

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

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# Overview

## 1 Introduction

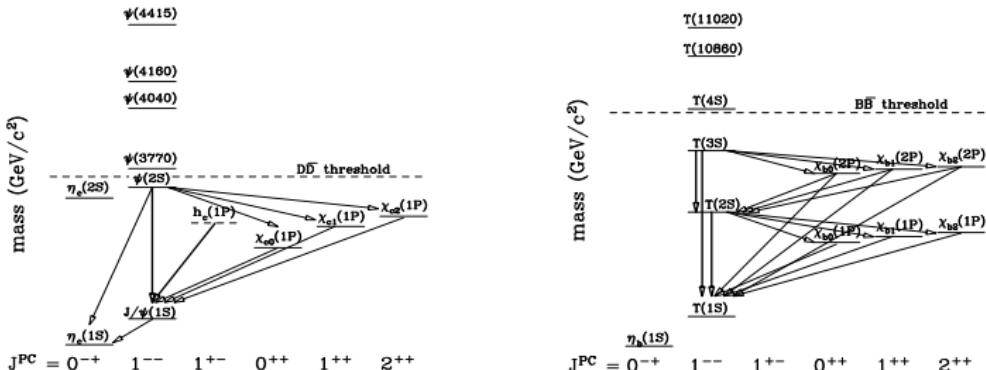
- Quarkonium
- Polarization
- The Polarization Puzzle

## 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  
→ different spin states  $^{2S+1}L_J$
- all color singlets  $^{2S+1}L_J[1]$
- produced in  $hh$ ,  $\gamma p$ ,  $\gamma\gamma$ , and  $e^+e^-$
- S states below the  $H\bar{H}$  ( $H = D, B$ ) threshold decay electromagnetically into  $\ell^+\ell^-$

# Polarization and Angular Distribution

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

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

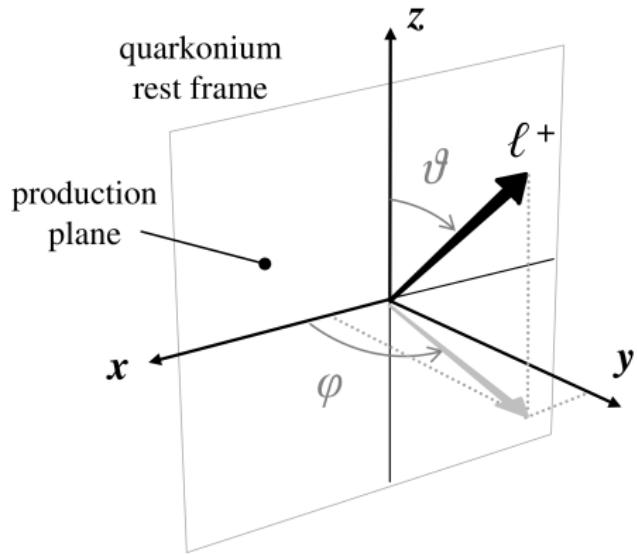
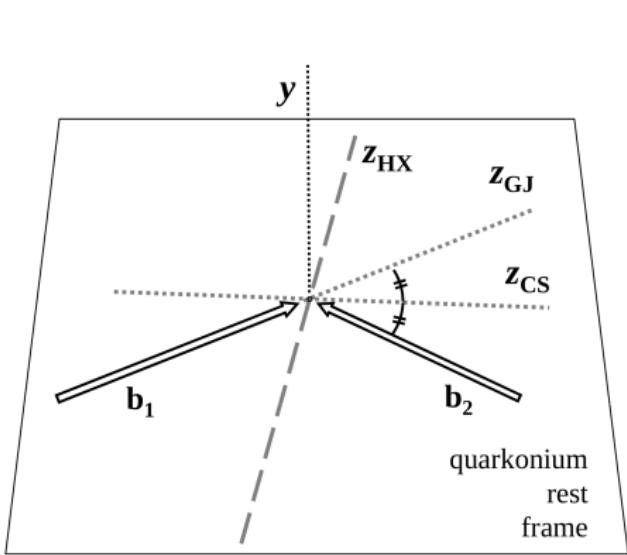
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{3 + \lambda_\vartheta} \left[ 1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos(2\varphi) + \lambda_{\vartheta\varphi} \sin(2\vartheta) \cos \varphi \right]$$

- 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

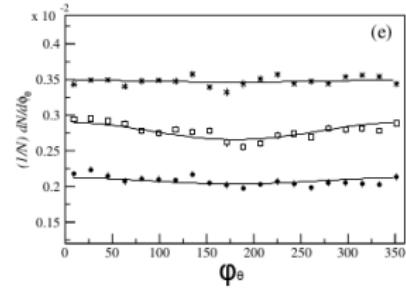
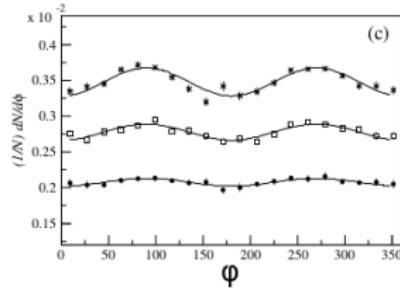
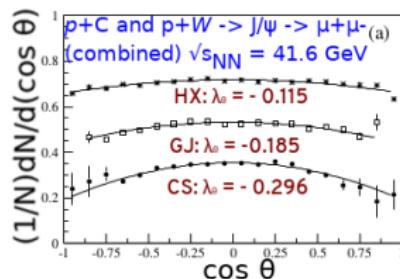


- There are three commonly used choices for the  $z$ -axis, namely  $z_{HX}$  (helicity),  $z_{CS}$  (Collins-Soper), and  $z_{GJ}$  (Gottfried-Jackson)
- $\vartheta$  is defined as the angle between the  $z$ -axis and the direction of travel for the  $\ell^+$  in the quarkonium rest frame

# Extracting Polarization

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

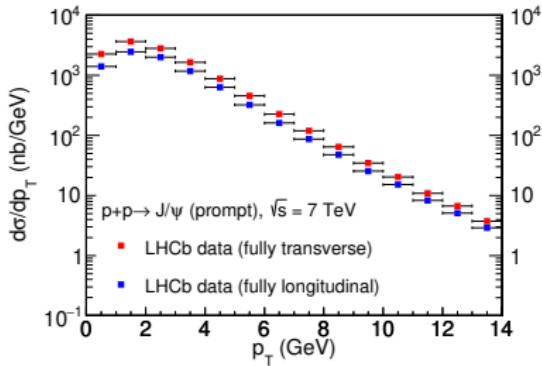
- Polarization parameters can be obtained by fitting the angular spectra as a function of  $\vartheta$  and  $\varphi$
- One can write  $\varphi_\vartheta = \varphi - \frac{\pi}{2} \mp \frac{\pi}{4}$  for  $\cos \vartheta \leqslant 0$ , then<sup>[1]</sup>
- $\frac{d\sigma}{d\varphi_\vartheta} \propto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



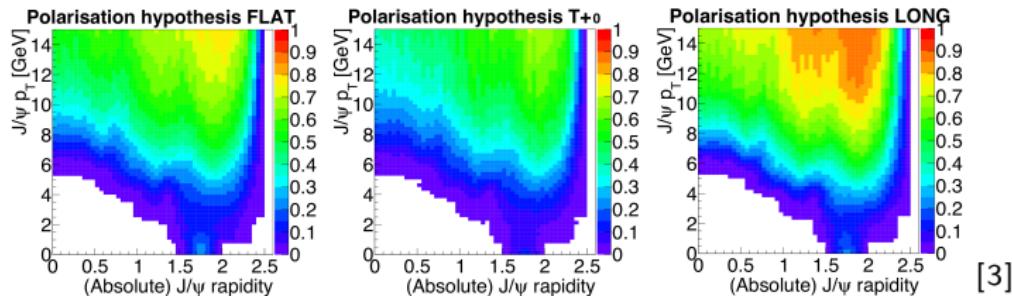
<sup>[1]</sup>I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

# Importance of Polarization

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



[2]



<sup>2</sup>R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **71**, 1645 (2011).

<sup>3</sup>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

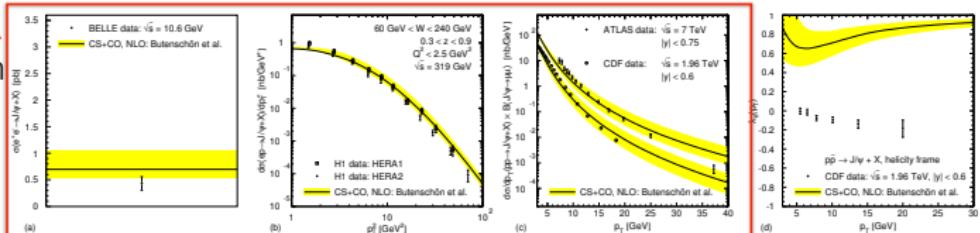
## Non Relativistic QCD (NRQCD) [Bodwin, Braaten, Lepage 95]

- e.g. for  $J/\psi$ ,  $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$
- 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

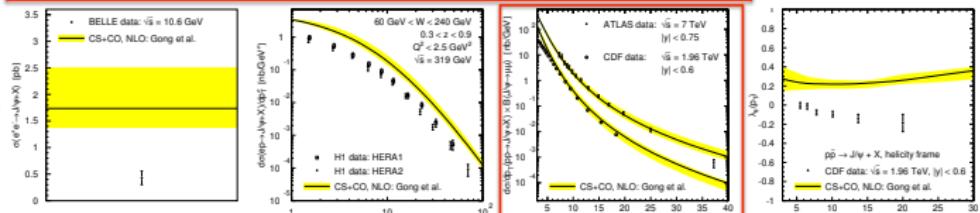
# Polarization Puzzle<sup>[4]</sup>

Included in fits

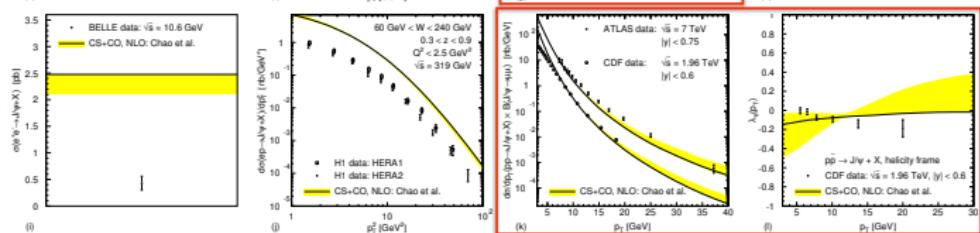
Butenschon  
& Kniehl  
 $p_T > 3 \text{ GeV}$



Gong et al.  
 $p_T > 5 \text{ GeV}$



Chao et al.  
 $p_T > 7 \text{ GeV}$



<sup>4</sup>N. Brambilla *et al.*, Eur. Phys. J. C 74, 2981 (2014)

# The Improved Color Evaporation Model (ICEM)

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

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

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

- all Quarkonium states are treated like  $Q\bar{Q}$  ( $Q = c, b$ ) below  $H\bar{H}$  ( $H = D, B$ ) threshold
- all diagrams for  $Q\bar{Q}$  production included, independent of color
- able to describe relative production of  $\psi(2S)$  to  $J/\psi$
- fewer parameters than NRQCD (one  $F_Q$  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
- $F_Q$  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  $\Upsilon$

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

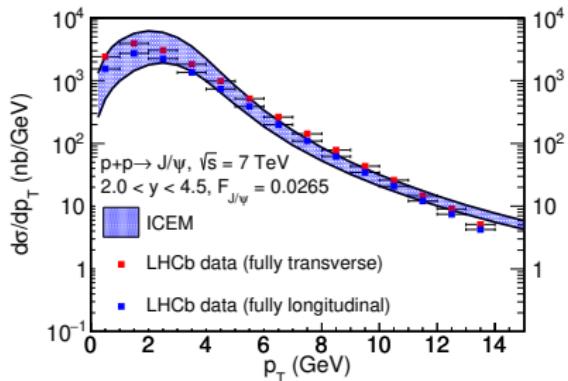
## Production distribution

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

- We consider all 16 diagrams from  $gg \rightarrow c\bar{c}g$ , 5(+5) from  $gq(\bar{q}) \rightarrow c\bar{c}$   $q(\bar{q})$ , and 5 from  $q\bar{q} \rightarrow c\bar{c}g$  with the projection operator applied at the diagram level.
- The  $c\bar{c}$  produced are the proto- $J/\psi$  before hadronization.
- 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
- $1.18 < m_c < 1.36 \text{ GeV}$ ,  $\mu_F/m_T = 2.1_{-0.85}^{+2.55}$ ,  $\mu_R/m_T = 1.6_{-0.12}^{+0.11}$
- same set of variations used in MV [2016] and NVF [PRC **87**, 014908 (2013)]

<sup>5</sup>V. Cheung and R. Vogt, submitted.

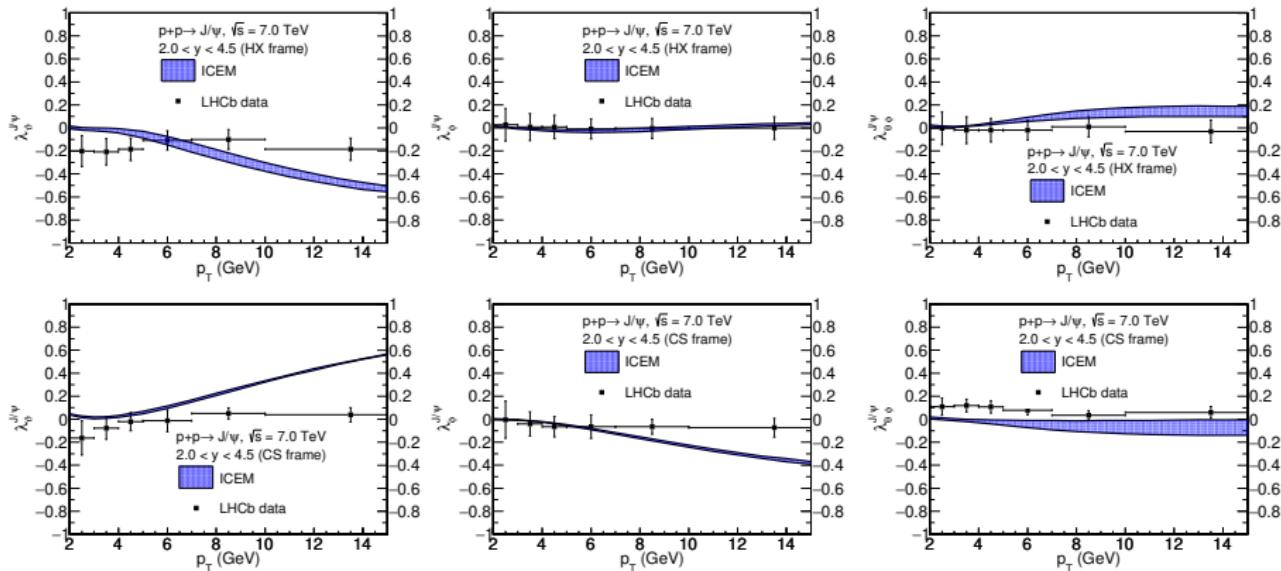
# Collinear ICEM Unpolarized Cross Sections<sup>[5]</sup>



- $k_T$ -smearing gives a small kick  $\langle k_T^2 \rangle \sim 1 \text{ GeV}^2$  to the initial state parton.
- The uncertainty band<sup>[5]</sup> 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<sup>[6]</sup>.

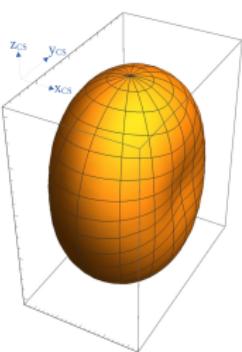
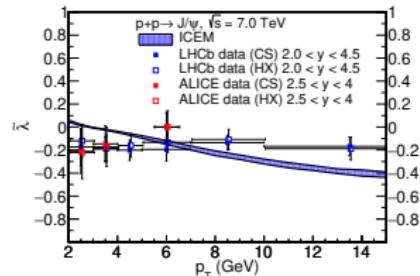
<sup>6</sup>R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **73**, 2631 (2013).

# Polarization Parameters in Collinear ICEM<sup>[5]</sup>

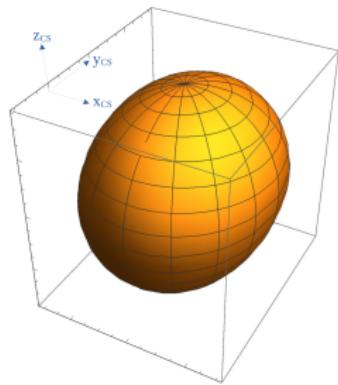


- We find agreement with LHCb data<sup>[6]</sup> at small and moderate  $p_T$ .
- Difference between the prediction and experimental results in high  $p_T$  is frame dependent.

# Invariant Polarization Parameter in Collinear ICEM<sup>[5]</sup>



ICEM ( $p_T = 12 \text{ GeV}$ )



LHCb data ( $10 < p_T < 15 \text{ GeV}$ )

- The frame-invariant polarization parameter  $\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$
- Comparing the frame-invariant polarization parameter removes frame-induced kinematic dependencies
- We find agreement with the invariant polarization measured by the LHCb<sup>[6]</sup>.

# Conclusion and Future

## (I) ICEM

- 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

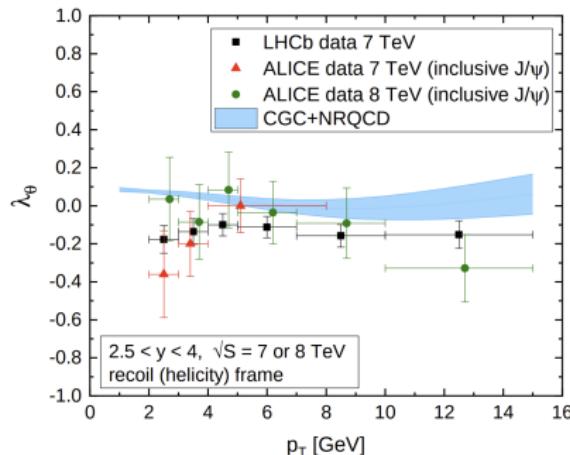
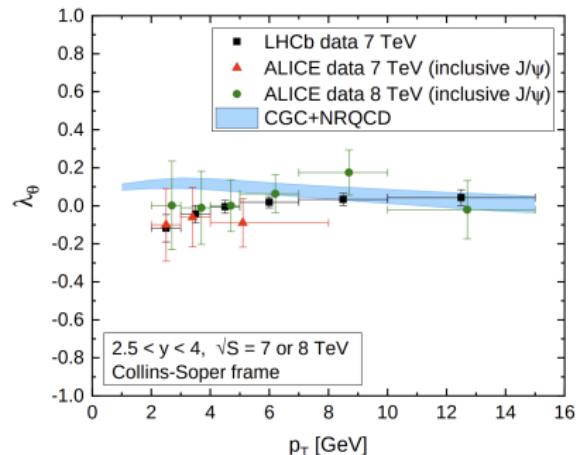
### In the future, we

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

# Backup Slides

# CGC+NRQCD<sup>[7]</sup>

- 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



<sup>7</sup>Y. Q. Ma, T. Stebel, R. Venugopalan, JHEP12 (2018) 057.