Review of heavy quarkonium production mechanism in $pp$ collisions from low to high $p_t$

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Overview

J/ψ polarization puzzle

Heavy quarkonia production at small $p_t$

Quarkonia production in proton-nucleus collisions

Summary
Overview

A good laboratory


- good features
  - Heavy enough for perturbative calculations
  - Clear signal
  - Simple structure

- $J/\psi$ suppression as a signature of quark-gluon plasma (QGP)\(^1\)
  - Hot-nuclear-matter (HNM) effects: $pA$ ($dA$) collisions
  - Cold-nuclear-matter (CNM) effects: $AA$ collisions

\(^1\)Matsui, Satz, PLB 178, 416 (1986)
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Overview

Colour-singlet Model (CSM)

- $\psi'$ ($J/\psi$) surplus
- IR divergence at LO: e.g. $h_c$ radiative decay

$^{2}$CDF Collaboration, PRL 69, 3704 (1992)
Overview

- Colour-evaporation Model (CEM)

- Poor agreement with $p_t$ spectrum of $\psi$ hadroproduction

- Wrong for ratio: e.g. $\sigma(\chi c_1) : \sigma(\chi c_2)$, $\sigma(\chi c) : \sigma(J/\psi)$

- Do not apply to polarization

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Schuler and Vogt, PLB 387, 181 (1996); ATLAS, NPB 850, 387 (2011)
Nonrelativistic QCD (NRQCD)\textsuperscript{5}

- Seperated scales $m_Q, m_Q v^2$
- $v^2 = 0.3$ for charmonium, $v^2 = 0.1$ for bottomonium
- Time scales: heavy quark pair fluctuation $\sim 1/m_Q$; hadronization $\sim 1/(m_Q v^2)$
- NRQCD Factorization (proof up to NNLO\textsuperscript{4})

$$d\sigma(H) = \sum_n df_n \langle \mathcal{O}^H(n) \rangle$$

- $f_n$: Short-distance coefficient (SDC): production of a heavy quark pair, to be calculated perturbatively
- $\langle \mathcal{O}^H(n) \rangle$: Long-distance matrix element (LDME): hadronization, to be extracted from experiment

\textsuperscript{4}Nayak, Qiu and Sterman, PRD 72, 114012 (2005)
\textsuperscript{5}Bodwin, Braaten and Lepage, PRD 51, 1125 (1995)
Overview

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Overview
Overview

NRQCD

- Expansion in $\nu$
  - $3S_1^{[1]}$, $1S_0^{[8]}$, $3S_1^{[8]}$ and $3P_J^{[8]}$ involved in $\psi$ ($\Upsilon$) production up to $O(\nu^4)$

- CSM and CEM are special cases
  - CSM: Colour-octet (CO) channels omitted
  - CEM: higher order in $\nu$ involved$^6$

- NRQCD tackled the weakness of CSM
  - IR divergences cancelled
  - NRQCD prediction for $\psi'$ hadroproduction

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$^6$Bodwin, Braaten and Lee, PRD 72, 014004 (2005)
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$J/\psi$ polarization puzzle

- LO NRQCD failed in the description of $\psi$ polarization\(^7\)

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

- high $p_t$ limit
  - dominant channel: $^3S_1^{[8]}$
  - dominant mechanism: gluon fragmentation $\rightarrow$ transversely polarized

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Review of heavy quarkonium production mechanism in pp collisions from low to high $p_t$ $J/\psi$ polarization puzzle

NLO era

NLO for CS$^8$ and CO$^9$

- CS: enhanced by one order, still far below the data
- $^1S_0^{[8]}$: $p_t^{-6} \rightarrow$ another small $p_t^{-4}$ part introduced
- $^3S_1^{[8]}$: almost unchanged
- $^3P_J^{[8]}$: positive $\rightarrow$ minus, $p_t^{-6} \rightarrow p_t^{-4}$

$$df(3P_J^{[8]}) = r_0 df(1S_0^{[8]}) + r_1 df(3S_1^{[8]})$$ (medium and high $p_t$, roughly)

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$^8$Campbell, Maltoni and Tranmontano, PRL 98, 252002 (2007)
P-wave states at NLO

- QCD corrections to s-wave LDMEs cancel the singularities in the SDCs
- $\chi_c$ production: $^3P_J^{[1]}$ and $^3S_1^{[8]}$ associated
- $J/\psi$ production: $^3P_J^{[8]}$, $^3S_1^{[8]}$ and $^3S_1^{[1]}$ associated
- Only the combination of the associated channels is divergence free and NRQCD scale ($\mu_\Lambda$) independent
Polarization at NLO

- Left\textsuperscript{10} (missing feeddown): Global fit, transversely polarized, bad agreement
- Middle\textsuperscript{11} (missing feeddown): $^1S_0^{[8]}$ dominance, agree with CDF Run II data
- Right\textsuperscript{12} (complete): agree with CDF Run I data, contradict CDF Run II data

Different fitting strategy $\rightarrow$ different LDMEs $\rightarrow$ different phenomenology

Three LDMEs to be determined, too many!

\textsuperscript{10} Butenschoen and Kniehl, PRL 108, 172002 (2012)
\textsuperscript{11} Chao, Ma, Shao, Wang and Zhang, PRL 108, 242004 (2012)
\textsuperscript{12} Gong, Wan, Wang and HFZ, PRL 110, 042002 (2013)
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J/$\psi$ polarization puzzle

$1S_0^{[8]}$ dominance picture faces challenge

Why $1S_0^{[8]}$ dominance?

- $p_t$ spectrum: NLO $1S_0^{[8]}$ similar to direct $J/\psi$
- Polarization: $1S_0^{[8]}$ unpolarized

Challenges

- Violate velocity scaling rule
- Violate $\eta_c$ hadroproduction data

$\sqrt{s} = 7$ TeV
LDMEs: Bodwin et al.

$\sqrt{s} = 7$ TeV
LDMEs: Chao et al.

$\sqrt{s} = 7$ TeV
LDMEs: Gong et al.

$\sqrt{s} = 7$ TeV
LDMEs: Butenschön et al.

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$^{13}$Butenschoen, He and Kniehl, PRL 114, 092004 (2015); LHCb, EPJC 75, 311 (2015)
$\eta_c$ and $J/\psi$ hadroproduction data reconciled

- $\eta_c$ data help to determine LDMEs, consistent with $J/\psi$ hadroproduction data\(^{14}\)

\(^{14}\)Han, Ma, Meng, Shao and Chao, PRL 114, 092005 (2015); HFZ, Sun, Sang and Li, PRL 114, 092006 (2015)
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$J/\psi$ polarization puzzle remains

- Bad agreement with $J/\psi$ polarization in midrapidity region
- $\sigma_T/\sigma_L$: 2.3 vs. 1.2

<table>
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<th>$p_t$ (GeV)</th>
<th>$\lambda$</th>
<th>$\sigma_T/\sigma_L$</th>
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<td>1</td>
<td>0</td>
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</tr>
</tbody>
</table>

- Tevatron $\sqrt{s} = 1.96$ TeV $|y| < 0.6$
- CDF Run I
- CDF Run II
- CMS data $\sqrt{s} = 7$ TeV $|y| < 0.6$
- NLO NRQCD

- Tevatron $\sqrt{s} = 1.96$ TeV $|y| < 0.6$
- CDF Run II
- CMS data $\sqrt{s} = 7$ TeV $|y| < 1.2$
- NLO NRQCD
Charmonia hadroproduction and polarization data reconciled\textsuperscript{15}

- New discovery in phenomenology 1)
  - The unique key parameter to govern the polarization:
    \[ R_{J/\psi} \equiv \langle O^{J/\psi}(3S_1^{[8]}) \rangle / \langle O^{J/\psi}(3P_0^{[8]}) \rangle \]
  - Equation to govern the yield: \[ \langle O^{\psi}(3S_1^{[8]}) \rangle = k_\psi \langle O^{\psi}(3P_0^{[8]}) \rangle + b_\psi \]
  - \( k_{J/\psi} = 0.367, \ b_{J/\psi} = 0.00348 \pm 0.00011 \text{GeV}^3, \ R_{J/\psi} = 0.546 \pm 0.006 \)
  - The polarization is extremely sensitive to \( R_{J/\psi} \)
  - narrow yield band \( \rightarrow \) huge polarization band

- Conclusion
  - Minimizing \( \chi^2 \) in the fit to yield data is not reasonable!
  - Yield data does not provide information for polarization!

\textsuperscript{15}Sun and HFZ, 1505.02675
Charmonia hadroproduction and polarization data reconciled

- **New discovery in phenomenology 2)**
  - $J/\psi$ polarization understood

- Relativistic corrections will improve CDF predictions
- $\psi(2s)$ polarization can also be understood
Charmonia hadroproduction and polarization data reconciled

- $J/\psi$ yield data can also be described
Review of heavy quarkonium production mechanism in \( pp \) collisions from low to high \( p_t \)

\( J/\psi \) polarization puzzle

\( \chi_c \), the best laboratory to test NRQCD

- Only one free parameter
- Good agreement with all the existing data\(^{16}\)

\[^{16}\text{Ma, Wang and Chao, PRD 83, 111503(R) (2011); Shao, Ma, Wang and Chao, PRL 112, 182003 (2014); HFZ, Yu, Zhang and Jia, 1410.4032 (2014)}\]
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Heavy quarkonia production at small $p_t$

Collins-Soper-Sterman (CSS) resummation

- $\Upsilon$: CSS+CEM\textsuperscript{17}

- $\Upsilon$ and $J/\psi$: CSS+NRQCD\textsuperscript{18}

\textsuperscript{17} Berger, Qiu and Wang, PRD 71, 034007 (2005)

\textsuperscript{18} Sun, Yuan and Yuan, PRD 88, 054008 (2013)
log(x) resummation is important for J/ψ

- Colour-singlet cross sections as a function of c.m. energy
- $d\sigma/dy$ is free of $\log^2(p_t/m_c)$, still negative cross sections
- The only large log: $\log(x)$
- $\Upsilon$ better than $J/\psi$

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$^{19}$Feng, Lansberg and Wang, EPJC 75, 313 (2015)
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**Colour Glass Condensate (CGC)**

- Dilute-dense approximation
  - $x > x_0$: dilute; $x < x_0$: dense
- Resum $\log(x)$
- JIMWLK evolution

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$^{20}$Mclerran and Venugopalan, PRD 49, 2233; 49, 3352; 50, 2225 (1994)
Review of heavy quarkonium production mechanism in pp collisions from low to high $p_T$. 

Bad agreement

MV$	ext{g}_{1118}^{\text{coll}}$ PHENIX pp

MV$	ext{g}_{1118}^{\text{coll}}$ ALICE pp

MV$	ext{g}_{1118}^{\text{coll}}$ LHCb pp

Fujii and Watanabe, NPA 915, 1 (2013)
Review of heavy quarkonium production mechanism in $pp$ collisions from low to high $p_t$
Heavy quarkonia production at small $p_t$

CGC+NRQCD$^{22}$

- Good agreement

- Not good in midrapidity region at low energy where dilute-dense approximation is ruined (HFZ)

$^{22}$Kang, Ma and Venugopalan, JHEP 1401, 056 (2013); Ma and Venugopalan, PRL 113, 192301 (2014)
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Quarkonia production in proton-nucleus collisions

\( J/\psi \) production in \( pA \) collisions at high \( p_t^{24} \)

- EPS09 employed\(^{23}\)
- \( p_t \) spectrum

\[ \begin{align*}
\text{\( y \) distribution} \\
\text{\( d\sigma/d\gamma (\text{nb}) \)}
\end{align*} \]

\(^{23}\) Eskola, Paukkunen and Salgado, JHEP 0904, 065 (2009)
\(^{24}\) HFZ and etc., in preparation
Two free parameters: $Q_{s0,A}$ and $R_A$

$Q_{s0,A}^2 = N \times Q_{s0,p}^2$

- $N \approx 3$ for $\gamma = 1.113$; $N \approx 1.5$ for $\gamma = 1$
- We set $\gamma = 1$, $N = 2$ as a tentative choice

$R_{pA} \equiv \frac{d\sigma_{pA}}{A \times d\sigma_{pp}}$

- $R_{pA} \rightarrow R_A^2 \frac{Q_{s0,A}^2}{Q_{s0,p}^2}$ (high $p_t$)
- $R_{pA} \rightarrow 1$ at high $p_t$, a natural assumption to determine $R_A$

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$^{25}$Ma, Venugopalan and HFZ, 1503.07772 (2015)
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Quarkonia production in proton-nucleus collisions

\( J/\psi \) production in \( pA \) collisions

\( p_t \) spectrum

\[ p_t \text{ spectrum} \]

\[ d\sigma_{NN}/dp_t \text{ (mb/GeV)} \]

\[ p_t \text{ (GeV)} \]

\( y \) distribution

\[ d\sigma_{NN}/dy \text{ (nb)} \]

\[ y \]

[Graphs showing the \( p_t \) and \( y \) distributions for different energy scales and models, including LHCb and RHIC data.]
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Quarkonia production in proton-nucleus collisions

\( J/\psi \) suppression

- \( R_{pA} \) as a function of \( p_t \)

\[ R_{pA} \text{ as a function of } p_t \]

- \( R_{pA} \) as a function of \( y \)

\[ R_{pA} \text{ as a function of } y \]
NRQCD can describe both $\psi$ production and polarization

Minimizing $\chi^2$ is not appropriate in the determination of the LDMEs

Small-$x$ resummation is required in small $p_t$ region

CGC+NRQCD provide good description of both $pp$ and $pA$ data

pQCD+NRQCD can describe the high-$p_t$ $J/\psi$ production data in $pA$ collision
Thanks!