Intrinsic charm in the nucleon and forward production of charm: a new constrain from IceCube Neutrino Observatory

Rafał Maciuła[1⋆], Victor P. Goncalves[2] and Antoni Szczurek[1,3]

1 Institute of Nuclear Physics, Polish Academy of Sciences,
ul. Radzikowskiego 152, PL-31-342 Kraków, Poland
2 Instituto de Física e Matemática, Universidade Federal de Pelotas (UFPel),
Caixa Postal 354, CEP 96010-900, Pelotas, RS, Brazil
3 University of Rzeszów, PL-35-959 Rzeszów, Poland

⋆ rafal.maciula@ifj.edu.pl

Abstract

The predictions for the atmospheric neutrino flux at high energies strongly depend on the contribution of prompt neutrinos, which are determined by the production of charmed meson in the atmosphere at very forward rapidities. Here we estimate the related cross sections taking into account the presence of an intrinsic charm (IC) component in the proton wave function. The impact on the predictions for the prompt neutrino flux is investigated assuming different values for the probability to find the IC in the nucleon.

1 Introduction

Recent experimental results obtained by the LHC, the Pierre Auger and IceCube Neutrino Observatories have challenged understanding of many interesting aspects of Quantum Chromodynamics in the high energy limit. In particular, in recent years, IceCube measured the astrophysical and atmospheric neutrinos fluxes at high ei (see e.g. [1]) while different collaborations from the LHC performed several analyses of the heavy meson production at high energies and forward rapidities (see e.g. [2]). Those different origin data sets are strictly interrelated, since the description of the heavy meson production at the LHC and higher center of mass energies is fundamental to make precise predictions of the prompt neutrino flux [3], which is expected to dominate the atmospheric ν flux for large neutrino energies [4].

This aspect motivates the development of new and/or more precise approaches to describe the perturbative and nonperturbative regimes of the Quantum Chromodynamics (QCD) needed to describe the charmed meson production in a kinematical range beyond that reached

in hadronic collisions at the LHC. For this new kinematical range, some topics are theme of intense debate. An important question, which motivates the present study, is whether the current and future IceCube data can put some constraints on the intrinsic charm concept in the nucleon.

2 Formalism

The atmospheric neutrinos are produced in cosmic-ray interactions with nuclei in Earth's atmosphere [4]. While at low neutrino energies ($E_\nu \lesssim 10^5$ GeV), these neutrinos arise from the decay of light mesons (pions and kaons), and the associated flux is denoted as the *conventional* atmospheric neutrino flux [5], for larger energies it is expected that the *prompt* atmospheric neutrino flux associated with the decay of hadrons containing heavy flavours become important [6].

Calculations of the prompt atmospheric neutrino flux at the detector level depend on the description of the production and decay of the heavy hadrons as well as the propagation of the associated particles through the atmosphere. Following our previous studies [3,7], we estimated the expected prompt neutrino flux in the detector ϕ_ν using the Z-moment method [6], which implies that ϕ_ν can be estimated using the geometric interpolation formula

$$\phi_\nu = \sum_H \frac{\phi_\nu^{H,low} \cdot \phi_\nu^{H,high}}{\phi_\nu^{H,low} + \phi_\nu^{H,high}}, \tag{1}$$

where $H = D^0, D^+, D_s^+, \Lambda_c$ for charmed hadrons and $\phi_\nu^{H,low}$ and $\phi_\nu^{H,high}$ are solutions of a set of coupled cascade equations for the nucleons, heavy meson and lepton (and their antiparticles) fluxes in the low- and high-energy ranges, respectively. They can be 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, as follows [6]:

$$\phi_\nu^{H,low} = \frac{Z_{NH}(E) Z_{H\nu}(E)}{1 - Z_{NN}(E)} \phi_N(E, 0), \tag{2}$$

$$\phi_\nu^{H,high} = \frac{Z_{NH}(E) Z_{H\nu}(E)}{1 - Z_{NN}(E)} \frac{\ln(\Lambda_H/\Lambda_N)}{1 - \Lambda_N/\Lambda_H} \frac{m_H c h_0}{E \tau_H} f(\theta) \phi_N(E, 0), \tag{3}$$

where $\phi_N(E, 0)$ is the primary flux of nucleons in the atmosphere, m_H is the decaying particle's mass, τ_H is the proper lifetime of the hadron, $h_0 = 6.4$ km, $f(\theta) \approx 1/\cos\theta$ for $\theta < 60^o$, and the effective interaction lengths Λ_i are given by $\Lambda_i = \lambda_i/(1 - Z_{ii})$, with λ_i being the associated interaction length ($i = N, H$). For $Z_{H\nu}$, our treatment of the semileptonic decay of D-hadrons follows closely Ref. [8]. For a detailed discussion of the cascade equations, see e.g. Ref. [6]. Assuming that the incident flux can be represented by protons ($N = p$), the charmed hadron Z-moments are given by

$$Z_{pH}(E) = \int_0^1 \frac{dx_F}{x_F} \frac{\phi_p(E/x_F)}{\phi_p(E)} \frac{1}{\sigma_{pA}(E)} \frac{d\sigma_{pA \to H}(E/x_F)}{dx_F}, \tag{4}$$

where E is the energy of the produced particle (charmed meson), x_F is the Feynman variable, σ_{pA} is the inelastic proton-Air cross section and $d\sigma/dx_F$ is the differential cross section for the charmed meson production.

As discussed in Ref. [9], the cross section for charm production at large forward rapidities, which is the region of interest for estimating the prompt ν_μ flux [3], can be expressed as

$$d\sigma_{pp \to charm} = d\sigma_{pp \to charm}(gg \to c\bar{c}) + d\sigma_{pp \to charm}(cg \to cg), \tag{5}$$

where the first and second terms represent the contributions associated with the $gg \rightarrow c\bar{c}$ and $cg \rightarrow cg$ mechanisms, with the corresponding expressions depending on the factorization scheme assumed in the calculations. In Ref. [9], a detailed comparison between the collinear, hybrid and k_T-factorization approaches was performed. In what follows, we will focus on the hybrid factorization model. In this approach, the differential cross sections for $gg^* \rightarrow c\bar{c}$ and $cg^* \rightarrow cg$ mechanisms are given by

$$d\sigma_{pp \rightarrow charm}(gg \rightarrow c\bar{c}) = \int dx_1 \int \frac{dx_2}{x_2} \int d^2k_t \, g(x_1, \mu^2) \, \mathcal{F}_{g^*}(x_2, k_t^2, \mu^2) \, d\hat{\sigma}_{gg^* \rightarrow c\bar{c}} \,, \qquad (6)$$

$$d\sigma_{pp \rightarrow charm}(cg \rightarrow cg) = \int dx_1 \int \frac{dx_2}{x_2} \int d^2k_t \, c(x_1, \mu^2) \, \mathcal{F}_{g^*}(x_2, k_t^2, \mu^2) \, d\hat{\sigma}_{cg^* \rightarrow cg} \,, \qquad (7)$$

where $g(x_1, \mu^2)$ and $c(x_1, \mu^2)$ are the collinear PDFs in the projectile, $\mathcal{F}_{g^*}(x_2, k_t^2, \mu^2)$ is the unintegrated gluon distribution (gluon uPDF) of the proton target, μ^2 is the factorization scale of the hard process and the subprocesses cross sections are calculated assuming that the small-x gluon is off mass shell and are obtained from a gauge invariant tree-level off-shell amplitude. In our calculations $c(x_1, \mu^2)$, similarly $\bar{c}(x_1, \mu^2)$, contain the intrinsic charm component.

As emphasized in Ref. [9], the hybrid model, already at leading-order, takes into account radiative higher-order corrections associated with extra hard emissions that are resummed by the gluon uPDF. In the numerical calculations below the intrinsic charm PDFs are taken at the initial scale $m_c = 1.3$ GeV, so the perturbative charm contribution is intentionally not taken into account when discussing IC contributions.

Considering the $cg^* \rightarrow cg$ mechanism one has to deal with the massless partons (minijets) in the final state. The relevant formalism with massive partons is not yet available. Therefore it is necessary to regularize the cross section that has a singularity in the $p_t \rightarrow 0$ limit. We follow here the known prescription adopted in PYTHIA, where a special suppression factor is introduced at the cross section level. The form factor depends on a free parameter p_{t0}, which can be fixed using experimental data for the D meson production in $p+p$ and $p+^4He$ collisions at $\sqrt{s} = 38.7$ GeV and 86 GeV, respectively (see e.g. Ref. [10]). In numerical calculations below we use $p_{t0} = 2$ GeV.

The predictions for the charm production strongly depend on modelling of the partonic content of the proton [9]. In particular, the contribution of the charm - initiated process is directly associated with the description of the extrinsic and intrinsic components (for a recent review see, e.g. Ref. [11]). Differently from the extrinsic charm quarks/antiquarks that are generated perturbatively by gluon splitting, the intrinsic one have multiple connections to the valence quarks of the proton and thus is sensitive to its nonperturbative structure. The presence of an intrinsic component implies a large enhancement of the charm distribution at large x (> 0.1) in comparison to the extrinsic charm prediction. In recent years, the presence of an intrinsic charm component have been included in the initial conditions of the global parton analysis [12], resulting in IC distributions that are compatible with the world experimental data. However, its existence is still a subject of intense debate, mainly associated with the amount of intrinsic charm in the proton wave function, which is directly related to the magnitude of the probability to find an intrinsic charm or anticharm (P_{ic}) in the nucleon.

In our analysis we will consider the collinear PDFs given by the CT14nnloIC parametrization [12] from a global analysis assuming that the x-dependence of the intrinsic charm component is described by the BHPS model [13]. Another important ingredient is the modelling of $\mathcal{F}_{g^*}(x_2, k_t^2, \mu^2)$. In our analysis here we will use the uPDF derived using the Kimber-Martin-Ryskin (KMR) prescription [14].
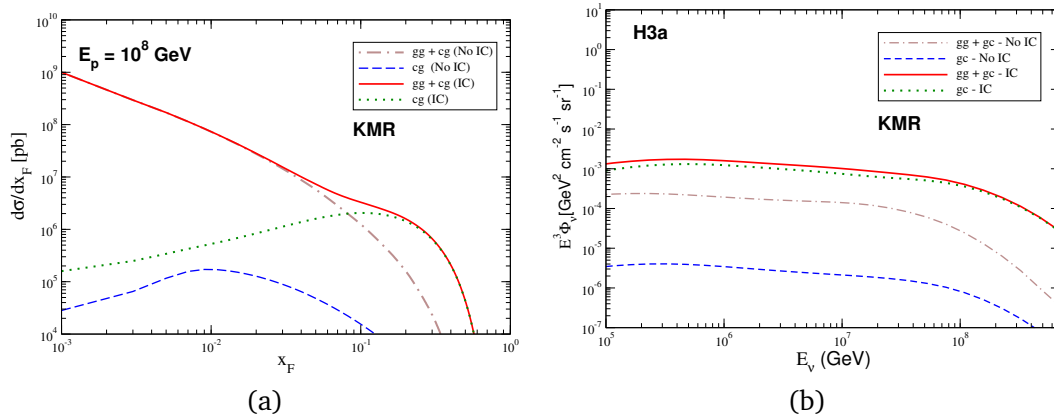
3 Numerical results

Figure 1: Predictions of the hybrid model for (a) the Feynman x_F - distributions for charm particles and (b) the prompt neutrino flux (rescaled by E_ν^3).

In Fig. 1 (a), we present our predictions for the Feynman x_F distribution of charm particles produced in pp collisions at the atmosphere, considering an incident proton with an energy of $E_p = 10^8$ GeV and the KMR model for the uPDF. We present separately the contribution associated with the $cg \to cg$ mechanism and the sum of the two mechanisms, denoted by "cg" and "gg + cg", respectively. Moreover, we compare the IC predictions, obtained using the CT14nnloIC parametrization for $P_{ic} = 1\%$, with those obtained disregarding the presence of the intrinsic component (denoted No IC hereafter). One has that for small $x_F(\equiv x_1 - x_2)$, the charm production is dominated by the $gg \to c\bar{c}$ mechanism, which is expected since for $x_F \approx 0$ and high energies both longitudinal momentum fractions x_i are very small and the proton structure is dominated by gluons. For the No IC case, the contribution of the $cg \to cg$ mechanism is smaller than the gluon fusion one for all values of x_F. In contrast, when intrinsic charm is included, the behavior of the distribution in the intermediate x_F range ($0.06 \le x_F \le 0.6$) is strongly modified. Such a behaviour is expected, since for this kinematical range, the charm production depends on the description of the partonic content of the incident proton at large values of the Bjorken x variable. The impact on the predictions for the prompt neutrino flux is presented in Fig. 1 (b). As expected from the analysis performed in Ref. [3], where we find that the dominant contribution to the neutrino flux comes typically from x_F in the region $0.2 < x_F < 0.5$, one has that the flux is enhanced by one order of magnitude when intrinsic charm is included. In agreement with the results presented in Fig. 1 (a), the contribution of the $cg \to cg$ mechanism is negligible for the No IC case. However, it becomes dominant in the IC case, with the normalization of the prompt flux dependent on the amount of IC.

In Fig. 2 we present our results for the atmospheric ν_μ flux, scaled by a factor E_ν^2, which is the sum of the conventional and prompt contributions. The predictions were obtained considering different values for P_{ic} in the calculation of the prompt contribution. Moreover, for the conventional atmospheric neutrino flux we assume the result derived in Ref. [5]. The resulting predictions are compared with the IceCube data obtained in Ref. [1] for the zenith-averaged flux of atmospheric neutrinos. One has that the prompt contribution enhances the flux at large neutrino energies, with the enhancement being strongly dependent on the magnitude of the $cg \to cg$ mechanism. If this mechanism is disregarded, the results represented by "Conv. + gg" in the figures indicate that the impact of the prompt flux is small in the current kinematical range probed by IceCube. On the other hand, the inclusion of the $cg \to cg$ mechanism
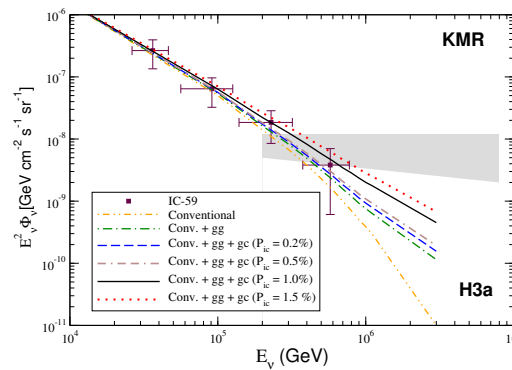
Figure 2: Comparison between our predictions and the experimental IceCube data [1] for the atmospheric ν_μ flux for the KMR uPDFs.

implies a large enhancement of the prompt flux at large E_ν, with the associated magnitude being strongly dependent on the value of P_{ic}. Our results for the KMR uPDF, presented in Fig. 2, indicate that a value of P_{ic} larger than 1.5% implies a prediction for neutrino flux that overestimate the IceCube data at high energies. This result sets the upper limit for the intrinsic charm ammount in the nucleon to $P_{ic} \leq 1.5\%$. Surely, future data can be more restrictive in the acceptable range of values for P_{ic}. It was also shown in our original paper [15] that presence of saturation effects leads to a slightly larger values for P_{ic} that are not discarded by the current IceCube data.

4 Conclusion

We have investigated the impact of the intrinsic charm component in the hadron wave function, which carries a large fraction of the hadron momentum, on the prompt neutrino flux. Our results has indicated that the inclusion of the $cg \rightarrow cg$ mechanism has a strong effect on the prompt neutrino flux. In particular, when the IC component is present, such a mechanism determines the energy dependence of the flux at high energies, with the normalization dependent on the value assumed for the probability to find the IC in the proton wave function.

Acknowledgements

References

[1] M. G. Aartsen et al. [IceCube], *Development of a General Analysis and Unfolding Scheme and its Application to Measure the Energy Spectrum of Atmospheric Neutrinos with IceCube*, Eur. Phys. J. C **75**, 116 (2015), doi:10.1140/epjc/s10052-015-3330-z.

[2] R. Aaij et al. [LHCb], *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s}$ = 13 TeV*, J. High Energy Phys. **03**, 159 (2016) [Erratum: J. High Energy Phys. **09**, 013 (2016); Erratum: J. High Energy Phys. **05**, 074 (2017)], doi:10.1007/JHEP03(2016)159.

[3] V. P. Goncalves, R. Maciuła, R. Pasechnik and A. Szczurek, *Mapping the dominant regions of the phase space associated with $c\bar{c}$ production relevant for the prompt atmospheric neutrino flux*, Phys. Rev. D **96**, 094026 (2017), doi:10.1103/PhysRevD.96.094026.

[4] M. Ahlers, K. Helbing and C. Pérez de los Heros, *Probing particle physics with IceCube*, Eur. Phys. J. C **78**, 924 (2018), doi:10.1140/epjc/s10052-018-6369-9.

[5] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, *Calculation of atmospheric neutrino flux using the interaction model calibrated with atmospheric muon data*, Phys. Rev. D **75**, 043006 (2007), doi:10.1103/PhysRevD.75.043006.

[6] M. Thunman, G. Ingelman and P. Gondolo, *Charm production and high energy atmospheric muon and neutrino fluxes*, Astropart. Phys. **5**, 309 (1996), doi:10.1016/0927-6505(96)00033-3.

[7] V. P. Goncalves, R. Maciuła and A. Szczurek, *From $D_s^{\pm}$ production asymmetry at the LHC to prompt ν_{τ} at IceCube*, Phys. Lett. B **794**, 29 (2019), doi:10.1016/j.physletb.2019.05.026.

[8] A. Bhattacharya, R. Enberg, Y. Seon Jeong, C. S. Kim, M. Hall Reno, I. Sarcevic and A. Stasto, *Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects*, J. High Energy Phys. **11**, 167 (2016), doi:10.1007/JHEP11(2016)167.

[9] R. Maciuła and A. Szczurek, *Intrinsic charm in the nucleon and charm production at large rapidities in collinear, hybrid and k_T-factorization approaches*, J. High Energy Phys. **10**, 135 (2020), doi:10.1007/JHEP10(2020)135.

[10] R. Maciuła and A. Szczurek, *Impact of the LHCb $p + {}^4$He fixed-target $D^0/\bar{D}^0$ data on the intrinisic $c\bar{c}$ component in the nucleon*, Phys. Rev. D **105**, 014001 (2022), doi:10.1103/PhysRevD.105.014001.

[11] S. J. Brodsky, G. I. Lykasov, A. V. Lipatov and J. Smiesko, *Novel heavy-quark physics phenomena*, Prog. Part. Nucl. Phys. **114**, 103802 (2020), doi:10.1016/j.ppnp.2020.103802.

[12] T.-J. Hou et al., *CT14 intrinsic charm parton distribution functions from CTEQ-TEA global analysis*, J. High Energy Phys. **02**, 059 (2018), doi:10.1007/JHEP02(2018)059.

[13] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, *The intrinsic charm of the proton*, Phys. Lett. B **93**, 451 (1980), doi:10.1016/0370-2693(80)90364-0.

[14] G. Watt, A. D. Martin and M. G. Ryskin, *Unintegrated parton distributions and inclusive jet production at HERA*, Eur. Phys. J. C **31**, 73 (2003), doi:10.1140/epjc/s2003-01320-4.

[15] V. P. Goncalves, R. Maciula and A. Szczurek, *Impact of intrinsic charm amount in the nucleon and saturation effects on the prompt atmospheric ν_{μ} flux for IceCube*, arXiv:2103.05503.