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J/ψ Production: Tevatron and Fixed-Target Collisions

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In this talk I show the results of a fit of the NRQCD matrix elements to the CDF data for direct J/ψ production, by including the radiative corrections to the $g\,g \to {}^3S_1^{[1]}\,g$ channel and the effect of the k_T-smearing. Furthermore I perform the NLO NRQCD analysis of J/ψ production in fixed-target proton-nucleon collisions and I fit the colour-octet matrix elements to the available experimental data. The results are compared to the Tevatron ones.

1. INTRODUCTION

The J/ψ production cross-section within the NRCQD factorization theory [1] is given by the expression:

$$d\sigma^{J/\psi} = \sum_n \langle 0|\mathcal{O}^{J/\psi}[n]|0\rangle d\hat{\sigma}(c\bar{c}[n]) \qquad (1)$$

where $n = {}^{2S+1}L_J^{[1,8]}$. The relevant long-distance matrix elements up to order v^4 are $\langle\mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$ and the linear combination $\Delta_8^{J/\psi}(k) = \langle\mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + k\,\langle\mathcal{O}_8^{J/\psi}({}^3P_0)\rangle/m^2$. The phenomenological consistency of the NRQCD factorization formalism rests upon the universality of the long-distance matrix elements. The phenomenological determination of the non-perturbative matrix elements relies on the accuracy in the computation of the short distance kernels. In this talk I consider the Tevatron VS fixed-target universality issue. First I perform a fit of $\langle\mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$ and $\Delta_8^{J/\psi}(3.5)$ matrix elements to the Tevatron CDF data [2] by considering two possible deviation from the standard fits [3–5], namely a) the $O(\alpha_s^4)$ colour-singlet contribution and b) the effect of the k_T-smearing. I successively perform a fit of the MEs to a wide fixed-target data sample based upon a NLO QCD analysis.

2. THE COLOUR-SINGLET $O(\alpha_s^4)$ CONTRIBUTION

The equation (1) is usually interpreted as a double expansion in the strong coupling α_s and the velocity v. In the J/ψ p_T-differential cross-section a third expansion parameter has to be considered, and specifically $1/p_T$ [6]. In the triple-expansion paradigm It is straightforward to realize that the process $i\,j \to {}^3S_1{}^{[1]}\,k\,l$ is a priori large. The scaling of its partonic cross-section is in fact $O(\alpha_s^4 v^0/p_T^6)$ as compared to $O(\alpha_s^3 v^4/p_T^6)$ of the C-even colour-octet configurations (${}^1S_0{}^{[8]}$ and ${}^3P_J{}^{[8]}$). In this section I will show the effect of the channels $i\,j \to {}^3S_1{}^{[1]}\,k\,l$ in the extraction of the colour-octet matrix elements at the Tevatron. The details of the calculation will appear in a forthcoming paper [7]. In the present document I just confine myself to draw the general lines of the computation. The three $O(\alpha_s^4)$ channels I am going to consider are:

$$q\,\bar{q} \to {}^3S_1{}^{[1]}g\,g, \qquad (2)$$

$$q\,g \to {}^3S_1{}^{[1]}q\,g, \qquad (3)$$

$$g\,g \to {}^3S_1{}^{[1]}g\,g. \qquad (4)$$

The one-loop colour-singlet channel is presently unknown for hadroproduction of J/ψ. It is only available for J/ψ photoproduction [8] and annihilation into light hadrons [9].

Nevertheless, scaling arguments show that the virtual channel gives a subleading contribution

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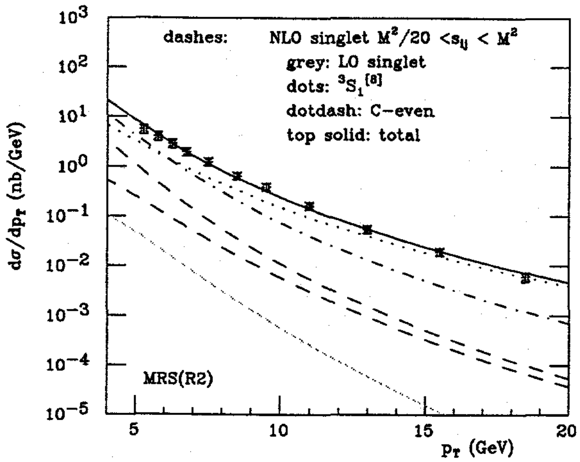

Figure 1. Different channels contributing to the J/ψ production at the Tevatron. The NLO ${}^3S_1^{[1]}$ channel is given by the dashed curves ($s_{\rm min} = M^2_{J/\psi}$ (lower dash) and $s_{\rm min} = M^2_{J/\psi}/20$ (upper dash)). The fit of the colour-octet MEs to data are performed by considering the upper dashed curve. The resulting fitted curves are shown (${}^3S_1^{[8]}$ (dots) and $\Delta_8^{J/\psi}(3.5)$ (dotdash)).

at high p_T, being $O(1/p_T^8)$ its fall-off (same as the born, which is already known to be negligible). The tree-level QED-like diagrams in the channel (4) are also suppressed at high p_T, but they have been included to double check the global gauge invariance of the process. The omission of the abelian diagrams would generate a $1/p_T^2$-suppressed gauge dependence. To evaluate the amplitudes relative to the processes (2)-(4) I make use of the covariant projection technique [11,12]. The evaluation of the channels (2) and (3) is straightforward. The process (4) demands the helicity amplitude formalism:

$$\mathcal{M}(P^\epsilon, {k_1}^{h_1}, {k_2}^{h_2}, {k_3}^{h_3}, {k_4}^{h_4}) = \frac{\delta_{ij}}{\sqrt{N}} {\rm Tr}\left\{(\not P + M)\gamma^\alpha \mathcal{A}_{ij}^{\mu_1\mu_2\mu_3\mu_4}\right\} \times \mathcal{E}_\alpha^\epsilon(P)\epsilon_{\mu_1}^{h_1}(k_1)\epsilon_{\mu_2}^{h_2}(k_2)\epsilon_{\mu_3}^{h_3}(k_3)\epsilon_{\mu_4}^{h_4}(k_4) \quad (5)$$

I use the Calkul collaboration representation for the external gluons [13]

$$\not\epsilon^{\pm}(k,p,q) = \frac{1}{[8(k\cdot p)(k\cdot q)(p\cdot q)]^{1/2}} \times [\not k \not p \not q (1 \mp \gamma_5) + \not q \not p \not k (1 \pm \gamma_5) - 2(p\cdot q)\not k] \quad (6)$$

	No NLO Sing	NLO Sing
$\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$	1.4 ± 0.26	1.5 ± 0.26
$\Delta_8^{J/\psi}(3.5)$	12.5 ± 2.8	9.6 ± 2.8

Table 1
NLO colour-singlet effect in the colour-octet MEs extraction at the Tevatron. The values are expressed in units of 10^{-2} GeV^3. In the first column is reported the standard fit. The second one shows the fit obtained by considering NLO ${}^3S_1^{[1]}$ contribution with a democratic cut on any jet pair $s_{ij} > s_{\rm min} = M^2_{J/\psi}/20$. The latter effect lowers the value of $\Delta_8^{J/\psi}(3.5)$ but leaves $\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$ essentialy unchanged.

which corresponds to the choice of a light-like axial gauge, being k the momentum of the given gluon and p, q the two light-like reference momenta. There are three independent helicity configurations, namely $(+,+,-,-)$, $(+,+,+,-)$, $(+,+,+,+)$. In particular the all-plus configuration turns out to be zero. Each helicity amplitude is expanded in terms of the six colour structures represented by the six traces ${\rm tr}(\lambda^{a_1}\lambda^{a_2}\lambda^{a_3}\lambda^{a_4})$. When the square is performed the C-parity symmetry allows the overall factorization of the colour.

Being the virtual-emission channel missing, in performing the numerical analysis one is forced to put phenomenological cuts to avoid collinear and soft regions of the phase space. In particular: a) azimuth-pseudorapidity separation cut between the two final jets, b) p_T cut on the two final jets. Another way to proceed is to put a minimum invariant mass cut on any jet pair: $s_{ij} = (k_i + k_j)^2 > s_{\rm min}$. I choose the latter way. The figure (1) shows the cut dependence

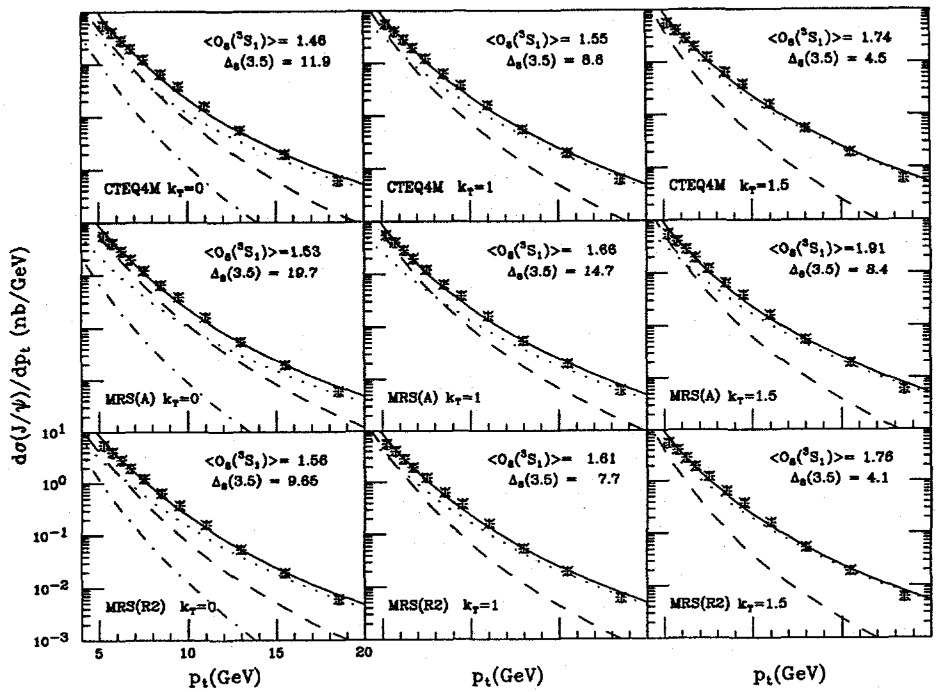

Figure 2. Different contributions to J/ψ production at the Tevatron. Dots: ${}^3S_1^{[8]}$. Dashes: ${}^1S_0^{[8]}+{}^3P_J^{[8]}$. Dotdash: NLO ${}^3S_1^{[1]}$. The effect of k_T-smearing is included for three different values of $\langle k_T\rangle$ ($\langle k_T\rangle = 0, 1, 1.5$ GeV). The results are given for three different sets of pdfs. The NLO ${}^3S_1^{[1]}$ effect is only included in the $\langle k_T\rangle = 0$ case.

		MRS(R2)	MRS(A)	CTEQ4M
$\Delta_8^{J/\psi}(3.5)$	$\langle k_T\rangle = 0$	9.6 ± 2.8	19.7 ± 3.7	11.9 ± 2.8
	$\langle k_T\rangle = 1$	7.7 ± 2.0	14.8 ± 2.7	8.6 ± 2.1
	$\langle k_T\rangle = 1.5$	4.1 ± 1.4	8.4 ± 1.9	4.5 ± 1.5
$\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$	$\langle k_T\rangle = 0$	1.5 ± 0.26	1.5 ± 0.26	1.5 ± 0.26
	$\langle k_T\rangle = 1$	1.6 ± 0.26	1.7 ± 0.26	1.5 ± 0.22
	$\langle k_T\rangle = 1.5$	1.7 ± 0.19	1.9 ± 0.23	1.7 ± 0.19

Table 2
Effects of intrinsic transverse momentum in the colour-octer MEs fit in J/ψ production at the Tevatron. Fits are performed for three different values of $\langle k_T\rangle$ and three pdfs. Values in units of 10^{-2} GeV^3.

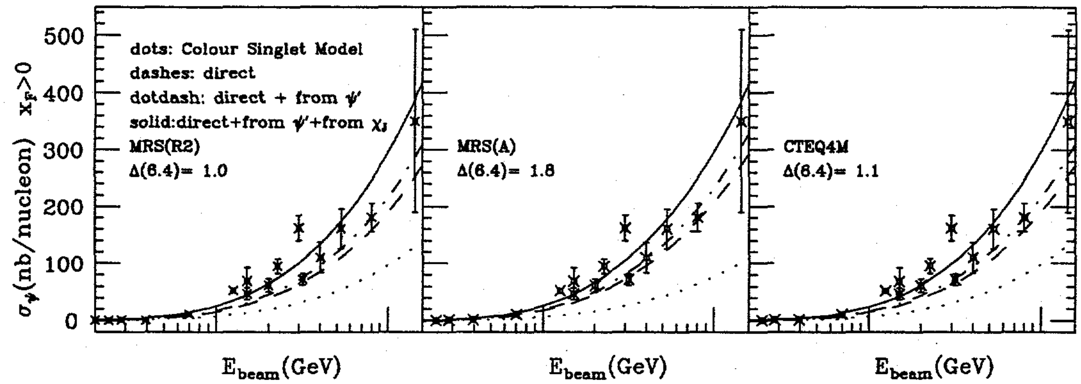

Figure 3. Fits of the matrix element $\Delta_8^{J/\psi}(6.4)$ to the fixed-target proton-nucleon collisions data. Fits are performed for three sets of pdfs. The value of $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ is taken from the above Tevatron fits (for any correspondent pdf) with $\langle k_T\rangle = 0$. (The value of $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ is only sligtly affected by the intrinsic k_T anyway. The indirect impact of the Tevatron k_T-smearing in the extraction of $\Delta_8^{J/\psi}(6.4)$ is not appreciable).

of the process for $M_\psi^2/20 < s_{\rm min} < M_\psi^2$. The NLO colour-singlet contribution is given by the dashed lines for $s_{\rm min} = M_\psi^2$ (lower dashes) and $s_{\rm min} = M_\psi^2/20$ (upper dashes). The colour-singlet matrix element[2] is set to $\langle \mathcal{O}_1^{J/\psi}(^3S_1)\rangle = 1.2\,{\rm GeV}^3$. As p_T increases, the cut sensitivity becomes milder and milder, like expected. The fit of the colour-octet MEs is performed by assuming $s_{\rm min} = M_\psi^2/20$ and compared to the standard fit (that is without $O(\alpha_s^4)$ correction). The results are summarized in the table (1). The NLO colour-singlet corrections lower the value of the matrix element $\Delta_8^{J/\psi}(3.5)$. The VEV $\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle$ instead is nailed by the high p_T tail of the data distribution and is quite insensitive to the low p_T effects. At high p_T the $^3S_1^{[8]}$ channel develops large collinear logarithms $(\alpha_s \log p_T/2\,m)^n$ which make the fixed order cross section unreliable. The leading logarithms are resummed by using the standard DGLAP equation for the fragmentation function of the gluon into J/ψ. The accuracy of the cross section in the whole Tevatron p_T-range is achieved by matching the fixed order to the fragmentation cross-section, according to the following equation:

$$\frac{d\sigma}{dp_T^2}(^3S_1^{[8]}) = \frac{d\sigma^{\rm FXD}}{dp_T^2} - \frac{d\sigma^{\rm ASY}}{dp_T^2} + \frac{d\sigma^{\rm FRG}}{dp_T^2} \qquad (7)$$

being

$$\frac{d\sigma^{\rm FRG}}{dp_T^2} = \frac{d\hat\sigma_g}{dp_{T,g}^2} \otimes D_{g\to\psi} \qquad (8)$$

$$\frac{d\sigma^{\rm ASY}}{dp_T^2} = \left.\frac{d\sigma^{\rm FXD}}{dp_T^2}\right|_{p_T\gg m}, \qquad (9)$$

where the meaning of the symbols is transparent. From the table (1) can be deduced that the inclusion of the $O(\alpha_s^4)$ $^3S_1^{[1]}$ contribution in the J/ψ production at the Tevatron does not affect in a dramatic way the extraction of the colour-octet MEs.

3. THE EFFECT OF THE INTRINSIC k_T

The effect of the intrinsic transverse momentum of the partons in the J/ψ differential cross-section at the Tevatron is phenomenologically implemented by performing a gaussian smearing of the p_T-distributions. The smearing is implemented channel by channel for three values

[2]For the the colour-singlet operator I use the original normalization defined in the ref. [1]

	MRS(R2)	MRS(A)	CTEQ4M
$\Delta_8^{J/\psi}(6.4)$	1.0	1.8	1.1

Table 3
Values of the fitted $\Delta_8^{J/\psi}(6.4)$ at fixed-target collisions for different pdfs. In units of 10^{-2} GeV^3.

of $\langle k_T \rangle = \langle k_T^2 \rangle^{1/2}$, namely $\langle k_T \rangle = 0, 1, 1.5\,\text{GeV}$ and for three pdf parameterizations (CTEQ4M, MRS(A) and MRS(R2)). The complete NLO calculation of colour-octet channels [10] shows that the Sudakov effect is likely confined below the 2 GeV p_T-region. The region we are analysing is therefore free of Sudakov effects. The figure (2) synthetizes the results of the Tevatron fits with both k_T-smearing and colour-singlet radiative corrections. Since the k_T-smearing essentially attacks the p_T-slope, the colour-octet C-even channels are stronger affected than the flatter $\langle \mathcal{O}_8^{J/\psi}(^3S_1) \rangle$ distribution, which is instead only slightly sensitive to the transverse momentum of the partons. The basic effect of the k_T-kick is to tilt clockwise the dashed curves in figure (2) and eventually lower the fitted value of the matrix element $\Delta_8^{J/\psi}(3.5)$. The obtained fits are also summarized in the table (2). The lack of accuracy of the NLO colour-singlet cross section at low p_T (due again to the fact that the one-loop channel is still unknown) might affect the shape at intermediate p_T once the k_T-smearing is turned on. That is why the NLO colour-singlet channel is only present in the $k_T = 0$ case.

4. FIXED-TARGET

In this section I perform the fit of NRQCD MEs to a compilation of fixed-target data by using the NLO QCD cross sections evaluated in the reference [10]. A comprehensive LO analysis can be found in the ref [15]. The references of the experimental data can be found in the papers [14,15]. Note that the quoted experiments do not distinguish the direct J/ψ from the ones coming from the ψ' and χ_J feed-down. Let me fix the VEVs relative to the feed-down first. For the χ_J feed-down I choose $\langle \mathcal{O}_1^{\chi_0}(^3P_0) \rangle / m^2 = 4.4 \times 10^{-2}\,\text{GeV}^3$ and $\langle \mathcal{O}_8^{\chi_0}(^3S_1) \rangle = 3.2 \times 10^{-3}\,\text{GeV}^3$. For the ψ': $\langle \mathcal{O}_8^{\psi'}(^3S_1) \rangle = 4.4 \times 10^{-3}\,\text{GeV}^3$ and $\Delta_8^{\psi'}(6.4) = 2.0 \times 10^{-3}\text{GeV}^3$ (the latter number is a result of an indepentent fit that will be shown somewherelse; the pdf-dependence of the ψ' VEVs is not considered here since its effect on the J/ψ cross section is negligible). Once the MEs relative to the χ_J and ψ' feed-down have been fixed, I focus on the direct component of J/ψ production. The cross section for direct J/ψ production according to the NRQCD factorization formalism is expressed by the formula:

$$\sigma(J/\psi) = \qquad (10)$$
$$\hat{\sigma}(^3S_1^{[1]}) \frac{\langle \mathcal{O}_1^{\psi}(^3S_1) \rangle}{m^5} + \hat{\sigma}(^3S_1^{[8]}) \frac{\langle \mathcal{O}_8^{\psi}(^3S_1) \rangle}{m^5} +$$
$$\hat{\sigma}(^1S_0^{[8]}) \frac{\langle \mathcal{O}_8^{\psi}(^1S_0) \rangle}{m^5} + \hat{\sigma}(^3P_J^{[8]}) \frac{\langle \mathcal{O}_8^{\psi}(^3P_0) \rangle}{m^7}$$

which is accurate up to order four in the velocity expansion. The second line of the previous equation can be rewritten as

$$\sigma = \frac{\hat{\sigma}(^1S_0^{[8]})}{m^5} \left(\langle \mathcal{O}_8^{\psi}(^1S_0) \rangle + k(E_{\text{beam}}) \frac{\langle \mathcal{O}_8^{\psi}(^3P_0) \rangle}{m^2} \right)$$

The coefficient $k(E_{\text{beam}})$ is independent of E_{beam} at LO ($k(E_{\text{beam}}) = 7$ at LO) and mildly dependent on E_{beam} at NLO: its average value is around 6.4 (k(100 GeV) = 6.6, k(1500 GeV) = 6.3). In fixed-target collisions the matrix element $\Delta_8^{J/\psi}(k)$ appears in a linear combination which is different from the Tevatron one. On the other hand at fixed-target it is not possible to fit simultaneously $\Delta_8^{J/\psi}(6.4)$ and $\langle \mathcal{O}_8^{J/\psi}(^3S_1) \rangle$ since the all channels have essentially the same shape in E_{beam}. Therefore –following the procedure adopted in the ref [15]– I use the value of $\langle \mathcal{O}_8^{J/\psi}(^3S_1) \rangle$ fitted at Tevatron and extract $\Delta_8^{J/\psi}(6.4)$ from the fixed-target data. In particular I pick the values of $\langle \mathcal{O}_8^{J/\psi}(^3S_1) \rangle$ obtained from the Tevatron at $k_T = 0$ (we have seen that $\langle \mathcal{O}_8^{J/\psi}(^3S_1) \rangle$ is not sensitive to the intrinsic k_T anyway) and I fit $\Delta_8^{J/\psi}(6.4)$ for three different pdfs. The fitted curves are shown in the figure (3). The table (3) reports the obtained values for

$\Delta_8^{J/\psi}(6.4)$. The NLO QCD corrections lower by about a factor of two the fitted value of $\Delta_8^{J/\psi}(6.4)$ at fixed-target.

5. CONCLUSIONS

Both the radiative corrections to the ${}^3S_1^{[1]}$ channel and the k_T-kick lower the value of $\Delta_8^{J/\psi}(3.5)$ extracted at the Tevatron. The previous effects vice versa don't have a significant impact on the determination of $\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle$. On the other hand the value of $\Delta_8^{J/\psi}(6.4)$ obtained by fitting the fixed-target data is still sensibly lower than $\Delta_8^{J/\psi}(3.5)$. If one believes that the NRQCD MEs are positive then $\Delta_8^{J/\psi}(6.4) > \Delta_8^{J/\psi}(3.5)$ should hold. Probably the gap would be partially bridged by the inclusion of the $O(\alpha_s^4)$ radiative corrections also for the colour-octet channels the Tevatron. The large theoretical uncertainties in the evaluation of the charmonium total cross-section certainly affect the reliability of the MEs extracted from fixed-target experiments. Even if one does not rely in the current understanding of the mechanisms of charmonium production at low-p_T, the reduction of the Tevatron colour-octet MEs is still welcome in the Hera-Tevatron universality perspective [16].

6. ACKNOWLEDGEMENTS

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