Double quarkonium production in hadron colliders from the perspective of NRQCD

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PRD83, 054015 (2011)

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Motivation

• Heavy quarkonium: probes perturbative and nonperturbative aspects of QCD.

• NRQCD has achieved great success.

- resolves IR divergence problem.

- the inclusive production of J/ψ from KEKB, LEP II, RHIC, HERA, Tevatron and LHC. (See talks by Chao and Butenschoen.)

- double quarkonium production at B factories.

He,Fan,Chao(2007);Bodwin,Lee,Yu(2007)

• there are still unresolved puzzles.

- polarization of prompt J/ψ at Tevatron.

- polarized J/ψ photoproduction. Butenschoen,Kniehl,1109.1476

Double quarkonium production

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

- suggested 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)

- Color-singlet contribution. Qiao 2002

- extended to the LHC. Li,Zhang,Chao(2009);Qiao,Sun,Sun(2009); Berezhnoy,Likhoded,Luchinsky,Novoselov(2011)
  - Polarized J/ψ pair hadroproduction. Qiao (QWG2010)

Double quarkonium production

- Double quarkonium production as a probe of double parton scattering

$$d\sigma^{2\,J/\psi}_{\rm DPS} = \frac{d\sigma^{J/\psi}_{\rm SPS}\, d\sigma^{J/\psi}_{\rm SPS}}{2\sigma_{\rm eff}}$$

Kom,Stirling,Kulesza(2011); Novoselov(2011)

the transverse structures of the proton

- k_t factorization vs collinear scheme. (See the talk by Baranov.)

- first measurements at the LHCb: LHCb, 1109.0963

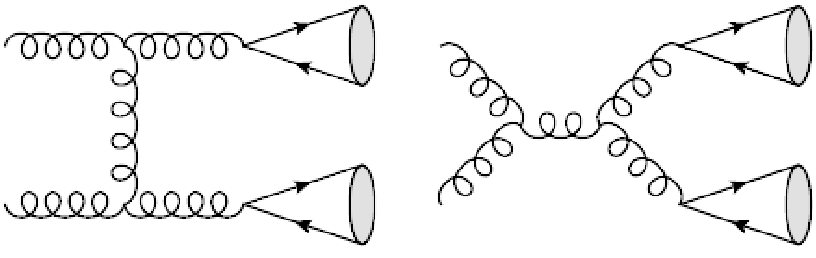
$$\sigma^{\rm J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb}.$$

(See the talk by Frosini.)

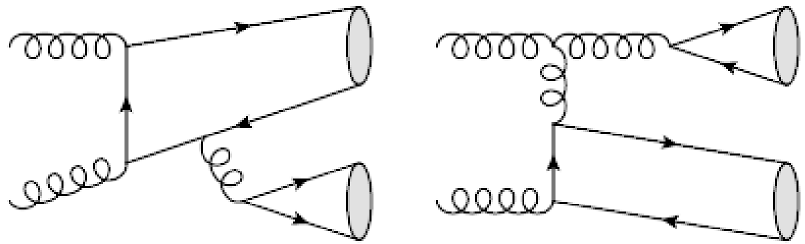
- Previous works based on NRQCD considered only the double quarkonium production of same flavor.
  - gluon fragmentation approximation for the CO contribution.

- In this talk: the double quarkonium production of different flavor.
  - calculate the CO contribution fully instead of gluon frag. approx.

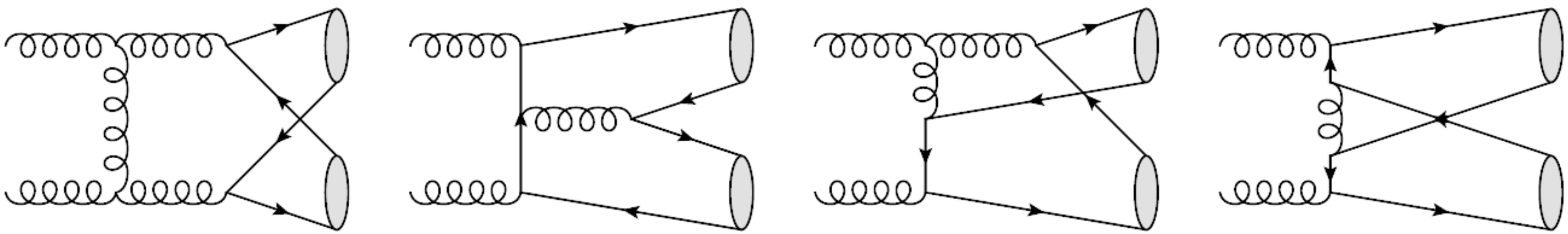
Typical diagrams



double fragmentation

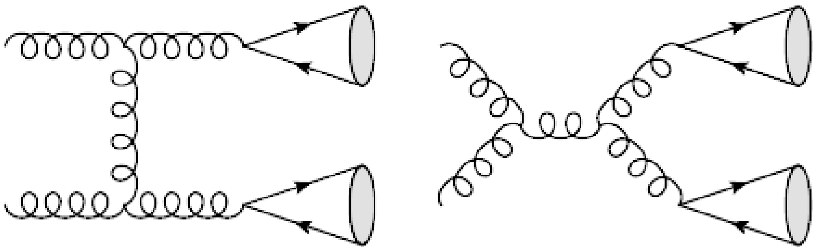


single fragmentation

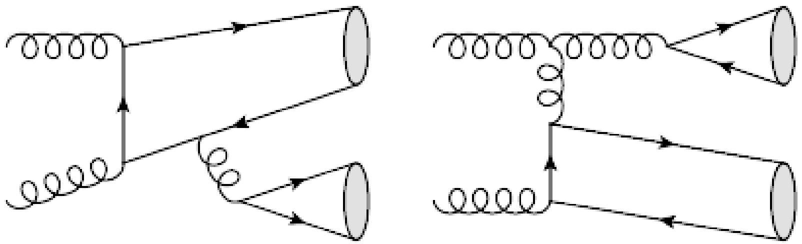


nonfragmentation

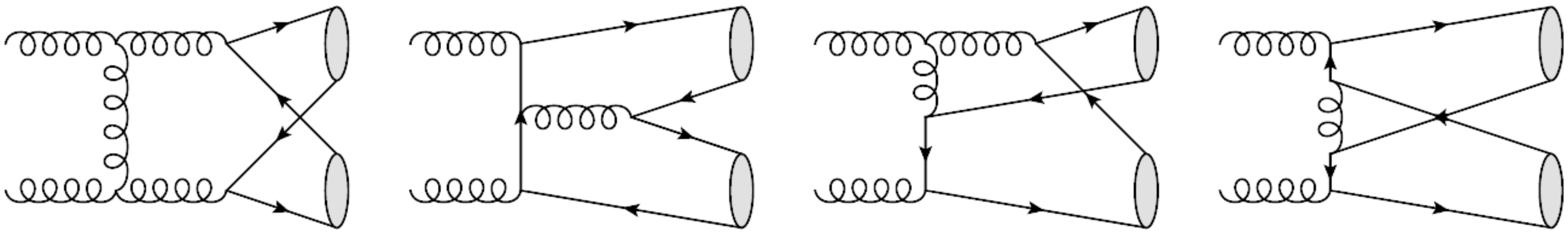
Typical diagrams



double fragmentation



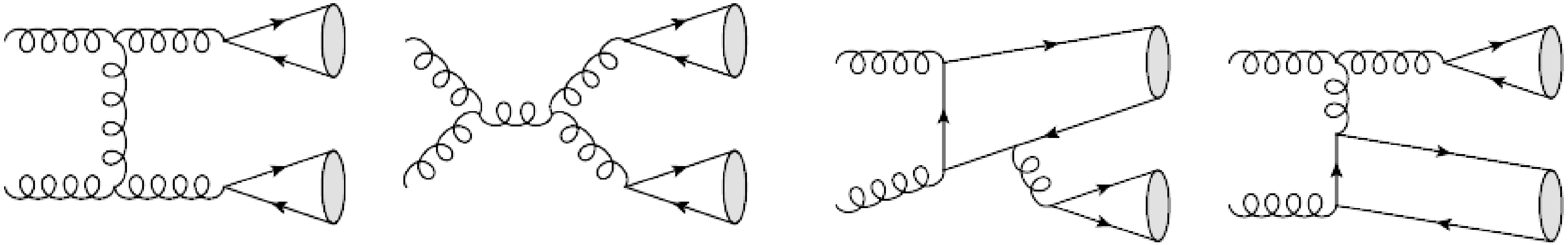
single fragmentation



nonfragmentation

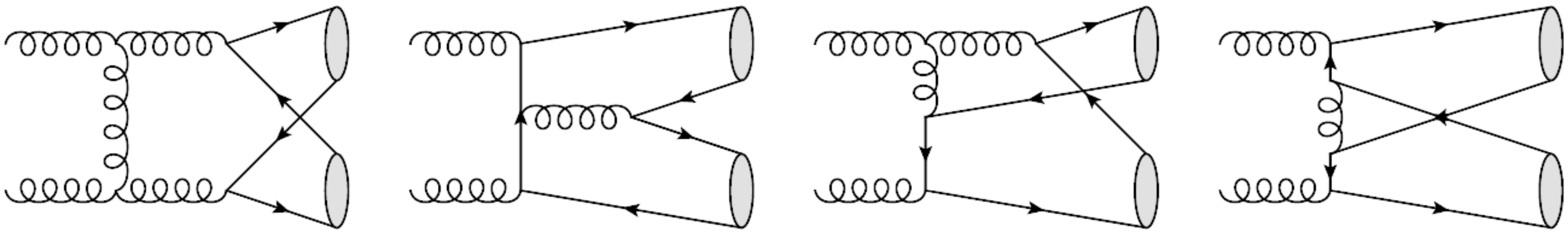
Color singlet

Typical diagrams



double fragmentation

single fragmentation



nonfragmentation

Color singlet

Color octet

Double quarkonium production

• The schematic form of the cross section is

$$d\sigma[pp \to H_1(P_1) + H_2(P_2)] = \sum_{i,j,n_1,n_2} \underbrace{f_{i/p} \otimes f_{j/p} \otimes d\hat{\sigma}[ij \to \mathcal{Q}_1^{n1} + \mathcal{Q}_2^{n2}]}_{\text{at least } \alpha_s^4(\mu)} \underbrace{\langle O_{n_1} \rangle_{H_1} \langle O_{n_2} \rangle_{H_2}}_{\text{NRQCD MEs}}$$

• potential large uncertainties come from the scale dependence of the strong coupling constant and NRQCD matrix elements.

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

• NRQCD matrix elements

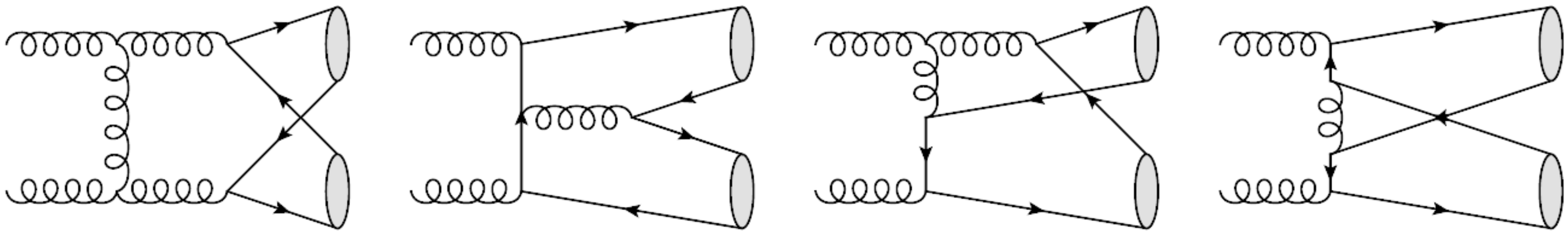
- CS: could be determined from EM decays of the quarkonium. (See the talks by Chung and Ma.)
- CO: lattice simulation, global fit from single quarkonium productions. (See the talk by Butenschoen.)

Double quarkonium production of same flavor

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

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

Color-singlet channel



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

$$g + g \to \mathcal{Q}_1 + \mathcal{Q}_2, \quad \text{dominant}$$
$$q + \bar{q} \to \mathcal{Q}_1 + \mathcal{Q}_2. \quad \text{subdominant}$$

- The leading contribution is the color-singlet channel

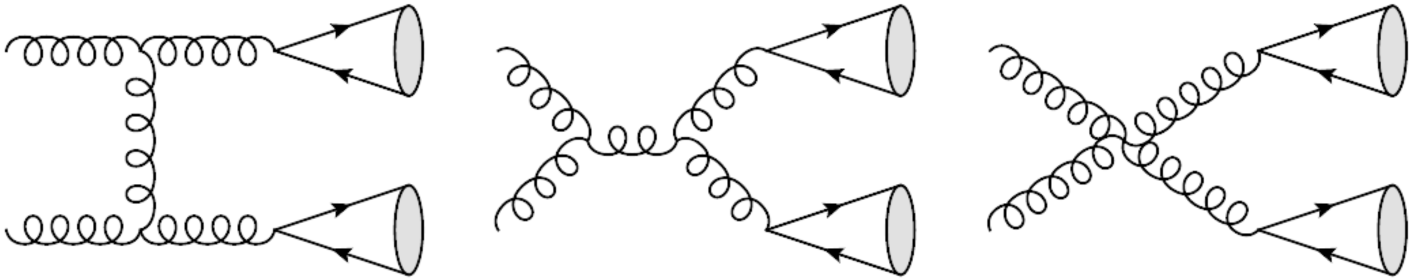
$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_1(^3S_1), Q\bar{Q}_1(^3S_1)]$$

- Color-octet channels are suppressed.

$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_8(^3S_1), Q\bar{Q}_8(^3S_1)] \quad \text{by } v^8$$
$$(\mathcal{Q}_1^{n_1}, \mathcal{Q}_2^{n_2}) = [Q\bar{Q}_1(^3S_1), Q\bar{Q}_8(^3S_1)] \quad \text{by } v^4$$

- 31 Feynman diagrams in the color-singlet channel.

Color-octet channel (gluon fragmentation approx.)



fragmentation diagrams

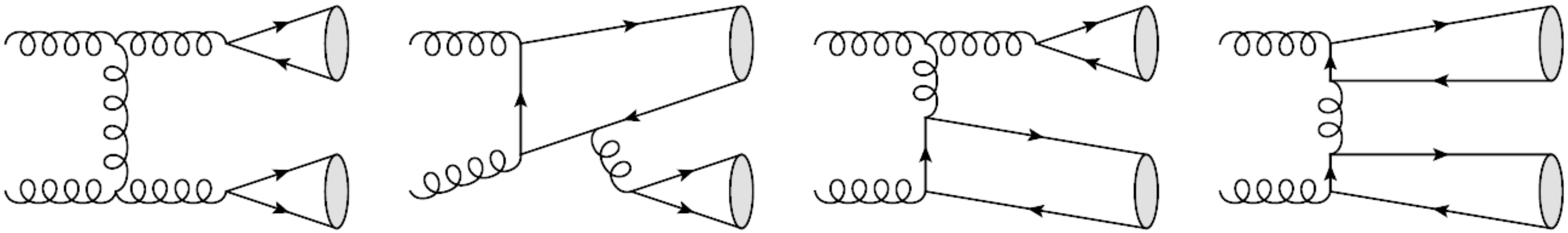
- The leading processes are of order α_s^4 .
- gluon fragmentation approximation.
  - two real gluon production, followed by the fragmentation of each gluon into a quarkonium in the $^3S_1$ color-octet state.
- 4 Feynman diagrams.
- The schematic form of the cross section is

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

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

- 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 (full calculation)



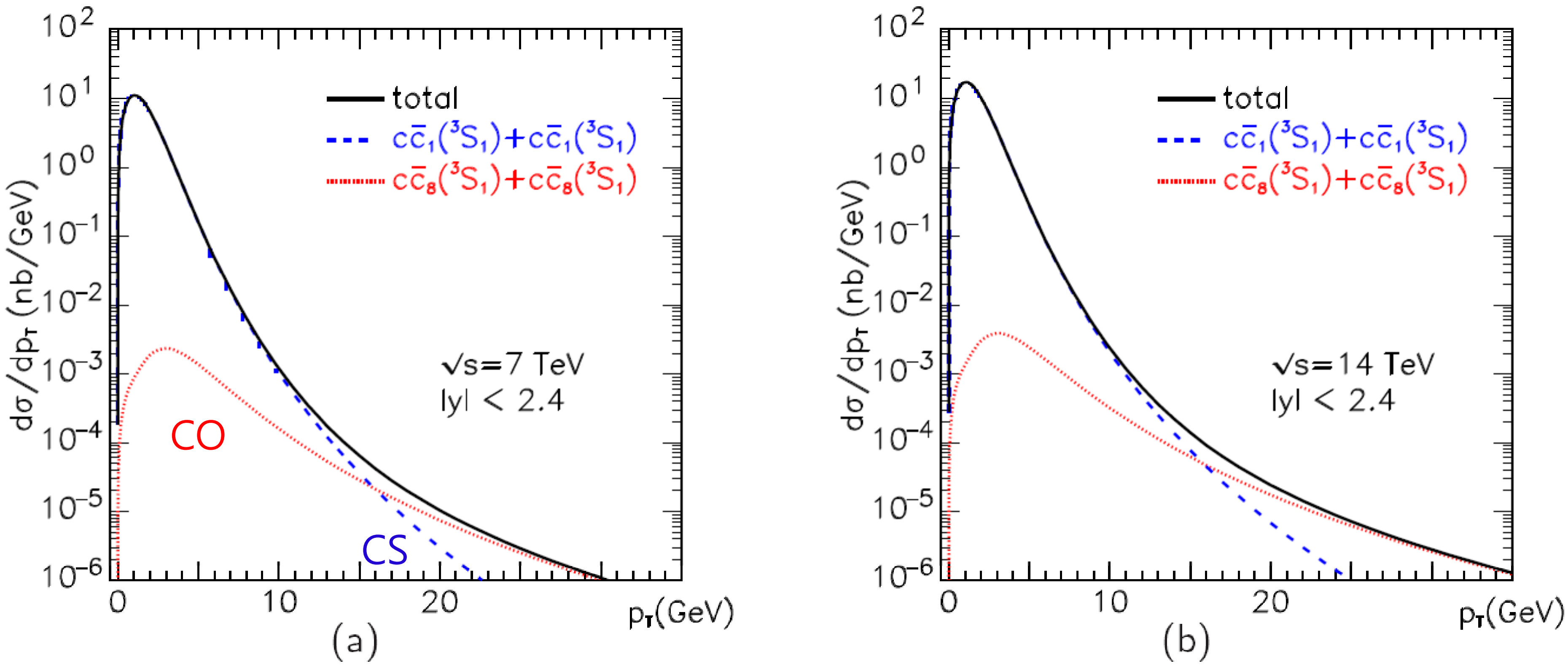
- various combinations of intermediate states are allowed.

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

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

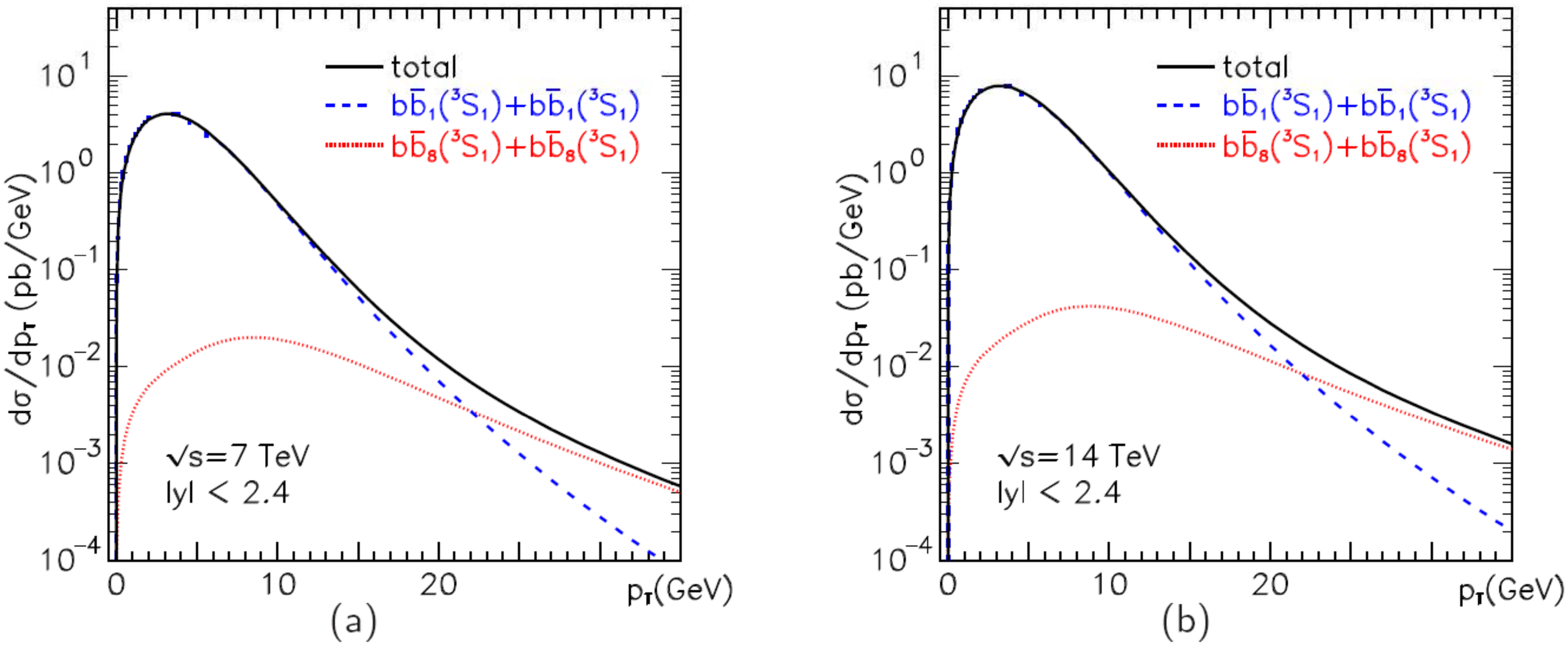
- We consider only ${}^3S_1^{(8)} + {}^3S_1^{(8)}$ combination because
  - ${}^1S_0$ and ${}^3P_0$ color-octet matrix elements may be much suppressed.
  - ${}^3S_1^{(8)} + {}^3S_1^{(8)}$ combination could be dominant at large p_T.
- 72 Feynman diagrams.

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



- The color-singlet contribution dominates at small and moderate 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

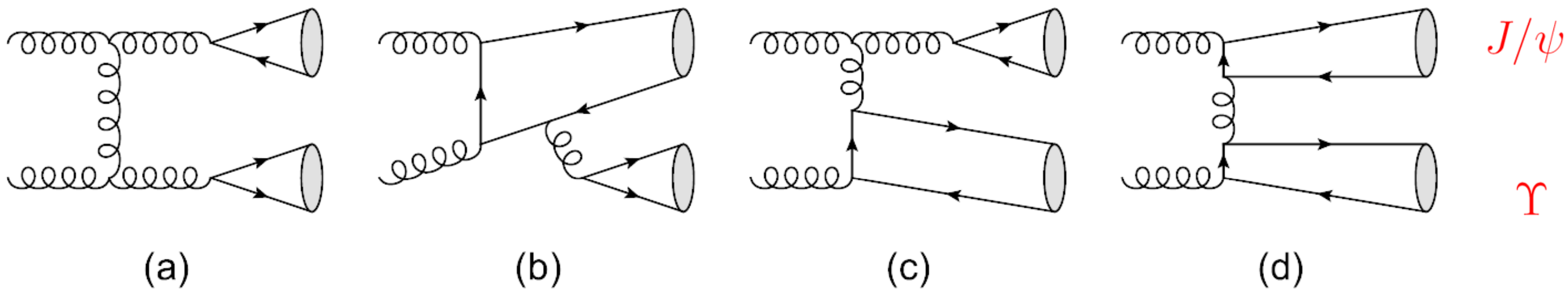
- double quarkonium production of same flavor can be tested at the LHC.
- If we consider the contributions from feeddown of $\psi(2S)$ and χ_{cJ}, it seems that the color-octet mechanism may be testable at the LHC
- The CS contribution might contaminate the CO contribution.
- We suggest the $J/\psi +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

Double quarkonium production of different flavor

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

Double quarkonium production (different flavor)

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



- 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.

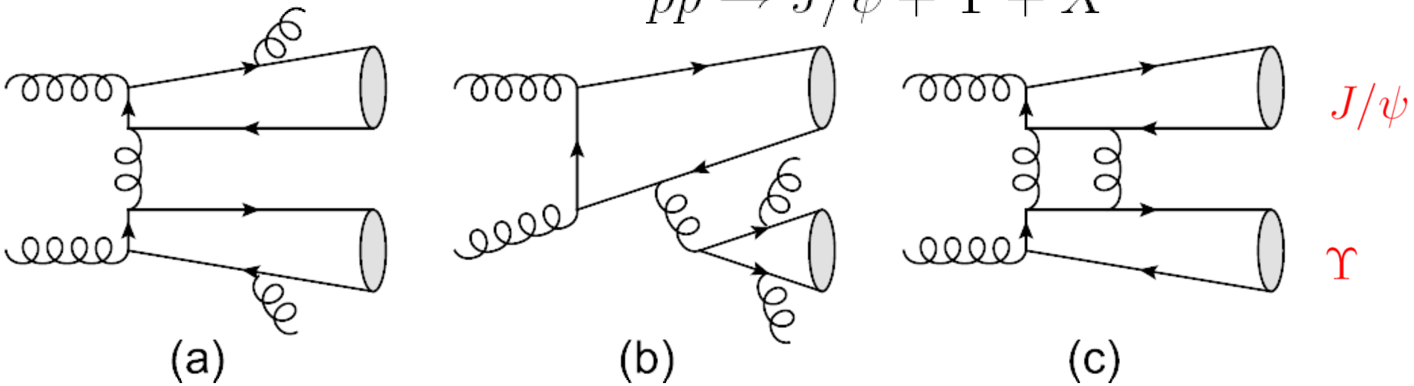
- Among various combinations of intermediate states, we consider

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

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.

- extra hard jets in the final state.

• The color-singlet contribution at one-loop level can appear via two-gluon exchange.

Double quarkonium production (different flavor)

- The relative size of the CS contribution to the CO contribution $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ at large p_T is

$$\frac{1}{(4\pi)^2}\,\frac{\alpha_s^2}{v_c^4 v_b^4}\left(\frac{m_\psi}{p_T}\,\frac{m_\Upsilon}{p_T}\right)^4$$

~ 0.005 at p_T=5 GeV.

- At small p_T, the factor p_T should be of order m_H.

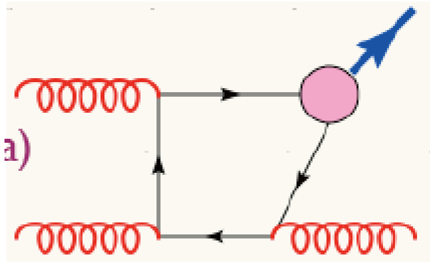
  - the suppression factors of the CS contribution to the mixed contributions $c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)$ and $c\bar{c}_8(^3S_1) + b\bar{b}_1(^3S_1)$ are

$$\frac{\alpha_s^2}{(4\pi)^2 v_b^4} \quad \text{or} \quad \frac{\alpha_s^2}{(4\pi)^2 v_c^4}$$

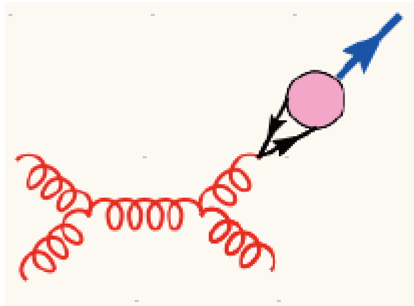
~ 0.3 or 0.003.

Single vs. double quarkonium production (diff. flavor)

Singlet quarkonium production



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



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

• The ratio of the CS and CO contributions for the single quarkonium production at large p_T is approximately

$$\frac{m_c^4}{v^4 p_T^4} \sim 0.07 \text{ at } p_T=5 \text{ GeV.}$$

cf. ~ 0.005 at p_T=5 GeV for double quarkonium production.

• At small p_T, there is no kinematic enhancement factor for the color-octet contribution.

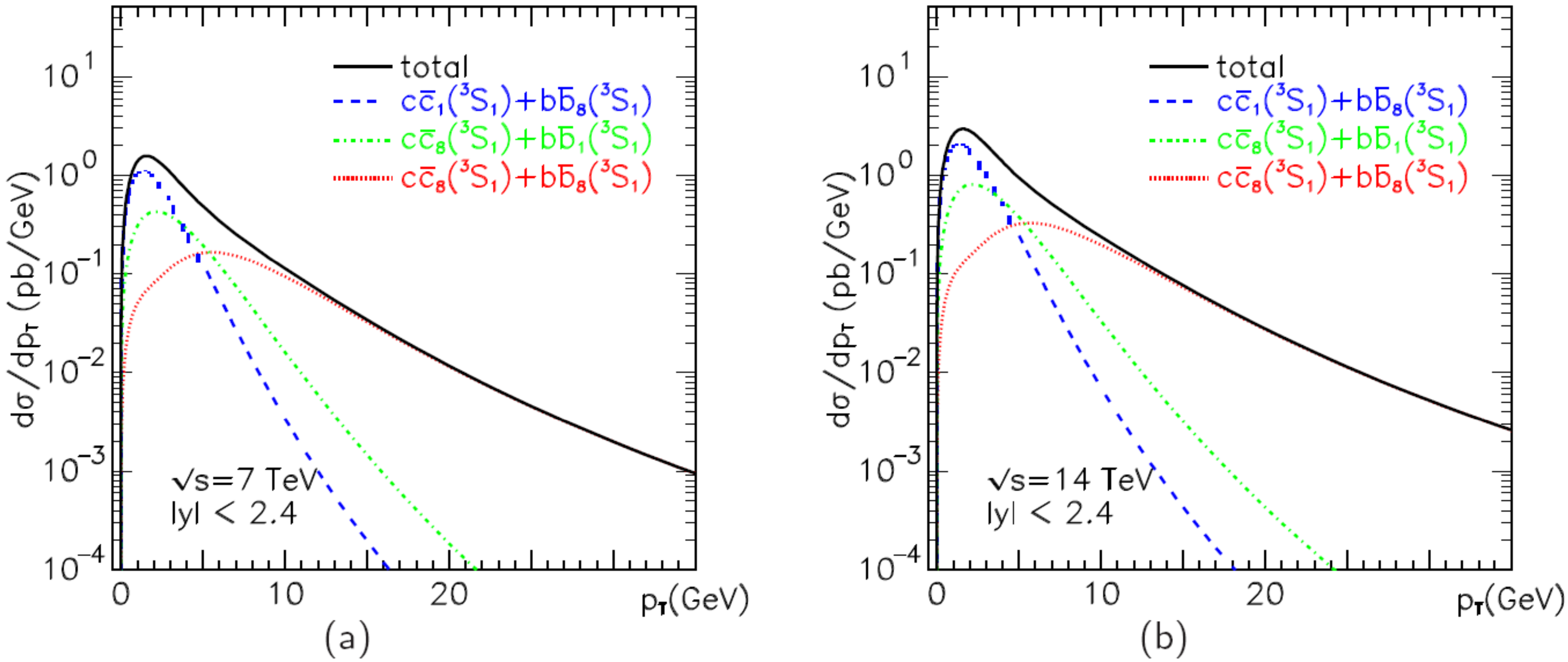
Double quarkonium production (different flavor)

- 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



- $c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$ 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)

$\sqrt{s} \setminus \sigma\,(\mathrm{pb})$	$c\bar{c}_1(^3S_1) + b\bar{b}_8(^3S_1)$	$c\bar{c}_8(^3S_1) + b\bar{b}_1(^3S_1)$	$c\bar{c}_8(^3S_1) + b\bar{b}_8(^3S_1)$	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.

- 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.

Double quarkonium production

- CO matrix element

$$\langle O_8^{J/\psi}(^3S_1)\rangle = 3.9\times10^{-3}\,\mathrm{GeV}^3$$
$$\langle O_8^{\Upsilon}(^3S_1)\rangle = 1.5\times10^{-1}\,\mathrm{GeV}^3$$

In this talk

$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	$(4.97\pm0.44)\times10^{-2}\ \mathrm{GeV}^3$
$\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	$(2.24\pm0.59)\times10^{-3}\ \mathrm{GeV}^3$
$\langle \mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	$(-1.61\pm0.20)\times10^{-2}\ \mathrm{GeV}^5$

Global fit
Butenschoen,Kniehl,1109.1476

- may decrease the cross section for the 2J/ψ and J/ψ+ Υ productions.

- Our calculation: considers the leading contribution of the expansion.

- ignored the $^1S_0^{(8)}$ and $^3P_J^{(8)}$ contribution but they could contribute to the double quarkonium production if the global fit values are correct.

- Feeddown, NLO corrections and relativistic corrections may be important.

Conclusions

• Double quarkonium production at hadron colliders provides another test ground of NRQCD.

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

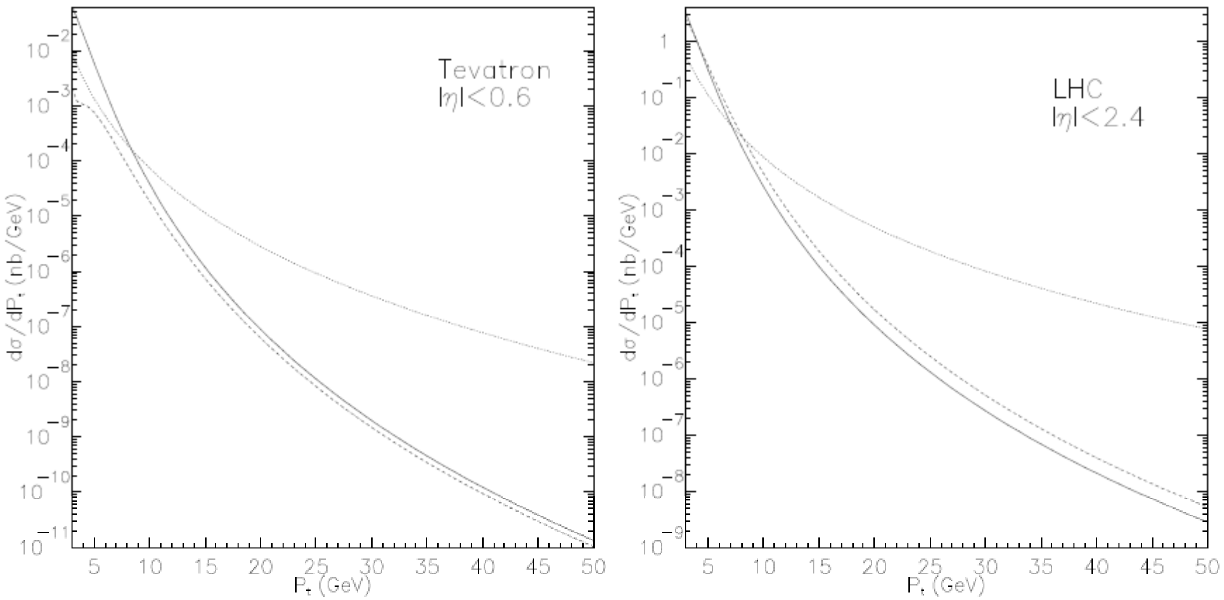
• If one cannot see the $J/\psi + \Upsilon$ events at the expected level, it would imply that the current color-octet matrix elements are overestimated.

• requires the higher-order contributions to predict the cross sections more precisely.

Backup slides

Comparison

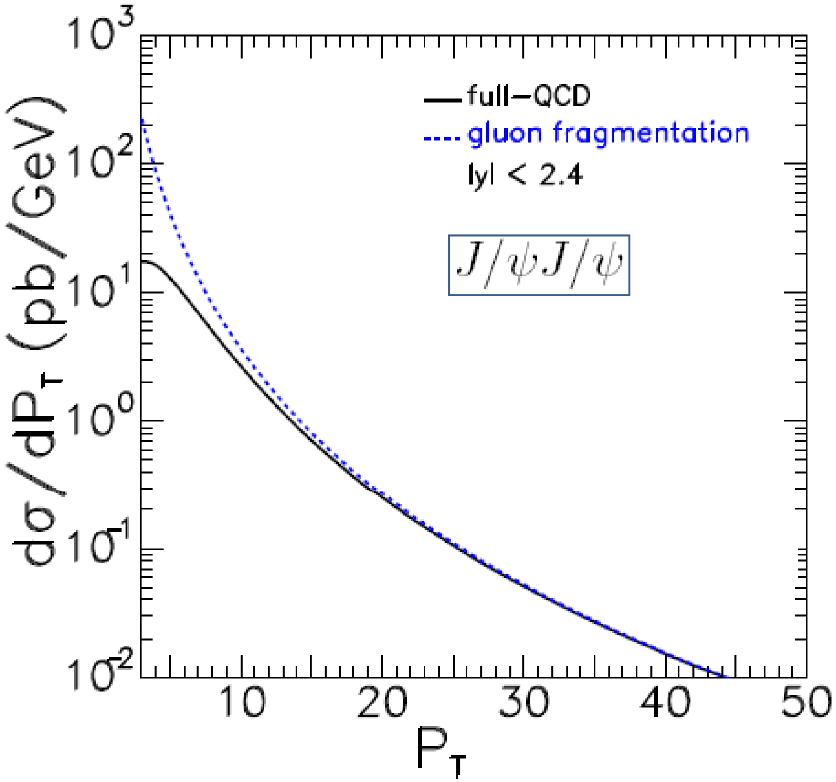
- 2 J/ψ production. Ma.,Zhang,Chao, PRL102, 162002 (2009)

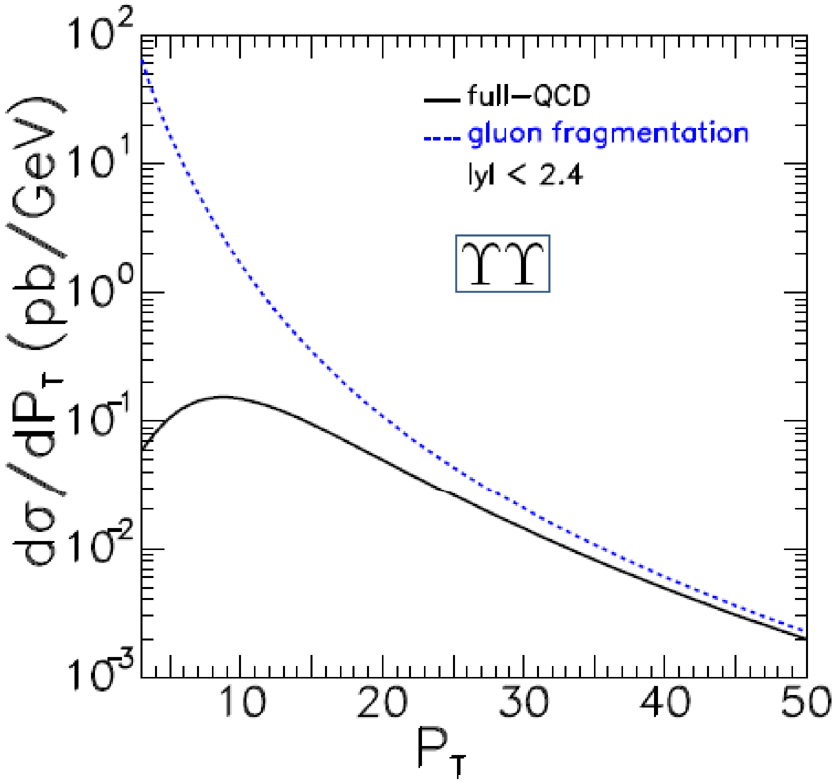


$Final\ States$	$\sigma_{Tevatron}[nb]$	$\sigma_{LHC}[nb]$
$\eta_c\eta_c$	3.32×10^{-3}	2.73
$J/\psi J/\psi$	5.63×10^{-2}	2.83
$\eta_b\eta_b$	1.87×10^{-5}	7.36×10^{-3}
$\Upsilon\Upsilon$	1.23×10^{-4}	1.51×10^{-2}
$B_c\bar{B}_c$	3.86×10^{-3}	2.72×10^{-1}
$B_c\bar{B}_c^*$	1.00×10^{-3}	8.37×10^{-2}
$B_c^*\bar{B}_c^*$	8.23×10^{-3}	7.08×10^{-1}

- CO: based on the gluon fragmentation approximation.

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.