

Y Production at Fermilab Tevatron and LHC Energies

P. Artoisenet,¹ J. Campbell,² J. P. Lansberg,³ F. Maltoni,¹ and F. Tramontano⁴

¹*Center for Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

²*Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

³*Institut für Theoretische Physik, Universität Heidelberg, D-69120 Heidelberg, Germany*

⁴*Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN, Sezione di Napoli, I-80126 Napoli, Italy*

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We update the theoretical predictions for direct $Y(nS)$ hadroproduction in the framework of non-relativistic QCD. We show that the next-to-leading order corrections in α_s to the color-singlet transition significantly raise the differential cross section at high p_T and substantially affect the polarization of the Y . Motivated by the remaining gap between the next-to-leading order yield and the cross-section measurements at the Fermilab Tevatron, we evaluate the leading part of the α_s^5 contributions, namely, those coming from $Y(nS)$ associated with three light partons. The differential color-singlet cross section at α_s^5 is in substantial agreement with the data, so that there is no evidence for the need of color-octet contributions. Furthermore, we find that the polarization of the $Y(nS)$ is longitudinal. We also present our predictions for $Y(nS)$ production at the LHC.

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Even though the discrepancy between experimental measurements and theoretical predictions for $Y(nS)$ hadroproduction is less dramatic than for J/ψ and ψ' , it is still unclear which are the dominant mechanisms at work in those processes [1]. The leading order (LO) α_s^3 result [2] in the v expansion of nonrelativistic QCD (NRQCD) [3] neither predicts the yield seen in the data [4,5], under-shooting it by a factor of 10 at p_T around 20 GeV, nor shows the correct p_T behavior. In this case it has been shown that the inclusion of higher- v corrections, in particular, those associated with the color-octet mechanism, allows the data to be described. The yield and the p_T shape can be reproduced, at the cost of introducing two unknown long-distance-matrix elements of NRQCD that can be determined from fits to the data [6]. However, the polarization predicted following this approach disagrees with both the published CDF [5] and new D0 measurements [7].

In view of such a puzzling situation, it is worth reexamining in detail the available theoretical predictions. In Refs. [8,9], the complete set of α_s^4 corrections to color-singlet production was calculated for the first time. The results confirmed the importance of the new channels that open up at this order, which is due to their different p_T scaling [see Figs. 1(c) and 1(d)]. In this Letter we apply those results to a phenomenological study of Y production at the Tevatron, comparing the differential cross section at next-to-leading order (NLO) with the data from the CDF collaboration. We also argue that some α_s^5 contributions coming from three-jet configurations, i.e., $Y + jjj$, such as those arising from gluon-fragmentation [Fig. 1(e)] and “high-energy enhanced” [Fig. 1(f)] channels are important. We show that by adding such α_s^5 contributions to the NLO yield, the experimental measurements are repro-

duced. We also predict the polarization of the Y from the angular distribution of the leptons produced in the decay.

We first present the NLO predictions for the p_T spectrum of the Y at leading order in v , following the same procedure as in Ref. [8] and adding information on the polarization of the quarkonium state. In our numerical evaluation of the differential cross section and polarization parameters, we have used $|R_{Y(1S)}(0)|^2 = 6.48 \text{ GeV}^3$ and $|R_{Y(3S)}(0)|^2 = 2.47 \text{ GeV}^3$ [1], $\mu_0 = \sqrt{(2m_b)^2 + p_T^2}$, $\text{Br}(Y(1S) \rightarrow \mu^+ \mu^-) = 0.0248$ and $\text{Br}(Y(3S) \rightarrow \mu^+ \mu^-) = 0.0218$, $m_b = 4.75 \text{ GeV}$, PDF set CTEQ6M [10]. For comparison, we also plot the LO yield, for which we used the PDF set CTEQ6L1.

The experimental results for the cross-section differential in p_T for prompt $Y(1S)$ and $Y(2S)$, as well as the cross section for direct $Y(3S)$ and the polarization for prompt $Y(1S)$ were obtained in Run I at $\sqrt{s} = 1.8 \text{ TeV}$ [5]. For Run II at $\sqrt{s} = 1.96 \text{ TeV}$, so far only D0 have analyzed data for $Y(1S)$ [11]. The comparison performed in [11] shows full agreement with [5], once the difference in \sqrt{s} is taken into account.

In order to compare our calculation for direct $Y(1S)$ production with the CDF data, we have multiplied the most recent prompt- $Y(1S)$ cross-section measurement of [5] by the direct fraction $F_{\text{direct}}^{Y(1S)} = 0.5 \pm 0.12$. This fraction was obtained from an older sample [4], where the selection cuts $|p_T| > 8 \text{ GeV}$ and $|\eta| < 0.7$ were applied. The similar p_T dependence observed for prompt- $Y(1S)$ and direct- $Y(3S)$ production, as shown in Fig. 2 of [5], confirms that this fraction should not depend very strongly on p_T . This justifies using the same fraction for the whole p_T range. The errors from the prompt cross section and the

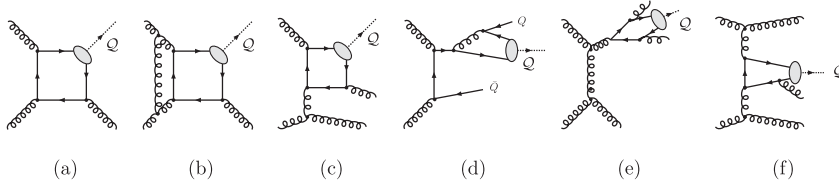


FIG. 1. Representative diagrams contributing to Y hadroproduction at orders α_S^3 (a), α_S^4 (b,c,d), α_S^5 (e,f). See discussions in the text.

direct fraction have been combined in quadrature. Similar information on the direct yield of $Y(2S)$ is not yet available.

Our results for direct production of $Y(1S)$ and $Y(3S)$ at $\sqrt{s} = 1.8$ TeV are shown in Fig. 2. The curves labeled as NNLO* will be discussed later on. In order to estimate the theoretical uncertainties, we have varied the renormalization and factorization scales between $0.5\mu_0$ and $2\mu_0$, keeping them equal. We have combined the resulting uncertainties in quadrature with those resulting from variation of the bottom quark mass, $m_b = 4.75 \pm 0.25$ GeV. The uncertainty associated with the nonperturbative parameter $|R_{Y(nS)}(0)|^2$ [6,12], corresponding to an overall

normalization, is not included. The curves for direct $Y(2S)$ production can be easily obtained—at this order in v —by adopting the corresponding values for the leptonic branching ratio and for the nonperturbative matrix element, $|R_{Y(2S)}(0)|^2$.

As a first comment, we note that the LO and NLO results are very similar at low p_T , i.e., where the bulk of the cross section is found. This implies that the α_S^4 corrections are small in this region and that the perturbative expansion of the total cross section is under control. On the other hand, the relative importance of the NLO corrections dramatically increases at larger p_T , where new p_T^{-6} channels [Fig. 1(c)] start to dominate. This behavior significantly reduces the discrepancy with the experimental data that is found at LO. However, the NLO prediction still drops too fast in comparison with the data. Note that the NLO calculation also takes into account associated production $Y + b\bar{b}$ [Fig. 1(d)]. This contribution, in spite of reproducing the shape of the data very well at both low and high p_T (asymptotically it behaves as p_T^{-4}), remains negligible up to at least $p_T = 30$ GeV.

Throughout our calculation, the polarization information of the Y can be traced through the angular distributions of the two decay leptons. Defining θ as the angle between the ℓ^+ direction in the quarkonium rest frame and the quarkonium direction in the laboratory frame, the normalized angular distribution $I(\cos\theta)$ reads

$$I(\cos\theta) = \frac{3}{2(\alpha + 3)}(1 + \alpha\cos^2\theta), \quad (1)$$

from which we have extracted the polarization parameter α bin by bin in p_T . Our results are shown in Fig. 3 along with the curves for the LO yield and for the associated produc-

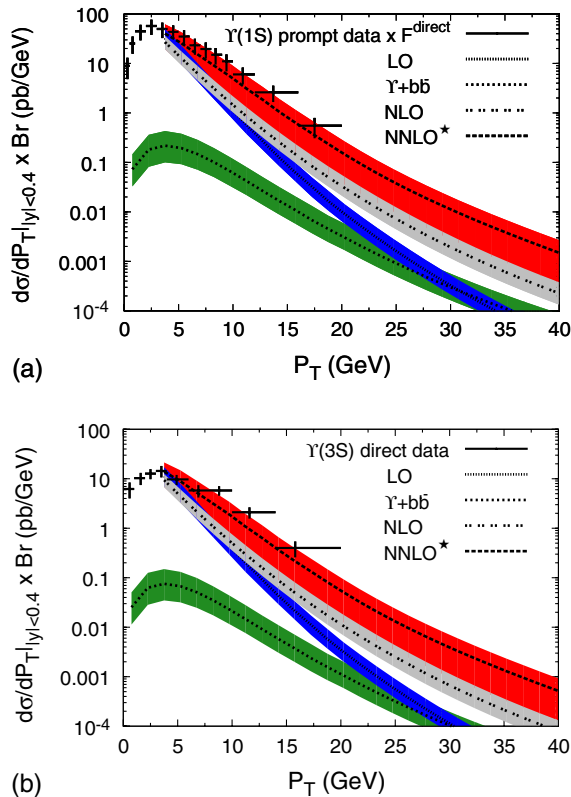


FIG. 2 (color online). Results for (a) $Y(1S) + X$ and (b) $Y(3S) + X$ at LO (α_S^3), for associated production (α_S^4), for full NLO ($\alpha_S^3 + \alpha_S^4$), and for NNLO* (up to α_S^5) compared with the direct yield at $\sqrt{s} = 1.8$ TeV measured by the CDF collaboration [5]. The theoretical-error bands for LO, NLO, and associated production come from combining the uncertainties resulting from the choice of μ_f , μ_r , m_b . The uncertainty of NNLO* includes the variation of the cutoff, s_{ij}^{\min} , between $0.5m_b^2$ and $2m_b^2$ and of the scales μ_r and μ_f .

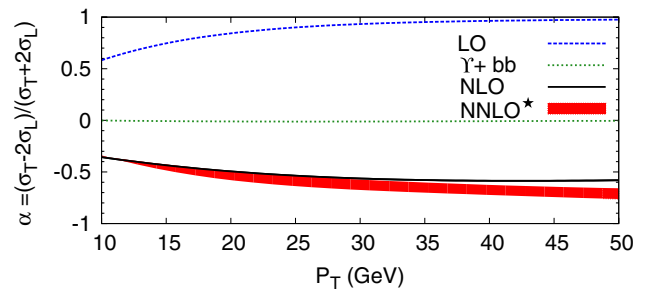


FIG. 3 (color online). Polarization for direct $Y(nS)$ ($n = 1, 2, 3$) production at $\sqrt{s} = 1.8$ TeV up to the order α_S^5 (NNLO*). Most of the uncertainties on α for LO, associated production and NLO cancel. The uncertainty band of the (NNLO*) result comes from the variation of the cutoff s_{ij}^{\min} .

tion alone. Even though the inclusion of NLO corrections brings the predictions closer to the prompt data, the discrepancy in the normalization makes such a comparison not very compelling.

As already noted, the discrepancy between the data and the full NLO (up to α_S^4) result in Fig. 2 increases with p_T . This might be taken as an indication that one or more processes with a more gentle p_T scaling than the α_S^4 contributions, which scale at most as p_T^{-6} (disregarding the subdominant $Y + b\bar{b}$ channel), are still missing. In this section, we argue that the α_S^5 terms provide us with the missing contributions. Indeed, the gluon-fragmentation channel [Fig. 1(e)] occurs for the first time at order α_S^5 and behaves like p_T^{-4} at large transverse momentum. At next-to-next-to-leading order (NNLO) “high-energy enhanced” channels [Fig. 1(f)] also appear for the first time, whose contributions have previously been approximated in the k_T factorization approach [13]. Both these contributions, which exhaust the possibilities of new kinematical enhancements at higher order, are at the Born level and therefore finite at α_S^5 . They are a subset of $p\bar{p} \rightarrow Y + jjj$ (j stands for u, d, s, c, g) and provide us with new mechanisms to produce a high- p_T Y with a lower kinematic suppression. They can be expected to dominate the differential cross section at NNLO accuracy in the region of large transverse momentum.

We present here an estimate of these dominant α_S^5 contributions at large p_T , bypassing the presently out-of-reach inclusive calculation of $p\bar{p} \rightarrow Y + X$ at NNLO accuracy. We consider the whole set of α_S^5 processes contributing to the color-singlet production of a Y associated with three light partons. The computation of the associated matrix elements is technically possible via the approach presented in Ref. [14]. In order to protect the integrated cross section from soft and collinear divergences, we impose a “democratic” invariant-mass cut s_{ij}^{\min} of the order of m_b^2 to any pair of light partons so that the phase-space integration remains finite. For new channels opening up at α_S^5 , the dependence on the value of s_{ij}^{\min} is expected to be small in the region $p_T \gg m_b$, since no collinear or soft divergences can appear there. For channels whose Born-level contribution occurs at α_S^3 or α_S^4 , the invariant-mass cut results in potentially large logarithms of s_{ij}/s_{ij}^{\min} in the differential cross sections. However, these logs factorize over lower order amplitudes that are suppressed by powers of p_T compared to the dominant α_S^5 contributions. The result is that the sensitivity to the value chosen for the minimal invariant-mass cut s_{ij}^{\min} is expected to die away as p_T increases.

In fact, this argument can be tested by using it to estimate the dominant contribution to the production of Y at NLO accuracy. The differential cross section for the real α_S^4 corrections, $Y + jj$ production, is displayed in Fig. 4. The gray band is obtained by varying the invariant-mass cut s_{ij}^{\min} between any pairs of light partons

from $0.5m_b^2$ to $2m_b^2$. The yield becomes insensitive to the value of s_{ij}^{\min} as p_T increases, and it reproduces very accurately the differential cross section at NLO accuracy.

The computation of $p\bar{p} \rightarrow Y + jjj$ at tree level is in principle straightforward, but technically quite challenging: several parton-level subprocesses contribute, each involving up to hundreds of Feynman diagrams. We follow the approach described in Ref. [14], which allows the automatic generation of both the subprocesses and the corresponding scattering amplitudes. We find that the subprocess $gg \rightarrow Y + ggg$ dominates, providing 50% of the whole yield. The uncertainty associated with the choice of the cut s_{ij}^{\min} is substantial, although, as can be seen in Fig. 4, it decreases at large p_T where these contributions are dominant.

The differential cross sections for $Y(1S)$ and $Y(3S)$ are shown in Fig. 2. The upper band (referred to as NNLO*) corresponds to the sum of the NLO yield and the $Y + jjj$ contributions. The contribution of Y production with three light partons fills the gap between the data and the NLO calculation. The α_S^5 contribution is very sensitive to the choice of the renormalization scale, μ_r . This is expected: for moderate values of the p_T , the missing virtual part might be important, whereas at large p_T , the yield is dominated by Born-level α_S^5 -channels from which we expect a large dependence on μ_r . Even though the uncertainty on the normalization is rather large, the prediction of the p_T shape is quite robust and agrees well with the behavior found in the data. At leading order in v , results for $Y(2S)$ can be obtained simply by changing $|R_{Y(nS)}(0)|^2$ and the branching ratio. The predictions for the polarization parameter α are only slightly affected by the NNLO* contributions and remain negative at high transverse momentum, Fig. 3. Finally, we show our predictions for the p_T distributions at the LHC ($\sqrt{s} = 14$ TeV) in Fig. 5.

Obviously, our analysis cannot be extended to rather low p_T , where the approximations on which it is based no

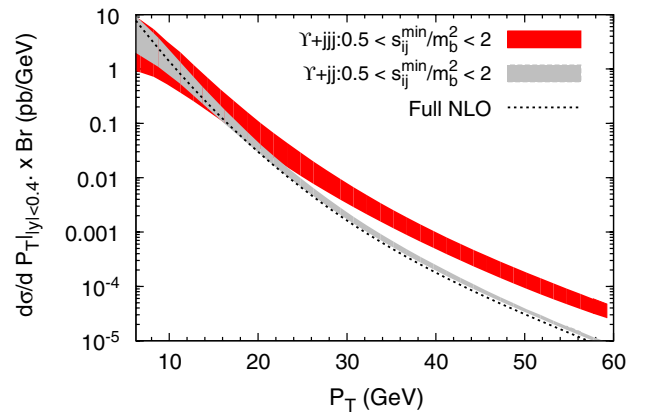


FIG. 4 (color online). Full computation at NLO for $Y + X$ (dashed line) vs $Y(1S) + 2$ light partons with a cut on s_{ij}^{\min} (thin band). The thick band shows the cross section for $Y(1S) + 3$ light partons with the same cut (see text for details).

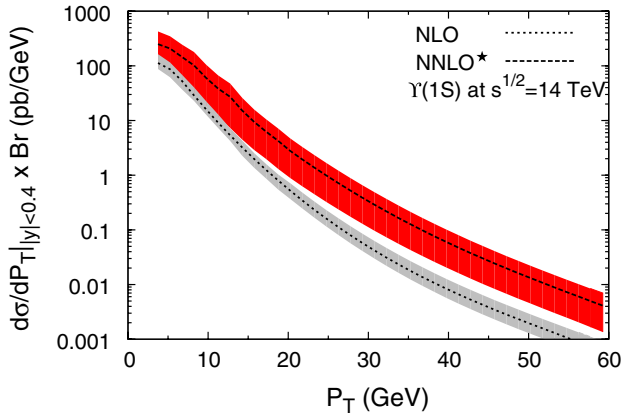


FIG. 5 (color online). $Y(1S) + X$ at $\sqrt{s} = 14$ TeV. Same parameters as for Fig. 2. Results for the $Y(3S) + X$ can be obtained by rescaling the curves by the ratio of the corresponding wave functions values at the origin and branching ratios.

longer hold. In this case, one could improve the predictions by merging the matrix elements with parton showers using one of the approaches available in the literature [15], or by performing an analytic resummation [16].

In conclusion, we have compared the full NLO (α_S^4) cross section for polarized direct hadroproduction of $Y(nS)$ to the data from the Tevatron. At this order, the polarization parameter α is negative and decreases with p_T . However, the yield is still too low compared to the data especially at high p_T .

This led us to consider a subset of the NNLO (α_S^5) corrections, namely, those corresponding to the production of a Y associated with three light partons and containing p_T^{-4} contributions. Integrating the amplitudes for such processes at α_S^5 leads to divergences in some phase-space regions that we avoided by imposing a minimal invariant mass between the light partons. This was motivated by the fact that the neglected contributions are proportional to α_S^4 amplitudes, which scale at most as p_T^{-6} , so that we expected this approach to give a reliable estimate of the full α_S^5 result at large p_T . We validated our expectations by comparing such an approach with the computation at α_S^4 and by explicitly checking the sensitivity of our results to the cutoff choice at high p_T . The estimated α_S^5 -contributions appear to fill the gap between the full NLO (α_S^4) and the data.

As a further result, we have predicted the polarization parameter α to be negative and only slightly decrease with p_T , indicating a longitudinally polarized yield. More accurate data, in particular, for $Y(3S)$ and possibly at higher p_T , are needed to check these predictions.

In summary, the comparison with the available data suggests that there is no need to include contributions

from color-octet transitions for $Y(nS)$ production. This mirrors the situation in inclusive Y decays where color-octet contributions are severely constrained by the data to be much smaller than the naïve expectations from NRQCD scaling rules [17]. For the ψ case, the situation is less clear since the addition of higher-order QCD corrections seems not to suffice to describe the data [8,18,19]. In this case, other mechanisms may be at work such as those recently discussed in Refs. [20,21].

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