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Improved predictions for J/ψ and Υ production

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I discuss J/ψ and Υ production at the Tevatron. Working in the framework of NRQCD, I review the current theoretical status. Motivated by the polarization puzzle at the Tevatron, I present the brand-new computation of higher-order α_s corrections to the color-singlet production and discuss the impact of these corrections on the differential cross sections. I finally comment on the relative importance of the various transitions that feed quarkonium hadroproduction.

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1. Introduction

Inclusive J/ψ and Υ production at colliders has always attracted physicits' interest. From the experimental point of view, such states have the right quantum numbers to decay into a pair of leptons via a virtual photon. Therefore they can be observed by reconstructing the invariant mass of the produced leptons. On the theoretical point of view, heavy quarkonium production implies both perturbative and non-perturbative physics. The theory of NRQCD [2] provides a prescription to separate high-energy from low-energy effects in a consistent way, provided that the relative velocity v in the quarkonium is not to large. The low-energy effects, that can not be handled perturbatively, are factorized into universal long distance matrix elements (LDME). Each of them accounts for the probability of the transition of a perturbative heavy-quark pair in a specific quantum state into a quarkonium state. They are process-independent, i.e., they do not depend on the details of the heavy-quark pair creation.

One well-known consequence of NRQCD is the color-octet transition: the heavy-quark pair can be created in a color-octet state. Its low-energy evolution into a quarkonium bound state implies the emission soft partons, which are accounted into specific LDME's. Although for J/ψ and Υ production, these transitions occur at higher order in v compared to the color-singlet transition, they can give a large contribution to the cross-section, when the production of a heavy-quark pair in a color-singlet state is suppressed.

Despite the successes of NRQCD, J/ψ and Υ production at the Tevatron is still subject of debate. Considering the P_T differential cross sections measured by the CDF collaboration, it seems that color-octet transitions are needed to fill the gap between the color-singlet yield and the data [3]. But once we use the color-octet LDME's fitted to reproduce the cross section, the NRQCD prediction for the polarization [4] disagrees with the CDF measurement [5]. Up to now, it is still unclear which transitions dominate heavy quarkonium hadroproduction (for a recent review, see [6]).

In view of this situation, it is worth to improve the accuracy of NRQCD predictions. For what concerns inclusive production, one should try to extend the knowledge of cross sections beyond the leading order in α_s. In this proceedings, I will present the impact of the recently computed α_s-corrections to the color-singlet production.

2. Higher-order corrections to the color-singlet production

The cross section for $p\bar{p} \to \mathcal{Q} + X$ with $\mathcal{Q} = J/\psi$ or Υ, has been computed in [7, 8] at NLO accuracy. Here we use the implementation in MCFM [1, 7, 11]. The quarkonium state has been decayed into leptons, keeping track of the spin correlation. This allows us to extract the polarization [1]. In our calculation, we set $m_c = 1.5$ GeV and $m_b = 4.75$ GeV. We use the PDF set CTEQ6L1 (resp. CTEQ6_M) [12] for LO (resp. NLO) cross sections, and always keep the factorization scale equal to the renormalization scale: $\mu_f = \mu_r$. The central scale is fixed at $\mu_0 = \sqrt{4m_c^2 + P_T^2}$. We use the saturation approximation to relate the long distance matrix elements for production to those involved in quarkonium decays. We then use the values related to the BT potential [13]: $\langle \mathcal{O}_1^{J/\psi}\left({}^3S_1\right)\rangle = 1.16$ GeV^3 and $\langle \mathcal{O}_1^{\Upsilon}\left({}^3S_1\right)\rangle = 9.28$ GeV^3.

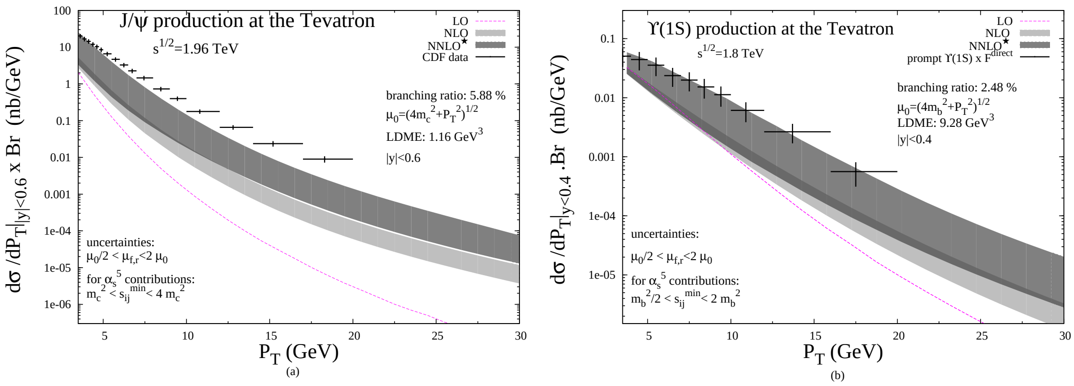

Figure 1: (a) J/ψ productions at the Tevatron, run II. The light-gray band is the NLO yield, the dark-gray band is the sum of the NLO plus the α_s^5 contributions (b) Υ production at the Tevatron, run I. Same legend as in (a).

In the following, we consider that the production is prompt (i.e. the quarkonium does not come from the decay of a B hadron) and direct (i.e. the quarkonium does not originate from the decay of an excited quarkonium state). The results are compared with the data collected by the CDF collaboration at the Tevatron. For J/ψ production, we consider the prompt measurement at $\sqrt{s} = 1.96$ TeV in ref. [14], multiplied by the average direct fraction obtained in [15]. For $\Upsilon(1S)$ production, we consider the prompt measurement at $\sqrt{s} = 1.8$ TeV in [16], multiplied by the average direct fraction obtained in [17].

The differential cross section at NLO is displayed in Fig. 1 (light-gray bands). The uncertainty bands correspond to the variation of the scale $\frac{\mu_0}{2} < \mu < 2\mu_0$, and to the variation of the heavy quark masses 1.4 GeV $< m_c <$ 1.6 GeV, 4.5 GeV $< m_b <$ 5 GeV. These uncertainties have been combined in quadrature. For comparison, we also show the LO cross section (dotted-line).

For J/ψ production, NLO contributions raise the cross section by more than one order of magnitude at large P_T. Indeed, at α_s^4, new channels become available to produce a high-P_T J/ψ at a lower kinematic price: the parton-level processes $gg \to J/\psi + gg$ and $gg \to J/\psi + c\bar{c}$ [9, 10] behaves like $\frac{1}{P_T^6}$ and $\frac{1}{P_T^4}$, respectively, at large transverse momentum. Although NLO contributions reduce the gap between the color-singlet prediction and the CDF data, there is still a discrepancy larger than an order of magnitude.

The situation for the $\Upsilon(1S)$ is similar, although the asymptotic behavior is reached at much higher values of P_T, due to the fact that $m_b > m_c$. In particular, the associated production $\Upsilon + b\bar{b}$ remains a subdominant fraction among the NLO contributions in the region $P_T < 30$ GeV, as it suffers from a phase-space suppression due to the large invariant mass in the final state. We also note that the gap between the color-singlet prediction at NLO and the CDF data is much smaller than in the case of J/ψ production. Still it seems that a production mechanism, with a soft P_T behavior, is missing.

If we consider the color-singlet production at α_s^5, new parton-level mechanisms become available. The gluon fragmentation channel via a color-singlet transition is one of them, and has the correct P_T shape (asymptotically like $\frac{1}{P_T^4}$). At this order, the quarkonium can also be produced by t-channel gluon exchange [1], a contribution that has been approximated in the k_t factorization approach [18]. These α_s^5 contributions, or more generally $p\bar{p} \to \mathscr{Q} + 3j$, provide us with new mechanisms to produce a high-P_T quarkonium at a lower kinematic cost. They are therefore expected to dominate over the productions $\mathscr{Q} + 1j$ and $\mathscr{Q} + 2j$ at sufficiently large transverse momentum.

In order to quantify these arguments, we present here an estimation of $\mathscr{Q} + 3j$ production at large P_T. We consider the whole set of α_s^5 processes contributing to the production of a quarkonium (either J/ψ or Υ) plus three light partons. We use MadOnia [19] to generate the squared amplitude of each subprocess. These real amplitudes can not be integrated over the phase-space without cuts, due to the presence of soft and collinear divergences. In order to protect the cross section from these divergences, we impose an invariant mass cut s_{ij}^{min} of the order of m_Q for any pair of light partons i, j. The resulting finite cross section depends on the value of the cut. However this dependence is expected to be rather small at large P_T, according to the argument presented in [1].

We now add the contribution from $\mathscr{Q} + 3$ jets to the NLO color-singlet cross section for direct quarkonium production, and compare the resulting curve (called NNLO*) with the CDF data. The corresponding plots are displayed in Fig. 1. We only consider the uncertainties resulting from the variation of the scales μ_r and μ_f, and from the variation of the cut s_{ij}^{min}. The values of the quark masses remain fixed at $m_c = 1.5$ GeV and $m_b = 4.75$ GeV.

In the case of J/ψ production, we see that the gap between the color-singlet yield and the CDF data is much smaller after the inclusion of $J/\psi + 3j$ channels. However the P_T shape is not well described: despite the inclusion of $J/\psi + 3$ jet channels, the differential cross section still drops too fast compared to the CDF data.

The situation for the Υ is rather different. First, all the experimental points are compatible with the NNLO* uncertainty band associated to the color-singlet production. Second, even if the prediction of the normalization is rather poor due to the large width of the uncertainty band, the experimental slope in P_T seems to be well reproduced.

3. Conclusion

In this proceedings, we have presented an updated prediction for inclusive J/ψ or Υ hadroproduction via a color-singlet transition, at the Tevatron.

For $\Upsilon(1S)$ production, higher order α_s corrections seem to resolve the discrepancy between the color-singlet production and the CDF data. The inclusion of $\Upsilon + 2j$ and $\Upsilon + 3j$ channels raise the differential cross section by a large factor, such that the result is compatible with the CDF measurement. The normalization of the predicted cross section suffers from a large uncertainty, originating from the choice of the factorization and renormalization scales, and from the invariant mass cut applied to the light partons in $\Upsilon + 3j$ channels. Nevertheless, the decrease in P_T is affected by these uncertainties by a much lesser degree, and agrees very well with the experimental measurement. From this analysis, it seems that there is no need to invoke color-octet transitions for $\Upsilon(1S)$ hadroproduction.

For J/ψ production, QCD corrections reduce dramatically the gap between the color-singlet production and the CDF data. However, the predicted differential cross section still drops too fast. Color-octet transitions could then be employed to fill the remaining gap. These should dominate the J/ψ production at large P_T to reproduce the experimental cross section in this region. With this assumption, the polarization measured by the CDF collaboration still remains unclear.

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