Polarization for Prompt $J/\psi$ and $\psi(2s)$ production at the Tevatron and LHC

Jian-Xiong Wang
Institute of High Energy, Chinese Academy of Science, Beijing

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Based on our recent work: PRL110, 042002, 2013, ArXiv:1205.6682,
B. Gong, L. P. Wan, J. X. Wang and H. F. Zhang
1 Introduction

2 $J/\psi$ production at the Tevatron and LHC
   - QCD Correction to color-singlet $J/\psi$ production
   - QCD Correction to color-octet $J/\psi$ production

3 Summary
Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since b and c-quark is heavy.
- Clear signal to detect $J/\psi$.
- Heavy quarkonium production is a good place to testify these theoretical framework.
- $J/\psi$ photoproduction at HERA
- $J/\psi$ production at the B factories
- $J/\psi$ production and polarization at the Tevatron
- $J/\psi$ production at the LHC
- LO theoretical predication were given before more than 15 years
- NLO theoretical predications were given within last 5 years.
- It seems that the QCD NLO calculations can adequately describe the experimental data.
- But there are still many difficulties.
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]).
The cross section of $h$ hadroproduction is

$$\sigma[pp \to hx] = \sum \int d\lambda_1 d\lambda_2 G_p^i G_p^j \hat{\sigma}[ij \to (c\bar{c})_n x] \langle O_n^h \rangle, \quad (1)$$

where $p$ is either a proton or anti-proton, the indices $i, j$ run over all the partonic species and $n$ represents the $c\bar{c}$ intermediate states $(^3S_1, ^3S_{18}, ^1S_{08}, ^3P_{J8})$ for $J/\psi$ and $\psi'$, and $(^3P_{J1}, ^3S_{18})$ for $\chi_{cJ}$.

- double expansions in $\alpha_s$ and the heavy-quark velocity $v$.
- predication can be systematically improved with these two perturbative expansions.
- limited number of universal long-distance matrix elements to be extracted from experiment.
Introduction

In last five years, there were a few very important progresses in the next-to-leading Order (NLO) QCD correction calculation:

- QCD Correction to color-singlet $J/\psi$ production
- QCD Correction to color-singlet $J/\psi$ polarization
- QCD Correction to color-octet $J/\psi (1S_0^8, 3S_1^8)$ production and polarization
- QCD Correction to color-octet $J/\psi (1S_0^8, 3S_1^8, 3P_J^8)$ production
- QCD Correction to color-octet $J/\psi (1S_0^8, 3S_1^8, 3P_J^8)$ polarization
- QCD Correction to $\chi_cJ (3S_1^8, 3P_J^1)$ production

Before our work, there are:

- $p_t$ distribution of $J/\psi$ yield for prompt $J/\psi$ hadroproduction at QCD NLO
- $p_t$ distribution of $J/\psi$ polarization for direct $J/\psi$ hadroproduction at QCD NLO
- Feeddown of $\chi_cJ$ about 20 – 30% to prompt $J/\psi$ production and very important. Prompt: included the $J/\psi$ feeddown from excited charmonium state than direct production

We need:

- $p_t$ distribution of $J/\psi$ polarization for prompt $J/\psi$ hadroproduction at QCD NLO

We have finished this work and presented in a recent paper ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang
QCD Correction to color-singlet $J/\psi$ production

$P_t$ distribution of $J/\psi$ production at QCD NLO was calculated in \textit{PRL98,252002 (2007)}, J. Campbell, F. Maltoni F. Tramontano

Some technique problems must be solved to calculate $J/\psi$ polarization

$P_t$ distribution of $J/\psi$ polarization at QCD NLO was calculated in \textit{PRL100,232001 (2008)}, B. Gong and J. X. Wang
QCD Correction to color-singlet $\Upsilon$ production

$\Upsilon$ polarization drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO.

$P_t$ distribution of $\Upsilon$ polarization at QCD NLO was calculated with detail in PRD78 074011 (2008), B. Gong and J. X. Wang.

A new factorization scheme for $J/\psi$ hadron production

The main point is to extend the fragmentation factorization from: one-parton fragment into hadron
to: two-parton fragment into hadron
There will be more fragmentation function needed in this scheme.
NLO QCD corrections to $J/\psi$ production
via S-wave color octet states

3 tree processes at LO

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

At NLO

\[ (267, 413) \]

\[ (49, 111) \]

Real Correction (8 processes at NLO)

\[ gg \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] gg, \quad gg \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] q\bar{q}, \]
\[ gq \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] gq, \quad qq \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] gg, \]
\[ q\bar{q} \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] q\bar{q}, \quad q\bar{q} \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] q'\bar{q}', \]
\[ qq \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] qq, \quad qq' \rightarrow J/\psi \left[ \begin{array}{c} 1S_0^{(8)} \\ 3S_1^{(8)} \end{array} \right] qq'. \]
QCD Correction to $J/\psi(3S_1^1, 1S_0^8, 3S_1^8)$ production and polarization without $3P^8_j$ contribution

To fit the Tevatron $P_t$ distribution give more $\langle O^\psi_8(S_0) \rangle = 0.075$ GeV$^3$ and less $\langle O^\psi_8(S_1) \rangle = 0.0021$ GeV$^3$ than they are at LO fitting. The experimental data with $p_t < 6$ GeV have to abandon.

QCD Correction to prompt $J/\psi(^3S_1^1{}, ^1S_0^8, ^3S_1^8, ^3P_0^8)$ production without calculation of polarization
QCD Correction to $J/\psi(3S^1_1, 1S^0_0, 3S^8_1, 3P^8_j)$ production without calculation of polarization

PRL 106, 022003,2011, Mathias Butenschoen, Bernd A. Kniehl
QCD Correction to polarization of $J/\psi(1S_0^8, 3S_1^8, 3P_J^8)$ direct production
QCD Correction to polarization of $J/\psi(3S_1^1, 1S_0^8, 3S_1^8, 3P_1^8)$ direct production

ALICE data: Collins-Soper frame
- $\lambda_y(p_T)$
- $2.5 < y < 4$
- $\sqrt{s} = 7$ TeV
- $pp \to J/\psi + X$

ALICE data: Helicity frame
- $\lambda_y(p_T)$
- $2.5 < y < 4$
- $\sqrt{s} = 7$ TeV
- $pp \to J/\psi + X$

CDF data: Run I / II
- $\lambda_y(p_T)$
- $|y| < 0.6$
- $\sqrt{s} = 1.96$ TeV
- $pp \pm \to J/\psi + X$

PRL 108, 172002, 2012, Mathias Butenschoen, Bernd A. Kniehl
QCD Correction to prompt $J/\psi(3S^1_1, 1S^0_0, 3S^1_0, 3P^8_0)$ production

Figure: $p_t$ distribution of prompt $J/\psi$ and $\psi'$ hadroproduction. The CDF and LHCb data are taken in the fitting.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang
QCD Correction to $\psi'(3S_1^1, 1S_0^8, 3S_1^8, 3P_8^j)$ polarization

Figure: Polarization parameter $\lambda$ of $J/\psi'$ in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang
QCD Correction to $\chi_cJ(3P^1_J, \ 3S^8_1) \rightarrow J/\psi$ polarization

Figure: Polarization parameter $\lambda$ of $J/\psi$ in helicity(left) and CS(right) frames.

PRL1100420022013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang
QCD Correction to prompt $J/\psi(3S_1^1, 1S_0^8, 3S_1^8, 3P_1^8)$ polarization

**Figure:** Polarization parameter $\lambda$ of prompt $J/\psi$ hadroproduction in helicity(left) and CS(right) frames.

PRL110, 042002, 2013, ArXiv:1205.6682, Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang
QCD Correction to color-octet $\Upsilon(3S_1^1, 1S_0^8, 3S_1^8)$ production without $3P_J^8$ contribution

Summary

- For B-factories: NRQCD at NLO of $\alpha_s$ and $\nu$ can well describe $J/\psi$ production data.

- The prediction on the polarization of prompt $J/\psi$ hadroproduction is archived at QCD NLO, but polarization puzzle is still unclear.

- The more precision experimental measurements at LHC are needed to clarify the situation.

- More theoretical progresses are needed on relativistic coorection, .... to solve the polarization puzzle.

- For $\Upsilon$, ......
Thank you!