EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-038
2024/02/28

CMS-BPH-23-002

Observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and studies of the Ξ_b^{*0} baryon in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

The first observation of the decay $\Xi_b^- \to \psi(2S)\Xi^-$ and measurement of the branching ratio of $\Xi_b^- \to \psi(2S)\Xi^-$ to $\Xi_b^- \to J/\psi\Xi^-$ are presented. The J/ψ and $\psi(2S)$ mesons are reconstructed using their dimuon decay modes. The results are based on proton-proton colliding beam data from the LHC collected by the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$ in 2016–2018, corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$. The branching fraction ratio is measured to be $\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)/\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-) = 0.84^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B})$, where the last uncertainty comes from the uncertainties in the branching fractions of the charmonium states. New measurements of the Ξ_b^{*0} baryon mass and natural width are also presented, using the $\Xi_b^-\pi^+$ final state, where the Ξ_b^- baryon is reconstructed through the decays $J/\psi\Xi^-$, $\psi(2S)\Xi^-$, $J/\psi\Lambda K^-$, and $J/\psi\Sigma^0K^-$. Finally, the fraction of the Ξ_b^- baryons produced from Ξ_b^{*0} decays is determined.

Submitted to Physical Review D

*See Appendix A for the list of collaboration members

1 Introduction

The Ξ_b family consists of baryons that form isodoublets composed of a triplet of b, s, and q quarks, where q corresponds to a u or d quark for the Ξ_b^0 and Ξ_b^- states, respectively. Three such isodoublets that are neither orbitally nor radially excited should exist [1]. These include one with the spin of the light diquark $j_{qs} = 0$ and spin-parity of the baryon $J^P = 1/2^+$ (Ξ_b ground states), one with $j_{qs} = 1$ and $J^P = 1/2^+$ (Ξ_b'), and another with $j_{qs} = 1$ and $J^P = 3/2^+$ (Ξ_b^*). The ground states were discovered more than a decade ago at the Fermilab Tevatron [2–4] via their decays to $J/\psi\Xi^-$ and $\Xi_c^+\pi^-$. Three of the four states with $j_{qs} = 1$ have been observed during the last decade at the CERN LHC [5–7] via their $\Xi_b^-\pi^+$ and $\Xi_b^0\pi^-$ decays, as expected from theoretical predictions [8–10]. The fourth state, $\Xi_b'^0$, is expected to have a mass lower than the $\Xi_b^-\pi^+$ mass threshold, making a strong decay to the Ξ_b^- baryon kinematically impossible. Several other more massive Ξ_b resonances were also observed recently by the CMS and LHCb Collaborations [11–15] via their decays to $\Xi_b^0\pi^-$, $\Xi_b^-\pi^+$, $\Xi_b^-\pi^+\pi^-$, $\Xi_b^0\pi^+\pi^-$, $\Lambda_b^0K^-$, and $\Lambda_b^0K^-\pi^+$. Various theoretical models and calculations predict a spectrum of excited Ξ_b baryons [8–10, 16–27], and the observed resonances are considered to be $1P$ isodoublets of Ξ_b or Ξ_b' states, and a $1D$ doublet. However, larger data samples are needed to measure the quantum numbers of these resonances. There is also the possibility that some of the observed wide resonances could instead be unresolved overlapping narrow states.

Besides the searches for excited Ξ_b states, the LHCb Collaboration has observed new ground-state Ξ_b decays and determined some of their branching fractions [28–33]. The spectrum of excited Ξ_b baryons can be classified relatively easily, especially with the guidance of the similar and well-established Ξ_c baryons [34]. By contrast, the wide variety of decay modes available in the weak decay of the ground-state baryons presents a significant theoretical challenge, and predictions of the branching fractions to various final states are less straightforward. Multi-body decays of Ξ_b baryons can contain rich resonant structures, including both conventional and exotic resonances, such as excited Ξ^- states and the $P_{\psi s}^{\Lambda}(4459)^0$ pentaquark reported in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay [35]. The search for new Ξ_b decays is also important in the quest for observing possible CP violation [36]. In general, both weak decays of heavy baryons and their strongly decaying excitations can be described in the framework of heavy-quark effective theory (HQET) [37–41]. Measurements of the decays and properties of both ground and excited Ξ_b states provide coherent and complementary input to HQET, which could improve our understanding of the quantum chromodynamic (QCD) mechanisms responsible for quark dynamics and the formation of hadrons.

In this paper, we study Ξ_b^- and Ξ_b^{*0} baryon states using a sample of proton-proton (pp) collisions from the LHC, collected by the CMS experiment in 2016–2018 at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $140\,\text{fb}^{-1}$ [42–44]. The inclusion of charge-conjugate states is implied throughout this paper, unless otherwise noted. We report the first observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and the measurement of its branching fraction with respect to the well-known $\Xi_b^- \to J/\psi\Xi^-$ decay. In both signal and normalization channels, the charmonium states are reconstructed through their dimuon decay modes, and Ξ^- decays to $\Lambda\pi^-$ with the following $\Lambda \to p\pi^-$ are used. Thus, the relative branching ratio R is measured using the following expression:

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = \frac{N(\Xi_b^- \to \psi(2S)\Xi^-)}{N(\Xi_b^- \to J/\psi\Xi^-)} \frac{\epsilon(\Xi_b^- \to J/\psi\Xi^-)}{\epsilon(\Xi_b^- \to \psi(2S)\Xi^-)} \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}, \quad (1)$$

where N and ϵ represent the measured number of signal events in data and the total efficiency from Monte Carlo (MC) simulation, respectively, for each of the respective decay modes. The values of the branching fractions $\mathcal{B}$ in the last term are taken from the PDG [34]. Even though the value of $\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)$ is not known, the choice of this normalization channel is quite natural since it has the same topology and similar kinematic properties as the signal channel, reducing the systematic uncertainty in the ratio related to the reconstruction of the muons and the other charged particle tracks from the Ξ_b^- decays.

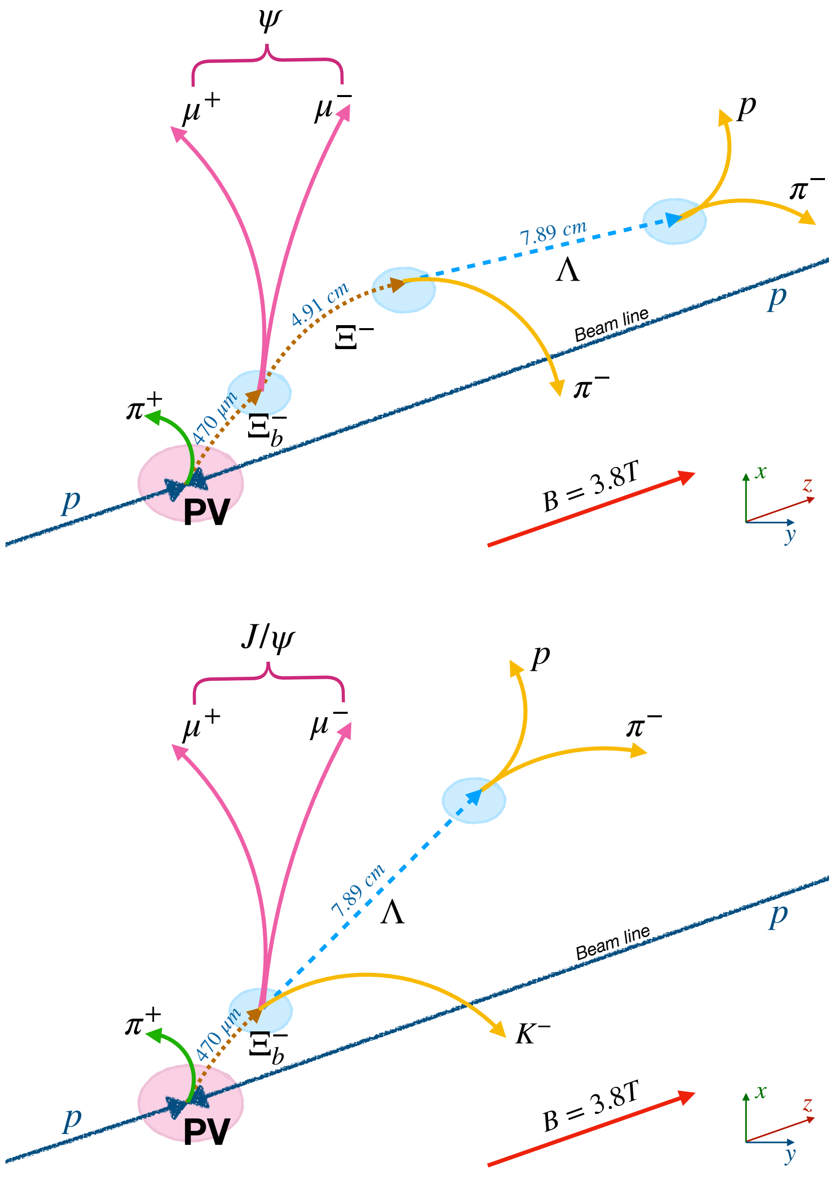

Figure 1: The $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay topology, where the Ξ_b^- baryon decays to $\psi\Xi^-$ with $\psi \to \mu^+\mu^-$ (upper) or $J/\psi\Lambda K^-$ (lower), where ψ refers to the J/ψ and $\psi(2S)$ mesons. The distances given are the average decay lengths, $c\tau$.

We also determine the Ξ_b^{*0} baryon mass and natural width, using the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay. The ground-state Ξ_b^- is reconstructed via its decays to $J/\psi\Xi^-$, $\psi(2S)\Xi^-$, and $J/\psi\Lambda K^-$. For the $\Xi_b^- \to \psi(2S)\Xi^-$ decay, both $\psi(2S) \to J/\psi\pi^+\pi^-$, with $J/\psi \to \mu^+\mu^-$, and $\psi(2S) \to \mu^+\mu^-$ modes are used in the analysis, and Ξ^- is again reconstructed via the $\Lambda\pi^-$ channel. For the $\Xi_b^- \to J/\psi\Lambda K^-$ decay, the presence of the partially reconstructed mode $J/\psi\Sigma^0 K^-$, where the low-energy photon from the $\Sigma^0 \to \Lambda\gamma$ decay is undetected, is included in the fit to the $\Xi_b^-\pi^+$ invariant mass spectrum. Pictorial representations of the decay topologies for $\Xi_b^{*0} \to \Xi_b^-\pi^+$ are shown in Fig. 1.

We also measure the ratio of the production cross sections $R_{\Xi_b^{*0}}$ for Ξ_b^{*0} and Ξ_b^- using the expression:

$$R_{\Xi_b^{*0}} = \frac{\sigma(\mathrm{pp} \to \Xi_b^{*0}X)\,\mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(\mathrm{pp} \to \Xi_b^- X)} = \frac{N(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{N(\Xi_b^-)} \frac{\epsilon(\Xi_b^-)}{\epsilon(\Xi_b^{*0} \to \Xi_b^-\pi^+)}, \quad (2)$$

where N and ϵ refer to similar quantities as those in Eq. (1). Following an analogous CMS measurement of the $B_c(2S)^+$ and $B_c^*(2S)^+$ production cross section ratios [45], the Ξ_b^- baryon is reconstructed in the phase space region defined by the Ξ_b^- baryon transverse momentum $p_T > 15$ GeV and rapidity $|y| < 2.4$; however, this measured ratio is intended to be representative of the entire phase space, given the small mass difference between the Ξ_b^{*0} and Ξ_b^- particles. The Ξ_b^{*0} baryon was the first new particle observed by the CMS Collaboration, using 5 fb^{-1} of data from 2011 [5]. With this paper we significantly improve and enrich our previous results for this state. Tabulated results are provided in the HEPData record for this analysis [46].

2 The CMS detector and simulated event samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [47]. More recent changes to the detector are described in Ref. [48]

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single-muon trigger efficiency exceeds 90% over the full η range, whereas the efficiency to reconstruct and identify muons is greater than 96%. Matching muons identified in the muon system to tracks measured in the silicon tracker results in a relative p_T resolution for muons with p_T up to 100 GeV of 1% in the barrel and 3% in the endcaps [49]. The silicon tracker used in 2016 measured charged particles within the range $|\eta| < 2.5$. For nonisolated particles of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions were typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [50]. At the start of 2017, a new pixel detector was installed [51]; the upgraded tracker measured particles up to $|\eta| < 3$ with typical resolutions of 1.5% in p_T and 20–75 μm in the transverse impact parameter [52] for nonisolated particles of $1 < p_T < 10$ GeV. The default track selection used in CMS analyses is the "high-purity" requirement. Because low momentum and displaced tracks share some features with nongenuine tracks such as not pointing back to the pp collision vertex and having fewer measurement points, the high-purity selection is less efficient for these tracks and so the less-restrictive "loose" requirement is often used.

Events of interest are selected using a two-tiered trigger system [53]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [54]. The second level, known as the high-level trigger (HLT), consists of a farm of computing processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. The events used in this analysis were selected at L1 by requiring the presence of at least two muons, and at the HLT by requiring that the two muons have opposite sign (OS), with various $|\eta|$ and p_{T} thresholds, compatible with being produced in the dimuon decay of J/ψ or $\psi(2\mathrm{S})$ mesons by requiring the corresponding invariant mass windows.

The PYTHIA 8.240 package [55] with the CP5 underlying event tune [56] is used to simulate the production of the Ξ_{b}^{-} and Ξ_{b}^{*0} states (where the Σ_{b}^{0} baryon, with a modified mass value, is used as a proxy for the Ξ_{b}^{*0} state). The $\Xi_{\mathrm{b}}^{*0} \to \Xi_{\mathrm{b}}^{-}\pi^{+}$, $\Xi_{\mathrm{b}}^{-} \to \mathrm{J}/\psi\Xi^{-}$, $\Xi_{\mathrm{b}}^{-} \to \psi(2\mathrm{S})\Xi^{-}$, $\Xi_{\mathrm{b}}^{-} \to \mathrm{J}/\psi\Lambda\mathrm{K}^{-}$ (including $\Xi_{\mathrm{b}}^{-} \to \mathrm{J}/\psi\Sigma^{0}\mathrm{K}^{-}$, $\Sigma^{0} \to \Lambda\gamma$), $\psi(2\mathrm{S}) \to \mu^{+}\mu^{-}$, $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^{+}\pi^{-}$, and $\mathrm{J}/\psi \to \mu^{+}\mu^{-}$ decays are modeled with EVTGEN 1.6.0 [57], where final-state photon radiation is included using PHOTOS 3.61 [58, 59]. The generated MC events are then passed to a detailed GEANT4-based simulation [60] of the CMS detector, which includes the long-lived hyperon decays $\Xi^{-} \to \Lambda\pi^{-}$ and $\Lambda \to \mathrm{p}\pi^{-}$. The simulated events are then put through the same trigger and reconstruction algorithms used for the collision data. The simulation includes effects from multiple pp interactions in the same or nearby bunch crossings (pileup) with a multiplicity distribution matching that in data.

3 Event reconstruction and selection

The Ξ_{b}^{-} ground state is reconstructed using two main decay modes: $\Xi_{\mathrm{b}}^{-} \to \psi\Xi^{-}$ (followed by $\psi \to \mu^{+}\mu^{-}$), where ψ refers to the J/ψ and $\psi(2\mathrm{S})$ mesons, or $\Xi_{\mathrm{b}}^{-} \to \mathrm{J}/\psi\Lambda\mathrm{K}^{-}$. We also reconstruct the decay chain $\Xi_{\mathrm{b}}^{-} \to \psi(2\mathrm{S})\Xi^{-}$, $\psi(2\mathrm{S}) \to \mathrm{J}/\psi\pi^{+}\pi^{-}$ to increase the number of events for the $\Xi_{\mathrm{b}}^{-}\pi^{+}$ studies. In all the cases, the J/ψ meson is identified through its dimuon decay. The selection criteria, described below, are mainly inherited from Ref. [13].

The reconstruction chain requires two OS muons forming a good-quality vertex, passing the CMS soft-muon selection [49], and with each having $p_{\mathrm{T}}(\mu) > 3\,\mathrm{GeV}$ and $|\eta(\mu)| < 2.4$. To be of good quality, the fit to a dimuon common vertex must have a χ^2 vertex fit probability greater than 1%. These requirements reinforce those applied at the trigger level during the online data taking. A J/ψ or $\psi(2\mathrm{S})$ candidate is required to have a dimuon invariant mass within 100 MeV of the corresponding world-average mass [34], which is about 3 times the mass resolution. Further, a kinematic constraint to the known ψ meson mass [34] is applied to the selected dimuon candidates.

The Λ candidates are formed from displaced two-prong vertices, assuming the decay $\Lambda \to \mathrm{p}\pi^{-}$, as described in Ref. [61]. The higher-momentum track is associated with the proton and the lower-momentum track with the pion. A Λ candidate must have $p_{\mathrm{T}} > 1.8\,\mathrm{GeV}$, and the $\mathrm{p}\pi^{-}$ invariant mass must be within 10 MeV of the known Λ mass [34] after the tracks are refit to a common vertex, corresponding to about 3 times the mass resolution. The vertex fit is then repeated with the $\mathrm{p}\pi^{-}$ invariant mass constrained to the Λ mass, and its momentum recomputed. The χ^2 probability of this fit must be greater than 1%.

For the $\Xi_{\mathrm{b}}^{-} \to \psi\Xi^{-}$ channel, the Ξ^{-} candidates are reconstructed by combining each selected Λ candidate with a charged particle track, assumed to be a pion. The track must have $p_{\mathrm{T}} > 0.3\,\mathrm{GeV}$ and satisfy the loose requirement [50]. A kinematic vertex fit of the $\Xi^{-} \to \Lambda\pi^{-}$ decay is performed, and the χ^2 probability is required to be greater than 1%. The $\Lambda\pi^{-}$ invariant mass must be within 10 MeV of the known Ξ^{-} mass [34], which is about 3 times the mass resolution. The resulting Ξ^{-} candidate must have $p_{\mathrm{T}} > 2.5\,\mathrm{GeV}$. Because Λ particles mainly decay much further from the Ξ^- decay vertex than our vertex resolution, we set a requirement on the pointing angle $\cos\alpha(\Lambda, \Xi^-) > 0.99$ between the momentum of the Λ candidate and the vector from the Ξ^- decay vertex to the Λ decay vertex in the plane perpendicular to the beam direction (the transverse plane).

To reconstruct the decay chain $\Xi_b^- \to \psi(2S)\Xi^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$, two additional OS tracks passing the high-purity requirement [50] are assigned the charged pion mass and added to the process. The higher-momentum pion must have $p_T > 0.6\,\text{GeV}$, and the other pion $p_T > 0.35\,\text{GeV}$. The invariant mass of the $\psi(2S)$ candidate, calculated via the formula $M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-) + m^{\text{PDG}}(J/\psi)$, is required to be within 18 MeV of the known $\psi(2S)$ mass [34], corresponding to about 3 times the mass resolution. Using this variable removes the $J/\psi \to \mu^+\mu^-$ detector invariant mass resolution from the measurement of the $M(\mu^+\mu^-\pi^+\pi^-)$ invariant mass. Here, and throughout the paper, the symbol M represents a reconstructed invariant mass and m^{PDG} the PDG world-average mass [34].

The Ξ_b^- candidates are selected by using the μ^+, μ^-, and Ξ^- particles in a kinematic fit that constrains their momentum vectors to a common vertex and the dimuon invariant mass to the world-average J/ψ or $\psi(2S)$ mass [34]. For the decay chain $\Xi_b^- \to \psi(2S)\Xi^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$, the two additional pions described above are added to the Ξ_b^- vertex fit. From all the reconstructed pp collision vertices in an event, the primary vertex (PV) is chosen as the one with the smallest pointing angle. The pointing angle is the angle between the Ξ_b^- candidate momentum and the vector joining the PV with the reconstructed Ξ_b^- candidate decay vertex. If any of the tracks used in the Ξ_b^- candidate reconstruction are included in the fit of the chosen PV, they are removed, and the PV is refit. The selected Ξ_b^- candidates are required to have $p_T(\Xi_b^-) > 10\,\text{GeV}$ and a χ^2 vertex fit probability greater than 1%. The pion from the $\Xi^- \to \Lambda\pi^-$ decay must satisfy an impact parameter significance requirement $d_{xy}/\sigma_{d_{xy}} > 1$, where d_{xy} is the closest distance between the track and the chosen PV in the transverse plane, and $\sigma_{d_{xy}}$ is its uncertainty. For the decay chain $\Xi_b^- \to \psi(2S)\Xi^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$, we require that the two pion tracks each have $d_{xy}/\sigma_{d_{xy}} > 0.4$. The pointing angle α between the Ξ^- momentum and the vector from the Ξ_b^- decay vertex to the Ξ^- vertex in the transverse plane must satisfy $\cos\alpha(\Xi^-, \Xi_b^-) > 0.999$. The analogous angle between the Ξ_b^- momentum and the vector from the PV to the Ξ_b^- vertex is required to have $\cos\alpha(\Xi_b^-, \text{PV}) > 0.99$. Additionally, the distance L_{xy} between the PV and the Ξ_b^- decay vertex in the transverse plane must fulfill the requirement $L_{xy}/\sigma_{L_{xy}} > 3$, where $\sigma_{L_{xy}}$ is its uncertainty.

For the $\Xi_b^- \to J/\psi\Lambda K^-$ decay channel, the J/ψ and Λ candidates are reconstructed in the same way as described above, with the additional requirement $p_T(\Lambda) > 2\,\text{GeV}$. However, instead of adding a pion track to the subsequent $\Xi^- \to \Lambda\pi^-$ fit, a charged particle track with a kaon mass assignment is selected. The track must have $p_T > 1.4\,\text{GeV}$ and satisfy the high-purity requirement [50]. The Ξ_b^- candidates are obtained by performing a kinematic vertex fit to the μ^+, μ^-, Λ, and K^- candidates, along with the same J/ψ mass constraint and PV selection as for the $\Xi_b^- \to \psi\Xi^-$ channel. The kaon impact parameter significance must satisfy $d_{xy}/\sigma_{d_{xy}} > 0.5$ with respect to the chosen PV. Because of the higher background in this channel more restrictive kinematic and topological requirements are applied: $p_T(\Xi_b^-) > 15\,\text{GeV}$ and $\cos\alpha(\Xi_b^-, \text{PV}) > 0.999$, along with the same requirements as above on the vertex fit and $L_{xy}/\sigma_{L_{xy}}$.

Since the lifetime of the excited Ξ_b states is expected to be negligible, the $\Xi_b^-\pi^+$ candidates are formed by combining the selected Ξ_b^- candidates with each charged particle track originating from the PV and satisfying the loose requirement [50] as done in Ref. [62], which are given the charged pion mass. The pion charge must be opposite to that of the pion from $\Xi^- \to \Lambda\pi^-$

or the kaon from $\Xi_b^- \to J/\psi\Lambda K^-$. The mass difference variable $\Delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-) - m_{\pi^+}^{PDG}$ is used instead of $M(\Xi_b^-\pi^+)$ since it is characterized by a better mass resolution as the effect of the Ξ_b^- mass resolution is removed. From simulation studies, this variable is found to be insensitive to potential mass shifts caused by the missing low-energy photon from the $\Sigma^0 \to \Lambda\gamma$ decay. As developed in Ref. [63], the Ξ_b^- candidate and all the tracks forming the PV are refit to a common vertex, further improving the $\Xi_b^-\pi^+$ invariant mass resolution from 1.07 ± 0.07 to 0.74 ± 0.04 MeV (statistical uncertainties only), as determined from simulation studies. If multiple Ξ_b^{*0} candidates (where the multiplicity comes from the soft pion reconstruction) in an event pass the selection requirements (which happens in 10–15% of events depending on the Ξ_b^- channel), only the highest p_T candidate is kept, which is found from simulation studies to improve the signal purity.

4 Observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay and studies of the Ξ_b^- signal

The invariant mass distributions of the selected $J/\psi\Xi^-$, $J/\psi\Lambda K^-$, and $\psi(2S)\Xi^-$ (with both $\psi(2S) \to \mu^+\mu^-$ and $\psi(2S) \to J/\psi\pi^+\pi^-$) candidates are shown in Fig. 2. An unbinned extended maximum likelihood fit is performed on each of these distributions. For all four channels, the signal component is described using the sum of two Gaussian functions with a common mean, whose widths and ratio between them are fixed to those determined from MC simulation. However, both widths are allowed to scale by the same free parameter in the fit to give a better description of the data. The background is described with a first-order polynomial for the $J/\psi\Xi^-$ and $\psi(2S)\Xi^-$ channels, and an exponential function for the $J/\psi\Lambda K^-$. In the latter fit, the signal contribution from the partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0 K^-$ decays is taken into account by including an asymmetric Gaussian (also known as skew normal) function in the fit, whose shape parameters are fixed to those found from simulation studies.

Table 1: The number of signal events N, the mean Ξ_b^- mass $m_{\Xi_b^-}^{fit}$, and the effective Ξ_b^- width σ_{eff} from the fits to the Ξ_b^- invariant mass distributions for each of the Ξ_b^- decay channels. The uncertainties are statistical only.

Decay channel	N	$m_{\Xi_b^-}^{fit}$ (MeV)	σ_{eff} (MeV)
$\Xi_b^- \to J/\psi\Xi^-$	846 ± 40	5797.1 ± 0.6	16.3 ± 1.0
$\Xi_b^- \to J/\psi\Lambda K^-$	920 ± 98	5798.8 ± 0.9	11.9 ± 1.5
$\Xi_b^- \to J/\psi\Sigma^0 K^-$	880 ± 170	—	—
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to \mu^+\mu^-$)	74 ± 11	5797.7 ± 1.4	11.1 ± 2.0
$\Xi_b^- \to \psi(2S)\Xi^-$ (with $\psi(2S) \to J/\psi\pi^+\pi^-$)	90 ± 14	5797.2 ± 1.7	13.1 ± 2.8

The number of signal events N, the mean Ξ_b^- mass $m_{\Xi_b^-}^{fit}$, and the effective Ξ_b^- width σ_{eff} from the fit are given in Table 1 for each of the Ξ_b^- decay channels, along with their statistical uncertainties. The value of σ_{eff} is calculated as $\sqrt{f_1\sigma_1^2 + (1-f_1)\sigma_2^2}$, where σ_1 (σ_2) is the width of the first (second) Gaussian, and f_1 is the fraction of signal events from the fit associated with the first Gaussian function. The measured resolution of the different channels is within the expectations from the available phase space and the final state threshold proximity. The fitted Ξ_b^- mass values are consistent with the world-average value $m_{\Xi_b^-}^{PDG} = 5797.0 \pm 0.6$ MeV [34].

This is the first observation of the $\Xi_b^- \to \psi(2S)\Xi^-$ decay. Its local statistical significance is eval-

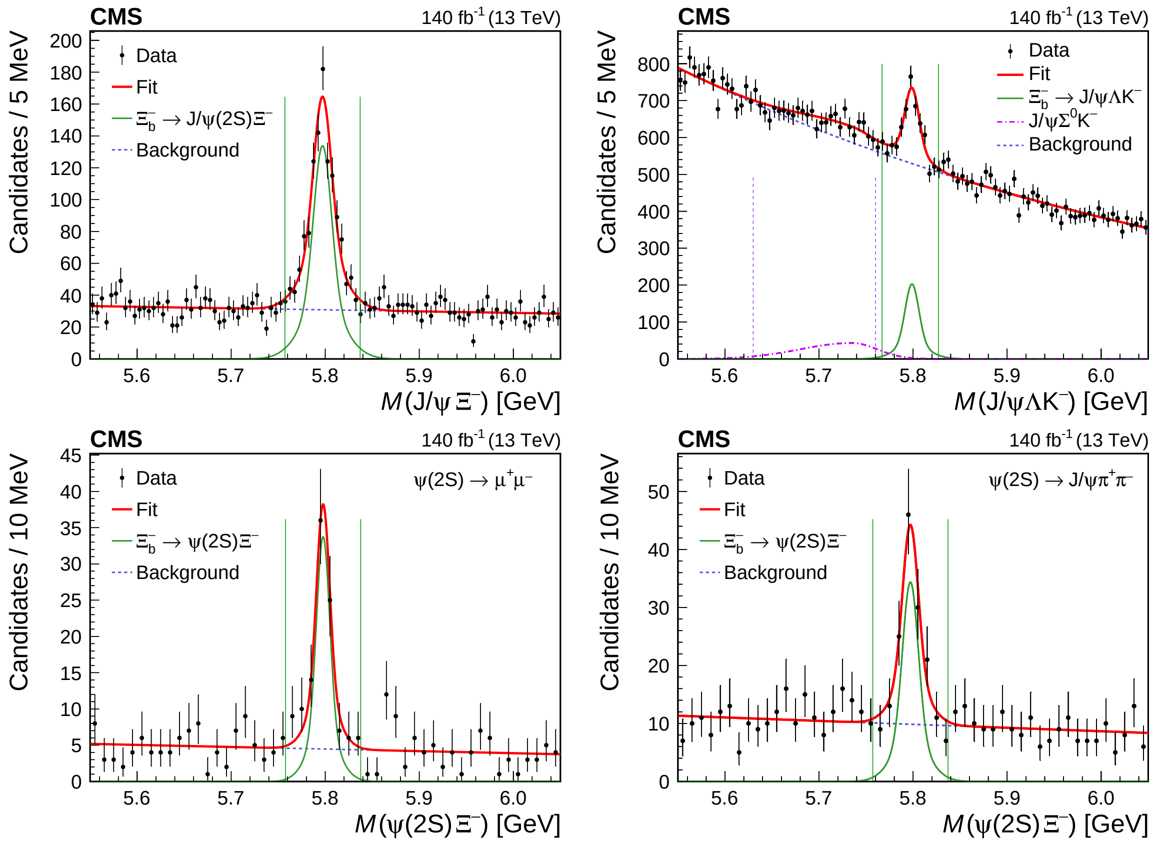

Figure 2: Invariant mass distributions of the selected $J/\psi\Xi^-$ (upper left), $J/\psi\Lambda K^-$ (upper right), and $\psi(2S)\Xi^-$ [lower row, with $\psi(2S) \to \mu^+\mu^-$ (left) and $\psi(2S) \to J/\psi\pi^+\pi^-$ (right) candidates]. The data are shown by the points, while the vertical bars represent the statistical uncertainties. The overall fit result is shown by the solid red curve, with the signal and background contributions given by the solid green and dashed blue curves, respectively. The vertical lines around each peak display the mass window required for a Ξ_b^- candidate to be used in the Ξ_b^{*0} studies. The dotted-dashed curve in the upper right plot shows the fitted contribution from the $\Xi_b^- \to J/\psi\Sigma^0K^-$ decay, with the accompanying vertical dotted lines indicating the mass window for this mode.

uated with the likelihood ratio technique, comparing the likelihood value from a fit to a signal-plus-background hypothesis to that for a background-only hypothesis. Since the conditions of Wilks' theorem [64] are satisfied, the asymptotic formulae of Ref. [65] (Eqs. (12) and (52)) are used to determine the $\Xi_b^- \to \psi(2S)\Xi^-$ signal significance, which is found to be well above 5 standard deviations for both the $\psi(2S) \to \mu^+\mu^-$ and $\psi(2S) \to J/\psi\pi^+\pi^-$ modes.

For the $\Xi_b^-\pi^+$ studies described in the next section, the Ξ_b^- candidates must have an invariant mass within 40 (30) MeV of the $m_{\Xi_b^-}^{\text{fit}}$ value for the $J/\psi\Xi^-$ and $\psi(2S)\Xi^-$ ($J/\psi\Lambda K^-$) decay channels. This corresponds to about (2.5–3) times σ_{eff}, as shown by the solid vertical lines around the peaks in Fig. 2. For the partially reconstructed $J/\psi\Sigma^0K^-$ decay channel, a mass window of 5.63–5.76 GeV, as in Ref. [13] and shown by the vertical dotted lines in Fig. 2 (upper right), is used for the reconstructed Ξ_b^- mass.

5 Studies of the Ξ_b^{*0} baryon

The measured ΔM distributions found by combining the selected Ξ_b^- candidates, as defined in Section 4, with charged particle tracks, consistent with coming from the PV and assumed to be pions, are shown in Fig. 3. The distributions are shown separately for the $\Xi_b^- \to J/\psi\Xi^-$, $\Xi_b^- \to \psi(2S)\Xi^-$ (combined $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\psi(2S) \to \mu^+\mu^-$ modes), $\Xi_b^- \to J/\psi\Lambda K^-$, and $\Xi_b^- \to J/\psi\Sigma^0 K^-$ channels. A significant near-threshold peak is evident in all 4 distributions, in agreement with previous CMS [5] and LHCb [6, 15] results. The ΔM distribution for the same-sign $\Xi_b^-\pi^-$ control sample is also displayed in Fig. 3. It shows no evidence of a peak and is consistent with the $\Xi_b^-\pi^+$ combinatorial background. No other structures are observed in this ΔM region for either the $\Xi_b^-\pi^+$ or $\Xi_b^-\pi^-$ distributions.

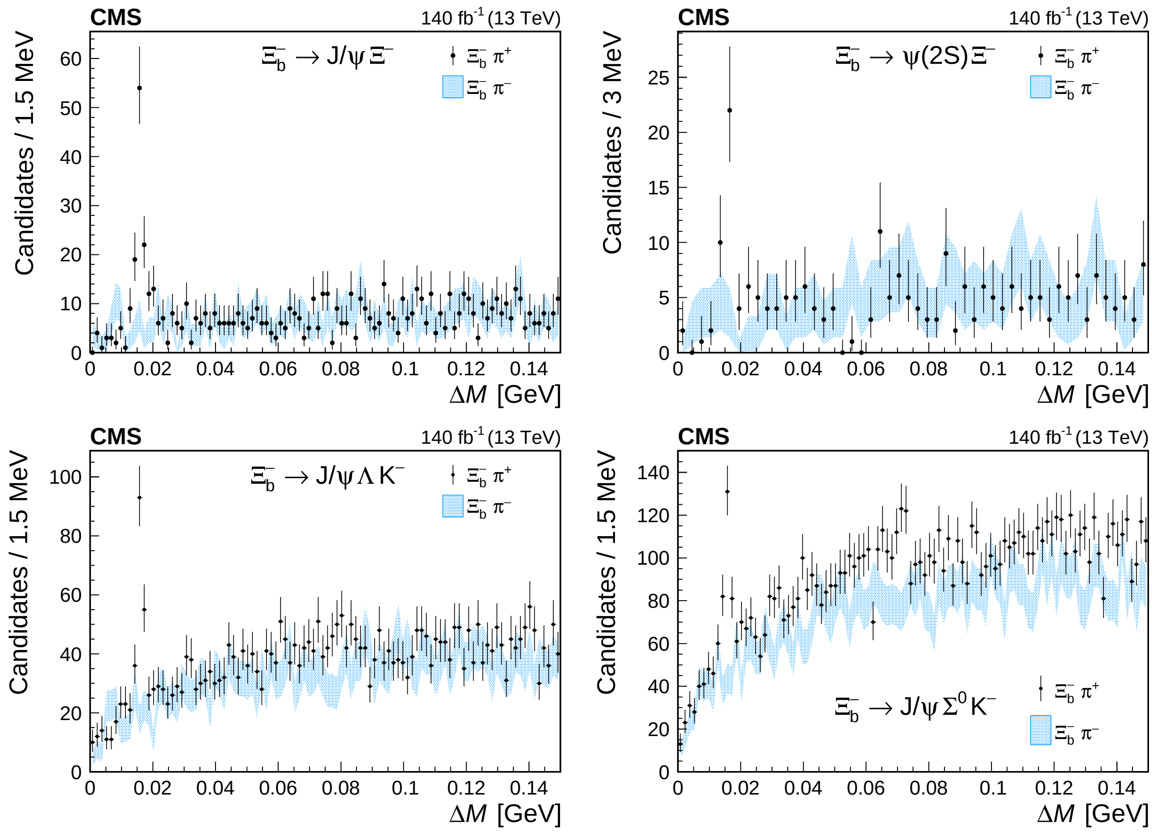

Figure 3: The mass difference ΔM distribution of the selected $\Xi_b^-\pi^\pm$ candidates for the decay channel labeled on each plot. The points show the correct-sign combinations and the blue bands the wrong-sign. The vertical bars on the points and the length of the bands represent the statistical uncertainties in each distribution, respectively.

We fit the Ξ_b^{*0} signal using a relativistic Breit–Wigner function, which accounts for the non-negligible natural width $\Gamma(\Xi_b^{*0})$, convolved with a Gaussian function describing the invariant mass resolution, whose parameters are extracted from MC simulation. Lattice QCD calculations [66] give $\Gamma(\Xi_b^{*0}) = 0.51 \pm 0.16$ MeV, the $^3P_0$ model predicts 0.85 MeV [67], and the latest LHCb result finds $\Gamma(\Xi_b^{*0}) = 0.87 \pm 0.06 \pm 0.05$ MeV [15]. The simulation studies predict that the invariant mass resolution is slightly different for each Ξ_b^- baryon decay channel, except for the $\Xi_b^- \to J/\psi\Sigma^0 K^-$ mode, where the missing low-energy photon from the Σ^0 baryon decay produces a much wider peak with a 26% larger mass resolution. In all cases, the measured widths from the fully reconstructed decay modes are in agreement within their uncertainties.

An unbinned extended maximum likelihood simultaneous fit of all four channels is applied, where the Ξ_b^{*0} mass and natural width are constrained to be equal for all the channels, while the mass resolutions, yields, and background parameters are different. The background component is modeled with a threshold function $(\Delta M)^\alpha$, where α is a free parameter. The fit results are shown in Fig. 4, and the fitted signal yields are given in Table 2.

The measured mass difference and natural width of the Ξ_b^{*0} state are $\Delta M^{\text{fit}} = 15.810 \pm 0.077\,\text{MeV}$ and $\Gamma(\Xi_b^{*0}) = 0.87\,^{+0.22}_{-0.20}\,\text{MeV}$, respectively, where the uncertainties are statistical only.

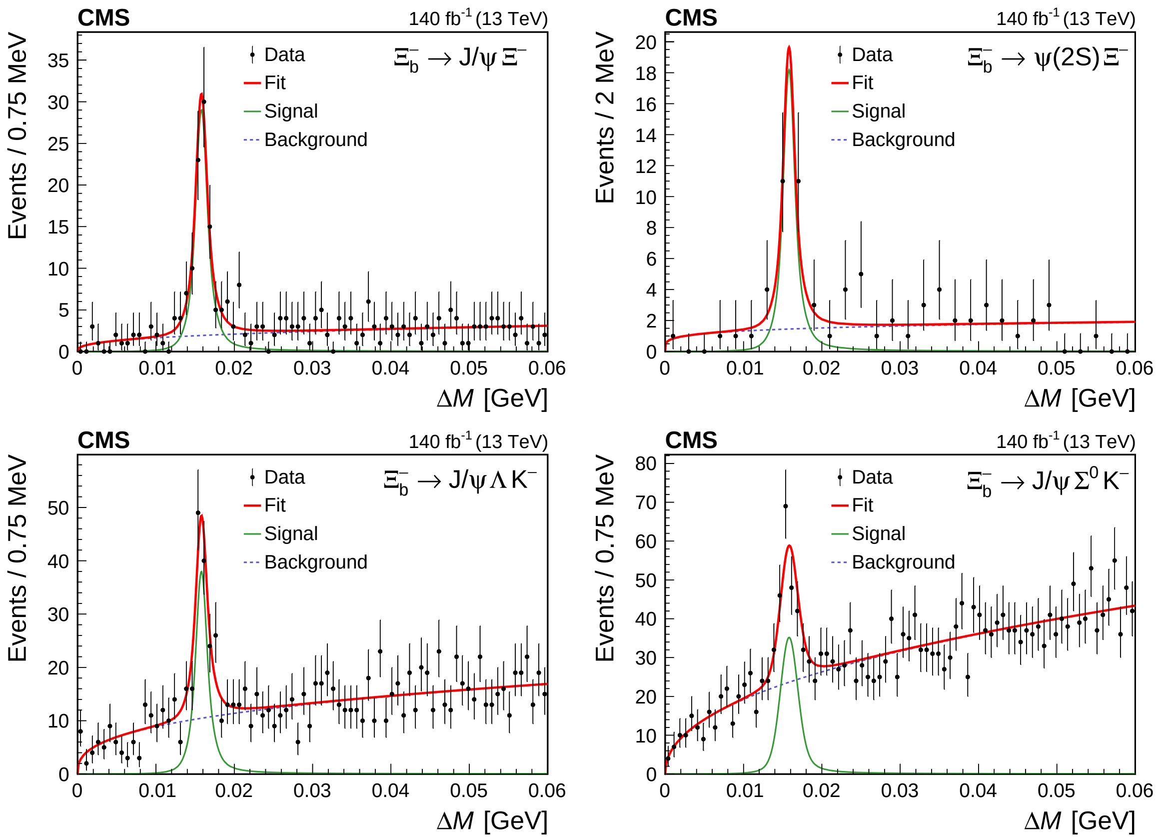

Figure 4: Results of the simultaneous fits to the ΔM invariant mass distributions for the Ξ_b^{*0} candidates in the decay channels given in each plot. The points show the data, with the vertical bars representing the statistical uncertainty. The solid red curve displays the overall fit result, with the solid green and dashed blue curves showing the signal and background contributions, respectively.

Table 2: The fitted signal yields of the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay for each of the listed Ξ_b^- decay channels. Uncertainties are statistical only.

Decay channel	$N(\Xi_b^{*0})$
$\Xi_b^- \to J/\psi\Xi^-$	$97\,^{+13}_{-12}$
$\Xi_b^- \to \psi(2S)\Xi^-$	$24\,^{+6}_{-5}$
$\Xi_b^- \to J/\psi\Lambda K^-$	$124\,^{+17}_{-16}$
$\Xi_b^- \to J/\psi\Sigma^0 K^-$	$155\,^{+22}_{-20}$

6 Efficiency and production ratio measurements

While in general the analysis uses events collected by a combination of different dimuon HLT paths, for the measurements of the ratios of efficiencies and the resulting branching fractions and production cross sections, a single dedicated trigger suitable for the decay topology is required in order to simplify the efficiency estimations and reduce the trigger-related systematic uncertainty. For the $\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to \psi(2S)\Xi^-$ channels, we use an inclusive dimuon HLT path, requiring the presence in the event of a J/ψ ($\psi(2S)$) meson with p_T exceeding 25 (18) GeV and decaying into two OS muons. This HLT path is only used for the 2017–2018 sample, while for the 2016 sample the similar trigger requires a minimum p_T of 20 (13) GeV for the J/ψ ($\psi(2S)$) meson. In the case of the $\Xi_b^- \to J/\psi\Lambda K^-$ channel, we use an HLT path requiring the presence of a $J/\psi \to \mu^+\mu^-$ decay and an additional track consistent with originating from the dimuon vertex and having $d_{xy}/\sigma_{d_{xy}} > 2$. The dimuon vertex must also be displaced from the PV, by requiring $L_{xy}/\sigma_{L_{xy}} > 3$.

These requirements are much stricter than those discussed in Section 3 — most ψ from Ξ_b^- decays are populated within the 10–20 GeV range of p_T. Thus, using them causes a significant decrease in the signal yields for the $\psi\Xi^-$ channels. Redoing the fitting procedure with the new requirements leads to total signal yields of 103^{+14}_{-13} and 38^{+8}_{-7} for $\Xi_b^- \to J/\psi\Xi^-$ and $\Xi_b^- \to \psi(2S)\Xi^-$ ($\psi(2S) \to \mu^+\mu^-$ mode), respectively. The $\Xi_b^- \to J/\psi\Lambda K^-$ signal with the tighter HLT requirement results in 606^{+67}_{-64} events. The fits to the $\Xi_b^{*0} \to \Xi_b^-\pi^+$ ΔM distributions are performed separately for each of the decay channels, with $\Gamma(\Xi_b^{*0})$ fixed to the value found from the simultaneous fit. The resulting signal yields are 13 ± 4 and 74 ± 11 for the $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ decay modes, respectively.

The efficiencies for the signal and normalization channels are calculated using simulated MC samples of events that have passed the more-restrictive HLT paths described above. The total efficiency includes several factorizable contributions such as the trigger, detector acceptance, and decay channel reconstruction efficiencies. The detector acceptance term is calculated as the ratio of the number of generator-level events within the CMS kinematic acceptance to the number of generated events without any restrictions (within the full phase space region). Efficiencies for different years of data taking are estimated separately and then combined with weights corresponding to the integrated luminosity collected in each year.

Since we measure branching fractions and production cross sections with respect to normalization channels, only the ratios of such efficiencies are needed. Thus, for example, the systematic uncertainties associated with the muon, charged particle track, and Λ candidate reconstruction are reduced. Table 3 reports three efficiency ratios, where the first is used in measuring the quantity R, the ratio of branching fractions defined in Eq. (1), and the latter two for finding the $\Xi_b^{*0}/\ \Xi_b^-$ production cross section ratio using two different decay channels: $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$.

Table 3: The measured efficiency ratios and their statistical uncertainties.

Efficiency ratio	Value
$\epsilon(\Xi_b^- \to J/\psi\Xi^-)/\epsilon(\Xi_b^- \to \psi(2S)\Xi^-,\ \psi(2S) \to \mu^+\mu^-)$	0.304 ± 0.014
$\epsilon(\Xi_b^- \to J/\psi\Xi^-)/\epsilon(\Xi_b^{*0} \to \Xi_b^-\pi^+,\ \Xi_b^- \to J/\psi\Xi^-)$	1.645 ± 0.108
$\epsilon(\Xi_b^- \to J/\psi\Lambda K^-)/\epsilon(\Xi_b^{*0} \to \Xi_b^-\pi^+,\ \Xi_b^- \to J/\psi\Lambda K^-)$	1.941 ± 0.085

Using the measured signal yields, the efficiency ratio, and Eq. (1), we determine the ratio R of the branching fraction for the newly observed $\Xi_b^- \to \psi(2S)\Xi^-$ decay to that of the $\Xi_b^- \to$

$J/\psi\Xi^-$ decay to be

$$R = 0.84^{+0.21}_{-0.19},$$

where the uncertainty is coming from the uncertainty in the measured yields. The uncertainty in the ratio of efficiencies is treated separately as a systematic uncertainty, as described in Section 7.1.

Applying Eq. (2), the ratio $R_{\Xi_b^{*0}}$ of the Ξ_b^{*0} to Ξ_b^- production is separately measured using two Ξ_b^- decay channels: $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$. The results are

$$R_{\Xi_b^{*0}}^{J/\psi\Xi^-} = 0.21 \pm 0.07$$

and

$$R_{\Xi_b^{*0}}^{J/\psi\Lambda K^-} = 0.24 \pm 0.04,$$

where the uncertainties are statistical only (again, the efficiency uncertainties are discussed in Section 7.1). Both values, obtained with fully independent data and simulation samples, are in good agreement with each other and with the previous measurement by the LHCb Collaboration [6].

7 Systematic uncertainties

The systematic uncertainties in the measurements given above are divided into two categories. The first is related to the uncertainties in the measured efficiency ratios and the Ξ_b^- and Ξ_b^{*0} signal yields. The second covers the uncertainties in the measured mass difference and natural width of the Ξ_b^{*0} baryon.

7.1 Systematic uncertainties in the measured ratios

Many systematic uncertainties related to muon reconstruction and identification, trigger effects and efficiencies, and charged particle track and Λ candidate reconstruction cancel out in the measured ratio R due to the identical topologies of the $\Xi_b^- \to \psi(2S)\Xi^-$ and $\Xi_b^- \to J/\psi\Xi^-$ decays. There is a similar cancellation in the determination of the production cross section ratio $R_{\Xi_b^{*0}}$, where the only topological difference between Ξ_b^{*0} and Ξ_b^- is an additional track from the $\Xi_b^{*0} \to \Xi_b^-\pi^+$ decay.

The systematic uncertainty related to the choice of fit functions used to describe the signal and background shapes in the invariant mass fits is evaluated by varying the functions used and recording the change in the number of signal events. For the three Ξ_b^- decay channels, we first perform the fit with the resolution scaling parameter for the sum of two Gaussian functions set to unity and note the change in the fit results. We then use a Student's t distribution [68] to model the signal, with the mean and the width allowed to be free and the n parameter (corresponding to the number of degrees of freedom) fixed from the simulation. This function, being symmetric and bell-shaped, also models a heavy-tailed distribution and thus is found to be a reliable alternative to the sum of two Gaussian functions. A single Gaussian function with free parameters is also tried for fitting the $\psi(2S)\Xi^-$ and $J/\psi\Xi^-$ signals. Using the largest change in the number of events, the resulting systematic uncertainty in R from this source is 8.8%.

Two alternative background functions are considered in fitting the $J/\psi\Xi^-$ and $\psi(2S)\Xi^-$ invariant mass distributions: an exponential function and a second-order polynomial. For the more complicated background shape in the $J/\psi\Lambda K^-$ distribution, we switch from an exponential function to a second-order polynomial. The resulting systematic uncertainty in R from this source is estimated as 4.5%. The combined signal-plus-background Ξ_b^- fit model uncertainties are estimated as 4.0 and 6.9% in the $R_{\Xi_b^{*0}}^{J/\psi\Xi^-}$ and $R_{\Xi_b^{*0}}^{J/\psi\Lambda K^-}$ values, respectively.

The alternative functions used in fitting the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ ΔM distribution are described in the next subsection when the systematic uncertainties in the measured Ξ_b^{*0} mass and width are discussed. The resulting systematic uncertainties due to the fitting functions in the $R_{\Xi_b^{*0}}$ production cross section ratio are 7.7 and 6.7% for the $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ decay modes, respectively.

For the R measurement, given that we are using different HLT paths for the $\Xi_b^- \to J/\psi\Xi^-$ and the $\Xi_b^- \to \psi(2S)\Xi^-$ signals, a cross-check of the correctness and robustness of such a procedure is performed. The similar branching fraction ratio $R_{B^+} = \mathcal{B}(B^+ \to \psi(2S)K^+)/\mathcal{B}(B^+ \to J/\psi K^+)$ was measured with the triggers we use for the Ξ_b^- signals, and the resulting value of 0.601 ± 0.030 is consistent with the world-average value [34] 0.605 ± 0.021. The 5% precision of the R_{B^+} value is taken conservatively as an additional systematic uncertainty in the R measurement.

As mentioned above, an additional source of uncertainty in the $R_{\Xi_b^{*0}}$ measurement comes from identifying the extra pion in the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay. The uncertainty in the tracking reconstruction efficiency for the low-p_T pion is estimated as 5.2% [69].

The uncertainty related to the finite size of the MC samples is also considered as a systematic uncertainty. It is estimated from the statistical uncertainty in the determinations of the efficiency ratios from the MC simulation. This corresponds to a systematic uncertainty of 4.6% in R, and 6.5 and 4.4% in $R_{\Xi_b^{*0}}$ for the $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ modes, respectively.

The systematic uncertainties in the R and $R_{\Xi_b^{*0}}$ measurements are summarized in Tables 4 and 5, respectively, along with the total systematic uncertainties, calculated from the sum in quadrature of the individual sources.

Table 4: Systematic uncertainties in percent in the ratio R from the different sources and the total uncertainty.

Source	Uncertainty (%)
Signal model	8.8
Background model	4.5
R_{B^+} uncertainty	5.0
MC finite size	4.6
Total	12.0

7.2 Systematic uncertainties in the Ξ_b^{*0} baryon mass and width measurements

Several sources of systematic uncertainty are considered in the simultaneous measurement of the Ξ_b^{*0} baryon mass difference and natural width. To evaluate the systematic uncertainties related to the choice of functions used to fit the Ξ_b^{*0} ΔM distributions, alternative functions are chosen and the maximum changes in the results of the fit are used to estimate the corresponding systematic uncertainty. We use a Student's t-distribution [68] as the alternative function to describe the invariant mass resolution, with the shape parameters determined from MC

Table 5: Systematic uncertainties in percent in the ratio $R_{\Xi_b^{*0}}$ from the different sources and the total uncertainty, separately for the $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ decay modes.

Source	$J/\psi\Xi^-$ (%)	$J/\psi\Lambda K^-$ (%)
Ξ_b^- fit model	4.0	6.9
Ξ_b^{*0} fit model	7.7	6.7
Tracking efficiency	5.2	5.2
MC finite size	6.5	4.4
Total	12.0	11.8

simulation. Fitting the data distributions leads to estimates for the systematic uncertainty of ± 0.003 MeV in the mass difference, while the change in the natural width is negligible.

We also vary the function used to describe the background in the fit. We use the threshold function described earlier, multiplied by a first-order polynomial, except for the $\Xi_b^- \to \psi(2S)\Xi^-$ decay channel, where the number of events is too small to allow a reasonable fit to the background for functions with more parameters. Another alternative model uses the baseline background model to fit the same-sign $\Xi_b^-\pi^-$ distributions. The α values obtained in these fits are then used as fixed parameters of the simultaneous fit. From this, we estimate systematic uncertainties from this source of ± 0.002 and ± 0.04 MeV in the mass difference and natural width, respectively.

The systematic uncertainty coming from the choice of the fit range is estimated by varying the ΔM fit region from [0, 0.05] to [0, 0.09] GeV. The maximum deviation of the fit parameters is used as the systematic uncertainty, giving ± 0.023 and ± 0.13 MeV in the mass difference and natural width, respectively.

The signal shape for the Ξ_b^{*0} ΔM distribution is fit with a Gaussian resolution function, convolved with a relativistic Breit–Wigner (RBW) and a Blatt–Weisskopf barrier factor [70], with the radial parameter in these functions set to $r = 3.5\,\text{GeV}^{-1}$ and the angular momentum (spin) to $\ell = 1$. To determine the systematic uncertainty associated with these choices, the fit is repeated with the value of r varied in the range 1–5 GeV^{-1} and ℓ set to 0 or 2. The change in r has a negligible effect, while the spin change leads to systematic uncertainties of ± 0.022 and ± 0.02 MeV in the mass difference and natural width measurements, respectively.

For the $\Xi_b^- \to J/\psi\Xi^-$ channel, we verify that the mass resolutions obtained in data and simulation agree to within the combined uncertainty of 7.5%. We obtain a systematic uncertainty associated with any potential disagreement in the ΔM mass resolution between data and simulation by repeating the Ξ_b^{*0} fit with the resolutions from MC scaled up or down by 1.075. The resulting systematic uncertainties are ± 0.004 and ± 0.08 MeV for the mass difference and natural width, respectively.

The systematic uncertainties described above are summarized in Table 6, together with the total systematic uncertainties, found from the quadrature sum of those from the individual sources.

8 Results

Our final result for the ratio of the branching fractions for the $\Xi_b^- \to \psi(2S)\Xi^-$ decay with respect to the $\Xi_b^- \to J/\psi\Xi^-$ normalization mode is

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2S)\Xi^-)}{\mathcal{B}(\Xi_b^- \to J/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B}),$$

Table 6: The systematic uncertainties in MeV in the measurement of the Ξ_b^{*0} mass difference and natural width from each of the sources, along with the total uncertainties.

Source	ΔM (MeV)	$\Gamma(\Xi_b^{*0})$ (MeV)
Signal model	0.003	< 0.01
Background model	0.002	0.04
Fit range	0.023	0.13
RBW shape	0.022	0.02
Mass resolution	0.004	0.08
Total	0.032	0.16

where the uncertainties are statistical, systematic, and related to the uncertainties in the J/ψ and ψ(2S) branching fractions, respectively. For the last term of Eq. (1), we used the lepton universality assumption of $\mathcal{B}(\mathrm{J}/\psi \to \mu^+\mu^-)/\mathcal{B}(\psi(2\mathrm{S}) \to \mu^+\mu^-) = \mathcal{B}(\mathrm{J}/\psi \to \mathrm{e}^+\mathrm{e}^-)/\mathcal{B}(\psi(2\mathrm{S}) \to \mathrm{e}^+\mathrm{e}^-) = 7.53 \pm 0.17$ from the PDG [34], since the dielectron modes are measured more precisely than the dimuon ones.

Including the systematic uncertainties described in the previous section, the Ξ_b^{*0} mass difference and natural width are found to be

$$M(\Xi_b^{*0}) - M(\Xi_b^-) - m^{\mathrm{PDG}}(\pi^\pm) = 15.810 \pm 0.077\,(\text{stat}) \pm 0.032\,(\text{syst})\,\text{MeV},$$
$$\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}\,(\text{stat}) \pm 0.16\,(\text{syst})\,\text{MeV}.$$

Using the world-average Ξ_b^- baryon mass [34], our ΔM^{fit} value corresponds to a Ξ_b^{*0} mass of $5952.4 \pm 0.1\,(\text{stat+syst}) \pm 0.6\,(m_{\Xi_b^-})$ MeV, where the first uncertainty includes the statistical and systematic components and the last comes from the uncertainty in the Ξ_b^- mass. These measurements of the Ξ_b^{*0} baryon mass and width are significantly more precise than the previous CMS results [5] and in agreement with those obtained by the LHCb experiment [6, 15]. Their recent measurement, using data corresponding to an integrated luminosity of 9 fb^{-1}, reported $\Delta M = 15.80 \pm 0.02 \pm 0.01$ MeV and $\Gamma(\Xi_b^{*0}) = 0.87 \pm 0.06 \pm 0.05$ MeV [15].

Finally, our measurement of the inclusive ratio of the Ξ_b^{*0} and Ξ_b^- production cross sections gives

$$R_{\Xi_b^{*0}} = \frac{\sigma(\mathrm{pp} \to \Xi_b^{*0}\mathrm{X})\,\mathcal{B}(\Xi_b^{*0} \to \Xi_b^-\pi^+)}{\sigma(\mathrm{pp} \to \Xi_b^-\mathrm{X})} = 0.23 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{syst}),$$

where we used the BLUE procedure [71–73] to combine the results from the $\Xi_b^- \to \mathrm{J}/\psi\Xi^-$ and $\Xi_b^- \to \mathrm{J}/\psi\Lambda\mathrm{K}^-$ decay modes. The statistical and systematic uncertainties are assumed to be uncorrelated, except for the tracking efficiency, which we treat as correlated.

9 Summary and conclusions

In this article, we present the first observation of the $\Xi_b^- \to \psi(2\mathrm{S})\Xi^-$ decay. We use data from LHC proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV, collected by the CMS experiment during 2016–2018, corresponding to an integrated luminosity of 140 fb^{-1}. We measure the ratio of the branching fraction for the new decay to that for $\Xi_b^- \to \mathrm{J}/\psi\Xi^-$ to be

$$R = \frac{\mathcal{B}(\Xi_b^- \to \psi(2\mathrm{S})\Xi^-)}{\mathcal{B}(\Xi_b^- \to \mathrm{J}/\psi\Xi^-)} = 0.84^{+0.21}_{-0.19}\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\mathcal{B}),$$

where the last uncertainty comes from the uncertainties in the J/ψ and ψ(2S) branching fractions.

This result is consistent with analogous measured ratios from $B_{(s)}$ and Λ_b^0 decays such as $B^+ \to \psi K^+$, $B^0 \to \psi K_S^0$, $B_s^0 \to \psi\phi$, and $\Lambda_b^0 \to \psi\Lambda$, whose values are in the range 0.5–0.6 [34] (here ψ refers to the J/ψ and $\psi(2S)$ mesons). In general, currently existing results for such ratios do not form any clear and unambiguous pattern. New measurements, such as the one reported here, and corresponding theoretical predictions are required to build a robust model that can reliably describe b hardon decays to charmonium states.

We reconstruct Ξ_b^{*0} candidates using the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay mode by combining tracks from the proton-proton collision vertex with Ξ_b^- candidates from four different decay modes. A simultaneous fit of all decay modes is used to extract the mass difference and natural width, which are consistent with our previous results [5], but with much better precision. They are also in agreement with the LHCb measurements [6, 15]. Using the world-average value for the Ξ_b^- baryon mass [34], we measure the mass of the Ξ_b^{*0} baryon to be

$$M(\Xi_b^{*0}) = 5952.4 \pm 0.1\,(\text{stat+syst}) \pm 0.6\,(m_{\Xi_b^-})\,\text{MeV},$$

where the last uncertainty comes from the uncertainty in the Ξ_b^- baryon mass. We measure the natural width to be $\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}\,(\text{stat}) \pm 0.16\,(\text{syst})\,\text{MeV}$.

Finally, our determination of the $\Xi_b^{*0}/\ \Xi_b^-$ relative production rate $R_{\Xi_b^{*0}} = 0.23 \pm 0.04\,(\text{stat}) \pm 0.02\,(\text{syst})$ is in good agreement with the LHCb result [6] of $0.28 \pm 0.03 \pm 0.01$ and is of a similar precision. From the measured values of this ratio, we conclude that about 1/4 of Ξ_b^- baryons are produced from the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ decay. The other major Ξ_b^{*0} decay is $\Xi_b^{*0} \to \Xi_b^0 \pi^0$. Since $\mathcal{B}(\Xi_b^* \to \Xi_b \pi)$ should be close to 100%, we expect $\mathcal{B}(\Xi_b^{*0} \to \Xi_b^- \pi^+) \approx 2\,\mathcal{B}(\Xi_b^{*0} \to \Xi_b^0 \pi^0) \approx 2/3$, where the factor of 2 comes from isospin differences and the Clebsch–Gordan coefficients [34]. Incorporating this estimate of $\mathcal{B}(\Xi_b^{*0} \to \Xi_b^- \pi^+)$ into our results for the ratio of production cross sections, we find that $\sigma(pp \to \Xi_b^{*0} X)/\sigma(pp \to \Xi_b^- X) \approx 1/3$. If the relative production rate for Ξ_b^{*-} to Ξ_b^- follows the same scheme, the corresponding ratio can be estimated as $R_{\Xi_b^{*-}} = [\sigma(pp \to \Xi_b^{*-} X)\mathcal{B}(\Xi_b^{*-} \to \Xi_b^- \pi^0)]/\sigma(pp \to \Xi_b^- X) \approx 1/3 \times 1/3 = 1/9$. Thus, we can conclude that about a third of the Ξ_b^- baryons are produced from Ξ_b^* decays.

Since decays from higher-mass excited Ξ_b baryons are also possible, such as the $\Xi_b(6227)$ doublet reported by the LHCb experiment [11, 12], less than two thirds of the Ξ_b^- baryons are expected to be directly produced from pp collisions. It is clear that further studies of different ground- and excited-state Ξ_b baryons are needed to fully understand this family of baryons.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia);

Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing, funded by the EU NexGeneration program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] D. Ebert, T. Feldmann, C. Kettner, and H. Reinhardt, "A diquark model for baryons containing one heavy quark", *Z. Phys. C* **71** (1996) 329, doi:10.1007/BF02906991, arXiv:hep-ph/9506298.

[2] D0 Collaboration, "Direct observation of the strange b baryon Ξ_b^-", *Phys. Rev. Lett.* **99** (2007) 052001, doi:10.1103/PhysRevLett.99.052001, arXiv:0706.1690.

[3] CDF Collaboration, "Observation and mass measurement of the baryon Ξ_b^-", *Phys. Rev. Lett.* **99** (2007) 052002, doi:10.1103/PhysRevLett.99.052002, arXiv:0707.0589.

[4] CDF Collaboration, "Observation of the Ξ_b^0 baryon", *Phys. Rev. Lett.* **107** (2011) 102001, doi:10.1103/PhysRevLett.107.102001, arXiv:1107.4015.

[5] CMS Collaboration, "Observation of a new Ξ_b baryon", *Phys. Rev. Lett.* **108** (2012) 252002, doi:10.1103/PhysRevLett.108.252002, arXiv:1204.5955.

[6] LHCb Collaboration, "Measurement of the properties of the Ξ_b^{*0} baryon", *JHEP* **05** (2016) 161, doi:10.1007/JHEP05(2016)161, arXiv:1604.03896.

[7] LHCb Collaboration, "Observation of two new Ξ_b^- baryon resonances", *Phys. Rev. Lett.* **114** (2015) 062004, doi:10.1103/PhysRevLett.114.062004, arXiv:1411.4849.

[8] E. E. Jenkins, "Model-independent bottom baryon mass predictions in the $1/N_c$ expansion", *Phys. Rev. D* **77** (2008) 034012, doi:10.1103/PhysRevD.77.034012, arXiv:0712.0406.

[9] M. Karliner, B. Keren-Zur, H. J. Lipkin, and J. L. Rosner, "The quark model and b baryons", *Ann. Phys.* **324** (2009) 2, doi:10.1016/j.aop.2008.05.003, arXiv:0804.1575.

[10] D. Ebert, R. N. Faustov, and V. O. Galkin, "Masses of excited heavy baryons in the relativistic quark model", *Phys. Lett. B* **659** (2008) 612, doi:10.1016/j.physletb.2007.11.037, arXiv:0705.2957.

[11] LHCb Collaboration, "Observation of a new Ξ_b^- resonance", *Phys. Rev. Lett.* **121** (2018) 072002, doi:10.1103/PhysRevLett.121.072002, arXiv:1805.09418.

[12] LHCb Collaboration, "Observation of a new Ξ_b^0 state", *Phys. Rev. D* **103** (2021) 012004, doi:10.1103/PhysRevD.103.012004, arXiv:2010.14485.

[13] CMS Collaboration, "Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\pi^+\pi^-$", *Phys. Rev. Lett.* **126** (2021) 252003, doi:10.1103/PhysRevLett.126.252003, arXiv:2102.04524.

[14] LHCb Collaboration, "Observation of two new excited Ξ_b^0 states decaying to $\Lambda_b^0 K^-\pi^+$", *Phys. Rev. Lett.* **128** (2022) 162001, doi:10.1103/PhysRevLett.128.162001, arXiv:2110.04497.

[15] LHCb Collaboration, "Observation of new baryons in the $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ systems", *Phys. Rev. Lett.* **131** (2023) 171901, doi:10.1103/PhysRevLett.131.171901, arXiv:2307.13399.

[16] W. Roberts and M. Pervin, "Heavy baryons in a quark model", *Int. J. Mod. Phys. A* **23** (2008) 2817, doi:10.1142/S0217751X08041219, arXiv:0711.2492.

[17] D. Ebert, R. N. Faustov, and V. O. Galkin, "Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture", *Phys. Rev. D* **84** (2011) 014025, doi:10.1103/PhysRevD.84.014025, arXiv:1105.0583.

[18] H. Garcilazo, J. Vijande, and A. Valcarce, "Faddeev study of heavy baryon spectroscopy", *J. Phys. G* **34** (2007) 961, doi:10.1088/0954-3899/34/5/014, arXiv:hep-ph/0703257.

[19] B. Chen, K.-W. Wei, and A. Zhang, "Assignments of Λ_Q and Ξ_Q baryons in the heavy quark-light diquark picture", *Eur. Phys. J. A* **51** (2015) 82, doi:10.1140/epja/i2015-15082-3, arXiv:1406.6561.

[20] I. L. Grach, I. M. Narodetskii, M. A. Trusov, and A. I. Veselov, "Heavy baryon spectroscopy in the QCD string model", in *Particles and Nuclei. Proceedings, 18th International Conference, PANIC08, Eilat, Israel*. 2008. arXiv:0811.2184.

[21] Q. Mao et al., "QCD sum rule calculation for P-wave bottom baryons", *Phys. Rev. D* **92** (2015) 114007, doi:10.1103/PhysRevD.92.114007, arXiv:1510.05267.

[22] Z.-G. Wang, "Analysis of the $1/2^-$ and $3/2^-$ heavy and doubly heavy baryon states with QCD sum rules", *Eur. Phys. J. A* **47** (2011) 81, doi:10.1140/epja/i2011-11081-8, arXiv:1003.2838.

[23] K.-L. Wang, Y.-X. Yao, X.-H. Zhong, and Q. Zhao, "Strong and radiative decays of the low-lying *S*- and *P*-wave singly heavy baryons", *Phys. Rev. D* **96** (2017) 116016, doi:10.1103/PhysRevD.96.116016, arXiv:1709.04268.

[24] Y. Kawakami and M. Harada, "Singly heavy baryons with chiral partner structure in a three-flavor chiral model", *Phys. Rev. D* **99** (2019) 094016, doi:10.1103/PhysRevD.99.094016, arXiv:1902.06774.

[25] Z.-Y. Wang, J.-J. Qi, X.-H. Guo, and K.-W. Wei, "Spectra of charmed and bottom baryons with hyperfine interaction", *Chin. Phys. C* **41** (2017) 093103, doi:10.1088/1674-1137/41/9/093103, arXiv:1701.04524.

[26] K. Thakkar, Z. Shah, A. K. Rai, and P. C. Vinodkumar, "Excited state mass spectra and Regge trajectories of bottom baryons", *Nucl. Phys. A* **965** (2017) 57, doi:10.1016/j.nuclphysa.2017.05.087, arXiv:1610.00411.

[27] K.-W. Wei et al., "Spectroscopy of singly, doubly, and triply bottom baryons", *Phys. Rev. D* **95** (2017) 116005, doi:10.1103/PhysRevD.95.116005, arXiv:1609.02512.

[28] LHCb Collaboration, "Studies of beauty baryon decays to $\mathrm{D^0ph^-}$ and $\Lambda_c^+\mathrm{h}^-$ final states", *Phys. Rev. D* **89** (2014) 032001, doi:10.1103/PhysRevD.89.032001, arXiv:1311.4823.

[29] LHCb Collaboration, "Evidence for the strangeness-changing weak decay $\Xi_b^- \to \Lambda_b^0\pi^-$", *Phys. Rev. Lett.* **115** (2015) 241801, doi:10.1103/PhysRevLett.115.241801, arXiv:1510.03829.

[30] LHCb Collaboration, "Observation of the decay $\Xi_b^- \to \mathrm{p}K^-K^-$", *Phys. Rev. Lett.* **118** (2017) 071801, doi:10.1103/PhysRevLett.118.071801, arXiv:1612.02244.

[31] LHCb Collaboration, "Observation of the $\Xi_b^- \to J/\psi\Lambda K^-$ decay", *Phys. Lett. B* **772** (2017) 265, doi:10.1016/j.physletb.2017.06.045, arXiv:1701.05274.

[32] LHCb Collaboration, "Measurement of branching fractions of charmless four-body Λ_b^0 and Ξ_b^0 decays", *JHEP* **02** (2018) 098, doi:10.1007/JHEP02(2018)098, arXiv:1711.05490.

[33] LHCb Collaboration, “Isospin amplitudes in $\Lambda_b^0 \to J/\psi\Lambda(\Sigma^0)$ and $\Xi_b^0 \to J/\psi\Xi^0(\Lambda)$ decays”, *Phys. Rev. Lett.* **124** (2020) 111802, doi:10.1103/PhysRevLett.124.111802, arXiv:1912.02110.

[34] Particle Data Group, “Review of particle physics”, *PTEP* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.

[35] LHCb Collaboration, “Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay”, *Sci. Bull.* **66** (2021) 1278, doi:10.1016/j.scib.2021.02.030, arXiv:2012.10380.

[36] LHCb Collaboration, “Search for *CP* violation in $\Xi_b^- \to pK^-K^-$ decays”, *Phys. Rev. D* **104** (2021) 052010, doi:10.1103/PhysRevD.104.052010, arXiv:2104.15074.

[37] A. G. Grozin, “Heavy quark effective theory”. Springer Berlin, Heidelberg, 2004. doi:10.1007/b79301.

[38] N. Isgur and M. B. Wise, “Spectroscopy with heavy quark symmetry”, *Phys. Rev. Lett.* **66** (1991) 1130, doi:10.1103/PhysRevLett.66.1130.

[39] M. A. Shifman and M. B. Voloshin, “Preasymptotic effects in inclusive weak decays of charmed particles”, *Sov. J. Nucl. Phys.* **41** (1985) 120.

[40] N. Isgur and M. B. Wise, “Weak decays of heavy mesons in the static quark approximation”, *Phys. Lett. B* **232** (1989) 113, doi:10.1016/0370-2693(89)90566-2.

[41] I. I. Y. Bigi, N. G. Uraltsev, and A. I. Vainshtein, “Nonperturbative corrections to inclusive beauty and charm decays: QCD versus phenomenological models”, *Phys. Lett. B* **293** (1992) 430, doi:10.1016/0370-2693(92)90908-M, arXiv:hep-ph/9207214. [Erratum: doi:10.1016/0370-2693(92)91287-J].

[42] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[43] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[44] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[45] CMS Collaboration, “Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **102** (2020) 092007, doi:10.1103/PhysRevD.102.092007, arXiv:2008.08629.

[46] HEPData record for this analysis, 2024. doi:10.17182/hepdata.146756.

[47] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[48] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, 2023. arXiv:2309.05466. Accepted by *JINST*.

[49] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[50] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[51] CMS Tracker Group, "The CMS Phase-1 pixel detector upgrade", *JINST* **16** (2021) P02027, doi:10.1088/1748-0221/16/02/P02027, arXiv:2012.14304.

[52] CMS Collaboration, "Track impact parameter resolution for the full pseudorapidity coverage in the 2017 dataset with the CMS Phase-1 pixel detector", CMS Detector Performance Note CMS-DP-2020-049, 2020.

[53] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[54] CMS Collaboration, "Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[55] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[56] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[57] D. J. Lange, "The EVTGEN particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[58] E. Barberio, B. van Eijk, and Z. Wąs, "PHOTOS: A universal Monte Carlo for QED radiative corrections in decays", *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

[59] E. Barberio and Z. Wąs, "PHOTOS: A universal Monte Carlo for QED radiative corrections. version 2.0", *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4.

[60] GEANT4 Collaboration, "GEANT4 — a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[61] CMS Collaboration, "CMS tracking performance results from early LHC operation", *Eur. Phys. J. C* **70** (2010) 1165, doi:10.1140/epjc/s10052-010-1491-3, arXiv:1007.1988.

[62] CMS Collaboration, "Observation of two excited B_c^+ states and measurement of the $B_c^+(2S)$ mass in pp collisions at $\sqrt{s} = 13$ TeV", *Phys. Rev. Lett.* **122** (2019) 132001, doi:10.1103/PhysRevLett.122.132001, arXiv:1902.00571.

[63] CMS Collaboration, "Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **803** (2020) 135345, doi:10.1016/j.physletb.2020.135345, arXiv:2001.06533.

[64] S. S. Wilks, "The large-sample distribution of the likelihood ratio for testing composite hypotheses", *Annals Math. Statist.* **9** (1938) 60, doi:10.1214/aoms/1177732360.

[65] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[66] 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. D* **85** (2012) 114508, doi:10.1103/PhysRevD.85.114508, arXiv:1203.3378.

[67] C. Chen et al., "Strong decays of charmed baryons", *Phys. Rev. D* **75** (2007) 094017, doi:10.1103/PhysRevD.75.094017, arXiv:0704.0075.

[68] S. Jackman, "Bayesian analysis for the social sciences". John Wiley & Sons, New Jersey, USA, 2009. doi:10.1002/9780470686621.

[69] CMS Collaboration, "Measurement of prompt open-charm production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **11** (2021) 225, doi:10.1007/JHEP11(2021)225, arXiv:2107.01476.

[70] J. M. Blatt and V. F. Weisskopf, "Theoretical nuclear physics". Springer, New York, 1952. doi:10.1007/978-1-4612-9959-2, ISBN 978-0-471-08019-0.

[71] L. Lyons, D. Gibaut, and P. Clifford, "How to combine correlated estimates of a single physical quantity", *Nucl. Instrum. Meth. A* **270** (1988) 110, doi:10.1016/0168-9002(88)90018-6.

[72] R. Nisius, "On the combination of correlated estimates of a physics observable", *Eur. Phys. J. C* **74** (2014) 3004, doi:10.1140/epjc/s10052-014-3004-2, arXiv:1402.4016.

[73] R. Nisius, "BLUE: combining correlated estimates of physics observables within ROOT using the best linear unbiased estimate method", *SoftwareX* **11** (2020) 100468, doi:10.1016/j.softx.2020.100468, arXiv:2001.10310.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, D. Hohov, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, Y. Hong, J. Knolle, L. Lambrecht, G. Mestdach, K. Mota Amarilo, C. Rendón, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, C. Caputo, C. Delaere, I.S. Donertas, A. Giammanco, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins[7], C. Mora Herrera, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, S. Thakur

Beihang University, Beijing, China
T. Cheng, T. Javaid, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, J. Liu, K. Yi[8,9]

Institute of High Energy Physics, Beijing, China
G.M. Chen[10], H.S. Chen[10], M. Chen[10], F. Iemmi, C.H. Jiang, A. Kapoor[11], H. Liao, Z.-A. Liu[12], R. Sharma[13], J.N. Song[12], J. Tao, C. Wang[10], J. Wang, Z. Wang[10], H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Levin, C. Li, Q. Li, Y. Mao, S.J. Qian, X. Sun, D. Wang, H. Yang, L. Zhang, C. Zhou

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
K. Jaffel, N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[14]

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[15]

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, S. Mishra, A. Starodumov[16], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, S. Konstantinou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[17,18], S. Elgammal[18]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, K.T.S. Kallonen, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[19], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, M. Chiusi, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, J. Motta, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[20], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, C. Grimault, R. Haeberle, A.-C. Le Bihan, M. Meena, G. Saha, M.A. Sessini, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[21], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[22], Z. Tsamalaidze[16]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[24], T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[25], K. Borras[26], A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[25], A. Geiser, A. Giraldi, V. Guglielmi, M. Guthoff, A. Hinzmann, A. Jafari[27], L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[28], W. Lohmann[29], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, A. Mussgiller, L.P. Nair, A. Nürnberg, Y. Otarid, J. Park, D. Pérez Adán, E. Ranken, A. Raspereza, D. Rastorguev, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Scham[30,26], S. Schnake[26], P. Schütze, C. Schwanenberger[25], D. Selivanova, K. Sharko, M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[26], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[31], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, B. Maier, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy,

I. Shvetsov, H.J. Simonis, M. Toms, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[31], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, Z. Painesis, A. Panagiotou, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[32], C. Hajdu, D. Horvath[33,34], K. Márton, A.J. Rádl[35], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[36], Á. Kadlecsik, P. Major, K. Mandal, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari, G. Zilizi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[37], F. Nemes[37], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[38], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[39], S. Bhattacharya, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, P. Jana, P. Kalbhor, J.R. Komaragiri[40], D. Kumar[40], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Tata Institute of Fundamental Research-A, Mumbai, India
S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, R.M. Chatterjee, R.K. Dewanjee[41], M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[42], C. Kar, D. Maity[43], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[43], K. Naskar[43], A. Nayak[43], P. Sadangi, S.K. Swain, S. Varghese[43], D. Vats[43]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[44], A. Alpana, S. Dube, B. Gomber[44], P. Hazarika, B. Kansal, A. Laha, B. Sahu[44], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[45], E. Khazaie[46], M. Zeinali[47]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[48], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, S. Tizchang

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,49], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,c], W. Elmetenawee[a,b,49], L. Fiore[a], G. Iaselli[a,c], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], G. Ramirez-Sanchez[a,c], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,50], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,51], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,51], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[52], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a,b], F. Brivio[a], F. Cetorelli[a], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,53], P. Paolucci[a,31], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,54], A. Bergnoli[a], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A. Bragagnolo[a,b], A.C.M. Bulla[a], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], E. Lusiani[a], M. Margoni[a,b], F. Marini[a], A.T. Meneguzzo[a,b], M. Migliorini[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], A. Triossi[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,55], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,56], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
C. Baldenegro Barrera[a,b], P. Barria[a], C. Basile[a,b], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], P. Meridiani[a], J. Mijuskovic[a,b], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b],

E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b], R. White[a]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, C. Huh, B. Kim, D.H. Kim, J. Kim, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, S. Yang

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, W. Jun, J. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, I. Yusuff[57], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[58], R. Lopez-Fernandez, C.A. Mondragon Herrera, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero,

M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, P. Leguina, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[59], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[60], K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, C. Botta, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, L. Forthomme, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, A.C. Marini, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, H. Qu, D. Rabady, M. Rovere, H. Sakulin, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[61], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[62], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[63], L. Caminada[63], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[63], L. Noehte[63], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[62], M. Backhaus, G. Bonomelli, A. Calandri, C. Caz-

zaniga, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[62], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, R. Seidita, J. Steggemann[62], D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[64], P. Bärtschi, M.F. Canelli, K. Cormier, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, U. Molinatti, A. Reimers, P. Robmann, S. Sanchez Cruz, M. Senger, E. Shokr, F. Stäger, Y. Takahashi, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[65], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[40], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[66], E. Eskut, Y. Guler[67], E. Gurpinar Guler[67], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, B. Tali[69], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Sokmen, M. Yalvac[70]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[71], O. Kaya[72], S. Tekten[73]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[66,74], G.G. Dincer, Y. Komurcu, S. Sen[75]

Istanbul University, Istanbul, Turkey
O. Aydilek[24], S. Cerci[69], V. Epshteyn, B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
B. Isildak[77], D. Sunar Cerci[69]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans,

H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[78], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[80], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, J. León Holgado, L. Lyons, A.-M. Magnan, S. Malik, M. Mieskolainen, J. Nash[81], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[31], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, E. Collins, J. Dittmann, K. Hatakeyama, J. Hiltbrand, B. McMaster, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, R. Chudasama, S.I. Cooper, S.V. Gleyzer, C.U. Perez, P. Rumerio[82], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
A. Akpinar, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Benelli, X. Coubez[26], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, S. Sagir[84], F. Simpson, M. Stamenkovic, N. Venkatasubramanian, X. Yan, W. Zhang

University of California, Davis, Davis, California, USA
S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, W. Wei, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si, S. Wimpenny†

University of California, San Diego, La Jolla, California, USA
J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, P. Palit, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, J. Dickinson, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], F. Ravera, A. Reinsvold Hall[86], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, A. Whitbeck, I. Zoi

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, L. Cadamuro, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Habibullah, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, S. Das, T. Elkafrawy[55], M. Hohlmann, R. Kumar Verma, M. Rahmani, E. Yanes

University of Illinois Chicago, Chicago, USA, Chicago, USA
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[87], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], J. Nachtman, O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[91], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, A. Kalogeropoulos, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, L. Wang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, I.A. Cali, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, A. Novak, C. Paus, D. Rankin, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, S. Pandey, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, D. Wood

Northwestern University, Evanston, Illinois, USA
J. Bueghly, Z. Chen, S. Dittmer, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[16], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, A. Shevelev, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA
D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, W. Li, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[92], E. Popova[92], R. Taus

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, O. Karacheban[29], I. Laflotte, A. Lath, R. Montalvo, K. Nash, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, O. Bouhali[93], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu, C.E. Perez Lara

Wayne State University, Detroit, Michigan, USA
S. Bhattacharya, P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, I. Azhgirey, A. Babaev, A. Belyaev, V. Blinov[95], E. Boos, V. Borshch, D. Budkouski, V. Chekhovsky, R. Chistov[95], M. Danilov[95], A. Dermenev, T. Dimova[95], D. Druzhkin[96], M. Dubinin[85], L. Dudko, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, K. Ivanov, Y. Ivanov, V. Kachanov, V. Karjavine, A. Karneyeu, V. Kim[95], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[97], D. Konstantinov, V. Korenkov, V. Korotkikh, A. Kozyrev[95], N. Krasnikov, A. Lanev, P. Levchenko[98], N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[95], V. Murzin, A. Nikitenko[99,97], S. Obraztsov, V. Oreshkin, V. Palichik, V. Perelygin, S. Petrushanko, S. Polikarpov[95], V. Popov, O. Radchenko[95], R. Ryutin, M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov,

O. Teryaev, I. Tlisova, A. Toropin, L. Uvarov, A. Uzunian, A. Vorobyev†, N. Voytishin, B.S. Yuldashev[100], A. Zarubin, I. Zhizhin, A. Zhokin

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[4]Also at Ghent University, Ghent, Belgium
[5]Also at Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[7]Also at UFMS, Nova Andradina, Brazil
[8]Also at Nanjing Normal University, Nanjing, China
[9]Now at The University of Iowa, Iowa City, Iowa, USA
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at China Center of Advanced Science and Technology, Beijing, China
[12]Also at University of Chinese Academy of Sciences, Beijing, China
[13]Also at China Spallation Neutron Source, Guangdong, China
[14]Now at Henan Normal University, Xinxiang, China
[15]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[16]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[17]Also at Suez University, Suez, Egypt
[18]Now at British University in Egypt, Cairo, Egypt
[19]Also at Purdue University, West Lafayette, Indiana, USA
[20]Also at Université de Haute Alsace, Mulhouse, France
[21]Also at Department of Physics, Tsinghua University, Beijing, China
[22]Also at Tbilisi State University, Tbilisi, Georgia
[23]Also at The University of the State of Amazonas, Manaus, Brazil
[24]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[25]Also at University of Hamburg, Hamburg, Germany
[26]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[27]Also at Isfahan University of Technology, Isfahan, Iran
[28]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[29]Also at Brandenburg University of Technology, Cottbus, Germany
[30]Also at Forschungszentrum Jülich, Juelich, Germany
[31]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[32]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[33]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[34]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[35]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[36]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[37]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[38]Also at Punjab Agricultural University, Ludhiana, India
[39]Also at University of Visva-Bharati, Santiniketan, India
[40]Also at Indian Institute of Science (IISc), Bangalore, India
[41]Also at Birla Institute of Technology, Mesra, Mesra, India
[42]Also at IIT Bhubaneswar, Bhubaneswar, India
[43]Also at Institute of Physics, Bhubaneswar, India

[44]Also at University of Hyderabad, Hyderabad, India
[45]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[46]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[47]Also at Sharif University of Technology, Tehran, Iran
[48]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[49]Also at Helwan University, Cairo, Egypt
[50]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[51]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[52]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[53]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[54]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[55]Also at Ain Shams University, Cairo, Egypt
[56]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[57]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[58]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[59]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[60]Also at Saegis Campus, Nugegoda, Sri Lanka
[61]Also at National and Kapodistrian University of Athens, Athens, Greece
[62]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[63]Also at Universität Zürich, Zurich, Switzerland
[64]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[65]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[66]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[67]Also at Konya Technical University, Konya, Turkey
[68]Also at Izmir Bakircay University, Izmir, Turkey
[69]Also at Adiyaman University, Adiyaman, Turkey
[70]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[71]Also at Marmara University, Istanbul, Turkey
[72]Also at Milli Savunma University, Istanbul, Turkey
[73]Also at Kafkas University, Kars, Turkey
[74]Now at stanbul Okan University, Istanbul, Turkey
[75]Also at Hacettepe University, Ankara, Turkey
[76]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[77]Also at Yildiz Technical University, Istanbul, Turkey
[78]Also at Vrije Universiteit Brussel, Brussel, Belgium
[79]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[80]Also at IPPP Durham University, Durham, United Kingdom
[81]Also at Monash University, Faculty of Science, Clayton, Australia
[82]Also at Università di Torino, Torino, Italy
[83]Also at Bethel University, St. Paul, Minnesota, USA
[84]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA

[87]Also at Bingol University, Bingol, Turkey
[88]Also at Georgian Technical University, Tbilisi, Georgia
[89]Also at Sinop University, Sinop, Turkey
[90]Also at Erciyes University, Kayseri, Turkey
[91]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[92]Now at an institute or an international laboratory covered by a cooperation agreement with CERN
[93]Also at Texas A&M University at Qatar, Doha, Qatar
[94]Also at Kyungpook National University, Daegu, Korea
[95]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[96]Also at Universiteit Antwerpen, Antwerpen, Belgium
[97]Also at Yerevan Physics Institute, Yerevan, Armenia
[98]Also at Northeastern University, Boston, Massachusetts, USA
[99]Also at Imperial College, London, United Kingdom
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan