Beauty Baryon Production in pp Collisions at LHC and b Quark Distribution in the Proton

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The production of charmed and beauty hadrons in proton-proton and proton-antiproton collisions at high energies are analyzed within the modified quark-gluon string model (QGSM) including the internal motion of quarks in colliding hadrons. We present some predictions for the future experiments on the beauty baryon production in pp collisions at LHC energies. This analysis allows us to find interesting information on the Regge trajectories of the heavy $(b\bar{b})$ mesons and the sea beauty quark distributions in the proton.

1 Introduction

Various approaches of perturbative QCD including the next-to-leading order calculations (NLO QCD) have been applied to construct 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 the distribution of light quarks like u, d, s in a proton. However, to find a reliable distribution of heavy quarks like $c(\bar{c})$ and especially $b(\bar{b})$ in a proton describing the experimental data on the DIS is a non-trivial task. It is mainly due to small values of D and B meson yields in the DIS at existing energies. Even at the Tevatron energies the B- meson yield is not so large. At LHC energies the multiplicity of these mesons produced in pp collisions will be significantly larger. Therefore one can try to extract a new information on the distribution of these heavy quarks in a proton. In this paper we suggest to study the distribution of heavy quarks like $c(\bar{c})$ and $b(\bar{b})$ in a proton from the analysis of the future LHC experimental data.

The multiple hadron production in hadron-nucleon collisions at high energies and large transfers is usually analyzed within the hard parton scattering model (HPSM) suggested in [1, 2]. This model was applied to the charmed meson production both in proton-proton and meson-proton interactions at high energies, see for example [3]. The HPSM is significantly improved by applying the QCD parton approach [4, 5], see details in [6] and references therein. Unfortunately the QCD including the next-to-leading order (NLO) has some uncertainties related to the renormalization parameters especially at small transverse momenta p_t [6].

In [6, 7] we studied the charmed and beauty meson production in pp and $p\bar{p}$ collisions at high energies within the QGSM [8] or the dual parton model (DPM) [9] based on the $1/N$ expansion in QCD [10, 11]. It was shown that this approach can be applied rather successfully at not very large values of p_t. In this paper we investigate the open charm and beauty baryon production in pp collisions at LHC energies and very small p_t within the QGSM to find new information on the Regge trajectories of the heavy $(c\bar{c})$ and $(b\bar{b})$ mesons and the sea beauty quark distributions in the proton.

2 General Formalism for Hadron Production in pp Collision within QGSM

Let us present briefly the scheme of the analysis of the hadron production in the pp collisions within the QGSM including the transverse motion of quarks and diquarks in colliding protons [12]. As is known, the cylinder type graphs for the pp collision presented in Fig. 1 make the main contribution to this process [8]. The left diagram of Fig. 1, the so-called one-cylinder graph, corresponds to the case where two colourless strings are formed between the quark/diquark (q/qq) and the diquark/quark (qq/q) in colliding protons; then, after their breakup, $q\bar{q}$ pairs are created and fragmented to a hadron, for example, D meson. The right diagram of Fig. 1, the so-called multicylinder graph, corresponds to creation of the same two colourless strings and many strings between sea quarks/antiquarks $q/\bar{q}$ and sea antiquarks/quarks $\bar{q}/q$ in the colliding protons. The general form for the invariant inclusive hadron spectrum within

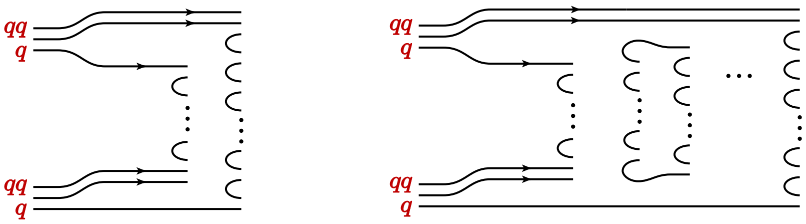

Figure 1: The one-cylinder graph (left diagram) and the multicylinder graph (right diagram) for the inclusive $pp \to hX$ process.

the QGSM is [13, 12]

$$E\frac{d\sigma}{d^3\mathbf{p}} \equiv \frac{2E^*}{\pi\sqrt{s}}\frac{d\sigma}{dxdp_t^2} = \sum_{n=1}^{\infty}\sigma_n(s)\phi_n(x,p_t) \ , \tag{1}$$

where $E, \mathbf{p}$ are the energy and the three-momentum of the produced hadron h in the laboratory system (l.s.) of colliding protons; E^*, s are the energy of h and the square of the initial energy in the c.m.s of pp; x, p_t are the Feynman variable and the transverse momentum of h; σ_n is the cross section for production of the n-Pomeron chain (or $2n$ quark-antiquark strings) decaying into hadrons, calculated within the "eikonal approximation" [14]. Actually, the function $\phi_n(x,p_t)$ is the convolution of the quark (diquark) distributions in the proton and their fragmentation functions (FF), see details in [8, 9, 6, 12]. To calculate the interaction function $\phi_n(x,p_t)$ we have to know all the quark (diquark) distribution functions in the nth Pomeron chain and the FF. They are constructed within the QGSM using the knowledge of the secondary Regge trajectories, see details in [8, 13].

3 Heavy Baryon Production within QGSM

3.1 Sea Charm and Beauty Quark Distribution in the Proton

Now let us analyze the charmed and beauty baryon production in the pp collision at LHC energies and very small p_t within the soft QCD, e.g., the QGSM. This study can be interesting for it may allow predictions for future LHC experiments like TOTEM and ATLAS and an opportunity to find new information on the distribution of sea charmed (c) and beauty (b) quarks at very low Q^2. According to the QGSM, the distribution of $c(\bar{c})$ quarks in the nth Pomeron chain (Fig. 1, right) is, see for example [12] and references therein,

$$f^{(n)}_{c(\bar{c})}(x) = C^{(n)}_{c(\bar{c})}\delta_{c(\bar{c})}x^{a_{cn}}(1-x)^{g_{cn}} \tag{2}$$

where $a_{cn} = -\alpha_\psi(0)$, $g_{cn} = \alpha_\rho(0) - 2\alpha_B(0) + (\alpha_\rho(0) - \alpha_\psi(0)) + n - 1$; $\delta_{c(\bar{c})}$ is the weight of charmed pairs in the quark sea, $C^{(n)}_{c(\bar{c})}$ is the normalization coefficient [13], $\alpha_\psi(0)$ is the intercept of the ψ- Regge trajectory. Its value can be -2.18 assuming that this trajectory $\alpha_\psi(t)$ is linear and the intercept and the slope $\alpha'_\psi(0)$ can be determined by drawing the trajectory through the J/Ψ-meson mass $m_{J/\Psi} \simeq 3.1$ GeV and the χ-meson mass $m_\chi = 3.554$ GeV [15]. Assuming that the ψ-Regge trajectory is nonlinear one can get $\alpha_\psi(0) \simeq 0$, which follows from perturbative QCD, as it was shown in [16]. The distribution of $b(\bar{b})$ quarks in the nth Pomeron chain (Fig. 1, right) has the similar form

$$f^{(n)}_{b(\bar{b})}(x) = C^{(n)}_{b(\bar{b})}\delta_{b(\bar{b})}x^{a_{bn}}(1-x)^{g_{bn}} \tag{3}$$

where $a_{bn} = -\alpha_\Upsilon(0)$, $g_{bn} = \alpha_\rho(0) - 2\alpha_B(0) + (\alpha_\rho(0) - \alpha_\Upsilon(0)) + n - 1$; $\alpha_\rho(0) = 1/2$ is the well known intercept of the ρ-trajectory; $\alpha_B(0) \simeq -0.5$ is the intercept of the baryon trajectory, $\alpha_\Upsilon(0))$ is the intercept of the Υ- Regge trajectory, its value also has an uncertainty. Assuming its linearity one can get $\alpha_\Upsilon(0)) = -8, -16$, while for nonlinear ($b\bar{b}$) Regge trajectory $\alpha_\Upsilon(0) \simeq 0$, see details in [17]. Inserting these values to the form for $f^{(n)}_{c(\bar{c})}(x)$ and $f^{(n)}_{b(\bar{b})}(x)$ we get the large sensitivity for the c and b sea quark distributions in the nth Pomeron chain. Note that the FFs also depend on the parameters of these Regge trajectories. Therefore, the knowledge of the intercepts and slopes of the heavy-meson Regge trajectories is very important for the theoretical analysis of open charm and beauty production in hadron processes.

Note that all the quark distributions obtained within the QGSM are different from the parton distributions obtained within the perturbative QCD which are usually compared with the experimental data on the deep inelastic lepton scattering (DIS) off protons. To match these two kinds of quark distributions one can apply the procedure suggested in [18]. The quantities g_{cn} or g_{bn} entering into Eq. (2) and Eq. (3) are replaced by the following new quantities depending on Q^2

$$\tilde{g}_{cn} = g_{cn}\left(1 + \frac{Q^2}{Q^2+c}\right) \ ; \ \tilde{g}_{bn} = g_{bn}\left(1 + \frac{Q^2}{Q^2+d}\right) \tag{4}$$

The parameters c and d are chosen such that the structure function constructed from the valence and sea quark (antiquark) distributions in the proton should be the same as the one at the initial conditions at $Q^2 = Q_0^2$ for the perturbative QCD evolution. A similar procedure can be used to get the Q^2 dependence for the powers a_{cn} and a_{bn} entering into Eqs. (2) and (3) [18]. Then, using the DGLAP evolution equation [19], we obtain the structure functions at large Q^2.

3.2 Charmed and Beauty Baryon Production in pp Collision

The information on the charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) Regge trajectories can be found from the experimental data on the charmed and beauty baryon production in pp collisions at

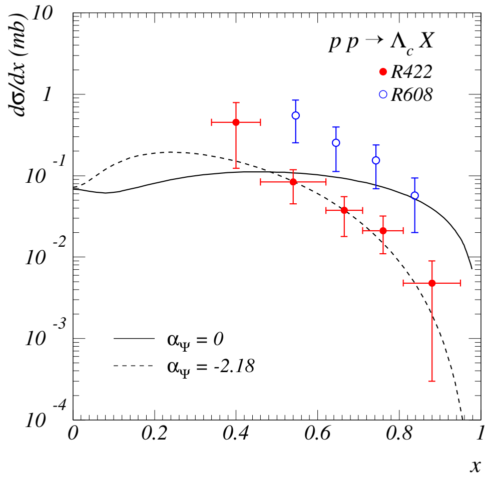

Figure 2: The differential cross section $d\sigma/dx$ for the inclusive process $pp \to \Lambda_c X$ at $\sqrt{s} =$ 62 GeV.

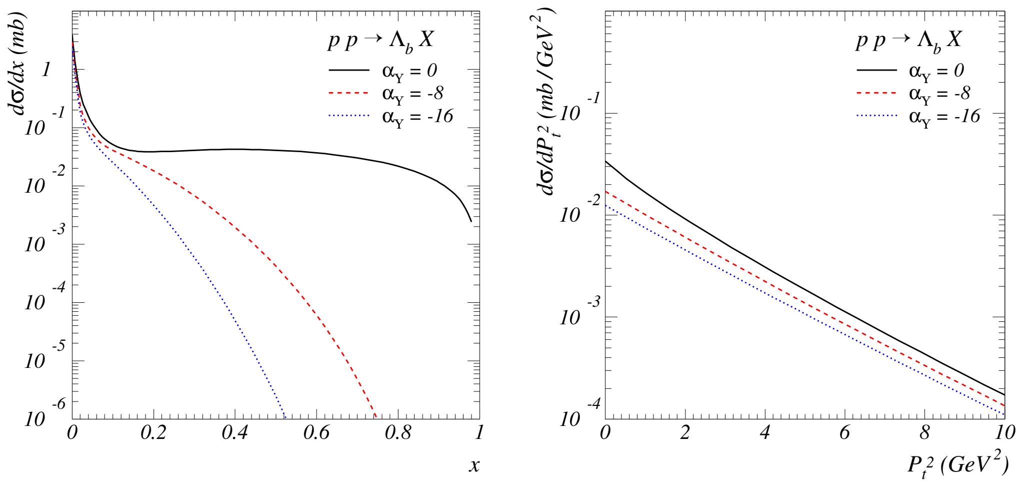

Figure 3: The differential cross section $d\sigma/dx$ (left) and $d\sigma/dP_t^2$ (right) for the inclusive process $pp \to \Lambda_b X$ at $\sqrt{s} = 4$ TeV.

high energies. For example, Fig. 2 illustrates the sensitivity of the inclusive spectrum $d\sigma/dx$ of the produced charmed baryons Λ_c to different values for $\alpha_\psi(0)$. The solid line corresponds to $\alpha_\psi(0) = 0$, whereas the dashed curve corresponds to $\alpha_\psi(0) = -2.18$. Unfortunately the experimental data presented in Fig. 2 have big uncertainties; therefore, one cannot extract the information on the $\alpha_\psi(0)$ values from the existing experimental data. A high sensitivity of the inclusive spectrum $d\sigma/dx$ of the produced beauty baryons Λ_b to different values for $\alpha_\Upsilon(0)$ is presented in Fig. 3 (left). The p_t-inclusive spectrum of Λ_b has much lower sensitivity to this quantity, according to the results presented in Fig. 3 (right). Actually, our results presented in Fig. 3 could be considered as some predictions for future experiments at LHC, see Fig. 4.

Now let us analyze the production of the beauty hyperon, namely Λ_b^0, at small scattering angles $\theta_{\Lambda_b^0}$ in the pp collision at LHC energies. This study would be reliable for the future forward experiments at LHC. The produced Λ_b^0 baryon can decay as $\Lambda_b^0 \to J/\Psi\Lambda^0$, and J/Ψ decays into $\mu^+\mu^-$, its branching ratio ($Br = \Gamma_j/\Gamma$) is 5.93 ± 0.06 percent, or into e^+e^- ($Br = 5.93 \pm 0.06\%$), whereas Λ^0 can decay into $p\pi^-$ ($Br = \Gamma_j/\Gamma = 63.9 \pm 05\%$), or into $n\pi^0$ ($Br = 35.8 \pm 0.5\%$), see Fig. 4.

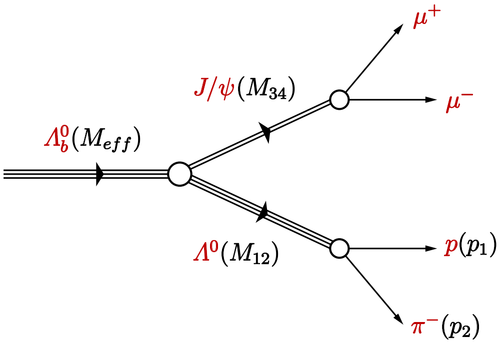

Figure 4: The decay $\Lambda_b \to J\Psi\ \Lambda^0 \to \mu^+\mu^-(e^+e^-)\ p\pi^-(n\pi^0)$.

$$\frac{d\sigma}{d^3p_1 dM_{34}} = \int \frac{d\sigma}{dM_{12}dM_{34}} \delta^{(3)}(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_{12})dM_{12}\ , \tag{5}$$

where

$$\frac{d\sigma}{dM_{12}dM_{34}} = \int d^2p_{t\Lambda_b} \frac{d\sigma_{pp\to\Lambda_b X}}{dx d^2p_{t\Lambda_b}} Br_{\Lambda_b\to J/\Psi} Br_{J/\Psi\to\mu^+\mu_-} Br_{\Lambda^0\to p\pi} \frac{\pi^3}{2M_{eff}^2 M_{12}M_{34}} \lambda^{1/2}(M_{eff}^2, M_{12}^2, M_{34}^2)\lambda^{1/2}(M_{12}^2, M_1^2, M_2^2)\lambda^{1/2}(M_{34}^2, M_3^2, M_4^2)\ ,$$

$Br_{\Lambda_b\to J/\Psi} = (4.7 \pm 2.8)\cdot 10^{-4}$; $Br_{J/\Psi\to\mu^+\mu_-} = (5.93 \pm 0.06)\%$; $Br_{\Lambda^0\to p\pi} = (63.9 \pm 0.5)\%$.
Here $\lambda(x^2, y^2, z^2) = ((x^2 - (y+z)^2)((x^2 - (y-z)^2)$
One can get the following relation

$$d^3p_1 \ = \ \frac{1}{2}p\xi_p d\phi_1 d\xi_p dt_p\ , \tag{6}$$

where $\xi_p = \Delta p/p$ is the energy loss, $t_p = (p_{in} - p_1)^2$ is the four-momentum transfer, ϕ_1 is the azimuthal angle of the final proton with the three-momentum $\mathbf{p}_1$.
Experimentally one can measure the differential cross section

$$\frac{d\sigma}{d\xi_p dt_p dM_{J/\Psi}} \ = \ \frac{1}{2}p\xi_p \int \frac{d\sigma}{d^3p_1 dM_{34}} d\phi_1 \tag{7}$$

This distribution could be reliable for the TOTEM experiment, where J/Ψ decays into $\mu^+\mu^-$ and Λ_b^0 decays into $\pi^- p$ or for the ATLAS forward experiment, where Λ_b^0 decays as $\Lambda_b^0 \to J/\Psi\ \Lambda^0 \to e^+e^-\ \pi^0 n$ (Fig. 4).

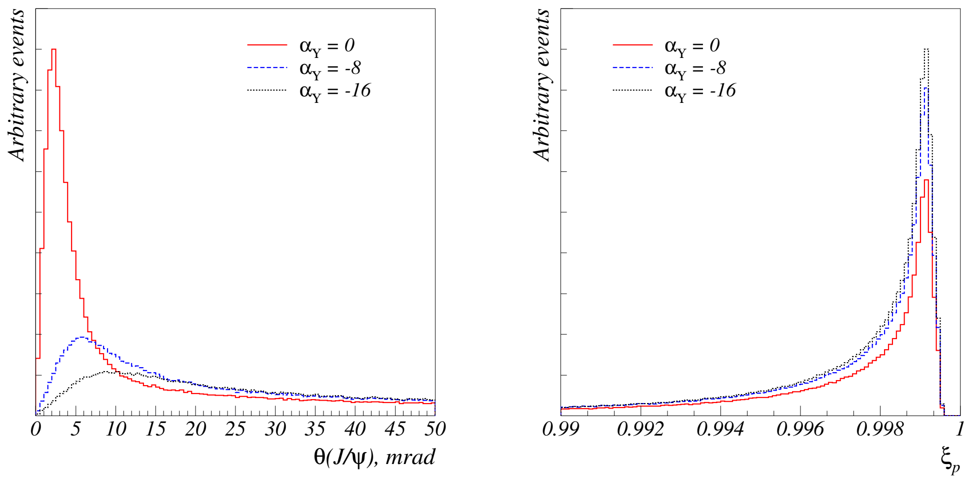

Figure 5: The distributions of $\theta_{J/\Psi}$ (left) and ξ_p (right) for the inclusive process $pp \to \Lambda_b X \to \mu^+\mu^- p\pi^- X$ at $\sqrt{s} = 4\,\text{TeV}$

In Fig. 5 the distributions over $\theta_{J/\Psi}$ (left) and ξ_p (right) are presented at different values of the intercept $\alpha_\Upsilon(0) = 0$ (solid line), $\alpha_\Upsilon(0) = -8$ (dashed line) and $\alpha_\Upsilon(0) = -16$ (dotted line), where $\theta_{J/\Psi}$ is the scattering angle for the final J/Ψ. Fig. 5 shows a sensitivity of these distributions to the intercept of the α_Υ Regge trajectory. Actually, the result presented in Fig. 5 is a prediction for future LHC experiments on the heavy flavour baryon production at the LHC energies.

4 Conclusion

It was shown [6, 7] that the modified QGSM including the intrinsic longitudinal and transverse motion of quarks (antiquarks) and diquarks in colliding protons allowed us to describe rather satisfactorily the existing experimental data on inclusive spectra of heavy hadrons produced in pp and $p\bar{p}$ collisions It allows us to make some predictions for future LHC forward experiments on the beauty baryon production in pp collisions which can give us new information on the beauty quark distribution in the proton and very interesting information on the Regge trajectories of $(b\bar{b})$ mesons.

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