Nucleon structure and hard p-p processes at high energies

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Abstract

The production of heavy flavour hadrons in \( pp \) collisions at large values of their transverse momenta can be a new unique source for estimation of intrinsic heavy quark contribution to the proton. We analyze the inclusive production of the open strangeness and the semi-inclusive hard processes of the photon and vector boson production accompanied by the \( c \)- or \( b \)-jets in \( pp \) collisions. We show that one should select the parton-level (sub)processes (and final-state signatures) that are the most sensitive to the intrinsic heavy quark contributions. We present some predictions for these processes made within the perturbative QCD including the intrinsic strangeness and intrinsic charm in the proton that can be verified in the NA61 experiment and at LHC.

1. Intrinsic heavy flavours in the proton

The NA61 (CERN), CBM (Darmstadt) and NICA (Dubna) experiments can be a useful laboratory for investigation of the unique structure of the proton, in particular for the study of the parton distribution functions (PDFs) with high accuracy. It is well known that the precise knowledge of these PDFs is very important for verification of the Standard Model and 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 QCD momentum transfer scale \( \mu \). For small values of \( \mu \), corresponding to the long distance scales less than \( 1/\mu_0 \), the PDF cannot be calculated from the first principles of QCD (although some progress in this direction has been recently achieved within the lattice methods [1]). The PDF \( f_a(x, \mu) \) at \( \mu > \mu_0 \) can be calculated by solving the perturbative QCD evolution equations (DGLAP) [2]. The unknown (input for the evolution) functions \( f_a(x, \mu_0) \) can usually 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 that took place at the LHC energies, including the 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 one 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 increasing \( Q^2 \)-scale through the gluon splitting in the DGLAP \( Q^2 \) evolution [2]. Direct measurement of the open charm and open bottom production in the deep
inelastic processes (DIS) confirms the perturbative origin of heavy quark flavours [5]. However, the description of these experimental data is not sensitive to the heavy quark distributions at relatively large $x$ ($x > 0.1$).

As was assumed by Brodsky with coauthors in [6, 7], there are extrinsic and intrinsic contributions to the quark-gluon structure of the proton. Extrinsic (or ordinary) quarks and gluons are generated on a short time scale associated with a large-transverse-momentum processes. Their distribution functions satisfy the standard QCD evolution equations. Intrinsic quarks and gluons exist over a time scale which is independent of any probe momentum transfer. They can be associated with bound-state (zero-momentum transfer regime) hadron dynamics and are believed to be of nonperturbative origin. Figure 1 gives a schematic view of a nucleon, which consists of three valence quarks $q_v$, quark-antiquark $q\bar{q}$ and gluon sea, and, for example, pairs of the intrinsic charm ($q^{c}_{in}\bar{q}^{c}_{in}$) and intrinsic bottom quarks ($q^{b}_{in}\bar{q}^{b}_{in}$).

![Figure 1: Schematic presentation of a nucleon consisting of three valence quarks $q_v$, quark-antiquark $q\bar{q}$ and gluon sea, and pairs of the intrinsic charm ($q^{c}_{in}\bar{q}^{c}_{in}$) and intrinsic bottom quarks ($q^{b}_{in}\bar{q}^{b}_{in}$).](image)

It was shown in [7] that the existence of intrinsic heavy quark pairs $c\bar{c}$ and $b\bar{b}$ within the proton state could 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 the five-quark component $|uudcc\rangle$ bound within the nucleon bag was estimated to be about 1–2%.

Initially in [6, 7] S.Brodsky with coauthors have proposed existence of the 5-quark state $|uudcc\rangle$ in the proton (Fig. 1). 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 [9]–
The probability to find the intrinsic charm (IC) in the proton (the weight of the relevant Fock state in the proton) was assumed to be 1–3.5%. The probability of the intrinsic bottom (IB) in the proton is suppressed by the factor \( m_c^2/m_b^2 \approx 0.1 \) [12], where \( m_c \) and \( m_b \) are the masses of the charmed and bottom quarks. Nevertheless, it was shown that the IC could result in a sizable contribution to the forward charmed meson production [13]. Furthermore, the IC “signal” can constitute almost 100% of the inclusive spectrum of \( D \)-mesons produced at high pseudorapidities \( \eta \) and large transverse momenta \( p_T \) in \( pp \) collisions at LHC energies [14].

If the distributions of the intrinsic charm or bottom in the proton are hard enough and are similar in shape to the valence quark distributions (have the valence-like form), then the production of the charmed (bottom) mesons or charmed (bottom) baryons in the fragmentation region should be similar to the production of pions or nucleons. However, the yield of this production depends on the probability to find the intrinsic charm or bottom in the proton, but this yield looks too small. The PDF which included the IC contribution in the proton have already been used in the perturbative QCD calculations in [9]-[11].

Due to the nonperturbative intrinsic heavy quark components one can expect some excess of the heavy quark PDFs over the ordinary sea quark PDFs at \( x > \)
0.1. The “signal” of these components can be visible in the observables of the heavy flavour production in semi-inclusive $ep$ DIS and inclusive $pp$ collisions at high energies. For example, it was recently shown that rather good description of the HERMES data on the $xf_i(x, Q^2) + xf_i(x, Q^2)$ at $x > 0.1$ and $Q^2 = 2.5$ GeV/$c^2$ [15, 16] could be achieved due to existence of \textit{intrinsic} strangeness in the proton, see Fig. 2. One can see from Fig. 2 that the inclusion of the intrinsic strangeness allows us to describe the HERA data rather satisfactorily in the whole $x$-region both at $x \leq 0.1$ and $x > 0.1$. The new HERMES data confirm that the $x$-dependence of $xS(x)$ at $Q^2 = 1.9$ (GeV/$c$)$^2$ is not decreasing at $x > 0.1$, see the presentation at the workshop DIS2013 [17].

Similarly, possible existence of the intrinsic charm in the proton can lead to some enhancement in the inclusive spectra of the open charm hadrons, in particular $D$-mesons, produced at the LHC in $pp$-collisions at high pseudorapidities $\eta$ and large transverse momenta $p_T$ [14].

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 [15]

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

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 (2) over $dx_1 \ldots dx_4$ one can get the probability to find the intrinsic charm with momentum fraction $x_5$ in the proton [?]:

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

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.

Figure 3 illustrates the IC contribution in comparison to the conventional sea charm quark distribution in the proton.

The solid line in Fig. 3 shows the standard perturbative sea charm density distribution $x_{c_{tg}}(x)$ (ordinary sea charm) in the proton from CTEQ6.6M [11] as a function of $x$ at $Q^2 = 1000$ GeV$^2$. The dashed curve in Fig. 3 is the sum of the intrinsic charm density $x_{c_{tg}}(x)$ from CTEQ6.6C2 BHPS with the IC probability $w_{1C} = 3.5\%$ and $x_{c_{tg}}(x)$ at the same $Q^2$ [11]. One can see from Fig. 3 that the IC distribution (with $w_{1C} = 3.5\%$) given by (2) has a rather visible enhancement at $x \sim 0.2 \ldots 0.5$ and
Figure 3: Distributions of the charm quark in the proton at $Q^2 = 1000 \text{ GeV}^2$. The solid line is the standard perturbative sea charm density distribution $x c_{rg}(x)$ only, whereas the dashed curve is the charm quark distribution function, for the sum of the intrinsic charm density $x c_{in}(x)$ (see (2)) and $x c_{rg}(x)$. 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 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 $p_T$ [14]. Furthermore, as we know from [6]-[11] 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]-[29].

In this paper, having in mind these considerations we will first discuss where the above-mentioned heavy flavour Fock states in the proton could be searched for at high energies. Following this we analyze in detail, and give predictions for, the open strangeness production in $pp$ collisions and the LHC semi-inclusive $pp$-production of prompt photons and vector bosons accompanied by $c$-jets or $b$-jets including the intrinsic strange or intrinsic charm component in the PDF.
2. Intrinsic heavy quarks in hard $pp$ collisions

2.1 Where can one look for the intrinsic heavy quarks?

It is known that in the $pp$ production of heavy flavour hadrons at large momentum transfer the hard QCD interactions of two sea quarks, two gluons and a gluon with a sea quark play the main role. According to the model of hard scattering [30]–[38] 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). This spectrum can be presented in the following general form [34]–[36] (see also [39, 40]):

$$E \frac{d\sigma}{d^3p} = \sum_{i,j} \int d^2k_{iT} \int d^2k_{jT} \int_{x_{i\text{min}}} x_i^{-1} \int_{x_{j\text{min}}} x_j^{-1} \ dx_i \times$$

$$\times f_i(x_i, k_{iT}) f_j(x_j, k_{jT}) \frac{d\sigma_{ij}(\hat{s}, \hat{t})}{d\hat{t}} \frac{D_{i,j}^{h}(z_h)}{\pi z_h}. \tag{3}$$

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 $j$; $z$ is the fraction of the hadron momentum from the parton momentum; $f_{i,j}$ is the PDF; and $D_{i,j}^{h}$ is the fragmentation function (FF) of the parton $i$ or $j$ into a hadron $h$.

When the transverse momenta of the partons are neglected in comparison with the longitudinal momenta, the variables $\hat{s}, \hat{t}, \hat{u}$ and $z_h$ can be presented in the following forms [34]:

$$\hat{s} = x_i x_j s, \quad \hat{t} = x_i \frac{t}{z_h}, \quad \hat{u} = x_j \frac{u}{z_h},$$

$$z_h = \frac{x_1}{x_i} + \frac{x_2}{x_j},$$

where

$$x_1 = -\frac{u}{s} = \frac{x_T}{2} \cot(\theta/2),$$

$$x_2 = -\frac{t}{s} = \frac{x_T}{2} \tan(\theta/2),$$

$$x_T = 2\sqrt{u + t}/s = 2p_T/\sqrt{s}.$$  \tag{5}

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 for the hadron $h$ in the $pp$ c.m.s. The lower limits of the integration in (3) are

$$x_{i\text{min}} = \frac{x_T \cot(\frac{\theta}{2})}{2 - x_T \tan(\frac{\theta}{2})},$$

$$x_{j\text{min}} = \frac{x_i x_T \tan(\frac{\theta}{2})}{2x_i - x_T \cot(\frac{\theta}{2})}. \tag{6}$$
The lower limits of the integration in (3) can be presented also in the following form:

\[ x_i^{\text{min}} = \frac{x_R + x_F}{2 - (x_R - x_F)}, \tag{7} \]

\[ x_j^{\text{min}} = \frac{x_i(x_R - x_F)}{2x_i - (x_R + x_F)}, \]

where the Feynman variable \( x_F \) of the produced hadron can be expressed via the variables \( p_T \) and \( \eta \), or \( \theta \) being the hadron scattering angle in the \( pp \) c.m.s:

\[ x_F \equiv \frac{2p_z}{\sqrt{s}} = \frac{2p_T}{\sqrt{s}} \frac{1}{\tan \theta} = \frac{2p_T}{\sqrt{s}} \sinh(\eta). \tag{8} \]

One can see from (7) that, at least, one of the low limits \( x_i^{\text{min}} \) of the integral (3) must be \( \geq x_F \). Thus if \( x_F \geq 0.1 \), then \( x_i^{\text{min}} > 0.1 \), where the ordinary (extrinsic) charm distribution is completely negligible in comparison with the intrinsic charm distribution. Therefore, at \( x_F \geq 0.1 \), or equivalently at the charm momentum fraction \( x_c > 0.1 \) the intrinsic charm distribution intensifies the charm PDF contribution into charm hadroproduction substantially (see Fig. 3). As a result, the spectrum of the open charm hadroproduction can be increased in a certain region of \( p_T \) and \( \eta \) (which corresponds to \( x_F \geq 0.1 \) in accordance to (7)). We stress that this excess (or even the very possibility to observe relevant events in this region) is due to the non-zero contribution of IC component at \( x_c > x_F > 0.1 \) (where non-IC component completely vanishes).

This possibility was demonstrated for the \( D \)-meson production at the LHC in [14]. It was shown that the \( p_T \) spectrum of \( D \)-mesons is enhanced at pseudorapidities of \( 3 < \eta < 5.5 \) and \( 10 \text{ GeV}/c < p_T < 25 \text{ GeV}/c \) due to the IC contribution, which was included using the CTEQ66c PDF [11]. For example, due to the IC PDF, with probability about 3.5 \%, the \( p_T \)-spectrum increases by a factor of 2 at \( \eta = 4.5 \). A similar effect was predicted in [41].

One expects a similar enhancement in the experimental spectra of the open bottom production due to the (hidden) intrinsic bottom (IB) in the proton, which could have a distribution very similar to the one given in (2). However, the probability \( w_{\text{IB}} \) to find the Fock state with the IB contribution \( |uuddb\bar{b}⟩ \) in the proton is about 10 times smaller than the IC probability \( w_{\text{IC}} \) due to relation \( w_{\text{IB}}/w_{\text{IC}} \sim m_c^2/m_b^2 \) [7, 12].

The IC “signal” can be studied not only in the inclusive open (forward) charm hadroproduction at the LHC, but also in some other processes, such as production of real prompt photons \( \gamma \) or virtual ones \( \gamma^* \), or \( Z^0 \)-bosons (decaying into dileptons) accompanied by \( c \)-jets in the kinematics available to the ATLAS and CMS experiments. The contributions of the heavy quark states in the proton could be investigated also in the \( c(b) \)-jet production accompanied by the vector bosons \( W^\pm, Z^0 \). Similar kinematics given by (4-8) can also be applied to these hard processes.
Actually, the parton distribution functions $f_i(x, k_T)$ also depend on the four-momentum transfer squared $Q^2$ that is related to the Mandelstam variables $\hat{s}, \hat{t}, \hat{u}$ for the elastic parton-parton scattering [36]

$$Q^2 = \frac{2\hat{s}\hat{t}\hat{u}}{\hat{s}^2 + \hat{t}^2 + \hat{u}^2}$$ \hfill (9)

Calculating spectra by Eq.(3) we used the PDF which includes the IS (and does not include it) [11], the FF of the type AKK08 [38] and $d\sigma_{ij}(\hat{s}, \hat{t})/d\hat{t}$ calculated within the LO QCD and presented, for example, in [37]. One can see from Eq.(8) that the Feynman variable $x_F$ of the produced hadron can be expressed via the variables $p_T$ and $\eta$, or $\theta$ the hadron scattering angle in the pp c.m.s. At small scattering angles of the produced hadron Eq.(8) becomes

$$x_F \sim \frac{2p_T}{\sqrt{s}} \frac{1}{\theta}.$$ \hfill (10)

It is clear that for fixed $p_T$ an outgoing hadron must possess a very small $\theta$ or very large $\eta$ in order to have large $x_F$ (to follow forward, or backward direction).

In the fragmentation region (of large $x_F$) the Feynman variable $x_F$ of the produced hadron is related to the variable $x$ of the intrinsic charm quark in the proton, and according to the longitudinal momentum conservation law, the $x_F \simeq x$ (and $x_F < x$). Therefore, the visible excess of the inclusive spectrum, for example, of $K$-mesons can be due to the enhancement of the IS distribution (see Fig. 2) at $x > 0.1$.

3. Intrinsic strangeness

3.1 Open strangeness production in hard $pp$ collisions

Let us analyze now how the possible existence of the intrinsic strangeness in the proton can be visible in $pp$ collisions. For example, consider the $K^-$-meson production in the process $pp \rightarrow K^- + X$. Considering the intrinsic strangeness in the proton [15] we calculated the inclusive spectrum $ED\sigma/d^3p$ of such mesons within the hard scattering model (Eq.(4)), which describes satisfactorily the HERA and HERMES data on the DIS. The FF and the parton cross sections were taken from [38, 37], respectively, as mentioned above. In Figs. (4,5) the inclusive $p_T$-spectra of $K^-$-mesons produced in $pp$ collision at the initial energy $E_p = 158$ GeV are presented at the rapidity $y = 1.3$ (Fig 4) and $y = 1.7$ (Fig 5). The solid lines in Figs. (4,5) correspond to our calculation ignoring the intrinsic strangeness (IS) in the proton and the dashed curves correspond to the calculation including the IS with the probability about 2.5%, according to [15]. The crosses show the ratio of our calculation with the IS and without the IS minus 1. One can see from Figs. (4,5), right axis, that the IS signal can be above 200 % at $y = 1.3$, $p_T = 3.6-3.7$ Gev/c and slightly
Figure 4: The $K^-$-meson distributions (with and without intrinsic strangeness contribution) over the transverse momentum $p_t$ for $pp \to K^- + X$ at the initial energy $E = 158$ GeV, the rapidity $y = 1.3$ and $p_t \geq 0.8$ GeV/c.

smaller, than 200 % at $y = 1.7$, $p_t \simeq 2.5$ GeV/c. Actually, this is our prediction for the NA61 experiment that is now under way at CERN.

4. Intrinsic charm

4.1 Prompt photon and $c$-jet production

Recently the investigation of prompt photon and $c(b)$-jet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV was carried out at the TEVATRON [19]-[22]. In particular, it was observed that the ratio of the experimental spectrum of the prompt photons, (accompanied by the $c$-jets) to the relevant theoretical expectation (based on the conventional PDF which ignored the intrinsic charm) increases with $p_T\gamma$ up to factor about 3 when $p_T\gamma$ reaches 110 GeV/c. Furthermore, taking into account the CTEQ66c PDF, which includes the IC contribution obtained within the BHPS model [6, 7] one can increase this ratio up to 1.5 [25]. For the $\gamma + b$-jets $p\bar{p}$-production no enhancement in the $p_T\gamma$-spectrum was observed at the beginning of the experiment [19, 22]. However in 2012 the DØ collaboration has confirmed observation of such an enhancement [21].

This intriguing observation stimulates our interest to look for a similar "IC sig-
Figure 5: The $K^-$-meson distributions (with and without intrinsic strangeness contribution) over the transverse momentum $p_t$ for $pp \rightarrow K^- + X$ at the initial energy $E = 158$ GeV, the rapidity $y = 1.7$ and $p_t \geq 0.8$ GeV/c.

nal" in $pp \rightarrow \gamma + c(b) + X$ processes at LHC energies.

The LO QCD Feynman diagrams for the process $c(b) + g \rightarrow \gamma + c(b)$ are presented in Fig. 6.

![Feynman diagrams](image)

Figure 6: The Feynman diagrams for the hard process $c(b)g \rightarrow \gamma c(b)$, the one-quark exchange in the s-channel (left) and the same in the t-channel (right).

These hard sub-processes give the main contribution to the reaction $pp \rightarrow \gamma + c(b)$-jet+$X$.

Within LO QCD, in addition to the main subprocesses illustrated in Fig. 6 one considers the subprocesses $gg \rightarrow c\bar{c}, \ qc \rightarrow qc, \ gc \rightarrow gc$ accompanied by the
bremstrahlung \( c(\bar{c}) \to c\gamma \), the contribution of which is sizable at low \( p_T^\gamma \) and can be neglected at \( p_T^\gamma > 60 \text{ GeV/c} \), according to [23]. The diagrams within the NLO QCD are more complicated than Fig. 6.

Let us illustrate qualitatively the kinematical regions where the IC component can contribute significantly to the spectrum of prompt photons produced together with a \( c \)-jet in \( pp \) collisions at the LHC. For simplicity we consider only the contribution to the reaction \( pp \to \gamma + c(\text{jet}) + X \) of the diagrams given in Fig. 6. According to (7) and (7), at certain values of the transverse momentum of the photon, \( p_T^\gamma \), and its pseudo-rapidity, \( \eta_\gamma \) (or rapidity \( y_\gamma \) ) the momentum fraction of \( \gamma \) can be \( x_{F\gamma} > 0.1 \), therefore the fraction of the initial \( c \)-quark must also be above 0.1, where the IC contribution in the proton is enhanced (see Fig. 3). Therefore, one can expect some non-zero IC signal in the \( p_T^\gamma \) spectrum of the reaction \( pp \to \gamma + c + X \) in this certain region of \( p_T^\gamma \) and \( y_\gamma \). In principle, a similar qualitative IC effect can be visible in the production of \( \gamma^*/Z^0 \) decaying into dileptons accompanied by \( c \)-jets in \( pp \) collisions.

Experimentally one can measure the prompt photons accompanied by the \( c(b) \)-jet corresponded to the hard subprocess \( c(b)g \to \gamma c(b) \) presented in Fig. 6, when \( \gamma \) and \( c(b) \)-jet are emitted back to back. Therefore, it would be interesting to look the contribution of this graph to the \( p_T^\gamma \) spectrum compared to total QCD calculation including the NLO corrections.

In Fig. 7 the distribution \( d\sigma/dp_T^\gamma \) of prompt photons produced in the reaction \( pp \to \gamma + c + X \) at \( \sqrt{s} = 8 \text{ TeV} \) is presented in the interval of the photon rapidity 1.52 \( |y_\gamma| < 2.37 \) and the \( c \)-jet rapidity \( |y_c| < 2.4 \). The calculation was carried out within PYTHIA8 [24] including only graphs in Fig. 6 and the radiation corrections for the initial (ISR) and final (FSR) states along with the multi-parton interactions (MPI) within PYTHIA8.

The upper line in the top of Fig. 7 is calculated with the CTEQ66c PDF and includes IC, while the lower line uses the CTEQ66 PDF where the charm PDF is radiatively generated only. The probability of the IC contribution used is about 3.5\% [11], this yields the highest sensitivity of the cross-section to the IC, however the intrinsic charm in the proton could also be about 1\% [10] and therefore the results in this case will yield a lesser difference when compared to the radiatively generated ones. The ratio of the spectra with IC and without IC as a function of \( p_T^\gamma \) is presented in the bottom of Fig. 7.

One can see from Fig. 7 that the inclusion of the IC contribution increases the spectrum by a factor of 4-4.5 at \( p_T^\gamma \simeq 400 \text{ GeV/c} \), however the cross section is too small here (about 1 fb). At \( p_T^\gamma \simeq 150-200 \text{ GeV/c} \) the cross section is about 8–30 fb 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 \( L = 20 \text{ fb}^{-1} \).

Naturally the \( p_T^\gamma \) distribution in Fig. 7 has the same form as the distribution over the transverse momentum of the \( c \)-quark, \( p_T^c \), when only the hard subprocess \( g + c \to \gamma + c \) in Fig. 6 is included.

According to this figure, the IC signal can be about 180\%-250\% at \( p_T^\gamma \simeq 150-200 \text{ GeV/c} \) and the cross section is about 10–40 fb, which corresponds to about 1000–
Figure 7: The distribution $d\sigma/dp_T^\gamma$ of prompt photons produced in the reaction $pp \to \gamma cX$ 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% [11]; 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.

4000 events in the 5 GeV/c bin at $L = 20$ fb$^{-1}$. The NLO QCD calculations showed the similar results [26].

4.2 $W$-boson and $b$-jet production

Let us analyze now another process, the production of vector boson accompanied by the $b$-jet in $pp$ collision. The LO QCD diagram for the process $c(\bar{c}) + g \rightarrow W^\pm + b(\bar{b})$ is presented in Fig. 8. These hard subprocesses can give the main contribution to the reaction $pp \rightarrow W^\pm (\rightarrow l^+ + l^-) + b(\bar{b}) - jet + X$, which could give us also the information on the IC contribution in the proton. In Fig. 9 the transverse momentum spectrum of $W^+$-boson accompanied by the $b$-jet produced in $pp$ collision at the LHC energy $\sqrt{s} = 8$ TeV is presented. The calculation was done within the MCFM generator [42]. The down line corresponds to the calculation without the IC, the upper curve is our result including the IC contribution in the PDF CTEQ6,6c with the probability about 3.5 % In Fig. 10 the ratio of spectra presented in Fig. 9 with
Figure 8: The Feynman diagrams for the hard process \( cg \rightarrow W^\pm b \), the one-quark exchange in the t-channel.

![Feynman diagrams](image)

Figure 9: The transverse momentum spectrum of \( W^\pm \)-boson accompanied by the \( b \)-jet produced in \( pp \) collision at the LHC energy \( \sqrt{s} = 8 \) TeV and at the \( b \)-jet pseudo-rapidity \( 1.5 < \eta_b < 2 \). The down line corresponds to the calculation without the IC; the upper curve is our result including the IC contribution in the PDF CTEQ6.6c with the probability about 3.5%.

![Transverse momentum spectrum](image)

and without IC contribution in the proton is presented. In Figs. (9,10) the sum of the \( p_T^{b-jet} \) spectra for the processes \( pp \rightarrow W^+ (\rightarrow e^+ + \nu) + \bar{b} + X \) (process 12) and
\( pp \to W^- (\to e^- + \bar{\nu}) + b + X \) (process 17) is presented. One can see from Figs. (9,10) that the inclusion of the IC contribution in the PDF results in the increase of the transverse momentum spectrum of \( W \)-bosons by a factor of 2 at \( p_{T}^{b\text{-jet}} \) 250-300 GeV/c.

### 5. Conclusion

We analyzed the inclusive \( K^- \)-meson production in \( pp \) collision at the initial energy \( E_p = 158 \) GeV and gave some predictions for the NA61 experiment going on at CERN. We showed that in the inclusive spectrum of \( K^- \)-mesons as a function of \( p_t \) at some values of their rapidities the signal of the intrinsic strangeness can be visible and reach about 200\% and more at large momentum transfer we took. The probability of the intrinsic strangeness to be about 2.5\%, as was found from the best description of the HERA and HERMES data on the DIS, see [15] and references therein. The similar predictions can be made for the open strangeness production at the energies of the CBM (Darmstadt) and NICA (Dubna) experiments. The main goal of such predictions is to show that at the certain kinematical region the contribution of the intrinsic strangeness in the proton can result in the enhancement in inclusive spectra by a factor of 2-3.

In this paper we also 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...
Figure 11: The transverse momentum spectrum of $W^\pm$-boson accompanied by the $b$-jet produced in $pp$ collision at the LHC energy $\sqrt{s} = 8$ TeV and at the $b$-jet pseudo-rapidity $2.0<\eta_b<2.5$. The down line corresponds to the calculation without the IC, the upper curve is our result including the IC contribution in the PDF CTEQ6,6c with the probability about 3.5%.

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, $p_T^\gamma$, distribution of the $c$-jet measured together with the above-mentioned prompt photon in the $pp \to \gamma + c$-jet+$X$ process.

As we have shown also, the possible signal of intrinsic charm could be observed in the production of vector mesons $W^\pm$ accompanied by the $b$-jet. Our prediction on the IC contribution in the process $pp \to W^\pm + b - jet + X$ is similar to to the one for the reaction $pp \to \gamma + c - jet + X$.
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pp→K^-X, s^{1/2}=7 \text{ TeV}, y=4.5

pp→K^-X, AKK, no IS
IS=2.5%
Ratio - 1
pp→K⁺ X, \( s^{1/2} = 7 \text{ TeV}, y = 4.5 \)

- pp→K⁺X, AKK, no IS
- IS=2.5%
- Ratio - 1

\( \frac{1}{\sigma_{inel}} \frac{d^2 \sigma}{dy dp_T} \) [GeV⁻²]

\( p_T \) [GeV/c]