$J/\psi$ production in hadron scattering: three-pomeron contribution

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Based on:


$J/\psi$ in $pp$ collisions—how is it produced?


Color Singlet Model & NRQCD corrections

(Reggeized) gluon=(cut) pomeron

Other mechanisms at large $p_T$?

- Co-production ($J/\psi + \bar{Q}Q$, ...)

(PRL 101 (2008) 152001)

- Quark and gluon fragmentation
  (EPJC 79 (2019) 241)

... ?

[Phys. Rev. D 96, no. 3, 034019 (2017)]:

<table>
<thead>
<tr>
<th>Color octet contributions</th>
<th>$\langle \mathcal{O}^{[3S_1(1)]}/\text{GeV}^3 \rangle$</th>
<th>$\langle \mathcal{O}^{[1S_0(8)]}/\text{GeV}^3 \rangle$</th>
<th>$\langle \mathcal{O}^{[3S_1(8)]}/\text{GeV}^3 \rangle$</th>
<th>$\langle \mathcal{O}^{[3P_0(8)]}/\text{GeV}^3 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>kT-factorization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0</td>
<td>1.97</td>
<td>0.0</td>
<td>$9.01 \times 10^{-4}$</td>
<td>0.0</td>
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<td>JH</td>
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<td>$2.83 \times 10^{-4}$</td>
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<td>KMR</td>
<td>1.58</td>
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<td>$2.32 \times 10^{-4}$</td>
<td>0.0</td>
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<td>Collinear factorization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[11]</td>
<td>1.32</td>
<td>$3.04 \times 10^{-2}$</td>
<td>$1.68 \times 10^{-3}$</td>
<td>$-9.08 \times 10^{-3}$</td>
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<tr>
<td>[15]</td>
<td>1.16</td>
<td>$9.7 \times 10^{-2}$</td>
<td>$-4.6 \times 10^{-3}$</td>
<td>$-2.14 \times 10^{-2}$</td>
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</table>

(CSM alone):
- Reasonable predictions for:
  - small-$p_T$ observables
  - $p_T$-integrated observables

Wrong behaviour for $p_T \gg m_{J/\psi}$

(NRQCD):
- Description for large-$p_T$

Challenge for NRQCD: LDMEs not universal?!
Multiplicty dependence of charmonia production

- Observable: $J/\psi$+ charged hadrons, study multiplicity $dN_{J/\psi}$ vs. $dN_{ch}$
- Enhancement (deviation from linear) seen both for $J/\psi$ and $D$ mesons
- So far not clear if the effect exists for $\psi(2S), \chi_c, \Upsilon$?
- Difficult to explain in terms of gluon-gluon fusion approach: if each reggeized gluon (cut pomeron) contributes approx. equal number $\bar{n}$ of charged hadrons, expect linear dependence
- Data hints that multipomeron mechanisms are pronounced (usually discarded as corrections).
- Production on nuclei: $\sim A^{1/3}$ enhancement
3-pomeron contributions

- Diagram (2) contributes additively to $d\sigma$
- Diagrams (1) and (3) might interfere:

Diagrams (1) and (2) include Parton Distributions with odd number of gluons
- ... such distributions are sensitive if the proton is polarized [PLB 668 (2008), 216, PRD 78 (2008), 014024, PRD 78 (2008), 114013].
- ... corresponding asymmetries are small, might neglect them [PHENIX Collaboration, PRD 82, 112008 (2010), PRD 86 (2012), 099904]

$\Rightarrow$ Additive contribution to the LO cross-section, as shown in (3).
CSM in dipole approach

LO diagrams

Large-$m_Q$ limit

- Dipole cross-section related to $k_\perp$ uPDF, e.g. for color singlet

$$\sigma_d(x, r_\perp) = \int \frac{d^2k_\perp}{(2\pi)^2} \mathcal{F}(x, k_\perp) \left(1 - e^{i k_\perp \cdot r_\perp}\right).$$

- Color octet dipole cross-section could be expressed as linear combinations of color singlets

Reasonable description of $pp$ data

Same diagrams as in $k_T$ factorization, we just express everything in terms of dipole framework.

[PRC95 (2017), 065203]
$J/\psi$ production cross-section in the dipole approach

[PRC95 (2017), 065203]

\[
\frac{d\sigma_{pp}}{dy} = \frac{9}{8} g(x_1(y)) \int d\alpha_G d\alpha_1 d^2r_1 d\alpha_2 d^2r_2 d^2\rho \Psi_M^*(\alpha_1 r_1) \Psi_M(\alpha_2 r_2) \times \\
\times \sum_{n,n'=1}^6 \eta_n \eta_{n'} \text{Tr} \left[ \Lambda_M \Phi_{g\rightarrow QQ} \left( \epsilon_n, \vec{r}_n^{(1)} \right) \Phi_{Q\rightarrow Qg} \left( \delta_n, \vec{\rho}_n \right) \right] \\
\times \text{Tr} \left[ \Lambda_M \Phi_{g\rightarrow QQ} \left( \epsilon_{n'}, \vec{r}_{n'}^{(2)} \right) \Phi_{Q\rightarrow Qg} \left( \delta_{n'}, \vec{\rho}_{n'} \right) \right]^* \\
\times \sigma(x_2, \vec{r}_n - \vec{r}_{n'})
\]

- $\Lambda_M$-spin projector on meson WF
- $\Phi_{g\rightarrow QQ}, \Phi_{Q\rightarrow Qg}$ are evaluated perturbatively ($m_c \rightarrow \infty$ limit)
- $\vec{r}_n^{(1,2)} \approx \vec{r}_{1,2} + \delta\vec{r}_n(\alpha, \alpha_G, r, \rho)$, $\vec{\rho}_n \approx \vec{\rho} + \delta\vec{\rho}_n(\alpha, \alpha_G, r, \rho)$
- Sum over 6 diagrams in amplitude and its conjugate is implied

For $p_T$-dependent cross-section, additional Fourier over difference of dipole impact parameter $\Delta\vec{b} = \vec{b}_1 - \vec{b}_2 \neq 0$; terms $\delta\vec{r}_n, \delta\vec{\rho}_n$ also depend on $\vec{b}_{1,2}$
3-gluon fusion in dipole approach

\[\frac{d\sigma (Y, Q^2)}{dy \, d^2q_T} = 4 \int \frac{d^2Q_T}{(2\pi)^2} \, S_h(Q_T) \, x_g \, G(x_g, M_{J/\psi}) \]
\[\times \int_0^1 dz \int_0^1 dz' \int \frac{d^2r}{4\pi} \frac{d^2r'}{4\pi} \, d^2b \, e^{-iq_T \cdot b} \]
\[\times \langle \Psi_g(r, z) \, \Psi_{J/\psi}(r, z) \rangle \langle \Psi_g(r', z') \, \Psi_{J/\psi}(r', z') \rangle \left( N \left( y; \, b - \frac{1}{2} (r - r') \right) \right)^2 \]
\[+ N \left( y; \, b + \frac{1}{2} (r - r') \right) - N \left( y; \, b + \frac{1}{2} (r + r') \right) - N \left( y; \, b - \frac{1}{2} (r + r') \right) \]
\[+ (y \rightarrow Y - y) \]

- **Note:** Results are defined up to nonperturbative normalization factor \(\sim \int \frac{d^2Q_T}{(2\pi)^2} \, S_h(Q_T)\), related to Fourier image of cut pomeron Green function. Can be related to \(\sigma_{\text{eff}}\) in DPDF.
Explanation of uncertainty in $k_T$-factorization language

- For gluon uPDF use KMR parametrization, $\mu_R = \mu_F = \sqrt{p_T^2 + M_{J/\psi}^2}$
- For DPDFs $\mathcal{F}^{c_1c_2,c'_1c'_2}(x_{1a}, k_{1a}, T, x_{1b}, k_{1b}, T, \Delta)$ can have different color structures,

\[
\mathcal{F}^{aa', bb'} = \frac{1}{64} \left[ F \delta^{aa'} \delta^{bb'} - \frac{\sqrt{8}}{3} A F f^{aa'} c f^{bb'} c + \frac{3\sqrt{8}}{5} S F d^{aa'} c d^{bb'} c \right. \\
\left. + \frac{4}{\sqrt{27}} 27 F t^{aa', bb'} + \frac{2}{\sqrt{10}} 10 F \left( t^{aa', bb'} + \left( t^{aa', bb'} \right)^* \right) \right],
\]

- We assume that the parameterization is given by

\[
\mathcal{F}^{c_1c_2, c'_1c'_2}(x_{1a}, k_{1a}, T, x_{1b}, k_{1b}, T) \sim \mathcal{F}(x_{1a}, k_{1a}, T) \mathcal{F}(x_{1b}, k_{1b}, T)
\]

- ... reproduces “pocket formula” for DPS

\[
d\sigma_{pp \rightarrow h_1 h_2 X} = \frac{1}{\sigma_{\text{eff}}} d\sigma_{pp \rightarrow h_1 X} \ d\sigma_{pp \rightarrow h_2 X}.
\]

\[
\Rightarrow \int \frac{d^2 Q_T}{(2\pi)^2} S_h^2(Q_T) \sim (\text{const}) \sigma_{\text{eff}}^{-1}
\]

- Caveat: the “universal” value of $\sigma_{\text{eff}}$ is not that universal; typical values are between 5 mb and 20 mb. [Eur.Phys.J. C77 (2017) no.2, 76]
Fixing uncertainty in 3-gluon fusion cross-section

\[
\frac{d\sigma (Y, Q^2)}{dy} = \left( \int \ldots \right) \langle \Psi_g (r, z) \, \Psi_{J/\psi} (r, z) \rangle \langle \Psi_g (r', z') \, \Psi_{J/\psi} (r', z') \rangle \\
\times \left( N \left( y; \frac{r - r'}{2} \right) - N \left( y; \frac{r + r'}{2} \right) \right)^2
\]

- Use diffractive photoproduction ($\gamma^* p \to J/\psi X$) data to fix normalization:

\[
\frac{d\sigma_{\text{diff}} (Y, Q^2)}{dy} = \left( \int \ldots \right) \langle \Psi_{\gamma^*} (r, z) \, \Psi_{J/\psi} (r, z) \rangle \langle \Psi_{\gamma^*} (r', z') \, \Psi_{J/\psi} (r', z') \rangle \\
\times N (y; r) \, N (y; r')
\]

For $Q^2 \to \infty$, $m_c \to \infty$, $r \to 0$, can use pQCD expression for both $\Psi_{\gamma^*} \sim \Psi_g$.

- The dipole amplitude $N (y; r) \sim (Q^2 s r^2)^{\bar{\gamma}}$ at small $r$, so rapidity dependence of $d\sigma$ and $d\sigma_{\text{eff}}$ is the same $\Rightarrow$ Can fix hadroproduction cross-section $d\sigma$ from diffractive photoproduction $d\sigma_{\text{diff}}$ studied at HERA:

- Theoretical estimates: three-pomeron fusion gives sizeable contribution

<table>
<thead>
<tr>
<th>$d\sigma (y, Q^2)/dy$</th>
<th>Theoretical estimates</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s} \approx 1.96$ TeV</td>
<td>2.1-2.6 $\mu$b</td>
<td>2.38 $\mu$b [67]</td>
</tr>
<tr>
<td>$\sqrt{s} \approx 7$ TeV</td>
<td>3.8-5.6 $\mu$b</td>
<td>5.8 $\mu$b [68]</td>
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</tbody>
</table>

- In what follows will show only shapes for $p_T$, rapidity, multiplicity dependence
Contribution of $3g \rightarrow J/\psi$ to phenomenological observables

**Multiplicity distributions**

- **BFKL**: $\bar{\gamma} \approx 0.63$, phenomenology: $\bar{\gamma} \in [0.67, 0.76]
- Data clearly favour 3-pomeron contribution.

$\Rightarrow$ Overall, reasonable description of $pp$ data might be achieved

- **$p_T$- and rapidity distribution**

  - **BFKL**: each gluon $\sim x^\alpha$ (dashed)
  - **Experiment**: add $\sim (1 - x)^5$ (solid)
Contribution of the $g + gg \rightarrow g + J/\psi$ process

- Use $k_T$ factorization, too difficult in dipole approach
  - Result expressed in terms of the gluon uPDFs and DPDFs of the proton

$$d\sigma = \frac{\pi\alpha_s^3(\mu)|R(0)|^2}{(x_1ax_1b\times_2s)^2} \frac{d^2k_{1a,T}}{\pi} \frac{d^2k_{1b,T}}{\pi} \frac{d^2k_{2,T}}{\pi}$$

\[
\times \frac{dyd^2p_T}{\pi} d\Delta^+ \frac{d^2\Delta_T}{\pi} dy_g dx_{1a} \\
\times M_{gg+g \rightarrow g J/\psi}^{c_1c_2, c_3} \left( k_{1a}, k_{1b}, k_2, p_{J/\psi} \right) \\
\times \left( M_{gg+g \rightarrow g J/\psi}^{c_1\bar{c}_2, c_3} \left( k_{1a} - \frac{\Delta}{2}, k_{1b} + \frac{\Delta}{2}, k_2, p_{J/\psi} \right) \right) \\
\times \mathcal{F}^{c_1c_2, \bar{c}_1\bar{c}_2} \left( x_1a, k_{1a,T}, x_1b, k_{1b,T}, \Delta \right) \mathcal{F}(x_2, k_{2\perp}) \\
\begin{aligned}
\text{DPDF} & \quad \text{uPDF} \\
\end{aligned}
\]

- For gluon uPDF use KMR parameterization.
- For gluon DPDF use factorized ansatz mentioned earlier
3-pomeron $J/\psi$ production with gluon emission

Result for the cross-section:

$\frac{d^2\sigma}{dy dp_T}, \text{pb/GeV}$

$\frac{d\sigma}{dp_T}, \text{GeV}$

Relative w.r.t. CSM+NRQCD

$g + g + g \rightarrow J/\psi + g$, we get sizeable contribution from the three-pomeron fusion to $J/\psi$ production (slightly smaller due to $O(\alpha_s(m_c))$)
The observed multiplicity of charged particles signals that 3-pomeron process gives a sizeable contribution to $J/\psi$ production.

We believe that similar studies of multiplicity dependencies for $\psi(2S)$, $\Upsilon(nS)$ should shed light on the role of the suggested mechanism in their formation.

Thank You for your attention