Two-body doubly charmful baryonic B decays with SU(3) flavor symmetry

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arXiv:2309.16919
(to appear in JHEP)

Outline:
1. Introduction
2. Formalism
3. Some results
4. Summary

Introduction

2-body baryonic B decays

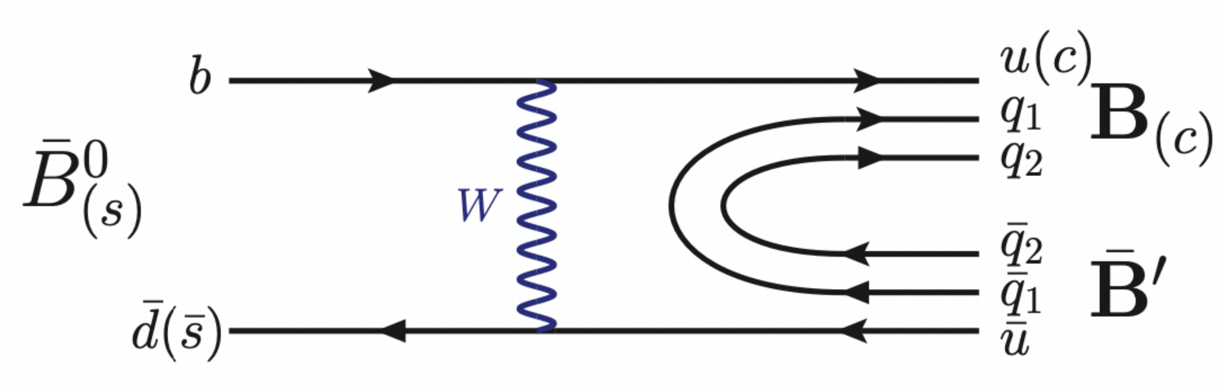
- $B \to \mathbf{B}\bar{\mathbf{B}}'$, $B \to \mathbf{B}_c\bar{\mathbf{B}}'$, $B \to \mathbf{B}_c\bar{\mathbf{B}}'_c$
- Decay configurations

Tree level

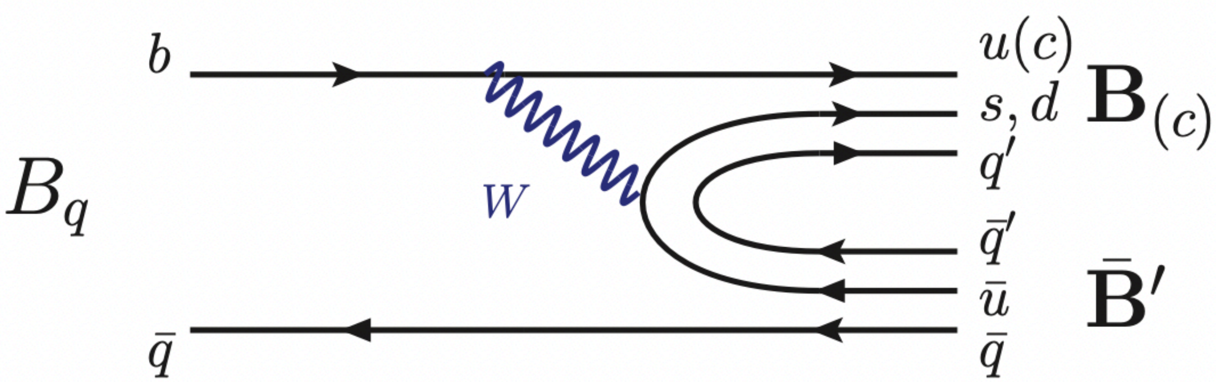
W-boson exchange ($W_{\rm ex}$)

W-boson annihilation ($W_{\rm an}$)

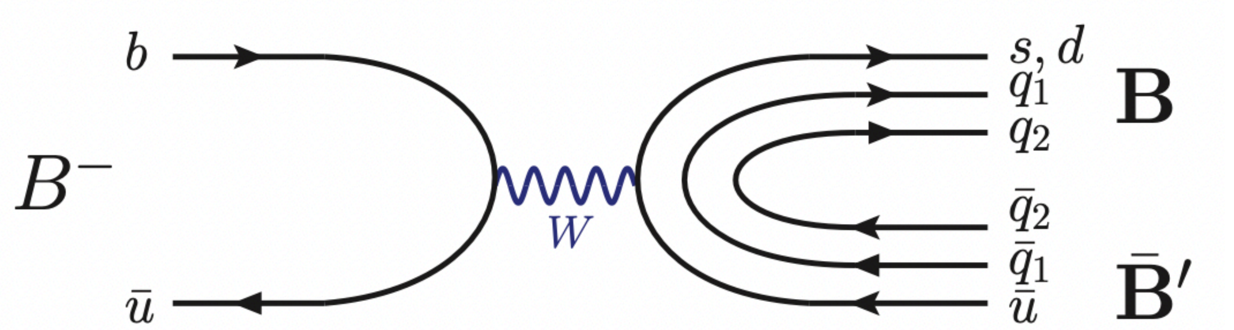
W-boson emission ($W_{\rm em}$)



(a)



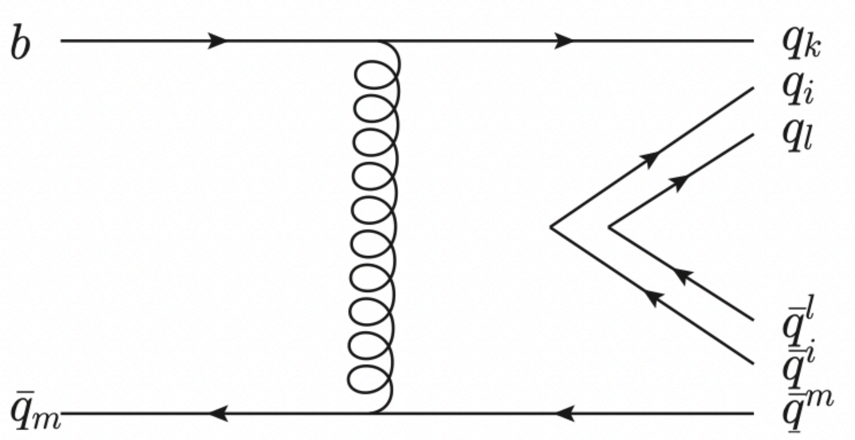
(b)

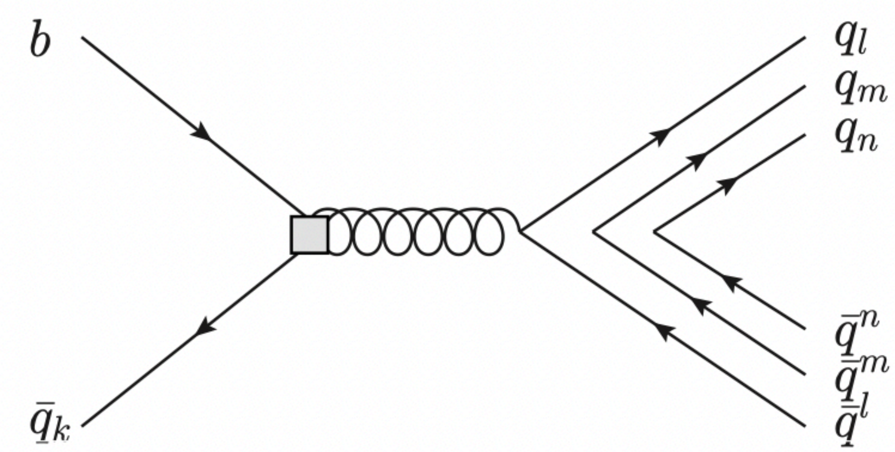


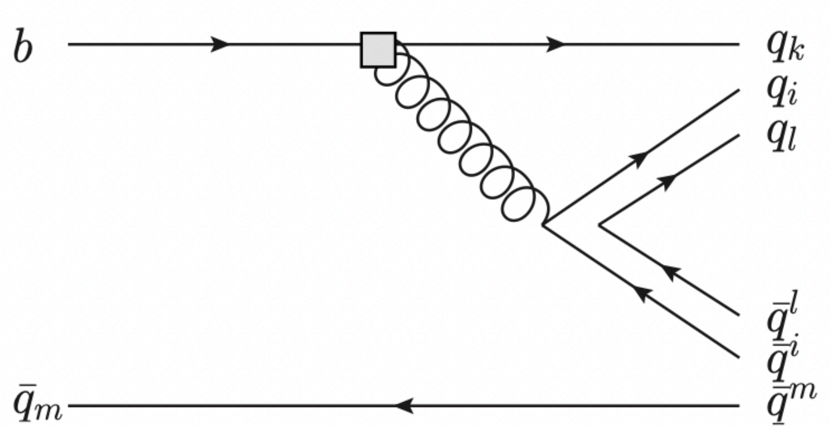
(c)

Penguin level

$G_{\rm ex}$, $G_{\rm an}$, $G_{\rm em}$ [Diagrams from C.K. Chua, PRD106, 036015 (2022).]



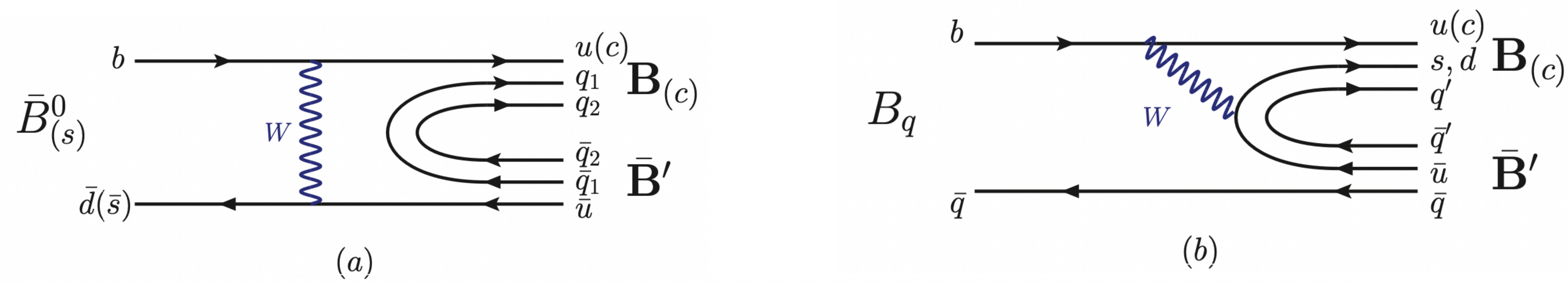




- $B \to \mathbf{B}\bar{\mathbf{B}}'$, suppressed.

$\mathcal{B}(\bar{B}^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$

LHCb, PRD108, 012007 (2023).



- $\mathbf{B}\bar{\mathbf{B}}'$ formation tends to occur

around the threshold area: $m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$

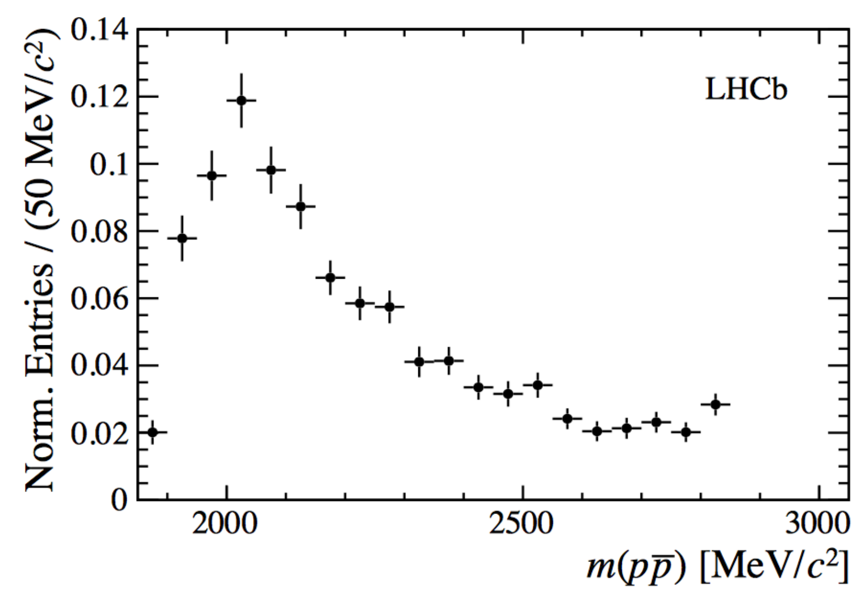
$\mathbf{B}(B \to \mathbf{B}\bar{\mathbf{B}}'M)$ with M releasing energy

for $m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$, enhanced to 10^{-6} (threshold effect).

$\mathbf{B}(B \to \mathbf{B}\bar{\mathbf{B}}')$, $\mathbf{B}\bar{\mathbf{B}}'$ formation at m_B scale,

far from the threshold area, suppressed.

W.S. Hou and A. Soni, PRL86, 4247 (2001).



• Threshold effect, mechanism

Gluon propagator, required to provide extra $q\bar{q}'$ in $\mathbf{B\bar{B}'}$,

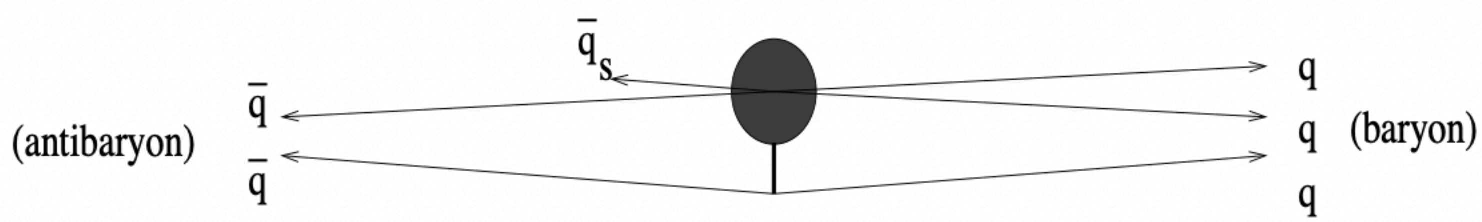
leading to $1/p^2$ with p^2 as energy transfer squared.

$1/(m_{\mathbf{B}} + m_{\mathbf{\bar{B}'}})^2 > 1/m_B^2$ corresponds to

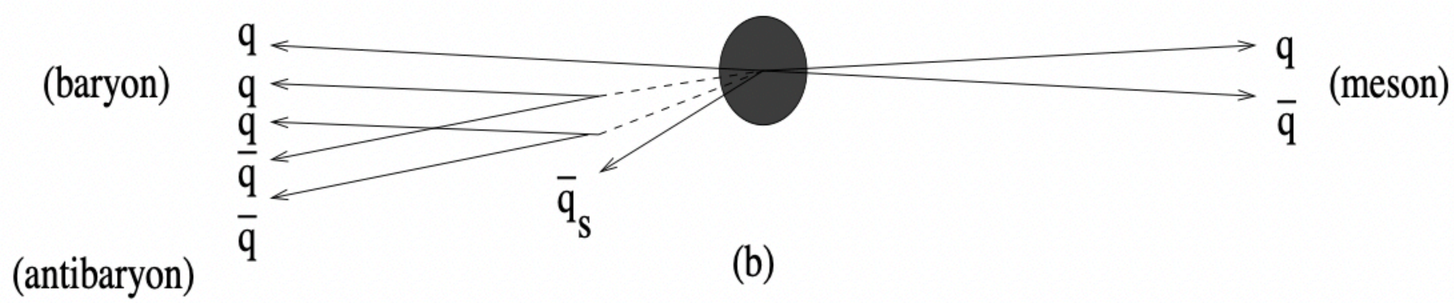
$\mathcal{B}(B \to \mathbf{B\bar{B}'}M) \simeq 100\mathcal{B}(B \to \mathbf{B\bar{B}'})$

M. Suzuki, "Partial waves of baryon-antibaryon

in three-body B meson decay," J. Phys. G **34**, 283 (2007).



(a)



(b)

- Semileptonic $B \to \ell\bar{\nu}$ decay

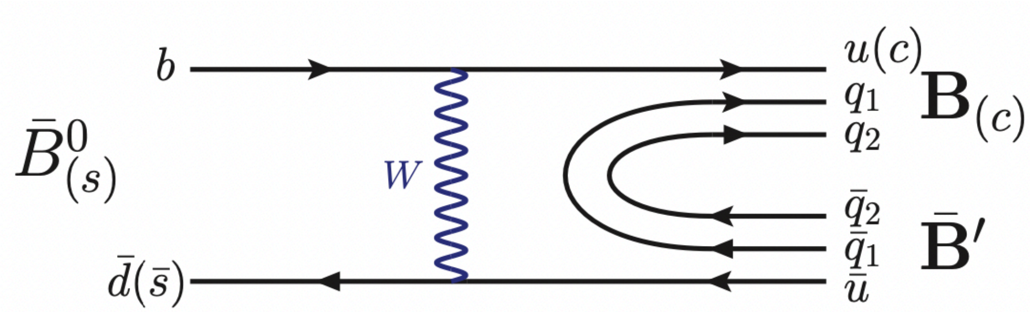
$\mathcal{M}_{\rm wan}(B \to \ell\bar{\nu}) \propto m_\ell \bar{u}_\ell (1+\gamma_5) v_{\bar{\nu}}$, $m_\mu = 106$ MeV.

$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) < 8.6 \times 10^{-7}$ (pdg), chiral suppression.

$\mathcal{M}_{\rm wex(wan)}(B \to {\bf B}\bar{\bf B}')$

$\propto m_- \langle {\bf B}\bar{\bf B}' | \bar{q} q' | 0 \rangle + m_+ \langle {\bf B}\bar{\bf B}' | \bar{q}\gamma_5 q' | 0 \rangle$, $m_\mp = m_q \mp m_{q'}$

for $\bar{B}^0 \to p\bar{p}$, $m_+ = m_u + m_d \simeq 10$ MeV.



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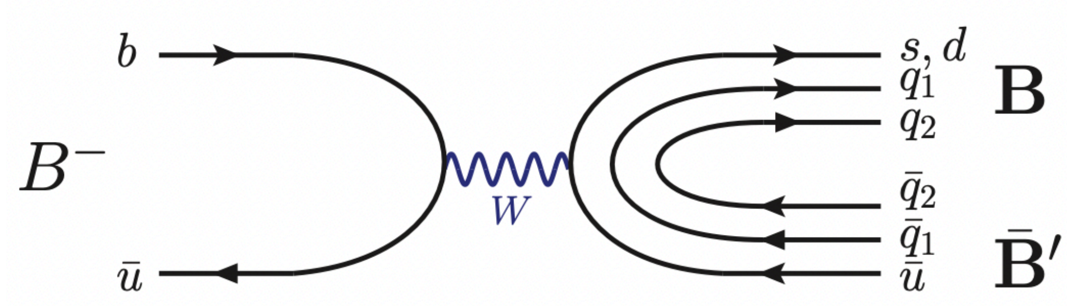


(c)

One hence neglects

$W_{\rm ex(an)}$ for $B \to ({\bf B}\bar{\bf B}', {\bf B}_c\bar{\bf B}', {\bf B}_c\bar{\bf B}'_c)$, and

$G_{\rm ex(an)}$ for $B \to {\bf B}\bar{\bf B}'$.

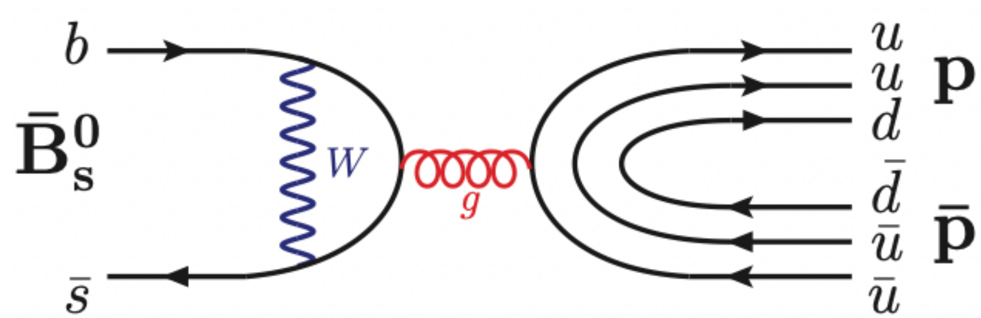
- Counter example:

$$\mathcal{M}(B^- \to \Lambda\bar{p}) = C_{\rm w}\langle\Lambda\bar{p}|(\bar{s}u)_{S+P}|0\rangle\langle 0|(\bar{u}b)_{S-P}|B^-\rangle$$

$$\mathcal{M}(B \to \Lambda\bar{p}\pi) = C_{\rm w}\langle\Lambda\bar{p}|(\bar{s}u)_{S+P}|0\rangle\langle \pi|(\bar{u}b)_{S-P}|B\rangle$$

$$\sqrt{2}C_{\rm w} \equiv G_F V_{tb} V_{ts}^* 2a_6$$

$$\mathcal{B}(B^- \to \Lambda\bar{p}) = (2.4^{+1.0}_{-0.9}) \times 10^{-7}\ \text{(pdg)}$$



- pure $G_{\rm an}$ decay $\bar{B}^0_s \to p\bar{p}$ as a test:

Hsiao, Geng, PRD91, 077501 (2015).

Nonetheless, it is measured that

$$\mathcal{B}(\bar{B}^0_s \to p\bar{p}) < 4.4\,(5.1) \times 10^{-9}\ \text{at 90 (95)\% C.L.}$$

LHCb, PRD108, 012007 (2023).

Singly charmful $B \to \mathbf{B}_c\bar{\mathbf{B}}'$ decays

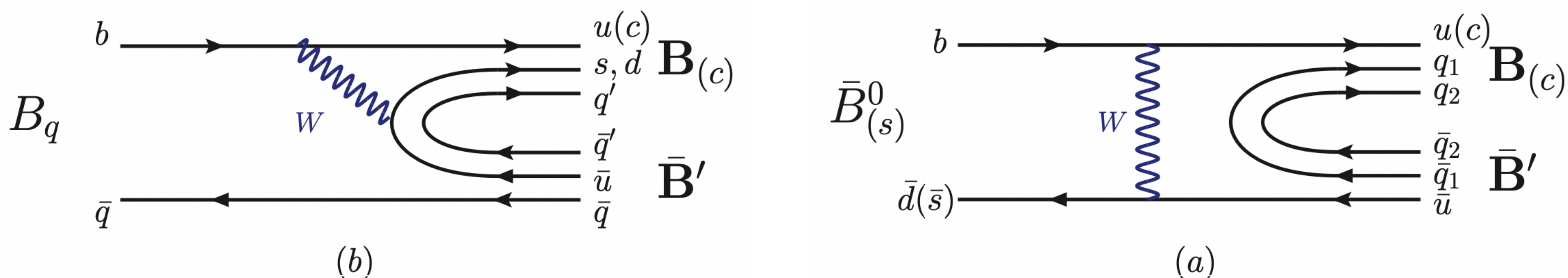
- keeping $W_{\rm em}$:

H.Y. Cheng and K.C. Yang, PRD67, 034008 (2003)

"Hadronic B decays to charmed baryons"

X.G. He, T. Li, X.Q. Li, Y.M. Wang, PRD75, 034011 (2007)

"Calculation of BR($\bar{B}^0 \to \Lambda_c^+ + \bar{p}$) in the PQCD approach"



- keeping $W_{\rm ex}$:

Hsiao, Tsai, C.C. Lih and E. Rodrigues, JHEP **04**, 035 (2020)

"Testing the W-exchange mechanism with two-body baryonic B decays"

$B \to \mathbf{B}_c\bar{\mathbf{B}}'$ the 2nd counterexample:

- $\mathcal{M}_{\rm wex(wan)}(B \to \mathbf{B}_c\bar{\mathbf{B}}') \propto m_c\langle \mathbf{B}_c\bar{\mathbf{B}}'|\bar{c}(1+\gamma_5)q|0\rangle$

$m_c \gg m_q$ alleviating helicity suppression.

- $\mathcal{B}(B \to \mathbf{B}_c\bar{\mathbf{B}}') = G_F^2|\vec{p}_{\mathbf{B}_c}|\tau_B/(8\pi)|a_2 V_{cb}V_{uq}^*|^2 f_B^2$

$$\times m_+^2\left[\mathcal{R}_m f_1^2\left(1-\frac{m_+^2}{m_B^2}\right)+g_1^2\left(1-\frac{m_-^2}{m_B^2}\right)\right]$$

$\mathcal{R}_m \equiv (m_-/m_+)^2$, $m_\pm^2 = (m_{\mathbf{B}_c} \pm m_{\bar{\mathbf{B}}'})^2$

- pure $W_{\rm ex}$ decays:

$\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+\bar{p}, \bar{B}^0 \to \Xi_c^+\bar{\Sigma}^-) \simeq 10^{-5}$

much more reachable than $\mathcal{B}(B \to \mathbf{B}\bar{\mathbf{B}}') \sim 10^{-8} - 10^{-7}$

Experimentally, existence of $W_{\rm ex}$ has not been confirmed.

2-body doubly charmful baryonic $B \to \mathbf{B}_c \bar{\mathbf{B}}'_c$ decays

- neglecting $W_{\rm ex}$:

H.Y. Cheng, C.K. Chua and S.Y. Tsai, PRD73, 074015 (2006),

"Doubly charmful baryonic B decays."

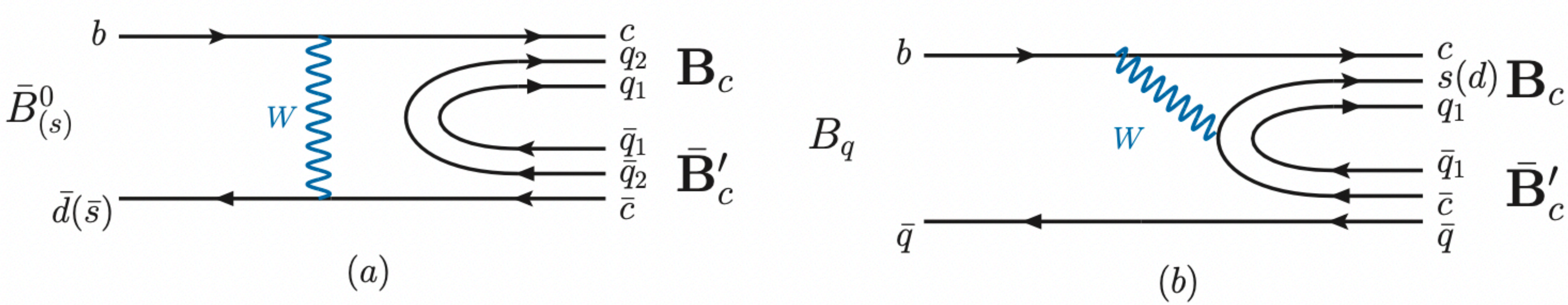
Belle, PRD77, 051101 (2008), "Search for $\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$ decay at Belle"

H.Y. Cheng, C.K. Chua and Y.K. Hsiao,

PRD79, 114004 (2009), "Study of $B \to \Lambda_c^+ \bar{\Lambda}_c^-$ and $B \to \Lambda_c^+ \bar{\Lambda}_c^- K$"

- $\mathcal{M}_{\rm wex}(B \to \mathbf{B}_c \bar{\mathbf{B}}'_c) \propto (m_c + m_c)\langle \mathbf{B}_c \bar{\mathbf{B}}'_c | \bar{c}\gamma_5 c | 0 \rangle$

Evidently not helicity suppressed.



- Experimental data

$\mathcal{B}(\bar{B}^0 \to \Xi_c^+ \bar{\Lambda}_c^-) = (1.2 \pm 0.8) \times 10^{-3}$ (pdg)

$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = (9.5 \pm 2.3) \times 10^{-4}$ (pdg)

$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.6 \times 10^{-5}$ (pdg, LHCb)

$\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) < 9.9 \times 10^{-5}$ (pdg, LHCb)

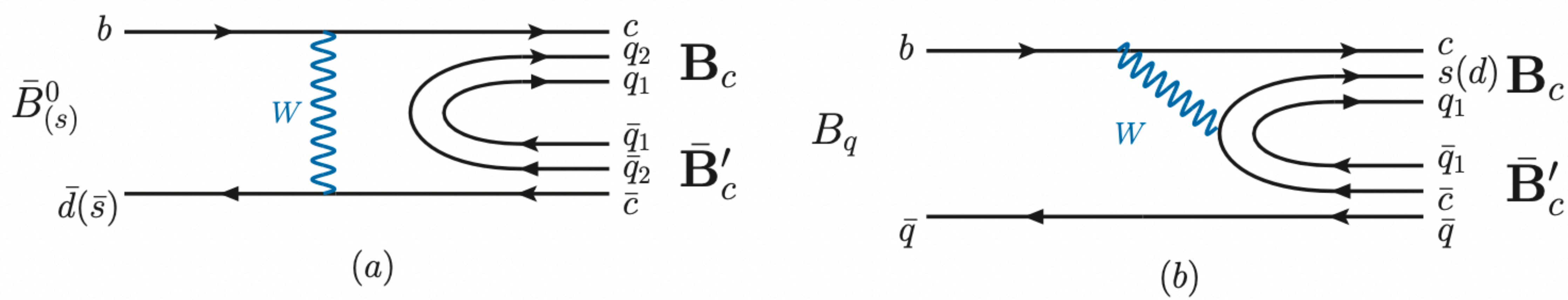
LHCb, PRL112, 202001 (2014),

"Study of beauty hadron decays into pairs of charm hadrons"

- Single $W_{\rm em}$ contribution:

1. $\mathcal{B}(\bar{B}^0 \to \Xi_c^+ \bar{\Lambda}_c^-) \simeq \mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-)$, consistent.
2. $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) \simeq (V_{cd}/V_{cs})^2 (\tau_{\bar{B}^0}/\tau_{B^-}) \mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-)$

$= (4.7 \pm 1.1) \times 10^{-5}$, **3 standard deviations.**



- A possible experimental indication:

1. $W_{\rm ex}$ contribution, overlooked in $\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-$, should be taken into account.

2. It can cause a destructive interfering effect, thus reducing the overestimated branching fraction.

3. With pure $W_{\rm ex}$ contribution, $\mathcal{B}(\bar{B}^0_s \to \Lambda_c^+ \bar{\Lambda}_c^-)$ warrants further examination.

$SU(3)_f$ approach for $B_{(c)} \to \mathbf{B}_c \bar{\mathbf{B}}'_c$

- Effective Hamiltonian:

$$\mathcal{H}_{eff}^{b\to c\bar{q}q'} = \frac{G_F}{\sqrt{2}} V_{cb} V_{qq'}^{*} \Big[c_1 (\bar{q}' q)(\bar{c} b) + c_2 (\bar{q}'_\beta q_\alpha)(\bar{c}_\alpha b_\beta) \Big]$$

$q = (u, c)$ and $q' = (s, d)$

- $\mathcal{H}_{eff}^{b\to c\bar{c}q'}$ and $\mathcal{H}_{eff}^{b\to c\bar{u}q'}$ in the $SU(3)_f$ representation:

$$H^2 = \lambda_{cd},\ H^3 = \lambda_{cs},\ H_1^2 = \lambda_{ud},\ H_1^3 = \lambda_{us},\ \lambda_{qq'} \equiv V_{cb} V_{qq'}^{*}$$

- Initial and final states:

$$B(B_i) = (B^-, \bar{B}^0, \bar{B}_s^0)$$

$$\mathbf{B}_c(\mathbf{B}_c^{ij}) = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix}$$

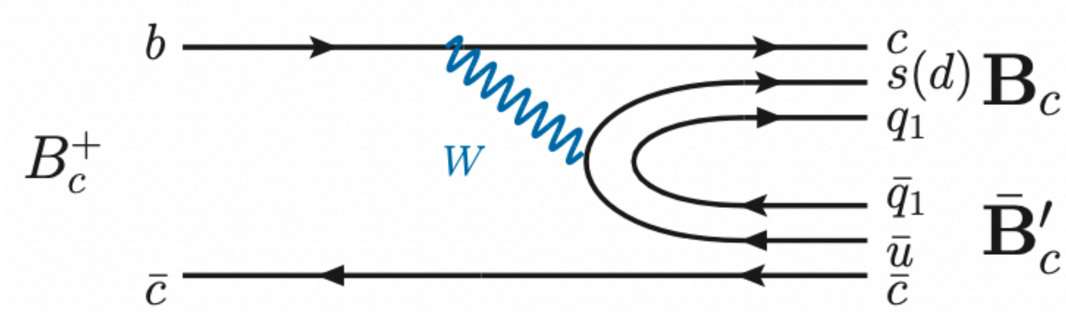
- $SU(3)_f$ amplitudes:

$$\mathcal{M}(B \to \mathbf{B}_c\bar{\mathbf{B}}'_c) = eB_iH^i\mathbf{B}_{c\,jk}\bar{\mathbf{B}}'^{jk}_c + c'B_iH^j\mathbf{B}_{c\,jk}\bar{\mathbf{B}}'^{ik}_c$$

$$\mathcal{M}(B_c \to \mathbf{B}_c\bar{\mathbf{B}}'_c) = \bar{c}'H^i_j\mathbf{B}_{c\,ik}\bar{\mathbf{B}}'^{jk}_c$$

Decay modes	Amplitudes	Decay modes	Amplitudes
$\bar{B}^0 \to \Xi_c^+\bar{\Lambda}_c^-$	$-\lambda_{cs}c'$	$\bar{B}^0 \to \Xi_c^0\bar{\Xi}_c^0$	$-\lambda_{cd}(2e+c')$
$B^- \to \Xi_c^0\bar{\Lambda}_c^-$	$\lambda_{cs}c'$	$\bar{B}^0 \to \Xi_c^+\bar{\Xi}_c^-$	$-\lambda_{cd}(2e)$
$\bar{B}_s^0 \to \Xi_c^0\bar{\Xi}_c^0$	$-\lambda_{cs}(2e+c')$	$\bar{B}^0 \to \Lambda_c^+\bar{\Lambda}_c^-$	$-\lambda_{cd}(2e+c')$
$\bar{B}_s^0 \to \Xi_c^+\bar{\Xi}_c^-$	$-\lambda_{cs}(2e+c')$	$B^- \to \Xi_c^0\bar{\Xi}_c^-$	$-\lambda_{cd}c'$
$\bar{B}_s^0 \to \Lambda_c^+\bar{\Lambda}_c^-$	$-\lambda_{cs}(2e)$	$\bar{B}_s^0 \to \Lambda_c^+\bar{\Xi}_c^-$	$-\lambda_{cd}c'$
$B_c^+ \to \Xi_c^+\bar{\Xi}_c^0$	$-\lambda_{ud}\bar{c}'$	$B_c^+ \to \Lambda_c^+\bar{\Xi}_c^0$	$\lambda_{us}\bar{c}'$

- 3 types: single $W_{\rm ex}$-induced decay, single $W_{\rm em}$-induced decay, $W_{\rm ex}$ and $W_{\rm em}$ mixing-induced one.



(c)

Determining c' and e

- $|c'|$ and $|e|e^{i\delta_e}$

$|c'| = (1.29 \pm 0.18)$ GeV^3

$|e| = (0.20 \pm 0.02)$ GeV^3, $\delta_e = 180^\circ$

- assuming $\bar{c}' = c'$ for $B_c \to \mathbf{B}_c \bar{\mathbf{B}}'_c$

- For the 1st time, e shown to be relatively small;

however, not negligible.

- Experimental data

$\mathcal{B}(\bar{B}^0 \to \Xi_c^+ \bar{\Lambda}_c^-) = (1.2 \pm 0.8) \times 10^{-3}$ (pdg)

$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = (9.5 \pm 2.3) \times 10^{-4}$ (pdg)

$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.6 \times 10^{-5}$ (pdg, LHCb)

$\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) < 9.9 \times 10^{-5}$ (pdg, LHCb)

Single $W_{\rm em}$ induced decay

$$\mathcal{B}(\bar{B}^0 \to \Xi_c^+ \bar{\Lambda}_c^-) = (7.2^{+2.1}_{-1.9}) \times 10^{-4},$$

$$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) = (7.8^{+2.3}_{-2.0}) \times 10^{-4},$$

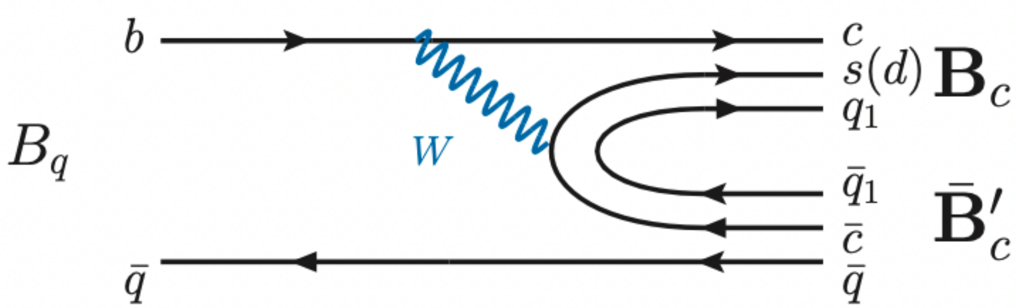
agreeing with the data. We also predict

$$\mathcal{B}(B^- \to \Xi_c^0 \bar{\Xi}_c^-) = (3.4^{+1.0}_{-0.9}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+ \bar{\Xi}_c^-) = (3.9^{+1.2}_{-1.0}) \times 10^{-5}.$$

$$\mathcal{B}(B_c^+ \to \Xi_c^+ \bar{\Xi}_c^0) = (2.8^{+0.9}_{-0.7}) \times 10^{-4},$$

$$\mathcal{B}(B_c^+ \to \Lambda_c^+ \bar{\Xi}_c^0) = (1.6^{+0.5}_{-0.4}) \times 10^{-5}, \text{ test } \bar{c}' = c'.$$



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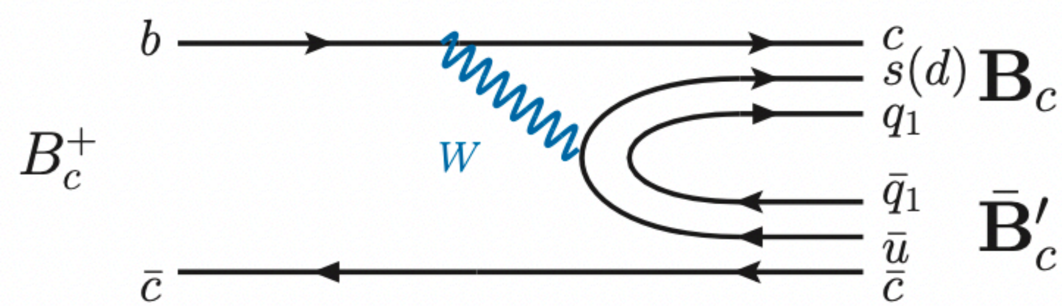


(c)

$W_{\rm ex}$-$W_{\rm em}$ **interfering decay**

$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) = (2.1^{+1.0}_{-0.8}) \times 10^{-5}$,

thus alleviating the discrepancy.

- prediction

$\mathcal{B}(\bar{B}_s^0 \to \Xi_c^{0(+)} \bar{\Xi}_c^{0(+)}) = (3.0^{+1.4}_{-1.1}) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to \Xi_c^0 \bar{\Xi}_c^0) = (1.5^{+0.7}_{-0.6}) \times 10^{-5}$

If $|e| = 0$: $\mathcal{B}(\bar{B}_s^0 \to \Xi_c^{0(+)} \bar{\Xi}_c^{0(+)}) = (6.3^{+1.9}_{-1.6}) \times 10^{-4}$

$\mathcal{B}(\bar{B}^0 \to \Xi_c^0 \bar{\Xi}_c^0) \simeq \mathcal{B}(B^- \to \Xi_c^0 \bar{\Xi}_c^-) \simeq 3.4 \times 10^{-5}$

Triangle relation: $\mathcal{M}_{\rm ex+em}(\bar{B}^0 \to \Xi_c^0 \bar{\Xi}_c^0)$

$= \mathcal{M}_{\rm em}(\bar{B}^0 \to \Xi_c^+ \bar{\Xi}_c^-) + \mathcal{M}_{\rm ex}(B^- \to \Xi_c^0 \bar{\Xi}_c^-)$

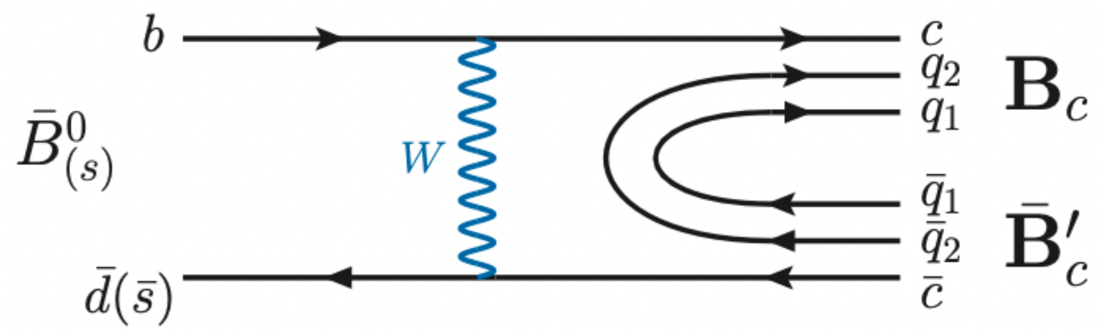
Pure $W_{\rm ex}$ induced decay

- prediction

$$\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+ \bar{\Lambda}_c^-) = (8.1^{+1.7}_{-1.5}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \to \Xi_c^+ \bar{\Xi}_c^-) = (3.0 \pm 0.6) \times 10^{-6},$$

used to test the non-zero $W_{\rm ex}$ contribution.



(a)

Summary

- We use $SU(3)_f$ approach to study $B_{(c)} \to \mathbf{B}_c\bar{\mathbf{B}}'_c$.
- We find that the non-negligible $W_{\rm ex}$ term

can alleviate the significant discrepancy between

the theoretical estimation and experimental data

for $\mathcal{B}(\bar{B}^0 \to \Lambda_c^+\bar{\Lambda}_c^-)$.

- It is very possible for the pure $W_{\rm ex}$ decay channels

to have non-zero branching fractions,

such as $\mathcal{B}(\bar{B}^0_s \to \Lambda_c^+\bar{\Lambda}_c^-) \sim$ a few $\times 10^{-5}$,

accessible to the experimental facilities like LHCb.

Thank You