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Investigating the dominant regions of the phase space associated with $c\bar{c}$ production relevant for the prompt atmospheric neutrino flux

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A detailed mapping of the dominant kinematical domains contributing to the prompt atmospheric neutrino flux at high neutrino energies is presented by studying their sensitivity to the cuts on several kinematical variables crucial for charm production in cosmic ray scattering in the atmosphere. This includes the maximal center-of-mass energy for proton-proton scattering, the longitudinal momentum fractions of partons in the projectile (cosmic ray) and target (nucleus of the atmosphere), and the Feynman x_F variable. We find that the production of neutrinos with energies larger than $E_\nu > 10^7$ GeV is particularly sensitive to the c.m. energies larger than the ones at the LHC and to the longitudinal momentum fractions in the projectile $10^8 < x < 10^5$. Our results indicate that the precision data on the prompt atmospheric neutrino flux can efficiently constrain the mechanism of heavy quark production and underlying QCD dynamics in kinematical ranges beyond the reach of the current collider measurements.

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1. Introduction

The recent detection of ultra-high energy neutrino events with deposited energies up to a few PeV by the IceCube Observatory sets the begining of neutrino astronomy [1, 2, 3] (for a review of IceCube potential for neutrino astronomy, see e.g. Ref. [4]). It is mandatory to know the flux of atmospheric neutrino produced in cosmic-ray interactions with nuclei in Earth's atmosphere at different energies with high precision as an unavoidable background for cosmic neutrino studies.

One of the main backgrounds for the study of cosmic neutrinos is the contribution of the *prompt* atmospheric neutrino flux, associated with the decay of heavy flavoured hadrons, composed of heavy quarks. The calculation of this contribution has been a theme of intense debate in the literature, mainly due to the fact that the calculation requires good knowledge of the heavy quark production cross section at high energies [5, 6, 7, 8, 9, 10, 11, 12, 13]. One has that the prompt neutrino flux measured in the kinematical range that is probed by the IceCube Observatory and future neutrino telescopes is directly associated with the treatment of the heavy quark cross section at high energies and forward rapidities (large values of the Feynmann x_F variable). Currently, different experiments at the LHC probe a limited range in rapidity. In particular, they do not cover rapidities larger than 4.5, which corresponds to relatively small values of $x_F \lesssim 0.1$. Therefore, the D-meson production in the kinematical range of large x_F values is not covered by the LHC detectors.

In this contribution we present a brief summary of the results obtained in Ref. [14], where we have presented a detailed mapping of the dominant kinematical domains contributing to the prompt atmospheric neutrino flux at high neutrino energies. As shown in what follows, our results indicate that the production of neutrinos with energies larger than $E_\nu > 10^7$ GeV is particularly sensitive to the c.m. energies larger than the ones at the LHC and to the longitudinal momentum fractions in the projectile $10^8 < x < 10^5$.

2. Formalism

The prompt neutrino flux is usually calculated using the semi-analytical Z-moment approach, proposed many years ago in Ref. [15] and discussed in detail e.g. in Refs. [16, 7], which describes the evolution of the inclusive particle fluxes in the Earth's atmosphere. In this approach, a set of coupled cascade equations for the nucleons, heavy mesons and leptons (and their antiparticles) fluxes is solved, with the equations being expressed in terms of the nucleon-to-hadron (Z_{NH}), nucleon-to-nucleon (Z_{NN}), hadron-to-hadron (Z_{HH}) and hadron-to-neutrino ($Z_{H\nu}$) Z-moments. For a detailed discussion of the cascade equations, see e.g. Refs. [15, 7]. These moments are inputs in the calculation of the prompt neutrino flux associated with production of a heavy hadron H and its decay into a neutrino ν in the low- and high-energy regimes.

In Ref. [14] we have solved the cascade equations considering vertical fluxes ($\theta = 0$) and assuming that the cosmic ray flux ϕ_N can be described by a broken power-law spectrum [17], with the incident flux being represented by protons ($N = p$). Moreover, we have assumed that the charmed hadron Z-moments can be expressed in terms of the charm Z-moment as follows: $Z_{pH} = f_H \times Z_{pc}$, where f_H is the fraction of charmed particle which emerges as a hadron H. As in Ref. [16], we have assumed that $f_{D^0} = 0.565$, $f_{D^+} = 0.246$, $f_{D_s^+} = 0.080$ and $f_{\Lambda_c} = 0.094$. The charm Z-moment at high energies is given by

$$Z_{pc}(E) = \int_0^1 \frac{dx_F}{x_F} \frac{\phi_p(E/x_F)}{\phi_p(E)} \frac{1}{\sigma_{pA}(E)} \frac{d\sigma_{pA\to charm}(E/x_F)}{dx_F} \,, \tag{2.1}$$

where E is the energy of the produced particle (charm), x_F is the Feynman variable, σ_{pA} is the inelastic proton-Air cross section, which we assumed to be given as in Ref. [6], and $d\sigma/dx_F$ is the differential cross section for the charm production, which we have assumed to be given by $d\sigma_{pA\to charm}/dx_F = 2d\sigma_{pA\to c\bar{c}}/dx_F$. The charm production cross section is estimated using the standard QCD collinear factorization formalism and the CT14LL parametrization [18].

3. Results

Our goal is to understand what is the range of several kinematical variables relevant for the production of the high energy neutrinos observed recently by IceCube or for higher energies than possible at present. To realize this goal we map the range of several kinematical variables such as: center-of-mass energies, parton momentum fractions in the projectile (x_1) and target (x_2), and the Feynman-x (x_F). All of them determine the size of the cross section and, as a consequence, the energy dependence of the prompt neutrino flux.

Let us analyze first how the flux of neutrinos from semileptonic decays of D mesons depends on the maximal center-of-mass collision energy included in the calculation. In Fig. 1 we present our results obtained for different values of the maximal energies considered in the analysis of the differential cross section in Eq. (2.1). As x_F is integrated and $d\sigma/dx_F$ is probed at the energy E/x_F, one have that $Z_{pc}(E)$ may be influenced by the behaviour of distribution at higher energies. In our calculation, we consider three different values for the maximum center-of-mass energy allowed in the pp collision that generates the heavy quark pair. For comparison the full prediction for the flux, denoted as "no cuts" in the figure, is presented. Here, no energy limitations were imposed. Moreover, for illustration, the energy range probed by the recent IceCube data [3] is shown as well. The figure demonstrates that the flux depends on of the cross section for heavy quark production in the LHC energy range and at even larger energies. The latter unexplored region can also have a direct impact on the flux at high neutrino energies ($E_\nu \geq 10^6$ GeV).

Moreover, our results indicate that the prompt neutrino flux for $E_\nu \gtrsim 10^7$ GeV is determined by the behaviour of the differential cross section in the energy range beyond that probed in the Run 2 of the LHC. Consequently, the detection of prompt atmospheric neutrinos in this range by the IceCube experiment, its upgrade or by other future neutrino telescope, can significantly contribute to our understanding of several aspects associated with the heavy quark production at high energies. Whether we control at present the cross section for energies above those for the LHC is an open question, at least, in our opinion.

In Fig. 2 (left panel) we present the sensitivity of the energy dependence of the prompt neutrino flux on x_1 cuts. The notation of the different curves indicate the range of x_1 values that is included in our calculations. As shown in Ref. [14], the x_1 cut has a direct impact on the x_F distribution, strongly suppressing the distribution at large x_F. Such behavior modifies the energy dependence of the neutrino flux. We observe that the main contribution comes from the intermediate x_1-range ($0.2 < x_1 < 0.6$). This result demonstrate that the significant portion of the neutrino flux comes

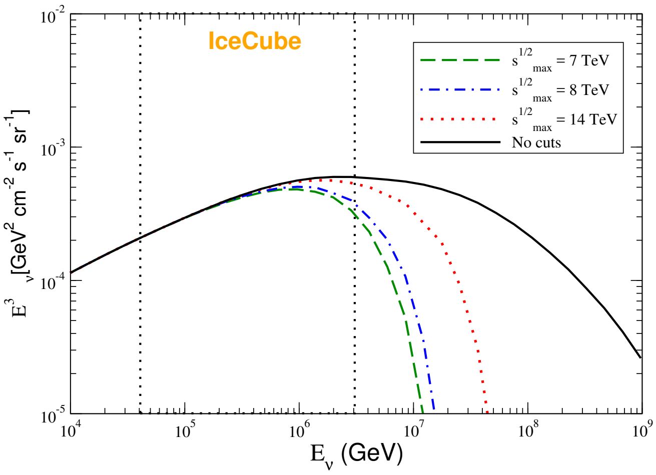

Figure 1: Impact of different cuts on the maximal center-of-mass pp collision energy for the prompt neutrino flux.

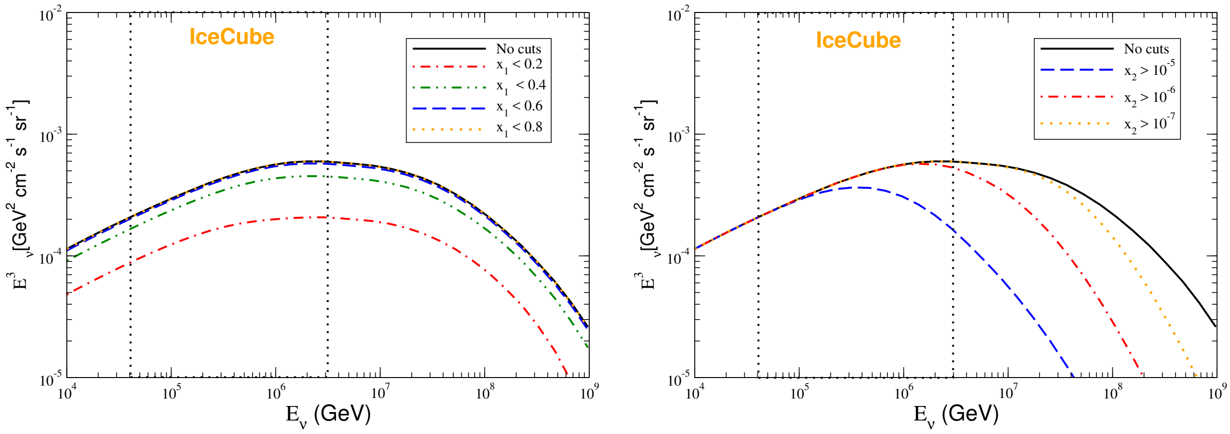

Figure 2: The effect of x_1 (left) and x_2 (right) cuts on the prompt neutrino flux.

from very forward (large x_F) charm production, with the incident parton energy larger than 20% of the projectile nucleon energy at any probed neutrino energy. Analogously, in Fig. 2 (right panel) we show the corresponding sensitivity to the cuts on the target momentum fraction x_2. Our results indicate that the main contribution to the distribution at proton energy $E_p = 10^9$ GeV comes from the $10^{-7} < x < 10^{-5}$ range of gluon longitudinal momentum fractions.

In Fig. 3 we present the results for the prompt neutrino flux for different cuts on the Feynman x_F variable. We find that the dominant contribution to the neutrino flux comes typically from x_F in the region $0.2 < x_F < 0.5$, which is consistent with our previous results for the impact of the x_1 and x_2 cuts. The previous results indicate that the dominant contribution comes from the region of $x_1 \in$ (0.2-0.6) and $x_2 \in (10^{-8}$ - $10^{-5})$. We wish to stress that in both these regions of longitudinal momentum fractions gluon distribution is poorly constrained (see e.g. Ref. [18]). Moreover, the behaviour of the x_F distribution at intermediate x_F is directly associated with the charm production

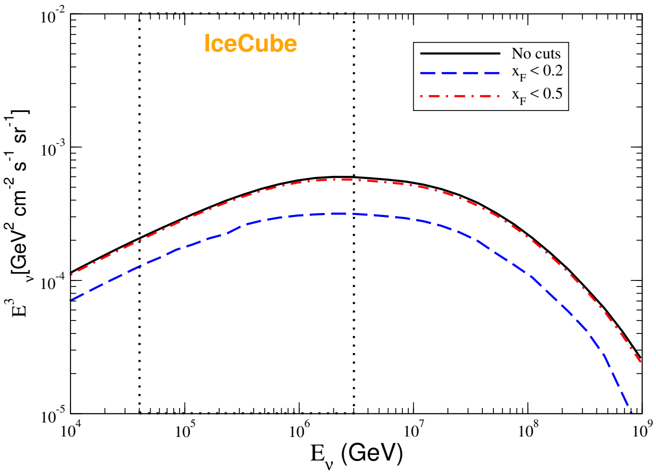

Figure 3: The effect of cuts on the Feynman variable x_F on the prompt neutrino flux.

at large rapidities, beyond those probed currently by the LHC detectors.

4. Summary

One of the current challenges in neutrino physics is to disentangle the signals of astrophysical origin from those associated with atmospheric interactions. The precise determination of the conventional and prompt atmospheric neutrino fluxes is fundamental for the interpretation of the results from neutrino observatories, such as the IceCube. Consequently, it is important to map the kinematical range that is probed by high-energy atmospheric neutrinos in order to clearly define the next steps that should be performed to obtain precise predictions for the atmospheric neutrino flux. This has been one of the main goals of the study presented in Ref. [14] and reviewed here.

In this contribution we have presented a detailed analysis of the kinematical domains that dominate the charm and prompt atmospheric neutrino production in cosmic rays relevant for the IceCube experiment by exploring the sensitivity of the corresponding neutrino flux and the charm cross section to the cuts on the maximal pp c.m. energy, the longitudinal momentum fraction in the target and projectile, the Feynman x_F and p_T variables included in the calculation. We have found that in order to address production of high-energy neutrinos ($E_\nu > 10^7$ GeV) one needs to know the charm production cross section for energies larger than those available at the LHC as well as the parton/gluon distributions for the longitudinal momentum fractions in the region $10^{-8} < x < 10^{-5}$. Since this region of x is not available at the collider measurements in the moment, the predictions in the collinear factorization approach and the k_T-factorization approach are not very reliable. If it was possible to disantagle the prompt atmospheric contribution from the cosmogenic one, it could perhaps become possible to put some contraints on the gluon distributions for extremely small longitudinal momentum fractions. This option requires a more dedicated study in the future.

Our results demonstrate that in order to predict the prompt neutrino flux for typical neutrino energies at the IceCube Observatory and future neutrino telescopes, we should extrapolate the behaviour of the heavy quark cross sections and energy distributions beyond the range accessible experimentally by current collider measurements. These results indicate that theoretical and experimental studies of the prompt atmospheric neutrino flux can provide an important information about the mechanism of heavy quark production as well as the description of the QCD dynamics in a kinematical range beyond that reached by the current colliders. At the current stage of research, it is premature to decide whether the measurement at the IceCube Observatory can provide a new information on the gluon distribution at very low longitudinal fractions $x \sim 10^{-7}$.

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