The atmospheric neutrino flux from decays of charmed particles

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Abstract. We calculate the high-energy component of the atmospheric neutrino flux which arises from decays of the charmed particles. Cross sections of the $D$ mesons and $\Lambda^+_c$ baryons production in $pA$ and $\pi A$ collisions are calculated within the framework of the quark-gluon string model (QGSM). The recent data on the cross sections of charmed meson production at high energies, obtained in experiments at the LHC, allow an improvement of the QGSM free parameters and new estimate of the prompt atmospheric neutrino flux. The newly-calculated flux of the prompt neutrinos is three times smaller than the flux predicted with the previous version of QGSM. We compare our result with the constraint derived from IceCube experiment as well as with predictions obtained with different charm production models.

1. Introduction

High-energy neutrinos from decays of mesons and baryons produced in collisions of cosmic rays with the Earth’s atmosphere form an unavoidable background in the detection of neutrinos from distant astrophysical sources. The detection of several tens of events in the IceCube experiment with energy deposition in the range $30\,\text{TeV} - 2\,\text{PeV}$ from neutrinos of cosmic origin [1, 2] and recent announcement of the blazar TXS 0506 + 056 as likely source of high energy neutrinos [3] increase significance of the calculation of atmospheric neutrino background.

Atmospheric neutrino fluxes consist of two components, which have different zenith-angle distribution and energy spectrum. The anisotropic component is produced in muon, pion and kaon decays and has the softer spectrum – these are the conventional ($\pi, K$)–neutrinos. The second one, quasi-isotropic and hard component is produced at high energies mainly in decays of short-lived heavy charmed mesons and baryons ($D, \Lambda^+_c$). Such neutrinos are called as prompt atmospheric neutrinos. The most uncertain contribution to the high-energy atmospheric neutrino flux arises from decays of charmed particles because of a wide spread in model predictions and lack of measurements of the charm production cross sections at high-energies.

We calculate the prompt neutrino flux using updated version of the quark-gluon string model (QGSM) [4]. The recent data on the cross sections of charmed particle production, obtained in experiments at the LHC [5, 6, 7, 8], allow an improvement of the QGSM free parameters. In the calculation we use the hadronic cascade model [9, 10, 11] and cross sections of $D$ meson and $\Lambda^+_c$ baryon production in $pA$ and $\pi A$ collisions which were computed for updated parameters of QGSM. We compare our result with the constraint obtained in the IceCube experiment as well as with predictions of dipole model (ERS) [12] and NLO pQCD (BEJKRSS) calculation [13].
2. Production of charmed particles in the quark-gluon string model

QGSM is a nonperturbative model which describes soft hadronic processes: production of nucleons, pions, kaons and charmed hadrons. The model is based on Reggeon calculus, topological $1/N_f$-expansion of the amplitudes (planar diagrams correspond to Reggeon contributions and cylinder ones correspond to Pomerons) and color string dynamics [14, 16, 15]. QGSM is phenomenological model, it contains a number of free parameters determined by experimental measurements. Besides parameters, which are determined from global fit of experimental data, there are free parameters: intercept of $c\bar{c}$-trajectory Regge $\alpha_2(0)$ and parameter $a_1$ that provides both an enhancement and unified description of the kinematic regions $x \to 0$ and $x \to 1$ ($x$ – Feynman variable) in case of the valence quark fragmentation. Now there are no clear arguments for choice of its value, and different authors apply various values in the range from $a_1 = 2$ [17] to $a_1 = 30$ [16]. As for the intercept of $c\bar{c}$-trajectory there are two possible values. The nonlinear trajectory with $\alpha_2(0) = 0$ is dictated by the perturbative quantum chromodynamics (pQCD). On the other hand by analogy with light quarks the Regge trajectory is linear and its intercept $\alpha_2(0) = -2.2$. Data on the production of charmed particles obtained in recent years indicate preferability of the value $\alpha_2(0) = -2.2$, which takes account of effects beyond the pQCD [18]. New measurements of the total cross sections of charmed meson production at high energies in the experiments ALICE [5, 6, 7], ATLAS [8] make it possible to check the predictions of the QGSM for these free parameters.

Figure 1 shows the total cross section of $D$ mesons production in $pp$ collisions calculated for four sets of free parameters in comparison to experimental data in a wide energy range [19, 20, 21, 22, 23, 24, 25, 26, 27] including LHC measurements [5, 6, 7, 8].

![Figure 1. Total cross sections of $D/\bar{D}$ mesons production in $pp$ collisions. QGSM calculations for $\alpha_2(0) = -2.2$ and $a_1 = 2$ (solid line) or $a_1 = 30$ (dashed); dash-dotted and dotted lines correspond to $\alpha_2(0) = 0$. Experimental data: $\blacktriangle$ – [5]; $\triangledown$ – [6]; $\blacklozenge$ – [7]; $\blacktriangleleft$ – [8]; $\blacklozenge$ – [19]; $\blackdiamondsuit$ – [20]; $\blacklozenge$ – [21]; $\blacktriangledown$ – [22]; $\bullet$ – [23]; $\blacklozenge$ – [24]; $\blacktriangledown$ – [25]; $\blacklozenge$ – [26]; $\blackdiamondsuit$ – [27].](image)

Calculation with $\alpha_2(0) = 0$ and $a_1 = 30$ does not agree with experimental data at $\sqrt{s} < 100$ GeV, while the calculations with $\alpha_2(0) = -2.2$ are in close agreement with the measurements in a wide energy range. At low energies the cross sections with $\alpha_2(0) = -2.2$ calculated for extreme values $a_1 = 2$ and $a_1 = 30$ differ by a factor $2 - 5$. With a rise of energy, the influence of the parameter $a_1$ decreases and becomes negligible at high energies ($\sqrt{s} > 1$ TeV). As can be seen in figure 2 the differential cross sections of $D$ mesons production are described better for $\alpha_2(0) = -2.2$, while the computation with the intercept $\alpha_2(0) = 0$ is not compatible
with the experimental data [22].

**Figure 2.** Differential cross sections of $D/\bar{D}$ mesons production in $pp$ collisions at $E_{\text{lab}} = 400$ GeV (left) and $E_{\text{lab}} = 800$ GeV (right). Experimental data: ● – [22]; ■ – [23]. The same notation for lines as in figure 1.

**Figure 3.** Differential cross sections of each type of $D$ mesons ($D^+, D^-, D_0, \bar{D}_0$) production in $pp$ collisions at $E_{\text{lab}} = 400$ GeV: calculations with $\alpha_2(0) = -2.2$ for $a_1 = 2$ (solid line) and $a_1 = 30$ (dashed). Experimental data: ● – [22].

Figure 3 presents comparison of the experimental measurements ($pp$ collisions, 400 GeV) [22] with the inclusive cross sections for each type of $D$ mesons production ($D^+, D^-, D_0, \bar{D}_0$)
performed for $\alpha_\psi(0) = -2.2$ and two values of the parameter $a_1$: $a_1 = 2$ and $a_1 = 30$. The cross sections of $D^+$ and $D^0$ mesons weakly depend on the parameter $a_1$, while the cross section of $D^-$ and $\bar{D}^0$ mesons calculated for $a_1 = 2$ is smaller (by a factor $2 - 10$) than that for $a_1 = 30$ and leads to better agreement with the experimental data. Production of $D^-$ and $\bar{D}^0$ mesons in $pp$ interactions has a higher probability because these mesons contain the valence quarks of colliding protons. The contribution of the leading fragmentation functions dominates in the $x$-distributions, and $x$-distribution of $D^-$ and $\bar{D}^0$ is harder in comparison with $D^+$ and $D^0$. The influence of the parameter $a_1$ on the cross section of all $D$ mesons production is also noticeable (figure 2).

![Cross section plot](image)

**Figure 4.** Differential (left) and total (right) cross sections of $\Lambda^+_c$ baryon production in $pp$ collisions: calculations for $\alpha_\psi(0) = -2.2$ (solid curve) and $\alpha_\psi(0) = 0$ (dotted). Experimental data: ● – [28]; □ – [29]; ▲ – [28].

Comparison of the cross section of $\Lambda^+_c$ baryon production in $pp$ collisions with experimental data is shown in figure 4. The differential cross section at $E_{lab} = 2.05$ TeV (left panel) is calculated for $\alpha_\psi(0) = -2.2$ and $\alpha_\psi(0) = 0$, the experimental data were obtained at energies $E_{lab} = 2.05$ TeV [28] and 2.1 TeV [29]. There is appreciable difference in the cross section data of these two experiments. The calculation with the parameter $\alpha_\psi(0) = -2.2$ agrees with the later experiment. The right panel of figure 4 shows the total cross section of $\Lambda^+_c$ production as a function of center-of-mass energy. The experimental points are taken from [28], the calculation is made for same parameter sets. The large spread of the total cross section measurement data does not allow making a definite choice of the intercept $\alpha_\psi(0)$.

### 3. Energy spectra of the atmospheric prompt neutrinos

In the present work the calculation of prompt neutrino fluxes is performed within method [9, 10] for QGSM and the parameterization of cosmic ray spectrum by Nikolsky, Stamenov, Ushev (NSU) [30] and the toy model by Thunman, Ingelman, Gondolo (TIG) [31]. The NSU spectrum which takes into account an elemental composition of primary cosmic rays was chosen in order to compare new results with the old one [10]. Simplified broken power law approximation TIG assuming only nucleon component of spectrum was chosen for comparison of our result with other calculations including dipole model prediction by ERS [12] which is used by IceCube as a benchmark model.

Figure 5 (left panel) shows the calculation of vertical flux of prompt atmospheric neutrinos: the band represents this work calculation with NSU-spectrum for the QGSM with the intercept $\alpha_\psi(0) = -2.2$. The band shows uncertainty due to change of the parameter $a_1$:...
extreme values of \(a_1\) lead to change of the neutrino flux by a factor 1.4 (\(a_1 = 2\) corresponds to lower bound and \(a_1 = 30\) to upper one). However, the intercept of Regge trajectory \(\alpha(0)\) makes substantial influence: the replacement of \(\alpha(0) = 0\) by \(\alpha(0) = -2.2\) reduces the flux by a factor 3 as compared to previous result (solid curve) obtained for similar scheme (QGSM+NSU) with intercept \(\alpha(0) = 0\).

![Figure 5.](image)

An influence of charm production models on neutrino fluxes is shown in figure 5 (right panel). All results are obtained for the same cosmic ray spectrum TIG. QGSM flux (shaded band) is comparable with the NLO pQCD [13] calculation (hatched area) at energies above 200 TeV. In the important energy range above 1 PeV, where atmospheric neutrinos from the decay of charmed particles dominate, QGSM leads to appreciably lower flux as compared to the dipole model result [12] (dashed line). As already noted the dipole model was used as the benchmark model in data processing in the IceCube experiment, although the cross sections of this model were not verified by comparison with experimental data, and the prompt neutrino flux was calculated with the toy model (TIG) of the cosmic ray spectrum.

In recent analysis [1], the upper limit on the prompt atmospheric neutrino flux was obtained by IceCube using high statistics collected over six years. The prompt neutrino flux was constrained based on the dipole model [12], but with usage of more realistic cosmic ray flux parametrization H3p [32]. We have found that our result is compatible with the IceCube limit up to 2 PeV.

4. Conclusion
The recent data on cross sections of charmed particle production obtained in the LHC experiments allow an improvement of the QGSM free parameters \(\alpha(0)\) and \(a_1\). Analysis showed that the intercept of Regge trajectory \(\alpha(0)\) appreciably affects the charm production cross section and so the prompt atmospheric neutrino flux. Updated version of QGSM leads to decrease of the prompt neutrino flux by a factor \(\sim 2-3\) as compared to the former QGSM prediction using \(\alpha(0) = 0\). In the energy region beyond 1 PeV, where atmospheric neutrinos from the decay of charmed particles dominate, the updated QGSM flux is noticeably lower in comparison with the dipole model which is used in the IceCube experiment as benchmark model. The QGSM flux obtained for intercept \(\alpha(0) = -2.2\) is compatible with the NLO pQCD calculation at \(E_\nu > 200\) TeV and does not contradict the IceCube limitation up to 2 PeV.
Acknowledgements
This work is supported in part by the Russian Federation Ministry of Science and Higher Education, agreement 3.9678.2017/8.9.

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