Double quarkonium production at hadron colliders

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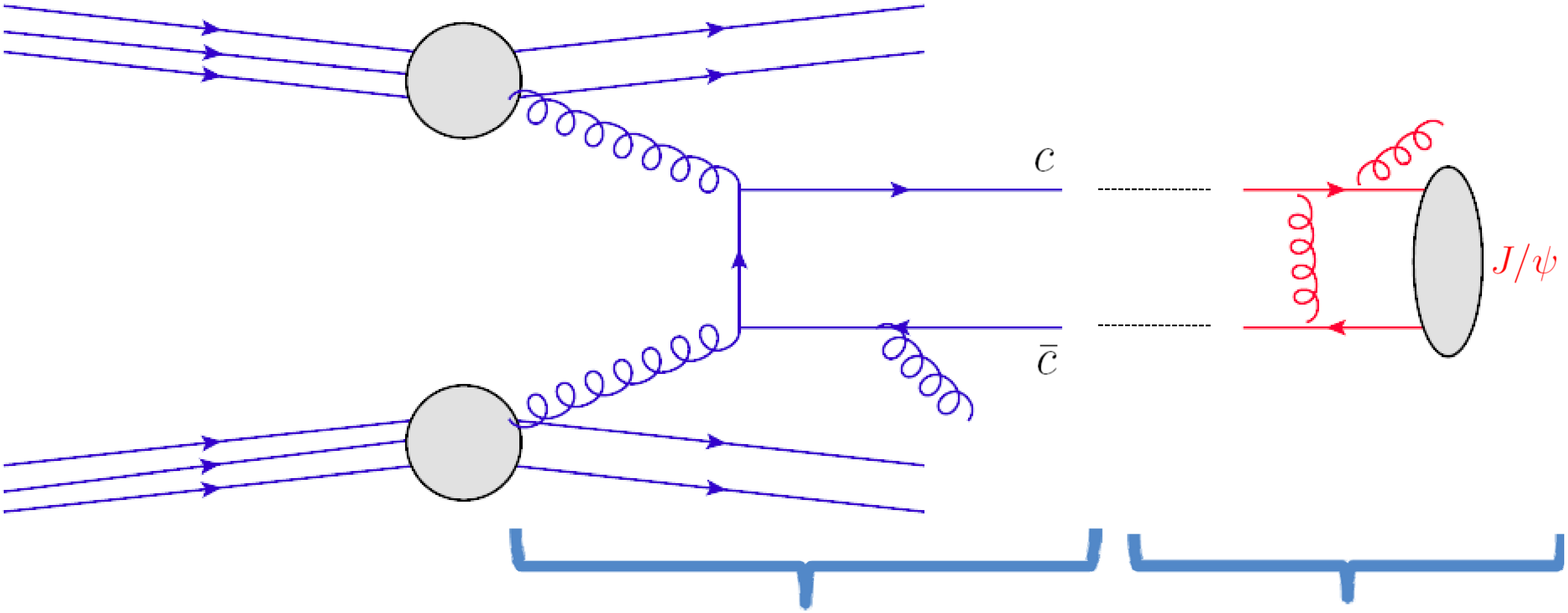
Outline

- Heavy quarkonium production
- Single quarkonium production at hadron colliders
- Double quarkonium production at hadron colliders
- Summary

Heavy quarkonium production



Factorization :

Perturbative
Short-distance coefficients
Series in α_s

Nonerturbative
long-distance ME
Series in v

$$\sigma(ij \to \mathcal{Q} + X) \sim \sum_n \hat{\sigma}_\Lambda(ij \to Q\bar{Q}(n) + X)\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle_\Lambda$$

- can be justified in NRQCD, which is an effective field theory of QCD.

Two sources of heavy quarkonium

Direct production

• production of a $Q\bar{Q}$ pair in the parton process through QCD interactions, which evolves into a heavy quarkonium.

• includes the feed-down from higher resonance states. → cannot be distinguished.

• prompt J/ψ.

Production from B meson decay

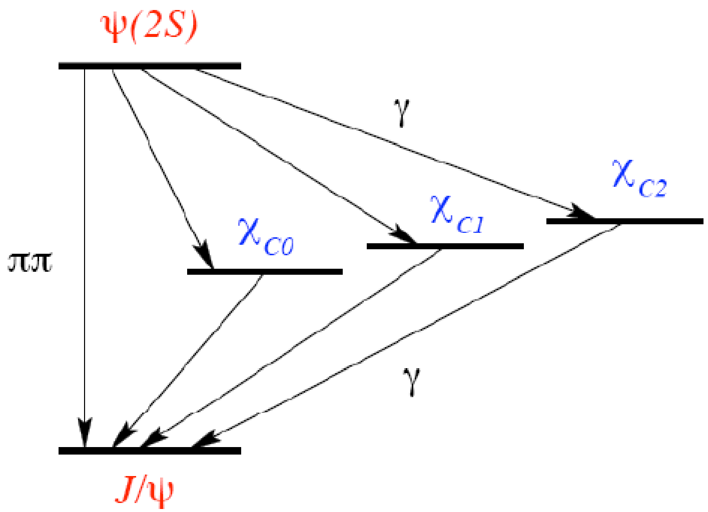
• $B \to J/\psi K_s, B \to J/\psi \pi, B \to \chi_{cJ} K \cdots$

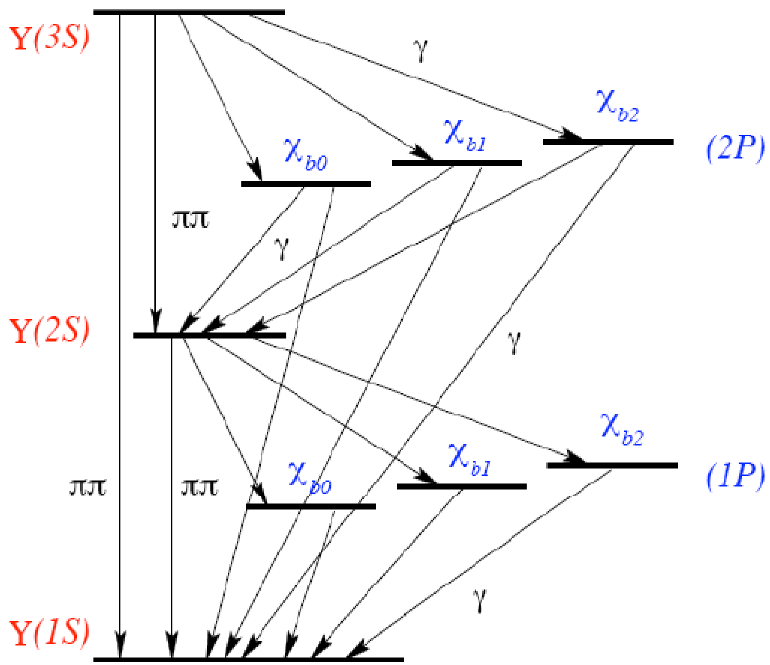
• includes weak interactions.

• can be identified by measuring the displacement between the primary and the secondary vertices.

We consider only the prompt heavy quarkonium.

Feed down

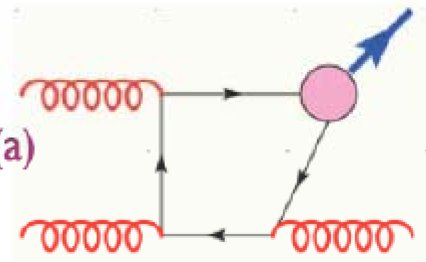




	S-wave	P-wave ...
$^{2S+1}L_J$	$^1S_0$ $^3S_1$	$^1P_1$ $^3P_{J,(J=0,1,2)}$
charmonium	η_c J/ψ	h_c χ_{cJ}
bottomonium	η_b Υ	h_b χ_{bJ}
c + anti-b	B_c B_c^*	

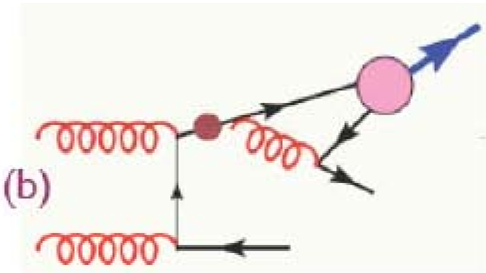
J/ψ production at the Tevatron

(a)



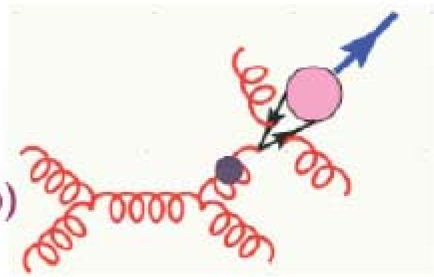
$$\alpha_S^3 \frac{(2m_c)^4}{p_T^8}$$

(b)

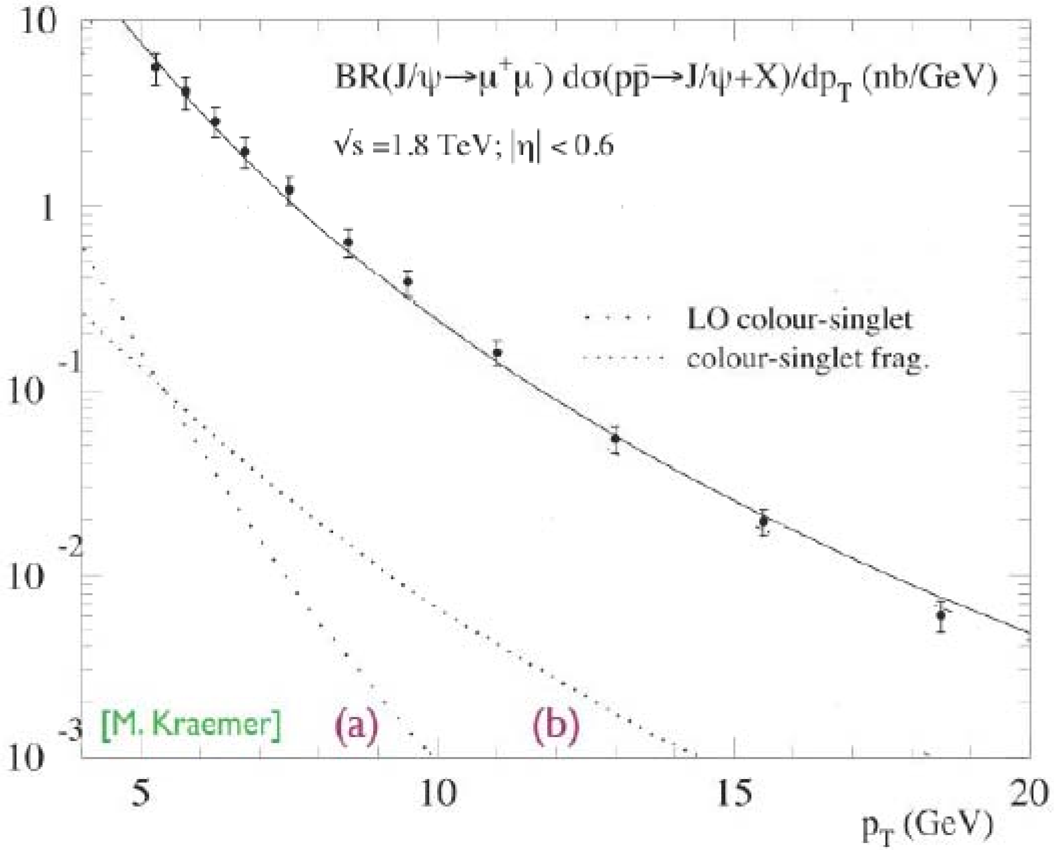


$$\alpha_S^4 \frac{1}{p_T^4}$$

(b)



$$\alpha_S^5 \frac{1}{p_T^4}$$



- (a) leading-order contributions in α_s.
- (b) some higher-order contributions through the fragmentaion approximation.

Color-octet revolution

• In NRQCD, the $Q\bar{Q}$ pair produced in a color-octet state. The pair can be evolved into a color-singlet quarkonium by emitting soft gluons.

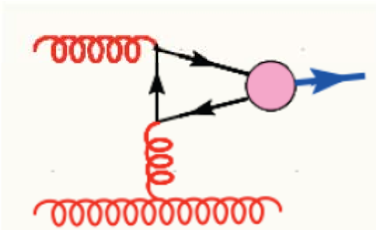
$$
\begin{aligned}
|J/\psi\rangle = & \; O(1)|Q\bar{Q}({}^3S_1^{[1]})\rangle \\
& + O(v)|Q\bar{Q}({}^3P_J^{[8]})g\rangle + O(v^2)|Q\bar{Q}({}^1S_0^{[8]})g\rangle \\
& + O(v)|Q\bar{Q}({}^3S_1^{[8]})gg\rangle + O(v^4).
\end{aligned}
$$

• The color-octet mechanism could resolve the long-standing IR divergence problems in the P-wave quarkonium decays.

$$
\mathrm{IR}_{\mathrm{CS}} + \mathrm{IR}_{\mathrm{CO}} = 0.
$$

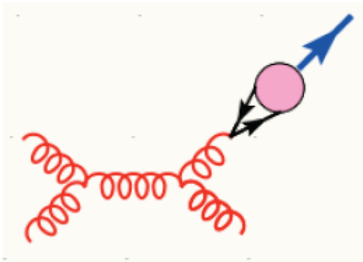
Color-octet J/ψ production at the Tevatron

(c)

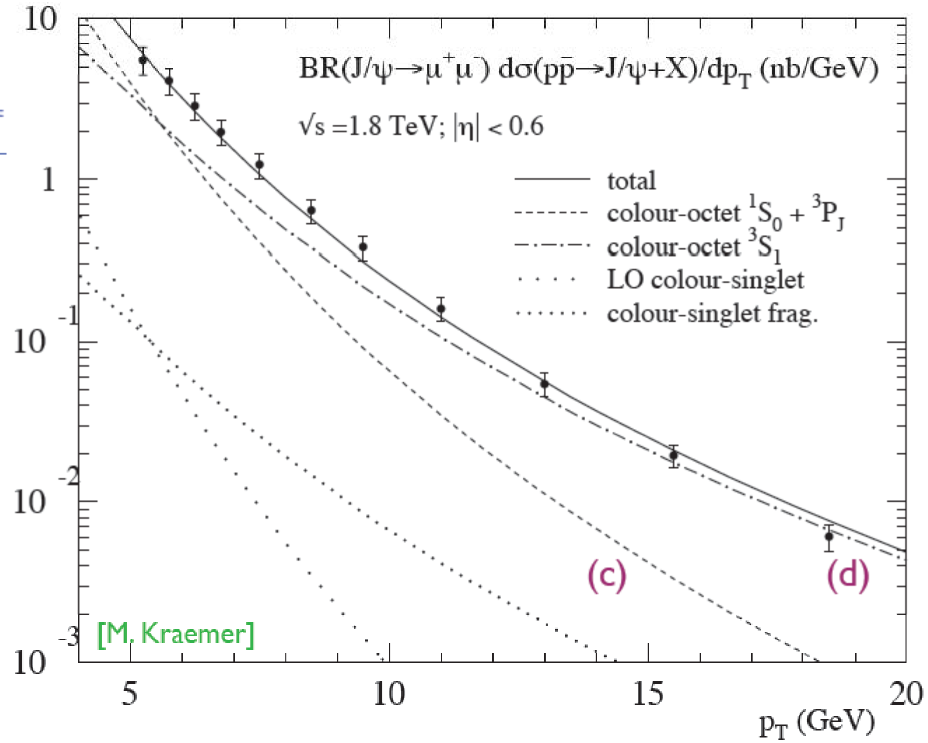


$$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^6}$$

(d)

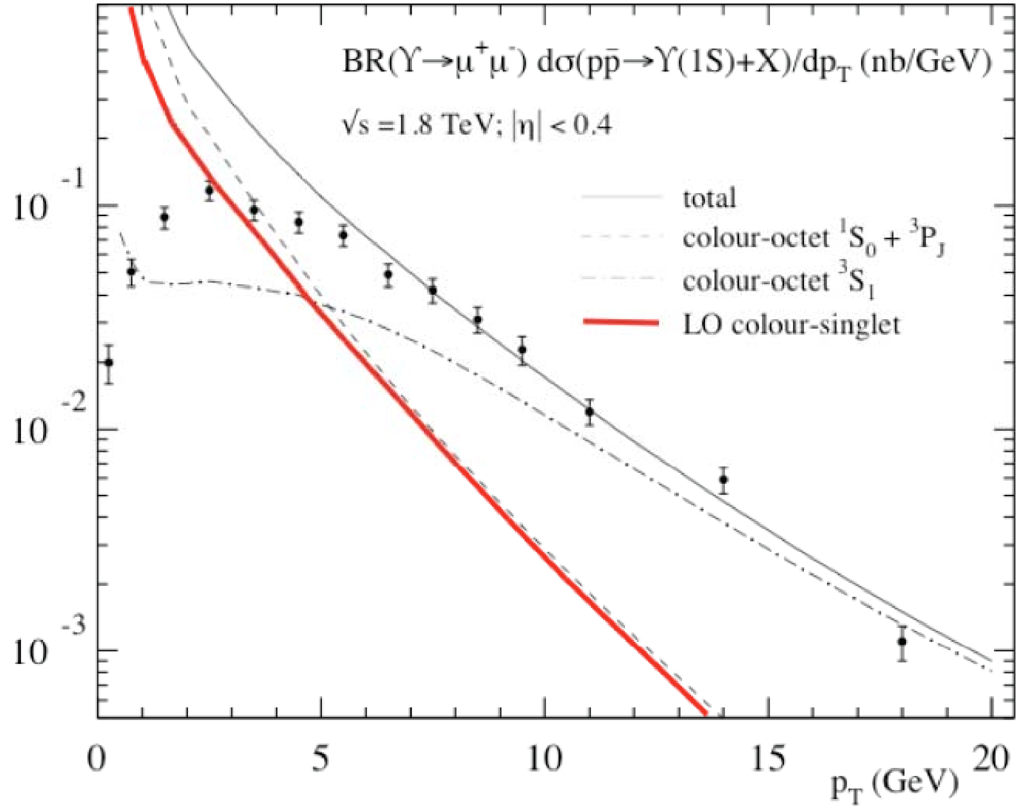


$$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^4}$$



- (c) $^1S_0$, ^3P_J octet, (d) $^3S_1$ octet production.
- can be explained by the t-channel gluon exchange or gluon fragmentation.
- The color-octet matrix elements are fitted to the data.

Υ production at the Tevatron

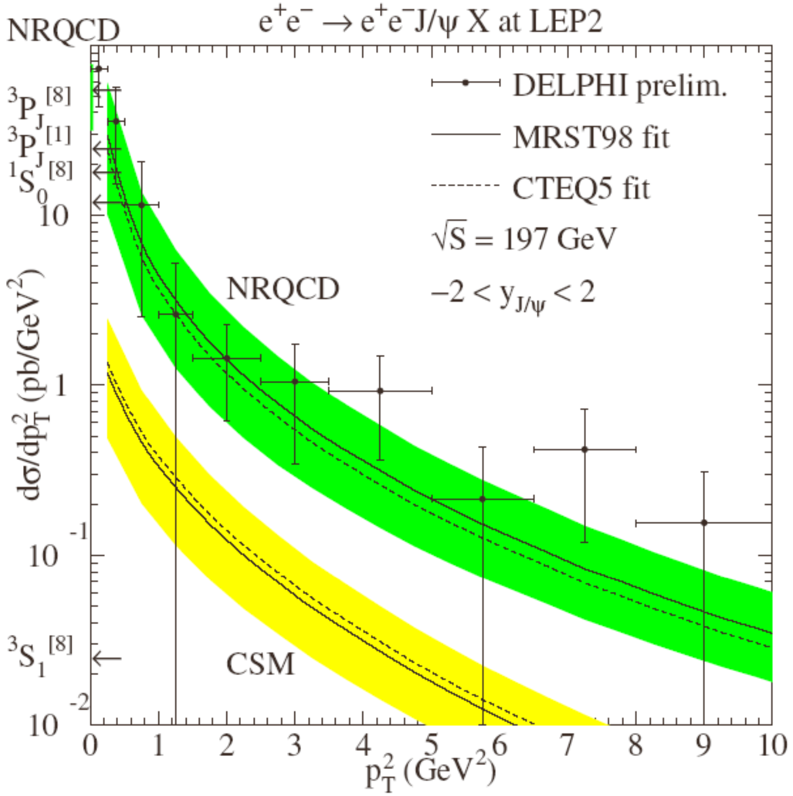


• Similar to the J/ψ production, but in this case, $v^2 \sim 0.1$ and the color-octet contributions are much suppressed.

• The resulting velocity scalings of the matrix elements are close to the predictions in NRQCD.

Success of the color-octet mechanism (?)

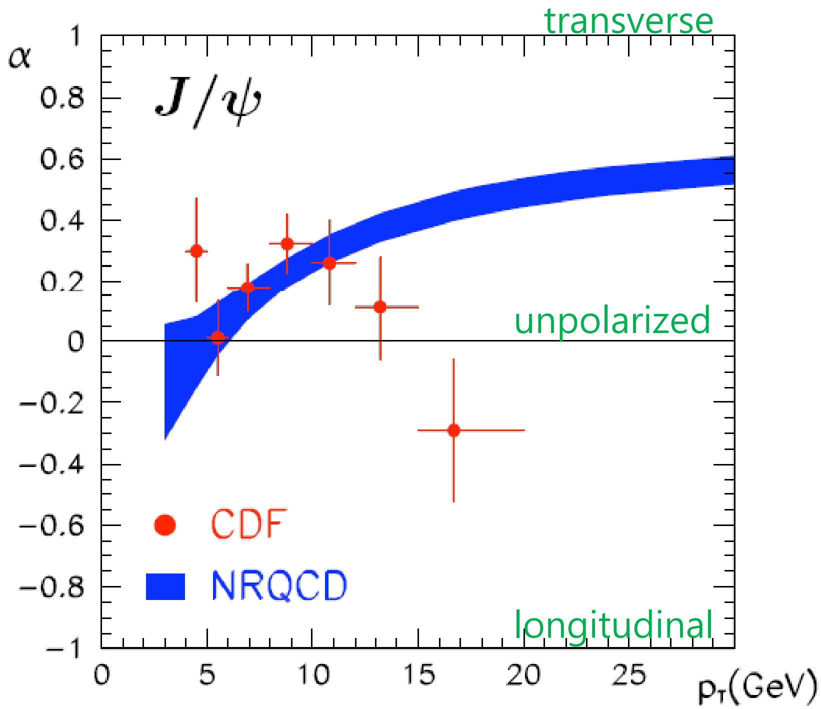
- The single J/ψ production at the Tevatron is a benchmark for the color-octet matrix elements.
- need to test the color-octet matrix elements for various processes.

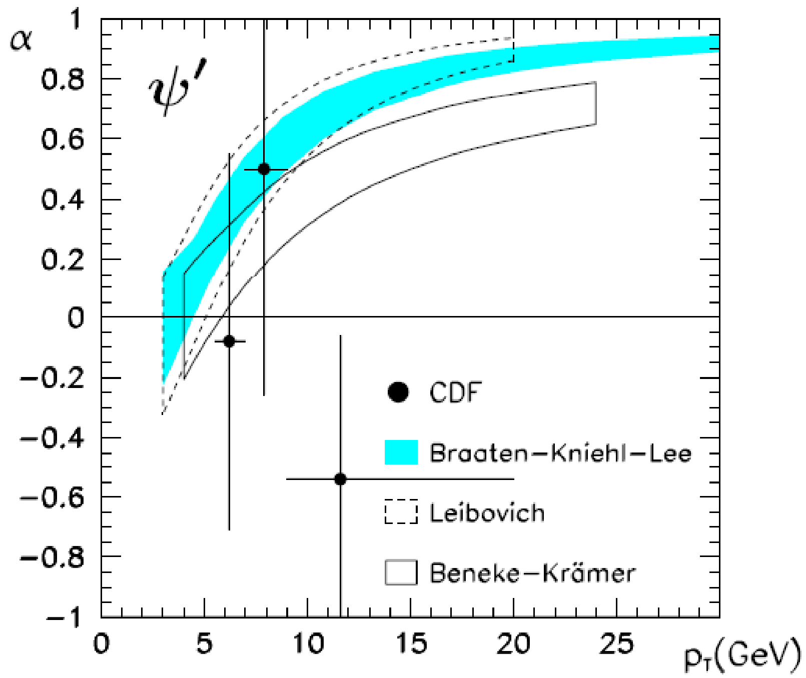


- favor the color-octet mechanism.

Polarization of J/ψ at the Tevatron Run I

- The color-octet dominance at large transverse momentum implies that the J/ψ is produced with a highly transverse polarization.

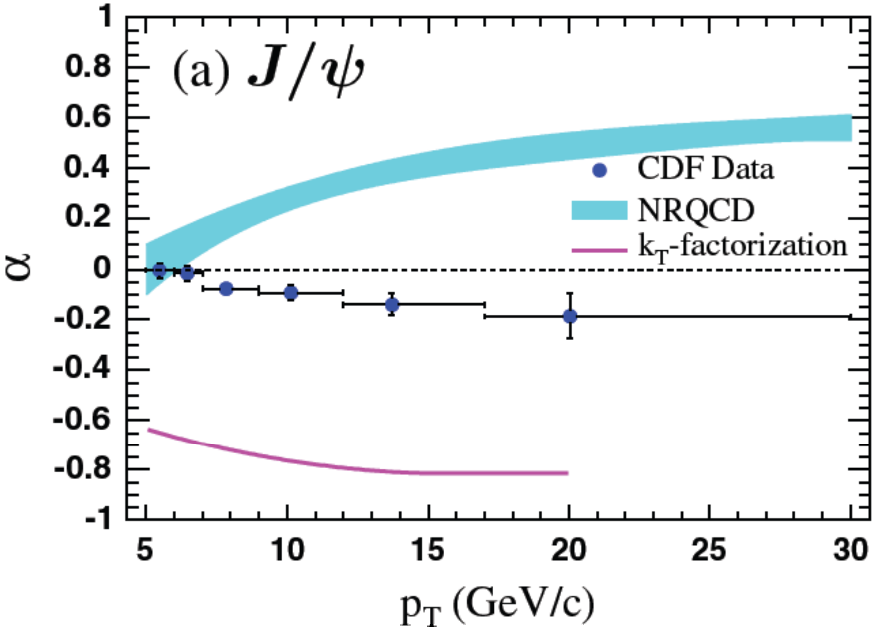


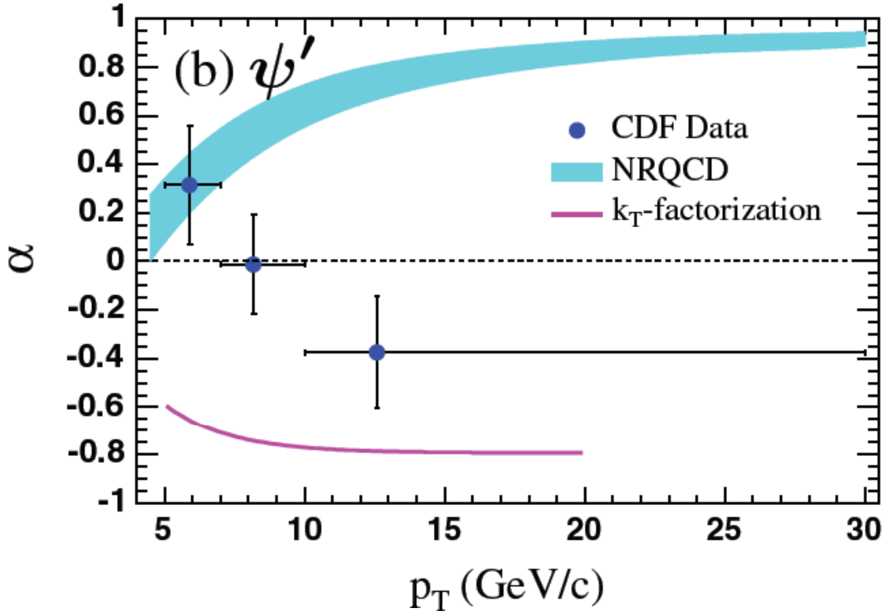


- agrees in the intermediate region.
- disagrees at the high transverse momentum.

$$\boxed{\alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}}$$

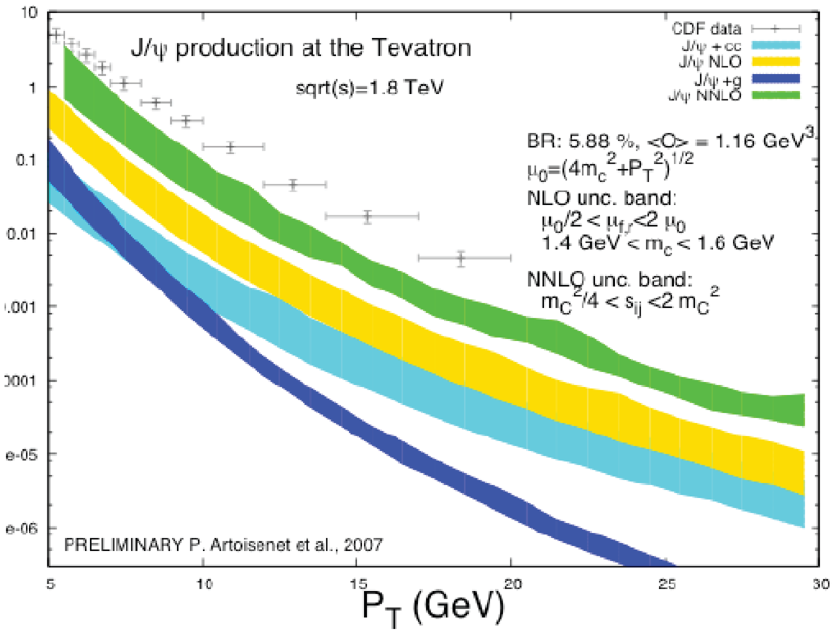
Polarization of J/ψ at the Tevatron Run II

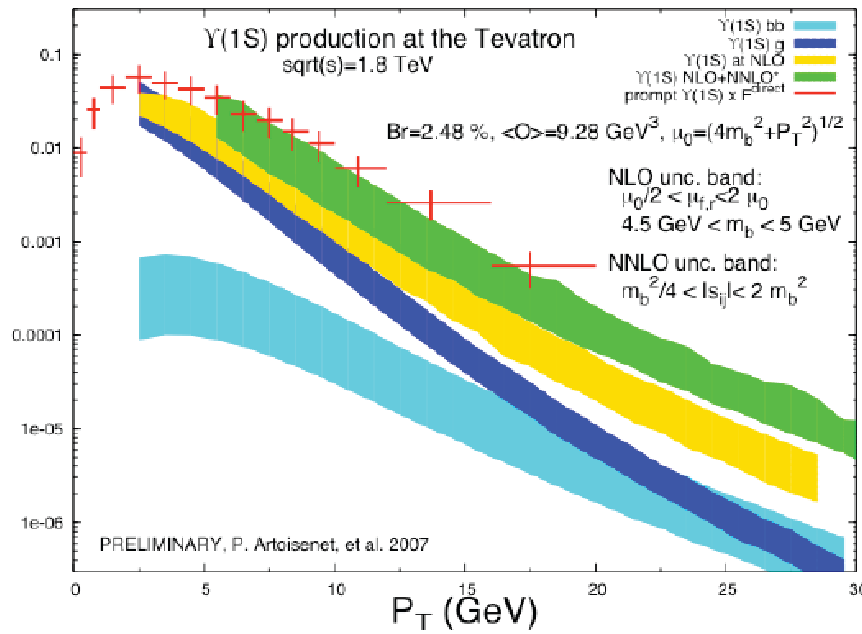




- Prompt polarization does not show the trend to the transverse polarization.
- CDF Run II data do not agree with CDF Run I data as well as NRQCD predictions.

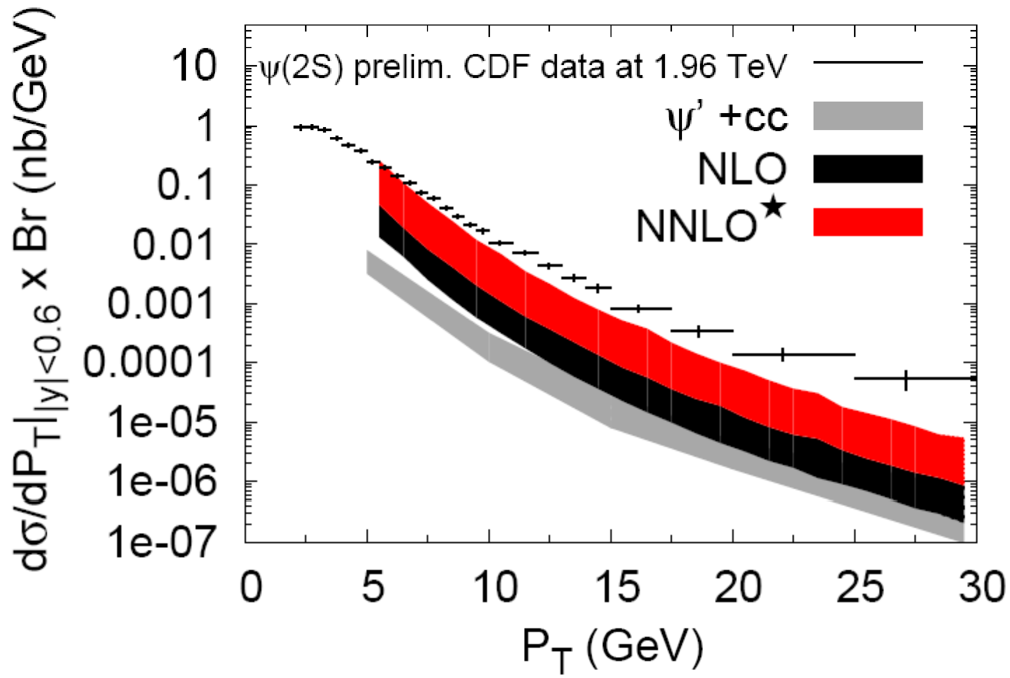
NLO corrections to the color-singlet contributions



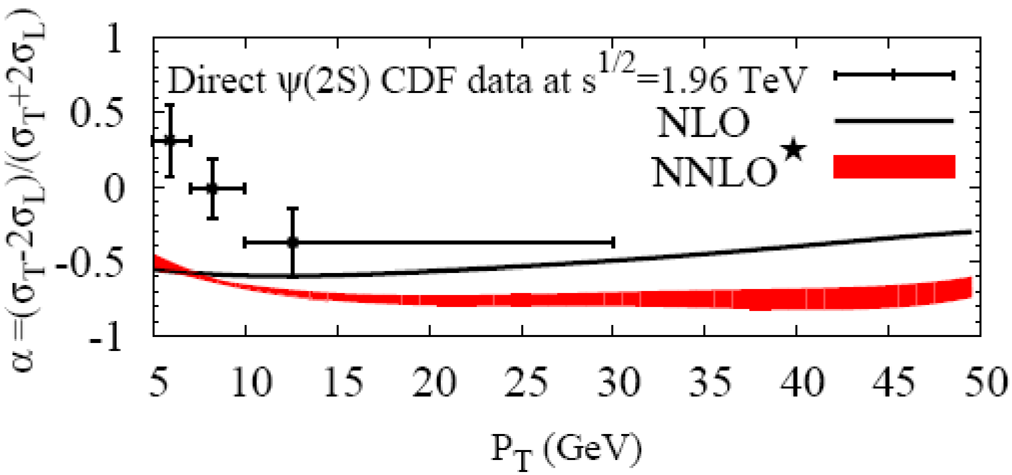


- Large NLO corrections.
- Incomplete NNLO corrections.
- Improved in shape and size, but still less than data.
- Color-octet contributions should be suppressed, but are they negligible?

$\psi(2S)$ production at the Tevatron



- a small gap at large p_T.



- Polarization is not explained by NNLO corrections.
- feed-down, color octet?

Lansberg, QWG'08

Double quarkonium production

• could not explain the data for the single quarkonium production rate and its polarization with only the color-singlet contributions.

• now the game for the production rate was moved to fill up the gap of 3 or 4 factors, which was of about order 2.

• the polarization should be moved to the unpolarized region.

• still room for the color-octet contributions.

• need to find the process in which the color-octet contributions are indeed dominant.

• Tevatron or LHC may open the double quarkonium production.

- color-octet mechanism, relativistic corrections.

Double quarkonium production

• need further test for the color-singlet and color-octet mechanisms in NRQCD.

• originally predicted to test the color-octet mechanism at the Tevatron.

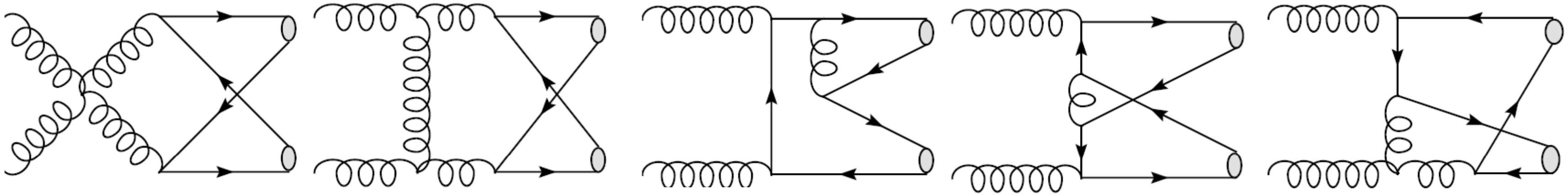
• recently extended to the LHC.

• clean signals : 4 muon events for $J/\psi J/\psi, J/\psi\Upsilon, \Upsilon\Upsilon$ production.

• $gg \to J/\psi\chi_c$ and $gg \to J/\psi\eta_c$ processes are forbidden in the color-singlet model, but allowed in the color-model.

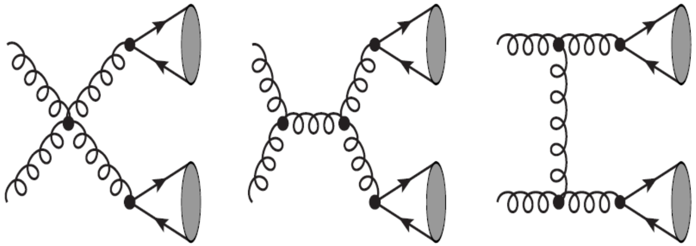
Double quarkonium production

Color singlet



- $gg \to Q_1 Q_2$ dominates over $q\bar{q} \to Q_1 Q_2$.
- 31 Feynman diagrams for $J/\psi J/\psi$ production.

Color octet



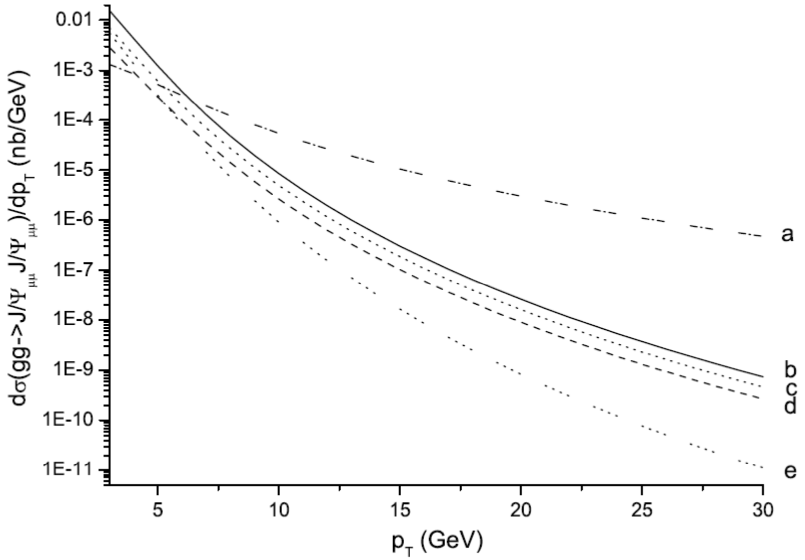
$$D_{g\to\mathcal{Q}}(z,\mu^2) = \sum_n d_{g\to n}(z,\mu^2)\langle \mathcal{O}_n^H \rangle.$$

$$d_{g\to\underline{8}^3S_1} = \frac{\pi\alpha_s(2m_Q)}{24m_Q^3}\delta(1-z).$$

- gluon fragmentation approximation

$$d\hat{\sigma}_{\mathcal{Q}_1+\mathcal{Q}_2} = \int_0^1 dz_1 \int_0^1 dz_2 D_{g\to\mathcal{Q}_1}(z_1, m_{\mathcal{Q}_1}) D_{g\to\mathcal{Q}_2}(z_2, m_{\mathcal{Q}_2}) d\hat{\sigma}_{gg}(E_1/z_1, E_2/z_2),$$

Cross section for $J/\psi J/\psi$ production at the LHC



Qiao,Sun,Sun(0903.0954)

a : color-octet (CO)
b : unpolarized color-singlet (CS)
c,d,e : polarizated color-singlet (CS)

	σ(events)	p_{Tcut}=3 GeV	p_{Tcut}=4 GeV	p_{Tcut}=5 GeV	p_{Tcut}=6 GeV	p_{Tcut}=7 GeV
CS	$\perp\perp$	5.83pb(58324)	1.74pb(17425)	0.56pb(5607)	0.20pb(1981)	0.077pb(767)
	$\parallel\parallel$	2.55pb(25543)	0.83pb(8262)	0.28pb(2786)	0.10pb(1014)	0.040pb(401)
	$\parallel\perp$	3.95pb(39425)	0.94pb(9445)	0.24pb(2380)	0.066pb(660)	0.020pb(204)
	tot	12.33pb(123319)	3.51pb(35131)	1.08pb(10773)	0.37pb(3656)	0.14pb(1372)
CO	$\perp_8\perp_8$	2.90pb(29022)	1.82pb(18205)	1.15pb(11461)	0.74pb(7399)	0.49pb(4925)

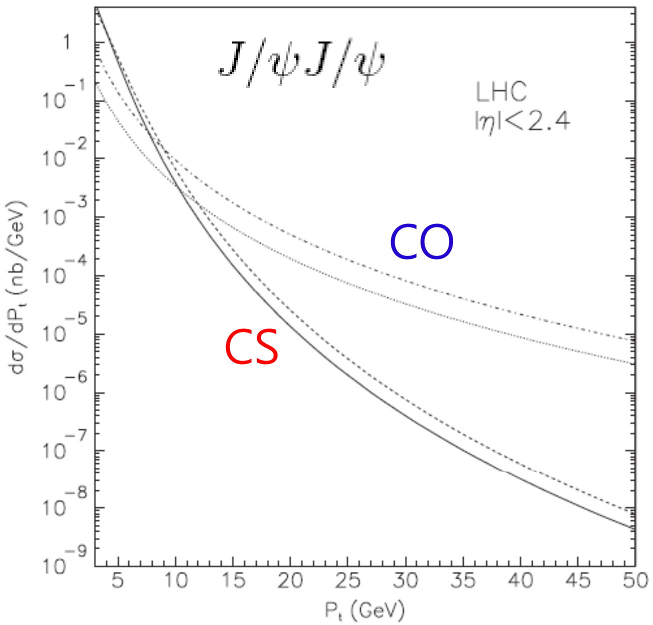
Cross section for double quarkonium production

- includes feed-down effects.

Li,Zhang,Chao('09)

$$gg \to J/\psi\psi(2S), gg \to J/\psi\chi_{cJ}, gg \to \psi(2S)\chi_{cJ}, \ldots$$

$$d\hat{\sigma}_{Q_1+Q_2} = d\hat{\sigma}_{gg}\left(\frac{\pi\alpha_s(4m_c^2)}{24m_c^3}\right)^2[\langle O_8^{J/\psi}(^3S_1)\rangle + \langle O_8^{\psi'}(^3S_1)\rangle Br(\psi' \to J/\psi) + \sum_{J=0}^{2}(2J+1)\langle O_8^{\chi_{c0}(1P)}(^3S_1)\rangle Br(\chi_{cJ} \to J/\psi)]^2.$$



$P_T \geq 3$ GeV Final States	CTEQ6L1 $\sigma_{\text{Tevatron}}[nb]$	CTEQ6L1 $\sigma_{\text{LHC}}[nb]$	CTEQ5L $\sigma_{\text{Tevatron}}[nb]$	CTEQ5L $\sigma_{\text{LHC}}[nb]$
$\eta_c\eta_c$	4.99×10^{-3}	4.10	4.35×10^{-3}	4.2
$J/\psi J/\psi$	8.46×10^{-2}	4.25	7.49×10^{-2}	4.6
$\eta_b\eta_b$			2.66×10^{-5}	1.16×10^{-2}
$\Upsilon\Upsilon$			1.74×10^{-4}	2.46×10^{-2}
$B_c\bar{B}_c$	3.86×10^{-3}	2.72×10^{-1}		
$B_c\bar{B}_c^*$	1.00×10^{-3}	8.37×10^{-2}		
$B_c^*\bar{B}_c^*$	8.23×10^{-3}	7.08×10^{-1}		

Double quarkonium production

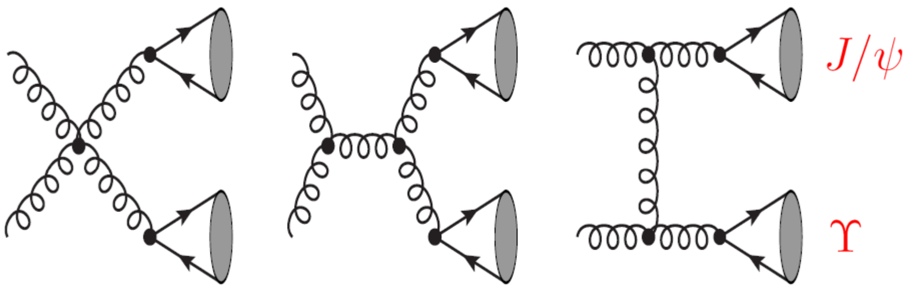
• Color-singlet contributions dominate at low P_T.

• Color-octet contributions may dominate at high P_T, but they might be much suppressed if the color-octet matrix elements are resized according to the recent works.

• We suggest the $J/\psi + \Upsilon$ production at the hadron colliders.

$J/\psi + \Upsilon$ production at the hadron colliders

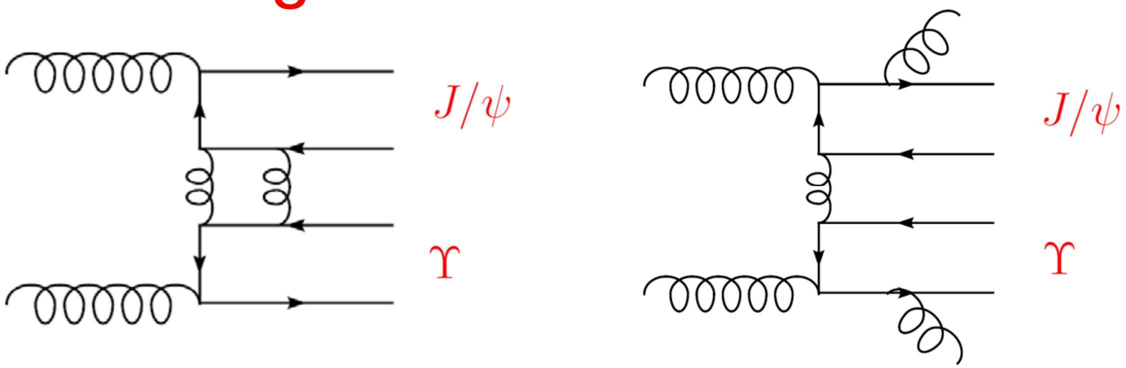
Color octet



$$\frac{d\hat{\sigma}}{dP_T^2} \sim \frac{\alpha_s^4 v_{J/\psi}^4 v_{\Upsilon}^4}{P_T^4}$$

- Gluon fragmentation approximation may be efficient.

Color singlet



$$\frac{\text{octet}}{\text{singlet}} \sim \frac{v_{J/\psi}^4 v_{\Upsilon}^4}{\alpha_s^2}\left(\frac{P_T^2}{m_c^2}\frac{P_T^2}{m_b^2}\right)^2$$

$$\sim \begin{cases} 4 \quad \text{for } P_T = 5 \text{ GeV} \\ 900 \ \text{for } P_T = 10 \text{ GeV} \end{cases}$$

- Color-singlet contributions are of order α_s^6.

$J/\psi + \Upsilon$ production at the hadron colliders

- The cross section for the color-octet pair can be obtained by the gluon fragmentation approximation.

	σ_{Tevatron} [pb]	σ_{LHC} [pb]
$J/\psi\Upsilon$	1.0	90

Preliminary

- Include the feed-down effects.

	σ_{Tevatron} [pb]	σ_{LHC} [pb]
$J/\psi\Upsilon$	4.5	392

- Integrated luminosity : Tevatron $\sim$ 4 fb^{-1}, LHC $\sim$ 100 fb^{-1}.
- might be measurable at the Tevatron and LHC.
- If we cannot observe these events at this level, we may conclude that the color-octet mechanism is overestimated.

Summary

- The production of a heavy quarkonium at the Tevatron cannot be explained by the color-singlet model.

- The polarization problem of a heavy quarkonium at the Tevatron is still open.

- require reducing the theoretically errors and higher-order corrections to the feed-down effects as well as the direct production of a heavy quarkonium.

- require tests of NRQCD for various processes.

- Double quarkonium production at hadron colliders may provide another test ground for NRQCD.

- $J/\psi + \Upsilon$ production may be used to test the color-octet mechanism, but the estimate based on the gluon fragmentation approximation may be overestimated. Full QCD calculation for this process is begin carried out.