Fluxes of Atmospheric Leptons in Large Underground Detectors

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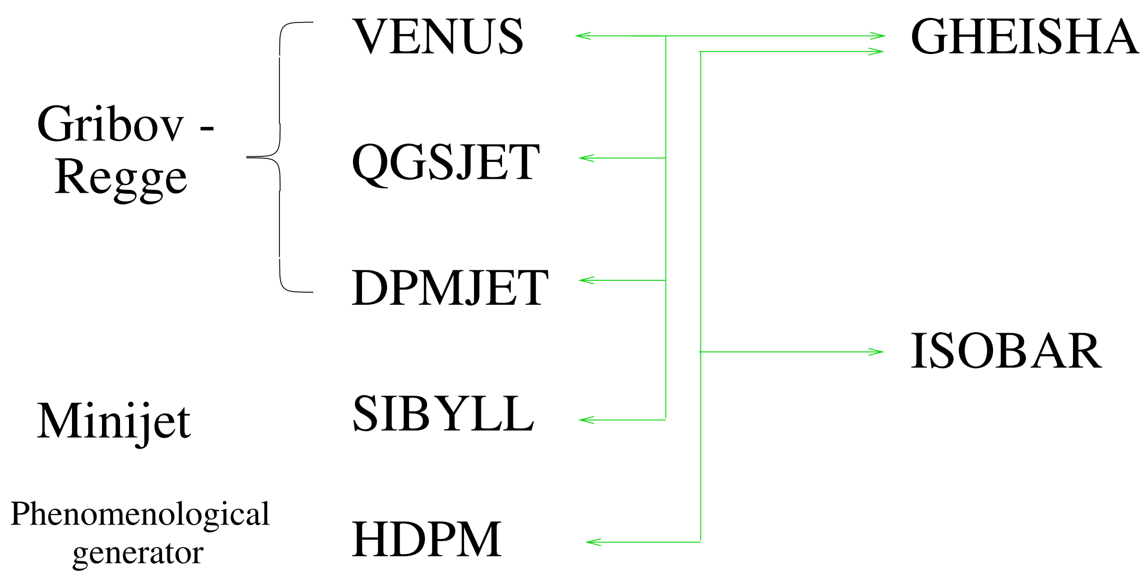
Primary Interactions in CORSIKA (v 5.42)



	VENUS	QGSJET	DPMJET	SIBYLL	HDPM
Gribov-Regge	+	+	+		+
Minijets		+	+	+	+
Sec. Interactions	+				
N-N Interactions	+	+	+		
Superposition				+	+
Max. Energy (GeV)	$2 \cdot 10^7$	10^{11}	10^{11}	10^{11}	10^8

This table was taken from “CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers” by D. Heck et. al.

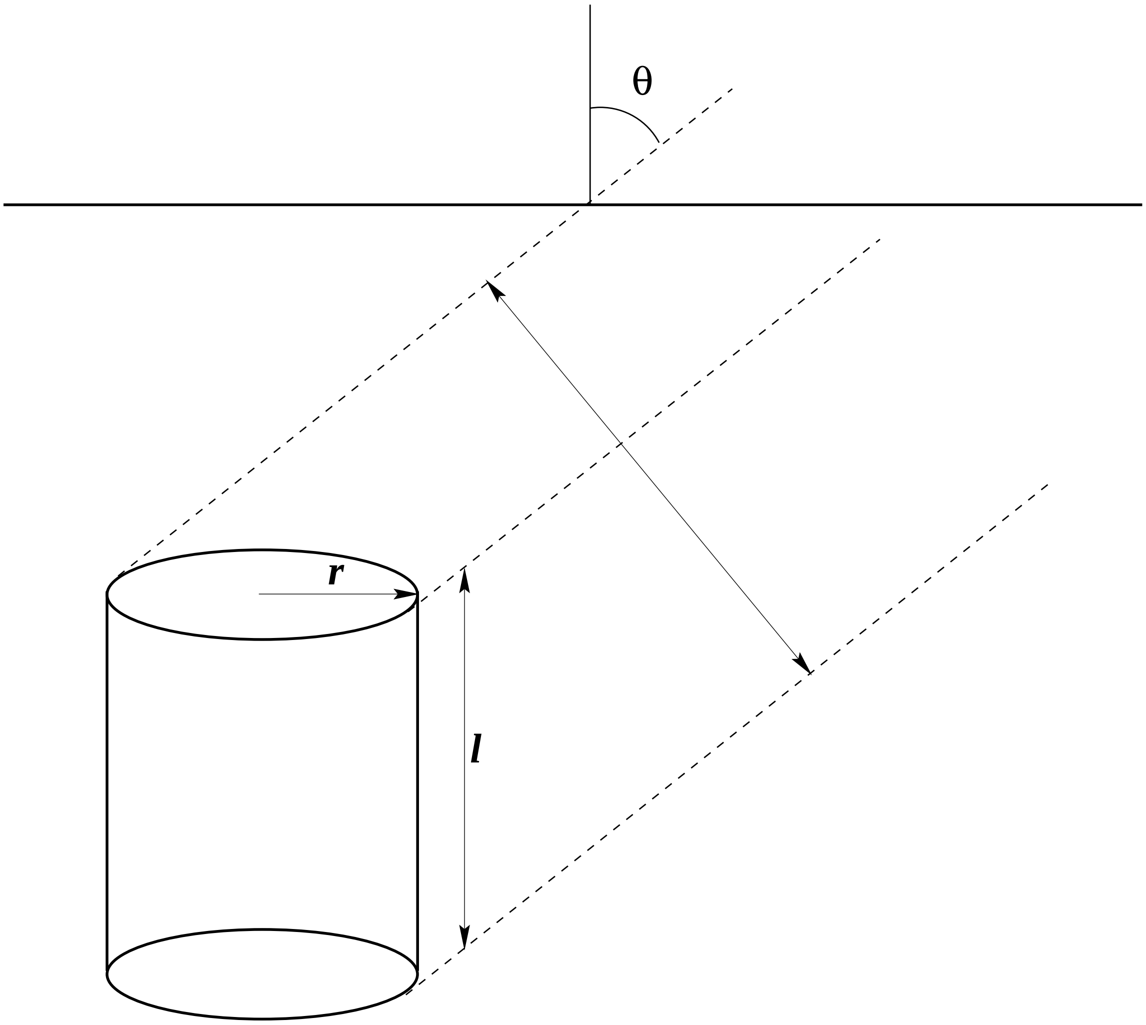
Electromagnetic interactions are considered with

1. EGS4 - Monte Carlo shower program
2. NKG - analytical formula

$$\boldsymbol{E = \Phi_0 E^{-\gamma}}$$

El-t.	At. #	Weight	Φ_0	$\sigma(\Phi_0)$	γ	$\sigma(\gamma)$	χ^2
H	1	1.00797	0.1057	0.003	2.76	0.02	0.7
He	2	4.0026	0.0673	0.002	2.63	0.02	2.1
Li	3	6.939	0.00208	0.00051	2.54	0.09	0.9
Be	4	9.0122	0.000474	4.8E-05	2.75	0.04	0.37
B	5	10.811	0.000895	7.9E-05	2.95	0.05	0.45
C	6	12.0112	0.0106	0.0001	2.66	0.02	1.42
N	7	14.0067	0.00235	8.E-05	2.72	0.05	1.91
O	8	15.9994	0.0157	0.0004	2.68	0.03	1.7
F	9	18.9984	0.000328	4.8E-05	2.69	0.08	0.47
Ne	10	20.183	0.0046	0.0001	2.64	0.03	3.14
Na	11	22.9898	0.000754	3.3E-05	2.66	0.04	0.36
Mg	12	24.312	0.00801	0.00026	2.64	0.04	0.1
Al	13	26.9815	0.00115	0.00015	2.66	0.04	1.24
Si	14	28.086	0.00796	0.00015	2.75	0.04	0.1
P	15	30.984	0.00027	2.E-05	2.69	0.06	0.68
S	16	32.064	0.00229	0.00024	2.55	0.09	0.44
Cl	17	35.453	0.000294	1.9E-05	2.68	0.05	2.36
Ar	18	39.948	0.000836	3.8E-05	2.64	0.06	0.45
K	19	39.102	0.000536	1.5E-05	2.65	0.04	4.58
Ca	20	40.08	0.00147	0.00012	2.7	0.06	0.6
Sc	21	44.956	0.000304	1.9E-05	2.64	0.06	0.81
Ti	22	47.9	0.00113	0.00014	2.61	0.06	5.67
V	23	50.942	0.000631	2.8E-05	2.63	0.05	6.83
Cr	24	51.996	0.00136	0.00012	2.67	0.06	3.41
Mn	25	54.938	0.00135	0.00014	2.46	0.22	5.38
Fe	26	55.847	0.0178	0.0018	2.6	0.09	1.81
Co	27	58.933	7.51E-05	3.7E-06	2.72	0.09	1.13
Ni	28	58.71	0.000996	4.3E-05	2.51	0.18	5.47

Geometry Consideration



$$dN \propto d\Omega \cdot (\pi r^2 \cdot \cos\vartheta + l \cdot 2r \cdot \sin\vartheta)$$

Nishimura, Kamata and Greisen (NKG) formula, as given in (Heck, et al., 1998):

$$\boldsymbol{\rho_e = \frac{N_e}{2\pi r_{mol}^2 s_m^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} \left(\frac{r}{r_{mol} s_m}\right)^{s-2} \left(1 + \frac{r}{r_{mol} s_m}\right)^{s-4.5}}$$

where $s_m = 0.78 - 0.21s$, $r_{mol} = 9.6 g \cdot cm^{-2}/\rho_{air}$ = Moliere radius.

Data Format (AMANDA):

Takes only about 5% of the default-format file space. x, y, z, θ, ϕ, E, l, τ and parent ID are saved for most particles.

Monte Carlo statistic:

model	QGSJET	SIBYLL	VENUS	HDPM
#'s of primaries generated	$1.5 \cdot 10^8$	$4.1 \cdot 10^7$	$3.0 \cdot 10^7$	$1.2 \cdot 10^7$
computing rate, 10^6/day	1.8	1.1	0.36	1.7

Calculation took 30 CPU weeks on 300 MHz Pentium IIs.

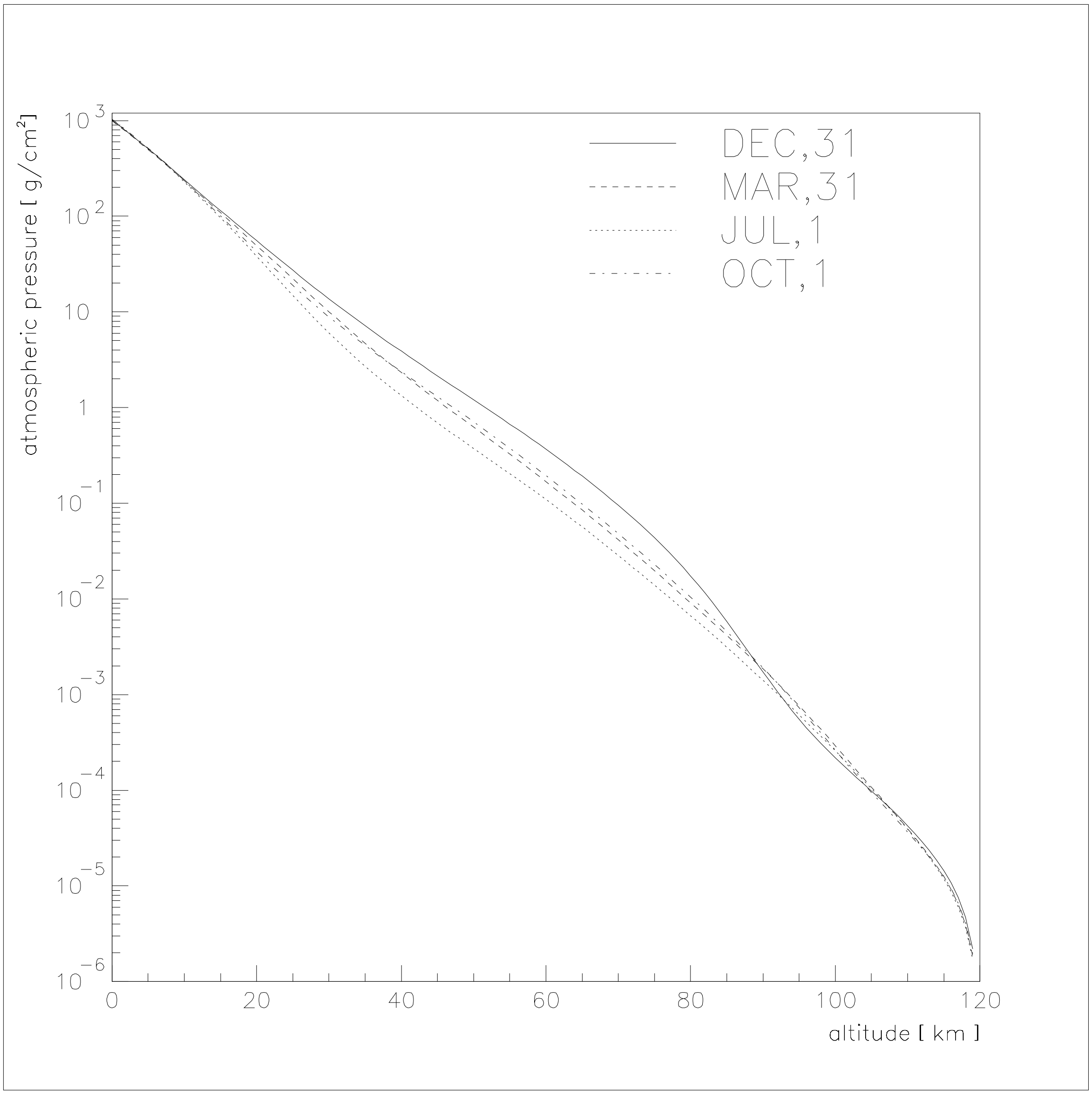
Atmosphere in CORSIKA is defined by giving 5 sets of parameters for 5 regions:

[0:4] km	A[i]+B[i]·exp(-height/C[i]), i=1...4
[4:10] km	
[10:40] km	
[40:100] km	
[100:112.8] km	A[5]-B[5]·height/C[5], B[5]=1

(fit to the table at http://nssdc.gsfc.nasa.gov/space/model)

Magnetic field of 55911 nT with the declination of $-27°43.0'$ and inclination of $-72°54.5'$ was obtained (http://www.ngdc.noaa.gov/seg/potfld/geomag.html).

Comparison of four atmospheres at the South Pole.



Most muons were produced at 24 ± 9 km.

Fit of the generated muon spectra

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{1}{1+\frac{1.1E_\mu \cos\vartheta}{115\ \mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1E_\mu \cos\vartheta}{850\ \mathrm{GeV}}}\right)$$

(Gaisser, 1990)

$$dE/dx = -(0.25 + 3.5 \cdot 10^{-4} E),$$

$$P^{-1} = \exp\left(\frac{l}{c\tau} \cdot \frac{M}{E}\right) > 1$$

Fit of the generated neutrino spectra

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{1}{1+\frac{6E}{E_{\pi}(\vartheta)}}+\frac{0.213}{1+\frac{1.44E}{E_{K^{\pm}}(\vartheta)}}\right), \quad \nu_{\mu}$$

$$\frac{dN}{dE} \propto E^{-\gamma}\left(\frac{0.05}{1+\frac{1.5E}{E_{K^{\pm}}(\vartheta)}}+\frac{0.185}{1+\frac{1.5E}{E_{K_2^0}(\vartheta)}}+\frac{11.4E^{\zeta(\vartheta)}}{1+\frac{1.21E}{E_{\pi}(\vartheta)}}\right), \; \nu_e$$

(Volkova, 1980)

Conclusions and further developments

1. γ_μ (from He) for all models is bigger than expected value (2.63). QGSJET, SIBYLL and VENUS agree with each other, while HDPM gives a significantly steeper spectrum.
2. All models agree with the measurements of γ_μ made in underground experiments.
3. QGSJET and VENUS agree with the $\gamma_{\nu(\mu)}$ value measured by (Frejus Coll., 1995).
4. $\gamma_{\nu(e)}$ agrees with the theoretical prediction of (Volkova, 1980) for SIBYLL, VENUS and HDPM models, while QGSJET gives a significantly bigger value.

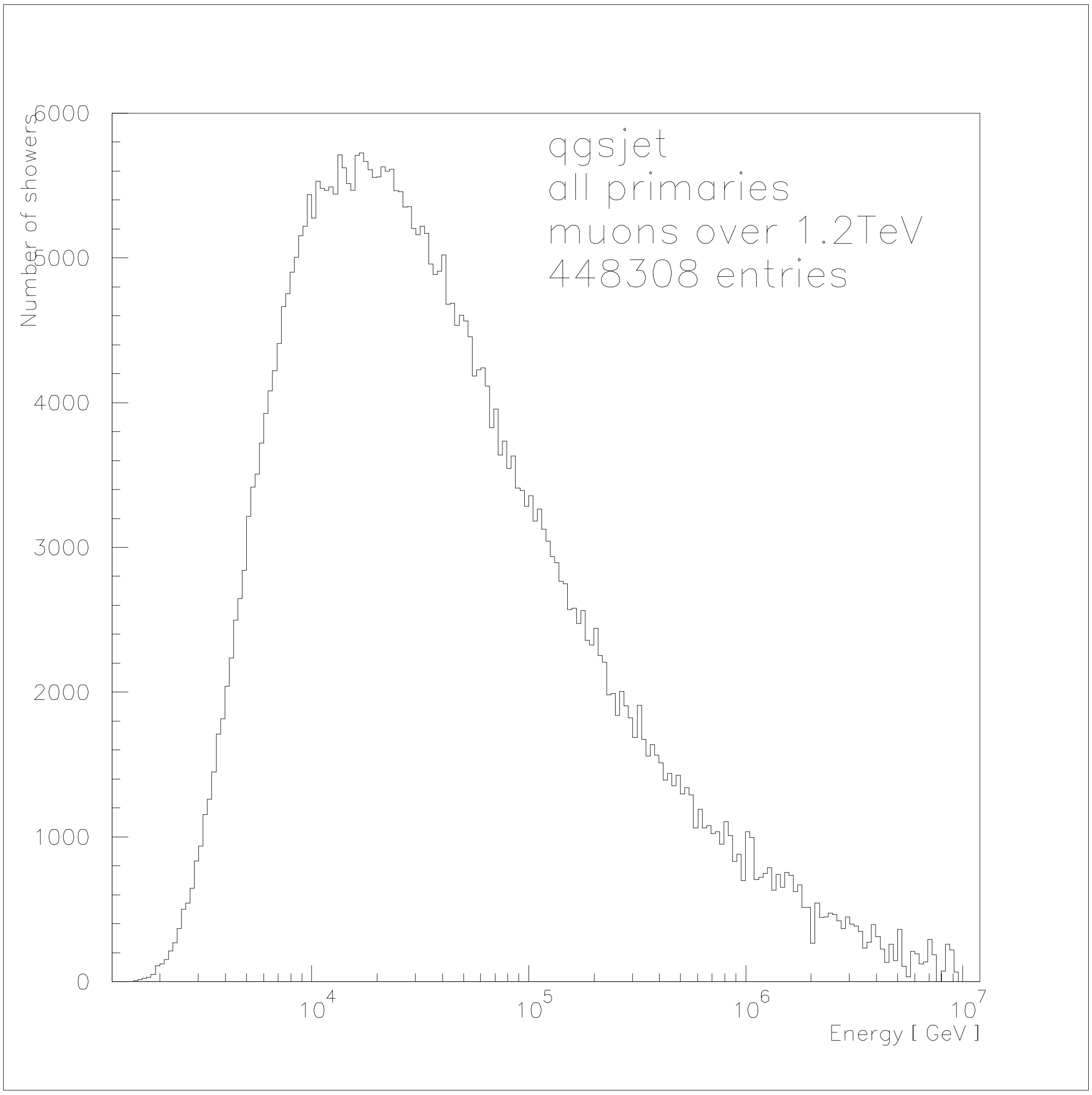
We ran the program for $\sim$ 300 CPU-weeks and have collected a large statistics (2.3 billion primaries analyzed). It will be used in further investigation of the behavior of the neutrino detectors.

Results:

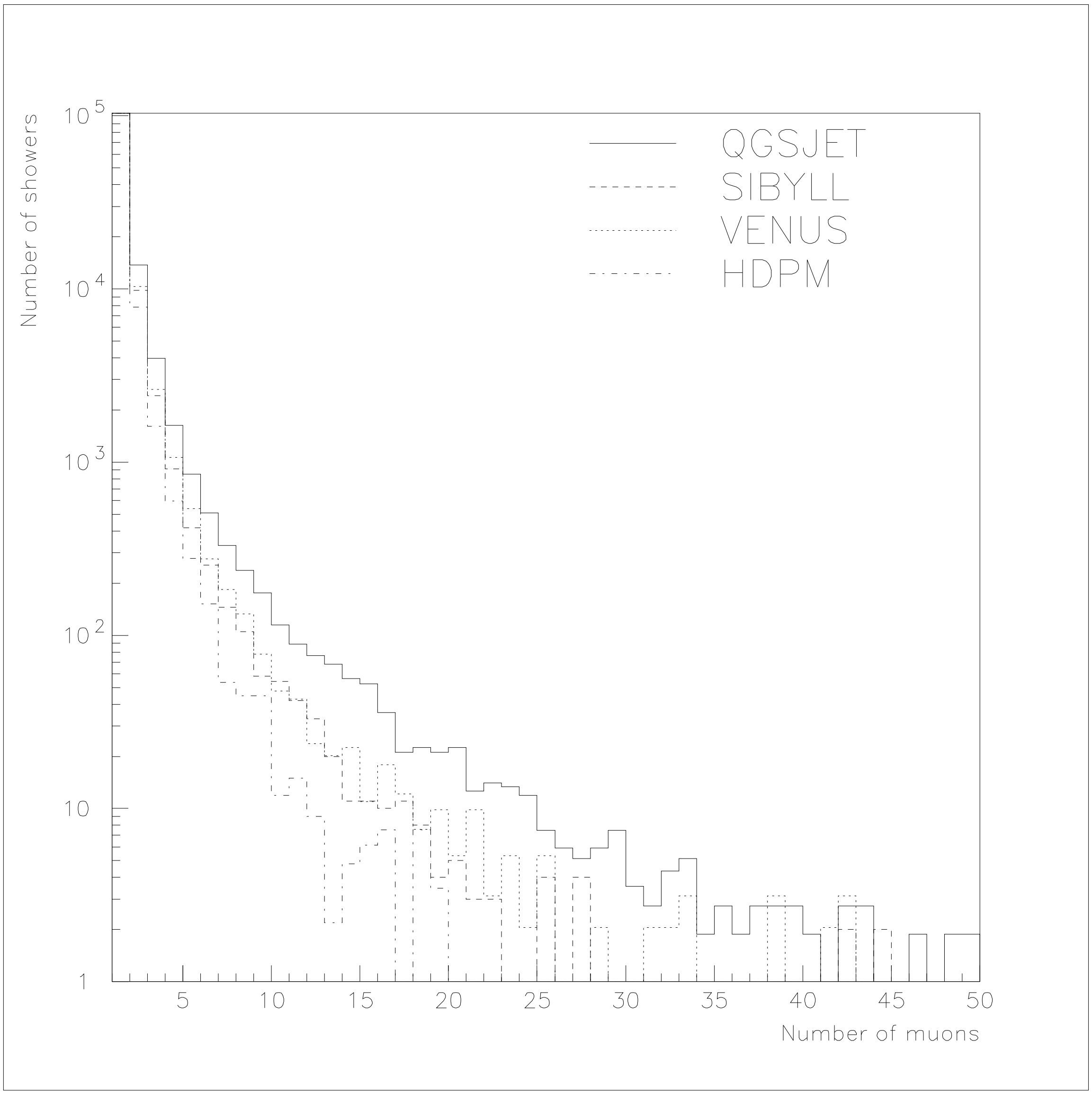
model	QGSJET	SIBYLL	VENUS	HDPM
γ_μ	2.733 ± 0.006	2.763 ± 0.011	2.736 ± 0.013	2.74 ± 0.02
$\gamma_{\nu(e)}$	2.936 ± 0.074	2.74 ± 0.08	2.80 ± 0.28	2.64 ± 0.70
$\gamma_{\nu(\mu)}$	2.698 ± 0.011	2.768 ± 0.023	2.739 ± 0.022	2.77 ± 0.04
μ multiplicity	1.769 ± 1.163	1.718 ± 0.963	1.788 ± 1.223	1.744 ± 1.073
e multiplicity	46730 ± 18740	26580 ± 16970	26060 ± 17110	52650 ± 19000
altitude, km	24.410 ± 8.944	23.990 ± 8.975	24.490 ± 8.966	23.780 ± 9.070
γ_μ, H only	2.772 ± 0.008	2.811 ± 0.013	2.783 ± 0.017	2.757 ± 0.024
γ_μ, He only	2.649 ± 0.011	2.669 ± 0.021	2.668 ± 0.023	2.74 ± 0.04

Experimental and theoretical values:

	theoretical values	experimental values
γ_μ	2.6851 ± 0.0017	2.78 ± 0.07 (Frejus) 2.78 ± 0.05 (LVD) 2.76 ± 0.05 (MACRO)
γ_μ, H only	2.758 ± 0.003 (2.76)	
γ_μ, He only	2.632 ± 0.003 (2.63)	
$\gamma_{\nu(\mu)}$		$2.66 \pm 0.05(stat) \pm 0.03(syst)$ (Frejus Coll., 1995)



The muon response for all primaries and $E_\mu \geq 1.2$ TeV.



Multiplicity of muons.