Testing the k_t-factorization approach with P-wave quarkonia production

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Abstract

A new qualitative test of the k_t-factorization approach is proposed. We analyse the production of P-wave quarkonium states with different spins χ_0, χ_1 and χ_2 in high energy proton proton interactions. The predictions of the usual parton model and the k_t-factorization approach are compared. We find that the shape of the transverse momentum distributions and, also, the ratio of the production rates $\sigma(\chi_1)/\sigma(\chi_2)$ are qualitatively different in the considered models. The referred processes may serve as an essential test of the validity of the k_t-factorization approach.

1. Introduction

Over the years, the k_t-factorization approach [1]-[4] has demonstrated its ability to describe a large body of experimental data (see [5] and references therein), including the photo- and electroproduction of D^* mesons, J/ψ mesons and forward jets, as well as specific kinematic correlations observed in the associated D^*+jets photoproduction at the DESY ep collider HERA. The semihard approach was also shown to reasonably describe the data on the hadroproduction of open charm and beauty, J/ψ, χ_c and Υ mesons at the Fermilab Tevatron. In many cases, however, the data can also be described within the usual (collinear) parton model, if the relevant next-to-leading order QCD corrections are taken into account or the so called colour-octet mechanism is included.

In this context, the theoretical predictions on J/ψ spin alignment made in Ref. [6] are of particular interest, as the collinear and k_t-factorization approaches show qualitatively different behaviour. Note that the k_t-factorization approach provides the only known (up to date) explanation of the J/ψ polarization phenomena observed at the Tevatron [7] and at HERA [8].

It would be interesting and important to find other examples, where the difference between the collinear and noncollinear approaches would manifest in such a clear and unumbiguous way. The goal of the present note is to show that such a process is found. We analyse the production of P-wave quarkonium states (namely, the χ_c and χ_b mesons) in high energy hadronic collisions and demonstrate the dramatic difference between the different theoretical calculations.

Naively, one could expect the difference from the fact that the production of χ_1 states in the $2 \to 1$ gluon-gluon fusion process is forbidden if the initial gluons are on shell, but is allowed if the gluons are off shell. However, the real situation is complicated by the necessity to take into account the $2 \to 2$ processes as well. The results of our analysis are presented in the next section.

2. Numerical results and discussion

We begin our discussion with showing the predictions of the collinear parton model on the production of P-wave charmonia at Tevatron conditions. The colour-singlet production scheme refers to the $2 \to 2$ gluon-gluon fusion subprocess

$$g + g \to \chi + g \tag{1}$$

(it would be inadequate to rely upon the $2 \to 1$ subprocess $g + g \to \chi$ in this case, because the final state particle would then be produced with zero transverse momentum, and thus, could not be detected experimentally). The computational technique is explained elsewhere [9],[10] in every detail and needs not to be reproduced here again.

For the sake of definiteness, we only present the parameter setting used in our calculations. Throughout the paper, we use the Leading Order GRV set [11] of gluon densities in the proton and the value of the χ_c wave function $|\mathcal{R}'_{\chi_c}(0)|^2 = 0.075$ GeV^5 taken from the potential model of Ref. [12]. The renormalization scale in the strong coupling constant $\alpha_s(\mu_R^2/\Lambda^2)$ is set to $\mu_R^2 = m_\chi^2 + p_{T,\chi}^2$ with Λ=200 MeV. The integration over the final state phase space is restricted to the pseudorapidity interval $-0.6 < \eta(\chi_c) < 0.6$, in accord with the experimental cuts used by the CDF collaboration [13]-[15].

Since the predictions based on the colour-singlet mechanism alone are known to be inconsistent with the data [13]-[15], the theory has to be amplified with the so called colour-octet contribution, as it is commonly assumed in the literature [10]. Unlike the predictions of the colour-singlet model, the size of the colour-octet matrix elements is not calculable within the theory. Therefore, the corresponding numerical results are always shown with arbitrary normalising factors (just chosen to fit the experimental data when possible).

The numerical predictions of the collinear parton model are summarised in Fig. 1 (left upper panel). At relatively low transverse momenta, the production of χ_c states is dominated by the colour singlet mechanism. The differential cross section $d\sigma/dp_T$ diverges when $p_T \to 0$ for χ_2 states, while it remains finite for χ_1 states. (In fact, it even goes to zero, but this effect is not visible with the histogram binning, which we are using.) The production of χ_1 states at zero p_T is suppressed (in accord with Landau-Yang theorem), because in the limit of very soft final state gluon the $2 \to 2$ gluon-gluon process degenerates into $2 \to 1$ process. The shape of the χ_0 spectrum is similar to that of χ_2 (up to an overall normalising factor), and this spectrum is not shown in the figure.

The production of χ_c mesons at high p_T is dominated by the colour-octet contribution, which mainly comes from the 'gluon fragmentation' diagrams. Here, the perturbative production of ${}^3S_1$ colour octet states

$$g + g \to \; {}^3S_1^8 + g, \tag{2}$$

is followed by a nonperturbative emission of soft gluons, that results in the formation of physical colour singlet χ_c mesons:

$${}^3S_1^8 \to \; {}^3P_J^1 + ng. \tag{3}$$

As the co-produced gluons in equ. (3) are assumed to be soft, the momentum distribution of χ_c mesons is taken identical to that of the colour-octet ${}^3S_1$ state in equ. (2). The nonperturbative matrix elements responsible for the process (3) are related to the fictituous colour-octet wave functions, which are used in calculations based on equ. (2) in place of the ordinary colour-singlet wave function: $<0|\mathcal{O}_8|0>= (9/2\pi)\,|\mathcal{R}_8(0)|^2$.

It should be noted that the fragmentation of an almost on-shell transversly polarised gluon into χ_1 state via the emission of a single additional gluon $g \to \; {}^3S_1^8 \to \chi_1 + g$ is suppressed in accord with Landau-Yang theorem — due to exactly the same reasons, which make the direct on-shell gluon-gluon fusion $g+g \to \chi_1$ or two-gluon decay $\chi_1 \to g+g$ impossible. In terms of the nonrelativistic approximation, it is equivalent to say that the formally leading colour-electric dipole transitions are forbidden. The fragmentation requires the emission of at least two additional gluons (respectively, in the nonrelativistic QCD, one must go to nonleading higher multipoles), and so, the fragmentation probability must be suppressed by some extra powers of v, the relative velocity of charmed quarks in the bound state under study. As the degree of this suppression is not calculable within the colour-octet model on its own, we rather arbitrarily set the suppression factor to 1/20, which corresponds to potential model expectations for the average value of v^2. Our numerical results on the colour-singlet contribution (1) agree with the ones presented in Ref. [10]. At the same time, we disagree about the colour-octet contributions (2),(3), because the results presented in [10] are not normalised to the available data [13]-[15], and, also, the suppression of χ_1 states in the gluon fragmentation channel is not taken into account in [10].

Now, we proceed with showing the results obtained in the k_t-factorization approach. In this case, the production of charmonium χ_c states can be successfully described within the colour-singlet model alone [7], or with only a minor admixture of colour-octet contribution [16]. The consideration is based on the $2 \to 1$ partonic subprocess

$$g + g \to \chi, \tag{4}$$

which represents the true leading order in perturbation theory. The nonzero transverse momentum of the final state meson comes from the momenta of the initial gluons. The computational technique, which we are using here is identical to the one described in detail in Ref. [7][1]. In the present calculations, we conserve the parameter setting described in the beginning of this section and accept the Blümlein's parametrization for the unintegrated gluon distributions [17], where the ordinary LO GRV functions [11] are taken as boundary conditions. This choice is fully consistent with our previous calculations [7].

[1]We use the FORTRAN code developed in [7]. This code is public and is available from the author on request.

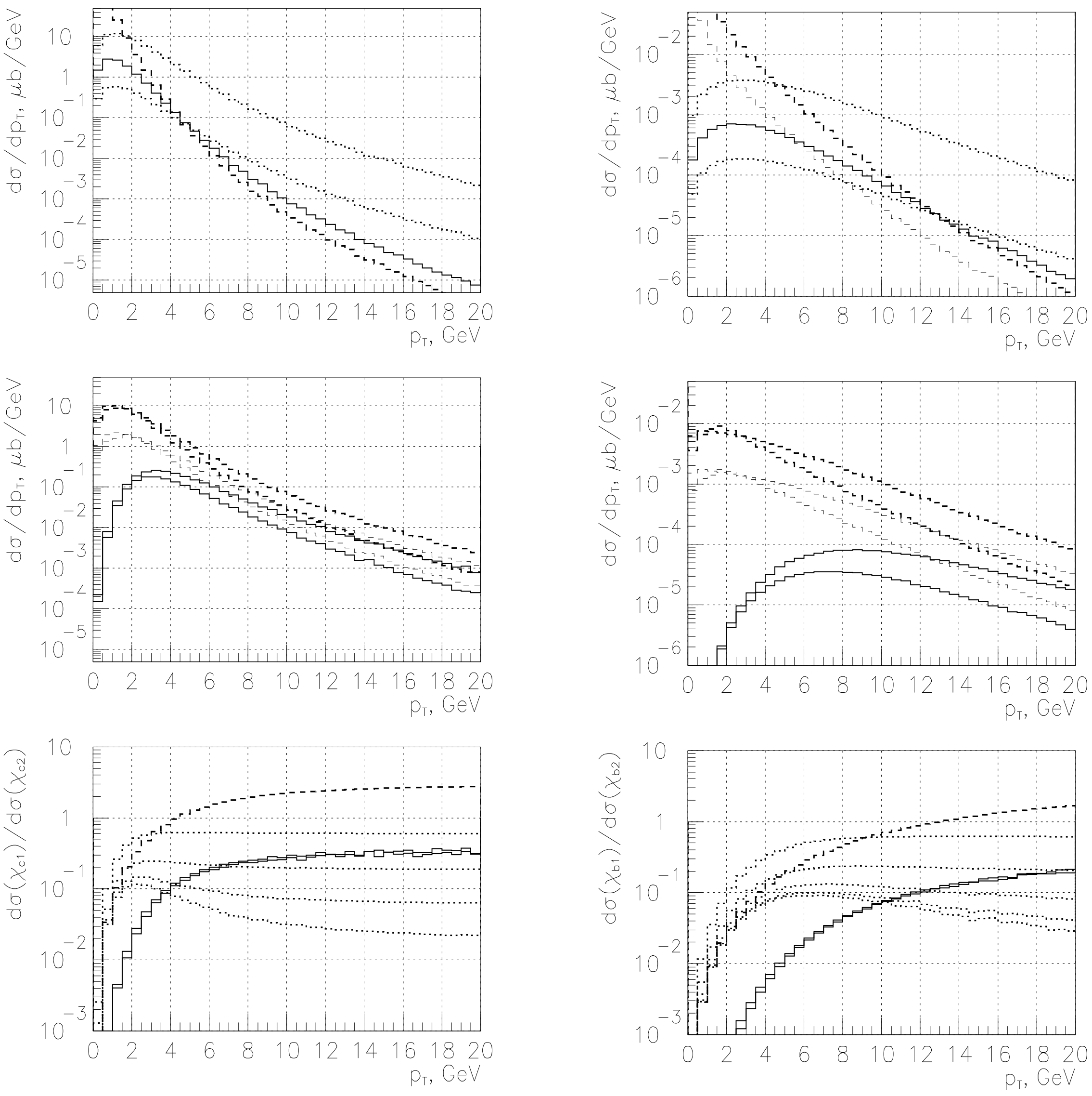

Figure 1. Theoretical predictions on the production of χ_c (left column) and χ_b (right column) mesons at Tevatron conditions.

Upper row. Predictions of the collinear parton model. Solid histogram, χ_1 production via colour-singlet mechanism; dashed histogram, χ_2 production via colour-singlet mechanism; the lower and the upper dotted histograms, χ_1 and χ_2 production via colour-octet mechanism, respectively.

Middle row. Predictions of the k_t-factorization approach. Solid histograms, χ_1 production; thin and thick dashed histograms, χ_0 and χ_2 production, respectively. The upper and the lower histograms of each type correspond to the gluon densities of Refs. [17] and [1]. Only the colour singlet mechanism is assumed in all cases.

Lower row. Predictions on the ratio of the differential cross sections $d\sigma(\chi_1)/d\sigma(\chi_2)$. Solid histograms, k_t-factorization approach with gluon densities of Refs. [17] and [1]; dashed histogram, collinear parton model, colour singlet contribution only; dotted histograms, collinear parton model with both singlet and octet production mechanisms taken into account. The different curves from top to bottom correspond to the colour-octet χ_1/χ_2 suppression factor set to 1, 0.3, 0.1 and 0.03, respectively).

In order to estimate the degree of theoretical uncertainty connected with the choice of unintegrated gluon density, we also use the prescription proposed in [1]. In this approach, the unintegrated gluon density is derived from the ordinary density $G(x, q^2)$ by differentiating it with respect to q^2 and setting $q^2 = k_T^2$. Among the different parametrizations available on the present-day theoretical market, the latter set shows the largest difference with Blümlein's density [17]. Thus, these two gluon densities can show the theoretical uncertainty band.

The numerical results are exhibited in Fig. 1 (left middle panel). In contrast with the collinear parton model, the differential cross sections are no longer divergent, even at very low p_T values. This property emerges from the fact that the relevant $2 \to 1$ matrix elements are always finite. One can see that the production of χ_1 states at low p_T is strongly suppressed because the initial gluons are almost on-shell. The suppression goes away at higher p_T, as the off-shellness of the initial gluons becomes larger.

In Fig. 1 (left lower panel) we compare the predictions of the collinear and k_t-factorization approaches by showing the ratio of the differential cross sections $d\sigma(\chi_{c1})/dp_T$ and $d\sigma(\chi_{c2})/dp_T$ plotted as a function of p_T. As far as the ratio of the nonperturbative colour-octet matrix elements $\mathcal{O}(^3S_1^8 \to \chi_1)/\mathcal{O}(^3S_1^8 \to \chi_2)$ is unknown, the predictions of the collinear parton model are very uncertain. However, in view of the expected suppression of χ_1 states (as discussed above), the band between the two lowest dotted histograms in fig. 1 (left lower panel) may be considered as the most realistic case.

The predictions of the collinear and k_t-factorization approaches clearly differ from each other in their absolute values and show just the opposite trend in the experimentally accessible region ($p_T > 5$ GeV). Although the exact shapes of the curves may change depending on the choice of model parameters, the qualitative difference between the models is undoubtful. One can also see from the figure that, even in the asymptotic p_T regime, the proportion between the production rates $\sigma(\chi_0) : \sigma(\chi_1) : \sigma(\chi_2)$ does not follow the naive rule $1 : 3 : 5$ based on the number of spin degrees of freedom.

We conclude our discussion with showing the predictions on the bottomonium states. The calculations are performed with the parameter setting as above, and with the value of the χ_b wave function set equal to $|\mathcal{R}'_{\chi_b}(0)|^2 = 1.4$ GeV^5 [18]. The integration over the final state phase space is now restricted to the pseudorapidity interval $-0.4 < \eta(\chi_b) < 0.4$, in accord with the CDF experimental cuts [13]-[15].

Our numerical results are displayed in Fig. 1 (right row). The qualitative features of the differential cross sections are similar to the ones which we have seen in the case of charmonium. It is worth recalling that the production of Υ mesons has been already measured by CDF collaboration [13]-[15] at p_T values close to zero. Although the p_T dependence of the direct ($\bar{p}p \to \Upsilon X$) and indirect ($\bar{p}p \to \chi_b X \to \Upsilon\gamma X$) contributions has not been studied separately, the net result seems to be at odds with collinear calculations. In fact, the predicted size of indirect contribution coming from the decays of χ_{b2} states at $p_T < 2$ GeV exceeds the total measured Υ production rate in this region. On the contrary, the measured differential cross section $d\sigma(\Upsilon)/dp_T$ decreases with decreasing p_T, in perfect agreement with k_t-factorization predictions [7].

3. Conclusions

We have considered the production of P-wave charmonium and bottomonium states with different spins in high energy proton proton interactions and compared the predictions of the usual parton model (with the colour-octet contributions taken into account) and the k_t-factorization approach. We have found that the shapes of the transverse momentum distributions and, also, the ratio of the production rates $\sigma(\chi_1)/\sigma(\chi_2)$ are qualitatively different in the considered models.

One major difference is connected with the behaviour of the differential cross section $d\sigma(\chi_2)/dp_T$ at low transverse momentum. This quantity remains finite in the k_t-factorization approach, while it diverges in the collinear parton model when p_T goes to zero. The latter prediction seems to be not supported by the available experimental data on the bottomonium production at the Tevatron.

Another well pronounced difference refers to the ratio of the production rates $d\sigma(\chi_1)/d\sigma(\chi_2)$. The underlying physics is promptly connected with gluon off-shellness. In the collinear parton model, the relative suppression of χ_1 states becomes stronger with increasing p_T because of the increasing role of the colour-octet contribution: in this approach, the leading-order fragmentation of an on-shell transversely polarised gluon into a vector meson is forbidden. In contrast with that, in the k_t-factorization approach, the increase in the final state p_T is only due to the increasing transverse momenta (resp., virtualities) of the initial gluons, and, consequently, the suppression motivated by Landau-Yang theorem becomes weaker at large p_T.

We derive the conclusion that the considered process may be proposed as a direct probe of the gluon virtuality, which can eventually testify for the validity of the noncollinear parton evolution. Our results seem especially promising in view of the fact that the difference between the two theoretical approaches is clearly pronounced at the conditions accessible for direct experimental measurements.

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