QCD Correction to $J/\psi$ Production

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Outline

1. Introduction
2. $J/\psi$ production at the B-factories
3. $J/\psi$ production at the Tevatron and LHC
4. $J/\psi$ production at the HERA
5. Inclusive $J/\psi$ production from $\Upsilon$ Decay
6. Summary
Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect $J/\psi$.
- Heavy quarkonium production is a good place to testify these theoretical frameworks.
- But there are still many difficulties.
  - $J/\psi$ photoproduction at HERA
  - $J/\psi$ production at the B factories
  - $J/\psi$ polarization at the Tevatron
- NLO corrections are important.
  - Data on inelastic $J/\psi$ photoproduction are adequately described by the color singlet channel alone at NLO
  - Double charmonium production at the B factories
FIG. 4 (color online). Prompt polarizations as functions of $p_T$: (a) $J/\psi$ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD [4] (the $k_T$-factorization model [9]).
LO NRQCD Prediction:

\[
e^+ e^- \to J/\psi + c\bar{c}
\]
0.07 - 0.20 pb

\[
e^+ e^- \to J/\psi + gg
\]
0.15 - 0.3 pb

\[
e^+ e^- \to J/\psi^{(8)}(P_J, S_0) + g
\]
0.3 - 0.8 pb

**Experimental Data:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>2.54 ± 0.21 ± 0.21</td>
</tr>
<tr>
<td>Belle</td>
<td>1.45 ± 0.10 ± 0.13</td>
</tr>
<tr>
<td>CLEO</td>
<td>1.9 ± 0.20</td>
</tr>
<tr>
<td>Belle</td>
<td>0.87^{+0.21}_{-0.19} ± 0.17</td>
</tr>
</tbody>
</table>

\[
\sigma[e^+ e^- \to J/\psi + c\bar{c} + X] \approx 0.6 \text{ pb}
\]
NLO QCD correction to $e^+e^- \rightarrow J/\psi + J/\psi$ at B factory

36 NLO diagrams with up to Six-point diagrams

\[
\sigma^{(1)} = \int dt \frac{d\sigma^{(0)}}{dt} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \tilde{K}(\hat{s}, \hat{t}) \right\} \\
= \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} K(\hat{s}) \right\}
\]

<table>
<thead>
<tr>
<th>$m_c$ (GeV)</th>
<th>$\mu$</th>
<th>$\alpha_s(\mu)$</th>
<th>$\sigma_{LO}$ (fb)</th>
<th>$\sigma_{NLO}$ (fb)</th>
<th>$\sigma_{NLO}/\sigma_{LO}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>$m_c$</td>
<td>0.369</td>
<td>7.409</td>
<td>-2.327</td>
<td>-0.314</td>
</tr>
<tr>
<td>1.5</td>
<td>$2m_c$</td>
<td>0.259</td>
<td>7.409</td>
<td>0.570</td>
<td>0.077</td>
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<tr>
<td>1.5</td>
<td>$\sqrt{s}/2$</td>
<td>0.211</td>
<td>7.409</td>
<td>1.836</td>
<td>0.248</td>
</tr>
<tr>
<td>1.4</td>
<td>$m_c$</td>
<td>0.386</td>
<td>9.137</td>
<td>-3.350</td>
<td>-0.367</td>
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<tr>
<td>1.4</td>
<td>$2m_c$</td>
<td>0.267</td>
<td>9.137</td>
<td>0.517</td>
<td>0.057</td>
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<tr>
<td>1.4</td>
<td>$\sqrt{s}/2$</td>
<td>0.211</td>
<td>9.137</td>
<td>2.312</td>
<td>0.253</td>
</tr>
</tbody>
</table>

This work was published in Phys. Rev. Lett. 100, 181803 (2008).
The total cross section and momentum distribution for $J/\psi$ production can be well accounted by the next-to-leading-order QCD correction calculation.
Recently NLO QCD corrections to $J/\psi$ hadron production have been calculated and the results show that the total cross section is boosted by a factor of about 2 while the $J/\psi$ transverse momentum $p_t$ distribution is enhanced more and more as $p_t$ becomes larger.


Real correction process $gg \rightarrow J/\psi c\bar{c}$ was calculated. It gives sizable contribution to $p_t$ distribution of $J/\psi$ at high $p_t$ region, and it alone gives almost unpolarized result.


So how about the $J/\psi$ polarization status when NLO QCD corrections are included?
\[ \frac{d\sigma}{dp_t} \rightarrow Jdp_t dy \] is applied to obtain transverse momentum distribution

\[ \sigma = \int dx_1 dx_2 dt G_g(x_1, \mu_f) G_g(x_2, \mu_f) \frac{d\hat{\sigma}}{dt} = \int Jdx_1 dp_t dy G_g(x_1, \mu_f) G_g(x_2, \mu_f) \frac{d\hat{\sigma}}{dt} \]

\[ \frac{d\sigma}{dp_t} = \int Jdx_1 dy G_g(x_1, \mu_f) G_g(x_2, \mu_f) \frac{d\hat{\sigma}}{dt} \]

polarization parameter \( \alpha \) is defined as:

\[ \alpha(p_t) = \frac{d\sigma_T}{dt} - 2 \frac{d\sigma_L}{dt} \]

\[ \frac{d\sigma_T}{dt} + 2 \frac{d\sigma_L}{dt} \]

\[ \alpha = +1: \text{fully transverse polarization} \]

\[ \alpha = -1: \text{fully longitudinal polarization} \]

\[
\begin{align*}
p_1 & = x_1 \frac{\sqrt{S}}{2} (1, 0, 0, 1) \\
p_2 & = x_2 \frac{\sqrt{S}}{2} (1, 0, 0, -1) \\
m_t & = \sqrt{M_{J/\psi}^2 + p_t^2} \\
p_3 & = (m_t \cosh y, p_t, 0, m_t \sinh y) \\
x_t & = \frac{2m_t}{\sqrt{S}} \\
\tau & = \frac{m_4^2 - M_{J/\psi}^2}{\sqrt{S}} \\
J & = \frac{4x_1x_2p_t}{2x_1 - x_t e^y} \\
x_2 & = \frac{2\tau + x_1 x_t e^{-y}}{2x_1 - x_t e^{-y}} \\
x_{1min} & = \frac{2\tau + x_t e^y}{2 - x_t e^{-y}}
\end{align*}
\]

\( d\sigma_T /dt, \frac{d\sigma_L}{dt} \) are differential cross section of transverse polarization and longitudinal one respectively.
NLO QCD corrections to $J/\psi$ polarization at the Tevatron and LHC

There is huge discrepancy between theoretical prediction and experimental measurement at the Tevatron for $J/\psi$ polarization.

$J/\psi$ polarization status drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO.

This work is published in Phys. Rev. Lett. 100, 232001 (2008),
3. NLO QCD corrections to $J/\psi$ production via S-wave color octet states at PP collider

3 tree processes at LO

At NLO

\[
g(p_1) + g(p_2) \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] (p_3) + g(p_4), \quad (267, 413)
\]

\[
g(p_1) + q(p_2) \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] (p_3) + q(p_4), \quad (49, 111)
\]

\[
q(p_1) + \bar{q}(p_2) \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] (p_3) + g(p_4). \quad (49, 111)
\]

Real Correction (8 processes at NLO)

\[
gg \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] gg, \quad gg \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] q\bar{q},
\]

\[
gq \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] gq, \quad q\bar{q} \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] gg,
\]

\[
qq \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] qq, \quad qq \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] q'q',
\]

\[
qq \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] qq, \quad qq' \rightarrow J/\psi \left[ ^1S_0^{(8)}, \ ^3S_1^{(8)} \right] qq'.
\]
NLO QCD corrections to $J/\psi$ production via S-wave color octet states at the Tevatron and LHC

3 tree processes at LO with 1000 one-loop diagrams at NLO and 8 real Correction processes at NLO. All of these must be calculated together to cancel infrared divergence. It is a very complicated and important calculation.

This work was published in Phys. Lett. B 673 (2009)
4. NLO QCD corrections to $J/\psi$ photo-production at HERA

$$\gamma + g \rightarrow J/\psi + g,$$
$$\gamma + g \rightarrow J/\psi + g + g,$$
$$\gamma + g \rightarrow J/\psi + q + \bar{q},$$
$$\gamma + q(\bar{q}) \rightarrow J/\psi + g + q(\bar{q}).$$

Chekanov et al. (ZEUS), Eur. Phys. J. C27,

P. Artoisenet, John M. Campbell, F. Maltoni
Chao-Hsi Chang, Rong Li, Jian-Xiong Wang.
\[ z \equiv \frac{(p_J / \psi \cdot p_p)}{(p_\gamma \cdot p_p)} \]

\[ \mu_r = \mu_f = \sqrt{(2m_c)^2 + p_t^2} \]

\[ \mu_f = \mu_r = 8m_c \]

**FIG. 2:** The energy fraction \( z \) distributions of polarization parameters \( \lambda, \nu, \mu \) with \( p_t > 1 \text{GeV} \), and transverse momentum \( p_t \) distributions with \( 0.4 < z < 1 \). Dashed lines are the LO results and the Dot-dashed lines are the NLO results. Solid lines present the results with \( \mu_r = \mu_f = 8m_c \). The experimental data (filled circles with bars) are taken from Ref. [17].
The situation for $J/\psi$ production in $\Upsilon$ decay

**LO NRQCD Predictions:**

$Br(\Upsilon \rightarrow J/\psi (3S_1^0) + gg) = 6.2 \times 10^{-4}$, M. Napsuciale, Phys. Rev. D 57, 5711 (1998)

$Br(\Upsilon \rightarrow J/\psi + c\bar{c}g) = 5.9 \times 10^{-4}$, S. Y. Li, Q. B. Xie and Q. Wang, Phys. Lett. B 482, 65 (2000)

$Br(\Upsilon \rightarrow J/\psi + gg) = \text{order at} \times 10^{-4}$, ????

**Experimental Data for $Br(\Upsilon \rightarrow J/\psi + X)$:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$(11 \pm 4 \pm 2) \times 10^{-4}$</td>
<td>Phys. Lett. B 224, 445</td>
</tr>
<tr>
<td>CLEO</td>
<td>$(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$</td>
<td>Phys. Rev. D70, 072001(2004)</td>
</tr>
</tbody>
</table>

The situation is quite strange ????
1. The leading order prediction is

\[ B_{\text{Direct}}(\Upsilon \rightarrow J/\psi + c\bar{c}g) = 3.9 \times 10^{-5}. \]

2. Part of NLO prediction from \( \Upsilon \rightarrow J/\psi + gg \) is

\[ B_{\text{Direct}}(\Upsilon \rightarrow J/\psi + X) = 3.1 \times 10^{-5}. \]

3. The full QCD correction for the inclusive \( J/\psi \) production in \( \Upsilon \) decay would be a very interesting and challenge work for explaining the experimental data.

4. Further experiment measurement on the problem is expected.
Summary

1. For $J/\psi$ production at the B-factories, the huge discrepancies between experimental measurements and leading-order theoretical predictions could be explained when NLO QCD Corrections are included. Further experimental measurements are expected for $J/\psi$ polarization which are given at NLO level.

2. For $J/\psi$ production at hadron collider Tevatron, NLO QCD correction to color-singlet contribution is huge to $p_t$ distribution of production rate and polarization. NLO QCD correction to color-octet contributions is small. The $p_t$ distribution of $J/\psi$ polarization can not be explained even at NLO level within NRQCD framework.

3. It is highly expected that experimental measurement at larger $p_t$ range from LHC would give more information to clarify the production mechanism of $J/\psi$.

4. For $J/\psi$ photoproduction at Hera, the theoretical uncertainties are huge and no definit conclusion can be made.

5. For $J/\psi$ production in $\Upsilon$ decay, the leading-order theoretical prediction is one order in magnitude smaller than experimental measurement. The full NLO QCD correction would be a very challenge work to explain the experimental data.
Thank you!