Quarkonium production and polarization

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Overview

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Quarkonia: bound states of $c\bar{c}$ or $b\bar{b}$

- combination of two spin 1/2 particles and orbital angular momentum $\rightarrow$ different spin states $2S+1 L_J$

- all color singlets $2S+1 L_J [1]$

- produced in $hh$, $\gamma p$, $\gamma\gamma$, and $e^+ e^-$

- states below the $H\bar{H}$ ($H = D, B$) threshold decay electromagnetically into $\ell^+ \ell^-$
Some Production Diagrams in Different Systems

\( hh \) (RHIC, Tevatron, LHC)

\( \gamma p \) (HERA)

\( \gamma \gamma \) (LEP)

\( e^+e^- \) (KEKB)
S states ($J^{PC} = 1^{--}$) decay to $\ell^+\ell^-$, so they can be observed as peaks in dimuon mass spectra.

$\chi(nP)$ states ($J^{PC} = J^{++}$) can be reconstructed by matching an S state with a low momentum photon.

$\eta_c$ and $\eta_b$ states ($J^{PC} = 0^{--}$) decay hadronically.
Polarization

- The tendency for quarkonium states of spin $J$ to be in a particular $|J, J_z\rangle$ state is known as polarization

- For $S$ state ($J = 1$) quarkonium, if $J_z = 0$, then it is longitudinally polarized

- If $J_z = \pm 1$, then it is transversely polarized

- It is typical to represent the polarization in terms of the polarization parameter, $\lambda_\vartheta$, which ranges from -1 to +1

- For the $S$ states, $\lambda_\vartheta = -1$ refers to pure longitudinal production while $\lambda_\vartheta = +1$ refers to pure transverse production

\[ J^P = 1^- \text{ (S states)}^{[1]} \]

\[
\lambda_\vartheta = \frac{\sigma_{J_z=+1} + \sigma_{J_z=-1} - 2\sigma_{J_z=0}}{\sigma_{J_z=+1} + \sigma_{J_z=-1} + 2\sigma_{J_z=0}}
\]

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Polarization

- For the $\chi_1$ ($J = 1$) and $\chi_2$ ($J = 2$) states, the polarization parameter is defined as the polarization parameter of the product $J/\psi$ or $\Upsilon(nS)$ if production comes purely from $\chi$ state feed down.

- $\chi_c \rightarrow J/\psi + \gamma$, $\chi_b \rightarrow \Upsilon(nS) + \gamma$

$J^P = 1^+$ ($\chi_1$ P states)$^2$

$$\lambda_\vartheta = \frac{2\sigma_{J_z=0} - \sigma_{J_z=+1} - \sigma_{J_z=-1}}{2\sigma_{J_z=0} + 3\sigma_{J_z=+1} + 3\sigma_{J_z=-1}}$$

$J^P = 2^+$ ($\chi_2$ P states)$^2$

$$\lambda_\vartheta = \frac{-6\sigma_{J_z=0} - 3\sigma_{J_z=+1} + 6\sigma_{J_z=+2} - 3\sigma_{J_z=-1} + 6\sigma_{J_z=-2}}{10\sigma_{J_z=0} + 9\sigma_{J_z=+1} + 6\sigma_{J_z=+2} + 9\sigma_{J_z=-1} + 6\sigma_{J_z=-2}}$$

There are three commonly used choices for the $z$-axis, namely $z_{HX}$ (helicity), $z_{CS}$ (Collins-Soper), and $z_{GJ}$ (Gottfried-Jackson).

$\theta$ is defined as the angle between the $z$-axis and the direction of travel for the $\ell^+$ in the quarkonium rest frame.
Extracting Polarization

\[
\frac{d\sigma}{d\Omega} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta) \cos \phi
\]

- Polarization parameters can be obtained by fitting the angular spectra as a function of \( \theta \) and \( \phi \)
- One can write \( \phi_\theta = \phi - \frac{\pi}{2} \mp \frac{\pi}{4} \) for \( \cos \theta \leq 0 \), then \(^3\)
- \[
\frac{d\sigma}{d\phi_\theta} \propto 1 + \frac{\sqrt{2}\lambda_{\theta\phi}}{3+\lambda_\theta} \cos \phi_\theta
\]

Importance of Polarization

- Polarization predictions are strong tests of production models
- Detector acceptance depends on polarization hypothesis
- Understanding polarization helps narrow systematic uncertainties

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Quarkonium Production Models

Still unsettled

- $J/\psi$ and $\Upsilon$ are discovered in 1974 and 1977 respectively
- The quarkonium production mechanism has not been solved
- Current models cannot describe yield and polarization simultaneously

Color Singlet Model (CSM) [Berger, Jones 81; Baier, Rückl 81]

- constrains the production of $c\bar{c}$ to the color singlet state only
- calculated up to $O(\alpha_s^4)$
Quarkonium Production Models

Non Relativistic QCD (NRQCD) [Bodwin, Braaten, Lepage 95]

- an Effective Field Theory where production is described as an expansion in powers of $\alpha_s$ and the relative velocity of the quarks, $v/c$

$$|\psi_Q\rangle = \mathcal{O}(1)|3S_1^{[1]}\rangle + \mathcal{O}(v)|3P_j^{[8]}g\rangle + \mathcal{O}(v^2)|3S_1^{[8]}gg\rangle + \mathcal{O}(v^2)|1S_0^{[8]}g\rangle$$

- At each order, the production is further factorized into perturbative Short Distance Coefficients and non-perturbative Long Distance Matrix Elements (LDMEs); e.g. for $J/\psi$, $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle O_{J/\psi}[n]\rangle$

- $\sigma_{c\bar{c}[n]}$ are cross sections in a particular color and spin state $n$ calculated by perturbative QCD

- $\langle O_{J/\psi}[n]\rangle$ are the LDMEs that describe the conversion of $c\bar{c}[n]$ state into final state $J/\psi$, assuming that the hadronization does not change the momentum

- LDMEs are conjectured to be universal and the mixing of LDMEs are determined by fitting to data
Quarkonium Production Models

Color Evaporation Model (CEM) [Fritzsch 77; Halzen 77; Glück, Owens, Reya 78; Gavai et al. 95; Schuler, Vogt 95]

Leading order cross section:

\[
\sigma = F_Q \sum_{i,j} \int_{4m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) \delta(\hat{s} - x_1 x_2 s),
\]

\( F_Q \) is a universal factor for the quarkonium state \( Q \) and is independent of the projectile, target, and energy.

- all Quarkonium states are treated like \( Q\bar{Q} (Q = c, b) \) below \( HH \) (\( H = D, B \)) threshold
- all diagrams for \( Q\bar{Q} \) production included, independent of color
- fewer parameters than NRQCD (one \( F_Q \) for each Quarkonium state)
- \( F_Q \) is fixed by comparison of NLO calculation of \( \sigma_Q^{CEM} \) to \( \sqrt{s} \) for \( J/\psi \) and \( \Upsilon \), \( \sigma(x_F > 0) \) and \( Bd\sigma/dy|_{y=0} \) for \( J/\psi \), \( Bd\sigma/dy|_{y=0} \) for \( \Upsilon \)
Quarkonium Production Models

Improved CEM (ICEM) [Ma, Vogt 16]

\[
\frac{d\sigma_\psi(P)}{dp_T} = F_\psi \int_{M_\psi}^{2M_D} dM \frac{M}{M_\psi} \frac{d\sigma_{c\bar{c}}(M, P')}{dM dp_T} \bigg|_{p_T=(M/M_\psi)p_T}
\]

\(M_\psi\) is the mass of the charmonium state, \(\psi\)

- first new advance in the basic CEM model since 1990s
- able to describe relative production of \(J/\psi\) and \(\psi(2S)\), where the ratio is flat in the traditional CEM
- distinction between the momentum of the \(c\bar{c}\) pair and that of charmonium so that the \(p_T\) spectra will be softer and thus may explain the high \(p_T\) data better
- employed to calculate production and polarization of all S states, and relative production of \(\chi\) states
Results in the CSM

Fragmentation:

- Leading order calculations at $O(\alpha_s^3)$ underestimate the Tevatron $p_T$ distributions
- Gluon fragmentation to $J/\psi$ is required to increase cross section to match data $[6,7]$ (effectively $\alpha_s^4$)
- only works with the $J/\psi$ (sometimes)

Disagreement with other data in the CSM

\( \psi(2S) \) at CDF (PLB 333, 548 (1994).) \quad \Upsilon(1S) \) at CDF (PRL 88, 161802 (2002).)

\( \frac{J}{\psi} \) at LEP2 (PLB 565, 76 (2003).) \quad \frac{J}{\psi} \) at ZEUS (EPJC 27, 173 (2003).)
Results in NRQCD - A global fit of LDMEs

$hh \ (p_T > 3 \ \text{GeV})$

$\gamma p \ (p_T > 3 \ \text{GeV})$

$\gamma\gamma \ (\text{Right: } p_T > 1 \ \text{GeV})$

$e^+e^-$

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Relative production in NRQCD

- $\psi(2S)$ to $J/\psi$ ratio agrees with data at most $p_T$ \[^{[10]}\]
- relative production of $\chi_c$ and $\chi_b$ are dominated by CSM contribution \[^{[11]}\]

\( \eta_c \) production in NRQCD


- all results so far overpredict LHCb \( \eta_c \) yields
- results can be described by CSM alone
- PRL 114, 092005 (2015) and PRL 114, 092006 (2015) describe the \( \eta_c \) results but not the \( J/\psi \) polarization
Results in the CEM\textsuperscript{[12]}

- one fitting factor for each quarkonium state
- great consistency with experimental results over large range of $\sqrt{s}$

\[ J/\psi \quad \sum \Upsilon \text{'s} \]

Results in the CEM\textsuperscript{[12,13]}

- overall less rigorous, but accurate predictions
- no advances in the basic model since 1990s

Results in the ICEM

\[
\frac{d\sigma_\psi(P)}{dp_T} = F_\psi \int_{M_\psi}^{2M_D} \frac{M}{dM} \frac{d\sigma_{c\bar{c}}(M, P')}{dp_T} \left| p'_T = (M/M_\psi) p_T \right|
\]


- explicit charmonium mass dependence \( \rightarrow \) the ratio of cross sections is no longer \( p_T \)-independent
- distinction between the momentum of the \( c\bar{c} \) pair and that of charmonium \( \rightarrow \) \( p_T \) spectra will be softer and thus may explain the high \( p_T \) data better
Relative production in the ICEM\cite{14,15}

\begin{align*}
\frac{d\sigma}{dp_T} \approx \frac{\sigma}{d}
\end{align*}

\begin{align*}
2 < y < 4.5
= 8 \text{ TeV s}, \quad b_{\chi} \rightarrow p+p
\end{align*}

\begin{align*}
14 \quad & \text{Y. Q. Ma and R. Vogt, Phys. Rev. D 94, 114029 (2016).} \\
\end{align*}
$J/\psi$ polarization problem in NRQCD\textsuperscript{[16]}

Included in fits

- $e^+e^-$
- ep

Butenschon & Kniehl

- $p_T > 3$ GeV

Gong et al.

- $p_T > 5$ GeV

Chao et al.

- $p_T > 7$ GeV

$\Upsilon(nS)$ Polarization in NRQCD


- polarization of $\Upsilon(nS)$ is better described than for $J/\psi$
- polarization prediction in NRQCD is improved by including the feed down decays from $\chi_b$ states (bottom row)
Polarization in the $k_T$-factorized ICEM\cite{15}

Feed-down production:

$$R_{J/\psi} = \sum_{Q,J_z} c_Q S_Q^J R_Q^J$$

Polarization of prompt $J/\psi$:

$$\lambda_{J/\psi} = \frac{1 - 3 R_{J/\psi}^{J_z=0}}{1 + R_{J/\psi}^{J_z=0}}$$

Polarization is independent of $F_Q$ and scales, mass is the only uncertainty.

- Charmonium is slightly longitudinally polarized in the CS frame.
- Bottomonium is nearly unpolarized in all frames.

## Comparison of Models

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Future

**NRQCD**
- Are the LDMEs universal?
- Can NRQCD describe $\eta_c$ and $J/\psi$ without breaking $J/\psi$ polarization and results from other experiments?

**ICEM**
- Consider more collision systems
- NLO in collinear factorization