Heavy Quarkonium Production at B factories

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  - $e^+e^- \longrightarrow J/\psi + gg$
  - $e^+e^- \longrightarrow J/\psi({}^3P_J^8, {}^1S_0^8) + g$
- ***Exclusive Double-Charmonia*** $J/\psi + \chi_{cJ}$ ***Production***
  - ***Introduction***
  - $e^+e^- \longrightarrow J/\psi + \chi_{cJ}$
- ***Summary***

1 Inclusive Charmonia Production and $R_{c\bar{c}}$

1.1. Introduction

Experimental data

- Belle02: $R_{c\bar{c}} = \frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]} = 0.59^{+0.15}_{-0.13} \pm 0.12$
- Belle03: $R_{c\bar{c}} = 0.82 \pm 0.15 \pm 0.14$
- Belle09:
  - $\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = 0.74 \pm 0.08^{+0.09}_{-0.08}$ pb
  - $\sigma[e^+e^- \to J/\psi + X_{\text{non-}c\bar{c}}] = 0.43 \pm 0.09 \pm 0.09$ pb
  - $\sigma[e^+e^- \to J/\psi + X] = 1.17 \pm 0.02 \pm 0.07$ pb

LO (in α_s) CS contributions

  - $\sigma[e^+e^- \to J/\psi + c\bar{c}] \sim 0.1$ pb
  - $\sigma[e^+e^- \to J/\psi + gg] \sim 0.3$ pb

- LO CS are inconsistent with data in both absolute and relative rates

LO CO contributions

- Numerator: CO contribution to $\sigma[J/\psi + c\bar{c}]$ is only about 7% [Liu, He, Chao'04]
- Denominator:
  - $\sigma_{\text{ex}}[e^+e^- \to J/\psi + X_{\text{non-}c\bar{c}}] - \sigma_{\text{lo-cs}}[e^+e^- \to J/\psi + gg] = 0.07 \pm 0.13$ pb
    * Leaves little room for a color-octet contribution $e^+e^- \to J/\psi + g$, [Braaten,Chen'96]
  - $\sigma[J/\psi + g] = 0.28$ pb [LO by Wang'03]; can be enhanced by NLO corrections with a K factor of 1.8 [Zhang, Ma, Wang, Chao, PRD81]
    * Based on standard estimates of CO MEs, which may be too large
    * Large CO contribution is bad for understanding the large ratio $R_{c\bar{c}}$
  - Kinematically, the CO contribution in the p_ψ spectrum will peak near the end-point $(z = 1)$
    * No evidence was found in Belle and BaBar data
    * But the CO spectrum near end-point can be smeared by soft-gluon-resummation and shape-function effects [Fleming, Leibovich'03]

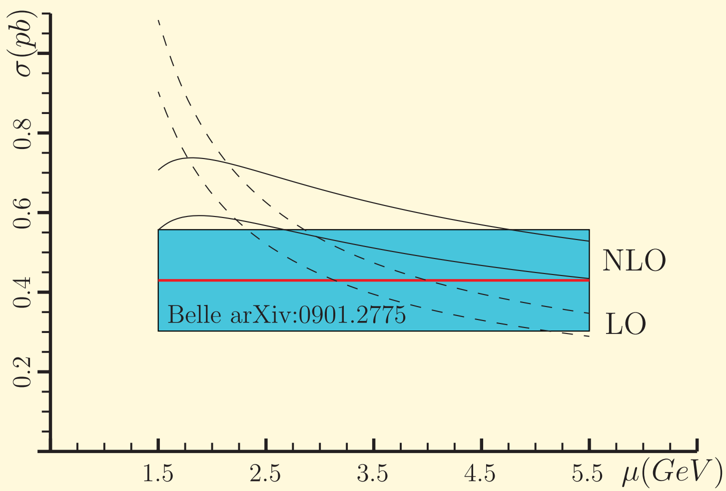
1.2. $e^+e^- \to J/\psi c\bar{c}$ (see talk of Wang for details)

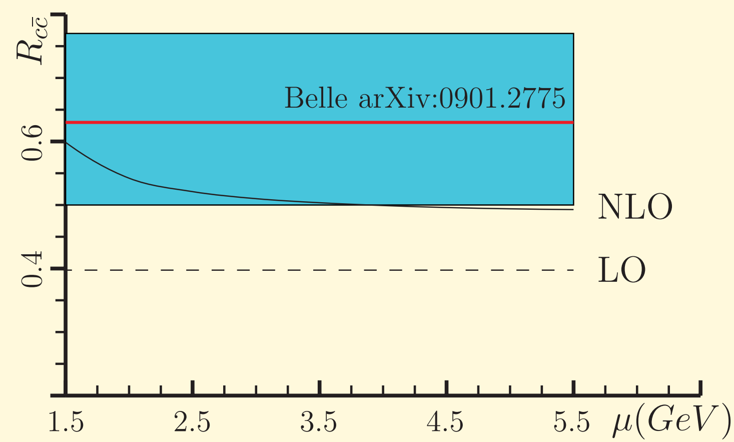
α_s corrections [Zhang, Chao'07; Gong, Wang'09]

- Large K factor
  - Direct K factor from NLO/LO is 1.8
  - Indirect K factor of about 1.8: NLO determination of MEs from $J/\psi \to e^+e^-$
- $\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = 0.71^{+0.94}_{-0.31}(0.53^{+0.59}_{-0.23})$ pb for $\mu = 2.8(5.3)$ GeV
  - Including QED corrections, two-photon processes and feeddown from $\psi(2S)$ and χ_c
  - The uncertainties come from $m_c = 1.4 \mp 0.2$ GeV
  - May resolve the discrepancy between theory and experiment
- Hidden uncertainty from nonperturbative region
  - There could be nonperturbative enhancement when one charm quark is co-moving with the J/ψ [Nayak, Qiu, Sterman'07]
  - Its size can be determined experimentally

1.3. $e^+e^- \to J/\psi gg$

- α_s corrections [Ma, Zhang, Chao, PRL'09]
  - Small K factor of 1.2-1.5
    - Cross checked by [Gong, Wang PRL'09]
  - μ dependent of $\sigma(J/\psi gg)$ and $R_{c\bar{c}}$

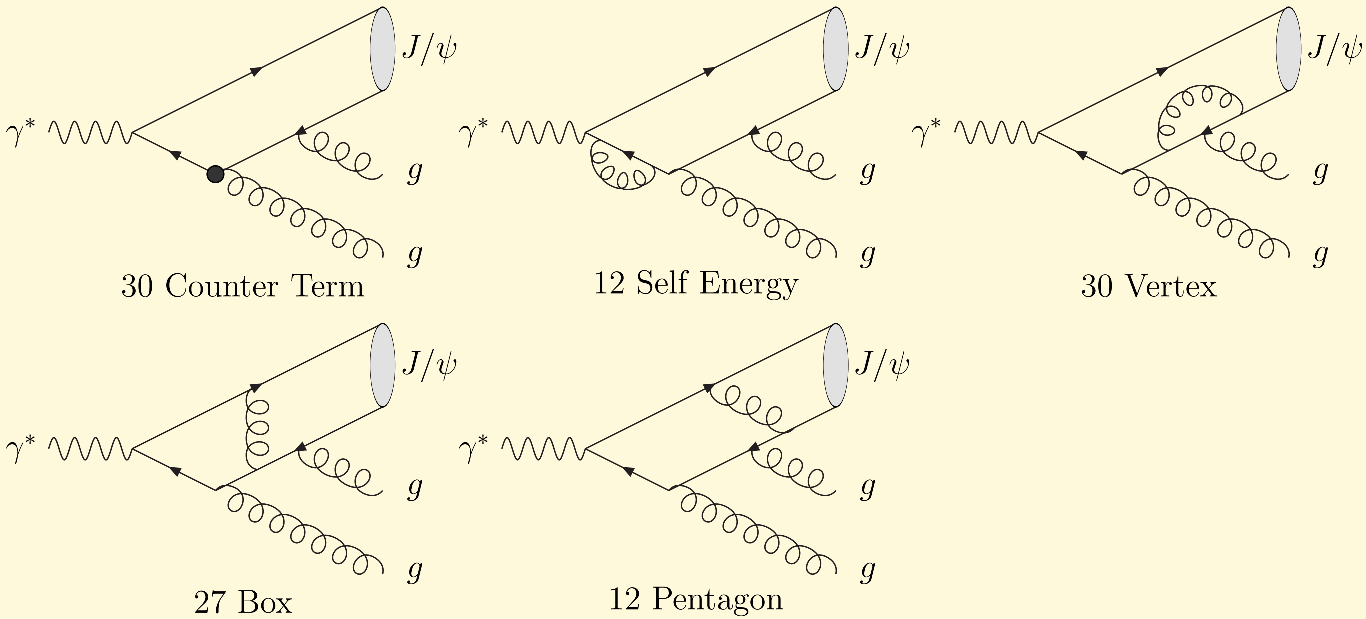




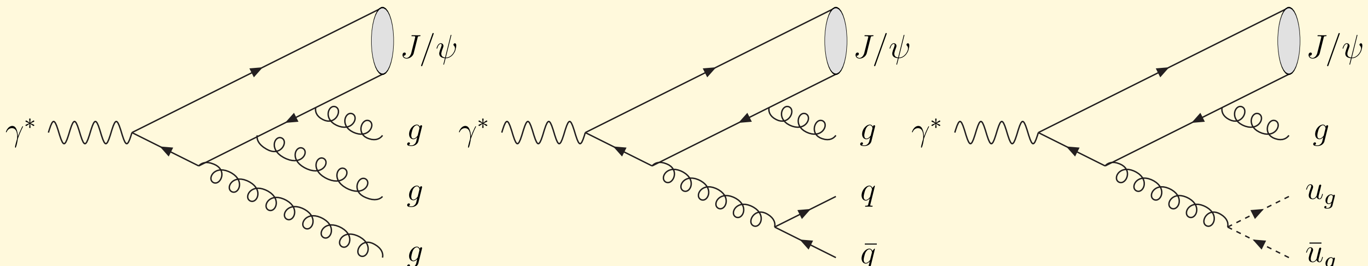
$m_c = 1.4$ GeV (upper); $m_c = 1.5$ GeV (lower) $\quad\quad$ $m_c = 1.4$ GeV

– The blue regions show the error bars of data

- Consistent with data both in absolute and relative rates



Virtual correction diagrams for $e^- e^+ \to J/\psi gg$.



42 Real ggg 6 Real $gq\bar{q}$ 6 Real $gu_g\bar{u}_g$

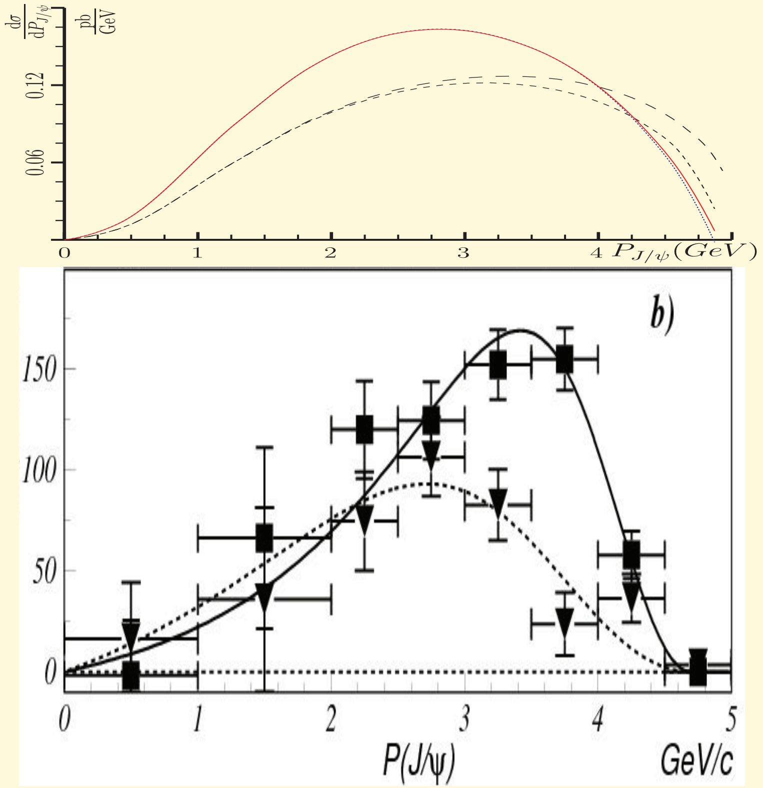
Real correction diagrams for $e^-e^+ \to J/\psi gg$**.**

Cross section

	$\mu = 2.8$, $m_c = 1.4$	$\mu = 3.0$, $m_c = 1.5$	$\mu = 5.3$, $m_c = 1.4$	$\mu = 5.3$, $m_c = 1.5$
$\alpha_s(\mu)$	0.267	0.259	0.211	0.211
$\sigma^{\text{LO}}(gg)$	0.42	0.32	0.26	0.22
$\sigma^{\text{NLO}}(gg)$	0.50	0.40	0.39	0.32
$\sigma^{\text{NLO}}_{\text{prompt}}(gg)$	0.67	0.54	0.53	0.44
$\sigma^{\text{LO}}(c\bar{c})$	0.27	0.18	0.17	0.12
$\sigma^{\text{NLO}}(c\bar{c})$	0.47	0.33	0.34	0.24
$\sigma^{\text{NLO}}_{\text{prompt}}(c\bar{c})$	0.71	0.51	0.53	0.39
$R^{LO}_{c\bar{c}}$	0.39	0.36	0.40	0.35
$R^{NLO}_{c\bar{c}}$	0.51	0.49	0.50	0.47

- Experimental data [Belle'09]
  - $\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = 0.74 \pm 0.08^{+0.09}_{-0.08}$ pb
  - $\sigma[e^+e^- \to J/\psi + X_{\text{non-}c\bar{c}}] = 0.43 \pm 0.09 \pm 0.09$ pb
- Consistent with data both absolute and relative rates
- Leave very little room for CO contribution
  - The upper limits for CO EMs could be given after NLO CO calculation

P_ψ spectrum



- Upper: NLO+LL (solid), NLO (dotted), LO+LL (short-dashed), LO (long-dashed)
- Lower [Belle'09]: dashed curve for $d\sigma(J/\psi X_{\text{non-}c\bar{c}})/dP_\psi$ in unit of fb$/0.5$GeV

- The LL resummation at the end point has little effect
- Consistent with the experimental spectrum

Relativistic corrections

- v^2 corrections can be neglected for $\sigma[J/\psi + c\bar{c}]$ [He, Fan, Chao'07]
- v^2 corrections to $\sigma[J/\psi + gg]$ [He, Fan, Chao'09; Jia'09]:
  - Fit experiment data at the NLO in α_s, with m_c =1.5Gev and $\alpha_s = 0.26$, we get

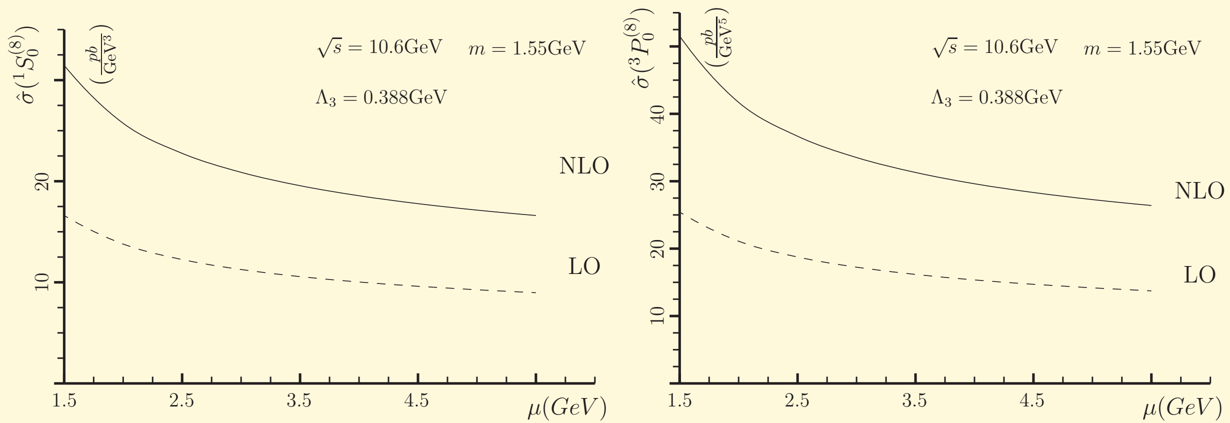
$$\frac{\langle 0|\mathcal{O}_1^{\psi}(^3S_1)|0\rangle}{3} = 0.572\mathrm{GeV}^3, \; \frac{\langle 0|\mathcal{P}_1^{\psi}(^3S_1)|0\rangle}{3m_c^2} = 0.512 \times 10^{-1}\mathrm{GeV}^3.$$

  - The relativistic correction enhances the cross section by $20 - 30\%$.
- CS contribution has saturated the observed $e^+e^- \to J/\psi + X_{\text{non-}c\bar{c}}$ cross section, CO contributions are further restricted.

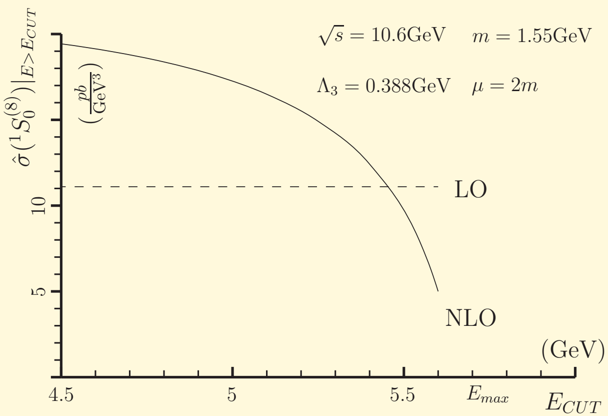
1.4. $e^+e^- \to J/\psi({}^3P_J^8, {}^1S_0^8) + g$

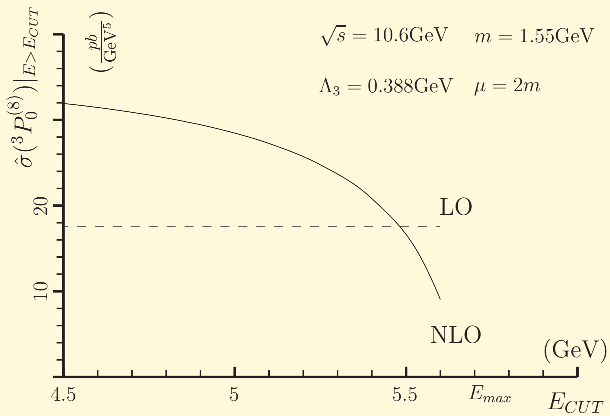
α_s corrections [Zhang, Ma, Wang, Chao, PRD'10]

- Large K factor
  - The K factor of $e^+e^- \to c\bar{c}({}^3P_J^8 or {}^1S_0^8) + g$ is about 1.9
  - The CO matrix elements should be even smaller.



- The peak at the endpoint in the J/ψ energy distribution can be smeared by NLO corrections.
  - But the major CO contribution still comes from the large energy region of J/ψ.





- The most stringent constraint of CO matrix elements
  - Setting the color-singlet contribution to be zero in $e^+e^- \longrightarrow J/\psi + X_{non-c\bar{c}}$
  - An upper limit of the color-octet matrix element is:
    $\langle 0|\mathcal{O}^{J/\psi}[{}^1S_0^{(8)}]|0\rangle + 4.0\,\langle 0|\mathcal{O}^{J/\psi}[{}^3P_0^{(8)}]|0\rangle/m_c^2 < (2.0 \pm 0.6) \times 10^{-2}\ \mathrm{GeV}^3$
  - This upper limit is smaller than the values extracted before by about a factor of 2.

2 Exclusive Double-Charmonia $J/\psi + \chi_{cJ}$ Production

2.1. Introduction

Experimental data $v.s.$ NRQCD at LO in α_s and v

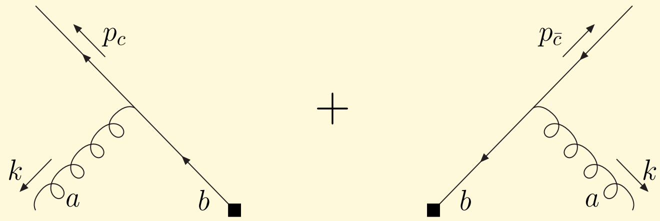
	$J/\psi + \eta_c$	$J/\psi + \chi_{c0}$	$J/\psi + \eta_c(2S)$
$\sigma \times B_{>2}$ (fb) (Belle)	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
$\sigma \times B_{>2}$ (fb) (BABAR)	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
σ (fb) (Liu, He, Chao)	5.5	6.9	3.7
σ (fb) (Braaten, Lee)	3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52

⋆ The two LO NRQCD results employ different choices of m_c, NRQCD MEs and α_s

- The LO results are much smaller than data. The NLO corrections in α_s [Zhang, Gao, Chao'06; Gong, Wang'08] and v [Bodwin et al.'07; He et al.'07] might bring theory into agreement with data for $J/\psi\eta_c$

Factorization for exclusive charmonium production in e^+e^- annihilation and B decay

- Two large scale: m_c and $\sqrt{s}(m_b)$



$$\sim \frac{p_c^\mu}{p_c \cdot k}\mathrm{Tr}_c(T^aT^b) - \frac{p_{\bar{c}}^\mu}{p_{\bar{c}} \cdot k}\mathrm{Tr}_c(T^bT^a)$$

$$\sim \frac{p^\mu}{p \cdot k}\mathrm{Tr}_c(T^aT^b - T^bT^a)$$

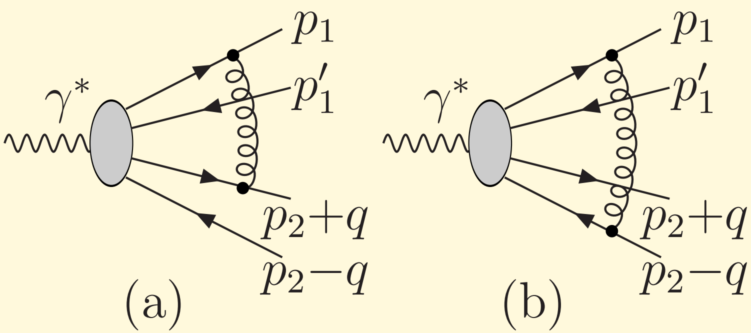
$$+\frac{2}{(p \cdot k)^2}(q^\mu(p \cdot k) - p^\mu(q \cdot k))\mathrm{Tr}_c(T^aT^b + T^bT^a)$$

$$\sim p^\mu q^\nu F^a_{\mu\nu}\mathrm{Tr}_c(T^aT^b) \sim \vec{x} \cdot \vec{E}^a\mathrm{Tr}_c(T^aT^b),$$

  - $p_c = p/2 + q;\ \ p_{\bar{c}} = p/2 - q$

- Factorization is OK for S-wave at LO in v: $e^+e^- \to J/\psi\eta_c;\ \ B \to J/\psi(\eta_c)K$
- Factorization is not OK for P-wave: $e^+e^- \to h_c\chi_c;\ \ B \to \chi_c(h_c)K$
  - B decay to P-wave at one-loop level [Song, Meng, Gao, Chao'03]
- Factorization can be restored in the case $mv^2 \gg \Lambda_{QCD}$ [Beneke, Vernazza'08]
- Factorization should be OK in the limit $m_c^2/s, m_c/m_b \to 0$
  - $p_c = up + O(m_c/\sqrt{s}),\ p_{\bar{c}} = \bar{u}p + O(m_c/\sqrt{s});\ \ u + \bar{u} = 1,\ u = 1/2 + O(v, m_c/\sqrt{s})$
  - $soft = O(m_c/\sqrt{s} \cdot m_c/\sqrt{s}), O(m_c/m_b)$
  - Be verified by more general analysis [Bodwin, Tormo, Lee'08]
  - Be indicated by B decay to P-wave at one-loop [Song, Meng, Gao, Chao'03]

Factorization is OK for $e^+e^- \to J/\psi\chi_c$, but not for $e^+e^- \to h_c\chi_c$ [Zhang, Ma, Chao, PRD'08]



- p_1 for J/ψ, p_2 for χ_c
- Soft gluon lines decouple to the hard kernel
- Soft interactions are canceled between (a) and (b)

2.2. $e^+e^- \to J/\psi\chi_{cJ}$

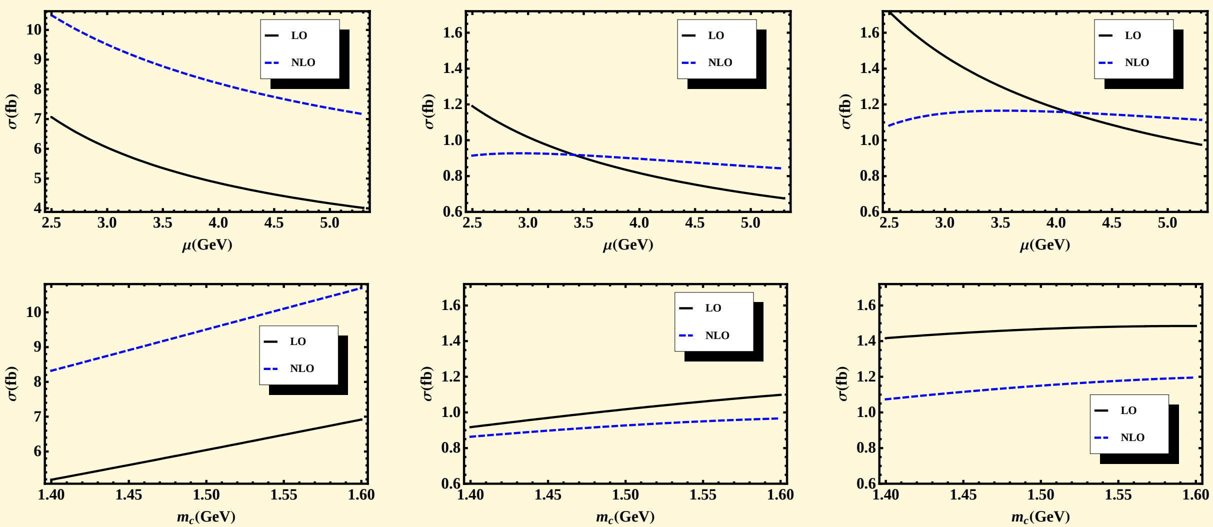
α_s Corrections [Wang, Ma, Chao, to appear]

- Direct K factor

	$J/\psi+\chi_{c0}$	$J/\psi+\chi_{c1}$	$J/\psi+\chi_{c2}$
$\mu=2m_c$	1.57	0.91	0.78
$\mu=\sqrt{s}/2$	1.79	1.25	1.14

  – Differences of K factors between $\chi_{cJ}(J=0,1,2)$ are in line with exp. data

- μ and m_c dependence



(a) $e^+ + e^- \to J/\psi + \chi_{c0}$ (b) $e^+ + e^- \to J/\psi + \chi_{c1}$ (c) $e^+ + e^- \to J/\psi + \chi_{c2}$

  – $m_c = 1.5$ GeV (upper); $\mu = 2m_c$ (lower)

Numerical results [Wang, Ma, Chao, to appear]

- The MEs are determined by $J/\psi \to e^+e^-$, $\chi_{c2} \to \gamma\gamma$ data

	Belle $\sigma \times \mathcal{B}_{>2(0)}$[3]	BaBar $\sigma \times \mathcal{B}_{>2}$[4]	Our result ($\mu = 2m_c$)	Our result ($\mu = \sqrt{s}/2$)
$\sigma(J/\psi + \chi_{c0})$	$6.4 \pm 1.7 \pm 1.0$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	9.5 ± 1.2	7.2 ± 1.2
$\sigma(J/\psi + \chi_{c1})$	-	-	$0.93^{+0.04}_{-0.07}$	$0.84^{+0.07}_{-0.09}$
$\sigma(J/\psi + \chi_{c2})$	-	-	$1.15^{+0.05}_{-0.08}$	$1.11^{+0.05}_{-0.07}$
$\sigma(J/\psi + \chi_{c1}) + \sigma(J/\psi + \chi_{c2})$	<5.3 at 90% CL	-	$2.08^{+0.08}_{-0.14}$	$1.96^{+0.11}_{-0.17}$
$\sigma(\psi(2S) + \chi_{c0})$	$12.5 \pm 3.8 \pm 3.1$	-	4.1 ± 0.5	3.1 ± 0.5
$\sigma(\psi(2S) + \chi_{c1})$	-	-	$0.40^{+0.01}_{-0.03}$	$0.36^{+0.03}_{-0.04}$
$\sigma(\psi(2S) + \chi_{c2})$	-	-	$0.49^{+0.02}_{-0.03}$	$0.48^{+0.02}_{-0.04}$
$\sigma(\psi(2S) + \chi_{c1}) + \sigma(\psi(2S) + \chi_{c2})$	<8.6 at 90% CL	-	$0.89^{+0.04}_{-0.06}$	$0.84^{+0.05}_{-0.07}$

  - [3] Belle, PRD'04; [4] BaBar, PRD'05
  - The error bar come from $m_c = 1.5 \pm 0.1$ GeV

The fully analytical results are also given

3 Summary

- NLO QCD radiative corredtions to CS contributions are very important
  - Quarkonium production at Tevatron (up to NNLO*)
  - J/ψ production at RHIC
  - Inelatic J/ψ photoproduction at HERA
  - Exclusive double-charmonium production at Belle and BaBar
  - Inclusive J/ψ production at Belle and BaBar
- In many cases, CO contributions are overestimated before these NLO results are taken into account
- Consistent with Lattice estimation of the CO decay MEs

- Resolved puzzles (might be)
  - $e^+e^- \to J/\psi\chi_{cJ}$
  - $e^+e^- \to J/\psi c\bar{c}$ and $R_{c\bar{c}}$
- Remaining puzzles:
  - Polarizations at Tevatron and in inelastic J/ψ photoproduction at HERA, as well as the cross sections?
  - The size of CO contributions for J/ψ: very small?
- Looking forward to higher luminosity, higher statistics and higher p_T: LHC (CMS, LHCb,...); SuperB, ...,and better theoretical approaches (higher order corrections should be under control).

Thanks!