From $D_s^\pm$ production asymmetry at the LHC to prompt $\nu_\tau$ at IceCube

Victor P. Goncalves
Instituto de Física e Matemática, Universidade Federal de Pelotas (UFPel),
Caixa Postal 354, CEP 96010-900, Pelotas, RS, Brazil

Rafał Maciula† and Antoni Szczurek‡
Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland

The description of the heavy meson production at large energies and forward rapidities at the LHC is fundamental to derive realistic predictions of the prompt atmospheric neutrino flux at the IceCube Observatory. In particular, the prompt tau neutrino flux is determined by the decay of $D_s$ mesons produced in cosmic ray - air interactions at high energies and large values of the Feynman - $x_F$ variable. Recent data from the LHCb Collaboration indicate a production asymmetry for $D_s^+$ and $D_s^-$ mesons, which cannot be explained in terms of the standard modelling of the hadronization process. In this paper we demonstrate that this asymmetry can be described assuming an asymmetric strange sea ($s(x) \neq \bar{s}(x)$) in the proton wave function and taking into account of the charm and strange fragmentation into $D_s$ mesons. Moreover, we show that the strange quark fragmentation contribution is dominant at large - $x_F$ ($\geq 0.3$). The prompt $\nu_\tau$ flux is calculated and the enhancement associated to the strange quark fragmentation contribution, disregarded in previous calculations, is estimated.

PACS numbers:

Keywords:

Introduction. The experimental results obtained in recent years by the LHC, the Pierre Auger and IceCube Neutrino Observatories have challenged and improved our understanding of Particle Physics. The discovery of the Higgs boson completed the Standard Model (SM), which is now a complete and self-consistent theory. On the other hand, the detection of astrophysical neutrinos by the IceCube Neutrino Observatory sets the beginning of the neutrino astronomy. In addition, the data from the Pierre Auger Observatory provide an unique opportunity to test Particle Physics at energies well beyond current accelerators. Such results motivated, in particular, the development of new and/or more precise approaches to describe the perturbative and nonperturbative regimes of the Quantum Chromodynamics (QCD). One example is the recent improvement in the description of the heavy meson production in hadronic collisions at the LHC, directly influenced by the need to constrain the magnitude of the prompt neutrino flux, which is crucial for a precise determination of the cosmic neutrino flux at the IceCube. In what follows we will explore this direct connection between the LHC and IceCube results and provide more precise predictions for the $D_s$ production at the LHC and the prompt tau neutrino flux at the IceCube.

The atmospheric neutrinos are produced in cosmic-ray interactions with nuclei in Earth’s atmosphere. 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. On the other hand, in the energy range $10^5 \text{ GeV} < E_\nu < 10^7$ GeV, it is expected that the prompt atmospheric neutrino flux associated with the decay of hadrons containing heavy flavours become important. In the particular case of the tau neutrino $\nu_\tau$ flux, it is dominated at low energies by the conventional atmospheric flux, via $\nu_\mu \rightarrow \nu_\tau$ oscillations. On the other hand, for $E_\nu > 10^4$ GeV, this contribution becomes negligible and the prompt $\nu_\tau$ flux is determined by the decay of $D_s$ mesons, which have a leptonic decay channel $D_s \rightarrow \tau \nu_\tau$ with a branching ratio of a few percent, with the subsequent $\tau$ decay that also contributes to the flux. A precise determination of the prompt $\nu_\tau$ flux is fundamental to identify the tau neutrinos of cosmic origin, which is considered another important signature of the cosmic ray origin of the highest neutrino flux. As demonstrated in Ref. 6, the prompt neutrino flux is determined by the heavy meson production at high energies and very forward rapidities. Therefore, the description of the $D_s$ production in the kinematical region probed by the LHCb Collaboration is a requisite to obtain a precise prediction of the prompt $\nu_\tau$ flux.

During the last years, the LHCb Collaboration released a large set of data associated with the $D$ and $B$ meson production. The data for the transverse momentum and rapidity distributions are, in general, quite well described by theoretical approaches. On the other hand, the description of the experimental data for the charge production asymmetries still is a challenge for the great majority of the theoretical approaches. In general, these production asymmetry are interpreted as arising during the nonperturbative process of hadronization as imple-
mented e.g. in the PYTHIA Monte Carlo, which is based on the Lund string fragmentation model. However, this approach fails to describe the recent LHCb data for the \( D^+_s \) production asymmetry, which have found evidence of a nonzero asymmetry. In particular, in contrast with PYTHIA that predicts a positive value, the experimental data indicate that the asymmetry is negative. Very recently, two of us have proposed in Ref. \[14\] an alternative approach to describe the asymmetry present in the \( D^+ \) and \( D^- \) production \[13\]. The basic idea is that subleading contributions for the parton fragmentation are nonnegligible at the LHC energies and that the asymmetry comes from the inherent asymmetry of the \( u \) and \( d \) valence distributions in the incident protons. In this paper we extend the approach for the \( D^+_s \) production and demonstrate that the LHCb data can be described if we assume that the strange quark sea in the proton is asymmetric, with \( s \neq \bar{s} \). Such asymmetry is predicted e.g. by the Meson Cloud Model (see e.g. Refs. \[15\]) and is not excluded by the recent data and by QCD global analysis. In reality, the strange sea in the proton is only poorly known, with its behavior being determined in a great extent by the neutrino - induced DIS data on charm production obtained by the CCFR/NuTeV and NOMAD experiments \[20\] \[21\]. Recent analysis of the LHC data for the \( W^{\pm} \) production improved our understanding of the strange distribution, especially at small - \( x \), but the existence or not of an asymmetric strange sea is still an open question \[22\]. As a consequence, assuming that our approach for the subleading parton fragmentation is correct, the results for the \( D^+_s \) asymmetry can be considered as a first signature that \( s \neq \bar{s} \) in the proton. Finally, the results presented in Ref. \[14\] and in what follows indicate that the subleading contributions to the parton fragmentation are nonnegligible and have a large impact on the Feynman - \( x_F \) distributions of the heavy mesons produced in hadronic collisions. As discussed e.g. in Refs. \[23\] \[24\], this distribution determines the prompt neutrino flux. Therefore, it is expected that the prompt \( \nu_\tau \) flux will be enhanced by these subleading contributions. One of the goals of this paper is to estimate this enhancement and provide realistic predictions for the tau neutrino flux that are based on a formalism that is in agreement with the recent LHCb data.

\( D_s \) production at the LHC. At high energies the charm quarks are produced dominantly by gluon - gluon interactions via the \( gg \rightarrow c\bar{c} \) subprocess and are believed to hadronize to \( D_s \) - mesons mainly through the \( c \rightarrow D_s \) fragmentation process. Therefore, at leading order, we expect an identical amount of \( D^+_s \) and \( D^-_s \) mesons, which implies that the charge asymmetry defined by

\[
AP(D^+_s) = \frac{\sigma(D^+_s) - \sigma(D^-_s)}{\sigma(D^+_s) + \sigma(D^-_s)}
\]

will be zero at this approximation. Consequently, the asymmetries are expected to be generated by subleading partonic subprocesses, initial state asymmetries and/or a distinct description of the hadronization process. Here we extend the approach proposed in Ref. \[14\], which explains the \( D^+/D^- \) asymmetry in terms of the unflavored fragmentation functions, which are responsible for light quark/antiquark fragmentation to \( D \) mesons, for \( D_s \) production. The fact that \( u \neq d \) in the incident protons, naturally leads to the \( D^+/D^- \) asymmetry when the subleading contribution for the fragmentation is taken into account. In contrast, in the case of \( D_s \) production, the inclusion of the subleading fragmentation, associated to the \( s \rightarrow D_s^- \) and \( s \rightarrow D^+_s \) transformations, implies \( AP(D^+_s) = 0 \) if \( s = \bar{s} \). Therefore, our interpretation of the LHCb data is that the \( D^+_s \) asymmetry arises due to an asymmetry in the strange quark sea. As explained before, such a behavior is predicted by some theoretical models and is not excluded by the recent QCD global analysis of the experimental data. In particular, the CTEQ Collaboration has performed a dedicated study of the strange parton distribution of the proton in Ref. \[23\] and obtained that the experimental data is quite well described also assuming that \( s \neq \bar{s} \). In the present paper we shall include the dominant \( g + g \rightarrow c + \bar{c} \) subprocess as well as the \( s/\bar{s} + g \rightarrow s/\bar{s} + g \) and \( g + s/\bar{s} \rightarrow g + s/\bar{s} \) terms with the strange partons from Ref. \[23\]. Moreover, we will include the subleading \( s/\bar{s} \rightarrow D^+_s \) fragmentation, which is described in terms of the probability of transition of a strange quark into a \( D_s \) meson \( (P_{s \rightarrow D_s}) \). Of course, the leading fragmentation is associated with the \( c \rightarrow D^+_s \) and \( \bar{c} \rightarrow D^-_s \) transitions with an associated transition branching of about 5-9% \[24\]. As in Ref. \[14\] the gluon - gluon channel will be calculated within \( k_T \)-factorization approach, with the cross section being expressed in terms of the unintegrated gluon distribution function (UGDF) and off-shell matrix element for the \( gg \rightarrow c\bar{c} \) subprocess.

In the present paper we use the Kimber-Martin-Ryskin (KMR) prescription for UGDF \[25\] which was shown to allow good description of charm production at the LHC \[26\]. In contrast, the \( s(\bar{s}) \rightarrow s(\bar{s}) g \) and \( gs(\bar{s}) \rightarrow gs(\bar{s}) \) processes are calculated within a leading-order collinear approach, with the regulation of small transverse momenta region being done as in Ref. \[14\]. Moreover, the \( c \rightarrow D_s \) fragmentation is described using the Peterson model (with \( \varepsilon = 0.05 \)), while the \( s \rightarrow D_s^- \) and \( s \rightarrow D^+_s \) fragmentation functions are parametrized as in Ref. \[14\] using the reversed-Peterson and triangular fragmentation functions. The only free parameter in our approach is \( P_{s \rightarrow D_s} \). In principle, it is expected to be larger than the value obtained in Ref. \[14\] for the \( u/d \rightarrow D \) transition, due to the larger mass of the strange quark. However, as this quantity is associated with a nonperturbative process, it is not possible to calculate its value from first principles. In what follows, we will constrain \( P_{s \rightarrow D_s} \) using the LHCb data for the charge production asymmetry \( AP(D^+_s) \).
In Fig. 1 we present our results for the $D_s^+ - D_s^-$ asymmetry for $\sqrt{s} = 7$ TeV (left panels) and $\sqrt{s} = 8$ TeV (right panels) using the reversed-Peterson and triangular fragmentation functions for the $s \to D_s$ transition. Rather reasonable agreement with the LHCb data is obtained assuming $P_{s \to D_s} = 7 \cdot 10^{-2}$. In other words, a small value for the unfavoured fragmentation function is sufficient to describe the LHCb data. The data statistics is still too low to perform a more detailed fit and/or to discriminate between the two models for the subleading fragmentation. However, the results indicate that the asymmetry in strangeness in the proton wave function, as described in the CTEQ parametrization, is able to generate the correct sign for $A_P(D_s^+)$, in contrast to PYTHIA [13], as well as the enhancement of the asymmetry at larger rapidities. In Fig. 2 (left panel) we present the resulting predictions for the transverse momentum distributions of $D_s^+ + D_s^-$ for the different ranges of the meson.
A quite well agreement with the LHCb data is achieved without free parameters. We have verified that the contribution of the subleading fragmentation for the $p_T$ -spectra is small ($\lesssim 5\%$) in the kinematical range probed by the LHCb Collaboration. In contrast, the behavior of the rapidity and Feynman - $x_F$ distributions are significantly modified at large values of $y_D$ and $x_F$. In Fig. 2 (right panel) we demonstrate that the asymmetry in the strange sea imply different behaviors for the $x_F$ - distributions of the $D^+_s$ and $D^-_s$ mesons at intermediate $x_F$. More important, while at small - $x_F$ the conventional contribution dominates, at large - $x_F$ the situation is reversed. One has that the contribution associated to the $\bar{s}g \to \bar{s}g$ channel becomes dominant for $x_F \gtrsim 0.05$. In particular, for $x_F \gtrsim 0.3$, the channels initiated by strange quarks, usually disregarded in the analysis of the $D_s$ production, are dominant. Such values of $x_F$ correspond to rapidities larger than those probed by the LHCb detector. However, as demonstrated in Ref. [29], this is exactly the kinematical region that determines the behavior of the prompt neutrino flux. Consequently, the presence of the subleading contributions for the $D_s$ production is expected to have direct impact on the predictions of the prompt tau neutrino flux.

**Prompt $\nu_\tau$ flux at the IceCube.** One of the current goals of the IceCube Observatory is the measurement of tau-neutrinos [28], which are considered an independent probe of the cosmic neutrinos. Such an expectation is strongly motivated by the fact that for cosmic neutrinos the decay of charged pions generated in astrophysical sources implies a ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at the Earth, while for atmospheric neutrinos this ratio is expected to be typically $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 0.1$ [5, 11]. As a consequence, the background associated to atmospheric tau neutrinos is usually predicted to be strongly reduced in comparison to the other flavours, with the measurement of a tau neutrino being considered a direct probe of cosmic neutrinos. However, previous analysis have disregarded the subleading contributions discussed in this paper. It is the aim of the present study to make a realistic estimate of the prompt $\nu_\tau + \overline{\nu}_\tau$ flux when using the current information from the LHC.

In order to estimate the prompt $\nu_\tau + \overline{\nu}_\tau$ flux, we will closely follow the procedure described in detail in Refs. [6, 7]. We will calculate the prompt tau neutrino flux using the semi-analytical $Z$-moment approach [10], where 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. These moments are inputs in the calculation of the prompt tau neutrino flux associated with the production of a $D_s$ meson and its decay into a $\nu_\tau$ in the low- and high-energy regimes. We will focus on vertical fluxes and will assume that the cosmic ray flux $\phi_N$ can be described by the H3a spectrum proposed in Ref. [29], with the incident flux being represented by protons. As in Ref. [11] we will include in our calculations the contribution of neutrinos produced in the direct $D_s \to \nu_\tau$ decay as well as those generated in the chain decay $D_s \to \tau \to \nu_\tau$. The contribution for the prompt $\nu_\tau$ flux associated to the decay of mesons heavier than $tD_s$ is negligible [6] and will not be included in our analysis.

In Fig. 3 (left) we show the flux of the prompt $\nu_\tau + \overline{\nu}_\tau$ flux scaled by $E_{\nu_\tau}^3$. In addition to the conventional component, associated to heavy quark production by a gluon-gluon fusion and represented by the solid black line, we...
Conclusions. In the present paper we propose, for the first time, the description of the production asymmetry for $D^+_s$ and $D^-_s$ mesons in terms of an asymmetry in the strange sea of the proton associated to the inclusion of the subleading fragmentation mechanisms $s \to D^-_s$ or $s \to D^+_s$. We have used asymmetric $s - \bar{s}$ distributions derived in a global analysis of different experimental data and that can be explained within meson cloud picture of the nucleon. We have demonstrate that a small value for the strange fragmentation function into $D_s$ mesons is sufficient to describe the LHCb data. Such a new contribution, disregarded in previous studies, becomes dominant at large values of $x_F$, that is the kinematical range that determines the prompt atmospheric $\nu_\tau$ flux at the IceCube Observatory. We have estimated the impact of this contribution and demonstrated that it implies an enhancement by a factor larger than 3 in the kinematical range probed by the IceCube Observatory. Our results indicate that a future experimental analysis of prompt tau neutrinos at the IceCube can be useful to probe the underlying mechanism of $D_s$ production at high energies and forward rapidities at the LHC.

We have found recently that the production of $\tau$-neutrinos was discussed very recently in the context of intrinsic charm in the nucleon [30] and the beam dump fixed target experiment SHiP at CERN [31]. No reference to the LHCb asymmetry was done there.

Acknowledgments. This study was partially supported by the Polish National Science Center grant DEC-2014/15/B/ST2/02528, by the Center for Innovation and Transfer of Natural Sciences and Engineering Knowledge in Rzeszów and by the Brazilian funding agencies CNPq, FAPERGS and INCT-FNA (process number 464898/2014-5).

[1] G. Aad et al. (ATLAS Collaboration), Phys. Lett. B 716, 1 (2012); S. Chatrchyan et al. (CMS collaboration), Phys. Lett. B 716, 30 (2012).
[2] M. G. Aartsen et al. (IceCube Collaboration), Science 342, 1242856 (2013).
[3] A. Aab et al. (Pierre Auger Collaboration), Phys. Rev. Lett. 117, no. 19, 192001 (2016).
[4] M. V. Garzelli, S. Moch and G. Sigl, JHEP 1510, 115 (2015); A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic and A. Stasto, JHEP 1506, 110 (2015);
R. Gauld, J. Rojo, L. Rottoli and J. Talbert, JHEP 1511, 009 (2015); R. Gauld, J. Rojo, L. Rottoli, S. Sarkar and J. Talbert, JHEP 1602, 130 (2016); F. Halzen and L. Wille, Phys. Rev. D 94, 014014 (2016); R. Laha and S. J. Brodsky, Phys. Rev. D 96, 123002 (2017); M. V. Garzelli et al. [PROSA Collaboration], JHEP 1705, 004 (2017); M. Benzke, M. V. Garzelli, B. Kniehl, G. Kramer, S. Moch and G. Sigl, JHEP 1712, 021 (2017).

[5] A. Bhattacharya, R. Enberg, Y. S. Jeong, C. S. Kim, M. H. Reno, I. Sarcevic and A. Stasto, JHEP 1611, 167 (2016).

[6] V. Goncalves, R. Maciula, R. Pasechnik and A. Szczurek, Phys. Rev. D96 (2017) 094026.

[7] A. V. Giannini, V. P. Goncalves and F. S. Navarra, Phys. Rev. D 98, no. 1, 014012 (2018).

[8] T. Gaisser and F. Halzen, Ann. Rev. Nucl. Part. Sci. 64, 101 (2014)

[9] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, Phys. Rev. D 75, 043006 (2007).

[10] P. Gondolo, G. Ingelman and M. Thunman, Astropart. Phys. 5, 309 (1996).

[11] L. Pasquali and M. H. Reno, Phys. Rev. D 59, 093003 (1999).

[12] R. Aaij et al. (LHCb Collaboration), Phys. Lett. B 718, 902 (2013).

[13] R. Aaij et al. (LHCb Collaboration), J. High Energy Phys. 08, 008 (2018).

[14] R. Maciula and A. Szczurek, Phys. Rev. D 97, no. 7, 074001 (2018).

[15] H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A569, 631 (1996).

[16] G. Q. Feng, F. G. Cao, X. H. Guo and A. I. Signal, Eur. Phys. J. C 72, 2250 (2012).

[17] E.R. Cazaroto, V.P. Goncalves, E.S. Navarra and M. Nielsen, Phys. Lett. B724, 108 (2013).

[18] X. G. Wang, C. R. Ji, W. Melnitchouk, Y. Salamu, A. W. Thomas and P. Wang, Phys. Lett. B 762, 52 (2016); Phys. Rev. D 94, no. 9, 094035 (2016).

[19] M. Goharipour, Nucl. Phys. A 973, 60 (2018).

[20] A. O. Bazarko et al. (CCFR Collaboration), Z. Phys. C 65, 189 (1995).

[21] G.P. Zeller et al. (NuTeV Collaboration), Phys. Rev. D65, 111103(R) (2002).

[22] A. M. Cooper-Sarkar and K. Wichmann, Phys. Rev. D 98, no. 1, 014027 (2018)

[23] H. L. Lai, P. M. Nadolsky, J. Pumplin, D. Stump, W. K. Tung and C.-P. Yuan, J. High Energy Phys. 04, 089 (2007).

[24] M. Lisovyi, A. Verbytskyi and O. Zenaiev, Eur. Phys. J. C 76, no. 7, 397 (2016).

[25] G. Watt, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C 31, 73 (2003).

[26] R. Aaij et al. (LHCb Collaboration), Nucl. Phys. B 871, 1 (2013).

[27] R. Maciula and A. Szczurek, Phys. Rev. D 87, no. 9, 094022 (2013).

[28] M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. D 93, no. 2, 022001 (2016); M. Usner [IceCube Collaboration], PoS ICRC 2017, 974 (2018).

[29] T. K. Gaisser, Astropart. Phys. 35, 801 (2012).

[30] W. Bai and M. Hall Reno, arXiv:1807.02746.

[31] M. Anelli et al. (SHiP Collaboration), arXiv:1504.04956.