



## Calculation of the atmospheric muon flux motivated by the ATIC-2 experiment

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**Abstract:** We calculate the cosmic ray muon flux at ground level using directly the primary cosmic ray spectrum and composition measured in the ATIC-2 balloon experiment. In order to extend the calculations to more high energies, up to 100 TeV, we use the data of the GAMMA experiment as well as Zatsepin and Sokolskaya model. This model supported by the ATIC-2 data comprises contributions to the cosmic ray flux of three classes of astrophysical sources – the shocks from exploding stars, nova and supernova of different types. The muon flux calculation is based on the method for solution of atmospheric hadron cascade equations in which we take into account rising total inelastic cross-sections of hadron-nuclear interactions as well as non-power-law character of the primary cosmic ray spectrum. The calculated muon spectrum agrees well with measurements of L3+Cosmic and BESS-TeV, CAPRICE, Frejus, MACRO, LVD as well as other experiments.

### Introduction

The muons produced through the cosmic ray interactions with the Earth atmosphere provide the tool for indirect study of the primary cosmic ray (PCR) spectra. May comparison of the predicted and measured atmospheric muon (AM) flux serve as reliability trial for PCR data? The answer depends on the relationship between size of the PCR uncertainties and that of AM flux. To attempt answering the question we calculate the cosmic ray muon flux at the ground level using directly the data on PCR spectrum and composition measured in the ATIC-2 experiment [1].

In order to compare the predictions with the high-energy measurements of the AM flux we extend the calculations to more high energies, up to 100 TeV, using also the PCR spectrum data of the GAMMA experiment [2]. The PCR model by Zatsepin and Sokolskaya [3] supported by the ATIC-2 data was applied as the nice instrument to extrapolate median energy data to high energy one. This model comprises contributions to the cosmic ray flux of three classes of astrophysical sources like supernova and nova blast waves (shocks). The muon flux calculation is based on the method

to solve the atmospheric hadron cascade equations [4, 5] in which we take into account rising total inelastic cross-sections of hadron-nuclear interactions as well as non-power-law character of the primary cosmic ray spectrum. A high algorithm convergence of the method provides an operative way for the calculation of secondary cosmic ray fluxes, that allows one to test "on-the-fly" models of the primary spectra.

Hadron fluxes were computed with slightly revised Kimel and Mokhov parametrization (see [6, 4]) for nucleon and meson production cross sections which are close to the SIBYLL mini-jet model [7].

### Primary cosmic ray spectra

The balloon borne experiment ATIC (Advanced Thin Ionization Calorimeter) [1] designed for measurements of cosmic rays energy spectra with individual charge resolution from protons to iron enabled one to obtain PCR spectra in the wide energy interval 50 GeV – 200 TeV with high statistical assurance. The differential spectra of protons and helium nuclei obtained in the ATIC-2 experiment are shown in figure 1 along with a bulk of data from balloon, satellite and ground based experiments –

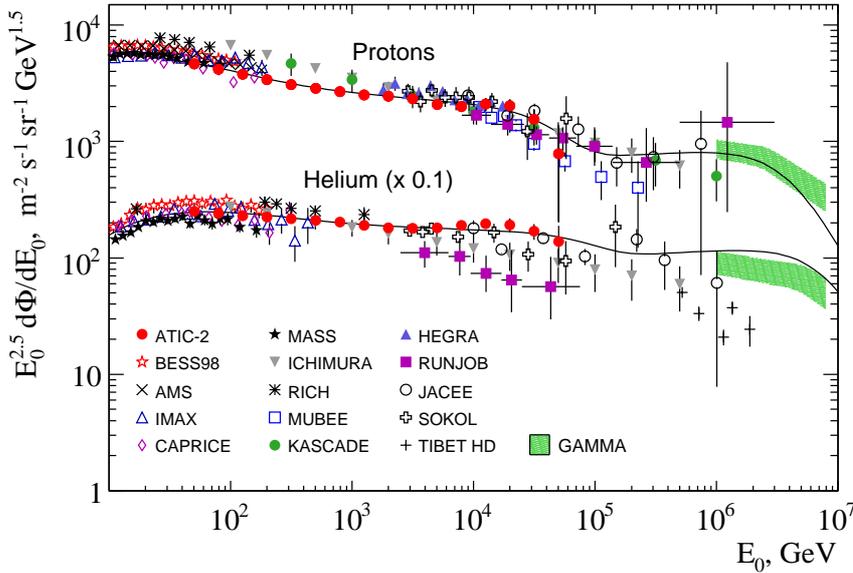


Figure 1: Primary proton and helium spectra, combining balloon, satellite and ground-based measurements. The solid curve presents Zatsepin and Sokolskaya model [3].  $E_0$  is the kinetic energy of the particle.

BESS [8], AMS [9], IMAX [10], CAPRICE [11], MASS [12], RICH [13], MUBEE [14], RUNJOB [15], JACEE [16], SOKOL [17], KASCADE SH [18], GAMMA [2], HEGRA [19], TIBET HD [20], ICHIMURA [21].

Proton and helium spectra measured in the ATIC-2 experiment have different slopes and differ from a simple power law. The ATIC-2 data are in agreement with the data of magnetic spectrometers (BESS, AMS, IMAX, CAPRICE, MASS) below 100 GeV. In the energy region  $1 < E < 10$  TeV the ATIC-2 data are consistent with the SOKOL measurements and with those of atmospheric Cherenkov light detector HEGRA. At energies above  $\sim 10$  TeV the spectra become steeper, and follow the data of emulsion chamber experiments MUBEE and JACEE, though the agreement is not so clear. The solid curves in figure 1 are to present the model suggested by Zatsepin and Sokolskaya (ZS) [3] that fits well the ATIC-2 experimental data and describe PCR spectra in the energy range  $10\text{--}10^7$  GeV. In order to extend our calculation to higher energies, the PCR spectra measured in the GAMMA [2] experiment was used. The energy spectra and elemental composition, obtained in the GAMMA experiment cover the  $10^3\text{--}10^5$  TeV range (shaded areas) and agree

with the corresponding extrapolations of known balloon and satellite data at the  $E \geq 10^3$  TeV. In the present calculation, a version of the spectra, reconstructed in the framework of 1, 2D combined analysis with the SIBYLL interaction model (see [2] for details), was utilized.

### Conventional atmospheric muons

Apart from evident sources of AM,  $\pi_{\mu 2}$  and  $K_{\mu 2}$  decays, we take into consideration three-particle semileptonic decays,  $K_{\mu 3}^{\pm}$ ,  $K_{\mu 3}^0$ . Also we take into account small fraction of the muon flux originated from decay chains  $K \rightarrow \pi \rightarrow \mu$  ( $K_S^0 \rightarrow \pi^+ + \pi^-$ ,  $K^{\pm} \rightarrow \pi^{\pm} + \pi^0$ ,  $K_L^0 \rightarrow \pi^{\pm} + \ell^{\mp} + \bar{\nu}_{\ell}(\nu_{\ell})$ ,  $\ell = e, \mu$ ). We do not consider here a conjectural prompt muon component of the flux (see e.g. [22, 23]). In figures 2, 3 presented are results of the calculation of the surface muon flux along with the data of muon experiments that comprise the direct measurements of CAPRICE [24], BESS-TeV [25], L3+Cosmic [26], Cosmo-ALEPH (see Ref. [27]), L3 and MASS (taken from [22]) as well as the data (converted to the surface) of underground experiments MSU [28], MACRO [29], LVD [30], Frejus [31], Baksan [32], Artyomovsk [33]. The

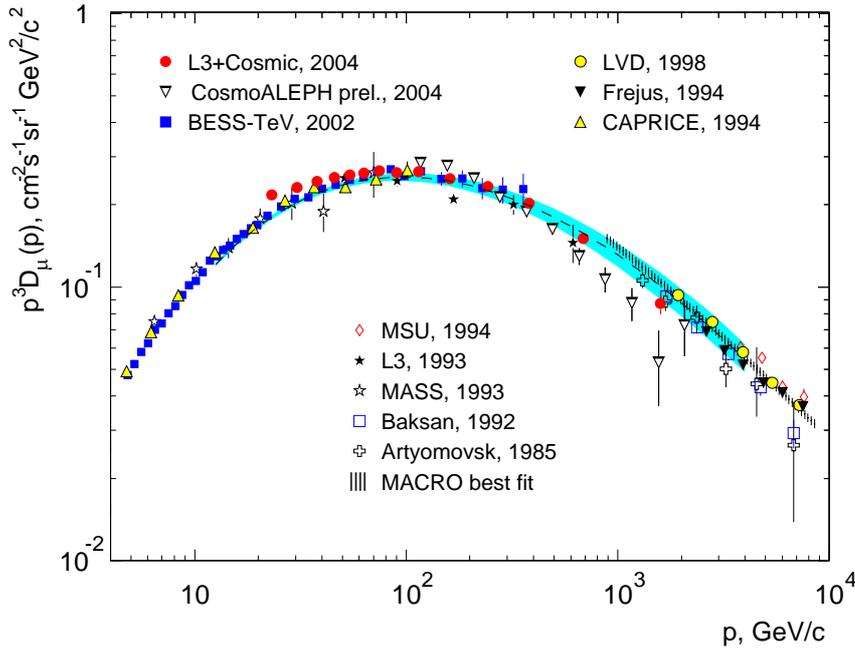


Figure 2: Energy spectrum of muons at ground level near vertical. The dashed-line curves and the shaded area present this work calculation with the ATIC-2 primary cosmic-ray spectrum.

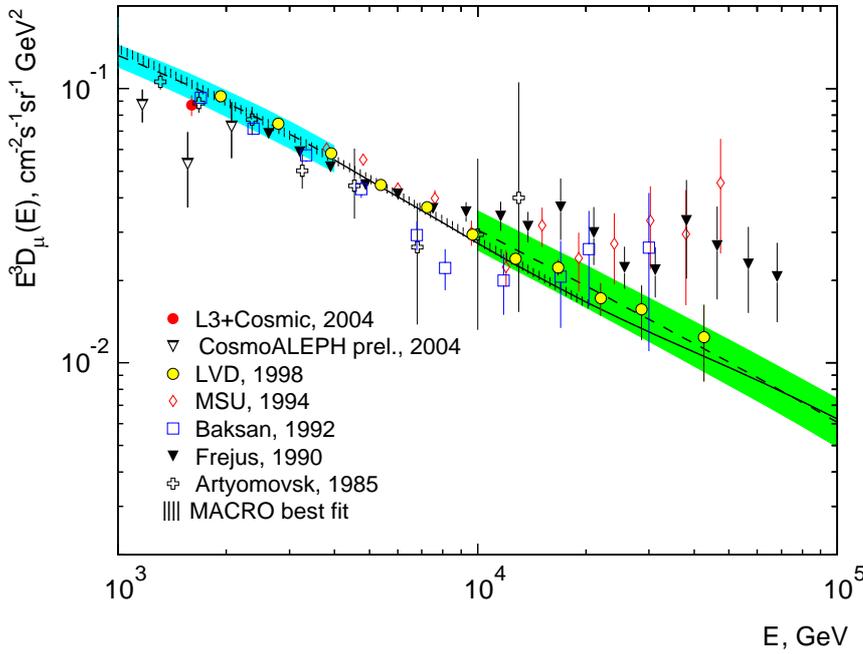


Figure 3: High-energy plot of the ground level muon spectrum. The dashed-line curves and shaded areas present this work calculations with the ATIC-2 primary spectrum (left) and GAMMA one (right). The solid curve presents the calculation with Zatsepin and Sokolskaya model.

light shaded areas in figure 2 and figure 3 (the left corner) show the muon spectrum calculated with the ATIC-2 primary spectra taking into consideration statistical errors (dashed curve corresponds to mean values). For the range 10 – 3000 GeV one sees fair accordance of the muon flux, calculated with the ATIC-2 spectra, and the recent measurements but the Cosmo-ALEPH data. The high-energy part of the muon flux is shown in figure 3, where the dark shaded area (at the right) presents our calculation with the GAMMA primary spectra input and the solid curve presents the muon flux computed with ZS primary spectrum model which appears to be a reliable bridge from TeV range to PeV one. It should be noted that without considering the prompt muon contribution above 10 TeV one can say about satisfactory agreement of calculated fluxes only with the data of MACRO and LVD measurements.

In conclusion, it may be said that the high accuracy of the ATIC-2 data results in the muon flux calculation uncertainty, comparable with rather high precision of the last decade muon flux measurements.

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