Quarkonium Production and Polarization in the Improved Color Evaporation Model

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Traditional Color Evaporation Model

All quarkonium states treated like heavy quark pairs (*Q = c, b*) below heavy hadron (*H = D, B*) threshold

Color and spin are averaged over in pair cross section so color is 'evaporated' during transition from quark pair to quarkonium without changing kinematics

Distributions for quarkonium family members assumed identical

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

Values of quark mass, *m*, and scale, μ, fixed from NLO calculation of heavy quark pair cross section

Scale factor F_Q fixed by comparison of $\sigma_Q^{\rm CEM}$ to energy dependence of J/ψ and Υ cross sections, $\sigma(x_F > 0)$ and $Bd\sigma/dy|_{y=0}$ for J/ψ, $Bd\sigma/dy|_{y=0}$ for Υ, only one F_Q for each state of quarkonium family

Spin always summed over so no previous predictions of polarization in CEM

Improved Color Evaporation Model

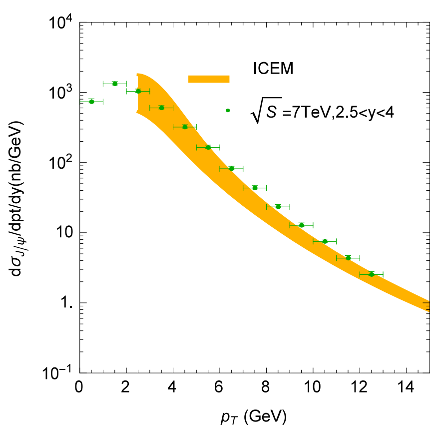
Relates average final state ψ momentum, <p_ψ>, to quark pair momentum *p*

$$\langle p_\psi \rangle = \frac{M_\psi}{M} p + \mathcal{O}(\lambda^2/m_c)$$

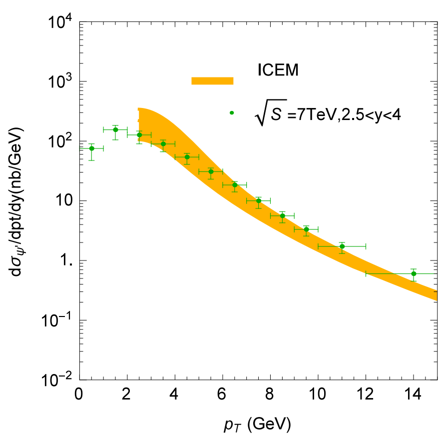
Lower limit on pair mass, *M*, has to be larger than <p_ψ>, lower limit on CEM integration has to be increased to M_ψ so that the transverse momentum distribution becomes

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

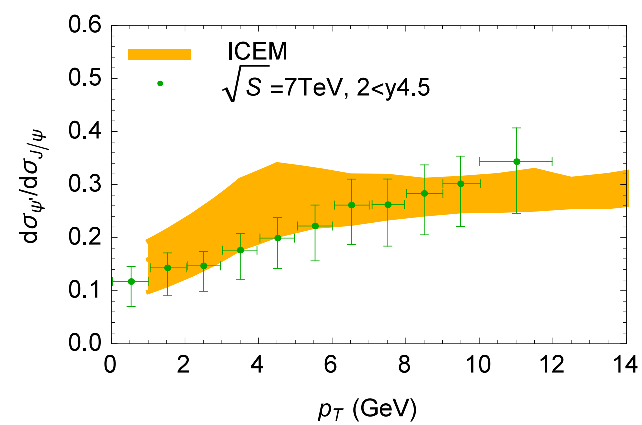
J/ψ



ψ'



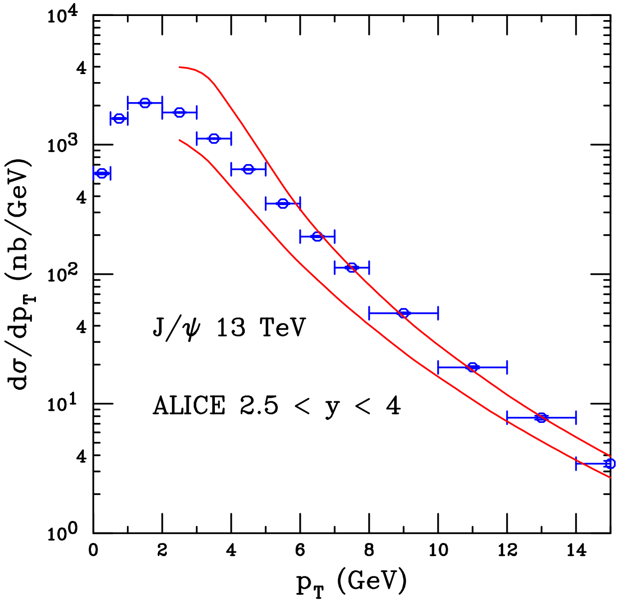
ψ'/ψ ratio

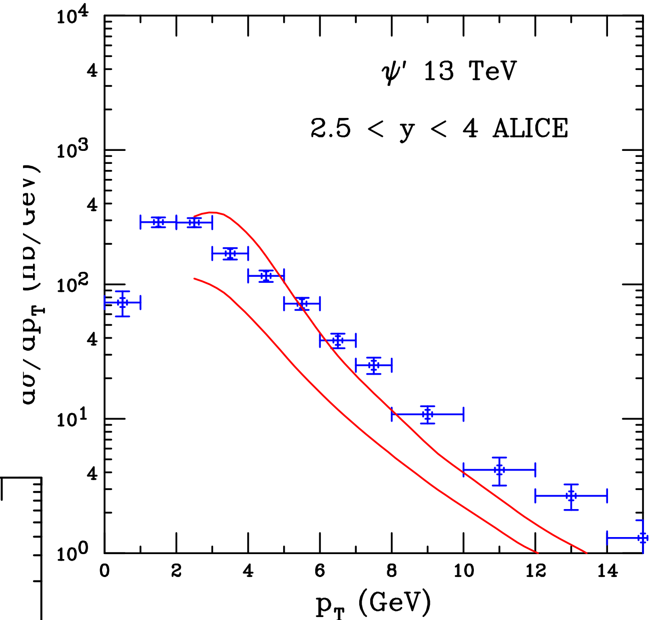


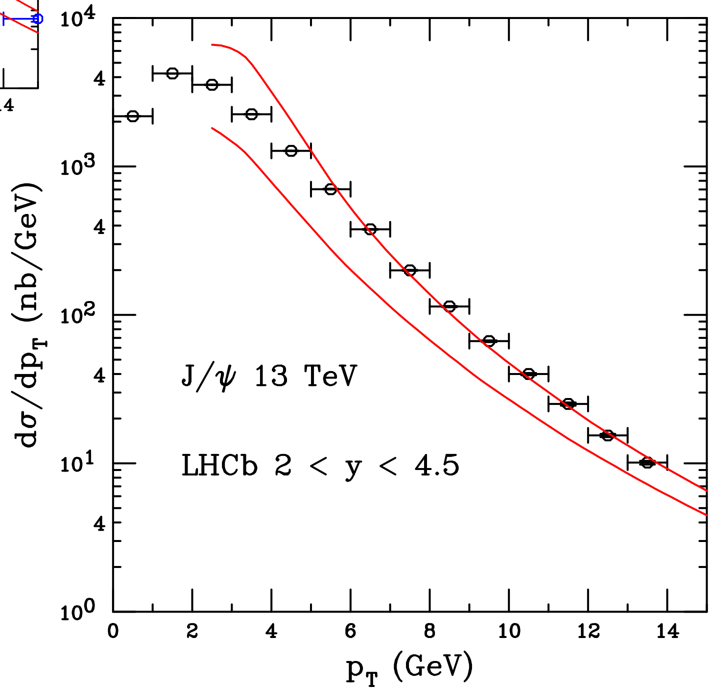
LHCb 7 TeV p+p

Y-Q Ma & RV, Phys. Rev. D

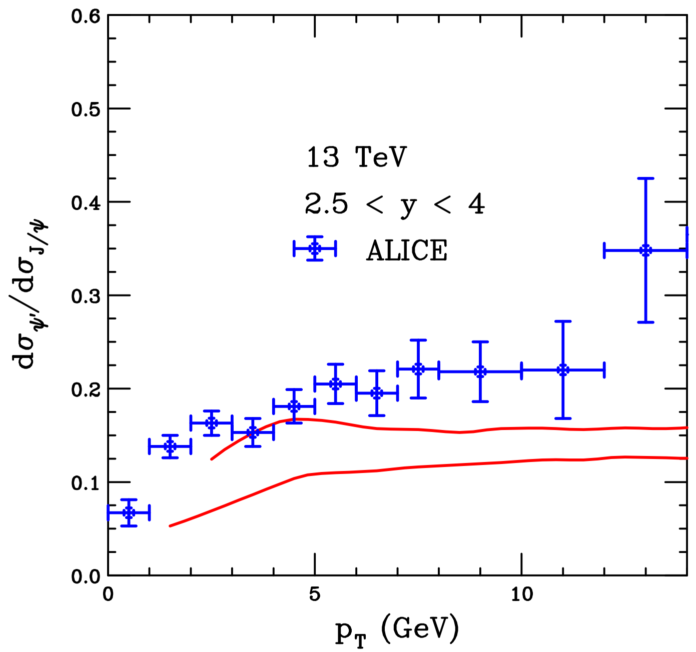
J/ψ and ψ′ at 13 TeV in the ICEM

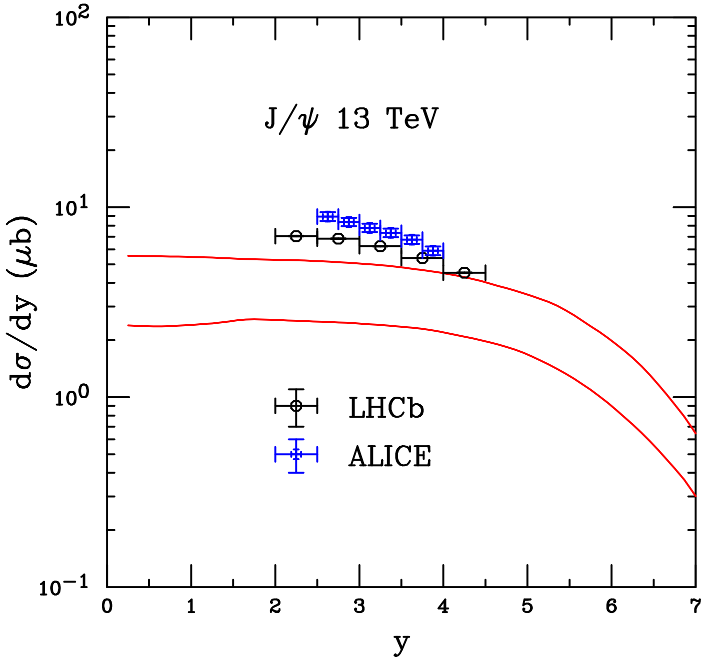




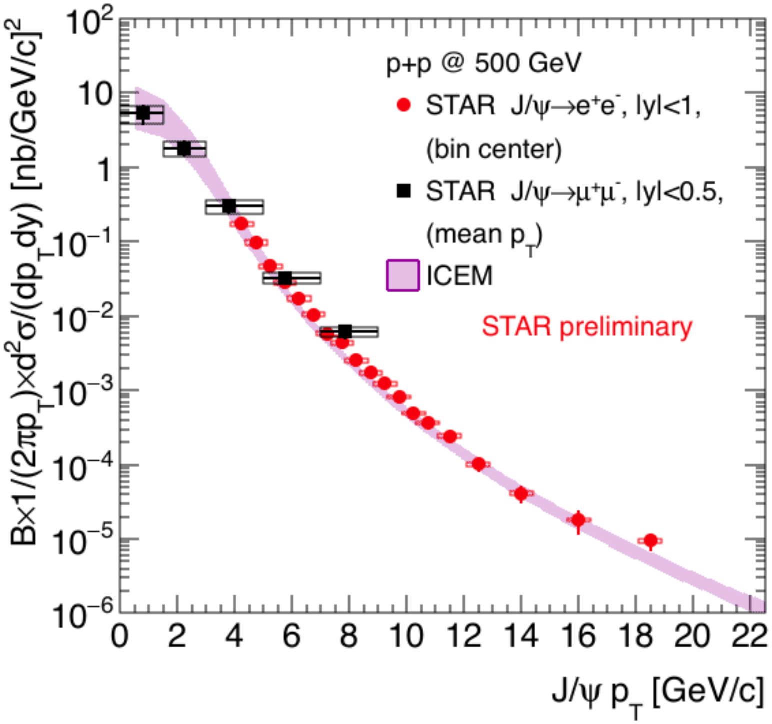


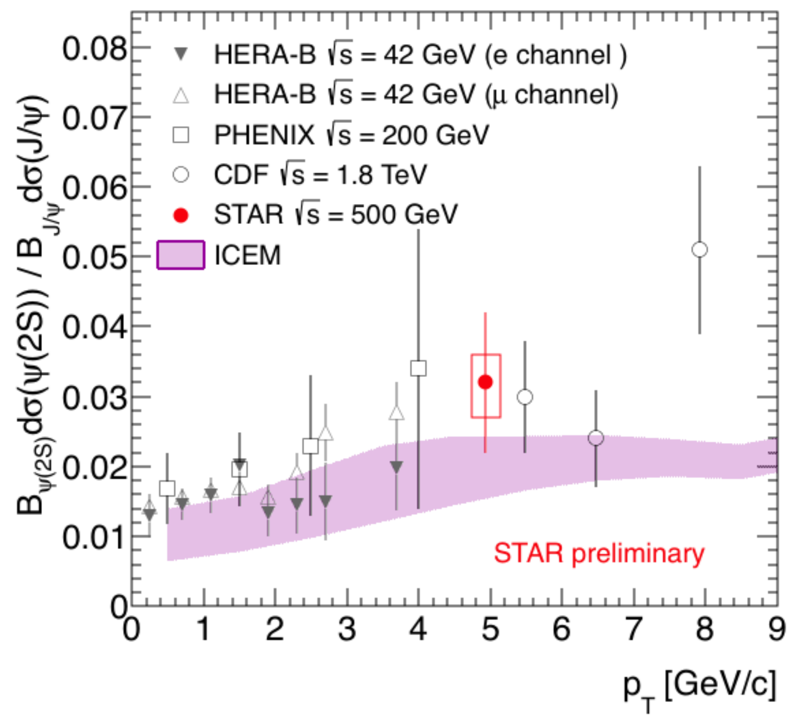
ψ'/J/ψ ratio at 13 TeV





J/ψ ICEM results for STAR at 500 GeV





Compliments of Z. Tang

k_T factorization calculation of production and polarization in ICEM

- First step toward obtaining full p_T dependence of quarkonium polarization in ICEM
- Use Reggeized gluons, off shell matrix elements and unintegrated gluon distribution (ccfm-JH-2013-set1)
- Normalization F_Q consistent with collinearly-factorized results given differences in calculations

$$
\begin{aligned}
\sigma &= F_Q \int_{m_Q^2}^{4m_H^2} d\hat{s} \int dx_1 \int dx_2 \int dk_{1T}^2 \int dk_{2T}^2 \int \frac{d\phi_1}{2\pi} \int \frac{d\phi_2}{2\pi} \\
&\times \Phi_1(x_1, k_{1T}, \mu_1)\Phi_2(x_2, k_{2T}, \mu_2)\hat{\sigma}(\mathcal{R}+\mathcal{R} \to Q\overline{Q})\delta(\hat{s} - x_1 x_2 s + |\vec{k}_{1T} + \vec{k}_{2T}|^2)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}(\mathcal{R}+\mathcal{R} \to Q\overline{Q}) &= \epsilon^\mu(k_1)\epsilon^\nu(k_2)\mathcal{A}_{\mu,\nu}(g+g \to Q\overline{Q}) \\
\mathcal{A}_{L=0} &= \frac{1}{2}\int_{-1}^{1} dx \mathcal{A}(x = \cos\theta)
\end{aligned}
$$

$$
k_1 = (x_1, s, \vec{k}_{1T}, x_1 s) \qquad k_2 = (x_2 s, \vec{k}_{2T}, -x_2 s)
$$

$$
\epsilon(k_1) = (0, \vec{k}_{1T}/|k_{1T}|, 0) \qquad \epsilon(k_2) = (0, \vec{k}_{2T}/|k_{2T}|, 0)
$$

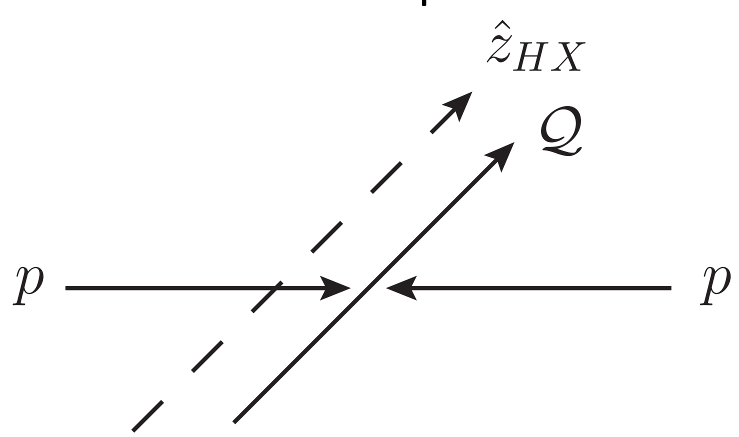
First polarization calculation in the ICEM

Done with UC Davis grad student Vincent Cheung, see Phys. Rev. D **96** (2017) 054014, 074021, in progress – I am representing his work here

Assume that, like kinematics (transverse momentum and rapidity), spin is ’frozen’ in and is not changed by the process of color ‘evaporation’

Sort contributions by spin but average over color as usual

First work studied energy and rapidity dependence only, work shown here is using k_T factorization approach to obtain p_T dependence, LO only so far but NLO calculation with collinear factorization is planned



Start with calculation of amplitudes

Take individual LO amplitudes, 1 quark-antiquark, 3 gluon-gluon and separate according to S_z of final state (quark-antiquark not included with k_T factorization)

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

Calculate projection onto L = 0 or 1

At LO there is no dependence on azimuthal angle so that $L_z = 0$

To extract the projection onto a state with orbital angular momentum L = 0 or 1, calculate corresponding Legendre component $\mathcal{A}_L$ in the amplitudes as

$$\mathcal{A}_{L=0} = \frac{1}{2}\int_{-1}^{1} dx \mathcal{A}(x = \cos\theta)$$

$$\mathcal{A}_{L=1} = \frac{3}{2}\int_{-1}^{1} dx \; x\mathcal{A}(x = \cos\theta)$$

Amplitudes and cross sections for |J,J_z>

Two helicity combinations resulting in S_z = 0 are added and normalized to give contributions to the spin triplet state S = 1, calculate amplitudes for J = 0, 1 and 2

S states (J = 1, S = 1, L = 0):

$$\begin{aligned}\mathcal{A}_{J=1,J_z=\pm1} &= \mathcal{A}_{L=0,L_z=0;S=1,S_z=\pm1}\\ \mathcal{A}_{J=1,J_z=0} &= \mathcal{A}_{L=0,L_z=0;S=1,S_z=0}\end{aligned}$$

P states (J = 0, 1, 2; L = S = 1):

$$\begin{aligned}\mathcal{A}_{J=0,J_z=0} &= -\sqrt{\frac{1}{3}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=0},\\ \mathcal{A}_{J=1,J_z=\pm1} &= \mp\frac{1}{\sqrt{2}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=\pm1}\\ \mathcal{A}_{J=1,J_z=0} &= 0\\ \mathcal{A}_{J=2,J_z=\pm2} &= 0\\ \mathcal{A}_{J=2,J_z=\pm1} &= \frac{1}{\sqrt{2}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=\pm1}\\ \mathcal{A}_{J=2,J_z=0} &= \sqrt{\frac{2}{3}}\mathcal{A}_{L=1,L_z=0;S=1,S_z=0}\end{aligned}$$

Calculation of Partonic Cross Sections

Partonic cross sections obtained by weighing amplitudes by appropriate color factors and summing contributions for given states

Contributions from different spins are added with appropriate Clebsch-Gordon coefficients

Feed down fractions give appropriate contribution to prompt J/ψ and Υ(1S)

$$\begin{aligned}
|\mathcal{M}_{gg}^{J,J_z}|^2 &= |C_{gg,\hat{s}}|^2|\mathcal{A}_{gg,\hat{s}}|^2 + |C_{gg,\hat{t}}|^2|\mathcal{A}_{gg,\hat{t}}|^2 \\
&+ |C_{gg,\hat{u}}|^2|\mathcal{A}_{gg,\hat{u}}|^2 + 2C^*_{gg,\hat{s}}C_{gg,\hat{t}}\mathcal{A}^*_{gg,\hat{s}}\mathcal{A}_{gg,\hat{t}} \\
&+ 2C^*_{gg,\hat{s}}C_{gg,\hat{u}}\mathcal{A}^*_{gg,\hat{s}}\mathcal{A}_{gg,\hat{u}} \\
&+ 2C^*_{gg,\hat{t}}C_{gg,\hat{u}}\mathcal{A}^*_{gg,\hat{t}}\mathcal{A}_{gg,\hat{u}}
\end{aligned}$$

$$\hat{\sigma}_{ij}^{J,J_z} = \int d\Omega \left(\frac{1}{8\pi}\right)^2 \frac{|\mathcal{M}_{ij}^{J,J_z}|^2}{\hat{s}} \sqrt{1 - \frac{4M^2}{\hat{s}}}$$

Contributions from feed down:

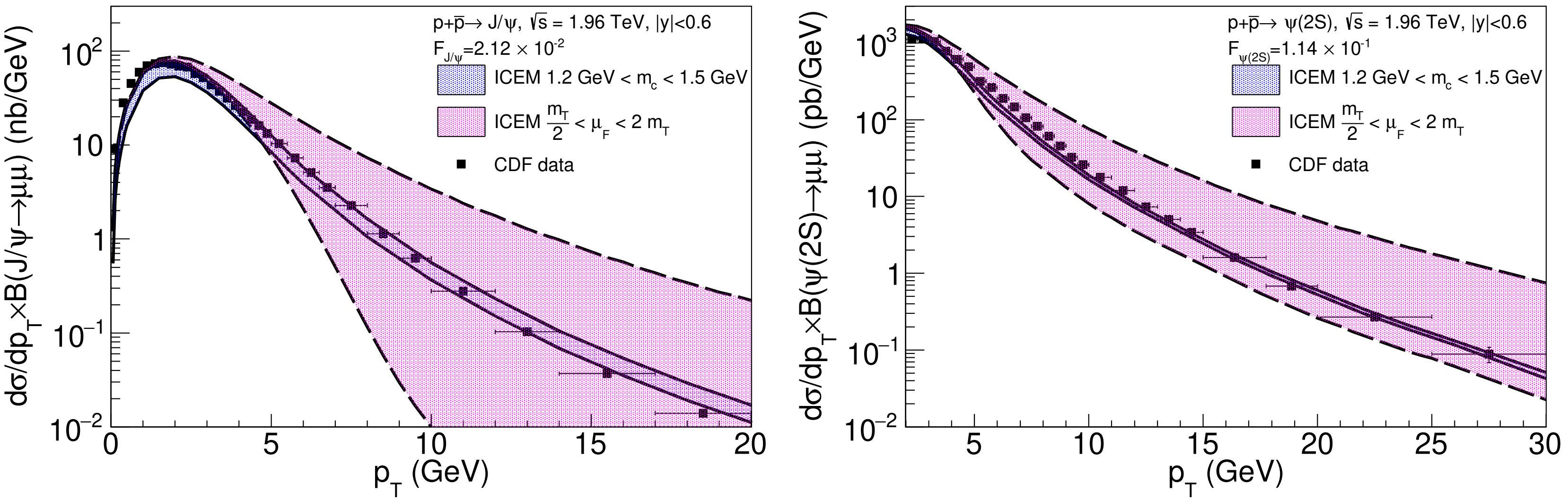
$$R_{J/\psi}^{J_z=0} = \sum_{\psi, J_z} c_\psi S_\psi^{J_z} R_\psi^{J_z}$$

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

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
$\psi(2\mathrm{S})$	3.69	0.08	1	0
$\chi_{c1}(1\mathrm{P})$	3.51	0.16	0	1/2
$\chi_{c2}(1\mathrm{P})$	3.56	0.14	2/3	1/2

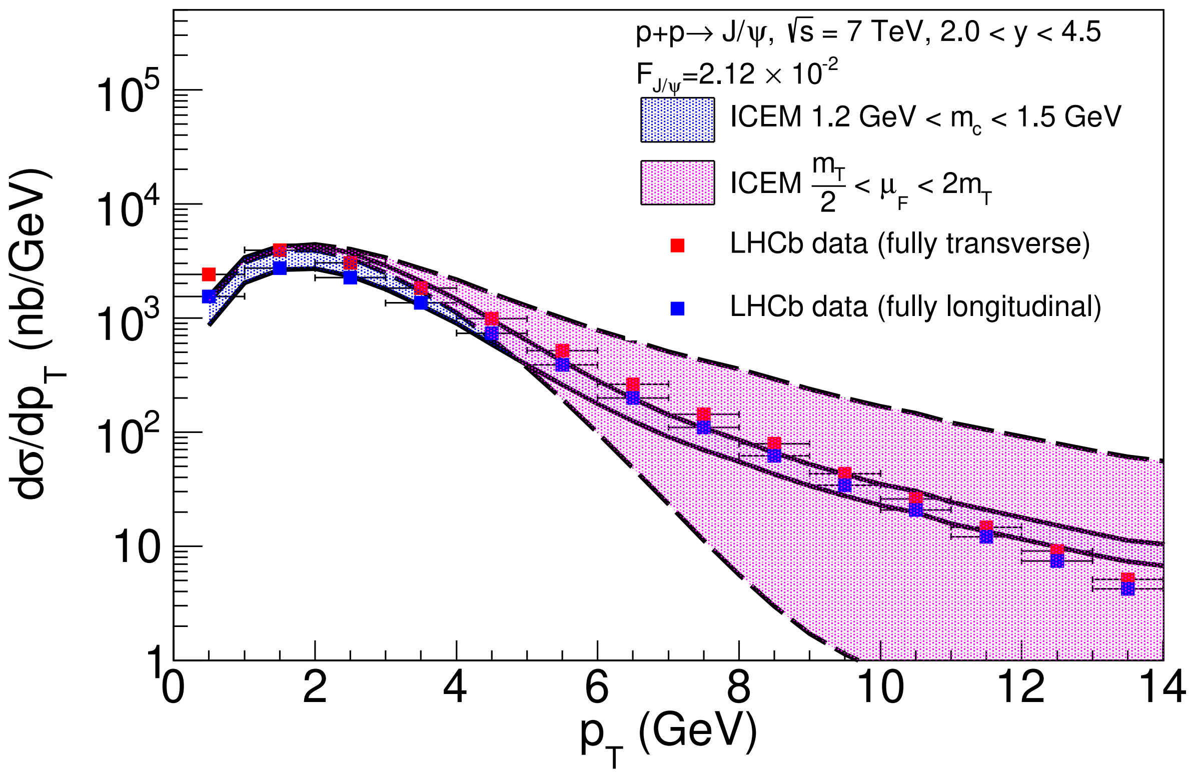
R^{J_z} is the $J_z = 0$ to unpolarized ratios for individual states, c is the feed down Fraction and S^{J_z} are Clebsch-Gordon coefficients

J/ψ and ψ’ ICEM p_T distributions at 1.96 TeV with k_T factorization



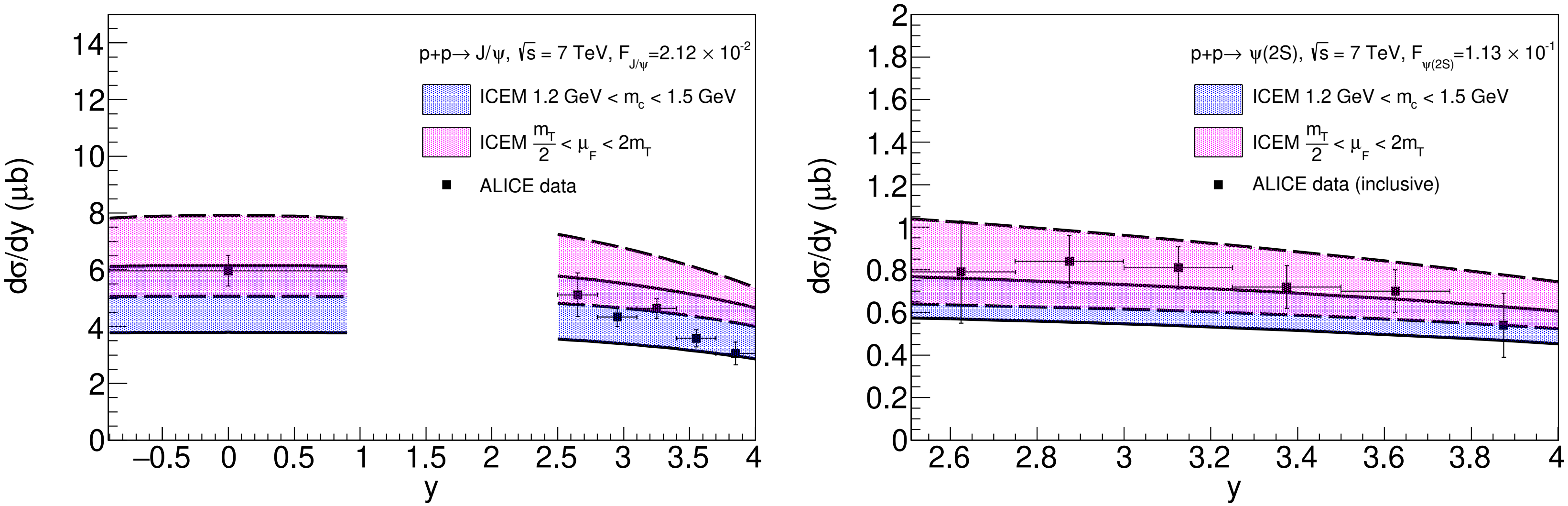
V. Cheung and RV, to be submitted

J/ψ ICEM p_T distribution at 7 TeV with k_T factorization



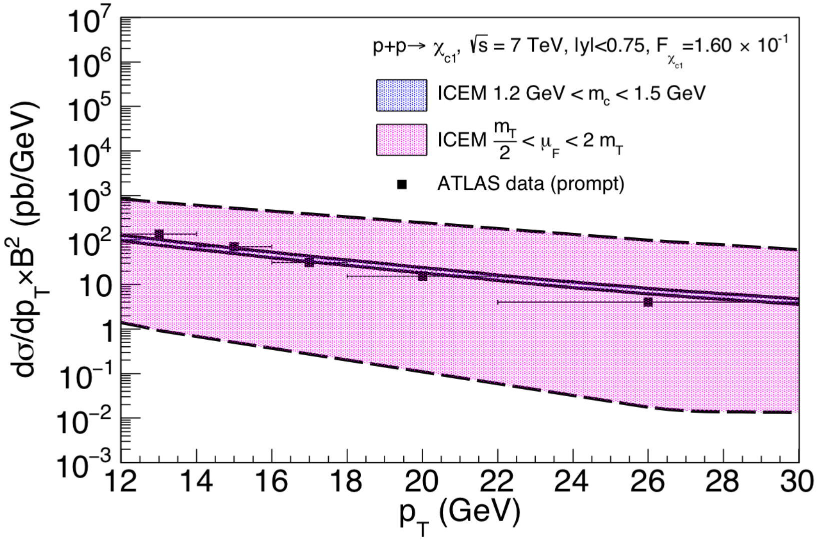
V. Cheung and RV, to be submitted

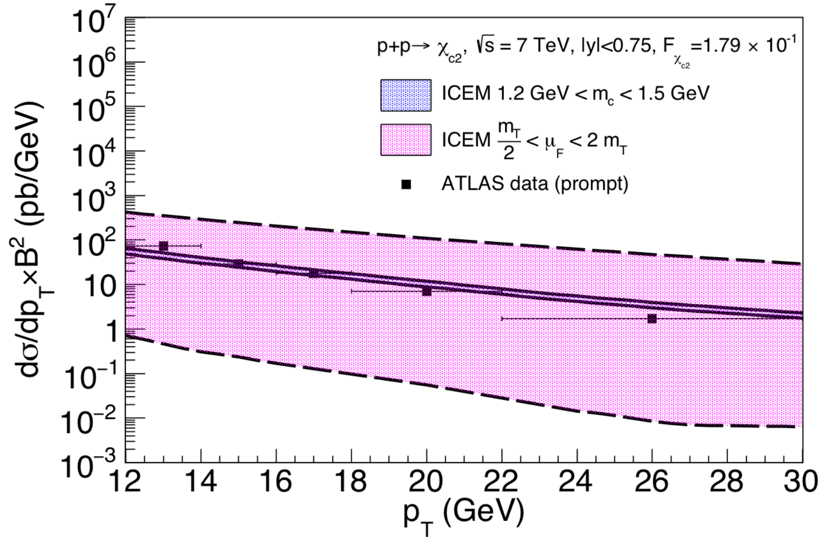
J/ψ and ψ' ICEM rapidity distributions at 7 TeV with k_T factorization

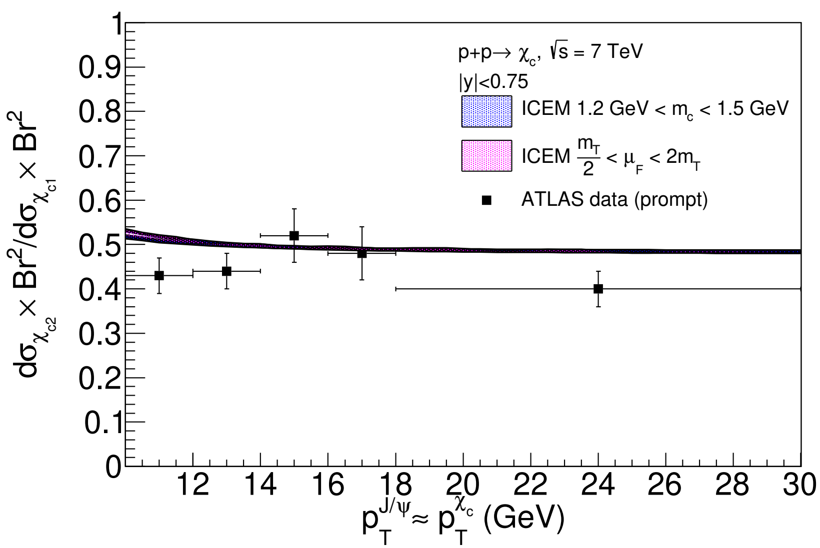


V. Cheung and RV, to be submitted

χ_{c1} and χ_{c2} ICEM p_T distributions at 7 TeV with k_T factorization







V. Cheung and RV,
to be submitted

Calculation of polarization parameters:

Use ratio of $J_z = 0$ to unpolarized ratios to calculate the polarization parameter λ_θ

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

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

$J^P = 1^+$ (χ_1 P state)

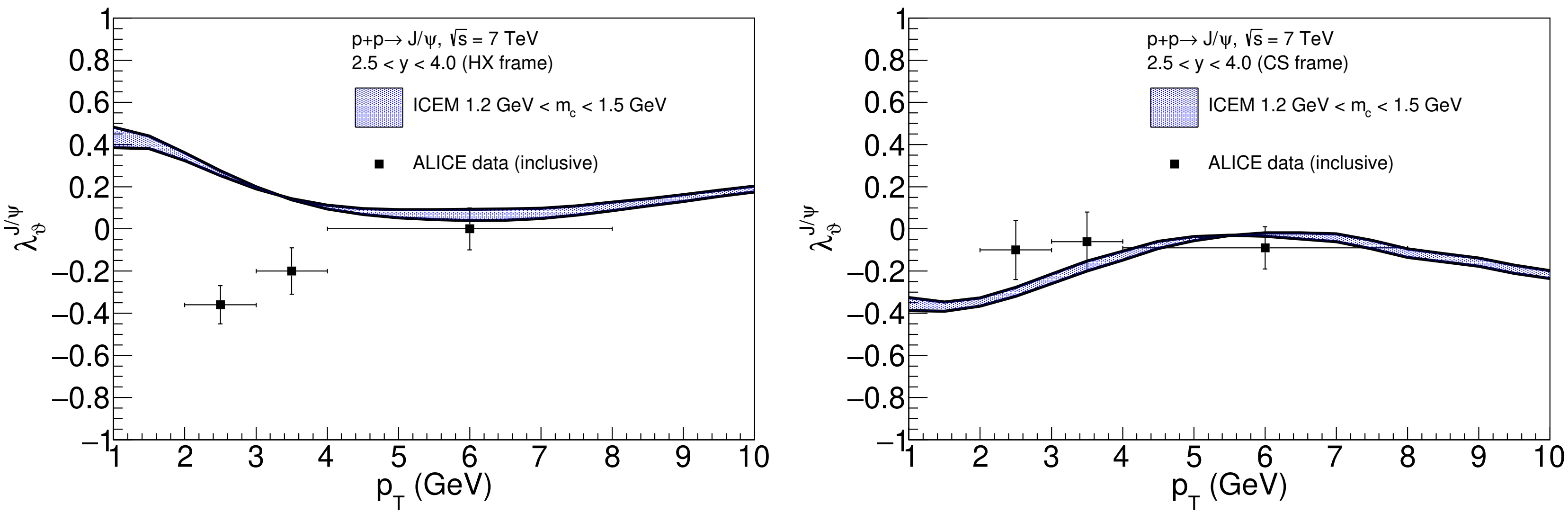
$$\lambda_\vartheta = \frac{-1 + 3R^{J_z=0}}{3 - R^{J_z=0}}$$

$J^P = 2^+$ (χ_2 P state)

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

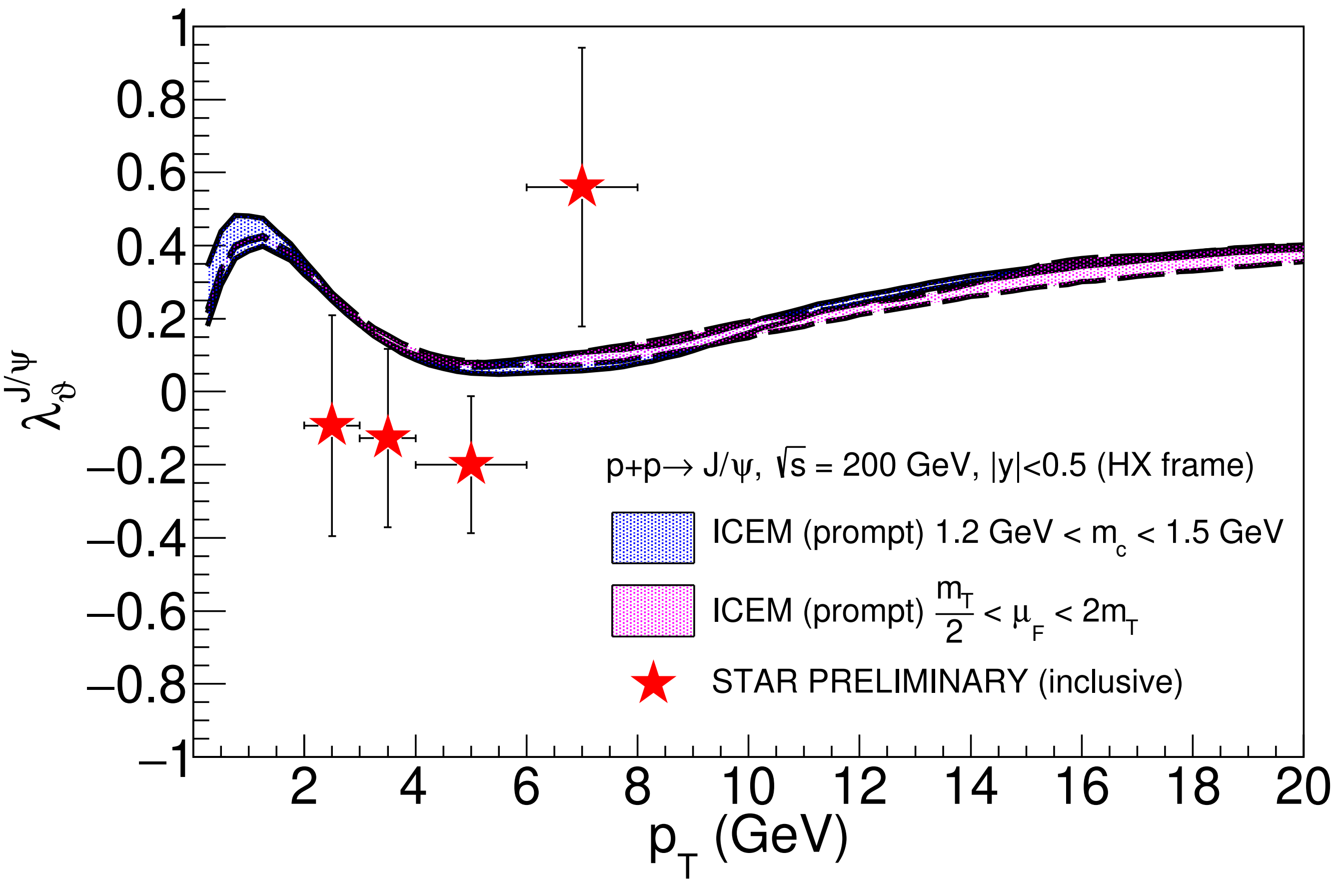
(Faccioli et al.)

J/ψ ICEM polarization at 7 TeV with k_T factorization, comparison of HX and CS frames



V. Cheung and RV, to be submitted

STAR ICEM J/ψ polarization at 200 GeV in k_T factorization approach



Summary

- Quarkonium production mechanism still not settled after more than 40 years
- New recent work on color evaporation may be helpful
- We have shown for the first time that the ICEM produces nonzero polarization at LO
- Calculated the p_T dependence and polarization of charmonium with k_T factorization before trying to tackle full NLO, paper should be submitted soon
- Upsilon results are in progress