Heavy flavor and quarkonium production in pp collisions

Vincent Cheung

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

This work was supported in part by the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, 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 number 23-LW-036.

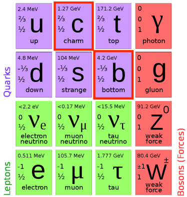
Oct 10, 2022

Lawrence Livermore National Laboratory

Overview

Scope of Heavy Flavor Production

- focus on charm and bottom production
- hadrons include mesons (D, B), baryons, onia (ψ and Υ)
- produced through QCD/QED processes
- in hh, $\gamma\gamma$, and e^+e^- collisions



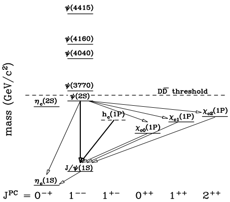
Color Evaporation Model (CEM) for total charm cross section

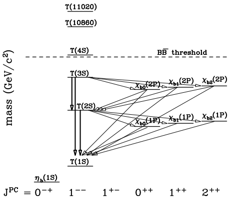
$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i^p(x_1,\mu_F) f_j^p(x_2,\mu_F) \hat{\sigma}_{ij},$$

In PRC.87.014908, an attempt to reduce the uncertainty on the total charm cross section,

- m_c was fixed at 1.27 ± 0.09 GeV ($\overline{\mathrm{MS}}$ scheme)
- $\mu_F/m_c = 2.1^{+2.55}_{-0.85}$ and $\mu_R/m_c = 1.6^{+0.11}_{-0.12}$

Quarkonium production





CEM [Fritzsch 77; Halzen 77; Glück, Owens, Reya 78; Gavai *et al.* 95; Schuler, Vogt 95]

$$\sigma = F_{\mathcal{Q}} \sum_{i,j=q,\bar{q},g} \int_{4m_c^2}^{4m_H^2} dM \int dx_1 dx_2 f_i^p(x_1,\mu_F) f_j^p(x_2,\mu_F) \hat{\sigma}_{ij},$$

- $m_c = 1.27 \pm 0.09$ GeV, $\mu_F/m_T = 2.1^{+2.55}_{-0.85}$, and $\mu_R/m_T = 1.6^{+0.11}_{-0.12}$
- where $m_T = \sqrt{m_c^2 + p_T^2}$, $p_T^2 = 0.5(p_{Tc}^2 + p_{T\bar{c}}^2)$

Quarkonium Production Models

Improved CEM (ICEM) [Ma, Vogt 16]

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

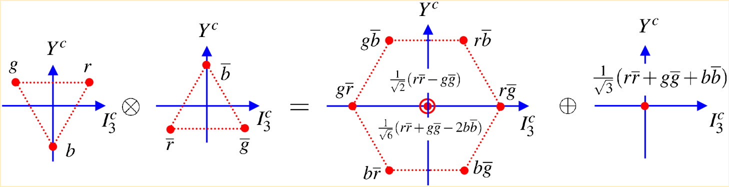
where M_ψ is the mass of the charmonium state, ψ.

- first new advance in the basic CEM model since 1990s
- able to describe relative production of ψ(2S) to J/ψ, 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 χ states

Color Singlet Model (CSM) [Berger, Jones 81; Baier, Rückl 81, Schuler 94, Lansberg 11]

- constrains the production of $Q\bar{Q}$ to the color singlet state only
- the produced $Q\bar{Q}$ pair does not change its color and spin between production and hadronization

$$d\sigma[\mathcal{Q}+X] = \sum_{i,j} \int dx_i dx_j f_i(x_i,\mu_F) f_j(x_j,\mu_F) d\hat{\sigma}_{i+j\to(Q\bar{Q})+x}(\mu_R,\mu_F) \times |R(0)|^2 .$$

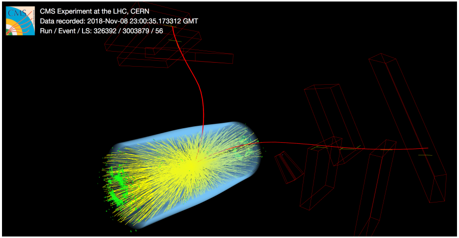


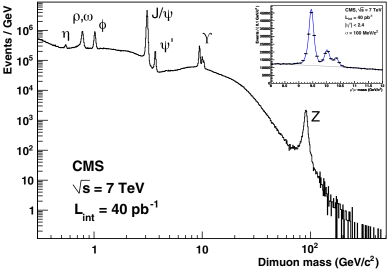
Quarkonium Production Models

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

- an Effective Field Theory where production is described as an expansion in powers of α_s and the heavy quark velocity, v/c
- 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/ψ, $\sigma_{J/\psi} = \sum_n \sigma_{c\bar{c}[n]} \langle \mathcal{O}^{J/\psi}[n] \rangle$
- $\sigma_{c\bar{c}[n]}$ are cross sections in a particular color and spin state n calcuated by perturbative QCD
- including ${}^3S_1^{[1]}$ (singlet), and ${}^3P_J^{[8]}, {}^3S_1^{[8]}$ and ${}^1S_0^{[8]}$ (octets)
- $\langle \mathcal{O}^{J/\psi}[n] \rangle$ are the LDMEs that describe the conversion of $c\bar{c}[n]$ state into final state J/ψ, 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

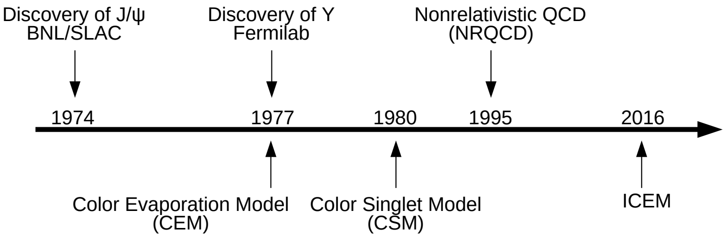
Models are tested against the data





- S states ($J^{PC} = 1^{--}$) decay to $\ell^+\ell^-$, so they can be observed as peaks in dilepton mass spectra
- $\chi(n\mathrm{P})$ states ($J^{PC} = J^{++}$) can be reconstructed by matching an S state with a low momentum photon
- η_c and η_b states ($J^{PC} = 0^{-+}$) decay hadronically

Discovery and Production Models



Color Evaporation Model [Fritzsch 77; Halzen 77; Glück, Owens, Reya 78]

- spins and colors are averaged

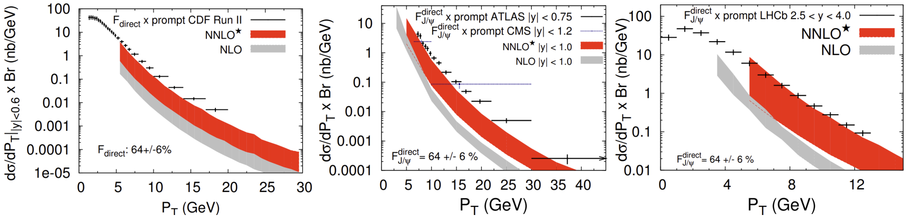
Color Singlet Model [Berger, Jones 81; Baier, Rückl 81, Schuler 94, Lansberg 11]

- only color singlet contribution is considered

Nonrelativistic QCD (NRQCD) [Bodwin, Braaten, Lepage 95]

- separate all spin and color states

Highlights in the CSM

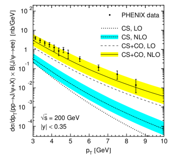


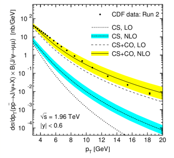
- LO and NLO calculations underestimate the Tevatron p_T distributions
- Recent advancements in CSM show that by adding real-emission contribution at NNLO, CSM can describe the distributions[1] (NNLO*)

[1] J.P. Lansberg, J. Phys. G **38**, 124110 (2011).

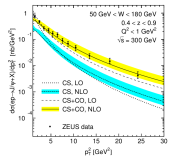
Highlights in NRQCD - A global fit of LDMEs[2]

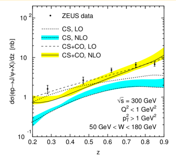
hh ($p_T > 3$ GeV)





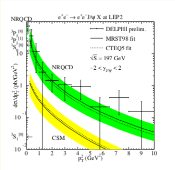
γp ($p_T > 3$ GeV)

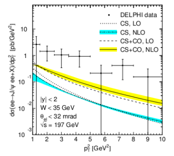




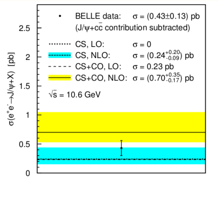
$\gamma\gamma$ (Right: $p_T > 1$ GeV)

[6]





e^+e^-

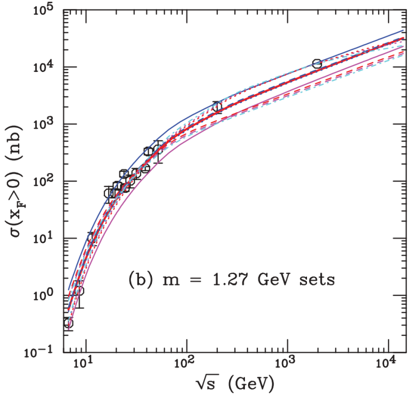


[2] M. Butenschoen and B. A. Kniehl, Nucl. Phys. Proc. Suppl. **222-224**, 151 (2012).
[3] M. Klasen *et. al*, DESY 01-202.

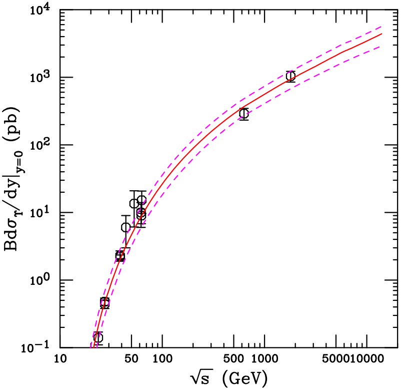
Results in the CEM[4]

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

J/ψ

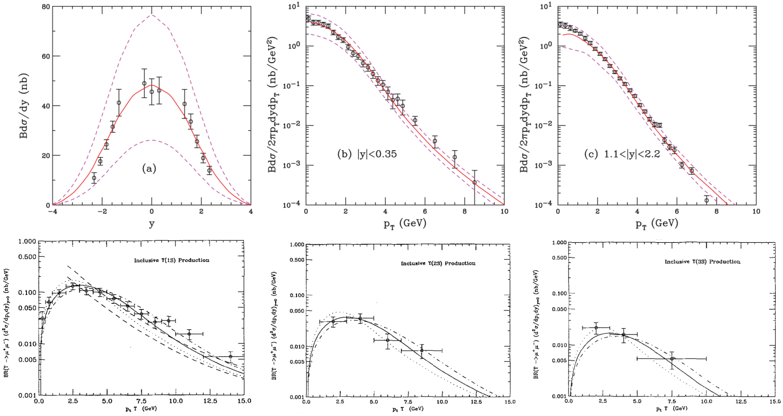


$\sum \Upsilon$'s



[4] R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C **87**, 014908 (2013).

Results in the CEM[5,6]



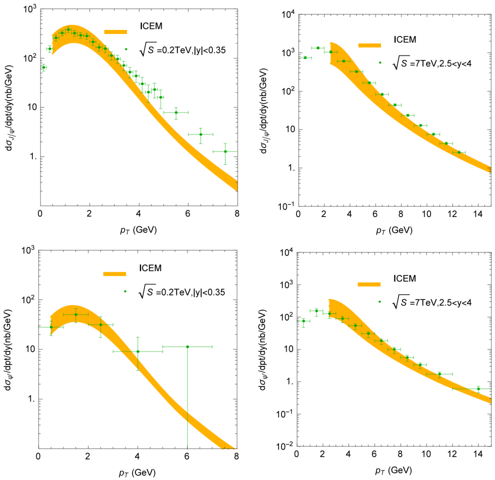
- overall less rigorous, but accurate predictions
- no advances in the basic model since 1990s

[5] R. E. Nelson, R. Vogt and A. D. Frawley, Phys. Rev. C **87**, 014908 (2013).

[6] G. A. Schuler and R. Vogt, Phys. Lett. B **387**, 181 (1996).

Results in the ICEM

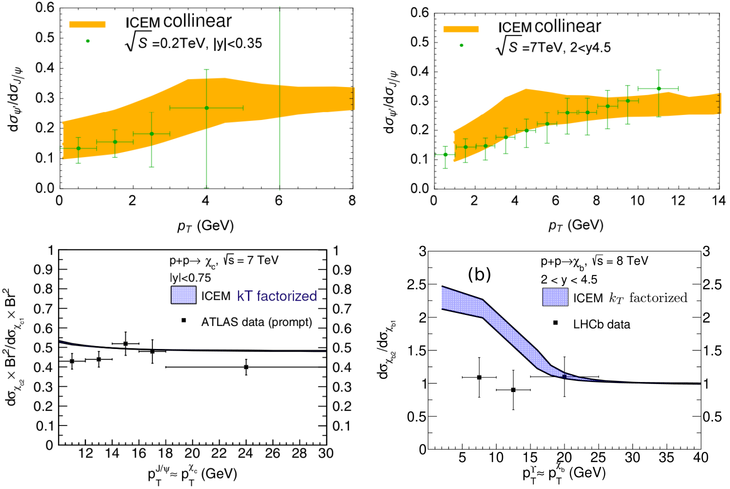
$$\frac{d\sigma_\psi(P)}{dp_T} = F_\psi \int_{M_\psi}^{2M_D} dM \frac{M}{M_\psi} \frac{d\sigma_{c\bar{c}}(M, P')}{dM\, dp'_T}\bigg|_{p'_T=(M/M_\psi)p_T}$$



Ma and Vogt, PRD 94, 114029 (2016).

- explicit charmonium mass dependence → 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 → p_T spectra will be softer and thus may explain the high p_T data better

Relative production in the ICEM[7,8]



[7] Y. Q. Ma and R. Vogt, Phys. Rev. D **94**, 114029 (2016).

[8] V. Cheung and R. Vogt, Phys. Rev. D **98**, 114029 (2018) and **99**, 034007 (2019).

Tests of Models

- CEM and NRQCD remain the most commonly used models today.
- They can predict yields and relative production of different quarkonium states.
- What about the relative production of different spin projection states of the same quarkonium state? $\rightarrow$ Polarization

(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

Polarization and Angular Distribution

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

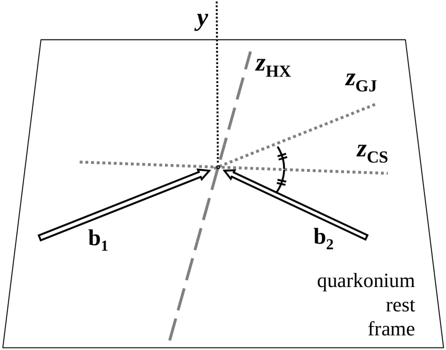
$$\lambda_\vartheta = \frac{1-3|a_0|^2}{1+|a_0|^2}, \qquad \lambda_\varphi = \frac{2Re[a_{+1}a^*_{-1}]}{1+|a_0|^2}, \qquad \lambda_{\vartheta\varphi} = \frac{\sqrt{2}Re[a^*_0(a_+ - a_-)]}{1+|a_0|^2}$$

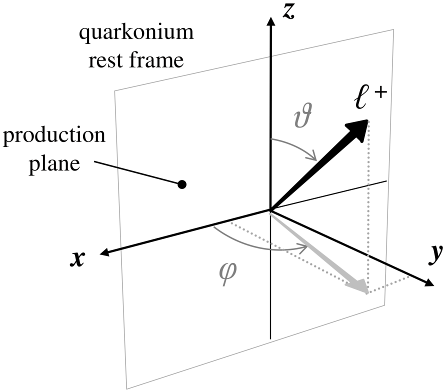
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{3+\lambda_\vartheta}\left[1+\lambda_\vartheta\cos^2\vartheta + \lambda_\varphi \sin^2\vartheta\cos(2\varphi) + \lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi\right]$$

- 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



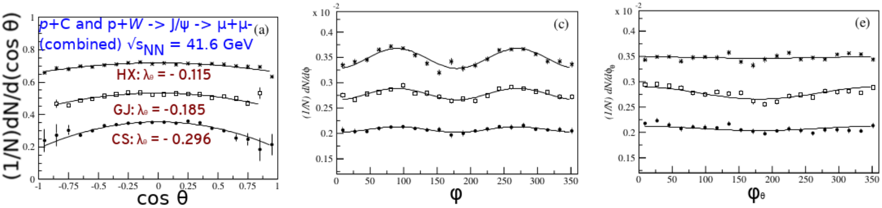


- There are three commonly used choices for the z-axis, namely z_{HX} (helicity), z_{CS} (Collins-Soper), and z_{GJ} (Gottfried-Jackson)
- ϑ is defined as the angle between the z-axis and the direction of travel for the ℓ^+ in the quarkonium rest frame

Extracting Polarization

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

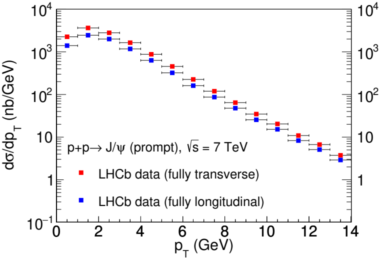
- Polarization parameters can be obtained by fitting the angular spectra as a function of ϑ and φ
- One can write $\varphi_\vartheta = \varphi - \frac{\pi}{2} \mp \frac{\pi}{4}$ for $\cos\vartheta \lessgtr 0$, then[9]
- $\frac{d\sigma}{d\varphi_\vartheta} \propto 1 + \frac{\sqrt{2}\lambda_{\vartheta\varphi}}{3+\lambda_\vartheta}\cos\varphi_\vartheta$



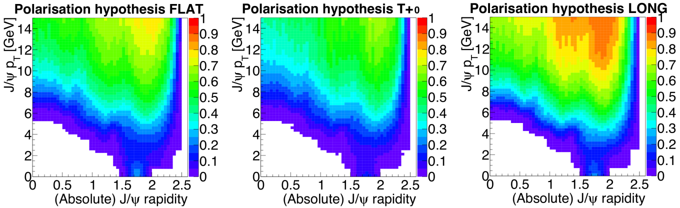
[9]I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

Importance of Polarization

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



[10]



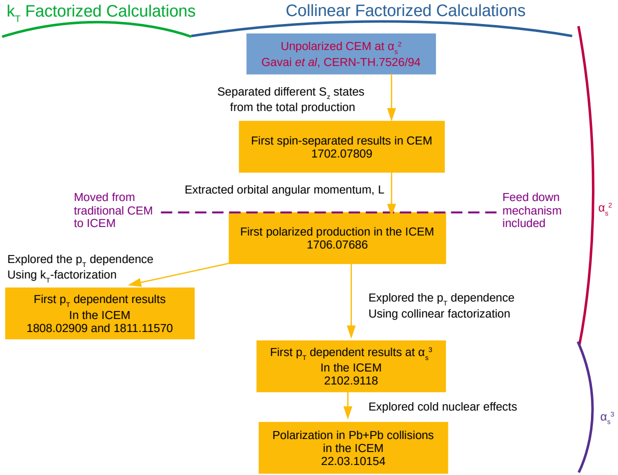
[11]

[10] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **71**, 1645 (2011).

[11] G. Aad *et al.* (ATLAS Collaboration), Nucl. Phys. B **850**, 387 (2011).

Polarized Production in the CEM and ICEM

- No polarization calculations made in the CEM family before 2017.
- It is worth revisiting back the CEM to calculate polarized results
- VC and Ramona Vogt made a few calculations using the (I)CEM.



How we started at $\mathcal{O}(\alpha_s^2)$

In terms of the Dirac spinors u and v, the individual amplitudes at leading order are

$$
\begin{aligned}
\mathcal{A}_{qq} &= \frac{g_s^2}{\hat{s}}[\overline{u}(p')\gamma_\mu v(p)][\overline{v}(k)\gamma^\mu u(k')] \,, \\
\mathcal{A}_{gg,s} &= -\frac{g_s^2}{\hat{s}}\Big\{ -2k'\cdot\epsilon(k)[\overline{u}(p')\not{\epsilon}(k')v(p)] \\
&+ 2k\cdot\epsilon(k')[\overline{u}(p')\not{\epsilon}(k)v(p)] \\
&+ \epsilon(k)\cdot\epsilon(k')[\overline{u}(p')(\not{k}'-\not{k})v(p)]\Big\} \,, \\
\mathcal{A}_{gg,t} &= -\frac{g_s^2}{\hat{t}-M^2}\overline{u}(p')\not{\epsilon}(k')(\not{k}-\not{p}+M)\not{\epsilon}(k)v(p) \,, \\
\mathcal{A}_{gg,u} &= -\frac{g_s^2}{\hat{u}-M^2}\overline{u}(p')\not{\epsilon}(k)(\not{k}'-\not{p}+M)\not{\epsilon}(k')v(p) \,,
\end{aligned}
$$

- $\mathcal{A}$'s are separated according to the $|S, S_z\rangle$ of the final state
- Orbital Angular Momentum is extracted before squaring the amplitudes

Orbital Angular Momentum

To extract the projection on a state with orbital-angular-momentum quantum number L, we determine the corresponding Legendre component $\mathcal{A}_L$ in the amplitudes by

$$\begin{aligned} \mathcal{A}_{L=0} &= \frac{1}{2}\int_{-1}^{1} dx\mathcal{A}(x=\cos\theta)\ , \\ \mathcal{A}_{L=1} &= \frac{3}{2}\int_{-1}^{1} dx\ x\mathcal{A}(x=\cos\theta)\ . \end{aligned}$$

$L=2$ amplitudes are not needed for S and χ states production.

Feed Down Production[12]

CEM polarization calculations assume two pions are emitted from an S state feed down and a photon is emitted from a P state feed down.

$$R^{J_z=0}_{J/\psi} = \sum_{\psi,J_z} c_\psi S^{J_z}_\psi R^{J_z}_\psi \,, R^{J_z=0}_{\Upsilon(1\mathrm{S})} = \sum_{\Upsilon,J_z} c_\Upsilon S^{J_z}_\Upsilon R^{J_z}_\Upsilon \,,$$

Q	M_Q (GeV)	c_Q	$S_Q^{J_z=0}$	$S_Q^{J_z=\pm 1}$
J/ψ	3.10	0.62	1	0
ψ(2S)	3.69	0.08	1	0
χ_{c1}(1P)	3.51	0.16	0	1/2
χ_{c2}(1P)	3.56	0.14	2/3	1/2
Υ(1S)	9.46	0.52	1	0
Υ(2S)	10.0	0.1	1	0
Υ(3S)	10.4	0.02	1	0
χ_{b1}(1P)	9.89	0.13	0	1/2
χ_{b2}(1P)	9.91	0.13	2/3	1/2
χ_{b1}(2P)	10.3	0.05	0	1/2
χ_{b2}(2P)	10.3	0.05	2/3	1/2

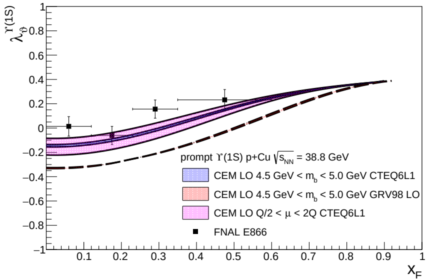
[12] S. Digal, P. Petreczky, and H. Satz, Phys. Rev. D **64**, 094015 (2001).

Comparing x_F Dependence with Fixed-Target Data[13]

CEM polarization calculation using collinear factorization:

$J^P = 1^-$ (S states)

$$\lambda_\vartheta = \frac{1 - 3R^{J_z=0}}{1 + R^{J_z=0}}$$



x_F $(x_1 - x_2)$ Dependence (EPS09 for Cu PDFs)

- longitudinally polarized at small $|x_F|$ and transversely polarized at large $|x_F|$
- prediction is consistent with the ~ 0 polarization for $\Upsilon(1S)$

[13] C. N. Brown *et al.* (NuSea Collaboration), Phys. Rev. Lett. **86**, 2529 (2001).

Calculation at $\mathcal{O}(\alpha_s^2)$ using k_T-factorization

In our calculations using k_T-factorization, we compute the scattering amplitdues $\mathcal{A}(\mathcal{R}\mathcal{R} \to Q\overline{Q})$:

$$\begin{aligned} \mathcal{A}(\mathcal{R}\mathcal{R} \to Q\overline{Q}) &= \epsilon(k)^\mu \epsilon(k')^\nu \mathcal{A}_{\mu\nu}(gg \to Q\overline{Q}) \,, \\ \epsilon(k)^\mu &= (0, \frac{\vec{k}_T}{|k_T|}, 0) \,, \end{aligned}$$

$\mathcal{A}$'s are separated according to the $|S, S_z\rangle$ of the final state. We then determine the corresponding Legendre component $\mathcal{A}_L$ in the amplitudes by

$$\begin{aligned} \mathcal{A}_{L=0} &= \frac{1}{2}\int_{-1}^{1} dx \mathcal{A}(x = \cos\theta) \,, \\ \mathcal{A}_{L=1} &= \frac{3}{2}\int_{-1}^{1} dx \, x\mathcal{A}(x = \cos\theta) \,. \end{aligned}$$

$L = 2$ amplitudes are not needed for S and χ states production. Only $\mathcal{A}_{gg}$'s are used in the k_T-factorization approach

Production in k_T-factorized ICEM

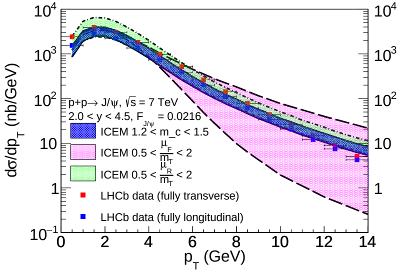
Production cross section

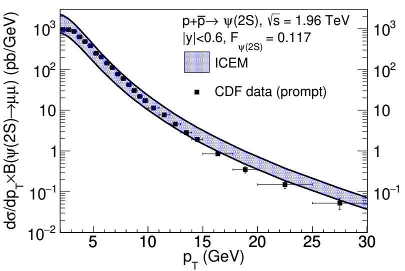
$$\sigma = F_Q \int_{M_Q^2}^{4m_H^2} d\hat{s} \int dx_1 \int dx_2 \int d{k_{1T}}^2 \int d{k_{2T}}^2 \int \frac{d\phi_1}{2\pi} \int \frac{d\phi_2}{2\pi}$$
$$\times \; \Phi_1(x_1, k_{1T}, Q_1)\Phi_2(x_2, k_{2T}, Q_2)\hat{\sigma}(\mathcal{R} + \mathcal{R} \to Q\overline{Q})$$
$$\times \; \delta(\hat{s} - x_1 x_2 s + |\vec{k}_{1T} + \vec{k}_{2T}|^2)$$

Parameters used

- We used JH-2013[5] unintegrated (transverse-momentum-dependent) PDF set for $\Phi(x, k_T, Q)$
- factorization scale set at $Q = m_T$
- $1.27 < m_c < 1.50$ GeV, $4.5 < m_b < 5.0$ GeV
- $\frac{1}{2} < \frac{\mu_r}{m_T} < 2$

Charmonium production in k_T-factorized ICEM[14]

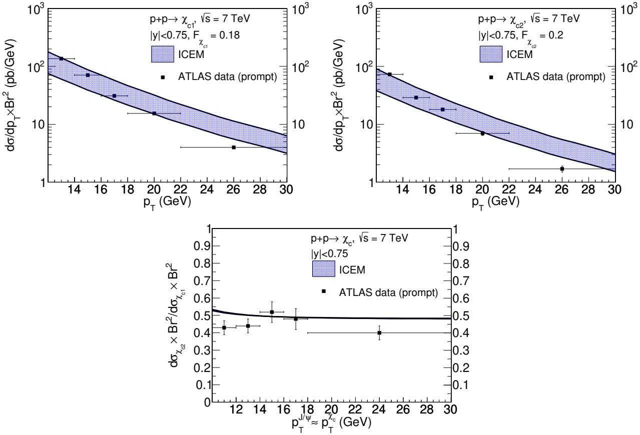




- We obtained $F_{J/\psi}$ while assumming a constant direct-to-inclusive ratio of 0.62 for J/ψ.
- We also compare our directly produced $\psi(2S)$ to the prompt production of $\psi(2S)$ to obtain $F_{\psi(2S)}$.
- The ICEM with k_T-factorization is able to describe the yield, but having a strong dependence on factorization scale at high p_T.

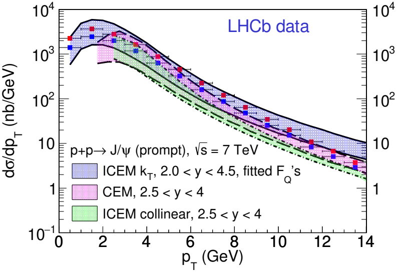
[14] V. Cheung and R. Vogt, Phys. Rev. D **98**, 114029 (2018) and **99**, 034007 (2019).

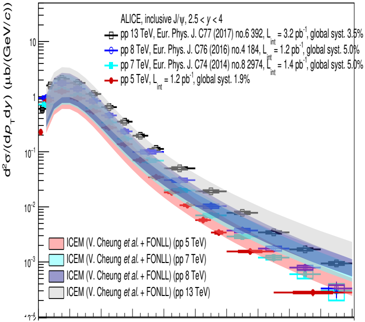
χ_c production in k_T-factorized ICEM[14]



- We also compare our results to χ_c production at ATLAS to obtain the $F_{\mathcal{Q}}$'s as well.
- We found the relative production is stable at high p_T. This is consistent with the data.

Prompt and inclusive J/ψ in k_T-factorized ICEM[14]

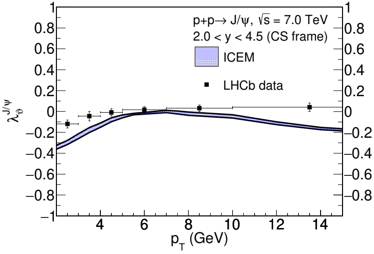


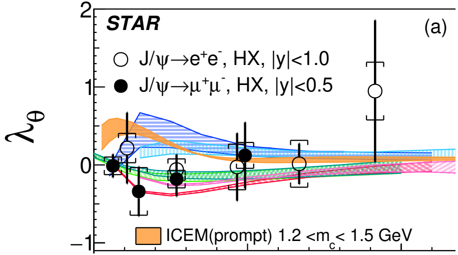


- With all the $F_{\mathcal{Q}}$'s fitted for all S states and P states, the prompt J/ψ yield can be calculated.
- The k_T-factorized ICEM agrees with previous collinear (I)CEM calculations.
- When B feed-down is also added using FONLL, we found agreement with inclusive J/ψ production in a large range of beam energies.

J/ψ polarization in k_T-factorized ICEM[14]

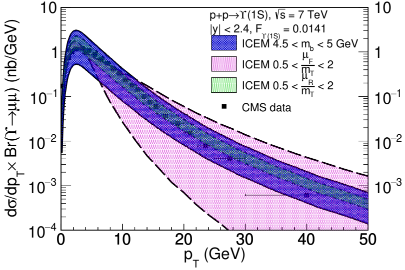
Polarization is independent of $F_{\mathcal{Q}}$ and scales, mass is the only uncertainty

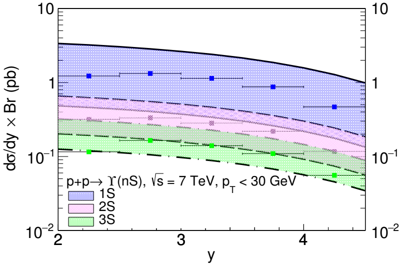




- We found the prompt production of J/ψ is slightly longitudinally polarized in the CS frame.
- Slightly transversely polarized in the HX frame.
- Agreement with polarization data is frame-dependent at low p_T.

Υ production in k_T-factorized ICEM[14]





- The p_T-distributions for Υ production also have a strong dependence on factorization scale at high p_T.
- When the factorization scale is set at m_T, both p_T and y distributions are described.

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

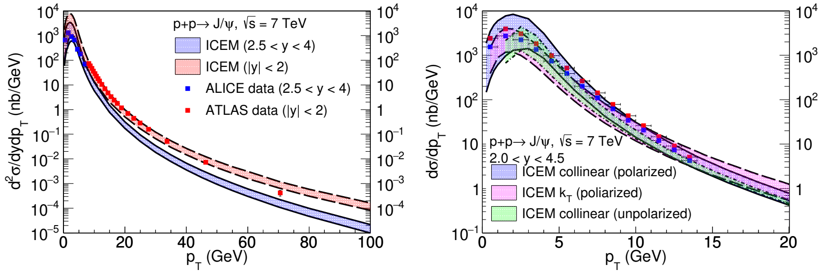
Production distribution

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

- We consider all 16 diagrams from gg→ c$\bar{c}$g, 5(+5) from gq($\bar{q}$)→ c$\bar{c}$ q($\bar{q}$), and 5 from q$\bar{q}$→ 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)]

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

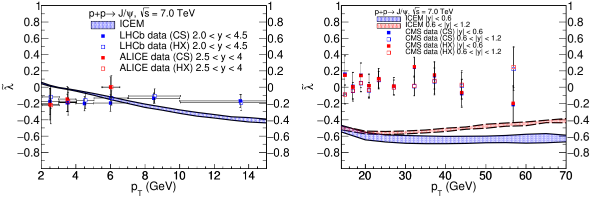
Collinear ICEM Unpolarized Cross Sections[15]



- a small kick of $< k_T^2 >\sim 1$ GeV^2 given to each initial 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[16].
- We also find agreement with the unpolarized ICEM calculations [MV (2016)].

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

Invariant Polarization Parameter in Collinear ICEM[16]



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].

J/ψ production in Pb+Pb collisions

How different is J/ψ 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/ψ 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

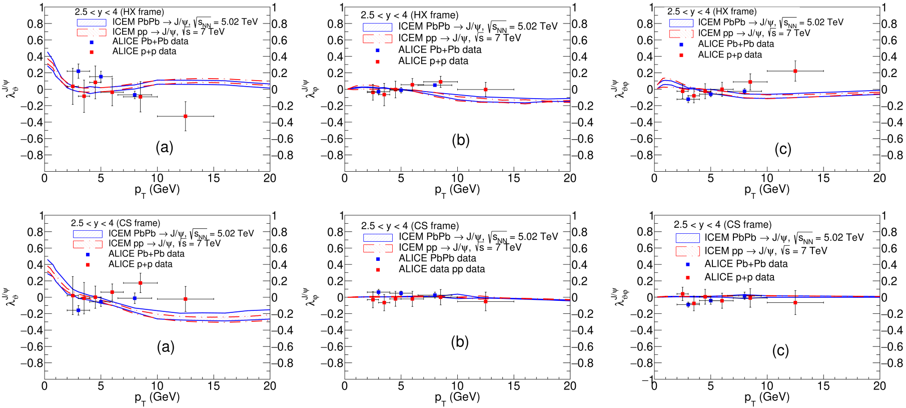
PRC.**105**.055202 (2022).

Production distribution

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

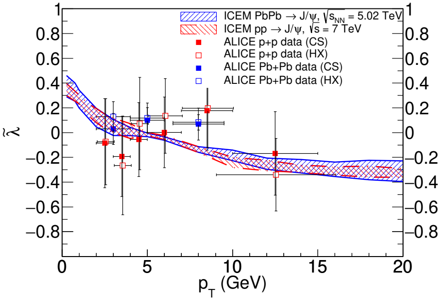
- We consider all diagrams that produces $c\bar{c}$ with a parton.
- The $c\bar{c}$ produced are the proto-J/ψ before hardonization.
- We used the CT14 PDFs and EPPS16 nuclear modifications in our calculations.
- k_T-smearing (gaussian) is applied to the initial state partons to provide better description at low p_T.
- $\langle k_T^2 \rangle = 1 + (1/12) \ln(\sqrt{s}/20 \text{ GeV})$
- 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/ψ 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
- ψ(2S) polarization as an independent check
  - much more difficult due to strong suppression

Photoproduction in ICEM at $\mathcal{O}(\alpha\alpha_s^2)$[17]

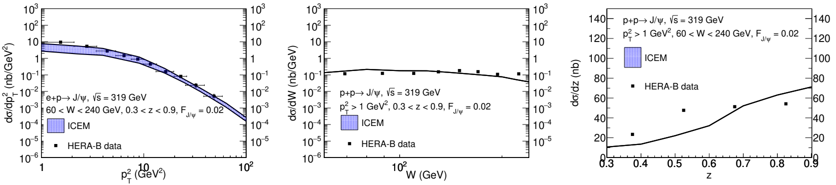
Production distribution

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

- Currently all 8 diagrams from $\gamma g \to c\bar{c}g$ channel are included
- 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

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

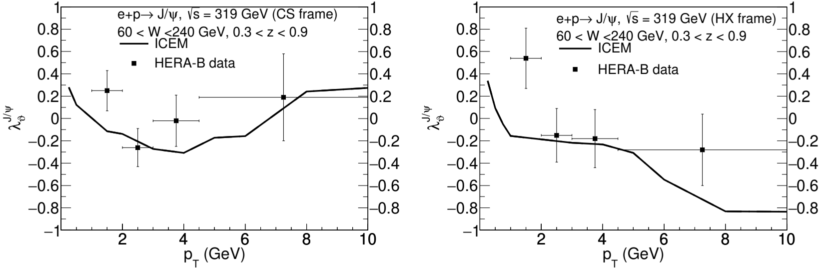
$$W^2 = (q+p)^2,\ z = (p_\psi \cdot p)/(q \cdot p)$$



- Our preliminary results find agreement with the p_T and W distribution at HERA[18],
- 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.

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

Photoproduction Results in ICEM[17]



- 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[18]

Conclusion and Future

In this talk, I

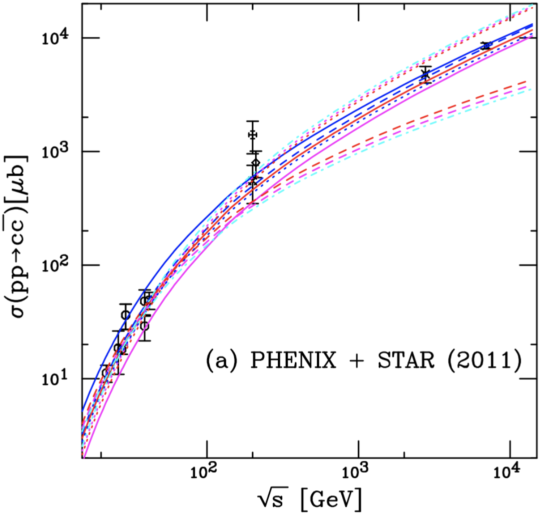
- showed recent attempts the describe quarkonium production using the (I)CEM
- showed expansions of our approach beyond $p + p$ collisions

We are working on

- including effects from feed down production.
- production in ep via photo-production.
- photo-production in CGC+NRQCD and CGC+ICEM.

Backup Slides

CEM Theory Band



How $|J, J_z\rangle$ states are formed

Two helicity combinations that result in $S_z = 0$ are added and normalized to give contribution to the spin triplet state ($S = 1$). We calculate the amplitudes for $J = 0, 1, 2$:

$$
\begin{aligned}
\mathcal{A}_{J=1,J_z=\pm1} &= \mathcal{A}_{L=0,L_z=0;S=1,S_z=\pm1}\ , \text{(S States)} \\
\mathcal{A}_{J=1,J_z=0} &= \mathcal{A}_{L=0,L_z=0;S=1,S_z=0}\ , \text{(S States)} \\
\mathcal{A}_{J=0,J_z=0} &= -\sqrt{\frac{1}{3}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=0}\ , (\chi_0 \text{ States}) \\
\mathcal{A}_{J=1,J_z=\pm1} &= \mp\frac{1}{\sqrt{2}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=\pm1}\ , (\chi_1 \text{ States}) \\
\mathcal{A}_{J=1,J_z=0} &= 0\ , (\chi_1 \text{ States}) \\
\mathcal{A}_{J=2,J_z=\pm2} &= 0\ , (\chi_2 \text{ States}) \\
\mathcal{A}_{J=2,J_z=\pm1} &= \frac{1}{\sqrt{2}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=\pm1}\ , (\chi_2 \text{ States}) \\
\mathcal{A}_{J=2,J_z=0} &= \sqrt{\frac{2}{3}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=0}\ . (\chi_2 \text{ States})
\end{aligned}
$$

Production formula in collinear CEM at $\mathcal{O}(\alpha_s^2)$

CEM using collinear factorization approach

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

- Convoluted with the CTEQ6L1 parton distribution functions (PDFs)
- α_s is calculated at one-loop level
- We took the factorization and renormalization scales to be $\mu^2 = \hat{s}$
- $1.27 < m_c < 1.50$ GeV, $4.5 < m_b < 5.0$ GeV
- Assumed that the polarization is unchanged by the transition from the parton level to the hadron level

Presenting 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, λ_ϑ, 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

$J^P = 1^-$ (S states)[19]

$$\lambda_\vartheta = \frac{\sigma^{J_z=+1} + \sigma^{J_z=-1} - 2\sigma^{J_z=0}}{\sigma^{J_z=+1} + \sigma^{J_z=-1} + 2\sigma^{J_z=+0}}$$

[19] P. Faccioli, C. Lourenco, J. Seixas, and H. K. Wohri, Eur. Phys. J. C **69**, 657 (2010).

Presenting Polarization

- For the χ_1 ($J = 1$) and χ_2 ($J = 2$) states, the polarization parameter is defined as the polarization parameter of the product J/ψ or $\Upsilon(n\mathrm{S})$ if production comes purely from χ state feed down
- $\chi_c \to J/\psi + \gamma$, $\chi_b \to \Upsilon(n\mathrm{S}) + \gamma$

$J^P = 1^+$ (χ_1 P states)[20]

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

$J^P = 2^+$ (χ_2 P states)[20]

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

[20] P. Faccioli *et al.*, Phys. Lett. B **773**, 476 (2017).

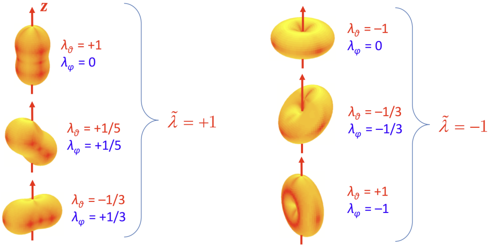
Visualizing invariant polarization

Azimuthal anisotropy[19]

$$\lambda_\phi = \frac{2Re[a_{+1}a^*_{-1}]}{\mathcal{N} + a_0^2}$$

Frame invariant parameter[19]

$$\tilde{\lambda} = \frac{\lambda_\theta - 3\lambda_\phi}{1 - \lambda_\phi}$$



- Calculating invariant $\tilde{\lambda}$ removes frame-induced kinematic dependencies

Polarization Puzzle[21]

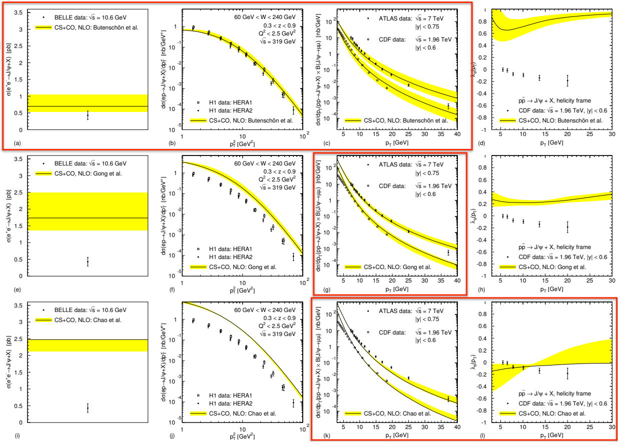
Difficult to describe both the yields and polarizations simultaneously within a given approach (e.g. NRQCD)

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

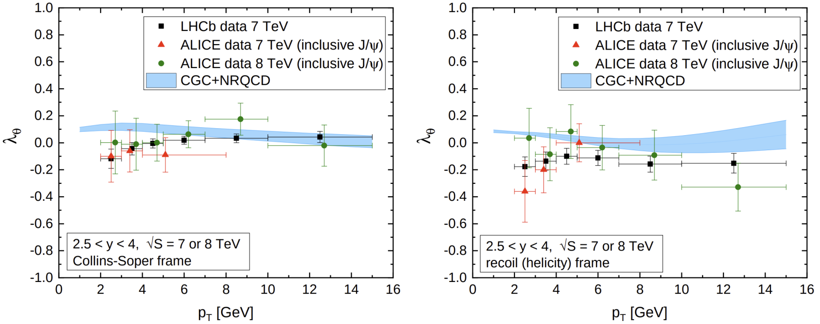
Chao et al. $p_T > 7$ GeV



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

CGC+NRQCD[22]

- 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



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