Polarization of prompt J/ψ in proton-proton collisions at RHIC

Chaehyun Yu (KIAS)

In collaboration with Hee Sok Chung, Jungil Lee (Korea Univ.), Seyong Kim (Sejong Univ.)

Based on PRD81, 014020 (2010)

KEKPH2010, Feb. 20, 2010
Outline

• Heavy quarkonium production (NRQCD)

• Polarization of prompt $J/\psi$ at Tevatron

• Polarization of prompt $J/\psi$ at RHIC

• Conclusions
Heavy quarkonium production

Factorization:
- Perturbative short-distance coefficients
- Series in $\alpha_s$

Nonperturbative long-distance ME
- Series in $\mathcal{V}$

\[
\sigma(ij \rightarrow Q + X) \sim \sum_n \hat{\sigma}_\Lambda(ij \rightarrow Q\bar{Q}(n) + X) \langle \mathcal{O}^Q(n) \rangle_\Lambda
\]

- can be justified in NRQCD, which is an effective field theory of QCD.
prompt $J/\psi = \text{direct production} + \text{decay of heavier quarkonium} + \text{decay of B mesons}$
Color-octet revolution

• In NRQCD, the $Q\bar{Q}$ pair can be produced in a color-octet state. The pair can evolve into a color-singlet quarkonium by emitting soft gluons.

$$|J/\psi\rangle = O(1)|Q\bar{Q}(^3S_1^{[1]})\rangle$$
$$+ O(v)|Q\bar{Q}(^3P_{J}^{[8]})g\rangle + O(v^2)|Q\bar{Q}(^1S_0^{[8]})g\rangle$$
$$+ O(v)|Q\bar{Q}(^3S_1^{[8]})gg\rangle + O(v^4).$$

• The color-octet mechanism could resolve the long-standing IR divergence problems in the P-wave quarkonium decays.

$$\text{IR}_{CS} + \text{IR}_{CO} = 0.$$
NRQCD matrix elements

• the probability to find a corresponding Fock state.

• nonperturbative, but calculable in lattice simulations in principle.

• universal (process independent).
  -holds up to corrections of $v^4$ under the vacuum saturation approximation.

• color-singlet MEs are determined from electromagnetic decays.

• How determine color-octet matrix elements? – CO dominant process.
the surplus $J/\psi$ production at the Tevatron

- (a) leading-order contributions in $\alpha_s$.
- (b) some higher-order contributions through the fragmentation approximation.

$\alpha_s^3 \frac{(2m_c)^4}{p_T^8}$

$\alpha_s^4 \frac{1}{p_T^4}$

$\alpha_s^5 \frac{1}{p_T^4}$

$p\bar{p} \rightarrow J/\psi + X$ CDF,PRL69,3704(1992)

$\text{BR}(J/\psi \rightarrow \mu^+\mu^-) \frac{d\sigma(p\bar{p} \rightarrow J/\psi + X)}{dp_T} \ (\text{nb/GeV})$

$\sqrt{s} = 1.8 \text{ TeV}; |\eta| < 0.6$

F. Maltoni
Color-octet $J/\psi$ production at the Tevatron

- (c) $^1S_0$, $^3P_J$ octet, (d) $^3S_1$ octet production.
- Gluon fragmentation dominance at large transverse momentum.
- The color-octet matrix elements are fitted to the data.
Polarization of $J/\psi$ at Tevatron Run I

• The color-octet dominance at large transverse momentum implies that the $J/\psi$ is produced with a highly transverse polarization.

\[ p\bar{p} \rightarrow J/\psi + X \]

\[ \alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} \]

• agrees in the intermediate region.
• disagrees at the high transverse momentum.

CDF, PRL85, 2886(2000)
Polarization of $J/\psi$ at Tevatron Run II

$p\bar{p} \rightarrow J/\psi + X$

- Prompt polarization does not show the trend to the transverse polarization.
- CDF Run II data do not agree with NRQCD predictions.
- discrepancy between RUN I and RUN II data in the intermediate region.
NLO corrections to CS at the Tevatron

\[ p\bar{p} \rightarrow J/\psi + X \]

- Large NLO corrections.
- Parts of NNLO corrections.
- Improved in shape and size, but still less than data.
- Color-octet contributions should be suppressed, but are they negligible?
Polarization of direct $\psi(2S)$ at the Tevatron

- Polarization is not explained by NNLO corrections.
- feed-down, color octet?

Lansberg, QWG’08
• Only slight change appears when NLO QCD corrections are included.
• The CO MEs fitted at NLO are the same order as those at LO.
• Large gap between prediction and data for polarization of quarkonium.
Color-octet mechanism?

• essential to avoid IR divergence problem.
• the size of CO matrix elements has not been well established.
• There is still much room for the color-octet contributions.
• need to test the CO mechanism for different colliders.

\[
\begin{align*}
\text{HERA} & \quad \gamma p \rightarrow J/\psi + X \\
\text{LEP II} & \quad \gamma\gamma \rightarrow J/\psi + X \\
\text{B factories} & \quad e^+e^- \rightarrow J/\psi + X \\
\text{RHIC} & \quad pp \rightarrow J/\psi + X
\end{align*}
\]
Relativistic Heavy Ion Collider (RHIC)

- **Central Arms:** Hadrons, photons, electrons;
  - $J/\psi \rightarrow e^+e^-$; $\psi' \rightarrow e^+e^-$; $\gamma_e \rightarrow e^+e^-\gamma$;
  - $|\eta| < 0.35$;
  - $p_e > 0.2$ GeV/c;
  - $\Delta \phi = \pi(2\; \text{arms} \times \pi/2)$

- **Forward rapidity Arms:** Muons
  - $J/\psi \rightarrow \mu^+\mu^-$
    - $1.2 < |\eta| < 2.2$
  - $p_\mu > 1$ GeV/c
  - $\Delta \phi = 2\pi$

- Proton-proton collisions at the c.m. energy 200 GeV.
Prompt $J/\psi$ production at RHIC

- PHENIX measured the differential cross section in pp collisions at $\sqrt{s} = 200$ GeV.
- PHENIX data include a B feed-down fraction (~4%).
- essentially the same as prompt $J/\psi$.

$$pp \rightarrow J/\psi + X$$
$p_T$ distribution of prompt $J/\psi$ at RHIC

- NRQCD agrees well with the data, but the LO color-singlet model does not.
- confirms previous results by Cooper, Liu, and Nayak (2004).

- Theoretical uncertainties come from
  - NRQCD Mes
  - scale dependence
  - charm quark mass
  - PDF
$p_T$ distribution of prompt $J/\psi$ at RHIC

- Feed-down contributions are small (10~20%).
- cannot observe gluon fragmentation dominance.
- $J/\psi$ is expected to be unpolarized.
Polarization of prompt $J/\psi$ at RHIC

- First prediction for $J/\psi$ polarization at RHIC.
- NRQCD agrees well with the data, but the LO color-singlet model does not.
Inclusive $J/\psi$ production at the RHIC

- Brodsky and Lansberg carried out calculations for prompt $J/\psi$ in the Color-singlet model at NLO in $\alpha_s$.
  - assume that fraction of feed-down is $\sim 40\%$ and independent of $y$.

\begin{itemize}
  \item integrated over $p_T$.
  \item cannot be compared with our results.
\end{itemize}

Brodsky, Lansberg, 0908.0754
s-channel cut

- Lansberg and Haberzettl proposed a new mechanism called the s-channel cut.

- Introduce a 4-point function (c-C-Q-g) to preserve the gauge invariance without any diagrammatic definition of this vertex.

- could explain the production rate and polarization of the prompt $J/\psi$ at Tevatron.
s-channel cut CSM prediction

- Haberzettl and Lansberg included s-channel cut contributions to CSM that accompany with two phenomenological parameters.

- The s-channel cut CSM prediction for the polarization agrees with the data in the mid-rapidity region.

PHENIX, 0912.2082
s-channel cut CSM prediction at Tevatron

- Artoisenet and Braaten showed that the s-channel cut contributions can be identified with the charm-pair rescattering.

- In NRQCD, this rescattering is a contribution to CSM at NNLO.

- The charm-pair rescattering contribution is not a dominant mechanism.

Artoisenet and Braaten, PRD80, 034018
Large rapidity region

- $1.2 < |y| < 2.2$

<table>
<thead>
<tr>
<th></th>
<th>cross section (nb/GeV²)</th>
<th>Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHENIX</td>
<td>1.06±0.16</td>
<td>0.02±0.16</td>
</tr>
<tr>
<td>NRQCD</td>
<td>2.24±1.82</td>
<td>0.15±0.10</td>
</tr>
<tr>
<td>LO CSM</td>
<td>0.08±0.05</td>
<td>0.19±0.03</td>
</tr>
</tbody>
</table>

$s$-channel cut 

$|y| < 0.35$

$s$-channel cut CSM $1.2 < |y| < 2.2$

PHENIX, NPBA830, 227C (2009)
Conclusions

• Polarization problem of the prompt \( J/\psi \) at Tevatron has not been resolved.

• The first NRQCD predictions for the polarization of the prompt \( J/\psi \) at RHIC were presented.

• The color-octet mechanism in NRQCD may explain the production rate and polarization of the prompt \( J/\psi \) at RHIC if the color-octet matrix elements are not much suppressed.

• But, need to include NLO calculations.

• LHC experiments will provide another test ground for COM.
Backup slides
**$p_T$** distribution of prompt $J/\psi$ at RHIC

- For lower $p_T$, order-$\alpha_s$ 2→1 processes, its NLO contribution, and soft-gluon emissions must be taken into account.

For higher $p_T$, fragmentation evolution using DGLAP equations must be considered.
NLO corrections

LHC $\sqrt{s}=14$ TeV

Tevatron $\sqrt{s}=1.96$ TeV

$p_T^p \rightarrow a_S[1](c\bar{c}) \rightarrow J/\psi + X$

$\mu_R=\mu_F=\sqrt{(2m_c)^2 + p_T^2}$

$\frac{d\sigma}{dp_T}$ [mb/GeV]
Inclusive \( J/\psi \) production in \( \gamma \gamma \) collisions

\[ \gamma \gamma \rightarrow J/\psi + X \]

- Data are more than an order of magnitude larger than the predictions of the color-singlet model.
- Favor the color-octet mechanism.

Klase, Kniehl, Mihaila, Steinhause, PRL 89, 032001 (2002)
Inclusive $J/\psi$ production in $\gamma p$ collisions

$\gamma p \rightarrow J/\psi + X$

\[ z = \frac{P_N \cdot P_{J/\psi}}{P_N \cdot q_\gamma} \]

- the differential cross sections in $z$ and $P_T$ underestimate the data.

PArtoisenet, QWG'08
Inclusive $J/\psi$ production in $\gamma p$ collisions

$\gamma p \rightarrow J/\psi + X$

\[ \frac{d\sigma}{d\Omega dy} \propto 1 + \lambda(y) \cos^2 \theta + \mu(y) \sin \theta \cos \phi + \frac{\nu(y)}{2} \sin^2 \theta \cos \phi \]

- the longitudinal polarization at large $P_T$ is not seen in the data.
\[ e^+e^- \rightarrow J/\psi + X \]

- NLO corrections in \( \alpha_s \) to CSM were completed.

\[
\sigma(e^+e^- \rightarrow J/\psi + non(\bar{c}c)) = (0.43 + 0.09 + 0.09) \text{ pb}.
\]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
m_c (GeV) & \alpha_s (\mu) & \sigma^{(0)} (pb) & a(\hat{s}) & \sigma^{(1)} (pb) & \sigma^{(1)}/\sigma^{(0)} \\
\hline
1.4 & 0.267 & 0.341 & 2.35 & 0.409 & 1.20 \\
1.5 & 0.259 & 0.308 & 2.57 & 0.373 & 1.21 \\
1.6 & 0.252 & 0.279 & 2.89 & 0.344 & 1.23 \\
\hline
\end{array}
\]

\[ \mu = 2m_c \]

- Cross section of prompt \( J/\psi \) production is

\[
\begin{array}{|c|c|c|c|c|}
\hline
\mu = 2.8 \text{GeV} & \mu = 2.8 \text{GeV} & \mu = 5.3 \text{GeV} & \mu = 5.3 \text{GeV} \\
\text{LO} & \text{NLO} & \text{LO} & \text{NLO} \\
\hline
\sigma(gg) & 0.57 & 0.67 & 0.36 & 0.53 \\
\sigma(\bar{c}c) & 0.38 & 0.71 & 0.24 & 0.53 \\
R_{\bar{c}c} & 0.40 & 0.51 & 0.40 & 0.50 \\
\hline
\end{array}
\]

Gong, Wang, PRL102, 162003 (2009)

Ma., Zhang, Chao, PRL102, 162002 (2009)
Cross section of direct $\psi(2S)$ at the Tevatron

Lansberg, QWG’08

- a small gap at large $p_T$. 
## Summary

at NLO

<table>
<thead>
<tr>
<th></th>
<th>$pp$</th>
<th>$e^-p$</th>
<th>$e^-e^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>not enough</td>
<td>not enough</td>
<td>may explain</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>disagree</td>
<td>inconsistent at high $P_T$</td>
<td>—</td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>may be needed</td>
<td>may be needed</td>
<td>unnecessary?</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>not completed</td>
<td>not yet</td>
<td>—</td>
</tr>
</tbody>
</table>

- the CS contributions could not explain the data.
- room for the color-octet contributions?