Direct Measurement of the Atmospheric Muon Spectrum with IceCube

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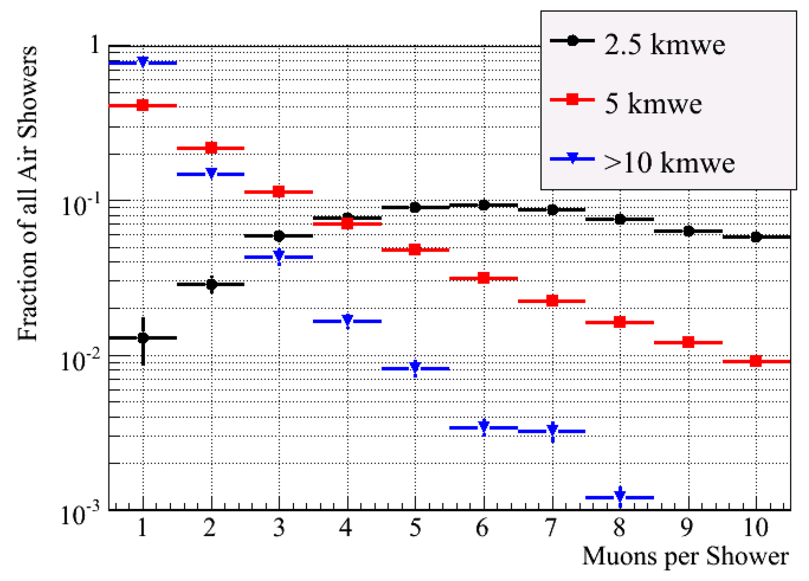
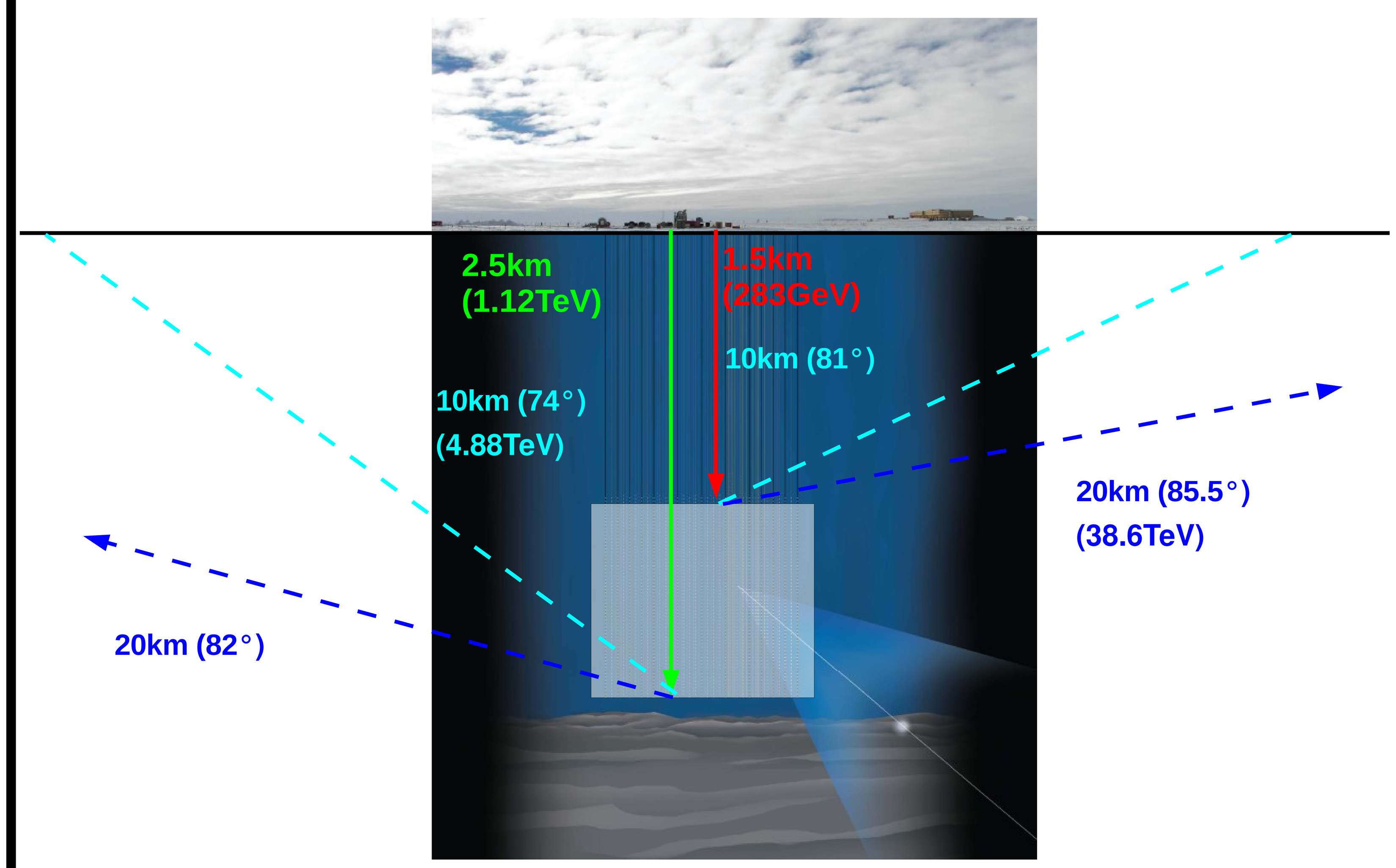
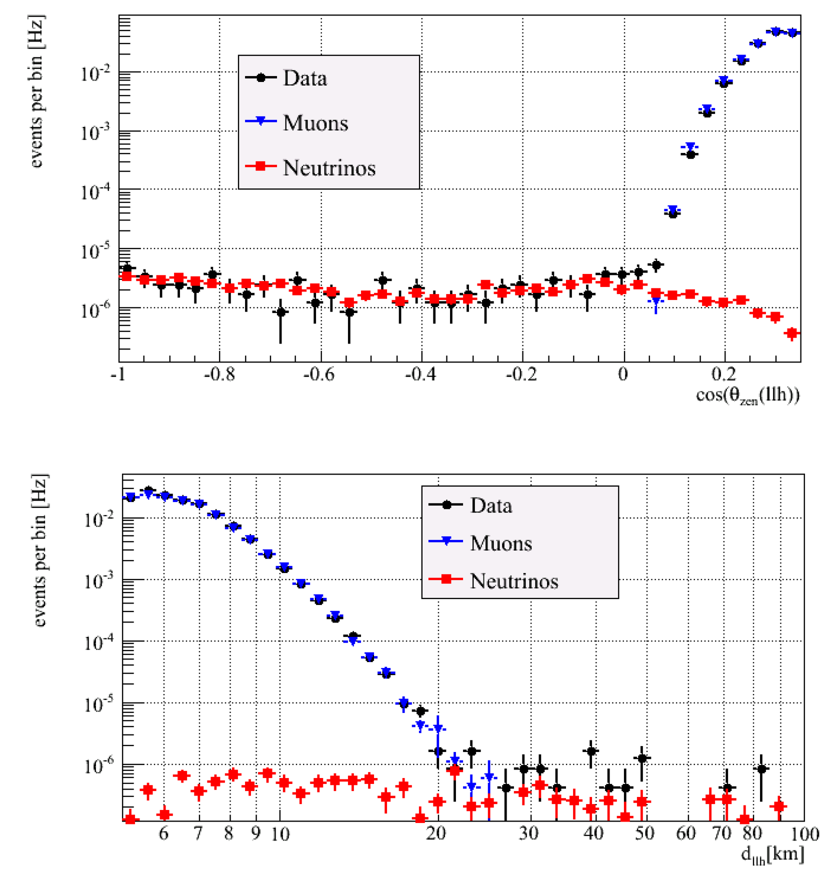
Abstract: Data from the IceCube detector in its 22-string configuration (IC22) were used to directly measure the atmospheric energy spectrum near the horizon. After passage through more than 10 km of ice, muon bundles from air showers are reduced to single muons, whose energy can be estimated from the total number of photons registered in the detector. The energy distribution obtained in this way is sensitive to the cosmic ray composition around the knee and is complementary to measurements by air shower arrays. The method described extends the physics potential of neutrino telescopes and can easily be applied in similar detectors. Presented is the result from the analysis of one month of IC22 data.



Muon Multiplicity (Simulated): With increasing slant depth, the number of muons per cosmic ray shower decreases. Since the granularity of IceCube is too coarse to resolve individual muons, constraining the measurement to angles near the horizon is the only way to obtain a single muon spectrum.



The IceCube Detector is located 1.5 km to 2.5 km under the ice at the geographic South Pole. Its instrumented volume will eventually reach 1km³. The trigger rate from downgoing muon bundles is of the order of 1 kHz. The arrows indicate the distance to the surface (slant depth) and the threshold energy (0.1% survival probability) for muons passing through the ice.



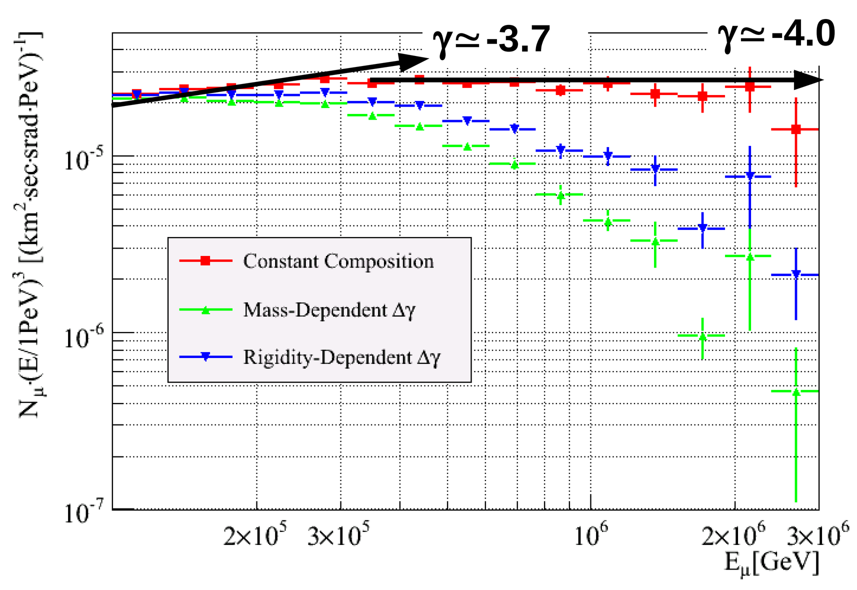
Data/Simulation Agreement: An important precondition for the feasibility of the muon energy spectrum is the suppression of mis-reconstructed muon tracks near the horizon, which could distort the spectrum at high energies. The two plots above demonstrate the smooth transition from down-going muons to up-going neutrinos.

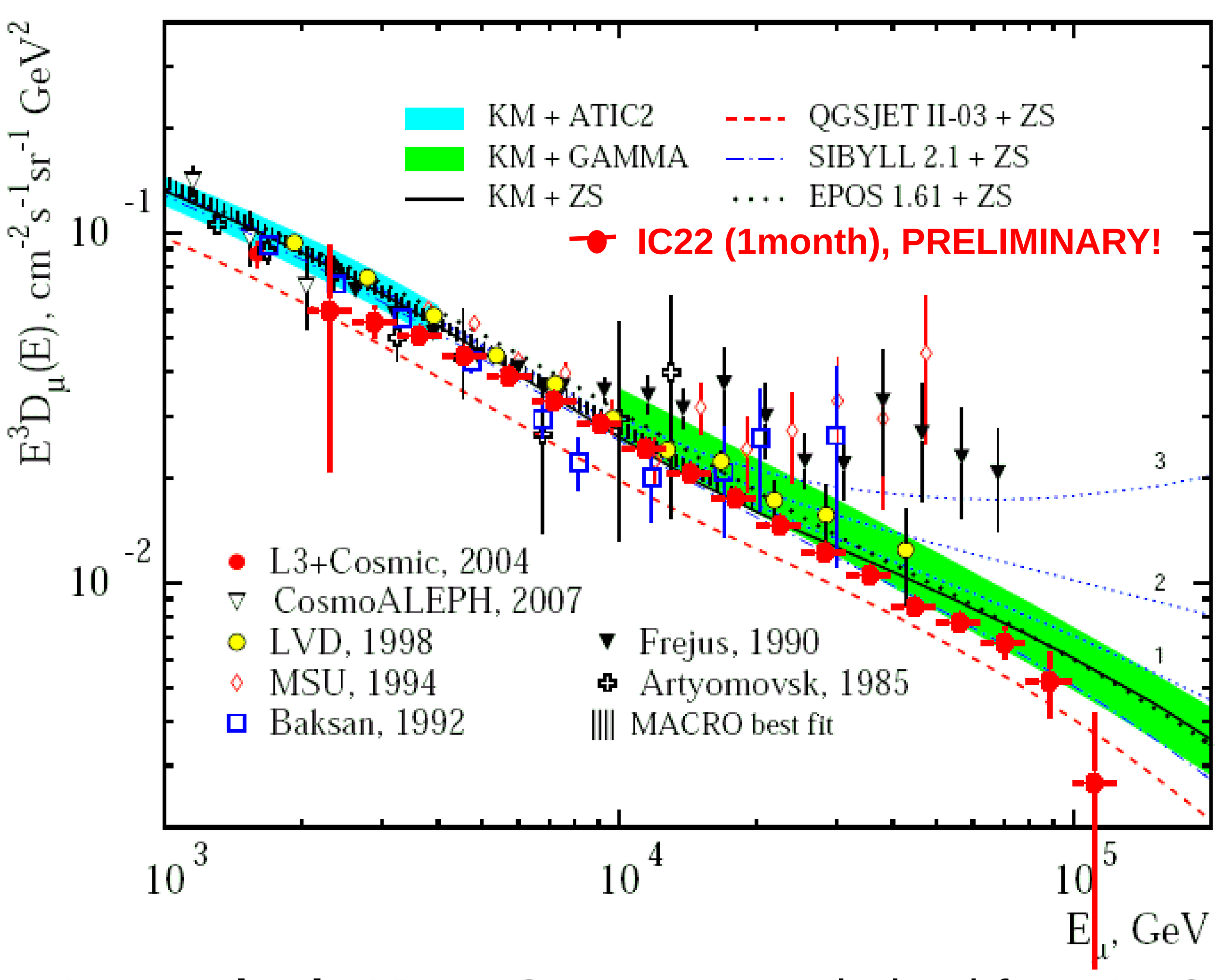
$$\frac{d\Phi_Z}{dE_0} = \Phi_Z^0 \left[1 + \left(\frac{E_0}{E_{trans}}\right)^{\epsilon_c}\right]^{\frac{-\Delta\gamma}{\epsilon_c}}$$

cut–off:	rigidity dependent	mass dependent	constant	
$\hat{E}_Z =$	$\hat{E}_p \cdot Z$	$\hat{E}_p \cdot A$	$\hat{E}_p$	
$\hat{E}_p$ [PeV] =	4.51 ± 0.52	3.66 ± 0.41	3.50 ± 0.38	common γ_c
$\gamma_c =$	-4.68 ± 0.23	-7.82 ± 1.09	-3.06 ± 0.02	
$\epsilon_c =$	1.87 ± 0.18	2.30 ± 0.23	1.94 ± 0.51	
χ^2/d.o.f. =	0.116	0.290	0.086	
$\hat{E}_p$ [PeV] =	4.49 ± 0.51	3.81 ± 0.43	3.68 ± 0.39	common $\Delta\gamma$
$\Delta\gamma =$	2.10 ± 0.24	5.70 ± 1.23	0.44 ± 0.02	
$\epsilon_c =$	1.90 ± 0.19	2.32 ± 0.22	1.84 ± 0.45	
χ^2/d.o.f. =	0.113	0.292	0.088	

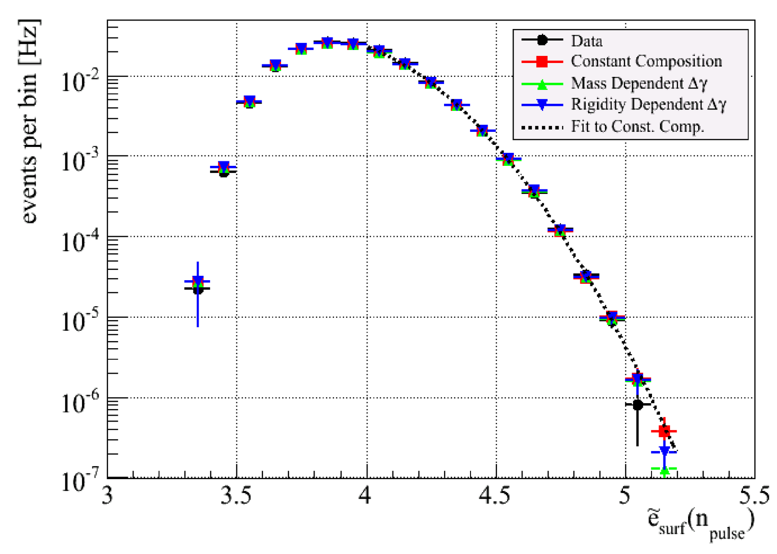
Rigidity Mass Constant

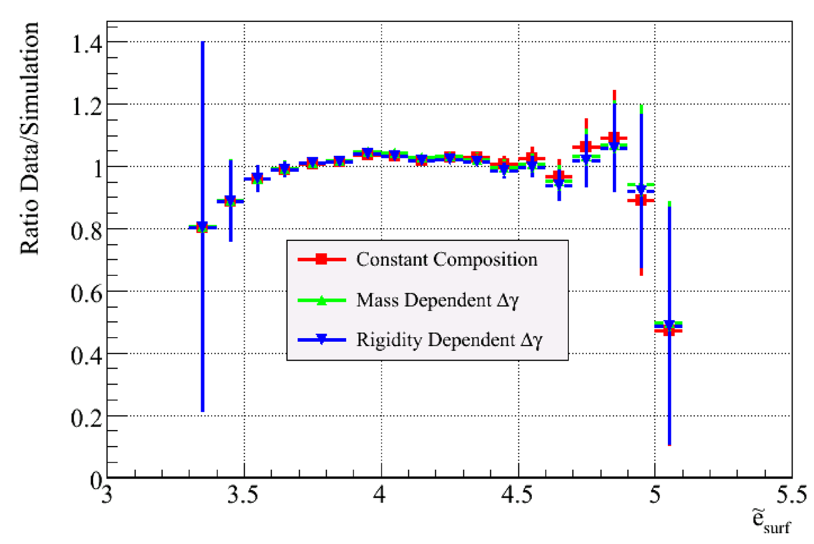
Poly-gonato Composition Models: The spectrum of cosmic rays around the knee can be explained through different composition models. The table above shows parametrizations for changing and constant cosmic ray compositions [1].
The ratio of median parent cosmic ray and muon energy is ≤ 10 at energies above 1 TeV [2]. A cutoff of the energy per nucleon in the cosmic ray spectrum as resulting from changing composition models will therefore lead to a steepening of the muon spectrum, as shown below.

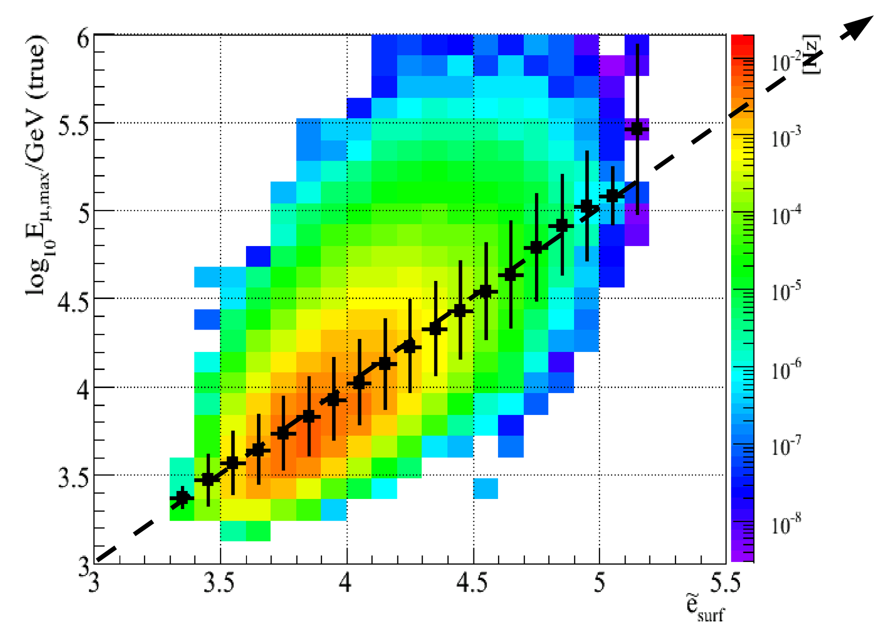




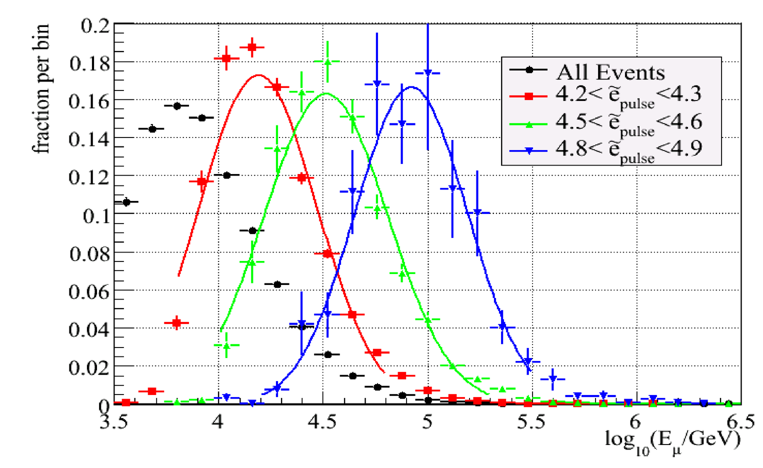
The Atmospheric Muon Spectrum as derived from IceCube data is shown above, compared to previous measurements and various theoretical predictions [3]. The error bars shown do not yet include systematic detector effects. Even though only about 10% of the entire data set has been unblinded, the energy range extends already significantly higher than previous measurements.
A comparison between data and CORSIKA/SIBYLL [4] simulation using different primary composition models can be seen on the bottom left. The graph on the bottom right shows the ratio between experimental data and simulation in dependence of the surface energy estimator value.
Future measurements of the muon energy spectrum with large-volume neutrino detectors will allow detailed probing of hadronic interaction models and the cosmic ray composition around the knee.

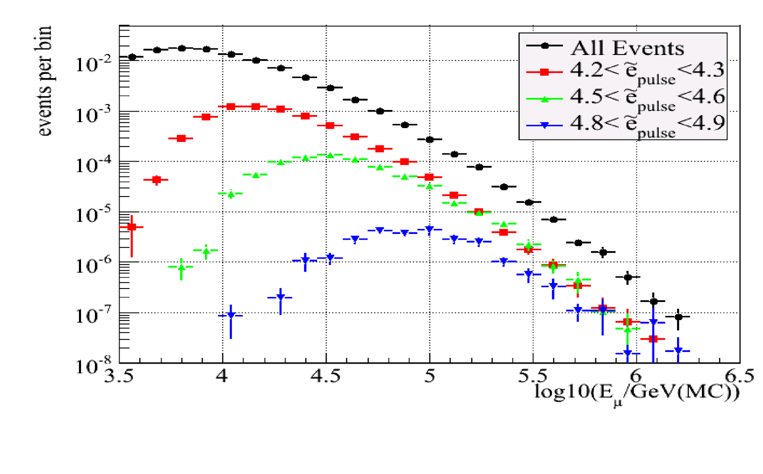






Muon Surface Energy Estimator: The slant depth measurement can be combined with calorimetric information. This way a parameter is obtained that is directly related to the surface energy of the most energetic muon in a cosmic ray shower.
The plot on top compares energy estimator and muon energy for simulated air showers. On the bottom, relative and absolute event rates (in IC22) are shown for three values of the energy estimator.





References:
[1]: J.R. Hörandel, Astropart. Phys. **19**, 193 (2003).
[2]: T. K. Gaisser, "Cosmic Rays and Particle Physics", Cambridge University Press, 1990.
[3]: A.A. Kochanov, T.S. Sinegovskaya and S.I. Sinegovsky, Astropart. Phys. **30**, 219 (2008).
[4]: CORSIKA : http://wwwik.fzk.de/corsika/,Comput.Phys.Commun. **56**, 105113 (1989).