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Expected spectra of muon-induced cascades in IceCube

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1

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Very high energy (VHE) muons

Muons with energies above 100 TeV are of a special interest, since changes of their energy spectrum can be caused by different physical reasons:

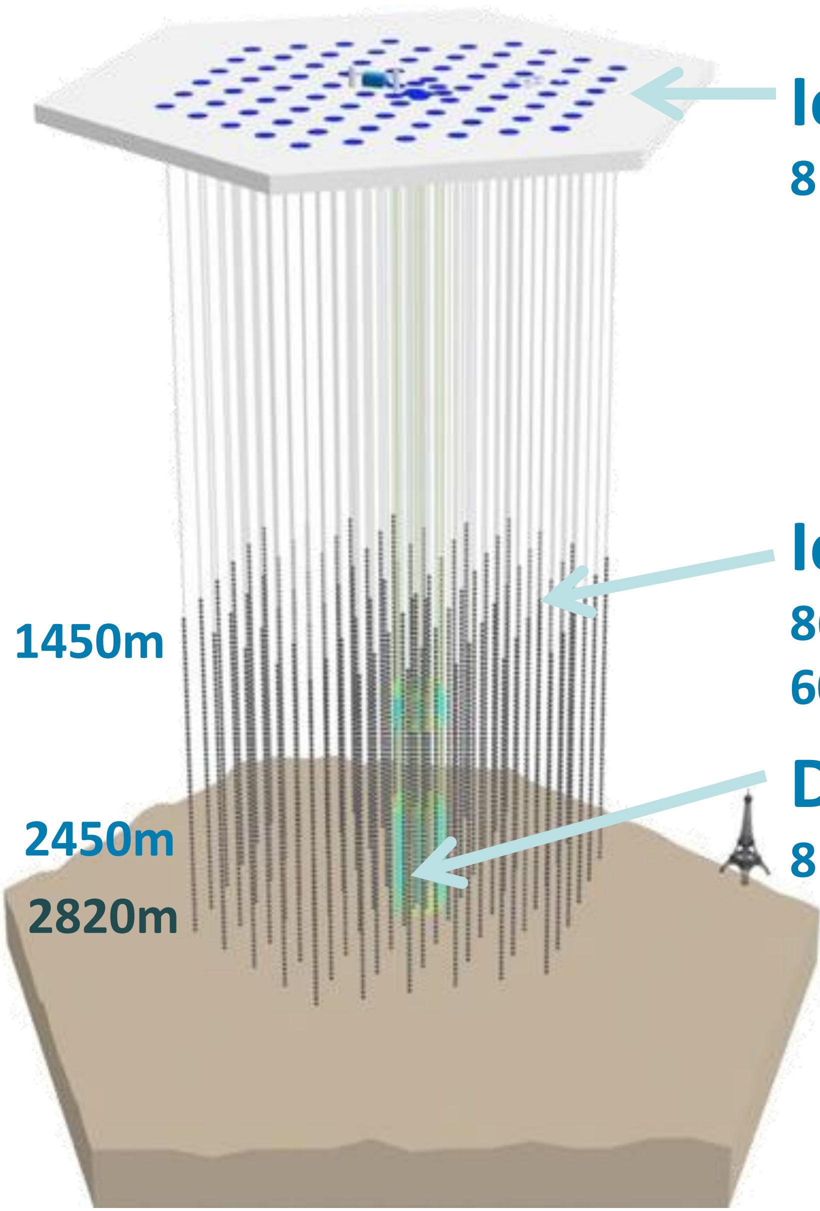
Decrease – by the decreasing CR energy spectrum above the knee.

Increase – due to inclusion of any additional rapid processes of muon generation: decays of charmed and other short-lived massive particles or appearance of a new state of matter.

One of the best ways for investigations of VHE muon spectrum is measuring the spectrum of stochastic energy losses (cascades).

Very large volume neutrino telescopes such as IceCube are suited for such an investigation.

IceCube Neutrino Observatory



IceTop air shower detector

81 pairs of water Cherenkov tanks

IceCube

86 strings including 8 Deep Core strings

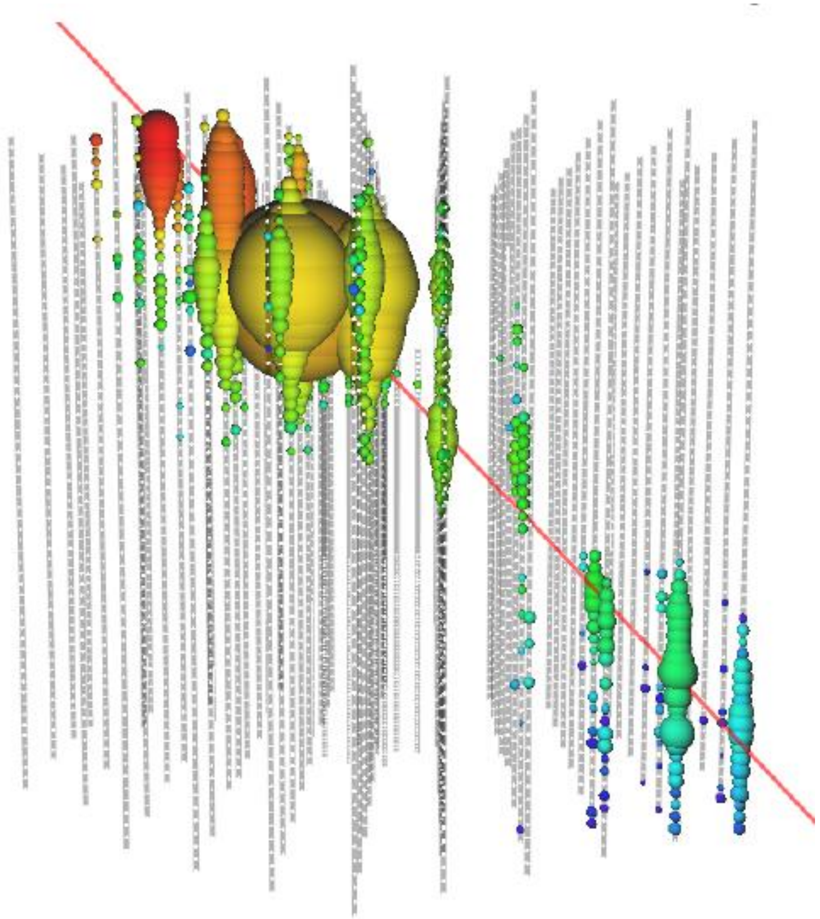
60 PMT per string

DeepCore

8 closely spaced strings

Rate of events with total response above 1000 ph.e. is 4 s^{-1}. These are mainly muon bundles.

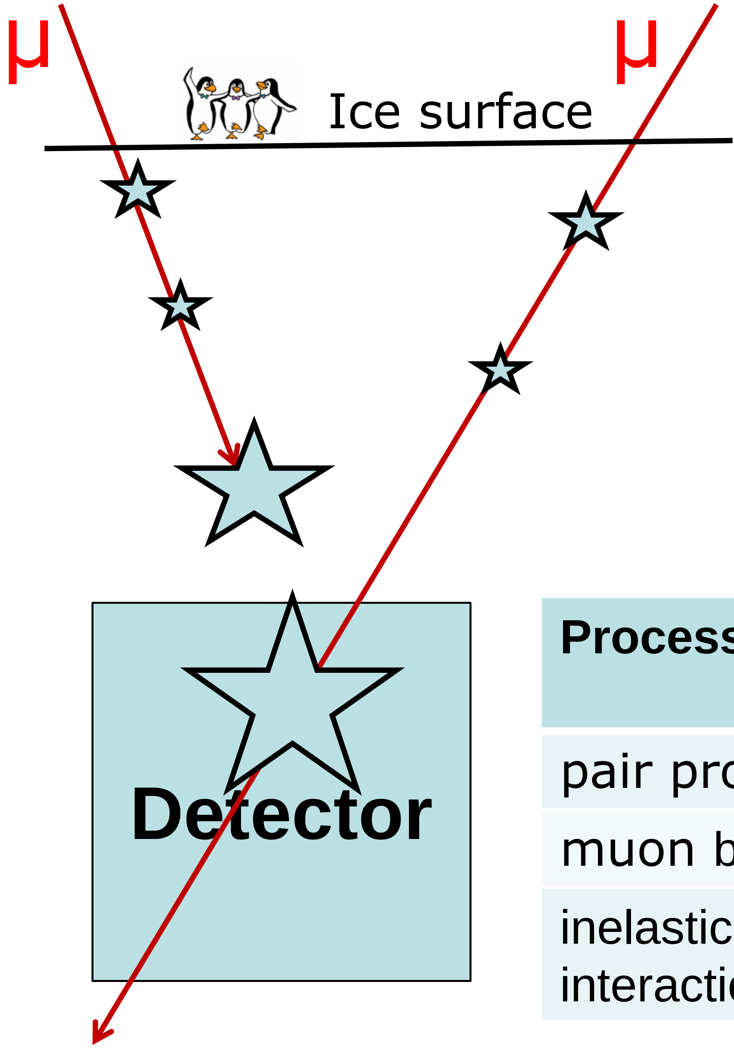
VHE muons in IceCube



IceCube is capable to reconstruct the energy spectrum of VHE muons by means of measurements of cascades.

G. Aartsen et al. "Characterization of the Atmospheric Muon Flux in IceCube", Astropart.Phys. 78, 1 (2016).

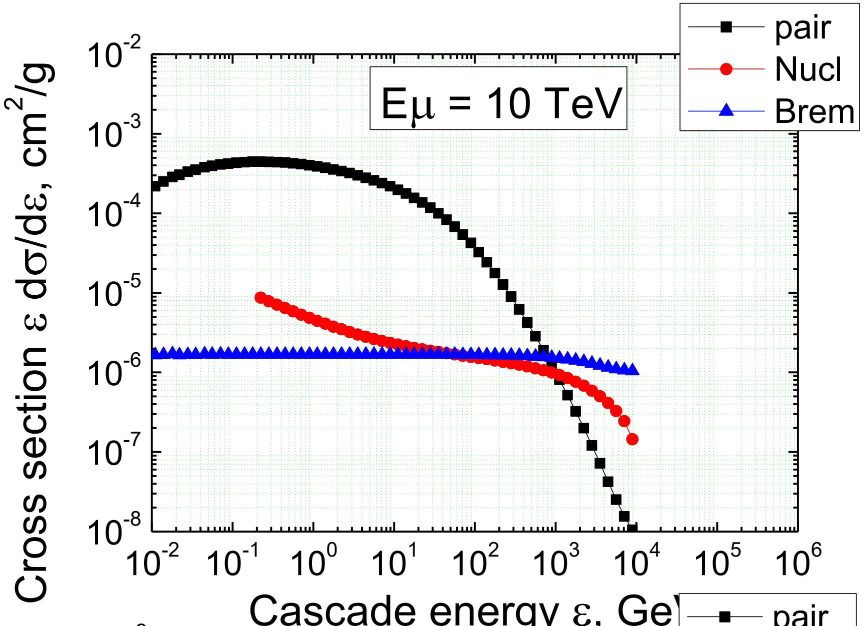
Influence of muon energy loss fluctuations

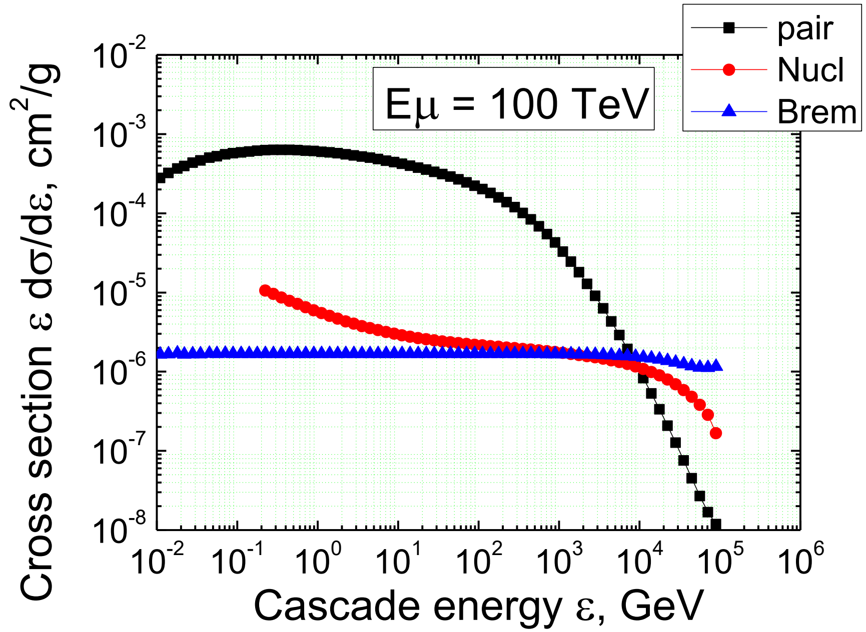


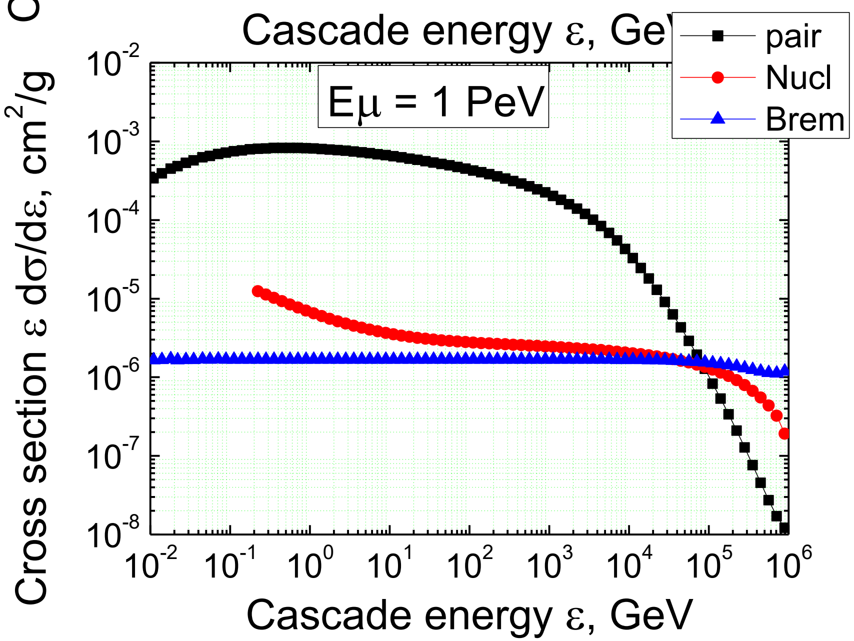
Process	Transfered energy	Fluctuations
pair production	$10^{-3} – 10^{-2}$	low
muon bremsstrahlung	$10^{-2} – 1$	high
inelastic muon interaction with nuclei	$10^{-2} – 1$	High

If we registered a muon with large cascade inside the detector volume, most likely it means that this muon did not generate large cascades over the detector. So, we can overestimate the average muon energy.

Cross sections of processes







Cross sections of processes are scaled:

$$\sigma_i(E,v) = \sigma_i(v).$$

where v = ε/E is raletive transferred energy.

Approach to muon spectra calculation

Average specific muon energy losses:

$$-\left(dE/dx\right) \simeq a + bE$$

Connection of muon energy on the ice surface and muon energy at depth x:

$$E_0 = \exp\left(bx\right)\left(E + \frac{a}{b}\right) - \frac{a}{b}.$$

Assuming a simple power law muon spectrum on the surface:

$$\mathrm{N}\left(E,0\right) = AE^{-\left(\gamma+1\right)},$$

we can calculate muon spectrum at the depth x:

$$\mathrm{N}\left(E,x\right) = A\exp\left(-\gamma bx\right)\left\{E + \frac{a}{b}\left[1 - \exp\left(-bx\right)\right]\right\}^{-\left(\gamma+1\right)}.$$

But it is necessary to take into account energy loss fluctuations.
It can be do by menas of two additional coefficients $b_{\mathrm{eff\_1}}$ and $b_{\mathrm{eff\_2}}$:

$$\mathrm{N}\left(E,x\right) = A\exp\left(-\gamma b_{eff\_1}x\right)\left\{E + \frac{a}{b_{eff\_2}}\left[1 - \exp\left(-b_{eff\_2}x\right)\right]\right\}^{-\left(\gamma+1\right)}.$$

$$b_i = \int_0^1 \sigma_i(v)v\,dv; \quad b_{eff\_1i} = \int_0^1 \sigma_i(v)\frac{1-(1-v)^{\gamma}}{\gamma}dv. \quad b_{eff\_2}/b = \left(\gamma b_{eff\_1}/b - 1\right)/\left(\gamma - 1\right);$$

Muon spectra on the ice surface

Two types of muon spectra have been assumed

1. Simple power low spectrum with $(\gamma_1+1) = 3.7$

$$N_1(E,\cos\theta) = A_1 E^{-3.7}/\cos\theta$$

2. Composite spectrum with $(\gamma_1+1) = 3.7$ and $(\gamma_2+1) = 2.7$

$$N_2(E,\cos\theta) = A_1 E^{-3.7}/\cos\theta + \; + A_2 E^{-2.7}$$

The second part of the composite spectrum assumes the manifestation of prompt muons at energies of hundreds of TeV.

The formula for A_1 was given from book of T.Gaisser “Cosmic rays and Particle Physics”, $A_1 = 20.5\ \mathrm{cm^2 sr^{-1} s^{-1} GeV^{2.7}}$, $A_2 = A_1/(E = 500\ \mathrm{TeV})$.

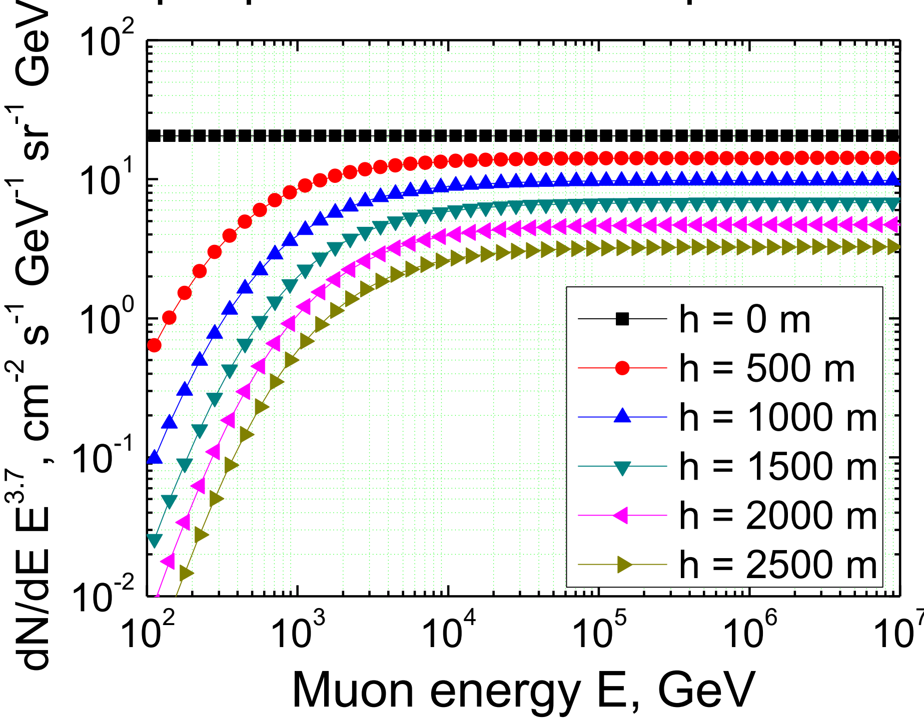
$b = 3.55 \cdot 10^{-6}\ \mathrm{cm^2/g}$

$(\gamma_1+1) = 3.7$: $b_{eff\_1} = 2.96 \cdot 10^{-6}\ \mathrm{cm^2/g}$; $b_{eff\_2} = 2.61 \cdot 10^{-6}\ \mathrm{cm^2/g}$.

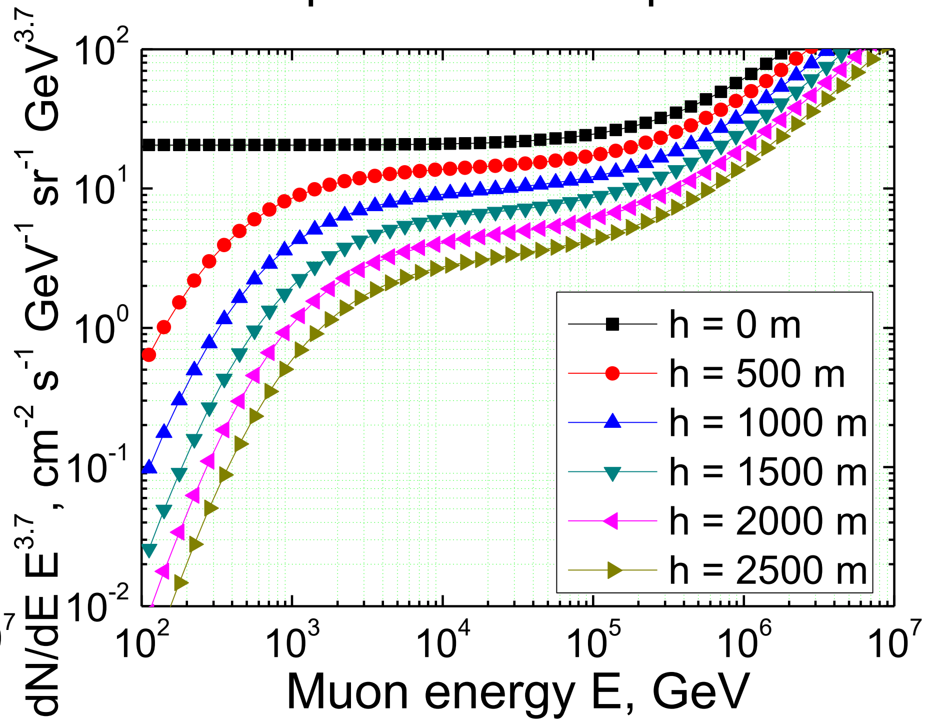
$(\gamma_2+1) = 2.7$: $b_{eff\_1} = 3.24 \cdot 10^{-6}\ \mathrm{cm^2/g}$; $b_{eff\_2} = 2.78 \cdot 10^{-6}\ \mathrm{cm^2/g}$.

Calculated muon spectra for different ice depths for the vertical direction

Simple power law muon spectrum



Composite muon spectrum



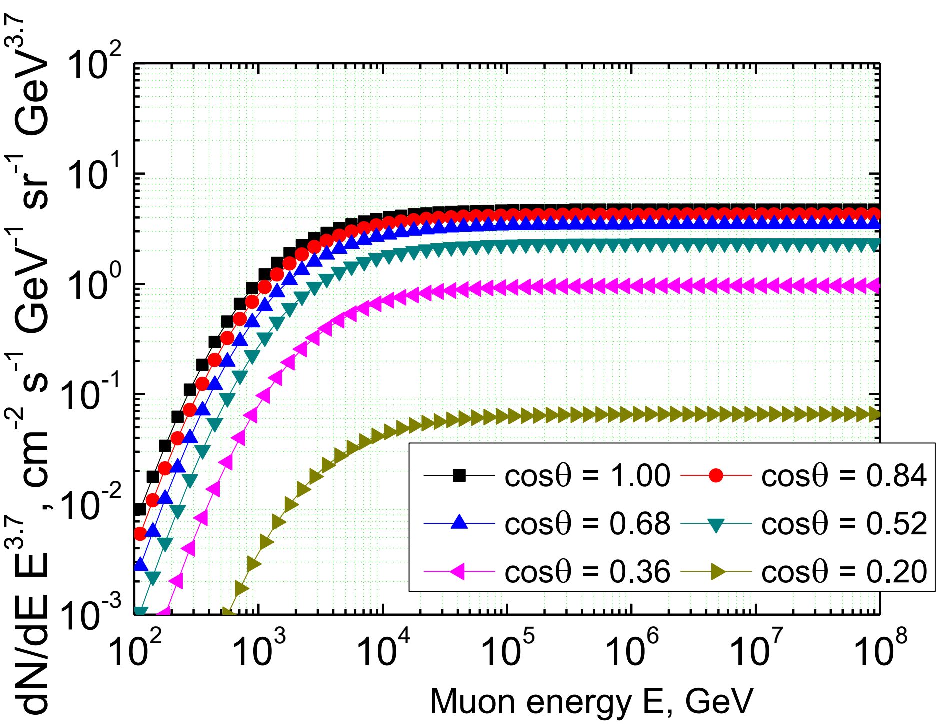
Average muon energy at the depth:

$$\langle E \rangle = \frac{a}{b_{eff\_2}} \frac{\left[1 - \exp\left(b_{eff\_2} x\right)\right]}{(\gamma - 1)}$$

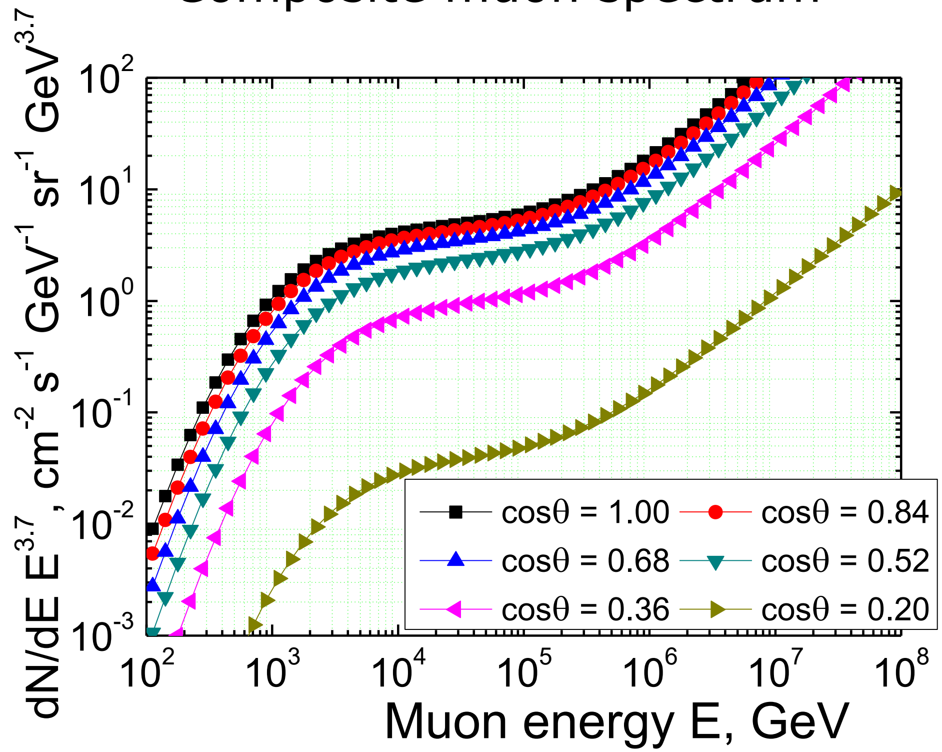
At the center of IceCube the average energy of vertical muons is <*E*> = 290 GeV and tends to the value of <*E*> = 770 GeV at great depth of ice.

Calculated muon spectra for different zenith angles at the ice depth of 2000 m

Simple power law muon spectrum



Composite muon spectrum



Muons with angles above 80° should be excluded from the analysis, since the background from muon neutrino events becomes a significant contributor at these angles.

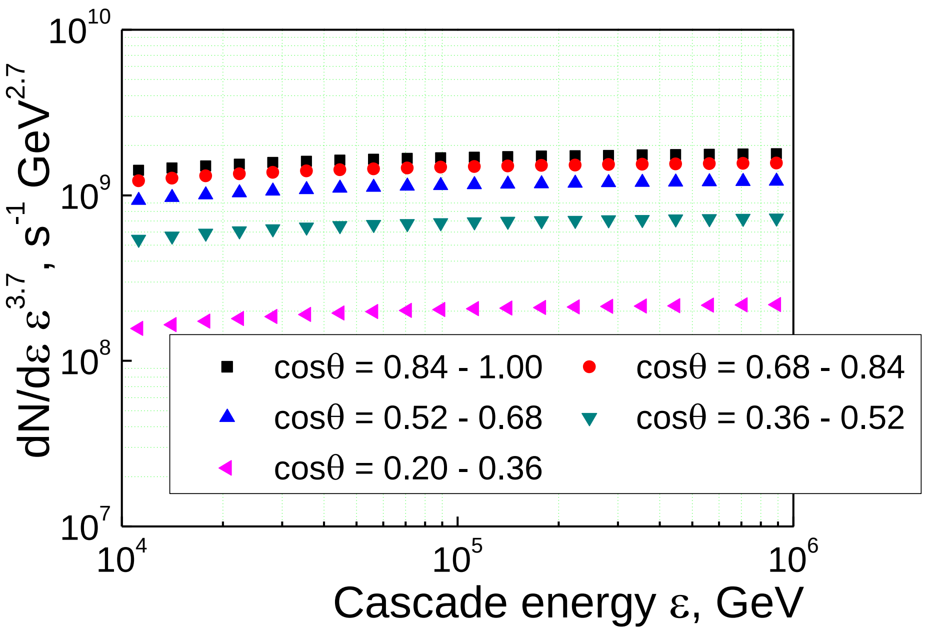
Calculation of spectra of muon-induced cascades

Differential spectrum of cascades at the depth h for zenith angles θ:

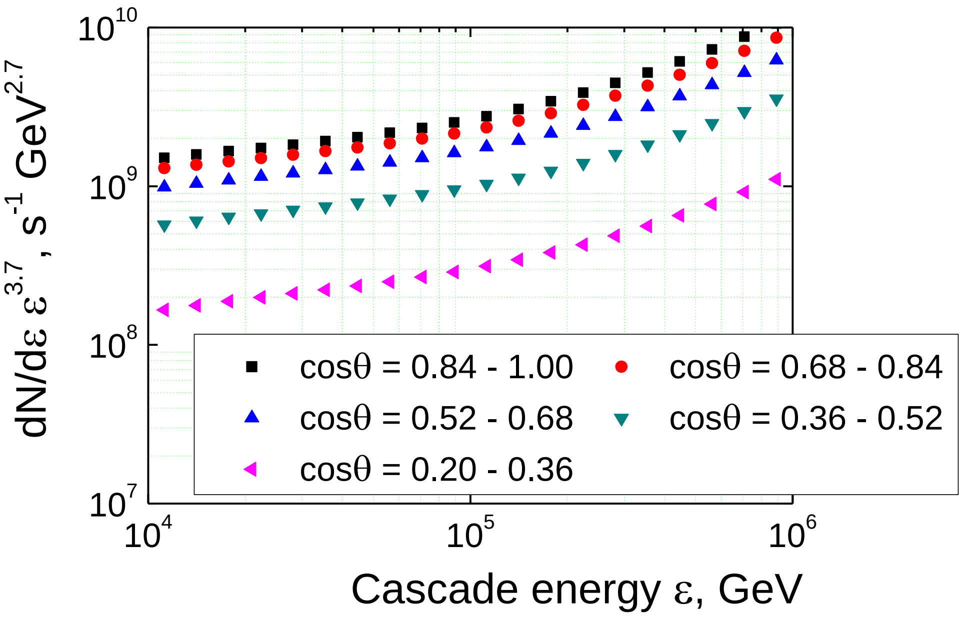
$$\mathbb{N}(\varepsilon, h, \cos\theta) = M \cdot \sum_i \int_{E\,\min}^{\infty} N_\mu(E, h, \cos\theta) \cdot \sigma_i(E, \varepsilon)\, dE$$

$M = \rho\pi R^2 dh$ is a mass of the target.
R = 500 m is a radius of the cylinder (IceCube).
Range of depths: 1500 - 2400 m.

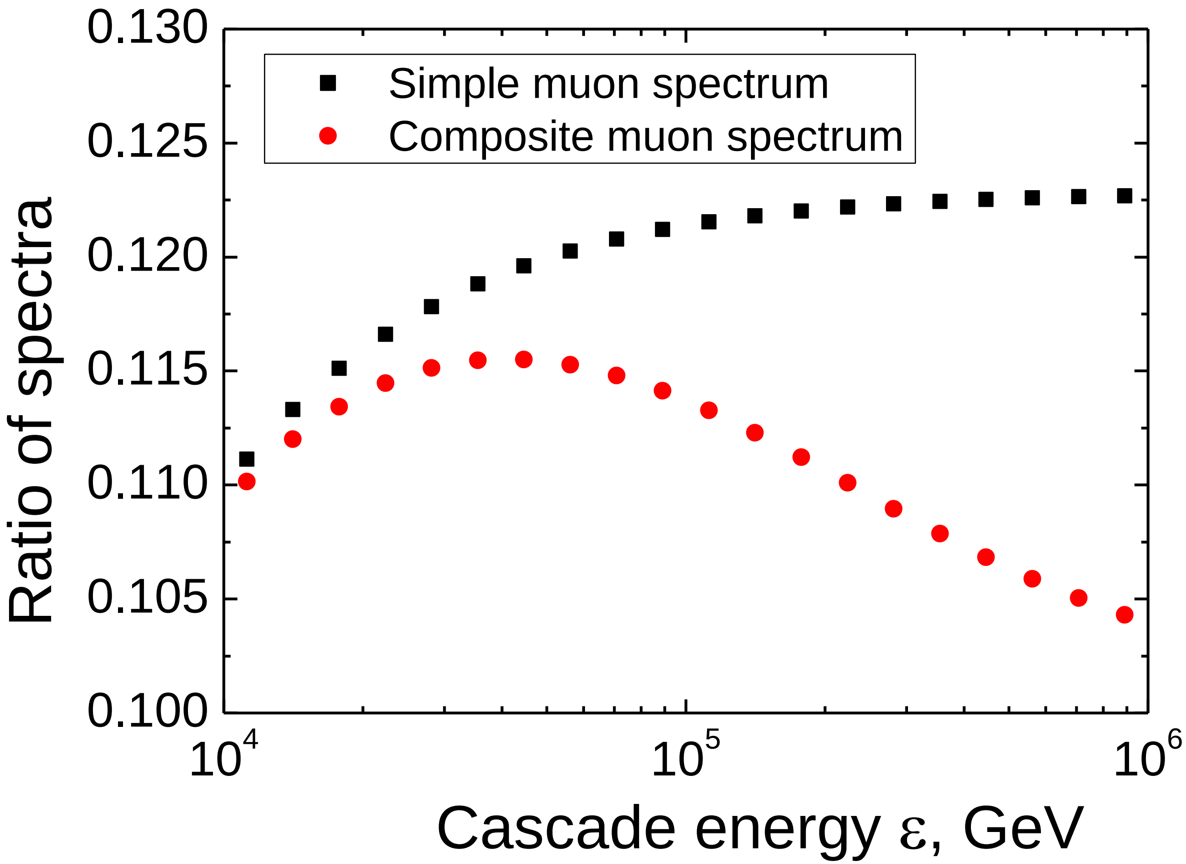
Simple power law muon spectrum



Composite muon spectrum

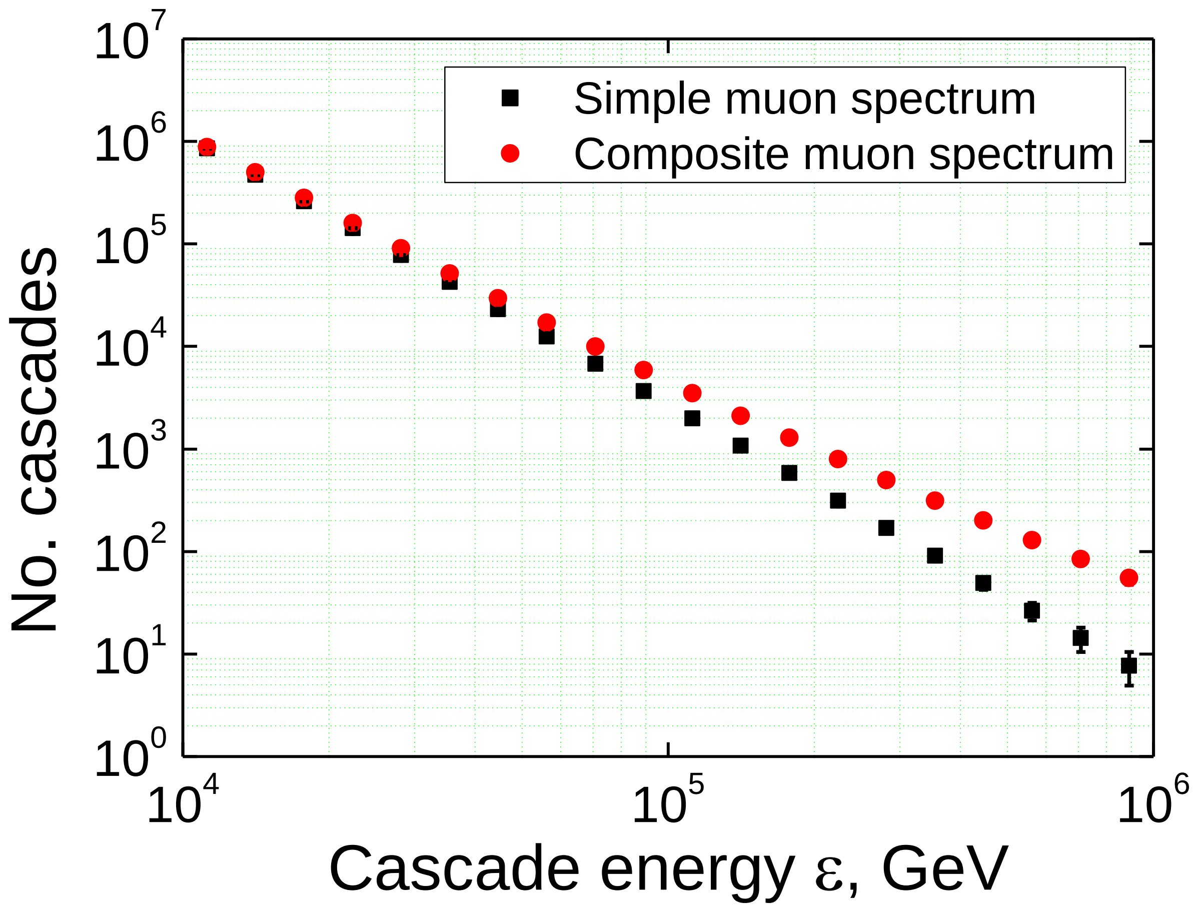


Ratio between cascade speactra with zenith angles cosθ = 0.84 – 1 and cosθ = 0.20 – 0.36



The ratio of cascade spectra at different zenith angles is sensitive to the form of the muon spectrum on the surface.

Estimated integral cascade spectra in IceCube for 1 year hypotetical runtimes



Number of cascades with energies above 300 – 500 TeV can be a good indicator of manifistation of prompt muons.

Summary

- **The expected spectra of cascades for two types of muon spectra on the ice surface have been estimated.**

- **The ratio of cascade spectra at different zenith angles is sensitive to the form of the muon spectrum on the surface.**

- **Number of muon-induced cascades with energies above 300 – 500 TeV can be a good indicator of manifistation of prompt muons.**

Thank you
for attention!