Production and polarization of J/ψ to $\mathcal{O}(\alpha_s^3)$ in the improved color evaporation model

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Overview

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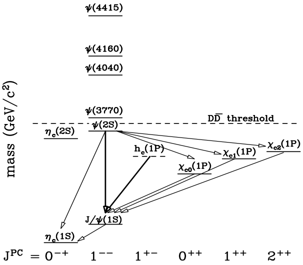
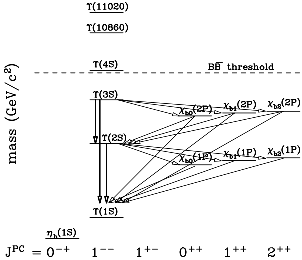
   - Polarization
   - The Polarization Puzzle
2. ICEM Approach
   - Unpolarized Yield
   - Polarization Parameters
   - Invariant Polarization Parameters
3. Conclusion and Future

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

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

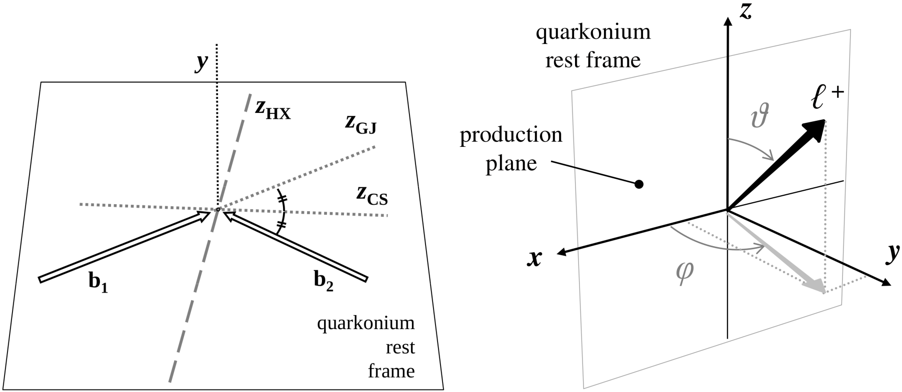
$$\lambda_\vartheta = \frac{1-3|a_0|^2}{1+|a_0|^2}, \qquad \lambda_\varphi = \frac{2Re[a_{+1}a^*_{-1}]}{1+|a_0|^2}, \qquad \lambda_{\vartheta\varphi} = \frac{\sqrt{2}Re[a_0^*(a_+ - a_-)]}{1+|a_0|^2}$$

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

- 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

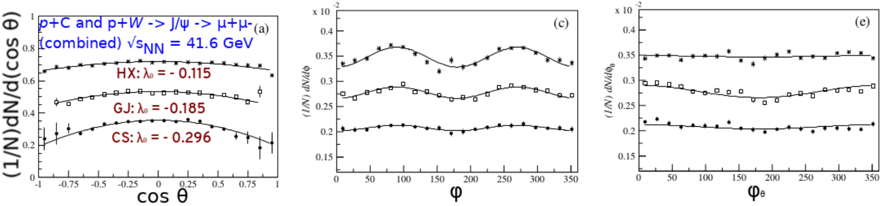


- There are three commonly used choices for the z-axis, namely z_{HX} (helicity), z_{CS} (Collins-Soper), and z_{GJ} (Gottfried-Jackson)
- ϑ is defined as the angle between the z-axis and the direction of travel for the ℓ^+ in the quarkonium rest frame

Extracting Polarization

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

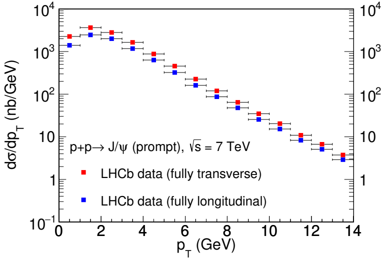
- Polarization parameters can be obtained by fitting the angular spectra as a function of ϑ and φ
- One can write $\varphi_\vartheta = \varphi - \frac{\pi}{2} \mp \frac{\pi}{4}$ for $\cos\vartheta \lessgtr 0$, then[1]
- $\frac{d\sigma}{d\varphi_\vartheta} \propto 1 + \frac{\sqrt{2}\lambda_{\vartheta\varphi}}{3+\lambda_\vartheta}\cos\varphi_\vartheta$



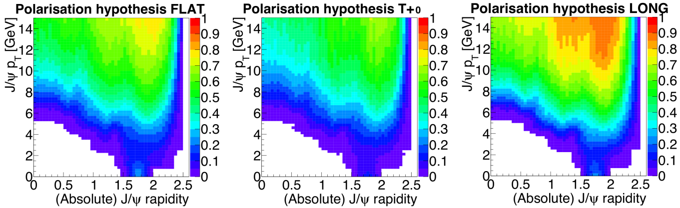
[1] I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

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 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

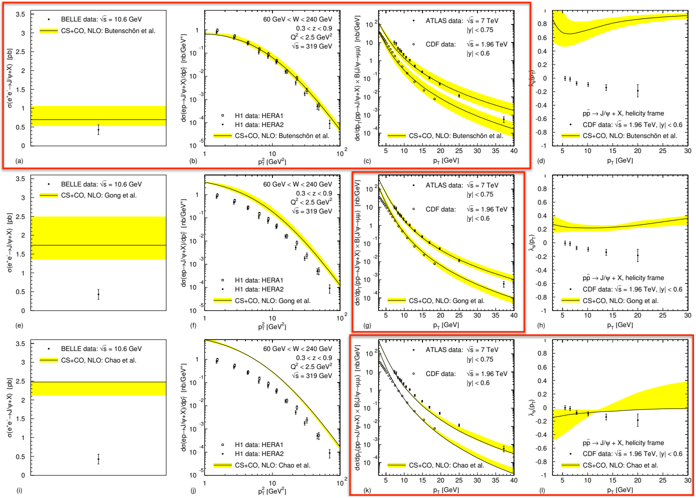
Included in fits

e+e-, ep, pp p_T distribution, pp polarization

Butenschon & Kniehl $p_T > 3$ GeV

Gong et al. $p_T > 5$ GeV

Chao et al. $p_T > 7$ GeV



[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

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

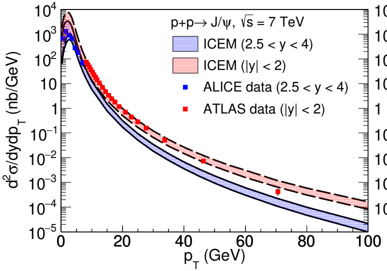
Production distribution

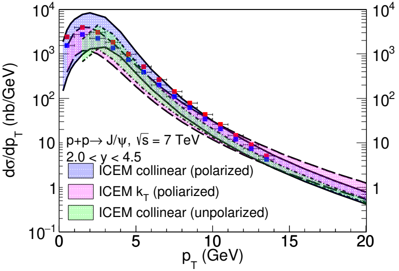
$$\frac{d^2\sigma}{dp_T dy} = F_{\mathcal{Q}} \sum_{i,j=\{q,\bar{q},g\}} \int_{M_{\mathcal{Q}}}^{2m_H} dM_\psi \int d\hat{s} dx_1 dx_2 f_{i/p}(x_1,\mu^2) f_{j/p}(x_2,\mu^2) d\hat{\sigma}_{ij\to c\bar{c}+X} \ ,$$

- 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 (accepted).

Collinear ICEM Unpolarized Cross Sections[5]

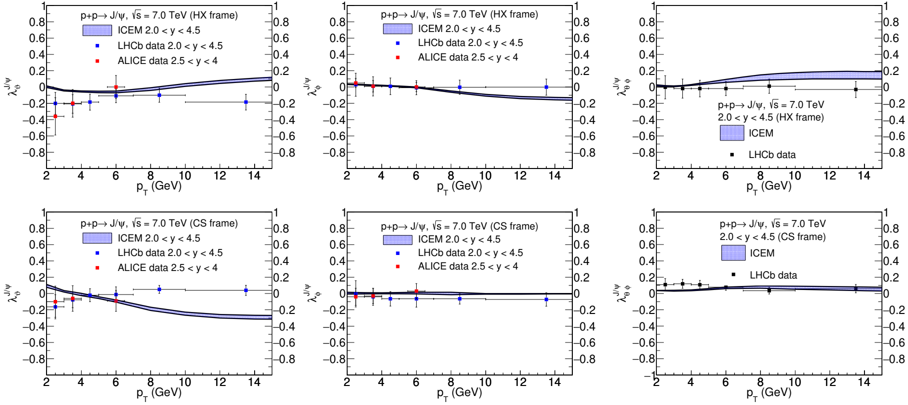




- k_T-smearing gives a small kick $< k_T^2 > \sim 1$ GeV^2 to the inital state parton.
- The uncertainty band[5] is constructed by varying the charm quark mass, factorization scale, and renormalization scale.
- We find agreement with the p_T-distribution measured by the LHCb[6].
- We also find agreement with the unpolarized ICEM calculations [MV (2016)].

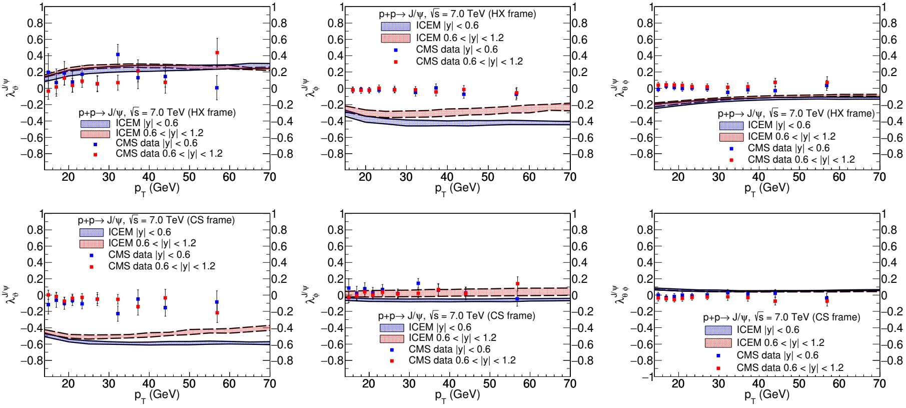
[6] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **73**, 2631 (2013).

Polarization Parameters in Collinear ICEM[5]



- We find agreement with LHCb data[6] at small and moderate p_T.
- Difference between the prediction and experimental results in high p_T is frame dependent.

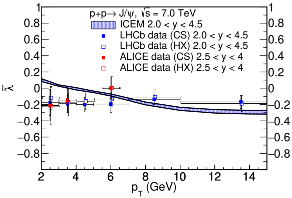
Polarization Parameters in Collinear ICEM[5]

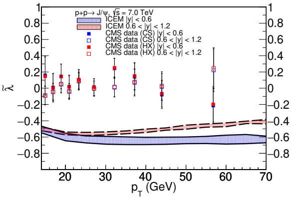


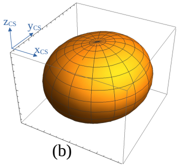
- We find partial agreement with CMS data[7] at high p_T
- Agreement is frame dependent.

[7] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **727**, 381-402 (2013).

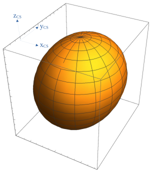
Invariant Polarization Parameter in Collinear ICEM[5]







ICEM (p_T = 12 GeV)



LHCb data (10 < p_T < 15 GeV)

- 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], but discrepancy between high p_T data at CMS[7].

Conclusion and Future

(I)CEM

- Less rigorous
- Fewer fit parameters
- Applied extensively to only hadroproduction (so far)

NRQCD

- More rigorous
- More fit parameters
- Applied to all collision systems

In this talk, I

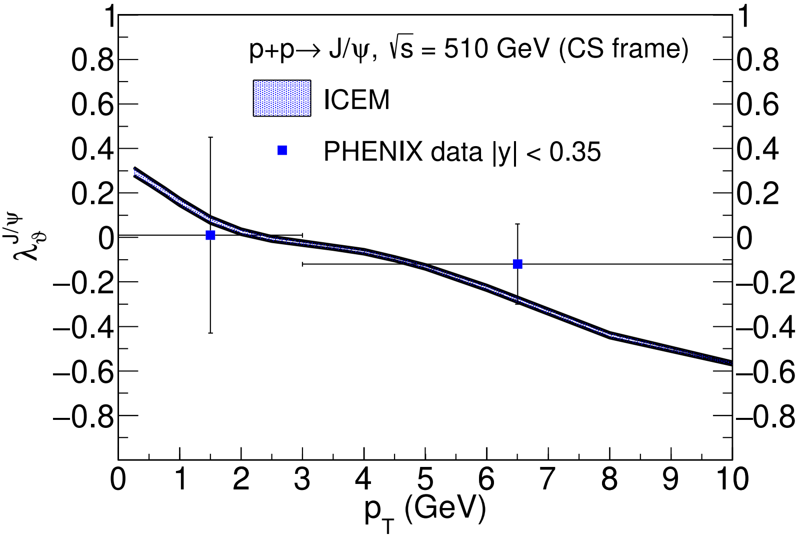
- outlined the quarkonium polarization puzzle
- showed the latest attempt to solve the polarization puzzle in the ICEM

In the future, we

- anticpate the feed down from P states can explain the discrepancies in high p_T.
- will move from hadroproduction to other collision systems.

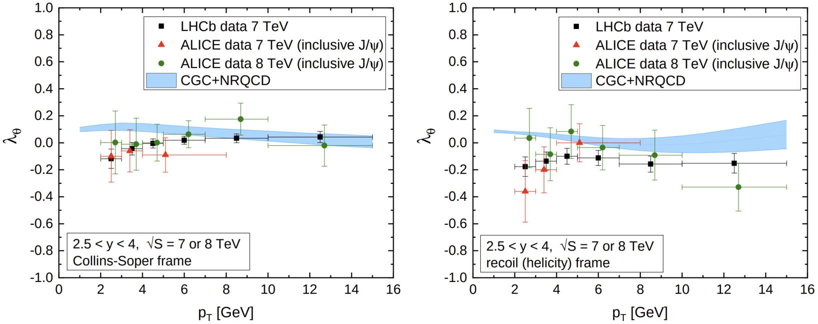
Backup Slides

Comparison to PHENIX Results



CGC+NRQCD[8]

- 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



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