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 $\Upsilon$ mesons at the Fermilab Tevatron is considered, and the comparisons of calculated $p_T$-distributions and spin alignment parameter $\alpha$ with the D0 experimental data are shown. We argue that measuring the double cross section and the polarization of upsilonium states can serve as a crucial test discriminating two competing theoretical approaches to parton dynamics in QCD.

1 Introduction

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 non-perturbative emission of soft gluons. This feature gives rise to two competing theoretical

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approaches known in the literature as the color-singlet \[3\] and color-octet \[4\] 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 $J/\psi$ production at HERA, both in the collinear \[5\] and the $k_T$-factorization \[6\] approaches. As it was shown in the analysis of recent ZEUS \[7\] data, there is no need in the color-octet contribution, neither in the collinear nor in the $k_T$-factorization approach.

The numerical estimates of CO 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 \[8\]. 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 \[9\] \[10\] \[11\] \[12\].

In the present note we want to compare the predictions of $k_T$-factorization approach \[13\] with the D0 experimental data on the $p_T$—distributions \[14\] and the polarizaton of $\Upsilon$ (1S) meson states produced at the Tevatron energies \[15\].

2 Numerical results

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 distribution $F_g(x,k_T^2,\mu^2)$, which depend on both the longitudinal momentum fraction $x$ and transverse momentum $k_T$:

$$\sigma_{pp} = \int F_g(x_1,k_{1T}^2,\mu^2) F_g(x_2,k_{2T}^2,\mu^2) \hat{\sigma}_{gg}(x_1,x_2,k_{1T}^2,k_{2T}^2,...) \, dx_1 \, dx_2 \, dk_{1T}^2 \, dk_{2T}^2. \tag{1}$$

In accord with the $k_T$-factorization prescriptions \[16\] \[17\] \[18\] \[19\], the off-shell gluon spin density matrix is taken in the form

$$\overline{\epsilon^\mu_g \epsilon^\nu_g} = p_+^\mu p_+^\nu x_g^2/|k_T|^2 = k_T^\mu k_T^\nu/|k_T|^2. \tag{2}$$

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. [16, 19] and [20]. In the first case [16], the unintegrated gluon density is derived from the ordinary (collinear) density $G(x, \mu^2)$ by differentiating it with respect to $\mu^2$ and setting $\mu^2 = k_T^2$. Here we use the LO GRV set [21] as the input collinear density. In the following, this will be referred to as dGRV parametrisation. The other unintegrated gluon density [20] is obtained as a solution of leading order BFKL equation [19] in the double-logarithm approximation. In the following, this will be referred to as JB parametrisation.

$$D, \text{ Run 2 Preliminary, 1.3 fb}^{-1}$$

![Figure 1: Predictions on the production of $\Upsilon (1S)$ mesons at the Tevatron: the double differential cross section (left panel), the spin alignment parameter (right panel) as function of $p_T$.](image)

The production of $\Upsilon$ mesons in $pp$ collisions can proceed via either direct gluon-gluon fusion or the production of $P$-wave states $\chi_b$ followed by their radiative decays $\chi_b \rightarrow \Upsilon + \gamma$. The direct mechanism corresponds to the partonic subprocess $g + g \rightarrow \Upsilon + g$ which includes the emission of an additional hard gluon in the final state. The production of $P$-wave mesons is given by $g + g \rightarrow \chi_b$ only. All essential parameters were taken from our previous paper [13]. Fig. 1 shows the comparison of our results for the $\Upsilon (1S)$ meson production with the D0 experimental data [14, 15].

The calculations presented here are also valid for the $\Upsilon (3S)$ state, except the lower total cross section (by an approximate factor of 1/3) because of the correspondingly lower value of the wave function $|\Psi_{\Upsilon(3S)}(0)|^2 = 0.13 \text{ GeV}^3$. The state $\Upsilon (3S)$ is produced
by the purely direct production mechanism and the prediction on the spin alignment parameter $\alpha$ becomes less uncertain.

\[
\alpha(P) = \frac{(d\sigma/dP - 3d\sigma_L/dP)}{(d\sigma/dP + d\sigma_L/dP)},
\]

where $\sigma$ is the reaction cross section and $\sigma_L$ 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 $\alpha$ as a function of the $\Upsilon$ transverse momentum: $P \equiv |p_T|$. The experimental definition of $\alpha$ is based on measuring the angular distributions of the decay leptons

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

(4)

where $\theta$ is the polar angle of the final state muon measured in the decaying meson rest frame. Fig. 1 (right panel) shows the comparison of our results for the $\Upsilon$ (1S) meson polarization with the D0 experimental data [15]. The integration limits over rapidity were adjusted to the experimental acceptances of D0 ($|y_\Upsilon| < 0.6$) at the Tevatron. The yellow band in Fig. 1 corresponds the NRQCD predictions, where the strong transverse polarization is connected with the gluon fragmentation mechanism.

In Fig. 2 we show the rapidity distribution for $\Upsilon$ (1S) production in more wide region than the D0 experimental data, and behaviour of the alignment parameter $\alpha$ as function of rapidity. We see that $\alpha$ becomes positive at large $y$. Therefore we propose to measure the double differential cross sections of quarkonium productions.

In summary we have considered the production of $\Upsilon$ mesons in high energy $pp$ collisions in the $k_T$-factorization approach and compared the predictions on the spin alignment parameter $\alpha(p_T)$ with new the D0 experimental data. We point out that the purest probe is provided by the polarization of $\Upsilon(3S)$ mesons. We proposed to measure the double cross section of quarkonium production and the spin alignment parameter in more widely kinematical region on the rapidity also.

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