# $J/\psi$ polarization in Pb+Pb collisions in the ICEM

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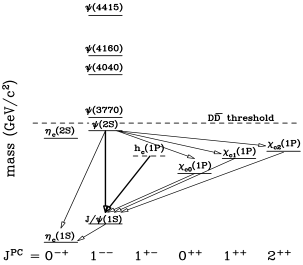
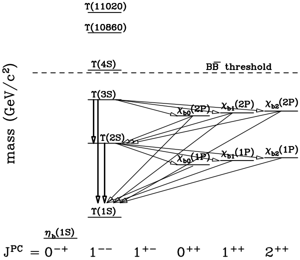
# Overview

1. Introduction
   - Quarkonium
   - Polarization
2. ICEM Approach
   - Results
3. Discussions
4. Conclusion and Future

# Quarkonium families studied in ICEM




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

- produced in hard QCD processes
- been studied in the ICEM in *hh*, $\gamma$p (in progress)
- also produced in $\gamma\gamma$, and $e^+e^-$

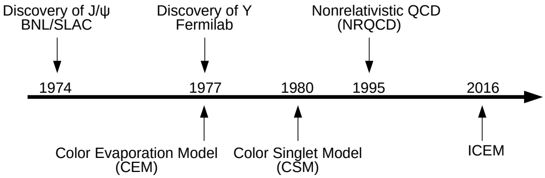
We started by investigating quarkonium production in *pp* as the production mechanism is not yet fully understood in elementary collisions

# Quarkonium Production Models

We are not able to accurately describe every observable associated with quarkonium production using one production model with one set of model parameters.

## Observables

- Yields and distributions of the S states, $\eta$'s and $\chi$'s
- Production of one state realtive to another (e.g. $\psi(2S)$ to $J/\psi$)
- Production of one spin-projection state relative to another (i.e. polarization)



# Polarization and Angular Distribution

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

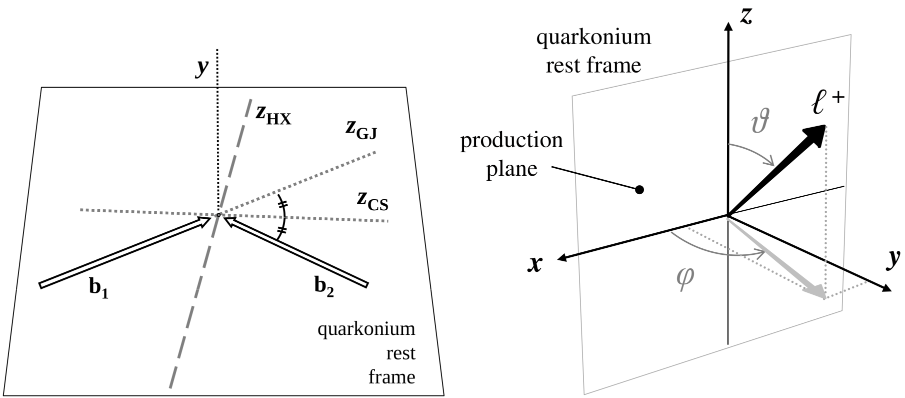
$$\lambda_\vartheta = \frac{1-3|a_0|^2}{1+|a_0|^2}, \qquad \lambda_\varphi = \frac{2Re[a_{+1}a^*_{-1}]}{1+|a_0|^2}, \qquad \lambda_{\vartheta\varphi} = \frac{\sqrt{2}Re[a^*_0(a_+ - a_-)]}{1+|a_0|^2}$$

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

- 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

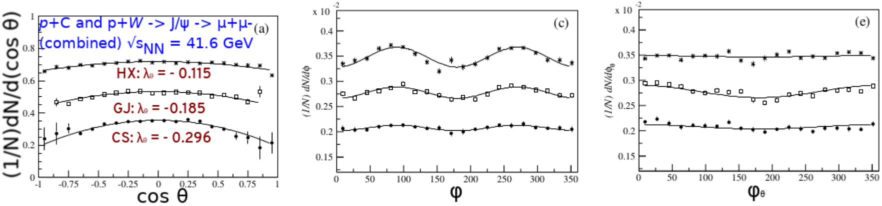



- There are three commonly used choices for the $z$-axis, namely $z_{HX}$ (helicity), $z_{CS}$ (Collins-Soper), and $z_{GJ}$ (Gottfried-Jackson)
- $\vartheta$ is defined as the angle between the $z$-axis and the direction of travel for the $\ell^+$ in the quarkonium rest frame

# Extracting Polarization

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

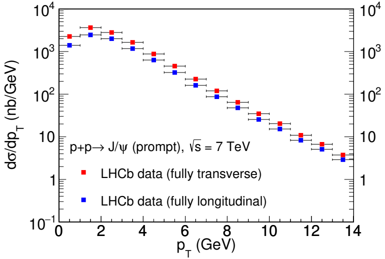
- Polarization parameters can be obtained by fitting the angular spectra as a function of $\vartheta$ and $\varphi$
- One can write $\varphi_\vartheta = \varphi - \frac{\pi}{2} \mp \frac{\pi}{4}$ for $\cos\vartheta \lessgtr 0$, then[1]
- $\frac{d\sigma}{d\varphi_\vartheta} \propto 1 + \frac{\sqrt{2}\lambda_{\vartheta\varphi}}{3+\lambda_\vartheta}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



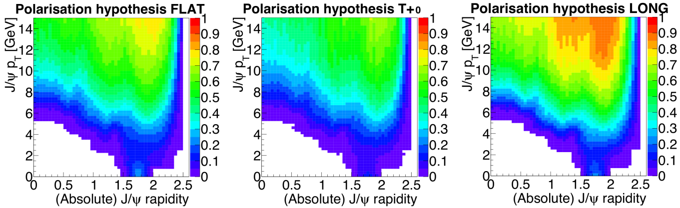

[1] I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

# Importance of Polarization

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




[2]



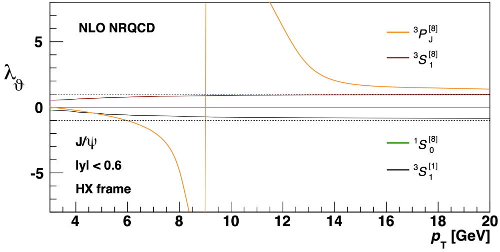

[3]

[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).

# Polarization in NRQCD

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

- e.g. for $J/\psi$, $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$
- 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 depends on the mixing: components have different polarizations




(1403.3970)

# Polarization Puzzle[4]

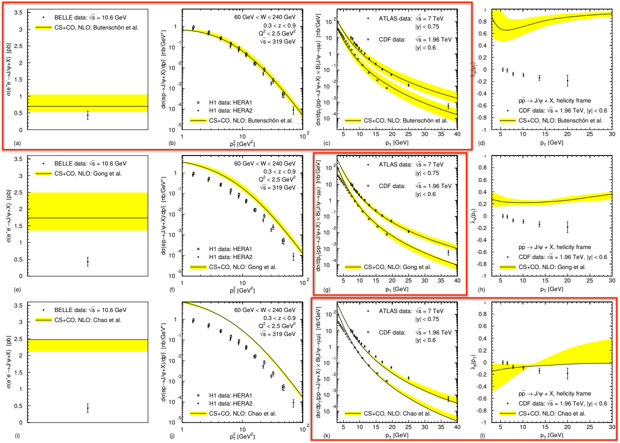
Difficult to describe both the yields and polarizations simultaneously within a given approach (e.g. NRQCD)

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).)]

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

where $M_\psi$ is the mass of the charmonium state, $\psi$.

- 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
- 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 $J/\psi$ and $\Upsilon$, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for $J/\psi$, $Bd\sigma/dy|_{y=0}$ for $\Upsilon$

# $J/\psi$ production in Pb+Pb collisions

## How different is $J/\psi$ in Pb+Pb compared to in $p+p$ collisions

- Suppression
  - higher mass states suppressed first
  - color singlets and color octets could have different suppression rates
- Regeneration from uncorrelated $c\bar{c}$ pairs
  - at low $p_T$ and particularly at midrapidity

## What $J/\psi$ polarization in Pb+Pb collisions can teach us

- If hadronization is a fast process, then polarization should not be significantly different than in $p+p$
- If it takes longer, then the polarization can be different as color singlets and octets have different polarization

## What we can do in ICEM (now)?

- Cold Nuclear Matter Effects
  - $k_T$-broadening
  - nPDFs

# Polarization in Pb+Pb using the ICEM Approach

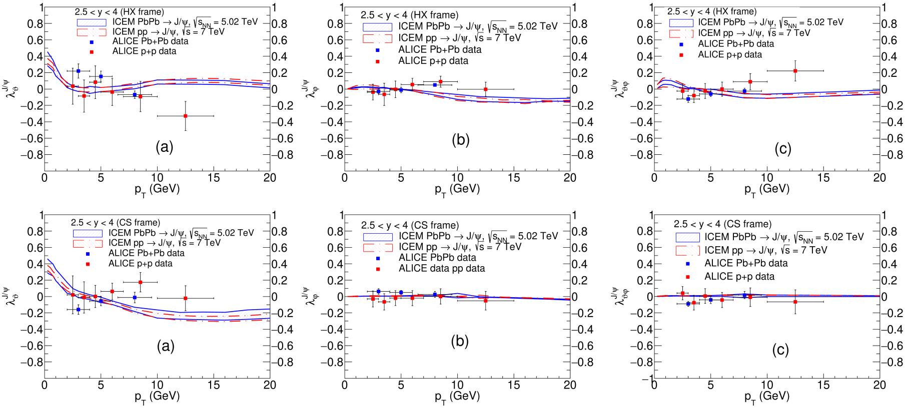
PRC.**105**.055202 (2022).

## Production distribution

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

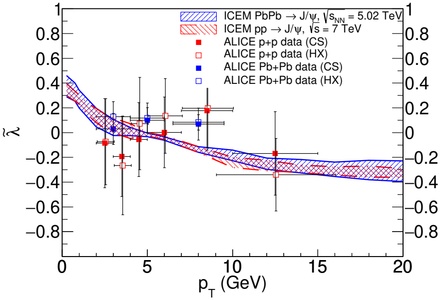
- We consider all diagrams that produces $c\bar{c}$ with a parton.
- The c$\bar{c}$ produced are the proto-$J/\psi$ before hardonization.
- We used the CT14 PDFs and EPPS16 nuclear modifications in our calculations.
- $k_T$-smearing (gaussian) is applied to the initial state partons to provide better description at low $p_T$.
- $\langle k_T^2 \rangle = 1 + (1/12)\ln(\sqrt{s}/20\ \mathrm{GeV})$
- An additional kick of 0.41 GeV$^2$ is added to partons from Pb nuclei.
- $1.18 < m_c < 1.36$ 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)]

# Polarization in Pb+Pb compared to $p$+$p$




- Note that there is a 40% difference in collision energy per nucleon.
- No significant differences between the $p+p$ and Pb+Pb.
- Choosing another shadowing set will not change the polarization.
- Similar lack of system and energy dependence is also expected from CGC+NRQCD approach (PRD 104, 034004)

# Invariant Polarization




- The polarization parameters shown on the previous slide $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ depend on the frame.
- It is possible to construct an invariant polarization parameter because the angular distribution is rotationally invariant:
- $\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$
- It is possible to remove the frame-induced kinematic dependences when comparing theoretical predictions to data by comparing $\tilde{\lambda}$.

# Discussions

## Lack of system and energy dependence in ICEM polarization

- Polarization parameters depend on the ratio of the polarized cross sections
- The numerator and denominator of the polarization parameters are affected similarly
- Although yields can be very different, polarization parameters are similar.

## There are effects that are not modeled

- No feed down are included, but data in this region are unable to tell the effect of potential loss of feed down due to large uncertanties
- Hot effects such as regeneration are neglected, but regeneration is concentrated at low $p_T$ and more important at midrapidity than at forward rapidity.
- Suppression by comovers is neglected.

# Discussions

## What the experimental results are showing

- The polarization in these two systems is consistent within uncertainties
- Feed down from excited states does not strongly affect the prompt $J/\psi$ polarization

## Possible further investigations

- Polarization of regenerated quarkonium states
- Centrality dependence of polarization
  - preliminary results from ALICE: no dependence
  - PoS HardProbes2020, 095 (2021)
- Extending the Pb+Pb polarization data to $p_T > 10$ GeV where regeneration is no longer important
- $\psi$(2S) polarization as an independent check
  - much more difficult due to strong suppression

# Conclusion and Future

## In this talk, I

- demonstrated what can be learned from polarization in Pb+Pb collisions
- showed the latest attempt to extend ICEM polarization calculation to Pb+Pb collisions

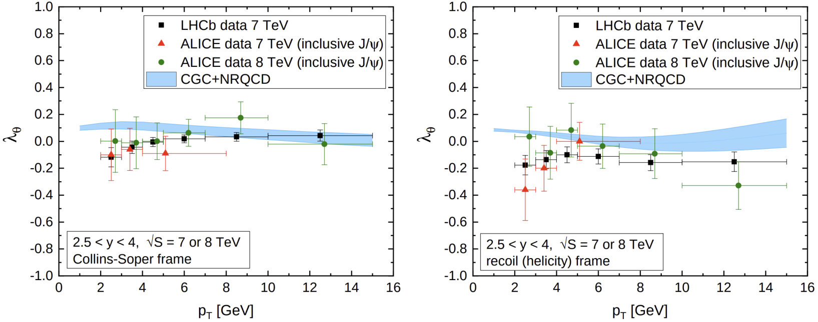
## We are working on

- including effects from feed down production.
- production in *ep* via photo-production.

# Backup Slides

# CGC+NRQCD[5]

- 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




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