



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

DANIEL BINDIG, CARLA BLEVE, KARL-HEINZ KAMPERT

University of Wuppertal, Gaußstrasse 20, D-42119 Wuppertal, Germany

bindig@physik.uni-wuppertal.de, bleve@physik.uni-wuppertal.de, kampert@uni-wuppertal.de

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 and 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 Rays 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 ~ 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 group

The KASCADE array provides informations about the mass composition of CRs around the knee. From the measurements at ground of the muonic and electromagnetic components of air showers, five elemental group spectra (H, He, C, Si, 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 J. 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

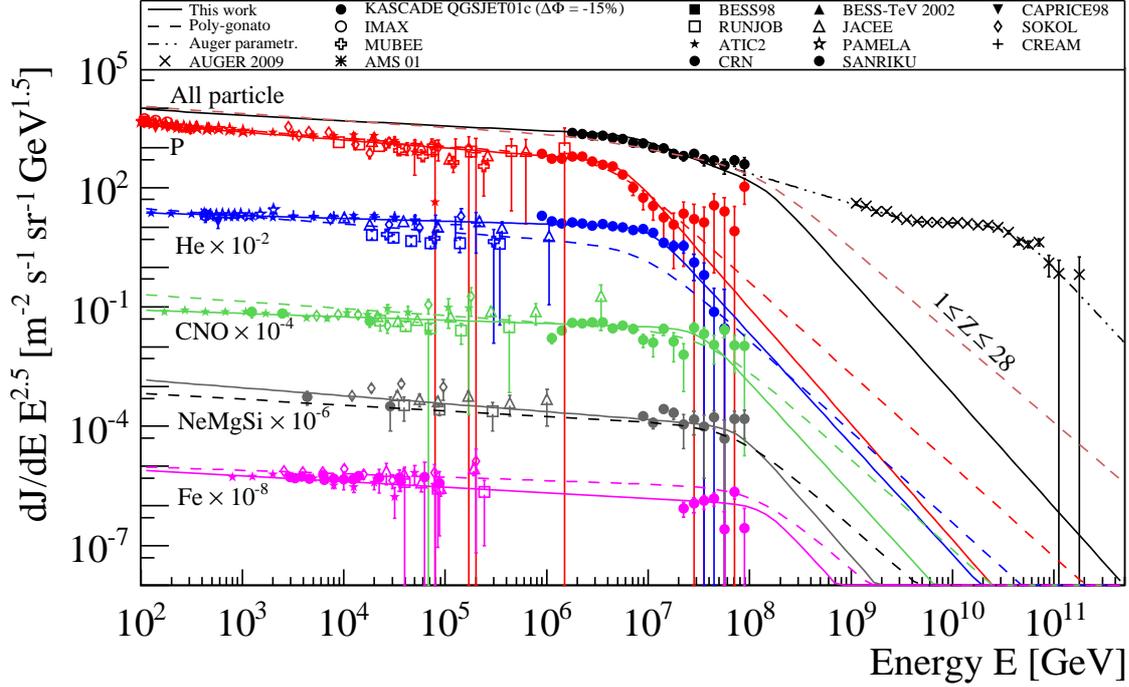


Figure 1: The spectra resulting from the QGSJET mass group parameterisation (continuous lines, see text) and the Poly-Gonato model prediction (dashed) are shown together with direct measurements (from [5]) and KASCADE data obtained with an unfolding procedure of the measured muonic and electromagnetic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

$$\frac{d\Phi_Z}{dE}(E) = \Phi_Z^0 \left(\frac{E}{10^6 \text{ GeV}} \right)^{-\gamma_Z} \left[1 + \left(\frac{E}{Z E_K} \right)^\epsilon \right]^{-\Delta\gamma/\epsilon}, \quad (1)$$

where Φ_Z^0 is the absolute normalization at $E = 1 \text{ PeV}$, γ_Z the spectral index below the knee of the component with charge Z , E_K is the knee energy for proton primaries (a rigidity dependent knee is assumed $E_{\text{knee}}(Z) = Z E_K$), 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:

- The KASCADE fluxes are reduced uniformly by a factor $\Delta\Phi = -15\%$ to guarantee consistency with the all particle fluxes measured at lower energy. The shift is within the systematic uncertainty of the unfolded spectra.
- Some Si and Fe 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.

- All five mass groups are fitted simultaneously. The spectral indexes below the knee are free parameters. The absolute normalizations of the mass groups are bounded to sum up to the best fit of the KASCADE all particle spectrum at 1 PeV. The χ^2 is a weighted sum of the χ^2 of individual elements, the weight being the percentage contribution to the total flux at 1 PeV as determined in the previous iteration of the fit procedure.

The values of the parameters obtained from the fit procedure are listed in Tab.1 for both hadronic interaction model. The best fit spectra for the QGSJET case are shown in Fig. 1 as continuous lines. The main difference with the Poly-Gonato predictions (dashed lines, obtained as sum of the Z bands: 1 for H, 2-5 for He, 6-13 for C, 14-22 for Si, 23-18 for Fe) are the steeper spectral index above the knee for all components, and a significantly higher contribution from He and C 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 (extragalactic) proton component.

Parameter	Unit	QGSJET	SIBYLL
E_K	GeV	$(5.4 \pm 1.1) \times 10^6$	$(3.7 \pm 1.6) \times 10^6$
$\Delta\gamma$	-	2.7 ± 0.7	2.9 ± 1.3
ϵ	-	3.8 ± 1.0	2.0 ± 0.4
γ_H		2.702 ± 0.003	2.723 ± 0.004
γ_{He}		2.571 ± 0.002	2.620 ± 0.003
γ_C	-	2.584 ± 0.006	2.508 ± 0.003
γ_{Si}		2.70 ± 0.06	2.80 ± 0.06
γ_{Fe}		2.64 ± 0.02	2.54 ± 0.06
Φ_H^0		6.21 ± 0.17	5.19 ± 0.19
Φ_{He}^0		12.14 ± 0.18	8.14 ± 0.17
Φ_C^0	10^{-13}	3.84 ± 0.19	7.21 ± 0.16
Φ_{Si}^0	$\text{GeV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$	2.3 ± 0.3	1.6 ± 0.2
Φ_{Fe}^0		2.1	4.0
χ^2/Ndof	-	1.3	1.2

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 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). Details of the observation height, atmosphere and geomagnetic field were set to match the ones at the IceCube site (Antarctica).

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 $(E/\text{GeV}) \times 10^{-8}$ (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 possible to easily use the same set of simulations to calculate for a given secondary particle, the flux predicted for any arbitrary model of the CR spectrum.

3.2 Neutrino and muon fluxes

Using the CR spectrum parameterisations derived in Sec. 2, we have calculated the fluxes for atmospheric muons and neutrinos at ground level. Results are shown in the two bottom panels of Fig. 2 for both interaction models. Fluxes

are multiplied by $E^{3.5}$ 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. The agreement to the data is remarkably good.

In the upper panel the same fluxes are 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 extragalactic 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 (heavier for SIBYLL than for QGSJET, 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. This seems to reflect the fact that the all particle spectra are in excellent agreement in the knee region, and again suggests that the flux are not very sensitive to the mass composition.

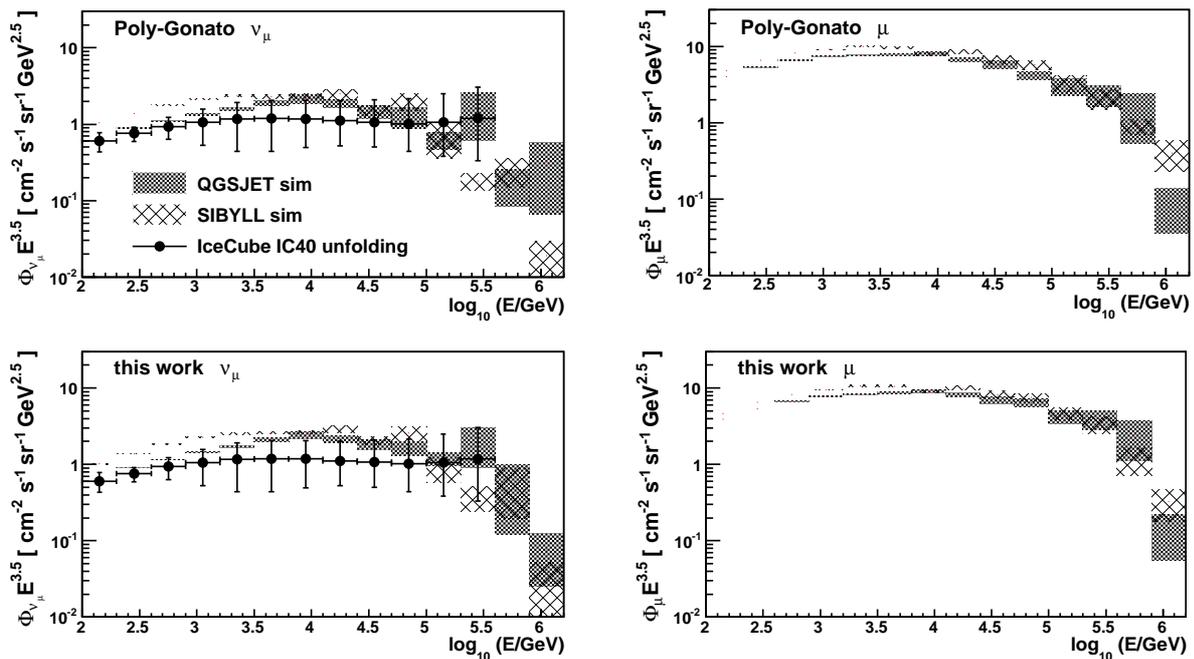


Figure 2: Fluxes, zenith averaged, of muon neutrinos (left plots) and muons (right plots) obtained from CORSIKA simulations done with QGSJET and SIBYLL high-energy interaction models, using respectively the Poly-Gonato spectra (top) and the parameterisation presented in the text (bottom) for the description of the primary cosmic ray spectra. The atmospheric neutrino flux measured with the IceCube detector is shown for comparison. Uncertainties bands for model predictions depend on simulation statistics only (including the reweighting). The uncertainty on the CR spectra parameterisation is not accounted for.

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