

# Measurement of the properties of the $\Xi_b^{*0}$ baryon

The LHCb collaboration<sup>†</sup>

## Abstract

We perform a search for near-threshold  $\Xi_b^0$  resonances decaying to  $\Xi_b^- \pi^+$  in a sample of proton-proton collision data corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$  collected by the LHCb experiment. We observe one resonant state, with the following properties:

$$\begin{aligned} m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) &= 15.727 \pm 0.068 \text{ (stat)} \pm 0.023 \text{ (syst)} \text{ MeV}/c^2, \\ \Gamma(\Xi_b^{*0}) &= 0.90 \pm 0.16 \text{ (stat)} \pm 0.08 \text{ (syst)} \text{ MeV}. \end{aligned}$$

This confirms the previous observation by the CMS collaboration. The state is consistent with the  $J^P = 3/2^+$   $\Xi_b^{*0}$  resonance expected in the quark model. This is the most precise determination of the mass and the first measurement of the natural width of this state. We have also measured the ratio

$$\frac{\sigma(pp \rightarrow \Xi_b^{*0} X) \mathcal{B}(\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+)}{\sigma(pp \rightarrow \Xi_b^- X)} = 0.27 \pm 0.03 \text{ (stat)} \pm 0.01 \text{ (syst)}.$$

Submitted to JHEP

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# 1 Introduction

Precise measurements of the properties of hadrons provide important metrics by which models of quantum chromodynamics (QCD), including lattice QCD and potential models employing the symmetries of QCD, can be tested. Studies of hadrons containing a heavy quark play a special role since the heavy quark symmetry can be exploited, for example to relate properties of charm hadrons to beauty hadrons. Measurements of the masses and mass splittings between the ground and excited states of beauty and charm hadrons provide a valuable probe of the interquark potential [1].

There are a number of  $b$  baryon states that contain both beauty and strange quarks. The singly strange states form isodoublets:  $\Xi_b^0$  ( $bsu$ ) and  $\Xi_b^-$  ( $bsd$ ). Theoretical estimates of the properties of these states are available (see, *e.g.*, Refs. [1–12]). There are five known  $\Xi_b$  states which, in the constituent quark model, correspond to five of the six low-lying states that are neither radially nor orbitally excited: one isodoublet of weakly-decaying ground states ( $\Xi_b^0$  and  $\Xi_b^-$ ) with  $J^P = \frac{1}{2}^+$ , one isodoublet ( $\Xi_b^{\prime 0}$  and  $\Xi_b^{\prime -}$ ) with  $J^P = \frac{1}{2}^+$  but different symmetry properties from the ground states, and one isodoublet ( $\Xi_b^{*0}$  and  $\Xi_b^{*-}$ ) with  $J^P = \frac{3}{2}^+$ . The large data samples collected at the Large Hadron Collider have allowed these states to be studied in detail in recent years. These studies include precise measurements of the masses and lifetimes of the  $\Xi_b^0$  and  $\Xi_b^-$  baryons [13, 14] by the LHCb collaboration, the observation of a peak in the  $\Xi_b^- \pi^+$  mass spectrum interpreted as the  $\Xi_b^{*0}$  baryon [15] by the CMS collaboration, and the observation of two structures in the  $\Xi_b^0 \pi^-$  mass spectrum, consistent with the  $\Xi_b^{\prime -}$  and  $\Xi_b^{*-}$  baryons [16] by LHCb.<sup>1</sup> The  $\Xi_b^{\prime 0}$  state was not observed by CMS; it is assumed to be too light to decay into  $\Xi_b^- \pi^+$ .

In this paper, we present the results of a study of the  $\Xi_b^- \pi^+$  mass spectrum, where the  $\Xi_b^-$  baryon is reconstructed through its decay to  $\Xi_c^0 \pi^-$ , with  $\Xi_c^0 \rightarrow p K^- K^- \pi^+$ . The measurements use a  $pp$  collision data sample recorded by the LHCb experiment, corresponding to an integrated luminosity of  $3 \text{ fb}^{-1}$ , of which  $1 \text{ fb}^{-1}$  was collected at  $\sqrt{s} = 7 \text{ TeV}$  and  $2 \text{ fb}^{-1}$  at  $8 \text{ TeV}$ . We observe a single peak in the  $\Xi_b^- \pi^+$  mass spectrum, consistent with the state reported in Ref. [15]. A precise determination of its mass and the first determination of a non-zero natural width are reported. We also measure the relative production rate between the  $\Xi_b^{*0}$  and  $\Xi_b^-$  baryons in the LHCb acceptance.

The LHCb detector [17, 18] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about  $4 \text{ Tm}$ , and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum,  $p$ , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at  $200 \text{ GeV}/c$ . The minimum distance of a track to a primary vertex (PV), the impact parameter, is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam, in  $\text{GeV}/c$ . Different types of charged hadrons are distinguished

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<sup>1</sup> Charge-conjugate processes are implicitly included throughout.

using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The online event selection is performed by a trigger, which consists of a hardware stage (L0), based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The software trigger requires a two-, three- or four-track secondary vertex which is significantly displaced from all primary  $pp$  vertices and for which the scalar  $p_T$  sum of the charged particles is large. At least one particle should have  $p_T > 1.7 \text{ GeV}/c$  and be inconsistent with coming from any of the PVs. A multivariate algorithm [19] is used to identify secondary vertices consistent with the decay of a  $b$  hadron.

In the simulation,  $pp$  collisions are generated using PYTHIA [20] with a specific LHCb configuration [21]. Decays of hadrons are described by EVTGEN [22], in which final-state radiation is generated using PHOTOS [23]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [24] as described in Ref. [25].

## 2 Candidate selection

Candidate  $\Xi_b^-$  decays are formed by combining  $\Xi_c^0 \rightarrow pK^-K^-\pi^+$  and  $\pi^-$  candidates in a kinematic fit [26]. All tracks used to reconstruct the  $\Xi_b^-$  candidate are required to have good track fit quality, have  $p_T > 100 \text{ MeV}/c$ , and have particle identification information consistent with the hypothesis assigned. The large lifetime of the  $\Xi_b^-$  baryon is exploited to reduce combinatorial background by requiring all of its final-state decay products to have a significant impact parameter with respect to all of the PVs in the event. The  $\Xi_c^0$  candidates are required to have invariant mass within  $20 \text{ MeV}/c^2$  of the known value [27], corresponding to about three times the mass resolution. To further suppress background, the  $\Xi_b^-$  candidate must have a decay vertex that is significantly displaced from all PVs in the event, and have a trajectory that points back to one of the PVs. The invariant mass spectra of selected  $\Xi_c^0$  and  $\Xi_b^-$  candidates are displayed in Fig. 1.

The  $\Xi_b^-$  candidates are then required to have invariant mass within  $60 \text{ MeV}/c^2$  of the peak value, corresponding to about three times the mass resolution. In a given event, each combination of  $\Xi_b^-$  and  $\pi^+$  candidates is considered, provided that the pion has  $p_T$  greater than  $100 \text{ MeV}/c$  and is consistent with coming from the same PV as the  $\Xi_b^-$  candidate. The  $\Xi_b^- \pi^+$  vertex is constrained to coincide with the PV in a kinematic fit, which is required to be of good quality. The  $\Xi_b^- \pi^+$  system is also required to have  $p_T > 2.5 \text{ GeV}/c$ .

The mass difference  $\delta m$  is defined as

$$\delta m \equiv m_{\text{cand}}(\Xi_b^- \pi^+) - m_{\text{cand}}(\Xi_b^-) - m(\pi^+), \quad (1)$$

where  $m_{\text{cand}}$  represents the reconstructed mass. The  $\delta m$  spectrum of  $\Xi_b^- \pi^+$  candidates passing all selection requirements is shown in Fig. 2. A clear peak is seen at about

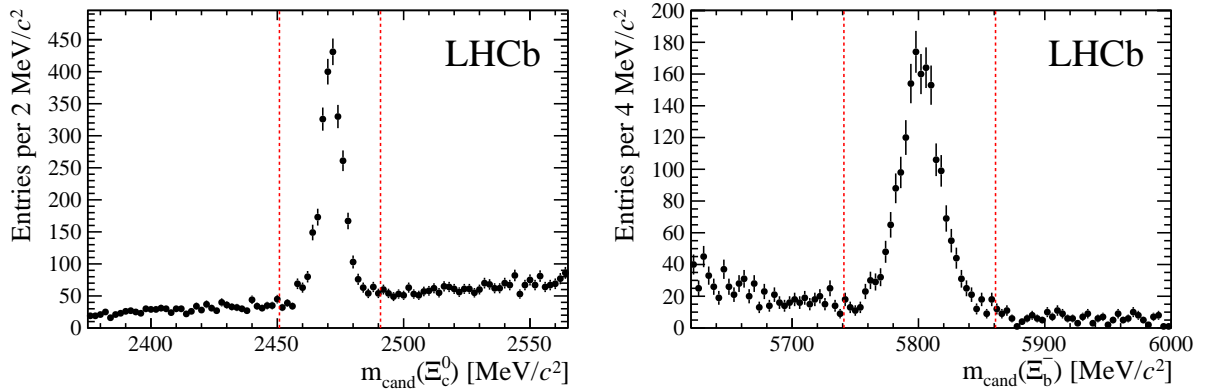


Figure 1: Mass spectra of (left)  $\Xi_c^0$  and (right)  $\Xi_b^-$  candidates after all selection requirements are imposed, except for the one on the mass that is plotted. The vertical dashed lines show the selection requirements used in forming  $\Xi_b^-$  and  $\Xi_b^{*0}$  candidates.

16  $\text{MeV}/c^2$ , whereas no such peak is seen in the wrong-sign ( $\Xi_b^- \pi^-$ ) combinations, also shown in Fig. 2.

To determine the properties of the  $\Xi_b^- \pi^+$  peak, we consider only candidates with  $\delta m < 45 \text{ MeV}/c^2$ ; this provides a large enough region to constrain the combinatorial background shape. There are on average 1.16 candidates per selected event in this mass region; all candidates are kept. In the vast majority of events with more than one candidate, a single  $\Xi_b^-$  candidate is combined with different  $\pi^+$  tracks from the same PV.

### 3 Mass and width of $\Xi_b^- \pi^+$ peak

Accurate determination of the mass, width, and signal yield requires knowledge of the signal shape, and in particular the mass resolution. This is obtained from simulated  $\Xi_b^{*0}$  decays in which the  $\delta m$  value is set to the approximate peak location seen in data. In this simulation, the natural width of the  $\Xi_b^- \pi^+$  state is fixed to a negligible value so that the shape of the distribution measured is due entirely to the mass resolution. The resolution function is parameterised as the sum of three Gaussian distributions with a common mean value. The weighted average of the three Gaussian widths is  $0.51 \text{ MeV}/c^2$ . In the fits to data, all of the resolution shape parameters are fixed to the values obtained from simulation.

Any  $\Xi_b^- \pi^+$  resonance in this mass region would be expected to have a non-negligible natural width  $\Gamma$ . The signal shape in fits to data is therefore described using a  $P$ -wave relativistic Breit–Wigner (RBW) line shape [28] with a Blatt–Weisskopf barrier factor [29], convolved with the resolution function described above.

The combinatorial background is modelled by an empirical threshold function of the

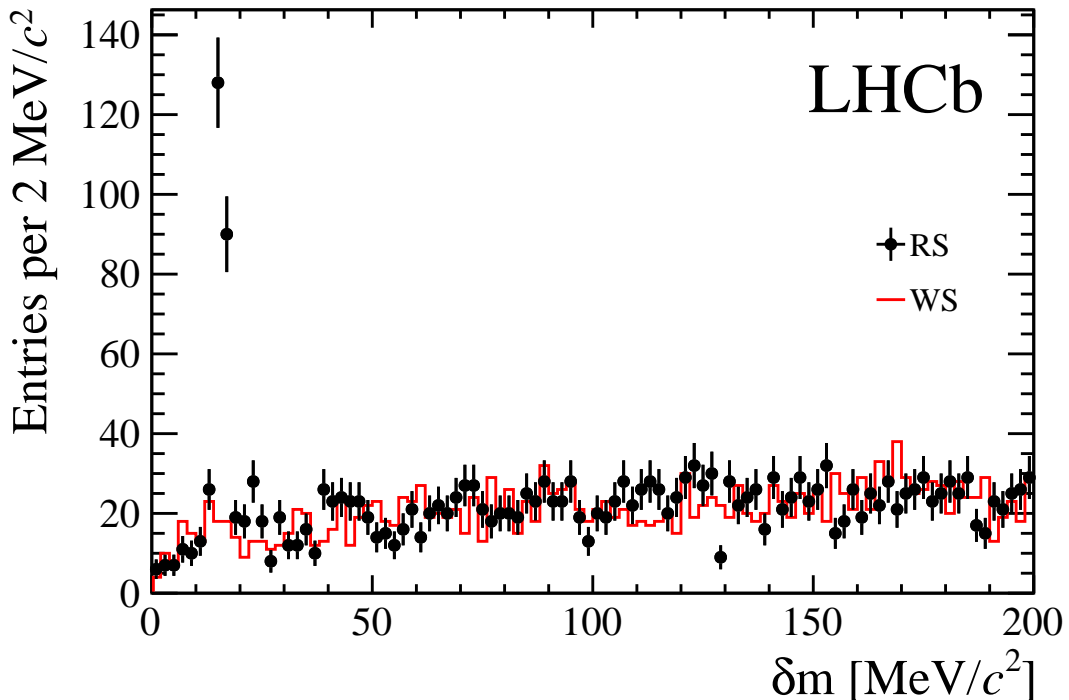


Figure 2: Distribution of  $\delta m$ . Right-sign candidates (RS,  $\Xi_b^- \pi^+$ ) are shown as points with error bars, and wrong-sign candidates (WS,  $\Xi_b^- \pi^-$ ) as a histogram. A single narrow structure is seen in the right-sign data.

form

$$f(\delta m) = (1 - e^{-\delta m/C}) (\delta m)^A, \quad (2)$$

where  $A$  and  $C$  are freely varying parameters determined in the fit to the data and  $\delta m$  is in units of  $\text{MeV}/c^2$ .

The mass, width and yield of events in the observed peak are determined from an unbinned, extended maximum likelihood fit to the  $\delta m$  spectrum using the signal and background shapes described above. The mass spectrum and the results of the fit are shown in Fig. 3. The fitted signal yield is  $232 \pm 19$  events. The nonzero value of the natural width of the peak,  $\Gamma = 0.90 \pm 0.16 \text{ MeV}$  (where the uncertainty is statistical only), is also highly significant: the change in log-likelihood when the width is fixed to zero exceeds 30 units.

We perform a number of cross-checks to ensure the robustness of the result. These include splitting the data by magnet polarity, requiring that one or more of the decay products of the signal candidate pass the L0 trigger requirements, dividing the data into subsamples in which the  $\pi^+$  candidate has  $p_T < 250 \text{ MeV}/c$  and  $p_T > 250 \text{ MeV}/c$ , varying the fit range in  $\delta m$ , and applying a multiple candidate rejection algorithm in which only

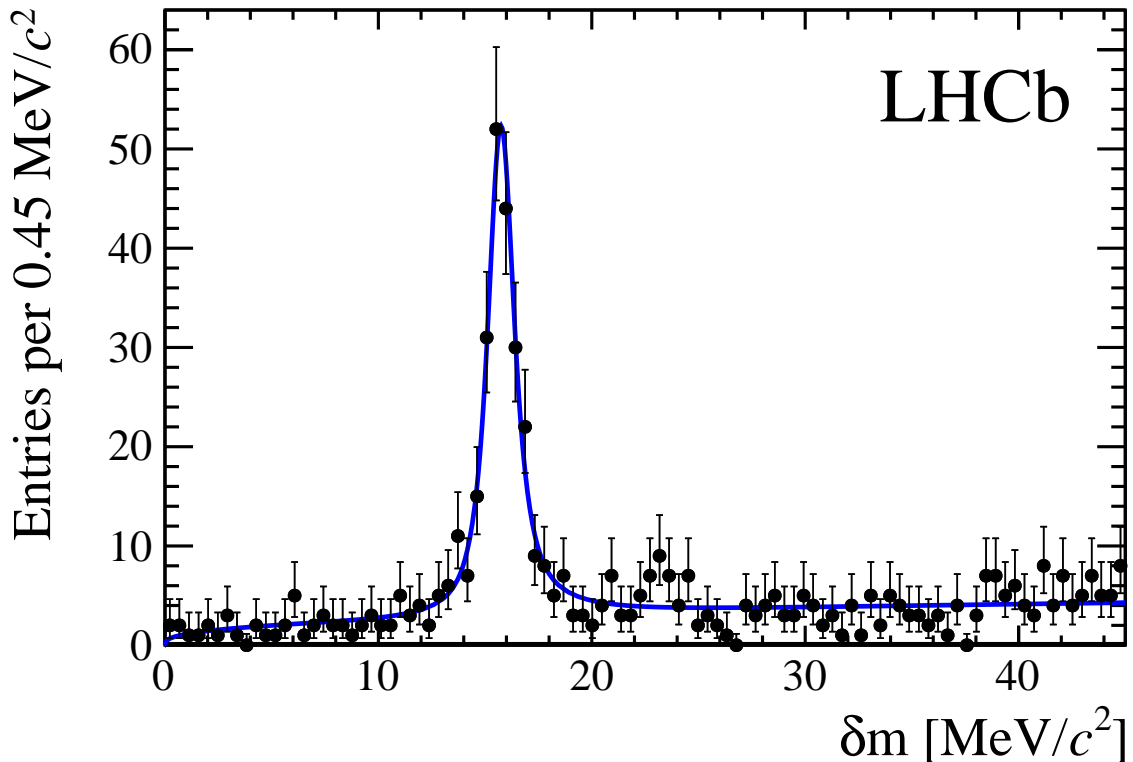


Figure 3: Distribution of  $\delta m$  along with the results of the fit described in the text.

one candidate, chosen at random, is retained in each event. In each of these cross-checks, the variation in fit results is consistent with statistical fluctuations.

Several sources of systematic effects are considered and are summarised in Table 1. Other than the first two systematic uncertainties described below, all are determined by making variations to the baseline selection or fit procedure, repeating the analysis, and taking the maximum change in  $\delta m$  or  $\Gamma$ . A small correction (16 keV, estimated with pseudoexperiments) to  $\Gamma$  is required due to the systematic underestimation of the width in a fit with limited yield; an uncertainty of the same size is assigned. This correction is already included in the value of  $\Gamma$  quoted earlier. The limited size of the sample of simulated events leads to uncertainties on the resolution function parameters. These uncertainties are propagated to the final results using the full covariance matrix. We assign a systematic uncertainty for a particular class of events with multiple  $\Xi_b^{*0}$  candidates in which the  $\Xi_b^-$  or  $\Xi_c^0$  baryon is misreconstructed. This uncertainty is determined by applying a limited multiple candidate rejection procedure in which only one  $\Xi_b^0$  candidate is accepted per event (but may be combined with multiple pions). The robustness of the resolution model is verified with control samples of  $\Xi_b^{\prime-} \rightarrow \Xi_b^0 \pi^-$  (see Ref. [16]) and  $D^{*+} \rightarrow D^0 \pi^+$ ; based on these tests, the uncertainty is assessed by increasing the  $\Xi_b^{*0}$  resolution width by 11%. This is the dominant uncertainty on  $\Gamma$ . An alternative background description, consisting of a

first-order polynomial multiplied by the two-body phase space, is used in the fit to check the dependence of the signal parameters on the background model. The calibration of the momentum scale has an uncertainty of 0.03% [30,31], the effect of which is propagated to the mass and width of the  $\Xi_b^{*0}$  baryon. As in Ref. [16], this is validated by measuring  $m(D^{*+}) - m(D^0)$  in a large sample of  $D^{*+}, D^0 \rightarrow K^- K^+$  decays. The mass difference agrees with a recent BaBar measurement [32] within  $6 \text{ keV}/c^2$ , corresponding to  $1.3\sigma$  when including the mass scale uncertainty for that decay. Finally, the dependence of the results on the relativistic Breit–Wigner lineshape is tested: other values of the assumed angular momentum (spin 0, 2) and radial parameter ( $1\text{--}5 \text{ GeV}^{-1}$ ) of the Blatt–Weisskopf barrier factor are used, and an alternative parameterisation of the mass-dependent width (from appendix A of Ref. [28]) is tested.

Table 1: Systematic uncertainties, in units of  $\text{MeV}/c^2$  (mass) and  $\text{MeV}$  (width).

Effect	$\delta m$	$\Gamma$
Fit bias correction		0.016
Simulated sample size	0.007	0.034
Multiple candidates	0.009	0.007
Resolution model	0.001	0.072
Background description	0.002	0.001
Momentum scale	0.009	0.001
RBW shape	0.017	0.011
Sum in quadrature	0.023	0.082
Statistical uncertainty	0.068	0.162

Taking these effects into account, the mass difference and width are measured to be

$$\begin{aligned}
 m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) &= 15.727 \pm 0.068 \pm 0.023 \text{ MeV}/c^2, \\
 \Gamma(\Xi_b^{*0}) &= 0.90 \pm 0.16 \pm 0.08 \text{ MeV},
 \end{aligned}$$

where the first uncertainties are statistical and the second are systematic. The observed peak is compatible with the  $J^P = \frac{3}{2}^+$  state expected in the quark model [2], and we therefore refer to it as the  $\Xi_b^{*0}$  baryon.

## 4 Relative production rate

In addition to the mass and width of the  $\Xi_b^{*0}$  state, we measure the rate at which it is produced in the LHCb acceptance relative to the  $\Xi_b^-$  baryon. The quantity that is measured is

$$\frac{\sigma(pp \rightarrow \Xi_b^{*0} X) \mathcal{B}(\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+)}{\sigma(pp \rightarrow \Xi_b^- X)} = \frac{N(\Xi_b^{*0})}{N(\Xi_b^-)} \frac{1}{\epsilon_{\Xi_b^{*0}}^{\text{rel}}}, \quad (3)$$



where  $\epsilon_{\Xi_b^{*0}}^{\text{rel}}$  is the ratio of the  $\Xi_b^{*0}$  to  $\Xi_b^-$  selection efficiencies, and  $N$  is a measured yield. Any variation in the ratio of cross-sections  $[\sigma(pp \rightarrow \Xi_b^{*0} X)] / [\sigma(pp \rightarrow \Xi_b^- X)]$  between  $\sqrt{s} = 7$  TeV and 8 TeV would be far below the sensitivity of our measurements, and is therefore neglected.

To minimize systematic uncertainties, all aspects of the  $\Xi_b^-$  selection are chosen to be common to the inclusive  $\Xi_b^-$  and  $\Xi_b^{*0}$  samples. Therefore an additional requirement, not applied to the sample used in the mass and width measurements, is imposed that at least one of the  $\Xi_b^-$  decay products passes the L0 hadron trigger requirements. The relative efficiency  $\epsilon_{\Xi_b^{*0}}^{\text{rel}}$  includes the efficiency of detecting the  $\pi^+$  from the  $\Xi_b^{*0}$  decay and the selection criteria imposed on it. It is evaluated using simulated decays, and small corrections (discussed below) are applied to account for residual differences between data and simulation. Including only the uncertainty due to the finite sizes of the simulated samples, the value of  $\epsilon_{\Xi_b^{*0}}^{\text{rel}}$  is found to be  $0.598 \pm 0.014$ .

The yields in data are obtained by fitting the  $\delta m$  and  $m_{\text{cand}}(\Xi_b^-)$  spectra after applying all selection criteria. For the  $\Xi_b^{*0}$  yield, the data are fitted using the same functional form as was used for the full sample. The fit is shown in Fig. 4, and the yield obtained is  $N(\Xi_b^{*0}) = 133 \pm 14$ . The results of an unbinned, extended maximum likelihood fit to the  $\Xi_b^-$  sample are shown in Fig. 5. The shapes used to describe the signal and backgrounds are identical to those described in Ref. [14]. In brief, the signal shape is described by the sum of two Crystal Ball functions [33] with a common mean. The background components are due to misidentified  $\Xi_b^- \rightarrow \Xi_c^0 K^-$  decays, partially-reconstructed  $\Xi_b^- \rightarrow \Xi_c^0 \rho^-$  decays, and combinatorial background. The  $\Xi_b^- \rightarrow \Xi_c^0 K^-$  contribution is also described by the sum of two Crystal Ball functions with a common mean. Its shape parameters are fixed to the values from simulation, and the fractional yield relative to that of  $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$  is fixed to 3.1%, based on previous studies of this mode [14]. The  $\Xi_b^- \rightarrow \Xi_c^0 \rho^-$  mass shape is described by an ARGUS function [34], convolved with a Gaussian resolution function. The resolution is fixed to  $14 \text{ MeV}/c^2$ , the approximate mass resolution for signal decays, and the yield is freely varied in the fit. The combinatorial background is described by an exponential function with freely varying shape parameter and yield. To match the criteria used for the  $\Xi_b^{*0}$  selection, only  $\Xi_b^-$  candidates within  $\pm 60 \text{ MeV}/c^2$  of the known mass contribute to the yield, which is found to be  $N(\Xi_b^-) = 812 \pm 32$ .

Several sources of uncertainty contribute to the production ratio measurement, either in the signal efficiency or in the determination of the yields. Most of the selection requirements are common to both the signal and normalization modes, and therefore the corresponding efficiencies cancel in the production ratio measurement. Effects related to the detection and selection of the  $\pi^+$  from the  $\Xi_b^{*0}$  decay do not cancel, and therefore contribute to the systematic uncertainty. The tracking efficiency is measured using a tag and probe procedure with  $J/\psi \rightarrow \mu^+ \mu^-$  decays [35], and for this momentum range a correction of  $(+7.0 \pm 3.0)\%$  is applied. Fit quality requirements on the  $\pi^+$  track lead to an additional correction of  $(-1.5 \pm 1.5)\%$ . The simulation is used to estimate the loss of  $\Xi_b^{*0}$  efficiency from decays in which the  $\pi^+$  is reconstructed but has  $p_T < 100 \text{ MeV}/c$ . This loss, 2.7%, is already included in the efficiency, and does not require an additional correction. Since the

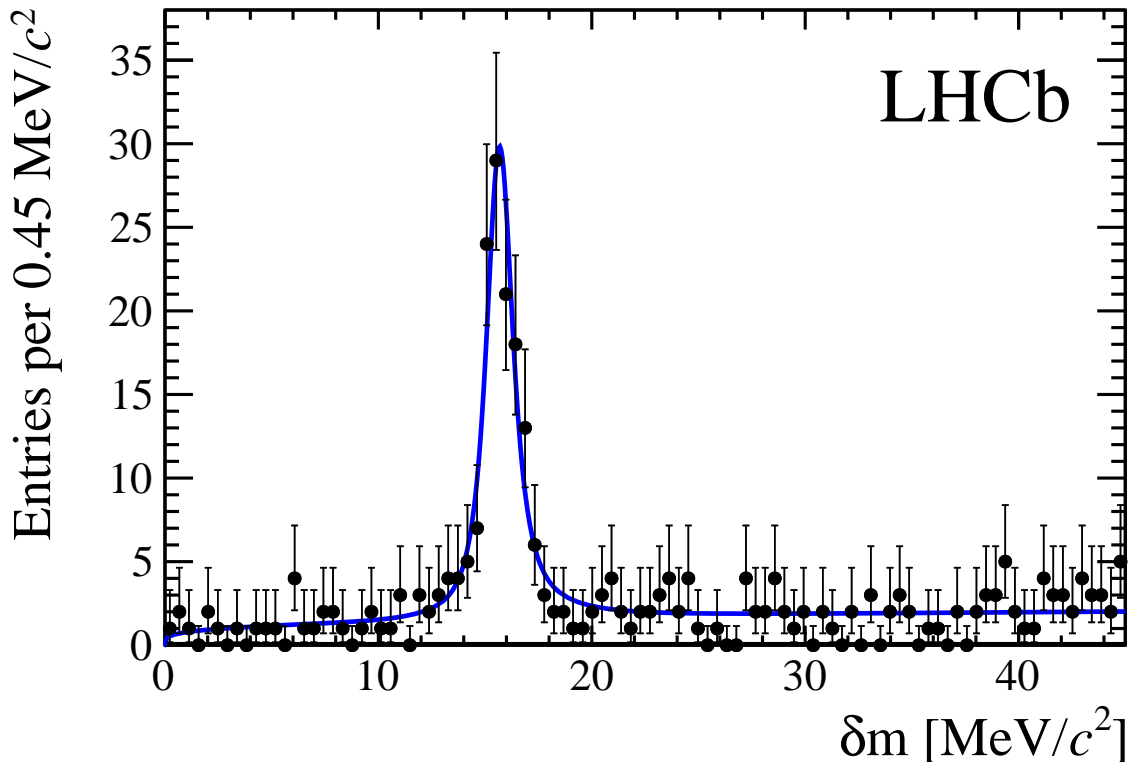


Figure 4: Distribution of  $\delta m$ , using only events in which one or more of the  $\Xi_b^-$  decay products pass the L0 hadron trigger requirements. The results of the fit are overlaid.

simulation reproduces the  $p_T$  spectrum well for  $p_T > 100 \text{ MeV}/c$ , we assign half of the value, 1.4%, as a systematic uncertainty associated with the extrapolation to  $p_T < 100 \text{ MeV}/c$ . Finally, the limited sample sizes of simulated events contribute an uncertainty of 2.4% to the relative efficiency. With these systematic sources included, the relative efficiency is found to be  $\epsilon_{\Xi_b^{*0}}^{\text{rel}} = 0.598 \pm 0.026$ .

For the  $\Xi_b^{*0}$  signal yield in data, we assign a 1% systematic uncertainty due to a potential peaking background in which a genuine  $\Xi_b^{*-} \rightarrow \Xi_b^- \pi^+$ ,  $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$  decay is found but the  $\Xi_c^0$  is misreconstructed. For the normalization mode, independent variations in the signal and background shapes are investigated, and taken together correspond to a systematic uncertainty in the normalisation mode yield of 2%.

Combining the relative efficiency, the yields, and the systematic uncertainties described above, we find

$$\frac{\sigma(pp \rightarrow \Xi_b^{*0} X) \mathcal{B}(\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+)}{\sigma(pp \rightarrow \Xi_b^- X)} = 0.27 \pm 0.03 \pm 0.01,$$

where the statistical uncertainty takes into account the correlation between  $N(\Xi_b^{*0})$  and  $N(\Xi_b^-)$ .

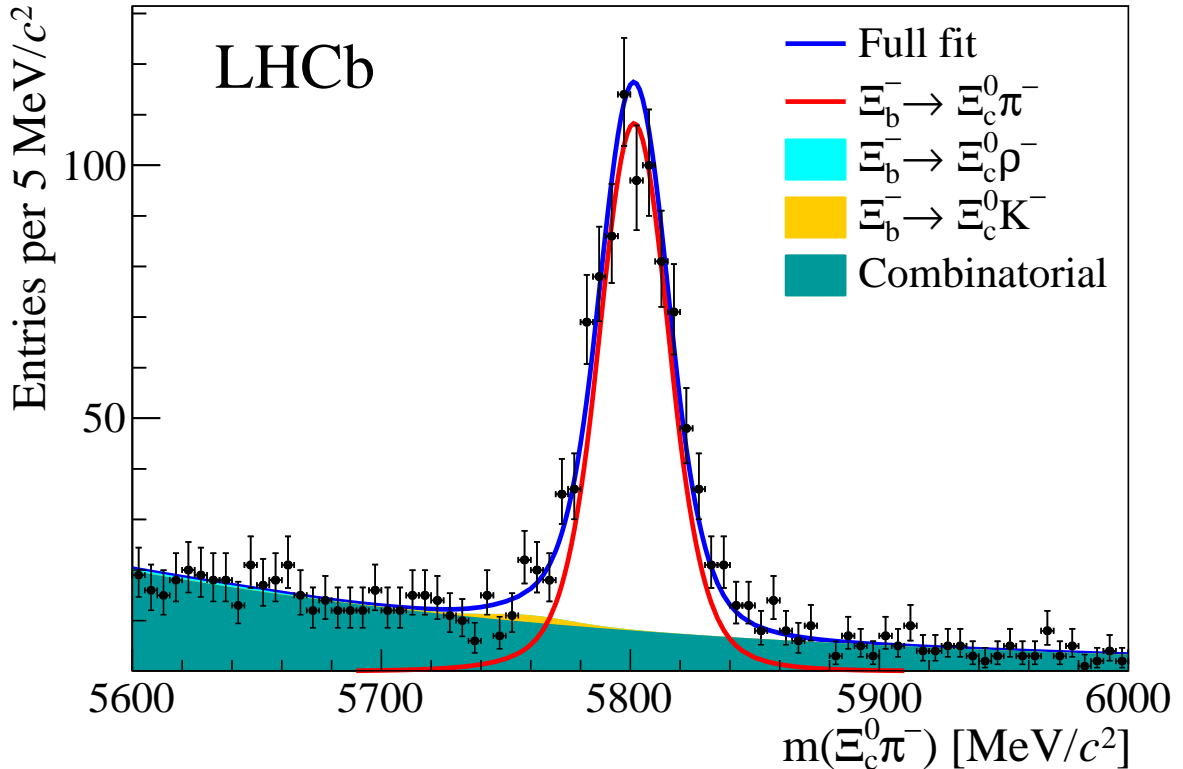


Figure 5: Invariant mass spectrum of selected  $\Xi_c^0\pi^-$  candidates. The fit described in the text is overlaid. The  $\Xi_b^-$  signal peak and background from combinatorial events are clearly visible, accompanied by small contributions from the peaking background processes  $\Xi_b^- \rightarrow \Xi_c^0\rho^-$  and  $\Xi_b^- \rightarrow \Xi_c^0K^-$ .

## 5 Summary

Using  $pp$  collision data from the LHCb experiment corresponding to an integrated luminosity of  $3\text{fb}^{-1}$ , we observe one highly significant structure in the  $\Xi_b^-\pi^+$  mass spectrum near threshold. There is no indication of a second state above the  $\Xi_b^-\pi^+$  mass threshold that would indicate the presence of the  $\Xi_b^{*0}$  resonance; from this we conclude that  $m(\Xi_b^{*0}) < m(\Xi_b^-) + m(\pi^+)$ . The mass difference and width of the  $\Xi_b^{*0}$  are measured to be:

$$\begin{aligned} m(\Xi_b^{*0}) - m(\Xi_b^-) - m(\pi^+) &= 15.727 \pm 0.068 \pm 0.023 \text{ MeV}/c^2, \\ \Gamma(\Xi_b^{*0}) &= 0.90 \pm 0.16 \pm 0.08 \text{ MeV}. \end{aligned}$$

We interpret the structure as the  $J^P = \frac{3}{2}^+$   $\Xi_b^{*0}$  state observed previously by the CMS collaboration through the decay chain  $\Xi_b^{*0} \rightarrow \Xi_b^-\pi^+, \Xi_b^- \rightarrow J/\psi \Xi^-$ . Our results are consistent with and about a factor of ten more precise than their measurements,  $\delta m = 14.84 \pm 0.74 \pm 0.28 \text{ MeV}/c^2$  and  $\Gamma = 2.1 \pm 1.7 \text{ (stat) MeV}$  [15]. The measured width of the

Table 2: Relative systematic uncertainties on the production ratio.

Effect	Uncertainty
Simulated sample size	2.4%
Tracking efficiency correction	3.0%
Fit quality efficiency correction	1.5%
Soft pion $p_T$ cut	1.4%
$\Xi_b^{*0}$ yield	1.0%
$\Xi_b^-$ yield	2.0%
Sum in quadrature	4.9%

state is in line with theory expectations: a calculation based on lattice QCD predicted a width of  $0.51 \pm 0.16$  MeV [36], and another using the  $^3P_0$  model obtained a value of 0.85 MeV [37].

Combining our measured value for  $\delta m$  with the most precise measured value of the  $\Xi_b^-$  mass,  $5797.72 \pm 0.46 \pm 0.16 \pm 0.26$  MeV/ $c^2$  [14], and the pion mass [27], we obtain

$$m(\Xi_b^{*0}) = 5953.02 \pm 0.07 \pm 0.02 \pm 0.55 \text{ MeV}/c^2,$$

where the third uncertainty is due to the  $m(\Xi_b^-)$  measurement. We further combine our result on  $\delta m(\Xi_b^{*0})$  with previous LHCb measurements of  $\delta m(\Xi_b^{*-}) \equiv m(\Xi_b^0 \pi^-) - m(\Xi_b^0) - m(\pi^-) = 23.96 \pm 0.12 \pm 0.06$  MeV/ $c^2$  [16], and of the ground state isospin splitting,  $m(\Xi_b^-) - m(\Xi_b^0) = 5.92 \pm 0.60 \pm 0.23$  MeV/ $c^2$  [14], to obtain the isospin splitting of the  $\Xi_b^*$  states,

$$\begin{aligned} m(\Xi_b^{*-}) - m(\Xi_b^{*0}) &= \delta m(\Xi_b^{*-}) - \delta m(\Xi_b^{*0}) - [m(\Xi_b^-) - m(\Xi_b^0)] \\ &= 2.31 \pm 0.62 \pm 0.24 \text{ MeV}/c^2. \end{aligned}$$

In combining the above measurements, the systematic uncertainties on the mass scale and the RBW shape are treated as fully correlated between the two  $\delta m$  measurements.

We have also measured the inclusive ratio of production cross-sections to be

$$\frac{\sigma(pp \rightarrow \Xi_b^{*0} X) \mathcal{B}(\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+)}{\sigma(pp \rightarrow \Xi_b^- X)} = 0.27 \pm 0.03 \pm 0.01.$$

This value is similar to the previously measured value from the isospin partner mode,  $\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-$ , of  $\frac{\sigma(pp \rightarrow \Xi_b^{*-} X) \mathcal{B}(\Xi_b^{*-} \rightarrow \Xi_b^0 \pi^-)}{\sigma(pp \rightarrow \Xi_b^0 X)} = 0.21 \pm 0.03 \pm 0.01$  [16]. Taking into account the neutral modes, e.g.  $\Xi_b^{*0} \rightarrow \Xi_b^0 \pi^0$  and  $\Xi_b^{*-} \rightarrow \Xi_b^- \pi^0$ , and contributions from  $\Xi_b'$  states [16], it is evident that in  $pp$  collisions at 7 and 8 TeV a large fraction of  $\Xi_b^-$  and  $\Xi_b^0$  baryons are produced through feed-down from higher-mass states.

## Acknowledgements

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); FOM and NWO (The Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FANO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (The Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). We are indebted to the communities behind the multiple open source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany), EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil Général de Haute-Savoie, Labex ENIGMASS and OCEVU, Région Auvergne (France), RFBR and Yandex LLC (Russia), GVA, XuntaGal and GENCAT (Spain), Herchel Smith Fund, The Royal Society, Royal Commission for the Exhibition of 1851 and the Leverhulme Trust (United Kingdom).

## References

- [1] M. Karliner, B. Keren-Zur, H. J. Lipkin, and J. L. Rosner, *The quark model and  $b$  baryons*, *Annals Phys.* **324** (2009) 2, [arXiv:0804.1575](#).
- [2] E. Klempt and J.-M. Richard, *Baryon spectroscopy*, *Rev. Mod. Phys.* **82** (2010) 1095, [arXiv:0901.2055](#).
- [3] R. Lewis and R. M. Woloshyn, *Bottom baryons from a dynamical lattice QCD simulation*, *Phys. Rev.* **D79** (2009) 014502, [arXiv:0806.4783](#).
- [4] D. Ebert, R. N. Faustov, and V. O. Galkin, *Masses of heavy baryons in the relativistic quark model*, *Phys. Rev.* **D72** (2005) 034026, [arXiv:hep-ph/0504112](#).
- [5] X. Liu *et al.*, *Bottom baryons*, *Phys. Rev.* **D77** (2008) 014031, [arXiv:0710.0123](#).
- [6] E. E. Jenkins, *Model-independent bottom baryon mass predictions in the  $1/N_c$  expansion*, *Phys. Rev.* **D77** (2008) 034012, [arXiv:0712.0406](#).
- [7] M. Karliner, *Heavy quark spectroscopy and prediction of bottom baryon masses*, *Nucl. Phys. Proc. Suppl.* **187** (2009) 21, [arXiv:0806.4951](#).
- [8] J.-R. Zhang and M.-Q. Huang, *Heavy baryon spectroscopy in QCD*, *Phys. Rev.* **D78** (2008) 094015, [arXiv:0811.3266](#).

- [9] Z.-G. Wang, *Analysis of the  $\frac{3}{2}^+$  heavy and doubly heavy baryon states with QCD sum rules*, Eur. Phys. J. **C68** (2010) 459, [arXiv:1002.2471](#).
- [10] Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, *Charmed bottom baryon spectroscopy from lattice QCD*, Phys. Rev. **D90** (2014) 094507, [arXiv:1409.0497](#).
- [11] A. Valcarce, H. Garcilazo, and J. Vijande, *Towards an understanding of heavy baryon spectroscopy*, Eur. Phys. J. **A37** (2008) 217, [arXiv:0807.2973](#).
- [12] A. Limphirat, C. Kobdaj, P. Suebka, and Y. Yan, *Decay widths of ground-state and excited  $\Xi_b$  baryons in a nonrelativistic quark model*, Phys. Rev. **C82** (2010) 055201.
- [13] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of the mass and lifetime of the  $\Xi_b^0$  baryon*, Phys. Rev. Lett. **113** (2014) 032001, [arXiv:1405.7223](#).
- [14] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of the mass and lifetime of the  $\Xi_b^-$  baryon*, Phys. Rev. Lett. **113** (2014) 242002, [arXiv:1409.8568](#).
- [15] CMS collaboration, S. Chatrchyan *et al.*, *Observation of a new  $\Xi_b$  baryon*, Phys. Rev. Lett. **108** (2012) 252002, [arXiv:1204.5955](#).
- [16] LHCb collaboration, R. Aaij *et al.*, *Observation of two new  $\Xi_b^-$  baryon resonances*, Phys. Rev. Lett. **114** (2015) 062004, [arXiv:1411.4849](#).
- [17] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.
- [18] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, [arXiv:1412.6352](#).
- [19] V. V. Gligorov and M. Williams, *Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree*, JINST **8** (2013) P02013, [arXiv:1210.6861](#).
- [20] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, [arXiv:hep-ph/0603175](#); T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, [arXiv:0710.3820](#).
- [21] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [22] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [23] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays*, Eur. Phys. J. **C45** (2006) 97, [arXiv:hep-ph/0506026](#).

- [24] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270; Geant4 collaboration, S. Agostinelli *et al.*, *Geant4: A simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.
- [25] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [26] W. D. Hulsbergen, *Decay chain fitting with a Kalman filter*, Nucl. Instrum. Meth. **A552** (2005) 566, [arXiv:physics/0503191](#).
- [27] Particle Data Group, K. A. Olive *et al.*, *Review of particle physics*, Chin. Phys. **C38** (2014) 090001, and 2015 update.
- [28] J. D. Jackson, *Remarks on the phenomenological analysis of resonances*, Nuovo Cim. **34** (1964) 1644.
- [29] J. Blatt and V. Weisskopf, *Theoretical nuclear physics*, John Wiley & Sons, 1952.
- [30] LHCb collaboration, R. Aaij *et al.*, *Measurements of the  $\Lambda_b^0$ ,  $\Xi_b^-$ , and  $\Omega_b^-$  baryon masses*, Phys. Rev. Lett. **110** (2013) 182001, [arXiv:1302.1072](#).
- [31] LHCb collaboration, R. Aaij *et al.*, *Precision measurement of D meson mass differences*, JHEP **06** (2013) 065, [arXiv:1304.6865](#).
- [32] BaBar collaboration, J. P. Lees *et al.*, *Measurement of the  $D^*(2010)^+$  natural line width and the  $D^*(2010)^+ - D^0$  mass difference*, Phys. Rev. **D88** (2013) 052003, Erratum *ibid.* **D88** (2013) 079902, [arXiv:1304.5009](#); BaBar collaboration, J. P. Lees *et al.*, *Measurement of the  $D^*(2010)^+$  meson width and the  $D^*(2010)^+ - D^0$  mass difference*, Phys. Rev. Lett. **111** (2013) 111801, Erratum *ibid.* **111** (2013) 169902, [arXiv:1304.5657](#).
- [33] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.
- [34] ARGUS collaboration, H. Albrecht *et al.*, *Measurement of the polarization in the decay  $B \rightarrow J/\psi K^*$* , Phys. Lett. **B340** (1994) 217.
- [35] LHCb collaboration, R. Aaij *et al.*, *Measurement of the track reconstruction efficiency at LHCb*, JINST **10** (2015) P02007, [arXiv:1408.1251](#).
- [36] W. Detmold, C. J. D. Lin, and S. Meinel, *Calculation of the heavy-hadron axial couplings  $g_1$ ,  $g_2$  and  $g_3$  using lattice QCD*, Phys. Rev. **D85** (2012) 114508, [arXiv:1203.3378](#).
- [37] C. Chen *et al.*, *Strong decays of charmed baryons*, Phys. Rev. **D75** (2007) 094017, [arXiv:0704.0075](#).

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