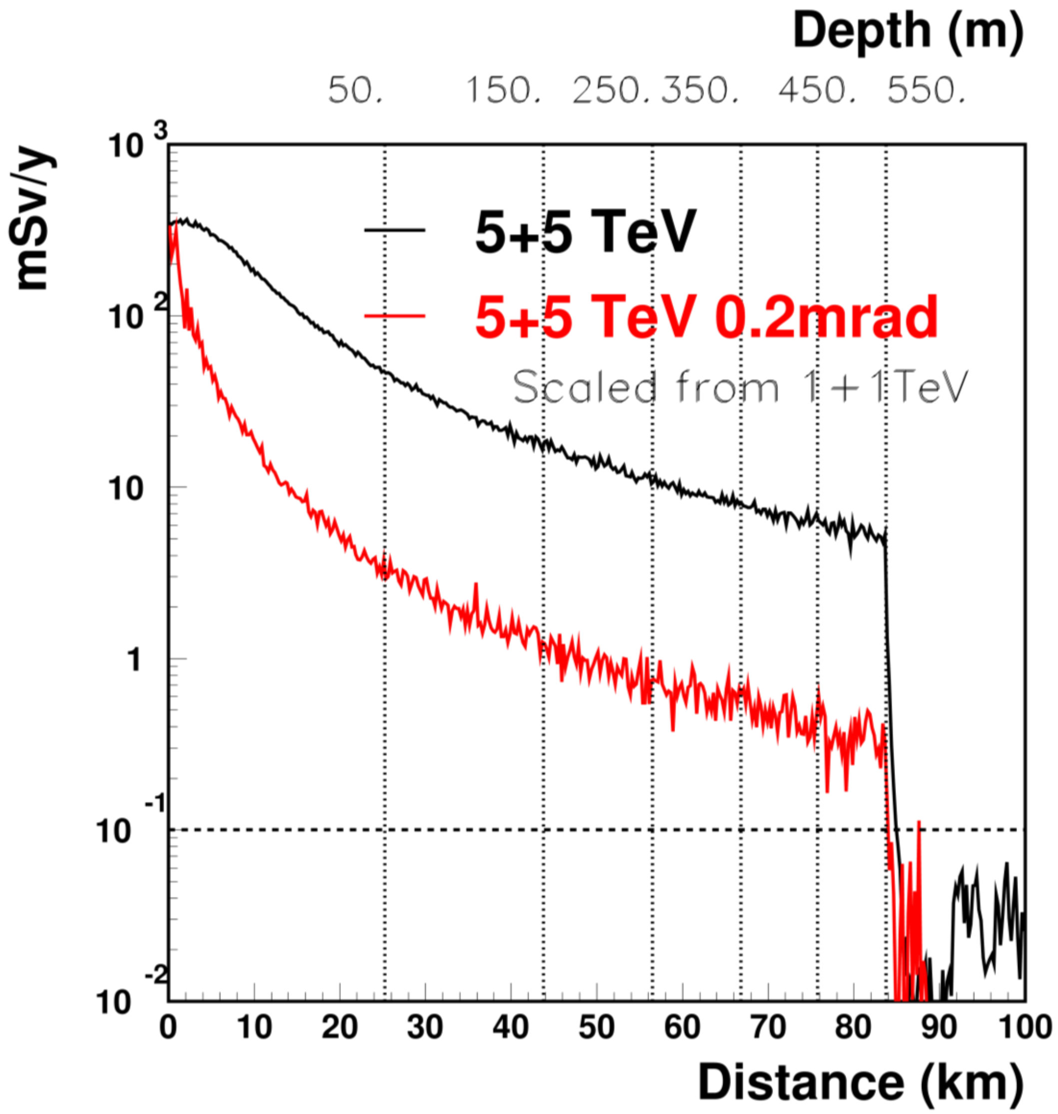
Dose scales linearly with section length (fraction of the beam that decays there)

Emittance can help, especially in vertical direction (Earth's curvature)

Orography can help: from preliminary investigations based on LHC straight sections (Youri,last workshop) , exit points as far as >200 km exist.

And, on one hot spot, we can build a super neutrino detector…

Can we go up? Straight sections



- Again: try to keep them as small as possible
- Play with emittance
- Reduce intensity to acceptable level
- Play with exit points
- For one of the exit points ..build a superb neutrino detector