Production of doubly heavy-flavored hadrons at e^+e^- colliders

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Based on Xu-Chang Zheng and Chao-Hsi Chang et al,

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Outline

1. Introduction

2. Production of doubly heavy-flavored hadrons

3. NLO fragmentation functions for Bc(Bc*) production

4. Conclusions and outlook

1、Introduction

Heavy flavor hadron： A hadron containing c- or b-quark

Heavy quarkonium：$c\bar{c}$, $b\bar{b}$（J/Ψ、ϒ···）

Explicit double heavy-flavored meson： $c\bar{b}$ （B_c、B_c^*···）

Double heavy baryon：QQ'q

- Production： perturbative, non-perturbative QCD
- Decay： weak interaction

Advantages of the production at e^+e^- colliders:

- The center-of-mass system of the process is known

  Angle distributions and forward-backward asymmetry of hadrons have proper meaning in understanding the production.

- There are less backgrounds at an e^+e^- collider

  e^+e^- collider is a good platform for precision measurements.

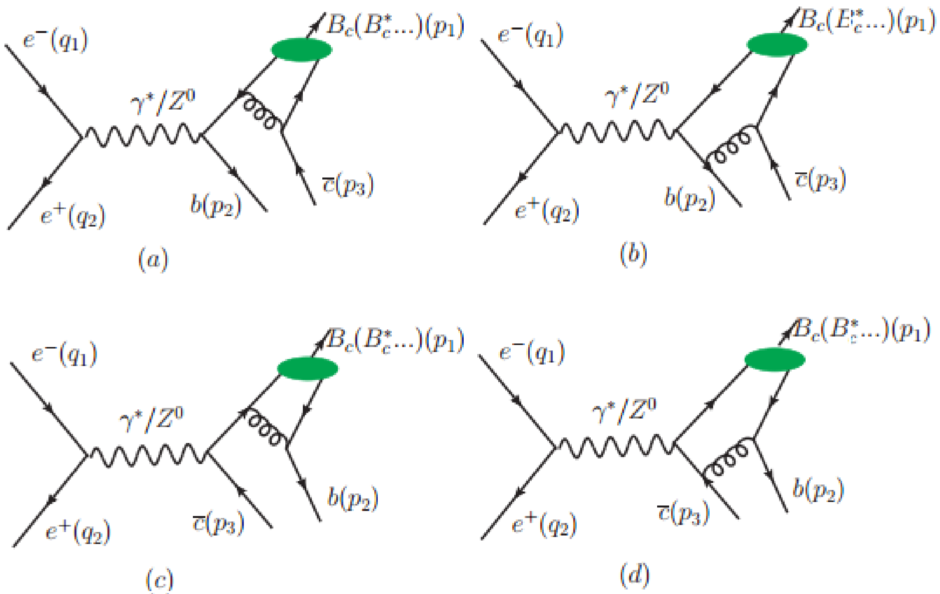
Running at Z-pole:

- Z-resonance effect

- ILC, FCC-ee,CEPC and Super Z-factory

2、Production of doubly heavy-flavored hadrons

- LO calculation



$$d\sigma(e^+ + e^- \to Bc + b + \bar{c})$$
$$= \sum_n d\hat{\sigma}(e^+ + e^- \to c\bar{b}[n] + b + \bar{c})\langle O^{Bc}(n)\rangle$$

NRQCD factorization

Numerical results

Phys. Rev. D 93, 034019, (2016), Xu-Chang Zheng, Chao-Hsi Chang et al.

contribution	total	$\bar{b}$-frag.	c-frag.	interference
$\sigma(B_c, {}^1S_0)$	2.734	2.613	5.20×10^{-2}	6.90×10^{-2}
$\sigma(B_c^*, {}^3S_1)$	3.823	3.722	4.45×10^{-2}	5.65×10^{-2}
$\sigma(B_c^{**}, {}^1P_1)$	0.271	0.269	3.01×10^{-3}	-1.01×10^{-3}
$\sigma(B_c^{**}, {}^3P_0)$	0.164	0.157	8.13×10^{-3}	-1.13×10^{-3}
$\sigma(B_c^{**}, {}^3P_1)$	0.340	0.331	5.77×10^{-3}	3.23×10^{-3}
$\sigma(B_c^{**}, {}^3P_2)$	0.365	0.366	3.87×10^{-4}	-1.39×10^{-3}

Cross section at Z pole (unit: pb)

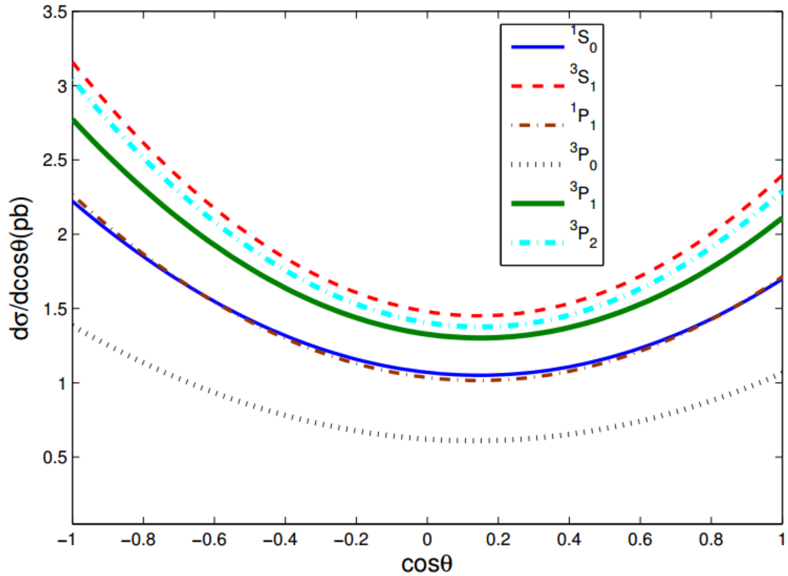
$\sqrt{s}$(GeV)	180	240
$\sigma(B_c, {}^1S_0)$	1.05	0.47
$\sigma(B_c^*, {}^3S_1)$	1.55	0.72
$\sigma(B_c^{**}, {}^1P_1)$	0.11	0.05
$\sigma(B_c^{**}, {}^3P_0)$	0.07	0.03
$\sigma(B_c^{**}, {}^3P_1)$	0.14	0.07
$\sigma(B_c^{**}, {}^3P_2)$	0.15	0.07

Cross section at other energies (unit: fb)

Contribution	Total	$\bar{b}$ frag.	c frag.
$\sigma(B_c, {}^1S_0)$	2.851	2.792	5.88×10^{-2}
$\sigma(B_c^*, {}^3S_1)$	3.974	3.923	5.08×10^{-2}
$\sigma(B_c^{**}, {}^1P_1)$	0.296	0.292	3.53×10^{-3}
$\sigma(B_c^{**}, {}^3P_0)$	0.169	0.160	9.08×10^{-3}
$\sigma(B_c^{**}, {}^3P_1)$	0.361	0.354	6.59×10^{-3}
$\sigma(B_c^{**}, {}^3P_2)$	0.395	0.395	4.74×10^{-4}

Results under fragmentation approach(unit: pb)

The luminosity of Z factory should be $10^{35\text{-}36} cm^{-2} s^{-1}$



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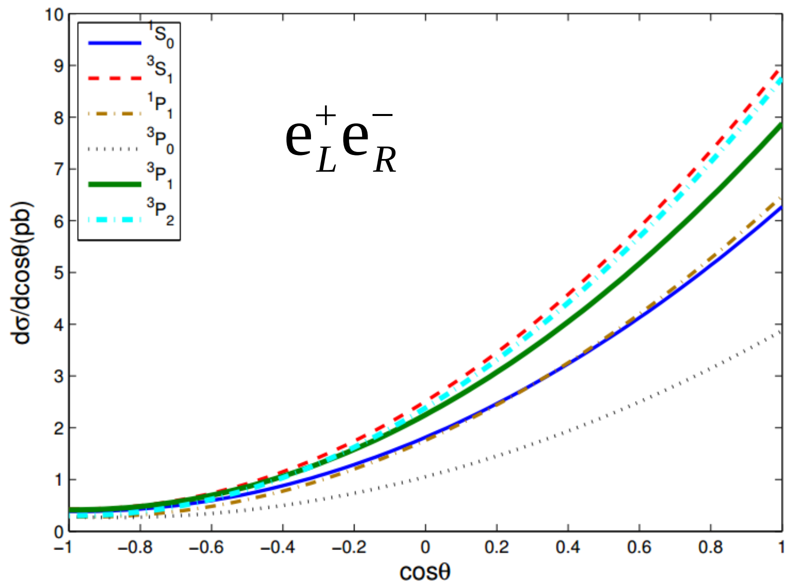
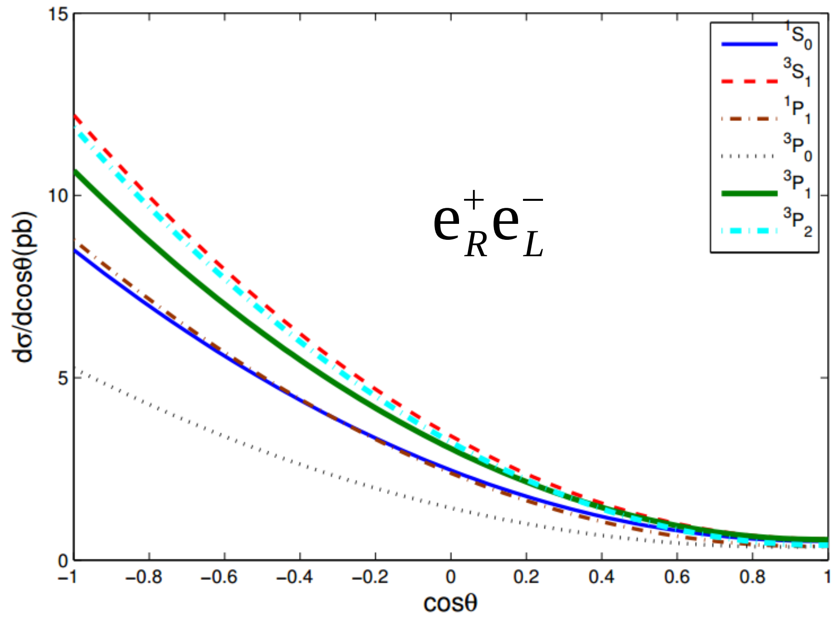
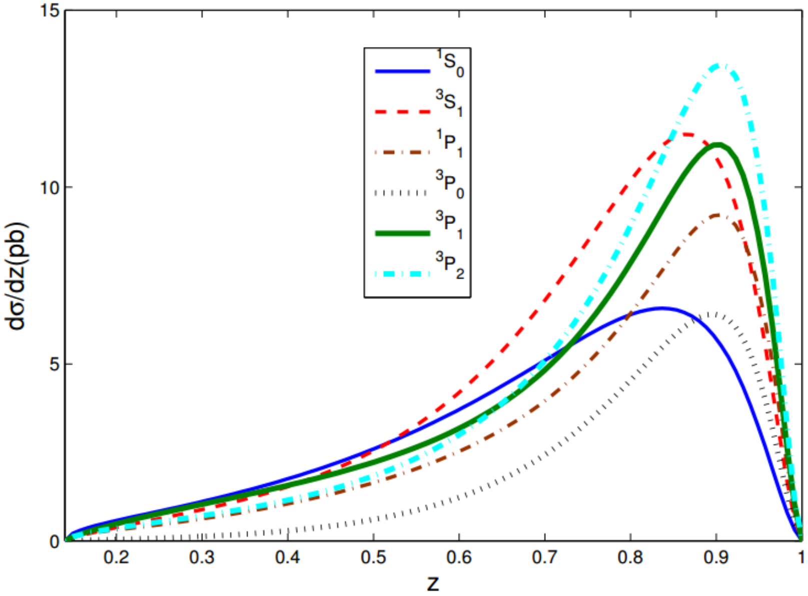




The angle distribution is forward-backward asymmetric.



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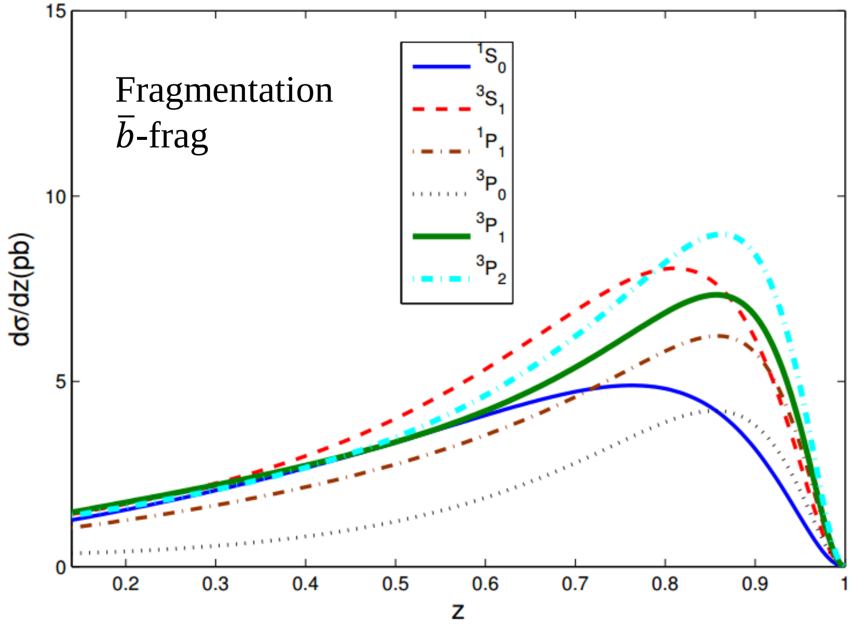
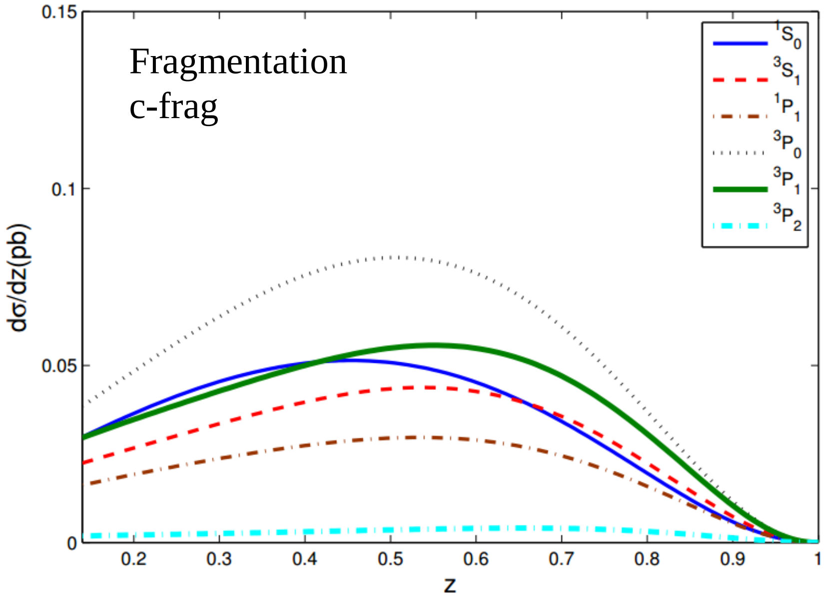
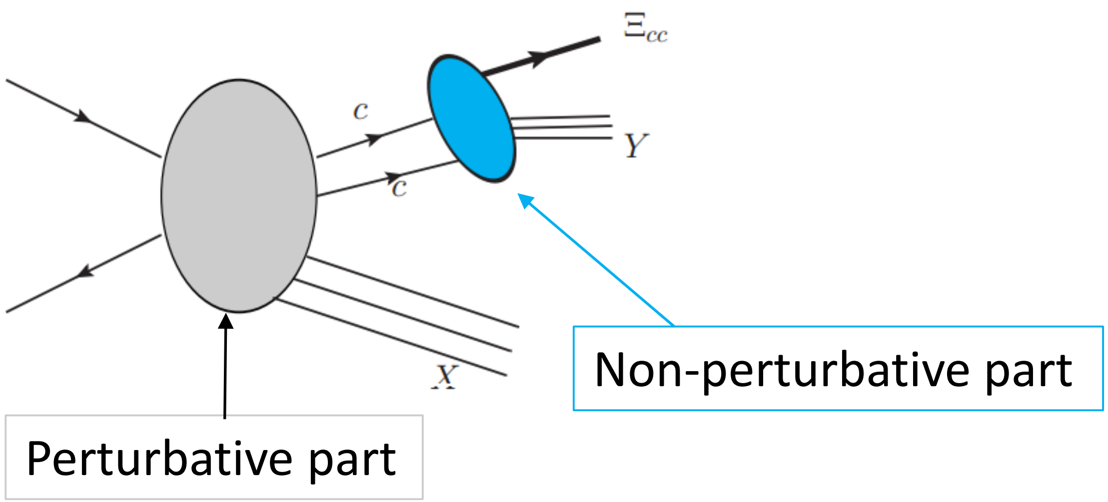




Production of doubly heavy baryons



1) Production of diquark

2) The diquark fragments into the doubly heavy baryon

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Xu-Chang Zheng, Chao-Hsi Chang et al.

Cross section:

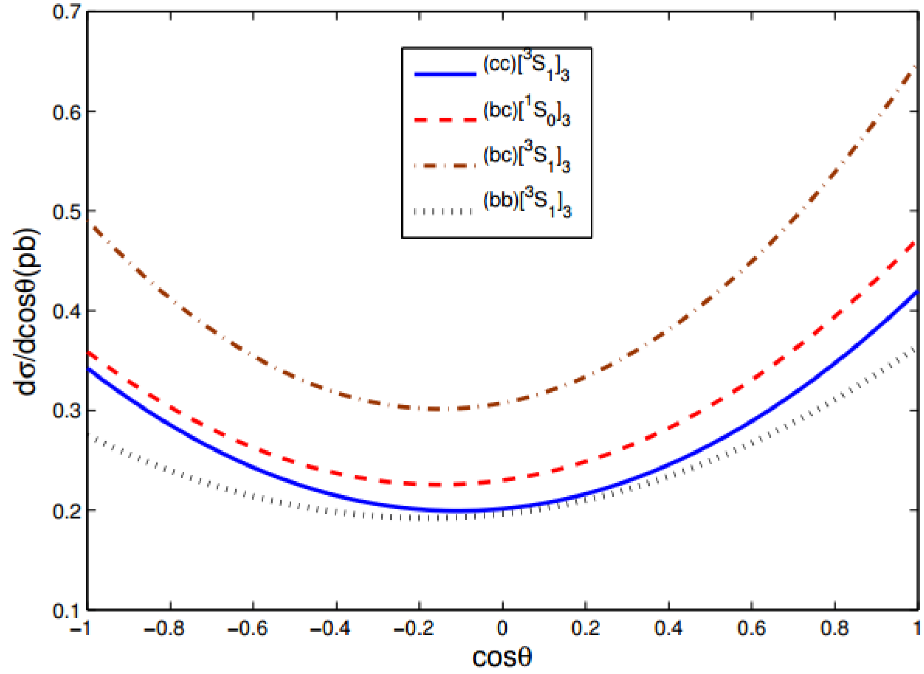
$$\sigma_{|(cc)_{\bar{3}},{}^3S_1\rangle} = 0.52 \text{ pb},$$

$$\sigma_{|(bc)_{\bar{3}},{}^1S_0\rangle} = 0.58 \text{ pb},$$

$$\sigma_{|(bc)_{\bar{3}},{}^3S_1\rangle} = 0.79 \text{ pb},$$

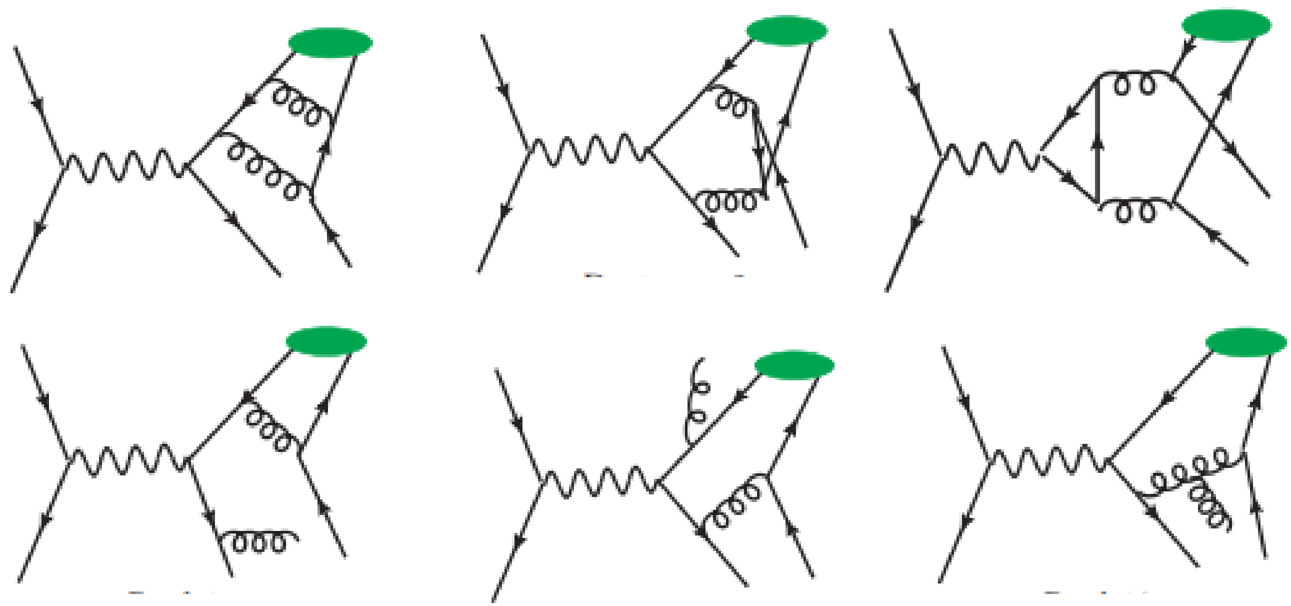
$$\sigma_{|(bb)_{\bar{3}},{}^3S_1\rangle} = 0.05 \text{ pb}.$$

Differential angle distribution



- NLO calculations for Bc and Bc*

- To see the changes of the physical observables from the LO calculations to the NLO calculations.
- To see how the dependence on the renormalization scale changes after including the NLO QCD corrections.



Calculation method

- Virtual corrections

  Passarino-Veltman tensor reduction,

  Integration-by-parts(IBP) reduction

- Real corrections

  The two-cutoff phase-space slicing method

Difficulties in the calculations:

- Two mass scales (mb,mc)
- Vecotor and axial-vector couplings

Numerical results

Sci. China-Phys.Mech. Astron. 61, 031012,(2018), Xu-Chang Zheng, Chao-Hsi Chang et al.

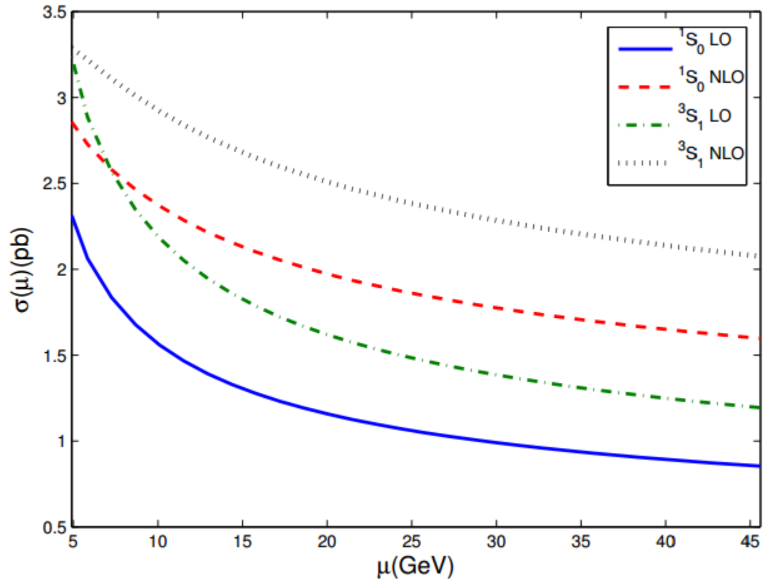
μ	$\alpha_s(\mu)$	$\sigma_{\rm LO}$(pb)	$\sigma_{\rm NLO}$(pb)	$\sigma_{\rm NLO}/\sigma_{\rm LO}$
$2m_b$	0.180	1.58	2.38	1.51
$m_z/2$	0.132	0.85	1.58	1.86

Cross section of Bc

μ	$\sigma_{\rm LO}$(pb)	$\sigma_{\rm NLO}$(pb)	$\sigma_{\rm NLO}/\sigma_{\rm LO}$
$2m_b$	2.20	2.93	1.33
$m_z/2$	1.18	2.06	1.74

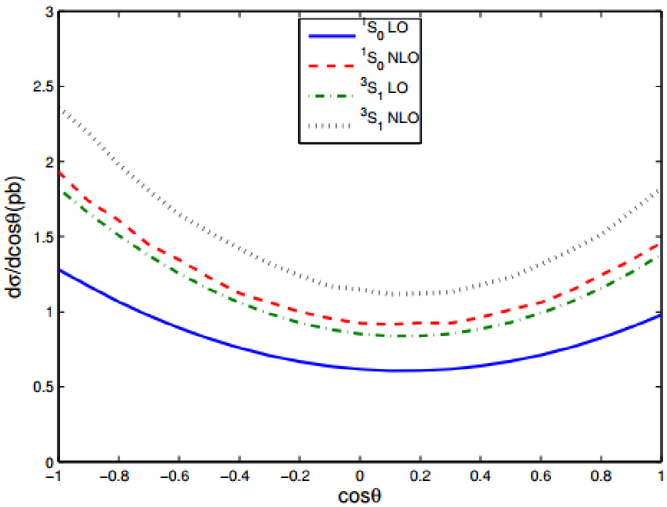
Cross section of Bc*

The NLO corrections are significant!

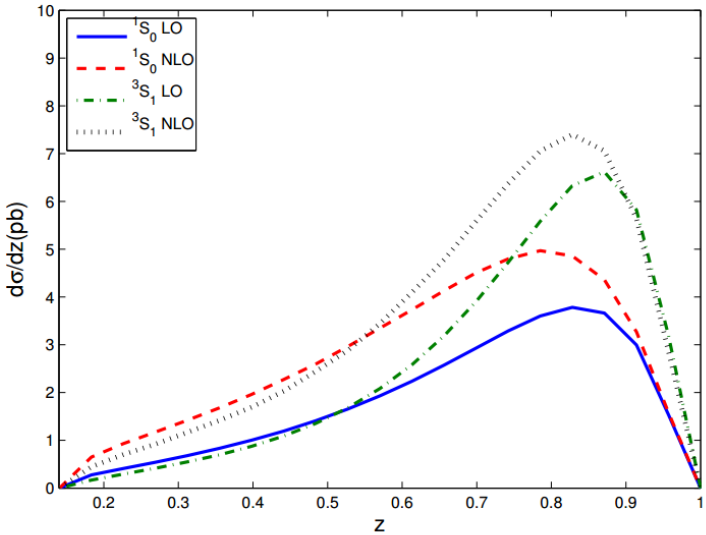


The dependence on μ is weaken significantly due to NLO corrections.

Sci. China-Phys.Mech. Astron. 61, 031012,(2018), Xu-Chang Zheng, Chao-Hsi Chang et al.



Differential angle distribution



Differential energy distribution

The K-factor changes very little with different θ;

The NLO corrections change the energy distribution significantly.

3、NLO fragmentation functions for Bc(Bc*) production

Fragmentation function approach

- NRQCD factorization

Energy scales: $\sqrt{s}, m_Q$

$$d\sigma(e^+ + e^- \to Bc + b + \bar{c})$$
$$= \sum_n d\sigma(e^+ + e^- \to (c\bar{b})[n] + b + \bar{c})\langle O^{Bc}(n)\rangle$$

Log-terms appear in short-distance coefficients:

$$\alpha_s^m \sum_{n=0}^{\infty} \alpha_s^n \ln^n(s/m_Q^2)$$

Collinear gluon emission

Broke or weak the convergence of the series

$\ln(p_t^2/m_Q^2)$ appearing in the production at a hadron collider

- Perturbative QCD factorization

Involving $\ln(s/\mu_F^2)$ $\mu_F = O(\sqrt{s})$

$$d\sigma(e^+ + e^- \to Bc(p) + b + \bar{c})$$
$$= \sum_i d\hat{\sigma}(e^+ + e^- \to i + X)(p/z, \mu_F) \otimes D_{i\to Bc}(z, \mu_F) + O(m_Q^2/s)$$

Fragmentation function

NRQCD factorization:

$$D_{i\to Bc}(z, \mu_{F0}) = \sum_n d_{i\to c\bar{b}[n]}(z, \mu_{F0}) \langle O^{Bc}(n) \rangle$$

$\mu_{F0} = O(m_Q)$

Involving $\ln(\mu_{F0}^2/m_Q^2)$

Evolution of fragmentation functions

$$\frac{d}{d\ln\mu_F^2} D_{i\to Bc}(z, \mu_F) = \sum_j P_{ij}(z/y, \ \alpha_s(\mu_F)) \otimes D_{i\to Bc}(y, \mu_F)$$

$$P_{ij}(z, \ \alpha_s(\mu_F)) = P_{ij}^{(0)}(z)\frac{\alpha_s(\mu_F)}{2\pi} + P_{ij}^{(1)}(z)\left(\frac{\alpha_s(\mu_F)}{2\pi}\right)^2 + O(\alpha_s^3)$$

Collinear log-terms have been resumed through DGLAP evolution.

- LO fragmentation function

Extracting from the LO calculation of process $Z^0 \to Bc + b + \bar{c}$

C-H. Chang, Y-Q. Chen, Phys. Rev. D 46, 3845, (1992);

Calculating from the definition:

J-P. Ma, Phys. Lett. B332, 398, (1994);

There are no NLO results for $D_{i\to Bc}(z, \mu_F)$

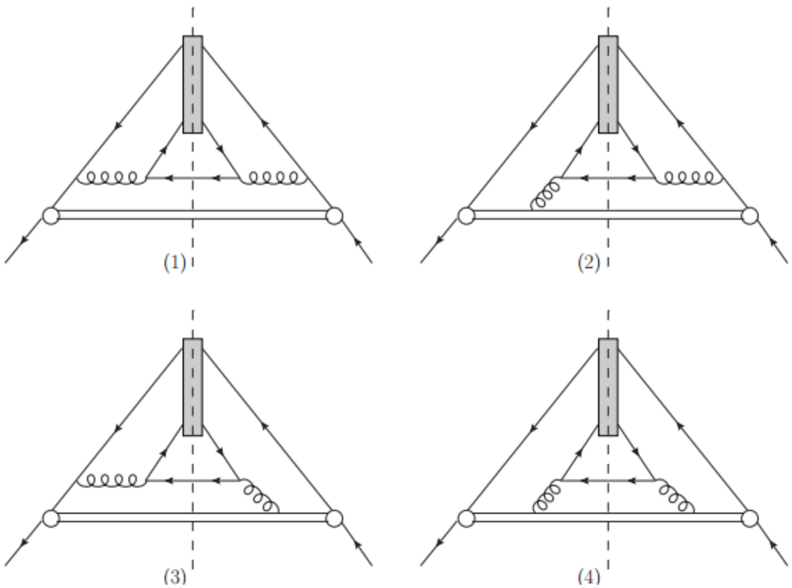
In order to obtain the theoretical predictions under fragmentation approach up to NLO QCD accuracy, the NLO results for $D_{i\to Bc}(z, \mu_F)$ are needed.

Fragmentation function calculation

Based on the definition of FFs by Collins and Soper.

Nucl. Phys. B 194, 445, (1982).

LO cut diagram

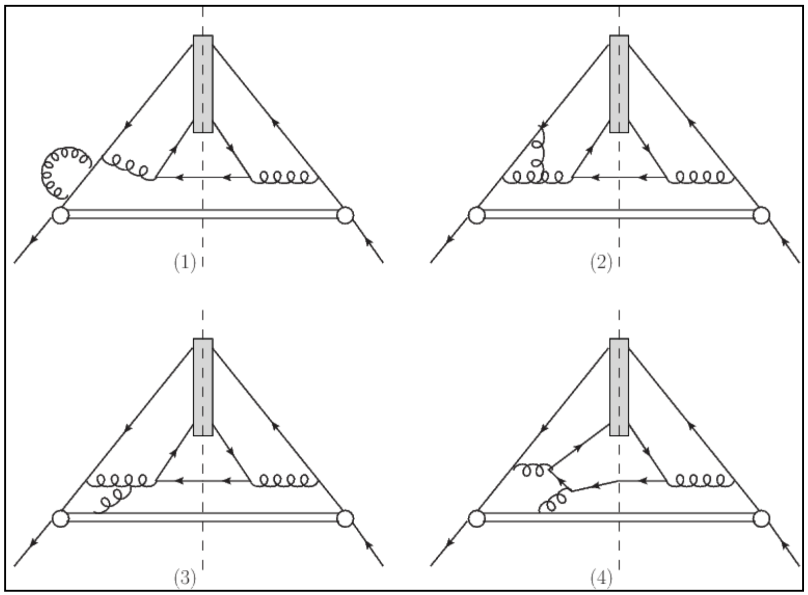


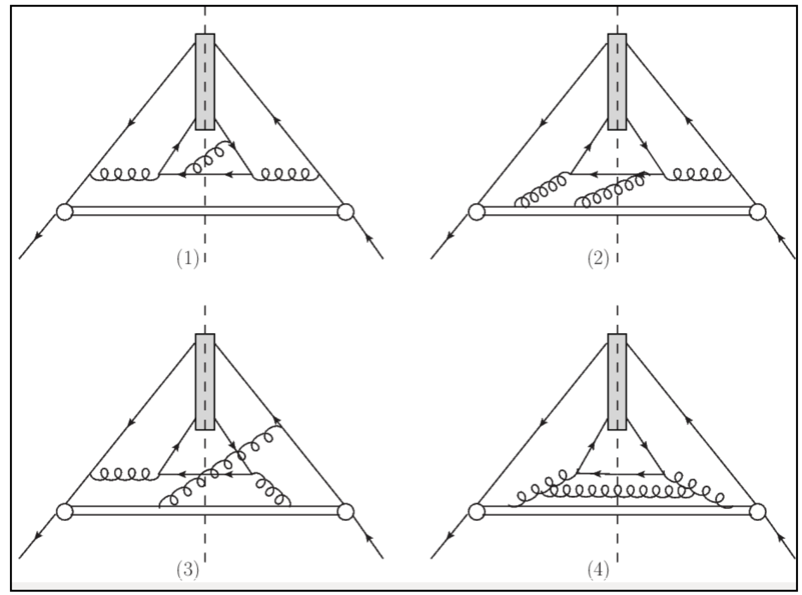
$$D^{\rm LO}_{\bar{b}\to B_c}(z) = \frac{2\alpha_s^2 z(1-z)^2|R_S(0)|^2}{81\pi r_c^2(1-r_b z)^6 M^3}[6-18(1-2r_c)z+(21-74r_c+68r_c^2)z^2 -2r_b(6-19r_c+18r_c^2)z^3+3r_b^2(1-2r_c+2r_c^2)z^4],$$

$$D^{\rm LO}_{\bar{b}\to B_c^*}(z) = \frac{2\alpha_s^2 z(1-z)^2|R_S(0)|^2}{27\pi r_c^2(1-r_b z)^6 M^3}[2-2(3-2r_c)z+3(3-2r_c+4r_c^2)z^2 -2r_b(4-r_c+2r_c^2)z^3+r_b^2(3-2r_c+2r_c^2)z^4].$$

NLO corrections

Typical cut diagrams





54 virtual cut diagrams， 72 real cut diagrams.

- Virtual correction

Tensor reduction, IBP reduction

Many integrals containing an eikonal line

$$\int \frac{d^D l}{[(l-p_1)^2 - m_1^2 + i\varepsilon][(l-p_2)^2 - m_2^2 + i\varepsilon][(l-p_3)^2 - m_3^2 + i\varepsilon](l \cdot n + i\varepsilon)}$$

- Real correction

UV and IR divergence!

$$\mathrm{D}_{\bar{b}\to Bc}^{real}(z) = \int N_{CS} d\phi_{real} (A_{real} - A_S) + \int N_{CS} d\phi_{real} A_S$$

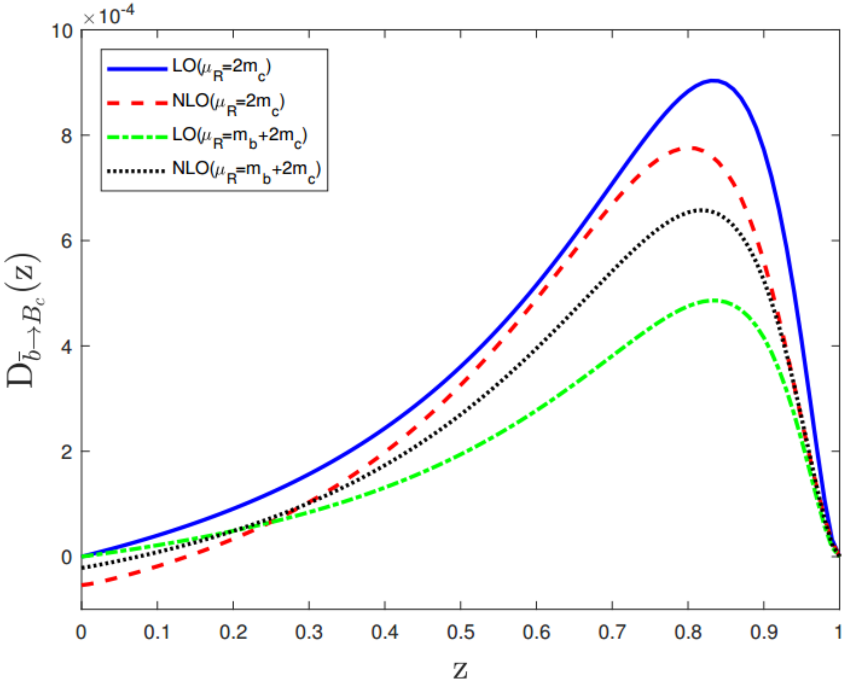
Calculated in 4-dimension

Calculated in d-dimension

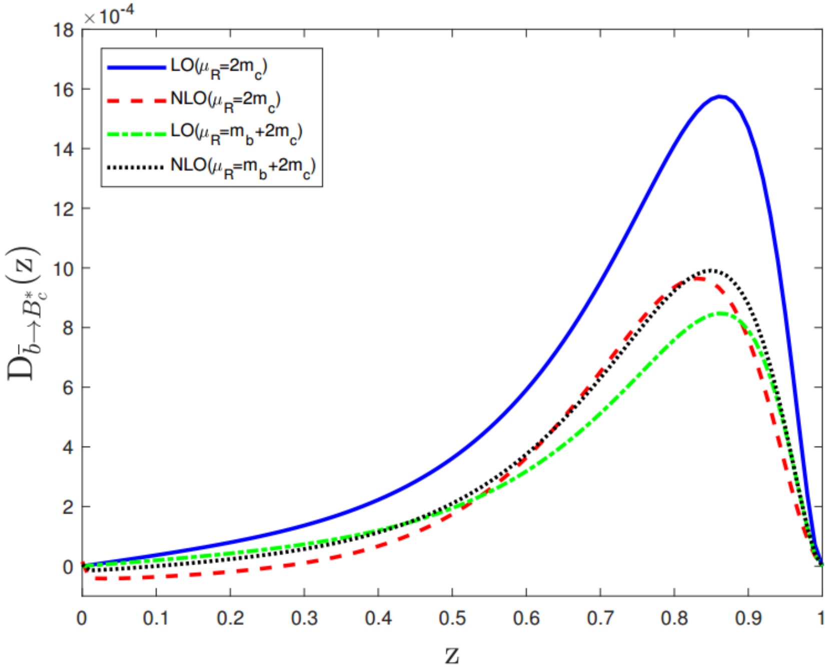
Various types of subtraction terms need to be integrated.

NLO results

Initial fragmentation functions



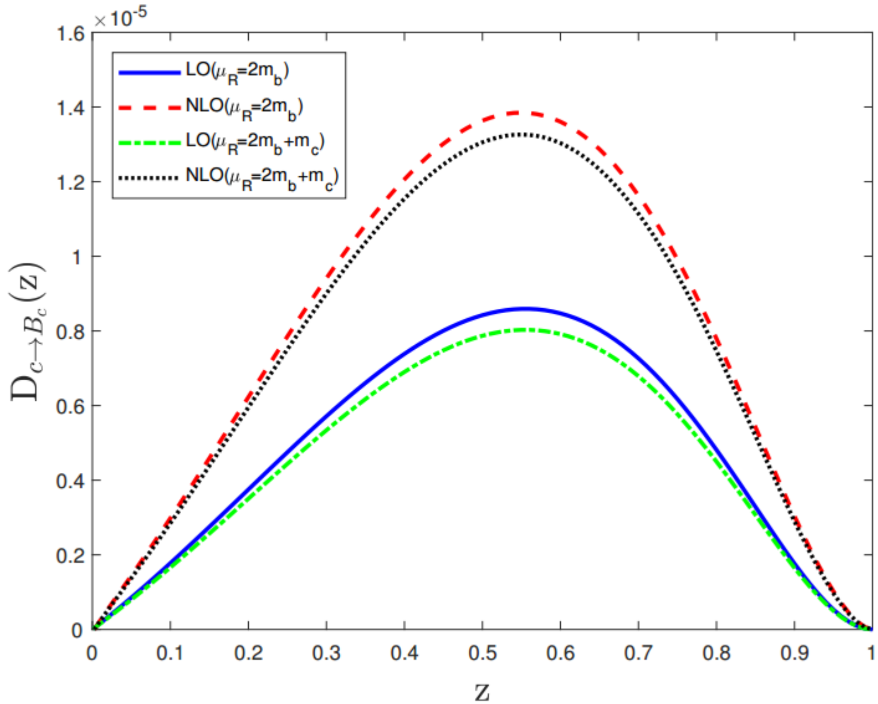
$$D_{\bar{b}\to Bc}(z,\mu_{F0}=m_b+2m_c)$$



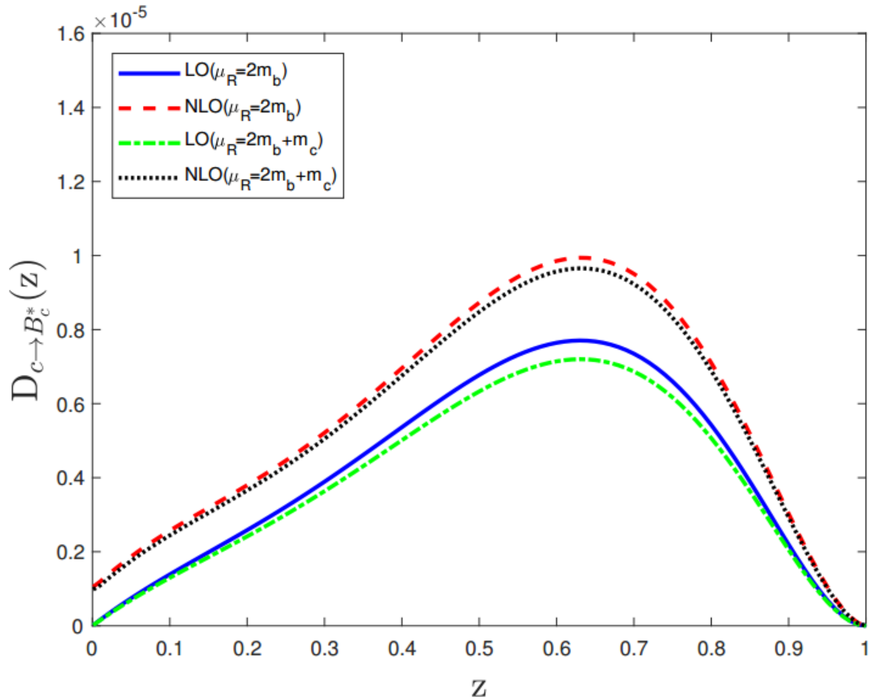
$$D_{\bar{b}\to B_c^*}(z,\mu_{F0}=m_b+2m_c)$$

NLO results

Initial fragmentation functions



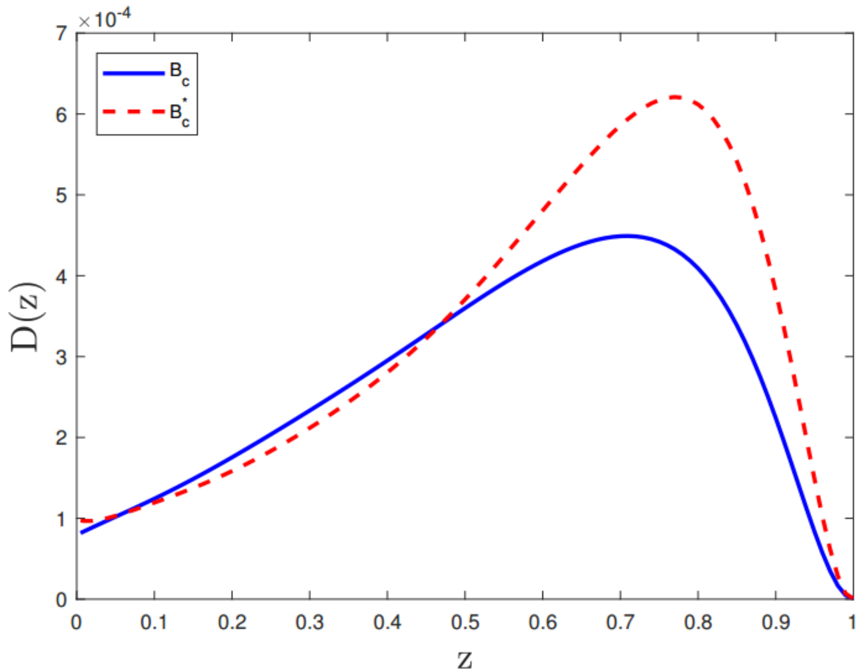
$D_{c\to Bc}(z,\mu_{F0}=m_b+2m_c)$



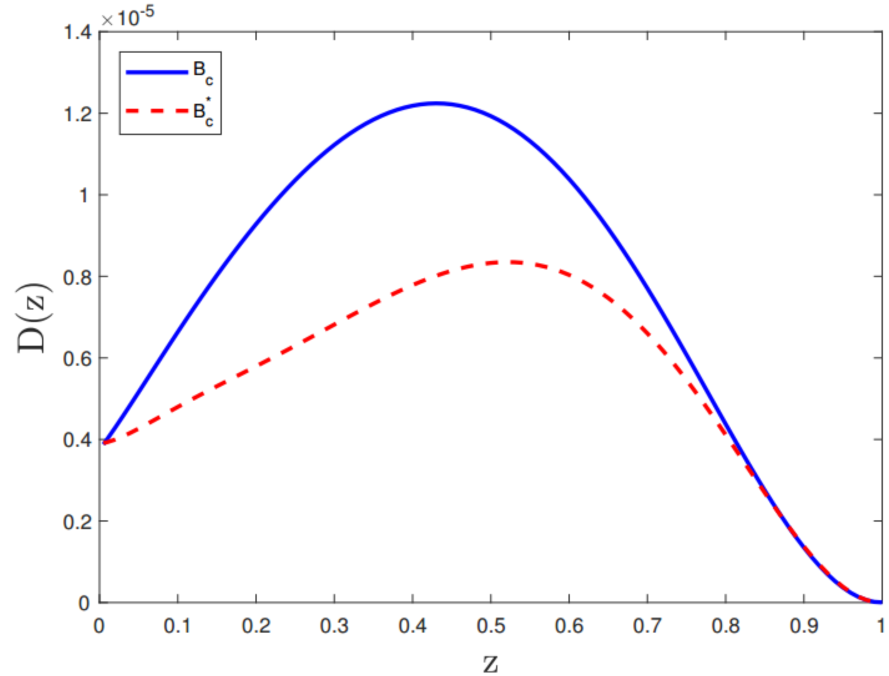
$D_{c\to B_c^*}(z,\mu_{F0}=m_b+2m_c)$

NLO results

The fragmentation functions at scale of m_Z

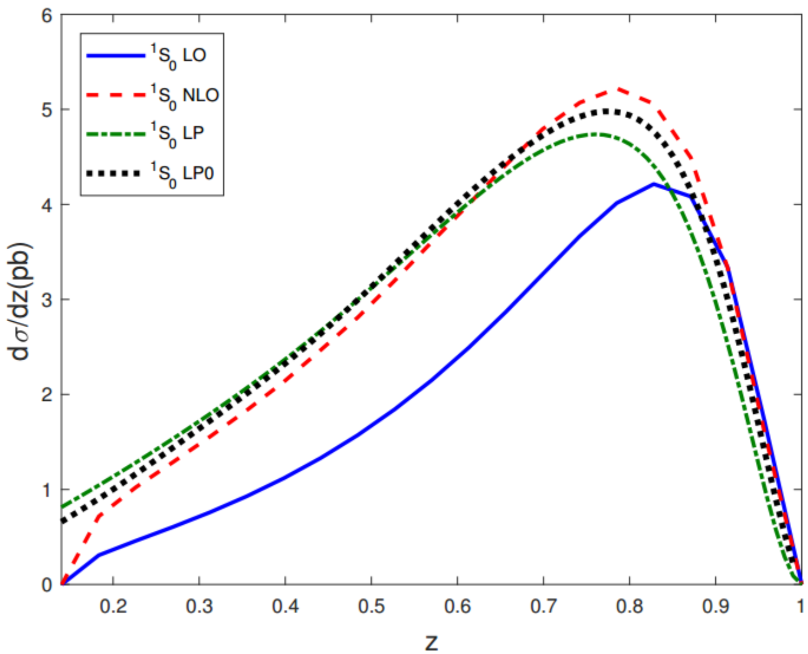


$$D_{\bar{b}\to Bc(Bc*)}(z,\mu_F=m_Z)$$

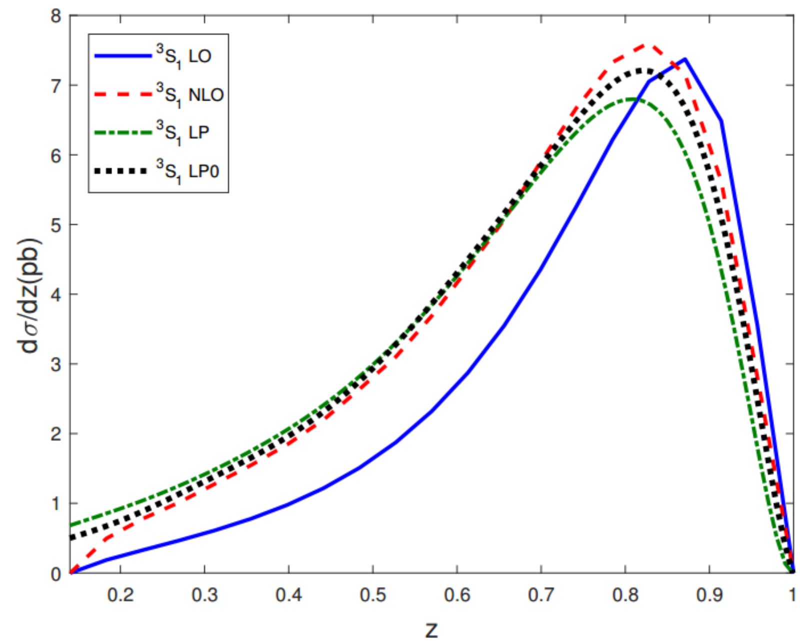


$$D_{c\to(Bc)B_c^*}(z,\mu_F=m_Z)$$

Bc and Bc* production at a Z-factory



$d\sigma / dz(Bc)$



$d\sigma / dz(Bc^*)$

LP0： fragmentation approach, no DGLAP evolution

LP： fragmentation approach, evolved with DGLAP equation

Conclusions

- The production of various doubly heavy hadrons at e^+e^- colliders is studied；
- There are many interesting properties in the production, such as the angle distribution is forward-backward asymmetric;
- The NLO corrections to the processes $e^+ + e^- \to Bc\,(Bc^*) + b + \bar{c}$ and the FFs for a heavy quark fragmentation into Bc(Bc*) are significant.

Outlook

- To study the production of the Bc meson at the LHC up to NLO QCD accuracy；
- To calculate the fragmentation functions for the production of other doubly heavy hadrons up to NLO QCD accuracy.

Thank you！