The 7th China LHC Physics Workshop

QCD sum rules analysis of weak decays of doubly heavy baryons

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SJTU

2021.11.25

Content

- Introduction
- QCD Sum Rules
- Phenomenological Applications
- Summary

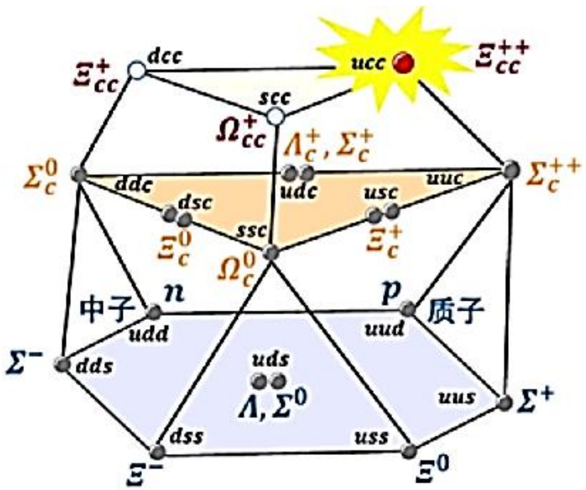
Content

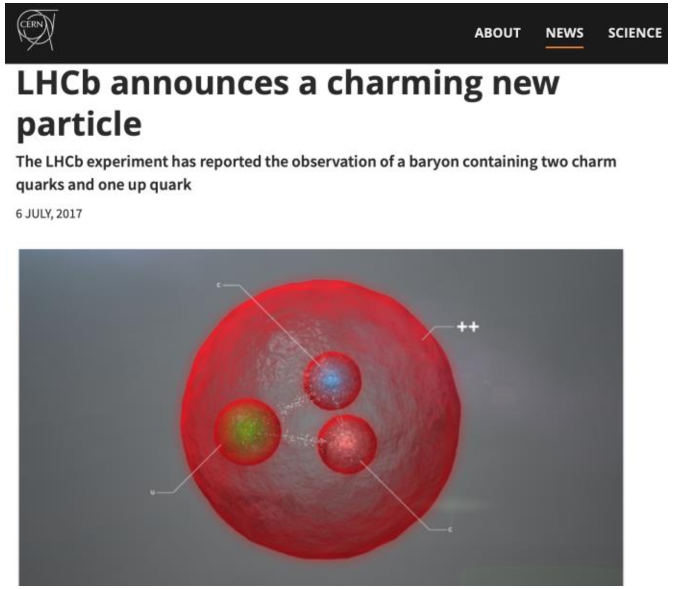
Discovery

- A new platform for precise testing standard model.
- A new platform for searching new physics.

$$\Xi_{cc}^{++}$$

$$\Lambda_c^+ K^- \pi^+ \pi^+$$

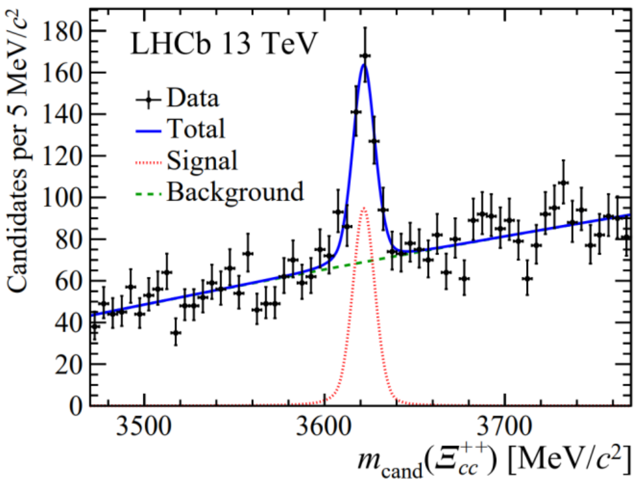



ABOUT NEWS SCIENCE

LHCb announces a charming new particle

The LHCb experiment has reported the observation of a baryon containing two charm quarks and one up quark

6 JULY, 2017



Experimental progress

✔ **Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}**

PhysRevLett.121.052002

$$0.256\,^{+0.024}_{-0.022}\,(\text{stat}) \pm 0.014\,(\text{syst})\,\text{ps}$$

$$\Lambda_c^+ K^- \pi^+ \pi^+$$

✔ **First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$**

PhysRevLett.121.162002

ABOUT NEWS SCIENCE

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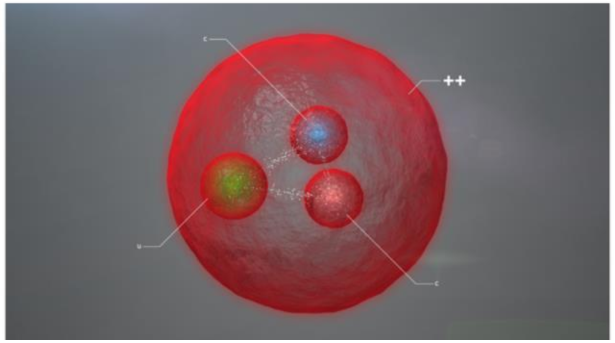

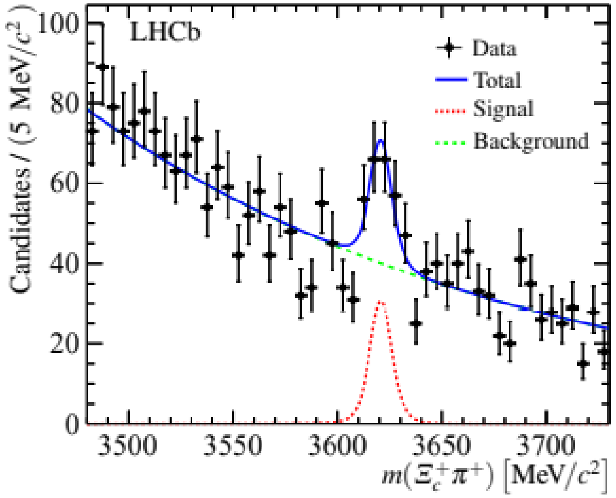

Experimental prograss

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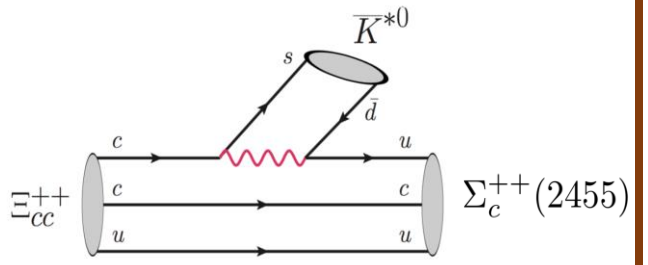
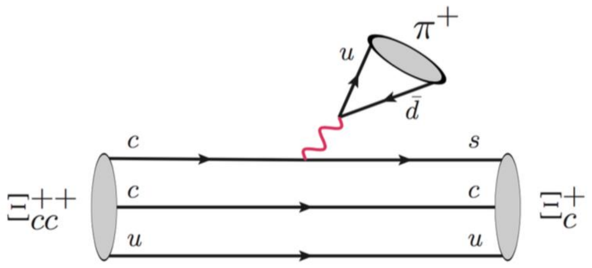
PhysRevLett.121.162002

Two most promising channels!



$$\Xi_{cc}^{++} \to \Sigma_c^{++}(2455)(\to \Lambda_c^+\pi^+)\overline{K}^{*0}(\to K^-\pi^+)$$



$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

Theorical progress

- **Weak decays of doubly heavy baryons: the 1/2→1/2 case**
  Eur.Phy.J.C(2017) 77:781

- **Discovery potentials of doubly charmed baryons**
  Chinese Physics C Vol.42,No.5(2018)051001

- **Weak decays of doubly heavy baryons: SU(3) analysis**
  Eur.Phy.J.C(2017) 77:800

Eur. Phys. J. C (2017) 77:781
https://doi.org/10.1140/epjc/s10052-017-5360-1
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Theoretical Physics

Weak decays of doubly heavy baryons: the 1/2 → 1/2 case

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Discovery potentials of doubly charmed baryons*

Fu-Sheng Yu(于福升)[1,2;1)] Hua-Yu Jiang(蒋华玉)[1,2] Run-Hui Li(李润辉)[3] Cai-Dian Lü(吕才典)[4,5;2)]
Wei Wang(王伟)[6;3)] Zhen-Xing Zhao(赵振兴)[6]
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[2] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[3] School of Physical Science and Technology, Inner Mongolia University, Hohhot 010021, China
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Eur. Phys. J. C (2017) 77:800
https://doi.org/10.1140/epjc/s10052-017-5363-y
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Theoretical Physics

Weak decays of doubly heavy baryons: SU(3) analysis

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Theorical progress

List of studies on weak decays

1. Doubly heavy baryon weak decays: $\Xi_{bc}^0 \to pK^-, \Xi_{cc}^+ \to \Sigma_c^{++}K^-$ 1701.03284
2. Discovery potentials of doubly charmed baryons 1703.09086
3. Weak decays of doubly heavy baryons: the 1/2 -> 1/2 case 1707.02834
4. Weak decays of doubly heavy baryons: SU(3) analysis 1707.06570
5. Weak decays of doubly heavy baryons: decay constant 1711.10289
6. Weak decays of doubly heavy baryons: Multi-body decays 1712.03830
7. Weak decays of doubly heavy baryons: the 1/2 -> 3/2 case 1805.10878
8. Weak decays of doubly heavy baryons: the FCNC processes 1807.03101
9. Weak decays of doubly heavy baryons: $B_{cc} \to B_c V$ 1810.00541
10. Weak decays of triply heavy baryons 1803.01476

……

- Most of them adopt QCD-based phenomenological model in which systematic errors can not be estimated
- QCD calculation is highly demanded

Eur. Phys. J. C (2020) 80:320
https://doi.org/10.1140/epjc/s10052-020-7851-8
The European Physical Journal C
Regular Article - Theoretical Physics

A comprehensive analysis of weak transition form factors for doubly heavy baryons in the light front approach

Xiao-Hui Hu[1,a], Run-Hui Li[2,b], Zhi-Peng Xing[1,c]
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Eur. Phys. J. C (2020) 80:398
https://doi.org/10.1140/epjc/s10052-020-7949-z
The European Physical Journal C
Regular Article - Theoretical Physics

Towards a heavy diquark effective theory for weak decays of doubly heavy baryons

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Eur. Phys. J. C (2020) 80:568
https://doi.org/10.1140/epjc/s10052-020-8096-2
The European Physical Journal C
Regular Article - Theoretical Physics

QCD Sum Rules Analysis of Weak Decays of Doubly-Heavy Baryons

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Received: 18 January 2020 / Accepted: 29 May 2020

Theorical progress

Motivation

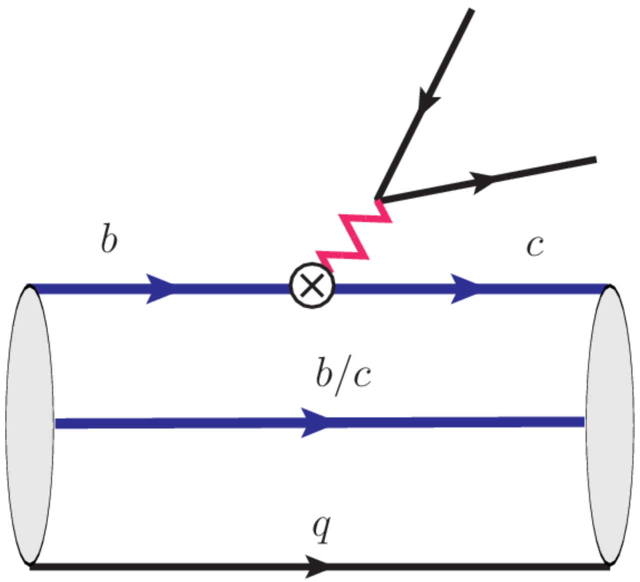
The quark model predictions:

	Model calculation(%) [1]
$B(\Xi_{bb} \to \Sigma_b l^- \bar{\upsilon})$	2.98×10^{-5}
$B(\Xi_{bb} \to \Xi_{bc} l^- \bar{\upsilon})$	3.38×10^{-2}
$B(\Xi_{bc} \to \Xi_b l^- \bar{\upsilon})$	1.81×10^{-2}
$B(\Xi_{bc} \to \Sigma_b l^- \bar{\upsilon})$	2.06×10^{-3}

- **Comparing to the $\Xi_{bb} \to \Sigma_b$ processes, the branching ratio of $\Xi_{bb} \to \Xi_{bc} \to \Xi_b / \Sigma_b$ is still larger.**
- **The processes of doubly heavy baryon decay to doubly heavy baryons are also important.**

[1]. 2001.06375

Feynman diagram



Content

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- **QCD Sum Rules**
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Form Factors

helicity Form Factors

$$
\begin{aligned}
\langle \mathcal{B}_2(P_2)|(V-A)_\mu|\mathcal{B}_1(P_1)\rangle \;=\; & \bar{u}(P_2,s_2)\Bigg[\frac{q_\mu}{q^2}(M_1-M_2)f_0(q^2)+\frac{M_1+M_2}{Q_+}\Big((P_1+P_2)_\mu-(M_1^2-M_2^2)\frac{q_\mu}{q^2}\Big)f_+(q^2) \\
& +\Big(\gamma_\mu-\frac{2M_2}{Q_+}P_{1\mu}-\frac{2M_1}{Q_+}P_{2\mu}\Big)f_\perp(q^2)\Bigg]u(P_1,s_1) \\
& -\;\bar{u}(P_2,s_2)\gamma_5\Bigg[\frac{q_\mu}{q^2}(M_1+M_2)g_0(q^2)+\frac{M_1-M_2}{Q_-}\Big((P_1+P_2)_\mu-(M_1^2-M_2^2)\frac{q_\mu}{q^2}\Big)g_+(q^2) \\
& +\Big(\gamma_\mu+\frac{2M_2}{Q_-}P_{1\mu}-\frac{2M_1}{Q_-}P_{2\mu}\Big)g_\perp(q^2)\Bigg]u(P_1,s_1)
\end{aligned}
$$

- **The parameterization are usually used in SCET and Lattice.**

1111.1844

- **In this parameterization all form factors are in same order.**

(Reducing calculation errors)

Numerical results

	$F(0)$
$f_+^{\Xi_{bb}\to\Xi_{bc}}$	$0.441^{+0.008}_{-0.008}(T_1^2,T_2^2)^{+0.020}_{-0.015}(s_1^0)^{+0.072}_{-0.037}(s_2^0)$
$f_0^{\Xi_{bb}\to\Xi_{bc}}$	$0.441^{+0.008}_{-0.008}(T_1^2,T_2^2)^{+0.020}_{-0.015}(s_1^0)^{+0.072}_{-0.037}(s_2^0)$
$f_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$0.816^{+0.009}_{-0.007}(T_1^2,T_2^2)^{+0.045}_{-0.047}(s_1^0)^{+0.114}_{-0.092}(s_2^0)$
$g_+^{\Xi_{bb}\to\Xi_{bc}}$	$-0.283^{+0.003}_{-0.003}(T_1^2,T_2^2)^{+0.033}_{-0.027}(s_1^0)^{+0.048}_{-0.050}(s_2^0)$
$g_0^{\Xi_{bb}\to\Xi_{bc}}$	$-0.283^{+0.003}_{-0.003}(T_1^2,T_2^2)^{+0.033}_{-0.027}(s_1^0)^{+0.048}_{-0.050}(s_2^0)$
$g_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$-0.287^{+0.003}_{-0.004}(T_1^2,T_2^2)^{+0.021}_{-0.016}(s_1^0)^{+0.038}_{-0.040}(s_2^0)$

Correlation functions

hadron level

Hadron quark duality

quark level

$$\Pi_\mu^{V,A}(P_1,P_2) = i^2\int d^4x d^4y e^{-iP_1\cdot x+iP_2\cdot y}\langle 0|T\{J_{\mathcal{B}_{cQq}}(y)(V_\mu,A_\mu)(0)\bar{J}_{\mathcal{B}_{bQq}}(x)\}|0\rangle$$

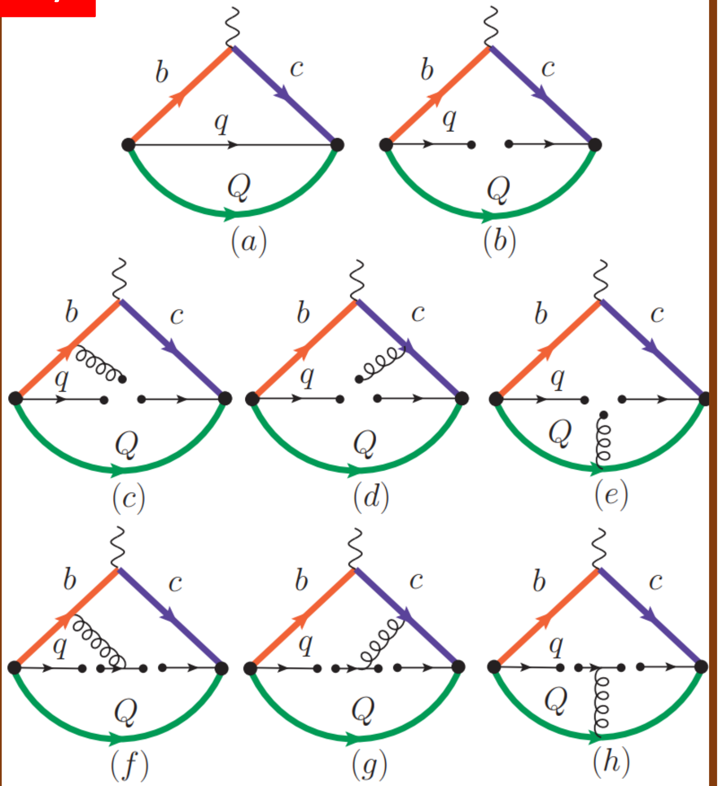
Hadron complete set

$$= \frac{\lambda_f^+\lambda_i^+}{(P_2^2-M_2^{+2})(P_1^2-M_1^{+2})}(\not{P}_2+M_2^+)\mathcal{V}_\mu^{++}(\not{P}_1+M_1^+) + \cdots$$

Form factors

- Consider the contribution of parity(+1) and (-1) .

- Masses and pole residue were also calculated using two point correlation functions.



Comparing to the Hadron level and extract the form factors

Content

Phenomenological results

Masses and pole residues

TABLE II: The pole residues.

	This work (without the LL corrections)	This work (with the LL corrections)
$\lambda_{\Xi_{bb}}$	0.760	$0.736^{+0.000}_{-0.000}(T^2)^{+0.053}_{-0.052}(s_0)$
$\lambda_{\Omega_{bb}}$	0.854	$0.825^{+0.000}_{-0.000}(T^2)^{+0.060}_{-0.059}(s_0)$
$\lambda_{\Xi_{bc}}$	0.379	$0.369^{+0.000}_{-0.000}(T^2)^{+0.028}_{-0.027}(s_0)$
$\lambda_{\Omega_{bc}}$	0.400	$0.388^{+0.000}_{-0.000}(T^2)^{+0.030}_{-0.029}(s_0)$
$\lambda_{\Xi_{cc}}$	0.130	$0.130^{+0.000}_{-0.000}(T^2)^{+0.011}_{-0.011}(s_0)$
$\lambda_{\Omega_{cc}}$	0.150	$0.149^{+0.000}_{-0.000}(T^2)^{+0.013}_{-0.012}(s_0)$

TABLE III: The masses.

	This work (without the LL corrections)	This work (with the LL corrections)	Lattice QCD [1]
$m_{\Xi_{bb}}$	10.166	$10.152^{+0.007}_{-0.009}(T^2)^{+0.079}_{-0.080}(s_0)$	10.143
$m_{\Omega_{bb}}$	10.291	$10.279^{+0.006}_{-0.007}(T^2)^{+0.080}_{-0.081}(s_0)$	10.273
$m_{\Xi_{bc}}$	6.948	$6.935^{+0.009}_{-0.007}(T^2)^{+0.080}_{-0.081}(s_0)$	6.943
$m_{\Omega_{bc}}$	7.002	$6.998^{+0.006}_{-0.008}(T^2)^{+0.081}_{-0.081}(s_0)$	6.998
$m_{\Xi_{cc}}$	3.634	$3.629^{+0.010}_{-0.012}(T^2)^{+0.078}_{-0.079}(s_0)$	3.621 [2]
$m_{\Omega_{cc}}$	3.747	$3.743^{+0.009}_{-0.011}(T^2)^{+0.079}_{-0.080}(s_0)$	3.738

the leading logarithmic corrections

$$\left(\frac{\log(\mu_0/\Lambda_{\rm QCD}^{(n_f)})}{\log(\mu/\Lambda_{\rm QCD}^{(n_f)})}\right)^{2\gamma_J-\gamma_O}$$

$$\mu_0 \sim 1\ \text{GeV}$$

$$\Lambda^{(3)}_{\rm QCD} = 223\ \text{MeV}$$

$$\Lambda^{(4)}_{\rm QCD} = 170\ \text{MeV}$$

[1]. 1409.0497
[2]. 1707.01621

Phenomenological results

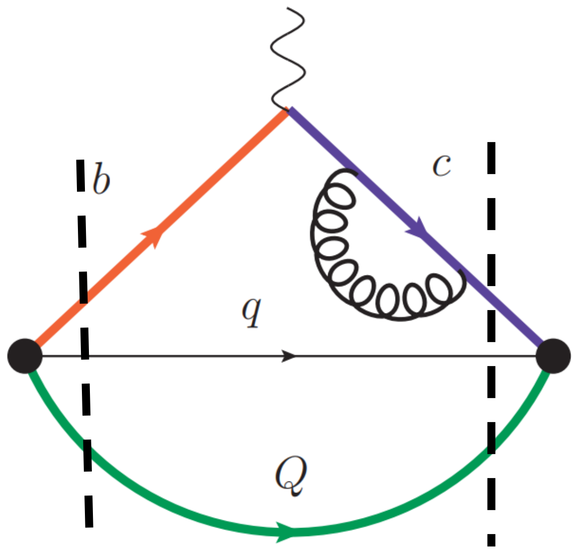
Convergence of OPE

$$f_{+,0}^{\Xi_{bb}\to\Xi_{bc}}(0) = 0.332(73.309\%)_{dim0} + 0.101(22.300\%)_{dim3} + 0.014(3.063\%)_{dim5} - 0.006(1.329\%)_{dim6}$$

$$f_{\perp}^{\Xi_{bb}\to\Xi_{bc}}(0) = 0.630(75.700\%)_{dim0} + 0.194(23.326\%)_{dim3} - 0.003(0.310\%)_{dim5} - 0.006(0.663\%)_{dim6}.$$

- For b decay processes, QCD Sum Rule calculations are dominate ed by perturbative term.
- The leading order correction in α_s of perturbative term need to considered.

next to α_s order



One of the 34 diagrams

Phenomenological results

next to α_s order contributions

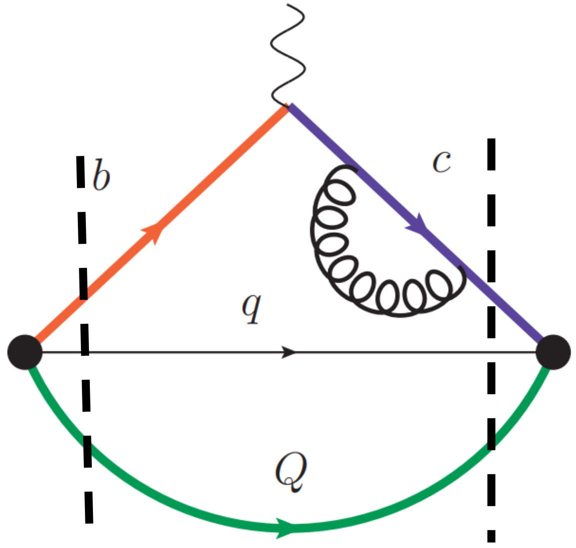
One diagram contribution

$$f_{+,0}^{\Xi_{bb}\to\Xi_{bc}}(0) = 0.332(73.309\%)_{dim0}+0.0002(0.048\%)_{\alpha_s}+0.101(22.300\%)_{dim3}$$
$$+0.014(3.063\%)_{dim5}-0.006(1.329\%)_{dim6}.$$

34 diagrams!!!

- **The complete correction of leading order in α_s is $\sim 5\%$.**
- **The leading order in α_s correcctions will be considered in the future.**

next to α_s order

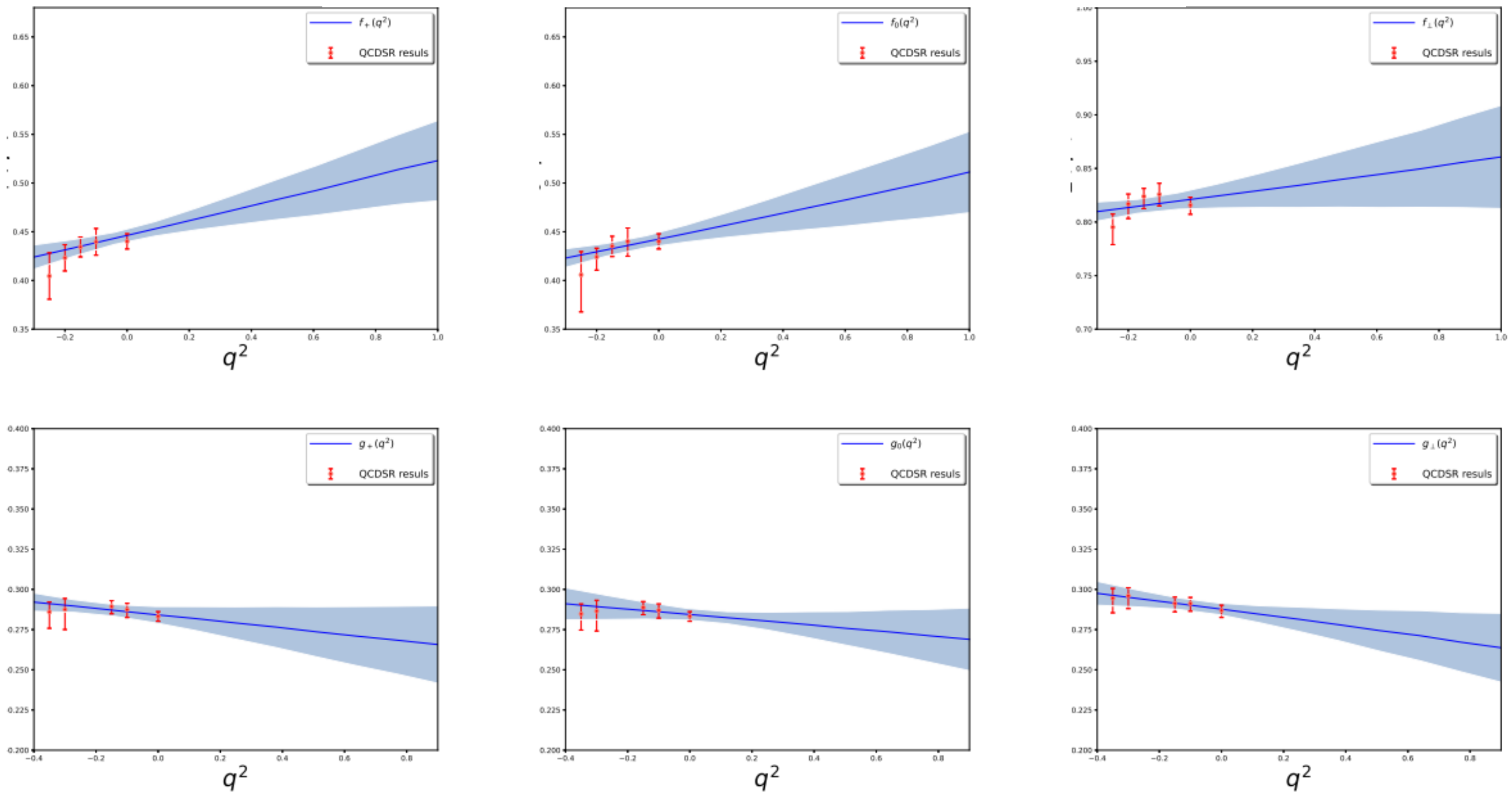


One of the 34 diagrams

Phenomenological results

q^2-dependence of form factors

$$f(q^2) = \frac{1}{1 - q^2/(m_{\rm pole})^2}(a + bz(q^2))$$



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$g_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$-0.287^{+0.003}_{-0.004}(T_1^2,T_2^2)^{+0.021}_{-0.016}(s_1^0)^{+0.038}_{-0.040}(s_2^0)$

	a
$f_+^{\Xi_{bb}\to\Xi_{bc}}$	$1.200 \pm 0.460(T_1^2,T_2^2) \pm 0.600(s_1^0,s_2^0)$
$f_0^{\Xi_{bb}\to\Xi_{bc}}$	$1.090 \pm 0.440(T_1^2,T_2^2) \pm 0.600(s_1^0,s_2^0)$
$f_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$1.030 \pm 0.480(T_1^2,T_2^2) \pm 0.710(s_1^0,s_2^0)$
$g_+^{\Xi_{bb}\to\Xi_{bc}}$	$0.040 \pm 0.26(T_1^2,T_2^2) \pm 0.710(s_1^0,s_2^0)$
$g_0^{\Xi_{bb}\to\Xi_{bc}}$	$-0.001 \pm 0.255(T_1^2,T_2^2) \pm 0.710(s_1^0,s_2^0)$
$g_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$0.100 \pm 0.250(T_1^2,T_2^2) \pm 0.590(s_1^0,s_2^0)$

	b
$f_+^{\Xi_{bb}\to\Xi_{bc}}$	$-10.1 \pm 6.1(T_1^2,T_2^2) \pm 7.9(s_1^0,s_2^0)$
$f_0^{\Xi_{bb}\to\Xi_{bc}}$	$-8.6 \pm 5.8(T_1^2,T_2^2) \pm 7.9(s_1^0,s_2^0)$
$f_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$-2.7 \pm 6.3(T_1^2,T_2^2) \pm 9.3(s_1^0,s_2^0)$
$g_+^{\Xi_{bb}\to\Xi_{bc}}$	$-4.3 \pm 3.4(T_1^2,T_2^2) \pm 9.3(s_1^0,s_2^0)$
$g_0^{\Xi_{bb}\to\Xi_{bc}}$	$-3.8 \pm 3.4(T_1^2,T_2^2) \pm 9.3(s_1^0,s_2^0)$
$g_\perp^{\Xi_{bb}\to\Xi_{bc}}$	$-5.1 \pm 3.3(T_1^2,T_2^2) \pm 7.8(s_1^0,s_2^0)$

Phenomenological results

Helicity amplitude method

$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_L}{dq^2} + \frac{d\Gamma_T}{dq^2},$$

$$\frac{d\Gamma_T}{dq^2} = \frac{G_F^2|V_{cb}|^2|P'||p_1|}{16(2\pi)^3 M_B^2\sqrt{q^2}} \frac{2(m_l^2-q^2)(m_l^2+2q^2)}{3q^2}\left(|H^{\frac{1}{2}}_{\frac{1}{2},1}|^2 + |H^{-\frac{1}{2}}_{-\frac{1}{2},-1}|^2\right),$$

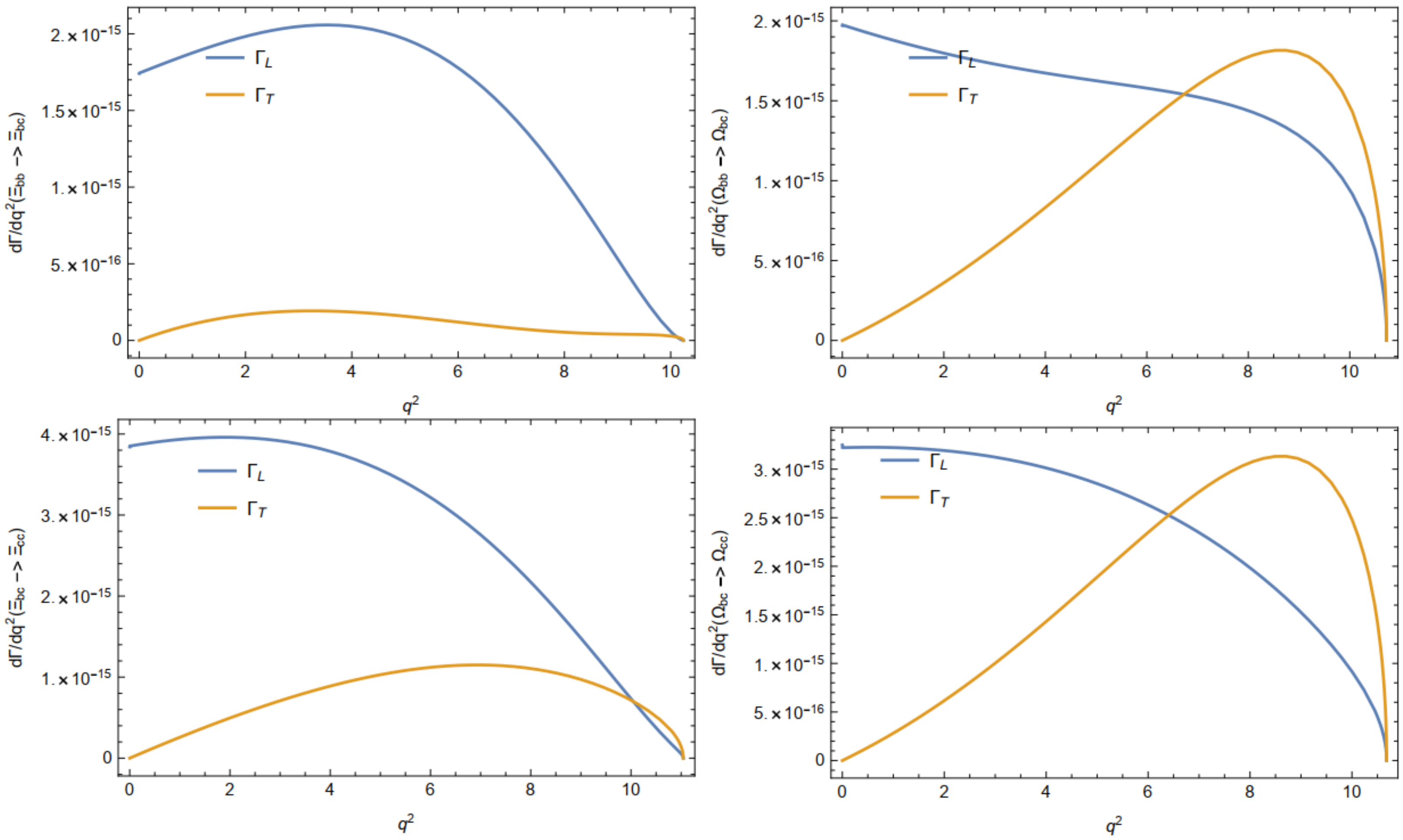
$$\frac{d\Gamma_L}{dq^2} = \frac{G_F^2|V_{cb}|^2|P'||p_1|}{16(2\pi)^3 M_B^2\sqrt{q^2}} \frac{2(m_l^2-q^2)}{3q^2}\left((m_l^2+2q^2)(|H^{\frac{1}{2}}_{-\frac{1}{2},0}|^2 + |H^{-\frac{1}{2}}_{\frac{1}{2},0}|^2) + 3m_l^2(|H^{\frac{1}{2}}_{-\frac{1}{2},t}|^2 + |H^{-\frac{1}{2}}_{\frac{1}{2},t}|^2)\right)$$

decay width

channel	decay width$(10^{-14}\mathrm{GeV})$
$\Gamma(\Xi_{bb}\to\Xi_{bc})$	$1.955\pm0.685(T_1^2,T_2^2)\pm1.673(s_1^0,s_2^0)$
$\Gamma_L(\Xi_{bb}\to\Xi_{bc})$	$1.728\pm0.658(T_1^2,T_2^2)\pm1.363(s_1^0,s_2^0)$
$\Gamma_T(\Xi_{bb}\to\Xi_{bc})$	$0.227\pm0.175(T_1^2,T_2^2)\pm0.342(s_1^0,s_2^0)$
$\Gamma(\Omega_{bb}\to\Omega_{bc})$	$3.005\pm0.780(T_1^2,T_2^2)\pm4.932(s_1^0,s_2^0)$
$\Gamma_L(\Omega_{bb}\to\Omega_{bc})$	$1.854\pm0.670(T_1^2,T_2^2)\pm2.363(s_1^0,s_2^0)$
$\Gamma_T(\Omega_{bb}\to\Omega_{bc})$	$1.151\pm0.382(T_1^2,T_2^2)\pm2.562(s_1^0,s_2^0)$
$\Gamma(\Xi_{bc}\to\Xi_{cc})$	$4.174\pm0.796(T_1^2,T_2^2)\pm4.933(s_1^0,s_2^0)$
$\Gamma_L(\Xi_{bc}\to\Xi_{cc})$	$3.260\pm0.730(T_1^2,T_2^2)\pm4.272(s_1^0,s_2^0)$
$\Gamma_T(\Xi_{bc}\to\Xi_{cc})$	$0.914\pm0.279(T_1^2,T_2^2)\pm0.66(s_1^0,s_2^0)$
$\Gamma(\Omega_{bc}\to\Omega_{cc})$	$4.799\pm1.095(T_1^2,T_2^2)\pm4.385(s_1^0,s_2^0)$
$\Gamma_L(\Omega_{bc}\to\Omega_{cc})$	$2.762\pm0.676(T_1^2,T_2^2)\pm2.931(s_1^0,s_2^0)$
$\Gamma_T(\Omega_{bc}\to\Omega_{cc})$	$2.037\pm0.867(T_1^2,T_2^2)\pm1.454(s_1^0,s_2^0)$

Phenomenological results

q^2-dependence of decay width



decay width

channel	decay width$(10^{-14}\mathrm{GeV})$
$\Gamma(\Xi_{bb}\to\Xi_{bc})$	$1.955\pm0.685(T_1^2,T_2^2)\pm1.673(s_1^0,s_2^0)$
$\Gamma_L(\Xi_{bb}\to\Xi_{bc})$	$1.728\pm0.658(T_1^2,T_2^2)\pm1.363(s_1^0,s_2^0)$
$\Gamma_T(\Xi_{bb}\to\Xi_{bc})$	$0.227\pm0.175(T_1^2,T_2^2)\pm0.342(s_1^0,s_2^0)$
$\Gamma(\Omega_{bb}\to\Omega_{bc})$	$3.005\pm0.780(T_1^2,T_2^2)\pm4.932(s_1^0,s_2^0)$
$\Gamma_L(\Omega_{bb}\to\Omega_{bc})$	$1.854\pm0.670(T_1^2,T_2^2)\pm2.363(s_1^0,s_2^0)$
$\Gamma_T(\Omega_{bb}\to\Omega_{bc})$	$1.151\pm0.382(T_1^2,T_2^2)\pm2.562(s_1^0,s_2^0)$
$\Gamma(\Xi_{bc}\to\Xi_{cc})$	$4.174\pm0.796(T_1^2,T_2^2)\pm4.933(s_1^0,s_2^0)$
$\Gamma_L(\Xi_{bc}\to\Xi_{cc})$	$3.260\pm0.730(T_1^2,T_2^2)\pm4.272(s_1^0,s_2^0)$
$\Gamma_T(\Xi_{bc}\to\Xi_{cc})$	$0.914\pm0.279(T_1^2,T_2^2)\pm0.66(s_1^0,s_2^0)$
$\Gamma(\Omega_{bc}\to\Omega_{cc})$	$4.799\pm1.095(T_1^2,T_2^2)\pm4.385(s_1^0,s_2^0)$
$\Gamma_L(\Omega_{bc}\to\Omega_{cc})$	$2.762\pm0.676(T_1^2,T_2^2)\pm2.931(s_1^0,s_2^0)$
$\Gamma_T(\Omega_{bc}\to\Omega_{cc})$	$2.037\pm0.867(T_1^2,T_2^2)\pm1.454(s_1^0,s_2^0)$

- The error of s_1^0, s_2^0 represent the dependence of s_1^0, s_2^0.
- The error of T_1^2, T_2^2 represent the error in calculation.

Phenomenological results

QCD Sum Rules compare with model calculation

	Our work (10^{-14}GeV)	Model calculation(10^{-14}GeV)[1]	Model calculation(10^{-14}GeV)[2]
$\Gamma(\Xi_{bb} \to \Xi_{bc} l^- \bar{\upsilon})$	1.9 ± 0.7	6.02	3.30
$\Gamma(\Xi_{bb} \to \Xi_{bc} l^- \bar{\upsilon})$	3.0 ± 0.8	5.24	3.69
$\Gamma(\Xi_{bb} \to \Xi_{bc} l^- \bar{\upsilon})$	4.1 ± 0.8	4.26	4.50
$\Gamma(\Xi_{bb} \to \Xi_{bc} l^- \bar{\upsilon})$	4.7 ± 1.1	4.11	3.94

- **Our predictions are consistent with model calculation.**

[1]. 2001.06375
[2]. 1707.02834

Content

- Introduction
- QCD Sum Rules
- Phenomenological Applications
- **Summary**

Summary

- We have adopted QCDSR to investigate the weak decays of spin-1/2 doubly-heavy baryon to spin-1/2 doubly-heavy baryon.
- On the OPE side, the $b \to c$ processes of doubly heavy baryon decays are perturbative term dominate.
- We estimate the next to α_s order contribution $\sim 5\%$.
- We have also considered the contribution from the negative parity baryons to eliminate the ambiguousness on the choice of the form factors.
- No model-dependent parameters are introduced.
- Our results are comparable to other works.

Thank you for your attention!