J/ψ, Υ, AND B MESON PRODUCTION IN PROTON–PROTON COLLISIONS AT THE LHC

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Mechanisms of J/ψ, Υ, and B meson production in proton-proton scattering at total energy 7 TeV are studied with the help of event generator Pythia 8. Uncertainties in the total and differential cross sections due to choice of the renormalization and factorization scales are analyzed for prompt J/ψ and Υ production. Sensitivity of the inclusive cross sections on contributions of J/ψ from decay of b–hadrons is also discussed. Results of the calculations are compared with the ALICE, ATLAS, CMS, and LHCb data in order to assess potentialities and validity of the approaches, in particular color singlet and octet models, used in the simulations.

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1. INTRODUCTION

Production of charmonium and bottomonium is known as an important tool for testing perturbative quantum chromodynamics (pQCD) and gaining a better understanding of effects beyond the leading order in strong–coupling constant. Detailed discussion of models for charmonium and bottonium production in hadron scattering can be found, e.g. in [1–5].

Widely–used approaches for analysis of the quarkonium hadroproduction are based on an approximation when the hard scattering of partons is separated from soft processes related to formation of the mesons that are thought as heavy–quark bound states. Amplitudes of short–distance partonic processes are computed within pQCD, while treatment of long–distance ones yields to consideration of nonperturbative dynamics. The cross section for quarkonium hadroproduction can be written in a factorized form as superposition of cross sections for hard scattering of initial–state partons, e.g. $g + g \to Q\bar{Q} + g$, convoluted with parton distribution functions (PDFs) for colliding hadrons that are then weighted with matrix elements describing how created heavy–quark pair $Q\bar{Q}$ evolves into a quarkonium state.

The cross sections of hard partonic scattering (PDFs) depend on renormalization (factorization) scale. In rigorous calculations, that should include contributions beyond leading order both in the amplitudes of short–distance processes and evolution equations for PDFs, the cross sections of the reactions are expected to be independent from a particular choice of the scales. High–order processes prove to affect visibly the cross sections and polarization in the quarkonium hadroproduction [6–10]. Nevertheless, the uncertainties, inherent to extensions of the leading–order approaches, still remain essential.

A growing interest in the last decade at studying the heavy–quarkonium production stems also from the hope to use these processes for the diagnostics of the quark–gluon medium produced in ultrarelativistic heavy–ion collisions [2, 5, 11, 12].

Purpose of this report is to study mechanisms of prompt J/ψ and Υ production, role of J/ψ, originating from b–hadron decays, and to determine quantitatively how variations of parameters, that define renormalization and factorization scales, influence the cross sections of the reactions. The present studies aim to test the color singlet and octet models for heavy–quarkonium production [4, 13–15], employing with this end results of recent experiments [16–22] at the Large Hadron Collider (LHC).

2. MODELS FOR QUARKONIA HADROPRODUCTION

In this paper the meson production is simulated making use of event generator Pythia 8 [23]. Production of prompt J/$\psi(1S)$ and $\Upsilon(1S)$ along with non–prompt J/$\psi(1S)$ is considered.

Prompt mesons originate from a heavy quark–antiquark pairs $Q\bar{Q}$ that hadronize into colorless states. It is assumed that the $Q\bar{Q}$ pairs, where $Q = c$ or b, are created in short–range processes:

$$g + g \to Q\bar{Q}\left[{}^{2S+1}L_J(a)\right] + g, \qquad (1)$$

$$q + g \to Q\bar{Q}\left[{}^{2S+1}L_J(a)\right] + q, \qquad (2)$$

$$q + \bar{q} \to Q\bar{Q}\left[{}^{2S+1}L_J(a)\right] + g, \qquad (3)$$

with definite values of orbital angular momentum L, spin S, and total angular momentum J in color singlet (CS) or octet (CO) states, that are indicated by $a = 1$ or 8, respectively.

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CS $Q\bar{Q}$ pairs with ${}^{2S+1}L_J = {}^3S_1$ spring from hard gluon scattering (1). CO $Q\bar{Q}$ states ${}^1S_0$ and ${}^3S_1$ are produced in all processes (1)–(3). CS and CO $Q\bar{Q}$ pairs in P–wave states ${}^3P_J$ with $J = 0, 1, 2$ and $J = 0$, respectively, are generated in (1)–(3). Subsequent transition between CO $Q\bar{Q}$ and colorless quarkonium states is accompanied by soft gluon emission.

The prompt mesons originate also from decays of higher quarkonium states, e.g.

$$\chi_{2c}(1P) \to \gamma + J/\psi(1S) \quad \text{or} \quad \chi_{0b}(1P) \to \gamma + \Upsilon(1S).$$

Decays of b–hadrons, such as B–mesons, Λ_b, Σ_b, Ξ_b, Ω_b, etc., serve as a source of non–prompt J/$\psi(1S)$, for example,

$$B^{+*} \to \gamma + B^+, \qquad B^+ \to J/\psi(1S) + K^+.$$

Cross sections for non–prompt J/$\psi(1S)$ production receive substantial contributions from the reaction $p + p \to B + X$. Description of the latter relies on the Lund string model [24] being a framework for implementation of fragmentation processes in Pythia.

3. CROSS SECTIONS OF QUARKONIA AND B MESON PRODUCTION

The simulation of the quarkonia production is performed with Pythia 8.145 using the default tune and PDFs CTEQ 6.6M [25]. The renormalization and factorization scales are expressed through the transverse masses of outgoing particles in (1)–(3)

$$Q_R^2 = c_R \left((M_{Q\bar{Q}}^2 + p_T^2)(M^2 + p_T^2) \right)^{1/2}, \qquad (4)$$

$$Q_F^2 = c_F \left(M^2 + p_T^2 \right), \qquad (5)$$

where p_T (M) denotes the transverse momentum (the mass) of u, d, s, c, b quark or gluon, $M_{Q\bar{Q}}$ is the mass of $Q\bar{Q}$ pair.

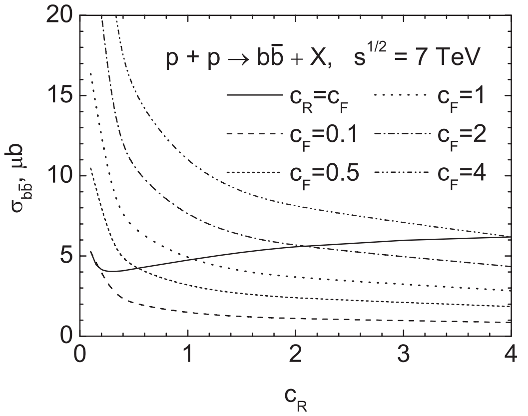

Fig. 1. *Dependence of the total cross section for $b\bar{b}$–pairs production on choice of the renormalization scale*

The total cross sections $\sigma_{Q\bar{Q}}$ for production of $c\bar{c}$ or $b\bar{b}$ pairs, obtained with (1)–(3), appear to be not independent from values of the renormalization and factorization scales. As seen in Figs. 1 and 2, functions $\sigma_{b\bar{b}}(c_R, c_F = \text{const})$ and $\sigma_{b\bar{b}}(c_R = \text{const}, c_F)$ vary rapidly for $c_R < c_F$. At the same time, decrease of $\sigma_{b\bar{b}}(c_R, c_F = \text{const})$ is relatively slow for $c_R \gtrsim 1$ and $c_R \gtrsim c_F$. The cross section $\sigma_{c\bar{c}}$ reveals qualitatively the same behaviour as in Figs. 1 and 2.

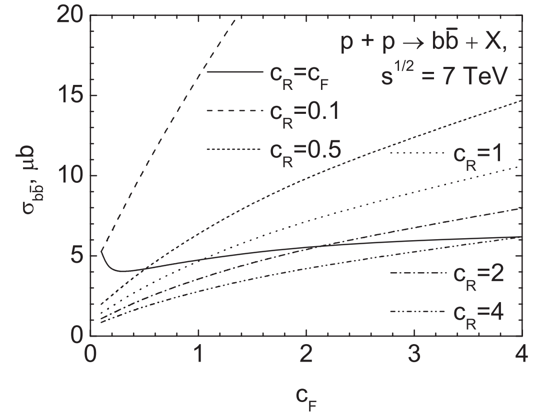

Fig. 2. *Dependence of the total cross section for $b\bar{b}$–pairs production on choice of the factorization scale*

Calculations of the differential cross sections under conditions of experiments [16–22] have been carried out for various sets of parameters c_R and c_F. Results for some sets both at the diagonal in (c_R, c_F)–plane and outside it are displayed in Figs. 3 – 6. Values $c_R = c_F = 0.49$ correspond to the minimum in $\sigma_{c\bar{c}}$ for $p + p \to c\bar{c} + X$.

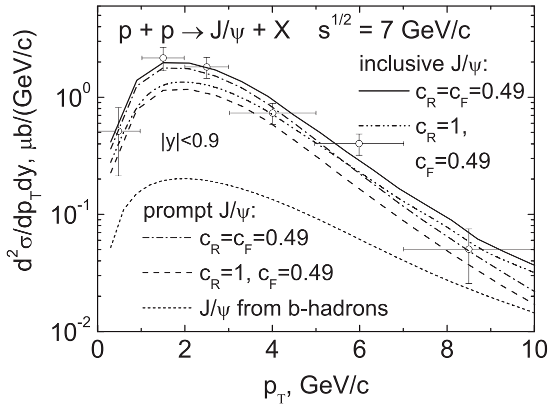

Fig. 3. *Differential cross section for J/ψ production in the central rapidity region. Points are taken from Ref. [17]*

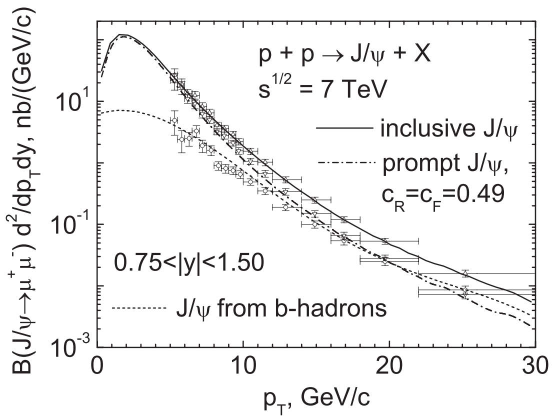

Fig. 4. *The same as in Fig. 3. The data are from Ref. [16]. The branching fraction of the J/ψ decay into two muons is $B(J/\psi \to \mu^+\mu^-)$*

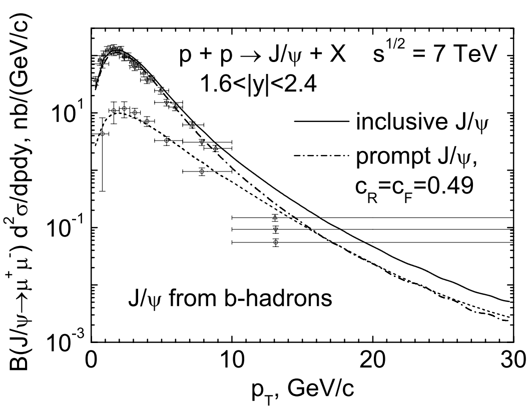

Fig. 5. *The same as in Fig. 3. The data are from Ref. [18]*

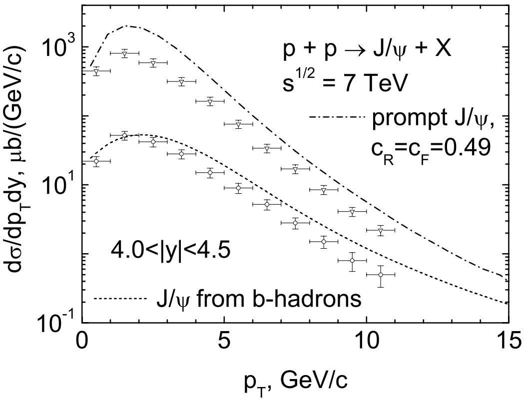

Fig. 6. *Differential cross section for J/ψ production in the forward rapidity region. The data are from Ref. [19]*

The analysis of the p_T distributions in Figs. 3–6 covers wide area of emission angles of the mesons from central to forward regions. Calculations show that the transverse–momentum spectra of $J/\psi(1S)$, measured by the ALICE, ATLAS, CMS, and LHCb collaborations in the central–rapidity region, lie within the band of theoretical uncertainties. Results of the LHCb in the forward region are near the low edge of this band. Note, that predictions [28] within the k_T–factorization approach in CS model agree with the LHC experimental data in both central and forward regions.

In Fig. 7 and 8 the differential cross sections for the reactions $pp \to B^{0,+}X$, obtained in the present report with Tune 4C in Pythia 8.153 and PDFs CTEQ6.6M, are compared with the results of measurements and simulations, performed by CMS collaboration [26, 27]. In CMS papers Pythia 6 with Tune D6T and PDFs CTEQ6L1 is used. Figs. 7 and 8 show that the different codes lead to the cross sections, that do not differ visibly at considered p_T–region and are close to the experimental data.

Cross sections for prompt $\Upsilon(1S)$ production, computed in the framework of the CS and CO models, turn out be strong scale sensitive, as can be inferred from Fig. 9.

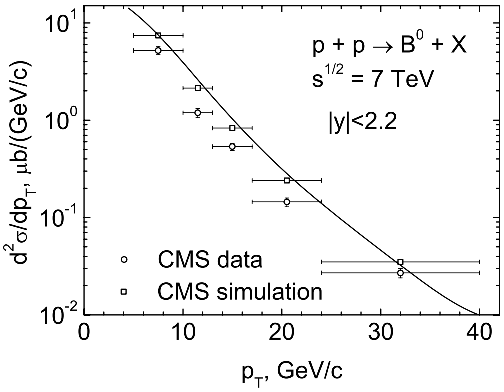

Fig. 7. *Differential cross section for B^0 production. The points are from Ref. [26]*

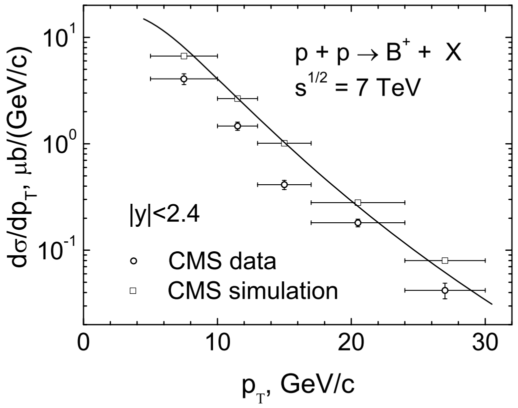

Fig. 8. *Differential cross section for B^+ production. The points are from Ref. [27]*

Transverse–momentum and rapidity dependencies of the cross sections are displayed in Figs. 9 and 10 under conditions of CMS experiment [21]. Comparison with ATLAS [20] and LHCb [22] data will be presented elsewhere.

Detailed analysis shows that process (1) with ${}^{2S+1}L_J(a) = {}^3P_1(1), {}^3P_2(1)$, and ${}^3P_0(8)$ gives main contributions to the cross section of J$/\psi(1S)$ production for $c_R = c_F = 0.49$. Thus, reaction mechanisms that involve creation of $\chi_{1c}(1P)$ and $\chi_{2c}(1P)$ mesons in the CS intermediate states are enhanced in the calculations. At $p_T \simeq 10$ GeV/c CS channel ${}^3P_1(1)$ turns out to be the most important.

Transitions via (1) with ${}^{2S+1}L_J(a) = {}^3P_2(1)$ and ${}^3P_0(8)$ (${}^3S_1(8)$) dominate in $\Upsilon(1S)$ production when scale parameters $c_R = c_F = 0.3$ ($c_R = c_F = 1.0$) are used in the calculations. For $c_R = c_F = 1.0$ ratio of CS and CO cross section for (1) is

$$\sigma_{b\bar{b}}({}^3S_1(1))/\sigma_{b\bar{b}}({}^3S_1(8)) = 0.45.$$

For $p_T \lesssim 40$ GeV/c both the CS and CO channels appear to be comparable. Strengthened contributions of the CO intermediate states may be responsible for the overestimation of the data by the theory as observed in Figs. 9 and 10.

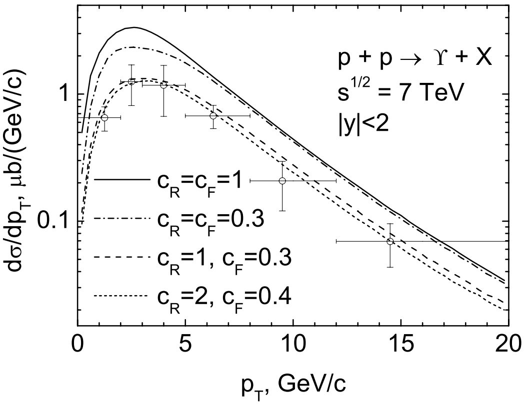

Fig. 9. *Transverse–momentum dependence of the differential cross section for $\Upsilon(1S)$ production. The points are from Ref. [21]*

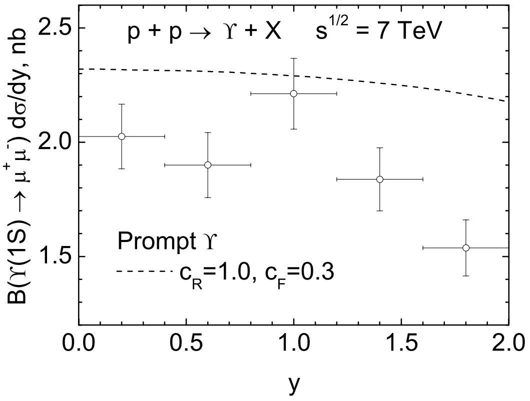

Fig. 10. *Rapidity dependence of the differential cross section for $\Upsilon(1S)$ production. The points are from Ref. [21]. The branching fraction of the $\Upsilon(1S)$ decay into two muons is $B(\Upsilon(1S) \to \mu^+\mu^-)$*

4. CONCLUSIONS

Production of J/ψ, Υ, and B mesons in proton-proton collisions at total energy 7 TeV is simulated with the help of event generator Pythia 8. Studies of the reactions $pp \to J/\psi(1S)X$ and $pp \to \Upsilon(1S)X$, performed within the color singlet and color octet models, have demonstrated the strong dependence of the cross sections to parameters, that define renormalization and factorization scales. Results of the calculations are compared with the experimental data, obtained by the ALICE, ATLAS, CMS, and LHCb collaborations at the LHC. Transverse–momentum distributions of the emitted mesons, computed in the central–rapidity region, agree reasonably with the data. Nevertheless, some discrepancies appear in the forward region.

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РОЖДЕНИЕ J/ψ-, Υ- И B-МЕЗОНОВ В ПРОТОН-ПРОТОННОМ РАССЕЯНИИ НА БОЛЬШОМ АДРОННОМ КОЛЛАЙДЕРЕ

В.В. Котляр, Н.В. Крупина

Механизмы рождения J/ψ-, Υ- и B-мезонов в рассеянии протонов с полной энергией 7 ТэВ изучаются с помощью генератора событий Пифия 8. Неопределённости в значениях полных и дифференциальных сечений реакций, которые обусловлены выбором шкал перенормировки и факторизации, анализируются для рождения мгновенных J/ψ- и Υ-мезонов. Исследуется также чувствительность инклюзивных сечений реакции к вкладам J/ψ, источником которых являются распады b–адронов. Для проверки моделей, используемых в моделировании рассмотренных процессов, результаты расчётов сравниваются с данными, полученными коллаборациями ALICE, ATLAS, CMS и LHCb.

НАРОДЖЕННЯ J/ψ-, Υ- ТА B-МЕЗОНІВ В ПРОТОН-ПРОТОННОМУ РОЗСІЯННІ НА ВЕЛИКОМУ АДРОННОМУ КОЛАЙДЕРІ

В.В. Котляр, Н.В. Крупіна

Механізми народження J/ψ-, Υ- та B-мезонів у розсіянні протонів з повною енергією 7 ТеВ вивчаються за допомогою генератора подій Піфія 8. Невизначеність повних та диференційних перерізів реакцій, що зумовлена вибором шкал перенормування та факторизації, аналізується для народження миттєвих J/ψ- та Υ-мезонів. Досліджується також чутливість інклюзивних перерізів реакцій до внесків J/ψ, джерелом яких є розпад b–адронів. Для перевірки моделей, що використовуються в моделюванні розглянутих процесів, результати розрахунків порівнюються з даними, що було отримано колабораціями ALICE, ATLAS, CMS та LHCb.