Double quarkonium production at the LHC

Chaehyun Yu (KIAS)

In collaboration with P. Ko (KIAS), Jungil Lee (Korea Univ.)

Based on arXiv:1006.3846; 1007.3095

ICHEP 2010, Paris, July 22 2010

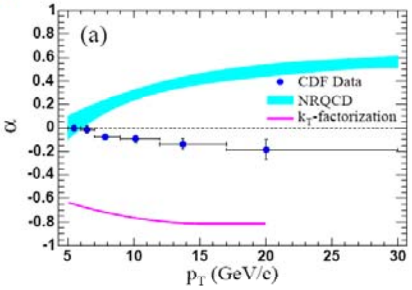
Outline

- Motivation
- Double quarkonium production of same flavor
  - $pp \to J/\psi + J/\psi + X, pp \to \Upsilon + \Upsilon + X$
- Double quarkonium production of different flavor
  - $pp \to J/\psi + \Upsilon + X$
- Conclusions

Motivation

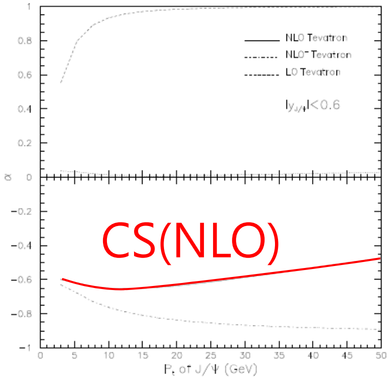
- Heavy quarkonium: probes perturbative and nonperturbative aspects of QCD.
- NRQCD has achieved great success.
  - resolves IR divergence problem.
  - the surplus production of J/ψ at Tevatron.
  - double quarkonium production at B factories, etc.
- there are still unresolved puzzles.
  - polarization of prompt J/ψ at Tevatron.

Run II:



Braaten,Kniehl,Lee,PRD62,094005(2000)

Gong,Wang,PRD78,074011(2008)



- the double quarkonium production at hadron colliders.
  - test NRQCD.
  - get hints for the puzzles.

Double quarkonium production

- still room for the color-octet contribution.

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

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

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

Barger,Fleming,Phillips('96)

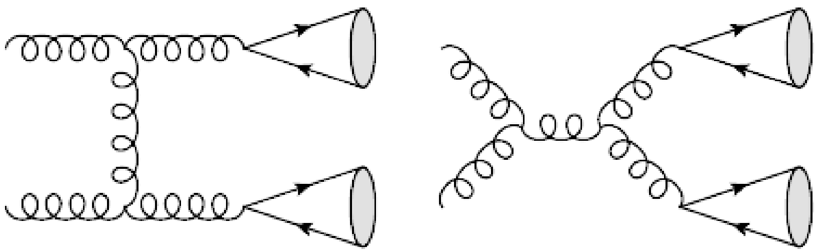
- recently extended to the LHC.

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

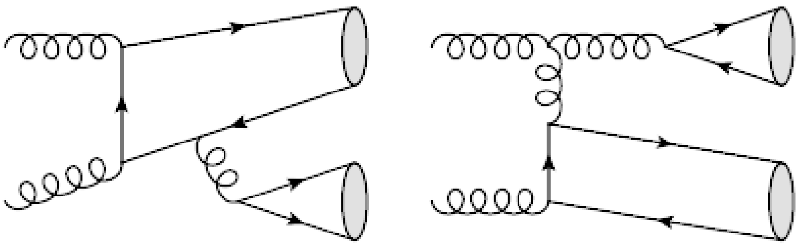
- Previous works considered only identical quarkonium pair production;
  - use gluon fragmentation approximation for the CO contribution.

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

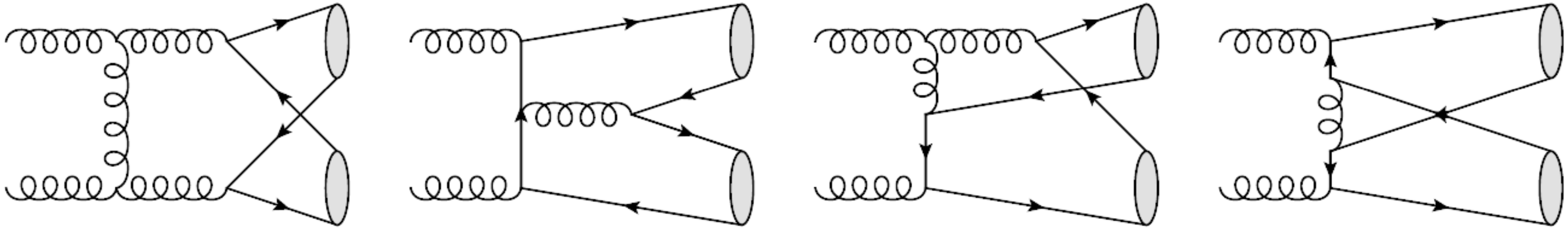
Double quarkonium production



double fragmentation



single fragmentation



nonfragmentation

- The schematic form of the cross section is

$$d\sigma[pp \to H_1(P_1) + H_2(P_2)] = \sum_{i,j,n_1,n_2} f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to Q_1^{n1} + Q_2^{n2}]\, \underline{\langle O_{n_1} \rangle_{H_1} \langle O_{n_2} \rangle_{H_2}}$$

scale as v.

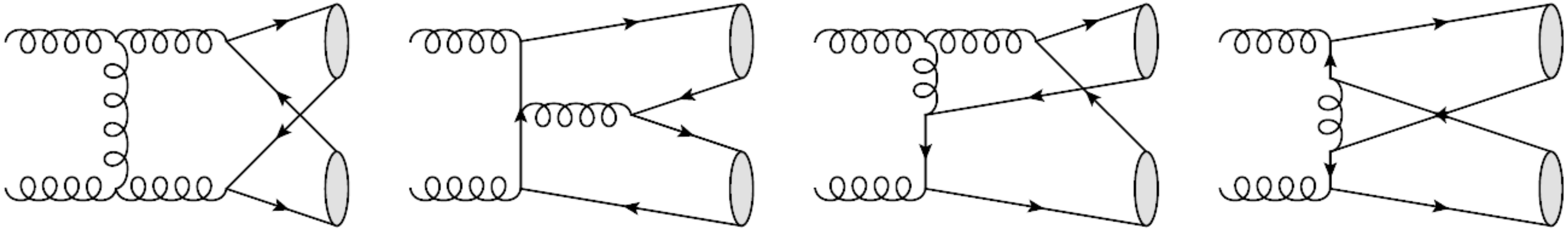
- $\mu_r = \mu_f = m_T = \sqrt{m_Q^2 + p_T^2}.$

Double quarkonium production of same flavor

$$pp \to J/\psi + J/\psi + X,$$

$$pp \to \Upsilon + \Upsilon + X$$

Color-singlet channel



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

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

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

- The leading contribution is the color-singlet channel

$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_1({}^3S_1), Q\bar{Q}_1({}^3S_1)]$$

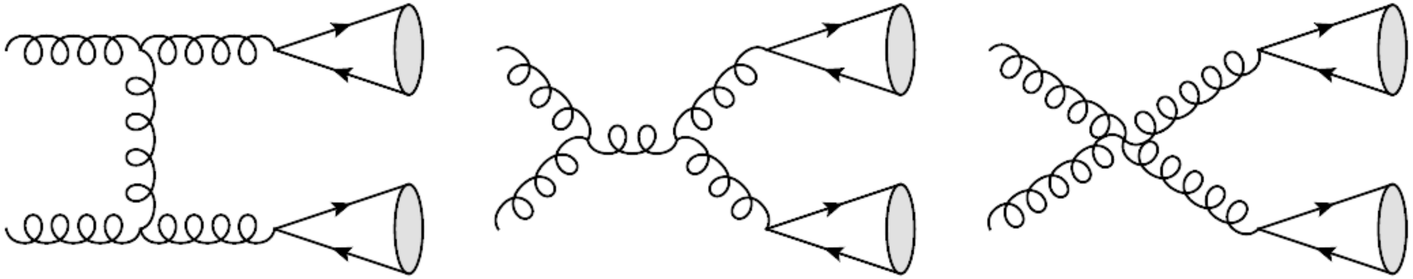
- Color-octet channels are suppressed.

$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_8({}^3S_1), Q\bar{Q}_8({}^3S_1)] \qquad \text{by } v^8$$

$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_1({}^3S_1), Q\bar{Q}_8({}^3S_1)] \qquad \text{by } v^4$$

- 31 Feynman diagrams in the color-singlet channel.

Color-octet channel (gluon fragmentation approx.)



fragmentation diagrams

- The leading precoesses are of order α_s^4 .

- gluon fragmentation approximation.
  - 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

$$d\sigma^{H_1(P_1)+H_2(P_2)} = f_{g/p} \otimes f_{g/p} \otimes d\hat{\sigma}_{gg\to gg} \otimes D_{g\to H_1} \otimes D_{g\to H_2},$$

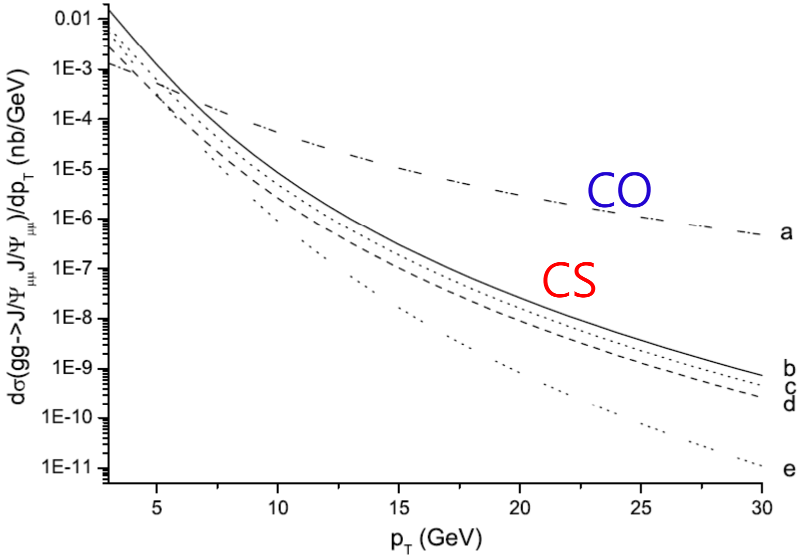
$$D_{g\to H_i}(z_i, m_{H_i}) = \frac{\pi\alpha_s}{24m_{H_i}^3}\delta(1-z_i)\langle O_8(^3S_1)\rangle_{H_i}.$$

- It is necessary to evaluate the frag. func. at the fac. scale $\mu_{\rm f} \sim p_T \gg m_Q$. by making use of Altarelli-Parisi evolution equation.

Color-octet channel (gluon fragmentation approx.)

- easy to include contributions from feeddown of $\psi(2S)$ and χ_{cJ}.
- increases the cross section by about a factor 6.
- recently carried out by two groups(Li,Zhang,Chao;Qiao,Sun,Sun).
- but evaluated at the threshold.

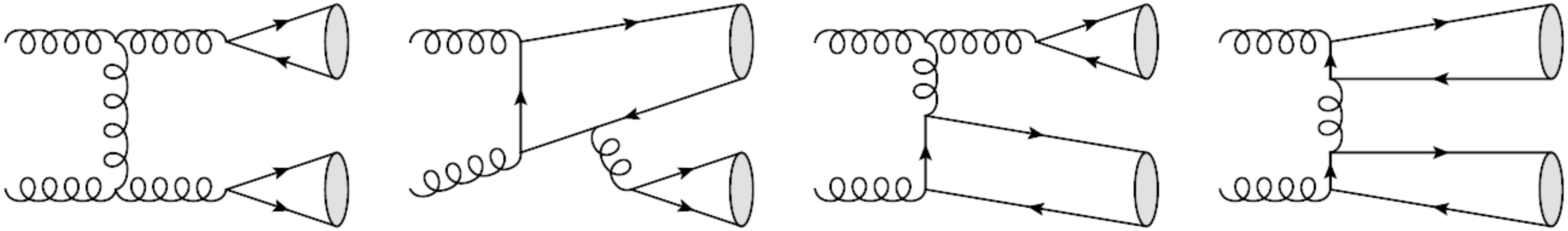
$$\alpha_s(m_{J/\psi}) = 0.286, \ \ \alpha_s(m_\Upsilon) = 0.201.$$



Qiao,Sun,Sun(0903.0954)

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

Color-octet channel (full calculation)



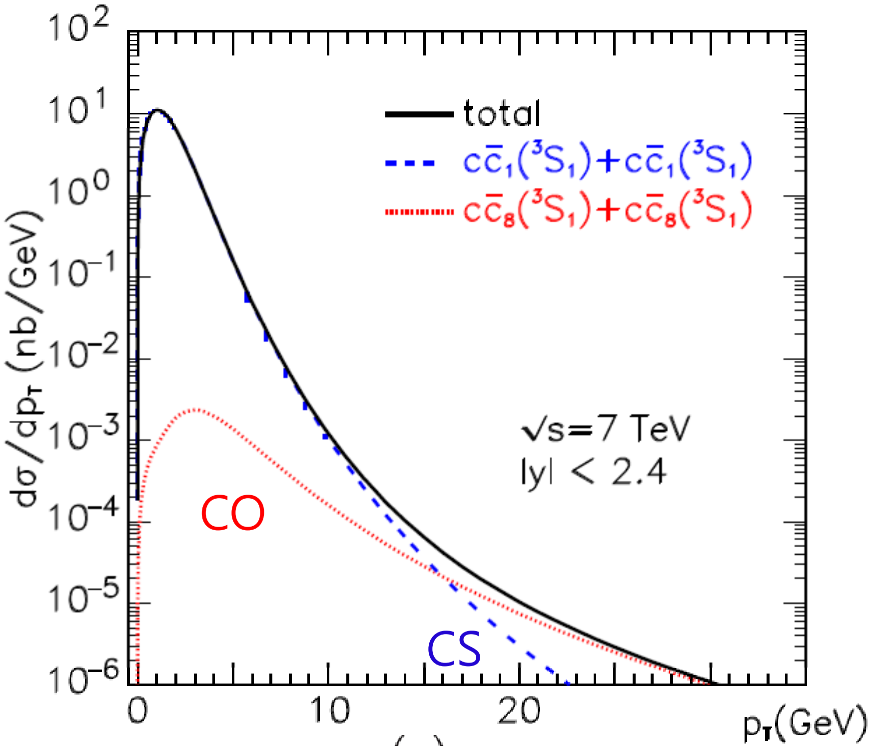
- various combinations of intermediate states are allowed.

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

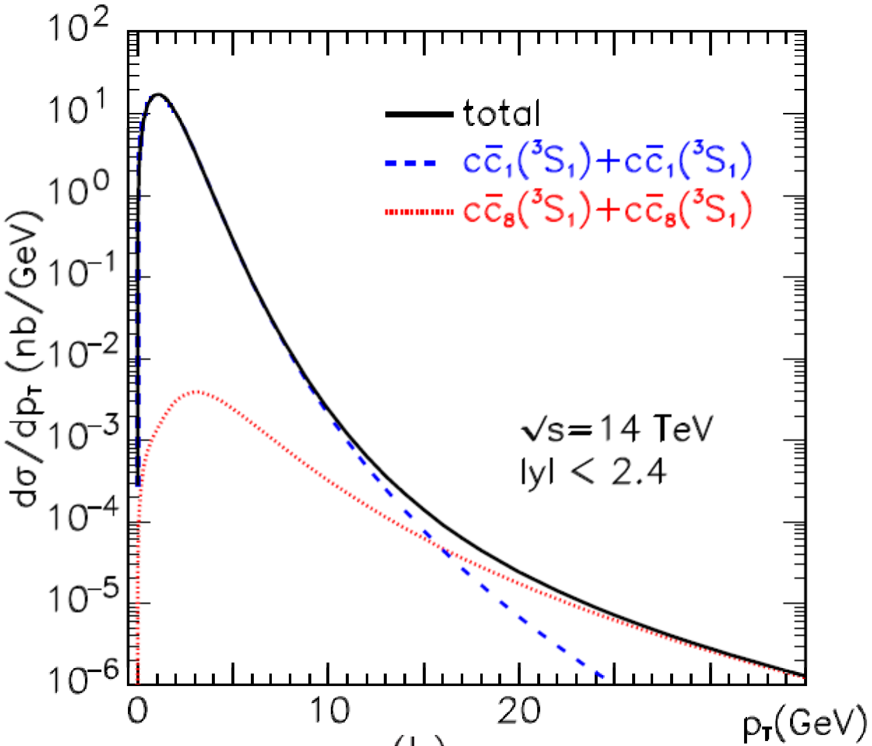
$$ {}^1S_0^{(8)} + {}^3P_0^{(8)},\ {}^3S_1^{(1)} + {}^3S_1^{(8)},\ {}^3S_1^{(1)} + {}^1S_0^{(8)}, \cdots . $$

- 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.
- 72 Feynman diagrams.

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



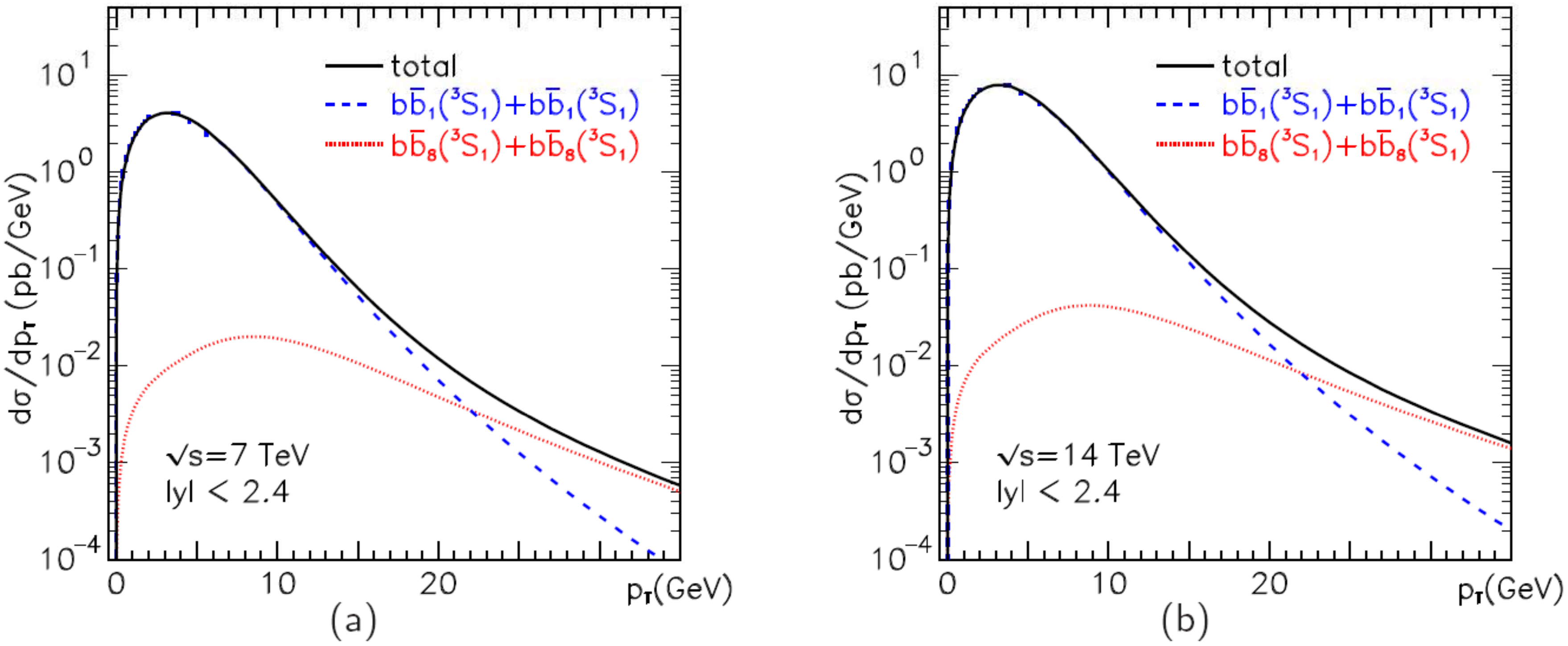
(a)



(b)

- The color-singlet contribution dominates at small p_T.
- The CO contribution dominates over the CS contribution at p_T>16 GeV.
- the spectrum vanishes at p_T=0, because both channels are free of infrared divergence.

ϒϒ production (full calculation)



- essentially the same as for the double J/ψ production.
- The CO contribution dominates over the CS contribution at p_T>24 GeV.

Double quarkonium production (same flavor)

$\sigma(pp \to 2J/\psi + X)$

$\sqrt{s} \setminus \sigma$ (nb)	$c\bar{c}_1(^3S_1) + c\bar{c}_1(^3S_1)$	$c\bar{c}_8(^3S_1) + c\bar{c}_8(^3S_1)$	total
7 TeV	22.3	0.011	22.3
14 TeV	34.8	0.019	34.8

$\sigma(pp \to 2\Upsilon + X)$

$\sqrt{s} \setminus \sigma$ (pb)	$b\bar{b}_1(^3S_1) + b\bar{b}_1(^3S_1)$	$b\bar{b}_8(^3S_1) + b\bar{b}_8(^3S_1)$	total
7 TeV	24.1	0.27	24.4
14 TeV	47.9	0.60	48.5

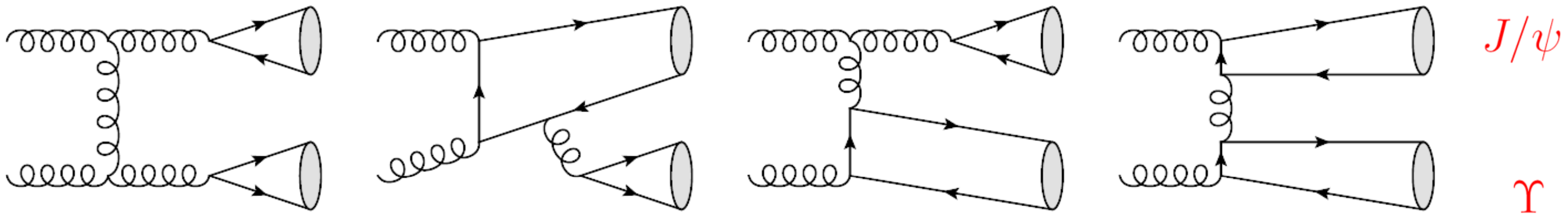
- double quarkonium production of same flavor can be tested at the LHC.
- If we consider the contributions from feeddown of $\psi(2S)$ and χ_{cJ}, it seems that the color-octet mechanism may be testable at the LHC
- The CS contribution might contaminate the CO contribution.
- We suggest the $J/\psi + \Upsilon$ production at the LHC as a clean probe of the color-octet mechanism.

Double quarkonium production of different flavor

$$pp \to J/\psi + \Upsilon + X$$

Double quarkonium production (different flavor)

Color octet channel $pp \to J/\psi + \Upsilon + X$



(a) (b) (c) (d)

- The leading processes are of order α_s^4 .

$c\bar{c}_8({}^3S_1) + b\bar{b}_8({}^3S_1)$	: (a),(b),(c),(d),	$v_c^4 v_b^4$	, double fragmentation
$c\bar{c}_1({}^3S_1) + b\bar{b}_8({}^3S_1)$	: (b),	v_b^4	, single fragmentation
$c\bar{c}_8({}^3S_1) + b\bar{b}_1({}^3S_1)$		v_c^4	
$c\bar{c}_8({}^3S_1) + b\bar{b}_8({}^1S_0)$	: (b),(c),(d),	$v_c^4 v_b^3$	, single fragmentation
$c\bar{c}_8({}^3S_1) + b\bar{b}_8({}^3P_J)$		$v_c^4 v_b^4$	

etc.

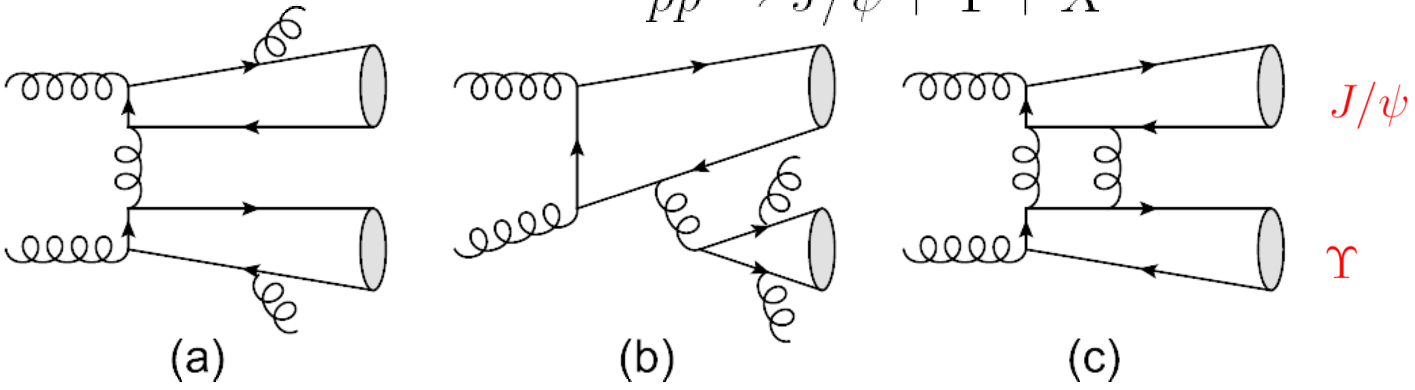
- Among various combinations of intermediate states, we consider

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

Double quarkonium production (different flavor)

Color singlet channel

$pp \to J/\psi + \Upsilon + X$



- Tree-level color-singlet contribution accompanies at least two hard gluons.
  - suppressed by a large factor of $\alpha_s^2[m_c/(v_c p_T)]^4[m_b/(v_b p_T)]^4$
  - 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 CS contribution to the CO is

$$\frac{1}{(4\pi)^2}\ \frac{\alpha_s^2}{v_c^4 v_b^4}\left(\frac{m_\psi}{p_T}\ \frac{m_\Upsilon}{p_T}\right)^4 \sim 0.002 \text{ at } p_T\text{=10 GeV}$$

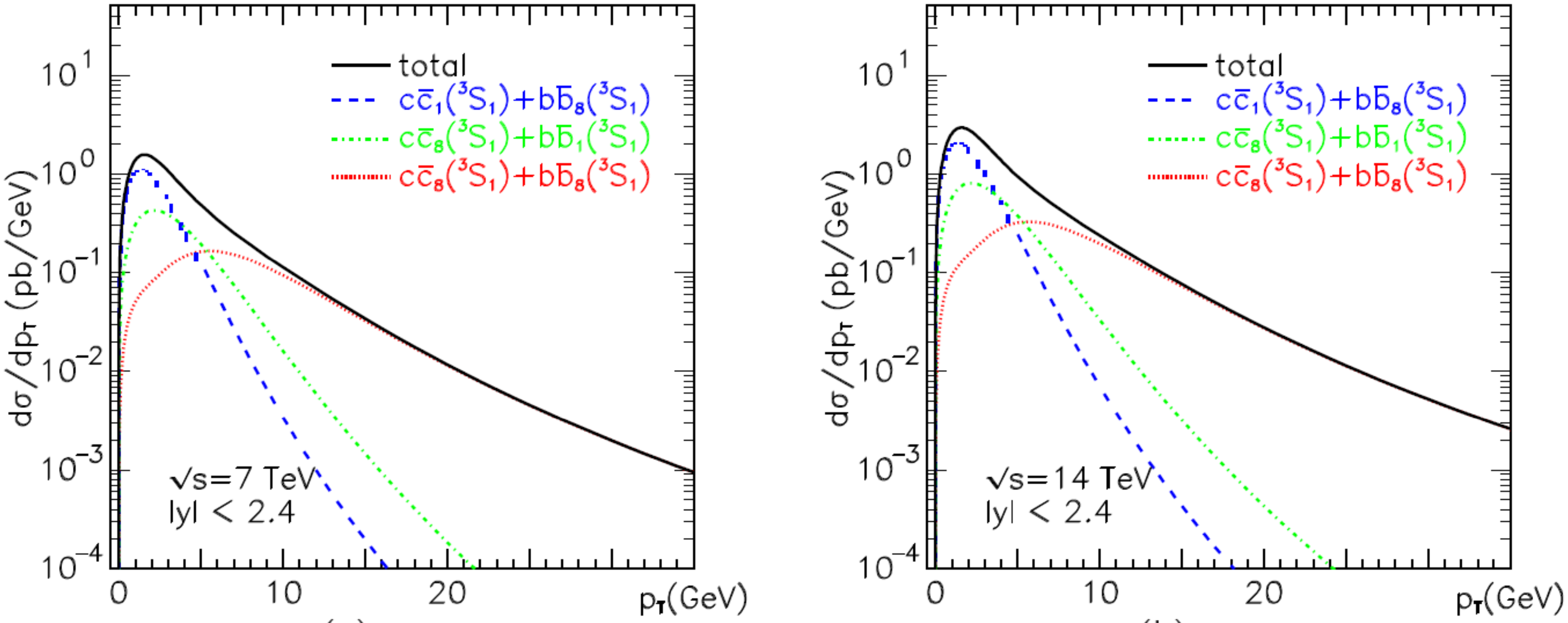
Double quarkonium production (different flavor)

- Thus we conclude that the color-singlet contribution is fully 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



(a) (b)

- $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ dominates at p_T>6 GeV.
- $c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)$ dominates at p_T<4 GeV.
- Three contributions compete among one another at 4 GeV < p_T < 6 GeV.

Double quarkonium production (different flavor)

- The spectrum is parametrized by

$$d\sigma/dp_T = a(p_T)y + b(p_T)x + c(p_T)xy$$

$$x = \langle O_8^{J/\psi}(^3S_1)\rangle \text{ and } y = \langle O_8^{\Upsilon}(^3S_1)\rangle$$

- very simple to fit the both MEs from the empirical p_T spectrum.

$\sqrt{s} \setminus \sigma\,(\text{pb})$	$c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)$	$c\bar{c}_8(^3S_1) + b\bar{b}_1(^3S_1)$	$c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$	total
7 TeV	3.18	1.95	1.63	6.76
14 TeV	6.00	3.72	3.36	13.08

- expects 7 pb ~ 13 pb at the LHC.

- about 1900 events assuming the integrated luminosity ~100^{-1}fb and considering branching fractions of J/ψ and Υ into a muon pair.

- Feeddown may enhance the cross section by an order of magnitude.

- Double quarkonium production of different flavor can be observed at the LHC.

Color octet mechanism

- The total cross section for $J/\psi + \Upsilon$ production is much less than that for double quarkonium production of same flavor.

- In order to probe the color-octet mechanism more accurately, we impose a lower p_T cut to remove most of the color-singlet contribution.

- At the c.m. energy 14 TeV,

$$\sigma[pp \to 2J/\psi + X]|_{p_T \gtrsim 16\,\mathrm{GeV}} = 0.2 \text{ pb}$$

$$\sigma[pp \to 2\Upsilon + X]|_{p_T \gtrsim 24\,\mathrm{GeV}} = 0.05 \text{ pb}$$

$$\sigma[pp \to J/\psi + \Upsilon + X] = 13 \text{ pb}$$

- conclude that the $pp \to J/\psi + \Upsilon + X$ channel is the most sensitive to the color-octet matrix elements among the three double-quarkonium final states.

Conclusions

- Double quarkonium production at hadron colliders provides 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.

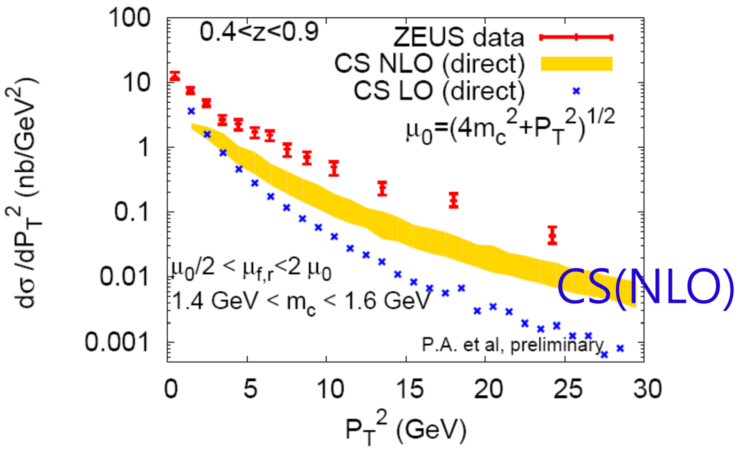
- If one cannot see the $J/\psi + \Upsilon$ events at the expected level, it would imply that the current color-octet matrix elements are overestimated.

Thank you

Backup slides

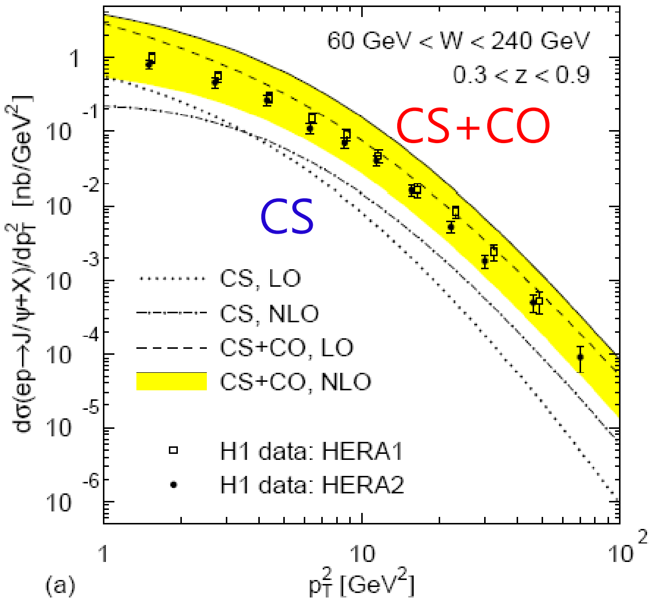
Color-octet mechanism

- has not been well established.
- J/ψ photoproduction at HERA.



P.Artoisenet, QWG'08

Butenschon, Kniehl, PRL104,072001(2010)



- inclusive J/ψ production at B factories.

$$\sigma(e^+e^- \to J/\psi + non(c\bar{c})) = (0.43 \pm 0.09 \pm 0.09)pb.$$

BELLE,0901.2775

	$\sigma_{\rm CS}$(pb)	$\sigma_{\rm CO}$(pb)
LO	0.28-0.57	0.50 - 0.55
NLO	0.4-0.7	0.93 - 1.08

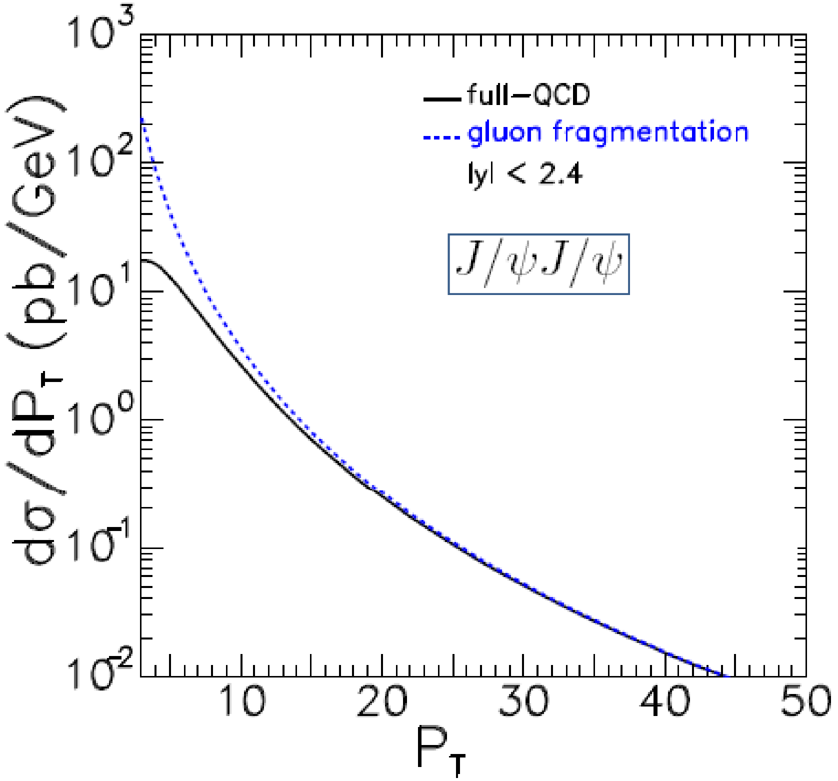
Gong,Wang, PRL102, 162003 (2009)

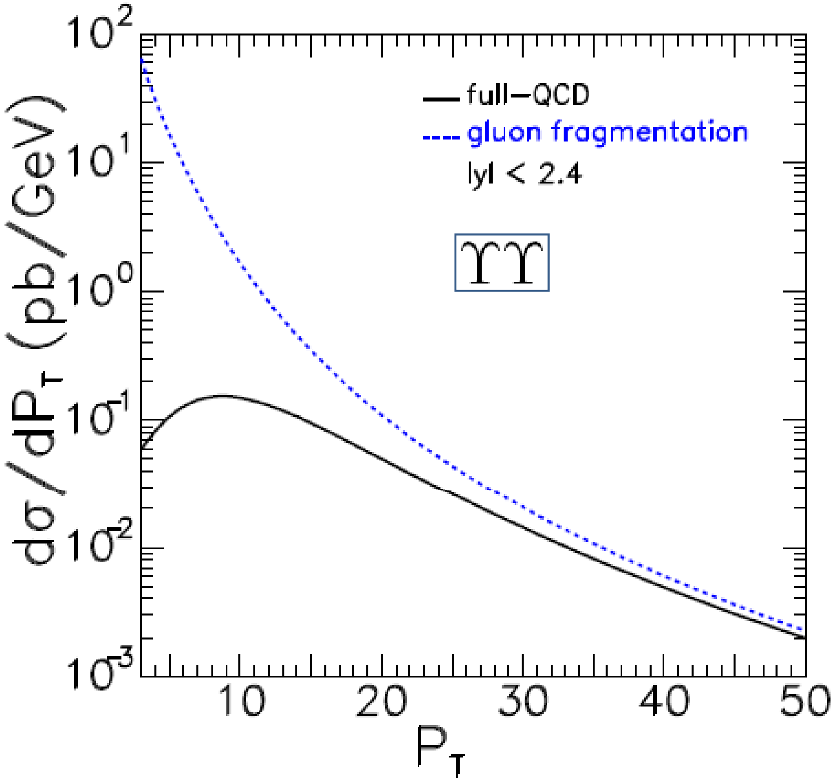
Ma.,Zhang,Chao, PRL102, 162002 (2009)

Zhang, Ma, Wang, Chao, PRD81, 034015 (2010)

- constraints on the $^1S_0$ and ^3P_J CO contributions, but no constraints on the $^3S_1$ CO contribution.

gluon frag. approx. 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 $O(m_c^2/\hat{s})$.
  - overestimates the cross section by about a factor of 6 or 40.