Polarization of quarkonium in $p+p$ and $h+A$

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Overview

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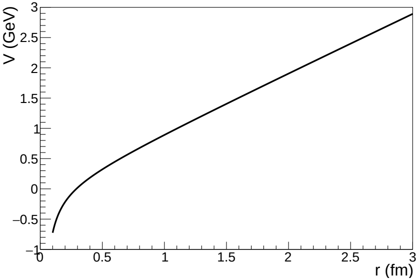
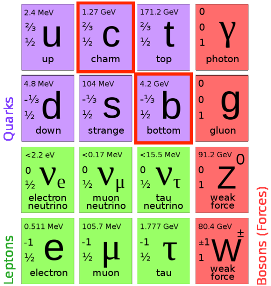
Quarkonium: A Bound State of $Q\overline{Q}$

Bound by the interquark potental: $V(r) = \sigma r - \alpha_c/r$[1]

- linear term refers to the confinement
- $1/r$ term refers to the Coulomb-like short distance behavior
- $\sigma = 0.192$ GeV^2, $\alpha_c = 0.471$[2]

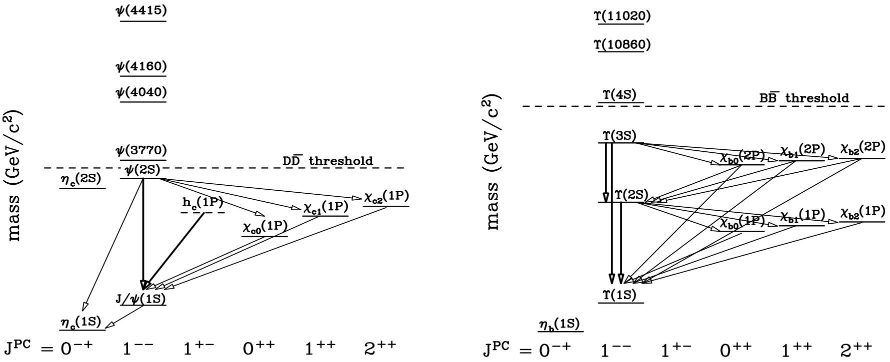




[1] E. Eichten *et al.*, Phys. Rev. D **17**, 3090 (1978).

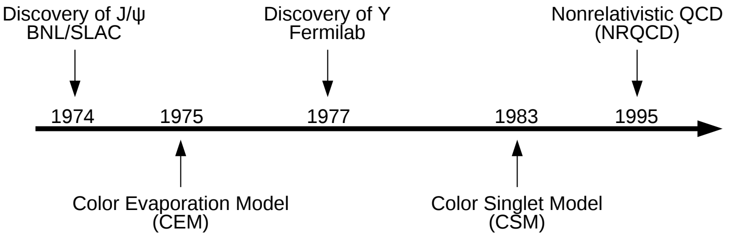
[2] F. Karsch, M. T. Mehr, and H. Satz, Z. Phys. C **37**, 617 (1988).

Quarkonium Families



- states above the $H\overline{H}$ ($H = D, B$) threshold decay hadronically
- states below the $H\overline{H}$ threshold decay electromagnetically to lower energy bound states (feed down)

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]

- only color singlet contribution is considered

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

- separate all spin and color states

Quarkonium Production Models

Non Relativistic QCD (NRQCD)

- 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
- $\langle \mathcal{O}^{J/\psi}[n] \rangle$ are nonperturbative Long Distance Matrix Elements (LDMEs) that describe the conversion of $c\bar{c}[n]$ state into final state J/ψ, assuming that the hadronization does not change the kinematics
- LDMEs are assumed to be universal and are expanded in powers of v/c and α_s
- leading term is $n = {}^3S_1^{[1]}$, corresponds to the color singlet model
- color octet states are subleading terms $n = \{{}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}\}$
- mixing of LDMEs are determined by fitting to data, usually p_T distributions above some p_T cut

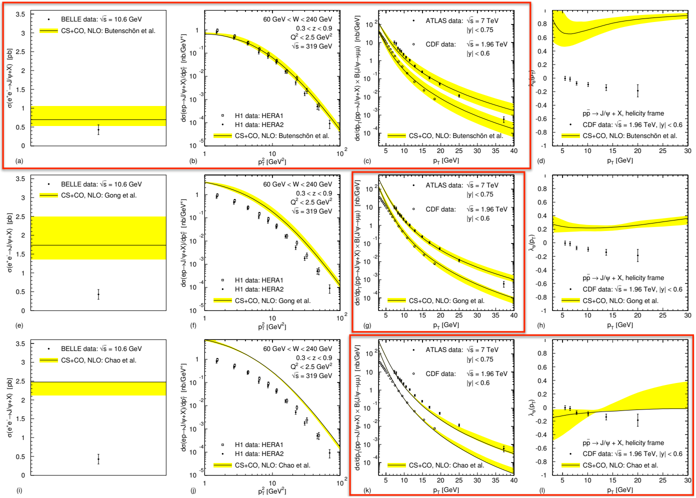
Polarization Puzzle[3]

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



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

Quarkonium Production Models

Revisiting the Color Evaporation Model

- all Quarkonium states are treated like $Q\overline{Q}$ ($Q = c, b$) below $H\overline{H}$ ($H = D, B$) threshold
- does not separate states into color (or spin)
- color is said to be 'evaporated' away during transition from pair to Quarkonium state while preserving the kinematics
- mostly calculated by perturbative QCD
- fewer parameters than NRQCD (one F_Q for each Quarkonium state)
- F_Q is fixed by comparison of NLO calculation of σ_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
- spin has been averaged over, no previous prediction of polarization in CEM until 2017

Improved Color Evaporation Model [Ma, Vogt 1609.06042]

Leading Order Total Cross Section

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

F_Q is a universal factor for the quarkonium state and is independent of the projectile, target, and energy.

Leading Order Rapidity Distribution

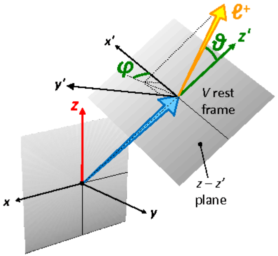
$$\frac{d\sigma}{dy} = F_Q \sum_{i,j} \int_{m_Q^2}^{4m_H^2} \frac{d\hat{s}}{s} f_{i/p}(x_1, \mu^2) f_{j/p}(x_2, \mu^2) \hat{\sigma}_{ij}(\hat{s}) ,$$

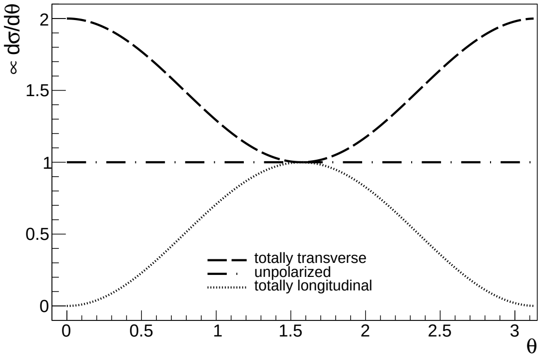
where $x_{1,2} = (\sqrt{\hat{s}/s}) \exp(\pm y)$.

and m_Q is the mass of the quarkonium state Q.

⚠ *In the tradition color evaporation model, the lower limit is* $4m_c^2$ *or* $4m_b^2$.

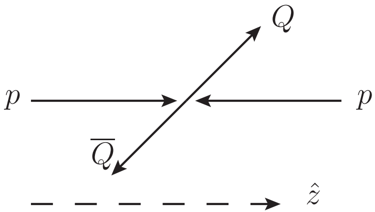
Polarization of Quarkonium





- defined as the tendency of quarkonium to be in a certain angular momentum state given its total angular momentum
- e.g. an unpolarized $J = 1$ production means $J_z =$ -1, 0, +1 production is equally likely
- longitudinal $\rightarrow$ peak at $\vartheta = \pi/2$; transverse $\rightarrow$ peaks at $\vartheta = 0, \pi$

Defining Polarization at Leading Order



Polarization in the Helicity Basis

- helicity is the projection of angular momentum onto the direction of momentum
- if the helicities are the same, then $J_z = 0$ (longitudinal)
- if the helicities are the opposite, then $J_z = \pm 1$ (transverse)

Scattering Amplitudes

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_z of the final state

Orbital Angular Momentum

At leading order, the final state $Q\overline{Q}$ is produced with no dependence on the azimuthal angle and thus $L_z = 0$. 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.

$|J, J_z\rangle$ States

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 $J = 0, 1, 2$:

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

Polarized Partonic Cross Section[4]

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

$$\hat{\sigma}_{q\bar{q}}^{J_z=0}(\hat{s}) = 0\,,$$
$$\hat{\sigma}_{q\bar{q}}^{J_z=\pm 1}(\hat{s}) = \frac{\pi\alpha_s^2}{9\hat{s}}\chi\,,$$
$$\hat{\sigma}_{gg}^{J_z=0}(\hat{s}) = \frac{7\pi\alpha_s^2}{48\hat{s}}\frac{M^2}{\hat{s}\chi}\left(\ln\frac{1+\chi}{1-\chi}\right)^2\,,$$
$$\hat{\sigma}_{gg}^{J_z=\pm 1}(\hat{s}) = \frac{\pi^3\alpha_s^2}{1536\hat{s}}\chi\frac{(\sqrt{\hat{s}}-2M)(37\sqrt{\hat{s}}+38M)}{(2M+\sqrt{\hat{s}})^2}\,.$$

where $\chi = \sqrt{1-4M^2/\hat{s}}$ and $M = \{m_c, m_b\}$.

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Polarized Partonic Cross Section[4]

$J^P = 0^+$ (χ_0 P States)

$$\hat{\sigma}_{q\bar{q}}^{J_z=0}(\hat{s}) = 0\ ,$$

$$\hat{\sigma}_{gg}^{J_z=0}(\hat{s}) = \frac{9\pi\alpha_s^2}{16\hat{s}}\frac{M^2}{\hat{s}\chi^3}\left(2\chi - \ln\frac{1+\chi}{1-\chi}\right)^2 .$$

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Polarized Partonic Cross Section[4]

$J^P = 1^+$ (χ_1 P States)

$$
\begin{aligned}
\hat{\sigma}_{q\bar{q}}^{J_z=0}(\hat{s}) &= 0\,, \\
\hat{\sigma}_{q\bar{q}}^{J_z=\pm1}(\hat{s}) &= \frac{\pi\alpha_s^2}{18\hat{s}}\chi\,, \\
\hat{\sigma}_{gg}^{J_z=0}(\hat{s}) &= 0\,, \\
\hat{\sigma}_{gg}^{J_z=\pm1}(\hat{s}) &= \frac{3\pi^3\alpha_s^2}{256\hat{s}}\chi\frac{(\sqrt{\hat{s}}-2M)(4\hat{s}-9M^2)}{(2M+\sqrt{\hat{s}})^3}\,.
\end{aligned}
$$

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Polarized Partonic Cross Section[4]

$J^P = 2^+$ (χ_2 P States)

$$\begin{aligned}
\hat{\sigma}_{q\bar{q}}^{J_z=0}(\hat{s}) &= 0\,, \\
\hat{\sigma}_{q\bar{q}}^{J_z=\pm 1}(\hat{s}) &= \frac{\pi\alpha_s^2}{18\hat{s}}\chi\,, \\
\hat{\sigma}_{gg}^{J_z=0}(\hat{s}) &= \frac{9\pi\alpha_s^2}{8\hat{s}}\frac{M^2}{\hat{s}\chi^3}\left(2\chi - \ln\frac{1+\chi}{1-\chi}\right)^2\,, \\
\hat{\sigma}_{gg}^{J_z=\pm 1}(\hat{s}) &= \frac{3\pi^3\alpha_s^2}{256\hat{s}}\chi\frac{(\sqrt{\hat{s}}-2M)(4\hat{s}-9M^2)}{(2M+\sqrt{s})^3}\,,
\end{aligned}$$

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Feed Down Production[5]

After obtaining their hadron level cross section by convoluting with PDFs, for each directly produced quarkonium state Q, we compute $R_Q^{J_z}$. We then compute their contribution to the final state $R_{J/\psi}^{J_z=0}$ or $R_{\Upsilon(1S)}^{J_z=0}$ assuming two pions are emitted from an S state feed down and a photon is emitted from a P state feed down by:

$$R_{J/\psi}^{J_z=0} = \sum_{\psi,J_z} c_\psi S_\psi^{J_z} R_\psi^{J_z} \, , R_{\Upsilon(1S)}^{J_z=0} = \sum_{\Upsilon,J_z} c_\Upsilon S_\Upsilon^{J_z} R_\Upsilon^{J_z} \, ,$$

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
$\psi(2S)$	3.69	0.08	1	0
$\chi_{c1}(1P)$	3.51	0.16	0	1/2
$\chi_{c2}(1P)$	3.56	0.14	2/3	1/2
$\Upsilon(1S)$	9.46	0.52	1	0
$\Upsilon(2S)$	10.0	0.1	1	0
$\Upsilon(3S)$	10.4	0.02	1	0
$\chi_{b1}(1P)$	9.89	0.13	0	1/2
$\chi_{b2}(1P)$	9.91	0.13	2/3	1/2
$\chi_{b1}(2P)$	10.3	0.05	0	1/2
$\chi_{b2}(2P)$	10.3	0.05	2/3	1/2

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

Polarization Parameters

$J^P = 1^-$ (S states)[6]

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

$J^P = 1^+$ (χ_1 P states)[7]

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

$J^P = 2^+$ (χ_2 P states)[7]

$$\lambda_\vartheta = \frac{-3 - 3R^{J_z=0}}{9 + R^{J_z=0}}$$

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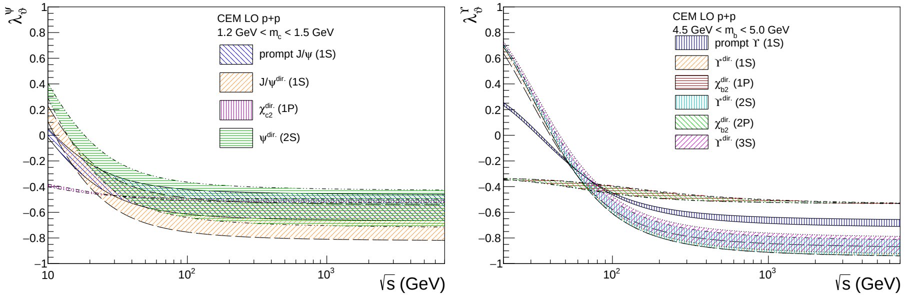
[6] P. Faccioli, C. Lourenço, J. Seixas, and H. K. Wohri, Eur. Phys. J. C **69**, 657 (2010).

[7] P. Faccioli, C. Lourenço, M. Araújo, V. Knünz, I. Krätschmer and J. Seixas, Phys. Lett. B **773**, 476 (2017).

Energy Dependence of Polarization Parameter[4]



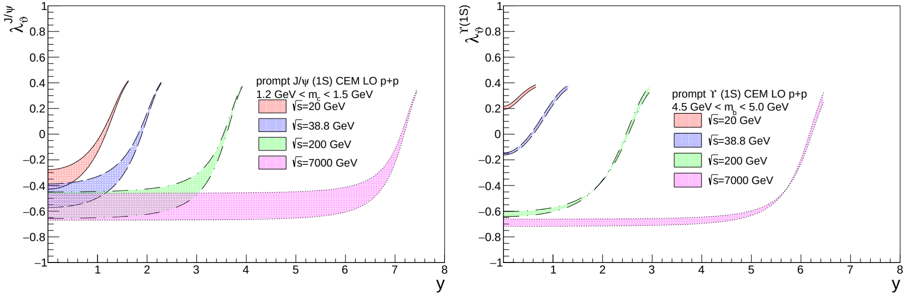
CTEQ6L1 is used for proton PDFs

Energy Dependence

- direct production: $\lambda_\vartheta^{1S} < \lambda_\vartheta^{2S} < \lambda_\vartheta^{3S}$
- prompt production: $\lambda_\vartheta^{\Upsilon(1S)} < \lambda_\vartheta^{J/\psi}$
- prompt J/ψ and $\Upsilon(1S)$ become longitudinally polarized at high $\sqrt{s}$

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Rapidity Dependence of Polarization Parameter[4]

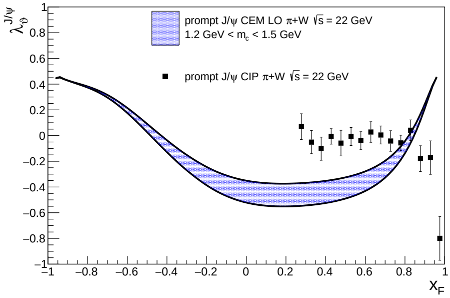


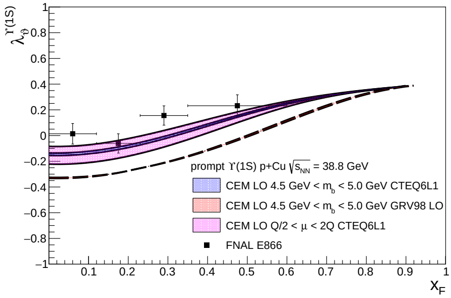
Rapidity Dependence

- λ_ϑ is most negative (longitudinal) at $y = 0$ and increases as $|y|$ increases
- production becomes transversely polarized at kinematics limits

[4]V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

Comparing x_F Dependence with Fixed-Target Data[8,9]



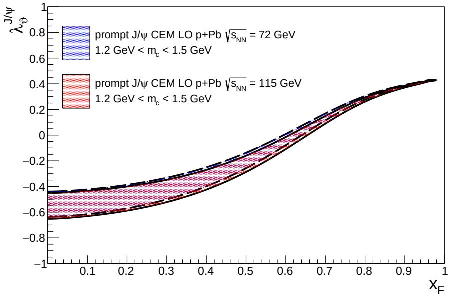


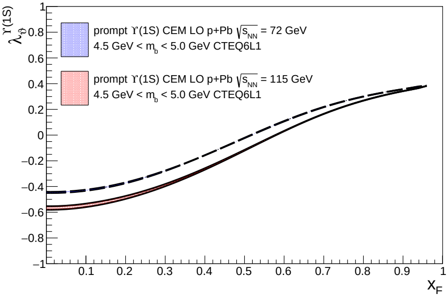
x_F $(x_1 - x_2)$ Dependence (GRS99 for π PDFs and EPS09 for W PDFs)

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

[8] T. H. Chang *et al.* (NuSea Collaboration), Phys. Rev. Lett. **91**, 211801 (2003).
[9] C. N. Brown *et al.* (NuSea Collaboration), Phys. Rev. Lett. **86**, 2529 (2001).

Predictions for p+Pb at Fixed-Target Energy at the LHC[4]





x_F Dependence

- at $\sqrt{s_{NN}} = 72$ and 115 GeV
- prompt J/ψ: polarization already starts to saturate $\rightarrow$ no difference
- prompt $\Upsilon(1S)$: more longitudinal for $\sqrt{s_{NN}} = 115$ GeV

[4] V. Cheung and R. Vogt, Phys. Rev. D **96,** 054014 (2017).

ICEM Polarization using k_T-factorization Approach

Motivation

- motivated by NRQCD calculations using k_T-factorization approach[10]
- obtain p_T-dependence using partonic cross section at $\mathcal{O}(\alpha_s^2)$ in the high-energy limit
- allows us to compare with more extensive p_T-dependent data
- see if p_T-averaged calculation is closer to data in x_F dependence

ICEM Cross Section using k_T-factorization Approach

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

[10] B. A. Kniehl, V. A. Saleev and D. V. Vasin, Phys. Rev. D **73,** 074022 (2006).

Setup of the Calculation

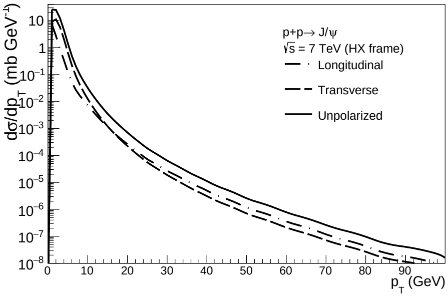
- high energy $\rightarrow$ production is dominated by t-channel gluon exchange
- transverse momenta (k_T) of the incoming gluons and their off-shell properties can no longer be neglected $\rightarrow$ Reggeized gluons $(\mathcal{R})$
- $\mathcal{A}(\mathcal{R}+\mathcal{R}\rightarrow Q\overline{Q}) = \epsilon^{\mu}(k_1)\epsilon^{\nu}(k_2)\mathcal{A}_{\mu,\nu}(g+g\rightarrow Q\overline{Q})$
- $\epsilon(k_1) = \left(0, \frac{\vec{k_{1T}}}{|k_{1T}|}, 0\right)$, $\epsilon(k_2) = \left(0, \frac{\vec{k_{2T}}}{|k_{2T}|}, 0\right)$
- $k_1 = (x_1 s, \vec{k_{1T}}, x_1 s)$, $k_2 = (x_2 s, \vec{k_{2T}}, -x_2 s)$
- calculated using JH-2013[11] unintegrated PDFs, $\Phi(x, k_T, Q)$
- factorization scale set at $Q^2 = m_T^2$
- renormalization scale set at $\mu^2 = \hat{s}$
- in Helcity (HX) Frame (to compare with data)

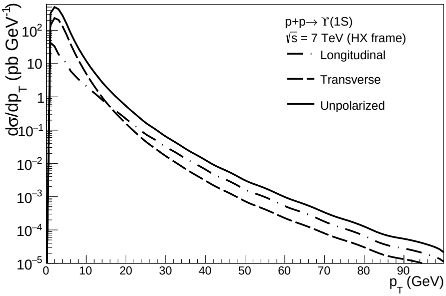
[11] F. Hautmann and H. Jung, Nucl. Phys. B **883**, 1 (2014).

p_T Distribution[12]

⚠ *F_Q is set to 1 here*

⚠ *Production is unpolarized when $\sigma_{\mathrm{Longitudinal}} = \sigma_{\mathrm{Transverse}}$*





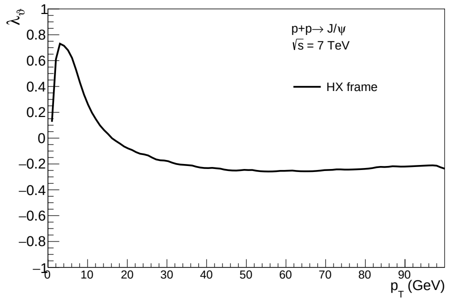
p_T distribution of direct J/ψ

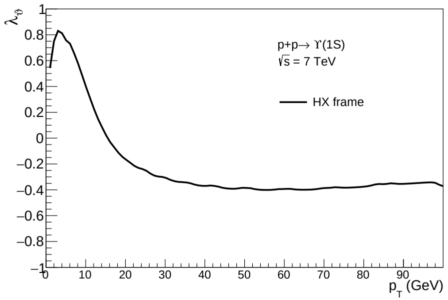
- unpolarized production falls off as $\sim p_T^{-5}$ to p_T^{-6}
- both J/ψ and $\Upsilon(1S)$ become unpolarized at $p_T \sim 15$ GeV

[12] V. Cheung and R. Vogt, in preparation.

p_T Dependence of Polarization Parameter[12]

⚠ λ_ϑ *is independent of* F_Q





p_T dependence of direct J/ψ and $\Upsilon(1S)$ polarization

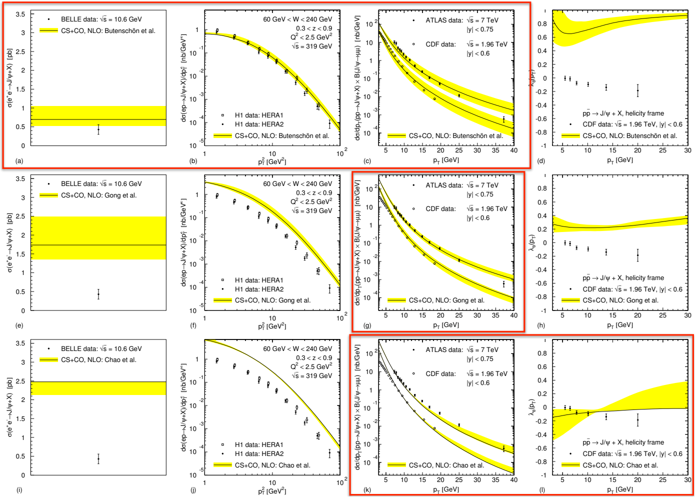
- transverse at small p_T and slightly longitudinal at large p_T
- the range for $\Upsilon(1S)$ is larger than that for J/ψ

[12] V. Cheung and R. Vogt, in preparation.

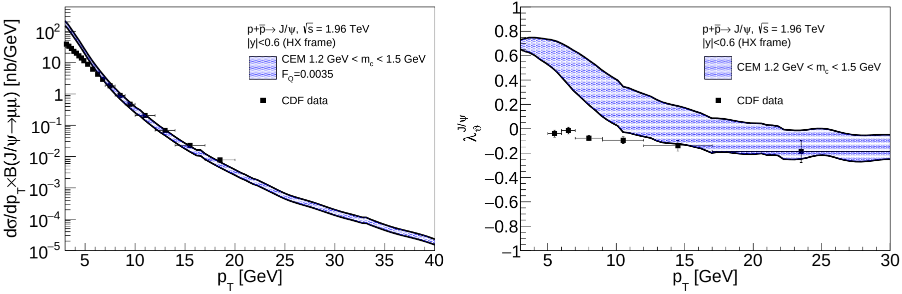
Revisiting the Polarization Puzzle with ICEM

Included in fits

	e^+e^-	ep	pp p_T distribution	pp polarization
Butenschon & Kniehl $p_T > 3$ GeV	(a)	(b)	(c)	(d)
Gong et al. $p_T > 5$ GeV	(e)	(f)	(g)	(h)
Chao et al. $p_T > 7$ GeV	(i)	(j)	(k)	(l)



p_T-dependence with $p\bar{p}$ data[12,13]



p_T-dependence of direct J/ψ polarization at $\sqrt{s} = 1.96$ TeV

- $|y| < 0.6$
- band is contructed by varying 1.2 GeV$< m_c <$ 1.5 GeV

[12] V. Cheung and R. Vogt, in preparation.

[13] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, 132001 (2007).

Conclusion and Future

- reviewed recent attempts to solve the polarization puzzle
- presented the energy, rapidity, and p_T dependence of the polarization of heavy quarkonium production in $p+p$ and $h+A$ collisions in ICEM

Polarization at Leading Order

- longitudinal at most energies and around central rapidity
- transverse at the kinematic limits

Polarization in k_T-factorization Approach

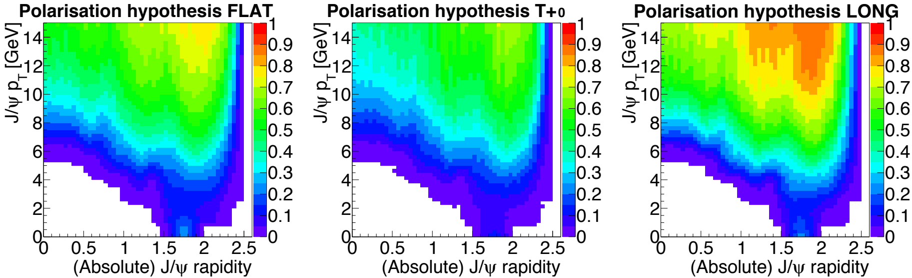
- transverse at small p_T, and preferrably unpolarized or slightly longitudinal at large p_T
- promising approach to have agreement in both yield and polarization

Future in the ICEM

- work on the feed down production treatment
- start full NLO polarization calculation in the CEM

Backup Slides

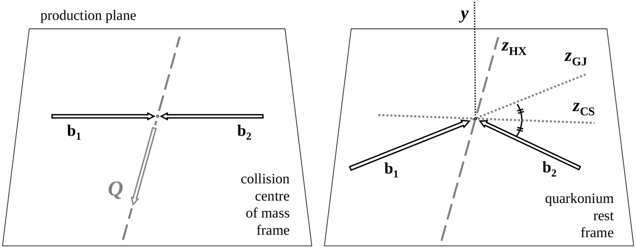
Polarization and Experimental Acceptance[14]



from left to right: unpolarized, totally transverse, totally longitudinal.

[14] The ATLAS Collaboration, Nucl. Phys. B **850**, 387 (2011).

Defining Polarization[6]

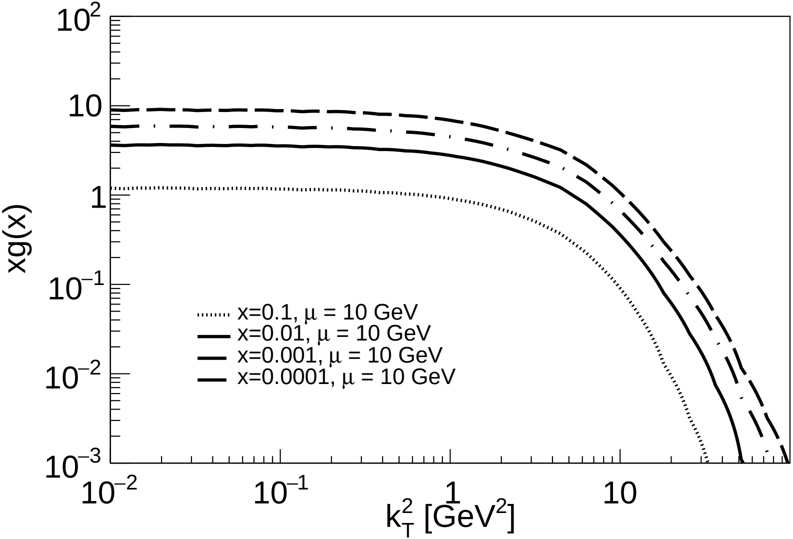


Polarization in the Helicity Basis

- z_{HX} is the flight direction of the quarkonium itself in the center-of-mass of the colliding beams
- If the helicities are the same, then $J_z = 0$ (longitudinal)
- If the helicities are the opposite, then $J_z = \pm 1$ (transverse)

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

JH-2013 uPDF[11]



[11] F. Hautmann and H. Jung, Nucl. Phys. B **883**, 1 (2014).