Double quarkonium production at the LHC

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Outline

- Motivation
- Heavy quarkonium production (NRQCD)
- Double quarkonium production at the LHC
- Conclusions

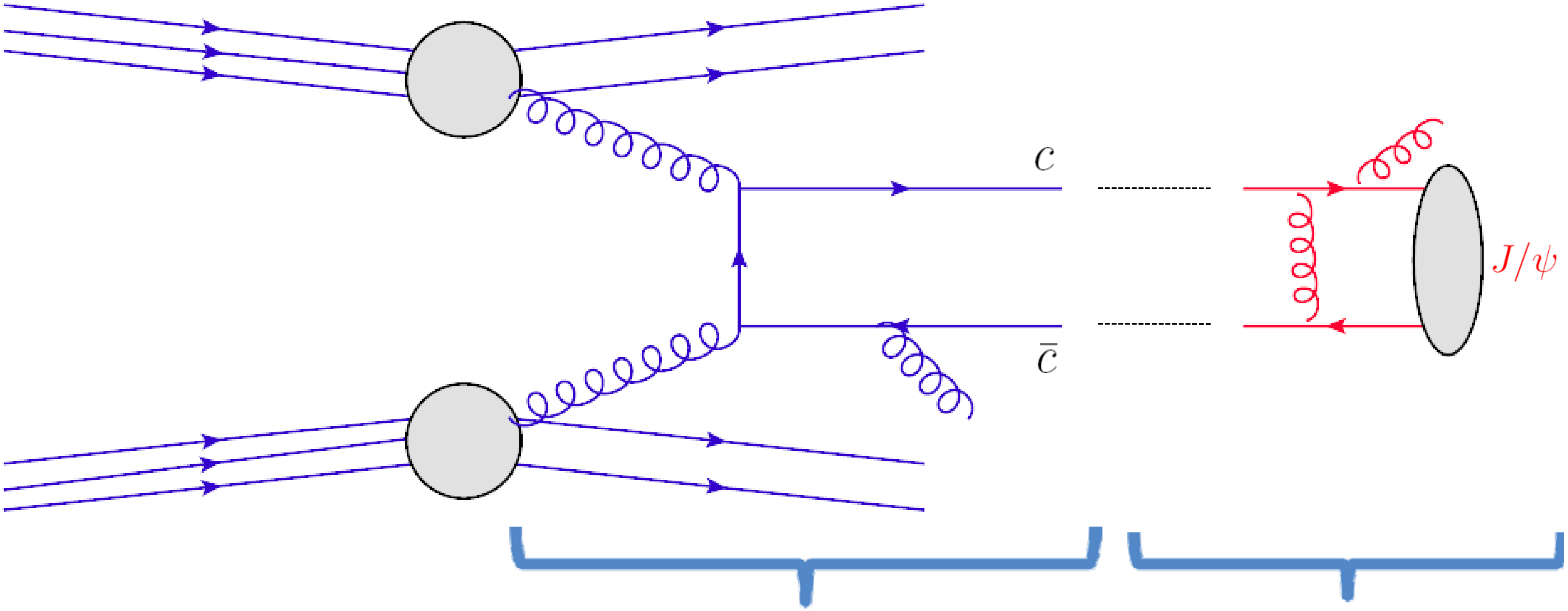
Motivation

- heavy quarkonium : a bound state of a heavy-quark-antiquark pair.
- almost nonrelativistic – has a hydrogenlike spectrum.

	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^*		

- probes perturbative and nonperturbative aspects of QCD.
- NRQCD has achieved great success in decay and production of a quarkonium and double quarkonium production at B factories, etc.
- but there are still unresolved puzzles – polarization of J/ψ at Tevatron…
- natural to probe the double quarkonium production at hadron colliders.

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 by NRQCD, which is an effective field theory of QCD.

NRQCD matrix elements

- the probability to find a corresponding Fock state in the final state.

- nonperturbative, but calculable in lattice simulations in principle.
  - suffers large uncertainties.

- universal (process independent).
  - holds up to corrections of v^4 under the vacuum saturation approximation.

- color-singlet MEs are determined from electromagnetic decays.

- How determine color-octet matrix elements?
  - color-octet dominant process.
  - J/ψ production at the Tevatron, etc.

Double quarkonium production

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

- the predictions for the polarization do not agree with data in the CSM.

- room for the color-octet contributions.

- need to find the process in which the color-octet contributions are indeed dominant.
  - double quarkonium production?

- Tevatron and LHC open the double quarkonium production channel.

- LHC will produce a huge number of heavy quarkonium.

Double quarkonium production

- already predicted to test the color-octet mechanism at the Tevatron.

Barger,Fleming,Phillips('96)

$$\sigma(p\bar{p} \to \psi_{\mu\mu}\psi_{\mu\mu}X) \approx 0.14 \text{ pb.}$$

- Double quarkonium production in the color-singlet model at the Tevatron.

Qiao('02)

  - color-singlet contribution dominates at $p_T < 4$ GeV.

- recently extended to the LHC.

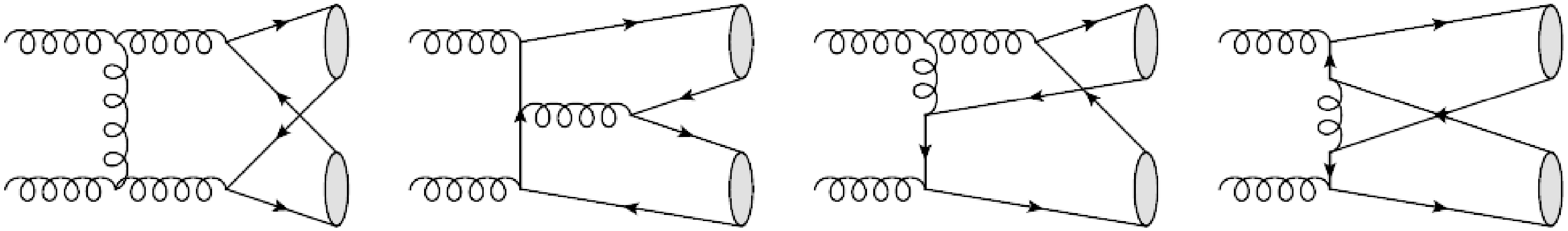
Li,Zhang,Chao(PRD80,014020);Qiao,Sun,Sun(0903.0954)

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

- Previous works considered only identical quarkonium pair production;
  - use gluon fragmentation approximation for the CO contributions

- extend the double quarkonium production of different flavor.
  - calculate the CO contributions fully instead of gluon frag. approx.

Color-singlet model



- The leading precoesses are of order α_s^4 .
- Two subprocesses at this order are

$$g + g \rightarrow \mathcal{Q}_1 + \mathcal{Q}_2, \qquad \text{dominant}$$

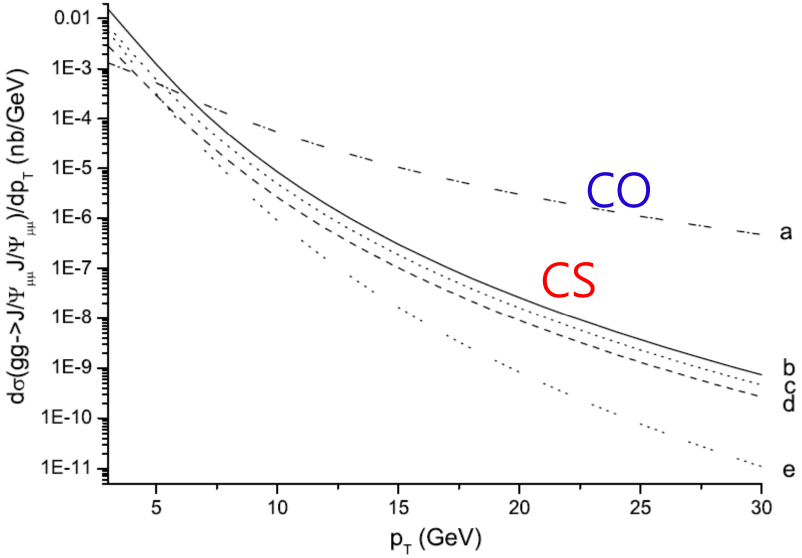
$$q + \bar{q} \rightarrow \mathcal{Q}_1 + \mathcal{Q}_2. \qquad \text{ignore}$$

- 31 Feynman diagrams.
- The schematic form of the cross section is

$$d\sigma[pp \rightarrow H_1(P_1) + H_2(P_2)] = \sum_{i,j,n_1,n_2} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \rightarrow \mathcal{Q}_1^{n1} + \mathcal{Q}_2^{n2}] \langle O_{n_1} \rangle_{H_1} \langle O_{n_2} \rangle_{H_2}$$

- $\mu_r = \mu_f = m_T = \sqrt{m_{\mathcal{Q}}^2 + p_T^2}.$

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)

- multiplied by branching fractions for J/ψ decay into muon pair.
- used the gluon fragmentation approximation.

- integrated cross section

	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)

Double quarkonium production (same flavor)

- The color-singlet contribution is dominant at low p_T.
  - about 10^8 events for $J/\psi J/\psi$ production with $\sqrt{s} = 14\ \mathrm{TeV}$ and $\mathcal{L} \sim 100\ \mathrm{fb}^{-1}$.

- The color-octet contribution may exceed the color-singlet one in the region $p_T > 6$ GeV.

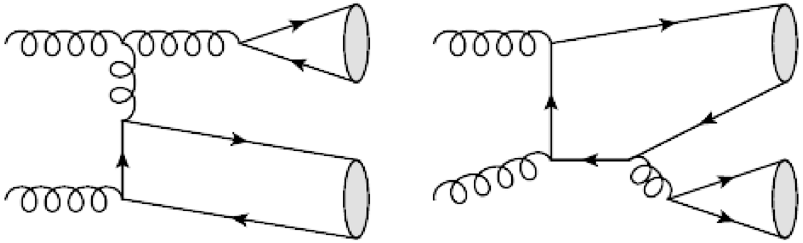
- Thus could be possible to test the color-octet mechanism by measuring the double quarkonium production events with high p_T.

- but, the fragmentation approximation is valid only at large p_T.

- requires the comparison with the full calculation.

- need to resolve the scale uncertainties.

Color-octet model (full calculation)



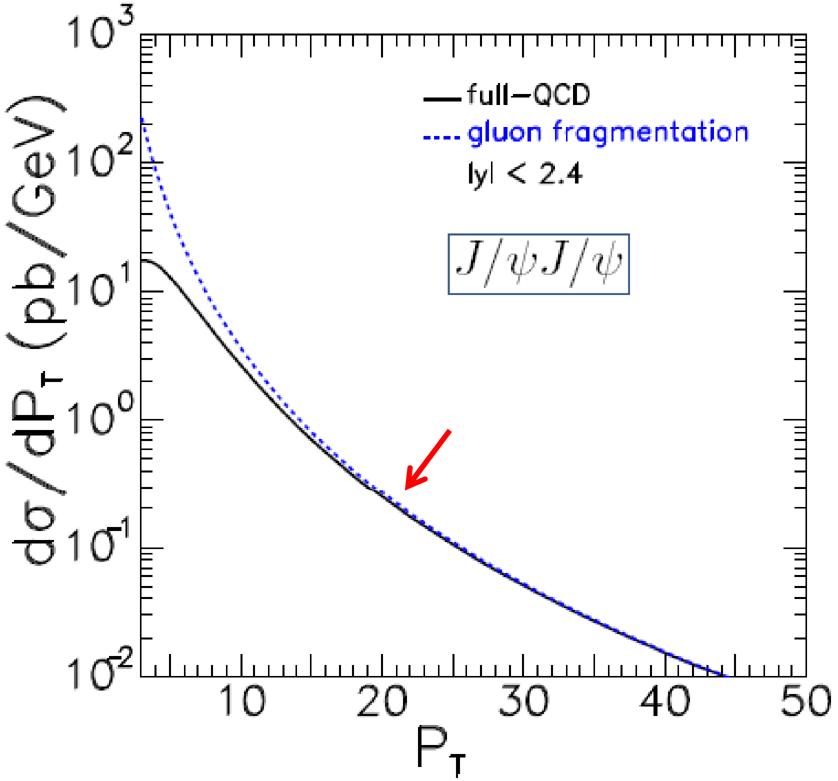
- various combinations of intermediate states are allowed.

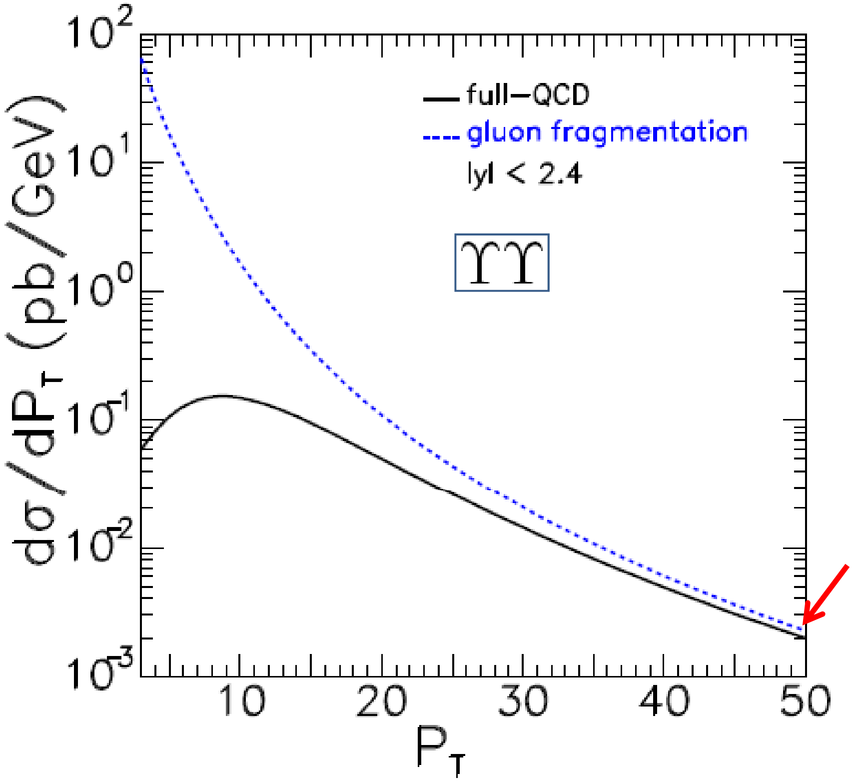
$$
{}^3S_1^{(8)} + {}^3S_1^{(8)},\ {}^3S_1^{(8)} + {}^1S_0^{(8)},\ {}^3S_1^{(8)} + {}^3P_J^{(8)},
$$

$$
{}^1S_0^{(8)} + {}^3P_0^{(8)},\ {}^3S_1^{(1)} + {}^3S_1^{(8)},\ {}^3S_1^{(1)} + {}^1S_0^{(8)},\cdots .
$$

- We consider only ${}^3S_1^{(8)} + {}^3S_1^{(8)}$ combination because
  - ${}^1S_0$ and ${}^3P_0$ color-octet matrix elements may be much suppressed.
  - ${}^3S_1^{(8)} + {}^3S_1^{(8)}$ combination will be dominant at large p_T.
- 68 Feynman diagrams.

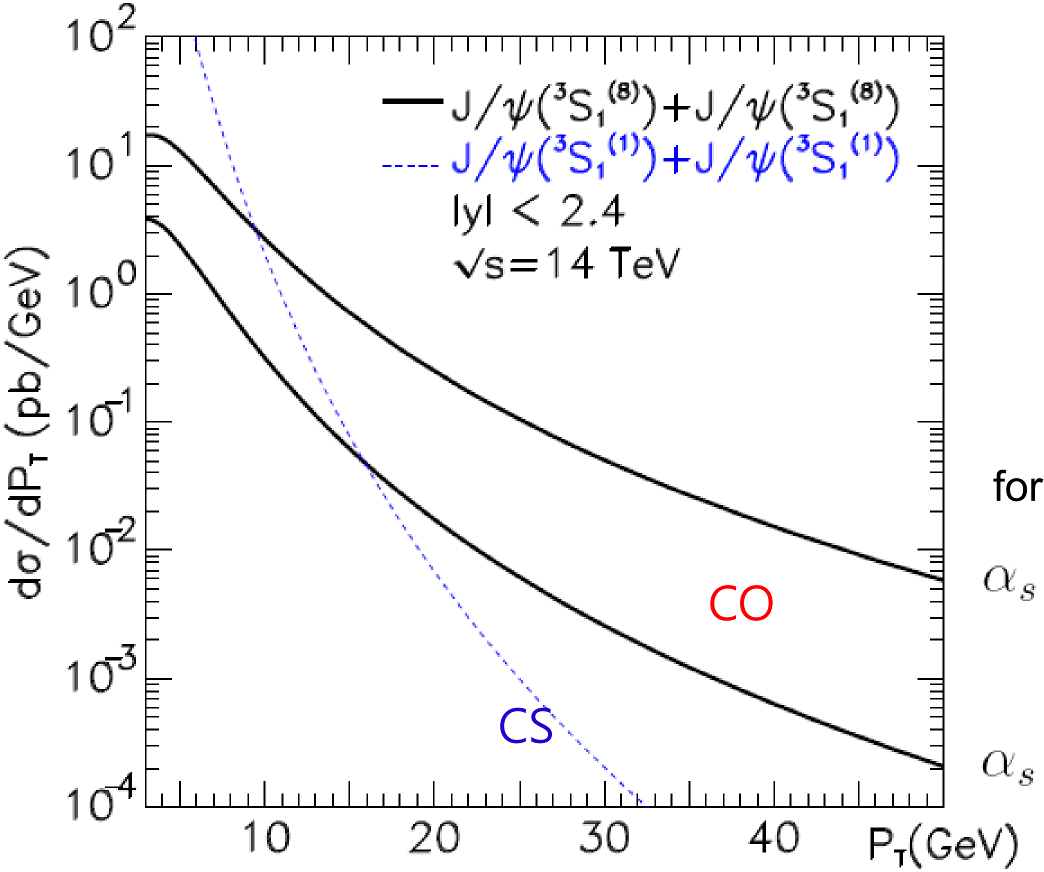
gluon frag. vs. full calculation





- $$\alpha_s = \begin{cases} \alpha_s(m_{J/\psi}), \alpha_s(m_\Upsilon), & \text{for fragmentation processes,} \\ \alpha_s(m_T), & \text{for nonfragmentation processes.} \end{cases}$$
- This choice violates gauge invariance with an error of $O(m_c^2/\hat{s})$.

$J/\psi J/\psi$ production (full calculation)



for fragmentation processes

$\alpha_s(m_{J/\psi})$

$\alpha_s(m_T)$

- The differential cross section varies by about a factor 6 at small p_T and by about a factor 40 at large p_T.
- The CO contribution dominates over the CS contribution at p_T>16 GeV.

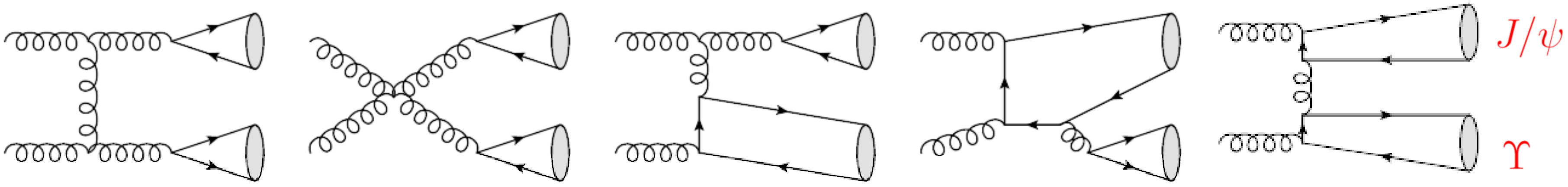
Double quarkonium production (same flavor)

Final quarkonia	States \ $P_{T\min}$ [GeV]	Cross section [pb] $\mu = m_H$ for fragmentation					Cross section [pb] $\mu = m_T$ for fragmentation					
		3	7	10	15	20	3	7	10	15	20	
$J/\psi + J/\psi$	${}^3S_1^{[8]} + {}^3S_1^{[8]}$	75.90	24.37	11.03	3.83	1.66	12.72	2.84	1.02	0.26	0.09	CO
	${}^3S_1^{[1]} + {}^3S_1^{[1]}$	-	-	-	-		2757	32.61	2.92	0.16	0.02	CS
$\Upsilon + \Upsilon$	${}^3S_1^{[8]} + {}^3S_1^{[8]}$	2.27	1.86	1.40	0.78	0.42	0.57	0.45	0.33	0.17	0.08	CO
	${}^3S_1^{[1]} + {}^3S_1^{[1]}$	-	-	-	-	-	32.79	8.32	2.35	0.30	0.05	CS

- Production of identical quarknia can be tested at the LHC.
- If we consider the contributions from feeddowns of $\psi(2S)$ and χ_{cJ}, it seems that the color-octet mechanism may be testable at the LHC
- However we must resolve the large uncertainty from the scale dependence.
- The CS contribution might contaminate the CO contribution.
- We suggest the $J/\psi + \Upsilon$ production at the LHC.

Double quarkonium production (different flavor)

Color octet



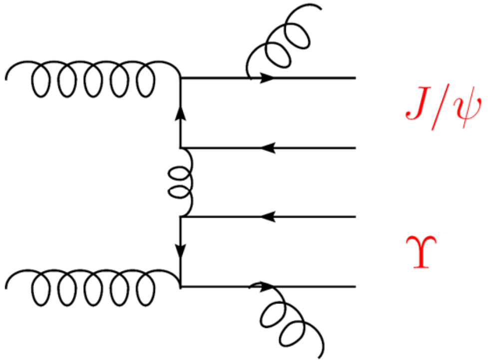
- The leading processes are of order α_s^4 .
- Among various combinations of intermediate states, we consider

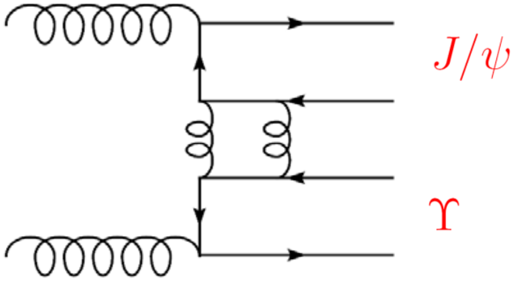
$${}^3S_1^{(8)} + {}^3S_1^{(8)},\ {}^3S_1^{(1)} + {}^3S_1^{(8)},\ {}^3S_1^{(8)} + {}^3S_1^{(1)}.$$

- 36 Feynman diagrams for the color-octet pair.
- 5 Feynman diagrams for the color-singlet + color-octet pair.

Double quarkonium production (different flavor)

Color singlet





- Tree-level color-singlet contribution accompanies at least two hard gluons.

  - suppressed by at least about a factor of $\alpha_s^2 m_c^2 m_b^2 / p_T^4$.
  - extra hard jets in the final state.

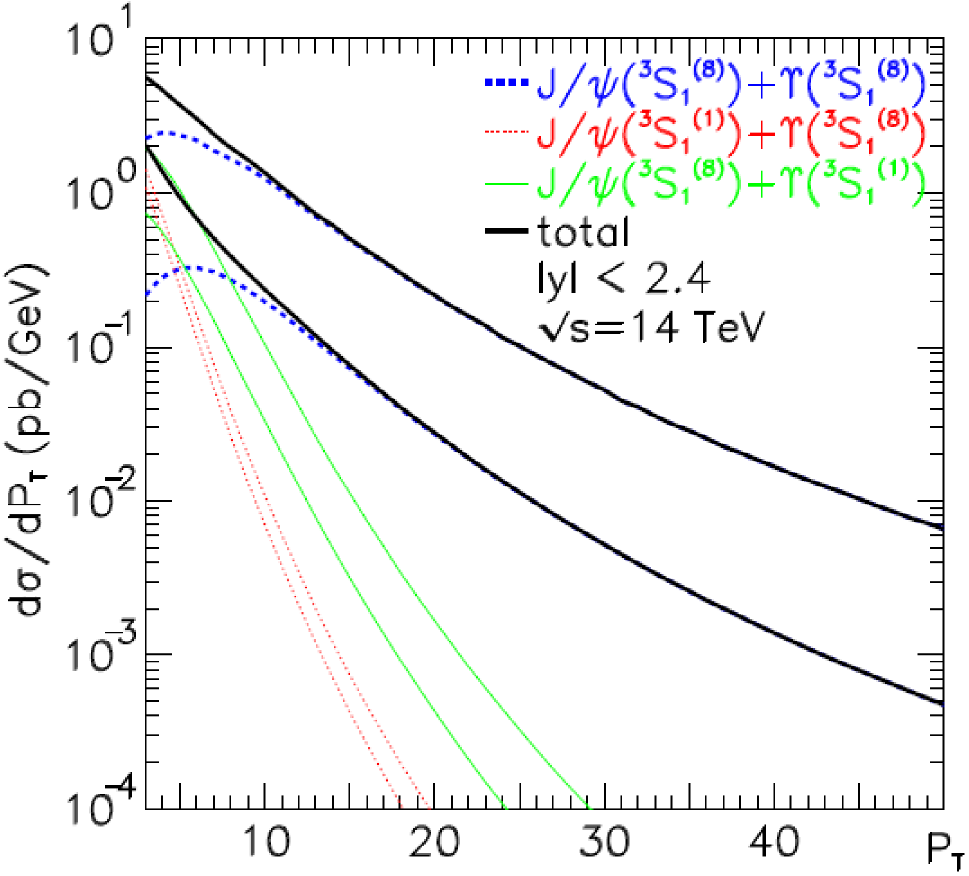
- The color-singlet contribution at one-loop level can appear via two-gluon exchange. The relative size of the CO contribution to this is

$$\frac{(4\pi)^2 v_{J/\psi}^4 v_\Upsilon^4}{\alpha_s^2}\left(\frac{p_T^2}{m_c^2}\frac{p_T^2}{m_b^2}\right)^2 \sim 500 \quad \text{at } p_T = 5 \text{ GeV}.$$

Double quarkonium production (different flavor)

- Thus we conclude that the color-singlet contribution is suppressed and also easily distinguishable.
- The $J/\psi + \Upsilon$ production at the LHC will provide good tests for the color-octet mechanism with less backgrounds and without color-singlet contamination.
- If we cannot observe the events at the expected level, it would imply that the current values of the color-octet matrix elements are overestimated.

$J/\psi\Upsilon$ production



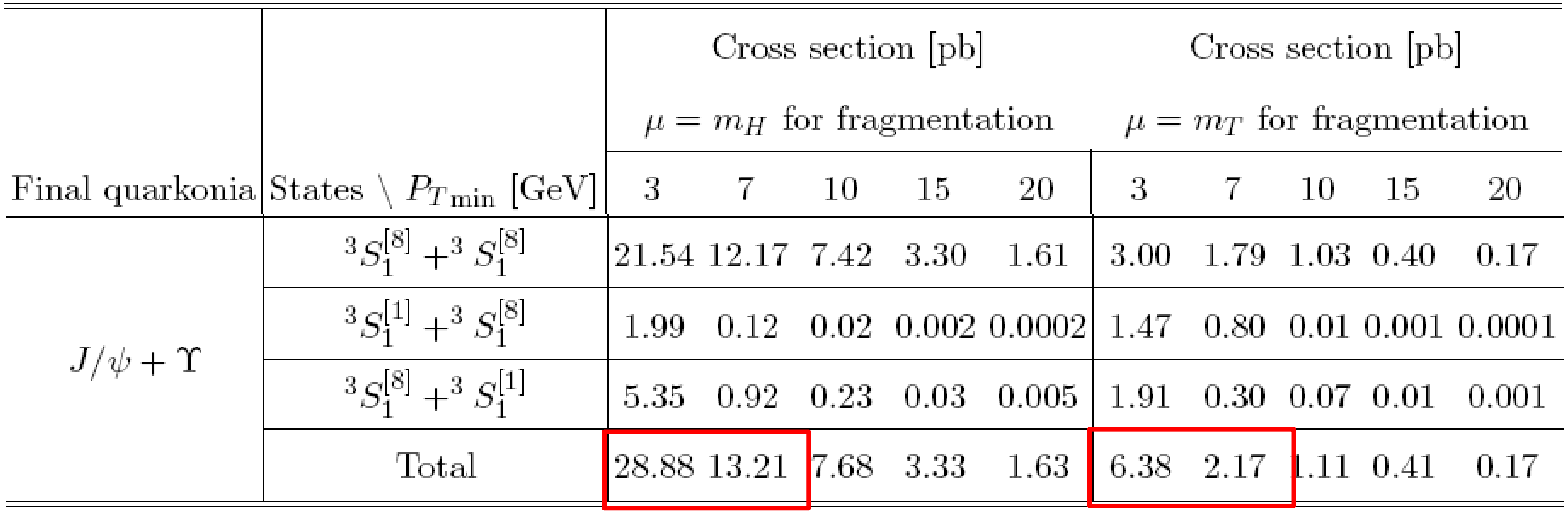
for fragmentation processes

$\alpha_s(m_{J/\psi})$

$\alpha_s(m_T)$

- The differential cross section varies by about a factor 11 at small p_T and by about a factor 14 at large p_T.

Double quarkonium production (different flavor)



Final quarkonia	States \ $P_{T\min}$ [GeV]	Cross section [pb] $\mu = m_H$ for fragmentation					Cross section [pb] $\mu = m_T$ for fragmentation				
		3	7	10	15	20	3	7	10	15	20
$J/\psi + \Upsilon$	${}^3S_1^{[8]} + {}^3S_1^{[8]}$	21.54	12.17	7.42	3.30	1.61	3.00	1.79	1.03	0.40	0.17
	${}^3S_1^{[1]} + {}^3S_1^{[8]}$	1.99	0.12	0.02	0.002	0.0002	1.47	0.80	0.01	0.001	0.0001
	${}^3S_1^{[8]} + {}^3S_1^{[1]}$	5.35	0.92	0.23	0.03	0.005	1.91	0.30	0.07	0.01	0.001
	Total	28.88	13.21	7.68	3.33	1.63	6.38	2.17	1.11	0.41	0.17

- expects 2 pb ~ 29 pb at the LHC.
- Feeddown may enhance the cross section by an order of magnitude.
- Production of different quarkonia can be observed at the LHC.

Conclusions

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

- presented the first full calculation for the color-octet contribution to the double quarkonium production at the LHC.

- $J/\psi + \Upsilon$ production may be used to test the color-octet mechanism with less backgrounds and without color-singlet contamination.

- If one cannot see the $J/\psi + \Upsilon$ events at the expected level, it would imply that the current color-octet matrix elements are overestimated.

Backup slides

Color-octet mechanism

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

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

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

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

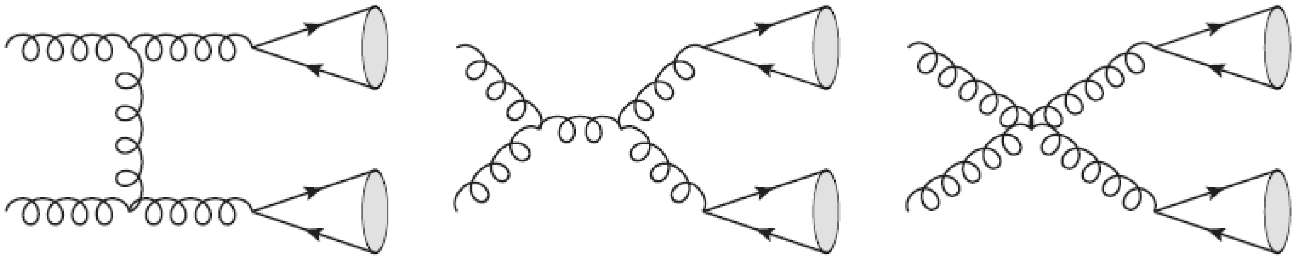
Summary of single quarkonium production

at NLO

		Tevatron	HERA	B factories
		$p\bar{p}$	e^-p	e^-e^+
CS	σ	not enough	not enough	may explain
	α	disagree	inconsistent at high P_T	—
CO	σ	may be needed	can explain	unnecessary?
	α	not completed	consistent	—

- the CS contributions could not explain the data.
- room for the color-octet contributions?
- no conclusive constraints on the $^3S_1$ color-octet matrix element.

Color-octet model (previous works)



fragmentation
diagrams

- The leading precoesses are of order α_s^4 .
- gluon fragmentation approximation.
  - dominant process is two real gluon production, followed by the fragmentation of each gluon into a quarkonium in the $^3S_1$ color-octet state.
- 4 Feynman diagrams.
- The schematic form of the cross section is

$$d\sigma^{H_1(P_1)+H_2(P_2)} = f_{g/p} \otimes f_{g/p} \otimes D_{g\to H_1}(z_1, m_{Q_1}) \otimes D_{g\to H_2}(z_2, m_{Q_2}) \otimes d\sigma_{gg\to gg}(E_1/z_1, E_2/z_2),$$

$$D_{g\to H_i}(z_i, m_{H_i}) = \frac{\pi\alpha_s}{24 m_{H_i}^3}\delta(1-z_i)\langle O_8(^3S_1)\rangle_{H_i}.$$

- $\alpha_s(m_{J/\psi}) = 0.286,\ \alpha_s(m_\Upsilon) = 0.201.$

Color-octet model (previous works)

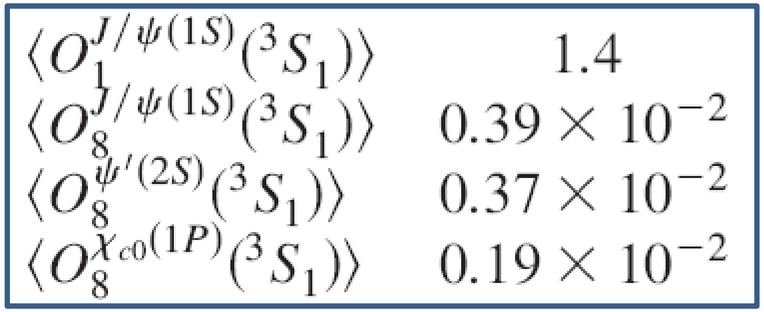
- easy to include contributions from feeddown of $\psi(2S)$ and χ_{cJ} .

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

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

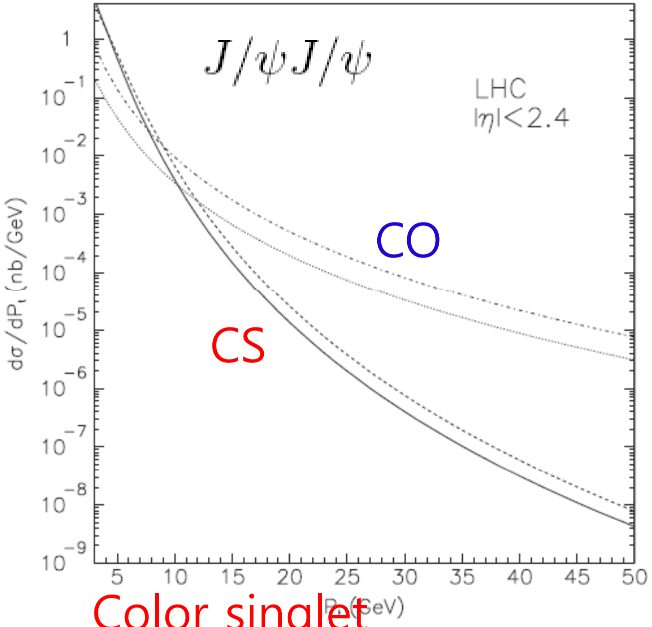
$$+\sum_{J=0}^{2}(2J+1)\langle O_8^{\chi_{c0}(1P)}(^3S_1)\rangle Br(\chi_{cJ} \to J/\psi)]^2.$$

- increases the cross section by about a factor 6 with the following choices for the matrix elements:



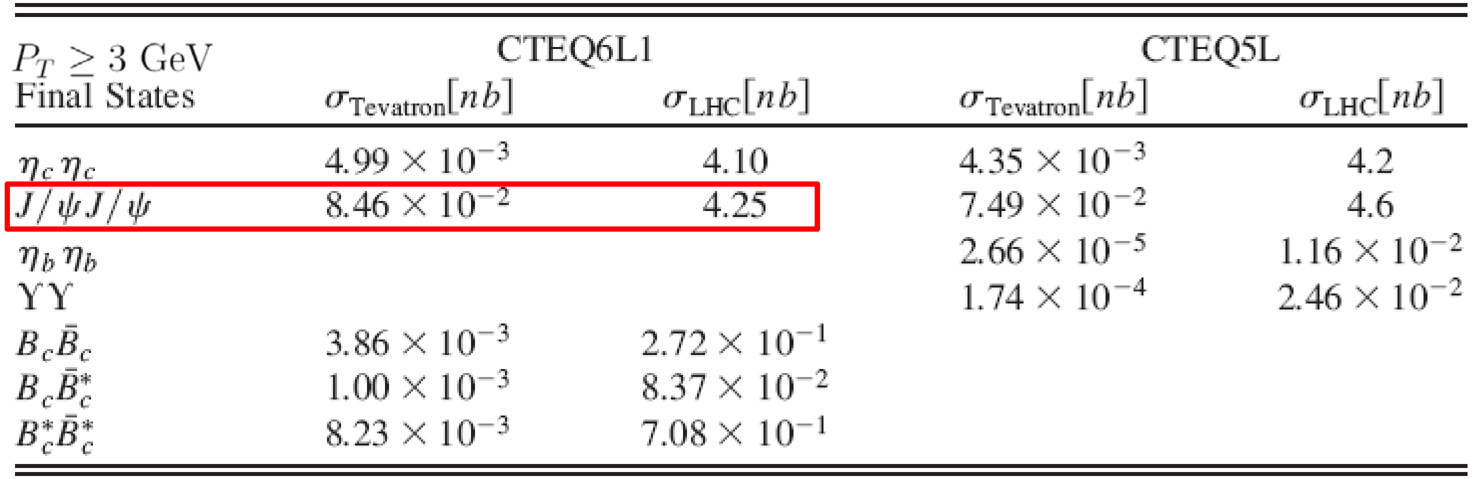
$\langle O_1^{J/\psi(1S)}(^3S_1)\rangle$	1.4
$\langle O_8^{J/\psi(1S)}(^3S_1)\rangle$	0.39×10^{-2}
$\langle O_8^{\psi'(2S)}(^3S_1)\rangle$	0.37×10^{-2}
$\langle O_8^{\chi_{c0}(1P)}(^3S_1)\rangle$	0.19×10^{-2}

Cross section for double quarkonium production



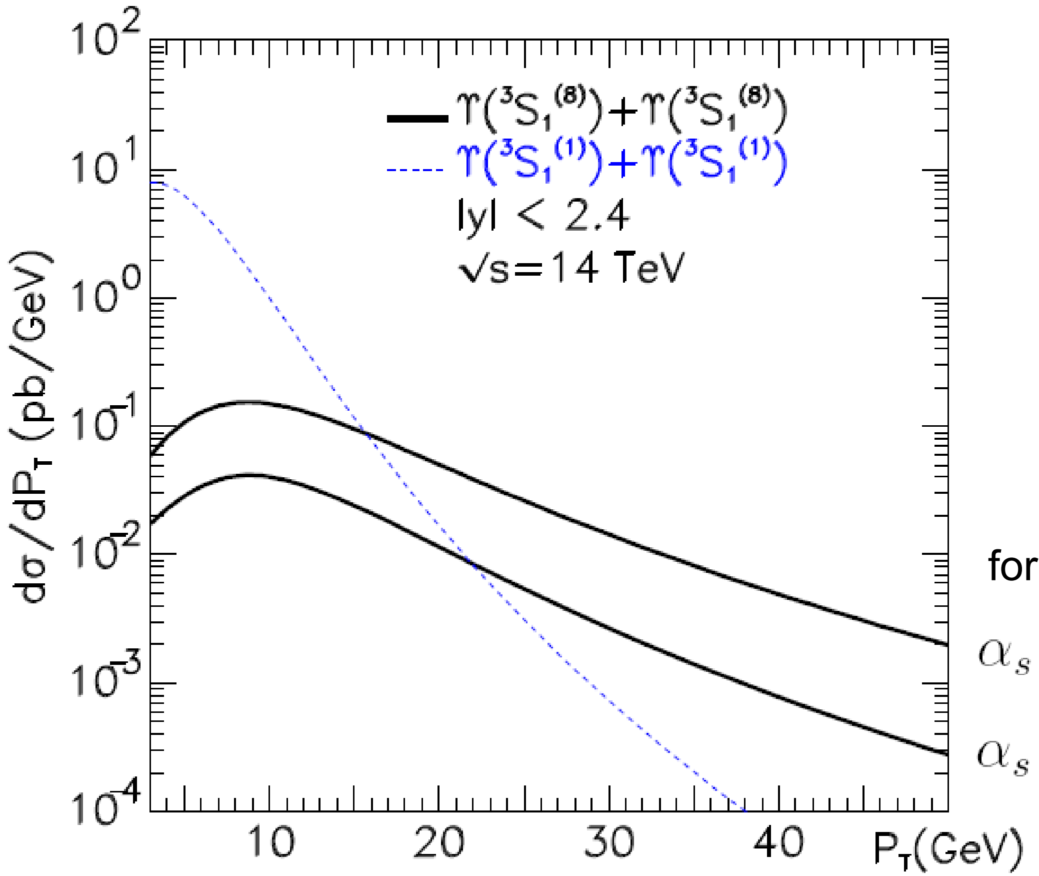
Color singlet

Li,Zhang,Chao(PRD80,014020)



$P_T \geq 3$ GeV	CTEQ6L1		CTEQ5L	
Final States	$\sigma_{\text{Tevatron}}[nb]$	$\sigma_{\text{LHC}}[nb]$	$\sigma_{\text{Tevatron}}[nb]$	$\sigma_{\text{LHC}}[nb]$
$\eta_c\eta_c$	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}		

$\Upsilon\Upsilon$ production (full calculation)



for fragmentation diagrams

$\alpha_s(m_{J/\psi})$

$\alpha_s(m_T)$

- The choices for the scale yield a factor 4 difference at small p_T.
- It becomes about a factor 6 at p_T=50 GeV.
- The CO contribution dominates over the CS contribution at p_T>22 GeV.