Atmospheric muon and neutrino fluxes and their relation to the Cosmic Ray mass composition at the knee

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DOI: 10.7529/ICRC2011/V01/1284

Abstract: The observation of astrophysical neutrinos by current high energy neutrino observatories, such as IceCube or ANTARES requires detailed understanding of the atmospheric neutrino background. This inevitable background is produced by extensive air showers and, as a consequence, its calculation requires detailed modeling of Cosmic-Ray energy spectra from TeV to EeV energies and beyond. The knee is the most prominent feature in this energy range. To simulate the absolute atmospheric neutrino and muon flux spectrum and to study their sensitivity to the mass composition in the knee energy range, we have parametrized the primary CR energy spectra of the H, He, C, Si, and Fe components based on direct experiments and on KASCADE unfolding results. The simulations were performed with CORSIKA employing different hadronic interaction models. We present the results, compare the simulated spectra with the ones measured by current neutrino telescopes, and discuss the potential of observing the knee in atmospheric muon and neutrino spectra and of inferring information about the mass composition of cosmic rays in the knee energy range.

Keywords: Cosmic-Ray spectrum, Neutrino telescopes, Atmospheric neutrino flux, Muon flux

1 Introduction

The primary goal of High-Energy (HE) neutrino telescopes is the detection of neutrinos sources. Neutrino fluxes of extraterrestrial origin have to be detected above the level of an overwhelming background of atmospheric neutrinos produced by Cosmic-Ray (CR) showers in the Earth's atmosphere. The flux of atmospheric neutrinos and muons are used to calibrate neutrino telescopes. A detailed modeling of the primary CR spectrum and their mass composition up to the Ultra-High Energy range (UHE, E$>10^{18}$ eV) is, therefore, mandatory for reducing calibration uncertainties. The knee region ($\simeq 10^{15}$-10^{17} eV) of the CR spectrum is the range yielding the main contribution to the μ/ν atmospheric fluxes above 100 GeV. While below the knee the mass composition is relatively well known from direct measurements performed with spectrometers on board of balloons and satellites, for E$>10^{15}$ eV only indirect measurements are available. Models of the extrapolation of the elemental spectra in the knee region are used instead.

A widely used description in the energy range between 10 GeV up to $\sim$100 PeV is the Poly-Gonato model [1]. The model parameters are constrained by direct measurements only up to $\simeq 10^6$ GeV.

In this work we aim to build a parameterisation of the CR spectra that includes the information about the mass group fluxes in the knee region coming from KASCADE indirect measurements. The model thus obtained will be used to estimate the atmospheric neutrino and muon fluxes above 100 GeV.

2 Modeling Cosmic-Ray spectra by elemental groups

The KASCADE array provides information about the mass composition of CRs around the knee. From the ground measurements of the muonic and electromagnetic components of air showers, five elemental groups, representing H, He, C, Si, and Fe are obtained through an unfolding procedure [2]. The unfolded spectra depend on the hadronic interaction model adopted to simulate air showers used in the analysis procedure. This produces two different sets of KASCADE spectra, respectively for the QGSJET [3] (shown in Fig. 1) and for the SIBYLL [4] model. We aim to fit the KASCADE spectra together with the direct measurement available at lower energy [5].

2.1 Model and parameterisation

The parameterisation used follows closely Hörandel's Poly-Gonato (multi-knee) model [1]. Poly-Gonato describes each element spectrum as a broken power law (smoothed) where the break point is the knee. A rigidity dependent knee energy is assumed and the same change of spectral index at the knee is used for all components. The

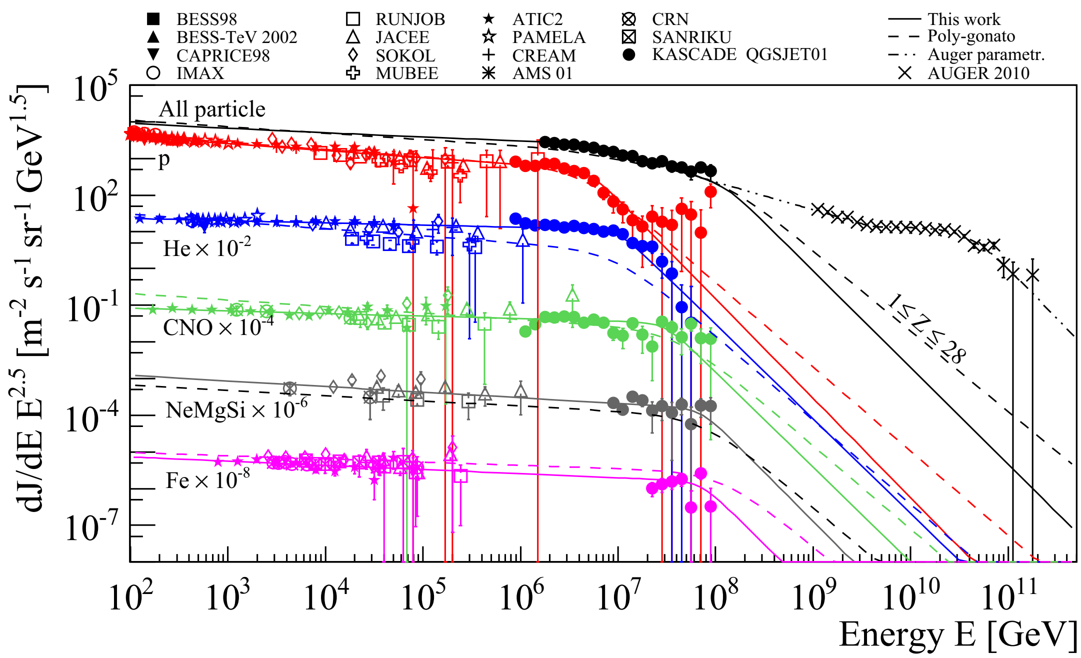

Figure 1: The spectra resulting form the QGSJET mass group parameterisation (continuous lines, see text) and the Poly-Gonato model prediction (dashed) are shown together with direct measurements (from [5]) and KASCADE data obtained with an unfolding procedure of the measured muonic and electromagnetic component [2].

spectral index below the knee is parameterised with a non-linear function of the nuclear charge Z.
We will describe the flux for each element as:

$$\frac{\mathrm{d}\Phi_Z}{\mathrm{dE}}(\mathrm{E}) = \Phi_Z^0 \left(\frac{\mathrm{E}}{1\,\mathrm{PeV}}\right)^{-\gamma_Z} \left[1+\left(\frac{\mathrm{E}}{\mathrm{Z\,E_K}}\right)^{\epsilon}\right]^{-\Delta\gamma/\epsilon}, \quad (1)$$

where Φ_Z^0 is the absolute normalization at $\mathrm{E}=1\,\mathrm{PeV}$, γ_Z the spectral index below the knee of the component with charge Z, $\mathrm{E_K}$ is the knee energy for proton primaries (a rigidity dependent knee is assumed $\mathrm{E_{knee}(Z)=Z\,E_K}$), ϵ is a smoothing parameter for the knee transition and $\Delta\gamma$ the difference between the spectral indexes above and below the knee. $\Delta\gamma$ and ϵ are assumed to be universal for all mass components.

The fit to the data (KASCADE and direct measurements) is a χ^2 minimization performed for each of the two interaction models with the following procedure:

- All five mass groups are fitted simultaneously. The spectral indexes below the knee are free parameters.
- Data points compatible with zero flux in the lowest KASCADE energy range have been excluded from the fit (and are not shown in Fig. 1), being in contradiction with the hypothesis of a single power law spectrum extending from 100 GeV up to the knee.

The values of the parameters obtained from the fit procedure are listed in Tab.1 for both hadronic interaction models. The best fit spectra for the QGSJET case are shown in Fig. 1 as continuous lines. The main difference to the Poly-Gonato parametrization (dashed lines, obtained as sum of the Z bands: 1 for H, 2-5 for He, 6-13 for C, 14-22 for Si, 23-28 for Fe) are the steeper spectral indices above the knee for all components, and a significantly higher contribution from the He- and NeMgSi- groups in the PeV range.

2.2 UHE component

To account for the CR flux up to the multi EeV region, we have used the spectrum measured with the Pierre Auger Observatory above 10^9 GeV (Fig. 1, crosses). The fit to the data given in [6] (dash dotted line in Fig. 1) is extrapolated downward in energy up to 100 PeV. The difference between the extrapolation and the sum of mass group spectra is attributed to a pure proton component.

3 Atmospheric muons and neutrinos

To derive the fluxes of atmospheric muons and neutrinos, a library of air shower simulations was produced, using the CORSIKA [7] code, for the five primaries representative of the mass groups, and both QGSJET and SIBYLL models (GEISHA was adopted for the description of low energy interactions for consistency with the KASCADE unfolding analysis). Details of the observation height, atmosphere and geomagnetic field were set to match the ones at the IceCube site (Antarctica).

Parameter	Unit	QGSJET	SIBYLL
E_K	PeV	$5.0^{+0.8}_{-0.6}$	$4.7^{+3.8}_{-1.4}$
$\Delta\gamma$	-	$2.5^{+0.6}_{-0.4}$	$3.4^{+2.8}_{-1.0}$
ϵ	-	$4.7^{+1.5}_{-0.9}$	$1.8^{+0.2}_{-0.2}$
γ_H	-	$2.691^{+0.002}_{-0.002}$	$2.703^{+0.003}_{-0.003}$
γ_{He}		$2.561^{+0.002}_{-0.002}$	$2.600^{+0.002}_{-0.002}$
γ_C		$2.571^{+0.003}_{-0.003}$	$2.487^{+0.002}_{-0.002}$
γ_{Si}		$2.653^{+0.023}_{-0.022}$	$2.711^{+0.015}_{-0.015}$
γ_{Fe}		$2.614^{+0.010}_{-0.010}$	$2.513^{+0.004}_{-0.004}$
Φ^0_H	10^{-13} $\mathrm{GeV^{-1}\,m^{-2}\,s^{-1}sr^{-1}}$	$6.78^{+0.14}_{-0.13}$	$6.15^{+0.16}_{-0.16}$
Φ^0_{He}		$13.26^{+0.20}_{-0.19}$	$9.57^{+0.19}_{-0.18}$
Φ^0_C		$4.29^{+0.12}_{-0.12}$	$8.58^{+0.16}_{-0.16}$
Φ^0_{Si}		$2.98^{+0.22}_{-0.22}$	$2.96^{+0.13}_{-0.13}$
Φ^0_{Fe}		$2.55^{+0.17}_{-0.17}$	$4.92^{+0.11}_{-0.11}$
χ^2/Ndof	-	5.0	5.3

Table 1: Parameters obtained from the simultaneous fit of the elemental group spectra from direct measurements and the KASCADE experiment (with the unfolding procedure using respectively the QGSJET, left, or the SIBYLL model, right). The definitions of the parameters and of the reduced χ^2 of the fit are given in Eq. (1) and in the text.

3.1 Simulation set

In the library of Monte Carlo simulations produced, the distribution of input primaries extends from 0° to 89.9° in zenith angle, and from 10^2 to 10^{12} GeV in energy following a piecewise E^{-1} spectrum. The number of showers in each half energy decade was adjusted to minimize statistical uncertainties in the output flux calculations. For energies above 10^8 GeV a thinning [8] algorithm was used, with thinning level 10^{-6} and weight limitation for hadrons and muons (E/GeV)$\times 10^{-8}$ (E being the energy of the primary). Neutrino and muon fluxes are obtained through a reweighting of the generated primary spectrum to the desired input one, and accounting for additional geometry and thinning weighting factors. With the simulation strategy adopted, it is easily possible to use the same set of simulations to calculate the flux predicted for any arbitrary model of the CR spectrum for a given secondary particle.

3.2 Neutrino and muon fluxes

Using the parameterisations derived in Sec. 2, we have calculated the total fluxes for atmospheric muons and neutrinos and the contributions from different mass components at ground level. Results are shown in Fig. 2 for both interaction models. Fluxes are multiplied by $E^{2.5}$ and $E^{3.5}$ to make the structures in the almost power law spectrum and the differences between model predictions more visible. The IceCube unfolded atmospheric neutrino measurements [9] are superimposed for comparison.

Fluxes were also calculated using the Poly-Gonato model. To have a consistent comparison we have used, in this case, the Poly-Gonato spectra up to $Z = 28$, and the same procedure described in Par. 2.2 to extend the Poly-Gonato spectrum up to the UHE range with an UHE component of proton primaries.

Since in the Poly-Gonato case the CR spectrum used is the same for the QGSJET and SIBYLL model (the difference being in the simulation set only), the discrepancy between the two calculated fluxes can be attributed to SIBYLL yielding a higher flux at lower energies than QGSJET for both muons and neutrinos. The trend has an inversion at $\simeq$ 100 TeV. Interestingly the parameterisations of QGSJET and SIBYLL unfolded KASCADE spectra have an almost identical difference between them as in the Poly-Gonato case, despite the different mass composition at the knee (see Tab.1). This result suggests that the fluxes of muons and neutrinos are more affected by the details of the shape of the all particle spectrum than by the actual composition at the knee. For the same set of simulations (e.g. QGSJET), the parameterisation derived in this work gives predictions of fluxes for both muons and neutrinos very close to the Poly-Gonato case in the PeV range. This again suggests that the fluxes are not very sensitive to the mass composition.

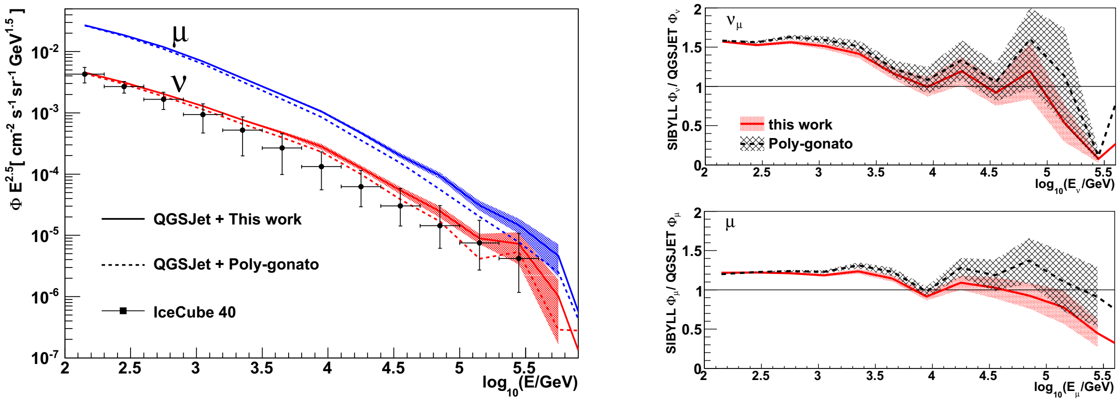

Figure 2: Fluxes, zenith averaged, of muon neutrinos and muons (left) obtained from CORSIKA simulations done with QGSJET, using Poly-Gonato spectra and the parameterisation (see text) for the description of the primary CR spectra. The atmospheric muon neutrino flux measured by IceCube is shown for comparison. The ratio of the SIBYLL to the QGSJET fluxes is shown on the right. Uncertainty bands for model predictions refer to simulation statistics only (including the reweighting).

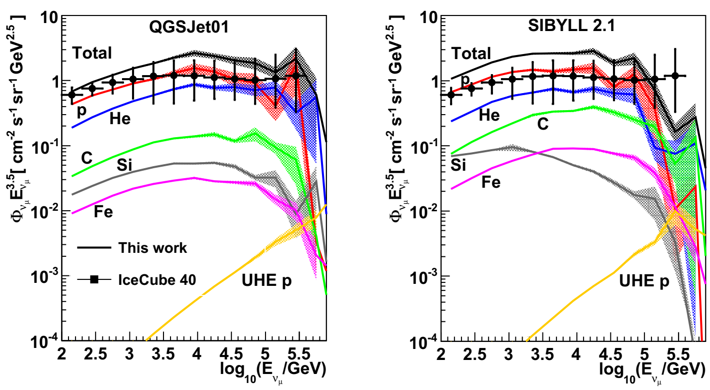

Figure 3: Contributions of the different elemental groups and the UHE component to the flux of muon neutrinos, using the parameterisation of CR spectra derived in this work, with, respectively, the QGSJET (left) and the SIBYLL (right) hadronic interaction model. Uncertainties have been calculated as in Fig. 2

4 Acknowledgements

This study has been partially funded by the BMBF.
C.B. wishes to thank W.G. Morozzo for useful discussions.

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