B 工厂中 J/ψ 的单举产生

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1 Introduction

Heavy quarkonia have been of great interest nowadays. An effective and successful theory for heavy quakonia is Non-Relativistic QCD (NRQCD)[*].

- Successes of NRQCD in heavy quakonia production
  - ⋆ Quarkonium Production at Tevatron and color-octet mechanism;
  - ⋆ $\gamma\gamma \to J/\psi$ at LEP;
- Puzzles in NRQCD Factorization Approach ← 选择课题
  - ⋆ J/ψ production in e^+e^- annihilation at B Factories.
  - ⋆ Polarization of quarkonium at Tevatron [**];
  - ⋆ Production cross sections ratio of χ_{c1} to χ_{c2} at Tevatron;

[*] G. T. Bodwin, E. Braaten and G. P. Lepage, Phys. Rev. D **51**, 1125 (1995)
[**] For new developments,
J. Campbell, *et al.*, Phys. Rev. Lett.**98**:252002,2007;

P. Artoisenet, *et al.*, Phys. Lett. B**653**:60-66,2007; Phys. Rev. Lett.**101**:152001,2008;

B. Gong,*et al.*, Phys. Rev. Lett.**100**:232001,2008; Phys. Rev. D**78**, 074011 (2008); arXiv:0805.4751.

NLO correction is very important.

- An accurate knowledge of a cross section requires its calculation to at least next-to-leading order (NLO).
- Moreover, a number of recent calculations[*] show that the NLO QCD correction to heavy quarkonia maybe very large.
- So, it is crucial to know the NLO correction to these puzzles.

[*] Y. J. Zhang and K. T. Chao, Phys. Rev. Lett. **98**, 092003 (2007); arXiv:0808.2985;

R. Li and J. X. Wang, arXiv:0811.0963;

B. Gong, *et al.*, arXiv:0805.4751; Phys. Rev. Lett. **100**, 232001 (2008); Phys. Rev. Lett. **100**, 181803 (2008);

J. Campbell, F. Maltoni, F. Tramontano, Phys. Rev. Lett. 98,252002(2007);

P. Artoisenet, J.P. Lansberg, F. Maltoni, Phys. Lett.B653, 60 (2007);

2 $e^+e^- \to J/\psi + X(non-c\bar{c})$

2.1. Motivation

The ratio $R_{c\bar{c}}$ measured by Belle is much larger than the theoretical prediction, where

$$R_{c\bar{c}} = \frac{\sigma[e^+e^- \to J/\psi + c\bar{c} + X]}{\sigma[e^+e^- \to J/\psi + X]}, \tag{1}$$

- The experiment data of Belle[*]:

$$R_{c\bar{c}} = 0.59^{+0.15}_{-0.13} \pm 0.12 \tag{2}$$

In EPS'2003 Belle's result[**]:

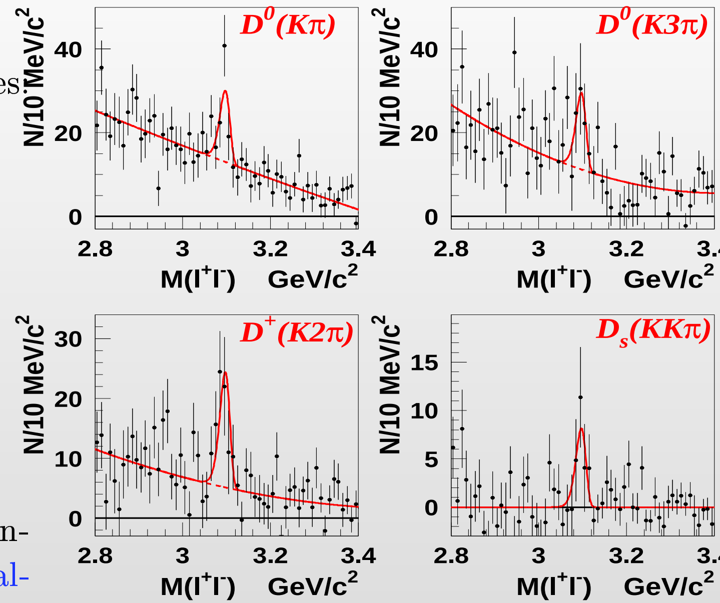
$$R_{c\bar{c}} = 0.82 \pm 0.15 \pm 0.14 \tag{3}$$

- LO theoretical prediction (including color-octet contribution) $\approx 0.1 \sim 0.3$ [***].

[*] K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **89**, 142001 (2002).
[**] T.V. Uglov, Eur. Phys. J. C **33**, S235 (2004).
[***]P. L. Cho and A. K. Leibovich, Phys. Rev. D **54**, 6690 (1996) ;F. Yuan, C. F. Qiao and K. T. Chao, Phys. Rev. D **56**, 321 (1997); ....

BELLE

- $\mathcal{L} = 101\,\text{fb}^{-1}$
- Reconstruct all charm ground states: D^0, D^+, D_s^+, Λ_c
- Fit $D(\Lambda_c)$ signals in $M_{\ell^+\ell^-}$ bins
- Fit J/ψ to yields distributions:
  $N_{D^0\to K\pi} = 49.6 \pm 13.3$ (3.7σ)
  $N_{D^0\to K3\pi} = 53.0 \pm 21.2$ (2.5σ)
  $N_{D^+\to K2\pi} = 56.2 \pm 15.4$ (3.6σ)
  $N_{D_s^+\to KK\pi} = 23.8 \pm 9.4$ (2.6σ)
  $N_{\Lambda_c\to Kp\pi} = 3.0 \pm 4.2$
- All $c\bar{c}$ final states except for Ξ_c reconstructed $\Rightarrow$ Do not need model to calculate $2(c\bar{c})$ X-section!



$$\left.\frac{\sigma(e^+e^-\to J/\psi\, c\bar{c})}{\sigma(e^+e^-\to J/\psi\, X)}\right|_{P_{J/\psi}>2.0\ \text{GeV}/c} = \frac{0.5(N_{D^0}+N_{D^+}+N_{D_s^+}+N_{\Lambda_c})+N_{(c\bar{c})_{res}}}{N_{J/\psi}} = 0.82 \pm 0.15 \pm 0.14$$

Belle's result of $R_{c\bar{c}}$ in EPS'2003.

Many theoretical studies were suggested in order to resolve the discrepancy, but the results are unsatisfactory.

- Liu, He, Chao considered two photons contribution[*].
- Kaidalov introduced the nonperturbative quark-gluon-string model [**].
- Kang, Lee, and Lee get $R_{c\bar{c}} = 0.049$ in color-evaporation-model[***].
- Berezhnoy calculate $\sigma[J/\psi + c\bar{c}]$ with the light cone wave function for massive charm quark, and found the effect can be neglected [****].
- Berezhnoy and Likhoded calculate $R_{c\bar{c}}$ with two pQCD methods: J/ψ wave function and quark-hadron duality. Their result is $R_{c\bar{c}} = 0.09 \sim 0.17$ [*****].

[*] K. Y. Liu, Z. G. He and K. T. Chao, arXiv:hep-ph/0301218, arXiv:hep-ph/0305084.
[**] A. B. Kaidalov, JETP Lett. **77**, 349 (2003) [arXiv:hep-ph/0301246].
[***] D. Kang, *et al.*, Phys. Rev. D **71**, 094019 (2005) [arXiv:hep-ph/0412381];
[****] A. V. Berezhnoy, arXiv:hep-ph/0703143.
[*****] A. V. Berezhnoy and A. K. Likhoded, Phys. Atom. Nucl. **67**, 757 (2004) [arXiv:hep-ph/0303145].

⋆ In NRQCD, $\sigma[J/\psi+X]$ includes color-singlet contributions $\sigma[J/\psi({}^3S_1^{[1]})+c\bar{c}]$ and $\sigma[J/\psi({}^3S_1^{[1]})+gg]$, and color-octet contribution $\sigma[J/\psi({}^3P_J^{[8]},{}^1S_0^{[8]})+g]$. Contributions of other Fock states are suppressed by α_s or v^2.

从自己的能力出发

⋆ The observed end point behavior of J/ψ and the large ratio $R_{c\bar{c}}$ might indicate that the color-octet matrix elements are much smaller than previously expected.

⋆ To test this thought we assume the color-octet contribution to be ignored and only consider the color-singlet contributions, then
$R_{c\bar{c}} = \frac{\sigma[J/\psi+c\bar{c}]}{(\sigma[J/\psi+c\bar{c}]+\sigma[J/\psi+gg])}$.

⋆ considering the crucially importance of the NLO QCD corrections found in many heavy quarkonium production processes, it is necessary to carry out the NLO QCD correction to $e^+e^- \rightarrow J/\psi + gg$, and give a prediction for $R_{c\bar{c}}$ at NLO in α_s.

Note that, at the end of our study, Belle reported a new (preliminary) measurement with higher statistics[*]:

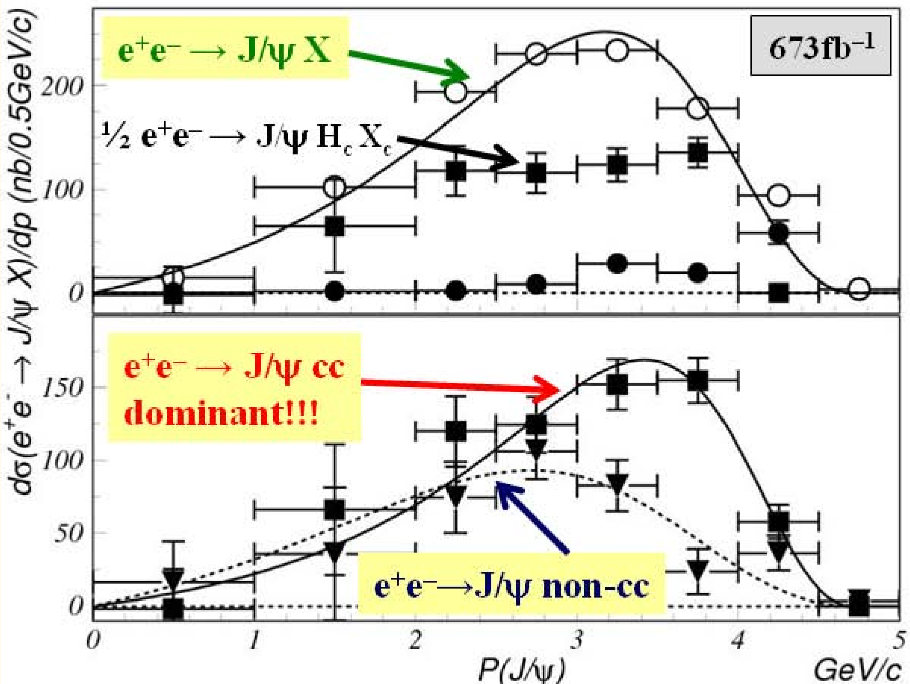
$$\sigma(e^+e^- \to J/\psi + c\bar{c}) = (0.74 \pm 0.08^{+0.09}_{-0.08})\, pb, \tag{4}$$

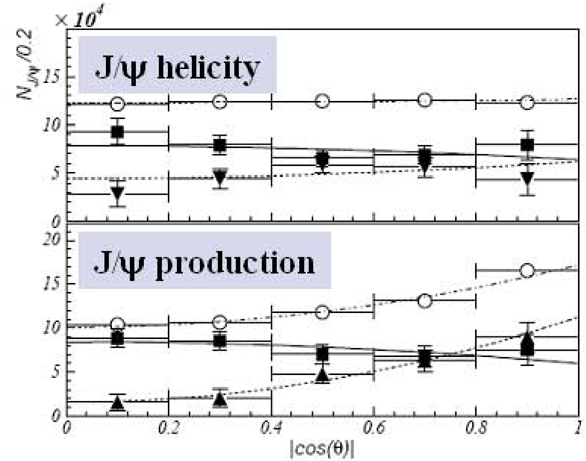
$$\sigma(e^+e^- \to J/\psi + non(c\bar{c})) = (0.43 \pm 0.09 \pm 0.09)\, pb. \tag{5}$$

which give the cross section of $\sigma(e^+e^- \to J/\psi + non(c\bar{c}))$ for the first time. It also should be interpreted in theoretics.

[*] P. Pakhlov, talk given at the International Workshop on Heavy Quarkonium 2008, Nara, Japan, Dec.2-5, 2008.

$e^+e^- \to J/\psi$ cc and non-cc cross sections





preliminary

Model independent full cross sections

$\sigma(e^+e^- \to J/\psi\ cc)$,pb	$0.74 \pm 0.08^{+0.09}_{-0.08}$
$\sigma(e^+e^- \to J/\psi$ non-cc), pb	$0.43 \pm 0.09 \pm 0.09$

No correction on for Nch requirement!

J/ψ from cascade decays included!

Perturbative QCD (no relativisitc corrections):

Kiselev et al. (1995)

$\sigma(e^+e^- \to J/\psi cc) \sim 0.05$pb

Perturbative QCD:

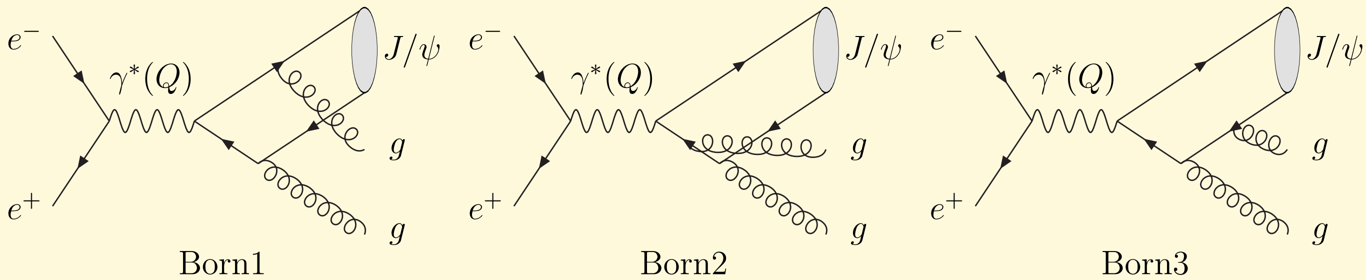
Berezhnoy-Likhoded (2003)

$$\frac{\sigma(e^+e^- \to J/\psi cc)}{\sigma(e^+e^- \to J/\psi gg)} \sim 0.1$$

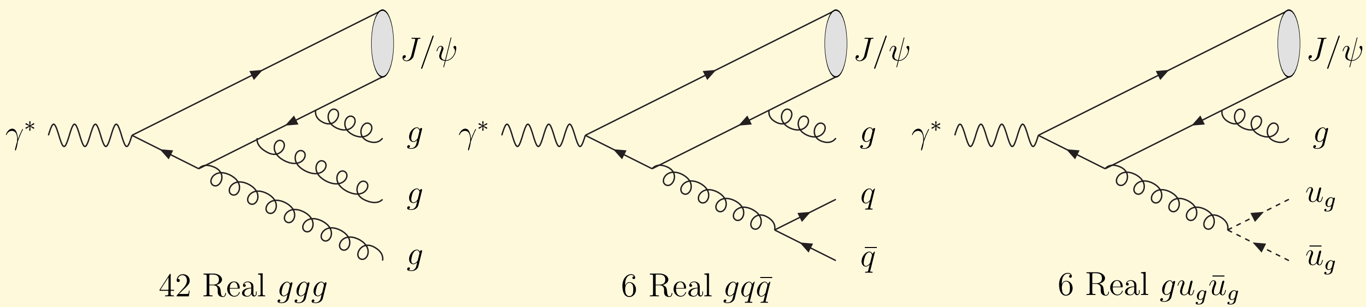
2.2. NLO Correction

The production amplitude:

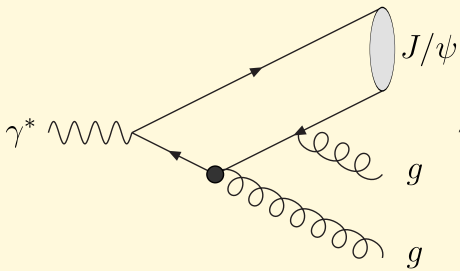
$$
\begin{aligned}
&\mathcal{A}(a+b\to Q\bar{Q}(^{2S_\psi+1}L_{J_\psi})(2p_1)+g(k_3)+g(k_4)\\
&\quad=\sqrt{C_{L_\psi}}\sum_{L_{\psi z}S_{\psi z}}\sum_{s_1,s_2}\sum_{jk,il}\\
&\quad\quad\times\langle s_1;s_2|S_\psi S_{\psi z}\rangle\langle L_\psi L_{\psi z};S_\psi S_{\psi z}|J_\psi J_{\psi z}\rangle\langle 3j;\bar{3}k|1\rangle\\
&\quad\quad\times\mathcal{A}(a+b\to Q_j(p_1)+\bar{Q}_k(p_1)+g(k_3)+g(k_4))
\end{aligned} \tag{6}
$$



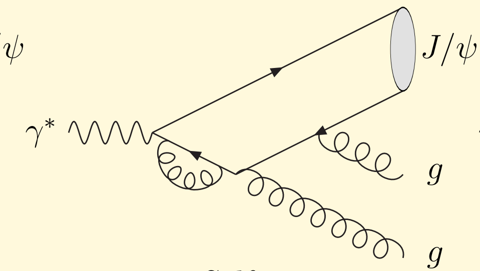
Half LO Feynman diagrams for $e^-(k_1)e^+(k_2) \rightarrow J/\psi(2p_1) + g(k_3) + g(k_4)$**.**



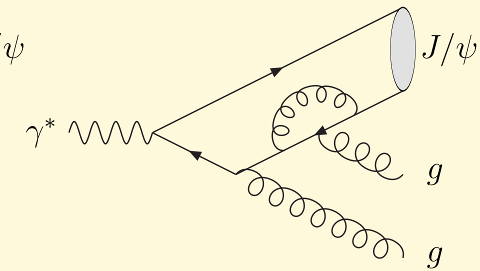
54 real Feynman diagrams for $e^-e^+ \rightarrow J/\psi gg$**.**



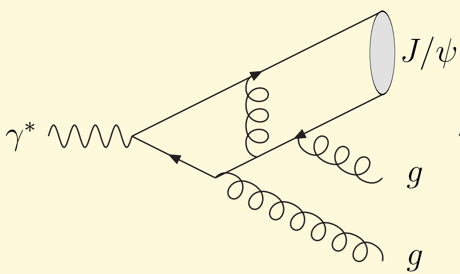
30 Counter Term



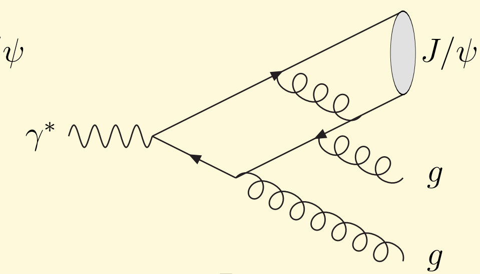
12 Self Energy



30 Vertex



27 Box



12 Pentagon

111 virtual Feynman diagrams for $e^-e^+ \to J/\psi gg$.

编程计算

UV-divergences from self-energy and triangle diagrams are removed by renormalization. Renormalization constants are defined as:

$$\begin{aligned}
\delta Z_m^{OS} &= -3C_F \frac{\alpha_s}{4\pi} N_\epsilon \left[\frac{1}{\epsilon_{UV}} + \frac{4}{3} \right], \\
\delta Z_2^{OS} &= -C_F \frac{\alpha_s}{4\pi} N_\epsilon \left[\frac{1}{\epsilon_{UV}} + \frac{2}{\epsilon_{IR}} + 4 \right], \\
\delta Z_3^{OS} &= \frac{\alpha_s}{4\pi} N_\epsilon \left[(\beta_0(n_{lf}) - 2C_A)(\frac{1}{\epsilon_{UV}} - \frac{1}{\epsilon_{IR}}) - \frac{1}{2\epsilon_{UV}} \right], \\
\delta Z_g^{\overline{MS}} &= -\frac{\beta_0(n_f)}{2} \frac{\alpha_s}{4\pi} N_\epsilon \left[\frac{1}{\epsilon_{UV}} + \ln \frac{m^2}{\mu^2} \right],
\end{aligned} \tag{7}$$

where $N_\epsilon = \left(\frac{4\pi\mu^2}{m^2}\right)^\epsilon \Gamma(1+\epsilon)$ is a overall factor in our calculation, $\beta_0(n_f) = \frac{11}{3}C_A - \frac{4}{3}T_F n_f$ is the one-loop coefficient of the QCD beta function, $n_f = 4$ is the number of active quark flavors, $n_{lf} = 3$ is the number of light quark flavors, and μ is the renormalization scale.

- Soft and collinear singularity coming from loop-integration and phase space integration of real correction cancel each other.
- We use the method in [*] to separate the soft and collinear singularities in the virtual corrections, and use phase space slicing method[**] to extract poles in real correction, then treat the singular parts analytically while the finite part numerically.

[*] S. Dittmaier, Nucl. Phys. B **675**, 447 (2003);
[**] B. W. Harris and J. F. Owens, Phys. Rev. D **65**, 094032 (2002).

When we separate the soft singularity, the Coulomb singularity three-point function also appears

$$C_0[m^2, 4m^2, m^2, 0, m^2, m^2] = \frac{1}{2m^2} N_\epsilon \left[-\frac{1}{\epsilon_{IR}} + 2 \right], \tag{8}$$

where the Coulomb pole will be mapped into the wave function of J/ψ.

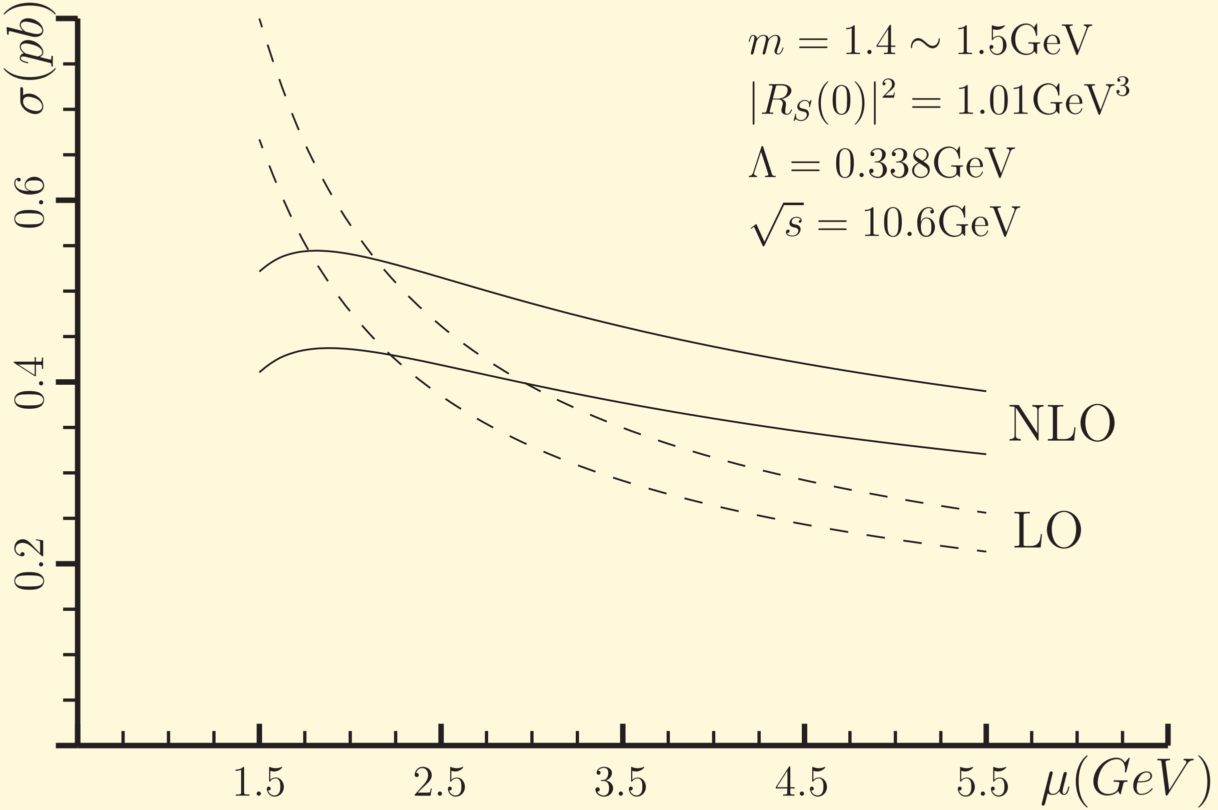
3 Conclusion and discussion

Input parameters: $|R_{J/\psi}(0)|^2 = 1.01 \text{ GeV}^3$, $m = 1.4 \text{ GeV}$, $m_{J/\psi} = 2m$, $\Lambda^{(4)}_{\overline{MS}} = 338 \text{ MeV}$. Then $\alpha_s(\mu) = 0.267$ for $\mu = 2m$, and the cross section at NLO in α_s is

$$\sigma(e^+e^- \to J/\psi gg) = 0.498 \text{ pb}, \tag{9}$$

which is a factor of 1.19 larger then the LO cross section 0.418 pb.

We see the NLO QCD correction improves the renormalization scale μ dependence substantially.



$\sigma[e^+e^- \to J/\psi gg]$ **as functions of renormalization scale** μ **at LO and NLO in** α_s**.**

- In contrast with $\sigma(e^+e^- \to J/\psi c\bar{c})$ at NLO in α_s [*], where correction is much larger
(K factor=1.8 for $m = 1.4$ GeV and $\mu = 2m$).

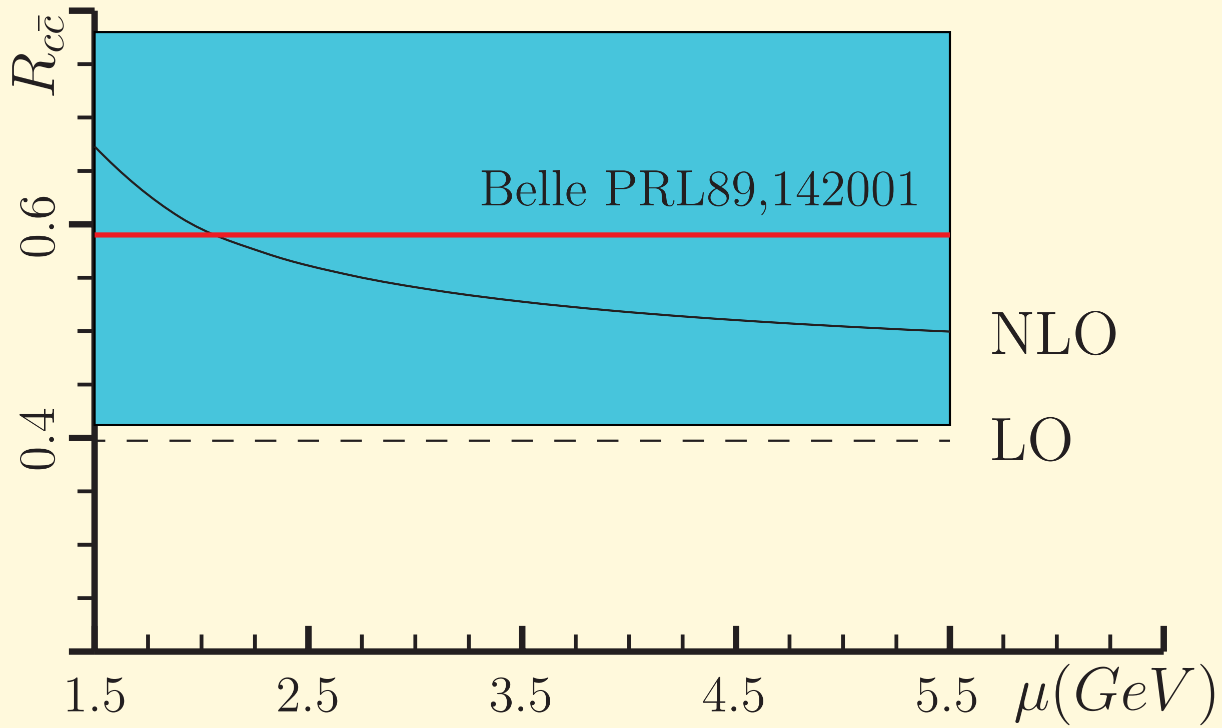
$\Longrightarrow R_{c\bar{c}}$ is 0.491 at NLO and 0.397 at LO.

- The contribution of $\psi(2S)$ decay into J/ψ should be included. It enhance the cross section by a factor 0.355[*].

[*] Y. J. Zhang and K. T. Chao, Phys. Rev. Lett. **98**, 092003 (2007).

- If we select $m = 1.4$ GeV and $\mu = 2m$, the prompt production cross section of $\sigma(e^+e^- \to J/\psi gg)$ is 0.68 pb at NLO in α_s and 0.57 pb at LO.
- The prompt production cross section of $\sigma(e^+e^- \to J/\psi c\bar{c})$ is given in Ref.[*], which is 0.70 pb at NLO and 0.43 pb at LO (color octet contributions is excluded).
- Then we give $R_{c\bar{c}} = 0.51$ at NLO and $R_{c\bar{c}} = 0.43$ at LO.

The LO $R_{c\bar{c}}$ is fix at 0.397 and much lower than the experiment data. The NLO QCD corrections can enhance $R_{c\bar{c}}$ to the band of the experiment data.



$R_{c\bar{c}}$ as functions of renormalization scale μ at LO and NLO in α_s. Here we choose $m_c = 1.4$ GeV.

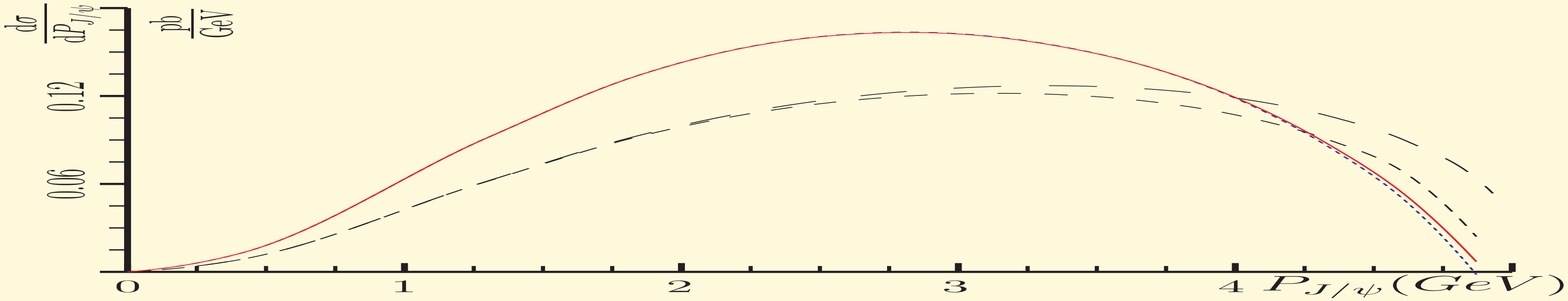
Compare with the newest data:

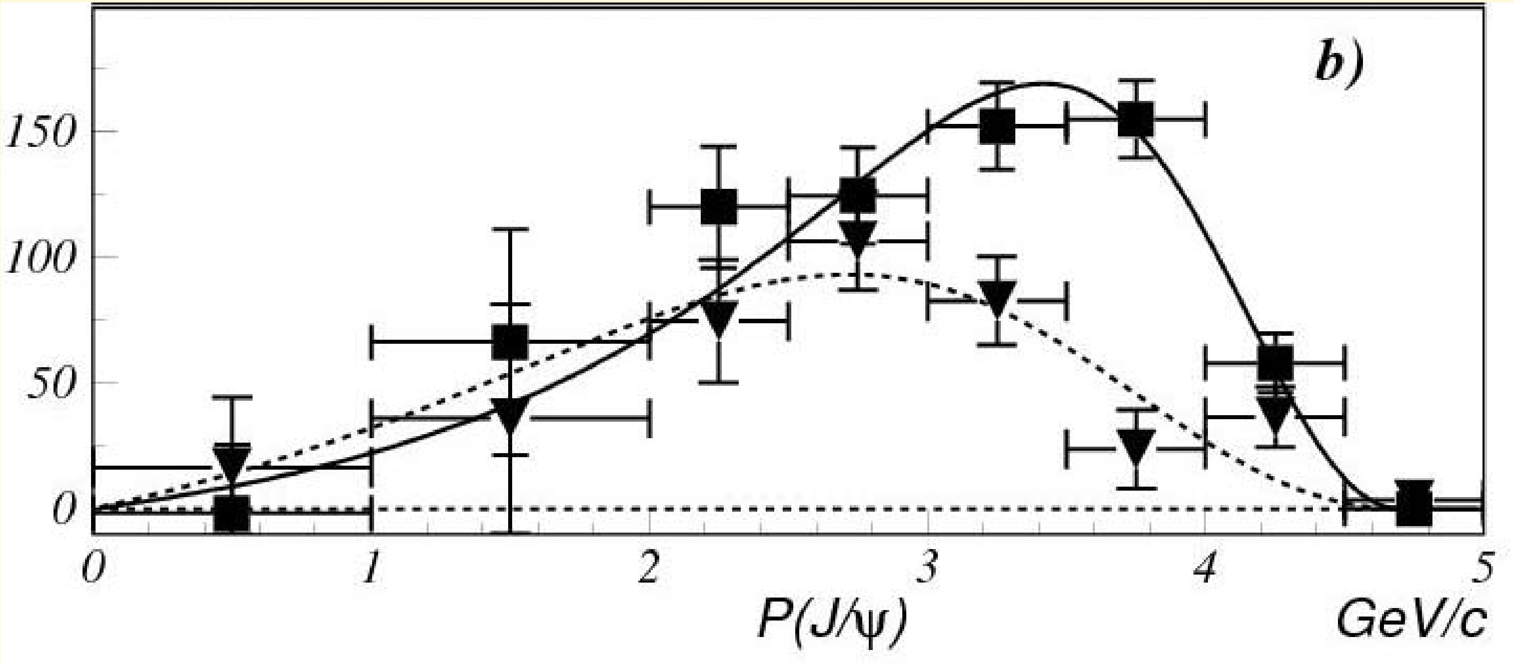
- With a smaller $|R_{J/\psi}(0)|^2 = 0.810\text{GeV}^3$ and $m = (1.4 \pm 0.1)\text{GeV}$, the predictions become $(0.54^{-0.11}_{+0.14})$ pb for $\mu = 2m$ and $(0.43^{-0.08}_{+0.09})$ pb for $\mu = \sqrt{s}/2$.
- Comparing with Belle data:

$$\sigma(e^+e^- \to J/\psi + non(c\bar{c})) = (0.43 \pm 0.09 \pm 0.09)\ pb. \tag{10}$$

- Our predictions (NLO with feeddown) for $\sigma(e^+e^- \to J/\psi + gg)$ are consistent with the new measurement of $\sigma(e^+e^- \to J/\psi + non(c\bar{c}))$ within certain uncertainties.
- Differential cross sections are shown following:

The differential cross section.





- We find that, although NLO correction to total cross section is small(about 0.2), it changes the differential cross section a lot which makes the theoretic calculation more consistent with the experiment data.
- Because the NLO correction is small, we have confidence that the NNLO and higher order correction will be even smaller, and the calculation to $e^+e^- \to J/\psi + gg$ is accurate enough.
- Both from total cross section and differential cross section, we find that, $e^+e^- \to J/\psi + gg$ might have already saturated the observed $e^+e^- \to J/\psi + non(c\bar{c})$.
- Conclusion: leaving no much room for the color-octet contributions.
- Especially, NLO to $e^+e^- \to J/\psi + g$ has considered in[*], which gives a K factor of 1.7. Thus, color octet matrix elements in production maybe much smaller than they were expected before.

[*] Yu-Jie Zhang, Yan-Qing Ma, Kuang-Ta Chao, To be submitted.

发光点

Thanks!

科研心得

- 合理选择课题
- 充分利用资源
- 全面呈现成果

合理选择课题

- ⋆ 一个人每天读什么样水平的文章，就决定了他能做什么样水平的文章;
- ⋆ 立足于当前的热点问题——除非你有创造热点的能力;
- ⋆ 课题难度要适度，既要对自己有些挑战，又不能太为难自己;

充分利用资源

- ⋆ 计算机程序是我们这代人的科研必备基础;
- ⋆ 师兄师姐是我们初入科研时的导向灯;
- ⋆ 与人合作是我们科研成长的台阶;
- ⋆ 如果我看得更远的话，那是因为我站在巨人的肩膀上:
  要学会把别人的科研成果应用在自己的科研过程中;

全面呈现成果

- ⋆ 对自己的科研成果要诚信;
- ⋆ 向导师学习，如何发现成果的发光点;
- ⋆ 合理的组织语言，多听别人的修改意见。

相关工作：

Yu-Jie Zhang, Yan-Qing Ma, Kuang-Ta Chao, Phys. Rev. D:78, 054006, (2008).
IF:5.050 Citation:18

Yan-Qing Ma, Yu-Jie Zhang, Kuang-Ta Chao, Phys. Rev. Lett:102,162002, (2009).
IF:7.180 Citation:16

Ying Fan,Yan-Qing Ma, Kuang-Ta Chao, Phys. Rev. D:79,114009, (2009).
IF:5.050 Citation:2

Ying Fan, Zhi-Guo He,Yan-Qing Ma, Kuang-Ta Chao, Phys. Rev. D:80,014001, (2009).
IF:5.050 Citation:1

Yu-Jie Zhang,Yan-Qing Ma, Kai Wang, Kuang-Ta Chao, arXiv:0911.2166