Simulation of Cosmic Ray Muon Flux at Shallow Depths Underground

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Abstract

Geant4 has been used to estimate the rate, energy spectrum and angular distribution of cosmic ray muons at underground depths between 300 and 1000 m.w.e. The results agree well with those from the MUSIC program when the same surface spectrum is used. Care has been taken to use a parameterization of the surface spectrum which agrees well with data for the relevant energies.

1 Goals

Knowledge of the underground cosmic ray muon flux is important for reactor experiments studying $\sin^2 2\theta_{13}$ for two main reasons. First, neutrons produced by cosmic ray muons in the rock surrounding the detector and in the scintillator itself are a source of background events. Second, the experiment would likely use cosmic ray muons passing through the detector for calibration purposes.

The sites being considered for such an experiment have detectors at depths between 300 and 1000 meters water equivalent. There are some measurements of the flux from vertical muons at such shallow depths, but to our knowledge, the only experiment to have measured the integrated muon flux at a shallow depth is CHOOZ [1]. In addition, some work has been done simulating the muon flux underground using the MUSIC [2] program.

Our goal in this work was to write a simple simulation in Geant4 which would give us another estimate of the muon flux at the depths of interest. As a second step the muon-induced neutron fluxes could be estimated. The muon fluxes obtained have been compared to results from the MUSIC simulation and to existing experimental results.

2 The Simulation

The simulation was written in Geant4, version 6.1 [3]. The geometry consisted of a layer of standard rock ($A = 22$, $Z = 11$, $\rho = 2.5$ g/cm^3) of a certain depth. Muons were generated over a small area at the surface of the rock layer, then were propagated through the rock. The flux was calculated by finding the ratio between the number of muons that reach a certain depth and the number of muons that were generated at the surface and multiplying by the integrated surface flux. To provide comparisons, we performed simulations with four different depths: 300, 500, 700, and 1000 meters water equivalent of rock.

The energy and zenith angle of the muons at the surface were generated from sea level muon flux distributions as discussed in detail in the next section.

3 Sea Level Muon Spectrum

An important aspect of finding the muon flux underground is knowing the muon flux spectrum as a function of energy and zenith angle at sea level. As shown in the second column of Table 1, for the depths we are considering, muons of energy around 100 to 500 GeV are most likely to be seen underground, so we need a spectrum that represents muons of these energies accurately.

A common form of the cosmic ray muon spectrum at sea level is given by Gaisser [4]

$$\frac{\mathrm{dN}}{\mathrm{dA\ dE\ d\Omega}} = \frac{0.14\ \mathrm{E}^{-2.7}}{\mathrm{cm^2\ sec\ sr\ GeV}} \left\{ \frac{1}{1 + \frac{1.1\mathrm{E}\cos\theta}{115\mathrm{GeV}}} + \frac{0.054}{1 + \frac{1.1\mathrm{E}\cos\theta}{850\mathrm{GeV}}} \right\}. \tag{1}$$

Figures 1 and 2 show comparisons of the Gaisser spectrum to data at zenith angles of 0° and 75° respectively. It is apparent that the Gaisser spectrum does not match the available data below 200 to 400 GeV, depending on zenith angle. Gaisser has noted that this is to be expected.

For vertical muons, or $\cos\theta = 1.0$, compilations and parameterizations of experimental results have been done by Bugaev [6] and Hebbeker and Timmermans [7]. These parameterizations are valid (compared to data) down to energies of about 10 GeV. They are compared to the data points in Figure 1; they clearly match the data better at low energies than the Gaisser spectrum.

For muons at 75° zenith angle, or $\cos\theta = 0.26$, Kiel-Desy [9] has a parameterization based on measurements obtained with an air gap magnetic spectrometer. Kellogg et al. [10] also performed a measurement with a magnetized iron spectrometer. Data points from both of these experiments are shown in Figure 2.

There are few measurements of the sea level muon flux at zenith angles between 0° and 75°. Kellogg et al. performed a measurement at 30° [10]. Figure 3 shows plots of the vertical muon flux from Hebbeker, the flux at 30 degrees from Kellogg, and the 75 degree muon flux from Kiel as a function of $\cos\theta$. The L3+C collaboration

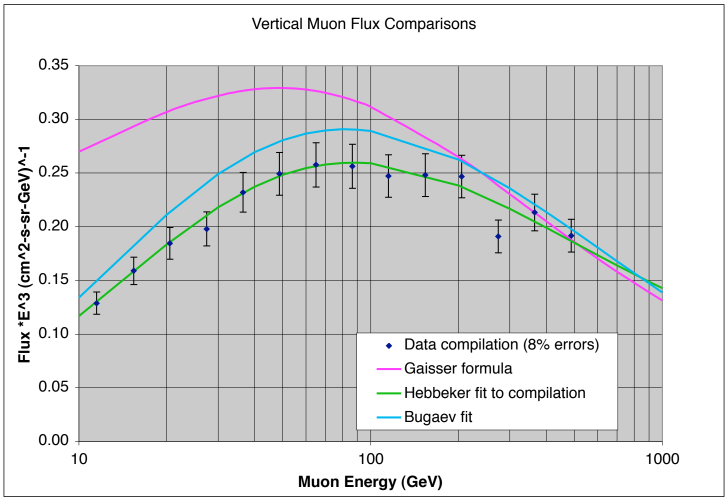

Figure 1: Comparison of several parameterizations with the measured vertical muon spectrum, as compiled by Hebbeker. The uniform error of 8% applied to all points is slightly larger than the point-by-point errors of the compilation.

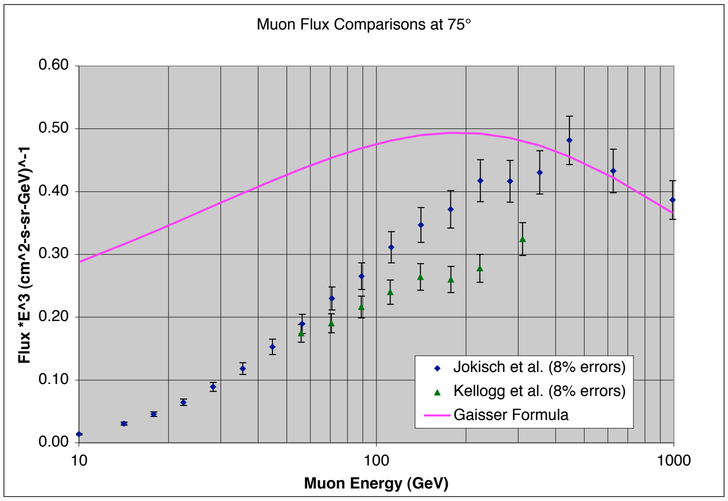

Figure 2: Comparison of measurements of the muon flux at $\cos\theta = 0.26$ with the Gaisser parameterization.

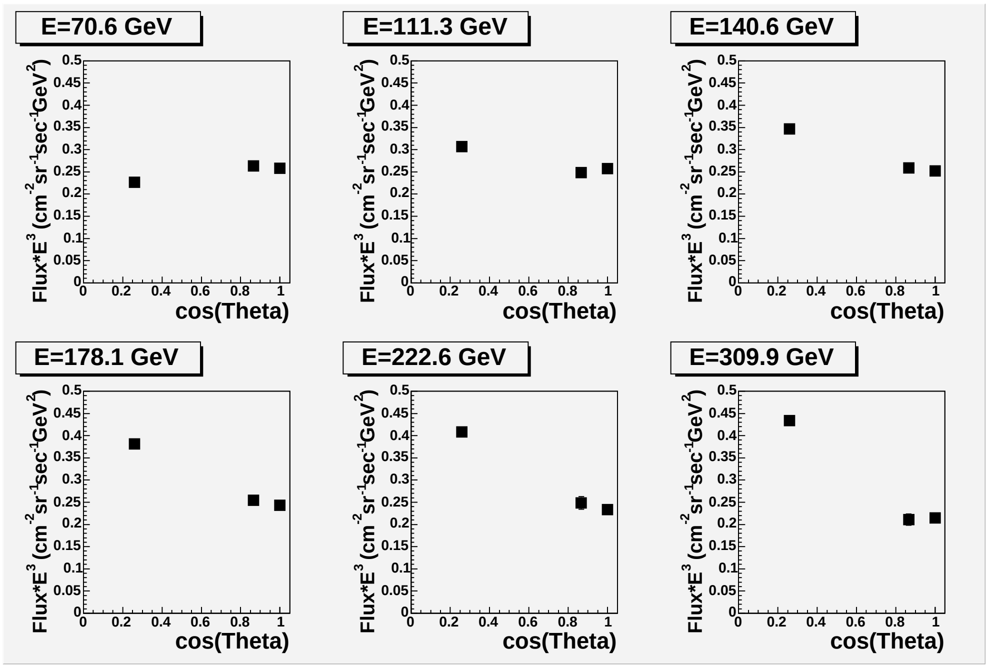

Figure 3: Comparison of muon fluxes at different zenith angles at energies from reference [10]. Points at $\cos\theta = 0.26$ are from ref. [9], those at $\cos\theta = 0.87$ from ref. [10], and those at $\cos\theta = 1.0$ from ref. [7].

has presented some similar plots for angles between $\cos\theta = 0.6$ and $\cos\theta = 1.0$ and energies between 40 and 1000 GeV in conference reports [11].

Based on Figure 3 and reference [11], we believe a reasonable way of combining the measurements at $\cos\theta = 0$ and $\cos\theta = 0.26$ is a linear interpolation in $\cos\theta$ for a given energy. Thus the sea level flux at a given energy is taken to be

$$\frac{\mathrm{dN}}{\mathrm{dE}\ \mathrm{d}\Omega} = \frac{\mathrm{dN}^{1.0}}{\mathrm{dE}} - \frac{\frac{\mathrm{dN}^{1.0}}{\mathrm{dE}} - \frac{\mathrm{dN}^{0.26}}{\mathrm{dE}}}{1 - 0.26}(1 - \cos\theta). \tag{2}$$

In the work presented here, two different sea level muon spectra are used. The Gaisser spectrum is used for easy comparison with the MUSIC simulation and other work. We also use the spectrum that we think gives the most accurate results, from Eq. 2, which will be referred to as the Hebbeker/Kiel spectrum.

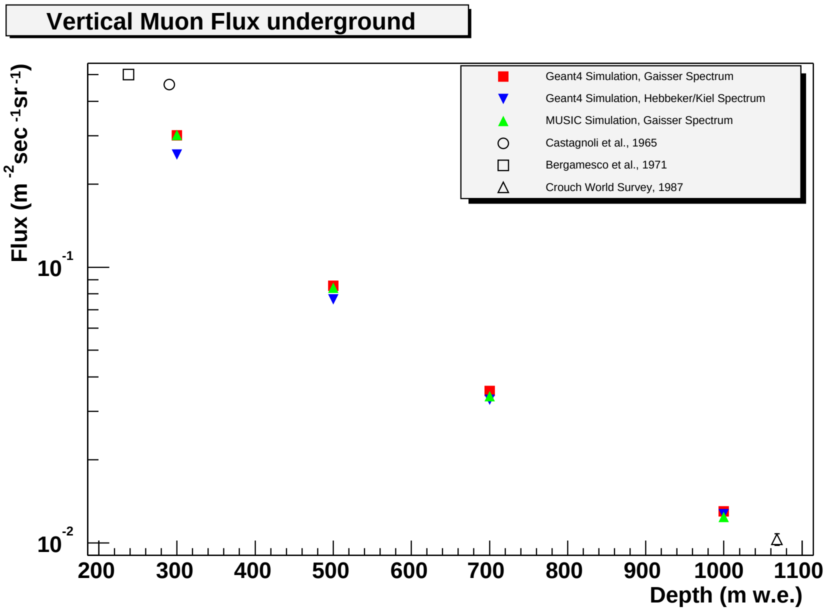

Figure 4: Vertical muon flux underground. Filled points show estimates using MUSIC and Geant4 simulations, and empty points represent measurements.

4 Results

The first step in our work was to generate only vertical muons and find the flux underground. The results are shown in Fig. 4 along with the predictions from the MUSIC simulation and some data points from early experiments ([12] [13] [14]). Using the Gaisser spectrum, the MUSIC and Geant4 flux calculations are in good agreement. Using the Hebbeker/Kiel spectrum gives a result which is 18% lower at 300 m.w.e. We believe this is a more accurate estimate for the muon energies involved.

Next we simulated fluxes over all zenith angles. The results for this are shown in Fig. 5. Here the only data point is from CHOOZ [1]. The MUSIC and Geant4 simulations using the Gaisser input spectrum differ by less than 8% over all depths. This gives confidence in the simulation code.

Using the Hebbeker/Kiel measurement of the input spectrum results in a flux at 300 m.w.e. which is 26% lower than the estimate based on the Gaisser spectrum. At 700 and 1000 m.w.e., where more energetic surface muons dominate, the two estimates agree. Our estimate of the flux at 300 m.w.e. using the Hebbeker/Kiel spectrum agrees with the number from CHOOZ to about 15%. (It should be noted that the CHOOZ experiment did not have a flat overburden, so the flux would not be expected to match our simulation exactly.)

Figure 6 shows the underground muon energy spectrum at four depths while Figure 7 shows their angular distribution. As can be seen from Fig. 7 the muons become more vertical with increasing depth but the effect is very small for the range

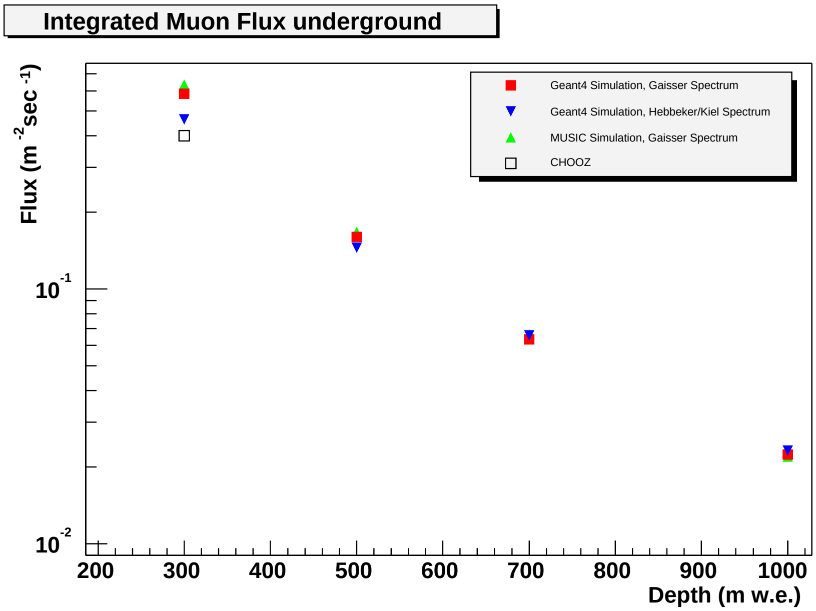

Figure 5: Muon flux underground over all solid angles. Estimates from simulations (filled points) and measurements (empty points) are plotted.

of depths considered.

Table 1 summarizes the expected flux at each depth and gives the counting rate of muons through in a 6.5-meter-diameter spherical detector. The Hebbeker-Kiel spectrum was used to arrive at these numbers. These estimates will be useful in weighing the advantages of a deep detector. The next step will be to use these muon fluxes with Geant4 to obtain estimates of the background from neutrons produced by cosmic ray muons.

Depth (m. w.e.)	Mean energy loss from surface (GeV)	Flux (/m^2/sec)	Mean energy (GeV)	Counting rate (Hz)
300	110	0.463	60.9	15.4
500	202	0.145	91.2	4.8
700	307	0.0657	120	2.2
1000	474	0.0232	154	0.8

Table 1: Result of Geant4 simulation at four depths underground. The counting rate listed corresponds to a 6.5-m-diameter spherical detector.

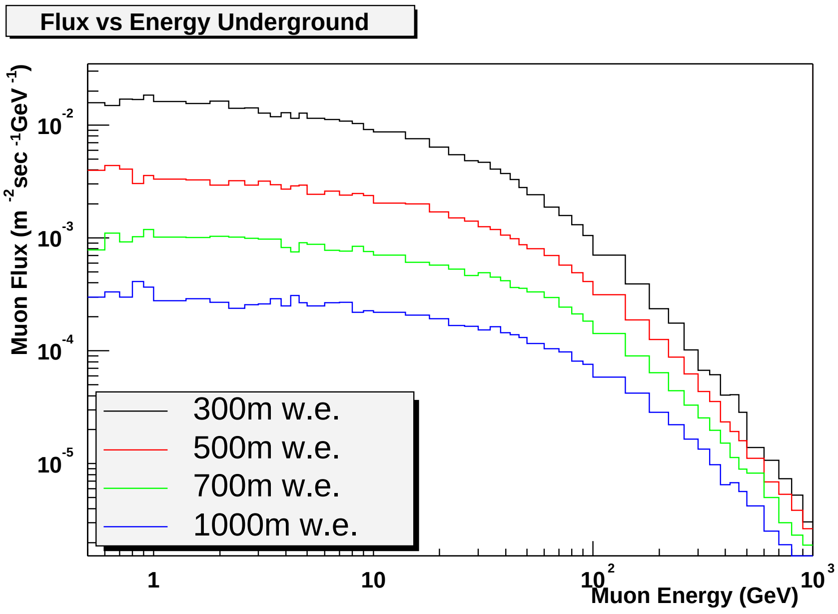

Figure 6: Energy spectrum of underground muons at four depths.

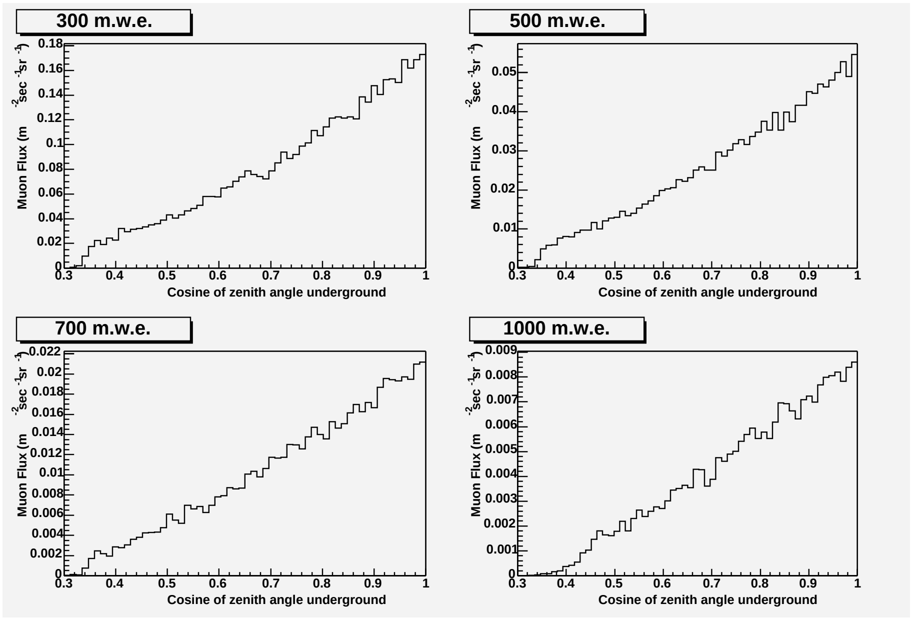

Figure 7: Angular distribution of underground muons at four depths.

References

[1] M. Apollonio *et al.*, Eur. Phys. J. **C27**, 331-374 (2003).

[2] V.A. Kudryavtsev, N.J.C. Spooner, J.E. McMillan, Nucl. Instrum. Meth. **A505** 683-687 (2003).

[3] `http://geant4.web.cern.ch/geant4`

[4] T.K. Gaisser, Cosmic Rays and Particle Physics, Cambridge University Press, 1990.

[5] M. Aglietta *et al.* Phys. Rev. D **58**, 092005 (1998).

[6] E.V. Bugaev *et al.* hep-ph/9803488

[7] T. Hebbeker, C. Timmermans, Astropart. Phys. **18**, 107-127 (2002).

[8] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[9] H. Jokisch *et al.*, Phys. Rev. D **19**, 1368 (1979).

[10] R.G. Kellogg, H. Kasha, R.C. Larsen, Phys. Rev. D, **17**, 98 (1978).

[11] M. Unger in *Proceedings of the 28th International Cosmic Ray Conference*, Tsukuba, Japan, 2003 or `http://l3cosmics.cern.ch:8000/l3c_www/paper/presentation/mu_icrc_2003.ps.gz`

[12] C. Castagnoli, A. DeMarco, A. Longhettho, and P. Penego, Nuovo Cimento **35**, 969 (1965).

[13] L. Bergamasco, B. D'Ettore Piazzoli, and P. Picchi, Nuovo Cimento **4 B**, 59 (1971).

[14] M. V. Crouch, in *Proceedings of the 20th International Cosmic Ray Conference*, Vol **6**, p. 165 (1987).