Heavy quarkonium production

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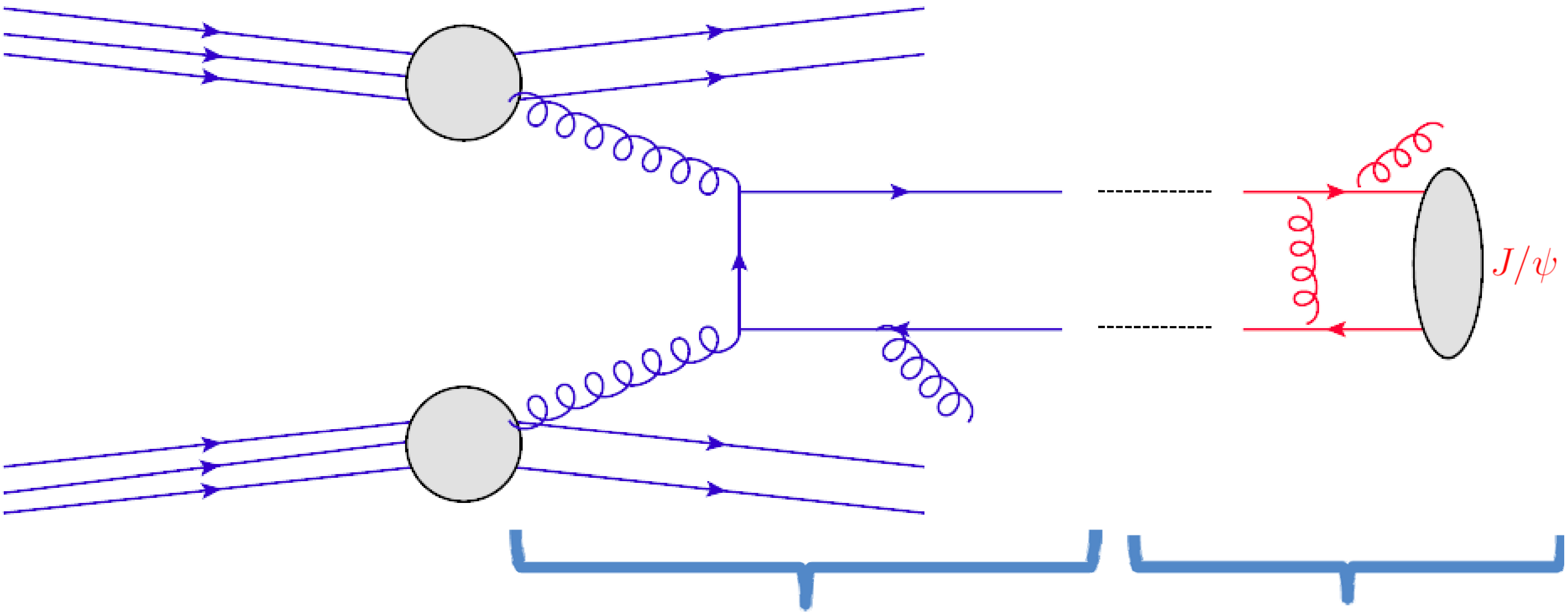
Outline

- Introduction
- Exclusive production of heavy quarkonium
  - $e^+e^- \to J/\psi + \eta_c$
  - $e^+e^- \to J/\psi + J/\psi$
  - $e^+e^- \to \eta_c + \gamma$
- Inclusive production of heavy quarkonium
  - $p\bar{p} \to J/\psi + X$, $ep \to J/\psi + X$, $e^-e^+ \to J/\psi + X$
  - $gg \to J/\psi\Upsilon$
- Summary

Heavy quarkonium production



Factorization :

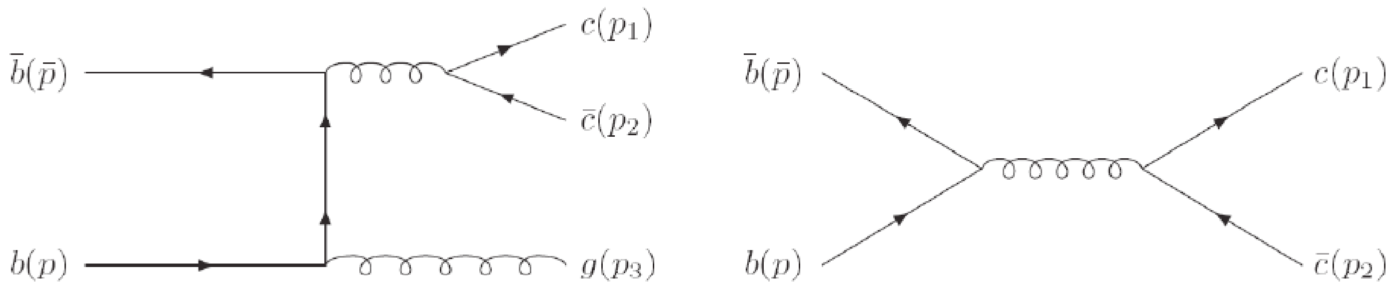
Perturbative
Short-distance coefficients
Series in α_s

Nonerturbative
long-distance ME
Series in v

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

Heavy quarkonium decay

- Early stage calculation of P-wave heavy quarkonium decay was plagued with IR divergence.
- It has been resolved by the color-octet mechanism of NRQCD factorization approach.
- Inclusive charm production in χ_b decays:



(a) (b)

(a) $b\bar{b}_1({}^3P_J) \to c\bar{c}g \propto C_J^{(c)}, C_8^{(c)}$

(b) $b\bar{b}_8({}^3S_1) \to g^* \to c\bar{c} \propto C_8^{(c)}$

$$\Rightarrow d\Gamma^{(c)} = dC_J^{(c)}(\Lambda)\frac{\langle \mathcal{O}_1({}^3P_J)\rangle}{m_b^4} + dC_8^{(c)}\frac{\langle \mathcal{O}_8({}^3S_1)\rangle^{(\Lambda)}}{m_b^2}$$

$$\mathcal{O}_8({}^3S_1) = \mathcal{O}_8({}^3S_1)^{(\Lambda)} + \frac{(4\pi e^{-\gamma})^{\epsilon}}{\epsilon_{\mathrm{UV}}}\frac{2C_F\alpha_s}{3\pi N_c m_b^2}\sum_{J=0}^{2}\mathcal{O}_1({}^3P_J)$$

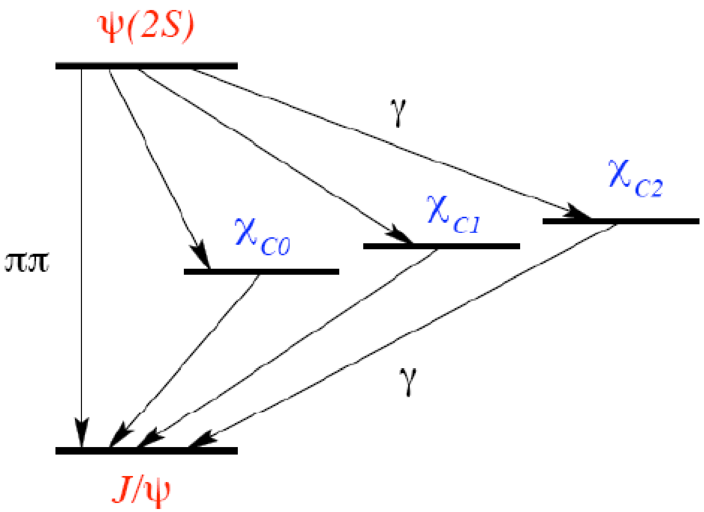
Exclusive vs. Inclusive

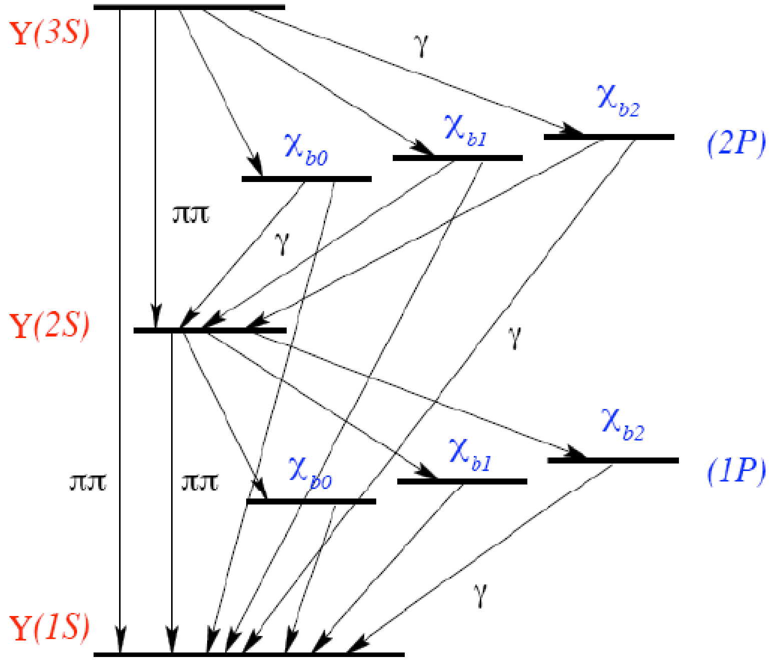
	Exclusive	Inclusive
Incident beam	lepton	lepton, hadron
Color-singlet	dominant	may be (sub)dominant
Color-octet	suppressed	may be (sub)dominant
QCD corrections	substantial	substantial
Relativistic corrections	large*	not so large**
Feed-down	-	moderate

$^{*}e^+e^- \to J/\psi\eta_c$ $^{**}e^+e^- \to J/\psi c\bar{c}$

- Exclusive production of heavy quarkonium provides a unique chance to investigate effects of relativistic corrections.
- Color-octet mechanism should be proved in the inclusive mode, but compete with effects from the color-singlet contributions as well as from the feed-down.

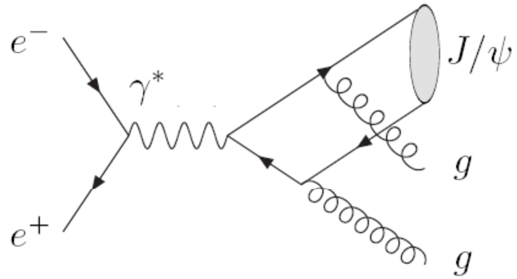
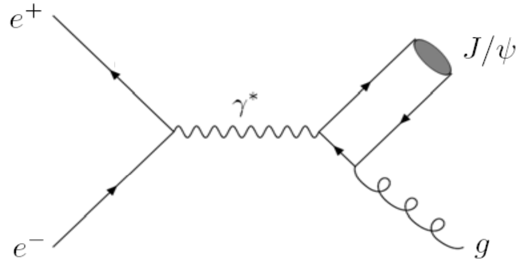
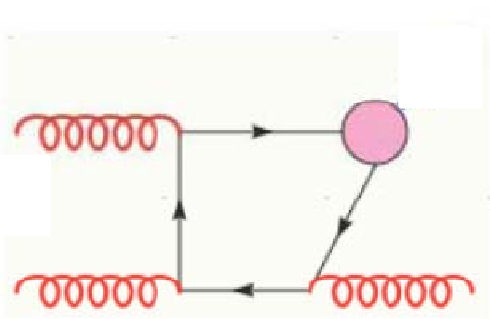
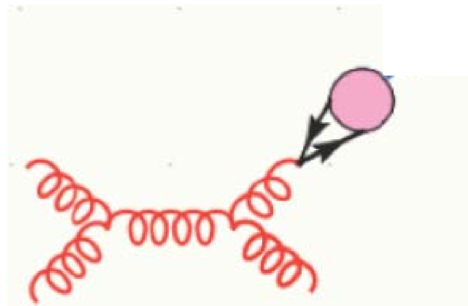
Feed down





	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^*	

Color singlet vs. Color octet

	color singlet	color octet
• $e^-e^+ \to J/\psi + X$		
	α_s^2	$\alpha_s v^4$
• $gg \to J/\psi + X$		
	$\alpha_S^3 \frac{(2m_c)^4}{p_T^8}$	$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^4}$

Exclusive production

Relativistic corrections to S-wave quarkonium

- parameterized by ratios of matrix elements of higher orders in v to the leading-order one.

$$\langle \boldsymbol{q}^{2n} \rangle_{J/\psi} = \frac{\langle J/\psi(\lambda)|\psi^\dagger(-\frac{i}{2}\overleftrightarrow{\boldsymbol{D}})^{2n}\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)\chi|0\rangle}{\langle J/\psi(\lambda)|\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}(\lambda)\chi|0\rangle}$$

- Gremm-Kapustin relation

Gremm,Kapustin,PLB407,323(1997)

$$\langle \boldsymbol{q}^2 \rangle \approx \epsilon_{\mathrm{B}} m_c = (M_H - 2m_c)m_c$$

ϵ_B:binding energy

- large uncertainty in the charm quark mass

$$m_c = 1.4 \pm 0.2 \text{ GeV}$$

$$-0.35 < \langle q^2 \rangle < 0.84.$$

- even the sign is unknown.

Relativistic corrections

- ϵ_B can be determined in the potential model.
- generalized Gremm-Kapustin relation

$$\langle \boldsymbol{q}^{2n} \rangle \approx (m_c \epsilon_{\mathrm{B}})^n \approx \langle \boldsymbol{q}^2 \rangle^n .$$

Bodwin,Kang,Lee,PRD74,014014(2006)

- the short-distance coefficients can be resummed.

$$A = \sum_n \underbrace{\frac{1}{n!} \left(\frac{\partial}{\partial \boldsymbol{q}^2} \right)^n H(\boldsymbol{q}^2) \bigg|_{\boldsymbol{q}^2=0}}_{\text{short-distance coeff.}} \langle \boldsymbol{q}^{2n} \rangle \langle \mathcal{O}_1 \rangle^{1/2}$$

$$A = H(\boldsymbol{q}^2)|_{\boldsymbol{q}^2=\langle \boldsymbol{q}^2 \rangle} \langle \mathcal{O}_1 \rangle^{1/2} .$$

- S-wave color-singlet NRQCD matrix elements are determined by the electromagnetic decay width and the potential model method.

Bodwin,Chung,Kang,Lee,Yu,PRD77,094017(2008)

$$\langle \mathcal{O}_1 \rangle_{J/\psi} = 0.440^{+0.067}_{-0.055}\ \text{GeV}^3, \quad \langle \boldsymbol{q}^2 \rangle_{J/\psi} = 0.441^{+0.140}_{-0.140}\ \text{GeV}^2$$

$$\Longrightarrow \langle v^2 \rangle_{J/\psi} = 0.225^{+0.106}_{-0.088}$$

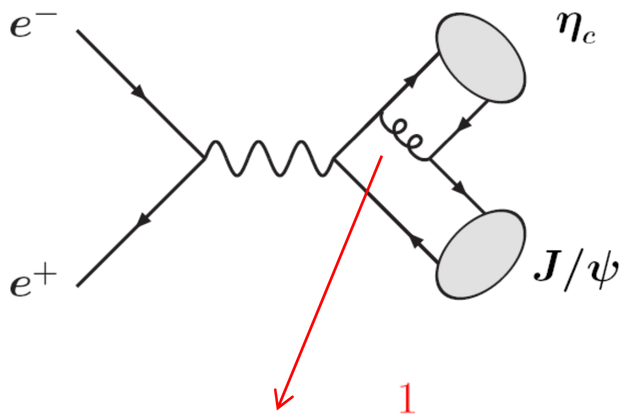
$$e^+e^- \to J/\psi + \eta_c$$

$J/\psi c\bar{c}$ (fb)	η_c	χ_{c0}	$\eta_c(2S)$
Belle [PRD70, 071102]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BABAR [PRD72,031101]	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
Braaten, Lee[PRD67, 054007]	3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
Liu, He, Chao [PLB557, 45]	5.5	6.7	3.7

- NRQCD at LO in α_s and v predicts a smaller value by an order of magnitude.
- The long-standing puzzle was resolved by the large QCD corrections and relativistic corrections.

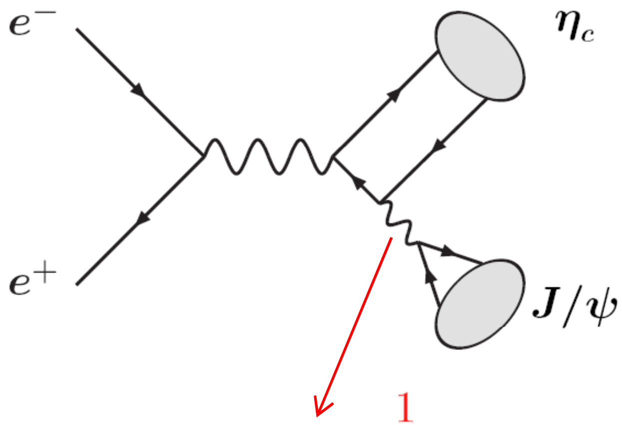
$$\underline{e^+e^- \to J/\psi + \eta_c}$$

- QCD diagram



$$\sim \frac{1}{(\sqrt{s}/2)^2}$$

- QED fragmentation diagram



$$\sim \frac{1}{m_{J/\psi}^2}$$

- QED contributions increase the cross section by about 19%.

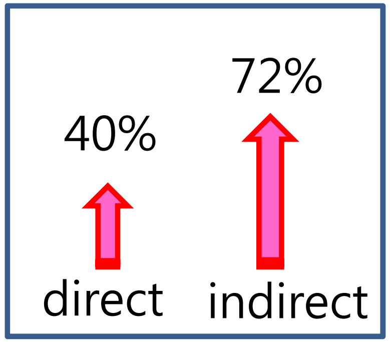
$$e^+e^- \rightarrow J/\psi + \eta_c$$

- K factor from QCD corrections is 1.96.

Zhang,Gao,Chao,PRL96,092001(2006); Gong,Wang,PRD77,054028(2008)

- Relativistic corrections can come from
  - direct corrections to the short-distance process.
  - indirect corrections through the NRQCD ME.

Bodwin,Lee,Yu,PRD77,094018(2008)



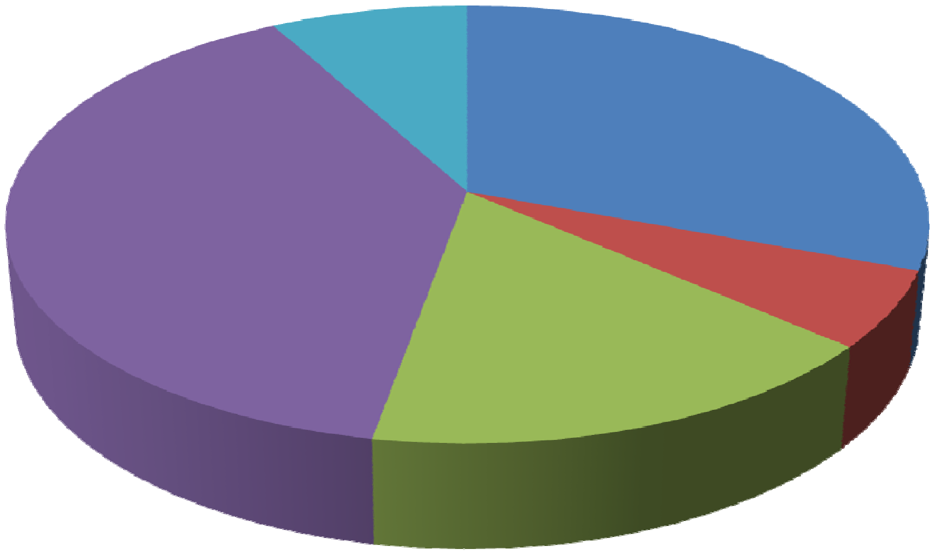
- A class of relativistic corrections are resummed.
  - resummation effects are about 12%.

- A few refinements:
  - VMD is used to calculate the photon fragmentation diagrams.
  - Running of EM coupling
  - interference between the relativistic corrections and NLO corrections in α_s.

$e^+e^- \rightarrow J/\psi + \eta_c$

Belle	25.6±4.4 fb
BABAR	17.6±3.5 fb

Total cross section = 17.6 fb



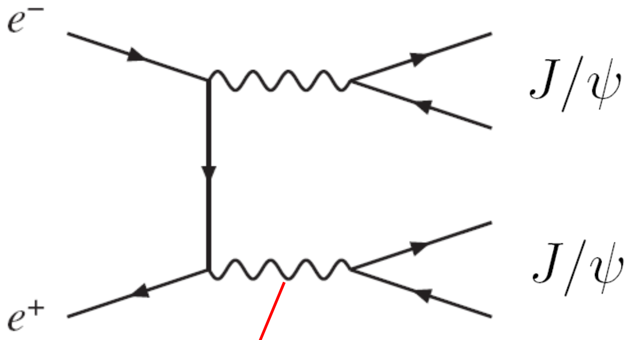
LO	5.4 fb
QED	1.0 fb
Rel. Corr.	2.9 fb
QCD Corr.	6.9 fb
Interference	1.4 fb

Bodwin,Lee,Yu,PRD77,094018(2008)

- It seems fair to say that the discrepancy between theory and experiments has been resolved.

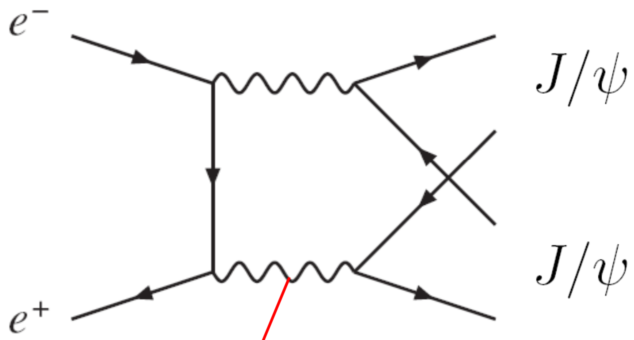
$\underline{e^+e^- \to J/\psi + J/\psi}$

- Two-photon exchange due to C parity conservation.
  - photon fragmentation diagram



$$\sim \frac{1}{m^2_{J/\psi}}$$

  - nonfragmentation diagram



$$\sim \frac{1}{(\sqrt{s}/2)^2}$$

- may be comparable to $\sigma_{e^+e^- \to J/\psi + \eta_c}$.

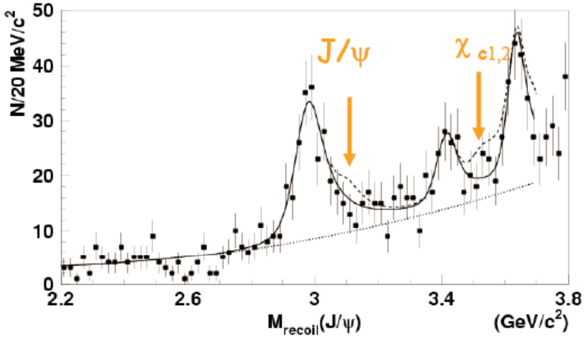
$e^+e^- \to J/\psi + J/\psi$

- originally suggested to resolve the $e^+e^- \to J/\psi + \eta_c$ puzzle.

Bodwin,Lee,Braaten,PRL90,162001(2003)

$H_1 + H_2$	σ (fb)
$J/\psi + J/\psi$	6.65 ± 3.02
$J/\psi + \psi(2S)$	5.52 ± 2.50
$\psi(2S) + \psi(2S)$	1.15 ± 0.52

- No evidence at Belle.



Belle,PRD70,071102(2004)

$$\sigma[e^+e^- \to J/\psi + J/\psi] \times \mathcal{B}_{>2}[J/\psi] < 9.1 \text{ fb},$$

$$\sigma[e^+e^- \to J/\psi + \psi(2S)] \times \mathcal{B}_{>2}[\psi(2S)] < 5.2 \text{ fb}.$$

- disfavored by the angular distribution analysis of $J/\psi + \eta_c$ events at Belle.

$e^+e^- \to J/\psi + J/\psi$

- use a VMD (vector-meson-dominance) model for the photon fragmentation diagram.

$$\langle J/\psi(\lambda)|J^\mu(x=0)|0\rangle = g_{J/\psi\gamma}\epsilon^\mu(\lambda)^*,$$

$$\Gamma[J/\psi \to e^+e^-] = \frac{4\pi\alpha^2 g_{J/\psi\gamma}^2}{3m_{J/\psi}^3}.$$

- The predictions are below the upper bounds at Belle.

Bodwin,Braaten,Lee,Yu,PRD74,074014(2006)

cross section	$J/\psi + J/\psi$	$J/\psi + \psi(2S)$	$\psi(2S) + \psi(2S)$
fragmentation	2.52 ± 0.13	1.81 ± 0.06	0.32 ± 0.02
interference	-0.98 ± 0.48	-1.09 ± 0.60	-0.30 ± 0.19
nonfragmentation	0.15 ± 0.16	0.23 ± 0.29	0.09 ± 0.14
total	1.69 ± 0.35	0.95 ± 0.36	0.11 ± 0.09

$e^+e^- \to J/\psi + J/\psi$

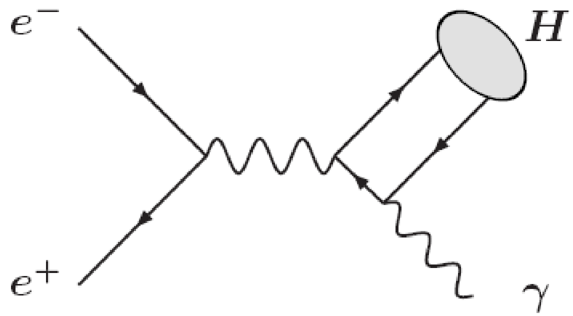
- Recently, the NLO corrections to $e^+e^- \to J/\psi + J/\psi$ were calculated. Gong,WangPRL100,181803(2008)

m_c(GeV)	μ	$\alpha_s(\mu)$	σ_{LO}(fb)	σ_{NLO}(fb)	σ_{NLO}/σ_{LO}
1.5	m_c	0.369	7.409	-2.327	-0.314
1.5	$2m_c$	0.259	7.409	0.570	0.077
1.5	$\sqrt{s}/2$	0.211	7.409	1.836	0.248
1.4	m_c	0.386	9.137	-3.350	-0.367
1.4	$2m_c$	0.267	9.137	0.517	0.057
1.4	$\sqrt{s}/2$	0.211	9.137	2.312	0.253

- inconsistent with the previous calculation?
- need to include relativistic corrections. (in progress)

$$e^+e^- \to \eta_c + \gamma$$

- C=+1 quarkonium : $\eta_c, \eta_c(2S), \chi_{cJ}, \eta_b, \chi_{bJ}$



- test ground for production of the color-singlet heavy quarkonium.
- test for the convergence of velocity expansion for the $\eta_c(2S)$ decay into two photons.
- QCD corrections and relativistic corrections are not available yet.

$$e^+e^- \longrightarrow \eta_c + \gamma$$

H	σ (fb)	σ_{cut} (fb)	E_γ (GeV)
η_c	$82.0^{+21.4}_{-19.8}$	$59.7^{+15.6}_{-14.4}$	4.87
$\eta_c(2S)$	$49.2^{+9.4}_{-7.4}$	$35.8^{+6.8}_{-5.4}$	4.66
η_b	$2.5^{+0.2}_{-0.2}$	$1.8^{+0.1}_{-0.1}$	1.12
χ_{c0}	$1.3^{+0.2}_{-0.2}$	$1.0^{+0.1}_{-0.1}$	4.74
χ_{c1}	$13.7^{+3.4}_{-3.1}$	$10.2^{+2.6}_{-2.3}$	4.71
χ_{c2}	$5.3^{+1.6}_{-1.3}$	$4.0^{+1.3}_{-1.0}$	4.69
χ_{b0}	$0.6^{+0.4}_{-0.2}$	$0.4^{+0.3}_{-0.2}$	0.95
χ_{b1}	$2.8^{+1.1}_{-0.7}$	$2.3^{+0.9}_{-0.6}$	0.66
χ_{b2}	$3.0^{+1.4}_{-0.9}$	$2.4^{+1.1}_{-0.7}$	0.57

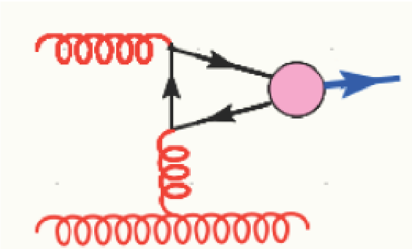
hard

Chung,Lee,Yu,PR78,074022(2008)

Inclusive production

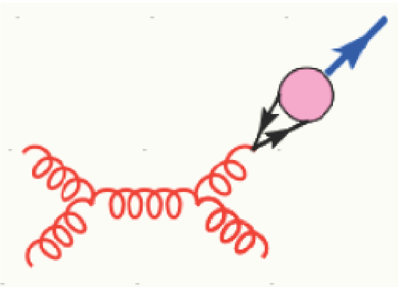
Color-octet contribution to J/ψ production

(c)

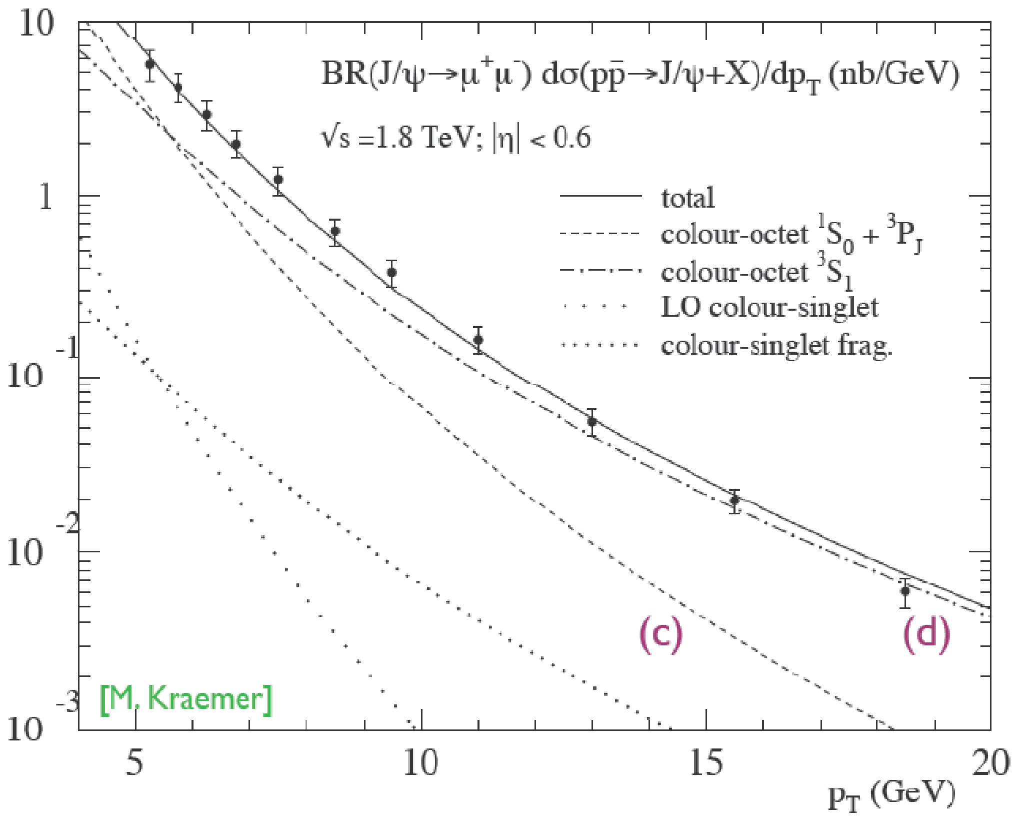


$$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^6}$$

(d)



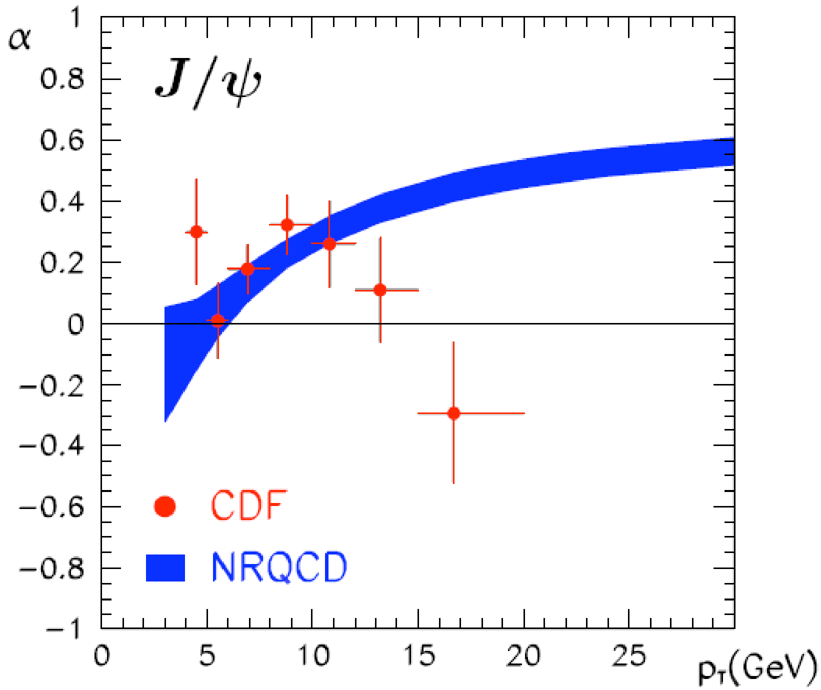
$$\alpha_S^3 \frac{(2m_c)^2 v^4}{p_T^4}$$

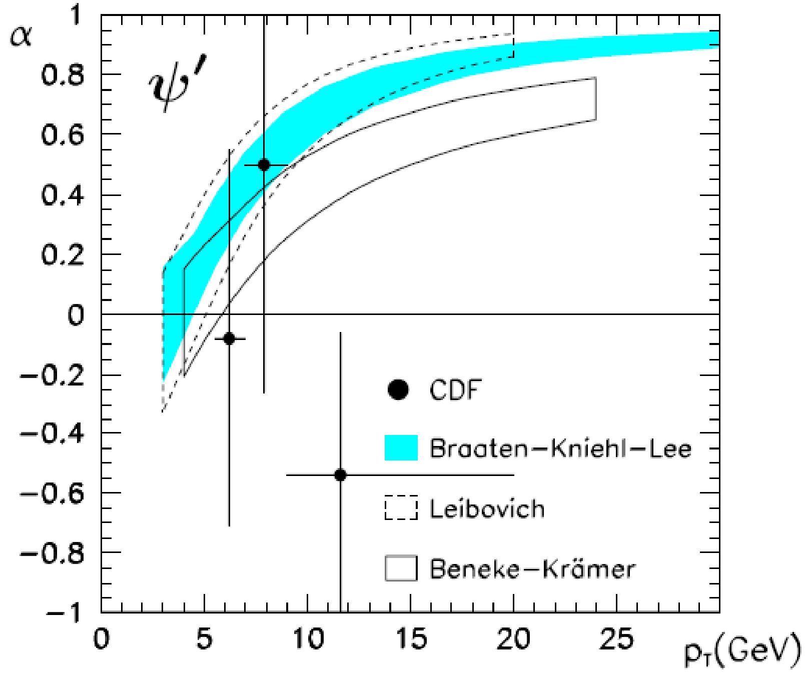


(c) & (d) are fitted to the data, but the resulting NP MEs are of the order predicted by the scaling rules of NRQCD.

F.Maltoni, QWG'07

Polarization of J/ψ at Tevatron Run I

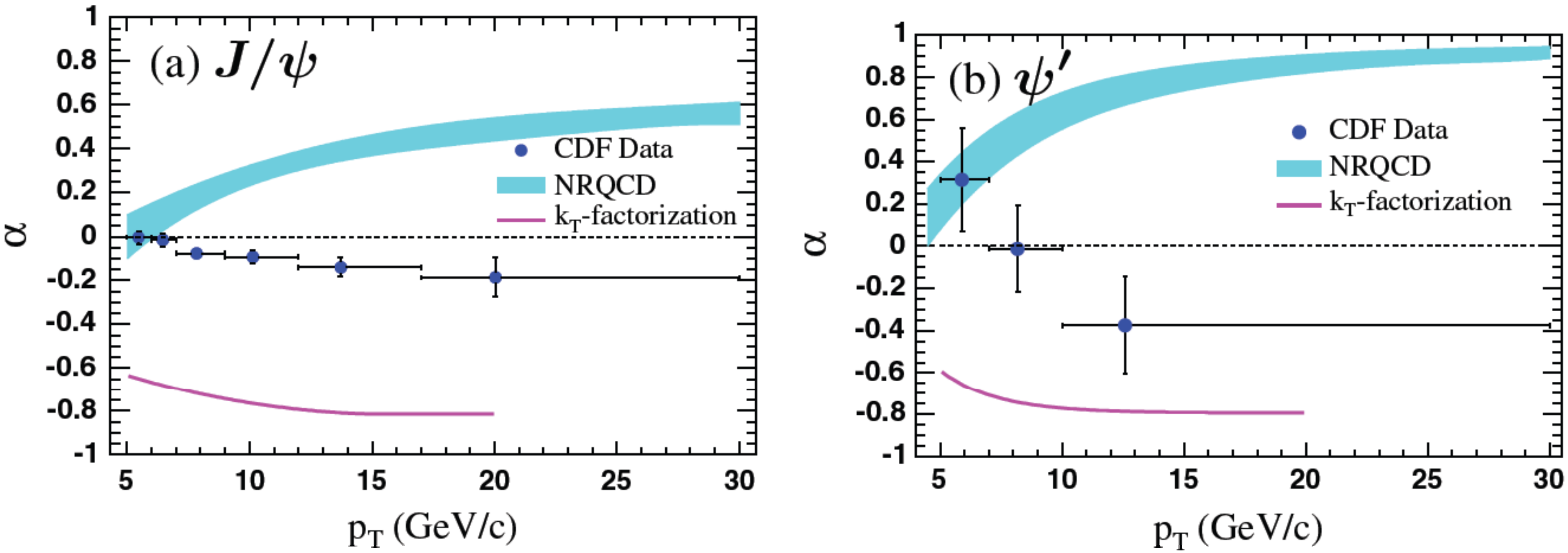




- agree in intermediate p_T.
- disagree in the hightest p_T bin.
- error bars are large.

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

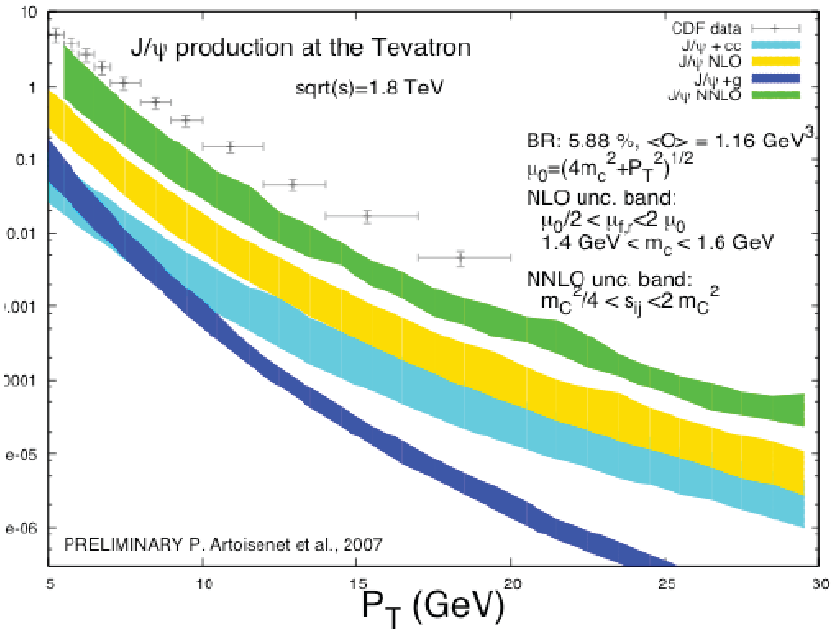
Polarization of J/ψ at Tevatron Run II

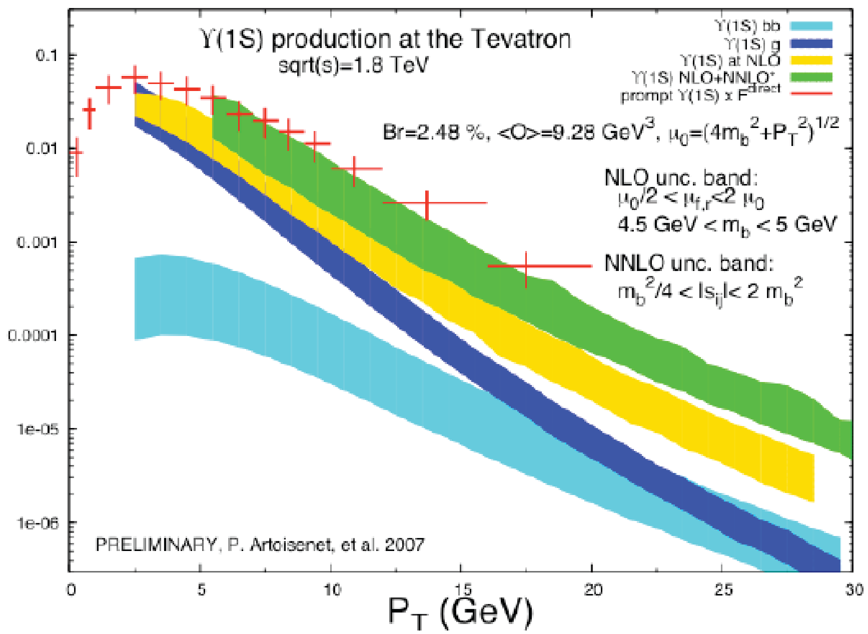


• Prompt polarization does not show the trend to the transverse polarization.

• CDF Run II data disagree with both CDF Run I and NRQCD.

NLO corrections to color-singlet contribution

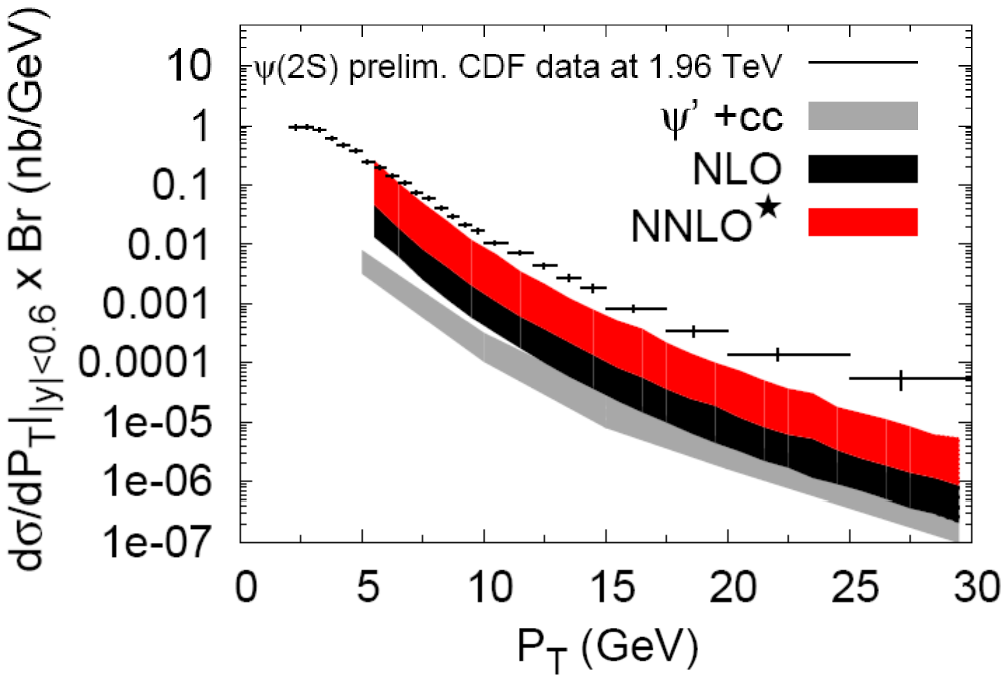




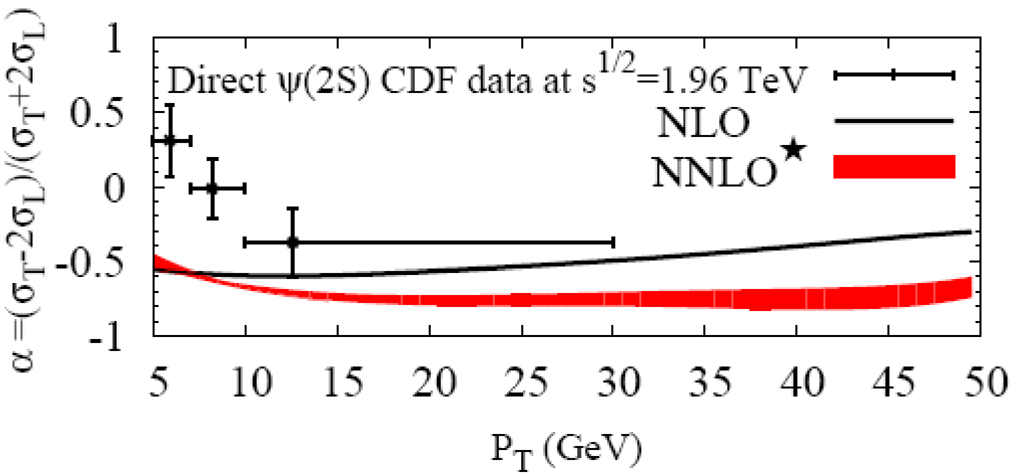
- NLO corrections : virtual (129 diags.) + real.
- Fragmentation approximation disregarded. (direct calculation)
- Incomplete NNLO corrections.
- Improved in shape and size, but smaller than data.
  → still needs ....

F.Maltoni, QWG'07

ψ' production



- a small gap at large p_T.



- Polarization is not explained by NNLO corrections.

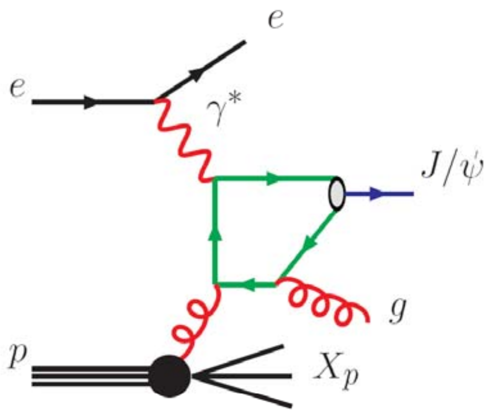
- feed-down, color octet?

Lansberg, QWG'08

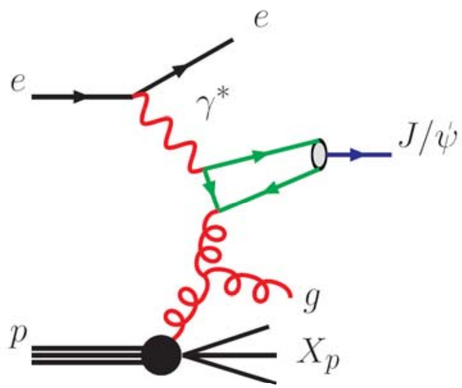
J/ψ production in ep collisions

J/ψ production in ep collisions

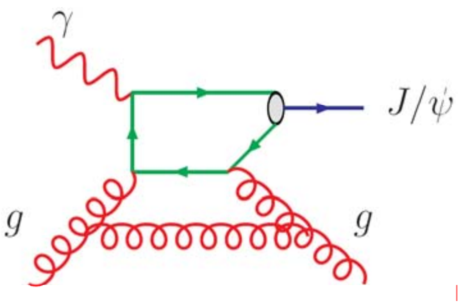
Color singlet



Color octet

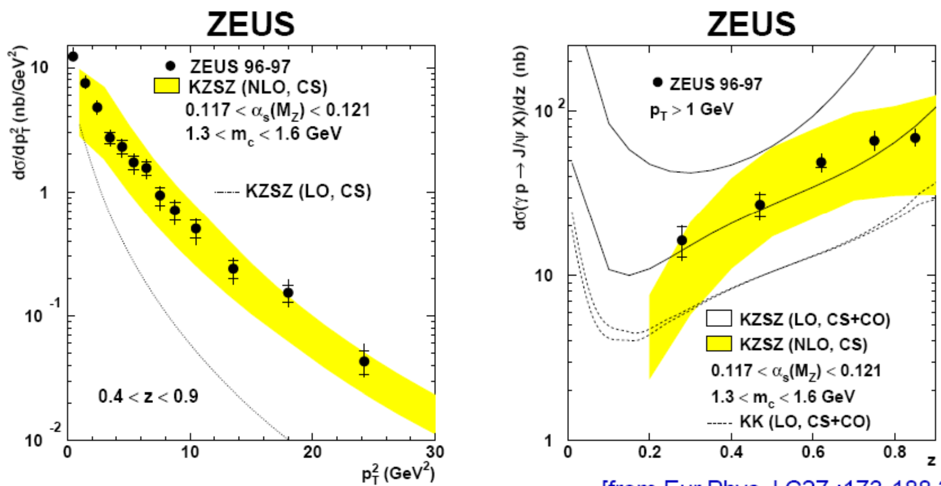


NLO corrections



NLO corrections in the CS model

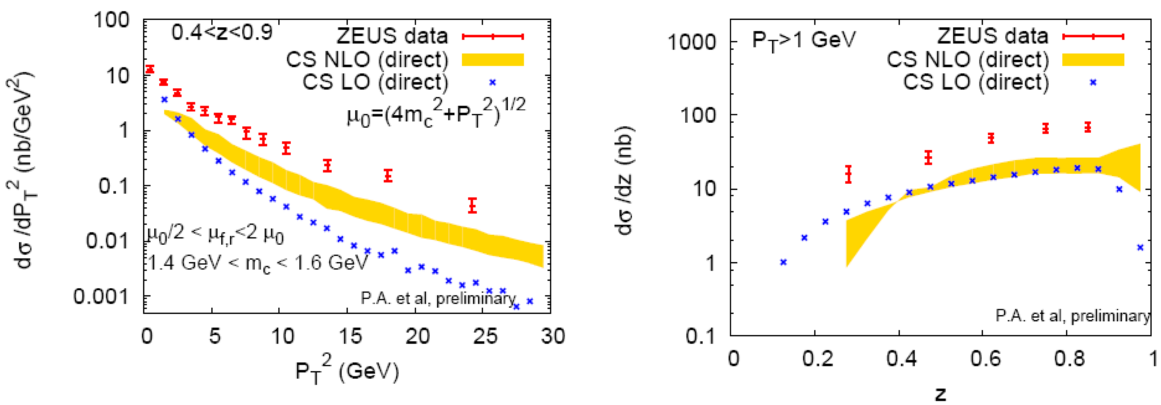
- the NLO corrections in CS model explain the data?



[from Eur.Phys.J.C27 :173-188,2003.]

$$z = \frac{P_N . P_{J/\psi}}{P_N . q_\gamma}$$

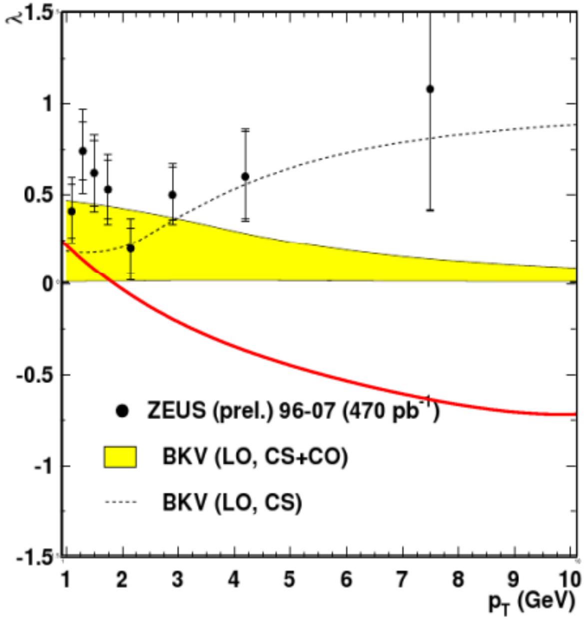
- choose a more natural choice of the scale:

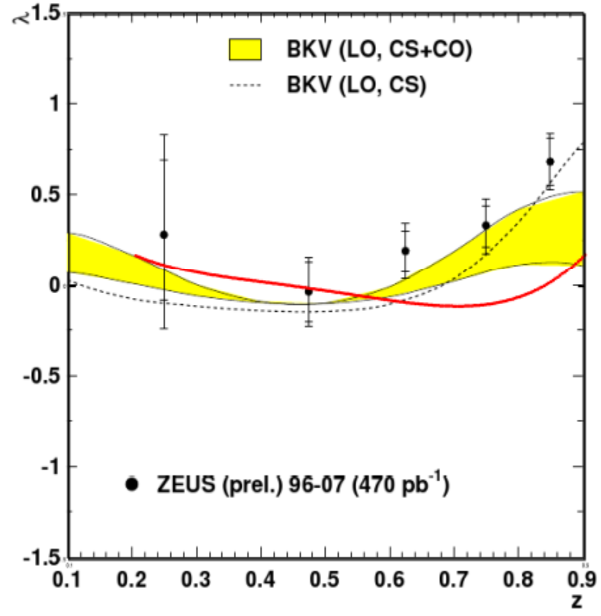


P.Artoisenet, QWG'08

Polarization

P.Artoisenet, QWG'08



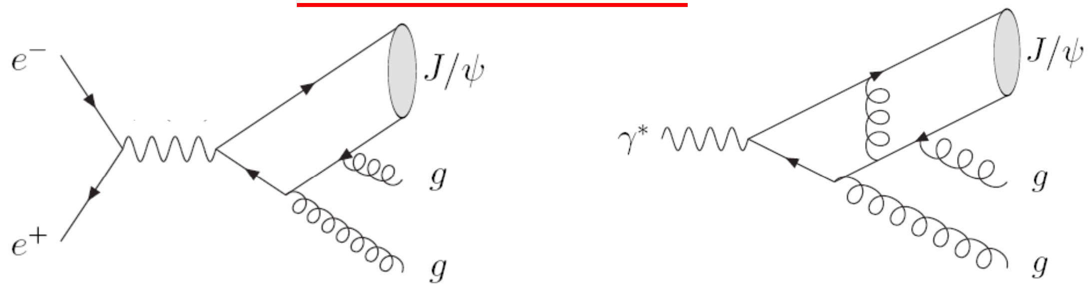


$$\frac{d\sigma}{d\Omega dy} \propto 1 + \lambda(y)\cos^2\theta + \mu(y)\sin 2\theta\cos\phi + \frac{\nu(y)}{2}\sin^2\theta\cos 2\phi$$

- the cross sections differential in z and P_T underestimate the data
- the longitudinal polarization at large P_T is not seen in the data

J/ψ production in e^+e^- collisions

Polarization



$$\sigma(e^+e^- \to J/\psi + non(c\bar{c})) = (0.43 \pm 0.09 \pm 0.09)pb.$$ BELLE,0901.2775

- NLO corrections in α_s in CSM were completed.

m_c(GeV)	$\alpha_s(\mu)$	$\sigma^{(0)}$(pb)	$a(\hat{s})$	$\sigma^{(1)}$(pb)	$\sigma^{(1)}/\sigma^{(0)}$
1.4	0.267	0.341	2.35	0.409	1.20
1.5	0.259	0.308	2.57	0.373	1.21
1.6	0.252	0.279	2.89	0.344	1.23

	$\mu = 2.8$GeV LO	$\mu = 2.8$GeV NLO	$\mu = 5.3$GeV LO	$\mu = 5.3$GeV NLO
$\sigma(gg)$	0.57	0.67	0.36	0.53
$\sigma(c\bar{c})$	0.38	0.71	0.24	0.53
$R_{c\bar{c}}$	0.40	0.51	0.40	0.50

Ma.,Zhang,Chao('08);Gong,Wang('09)

the color-octet contributions?

at NLO

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

- the CS contributions could not explain the data.
- room for the color-octet contributions?

Need to find the process in which the CO mechanism is indeed dominant.

double quarkonium production at the LHC

Motivations for double quarkonium production

- need further tests for the CS and CO mechanisms in NRQCD.

- predicted to test the color-octet mechanism at the Tevatron. Brager,Fleming,Phillips('96);Qiao('02)

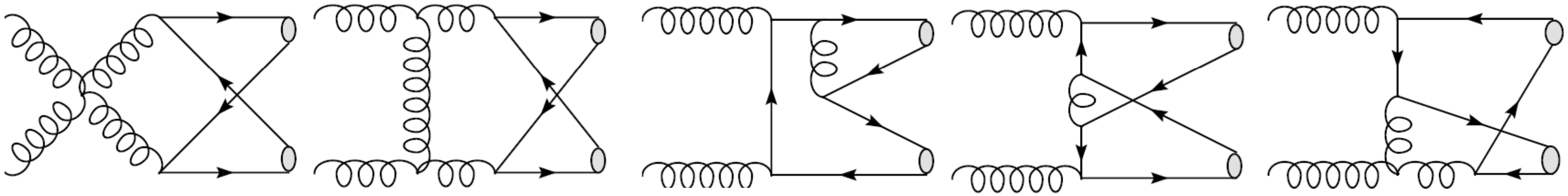
- recently extended to the LHC.
  Li,Zhang,Chao(0903.2250);Qiao,Sun,Sun(0903.0954)

- clean signals.

4 μ's events for $J/\psi J/\psi, J/\psi\Upsilon, \Upsilon\Upsilon$ production.

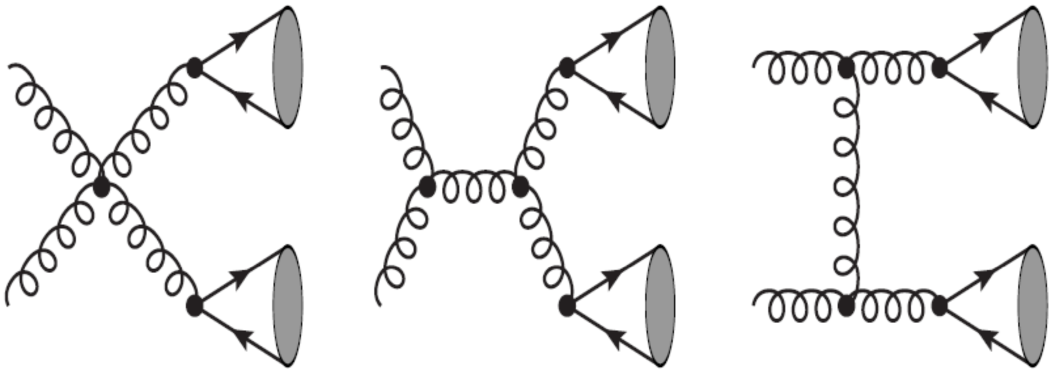
- $gg \to J/\psi\chi_c$ and $gg \to J/\psi\eta_c$ are forbidden in the CS model, but allowed in the CO model.

Color singlet



- $gg \to \mathcal{Q}_1\mathcal{Q}_2$ dominates over $q\bar{q} \to \mathcal{Q}_1\mathcal{Q}_2$.
- 31 Feynman diagrams for $J/\psi J/\psi$ and $B_c(B_c^*)\bar{B}_c(\bar{B}_c^*)$ production.
- 39 Feynman diagrams for $\eta_c\eta_c$ production.

Color octet



• gluon fragmentation to an color-octet $c\bar{c}$ pair dominates.

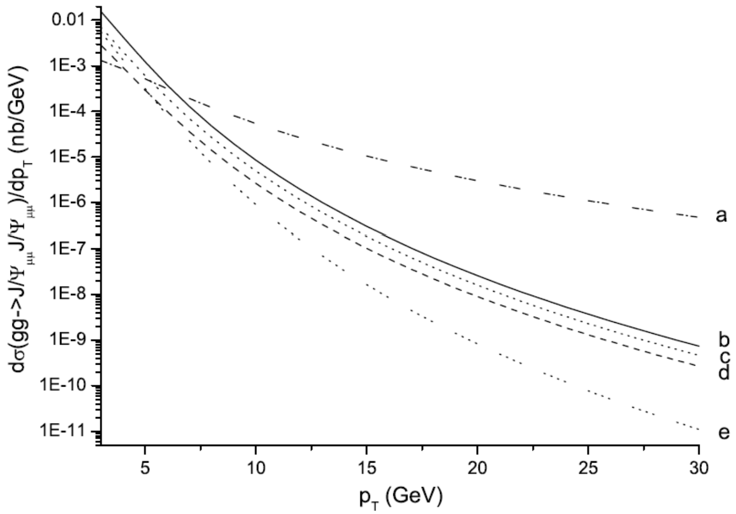
$$d\hat{\sigma}_{\mathcal{Q}_1+\mathcal{Q}_2} = \int_0^1 dz_1 \int_0^1 dz_2 D_{g\to\mathcal{Q}_1}(z_1, m_{Q_1}) D_{g\to\mathcal{Q}_2}(z_2, m_{Q_2}) d\hat{\sigma}_{gg}(E_1/z_1, E_2/z_2),$$

• gluon fragmentation function is

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

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

Cross section



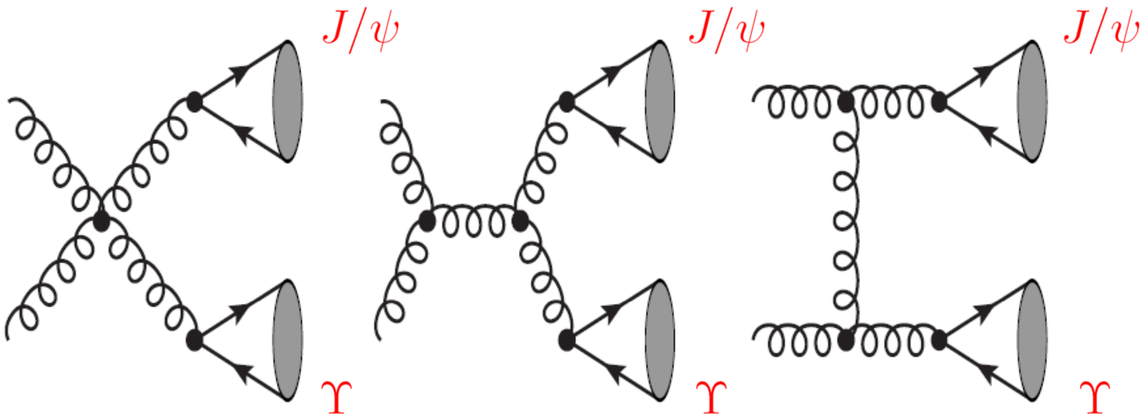
Qiao,Sun,Sun(0903.0954)

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

σ(events)	$p_{T\,cut}$=3 GeV	$p_{T\,cut}$=4 GeV	$p_{T\,cut}$=5 GeV	$p_{T\,cut}$=6 GeV	$p_{T\,cut}$=7 GeV
$\perp\perp$	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)
$\perp_8\perp_8$	2.90pb(29022)	1.82pb(18205)	1.15pb(11461)	0.74pb(7399)	0.49pb(4925)

$J/\psi + \Upsilon$ production at the LHC

gluon fragmentation

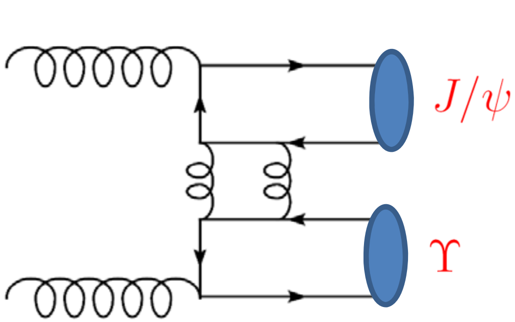


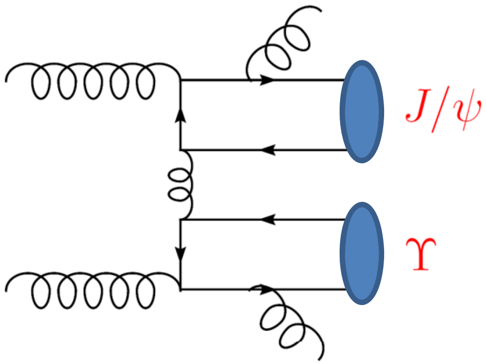
- gluon fragmentation into a heavy quarkonium may be dominant.

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

color singlet

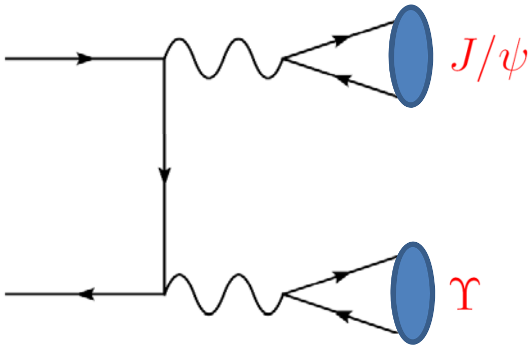
- the color-singlet yield appears at $\alpha_s{}^6$ order.





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

- QED contributions are suppressed.



$$\frac{d\hat{\sigma}}{dP_T^2} \sim \frac{16\alpha^4}{9^4 P_T^4}$$

- further suppression factor from PDF.

cross section

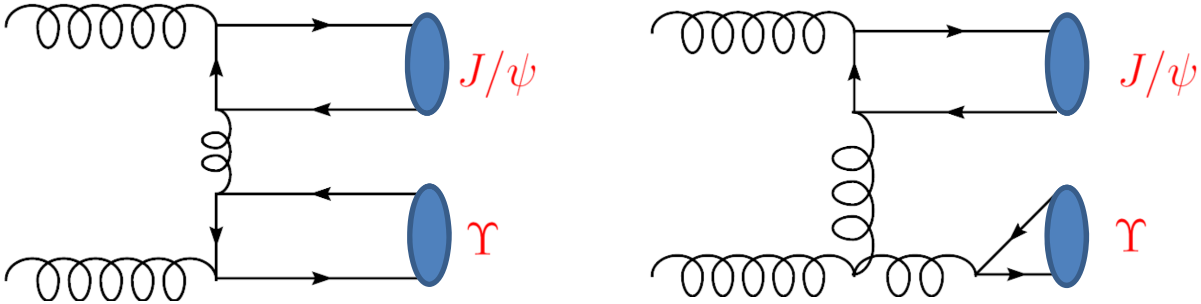
- in the gluon fragmentation approximation

- this mode could be observed soon at the LHC.

- if we could not observe, then the color-octet mechanism should be suppressed.

color octet

- the gluon fragmentation approximation is a bad approximation.
- the full calculation is being carried out. (36 diagrams)



- are these diagrams really suppressed?

Summary

• Heavy quarkonium production provides a test for the color-singlet and color-octet mechanism.

• Exclusive production of heavy quarkonium : relativistic corrections

• Inclusive production of heavy quarkonium : color-octet mechanism