Quarkonium production and polarization

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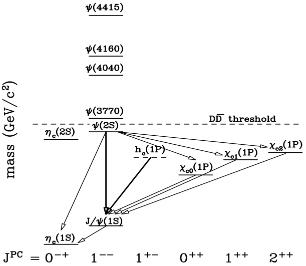
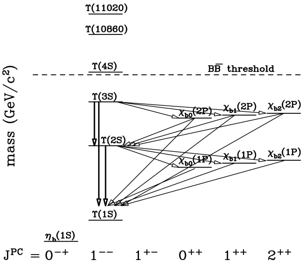
Overview



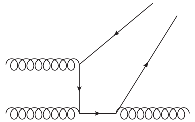


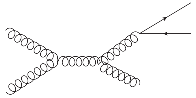
Quarkonia: bound states of $c\bar{c}$ or $b\bar{b}$

- combination of two spin 1/2 particles and orbital angular momentum $\rightarrow$ different spin states ${}^{2S+1}L_J$
- all color singlets ${}^{2S+1}L_J$[1]
- produced in hh, γp, $\gamma\gamma$, and e$^+$e$^-$
- states below the $H\overline{H}$ ($H = D, B$) threshold decay electromagnetically into $\ell^+\ell^-$

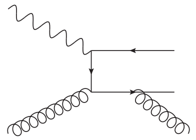
Some Production Diagrams in Different Systems

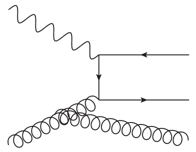
hh (RHIC, Tevatron, LHC)



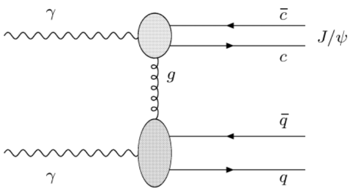


γp (HERA)

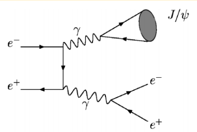


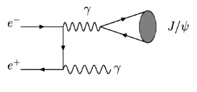


$\gamma\gamma$ (LEP)

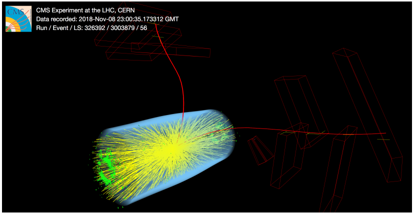


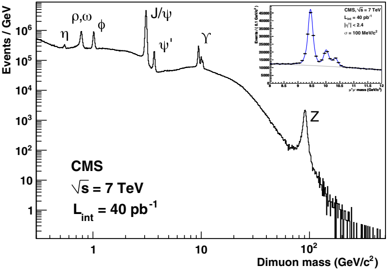
e^+e^- (KEKB)





Detection





- S states ($J^{PC} = 1^{--}$) decay to $\ell^+\ell^-$, so they can be observed as peaks in dimuon 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

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)[1]

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

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

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)[2]

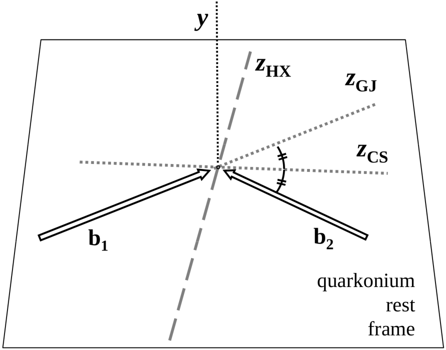
$$\lambda_\vartheta = \frac{2\sigma^{J_z=0} - \sigma^{J_z=+1} - \sigma^{J_z=-1}}{2\sigma^{J_z=0} + 3\sigma^{J_z=+1} + 3\sigma^{J_z=-1}}$$

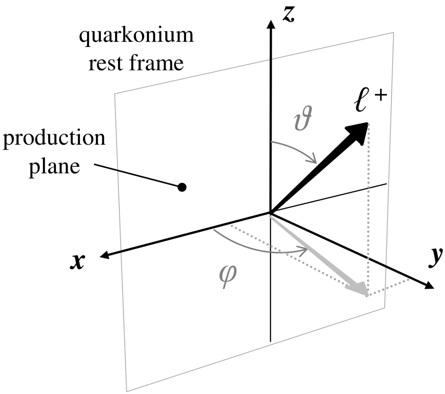
$J^P = 2^+$ (χ_2 P states)[2]

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

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

Polarization Measurement



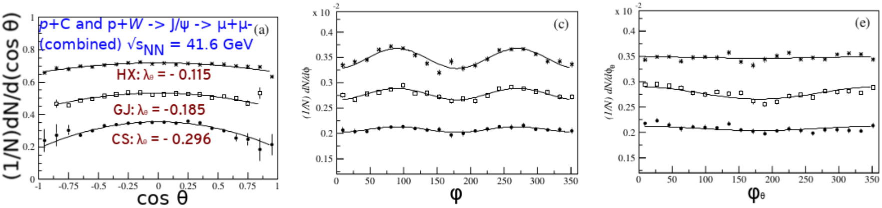


- There are three commonly used choices for the z-axis, namely z_{HX} (helicity), z_{CS} (Collins-Soper), and z_{GJ} (Gottfried-Jackson)
- θ is defined as the angle between the z-axis and the direction of travel for the ℓ^+ in the quarkonium rest frame

Extracting Polarization

$$\frac{d\sigma}{d\Omega} \quad \propto \quad 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta) \cos\phi$$

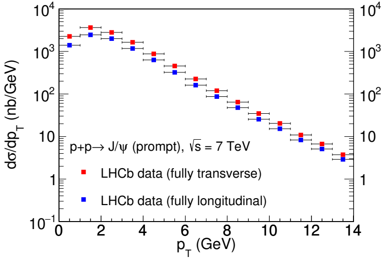
- Polarization parameters can be obtained by fitting the angular spectra as a function of θ and ϕ
- One can write $\phi_\theta = \phi - \frac{\pi}{2} \mp \frac{\pi}{4}$ for $\cos\theta \lessgtr 0$, then [3]
- $\frac{d\sigma}{d\phi_\theta} \propto 1 + \frac{\sqrt{2}\lambda_{\theta\phi}}{3+\lambda_\theta}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



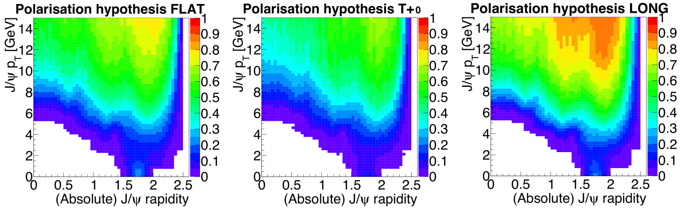
[3] I. Abt *et al.* (HERA-B Collaboration), Eur. Phys. J. C **60**, 517 (2009).

Importance of Polarization

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



[4]



[5]

[4] R. Aaij *et al.* (LHCb Collaboration), Eur. Phys. J. C **71**, 1645 (2011).
[5] G. Aad *et al.* (ATLAS Collaboration), Nucl. Phys. B **850**, 387 (2011).

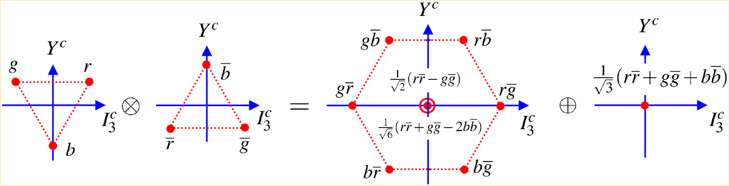
Quarkonium Production Models

Still unsettled

- J/ψ and Υ are discovered in 1974 and 1977 respectively
- The quarkonium production mechanism has not been solved
- Current models cannot describe yield and polarization simultaneously

Color Singlet Model (CSM) [Berger, Jones 81; Baier, Rückl 81]

- constrains the production of $c\bar{c}$ to the color singlet state only
- calculated up to $\mathcal{O}(\alpha_s^4)$



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 relative velocity of the quarks ,v/c
- $|\psi_{\mathcal{Q}}\rangle = \mathcal{O}(1)|^3S_1^{[1]}\rangle + \mathcal{O}(v)|^3P_J^{[8]}g\rangle + \mathcal{O}(v^2)|^3S_1^{[8]}gg\rangle + \mathcal{O}(v^2)|^1S_0^{[8]}g\rangle$
- 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
- $\langle\mathcal{O}^{J/\psi}[n]\rangle$ 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

Quarkonium Production Models

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

Leading order cross section:

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

$F_{\mathcal{Q}}$ is a universal factor for the quarkonium state ($\mathcal{Q}$) and is independent of the projectile, target, and energy.

- all Quarkonium states are treated like $Q\overline{Q}$ ($Q = c, b$) below $H\overline{H}$ ($H = D, B$) threshold
- all diagrams for $Q\bar{Q}$ production included, independent of color
- fewer parameters than NRQCD (one $F_{\mathcal{Q}}$ for each Quarkonium state)
- $F_{\mathcal{Q}}$ is fixed by comparison of NLO calculation of $\sigma_{\mathcal{Q}}^{CEM}$ 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

Quarkonium Production Models

Improved CEM (ICEM) [Ma, Vogt 16]

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

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 J/ψ and ψ(2S), 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

Results in the CSM

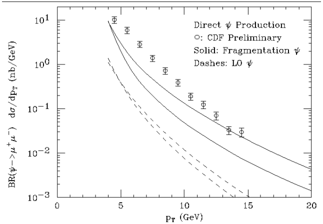


Figure 2

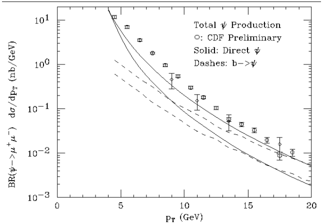
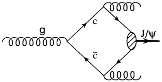


Figure 3

Fragmentation:



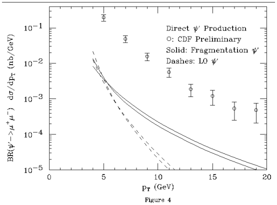
- Leading order calculations at $\mathcal{O}(\alpha_s^3)$ underestimate the Tevatron p_T distributions
- Gluon fragmentation to J/ψ is required to increase cross section to match data [6,7] (effectively α_s^4)
- only works with the J/ψ (sometimes)

[6] M. Cacciari and M. Greco, Phys. Rev. Lett. **73**, 1586 (1994).

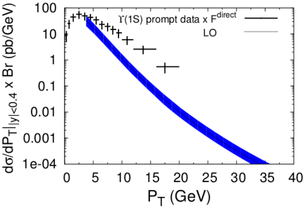
[7] E. Braaten *et al.*, Phys. Lett. B **333**, 548 (1994).

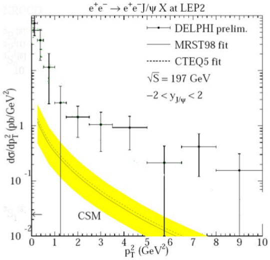
Disagreemnt with other data in the CSM

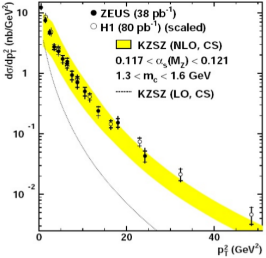
$\psi(2S)$ at CDF✗ (PLB **333**, 548 (1994).)



$\Upsilon(1S)$ at CDF✗ (PRL **88**, 161802 (2002).)



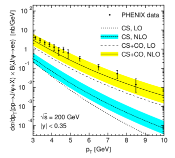


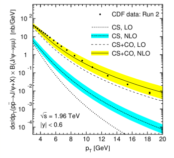


J/ψ at LEP2✗ (PLB **565**, 76 (2003).) J/ψ at ZEUS✓ (EPJC **27**, 173 (2003).)

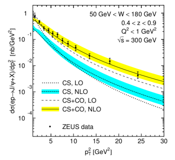
Results in NRQCD - A global fit of LDMEs[8]

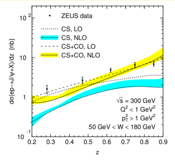
hh ($p_T > 3$ GeV)





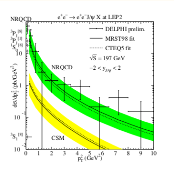
γp ($p_T > 3$ GeV)

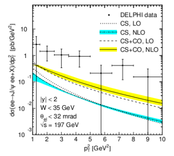




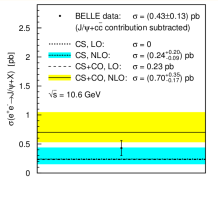
$\gamma\gamma$ (Right: $p_T > 1$ GeV)

[9]





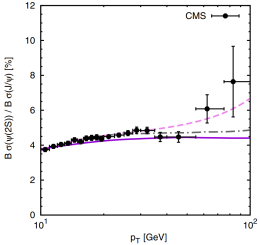
e^+e^-

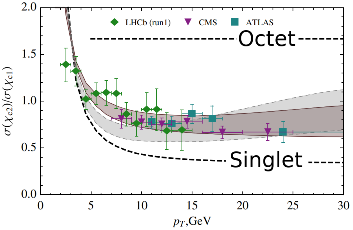


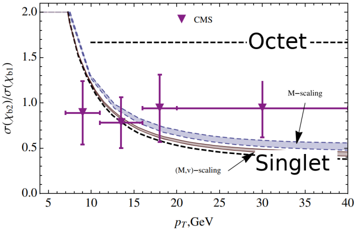
[8]M. Butenschoen and B. A. Kniehl, Nucl. Phys. Proc. Suppl. **222-224**, 151 (2012).
[9]L. Chang, Y. X. Liu and C. D. Roberts, Phys. Rev. Lett. **106**, 072001 (2011).

Relative production in NRQCD

- $\psi(2S)$ to J/ψ ratio agrees with data at most p_T [10]
- relative production of χ_c and χ_b are dominated by CSM contribution [11]



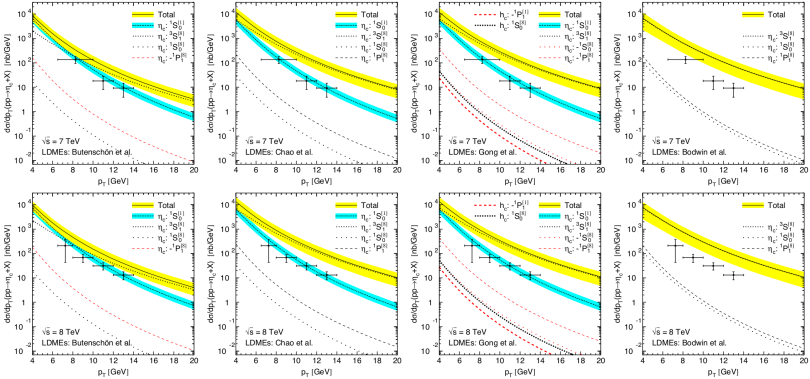




[10] S. P. Baranov and A. V. Lipatov, Phys. Rev. D **96**, 034019 (2017).
[11] A. K. Likhoded *et al.*, Phys. Rev. D **90**, 074021 (2014).

η_c production in NRQCD

M. Butenschoen, Z-G He, and B. A. Kniehl, Phys. Rev. Lett. **114**, 092004 (2015).

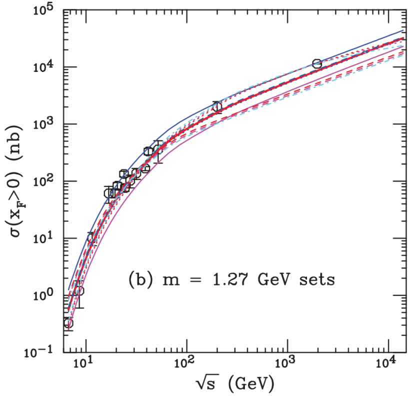


- all results so far overpredict LHCb η_c yields
- results can be described by CSM alone
- PRL 114, 092005 (2015) and PRL 114, 092006 (2015) describe the η_c results but not the J/ψ polarization

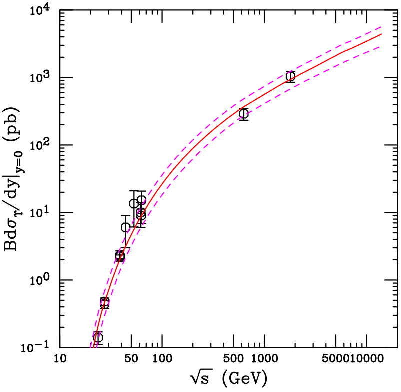
Results in the CEM[12]

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

J/ψ

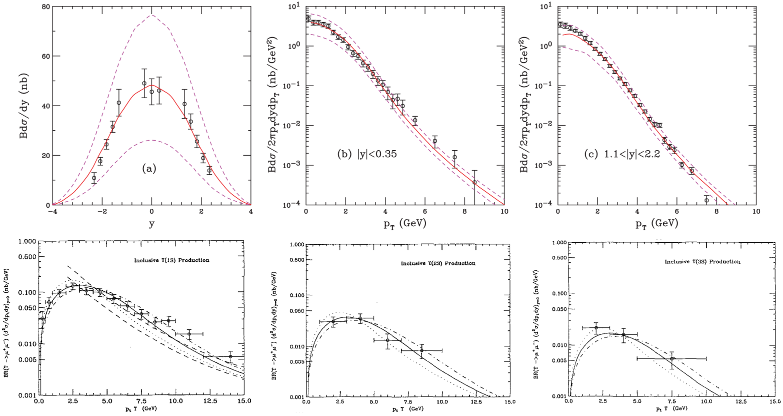


$\sum \Upsilon$'s



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

Results in the CEM[12,13]



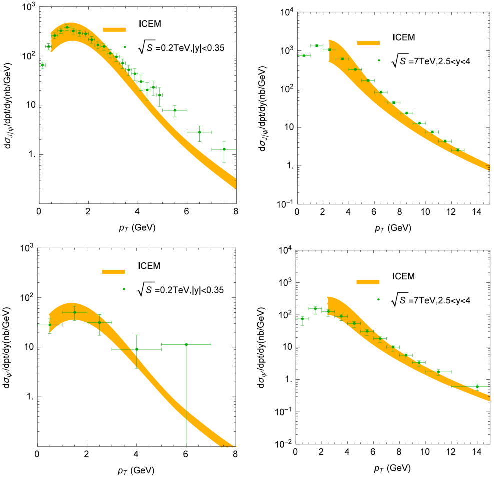
- overall less rigorous, but accurate predictions
- no advances in the basic model since 1990s

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

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

Results in the ICEM

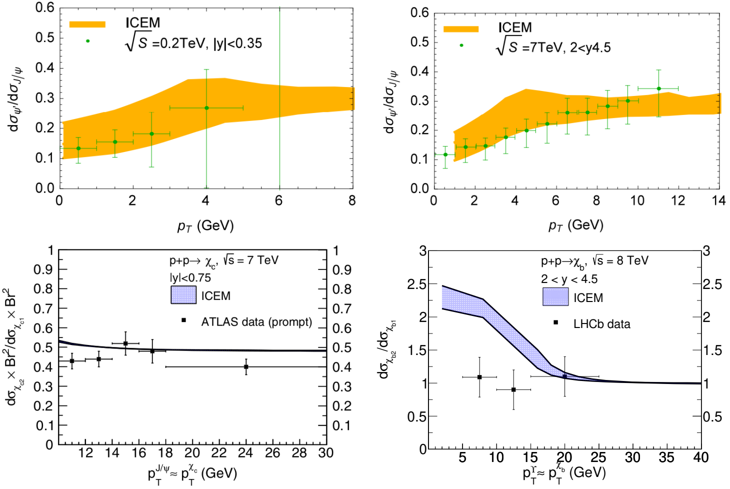
$$\frac{d\sigma_\psi(P)}{dp_T} = F_\psi \int_{M_\psi}^{2M_D} dM \, \frac{M}{M_\psi} \, \frac{d\sigma_{c\bar{c}}(M, P')}{dM\, dp'_T}\Big|_{p'_T=(M/M_\psi)p_T}$$



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

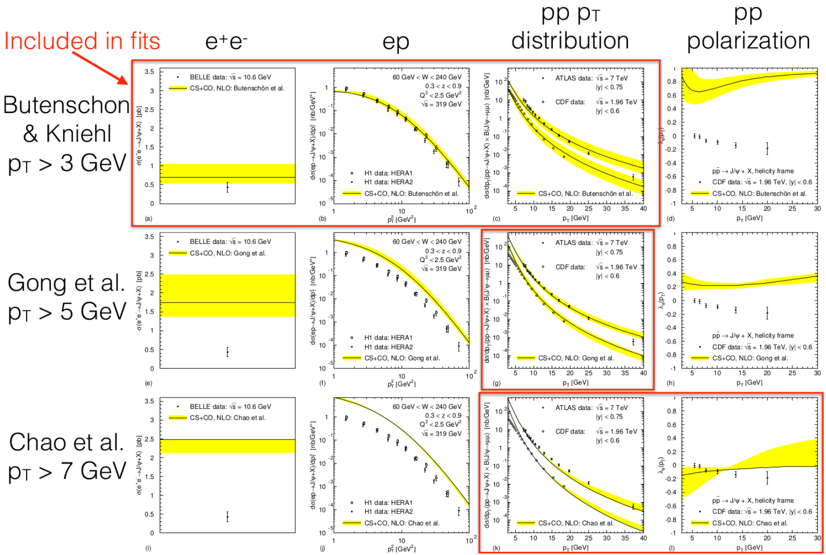
Relative production in the ICEM[14,15]



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

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

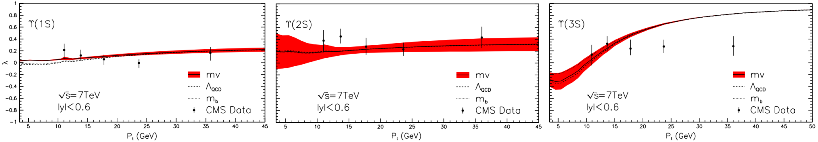
J/ψ polarization problem in NRQCD[16]



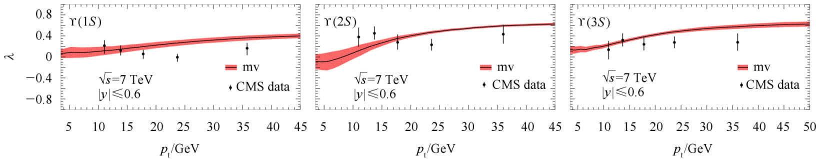
[16]N. Brambilla et al., Eur. Phys. J. C **74**, 2981 (2014)

$\Upsilon(nS)$ Polarization in NRQCD

B. Gong, L. P. Wan, J. X. Wang and H. F. Zhang, Phys. Rev. Lett. **112**, 032001 (2014).



Update: Y. Feng, B. Gong, L. P. Wan, and J. X. Wang, Chin. Phys. **C39**, 123102 (2015).



- polarization of $\Upsilon(nS)$ is better described than for J/ψ
- polarization prediction in NRQCD is improved by including the feed down decays from χ_b states (bottom row)

Polarization in the k_T-factorized ICEM[15]

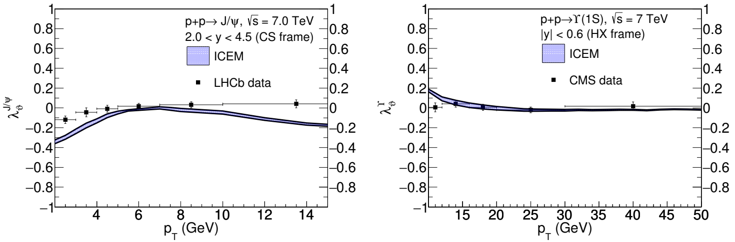
Feed-down production:

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

Polarization of prompt J/ψ:

$$\lambda_\vartheta^{J/\psi} = \frac{1-3R_{J/\psi}^{J_z=0}}{1+R_{J/\psi}^{J_z=0}}$$

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



- charmonium is slightly longitudinally polarized in the CS frame
- bottomonium is nearly unpolarized in all frames

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

Comparison of Models

Model Properties	NRQCD	CEM	ICEM
hadronization model	in terms of LDMEs	in terms of $F_{\mathcal{Q}}$	
n in $\mathcal{O}(\alpha_s^n)$	4	3	3 (production) 2 (polarization)
collision systems	all	$h+h$ only so far	
production uncertainty	LDMEs	m_Q, μ_R, μ_F	
polarization	J/ψ ✗ Υ ✓	not calculated	J/ψ ✓ Υ ✓
polarization uncertainty	feed down contribution	N/A	m_Q

Future

NRQCD

- Are the LDMEs universal?
- Can NRQCD describe η_c and J/ψ without breaking J/ψ polarization and results from other experiments?

ICEM

- Consider more collision systems
- NLO in collinear factorization