



# Searching for intrinsic charm in the proton at the LHC <sup>☆</sup>



V.A. Bednyakov <sup>a</sup>, M.A. Demichev <sup>a</sup>, G.I. Lykasov <sup>a</sup>, T. Stavreva <sup>b,\*</sup>, M. Stockton <sup>c</sup>

<sup>a</sup> Joint Institute for Nuclear Research, Dubna 141980, Moscow region, Russia

<sup>b</sup> Laboratoire de Physique Subatomique et de Cosmologie, UJF, CNRS/IN2P3, INPG, 53 avenue des Martyrs, 38026 Grenoble, France

<sup>c</sup> Department of Physics, McGill University, Montreal, QC, Canada

## ARTICLE INFO

### Article history:

Received 21 May 2013

Received in revised form 9 December 2013

Accepted 9 December 2013

Available online 16 December 2013

Editor: D.F. Geesaman

## ABSTRACT

Despite rather long-term theoretical and experimental study, the hypothesis of the non-zero intrinsic (or valence-like) heavy quark component of the proton distribution functions has not yet been confirmed or rejected. The LHC with  $pp$ -collisions at  $\sqrt{s} = 7\text{--}14$  TeV will obviously supply extra unique information concerning the above-mentioned component of the proton. To use the LHC potential, first of all, one should select the parton-level (sub)processes (and final-state signatures) that are the most sensitive to the intrinsic heavy quark contributions. To this end inclusive production of  $c(b)$ -jets accompanied by photons is considered. On the basis of performed theoretical study it is demonstrated that investigation of the intrinsic heavy quark contributions looks very promising at the LHC in processes like  $pp \rightarrow \gamma + c(b) + X$ .

© 2013 The Authors. Published by Elsevier B.V. All rights reserved.

## 1. Introduction

The Large Hadron Collider (LHC) opens up new and unique kinematical regions with high accuracy for the investigation of the structure of the proton, in particular for the study of the parton distribution functions (PDFs). It is well known that the precise knowledge of the PDFs is very essential for the verification of the Standard Model and the search for New Physics.

By definition, the PDF  $f_a(x, \mu)$  is a function of the proton momentum fraction  $x$  carried by parton  $a$  (quark  $q$  or gluon  $g$ ) at the momentum transfer scale  $\mu$ . For small values of  $\mu$ , corresponding to long distance scales less than  $1/\mu_0$ , the PDF currently cannot be calculated from the first principles of QCD [1]. At  $\mu > \mu_0$  the  $f_a(x, \mu)$  can be obtained by means of solving the perturbative QCD evolution equations (DGLAP) [2]. At  $\mu < \mu_0$  some progress in calculation of the PDFs has been achieved within the lattice methods [1]. The unknown (input for the evolution) functions  $f_a(x, \mu_0)$  usually can be found empirically from some “QCD global analysis” [3,4] of a large variety of data typically at  $\mu > \mu_0$ .

In general, almost all  $pp$  processes at LHC energies, including Higgs boson production, are sensitive to the charm  $f_c(x, \mu)$

or bottom  $f_b(x, \mu)$  PDFs. Nevertheless, within the global analysis the charm content of the proton at  $\mu \sim \mu_c$  and the bottom at  $\mu \sim \mu_b$  are both assumed to be negligible. Here  $\mu_c$  and  $\mu_b$  are typical energy scales relevant to the  $c$ - and  $b$ -quark QCD excitation in the proton. These heavy quark components arise in the proton only perturbatively with increases in the  $Q^2$ -scale through the gluon splitting in the DGLAP  $Q^2$  evolution [2]. Direct measurement of open charm and open bottom production in deep inelastic processes (DIS) confirms the perturbative origin of heavy quark flavors [5]. However, modern descriptions of these experimental data are not sensitive enough to the above-mentioned perturbative sea heavy quark distributions at relatively large  $x$  values ( $x > 0.1$ ).

Analyzing hadroproduction of so-called leading hadrons Brodsky et al. [6,7] (about thirty years ago) has assumed co-existing of *extrinsic* and *intrinsic* contributions to the quark–gluon structure of the proton. The *extrinsic* (or ordinary) quarks and gluons are generated on a short time scale associated with large-transverse-momentum processes. Their distribution functions satisfy the standard QCD evolution equations. The *intrinsic* quarks and gluons exist over a time scale which is independent of any probe momentum transfer. They can be associated with a bound-state (zero-momentum transfer regime) hadron dynamics and one believes they have a nonperturbative origin.

It was shown in [7] that the existence of *intrinsic* heavy quark pairs  $c\bar{c}$ , and  $b\bar{b}$  within the proton state can be due to the virtue of gluon-exchange and vacuum-polarization graphs. On this basis, within the MIT bag model [8], the probability to find a five-quark component  $|uudc\bar{c}\rangle$  bound within the nucleon bag is non-zero and can be about 1–2%.

<sup>☆</sup> This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

\* Corresponding author.

E-mail addresses: Vadim.Bednyakov@cern.ch (V.A. Bednyakov), Mikhail.Demichiev@cern.ch (M.A. Demichev), gennady.lykasov@cern.ch (G.I. Lykasov), stavreva@ipsc.in2p3.fr (T. Stavreva), mark.stockton@cern.ch (M. Stockton).

Initially in [6,7] S. Brodsky and coauthors proposed the existence of the 5-quark state  $|uudc\bar{c}\rangle$  in the proton. Later some other models were developed. One of them considered a quasi-two-body state  $\bar{D}^0(u\bar{c})\Lambda_c^+(udc)$  in the proton [9]. In order to not contradict the DIS HERA data the probability to find the intrinsic charm (IC) in the proton (the weight of the relevant Fock state in the proton) was found to be less than 3.5% [9–12]. The probability of finding an intrinsic bottom state (IB) in the proton is suppressed by a factor of  $m_c^2/m_b^2 \simeq 0.1$  [13], where  $m_c \simeq 1.3$  GeV and  $m_b = 4.2$  GeV are the current masses of the charm and bottom quarks. Therefore, the experimental search for a possible IC signal in  $pp$  collisions at the LHC energies is more promising than the search for the IB contribution.

If the distributions of the intrinsic charm or bottom in the proton are hard enough and similar in the shape to the valence quark distributions (i.e. have valence-like form), then one expects the production of the charmed (bottom) mesons or charmed (bottom) baryons in the fragmentation region to be similar to the production of pions or nucleons (from the light quarks). However, the yield of this production depends on the probability to find intrinsic charm or bottom in the proton, but this amount looks too small. The PDFs that include the IC contribution in the proton have already been used in perturbative QCD calculations in [9–12].

The probability distribution for the 5-quark state ( $|uudc\bar{c}\rangle$ ) in the light-cone description of the proton was first calculated in [6]. The general form for this distribution calculated within the light-cone dynamics in the so-called BHPS model [6,7] can be written as [11]

$$P(x_1, \dots, x_5) = N_5 \delta\left(1 - \sum_{j=1}^5 x_j\right) \left(m_p^2 - \sum_{j=1}^5 \frac{m_j^2}{x_j}\right)^{-2}, \quad (1)$$

where  $x_j$  is the momentum fraction of the parton,  $m_j$  is its mass and  $m_p$  is the proton mass. Neglecting the light quark ( $u, d, s$ ) masses and the proton mass in comparison to the  $c$ -quark mass and integrating (1) over  $dx_1 \dots dx_4$  one can get the probability to find the intrinsic charm with momentum fraction  $x_5$  in the proton [11]:

$$P(x_5) = \frac{1}{2} \tilde{N}_5 x_5^2 \left[ \frac{1}{3} (1 - x_5) (1 + 10x_5 + x_5^2) - 2x_5 (1 + x_5) \ln(x_5) \right], \quad (2)$$

where  $\tilde{N}_5 = N_5/m_{4,5}^4$ ,  $m_{4,5} = m_c = m_{\bar{c}}$ , the normalization constant  $N_5$  determines some probability  $w_{1C}$  to find the Fock state  $|uudc\bar{c}\rangle$  in the proton. Fig. 1 illustrates the IC contribution in comparison to the conventional sea charm quark distribution in the proton.

The solid line in Fig. 1 shows the standard perturbative sea charm density distribution  $x_{c_{\text{reg}}}(x)$  (ordinary sea charm) in the proton from CTEQ6.6M [12] as a function of  $x$  at  $Q^2 = 1000$  GeV<sup>2</sup>. The dashed curve in Fig. 1 is the sum of the intrinsic charm density  $x_{c_{\text{in}}}(x)$  from CTEQ6.6C2 BHPS with the IC probability  $w_{1C} = 3.5\%$  and  $x_{c_{\text{reg}}}(x)$  at the same  $Q^2$  [12]. One can see from Fig. 1 that the IC distribution (with  $w_{1C} = 3.5\%$ ) given by (2) has a rather visible enhancement at  $x \sim 0.2-0.5$  and this distribution is much larger (by an order and more of magnitude) than the sea (ordinary) charm density distribution in the proton.

As a rule, the gluons and sea quarks play the key role in hard processes of open charm hadroproduction. Simultaneously, due to the nonperturbative *intrinsic* heavy quark components one can expect some excess of these heavy quark PDFs over the ordinary sea quark PDFs at  $x > 0.1$ . Therefore the existence of this intrinsic charm component can lead to some enhancement in the

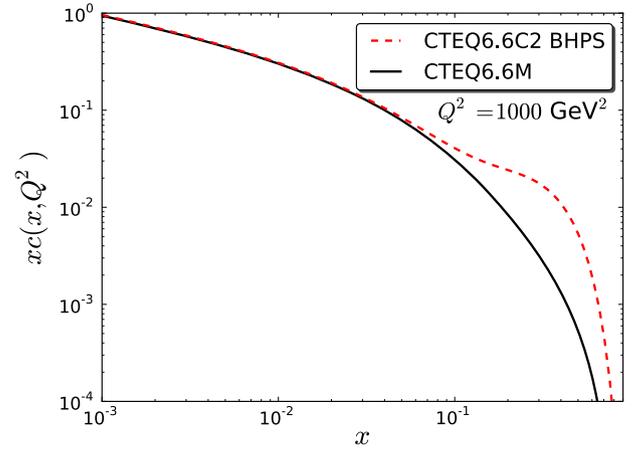


Fig. 1. Distributions of the charm quark in the proton at  $Q^2 = 1000$  GeV<sup>2</sup>. The solid line is the standard perturbative sea charm density distribution  $x_{c_{\text{reg}}}(x)$  only, whereas the dashed curve is the charm quark distribution function, for the sum of the intrinsic charm density  $x_{c_{\text{in}}}(x)$  (see (2)) and  $x_{c_{\text{reg}}}(x)$ .

inclusive spectra of open charm hadrons, in particular  $D$ -mesons, produced at the LHC in  $pp$ -collisions at large pseudorapidities  $\eta$  and large transverse momenta  $p_T$  [15]. Furthermore, as we know from [6–12] photons produced in association with heavy quarks  $Q$  ( $\equiv c, b$ ) in the final state of  $pp$ -collisions provide valuable information about the parton distributions in the proton [9–23].

In this Letter, having in mind these considerations we will first discuss where the above-mentioned heavy flavor Fock states in the proton could be searched for at the LHC energies. Following this we analyze in detail, and give predictions for, the LHC semi-inclusive  $pp$ -production of prompt photons accompanied by  $c$ -jets including the *intrinsic* charm component in the PDF.

## 2. The intrinsic charm and beauty

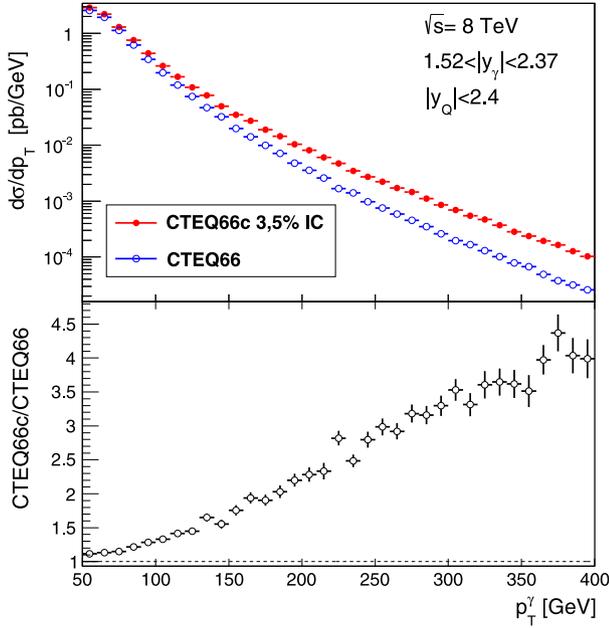
According to the model of hard scattering [24–29] the relativistic invariant inclusive spectrum of the hard process  $p + p \rightarrow h + X$  can be related to the elastic parton-parton subprocess  $i + j \rightarrow i' + j'$ , where  $i, j$  are the partons (quarks and gluons), by the formula [26,27]:

$$E \frac{d\sigma}{d^3p} = \sum_{i,j} \int d^2k_{iT} \int_{x_i^{\min}}^1 d^2k_{jT} \int_{x_j^{\min}}^1 dx_i \int dx_j f_i(x_i, k_{iT}) f_j(x_j, k_{jT}) \frac{d\sigma_{ij}(\hat{s}, \hat{t})}{d\hat{t}} \frac{D_{i,j}^h(z_h)}{\pi z_h}. \quad (3)$$

Here:  $k_{i,j}$  and  $k'_{i,j}$  are the four-momenta of the partons  $i$  or  $j$  before and after the elastic parton-parton scattering, respectively;  $k_{iT}, k_{jT}$  are the transverse momenta of the partons  $i$  and  $j$ ;  $f_{i,j}$  are the PDFs of partons  $i, j$  inside the proton;  $D_{i,j}^h$  is the fragmentation function (FF) of the parton  $i$  or  $j$  to a hadron  $h$ ; and  $z_h$  is the fraction of the final state hadron momentum from the parton momentum.

When the transverse momenta of the partons are neglected in comparison to the longitudinal momenta, the variables  $\hat{s}, \hat{t}, \hat{u}$  and  $z_h$  can be presented in the following form [26]:  $\hat{s} = x_i x_j s$ ,  $\hat{t} = x_i \frac{t}{z_h}$ ,  $\hat{u} = x_j \frac{u}{z_h}$ ,  $z_h = \frac{x_1}{x_i} + \frac{x_2}{x_j}$ , where  $x_1 = -\frac{u}{s} = \frac{x_T}{2} \cot(\theta/2)$ ,  $x_2 = -\frac{t}{s} = \frac{x_T}{2} \tan(\theta/2)$ ,  $x_T = 2\sqrt{tu}/s = 2p_T/\sqrt{s}$ . Here as usual,  $s = (p_1 + p_2)^2$ ,  $t = (p_1 - p'_1)^2$ ,  $u = (p_2 - p'_1)^2$ , and  $p_1, p_2, p'_1$  are the 4-momenta of the colliding protons and the produced hadron  $h$ , respectively;  $\theta$  is the scattering angle of hadron  $h$  in the  $pp$  c.m.s. The lower





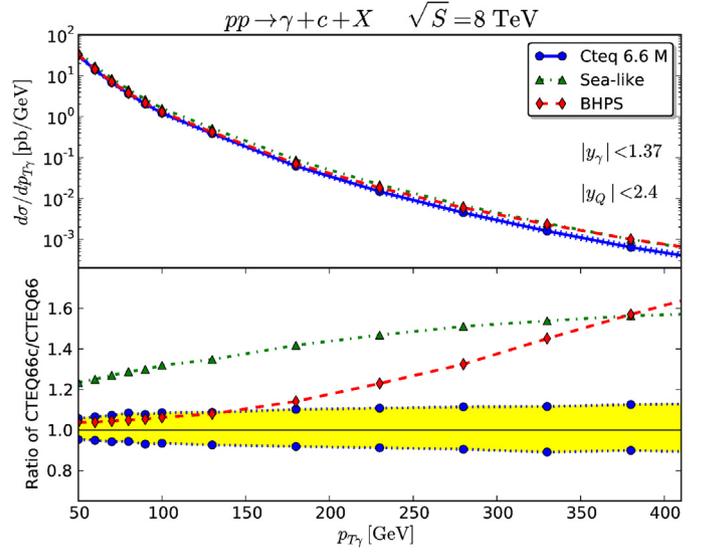
**Fig. 3.** The distribution  $d\sigma/dp_T^\gamma$  of prompt photons produced in the reaction  $pp \rightarrow \gamma c X$  over the transverse momentum  $p_T^\gamma$  integrated over  $dy$  in the interval  $1.52 < |y_\gamma| < 2.37$ ,  $|y_c| < 2.4$  at  $\sqrt{s} = 8$  TeV. The red open points correspond to the inclusion of the IC contribution in PDF CTEQ66c with the IC probability of about 3.5% [12]; the blue solid points is our calculation using the CTEQ66 without the IC contribution in the proton. The calculation was done within PYTHIA8 using the LO QCD and including the ISR, FSR and MPI.

if the IC is included and the IC signal reaches 250–300%. It corresponds to 800–3000 events in the 5 GeV/c bin for the luminosity  $L = 20 \text{ fb}^{-1}$ . This means that even if the ATLAS/CMS  $c$ -jet reconstruction efficiency is low, there would still be plenty of statistics to make this measurement (even more so as the experimental bins are likely to be larger than the 5 GeV resolution shown here). Note that experimentally one can select the light and heavy ( $c$  and  $b$ ) jets at the LHC. Some estimations of this are in progress now.

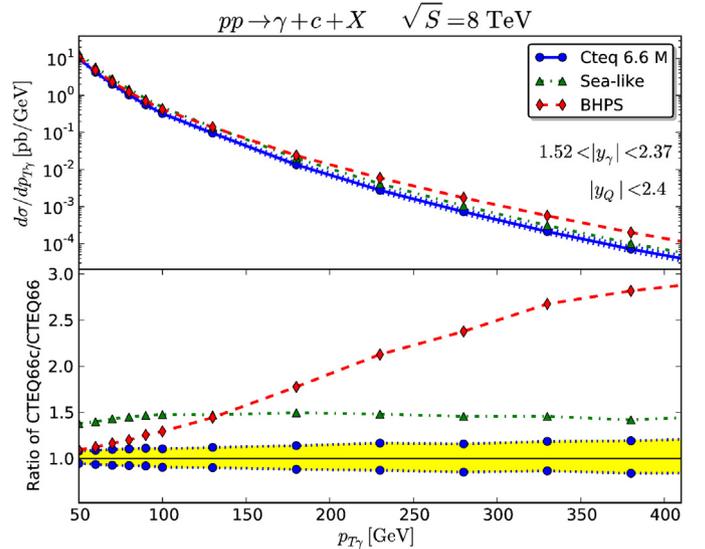
Naturally the  $p_T^\gamma$  distribution in Fig. 3 has the same form as the distribution over the transverse momentum of the  $c$ -quark,  $p_T^c$ , when only the hard subprocess  $g + c \rightarrow \gamma + c$  in Fig. 2 is included.

In Fig. 4 the differential cross-section  $d\sigma/dp_T^\gamma$  calculated at NLO in the massless quark approximation as described in [31] is presented as a function of the transverse momentum of the prompt photon. The following cuts are applied:  $p_T^\gamma > 45$  GeV,  $p_T^c > 20$  GeV with the  $c$ -jet pseudorapidity in the interval  $|y_c| \leq 2.4$  and the photon pseudorapidity in the central region  $|y_\gamma| < 1.37$ . The solid blue line represents the differential cross-section calculated with the radiatively generated charm (CTEQ66), the dash-dotted green line uses as input the sea-like PDF (CTEQ66c4) and the dashed red line the BHPS PDF (CTEQ66c2). In the lower half of Fig. 4 the above distributions normalized to the distribution acquired using the CTEQ66 PDF and  $\mu_r = \mu_f = \mu_F = p_T^\gamma$ , are presented. The shaded yellow region, represents the scale dependence. Clearly the difference between the spectrum using the BHPS IC PDF and the one using the radiatively generated PDF increases as  $p_T^\gamma$  increases.

In Fig. 5 the same distributions as in Fig. 4 are shown, however for forward photon rapidity  $1.52 < |y_\gamma| < 2.37$ . In this case larger  $x$  values are probed and therefore we start to observe the difference between the solid and dashed (dash-dotted) lines at smaller  $p_T^\gamma$  values than in Fig. 4. The difference when using the BHPS IC PDFs is about 200% at  $p_T^\gamma \sim 200$  GeV. In this rapidity region the difference between the BHPS and sea-like spectra is clearly visible even as early as  $p_T^\gamma \sim 200$  GeV. However, while the IC is more



**Fig. 4.** The  $d\sigma/dp_T^\gamma$  distribution versus the transverse momentum of the photon for the process  $pp \rightarrow \gamma + c + X$  at  $\sqrt{s} = 8$  TeV using CTEQ6.6M (solid blue line), BHPS CTEQ6c2 (dashed red line) and sea-like CTEQ6c4 (dash-dotted green line), for central photon rapidity  $|y_\gamma| < 1.37$  (top). The ratio of these spectra with respect to the CTEQ6.6M (solid blue line) distributions (bottom). The calculation was done within the NLO QCD approximation.

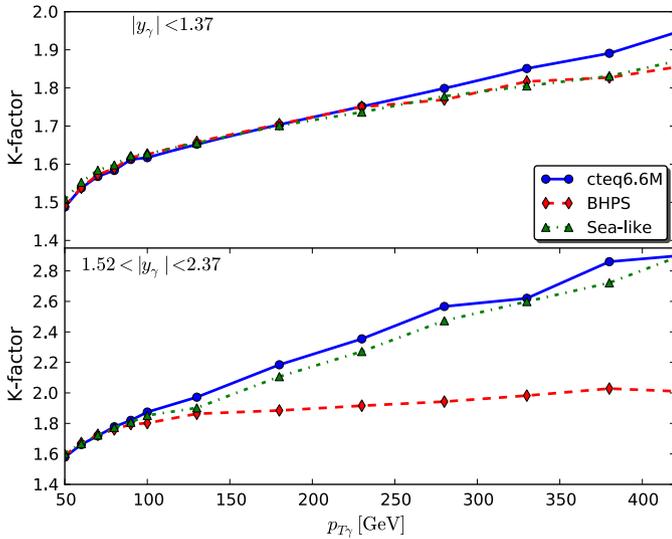


**Fig. 5.** The same as Fig. 4, but for forward photon rapidity  $1.52 < |y_\gamma| < 2.37$ .

accentuated, the cross-section and hence the number of events is less than those for the photon central rapidity in Fig. 4.

Note that comparing Fig. 3 to Fig. 5 one can see that both the LO QCD and NLO QCD cross-section results in approximately the same IC contribution, which increases when the photon transverse momentum grows. Nevertheless the values of the spectra calculated within the NLO QCD are larger by a factor of about 1.3 than the ones obtained within the LO QCD at  $p_T^\gamma > 100$  GeV/c including the ISR, FSR and the MPI. Note that all the calculations presented in Figs. 3–5 were done for the isolated photons.

Therefore Figs. 3, 5 show that the IC signal could be visible at the LHC energies with both the ATLAS and CMS detectors in the process  $pp \rightarrow \gamma + c + X$  when  $p_T^\gamma \simeq 150$  GeV/c. In the region the IC signal dominates over the all non-intrinsic charm background with significance at a level of a factor of 2 (in fact 170%).



**Fig. 6.** The so-called QCD K-factor, or the ratio of the NLO contribution to the LO one, for the central photon rapidity region  $|y_\gamma| < 1.37$  (top), and the forward photon rapidity  $1.52 < |y_\gamma| < 2.37$  (bottom).

In Fig. 6 the K-factor, or the ratio between the NLO and LO contributions to the photon and charm jet cross-section, for the central and forward rapidity regions is presented showing the dependence of the different initial state PDFs. It is clear that the K-factor using the BHPs PDF at  $p_{T\gamma}$  ranges where the  $x$  is large is much smaller with respect to the one using the radiatively generated charm PDF. The dependence on the heavy quark PDF is felt in the LO Compton subprocess ( $gQ \rightarrow \gamma Q$ ), whose contribution increases. At NLO it is the higher order correction,  $gQ \rightarrow gQ\gamma$  to the Compton subprocess that dominates the cross-section [34], which also increases when using the BHPs PDF, while the rest of the NLO contributions not dependent on the heavy quark PDF remain the same. This increase in the LO with respect to the NLO when using the BHPs PDFs causes the K-factor for the BHPs to decrease, at high  $p_T$ , as well as in particular in the forward rapidity range, where an even higher  $x$  is probed.

#### 4. Conclusion

In this Letter we have shown that the possible existence of the intrinsic heavy quark components in the proton can be seen not only in the forward open heavy flavor production in  $pp$ -collisions (as it was believed before) but it can be visible also in the semi-inclusive  $pp$ -production of prompt photons and  $c$ -jets at rapidities  $1.5 < |y_\gamma| < 2.4$ ,  $|y_c| < 2.4$  and large transverse momenta of photons and jets. In the inclusive photon spectrum measured together with a  $c$ -jet a rather visible enhancement can appear due to the intrinsic charm (IC) quark contribution. In particular, it was shown that the IC contribution can produce much more events (factor 2 or 3) at  $p_T^\gamma > 150$  GeV/ $c$  and forward  $y_\gamma$  in comparison with the relevant number expected in the absence of the IC. Furthermore the same enhancement is also coherently expected in the transverse momentum,  $p_T^c$ , distribution of the  $c$ -jet measured together with the above-mentioned prompt photon in the  $pp \rightarrow \gamma + c\text{-jet} + X$  process.

Searching for the signal of *intrinsic* charm in such processes is more pronounced than the search for the *intrinsic* bottom because

the IB probability is, at least, in 10 times smaller than the IC probability in the proton.

Experimentally, measuring this channel will be complicated due to the light and bottom quark backgrounds, but with such a large difference between models it should still be visible in the kinematic ranges suggested here.

#### Acknowledgements

We thank S.J. Brodsky and A.A. Glasov for extremely helpful discussions and recommendations by the study of this topic. The authors are grateful to H. Jung, A.V. Lipatov, V.A.M. Radescu, A. Sarkar and N.P. Zotov for very useful discussions and comments. This research was also supported by the RFBR grants No. 11-02-01538-a and No. 13-02001060.

#### References

- [1] J.W. Negele, et al., Nucl. Phys. B, Proc. Suppl. 128 (2004) 170; W. Schroers, Nucl. Phys. A 755 (2005) 333.
- [2] V.N. Gribov, L.N. Lipatov, Sov. J. Nucl. Phys. 15 (1972) 438; G. Altarelli, G. Parisi, Nucl. Phys. B 126 (1997) 298; Yu.L. Dokshitzer, Sov. Phys. JETP 46 (1977) 641.
- [3] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky, W.K. Tung, J. High Energy Phys. 0207 (2002) 012; D.R. Stump, J. Huston, J. Pumplin, W.K. Tung, H.L. Lai, S. Kuhlmann, J.F. Owens, J. High Energy Phys. 0310 (2003) 046.
- [4] R.S. Thorne, A.D. Martin, W.J. Stirling, R.G. Roberts, arXiv:hep-ph/0407311.
- [5] A. Aktas, et al., H1 Collaboration, Eur. Phys. J. C 40 (2005) 349, arXiv:hep-ex/0507081.
- [6] S. Brodsky, P. Hoyer, C. Peterson, N. Sakai, Phys. Lett. B 93 (1980) 451.
- [7] S. Brodsky, C. Peterson, N. Sakai, Phys. Rev. D 23 (1981) 2745.
- [8] J.F. Donoghue, E. Golowich, Phys. Rev. D 15 (1977) 3421.
- [9] J. Pumplin, Phys. Rev. D 73 (2006) 114015.
- [10] J. Pumplin, H.L. Lai, W.K. Tung, Phys. Rev. D 75 (2007) 054029.
- [11] Jen-Chien Peng, Wen-Chen Chang, in: Sixth Intern. Conf. on Quarks and Nuclear Physics, Ecole Polytechnique Palaiseau, Paris, April 16–20, 2012, arXiv:1207.2193 [hep-ph].
- [12] P.M. Nadolsky, et al., Phys. Rev. D 78 (2008) 013004.
- [13] M.V. Polyakov, A. Schafer, O.V. Teryaev, Phys. Rev. D 60 (1999) 051502.
- [14] V. Goncalves, F. Navarra, Nucl. Phys. A 842 (2010) 59.
- [15] G.I. Lykasov, V.A. Bednyakov, A.F. Pikelner, N.I. Zimin, Europhys. Lett. 99 (2012) 21002, arXiv:1205.1131v2 [hep-ph].
- [16] V.A. Litvine, A.K. Likhoded, Phys. At. Nucl. 62 (1999) 679.
- [17] V.M. Abazov, et al., Phys. Rev. Lett. 102 (2009) 192002, arXiv:0901.0739 [hep-ex].
- [18] V.M. Abazov, et al., Phys. Lett. B 719 (2013) 354, arXiv:1210.5033 [hep-ex].
- [19] V.M. Abazov, et al., Phys. Lett. B 714 (2012) 32, arXiv:1203.5865 [hep-ex].
- [20] T. Aaltonen, et al., Phys. Rev. D 81 (2010) 052006, arXiv:0912.3453 [hep-ex].
- [21] R. Vogt, Prog. Part. Nucl. Phys. 45 (2000) S105.
- [22] F.S. Navarra, M. Nielsen, C.A.A. Nunes, M. Teixeira, Phys. Rev. D 54 (1996) 842.
- [23] W. Melnichouk, A.W. Thomas, Phys. Lett. B 414 (1997) 134.
- [24] A.V. Efremov, Sov. J. Nucl. Phys. 19 (1974) 176.
- [25] P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. B 327 (1989) 49.
- [26] R.D. Field, R.P. Feynman, Phys. Rev. D 15 (1977) 2590.
- [27] R.P. Feynman, R.D. Field, G.C. Fox, Phys. Rev. D 18 (1977) 3320.
- [28] M.L. Mangano, Phys. Usp. 53 (2010) 109.
- [29] S. Albino, B.A. Kniehl, G. Kramer, AKK08, Nucl. Phys. B 803 (2008) 42.
- [30] B. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, Eur. Phys. J. C 72 (2012) 2082, arXiv:1202.0439v1 [hep-ph].
- [31] T.P. Stavreva, J.F. Owens, Phys. Rev. D 79 (2009) 054017, arXiv:0901.3791 [hep-ph].
- [32] A.V. Lipatov, M.A. Malyshev, N.P. Zotov, J. High Energy Phys. 1205 (2012) 104, arXiv:1204.3828 [hep-ph].
- [33] T. Sjostrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. 178 (2008) 852.
- [34] T. Stavreva, et al., J. High Energy Phys. 1101 (2011) 152, arXiv:1012.1178 [hep-ph].
- [35] ATLAS Collaboration, J. Instrum. 3 (2008) S08003.
- [36] CMS Collaboration, J. Instrum. 3 (2008) S08004.