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 gg → 3S1 [1] channel and the effect of the kT-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 NRQCD factorization theory [1] is given by the expression:

\[ \frac{d\sigma}{d^3q} = \sum_n \langle 0|O_{J/\psi}^{(n)}|0\rangle d\sigma(c\bar{c}^{(n)}) \]

where \( n = 2^{S+1}L_{ij}^{[1,8]} \). The relevant long-distance matrix elements up to order \( v^4 \) are \( \langle O_{J/\psi}^{(3S_1)} \rangle \) and the linear combination \( \Delta_{J/\psi}^{(k)}(k) \). 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 the MEs to the Tevatron CDF data [2] by considering two possible deviation from the standard fits [3,4], namely a) the \( O(\alpha_s^4) \) colour-singlet contribution and b) the effect of the kT-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 \( \alpha_s \) and the velocity \( v \). In the J/ψ pT-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 \( ij \rightarrow 3S_1^{[1]} k l \) is a priori large. The scaling of its partonic cross-section is in fact \( O(\alpha_s^4 v^0/p_T^2) \) as compared to \( O(\alpha_s^4 v^4/p_T^2) \) 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 \( ij \rightarrow 3S_1^{[1]} k l \) 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:

\[
q\bar{q} \rightarrow 3S_1^{[1]} gg, \\
q g \rightarrow 3S_1^{[1]} qg, \\
gg \rightarrow 3S_1^{[1]} gg.
\]

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.
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 (1) 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 (3), I make use of the covariant projection technique (1, 2). The evaluation of the channels (3) and (4) is straightforward. The process (4) demands the helicity amplitude formalism:

$$\mathcal{M}(P^e, k_1^{h_1}, k_2^{h_2}, k_3^{h_3}, k_4^{h_4}) = \frac{\delta_{ij}}{\sqrt{N}} \text{Tr} \left( (P + M) \gamma^\alpha A_{ij}^{\mu_1 \mu_2 \nu_1 \nu_2} \right) \times \mathcal{E}_{\alpha_1}(P) e_{\mu_1}^{h_1}(k_1) e_{\mu_2}^{h_2}(k_2) e_{\nu_1}^{h_3}(k_3) e_{\nu_2}^{h_4}(k_4)$$

I use the Calkul collaboration representation for the external gluons (3):

$$\hat{f}^\pm(k, p, q) = \frac{1}{[8(k \cdot p)(k \cdot q)(p \cdot q)]^{1/2}} \times \left[ \hat{g} \cdot \hat{g} (1 + \gamma_5) + \hat{g} \cdot \hat{g} (1 + \gamma_5) - 2(p \cdot q) \right]$$

Table 1

| No NLO Sing | NLO Sing |
|-------------|----------|
| $\langle O_{S_1}^{J/\psi}(3 S_1) \rangle$ | $1.4 \pm 0.26$ | $1.5 \pm 0.26$ |
| $\Delta_{S_1}^{J/\psi}(3.5)$ | $12.5 \pm 2.8$ | $9.6 \pm 2.8$ |

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 $3 S_1^{[1]}$ contribution with a democratic cut on any jet pair $s_{ij} > s_{\text{min}} = M_{j/k}^2/20$. The latter effect lowers the value of $\Delta_{S_1}^{J/\psi}(3.5)$ but leaves $\langle O_{S_1}^{J/\psi}(3 S_1) \rangle$ essentially unchanged.

Figure 1. Different channels contributing to the $J/\psi$ production at the Tevatron. The NLO $3 S_1^{[1]}$ channel is given by the dashed curves ( $s_{\text{min}} = M_{j/k}^2$ (lower dash) and $s_{\text{min}} = M_{j/k}^2/20$ (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 ($3 S_1^{[8]}$ (dots) and $\Delta_{S_1}^{J/\psi}(3.5)$ (dotdash)).
Figure 2. Different contributions to $J/\psi$ production at the Tevatron. Dots: $[^3S_1^1]$. Dashes: $[^1S_0^1]+[^3P_0^1]$. 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.

Table 2

|                  | MRS(R2)  | MRS(A)  | CTEQ4M |
|------------------|----------|---------|---------|
| $\Delta_{[^3S_1^1]}^{J/\psi}(3.5)$ | $\langle k_T \rangle = 0$ | 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 |
| $\langle \sigma_{[^3S_1^1]}^{J/\psi}(3.5) \rangle$ | $\langle k_T \rangle = 0$ | 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-octet MEs fit in $J/\psi$ production at the Tevatron. Fits are performed for three different values of $\langle k_T \rangle$ and three pdfs. Values in units of $10^{-3}$ GeV$^3$.
Figure 3. Fits of the matrix element $\Delta_{J/\psi}(6.4)$ to the fixed-target proton-nucleon collisions data. Fits are performed for three sets of pdfs. The value of $\langle O_{J/\psi}(3S_1) \rangle$ is taken from the above Tevatron fits (for any correspondent pdf) with $\langle k_T \rangle = 0$. (The value of $\langle O_{J/\psi}(3S_1) \rangle$ is only slightly affected by the intrinsic $k_T$ anyway. The indirect impact of the Tevatron $k_T$-smearing in the extraction of $\Delta_{J/\psi}(6.4)$ is not appreciable.).

Figure (1) shows the cut dependence of the process for $M_{2J/\psi}^2 < s_{\text{min}} < M_{2J/\psi}^2$. The NLO colour-singlet contribution is given by the dashed lines for $s_{\text{min}} = M_{2J/\psi}^2$ (lower dashes) and $s_{\text{min}} = M_{2J/\psi}^2/20$ (upper dashes). The colour-singlet matrix element is set to $\langle O_{J/\psi}(3S_1) \rangle = 1.2 \text{ GeV}^3$. As $p_T$ increases, the cut sensitivity becomes milder and milder, like expected. The fit of the colour-octet MEs is performed by assuming $s_{\text{min}} = M_{2J/\psi}^2$ and compared to the standard fit (that is without $O(\alpha_4^2 s)$ correction). The results are summarized in the table (1). The NLO colour-singlet corrections lower the value of the matrix element $\Delta_{J/\psi}(3.5)$. The VEV $\langle O_{J/\psi}(3S_1) \rangle$ 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 ($\alpha_s \log p_T/2m$) 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 $J/\psi$. 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:

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

being

$$\frac{d\sigma_{\text{FRG}}}{dp_T^2} = \frac{d\sigma_{g}}{dp_T^2} \otimes D_{g \rightarrow \psi}$$

$$\frac{d\sigma_{\text{ASY}}}{dp_T^2} = \frac{d\sigma_{\text{FXD}}}{dp_T^2} \bigg|_{p_T \gg m}$$

where the meaning of the symbols is transparent. From the table (1) it can be deduced that the inclusion of the $O(\alpha_4^2 S_1^{[1]})$ contribution in the $J/\psi$ 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 $J/\psi$ differential cross-section at the Tevatron is phenomenologically implemented by performing a gaussian smear-
ing of the $p_T$-distributions. The smearing is implemented channel by channel for three values 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 \cite{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 $\langle O_8^{J/\psi}(3S_1) \rangle$ 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 \cite{11}. A comprehensive LO analysis can be found in the ref \cite{12}. The references of the experimental data can be found in the papers \cite{11,12}. Note that the quoted experiments do not distinguish the direct $J/\psi$ from the ones coming from the $\psi'$ and $\chi_J$ feed-down. Let me fix the VEVs relative to the feed-down first. For the $\chi_J$ feed-down I choose $\langle O_1^{\psi}(3P_0) \rangle/m^2 = 4.4 \times 10^{-2} \text{ GeV}^3$ and $\langle O_8^{\psi}(3S_1) \rangle = 3.2 \times 10^{-3} \text{ GeV}^3$. For the $\psi'$: $\langle O_8^{\psi'}(3S_1) \rangle = 4.4 \times 10^{-3} \text{ GeV}^3$ and $\Delta_8^{\psi'}(6.4) = 2.0 \times 10^{-3} \text{ GeV}^3$ (the latter number is a result of an independent fit that will be shown somewhere; the pdf-dependence of the $\psi'$ VEVs is not considered here since its effect on the $J/\psi$ cross section is negligible). Once the MEs relative to the $\chi_J$ and $\psi'$ feed-down have been fixed, I focus on the direct component of $J/\psi$ production. The cross section for direct $J/\psi$ production according to the NRQCD factorization formalism is expressed by the formula:

$$
\sigma(J/\psi) = \frac{\hat{\sigma}(1S_0^{[8]})}{m^5} \left( \langle O_8^{J/\psi}(1S_0) \rangle + k(\text{E}_{\text{beam}}) \langle O_8^{J/\psi}(3P_0) \rangle \right)
$$

The coefficient $k(\text{E}_{\text{beam}})$ is independent of $\text{E}_{\text{beam}}$ at LO ($k(\text{E}_{\text{beam}}) = 7$ at LO) and mildly dependent on $\text{E}_{\text{beam}}$ 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 $\langle O_8^{J/\psi}(3S_1) \rangle$ since the all channels have essentially the same shape in $\text{E}_{\text{beam}}$. Therefore –following the procedure adopted in the ref \cite{12} – I use the value of $\langle O_8^{J/\psi}(3S_1) \rangle$ fitted at Tevatron and extract $\Delta_8^{J/\psi}(6.4)$ from the fixed-target data. In particular I pick the values of $\langle O_8^{J/\psi}(3S_1) \rangle$ obtained from the Tevatron at $k_T = 0$ (we have seen that $\langle O_8^{J/\psi}(3S_1) \rangle$ is not sensitive to the intrinsic $k_T$ anyway) and I fit $\Delta_8^{J/\psi}(6.4)$ for three different

| $\Delta_8^{J/\psi}(6.4)$ | MRS(R2) | MRS(A) | CTEQ4M |
|-------------------------|---------|--------|--------|
| 1.0                     | 1.8     | 1.1    |
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 $^{3}S_{1}^{[1]}$ 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 $\langle O_{8}^{J/\psi}(^{3}S_{1}) \rangle$. 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 $O(\alpha_s^2)$ 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 (3).

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