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MONITORING OF CHARMED AND BEAUTY QUARK DISTRIBUTIONS IN PROTON AT LHC

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A short review on charmed and beauty hadron production in the lepton deep inelastic scattering off proton, in proton-proton and proton-antiproton collisions at high energies is presented. It is shown that the existing theoretical and experimental information on charmed and beauty quark distributions in a proton is not satisfactory. A procedure to study these distributions at LHC energies is suggested.

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1. *Introduction*

Various approaches of the perturbative QCD, including the next-to-leading order calculations, have been used to construct the distributions of quarks in a proton. The theoretical analysis of the lepton deep inelastic scattering (DIS) off protons and nuclei provides rather realistic information on distribution of light quarks like u, d, s in the proton. However, to find a realistic distribution of heavy quarks like $c(\bar{c})$ and especially $b(\bar{b})$ in the proton describing the experimental data on the DIS is a non-trivial task. It is mainly due to the small values of D- and B- meson yields produced in the DIS at existing energies. Even at the Tevatron energies, the B- meson yield is not so large. However, at LHC energies the multiplicity of D- and B- mesons produced in $p-p$ collisions will be significantly larger. Therefore, one can try to extract new information on the distribution of these heavy mesons in the proton. In this paper we propose a study of the distribution of heavy quarks like $c(\bar{c})$ and $b(\bar{b})$ in the proton based on the analysis of the future LHC experimental data.

2. Hard parton scattering model

Usually, the multiple hadron production in hadron-nucleon collisions at high initial energies and large transfers is analyzed within the hard parton scattering model (HPSM) suggested in Refs. [1], [2] and [3]. For example, the inclusive spectrum of hadrons produced in the hard $p-p$ interaction is presented in the following convolution form

$$E_h \frac{\mathrm{d}\sigma}{\mathrm{d}^3 p_h} = \sum_{q_f,g} \int G^{p_1}_{q_f,g}(x_1,k_{1t}) G^{p_2}_{q_f,g}(x_2,k_{2t}) \frac{\hat{s}}{\pi} \frac{\mathrm{d}\sigma(\hat{s},\hat{t})}{\mathrm{d}\hat{t}} \frac{1}{z^2} D^h_{q_f,g}(z) \delta(\hat{s}+\hat{t}+\hat{u}) \mathrm{d}x \mathrm{d}^2 k_t \mathrm{d}z, \tag{1}$$

where E_h, p_h are the energy and three-momentum of the produced hadron h, $G^{p_1}_{q_f,g}(x_1,k_{1t})$ is the distribution of the quark with flavor f or the gluon in the first colliding proton depending on the Feynman variable x_1 and the transverse momentum k_{1t}, $G^{p_2}_{q_f,g}(x_2,k_{2t})$ is the same quark or gluon distribution in the second colliding proton, $\hat{s},\hat{t}$ and $\hat{u}$ are the Mandelstam variables corresponding to the colliding quarks, $d\sigma(\hat{s},\hat{t})/d\hat{t}$ is the differential cross section of the elastic parton-parton scattering and z is the fraction of the produced hadron h [1, 2].

The HPSM has been significantly improved by applying the QCD parton approach implemented in the modified minimal-subtraction renormalization and factorization scheme. It provides a rigorous theoretical framework for a global data analysis. Within this framework, there are two distinct approaches to the next-to-leading order (NLO) calculations in perturbative QCD.

The first calculation scheme is the so-called massive scheme or fixed-flavor-number scheme (FFNS) developed in Refs. [4, 5]. In this approach, the number of active flavors in the initial state is limited to $n_f = 4$, e.g., $u(\bar{u}), d(\bar{d}), s(\bar{s})$ and $c(\bar{c})$ quarks are the initial partons, whereas the $b(\bar{b})$ quark appears only in the final state. In this case, the beauty quark is always treated as a heavy particle and not as a parton. In this scheme, the mass of heavy quarks acts as a cutoff parameter for the initial- and final-state collinear singularities and sets the scale for perturbative calculations. Actually, the FFNS with $n_f = 4$ is limited to a rather small range of transverse momenta p_t of produced D- or B-mesons less than the masses of the c or b quarks. In this scheme, the $m^2_{c,b}/p^2_t$ terms are fully included.

The other approach is the so-called zero-mass variable-flavor-number scheme (ZM-VFNS), see Refs. [6, 7] and references therein. It is the conventional parton model approach, the zero-mass parton approximation is also applied to the b quark, although its mass is certainly much larger than the asymptotic scale parameter Λ_{QCD}. In this approach, the $b(\bar{b})$ quark is treated as an incoming parton originating from colliding protons. This approach can be used in the region of large transverse momenta of produced charmed or beauty mesons, e.g., at $p_t \geq m_{c,b}$. Within this scheme, the terms of the order $m^2_{c,b}/p^2_t$ can be neglected. Recently, the experimental inclusive p_t- spectra of B-mesons in $p-\bar{p}$ collisions obtained by the CDF Collaboration [8, 9] at the Tevatron energy $\sqrt{s}$=1.96 TeV in the rapidity region $-1 \leq y \leq 1$ have been described rather satisfactorily within this ZM-VFNS approach in Ref. [10] at $p_t \geq 10(\text{GeV}/c)$ using the non-perturbative structure functions. In another kinematic region, e.g., at $2.5(\text{GeV}/c \leq p_t \leq 10(\text{GeV}/c)$ the FFNS model mentioned above allowed the CDF data to be described without using fragmentation functions of b quarks to B-mesons. Both these schemes have some uncertainties related to the renormalization parameters.

Comparing the CDF data on the p_t-spectra of B-mesons produced in $p - \bar{p}$ collisions at the Tevatron energies published in Ref. [8, 9], one can find a difference between them especially at high values of p_t. Therefore, it would be very useful to have more precise data at different LHC energies.

The experimental inclusive p_t-spectra of D-mesons obtained by the CDF Collaboration at the same Tevatron energy and in the same rapidity region [11] at $p_t \geq 5$ (GeV/c) were described satisfactorily within the so-called general-mass variable-flavor-number scheme (GM-VFN) [12] assuming non-zero mass for c quarks.

To calculate the inclusive spectrum of hadrons employing Eq. (1), for example of heavy mesons, we have to know the distributions of quarks and gluons and their fragmentation functions (FF). Usually, they are calculated within QCD using the experimental information from the DIS of leptons off protons and in the $e^+ - e^-$ annihilation. The information on the gluon distribution and gluon fragmentation function can be extracted from the experimental data on the jet production [13] and their theoretical analysis [14, 15]. Unfortunately, the theoretical QCD calculation of the jet production has different sources of uncertainty. As is shown in Ref. [13], the main contribution comes from the uncertainty about the parton distribution functions (PDFs) and is computed within the method suggested in Ref. [16]. At low transverse momenta of jets p_t^{jet}, the uncertainty is small and approximately independent of the jet rapidity y^{jet}. The uncertainty increases as p_t^{jet} and $\mid y^{\text{jet}} \mid$ increase. It can become about 130 percent [13]. To analyze the jet and heavy quark production at low p_t and large y or large Feynman variable x_F, one can apply another nonperturbative QCD model, the so-called quark-gluon string model (QGSM).

3. *The quark-gluon string model*

The QGSM is based on the $1/N$ expansion in QCD suggested in Refs. [17] and [18] instead of the α_s expansion that has the infrared divergence problem at $Q^2 \to 0$. Here N is the number of flavors or colors. The relation of the topological expansion in $1/N$ of the hadron-hadron scattering amplitude to its t-channel expansion in Regge poles was suggested in Refs. [19] and [20]. This approach was used to analyze soft hadron processes at high energies, see for example Ref. [21].

It has been shown [21] that the main contribution to the inclusive spectrum of the hadron produced in $p - p$ collisions at high energies comes from the so-called cylinder graphs corresponding to the one-Pomeron and multi-Pomeron exchanges which are presented in Fig. 1. According to the QGSM, between quark q (diquark qq) and diquark qq (quark q) in colliding protons (Fig. 1, left), the colorless strings are formed, then, after their breakup $q\bar{q}$ pairs are created and fragmentate to the

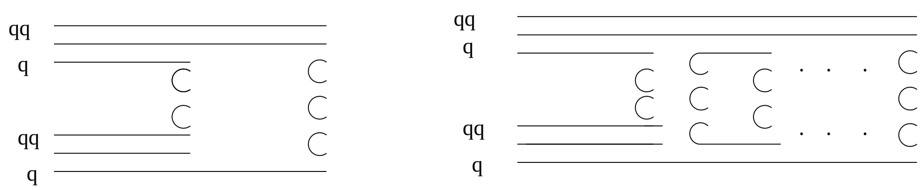

Fig. 1. The cylinder graph corresponding to the one-Pomeron exchange (left) and the multi-cylinder graph corresponding to the multi-Pomeron exchanges (right).

hadron h. The right graph in Fig. 1 corresponds to the creation of two colorless quark-diquark and diquark-quark strings and $2(n-1)$ chains between the see quark (antiquark) and the antiquark (quark). The inclusive spectrum ρ_h of the hadron h produced in $p-p$ collision corresponding to the one-Pomeron graph (Fig. 1, left graph) has the following form

$$\rho_h(x,\mathbf{p}_t) = F_q^h(x_+,p_t)F_{qq}^h(x_-,\mathbf{p}_t) + F_{qq}^h(x_+,\mathbf{p}_t)F_q^h(x_-,p_t)\,, \tag{2}$$

where

$$F_{q(qq)}^h(x_\pm,\mathbf{p}_t)=\int_{x_\pm}^{1}\mathrm{d}x_1\int\mathrm{d}^2p_{1t}\,\mathrm{d}^2p_{2t}\,f_{q(qq)}(x_1,\mathbf{p}_{1t})\,D_{q(qq)}^h(\frac{x_\pm}{x_1},\mathbf{p}_{2t})\delta^{(2)}(\mathbf{p}_{1t}+\mathbf{p}_{2t}-\mathbf{p}_t), \tag{3}$$

Here $f_{q(qq)}(x_1,\mathbf{p}_{1t})$ is the quark or diquark distribution function depending on the Feynman variable x_1 and the transverse momentum of the quark or diquark, $D_{q(qq)}^h$ is the fragmentation function of quark or diquark to the hadron h; $x_\pm = \frac{1}{2}(\sqrt{x_t^2+x^2} \pm x)$ and $x_t = 2m_{ht}/\sqrt{s}$, $m_{ht} = \sqrt{m_h^2+p_t^2}$, and s is the square of the initial energy in the $p-p$ c.m.s. Actually, the interaction function $F_{q(qq)}^h(x_+,p_t)$ corresponds to the fragmentation of the upper quark (diquark) to the hadron h, whereas $F_{qq(q)}^h(x_-,p_t)$ corresponds to the fragmentation of the down diquark (quark) to h, see Fig. 1 (left diagram). The expression for the inclusive spectrum of the hadron h produced in $p-p$ collision corresponding to the right graph of Fig. 1 has a more complicated form, see details in Refs. [22] and [23].

All quark distributions and fragmentation functions are related to the intercepts and slopes of Regge trajectories. For example, the distribution of $c(\bar{c})$ quarks in a proton obtained within the QGSM and the Regge theory has the following form [22]

$$f_{c(\bar{c})}^{(n)} = C_{see}^{(n)}\delta_{c(\bar{c})}x^{-\alpha_\psi(0)}(1-x)^{\alpha_R(0)-2\alpha_N(0)+(\alpha_R(0)-\alpha_\psi(0)+n-1}\,, \tag{4}$$

where n is the number of Pomeron exchanges, $\alpha_R(0)$ and $\alpha_N(0)$ are the intercepts of the Reggeon and nucleon Regge trajectories, $\alpha_\psi(0)$ is the intercept of the ψ-Regge trajectory, and $\delta_{c(\bar{c})}$ is a probability fraction of $c(\bar{c})$ pairs in a quark see of the proton.

The intercepts $\alpha_R(0)$ and $\alpha_N(0)$ are known very well from the experimental data on the soft hadron processes and they have linear behavior as a function of the transfer t. As for the Regge trajectory $\alpha_\psi(t)$, the information on its t-dependence is rather poor. As a function of t, it can be linear or nonlinear.

The $b(\bar{b})$ quark distributions and the fragmentation functions of $b(\bar{b})$ to B-mesons can also be obtained within the Regge theory and the QGSM. They are related to the conventional Regge trajectories of light mesons and the Regge trajectory of the Υ-meson consisting of a $b\bar{b}$ pair. The information on the t-dependence of the Υ-Regge trajectory is also uncertain.

The modified version of the QGSM suggested in Refs. [22] and [23], including the transverse momentum dependence of the interaction functions $F^h_{q,qq}(x_\pm, p_t)$, allowed the description of the experimental data on inclusive spectra of D-mesons produced in $p{-}p$ collisions at the ISR energies and at moderate transverse momenta up to $p_t \simeq 4-5(\mathrm{GeV}/c)$. However, the results are very sensitive to the value of the intercept $\alpha_\psi(0)$. Note that the QGSM, in contrast to the perturbative QCD, has no uncertainty related to the mass parameter.

4. *Proposal*

Concluding this short review on the HPMS and the QGSM, we would like to propose to do a complex theoretical analysis of both the jet production in $p-p$ and $p-\bar{p}$ collisions within the perturbative QCD and the semi-hard production of D- and B-mesons in these reactions within the modified version of the QGSM. The semi-hard hadron processes mean the inclusive production of heavy mesons at not large transverse momenta p_t and not small values of x_F. We are going to extract the gluon distribution in a proton and gluon fragmentation functions to heavy mesons from the QCD analysis of the jet production in $p-p$ and $p-\bar{p}$ inelastic processes. Constructing a new modified version of the QGSM based on Refs. [22] and [23], we intend to include the gluon-gluon and gluon-quark interactions using the previously obtained gluon distributions in the proton and gluon FF. Then, we will use the suggested approach to describe all existing experimental data on D- and B-mesons produced in $p-p$ and $p-\bar{p}$ collisions at high energies and to make corresponding predictions at LHC energies. From this analysis, we hope to extract new information on the distribution of charmed and beauty quarks in the proton.

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ISPITIVANJE RASPODJELA KVARKOVA c I b U PROTONU NA LHC

Izlažemo kratak pregled tvorbe kvarkova c i b u leptonskom duboko-neelastičnom raspršenju na protonu, i u sudarima proton-proton te proton-antiproton na visokim energijama. Ukazuje se kako sadašnja teorijska i eksperimentalna saznanja o raspodjelama kvarkova c i b u protonu nisu dostatna. Predlaže se postupak za nalaženje tih raspodjela na energijama LHC.