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B_c Production in Z^0 and Higgs Decays

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Contents

- Research Background
- NLO Corrections to B_c^* Production in Z^0 Decays

  J. Jiang, L. B. Chen and C. F. Qiao, Phys. Rev. D91 (2015) 034033.
- B_c Production in Higgs Decays

  J. Jiang, L. B. Chen and C. F. Qiao, Phys. Rev. D93 (2016) 054031.
- Summary

Research Background

Direct B_c Production

1. Hadronic Production (Theoretical Study)

$$p + p(\bar{p}) \to g(q) + g(q) \to B_c + \bar{c} + b$$

S-wave $B_c^{(*)}$ (Complete calculation):

C. H. Chang etc., 1993/95; S. R. Slabospitsky, 95;

A. V. Berezhnoy, 95/96; M. Masetti and F. Sartogo, 95;

K. Kolodziej, A. Leike and R. Ruckl, 95;

K. M. Cheung, 2000; etc.

Heavy quark fragmentation calculation:

E. Braaten, K. M. Cheung and T. C. Yuan, 93~96;

C. H. Chang, Y. Q. Chen, G. P. Han and H. T. Jiang, 95;

V.A. Saleev, D.V. Vasin, 2005; etc.

P-wave, Color-octet, 'Intrinsic charm and bottom mechanisms':

C. H. Chang, C. F. Qiao, J. X. Wang and X. G. Wu, 2004~2005.

Generator:

BCVEGPY 1.0~2.2,

C. H. Chang, C. Driouichi, P. Eerola, J. X. Wang and X. G. Wu, X. Y. Wang, 2004~2015.

Auto calculation program:

HELAC-Onia 1.0-2.0,

H. S. Shao, 2013~2016.

Research Background

Direct B_c Production

2. Hadronic Production (Experimental Study)

Firstly observed by CDF at Tevatron in 1998 through $B_c^{\pm} \to J/\psi + l^{\pm} + \nu$.

Excited state $B_c(2S)$ was found by ATLAS at LHC in 2014 through $m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2m(\pi^{\pm})$.

$B_c^{\pm} \to J/\psi + \pi^{\pm}$.

CDF run2 data (2016):

$$\mathcal{R} = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

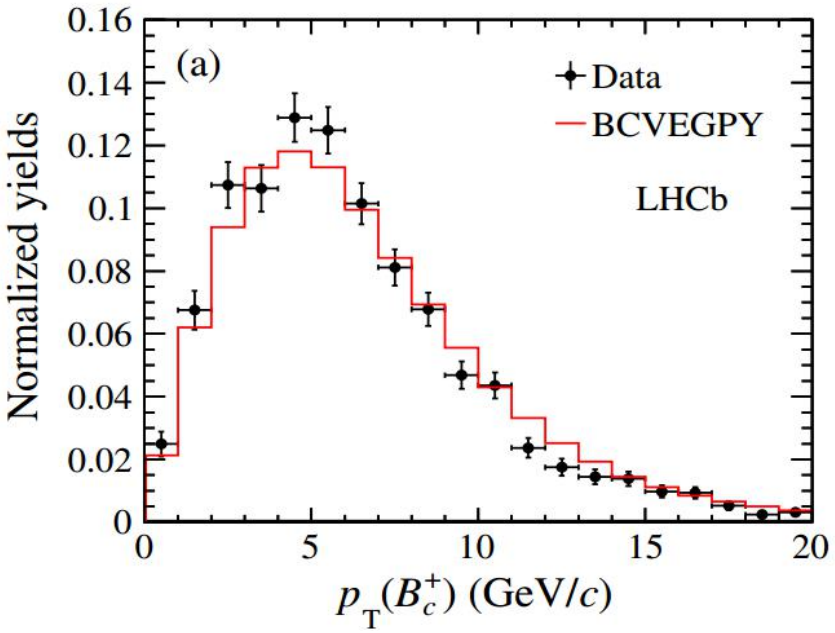
$$= 0.211 \pm 0.012(\text{stat})\,^{+0.021}_{-0.020}\,(\text{syst})$$

$$\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu)$$

$$= 0.602 \pm 0.034(\text{stat})\,^{+0.060}_{-0.063}\,(\text{syst}) \pm 0.055(\text{other})\ \text{nb}$$

for $p_T(B_c^+) > 6\ \text{GeV}/c$ and $|y| < 1$.

LHCb 8TeV (2015):



Research Background

Direct B_c Production

3. Other Production Mechanisms

Electron positron collision:

Z. Yang, X. G. Wu, etc., 2012.

In a super-Z factory, Z^0 resonance effect would enhance the production rate heavily.
Generator: BEEC (2013).

Photon photon interaction:

K. Kolodziej, A. Leike and R. Ruckl, 95;

A. V. Berezhnoy, V. V. Kiselev, A. K. Likhoded,96.

Electron proton collision :

A. V. Berezhnoy, V. V. Kiselev and A. K. Likhoded, 98;

A. V. Berezhnoy, A. K. Likhoded, 04.

Pb Pb interaction :

Y. Liu, C. Greiner and A. Kostyuk, 13;

E. Norbeck, J. Nachtman and Y. Onel, 13.

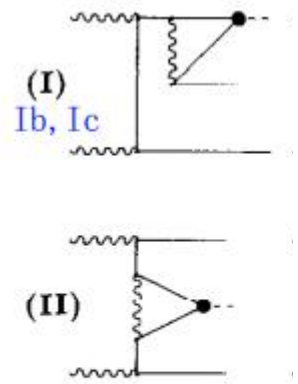
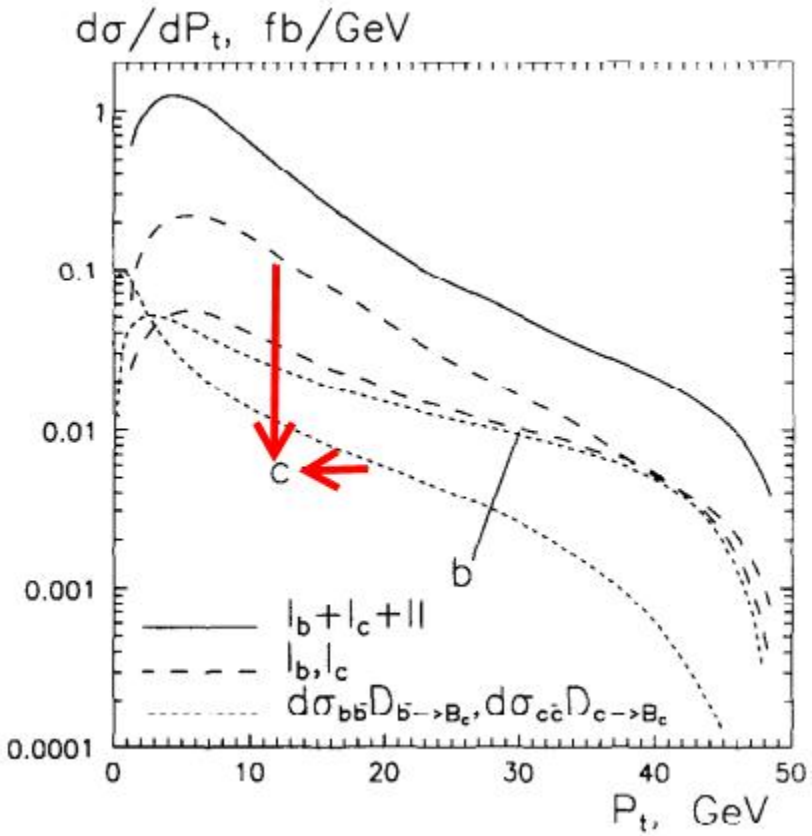
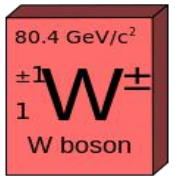


Fig. 1. Different topologi
contributing to $\gamma\gamma \to B_c$



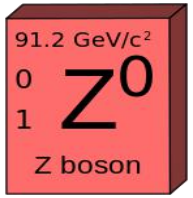
Research Background

Indirect B_c Production



LO calculation:

C. F. Qiao, etc., 2011; Q. L. Liao, etc., 12.



LO calculation:

C. H. Chang etc., 92; V. V. Kiselev, etc., 94; X. G. Wu, etc., 10/11.

NLO calculation: **C. F. Qiao, L. P. Sun and R. L. Zhu, 11;**

J. Jiang, L. B. Chen and C. F. Qiao, 15.

LO calculation:

J. Jiang, L. B. Chen and C. F. Qiao, 2016.

LO calculation:

C. F. Qiao, C. S. Li and K. T. Chao, 96; C. H. Chang, J. X. Wang and X. G. Wu, 08/09.

NLO calculation: **P. Sun, L. P. Sun and C. F. Qiao, 10.**

NLO corrections to B_c^* production in Z^0 decays

- Decay Widths & Uncertainties

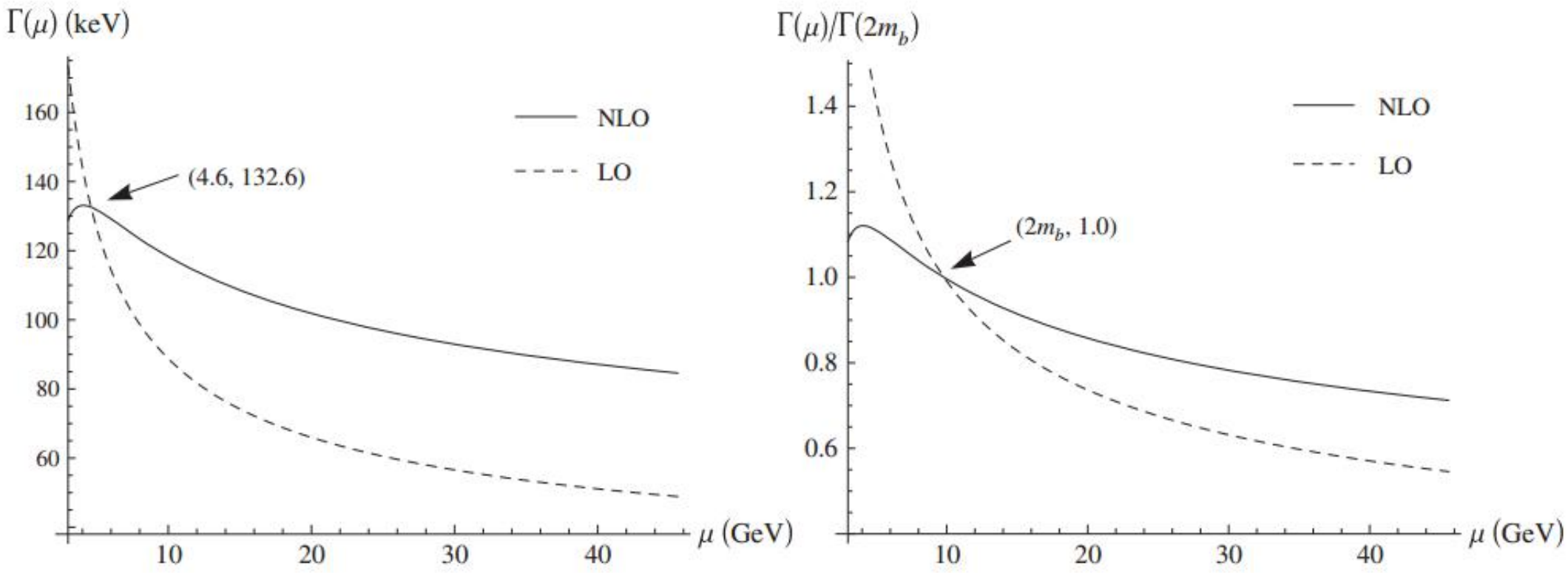


FIG. 8. The decay width $\Gamma(\mu)$ and the ratio $\Gamma(\mu)/\Gamma(2m_b)$ versus renormalization scale μ for μ running from $2m_c$ to $m_Z/2$.

NLO corrections to B_c^* production in Z^0 decays

Decay Widths & Uncertainties

TABLE I. Decay widths $\Gamma(\mu)$ (keV) of $Z^0 \to B_c^* + \bar{c} + b$ at leading order and next-to-leading order. The first errors are caused by $m_c = 1.5 \pm 0.1$ GeV and the second ones by $m_b = 4.9 \pm 0.2$ GeV at $\mu = 2m_b$, 28 GeV, $m_Z/2$.

$\Gamma(\mu)$ (keV)	LO	NLO	K-factor
$\mu = 2m_b$	$89.56^{-17.10+0.71}_{+22.85-0.71}$	$118.77^{-23.11+0.37}_{+31.53+0.07}$	$1.33^{-0.01-0.01}_{+0.01+0.01}$
$\mu = 28$	$58.02^{-11.08+0.46}_{+14.80-0.46}$	$94.40^{-18.25+0.45}_{+24.73-0.22}$	$1.63^{-0.00-0.01}_{+0.01+0.01}$
$\mu = m_Z/2$	$48.87^{-9.33+0.39}_{+12.47-0.39}$	$84.60^{-16.33+0.44}_{+22.08-0.26}$	$1.73^{-0.00-0.00}_{+0.01+0.01}$

Conclusions:

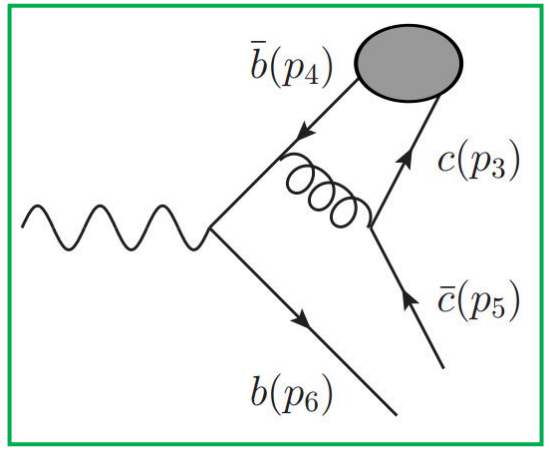
$\mu \uparrow, \Gamma_{LO,NLO} \downarrow;$

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

Uncertainties caused by varying m_c are much larger than those caused by varying m_b.

NLO corrections to B_c^* production in Z^0 decays

- Decay Widths & Uncertainties



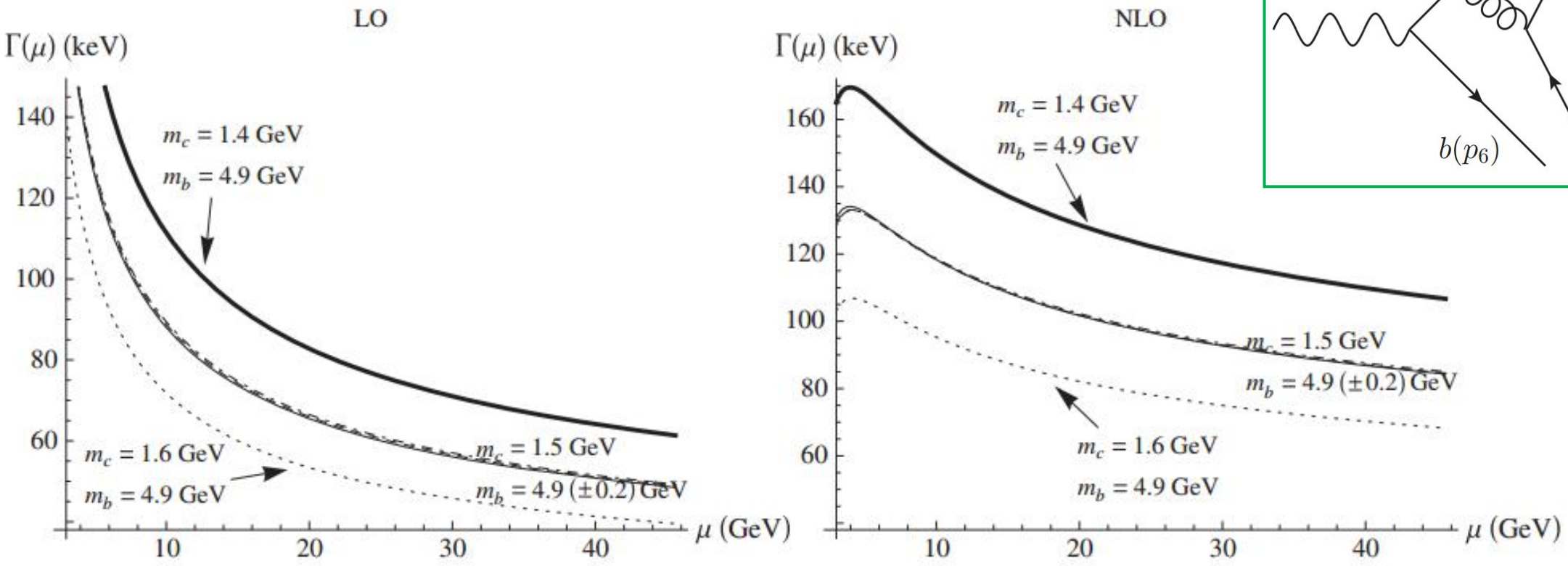


FIG. 9. The decay widths of LO (left) and NLO (right) with different quark masses versus running renormalization scale μ, from $2m_c$ to $m_Z/2$.

NLO corrections to B_c^* production in Z^0 decays

Branching Fractions & Events

$$Br_{LO}(Z^0 \to B_c^* + \bar{c} + b) = 3.6\times10^{-5},$$
$$Br_{NLO}(Z^0 \to B_c^* + \bar{c} + b) = 4.8\times10^{-5}.$$

Vector B_c^*

$$Br_{LO}(Z^0 \to B_c + \bar{c} + b) = 2.9\times10^{-5},$$
$$Br_{NLO}(Z^0 \to B_c + \bar{c} + b) = 3.1\times10^{-5}.$$

Pseudoscalar B_c

$$Br_{LO}(Z^0 \to B_c + X) = 6.5\times10^{-5},$$
$$Br_{NLO}(Z^0 \to B_c + X) = 7.9\times10^{-5}.$$

B_c detection efficiency:

$$Br(B_c^\pm \to J/\psi + \pi^\pm) = (1.35 - 2.54)\times10^{-3}$$

Z. J. Xiao, X. Liu, 2014.

$$Br(J/\psi \to l^+l^-, l = e, \mu) \approx 6\%$$

Low efficiency: (0.81~1.52) in 10^4.

Depression factor: 1.6×10^{-8} !

Is it possible to detect the B_c signals in Z^0 decays experimentally?

NLO corrections to B_c^* production in Z^0 decays

Branching Fractions & Events

B_c indirect production at Z factory:

Z factory: $E_{CM} \sim Z^0$ mass pole

$L \sim 10^{35\sim36}\ cm^{-2}s^{-1}$

Z^0 events ~ $10^{10\text{-}11}$/year

Depression factor: 1.6×10^{-8}

$$Z^0 \to B_c(\to J/\psi(\to l^+l^-)+\pi^+)+X$$

B_c events: $1.6\times10^{2\text{-}3}$ events/year.

Search for B/c and Upsilon in hadronic Z decays

ALEPH Collaboration (M. McNeil (CERN) for the collaboration)

1997 - 10 pages

Int.J.Mod.Phys. A12 (1997) 3921-3930
DOI: 10.1142/S0217751X97002073
Prepared for Conference: C96-06-13.1 Proceedings
Experiment: CERN-LEP-ALEPH

Abstract (WSP)
Out of 3.9 million hadronic Z decays collected by the ALEPH detector, a sample of approximately 700 J/ψ events decaying into e+ e- or μ+μ- are selected. A search for the Bc meson decaying into the channels J/ψπ+, J/ψe+νe and J/ψμ+νμ is then performed, resulting in the observation of 0, 1 and 1 candidate in each of these channels respectively, with 0.37, 0.28 and 0.36 background events expected. The following 90% confidence level upper limits are derived:

$$\frac{\mathrm{Br}(Z\to B_c X)}{\mathrm{Br}(Z\to q\bar{q})}\mathrm{Br}(B_c^+\to J/\psi\pi^+) < 3\times10^{-5},$$

$$\frac{\mathrm{Br}(Z\to B_c X)}{\mathrm{Br}(Z\to q\bar{q})}\mathrm{Br}(B_c^+\to J/\psi\ell^+\nu_\ell) < 5\times10^{-5}.$$

An intriguing candidate, found in an independent analysis, is also described in detail. Using the same data sample, a search is performed for the Υ(1S), Υ(2S) and Υ(3S) states, decay...

B_c production in Higgs decays

- Decay Widths & Uncertainties

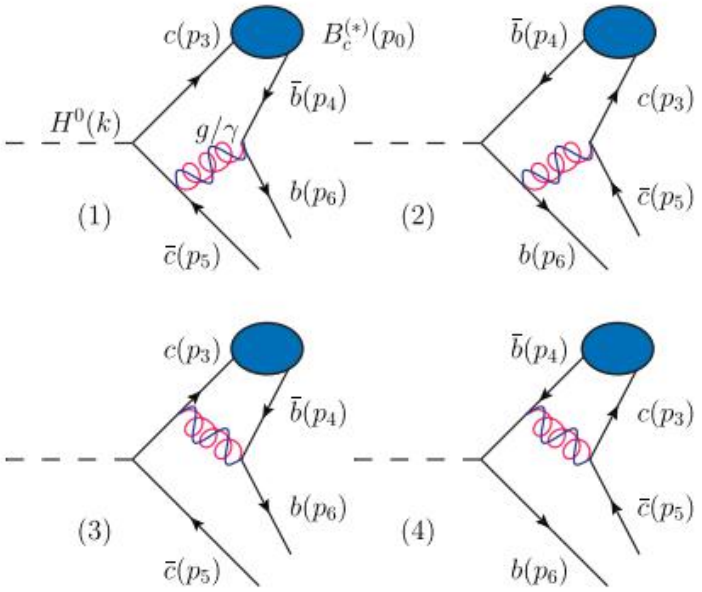


FIG. 1. The QCD/QED Feynman diagrams of the processes $H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$, where convolved/waved lines represent the gluon/photon propagators.

New Physics!

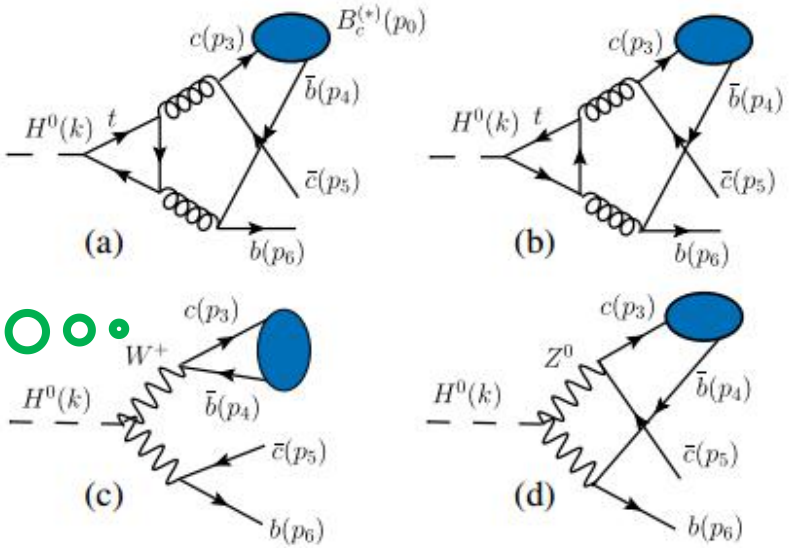


FIG. 2. The top quark triangle loop (a, b) and W/Z boson (c, d) propagated Feynman diagrams of processes $H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$.

Contributions	Order	B_c	B_c^*
Fig. 1 (QCD only)	$\alpha_{ew}\alpha_s^2$	1.53	2.08
cross terms of Figs. 1, 2(a), 2(b)	$\alpha_{ew}\alpha_s^3$	$5.32 \times 10^{-2}(+3.5\%)$	$6.98 \times 10^{-3}(+0.34\%)$
Fig. 2(c)	$\alpha_{ew}^3 V_{cb}^4$	$2.58 \times 10^{-7}(+0.0\%)$	$2.67 \times 10^{-7}(+0.0\%)$
Fig. 2(d)	α_{ew}^3	$1.65 \times 10^{-3}(+0.11\%)$	$1.67 \times 10^{-3}(+0.08\%)$
cross terms of Figs. 1, 2(c), 2(d)	—	$-5.69 \times 10^{-4}(-0.037\%)$	$8.23 \times 10^{-6}(+0.0\%)$

B_c production in Higgs decays

Decay Widths & Uncertainties

Decay widths:

QCD

QED

$$\Gamma_{B_c} = 4256.68\alpha_s^2\alpha - 1417.96\alpha_s\alpha^2 + 117.991\alpha^3,$$

$$\Gamma_{B_c^*} = 5773.29\alpha_s^2\alpha - 1932.84\alpha_s\alpha^2 + 159.392\alpha^3.$$

Total decay widths and branching fractions:

$$\Gamma_{total}(H^0 \to B_c + \bar{c} + b) = 3.57(^{-0.67}_{+0.88})keV,$$

$$Br_{total}(H^0 \to B_c + \bar{c} + b) = 8.50(^{-1.6}_{+2.1}) \times 10^{-4}.$$

TABLE II. Uncertainties of the decay widths $\Gamma(H^0 \to B_c^{(*)} + \bar{c} + b)$ (units: keV) caused by the matrix element $\langle B_c^{(*)}|\mathcal{O}[^1S_0(^3S_1)]|B_c^{(*)}\rangle$ (units: GeV^3). Percentages in brackets are corrections relative to the QCD (B-T) one.

$\langle B_c^{(*)}\|\mathcal{O}[^1S_0(^3S_1)]\|B_c^{(*)}\rangle$	B_c	B_c^*
QCD (B-T): 0.1306	1.51	2.06
Power law: 0.1361	1.57(+4%)	2.15(+4%)
Logarithmic: 0.1200	1.39(−8%)	1.89(−8%)
Cornell: 0.2534	2.93	4.00

TABLE III. Uncertainties of the decay widths $\Gamma(H^0 \to B_c^{(*)} + \bar{c} + b)$ (units: keV) caused by the mass parameters m_b and m_c (units: GeV). When $m_b(m_c)$ varies, $m_c(m_b)$ is fixed at its central value.

$m_{b,c}$	B_c	B_c^*
$m_b = 4.9^{+0.2}_{-0.2}$	$1.51^{+0.12}_{-0.12}$	$2.06^{+0.20}_{-0.19}$
$m_c = 1.5^{+0.1}_{-0.1}$	$1.51^{-0.27}_{+0.35}$	$2.06^{-0.40}_{+0.53}$

B_c production in Higgs decays

- Differential Distributions

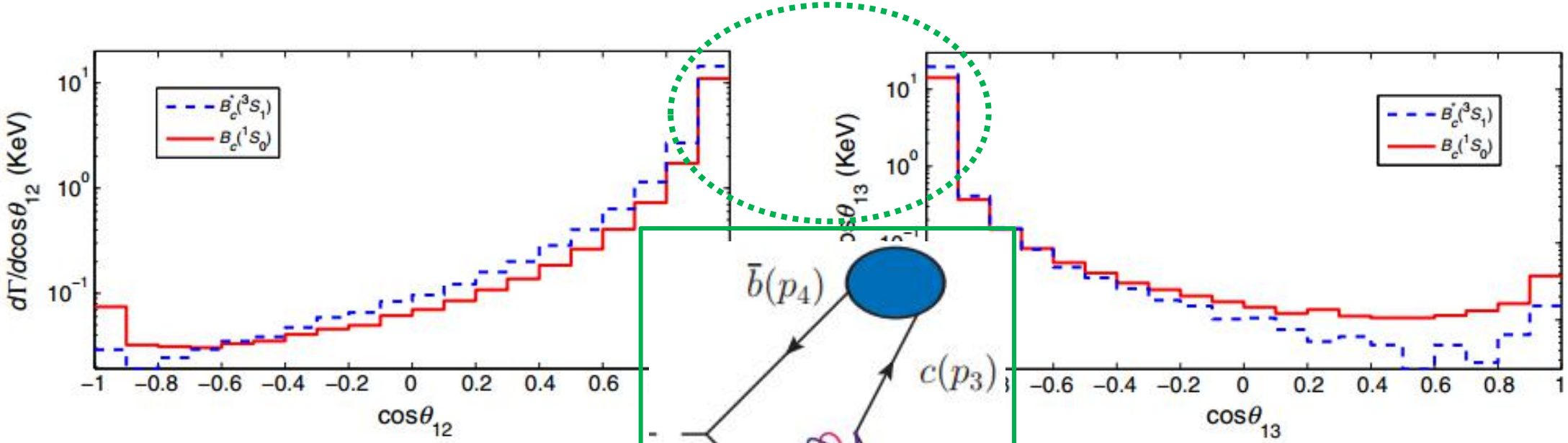
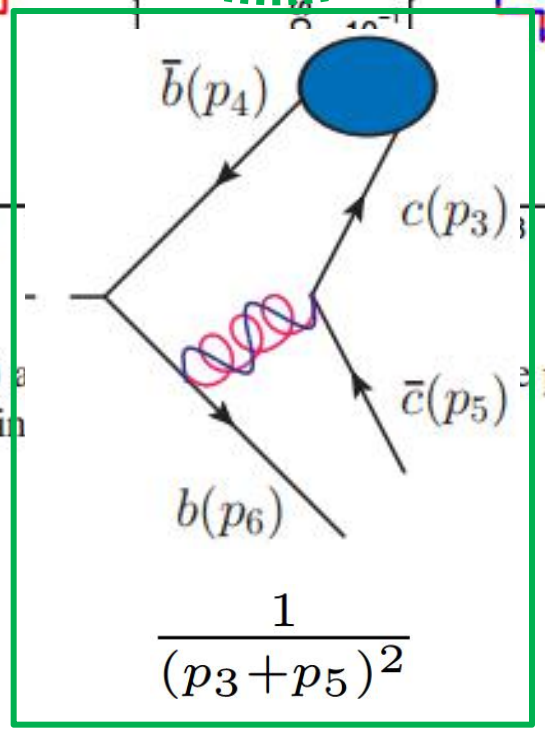


FIG. 4. Differential decay widths $d\Gamma/d\cos\theta_{12}$ (left) a processes $H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$, where $\theta_{12}(\theta_{13})$ is the angle between $\vec{p}_0$ and $\vec{p}_5(\vec{p}_6)$ in



$$\frac{1}{(p_3+p_5)^2}$$

B_c production in Higgs decays

- In Comparison with Fragmentation Calculation

TABLE V. Branching fractions of $H^0(k) \to B_c^{(*)}(p_0) + \bar{c}(p_5) + b(p_6)$ through complete leading-order NRQCD calculation (QCD contributions only). The percentages in brackets are ratios of the contributions from the three groups relative to the total branching fractions.

	B_c	B_c^*
Total branching fractions (QCD only)	3.65×10^{-4}	4.96×10^{-4}
$Hb\bar{b}$ coupling	$3.61 \times 10^{-4}(+98.9\%)$	$4.97 \times 10^{-4}(+100.2\%)$
$Hc\bar{c}$ coupling	$8.82 \times 10^{-7}(+0.2\%)$	$7.32 \times 10^{-7}(+0.2\%)$
Cross-terms	$3.34 \times 10^{-6}(+0.9\%)$	$-1.85 \times 10^{-6}(-0.4\%)$

TABLE VI. Branching fractions of $H^0 \to B_c^{(*)}$ through $\bar{b}$ and c quark fragmentation calculation.

	B_c	B_c^*
$H^0 \to b\bar{b} \to B_c^{(*)}$	3.10×10^{-4}	4.36×10^{-4}
$H^0 \to c\bar{c} \to B_c^{(*)}$	2.00×10^{-7}	1.73×10^{-7}

$$Br(H^0 \to b\bar{b}) = 56.6\%,$$

$$Br(H^0 \to c\bar{c}) = 2.85\%.$$

B_c production in Higgs decays

- In Comparison with Higgs Decays to Quarkonia

NRQCD calculation:

$$Br(H^0 \to B_c + \bar{c} + b) = 3.65 \times 10^{-4},$$
$$Br(H^0 \to B_c^* + \bar{c} + b) = 4.96 \times 10^{-4};$$

Fragmentation calculation:

$$Br(H^0 \to b\bar{b} \to B_c) = 3.10 \times 10^{-4},$$
$$Br(H^0 \to b\bar{b} \to B_c^*) = 4.36 \times 10^{-4}.$$

$$Br(H^0 \to \eta_c + \bar{c} + c) = 7.87 \times 10^{-5},$$
$$Br(H^0 \to J/\psi + \bar{c} + c) = 7.59 \times 10^{-5};$$
$$Br(H^0 \to \eta_b + \bar{b} + b) = 8.89 \times 10^{-5},$$
$$Br(H^0 \to \Upsilon + \bar{b} + b) = 6.61 \times 10^{-5}.$$

$$Br(H^0 \to c\bar{c} \to \eta_c) = 1.65 \times 10^{-5},$$
$$Br(H^0 \to c\bar{c} \to J/\psi) = 1.70 \times 10^{-5};$$
$$Br(H^0 \to b\bar{b} \to \eta_b) = 3.25 \times 10^{-5},$$
$$Br(H^0 \to b\bar{b} \to \Upsilon) = 3.35 \times 10^{-5}.$$

$$Br(H^0 \to J/\psi + \gamma) \sim 10^{-6},$$
$$Br(H^0 \to \Upsilon(nS) + \gamma) \sim 10^{-9}.$$

G. T. Bodwin, etc., 2014.

M. Konig and M. Neubert, 2015.

Summary

- B_c indirect production through Z^0 and Higgs decays

  - NLO correction to B_c^* production in Z^0 decays

    NLO corrections enhance the LO contributions by 30%.

    Scale dependence is reduced. Uncertainties caused by quark masses are discussed.

    Experimental study in future Z factories is doable.

  - B_c production in Higgs decays

    The processes are **dominated by Higgs and b quark couplings**.

    Branching fractions are **5 times bigger than those of Higgs decays to quarkonia**.

THANK YOU!

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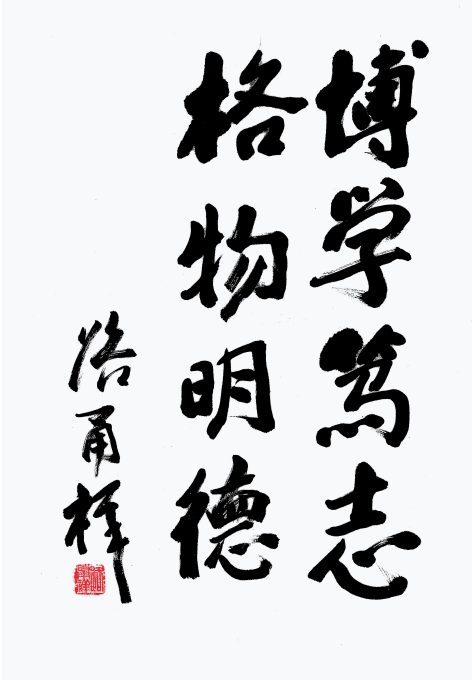
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