J/ψ production in $e + p$ collisions in the improved color evaporation model

Vincent Cheung

Nuclear Data and Theory Group,
Nuclear and Chemical Sciences Division,
Lawrence Livermore National Laboratory

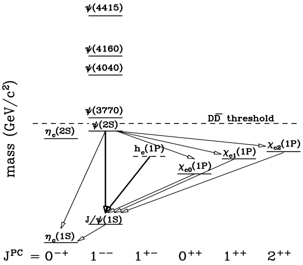
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics (Nuclear Theory) under contract number DE-SC-0004014, and the LLNL-LDRD Program under Project No. 21-LW-034.

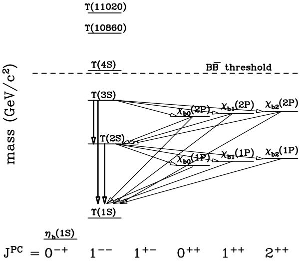
Jul 18, 2022

Lawrence Livermore National Laboratory

Overview

Quarkonium Families





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

- combination of two spin 1/2 particles with orbital angular momentum $\rightarrow$ different spin states ${}^{2S+1}L_J$
- all color singlets ${}^{2S+1}L_J{}^{[1]}$
- produced in hh, γp, $\gamma\gamma$, and e^+e^-
- S states below the $H\overline{H}$ ($H = D, B$) threshold decay electromagnetically into $\ell^+\ell^-$

Polarization and Angular Distribution

$$|\psi\rangle = a_{-1}\,|J_z=-1\rangle + a_0\,|J_z=0\rangle + a_{+1}\,|J_z=+1\rangle, \qquad \sum |a_{J_z}|^2 = 1$$

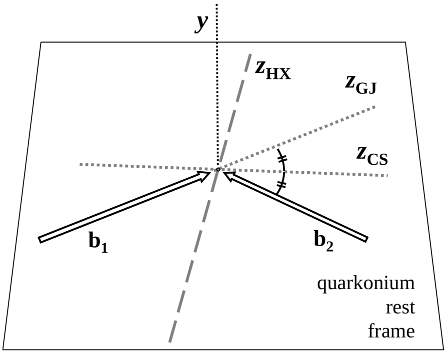
$$\lambda_\vartheta = \frac{1-3|a_0|^2}{1+|a_0|^2}, \qquad \lambda_\varphi = \frac{2Re[a_{+1}a^*_{-1}]}{1+|a_0|^2}, \qquad \lambda_{\vartheta\varphi} = \frac{\sqrt{2}Re[a_0^*(a_+ - a_-)]}{1+|a_0|^2}$$

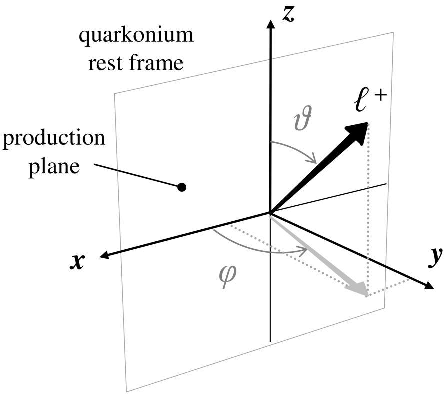
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{3+\lambda_\vartheta}\left[1 + \lambda_\vartheta\cos^2\vartheta + \lambda_\varphi\sin^2\vartheta\cos(2\varphi) + \lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi\right]$$

- For a single elementary process, the polarized-to-total cross section can be calculated as a_{J_z}'s. Combinations of a_{J_z}'s gives different angular distributions.
- However, there is no combination that would give $\lambda_\vartheta = \lambda_\varphi = \lambda_{\vartheta\varphi} = 0$.
- An unpolarized production can only be described by a mixture of sub-processes or randomization modeling.

Pietro Faccioli, QWG 2010.

Polarization Measurement



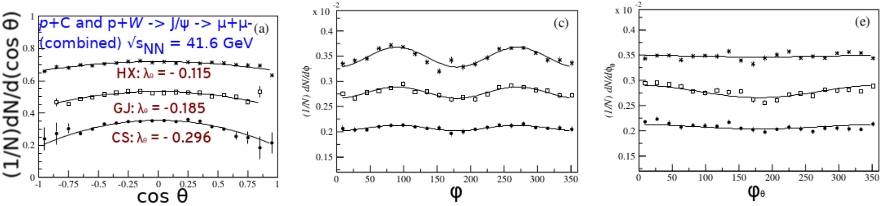


- There are three commonly used choices for the z-axis, namely z_{HX} (helicity), z_{CS} (Collins-Soper), and z_{GJ} (Gottfried-Jackson)
- ϑ is defined as the angle between the z-axis and the direction of travel for the ℓ^+ in the quarkonium rest frame

Extracting Polarization

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{3+\lambda_\vartheta}[1+\lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta\cos(2\varphi) + \lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi]$$

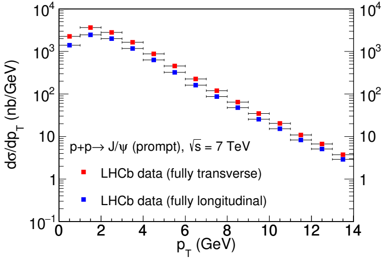
- Polarization parameters can be obtained by fitting the angular spectra as a function of ϑ and φ
- One can write $\varphi_\vartheta = \varphi - \frac{\pi}{2} \mp \frac{\pi}{4}$ for $\cos\vartheta \lessgtr 0$, then[1]
- $\frac{d\sigma}{d\varphi_\vartheta} \propto 1 + \frac{\sqrt{2}\lambda_{\vartheta\varphi}}{3+\lambda_\vartheta}\cos\varphi_\vartheta$



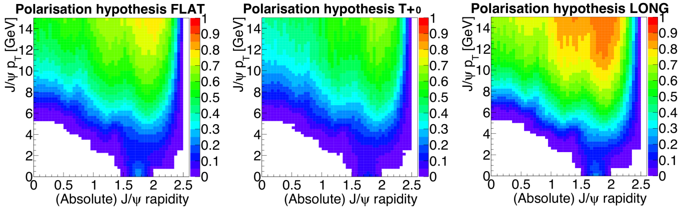
[1] I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

Importance of Polarization

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



[2]



[3]

[2] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **71**, 1645 (2011).
[3] G. Aad *et al.* (ATLAS Collaboration), Nucl. Phys. B **850**, 387 (2011).

Quarkonium production at the EIC

Why quarkonia?

- large mass of quarkonia ($m_{\mathcal{Q}} > \Lambda_{\mathrm{QCD}}$) allows perturbative expansion
- Quarkonium production mechanism is not fully understood yet.
- Studying quarkonium production in $e + p$ and $e + A$ collisions may settle the debate

Quarkonium Polarization Puzzle

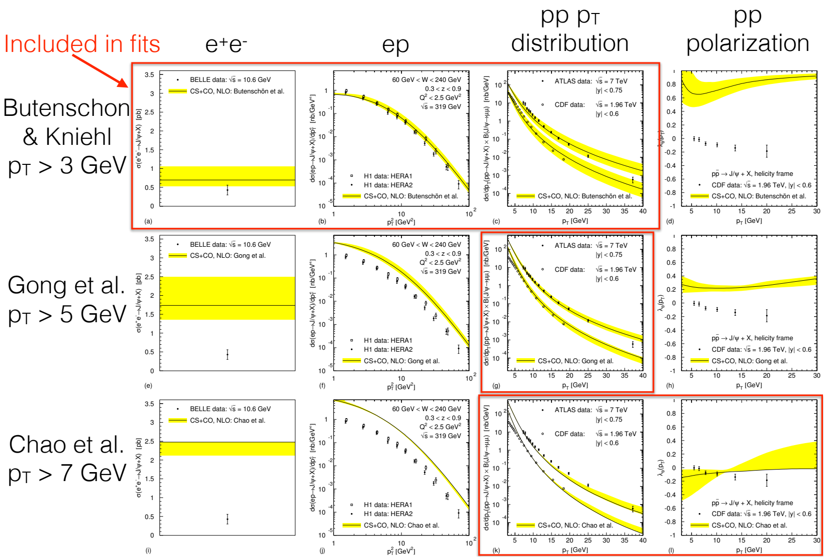
Quarkonium Polarization Puzzle

- mechanism of producing quarkonium has not yet been understood
- non-relativistic QCD (NRQCD), a common method to calculate quarkonium production, has difficulties describing yield and polarization simultaneously with a low-p_T cut

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

- e.g. for J/ψ, $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$
- both color singlet term $n = {}^3S_1^{[1]}$ and color octet terms ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$, and ${}^3P_J^{[8]}$ contributes to the production
- mixing of Long Distance Matrix Elements (LDMEs $= \langle \mathcal{O}^{J/\psi}[n] \rangle$) are determined by fitting to data, usually p_T distributions above some p_T cut

Polarization Puzzle[4]



[4]N. Brambilla *et al.*, Eur. Phys. J. C **74**, 2981 (2014)

The Improved Color Evaporation Model (ICEM)

[Ma, Vogt (PRD **94**, 114029 (2016).)]

$$\sigma = F_{\mathcal{Q}} \sum_{i,j} \int_{M_\psi}^{2m_H} dM \int dx_i dx_j f_i(x_i,\mu_F) f_j(x_j,\mu_F) d\hat{\sigma}_{ij\to c\bar{c}+X}(p_{c\bar{c}},\mu_R)|_{p_{c\bar{c}}=\frac{M}{M_\psi}p_\psi},$$

where M_ψ is the mass of the charmonium state, ψ.

- all Quarkonium states are treated like $Q\overline{Q}$ ($Q = c, b$) below $H\overline{H}$ ($H = D, B$) threshold
- all diagrams for $Q\overline{Q}$ production included, independent of color
- able to describe relative production of ψ(2S) to J/ψ
- fewer parameters than NRQCD (one $F_{\mathcal{Q}}$ for each Quarkonium state)
- 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
- $F_{\mathcal{Q}}$ is fixed by comparison of NLO calculation of $\sigma_{\mathcal{Q}}^{CEM}$ to $\sqrt{s}$ for J/ψ and Υ, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for J/ψ, $Bd\sigma/dy|_{y=0}$ for Υ

Hadroproduction in Collinear ICEM at $\mathcal{O}(\alpha_s^3)$[5]

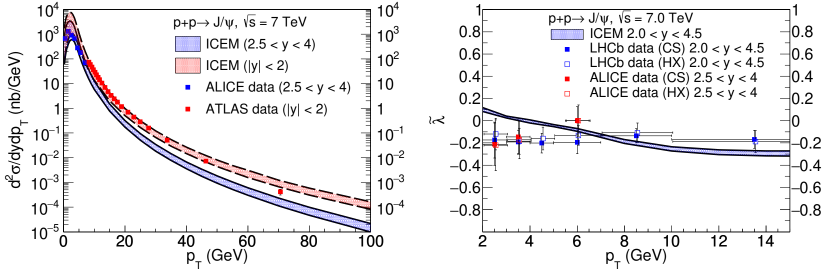
Production distribution

$$\frac{d^2\sigma}{dp_T dy} = F_{\mathcal{Q}} \sum_{i,j=\{q,\bar{q},g\}} \int_{M_{\mathcal{Q}}}^{2m_H} dM_\psi \int d\hat{s} dx_1 dx_2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) d\hat{\sigma}_{ij\to c\bar{c}+X} \ ,$$

- We consider all 16 diagrams from gg$\to$ c$\bar{c}$g, 5(+5) from gq($\bar{q}$)$\to$ c$\bar{c}$ q($\bar{q}$), and 5 from q$\bar{q}\to$ c$\bar{c}$g with the projection operator applied at the diagram level.
- The c$\bar{c}$ produced are the proto-J/ψ before hardonization.
- We used the CT14 PDFs in our calculations.
- k_T-smearing is applied to the initial state partons to provide better description at low p_T
- First p_T-dependent polarization results using collinear factorization
- $1.18 < m_c < 1.36$ GeV, $\mu_F/m_T = 2.1^{+2.55}_{-0.85}$, $\mu_R/m_T = 1.6^{+0.11}_{-0.12}$
- same set of variations used in MV (2016) and NVF [PRC **87**, 014908 (2013)]

[5] V. Cheung and R. Vogt, PRD 104, 094026 (2021).

Hadroproduction Results in ICEM[5]



- The frame-invariant polarization parameter $\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$
- Comparing the frame-invariant polarization paremeter removes frame-induced kinematic dependencies
- We find agreement with the invariant polarization at LHCb[6]
- p_T distributions agree with data and previous ICEM calculations [MV (2016)].

[6] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **73**, 2631 (2013).

Photoproduction in ICEM at $\mathcal{O}(\alpha\alpha_s^2)$[6]

Production distribution

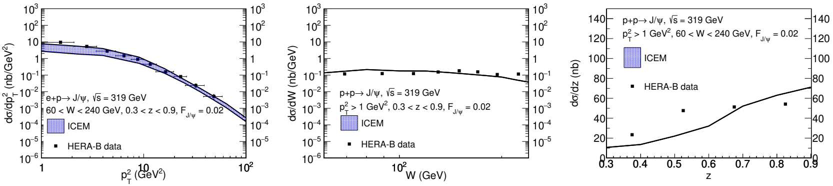
$$\frac{d^2\sigma}{dp_T^2 dW^2 dz} = F_{\mathcal{Q}} \sum_{i,j=\{q,\bar{q},g\}} \int_{M_{\mathcal{Q}}}^{2m_H} dM_\psi \int dy dx_2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) d\hat{\sigma}_{ij\to c\bar{c}+X} \,,$$

- We consider all 8 diagrams from $\gamma g \to c\bar{c}g$ channel
- The $c\bar{c}$ produced are the proto-J/ψ before hardonization.
- We used the CT14 PDFs and Weizsacker-Williams Approximation in our calculations.
- k_T-smearing is applied to the hadronic initial state partons
- First photoproduction results in the ICEM
- $1.18 < m_c < 1.36$ GeV, $\mu_F/m_T = 2.1^{+2.55}_{-0.85}$, $\mu_R/m_T = 1.6^{+0.11}_{-0.12}$
- Preliminary results are compared to low Q^2 measurements

[6] V. Cheung and R. Vogt, in progress.

Photoproduction Results in ICEM[6]

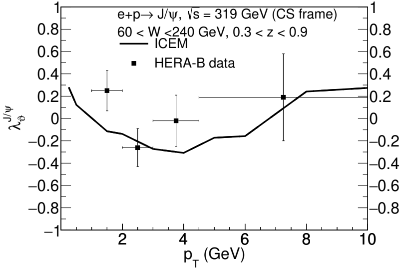
$W^2 = (q+p)^2$, $z = (p_\psi \cdot p)/(q \cdot p)$

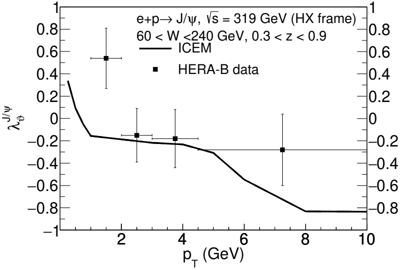


- Our preliminary results find agreement with the p_T and W distribution at HERA[7],
- and fair agreement with the z distribution.
- The fit parameter in the model, $F_{\mathcal{Q}}$, is about 2%, consistent with previous CEM results in hadroproduction.

[7] F. D. Aaron *et al.* (H1 Collaboration), Eur. Phys. J. C **68**, 401-420 (2010).

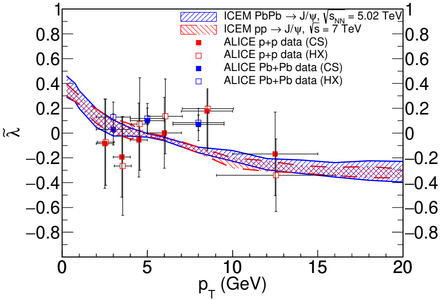
Photoproduction Results in ICEM[6]





- In the CS frame, the polarization is slightly transverse at low p_T, then slightly longitudinal at moderate p_T, and becomes slightly transverse again as p_T grows.
- In the HX frame, the polarization is transverse at low p_T, then becomes longitudinal as p_T grows.
- These trends from our preliminary results are consistent with the HERA-B data[7]

Investigating Nuclear Effects in the Future



- In the ICEM, some cold nuclear effects have been introduced to extend from proton projectile to an ion projectile, including
- enhanced k_T-broadening and
- nuclear modifications
- In hadroproduction[8], we find these nuclear effects affect the production but not the polarization.

[8]V. Cheung and R. Vogt, PRC 105, 055202 (2022).

Conclusion and Future

In this talk, I

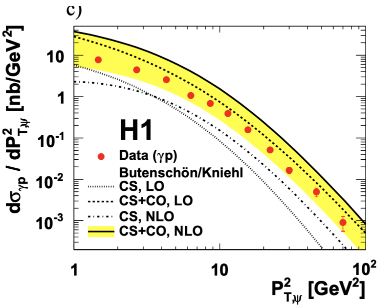
- showed the latest attempt to J/ψ production in $e+p$ collisions in the ICEM

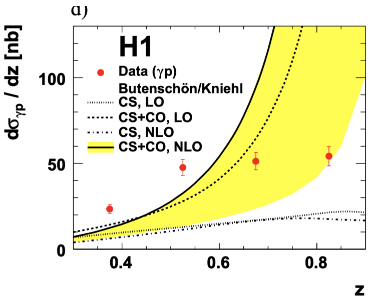
In the future, we will

- investigate the effect from feed down contributions
- investigate nuclear matter effects in $e+A$ collisions
- calculate the production using the small-x framework

Backup Slides

NRQCD Global Fit[9]

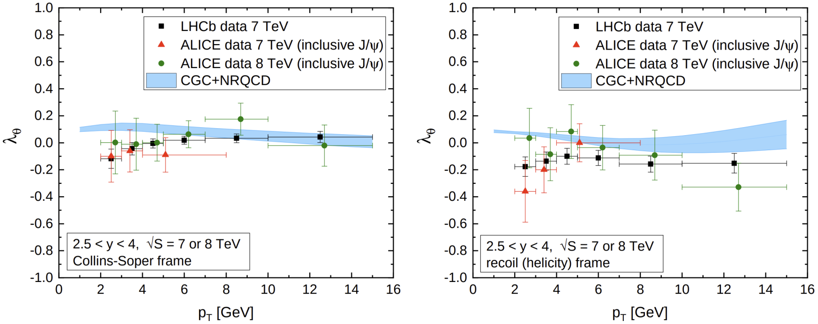




9Butenschoen and Kniehl, PRD 84, 051501 (2011).

CGC+NRQCD[10]

- is a solution to the polarization puzzle where gluon distribution is calculated using CGC and the conversion of $Q\bar{Q}$ is described by NRQCD formulation
- able to describe all polarization parameters for $p_T < 15$ GeV



[10]Y. Q. Ma, T. Stebel, R. Venugopalan, JHEP12 (2018) 057.