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J/ψ Production at the LHC *

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Abstract

We firstly re-examine hadroproduction of prompt J/ψ's at the Fermilab Tevatron finding that those colour-octet matrix elements presented in literature are systematically overestimated due to the overlooking of the effective primordial transverse momentum of partons (i.e. dynamically generated via initial-state radiation). We estimate the size of these effects using different parton distribution functions in a Monte Carlo framework. Finally, we extrapolate up to LHC energies making a prediction on the expected p_t differential cross-section for charmonium.

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1 Introduction

Heavy quarkonia have been playing an important role over the past decades in the development of the theory of the strong interaction and such beneficial influence seems far from ending. Indeed, the experimental discovery at Fermilab [1] of an excess of inclusive production of prompt heavy quarkonia (mainly for J/ψ and $\psi(2S)$ resonances) in antiproton-proton collisions triggered an intense theoretical activity beyond what was considered conventional wisdom until recently [2, 3]. The discrepancy between the so-called colour-singlet model (CSM) in hadroproduction [4] and the experimental data amounts to more than an order of magnitude and cannot be attributed to those theoretical uncertainties arising from the ambiguities on the choice of a particular parton distribution function (PDF), the heavy quark mass or different energy scales.

Recently it has been argued that the surplus of charmonia production can be accounted for by assuming that the heavy quark pair not necessarily has to be produced in a colour-singlet state at the short-distance partonic process itself [5]. Alternatively, it can be produced in a colour-octet state evolving non-perturbatively into quarkonium in a specific final state with the correct quantum numbers according to some computable probabilities governed by the internal velocity of the heavy quark. This mechanism, usually named as the colour-octet model (COM), can be cast into the rigorous framework of an effective non-relativistic theory for the strong interactions (NRQCD) deriving from first principles [6].

However, the weakness of the COM lies in the fact that the non-perturbative parameters characterizing the long-distance hadronization process beyond the colour-singlet contribution (i.e. the colour-octet matrix elements) are so far almost free parameters to be adjusted from the fit to experimental data, though expected to be mutually consistent according to the NRQCD power counting rules.

On the other hand, an attractive feature of the colour-octet hypothesis consists of the universality of the NRQCD matrix elements entering in other charmonium production processes like photoproduction from electron-proton collisions at HERA [7]. Let us look below in some detail at the way hadronization is folded with the partonic description of hadrons, focusing for concreteness on the couple of related papers [8, 9].

In the first paper [8], Cho and Leibovich considered for charmonium production (in addition to the CSM) the $^3S_1$ coloured intermediate state as a first approach, computing the squared amplitudes as products of perturbative parts standing for the short-distance partonic processes, and the colour-octet matrix element concerning the long-distance hadronization. Finally, a convolution of concrete parton distribution functions and the differential cross-section for the $Q\bar{Q}$ production subprocess was performed, whereby the p_t dependence of the charmonia production exclusively coming from the latter.

In Ref. [9] the same authors take into account further contributions from new coloured states (for more details see the quoted references) concluding finally that at high enough p_t a two-parameter fit is actually required to explain the observed inclusive

p_t distribution of charmonia production at the Tevatron.

Notice, however, that such calculations were carried out based on a possibly over-simplified picture of the hadronic interaction. Indeed, it is already well-known a long time ago that higher-order QCD effects (K factors) play an important role in inclusive hadroproduction. In particular, beyond the primordial transverse momentum k_t of partons in hadrons due to Fermi motion relevant at small p_t, initial-state radiation of gluons by the interacting partons add up yielding an *effective* intrinsic transverse momentum which certainly has to be considered in hadroproduction at high p_t [10]. As we shall see, if overlooked at all in charmonia production, the specific effect on the fit parameters (and ultimately on the colour-octet matrix elements) amounts to a *systematic* overestimate.

2 Extraction of NRQCD matrix elements from Tevatron data

In this work we have implemented the colour-octet mechanism in the event generator PYTHIA 5.7 [11] via the following α_s^3 partonic processes: $g+g{\rightarrow}J/\psi+g$, $q+g{\rightarrow}J/\psi+q$ and $q+\bar{q}{\rightarrow}J/\psi+g$ [1], including the $^3S_1$ and $^1S_0+^3P_0$ contributions as coloured intermediate states. The corresponding differential cross sections can be found in [8, 9]. We conclude from our simulation that gluon-gluon fusion actually stands for the dominant process as expected, gluon-quark scattering contributes appreciably, whereas quark-antiquark scattering represents a tiny contribution. Let us stress that initial- and final-state radiation were incorporated within the Lund Monte Carlo framework [13]. Of course, the PYTHIA treatment of the effective k_t is not guaranteed to be perfect but, nevertheless, should give a reasonable estimate of such effects.

Using the same numerical values for the colour-octet matrix elements as reported in tables I and II of Ref. [9], if initial- and final-state radiation are turned off (there exists this possibility in PYTHIA [11]), there is a good agreement between the theoretical curve and the experimental points (see Fig. 1), as should be reasonably expected.

However, if initial- and final-state radiation [2] are switched on, the predicted curve stands well above the experimental data over the p_t range examined, in accordance with the expected "kick" caused by the *effective* primordial transverse momentum of partons [10]. Accordingly, keeping radiation effects on in the modelling of the full hadronic production process, it turns out that the values of the colour-octet matrix elements have to be lowered by significant factors.

[1] Originally PYTHIA generates direct production of J/ψ's via the CSM [11]. In an earlier work [12] we considered only the gluon-gluon fusion but with the colour mechanism implemented in

[2] It should be noted that initial-state radiation and final-state radiation have opposite effects in the p_t spectrum, the former enhancing the high p_t tail whereas the latter softens the distribution

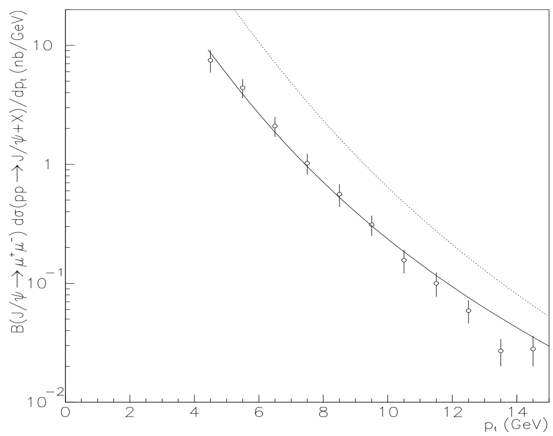

Figure 1: Curves obtained from PYTHIA (not fit) including the colour-octet mechanism for prompt J/ψ production at the Tevatron using the same parameters as in Ref. [9]. The solid line corresponds to initial- and final-state radiation off and the dotted line to initial- and final-state radiation on. The MRSD0 parton distribution function and $M_c = 1.48$ GeV were employed as in [9].

In order to assess the impact of the effective intrinsic k_t upon the NRQCD matrix elements we have made three different choices for the proton PDF [3]:

a) the leading order CTEQ 2L (by default in PYTHIA 5.7)

b) the next to leading order MRSD0 (the same as used in [9])

c) the next to leading order GRV 94 HO

As already mentioned before, the theoretical curve of the inclusive p_t distribution of prompt J/ψ's stands in all cases above Tevatron experimental points if the set of parameters from [9] are blindly employed in the PYTHIA generation with initial-state radiation on. Motivated by this systematic discrepancy, we performed new fits for the prompt J/ψ direct production at Tevatron (feed-down from radiative decay of χ_{cJ} resonances was experimentally removed). The corresponding colour-octet matrix elements are shown in table 1 and the plots for cases a) and b) in Fig. 2. We found $\chi^2/N_{DF} = 1.8,\ 2.5$ and 1.1 for a) , b) and c) respectively.

Notice that our new results for the matrix elements are in general slightly smaller than those presented in our previous work [12]. This is in accordance with the fact that we are including new contributions not considered before so that the fit parameters have to be further lowered accordingly.

[3]See [14] for technical details about the package of Parton Density Functions available at the CERN Program Library. References therein

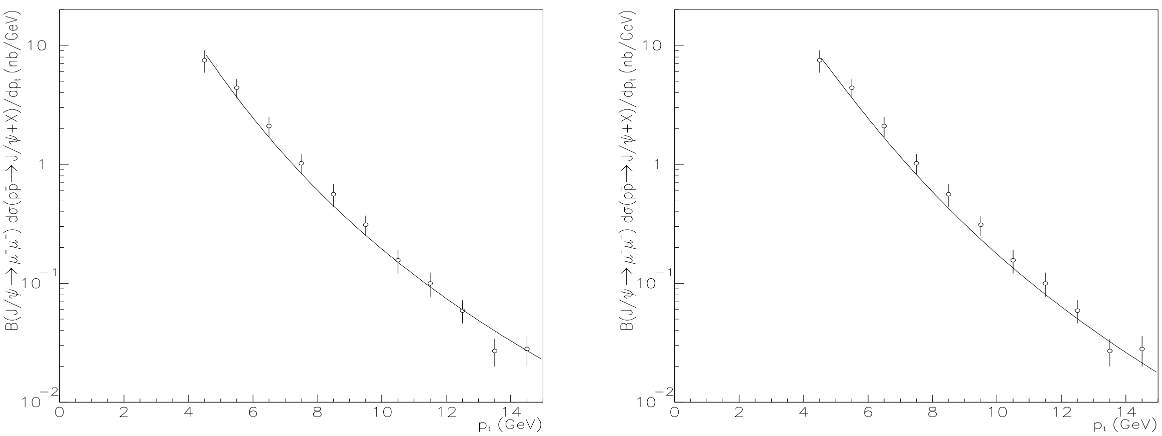

Figure 2: Two-parameter fits to the experimental Tevatron data using CSM + COM, where initial- and final-state radiation were incorporated via PYTHIA generation. The CTEQ 2L (MRSD0) parton distribution function was employed in the left (right) plot.

Table 1: Colour-octet matrix elements (in units of GeV^3) from the best fit to Tevatron data on prompt J/ψ production using different parton distribution functions. The error bars are statistical only. For comparison we quote the values given in Ref. [9]: $(6.6\pm2.1)\times10^{-3}$ and $(2.2\pm0.5)\times10^{-2}$ respectively.

matrix element:	$< 0\vert O_8^{J/\psi}(^3S_1)\vert 0 >$	$\frac{<0\vert O_8^{J/\psi}(^3P_0)\vert 0>}{M_c^2} + \frac{<0\vert O_8^{J/\psi}(^1S_0)\vert 0>}{3}$
CTEQ2L	$(3.3\pm0.5)\times10^{-3}$	$(4.8\pm0.7)\times10^{-3}$
MRSD0	$(2.1\pm0.5)\times10^{-3}$	$(4.4\pm0.7)\times10^{-3}$
GRV 94 HO	$(3.4\pm0.4)\times10^{-3}$	$(2.0\pm0.4)\times10^{-3}$

3 Extrapolation to LHC

Finally, we have generated prompt J/ψ's in proton-proton collisions at LHC energies (center-of-mass energy = 14 TeV) by means of our "modified" version of PYTHIA with the colour-octet matrix elements as shown in Table 1 - i.e. after normalization to Tevatron data. Indeed, an order-of-magnitude estimate for the expected production of charmonia at the LHC is suitable from many points of views [15]: J/ψ can be considered either as a signal in its own right or as a source of background for other interesting processes involving J/ψ's, like CP studies from the cascade channel $B_d^0 \to J/\psi\ K_s^0$.

In Fig. 3 we show altogether the p_t inclusive distributions of direct prompt J/ψ's at the LHC obtained for the three PDF's employed in our study. Comparing them with the distribution obtained by Sridhar [16], we find our predictions standing below his theoretical curve at large p_t. In fact this is not surprising since Sridhar considered only

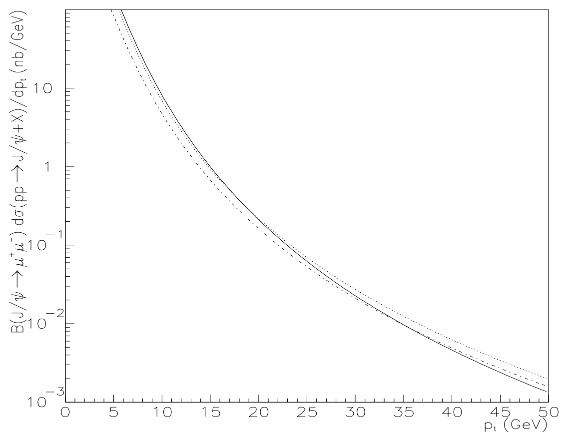

Figure 3: Our prediction for prompt J/ψ direct production at the LHC using PYTHIA with the colour-octet matrix elements from Table 1: a) dotted line: CTEQ 2L, b) dot-dashed line: MRSD0, and c) solid line: GRV HO. The rapidity cut $|y| < 2.5$ on the J/ψ was required.

the ${}^3S_1$ coloured intermediate state, whose NRQCD matrix element was taken larger than the one used in this work. The argument ends by noticing that at high enough p_t the dominant production comes from the ${}^3S_1$ contribution as the combined ${}^1S_0 +^3 P_0$ contribution falls off faster.

4 Conclusions

In this paper we have extended our preliminary study [12] considering all three possible short-distance processes, namely $g + g \rightarrow J/\psi + g$, $q + g \rightarrow J/\psi + q$ and $q + \bar{q} \rightarrow J/\psi + g$, contributing at order α_s^3 to charmonia production including the colour-octet mechanism.

We have investigated higher-order effects induced by initial-state radiation on the extraction of the NRQCD matrix elements from hadroproduction at high p_t by means of an event generator (PYTHIA 5.7) with colour-octet mechanisms implemented in. We conclude that the overlooking of the *effective* primordial k_t leads systematically to a significant overestimate of the colour parameters. We have re-calculated those colour-octet matrix elements for J/ψ production from fits to Tevatron data using three different sets of proton PDF's.

Finally we have estimated the prompt J/ψ production at the LHC, finding an overall relative good accordance among the three choices for the proton PDF. Under the assumption of the validity of the COM, our prediction can be used for simulation purposes at LHC experiments (see the Web page at http://wwwcn.cern.ch/~msmizans/production/0.html for a general view of the B physics simulation status in ATLAS).

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