Beauty baryon to double open-charm decays at LHCb

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Outline

- Motivation
- LHCb experiment
- New beauty baryon to double open-charm decays
  - Observation of $\Xi_b^{0(-)} \to \Xi_c^{0(+)} D_s^-$ decays [arXiv:2310.13546]
  - Measurement of the relative branching fractions of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays [LHCb-PAPER-2023-034]
- Summary

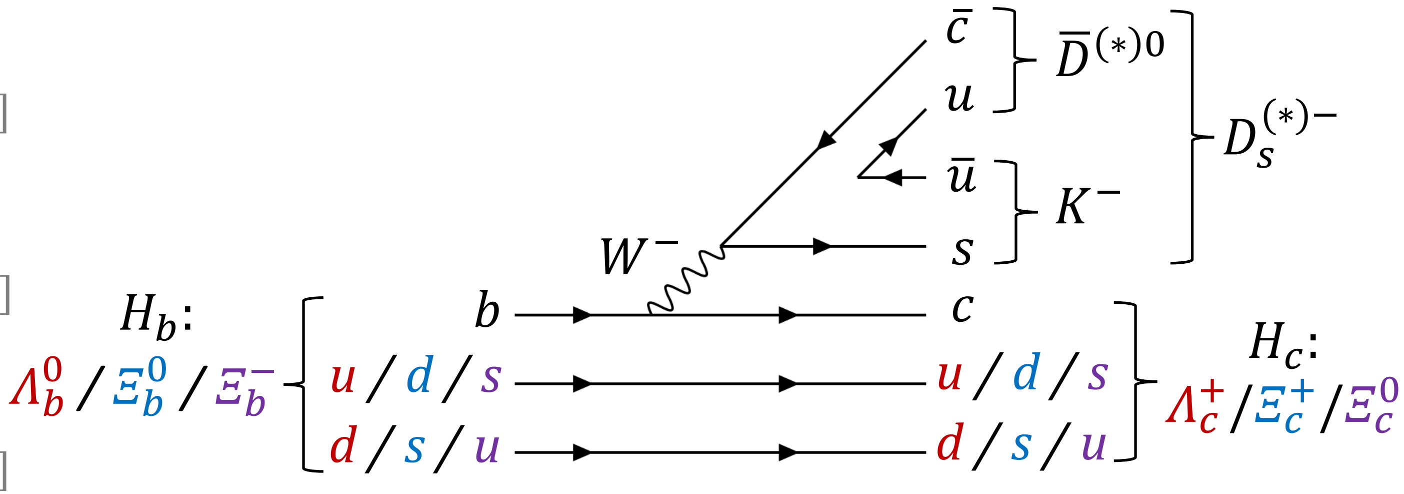
Motivation

- Measurement of $\mathcal{B}(\overset{\Lambda_b^0,\Xi_b}{H_b} \to \overset{\Lambda_c^+,\Xi_c}{H_c} D_s^{(*)-})$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-)$ can test theory predictions
  - Heavy quark effective theory (HQET)
    - Decays dominated by $b \to c$, while light quarks serve as spectators. According to HQET, they should have approximately the same partial width.
  - Numeric calcualtions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.75\sim2.25^{[1-13]}$$

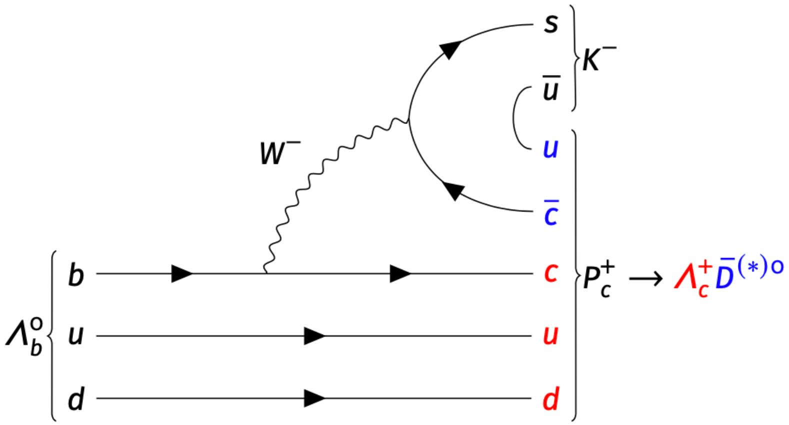
$$\frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.91\sim1.06^{[14-16]}$$

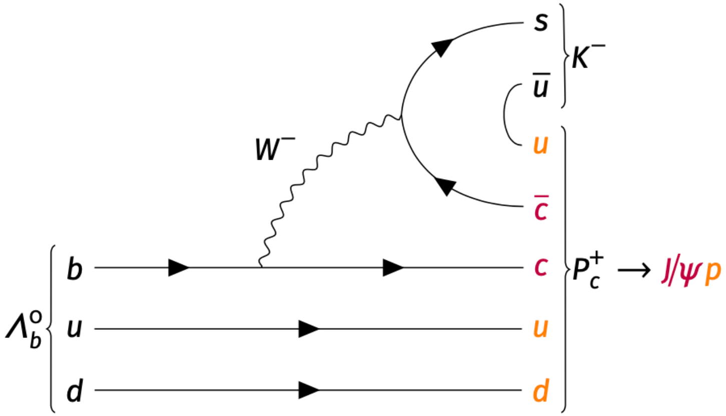
$$\frac{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 0.97\sim1.06^{[14-16]}$$

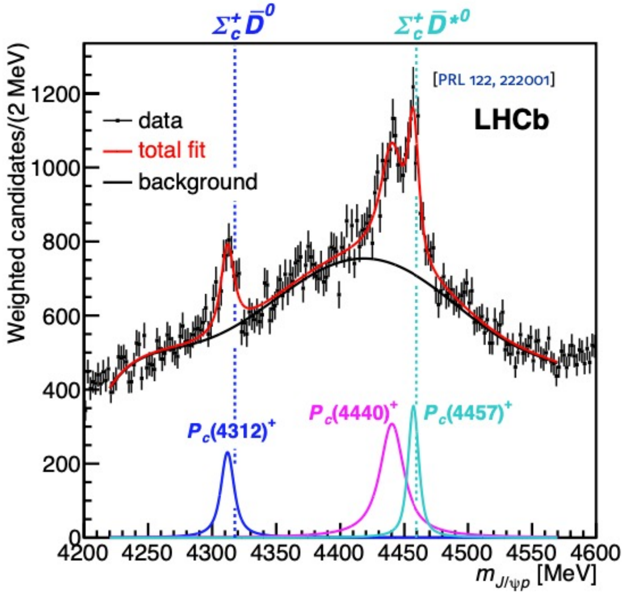


Motivation for $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-$

- Pentaquark P_c^+ seen in $\Lambda_b^0 \to J/\psi p K^-$ and $\Lambda_b^0 \to J/\psi p \pi^-$
- Decays to $\Lambda_c^+ \bar{D}^{(*)0}$ are open-charm equivalent of $J/\psi p$







$f_X(P_c^+)$ denotes fraction of $\Lambda_b^0 \to XK^-$ via P_c^+

$$\frac{\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \bar{D}^{(*)0}\right)}{\mathcal{B}\left(P_c^+ \to J/\psi p\right)} \overset{\substack{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\text{ are same in}\\ \Lambda_b^0 \to J/\psi p K^- \text{ and } \Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-}}{=\!=\!=} \frac{f_{\Lambda_c^+ \bar{D}^{(*)0}}\left(P_c^+\right)}{f_{J/\psi p}\left(P_c^+\right)} \times \frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{(*)0} K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}$$

Theory predictions vary significantly yet[17-28]

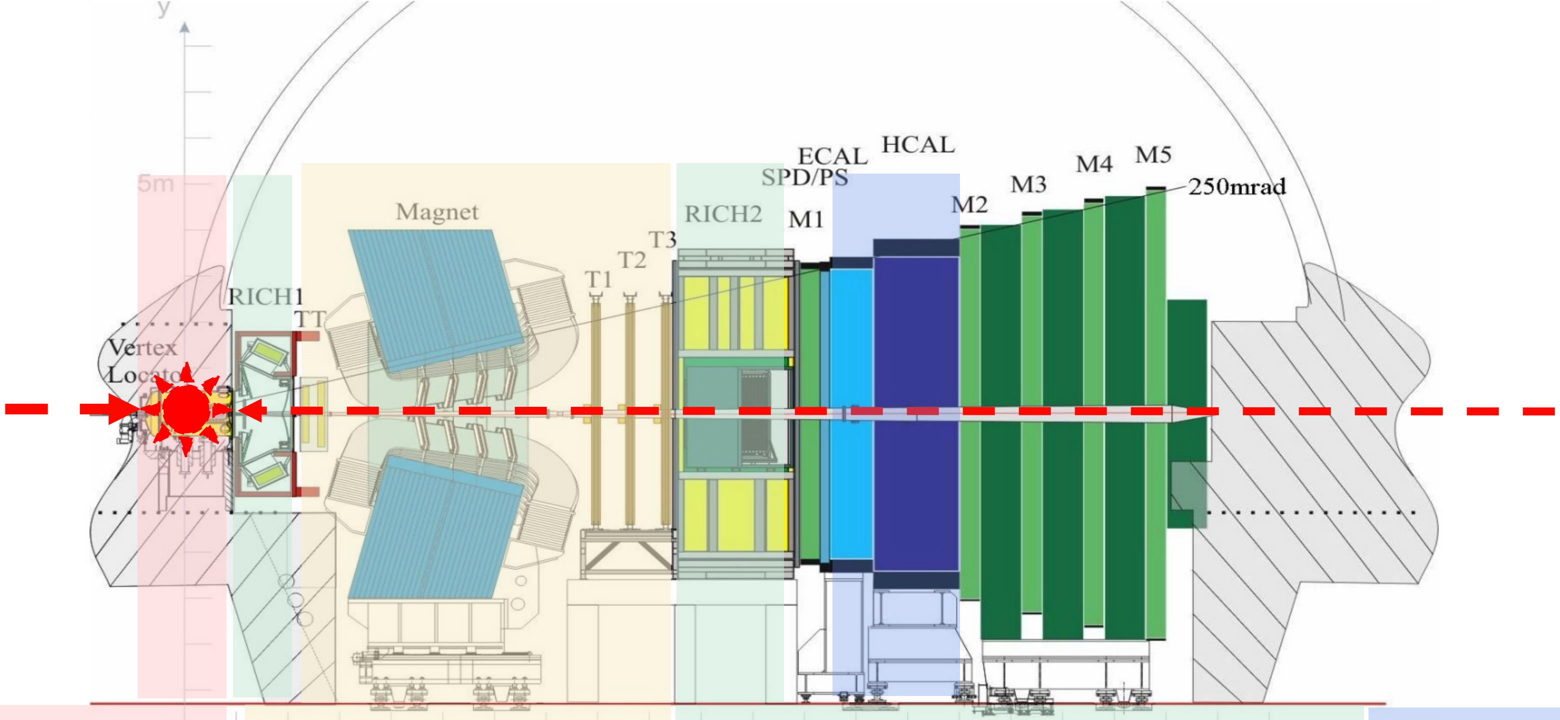
Wait for future measurement to compare with models

Measured [Phys. Rev. Lett. 122 (2019) 222001]

Measured by the new analysis covered here [LHCb-PAPER-2023-034]

Where are we looking at ? —— LHCb!

- Single-arm forward spectrometer, designed to study CP violation and rare decays within beauty and charm hadrons



Excellent vertex resolution
$\sigma_{\mathrm{IP}} = 20\ \mu\mathrm{m}$

Tracking system
$\varepsilon_{\mathrm{tracking}} \sim 96\%$
$\Delta p/p \approx 0.7\%$

Precise particle identification
$\epsilon(K \to K) \sim 95\%$
$\text{mis-ID}\ \epsilon(\pi \to K) \sim 5\%$

Calorimeters further help to identify the particles from the energy deposits.

Observation of $\Xi_b^{0(-)} \to \Xi_c^{+(0)} D_s^-$ decays

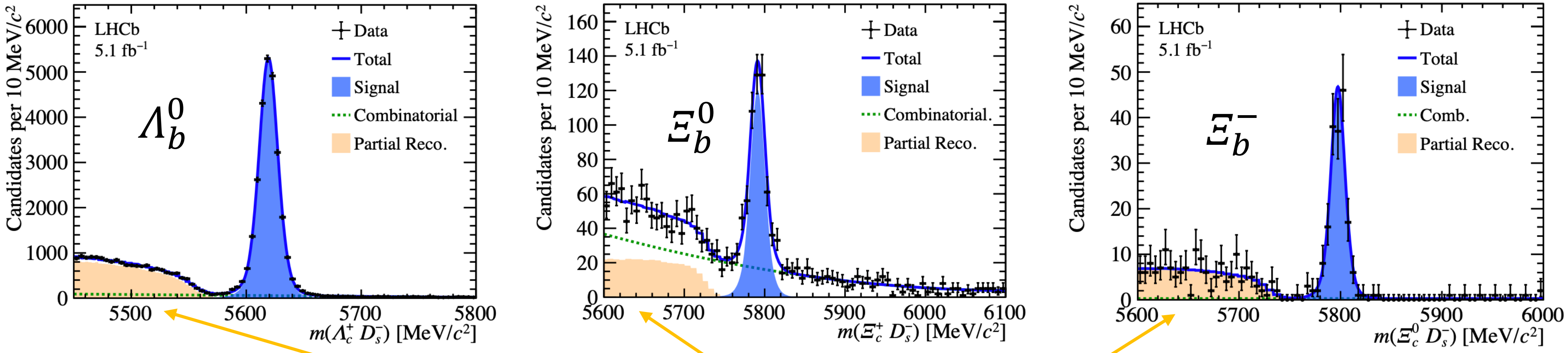
[arXiv:2310.13546]

Analysis strategy

- Data samples
  - 5.1 fb^{-1} proton-proton collisions collected at $\sqrt{s} = 13\text{TeV}$ by LHCb in 2016-2018
- Measurement of cross-section ratio times branching fraction ratio
  - $R\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) \equiv \frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \times \frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \underbrace{\frac{N(\Xi_b^0 \to \Xi_c^+ D_s^-)}{N(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}}_{\text{Mass fit}} \times \underbrace{\frac{\varepsilon(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}{\varepsilon(\Xi_b^0 \to \Xi_c^+ D_s^-)}}_{\text{Simulation}} \times \underbrace{\frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}}_{\text{Input from PDG}}$
    - $R\left(\frac{\Xi_b^-}{\Lambda_b^0}\right)$ and $R\left(\frac{\Xi_b^0}{\Xi_b^-}\right)$ defined similarly
- Ξ_b mass measurement
  - Energy release Q in $\Xi_b \to \Xi_c D_s^-$ are small, so the momentum scale induced uncertainty is small.
- Charm hadron reconstruction: $\Xi_c^+(\Lambda_c^+) \to pK^-\pi^+, \Xi_c^0 \to pK^-K^-\pi^+, D_s^- \to K^+K^-\pi^-$

Signal yield determination

- Selections suppress backgrounds
- Fit to the invariant mass of H_b



Partially reconstructed background
$H_b \to H_c\ (D_s^{*-} \to D_s^- \gamma)$ with missing γ

$$N(\Lambda_b^0) = 26090 \pm 170(\text{stat.}),\quad N(\Xi_b^0) = 462 \pm 29(\text{stat.}),\quad N(\Xi_b^-) = 175 \pm 14(\text{stat.})$$

First observation of $\Xi_b^0 \to \Xi_c^+ D_s^-$ and $\Xi_b^- \to \Xi_c^0 D_s^-$ decays

Efficiencies and systematic uncertainties

- Effiencies taken from simulation
  - Data-driven corrections to: PID responses, track reconstruction efficiency, production- and decay-kinematics, track multiplicity

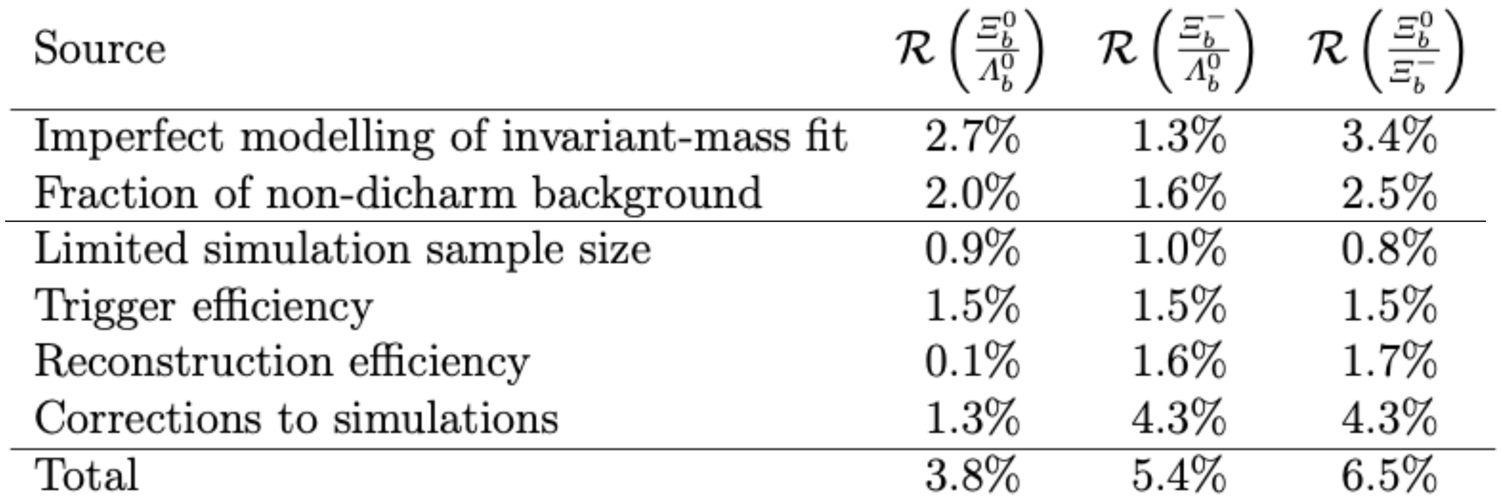
$$\frac{\varepsilon(\Xi_b^0)}{\varepsilon(\Lambda_b^0)} = 1.101 \pm 0.010(\text{MC stat.}),$$

← $\varepsilon(\Xi_b^0) \approx \varepsilon(\Lambda_b^0)$ due to similar kinematics

$$\frac{\varepsilon(\Xi_b^-)}{\varepsilon(\Lambda_b^0)} = 0.515 \pm 0.005(\text{MC stat.}),$$

← $\varepsilon(\Xi_b^-) \approx 0.5\varepsilon(\Xi_b^0)$ due to reconstruction efficiency of an additional K^-

- Systmatic uncertainties



	Source	$\mathcal{R}\left(\frac{\Xi_b^0}{\Lambda_b^0}\right)$	$\mathcal{R}\left(\frac{\Xi_b^-}{\Lambda_b^0}\right)$	$\mathcal{R}\left(\frac{\Xi_b^0}{\Xi_b^-}\right)$
on signal yields	Imperfect modelling of invariant-mass fit	2.7%	1.3%	3.4%
	Fraction of non-dicharm background	2.0%	1.6%	2.5%
on efficiencies	Limited simulation sample size	0.9%	1.0%	0.8%
	Trigger efficiency	1.5%	1.5%	1.5%
	Reconstruction efficiency	0.1%	1.6%	1.7%
	Corrections to simulations	1.3%	4.3%	4.3%
	Total	3.8%	5.4%	6.5%

Results of branching fraction ratios

LHCb measurement of $R\left(\frac{H_b^1}{H_b^2}\right) \equiv \frac{f(H_b^1)}{f(H_b^2)} \times \frac{\mathcal{B}(H_b^1\to H_c^1 D_s^-)}{\mathcal{B}(H_b^2\to H_c^2 D_s^-)}$	LHCb measurement of branching fraction $\mathcal{B}$ ratios	Theory predictions of $\mathcal{B}$ ratios
$R\left(\frac{\Xi_b^0}{\Lambda_b^0}\right) = (15.8 \pm \overset{\text{stat}}{1.1} \pm \overset{\text{syst}}{0.6} \pm \overset{\mathcal{B}(H_c)}{7.7})\%$	$\frac{\mathcal{B}(\Xi_b^0 \to \Xi_c^+ D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 1.92 \pm 1.15$	0.91~1.06[14−16]
$R\left(\frac{\Xi_b^-}{\Lambda_b^0}\right) = (16.9 \pm 1.3 \pm 0.9 \pm 4.3)\%$	$\frac{\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = 2.06 \pm 0.88$	0.97~1.06[14−16]
$R\left(\frac{\Xi_b^-}{\Xi_b^0}\right) = (93.6 \pm 9.6 \pm 6.1 \pm 51.0)\%$		

- $R(\Xi_b^-/\Xi_b^0)$ consistent with isospin symmetry
- R are valuable input for $f(\Xi_b)/f(\Lambda_b^0)$

Input fragmentation ratio

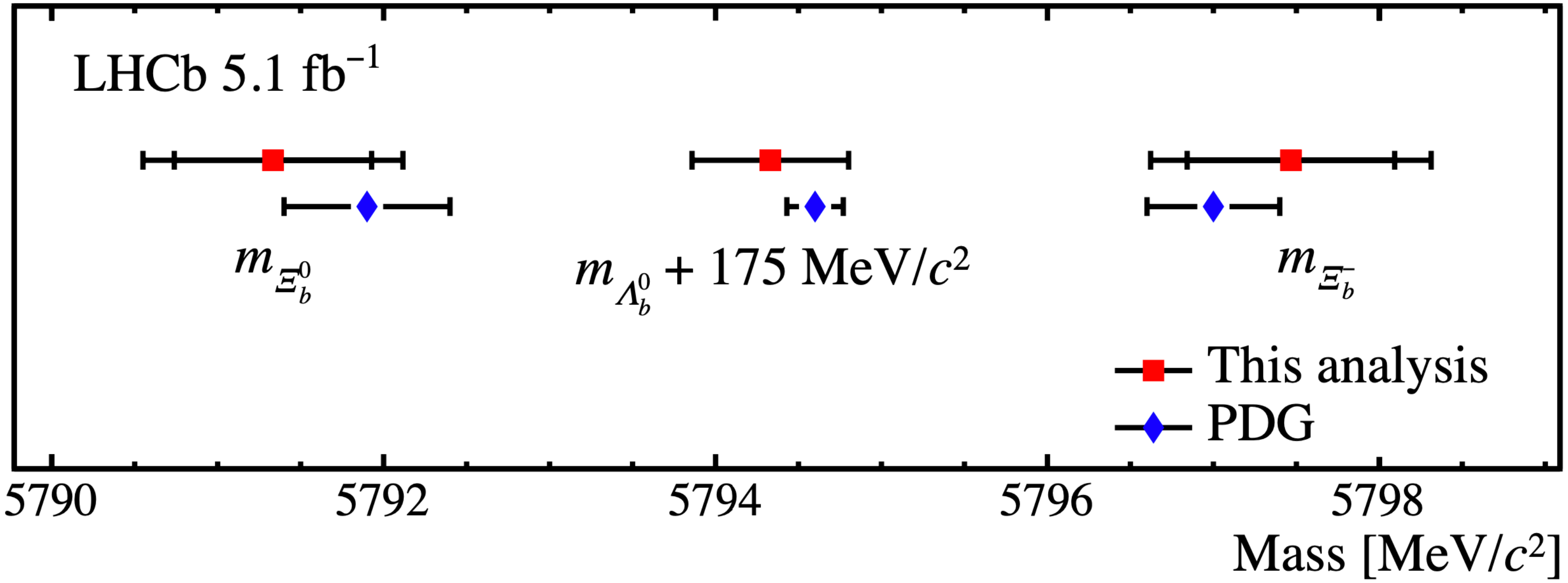
$f(\Xi_b^-)/f(\Lambda_b^0) = (8.2 \pm 2.7)\%$

measured with $\Xi_b^- \to J/\psi\Xi^-$ and $\Lambda_b^- \to J/\psi\Lambda$

assuming SU(3) symmetry [PRD99(2019)050026]

Assume $f(\Xi_b^-)/f(\Xi_b^0) = 1$

Results of Ξ_b mass



- New LHCb measurements are consistent with PDG values[29]
  - Dominant systematic uncertainty comes from momentum scale calibration

Measurement of the relative branching fractions of $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ and $\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}$ decays

[LHCb-PAPER-2023-034]

Analysis strategy

- Data samples
  - 5.4 fb^{-1} proton-proton collisions collected at $\sqrt{s} = 13$ TeV by LHCb in 2015-2018
- Relative branching fraction

Mass fit

Simulation

Input from PDG

$$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\bar{D}^{(*)0}K^-)}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)} = \frac{N(\Lambda_b^0\to\Lambda_c^+\bar{D}^{(*)0}K^-)}{N(\Lambda_b^0\to\Lambda_c^+D_s^-)} \times \frac{\varepsilon(\Lambda_b^0\to\Lambda_c^+D_s^-)}{\varepsilon(\Lambda_b^0\to\Lambda_c^+\bar{D}^{(*)0}K^-)} \times \frac{\mathcal{B}(D_s^-\to K^-K^+\pi^-)}{\mathcal{B}(\bar{D}^0\to K^+\pi^-)}$$

$$\frac{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^{*-})}{\mathcal{B}(\Lambda_b^0\to\Lambda_c^+D_s^-)} = \frac{N(\Lambda_b^0\to\Lambda_c^+D_s^{*-})}{N(\Lambda_b^0\to\Lambda_c^+D_s^-)} \times \frac{\varepsilon(\Lambda_b^0\to\Lambda_c^+D_s^-)}{\varepsilon(\Lambda_b^0\to\Lambda_c^+D_s^{*-})}$$

- Charm hadron reconstruction
  - $\Lambda_c^+ \to pK^-\pi^+$, $\bar{D}^0 \to K^+\pi^-$, $D_s^- \to K^+K^-\pi^-$
  - D_s^{*-} and $\bar{D}^{*0}$ reconstructed partially in $K^+K^-\pi^-$ and $K^+\pi^-$ respectively

Signal yield determination

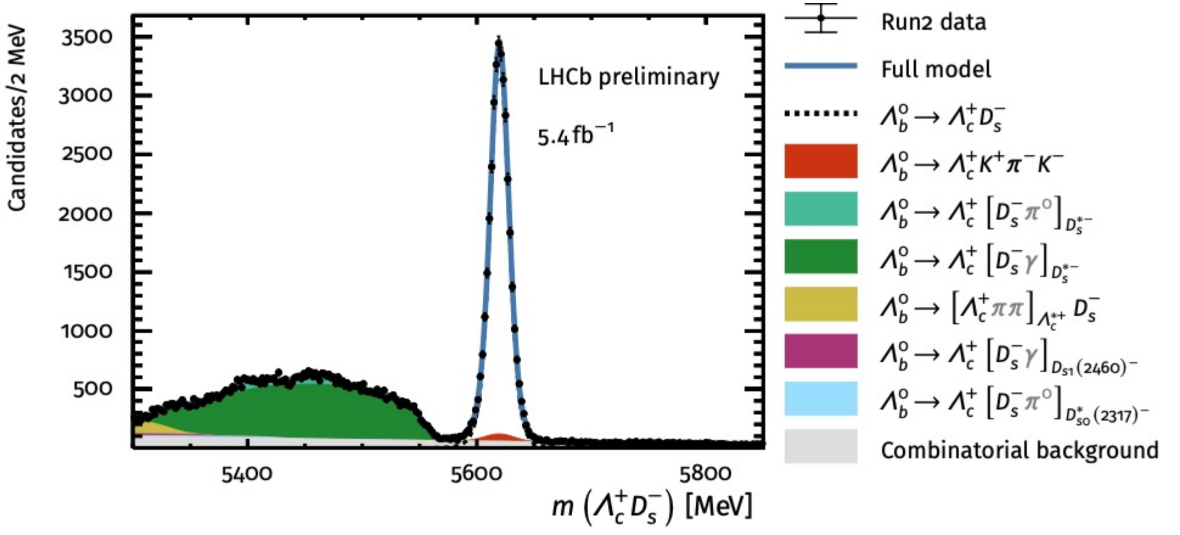
- Measure $N\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-\right)$ and $N\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right)$ through partial reconstruction. π^0 or γ from $\overline{D}^{*0}$ or D_s^{*-} not reconstructed.
- Invariant mass distribution of partially reconstructed decays determined by kinematics and dynamics i.e. amplitude composition

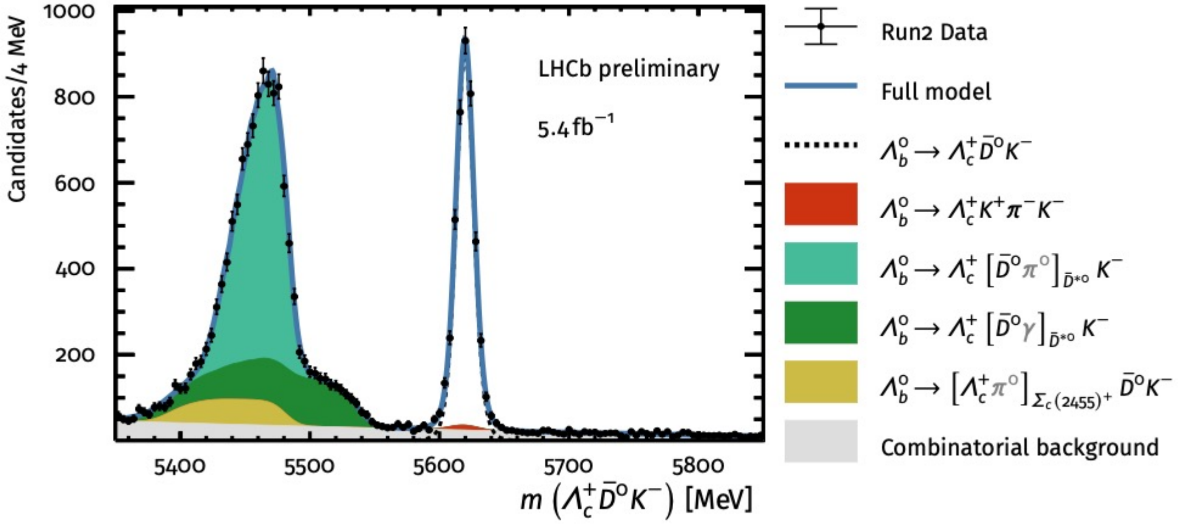
$$N\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right) = 46400 \pm 500(\text{stat.})$$

$$N\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right) = 35450_{-210}^{+200}(\text{stat.})$$

$$N\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-\right) = 10560_{-290}^{+310}(\text{stat.})$$

$$N\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-\right) = 4010 \pm 70(\text{stat.})$$





Efficiencies and systematic uncertainties

- Effficiency taken from simulation
  - Data-driven corrections to: production and decay kinematics, track multiplicity, BDT response for $\Lambda_c^+ \to pK^-\pi^+$

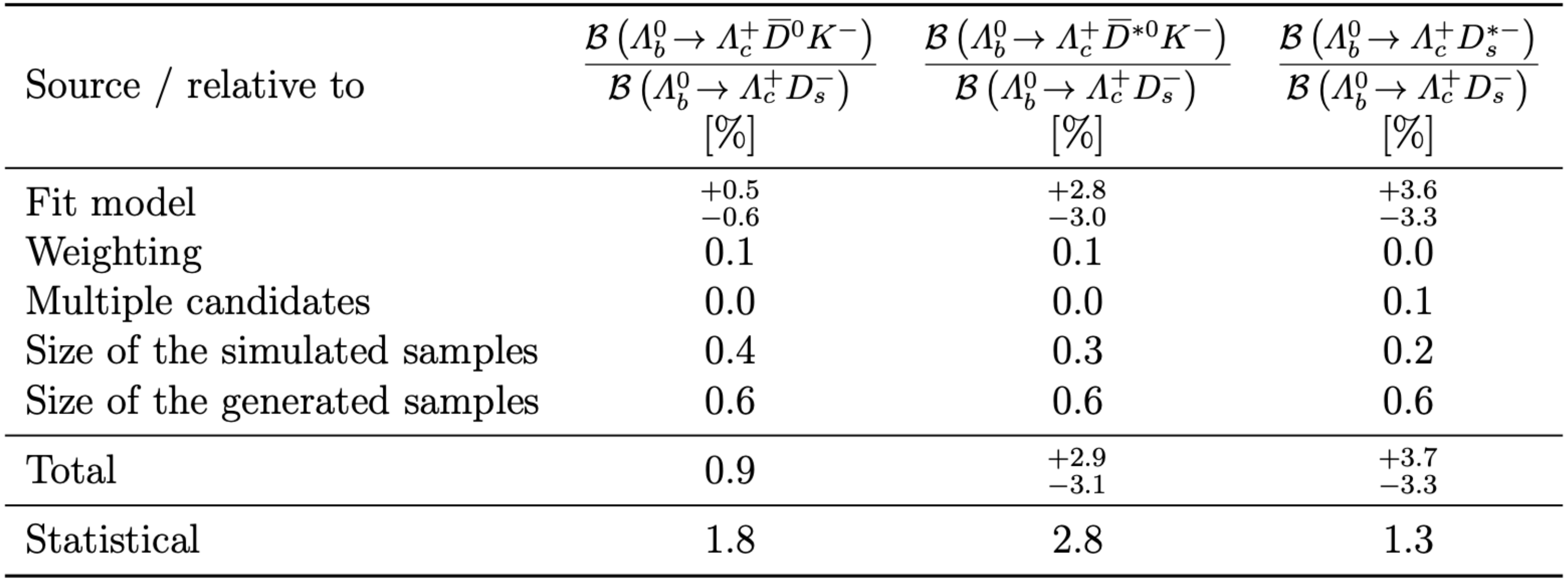
$$\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^0 K^-\right)/\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right) = 0.809 \pm 0.006(\text{MC stat})$$

$$\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^{*0} K^-\right)/\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right) = 0.680 \pm 0.005(\text{MC stat})$$

$$\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right)/\varepsilon\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right) = 0.785 \pm 0.005(\text{MC stat})$$

Efficiency of partially reconstructed Λ_b^0 is lower, because its track does not point to PV

- Systematic uncertainties



Source / relative to	$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^0 K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)}$ [%]	$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^{*0} K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)}$ [%]	$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)}$ [%]
Fit model	$^{+0.5}_{-0.6}$	$^{+2.8}_{-3.0}$	$^{+3.6}_{-3.3}$
Weighting	0.1	0.1	0.0
Multiple candidates	0.0	0.0	0.1
Size of the simulated samples	0.4	0.3	0.2
Size of the generated samples	0.6	0.6	0.6
Total	0.9	$^{+2.9}_{-3.1}$	$^{+3.7}_{-3.3}$
Statistical	1.8	2.8	1.3

Results

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^0 K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = 0.1908^{+0.0036}_{-0.0034}(\text{stat})^{+0.0016}_{-0.0018}(\text{syst}) \pm 0.0038(\mathcal{B})$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^{*0} K^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = 0.589^{+0.018}_{-0.017}(\text{stat})^{+0.017}_{-0.018}(\text{syst}) \pm 0.012(\mathcal{B})$$

$$\frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^{*-}\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ D_s^-\right)} = \boxed{1.668} \pm 0.022(\text{stat})^{+0.061}_{-0.055}(\text{syst})$$

Prefer the following theories (1.45~1.84)

- factorization approximation, using the quark model, treating ξ=1/N_c as a free parameter [4]
- the light-front approach under the diquark picture[11, 15]
- the light-front quark model [10]
- HQET with 1/m_Q corrections and factorization approximation [3]
- the covariant confined quark model [9]
- the covariant oscillator quark model [5]

Do not prefer the following theories (0.75~1.29, 2.25)

- HQET and factorization [1]
- the nonrelativistic quark model [2]
- a covariant light-front quark model, diquark approximation, QCD factorization approach[6]
- a detailed angular momentum formulation[8]
- a model based on Cornell potential plus logarithmic term in the hyperspherical coordinates [12]
- the contact-range effective field theory approach, the pentaquark molecules are produced in the Λ_b^0 decay via the triangle diagrams[13]

Results

Wait for future measurement to test models

$f_X(P_c^+)$ denotes fraction of $\Lambda_b^0 \to XK^-$ via P_c^+

$$\frac{\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \overline{D}^{(*)0}\right)}{\mathcal{B}(P_c^+ \to J/\psi p)} = \frac{f_{\Lambda_c^+ \overline{D}^{(*)0}}(P_c^+)}{f_{J/\psi p}(P_c^+)} \times \frac{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-\right)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

Theory prediction vary significantly yet[17-28]

Measured

[Phys. Rev. Lett. 122 (2019) 222001]

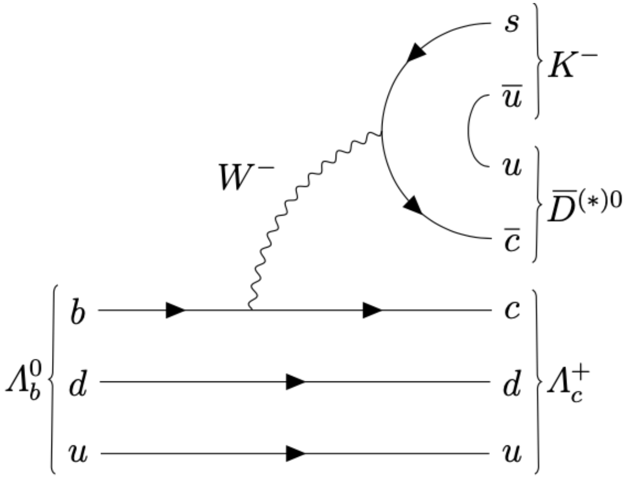
$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-)} = 0.152^{+0.032}_{-0.028}$$

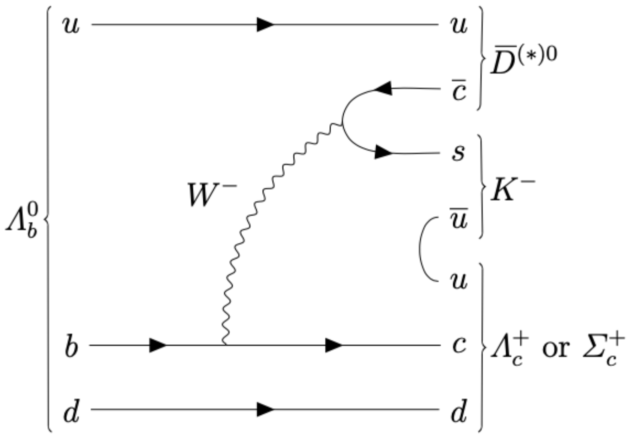
$$\frac{\mathcal{B}\left(\Lambda_b^0 \to J/\psi p K^-\right)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K^-)} = 0.049^{+0.011}_{-0.009}$$

Results

- Comparing $\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-\right)$ to mesonic counterpart allows to estimate strength of color-suppressed amplitudes, which are absent for meson decays
  - Define $\mathcal{DR}^{(*)}(M_b) \equiv \left[\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)}\right] / \left[\frac{\mathcal{B}(M_b \to M_c \overline{D}^{(*)0} K^-)}{\mathcal{B}(M_b \to M_c D_s^-)}\right]$

M_b or M_c is a beauty or charm meson.
$\mathcal{DR}^{(*)}$ denotes $\overline{D}^0$ ground state or $\overline{D}^*(2007)^0$ vector state.





$\mathcal{DR}(\bar{B}^0) = 1.29 \pm 0.20,$ $\mathcal{DR}^*(\bar{B}^0) = 1.28 \pm 0.19,$

$\mathcal{DR}(B^-) = 1.20 \pm 0.30,$ $\mathcal{DR}^*(B^-) = 0.87 \pm 0.12,$

$\mathcal{DR}(B_c^-) = 1.3 \pm 0.5,$ $\mathcal{DR}^*(B_c^-) = 0.8 \pm 0.4.$

  - $\mathcal{DR}$ of decays via $\overline{D}^0$ hint towards larger baryonic branching ratio, while those corresponding to the $\overline{D}^{*0}$ are inconclusive.
  - Larger baryonic branching fractions are expected, due to an additional color-suppressed amplitude in the Λ_b^0 decay, which does not exist for mesons.

Summary

- LHCb is capable of reconstructing fully hadronic beauty to double open-charm decays with 6 and 7 particles in the final state, reaching down to percent-level precision!
- The presented branching fractions show sensitivity to test models.
- $\mathcal{B}\left(\Xi_b^0 \to \Xi_c^+ D_s^-\right)$ and $\mathcal{B}(\Xi_b^- \to \Xi_c^0 D_s^-)$ are valuable input to Ξ_b/Λ_b^0 fragmentation ratios.
- Ξ_b mass measurements consistent with and will improve the world averages.
- $\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+ \overline{D}{}^0 K^-\right)$ needs for upcoming pentaquark searches in these channels to test predictions of $\mathcal{B}\left(P_c^+ \to \Lambda_c^+ \overline{D}{}^{(*)0}\right)/\mathcal{B}(P_c^+ \to J/\psi p)$.

Reference

[1] Z. Phys. C 59, 179
[2] Phys. Rev. D 56, 2799
[3] Mod. Phys. Lett. A 13 (1998) 23
[4] Phys. Rev. D 58, 014016
[5] Prog. Theor. Phys. 101, 959
[6] Phys. Rev. D 99, 054020
[7] Chinese Phys. C 42 093101
[8] Eur. Phys. J. C 78, 528
[9] Phys. Rev. D 98, 074011
[10] Eur. Phys. J. C 79, 540
[11] Phys. Rev. D 100, 034025
[12] Eur. Phys. J. C 80, 636
[13] arXiv:2309.12050
[14] Phys. Rev. D 56, 2799
[15] Chinese Phys. C 42 093101
[16] Phys. Rev. D 100, 034025
[17] arXiv:2309.12050.
[18] Phys. Lett. B793 (2019) 144
[19] Phys. Rev. D100 (2019) 014021
[20] Phys. Rev. D100 (2019) 016014
[21] Phys. Rev. D100 (2019) 034020
[22] Phys. Rev. D100 (2019) 056005
[23] Eur. Phys. J. A56 (2020) 142
[24] Eur. Phys. J. C80 (2020) 945
[25] Eur. Phys. J. C80 (2020) 341
[26] Chin. Phys. C45 (2021) 063104
[27] Phys. Rev. D102 (2020) 056018
[28] Phys. Rev. D108 (2023) 056015
[29] Prog. Theor. Exp. Phys. 2022 (2022) 083C01.