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Upsilonium polarization as a touchstone in understanding the parton dynamics in QCD

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In the framework of the k_t-factorization approach, the production of Υ mesons at the Fermilab Tevatron and CERN LHC is considered, and the predictions on the spin alignment parameter α are presented. We argue that measuring the polarization of quarkonium states can serve as a crucial test discriminating two competing theoretical approaches to parton dynamics in QCD.

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Nowadays, the production of heavy quarkonium states at high energies is under intense theoretical and experimental study [1, 2]. The production mechanism involves the physics of both short and long distances, and so, appeals to both perturbative and nonperturbative methods of QCD. The creation of a heavy quark pair $Q\bar{Q}$ proceeds via the photon-gluon or gluon-gluon fusion (respectively, in ep and pp collisions) referring to small distances of the order of $1/2m_Q$, while the formation of the colorless final state refers to longer distances of the order of $1/m_Q\,\alpha_s(m_Q)$. These distances are longer than the distances typical for hard interaction but are yet shorter than the ones responsible for hadronization (or confinement). Consequently, the production of heavy quarkonium states is under control of perturbative QCD but, on the other hand, is succeeded by nonperturbative emission of soft gluons. This feature gives rise to two competing theoretical approaches known in the literature as the color-singlet [3, 4] and color-octet [5] models. According to the color-singlet approach, the formation of a colorless final state takes place already at the level of the hard partonic subprocess (which includes the emission of hard gluons when necessary). In the color-octet model, also known as nonrelativistic QCD (NRQCD), the formation of a meson starts from a color-octet $Q\bar{Q}$ pair and proceeds via the emission of soft nonperturbative gluons. The former model has a well defined applicability range and has already demonstrated its predictive power in describing the J/ψ production at HERA, both in the collinear [6] and the k_t-factorization [7] approaches. As it was shown in the analysis of recent ZEUS [8] data, there is no need in the color-octet contribution, neither in the collinear nor in the k_t-factorization approach.

Originally, the color-octet model was introduced to overcome the discrepancy between the large J/ψ production cross section measured in pp interactions at the Tevatron [9 – 11] and the results of theoretical calculations based on the standard perturbative QCD technique. The problem was apparently solved by attributing the discrepancy to the hypothetical contributions from the intermediate color-octet states, which must obey certain hierarchy in powers of the relative velocity of the quarks in a bound system. However, the numerical estimates of these contributions extracted from the analysis of Tevatron data are at odds with the HERA data, especially as far as the inelasticity parameter $z = E_\psi/E_\gamma$ is concerned [12]. In the k_t-factorization approach, the values of the color-octet contributions obtained as fits of the Tevatron data appear to be substantially smaller than the ones in the collinear scheme, or even can be neglected at all [13 – 16].

In the present note we want to stress once again that measuring the polarizaton of quarkonium states produced at high energies may serve as an important and crucial test discriminating the different theoretical concepts. The first attempts to solve the quarkonium polarization problem within the k_t-factorization approach were made in the pioneering work [17] (see also [18]) for ep collisions and in Refs. [13, 19] for pp collisions. It was emphasised that the off-shellness of the initial gluons, the intrinsic feature of the k_t-factorization approach, has an immediate consequence (by analogy with longitudinal photons) in the longitudinal polarization of the final state J/ψ mesons. The theoretical predictions [17] have stimulated experimental investigation of J/ψ spin alignment at the collider HERA. The first results obtained by the collaborations H1 and ZEUS have been described in Ref.[7]. These results have qualitatively

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confirmed the predictions on the dominance of longitudinal polarization.

The preliminary results on the J/ψ polarization at the Tevatron obtained by the collaborations E537 [20] and CDF [21] also point to logitudinal polarization with the average value of spin alignment parameter $\alpha \approx -0.2$ over the whole range of J/ψ transverse momentum p_T. The collaboration D0 is currently analysing the data on the spin alignment of Υ mesons.

In the NRQCD approach, the problem of quarkonium polarization remains unsolved [1, 2]. The gluon fragmentation mechanism leads to strong transverse polarization. Including the next-to-leading QCD corrections makes the transverse polarization even stronger. The only way out is seen in increasing the fraction of unpolarized mesons by attributing large contributions to the certain color-octet channels [19], which, however, violates the expected NRQCD hierarchy. The role of the color-octet contributions taken into account in the analysis of recent ZEUS data is obscure and does not lead to a conclusive description of J/ψ polarization parameters (see [2]).

The goal of this paper is to derive theoretical predictions on the polarization of Υ mesons produced at the Fermilab Tevatron and CERN LHC. In the k_t-factorization approach, the cross section of a physical process is calculated as a convolution of the partonic cross section $\hat{\sigma}$ and the unintegrated parton distribustion $\mathcal{F}_g(x, k_T^2, \mu^2)$, which depend on both the longitudinal momentum fraction x and transverse momentum k_T:

$$\sigma_{pp} = \int \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2) \times \\ \times\, \hat{\sigma}_{gg}(x_1, x_2, k_{1T}^2, k_{2T}^2, ...)\, dx_1\, dx_2\, dk_{1T}^2\, dk_{2T}^2. \quad (1)$$

In accord with the k_t-factorization prescriptions [22–25], the off-shell gluon spin density matrix is taken in the form

$$\overline{\epsilon_g^{\mu} \epsilon_g^{*\nu}} = p_p^{\mu} p_p^{\nu} x_g^2 / |k_T|^2 = k_T^{\mu} k_T^{\nu} / |k_T|^2. \quad (2)$$

In all other respects, our calculations follow the standard Feynman rules.

In order to estimate the degree of theoretical uncertainty connected with the choice of unintegrated gluon density, we use two different parametrizations, which are known to show the largest difference with each other, namely, the ones proposed in Refs. [22, 25] and [26].

In the first case [22], the unintegrated gluon density is derived from the ordinary (collinear) density $G(x, \mu^2)$ by differentiating it with respect to μ^2 and setting $\mu^2 = k_T^2$. Here we use the Leading Order Glück-Reya-Vogt set [27] as the input colinear density. In the following, this will be referred to as derivative of GRV parametrisation. The other unintegrated gluon density [26] is obtained as a solution of leading order Balitsky-Fadin-Kuraev-Lipatov equation [25] in the double-logarithm approximation. Technically, it is calculated as the convolution of the ordinary gluon density with some universal weight factor. In the following, this will be referred to as J.Blümlein parametrisation.

The production of Υ mesons in pp collisions can proceed via either direct gluon-gluon fusion or the production of P-wave states χ_b followed by their radiative decays $\chi_b \to \Upsilon + \gamma$. The direct mechanism corresponds to the partonic subprocess

$$g + g \to \Upsilon + g \quad (3)$$

which includes the emission of an additional hard gluon in the final state. The production of P-wave mesons is given by

$$g + g \to \chi_b, \quad (4)$$

and there is no emittion of any additional gluons. As we have already mentioned above, we see no need in taking the color-octet contributions into consideration.

The other essential parameters were taken as follows: the b-quark mass $m_b = m_\Upsilon/2 = 4.75$ GeV; the Υ meson wave function $|\Psi_\Upsilon(0)|^2 = 0.4$ GeV^3 (known from the leptonic decay width $\Gamma_{l^+l^-}$ [28]); the wave function of P-wave states $|\Psi'_\chi(0)|^2 = 0.12$ GeV^5 (taken from the potential model [29]); the radiative decay branchings $Br(\chi_{b,J} \to \Upsilon\gamma) = 0.06,\ 0.35,\ 0.22$ for $(J = 0, 1, 2)$ [28]; the renormalization and factorization scale $\mu^2 = m_\Upsilon^2 + p_T^2$.

The polarization state of a vector meson is characterized by the spin alignment parameter α which is defined as a function of any kinematic variable as

$$\alpha(\mathcal{P}) = (d\sigma/d\mathcal{P} - 3 d\sigma_L/d\mathcal{P}) / (d\sigma/d\mathcal{P} + d\sigma_L/d\mathcal{P}), \quad (5)$$

where σ is the reaction cross section and σ_L is the part of cross section corresponding to mesons with longitudinal polarization (zero helicity state). The limiting values $\alpha = 1$ and $\alpha = -1$ refer to the totally transverse and totally longitudinal polarizations. We will be interested in the behavior of α as a function of the Υ transverse momentum: $\mathcal{P} \equiv |\mathbf{p}_T|$. The experimental definition of α is based on measuring the angular distributions of the decay leptons

$$d\Gamma(\Upsilon \to \mu^+\mu^-)/d\cos\theta \sim 1 + \alpha \cos^2\theta, \quad (6)$$

where θ is the polar angle of the final state muon measured in the decaying meson rest frame.

The results of our calculations for the kinematic conditions of the Tevatron and LHC are displayed in Figs.1 and 2. In both cases, the integration limits over rapidity were adjusted to the experimental acceptances of CDF ($|y_\Upsilon| < 0.6$) at the Tevatron and ATLAS ($|y_\Upsilon| < 2.5$) at the LHC. The upper panels show the predicted transverse momentum distributions. Separately shown are the contributions from the direct (dashed lines) and P-wave decay (dotted lines) mechanisms. Note that, in spite of the suppression due to smaller values of P-wave finctions compared to S-wave finctions, the dominant contribution comes from the subprocess (4) rather than from (3). The reason can be seen in the much smaller values of the final state invariant masses, $m_\chi << m_{\psi g}$. Our conclusion on the relative size of two contributions is compatible with the preliminary estimates obtained by the collaboration CDF [11]. The p_T shape of the individual contributions yet has not been meaured experimentally. In the k_t-factorization approach, this shape is determined by the unintegrated gluon density. The average p_T is a bit lower in the process (3), because the total transverse momentum (equal to that of the initial gluons) is shared between the two final state particles; at the same time, the contribution from the matrix element is nearly unimportant.

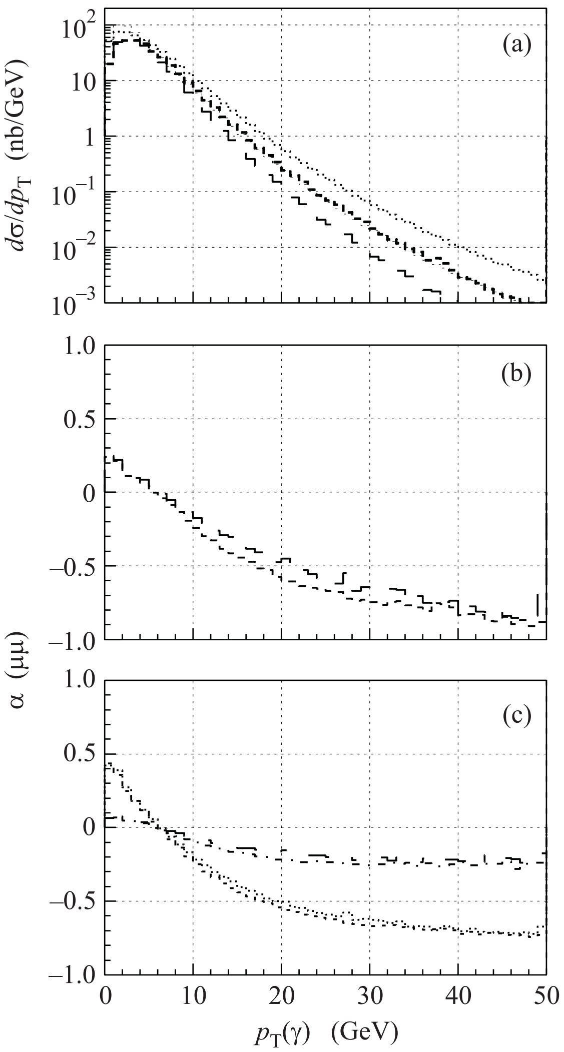

Fig.1. Predictions on the production of Υ mesons at the Tevatron. Thick lines, JB parametrization; thin lines, dGRV parametrization. (a) Transverse momentum distribution. (b) Spin alignment parameter α for the direct contribution. (c) Spin alignment parameter α with feed-down from χ_b decays taken into account. Dotted lines, the quark spin conservation hypothesis; dash-dotted lines, the full depolarization hypothesis

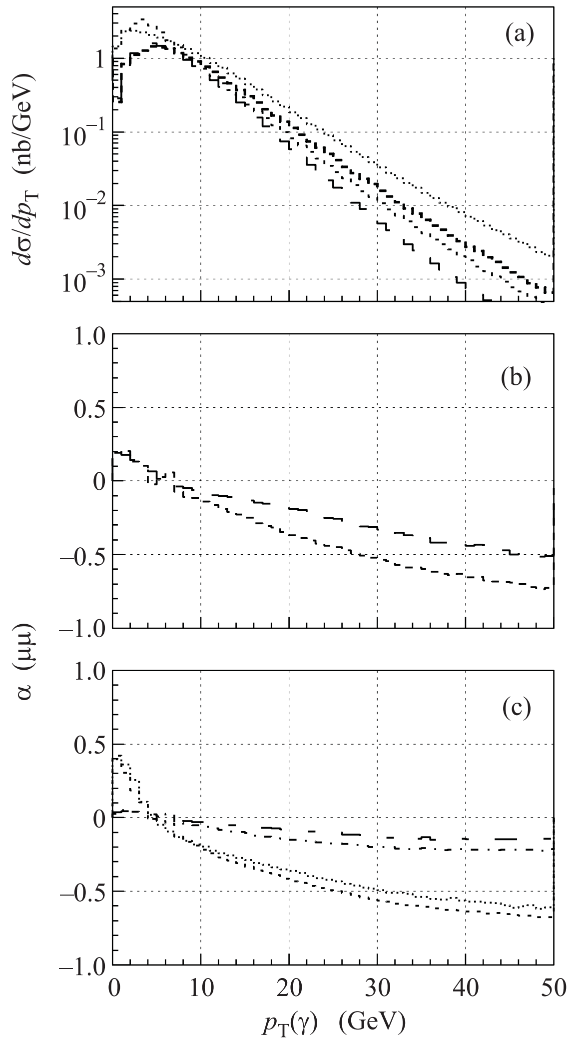

Fig.2. Same as Fig. 1, but for the LHC conditions

It is worth noting that the production of χ_b mesons can hardly be described in a consistent way within the collinear factorization scheme. The leading order contribution coming from the subprocess (4) shows unphysical δ-like p_T spectrum. The usual lame excuses that the particles produced at zero p_T disappear in the beam pipe and remain invisible do not work, because the decay products do have nonzero p_T and, undoubtedly, can be detected. At the same time, the introduction of next-to-leading contributions (i.e., the processes with extra gluons in the final state) causes the problem of infrared divergences.

The central panels in Figs.1 and 2 show the behavior of the spin alignment parameter α for Υ mesons produced in the direct subprocess (3). The increase in the fraction of longitudinally polarised mesons is promptly connected with the increasing virtuality (and, consequently, the strenghtening longitudinal polarization) of the initial gluons.

As far as the decays of P-wave states are concerned, nothing is known on the polarization properties of these decays. If we assume that the quark spin is conserved in radiative transitions, and the emission of a photon only changes the quark orbital momentum (as it is known to be true in the electric dipole transitions in atomic physics, $\Delta S = 0$, $\Delta L = \pm 1$), then the predictions on α appear to be similar to those made for the direct channel (see lower panels in Figs.1 and 2, dotted curves). If, on the contrary, we assume that the the transition $\chi_b \to \Upsilon + \gamma$ leads to complete depolarization, then we arrive at a more moderate behavior of the parameter α (dash-dotted curves in Figs. 1 and 2). The overall polarization remains slightly longitudinal ($\alpha \simeq -0.2$) in the whole range of p_T due to the 'direct' contribution. A comparison between the data on J/ψ and ψ' polarization at the Tevatron [21] seems to give support to the depolarization hypothesis. The difference between the J/ψ and ψ' polarization data can be naturally explained by the presence of the depolarizing contribution in the case of J/ψ and the absense of this contribution in the case of ψ'.

A state with purely direct production mechanism in the bottomonium family is the $\Upsilon(3S)$ meson. The calculations presented here are also valid for this state, except the lower total cross section (by an approximate factor of 1/3) because of the correspondingly lower value of the wave function $|\Psi_{\Upsilon(3S)}(0)|^2 = 0.13$ GeV^3. At the same time, the predictions on the spin alignment parameter α remain intact (central panels in Figs.1 and 2).

We have considered the production of Υ mesons in high energy pp collisions in the k_t-factorization approach and derived predictions on the spin alignment parameter $\alpha(p_T)$. We point out that the predicted value of $\alpha(p_T)$ is typically negative in the whole range of p_T and shows variations from $\alpha \simeq (-0.2)$ to $\alpha \simeq (-0.7)$ depending on the hypothesis assumed for the decays $\chi_b \to \Upsilon(1S) + \gamma$. At the LHC energies, the theoretical predictions possess less sensitivity to the choice of unintegrated gluon distributions. The purest probe is provided by the polarization of $\Upsilon(3S)$ mesons. In that case, the polarization is the strongest and the predictions are free from uncertainties coming from the unknown properties of χ_b decays.

We do not discuss the behavior of the parameter $\alpha(p_T)$ at asymptotically large transverse momenta where the applicability of the k_t-factorization approach is questionable.

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