NLO QCD corrections to $B_c(B_c^*)$ production around the Z pole at an e^+e^- collider

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Outline

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    - B_c meson production at e^+e^- colliders

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    - Calculating method
    - Numerical results

3. Conclusions and outlook

Introduction

An introduction to B_c meson:

- The unique explicitly doubly heavy-flavored meson in the Standard Model
- Its production can be calculated through NRQCD factorization
- The production mechanism of B_c is simpler than that of heavy quarkonium

  For example, the color-octet contributions are sometimes important in the J/Ψ or Υ production, but the color-octet contributions are always suppressed in the production of B_c meson.

Introduction

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

- The center-of-mass system of the process is known
  Angle distributions and forward-backward asymmetry of B_c meson 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.

At an e^+e^- collider, the production of B_c meson at Z pole is greatly enhanced by the resonance effect. There are several plans are under consideration:

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

which plan to run at energies around the Z pole for a long period and with much higher luminosity than that of LEP-I.

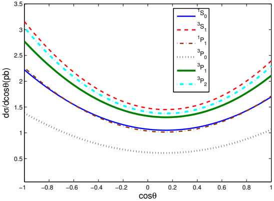
Introduction

LO calculations:

X.C. Zheng, et al, Phys.Rev. D93 (2016)034019.

States	Cross section
$B_c(^1S_0)$	2.73 pb
$B_c^*(^3S_1)$	3.82 pb
$B_c^{**}(^1P_1)$	0.27 pb
$B_c^{**}(^3P_0)$	0.16 pb
$B_c^{**}(^3P_1)$	0.34 pb
$B_c^{**}(^3P_2)$	0.37 pb
Ξ_{cc}	0.52 pb
Ξ_{bc}	1.37 pb
Ξ_{bb}	0.04 pb

Table : Cross section of $e^+e^- \to B_c(B_c^* \cdots) + b + \bar{c}$ at the Z pole.



Differential angle distribution:

The differential angle distribution is forward-backward asymmetric due to the Z-boson exchange. The forward-backward asymmetry (A_{FB}) depends on the value of the weak mixing angle θ_W.

Introduction

LO calculations:

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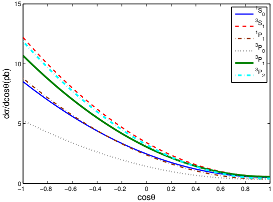
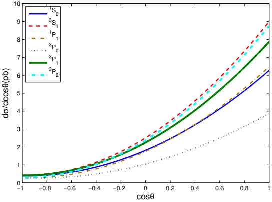
Differential angle distribution for $e_R^+ e_L^-$:



Differential angle distribution for $e_L^+ e_R^-$:



The forward-backward asymmetry is remarkable when the initial e^+e^- are polarized.

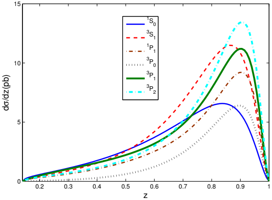
Introduction

LO calculations:

X.C. Zheng, et al, Phys.Rev. D93 (2016)034019.

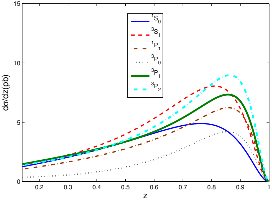
Differential energy distribution

under fixed-order(LO) calculation:



Differential energy distribution

under fragmentation approach:



For the framentation approach, the leading logarithms of $m_z^2/m_{B_c}^2$ have been resummed by use of DGLAP evolution equation.

Introduction

From LO calculations:

- There are about a million of the B_c mesons may be produced per year at a Z factory with a luminosity such as $10^{35} cm^{-2} s^{-1}$.
- The differential angle distribution is forward-backward asymmetric, and it can be used to examine the value of $\sin\theta_w$.
- The differential energy distribution is obtained through fixed-order(LO) calculation and fragmentation approach.

The NLO calculations are needed:

- 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.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Calculating method

NRQCD factorization:

$$
\begin{aligned}
& d\sigma(e^+e^- \to B_c(B_c^*) + b + \bar{c} + X) \\
& = \sum_n d\hat{\sigma}(e^+e^- \to (c\bar{b})[n] + b + \bar{c} + X)\langle \mathcal{O}^H(n) \rangle
\end{aligned}
$$

- LO calculation

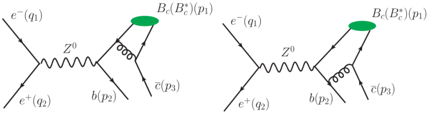
  Color prejector:

  $\mathcal{C}_1 = \frac{\delta_{ij}}{\sqrt{N_c}}$

  Spin prejectors:

  $\frac{-\sqrt{M}}{4m_b m_c}(\not{p}_{12} - m_b)\gamma_5(\not{p}_{11} + m_c)$ for B_c

  $\frac{-\sqrt{M}}{4m_b m_c}(\not{p}_{12} - m_b)\not{\epsilon}(p_1)(\not{p}_{11} + m_c)$ for B_c^*



Two of the LO Feynman diagrams.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Calculating method

NLO corrections:

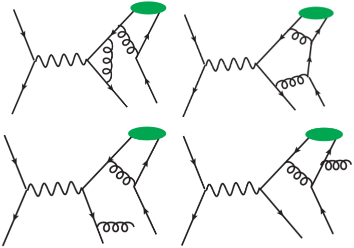
- Virtual corrections

  Passarino-Veltman tensor reduction,

  Integration-by-parts(IBP) reduction.

- Real corrections

  The two-cutoff phase-space slicing method.



Four of the correction Feynman diagrams.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Difficulties in the calculations:

- There are three mass scales(m_z, m_b and m_c) in this process, which leads to the calculations very complicated.
- There are many tensors in the hadronic part need to be calculated before contracting with the leptonic tensor.
- There are vector and axial-vector couplings of Z-boson involved in this process.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

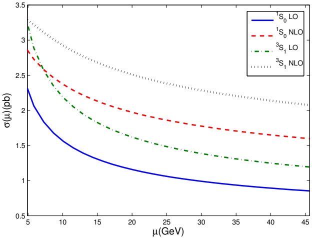
Numerical results:

μ	$\sigma^{LO}_{B_c}(pb)$	$\sigma^{NLO}_{B_c}(pb)$	K-factor
$2m_b$	1.576	2.387	1.515
$m_z/2$	0.847	1.587	1.874

Table : Total cross section of $e^+e^- \to B_c + b + \bar{c} + X$ at the Z pole.

μ	$\sigma^{LO}_{B_c^*}(pb)$	$\sigma^{NLO}_{B_c^*}(pb)$	K-factor
$2m_b$	2.204	2.930	1.329
$m_z/2$	1.185	2.059	1.738

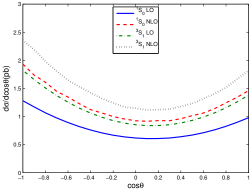
Table : Total cross section of $e^+e^- \to B_c^* + b + \bar{c} + X$ at the Z pole.



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

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Differential angle distribution:



$cos\theta$	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8
$d\sigma/dcos\theta(B_c, LO)$	1.066	0.892	0.759	0.667	0.617	0.608	0.639	0.711	0.825
$d\sigma/dcos\theta(B_c, NLO)$	1.606	1.346	1.150	1.014	0.939	0.924	0.969	1.075	1.242
$K(B_c)$	1.506	1.509	1.515	1.520	1.522	1.520	1.516	1.512	1.505
$d\sigma/dcos\theta(B_c^*, LO)$	1.507	1.254	1.060	0.926	0.853	0.839	0.884	0.990	1.156
$d\sigma/dcos\theta(B_c^*, NLO)$	1.990	1.662	1.414	1.240	1.144	1.125	1.183	1.317	1.529
$K(B_c^*)$	1.320	1.325	1.334	1.339	1.341	1.341	1.338	1.330	1.323

- The differential angle distribution is forward-backward asymmetric due to Z-boson exchange.
- The K-factor changes very little with different θ.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Forward-backward asymmetry:

$$\begin{aligned} A_{FB}^{LO}(B_c) &= -9.58 \times 10^{-2}\,, \\ A_{FB}^{NLO}(B_c) &= -9.50 \times 10^{-2}\,, \\ A_{FB}^{LO}(B_c^*) &= -9.97 \times 10^{-2}\,, \\ A_{FB}^{NLO}(B_c^*) &= -9.83 \times 10^{-2}\,, \end{aligned}$$

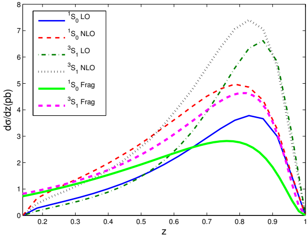
where

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}.$$

- The measurements of the forward-backward asymmetry of B_c and B_c^* can be used to examine the value of $\sin\theta_W$.

NLO QCD corrections to $e^+e^- \to B_c(B_c^*) + b + \bar{c}$

Differential energy distribution:



z	0.183	0.269	0.355	0.441	0.527	0.613	0.699	0.785	0.871	0.957
$d\sigma/dz(B_c, LO)$	0.276	0.543	0.833	1.195	1.655	2.237	2.932	3.603	3.664	1.534
$d\sigma/dz(B_c, NLO)$	0.650	1.173	1.682	2.274	2.964	3.732	4.508	4.970	4.360	1.578
$K(B_c)$	2.355	2.160	2.019	1.903	1.791	1.668	1.538	1.379	1.190	1.029
$d\sigma/dz(B_c^*, LO)$	0.167	0.417	0.699	1.091	1.681	2.582	3.905	5.584	6.617	3.187
$d\sigma/dz(B_c^*, NLO)$	0.446	0.920	1.418	2.029	2.884	4.098	5.586	7.056	7.058	2.852
$K(B_c^*)$	2.671	2.206	2.029	1.860	1.716	1.587	1.430	1.264	1.067	0.895

The energy distribution predicted by fragmentation approach is also presented in the figure.

- The NLO corrections change the energy distribution significantly.
- The K-factor changes remarkably with different z.

Conclusions and outlook

Conlusions:

- e^+e^- collider is a good platform to study the production of B_c meson and the other doubly heavy hadrons.
- Due to the Z-boson resonance, the production rate of B_c meson is greatly enhanced.
- The differential angle distribution and forward-backward asymmetry of the B_c (B_c^*) have been obtained up-to NLO accuracy, and $\sin\theta_W$ can be examined precisely through measuring these observables.
- The differential energy distribution up-to NLO accuracy has been obtained.

Conclusions and outlook

Outlook:

- There are large logrithms of m_z^2/m_{Bc}^2 in each order of perturbative expansion for the differential energy distribution.
- These large logrithms can be resummed through DGLAP equation under the fragmentation approach.
- We are working on the fragmentation approach up-to NLO accurracy, some results have been obtained, and the paper is in preparation.

Thanks!