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NLO Corrections to h_c, χ_{cJ} Production at B factories

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- NLO Corrections to h_c + η_c Production at B factories
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Research Status

Research at B factories

BES III at BEPC-II:

τ-charm factory: the largest sample of charmonia.

B factories (ϒ(4S)):

Belle: KEKB collier in Japan.

BaBar: PEP-II collider at SLAC in USA.

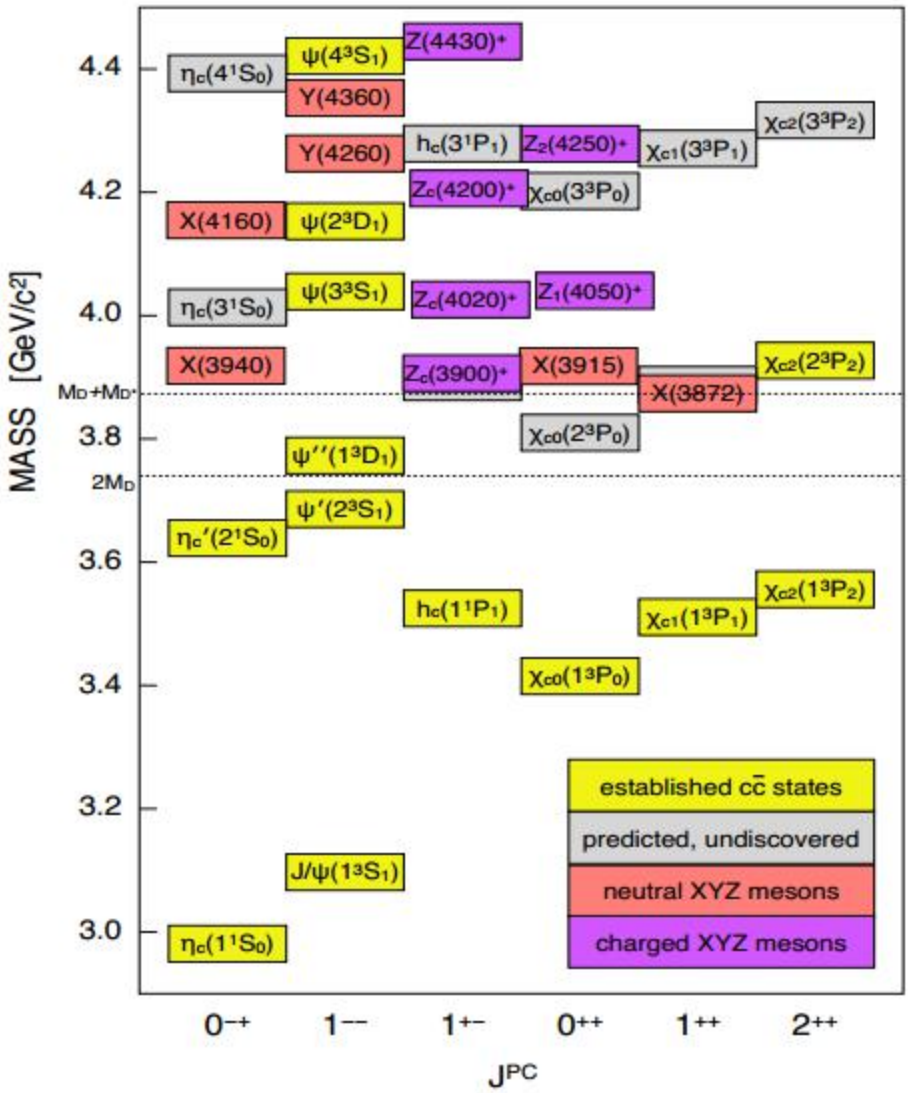
Highlights: CP violation, CKM matrix, etc.

Super B factories:

Belle II in Japan; SuperB in Italy.

↓

SuperKEKB succeeded in circulating and storing positron/electron beams in the rings in Feb., 2016.



S. L. Olsen, 2015.

Research Status

Research at B factories

1. Double Charmonium Problem

Experiments:

Belle, 2002/2004; BaBar, 2005.

$$\sigma[e^+e^- \to J/\psi + c\bar{c} + X] = 0.87^{+0.21}_{-0.19} \pm 0.17\, pb.$$

$$\sigma[J/\psi + \eta_c] \times B^{\eta_c}[>2] = 25.6 \pm 2.8 \pm 3.4\, fb,$$

$$\sigma[J/\psi + \eta_c] \times B^{\eta_c}[>2] = 17.6 \pm 2.8^{+0.5}_{-2.1}\, fb.$$

LO (inclusive processes) **~0.171 pb**

V. V. Kiselev, A. K. Likhoded and M. V. Shevlyagin, 94;

P. L. Cho and A. K. Leibovich, 96;

F. Yuan, C. F. Qiao and K. T. Chao, 97/97;

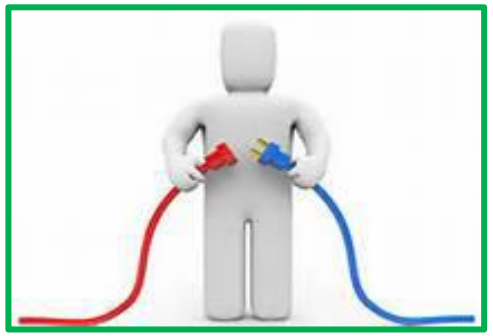
K. Y. Liu, Z. G. He and K. T. Chao, 96/97.

LO (exclusive processes) **~(2.3-5.5) fb**

E. Braaten and J. Lee, 03;

K. Hagiwara, E. Kou and C. F. Qiao, 03;

K. Y. Liu, Z. G. He and K. T. Chao, 03.



NLO corrections:

Y. J. Zhang, Y. J. Gao and K. T. Chao, 06;

Y. J. Zhang and K. T. Chao, 07;

B. Gong and J. X. Wang, 08/09;

H. R. Dong, F. Feng and Y. Jia, 12.

Research Status

Research at B factories

2. Other Double Charmonia Processes

Exclusive:

$$e^+e^- \to H_1 + H_2 \ at\ LO,$$

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

NLO correction:

$$e^+e^- \to \gamma^* \to \eta_c(1^1S_0) + h_c(1^1P_1)/\psi_{1,2}(1^3D_{1,2})$$

L. B. Chen, J. Jiang and C. F. Qiao, Chin. Phys. C39 (2015) 103101.

Inclusive:

$$e^+e^- \to \eta_c + c\bar{c} \ at\ LO,$$

$$e^+e^- \to \chi_{cJ} + c\bar{c} \ at\ LO.$$

NLO correction:

$$e^+e^- \to \gamma^* \to \chi_{cJ}(^3P_J^{[1]}, ^3S_1^{[8]}) + c\bar{c}(gg, q\bar{q}) + X, (J = 0,1,2; q = u,d,s).$$

L. B. Chen, J. Jiang and C. F. Qiao, Phys. Rev. D91 (2015) 094031.

L. K. Hao, K. Y. Liu and K. T. Chao, 02; E. Braaten and J. Lee, 03; K. Y. Liu, Z. G. He and K. T. Chao, 08.

K. Wang, Y. Q. Ma and K. T. Chao, 11; H. R. Dong, F. Feng and Y. Jia, 11.

Y. Jia, W. L. Sang and J. Xu, 12; J. X. Wang and H. F. Zhang, 12.

K. Y. Liu, Z. G. He, and K. T. Chao, 03.

Research Status

Motivation

NLO corrections to

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

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

are huge.

How are NLO corrections to

$$e^+e^- \to h_c(1^1P_1) + \eta_c,$$

$$e^+e^- \to \chi_{cJ}(^3P_J^{[1]}, {}^3S_1^{[8]}) + c\bar{c}(gg, q\bar{q}) + X.$$

going?

$\eta_c(1^1S_0, J^{PC} = 0^{-+}), m = 2983.7MeV, \Gamma = 32.0MeV.$ Crystal Ball NaI(Tl) detector at SPEAR (1980).

$h_c(1^1P_1, J^{PC} = 1^{+-}), m = 3525.38MeV, \Gamma = 0.7MeV.$

E760 experiment at Fermi Lab (1992).

$\chi_{cJ}(1^3P_J, J^{PC} = J^{+-}; J = 0,1,2).$

χ_{c1}: DASP detector at DESY DORIS (1975.7).

SLAC-LBL magnetic detector at SPEAR (1975.9).

$\psi'(3684) \to J/\psi + \gamma + \gamma$

NLO Corrections to $h_c + \eta_c$ Production

- Cross Sections & Uncertainties

L. B. Chen, J. Jiang and C. F. Qiao, Chin. Phys. C39 (2015) 103101.

Table 1. Cross sections $\sigma(\mu)$(fb) of $e^+e^- \to \eta_c + h_c(1P)$ at leading order and next-to-leading order at $\mu=2m_c$ and $\sqrt{s}/2$. The errors are induced by $m_c=1.7\pm0.2$ GeV.

$e^+e^- \to \eta_c + h_c(1P)$			
$\sigma(\mu)$/fb	LO	NLO	K-factor
$\mu=2m_c$	$0.278^{-0.143}_{+0.315}$	$0.331^{-0.154}_{+0.309}$	$1.19^{+0.12}_{-0.11}$
$\mu=\sqrt{s}/2$	$0.207^{-0.107}_{+0.235}$	$0.291^{-0.139}_{+0.287}$	$1.40^{+0.11}_{-0.10}$

Conclusions:

$\mu\uparrow, \sigma_{LO,NLO}\downarrow;$

$\mu\uparrow, K=\sigma_{NLO}/\sigma_{LO}\uparrow.$

When NLO corrections are taken into account, uncertainties induced by varying m_c and scale are depressed.

NLO Corrections to $h_c + \eta_c$ Production

- Cross Sections & Uncertainties

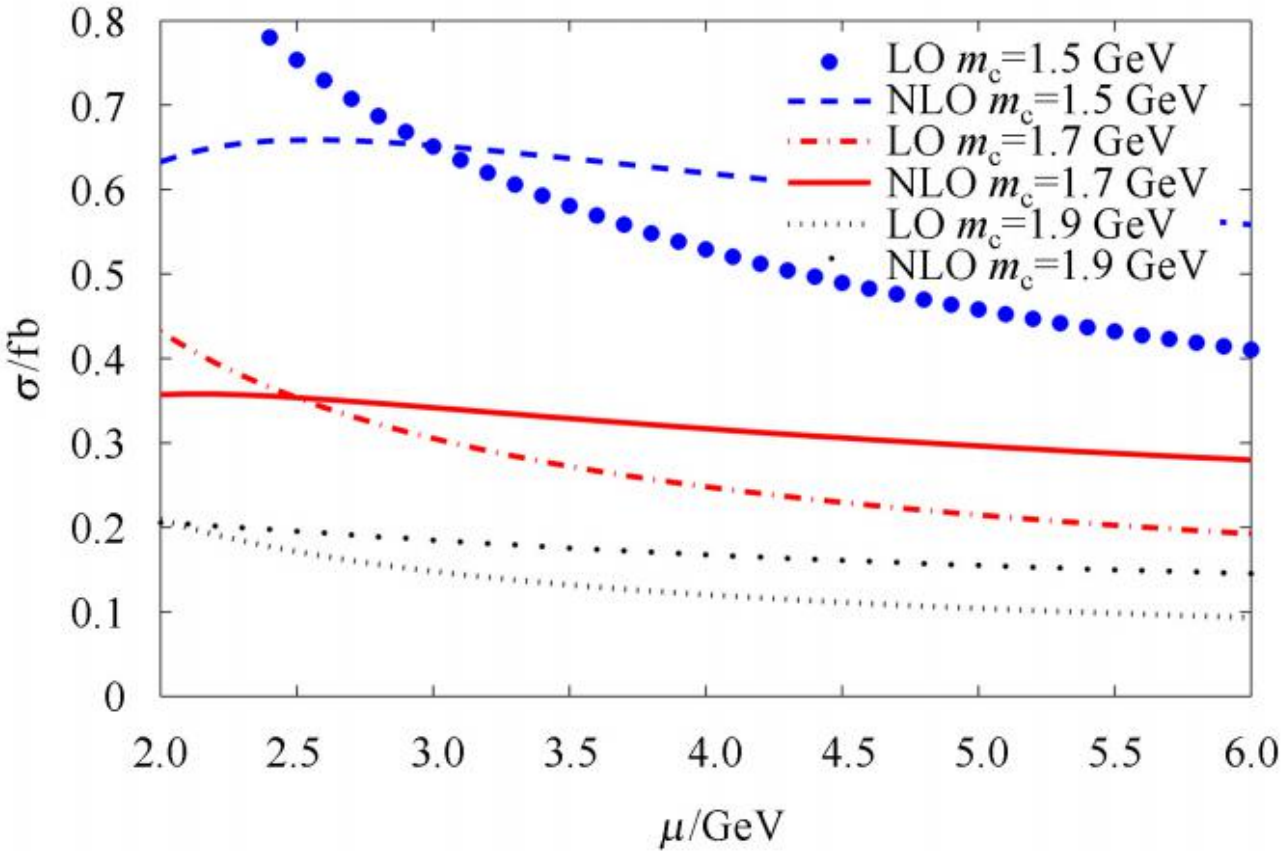


Fig. 2. (color online) LO and NLO cross sections with different m_c versus running scale μ for $e^+e^- \to \eta_c + h_c(1P)$.

NLO Corrections to $h_c + \eta_c$ Production

- Running with the Center-of-mass Energy

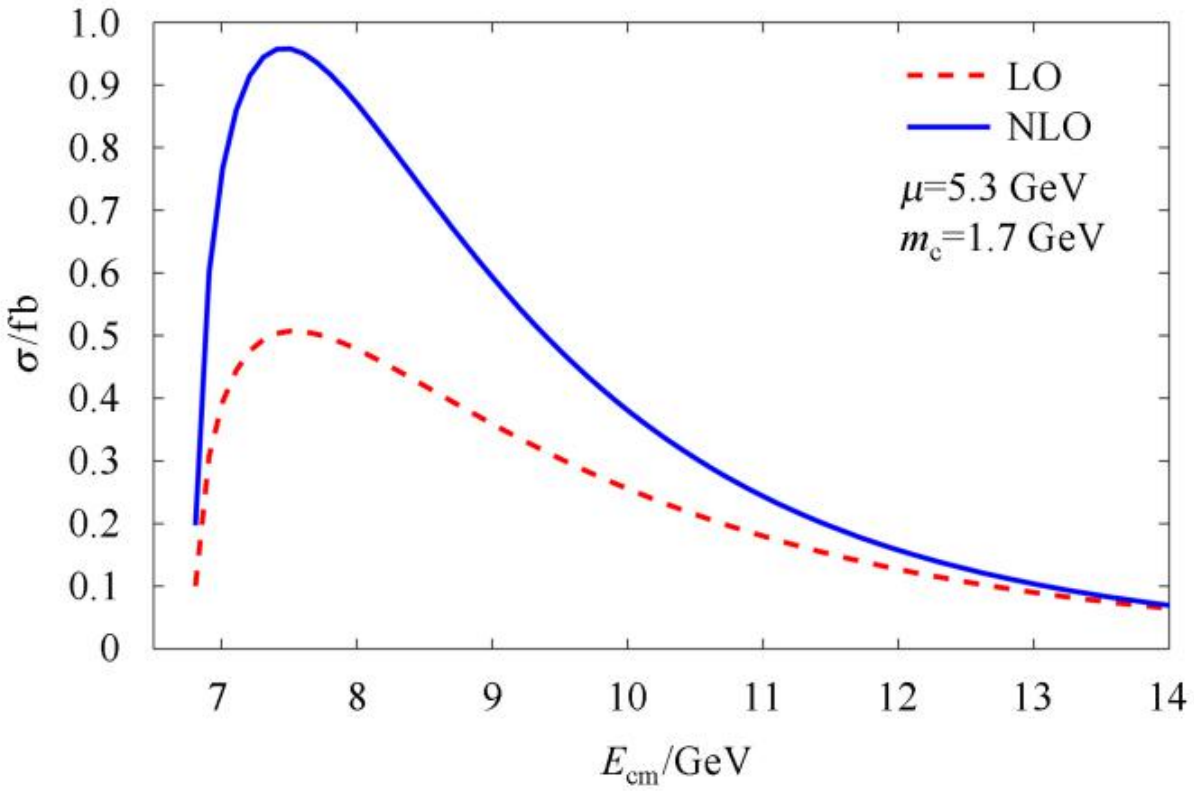


Fig. 5. (color online) LO and NLO cross sections versus running energy of center-of-mass (E_{cm}) for $e^+e^- \to \eta_c + h_c(1P)$ with $m_c = 1.7$ GeV at $\mu = 5.3$ GeV.

Note:
NRQCD factorization holds only when E_{cm} is much larger than m_c.

G. T. Bodwin, X. Garcia i Tormo, J. Lee, 2008; G. C. Nayak , J.-W. Qiu, G. F. Sterman, 2007.

NLO Corrections to $h_c + \eta_c$ Production

Experimental Detection

Belle II at SuperKEKB:

"nano-beam large-angle crossing collision scheme"
the **beam size** will be reduced to **1/20th** of that of KEKB,
the stored **beam current** will be increased to **twice** of that of KEKB.
Luminosity would be 8.4×10^{35} cm^{-2}s^{-1}.

$$R_c = \frac{\sigma[e^+e^- \to h_c + \eta_c]}{\sigma[e^+e^- \to J/\psi + \eta_c]}$$

$$\approx 0.02 \; at \; NLO \; accuracy.$$

$h_c(1P)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$J/\psi(1S)\pi^0$		
Γ_2	$J/\psi(1S)\pi\pi$	not seen	
Γ_3	$p\overline{p}$	$< 1.5 \times 10^{-4}$	90%
Γ_4	$\eta_c(1S)\gamma$	(51 ± 6) %	
Γ_5	$\pi^+\pi^-\pi^0$	$< 2.2 \times 10^{-3}$	
Γ_6	$2\pi^+2\pi^-\pi^0$	$(2.2^{+0.8}_{-0.7})$ %	
Γ_7	$3\pi^+3\pi^-\pi^0$	< 2.9 %	

NLO Corrections to $\psi_{1,2}$ + η_c Production

L. B. Chen, J. Jiang and C. F. Qiao, Chin. Phys. C39 (2015) 103101.

- $\psi_{1,2}$+ η_c Production

$$\psi_1(1^3D_1, J^{PC}=1^{--}) = \psi(3770), m = 3773.15MeV, \Gamma = 27.2MeV$$

$$\psi_2(1^3D_2, J^{PC}=2^{--})$$

ψ(3770): SLAC-LBL magnetic detector at SPEAR (1977).

ψ_2: ψ(3836) by E750 experiment at Fermi Lab (1994, 2.6σ);

ψ(3823) by Belle (2013, 3.8σ) and BES III (2015, 6.2σ).

$e^+e^- \to \eta_c + \psi_1(1D)$			
$\sigma(\mu)$/fb	LO	NLO	K-factor
$\mu=2m_c$	$0.217^{-0.124}_{+0.273}$	$0.129^{-0.078}_{+0.181}$	$0.596^{-0.046}_{+0.038}$
$\mu=\sqrt{s}/2$	$0.162^{-0.093}_{+0.203}$	$0.144^{-0.085}_{+0.193}$	$0.890^{-0.039}_{+0.033}$

$e^+e^- \to \eta_c + \psi_2(1D)$			
$\sigma(\mu)$(fb)	LO	NLO	K-factor
$\mu=2m_c$	$0.869^{-0.520}_{+1.247}$	$0.605^{-0.341}_{+0.678}$	$0.696^{+0.058}_{-0.090}$
$\mu=\sqrt{s}/2$	$0.648^{-0.388}_{+0.929}$	$0.632^{-0.365}_{+0.785}$	$0.976^{+0.050}_{-0.077}$

NLO Corrections to χ_{cJ} Inclusive Production

L. B. Chen, J. Jiang and C. F. Qiao, Phys. Rev. D91 (2015) 094031.

- Cross Sections & Uncertainties

$$e^+e^- \to \gamma^* \to \chi_{cJ}(^3P_J^{[1]}, ^3S_1^{[8]}) + c\bar{c}(gg, q\bar{q}) + X, (J = 0,1,2; q = u, d, s).$$

$$\sigma_{\rm NLO} = \sigma_{\rm LO}\left(1 + \frac{\alpha_s}{\pi}\left(\frac{\beta_0}{2}\ln\left(\frac{\mu^2}{s}\right) + C\right)\right)$$

TABLE I. Cross sections of $e^+e^- \to \chi_{cJ}(^3P_J^{[1]}) + c + \bar{c} + X$ at leading order and next-to-leading order, all in units of fb, with $m_c = 1.5 \pm 0.1$ GeV, and $\mu \in \{2m_c, \sqrt{s}/2\}$.

σ(fb)	LO$\chi_{c0}^{[1]}$	NLO$\chi_{c0}^{[1]}$	LO$\chi_{c1}^{[1]}$	NLO$\chi_{c1}^{[1]}$	LO$\chi_{c2}^{[1]}$	NLO$\chi_{c2}^{[1]}$
$\mu = 2m_c$	$34.2^{+4.9}_{-4.6}$	$84.3^{+20.7}_{-12.6}$	$9.5^{+3.0}_{-2.5}$	$4.0^{+0.4}_{-0.7}$	$4.4^{+1.3}_{-1.0}$	$0.8^{+1.8}_{-0.8}$
$\mu = \sqrt{s}/2$	$23.2^{+3.3}_{-3.1}$	$58.3^{+15.5}_{-7.3}$	$6.4^{+2.1}_{-1.6}$	$5.3^{+1.3}_{-1.1}$	$3.0^{+0.8}_{-0.7}$	$1.9^{+0.6}_{-0.8}$

NLO Corrections to χ_{cJ} Inclusive Production

Cross Sections & Uncertainties

TABLE II. Cross sections of $e^+e^- \to \chi_{cJ}(^3S_1^{[8]}) + c\bar{c}(gg; q\bar{q}) + X$ at leading order and next-to-leading order, all in units of fb, with $m_c = 1.5 \pm 0.1$ GeV, and $\mu \in \{2m_c, \sqrt{s}/2\}$.

$e^+e^- \to \chi_{cJ}(^3S_1^{[8]}) + c + \bar{c} + X$

σ(fb)	LO$\chi_{c0}^{[8]}$	NLO$\chi_{c0}^{[8]}$	LO$\chi_{c1}^{[8]}$	NLO$\chi_{c1}^{[8]}$	LO$\chi_{c2}^{[8]}$	NLO$\chi_{c2}^{[8]}$
$\mu = 2m_c$	$0.60^{+0.25}_{-0.18}$	$1.47^{+0.55}_{-0.59}$	$1.80^{+0.75}_{-0.54}$	$4.41^{+1.65}_{-1.77}$	$3.00^{+1.25}_{-0.90}$	$7.35^{+2.75}_{-2.95}$
$\mu = \sqrt{s}/2$	$0.41^{+0.17}_{-0.13}$	$1.02^{+0.39}_{-0.39}$	$1.23^{+0.51}_{-0.39}$	$3.06^{+1.17}_{-1.17}$	$2.05^{+0.85}_{-0.65}$	$5.1^{+1.95}_{-1.95}$

$e^+e^- \to \chi_{cJ}(^3S_1^{[8]}) + g + g + X$

σ(fb)	LO$\chi_{c0}^{[8]}$	NLO$\chi_{c0}^{[8]}$	LO$\chi_{c1}^{[8]}$	NLO$\chi_{c1}^{[8]}$	LO$\chi_{c2}^{[8]}$	NLO$\chi_{c2}^{[8]}$
$\mu = 2m_c$	$0.65^{+0.02}_{-0.03}$	$1.31^{+0.06}_{-0.06}$	$1.95^{+0.06}_{-0.09}$	$3.93^{+0.18}_{-0.18}$	$3.25^{+0.10}_{-0.15}$	$6.55^{+0.30}_{-0.30}$
$\mu = \sqrt{s}/2$	$0.44^{+0.02}_{-0.02}$	$0.91^{+0.05}_{-0.04}$	$1.32^{+0.06}_{-0.06}$	$2.73^{+0.15}_{-0.12}$	$2.20^{+0.10}_{-0.10}$	$4.55^{+0.25}_{-0.20}$

$e^+e^- \to \chi_{cJ}(^3S_1^{[8]}) + q + \bar{q} + X$

σ(fb)	LO$\chi_{c0}^{[8]}$	NLO$\chi_{c0}^{[8]}$	LO$\chi_{c1}^{[8]}$	NLO$\chi_{c1}^{[8]}$	LO$\chi_{c2}^{[8]}$	NLO$\chi_{c2}^{[8]}$
$\mu = 2m_c$	$1.82^{+0.52}_{-0.40}$	$4.09^{+1.11}_{-0.85}$	$5.46^{+1.56}_{-1.20}$	$12.27^{+3.33}_{-2.55}$	$9.10^{+2.60}_{-2.00}$	$20.45^{+5.55}_{-4.25}$
$\mu = \sqrt{s}/2$	$1.24^{+0.35}_{-0.27}$	$2.88^{+0.79}_{-0.60}$	$3.72^{+1.05}_{-0.81}$	$8.64^{+2.37}_{-1.80}$	$6.20^{+1.75}_{-1.35}$	$14.4^{+3.95}_{-3.00}$

NLO Corrections to χ_{cJ} Inclusive Production

- Cross Sections & Uncertainties

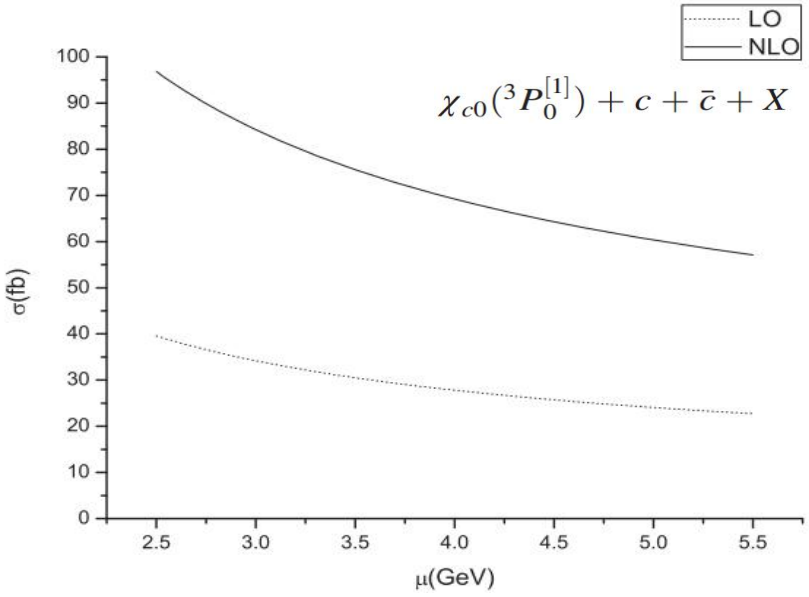
TABLE III. Cross sections for associate production of $\chi_{cJ} + c\bar{c}$ and $\chi_{cJ} + X_{\text{non}-c\bar{c}}$ at leading order and next-to-leading order, all in units of fb, with $m_c = 1.5 \pm 0.1$ GeV.

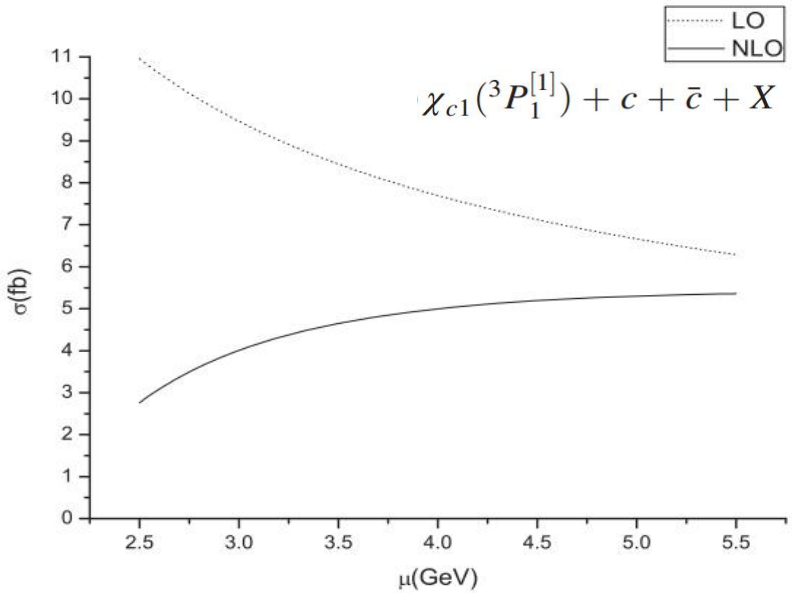
$\chi_{cJ} + c\bar{c} + X$						
σ(fb)	LOχ_{c0}	NLOχ_{c0}	LOχ_{c1}	NLOχ_{c1}	LOχ_{c2}	NLOχ_{c2}
$\mu = 2m_c$	$34.80^{+5.15}_{-4.78}$	$85.77^{+21.25}_{-13.19}$	$11.30^{+3.75}_{-3.04}$	$8.41^{+2.05}_{-2.47}$	$7.40^{+2.55}_{-1.90}$	$8.15^{+4.55}_{-3.75}$
$\mu = \sqrt{s}/2$	$23.61^{+3.47}_{-3.23}$	$59.32^{+15.89}_{-7.69}$	$7.63^{+2.61}_{-1.99}$	$8.36^{+2.47}_{-2.27}$	$5.05^{+1.65}_{-1.35}$	$7.00^{+2.55}_{-2.75}$
$\chi_{cJ} + X_{\text{non}-c\bar{c}}$						
σ(fb)	LOχ_{c0}	NLOχ_{c0}	LOχ_{c1}	NLOχ_{c1}	LOχ_{c2}	NLOχ_{c2}
$\mu = 2m_c$	$2.47^{+0.54}_{-0.43}$	$5.40^{+1.17}_{-0.91}$	$7.41^{+1.62}_{-1.29}$	$16.20^{+3.51}_{-2.73}$	$12.35^{+2.70}_{-2.15}$	$27.00^{+5.85}_{-4.55}$
$\mu = \sqrt{s}/2$	$1.68^{+0.37}_{-0.29}$	$3.79^{+0.84}_{-0.64}$	$5.04^{+1.11}_{-0.87}$	$11.37^{+2.52}_{-1.92}$	$8.40^{+1.85}_{-1.45}$	$18.95^{+4.20}_{-3.20}$

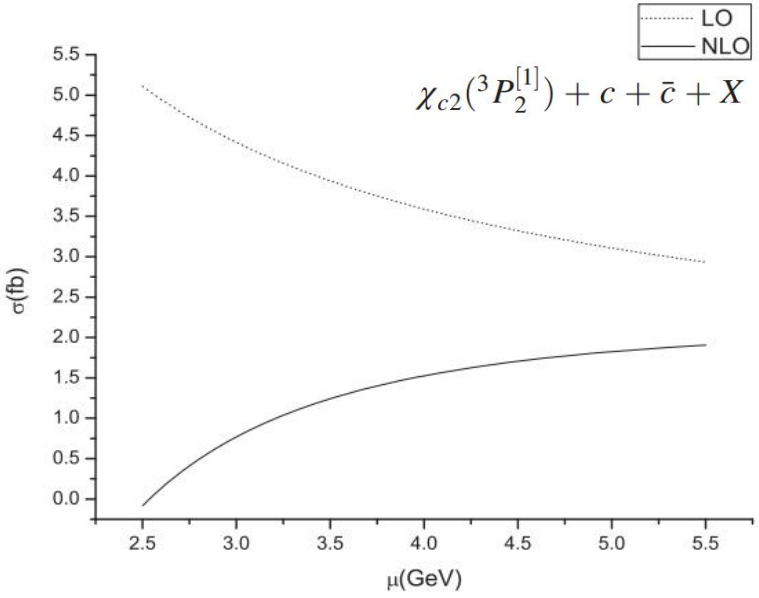
NLO Corrections to χ_{cJ} Inclusive Production

- Scale Dependence

Color-singlet:



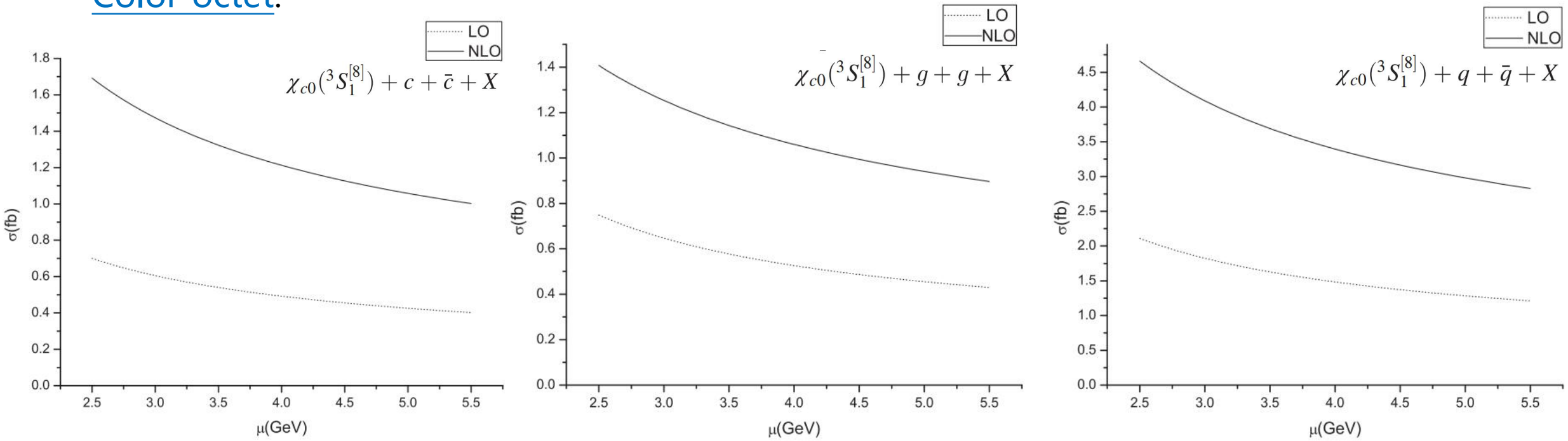




NLO Corrections to χ_{cJ} Inclusive Production

- Scale Dependence

Color-octet:



$$\sigma_{\mathrm{NLO}} = \sigma_{\mathrm{LO}}\left(1 + \frac{\alpha_s}{\pi}\left(\frac{\beta_0}{2}\ln\left(\frac{\mu^2}{s}\right) + C\right)\right)$$

NLO Corrections to χ_{cJ} Inclusive Production

- Experimental Detection

$$NLO: \sigma[e^+e^- \to \chi_{cJ} + X] = (91.17,\ 24.61,\ 35.15)\, fb\ for\ J = (0,1,2).$$

$$BaBar: \sigma^{prompt}_{N_{ch}>2}(\chi_{c1} + X) < 77\, fb,\ \sigma^{prompt}_{N_{ch}>2}(\chi_{c2} + X) < 79\, fb.$$

B. Aubert et al. (BABAR Collaboration), 2007.

$$\sigma[\chi_{cJ} + \gamma] = (1.36, 10.9, 1.95)\, fb\ for\ J = (0,1,2)\ at\ \mu = 2m_c.$$

W. L. Sang and Y. Q. Chen, 2010.

$$\sigma[\chi_{cJ} + X] \approx (90, 35, 35)\, fb\ for\ J = (0,1,2).$$

χ_{cJ} experiments at Belle II:

1. Confirmation of the huge NLO corrections to χ_{c0} inclusive production.
2. Color-octet study through the χ_{c1} and χ_{c2} channels.

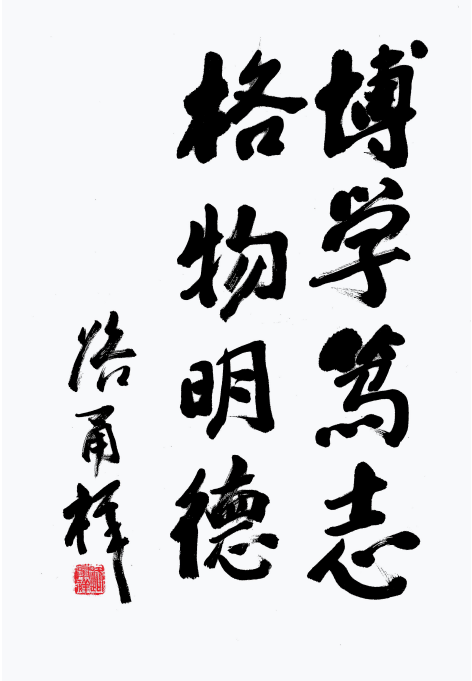
Summary & OutLook

◆NLO corrections to h_c, χ_{cJ} production in B factories

- Exclusive process: $h_c + \eta_c$
- Inclusice process: χ_{cJ} + X

1. The NLO corrections enhance $h_c + \eta_c$ cross section slightly.
2. NLO corrections to χ_{cJ} + X cross section are quite huge.
3. **Both channels are worth a try in future Belle II experiments.**

$$R_c = \frac{\sigma[e^+e^- \to h_c(\to \eta_c\gamma) + \eta_c]}{\sigma[e^+e^- \to J/\psi(\to l^+l^-) + \eta_c]}$$

σ(fb)	LO$\chi_{c0}^{[1]}$	NLO$\chi_{c0}^{[1]}$
$\mu = 2m_c$	$34.2^{+4.9}_{-4.6}$	$84.3^{+20.7}_{-12.6}$
$\mu = \sqrt{s}/2$	$23.2^{+3.3}_{-3.1}$	$58.3^{+15.5}_{-7.3}$

THANK YOU!