Direct hits of atmospheric muons on neutrino detectors

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Preliminary results in: D. Garg et al., 2308.13655, PoS ICRC2023

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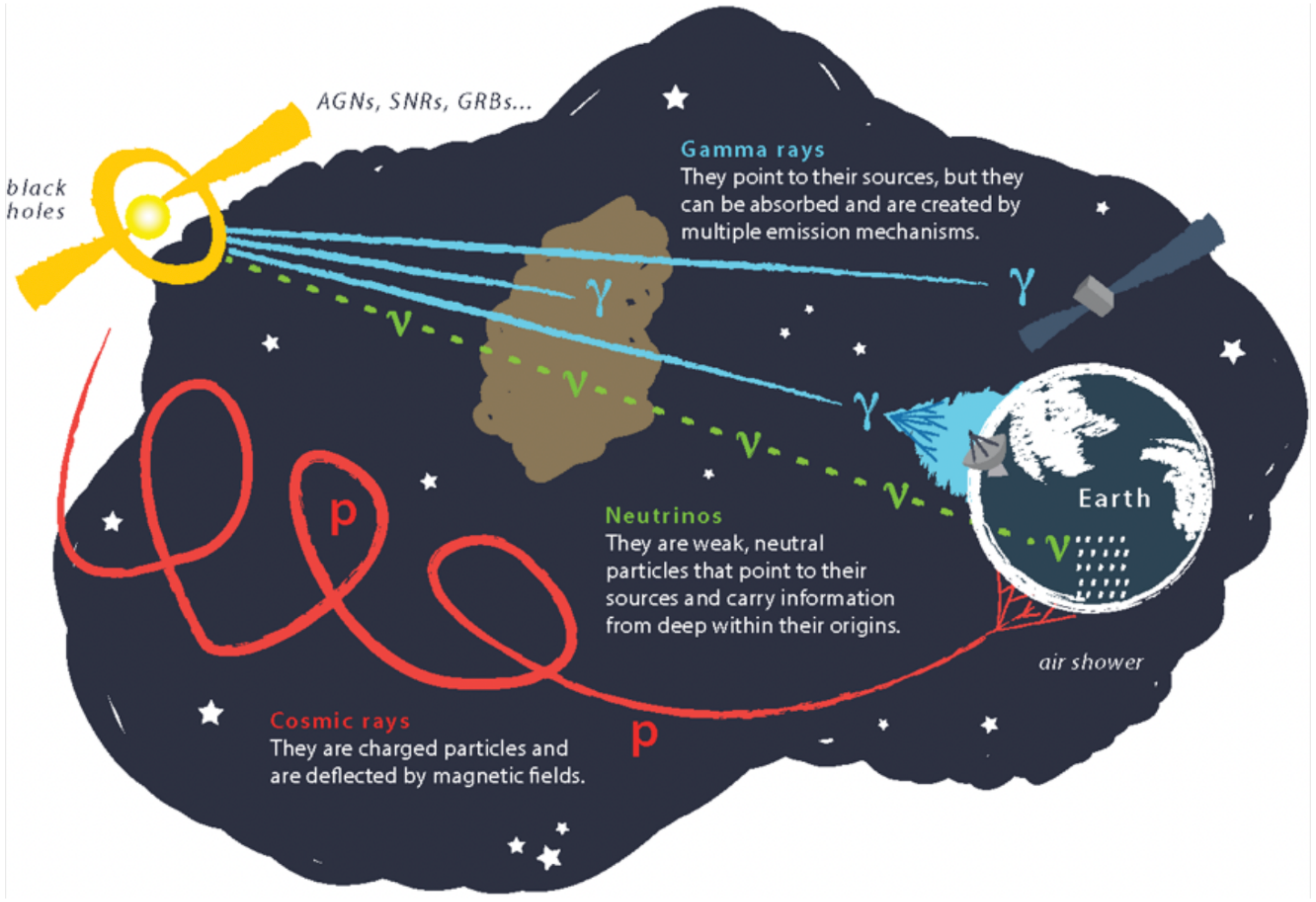
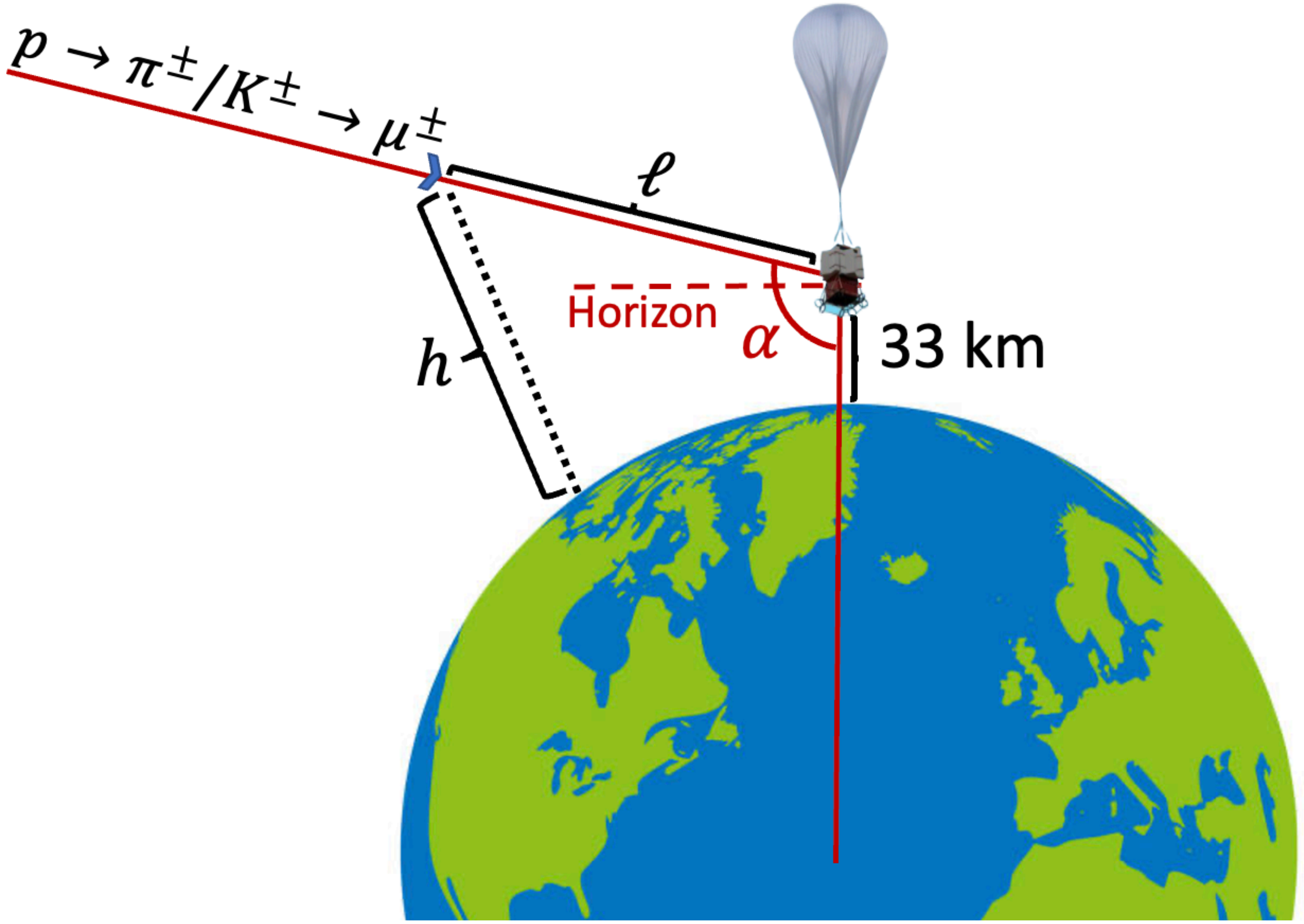
Introduction

- Extensive-air-showers (EASs) are produced from cosmic rays interacting with the Earth's atmosphere.
- EASs have Cherenkov, radio and fluorescence emission that can be detected by experiments.
- Experiments on the ground, sub-orbital and orbital designed to detect cosmic rays and neutrinos.



Direct muon flux from cosmic rays

- Cosmic rays interact with atmosphere to produce flux of muons from pion and kaon decays.
- The muons can directly hit the detectors acting as a potential background for the instrument.
- Using technique of cascade equations in **MCEq**[1] to calculate the muon propagation in the atmosphere for different trajectories.



[1]: https://github.com/mceq-project/MCEq

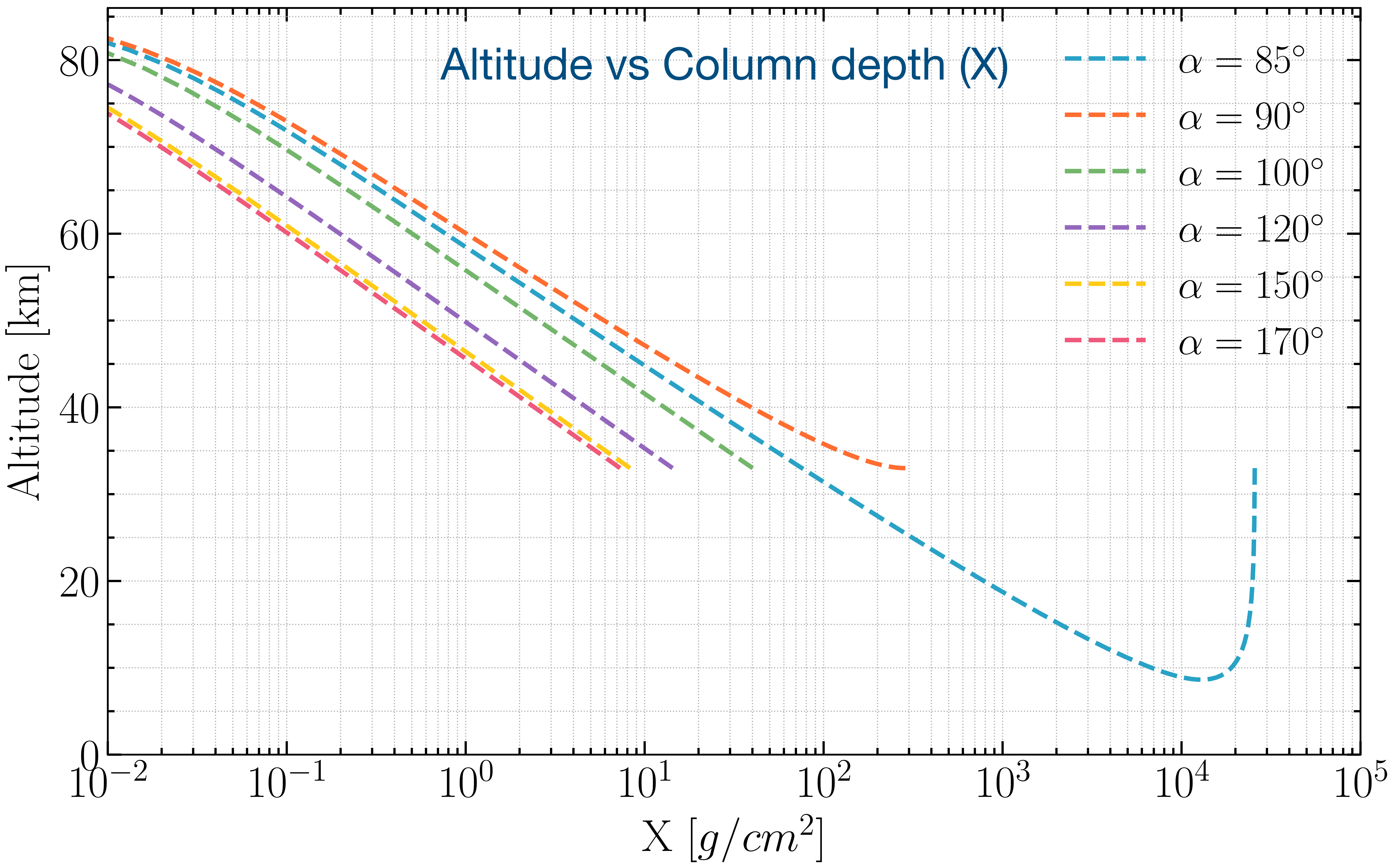
Matrix Cascade Equations (MCEq)

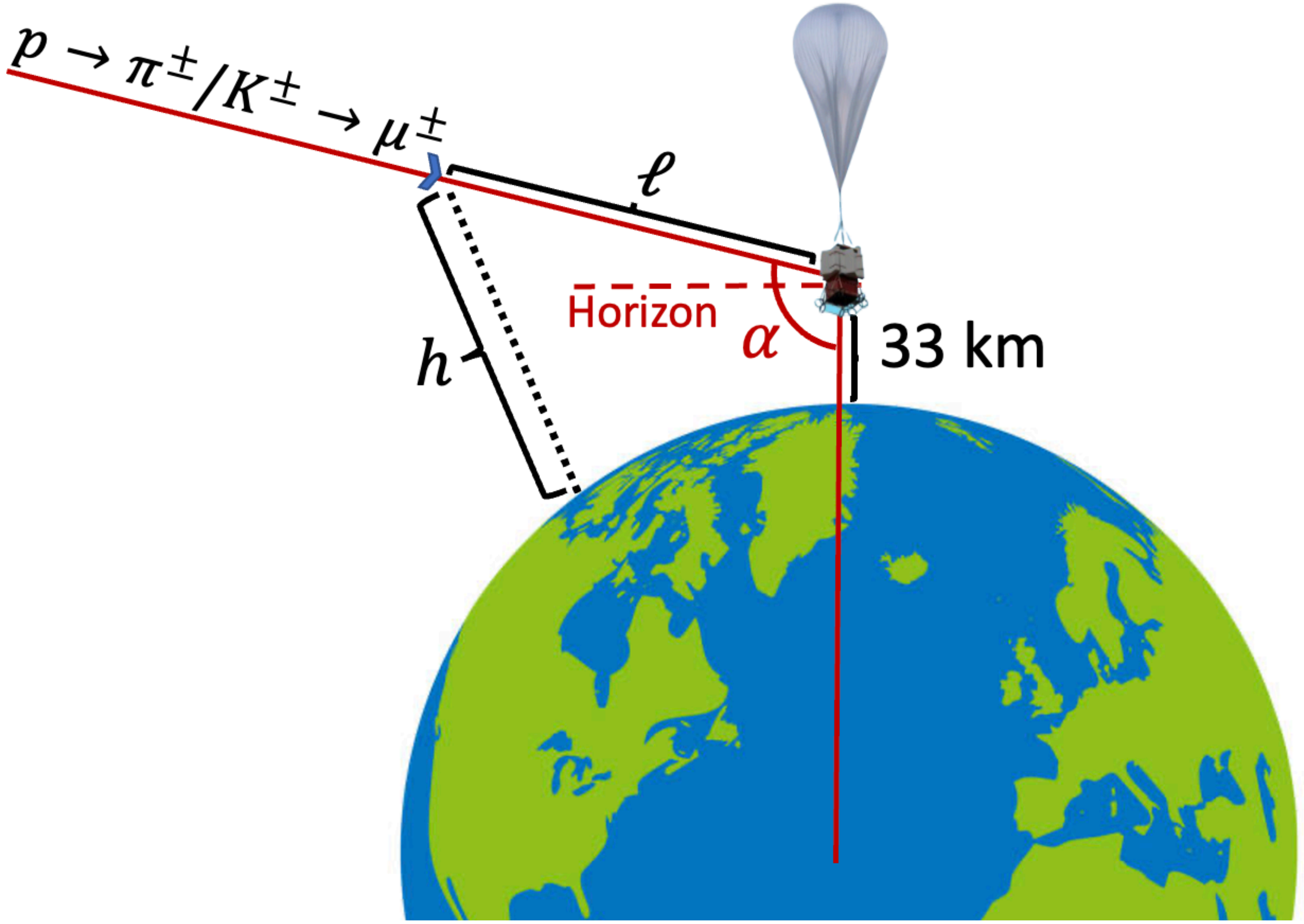
- Corsika Earth atmosphere[1]
- Cosmic ray flux - Gaisser Hillas model H3a[2]
- Hadronic interaction model - Sibyll2.3c[3]
- Continuous energy loss for particles considered.
- No Earth's magnetic field considered.

[1]: D. Heck et al., Tech. Rep. FZKA 6019, Karsruhe (1998)
[2]: Gaisser, T.K., Astroparticle Physics 35, 801 (2012)
[3]: F. Riehn et al., PoS ICRC2017

Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX.





Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX:

- Muon flux:

Loss from decay

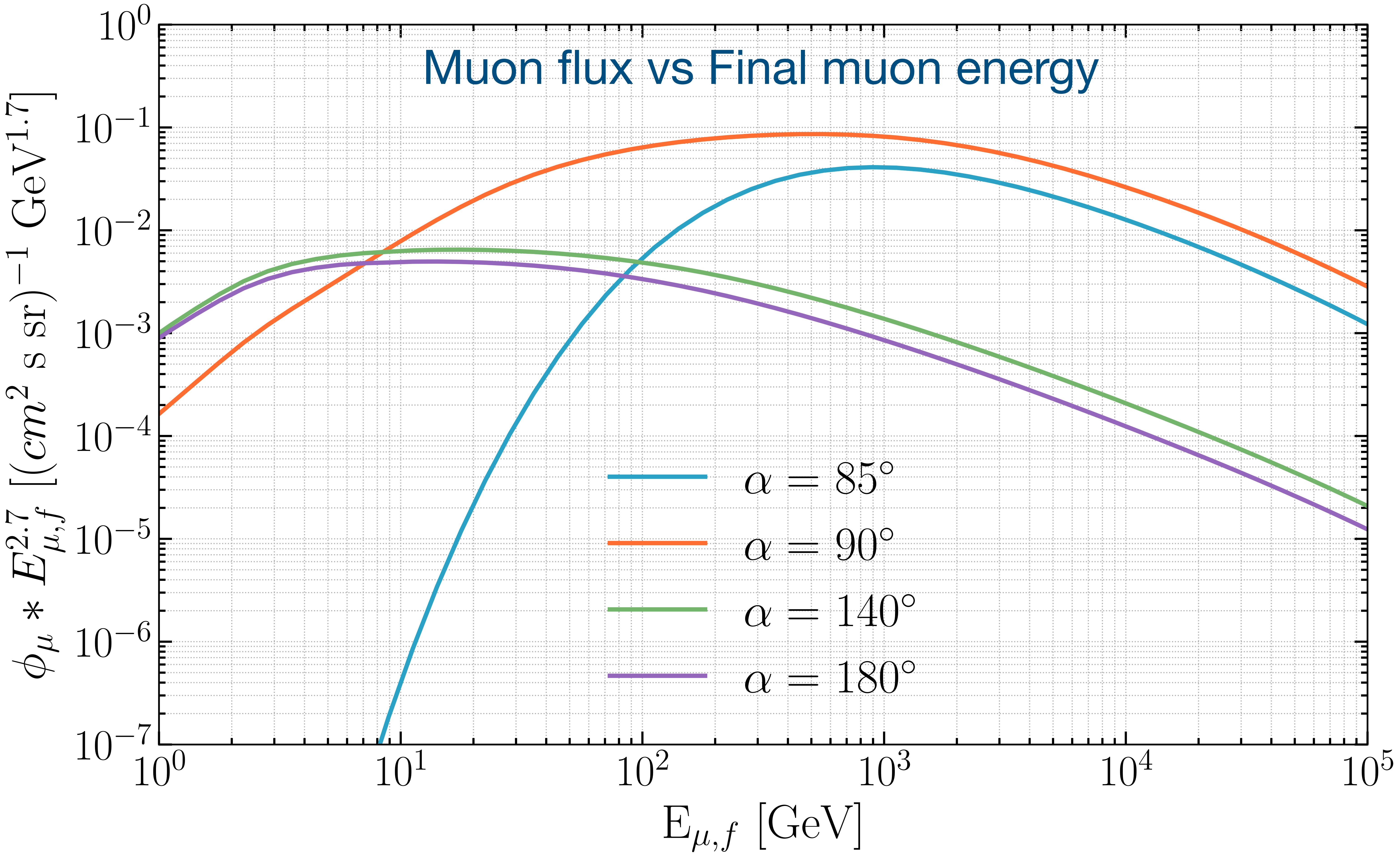
$$\phi_\mu(E, X + \Delta X) = \left[\phi_\mu(E', X)\left(1 - \frac{\Delta X}{\lambda_\mu^{\text{dec}}}\right) + \sum_{j=\pi,K} Z_{j\to\mu}\phi_j(E', X)\frac{\Delta X}{\lambda_j^{\text{dec}}}\right]\exp(b\Delta X)$$

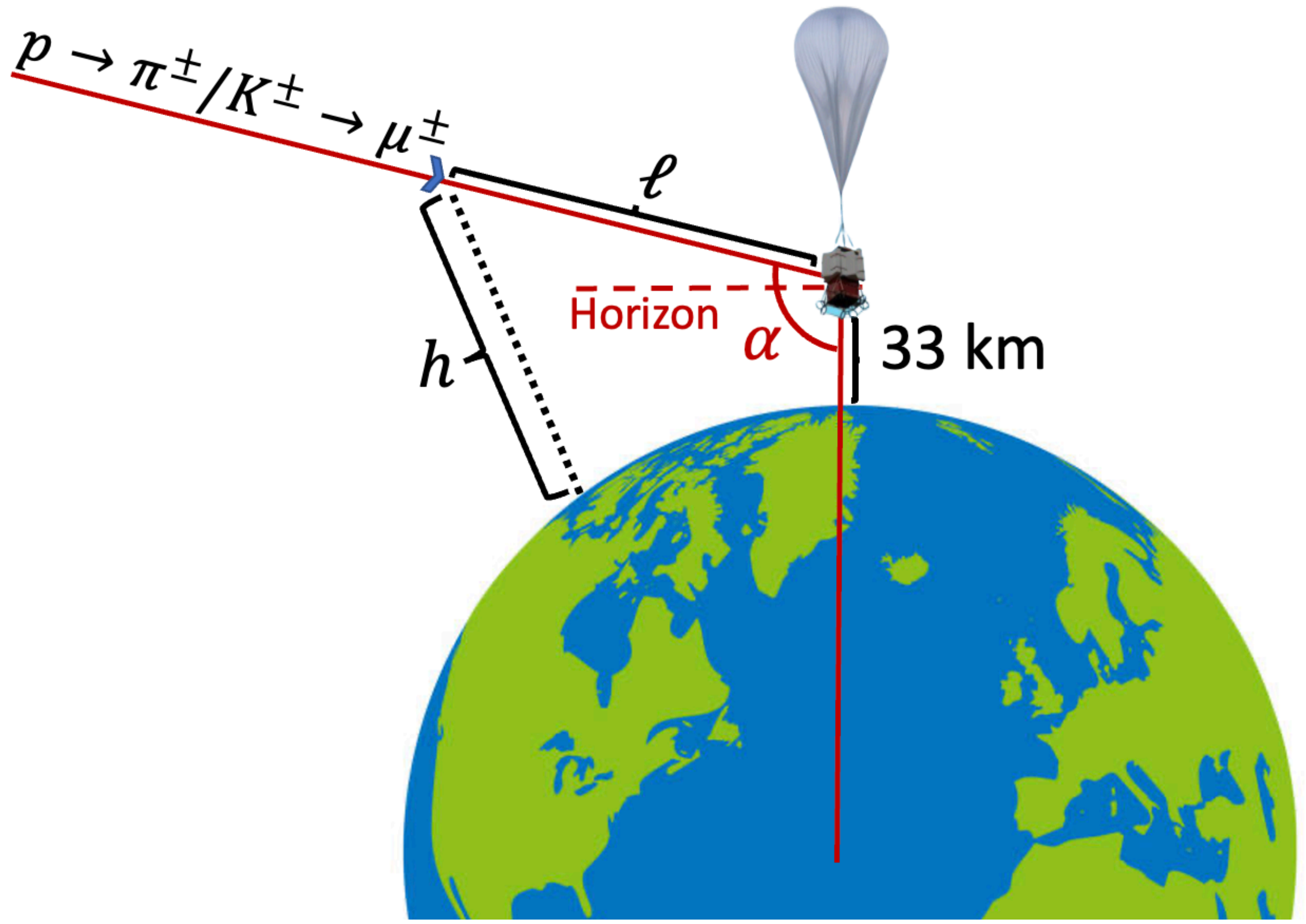
Muon flux at previous X step

Source term

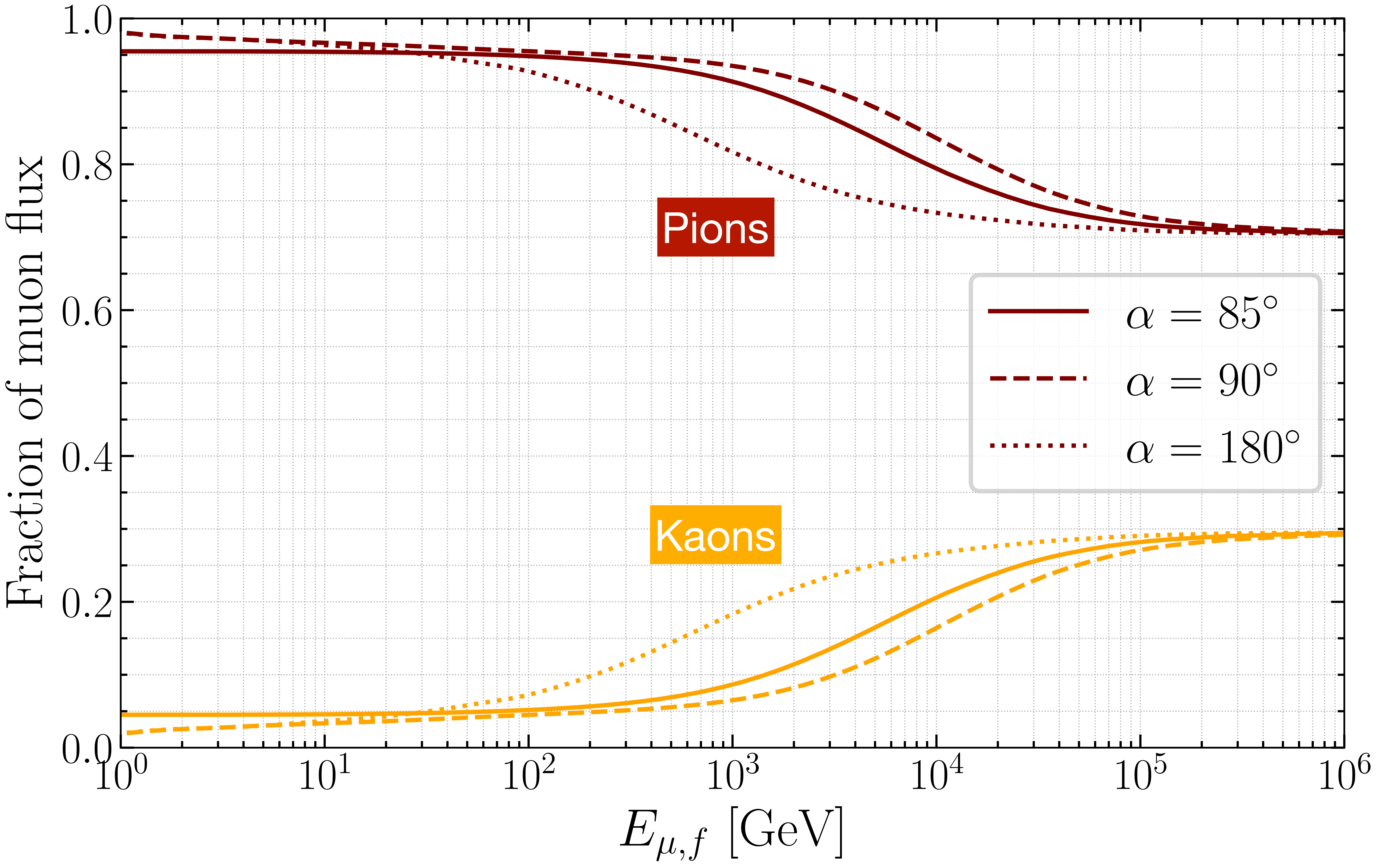
$$\boxed{E' > E}$$

Muon flux @33 km altitude

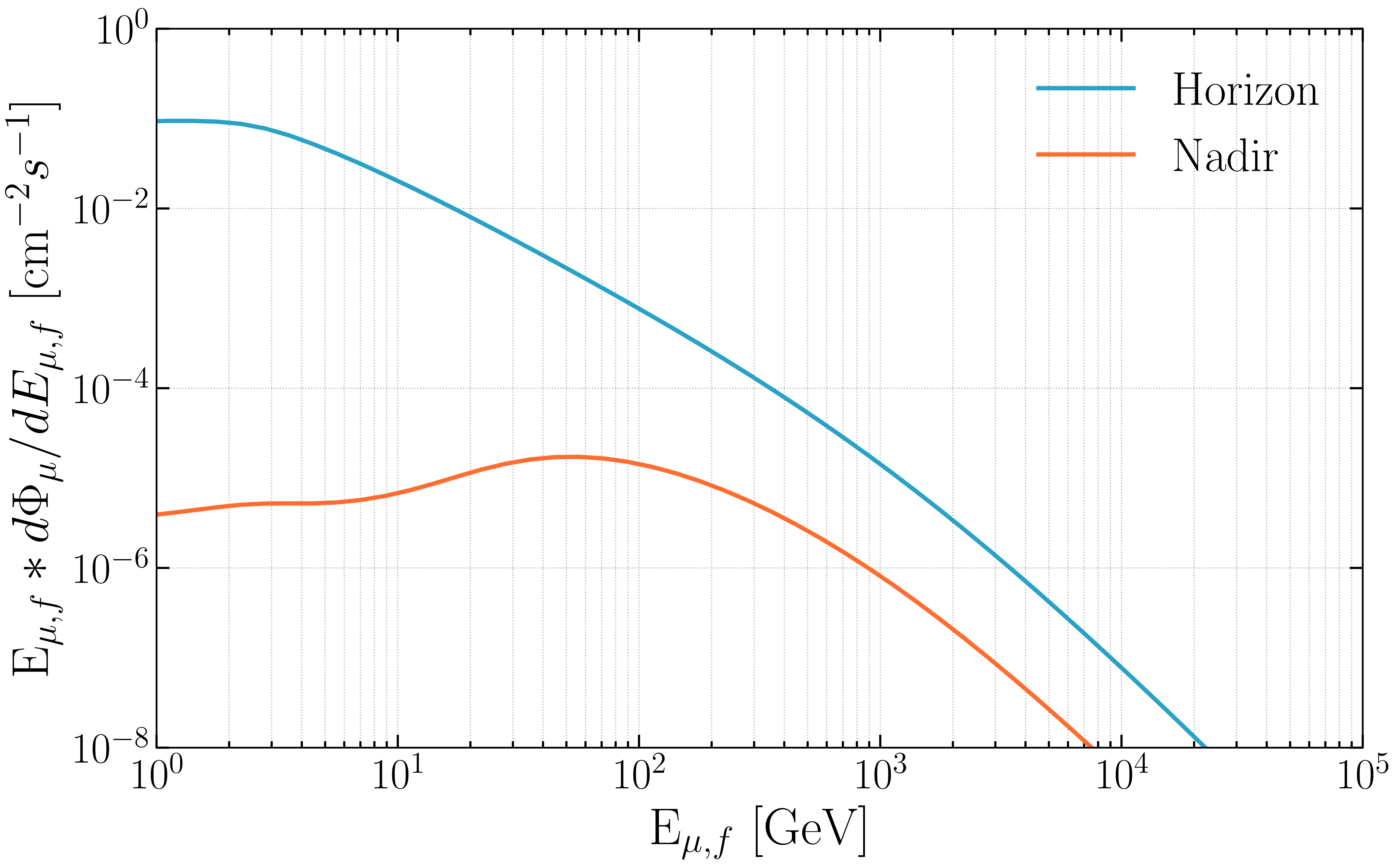


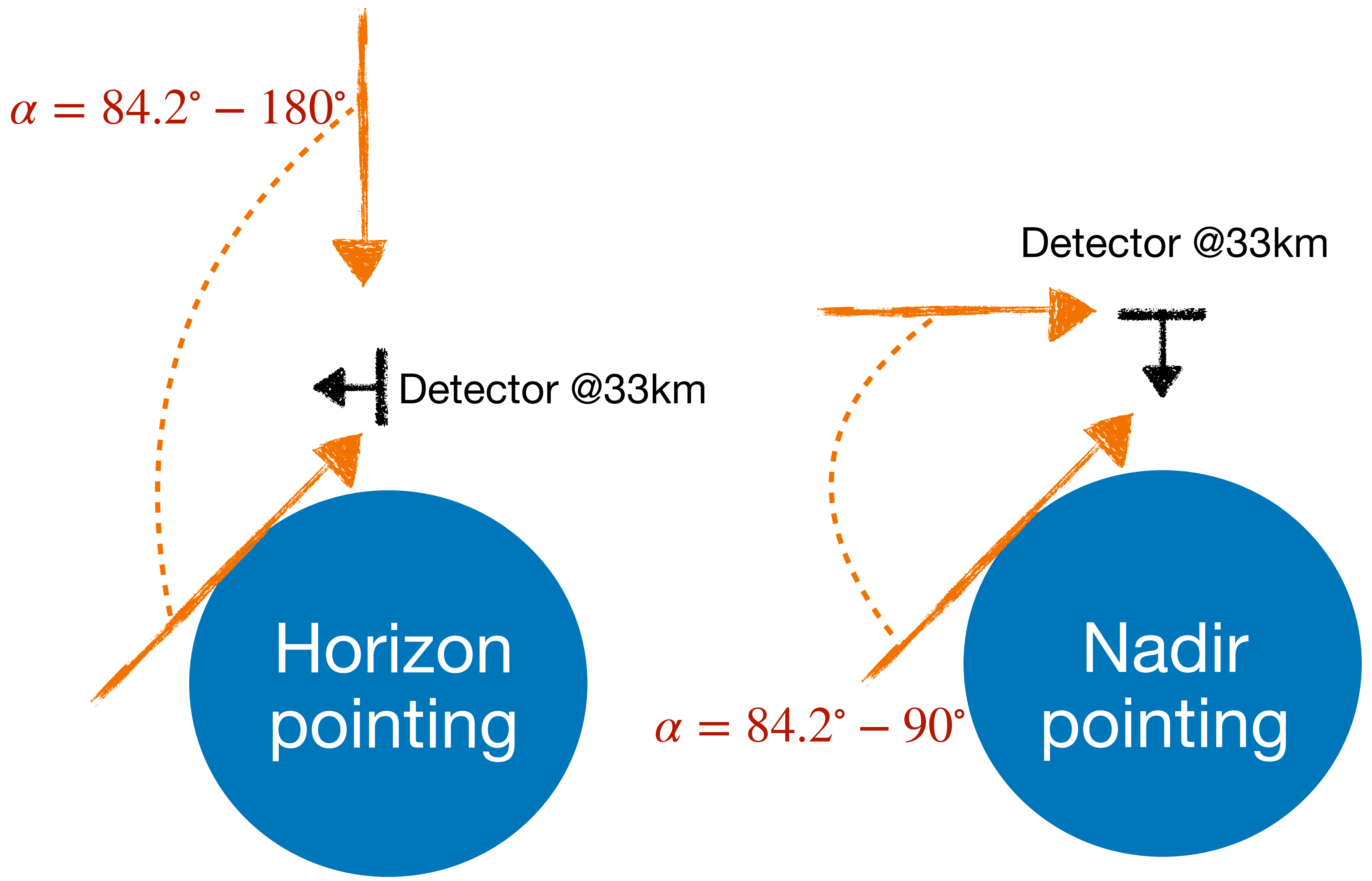


Fractional contribution to muons @33 km



Muon flux @33km - integrated over solid angle



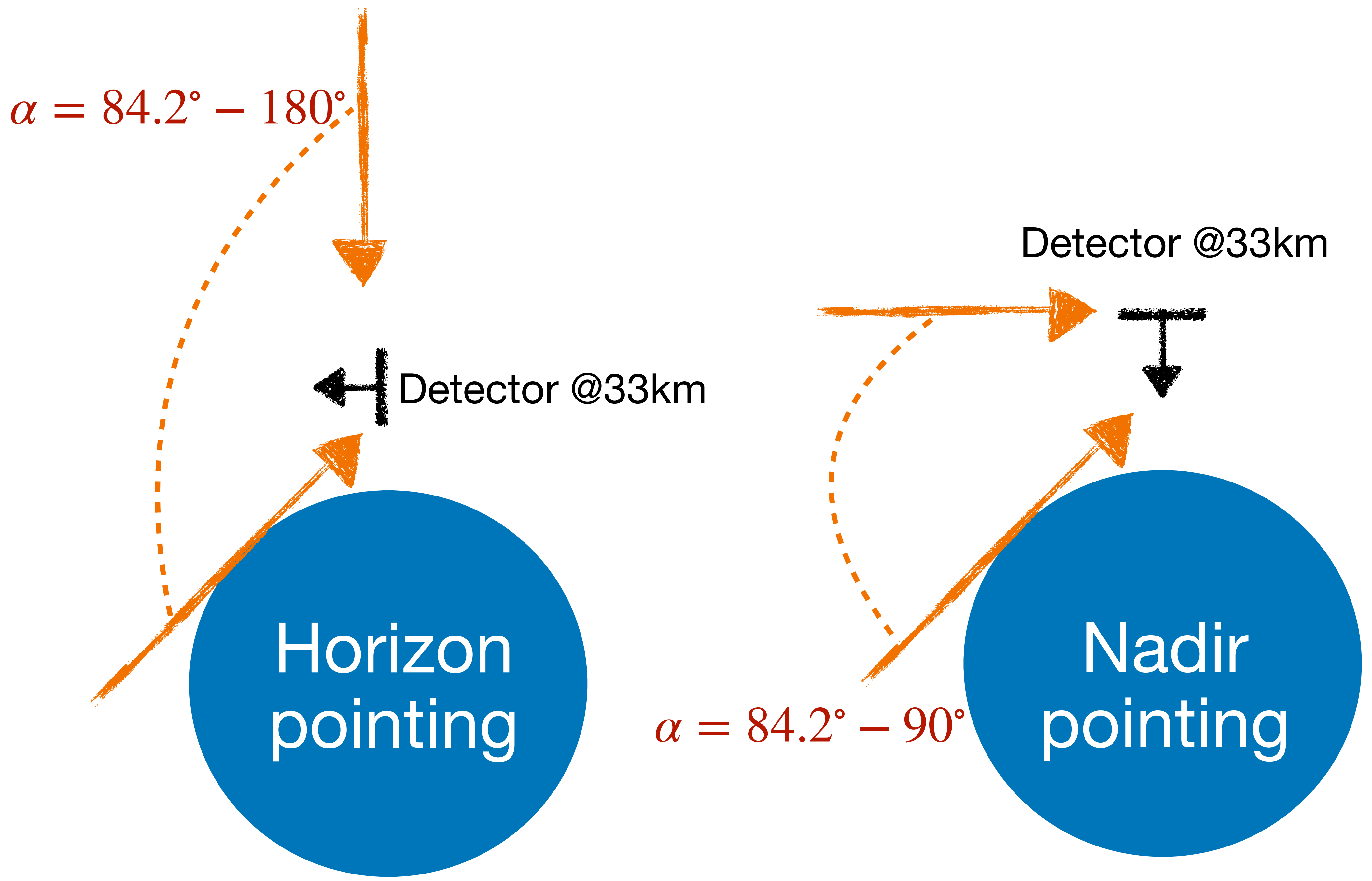


Muon number @33 km

Integrated over solid angle and muon energy

Muons Energy	Horizon [cm^{-2} s^{-1}]	Nadir [cm^{-2} s^{-1}]
Above 1 GeV*	0.177	5.7E-05
Above 10 GeV	0.013	4.44E-05

*Earth magnetic field not considered



Total muon flux @33km in Hz

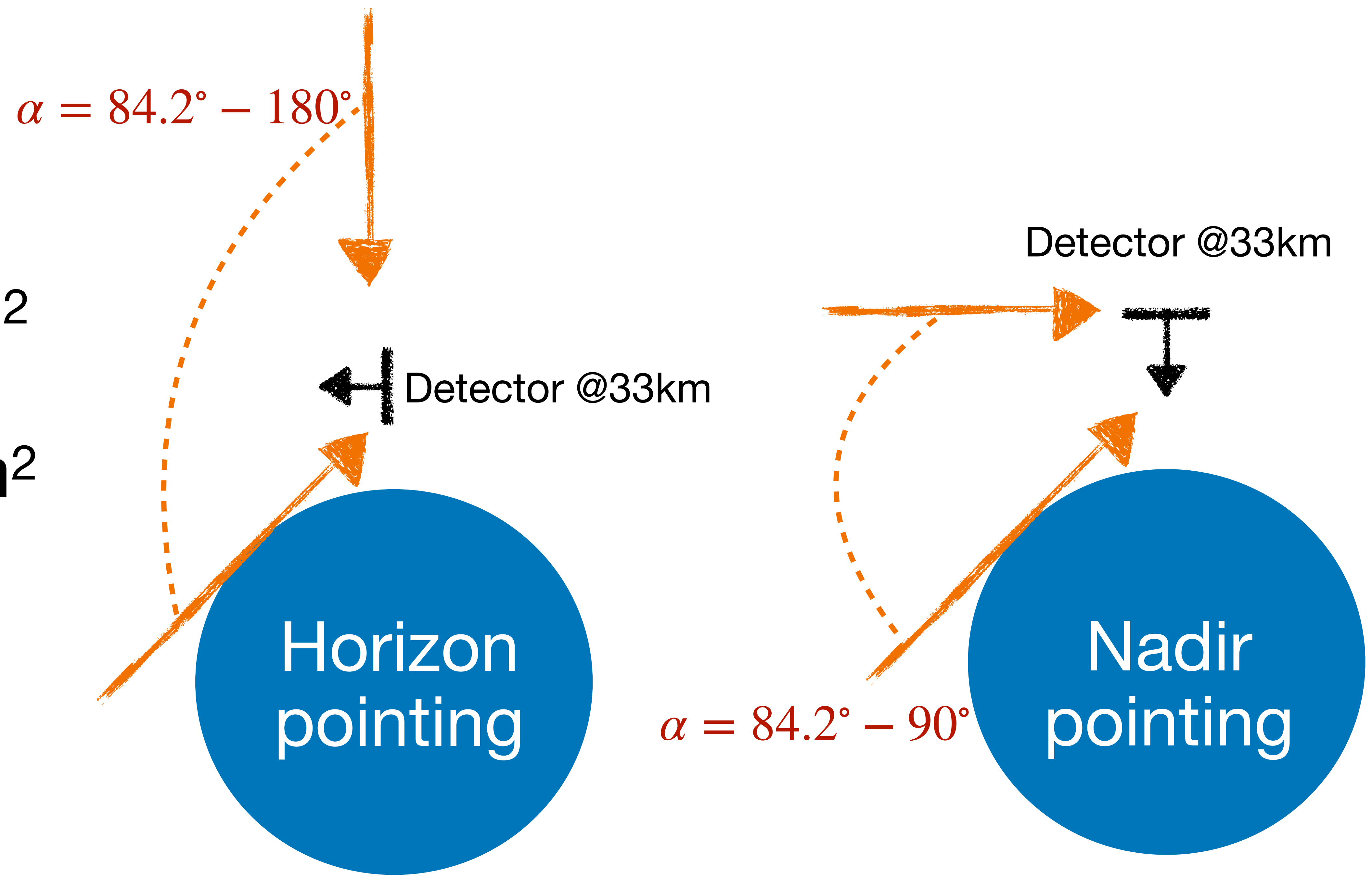
<u>For EUSO-SPB2 experiment</u>:

Area of Cherenkov telescope (Horizon pointing): 184 cm^2

Area of Fluorescence telescope (Nadir pointing): 622 cm^2

Muons Energy	Horizon [Hz]	Nadir [Hz]
Above 1 GeV*	32.5	0.0357
Above 10 GeV	2.3	0.0276

*Earth magnetic field not considered

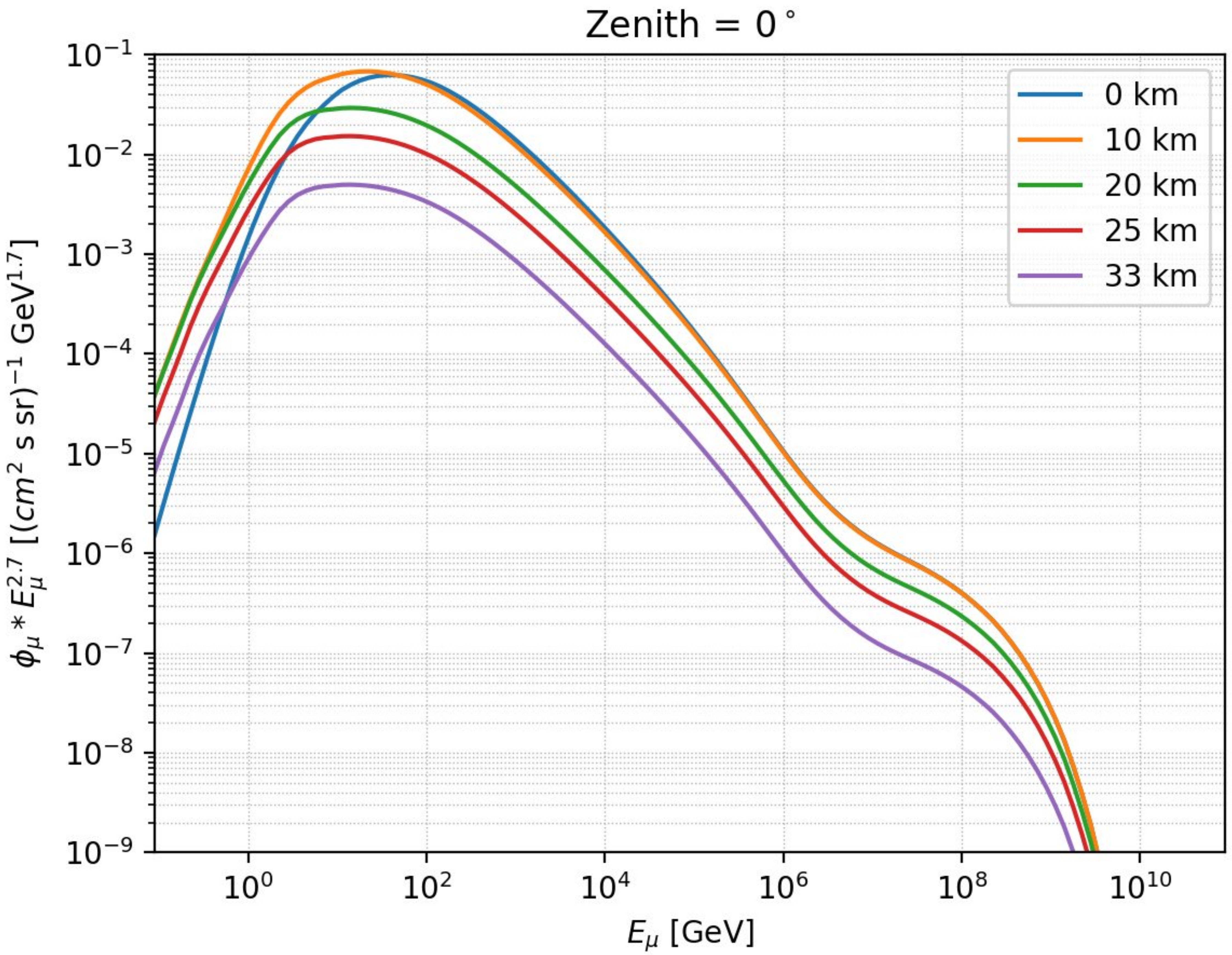


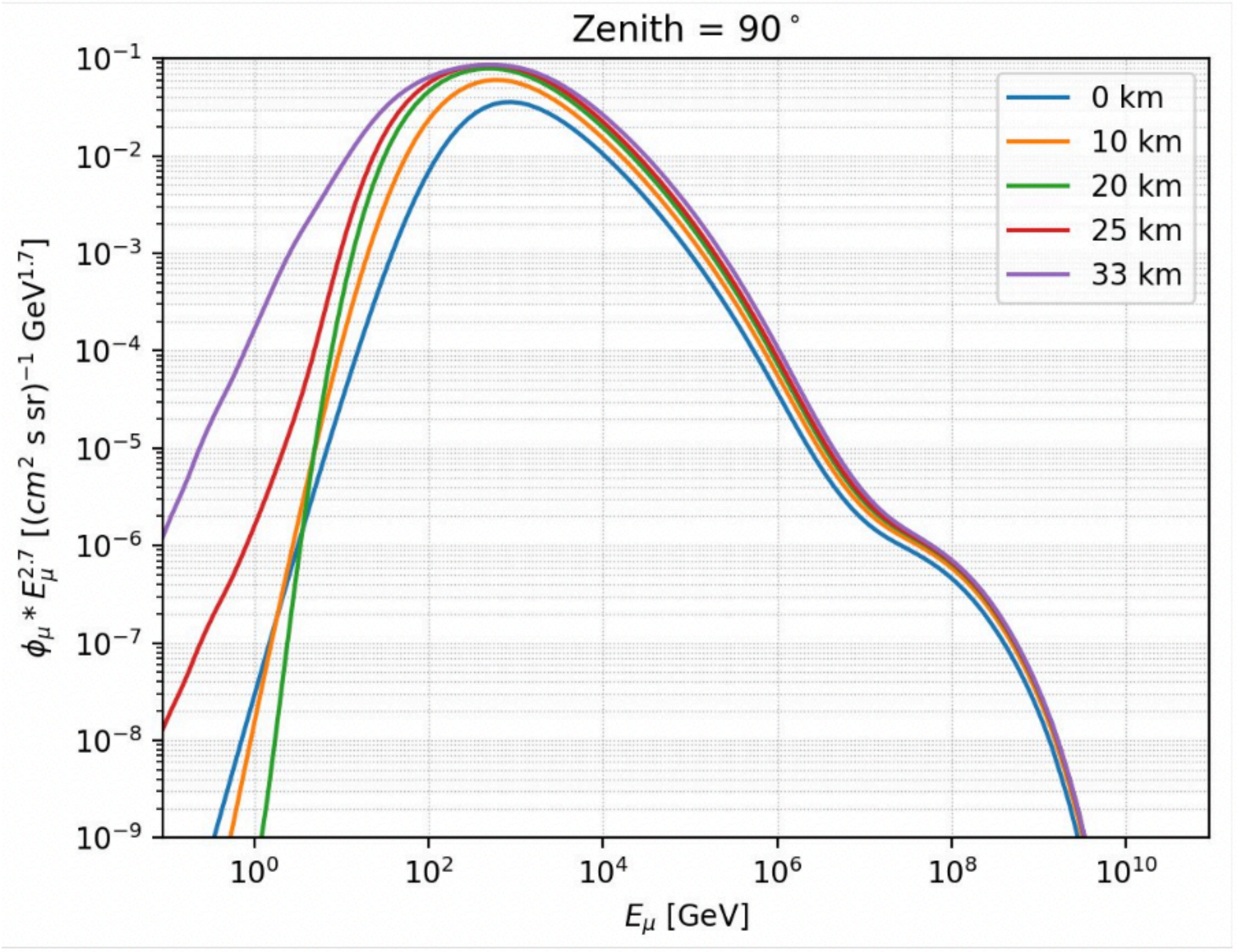
Summary

- Evaluated muon flux reaching a detector at an altitude.
- Gives a potential background to EUSO-SPB2 and other sub-orbital telescope experiments.
- If no mechanism for avoiding direct muon hits then useful result for background studies.
- Pion-to-kaon ratio for p-air collisions is not very relevant since $\Phi_\mu^K \ll \Phi_\mu^\pi$ at $E_\mu \sim 10$ GeV for diffuse calculations.

Backup Slides

Muon flux at different altitudes





Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX:

- Muon flux:

$$\phi_\mu(E, X+\Delta X) = \left[\phi_\mu(E', X)\left(1 - \frac{\Delta X}{\lambda_\mu^{\rm dec}}\right) + \sum_{j=\pi,K} Z_{j\to\mu}\phi_j(E', X)\frac{\Delta X}{\lambda_j^{\rm dec}}\right]\exp(b\Delta X)$$

- Meson flux like Pion and Kaon:

Loss from decay and interaction

$$\phi_j(E, X+\Delta X) = \phi_j(E, X)\left(1 - \frac{\Delta X}{\Lambda_j} - \frac{\Delta X}{\lambda_j^{\rm dec}}\right) + Z_{N\to j}\phi_N(E, X)\frac{\Delta X}{\lambda_N}$$

Meson flux at previous X step

Source term

Cascade equations

To evaluate the flux of muons, we step through the column depth of the atmosphere with steps ΔX:

- Muon flux:

$$\phi_\mu(E, X+\Delta X) = \left[\phi_\mu(E', X)\left(1 - \frac{\Delta X}{\lambda_\mu^{\mathrm{dec}}}\right) + \sum_{j=\pi,K} Z_{j\to\mu}\phi_j(E', X)\frac{\Delta X}{\lambda_j^{\mathrm{dec}}}\right]\exp(b\Delta X)$$

- Meson flux like Pion and Kaon:

$$\phi_j(E, X+\Delta X) = \phi_j(E, X)\left(1 - \frac{\Delta X}{\Lambda_j} - \frac{\Delta X}{\lambda_j^{\mathrm{dec}}}\right) + Z_{N\to j}\phi_N(E, X)\frac{\Delta X}{\lambda_N}$$

- Cosmic ray flux:

CR flux at previous X step

Loss from interaction

$$\phi_N(E, X+\Delta X) = \phi_N(E, X)\left(1 - \frac{\Delta X}{\Lambda_N}\right)$$

Z-moments

- $S(k \to j) = \left[\int_E^\infty dE' \frac{\phi_k(E',X)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \right]$

- $S(k \to j) = \left[\int_E^\infty dE' \frac{\phi_k(E',X)}{\phi_k(E,X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \right] \frac{\phi_k(E,X)}{\lambda_k(E)}$

- $S(k \to j) = \left[\int_E^\infty dE' \frac{E'^\alpha \phi_k(X)}{E^\alpha \phi_k(X)} \frac{\lambda_k(E)}{\lambda_k(E')} \frac{dn(k \to j; E', E)}{dE} \right] \frac{\phi_k(E,X)}{\lambda_k(E)}$

- $S(k \to j) = Z_{kj}(E) \frac{\phi_k(E,X)}{\lambda_k(E)}$

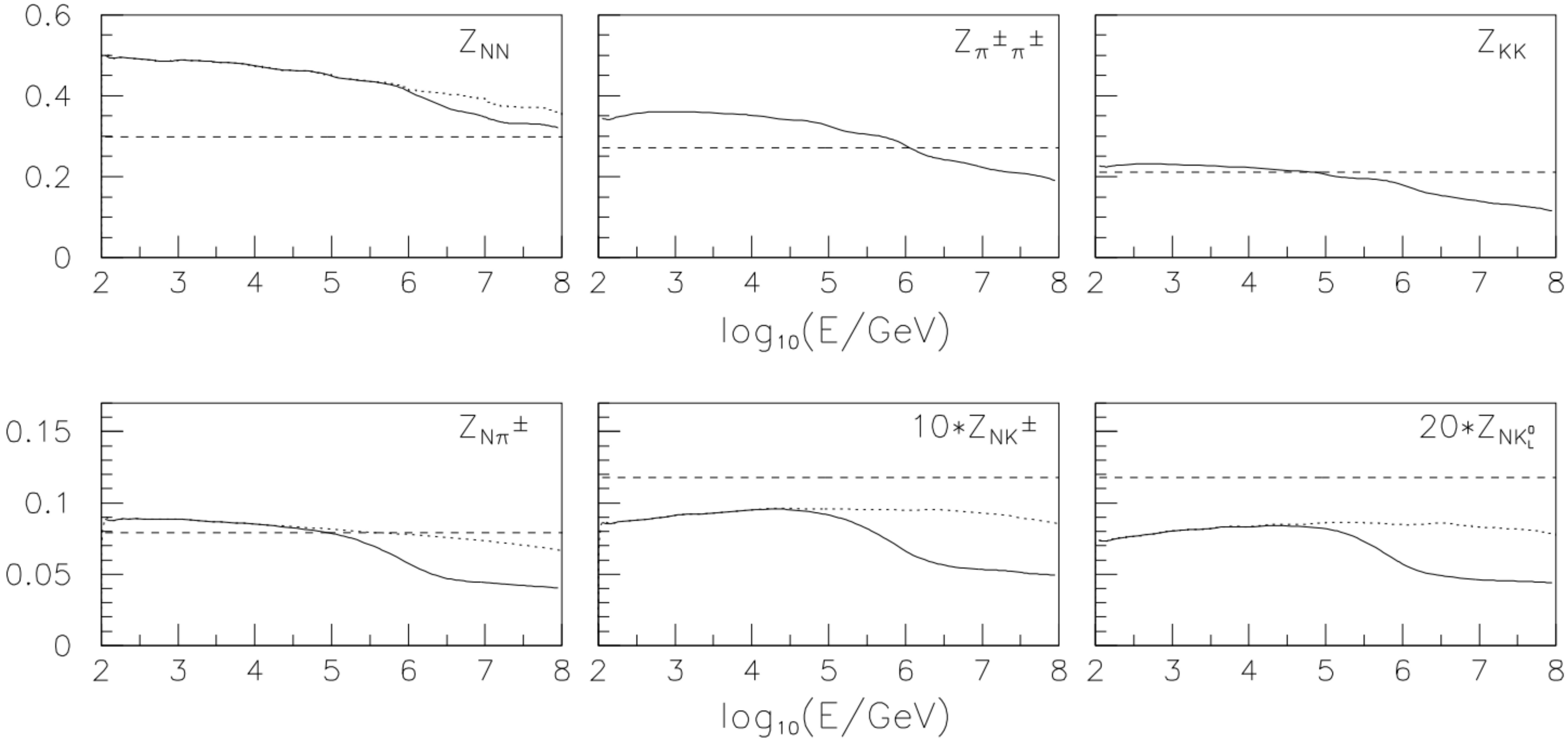
- $\frac{dn(k \to j; E', E)}{dE} = \frac{1}{\sigma_{kA}(E')} \frac{d\sigma(kA \to jY; E', E)}{dE}$; interaction

- $\frac{dn(k \to j; E', E)}{dE} = \frac{1}{\Gamma_k(E')} \frac{d\Gamma(k \to jY; E', E)}{dE}$; decay

[1]: P. Lipari, Lepton spectra in the earth's atmosphere, Astropart. Phys. 1, 1993

[2]: M. Thunman et al., Astropart. Phys., 1996

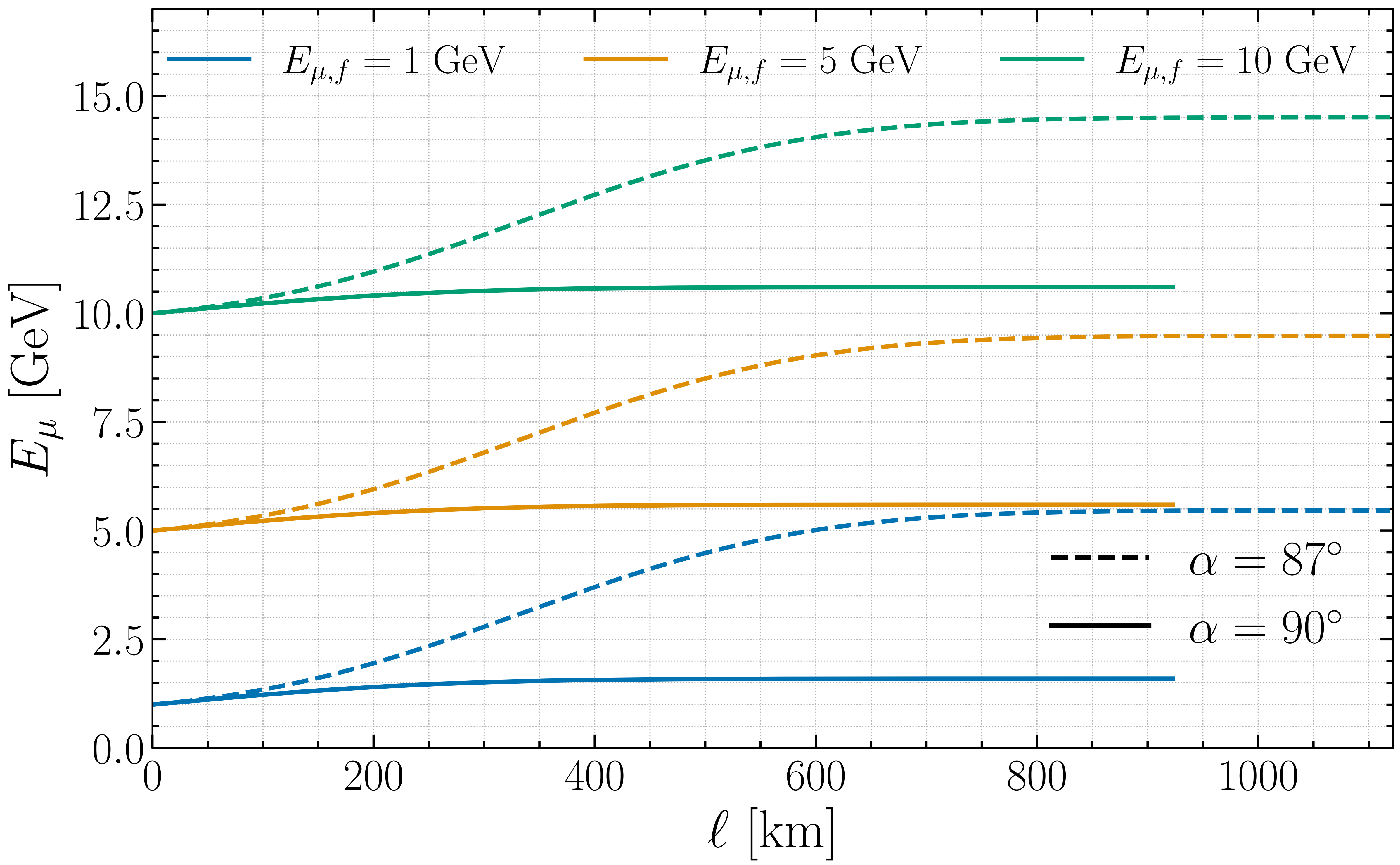
Z-moments



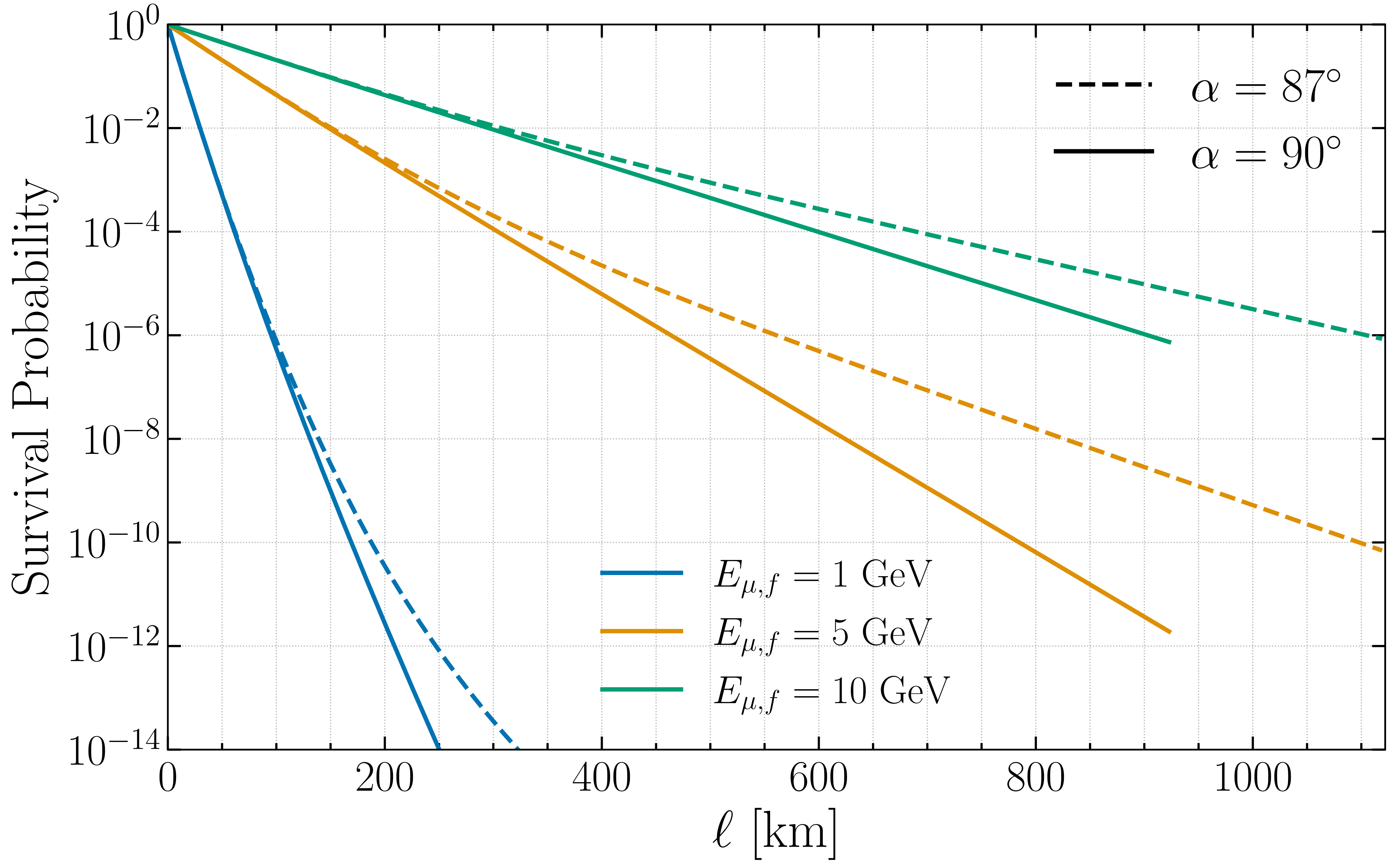
M. Thunman et al., Astropart. Phys., 1996

Muon energy loss and survival probability

Muon energy loss vs trajectory length



Survival probability of muons vs trajectory length



Cal muon flux

$$\Phi_\mu(E_{\mu,f}) \equiv \int_{E_{\mu,f}} dE_\mu \int_{\varphi=-\pi/2}^{\varphi=\pi/2} \int_{\alpha=84.2^\circ}^{\alpha=180^\circ} \phi_\mu(E_\mu,\alpha)\sin^2\alpha\cos\varphi\, d\alpha\, d\varphi, \quad \text{horizontal} \quad (14)$$

$$\Phi_\mu(E_{\mu,f}) \equiv \int_{E_{\mu,f}} dE_\mu \int_{\varphi=0}^{\varphi=2\pi} \int_{\alpha=84.2^\circ}^{\alpha=90^\circ} \phi_\mu(E_\mu,\alpha)\cos\alpha\sin\alpha\, d\alpha\, d\varphi, \quad \text{nadir}\,. \quad (15)$$

For EUSO-SPB2:

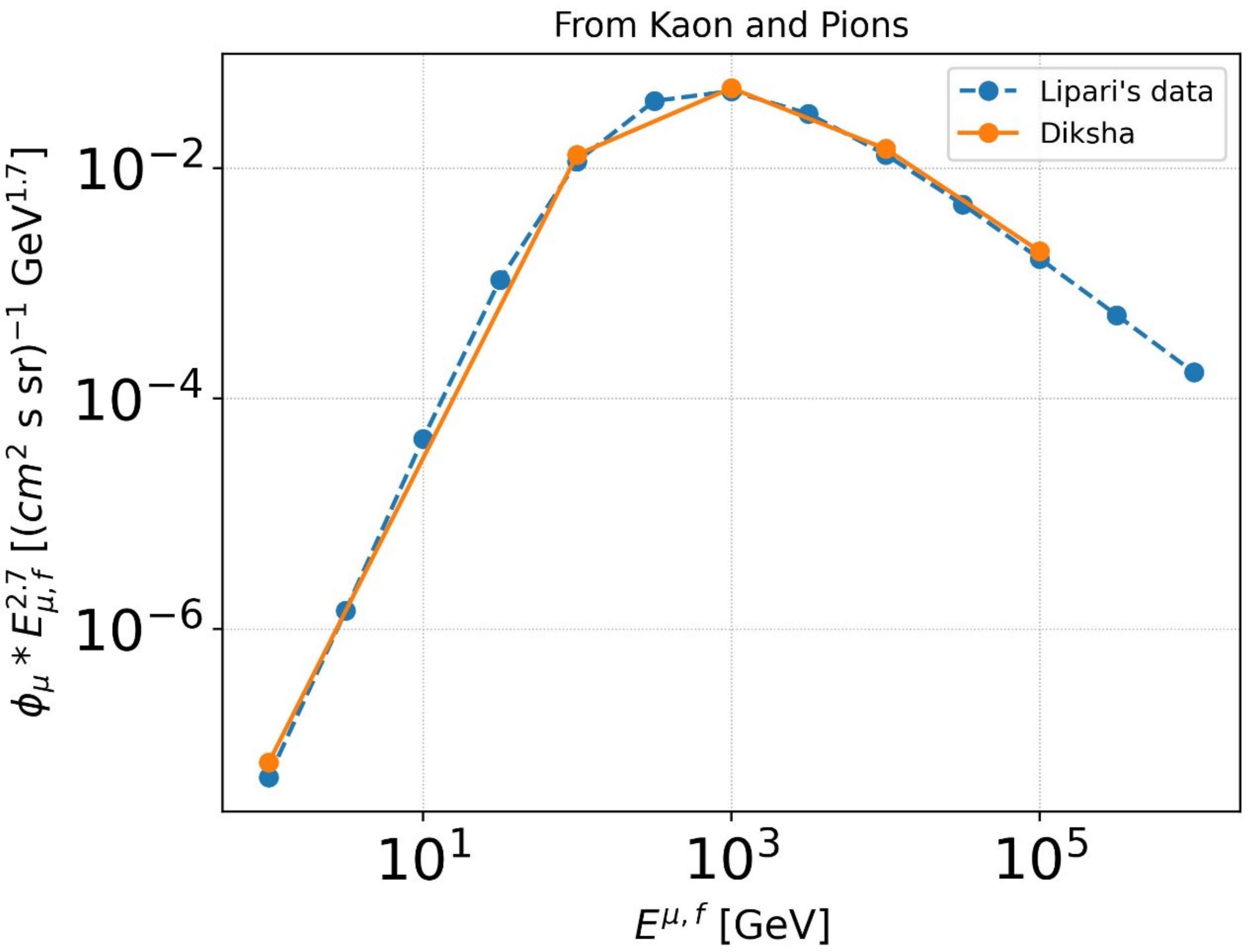
Muons Energy (GeV)	Horizon (Hz)	Nadir (Hz)
Above 1	1.21	1.3×10^{-3}
Above 10	6.6×10^{-2}	8.1×10^{-4}

Area of CT (horizon pointing): 184 cm^2.

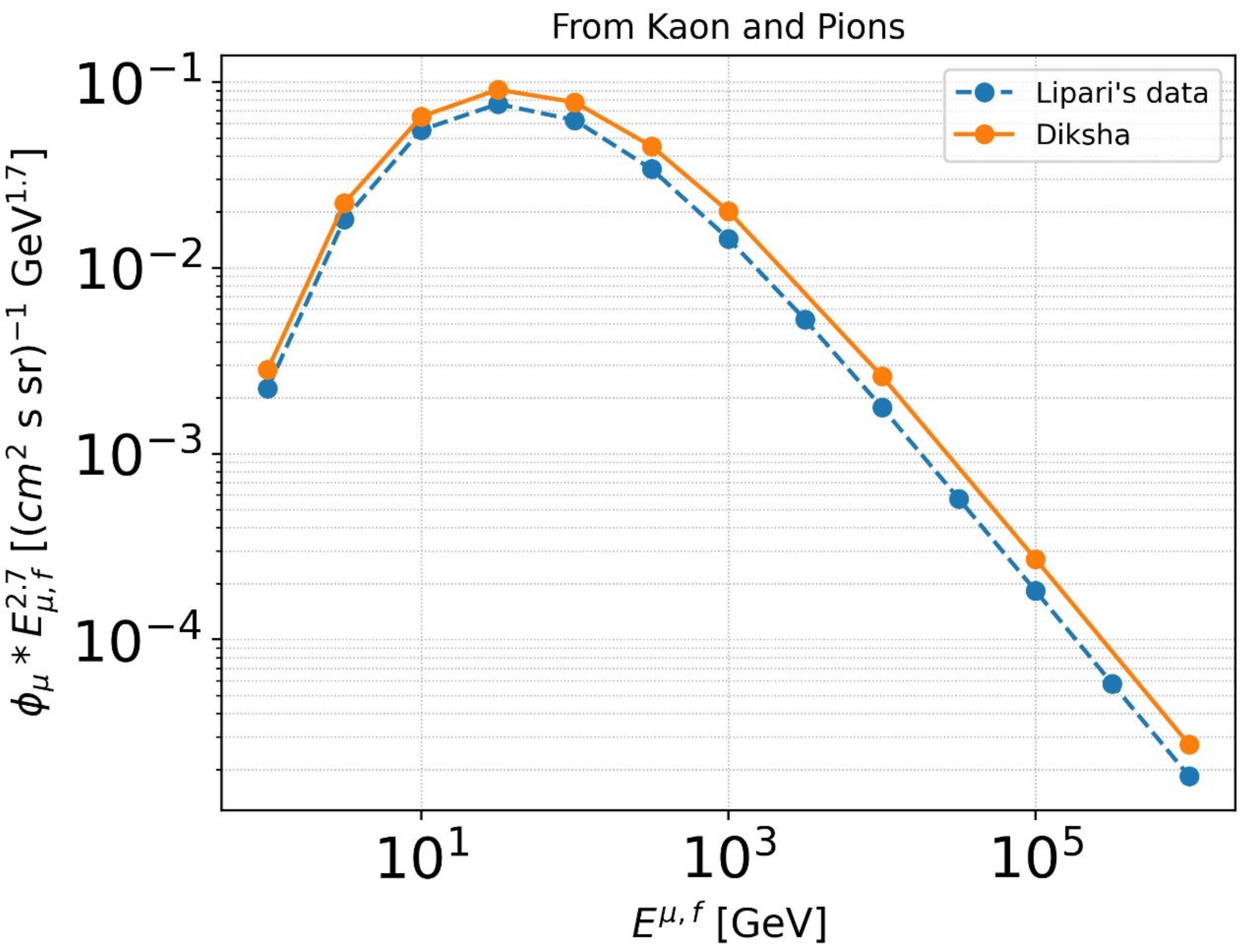
Area of FT (nadir pointing): 622 cm^2.

Comparison with Lipari data (to ground)

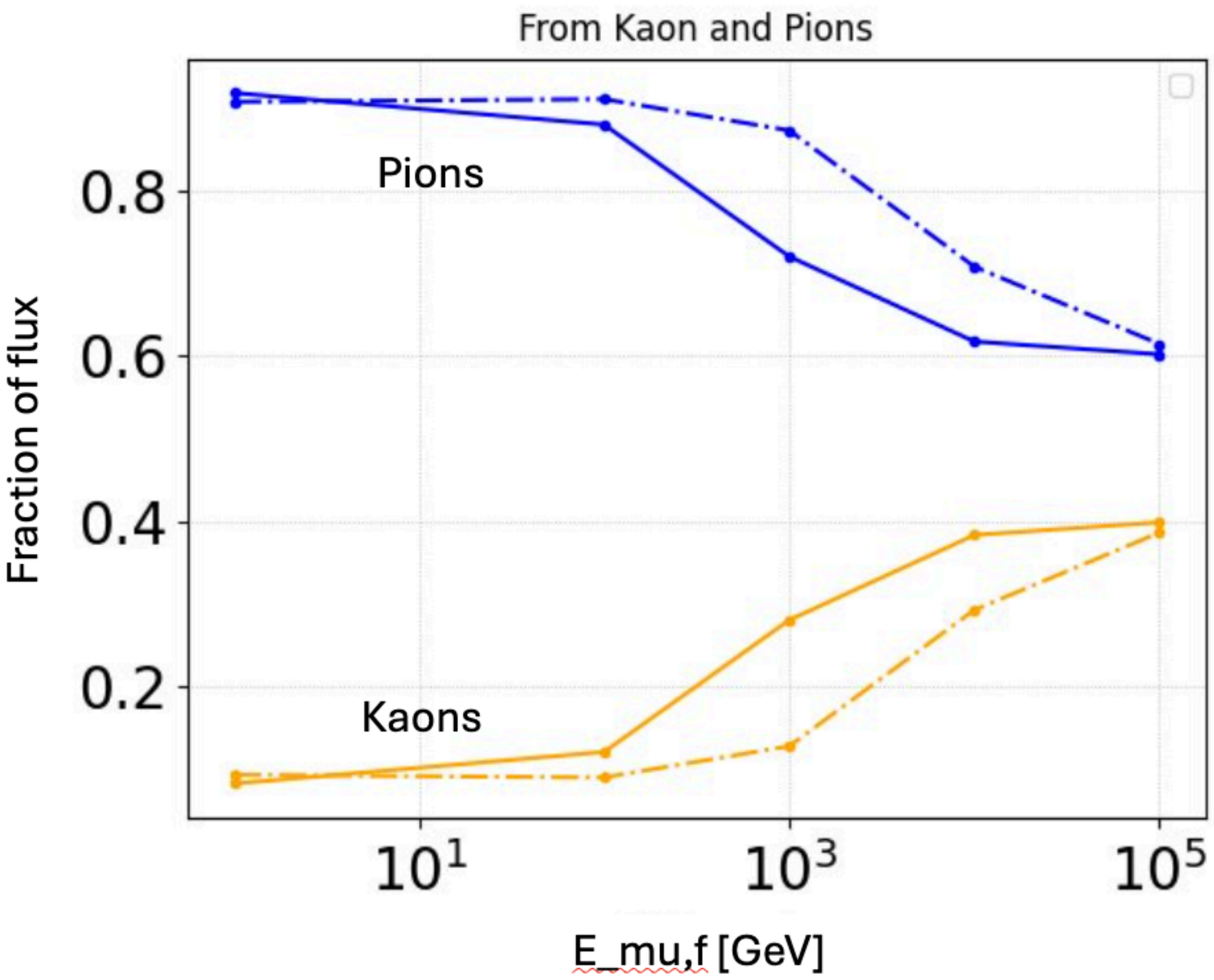
Zenith = 0°



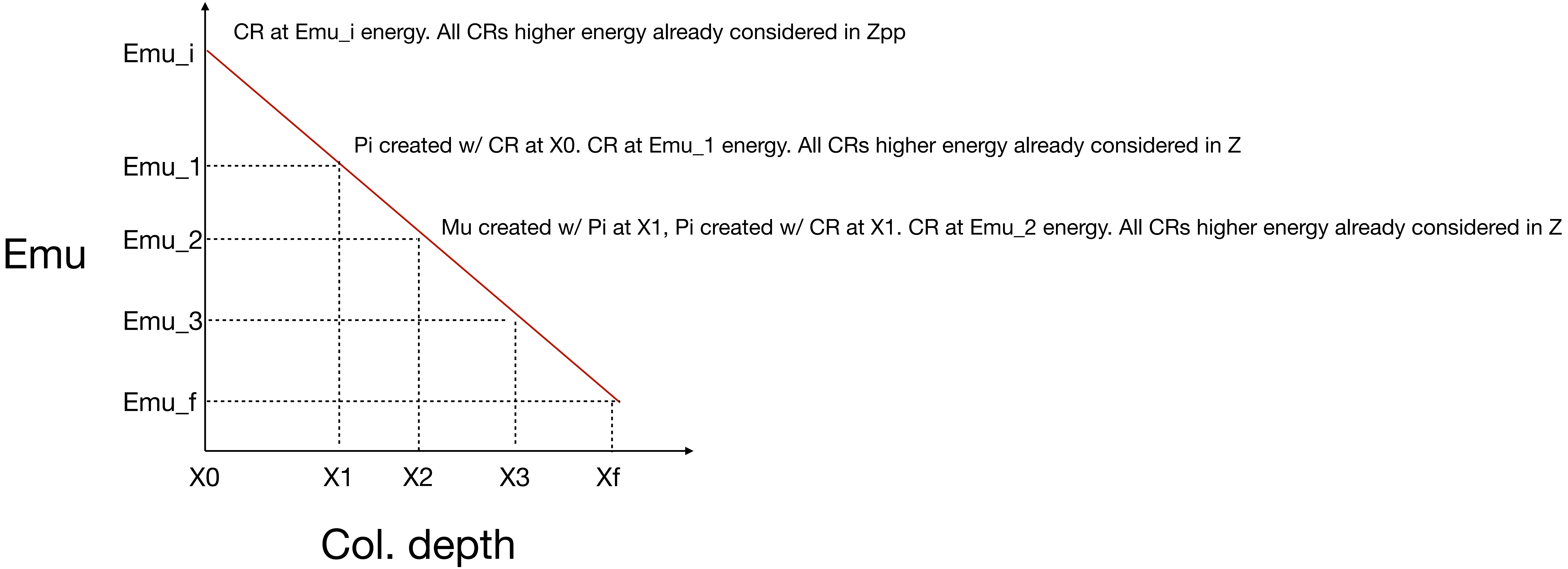
Zenith = 90°



Comparison with Lipari data (to ground)



Solid: Theta=0 degrees
Dashed: Theta=90 degrees

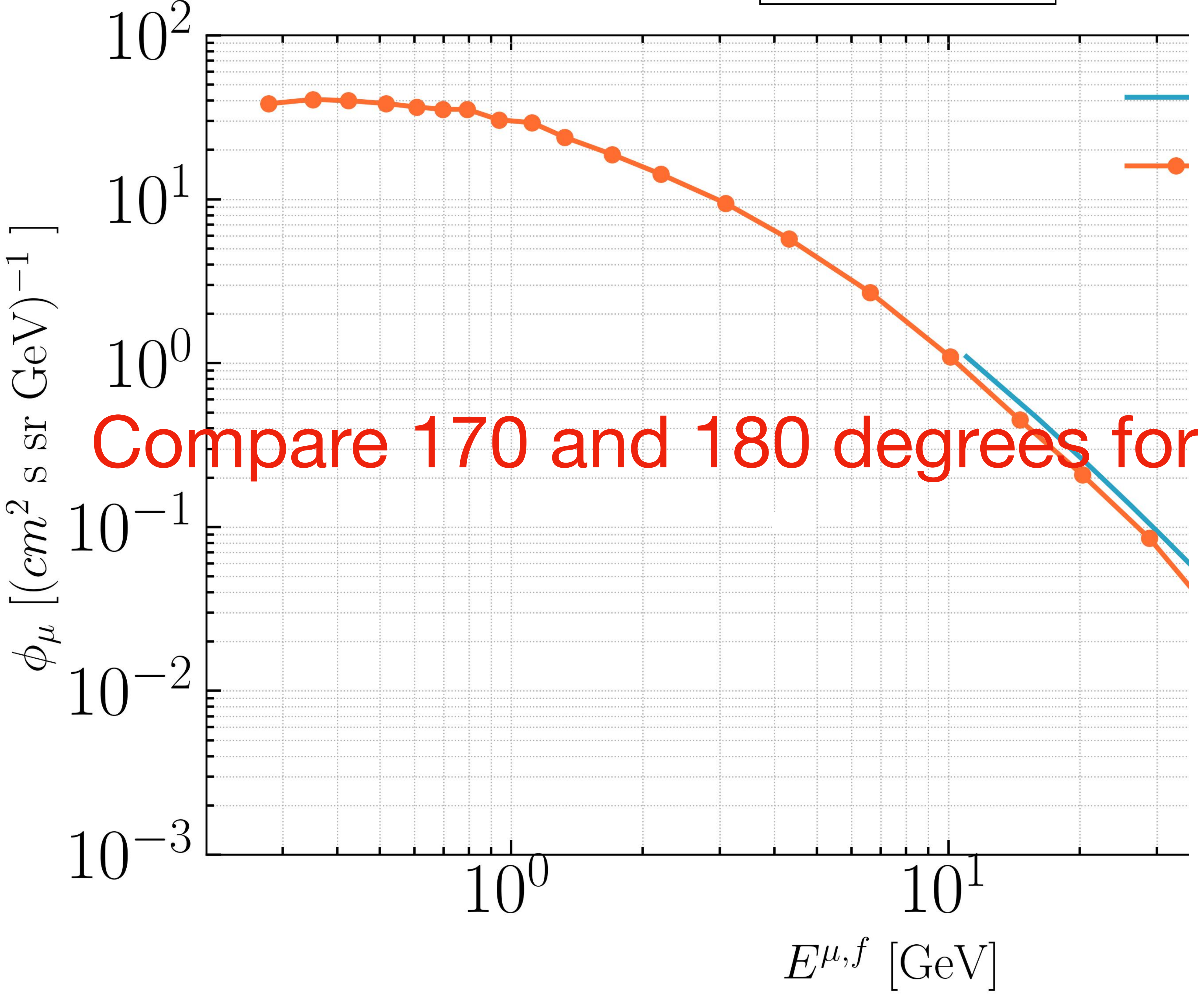


All CRs created at X0, X1, … and Pions created at X1,X2,.. are still going to keep propagating thru dX steps till they reach Xf. In all those steps we are going to lose some CR and pions, but we are also going to gain some at each energy step.

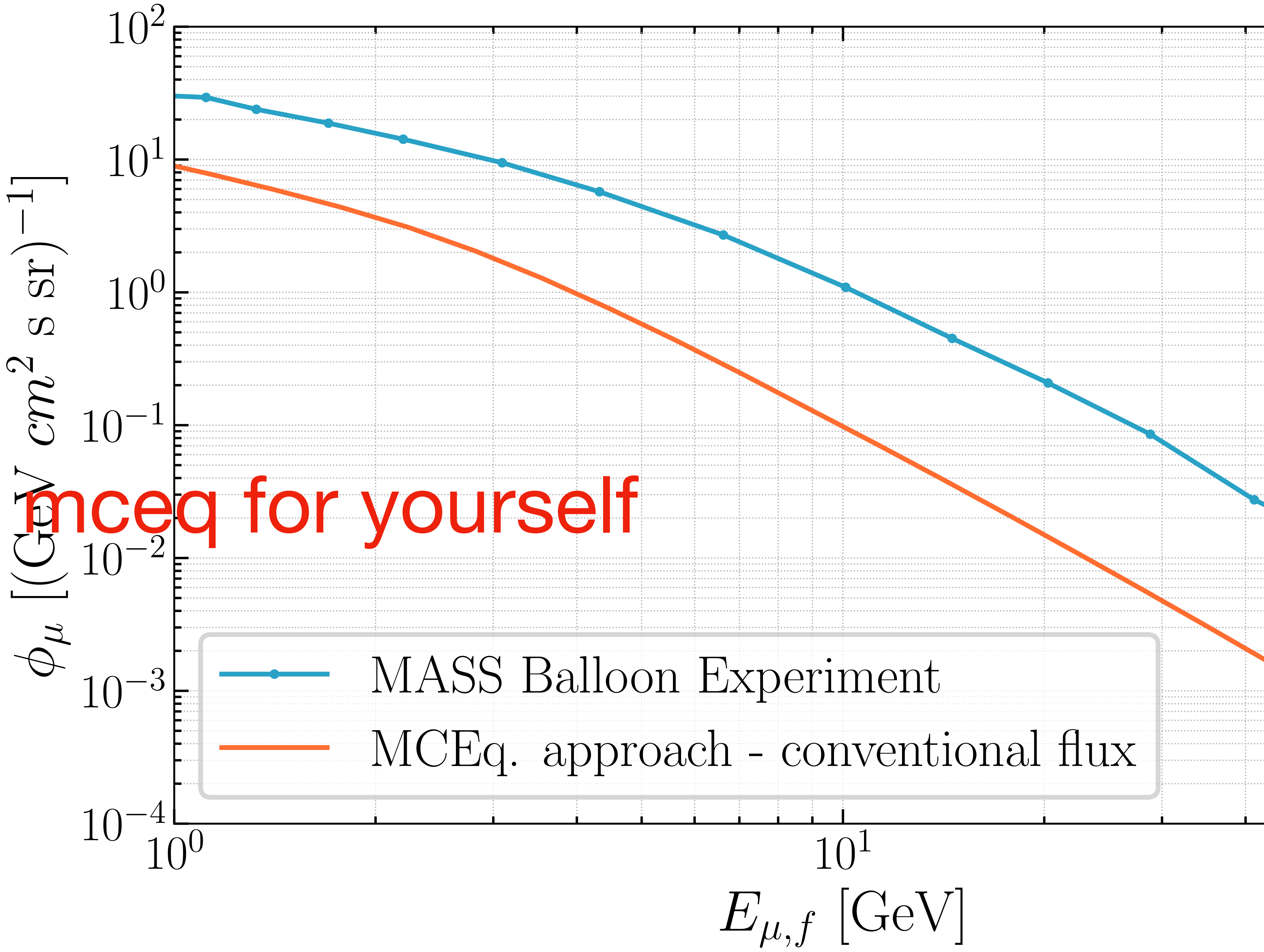
The Z moments cover if CR created at step X0 from Emu_i energy, then Z moment got covered all CRs that were created at E>Emu_i. So the muons reaching the detector at Ef are coming from a whole spectrum of CRs and not only one energy. And same pions are also a whole spectrum of energies.

Muon flux at 600 m above sea level - MASS expt.

Zenith = 0°



Compare 170 and 180 degrees for mceq for yourself



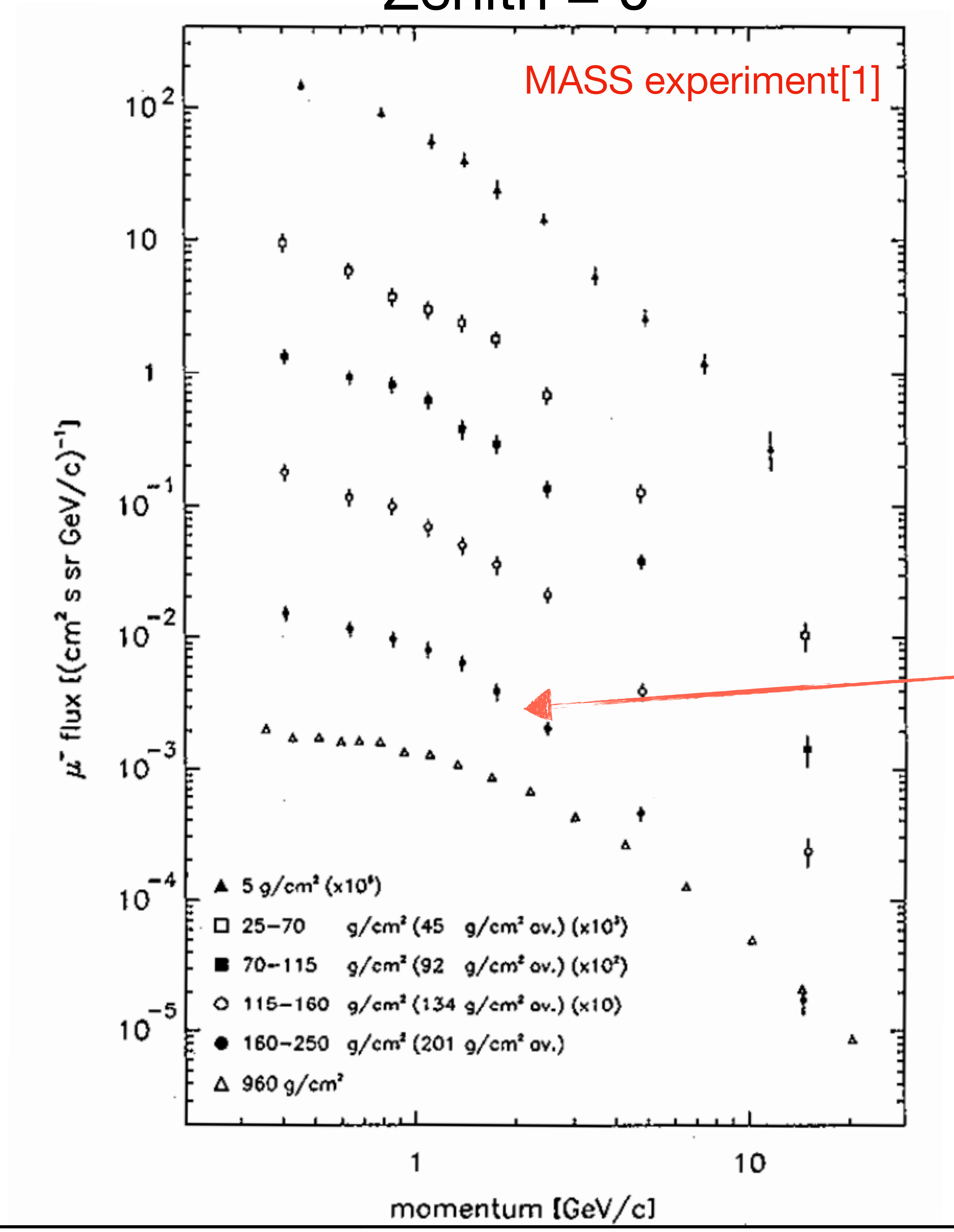
10^{2}

[1]: M.P. De Pascal et al., J. Geophys. Res, 1993

[1]: R. Bellotti et al., PRD, 1996

Negative muon flux for 160-250 g/cm²

Zenith = 0°



Zenith = 0°