Workshop on Physics at the CEPC

Bc Production and Decays

Cong-Feng Qiao

UNIVERSITY OF CAS

2015-08-12

Contents:

- The Bc Meson
- Bc Production
- Bc Decays
- Conclusion & Outlook

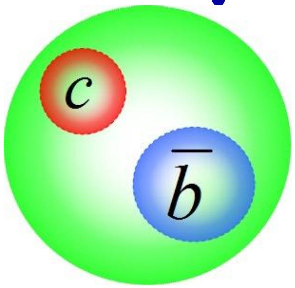
Contents:

- The Bc Meson
- Bc Production
- Bc Decays
- Conclusion & Outlook

The Bc Meson—a portrait

- Bc is the ground state of $\bar{b}c$ system, which carries two different heavy flavors

- Bc cannot decay through strong or electromagnetic interactions, which makes weak interaction the only possible decay mechanism



The Bc Meson—a portrait

- Bc system provides an opportunity for studying the heavy-quark dynamics that is different from charmonium and bottomonium

- The $\bar{b}c$ system has a rich spectroscopy of the orbital and angular-momentum exitations. Below the B –D threshold , there should exist 16 extremely narrow states, which cascadely decay into the ground pseudoscalar state

The Bc Meson—a portrait

- The production mechanism for $\bar{b}c$ system is more complicated relative to quarkonium, and hence the direct production rate of Bc is usually lower than that of quarkonium

- At the LHC, with a luminosity of 10^{34} cm^{-2} s^{-1}, one expects about 10 billions of Bc produced per year

The Bc Meson—a portrait

- Of the total Bc decay width, 70% is due to the charm quark decays, 20% due to the bottom quark decays, and 10% to the weak annihilation **[I.P. Gouz et al.,phys. Atom. Nucl.67,1559(2004)]**

- Bc meson was first observed at Tevatron in three decay modes, i.e. $Bc \to J/\psi\ \pi$, $Bc \to J/\psi\ \mu\ \nu_{\mu}$, and $Bc \to J/\psi\ e\ \nu_e$, through b-quark decays **[The CDF Collaboration, PRL 81, 2432 (1998)]**

The Bc Meson—a portrait

- Similar to quarkonium, the mass spectrum of $\bar{b}c$ family can be computed by potential model, pNRQCD, and lattice QCD, etc.

[E. Eichen and C. Quigg, Phys. Rev. D 49, 5845(1994); Y.Q. Chen and Y.P. Kuang, Phys. Rev. D 46, 1165(1992); S. Goldfrey, Phys. Rev. D 70, 054017 (2004)]

[N. Brambilla, Y. Sumino and A. Vairo, Phys. Rev. D 65 034001, (2002)]

[QCDHP, Fermilab Lattice and UKQCD Collaborations, I.F. Allison et al, Phys. Rev.Lett. 94, 172001 (2005); Nucl. Phys. B, Proc. Suppl. 129 340 (2004); Nucl. Phys. B,Proc. Suppl. 140 440 (2005); UKQCD Collaboration, H.P. Shanahan et al, Phys. Lett. B 453, 289 (1999)]

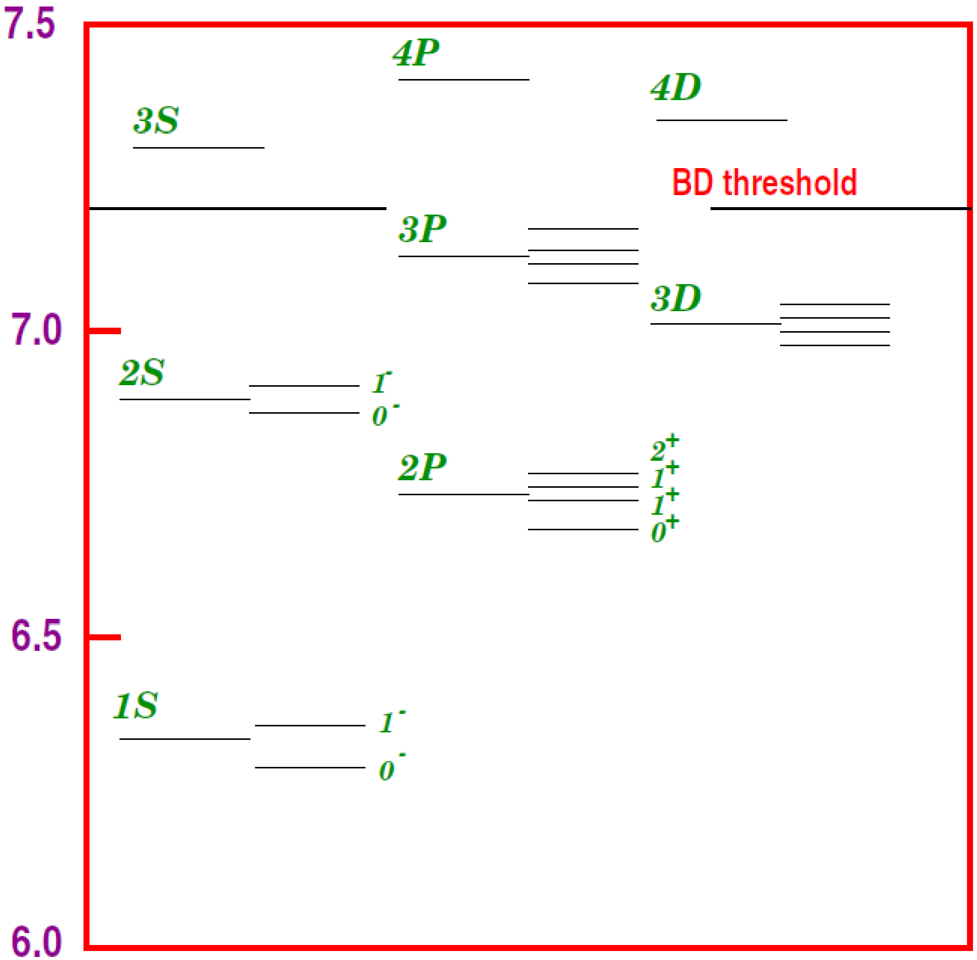
[E. Eichen and C. Quigg, Phys. Rev. D 49, 5845(1994);

TABLE IV. $c\bar{b}$ masses (in GeV/c^2) in the Buchmüller-Tye potential.

Level	Calculated Mass	Eichten & Feinberg[a]	Gershteĭn et al.[b]	Chen & Kuang[c]
1^1S_0 (B_c)	6.264	6.243	6.246	6.310
1^3S_1 (B_c^*)	6.337	6.339	6.329	6.355
2^3P_0	6.700	6.697	6.645	6.728
$2\ 1^{+\prime}$	6.736	6.740	6.741	6.760
$2\ 1^{+}$	6.730	6.719	6.682	6.764
2^3P_2	6.747	6.750	6.760	6.773
2^1S_0	6.856	6.969	6.863	6.890
2^3S_1	6.899	7.022	6.903	6.917
3^3D_1	7.012			
3^3D_2	7.012			
3^3D_3	7.005		(7.008)	
3^1D_2	7.009			
3^3P_0	7.108		7.067	7.134
$3\ 1^{+\prime}$	7.142		7.129	7.159
$3\ 1^{+}$	7.135		7.099	7.160
3^3P_2	7.153		7.143	7.166
3^1S_0	7.244		(7.327)	
3^3S_1	7.280			
4^1S_0	7.562			
4^3S_1	7.594			

[a]See Ref. [14]. [b]See Ref. [27]. [c]See Ref. [28]; the masses correspond to Potential I with $\Lambda_{\overline{MS}} = 150$ MeV.

[I.P. Gouz et al.,phys. Atom. Nucl.67,1559(2004)]



state	Martin	BT
1^1S_0	6.253	6.264
1^1S_1	6.317	6.337
2^1S_0	6.867	6.856
2^1S_1	6.902	6.899
2^1P_0	6.683	6.700
$2P\ 1^+$	6.717	6.730
$2P\ 1'^+$	6.729	6.736
2^3P_2	6.743	6.747
3^1P_0	7.088	7.108
$3P\ 1^+$	7.113	7.135
$3P\ 1'^+$	7.124	7.142
3^3P_2	7.134	7.153
$3D\ 2^-$	7.001	7.009
3^5D_3	7.007	7.005
3^3D_1	7.008	7.012
$3D\ 2'^-$	7.016	7.012

The Bc Meson—a portrait

- Up to date, the world`s most precise single measurement of the Bc mass is:

$$M_{Bc} = 6276.28 \pm 1.44 \pm 0.36 \text{ MeV}$$

[LHCb Collaboration, PRD 87 (2013) 112012]

- The recent Bc lifetime measuremt gives

$$\tau_{Bc} = 509 \pm 8 \pm 12 \text{ fs}$$

[LHCb Collaboration, EPJC 74 (2014) 2839]

- Agree with theoretical expectations

Contents:

- The Bc Meson
- **Bc Production**
- Bc Decays
- Conclusion & Outlook

Bc Production

- Up to date, Bc mesons have not been observed in machines, e.g. LEP, other than hadronic colliders

- Before next generation leptonic colliders appear, hadronic production would be the only source of Bc production

Bc Inclusive Hadroproduction

- For heavy quark production, the pQCD is applicable, order by order

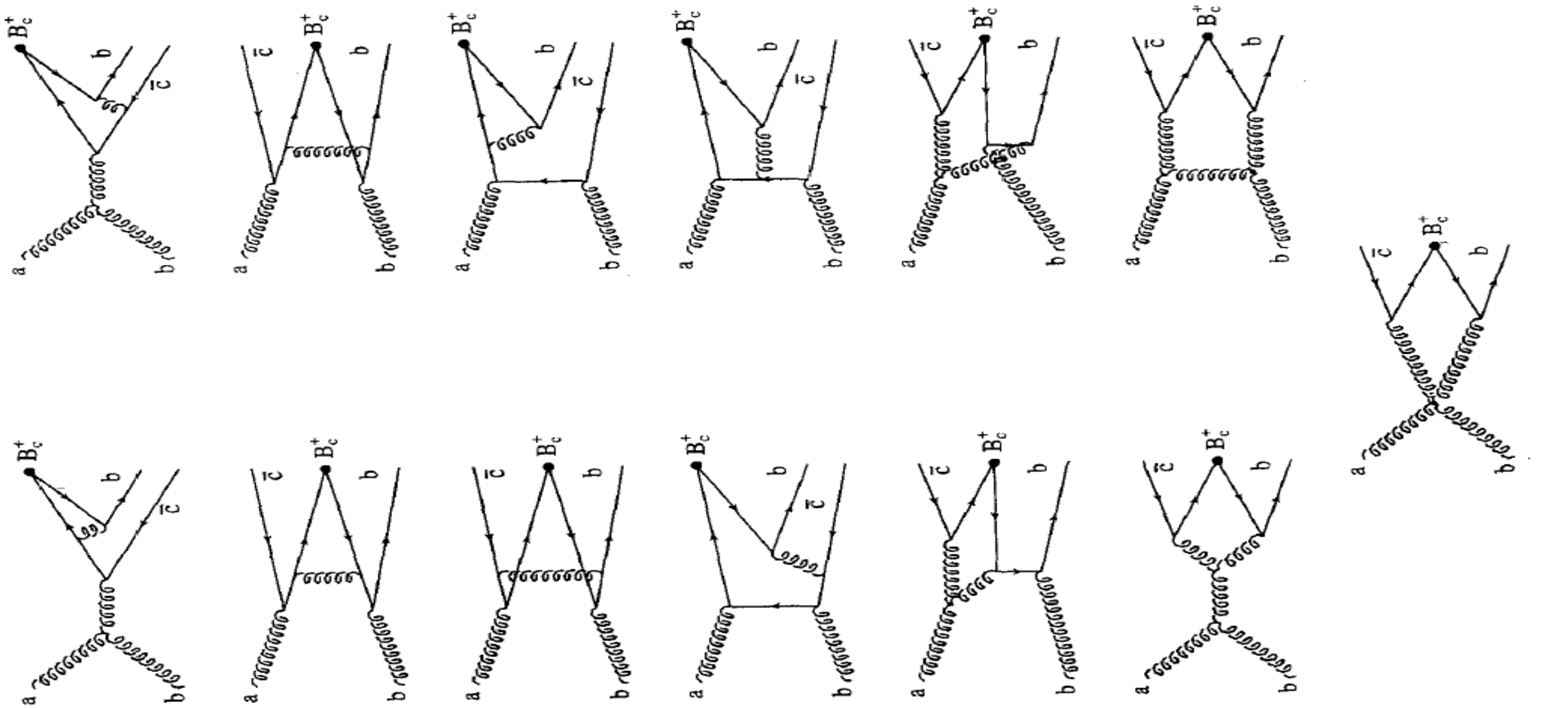
- The combination of two produced heavy quarks into Bc meson experiences nonpertubative effect, which can be estimated by NRQCD formalism or color-singlet model

Bc Inclusive Hadroproduction

- By NRQCD, the relativistic corrections can in principle be accounted for to any order

- while for NRQCD, the operator expansion in relative velocity between heavy quarks may not converge well

Bc Inclusive Hadroproduction



Feynman diagrams of Bc hadroproduction

Bc Inclusive Hadroproduction

	CTEQ6L	GRV98L	MRST2001L	CTEQ6L	GRV98L	MRST2001L
-	$Q^2 = \hat{s}/4$			$Q^2 = p_T^2 + m_{B_c}^2$		
-	TEVATRON					
$\sigma_{B_c(1^1S_0)}$	3.79	3.27	3.40	5.50	4.54	4.86
$\sigma_{B_c^*(1^3S_1)}$	9.07	7.88	8.16	13.4	11.1	11.9
-	LHC					
$\sigma_{B_c(1^1S_0)}$	53.1	53.9	47.5	71.1	70.0	61.4
$\sigma_{B_c^*(1^3S_1)}$	130.	131.	116.	177.	172.	153.

The LO total cross section for hadronic production of Bc and Bc* at Tevatron and LHC, in unit of nb

[C.H. Chang and X.G. Wu, Eur.Phys. J.C. 38,267(2004)]

Bc Inclusive Hadroproduction

➢ The transverse momentum distribution of Bc hadroproduction, and with various paramter inputs, have been evaluated in the literature

[C.H. Chang and Y.Q. Chen, Phys. Rev. D48, 4230(1993)]

[C.H. Chang, et al., Phys. Lett. B364, 78(1996)]

[K.Kolodziej, A. Leike and R. Rueckl, Phys. Lett.B355, 337(1995)]

[A.V. Berezhnoy, V.V. Kiselev, and A.K. Likehoded, Z.Phys.A356, 79(1996)]

[S.P. Baranov, Phys. Rev. D56, 3046(1997)]

…..

Bc Inclusive Hadroproduction

➤ The excited P-wave Bc production via color-singlet and also color-octet component s were evaluated, and it as found the production rate at the LHC is quite large

-	$\lvert({}^1S_0)_1\rangle$	$\lvert({}^3S_1)_1\rangle$	$\lvert({}^1S_0)_8 g\rangle$	$\lvert({}^3S_1)_8 g\rangle$	$\lvert({}^1P_1)_1\rangle$	$\lvert({}^3P_0)_1\rangle$	$\lvert({}^3P_1)_1\rangle$	$\lvert({}^3P_2)_1\rangle$
LHC	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

Total cross section for hadronic production of p-wave Bc mesons at Tevatron and LHC, in unit of nb

[C.H. Chang, CFQ, J.X. Wang and X.G. Wu, Phys.Rev. D 71, 074012 (2005)]

Bc Inclusive Hadroproduction

- It was notice that confront to experimental measurement of Bc hadroproduction cross section and it semileptonic decay rate, there exists an disagreement between theoretical expectation and data

  Theory: $\frac{\sigma(B_c)}{\sigma(B)} \sim 10^{-3}$

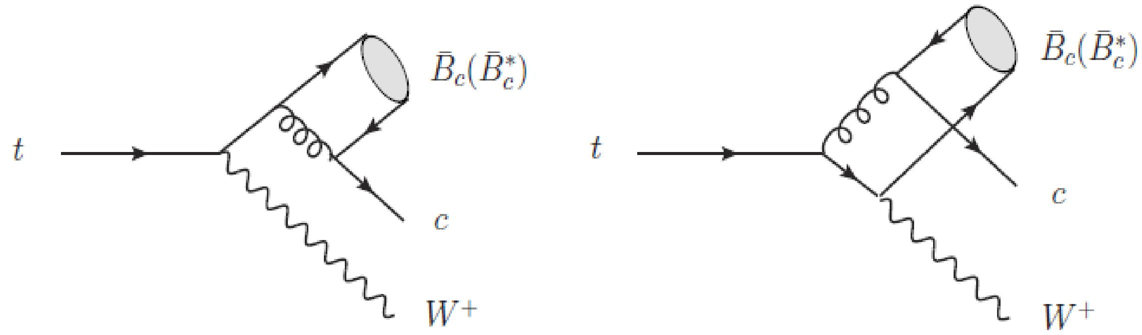
  Experiment: $\frac{\sigma(B_c)}{\sigma(B)} = R_e \cdot \frac{Br(B \to J/\psi K^{\pm})}{Br(B_c \to J/\psi e^{\pm} \nu)} \simeq 1.4 \cdot 10^{-2}$

- detailed study with LHC data is necesary

[A. Rakitin and S. Koshkarev, Phys. Rev. D81, 014005(2010)]

Bc Indirect production

➢ Bc production in top decay

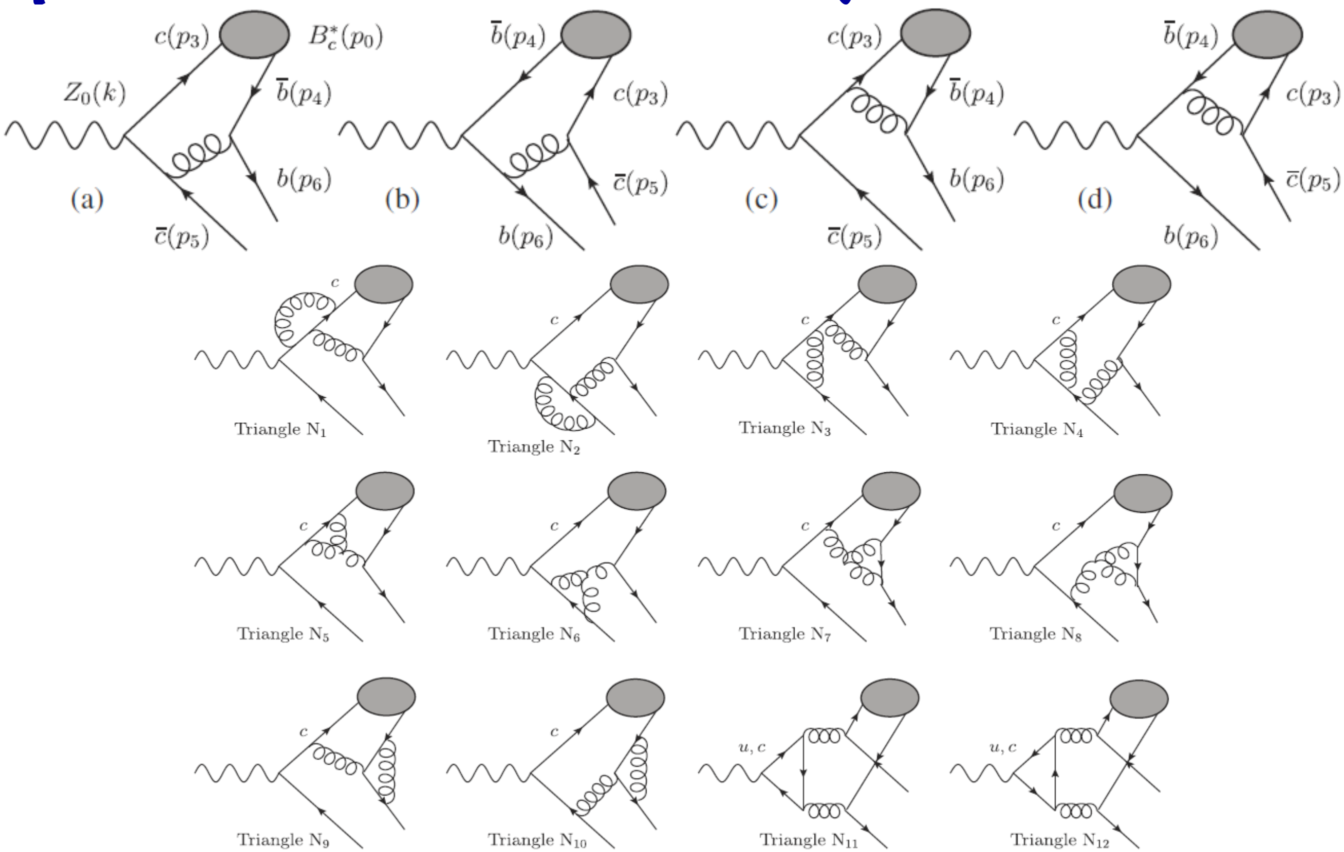


	$t \to \bar{B}_c^* + W^+ + c$		$t \to \bar{B}_c + W^+ + c$		$t \to \Upsilon + W^+ + b$		$t \to \eta_b + W^+ + b$	
μ	$2m_c$	m_t	$2m_c$	m_t	$2m_b$	m_t	$2m_b$	m_t
Γ_{LO}	0.793MeV	0.151MeV	0.572MeV	0.109MeV	26.8keV	9.54keV	27.1keV	9.67keV
Γ_{NLO}	0.619MeV	0.307MeV	0.514MeV	0.227MeV	52.3keV	28.2keV	34.3keV	24.5keV

[P. Sun, L.P. Sun and CFQ, Phys. Rev. D81, 114035(2010)],……

Bc Indirect production

➢ Bc production in Z^0 decay



[J. Jiang, L.B. Chen and CFQ, Phys. Rev. D91, 034033 (2015)], …..

Bc Indirect production

$$\mathrm{Br}_{\mathrm{LO}}(Z^0 \to B_c + \bar{c}b) = \frac{\Gamma_{\mathrm{LO}}(B_c)}{\Gamma_Z} = 2.9 \times 10^{-5},$$

$$\mathrm{Br}_{\mathrm{NLO}}(Z^0 \to B_c + \bar{c}b) = \frac{\Gamma_{\mathrm{NLO}}(B_c)}{\Gamma_Z} = 3.1 \times 10^{-5},$$

$$\mathrm{Br}_{\mathrm{LO}}(Z^0 \to B_c^* + \bar{c}b) = \frac{\Gamma_{\mathrm{LO}}(B_c^*)}{\Gamma_Z} = 3.6 \times 10^{-5},$$

$$\mathrm{Br}_{\mathrm{NLO}}(Z^0 \to B_c^* + \bar{c}b) = \frac{\Gamma_{\mathrm{NLO}}(B_c^*)}{\Gamma_Z} = 4.8 \times 10^{-5},$$

- Bc is measurable in future CEPC or Z-facotry

Bc Indirect production

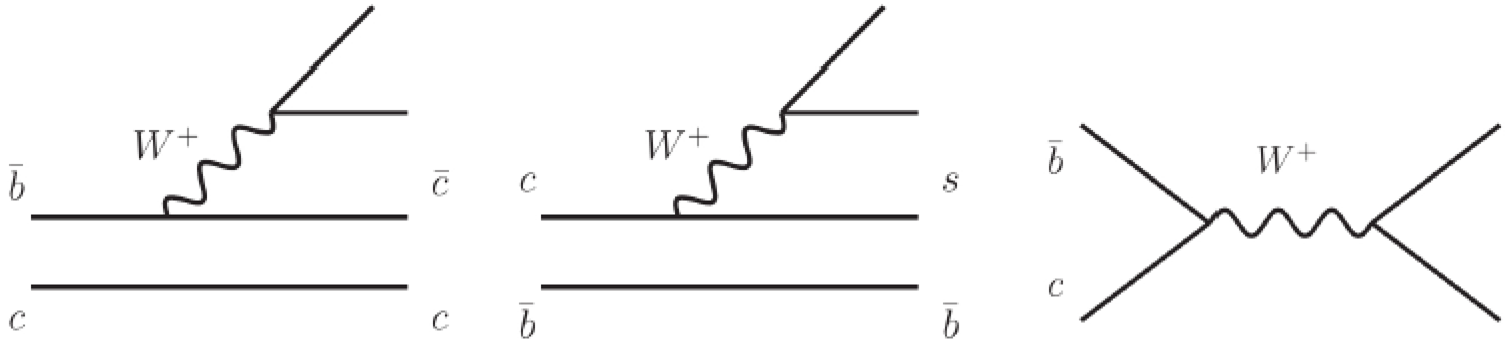
◆There are still several other possibilities of Bc production, like:

I. Bc production in W decay;
II. Bc production in Higgs decay;
III. Bc production in photon-photon collision, the photon collider
IV. …

Contents:

- The Bc Meson
- Bc Production
- **Bc Decays**
- Conclusion & Outlook

Bc Decays



- ➢ Feynman diagrams of Bc decays with c-quark as a spectator, b-quark as a spectator and annihilation process

[Lucio Anderlini, arXiv: 1407.8066]

Bc Decays

$\Gamma(J/\psi(1S)l^{+}\nu_{l}anything)/\Gamma_{total}\times Br(\bar{b}\to B_{c})$	$(5.2^{+2.4}_{-2.1})\times 10^{-5}$	CDF ,98
$\Gamma(J/\psi(1S)K^{+})/\Gamma(J/\psi(1S)\pi^{+})$	$0.069\pm 0.019\pm 0.005$	$LHCb$,13
$\Gamma(J/\psi(1S)K^{+}K^{-}\pi^{+})/\Gamma(J/\psi(1S)\pi^{+})$	$0.53\pm 0.10\pm 0.05$	$LHCb$,13
$\Gamma(\psi(2S)\pi^{+})/\Gamma(J/\psi(1S)\pi^{+})$	$0.250\pm 0.068\pm 0.015$	$LHCb$,13
$\Gamma(J/\psi(1S)D_{s}^{+})/\Gamma(J/\psi(1S)\pi^{+})$	$2.90\pm 0.57\pm 0.24$	$LHCb$,13
$\Gamma(J/\psi(1S)D_{s}^{*+})/\Gamma(J/\psi(1S)D_{s}^{+})$	$2.37\pm 0.56\pm 0.10$	$LHCb$,13
$\Gamma(B_{s}^{0}\pi^{+}/Br(\bar{b}\to B_{s}))/\Gamma_{total}\times Br(\bar{b}\to B_{c})$	$(2.37\pm 0.31\pm 0.11^{+0.17}_{-0.13})\times 10^{-3}$	$LHCb$,13
$\Gamma(J/\psi(1S)3\pi^{+}2\pi^{-})/\Gamma(J/\psi(1S)\pi^{+})$	$1.74\pm 0.44\pm 0.24$	$LHCb$,14
$\Gamma(J/\psi(1S)p\bar{p}\pi^{+})/\Gamma(J/\psi(1S)\pi^{+})$	$0.143^{+0.039}_{-0.034}\pm 0.013$	$LHCb$,14
$\Gamma(B_{c}^{+}\to J/\psi(1S)\pi^{+})/\Gamma(B^{+}\to J/\psi(1S)K^{+})$	$(6.83\pm 0.18\pm 0.09)\times 10^{-3}$	$LHCb$,14
$\Gamma(J/\psi(1S)\pi^{\pm}\pi^{\pm}\pi^{\mp})/\Gamma(J/\psi(1S)\pi^{\pm})$	$2.55\pm 0.80\pm 0.33^{+0.04}_{-0.01}$	CMS ,14

Observed Bc decays channels

Bc Decays

$\Gamma(J/\psi(1S)a_1(1260))/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<1.2\times10^{-3}(90\%CL)$	$OPAL,98$
$\Gamma(D^*(2010)^+\bar{D}^0)/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<6.2\times10^{-3}(90\%CL)$	$ALEP,98$
$\Gamma(D^+K^{*0})/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<0.2\times10^{-6}(90\%CL)$	$LHCb,13$
$\Gamma(D^+\bar{K}^{*0})/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<0.16\times10^{-6}(90\%CL)$	$LHCb,13$
$\Gamma(D_s^+K^{*0})/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<0.28\times10^{-6}(90\%CL)$	$LHCb,13$
$\Gamma(D_s^+\bar{K}^{*0})/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<0.4\times10^{-6}(90\%CL)$	$LHCb,13$
$\Gamma(D_s^+\phi)/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<0.32\times10^{-6}(90\%CL)$	$LHCb,13$
$\Gamma(K^+K^0)/\Gamma_{total}\times Br(\bar{b}\to B_c)$	$<4.6\times10^{-7}(90\%CL)$	$LHCb,13$

Unobserved Bc decays limits

Bc Decays

- Though $m_b > m_c$, since CKM matrix elements $|V_{bc}| \gg |V_{cs}|$, b-quark spectator process is dominant over c-quark spectator process

- The Bc decays can therefore be classified as

$$\Gamma(Bc \to X) = \Gamma(b \to X) + \Gamma(c \to X) + \Gamma(ann) + \Gamma(Int)$$

Bc Decays

B_c decay mode	OPE, %	PM, %	SR, %
$\bar{b} \to \bar{c} l^+ \nu_l$	3.9 ± 1.0	3.7 ± 0.9	2.9 ± 0.3
$\bar{b} \to \bar{c} u \bar{d}$	16.2 ± 4.1	16.7 ± 4.2	13.1 ± 1.3
$\sum \bar{b} \to \bar{c}$	25.0 ± 6.2	25.0 ± 6.2	19.6 ± 1.9
$c \to s l^+ \nu_l$	8.5 ± 2.1	10.1 ± 2.5	9.0 ± 0.9
$c \to s u \bar{d}$	47.3 ± 11.8	45.4 ± 11.4	54.0 ± 5.4
$\sum c \to s$	64.3 ± 16.1	65.6 ± 16.4	72.0 ± 7.2
$B_c^+ \to \tau^+ \nu_\tau$	2.9 ± 0.7	2.0 ± 0.5	1.8 ± 0.2
$B_c^+ \to c \bar{s}$	7.2 ± 1.8	7.2 ± 1.8	6.6 ± 0.7

Branching ratios of different Bc decay modes in the estimation of OPE, potential model(PM), and QCD Sum Rules(SR) **[I.P. Gouz, et al., arXiv: 0211432]**

Bc Decays: example 1

Bc to charmonium + light meson exclusive processes

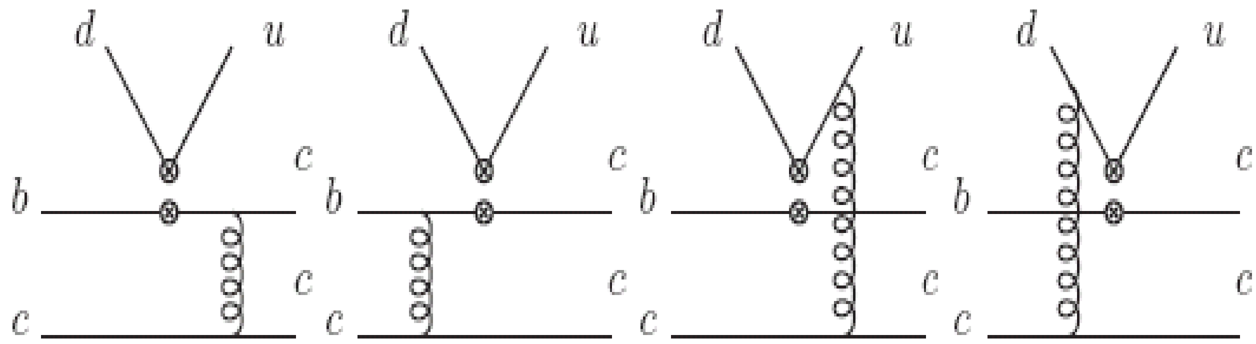


Figure 1: The quark-level Feynman diagrams in leading order for $B_c \to J/\Psi(\eta_c)\pi$. The 4-vertex "$\otimes$ $\otimes$" denotes the insertion of a 4-fermion operator Q_i. And the vivid figure in hadronic level is: B_c^+ annihilated to a pair of $\bar{b}c$ quarks; then strong and weak interactions appeared among quarks, followed by the annihilation of the $\bar{b}$ quark and the creation of a $\bar{c}$ and a pair of $u\bar{d}$ quarks; at last, $u\bar{d}$ bound to Pion while $c\bar{c}$ to S-Wave charmonium.

[CFQ, P.Sun, D.S.Yang, and R.L. Zhu, Phys.Rev.D89,034008(2014)]

Bc Decays: example 1

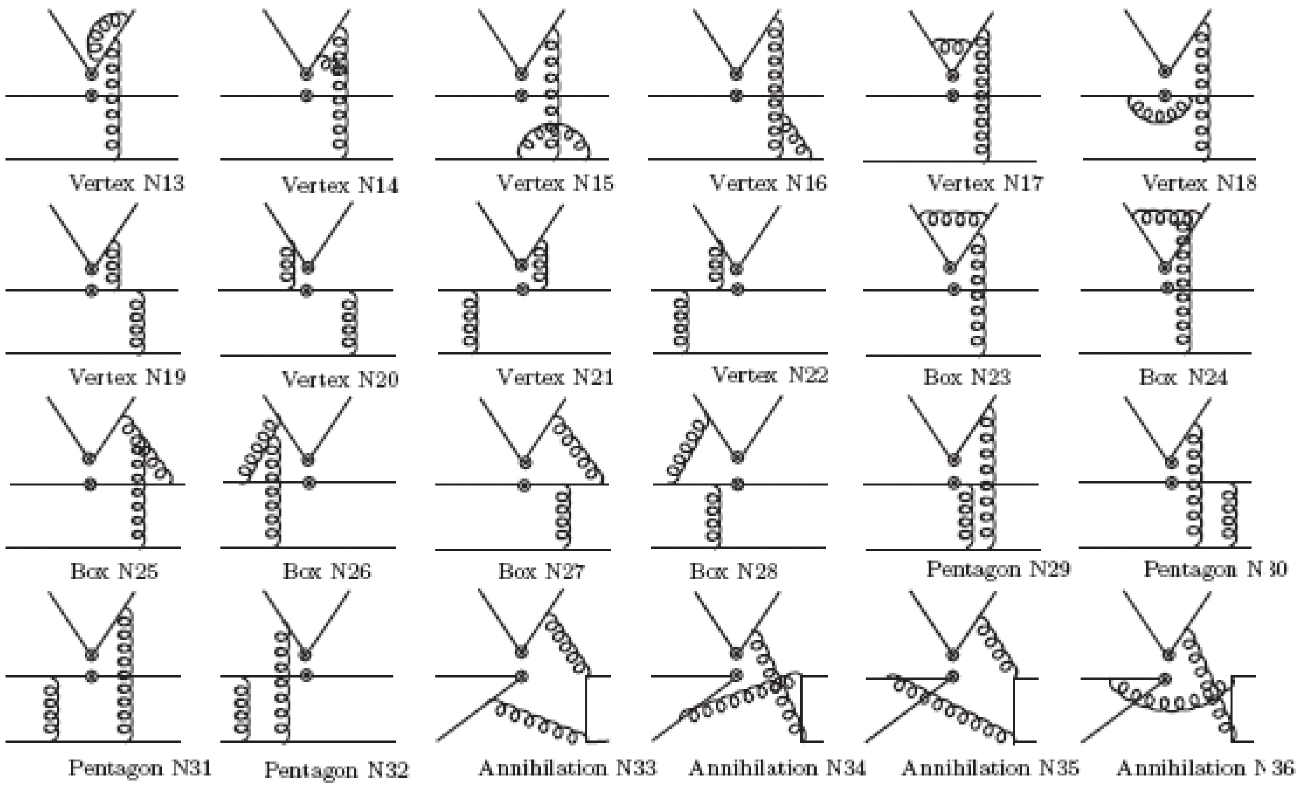


Figure 4: twenty-four of the sixty-five one loop non-factorizable diagrams contribute to $\langle Q_8 \rangle$. Another twenty-three diagrams can be obtained by interchanging u and d quark. In addition, the left eighteen comes from the diagrams Vertex N1 to Pentagon N9 in Figure 3 and their symmetrical partners.

Bc Decays: example 1

Table 3: Branching ratios (in ‰) of exclusive non-leptonic B_c decays into ground state charmonium states. For the lifetime of the B_c we take $\tau(B_c) = 0.453$ ps. In our work, we chose the quantities $m_c = 1.4$ GeV, $m_b = 4.9$ GeV and $\mu = 3$ GeV. The uncertainty in the first column of the value is from varying the renormalization scale μ from 2.5 GeV to 5 GeV; while the uncertainty in the second column comes from varying the quark mass m_c/m_b from 1.5/4.8 to 1.3/5.0.

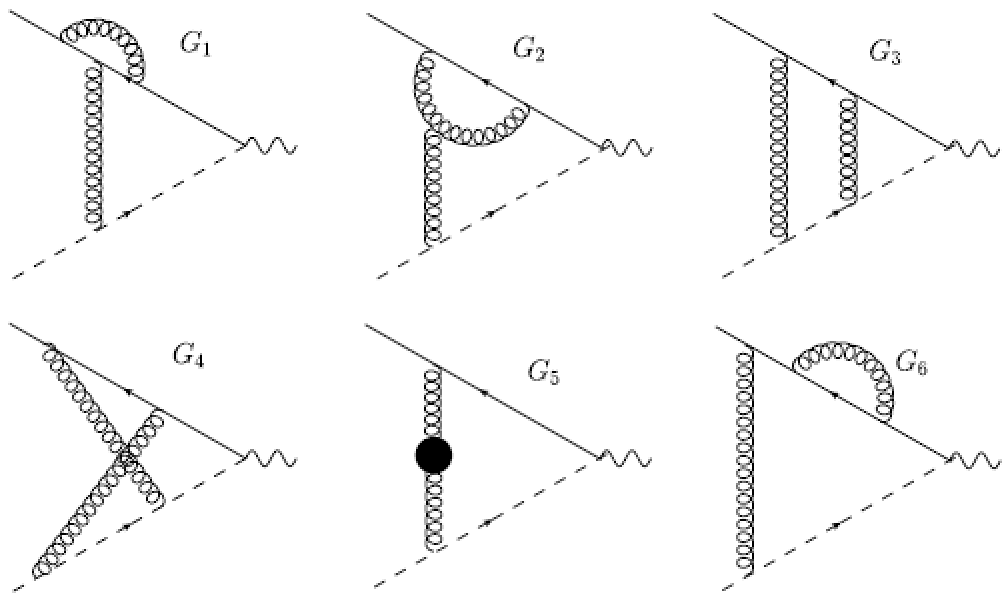
Mode	This work(NLO)	LO	[37,38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]
$B_c^+ \to \eta_c \pi^+$	$5.19^{+0.44+0.55}_{-1.01-0.34}$	2.95	2.0	1.8	1.3	0.26	0.85	1.4	1.9	2.1
$B_c^+ \to \eta_c \rho^+$	$14.5^{+1.29+1.53}_{-2.92-0.95}$	7.89	4.2	4.9	3.0	0.67	2.0	3.3	4.5	-
$B_c^+ \to \eta_c K^+$	$0.38^{+0.03+0.04}_{-0.07-0.02}$	0.21	0.13	0.14	0.13	0.02	0.06	0.11	0.15	-
$B_c^+ \to \eta_c K^{*+}$	$0.77^{+0.07+0.08}_{-0.16-0.05}$	0.41	0.20	0.25	0.21	0.04	0.11	0.18	0.25	-
$B_c^+ \to J/\psi \pi^+$	$2.91^{+0.15+0.40}_{-0.42-0.27}$	2.22	1.3	1.8	0.73	1.3	0.61	1.1	1.7	1.9
$B_c^+ \to J/\psi \rho^+$	$8.08^{+0.45+1.09}_{-1.21-0.73}$	6.03	4.0	5.3	2.1	3.7	1.6	3.1	4.9	-
$B_c^+ \to J/\psi K^+$	$0.22^{+0.01+0.03}_{-0.03-0.02}$	0.16	0.11	0.14	0.07	0.07	0.05	0.08	0.13	-
$B_c^+ \to J/\psi K^{*+}$	$0.43^{+0.02+0.06}_{-0.07-0.04}$	0.32	0.22	0.29	0.16	0.20	0.10	0.18	0.28	-

The NLO corrections to these processes are big

Bc Decays: example 2

Bc leptonic two-body decays

$$\Gamma(B_c \to \ell^+ \nu_\ell) = \frac{1}{8\pi} |V_{bc}|^2 G_F^2 M f_{B_c}^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{M^2}\right)^2$$



[L.B. Chen and CFQ, Phys.Lett.B748, 443(2015)]

Bc Decays: example 2

In the end, we find up to two-loop order

$$f_{B_c} = (1 - 1.39(\frac{\alpha_s(m_b)}{\pi}) - 23.7(\frac{\alpha_s(m_b)}{\pi})^2) f_{B_c}^{NR}$$

$$Br(B_c \to \tau^+ \nu_\tau) \approx 1.8 \times 10^{-2}\, ,\; Br(B_c \to \mu^+ \nu_\mu) \approx 7.6 \times 10^{-5}$$

Precise measurements on Bc leptonic decays are important to determine decay constant, and even to CKM matrix element V_{bc}

[L.B. Chen and CFQ, Phys.Lett.B748, 443(2015)]

Contents:

- The Bc Meson
- Bc Production
- Bc Decays
- **Conclusion & Outlook**

Conclusion & Outlook

◆The door to the mysterious Bc world is just opened , there are many interesting questions waiting for answer

Experiment:

➢ The Bc mass spectrum is far from complete in experiment

➢ Precise measurement on Bc production cross section may tell us more about the production mechanism and pQCD information

Conclusion & Outlook

- The LHC experiments now restart data-taking on higher energy and luminosity. Huge number of Bc meson will be produced and measured. Many unobserved Bc decay channels may become accessible
- Beyond LHC, next-generation machine may explore more subtle natures of Bc meson, e.g., CP vilolation, FCNC proceese, CKM matrix element measurement, etc.

Conclusion & Outlook

Theory:

- The NLO QCD corrections to Bc production in gluon-gluon fusion process is very important
- Effective theory more suitable for Bc physics is necessary
- For Bc meson hadronic decays, higher order corrections and factorization theorem are meaningful

The end

Contents:

1）Bc Exclusive Decays to Charmonia and Light Mesons in QCD Factorization at Next-to-Leading Order Accuracy

Cong-Feng Qiao, Peng Sun, Deshan Yang, Rui-Lin Zhu. arXiv:1209.5859

2）Estimation of Semileptonic Decays of Bc Meson to S-wave Charmonia with NRQCD

Cong-Feng Qiao, Rui-Lin Zhu， arXiv:1208.5916

3）The NLO QCD Corrections to Bc Meson Production in Z 0   Decays

Cong-Feng Qiao, Li-Ping Sun, Rui-Lin ， JHEP 1108 (2011) 131

4）NLO QCD Corrections to Bc-to-Charmonium Form Factors

Cong-Feng Qiao, Peng Sun， JHEP 1208 (2012) 087

5）W Boson Inclusive Decays to Quarkonium at the LHC

Cong-Feng Qiao, Li-Ping Sun, De-Shan Yang, Rui-Lin Zhu， Eur.Phys.J. C71 (2011) 1766

6）The Next-to-Leading Order Corrections to Top Quark Decays to Heavy Quarkonia

Peng Sun, Li-Ping Sun, Cong-Feng Qiao， Phys.Rev. D81 (2010) 114035

7）**Hadronic production of B c (B*c) meson induced by the heavy quarks inside the collision hadronsuracy**

Chao-Hsi Chang, Cong-Feng Qiao, Jian-Xiong Wang, Xing-Gang, **Phys.Rev. D72 (2005) 114009**

8）**The Color-octet contributions to P-wave Bc meson hadroproduction**

Chao-Hsi Chang, Cong-Feng Qiao, Jian-Xiong Wang,Xing-Gang Wu, **Phys.Rev. D71 (2005) 074012**

9）**Top quark decays into heavy quark mesons**

Cong-Feng Qiao, Chong Sheng Li, Kuang-Ta Chao, **Phys.Rev. D54 (1996) 5606-5610**

10) **Two-loop QCD corrections to Bc leptonic decays**

Cong-Feng Qiao and Long-Bin Chen, **Phys.Lett. B748 (2015) 433**