Observation and investigation of the $T_{c\bar{c}1}(4430)^+$ structure in $B^+ \to \psi(2S)K^0_S\pi^+$ decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 27 November 2025; accepted 12 February 2026; published 7 April 2026)

The first four-dimensional amplitude analysis of the $B^+ \to \psi(2S)K^0_S\pi^+$ decay is performed with proton-proton collision data collected by the LHCb experiment at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 5.4 fb^{-1}. The data cannot be fully explained by $B^+ \to \psi(2S)K^{*+}$ contributions alone. A significantly better description of the data is obtained by adding a $T^+_{c\bar{c}}$ contribution decaying to $\psi(2S)\pi^+$. The properties of the $T^+_{c\bar{c}}$ structure are consistent with the exotic state $T_{c\bar{c}1}(4430)^+$ reported in the isospin-related $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decay. Effects of a possible $T_{c\bar{c}1}(4430)^+ \to \bar{D}^*_1(2600)^0 D^+$ decay mode on the $T_{c\bar{c}1}(4430)^+ \to \psi(2S)\pi^+$ mass distribution are investigated through a Flatté parametrization, providing constraints on the relative decay strength. A description of the $T_{c\bar{c}1}(4430)^+$ structure using the triangle singularity mechanism is studied and also found to be consistent with the data.

DOI: 10.1103/rcfs-ynh2

Hadrons beyond conventional $q\bar{q}$ mesons or qqq baryons have been anticipated since the introduction of the quark model [1]. Referred to as exotic states, such hadrons serve as distinctive showcases of the intricate nonperturbative nature of QCD at low energies. A wealth of exotic candidates has been observed experimentally, whose properties do not fit in the known conventions of hadron spectroscopy [2–8]. The first evidence for a charged charmoniumlike structure was found in the $\psi(2S)\pi^+$ final state of the $B \to \psi(2S)K\pi^+$ decay [9,10].[1] The minimum quark content of the observed structure, referred to as $T_{c\bar{c}1}(4430)^+$ in the following, is $c\bar{c}u\bar{d}$, and its spin-parity has been determined by an amplitude analysis to be $J^P = 1^+$ [11–13].

Many theoretical interpretations of the $T_{c\bar{c}1}(4430)^+$ structure using kinematic effects or dynamical models have been proposed. In dynamical interpretations, the $T_{c\bar{c}1}(4430)^+$ structure is regarded as a genuine exotic state, described as a hadronic molecule with meson-meson interactions [14–16] or a compact tetraquark formed by color-exchange interactions [17–20]. However, these dynamical interpretations face challenges in explaining the $T_{c\bar{c}1}(4430)^+$ structure. In the hadronic molecular scenario, the $T_{c\bar{c}1}(4430)^+$ structure is interpreted as an S-wave $\bar{D}^*D_1$ hadronic molecule with possible spin-parity quantum numbers $J^P = 0^-, 1^-$ or 2^- [14–16], which is strongly disfavored by the LHCb analysis reported in Ref. [12]. In the compact tetraquark scenario, an octet group of meson states is predicted; however none of these, apart from the possible $T_{c\bar{c}1}(4430)^+$ state, have been observed. In contrast, in the kinematical interpretations, the $T_{c\bar{c}1}(4430)^+$ structure is generated as a kinematical singularity in the B-decay amplitude [21–23]. In one possible model [24], the rescattering of $\psi(4230)\pi^+$ hadrons in the $\bar{B}^0 \to \bar{K}^*(892)^0\psi(4230)$, $\bar{K}^*(892)^0 \to K^-\pi^+$ cascade decay could form a peaking structure in the $\psi(2S)\pi^+$ final state, consistent with the measured $T_{c\bar{c}1}(4430)^+$ properties. Additionally, lattice QCD simulations cannot predict the $T_{c\bar{c}1}(4430)^+$ state due to the entanglement of many possible decay channels [25]. To date, there is no consensus on the nature of $T_{c\bar{c}1}(4430)^+$ structure. Further experimental and theoretical studies are needed for new insights.

This paper reports on an amplitude analysis performed on the $B^+ \to \psi(2S)K^0_S\pi^+$ decay, analogous to the isospin-related decay channel $\bar{B}^0 \to \psi(2S)K^-\pi^+$. The data used are proton-proton (pp) collisions recorded by the LHCb experiment, at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 5.4 fb^{-1}. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [26,27]. Candidate $B^+ \to \psi(2S)K^0_S\pi^+$ decays are formed by combining π^+ candidate tracks with $\psi(2S)$ and K^0_S meson candidates reconstructed in the $\psi(2S) \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$ decay modes, respectively. Particle

---

[*] Full author list given at the end of the article.

[1] Unless otherwise specified, charge-conjugated states or decays are implied throughout this paper.

identification, track quality, and impact parameter requirements are applied to all final-state particles to ensure consistency with the signal decay. The reconstructed B^+, $\psi(2S)$ and K_S^0 mesons are required to have good vertex-fit χ^2 and invariant masses close to their known values [28]. The background, dominated by random combinations of $\psi(2S)$, π^+, and K_S^0 candidates, is further suppressed by a boosted decision tree (BDT) [29,30] classifier. The classifier is implemented with the TMVA toolkit [31,32] and uses as discriminating variables the transverse momenta, vertex-fit quality, and particle-identification information of the final-state particles. A simulated sample of $B^+ \to \psi(2S)K_S^0\pi^+$ decays, generated with the software packages described in Refs. [33–35], is used to model the effects of the detector acceptance and the imposed selection requirements. The simulated decays are subjected to the same reconstruction and selection procedures as the data.

The B^+ candidate invariant-mass distribution, calculated with the $\psi(2S)$ and K_S^0 masses constrained to their known values [28], is shown in the Supplemental Material [36]. The signal yield is found to be 9600 ± 100, determined from an unbinned extended maximum-likelihood fit to the B^+ mass spectrum, where the signal component is modeled by a modified Gaussian function [37] with power-law tails on both sides, and the combinatorial background is described by an exponential function. The fit result is further used to assign a signal weight [38,39] to each candidate, which is employed to perform background subtraction in the subsequent analysis steps following the sFit technique [39–41].

An amplitude analysis is performed to investigate the various contributions in the $B^+ \to \psi(2S)K_S^0\pi^+$ decay, where the amplitude models are developed following the helicity formalism [42]. The first model includes only $B^+ \to \psi(2S)K^{*+}$ contributions, with excited K^{*+} mesons decaying into $K_S^0\pi^+$. Four independent variables are needed to describe the kinematics of the cascade decay, referred to as the K^* chain: $B^+ \to \psi(2S)K^{*+}$, $K^{*+} \to K_S^0\pi^+$, $\psi(2S) \to \mu^+\mu^-$. The variables are chosen in the fit to be the K^{*+} invariant mass, $m_{K\pi}$, the cosines of the helicity angles of the K^* and $\psi(2S)$ decays, $\cos\theta_{K^*}$ and $\cos\theta_\psi$, and the angle between the K^{*+} and $\psi(2S)$ decay planes ϕ, as defined in the Supplemental Material [36]. The four independent variables are calculated with the B^+ and $\psi(2S)$ masses constrained to their known values [28].

The total amplitude model is constructed using the isobar approach [43], where a coherent sum is taken over various K^{*+} resonances and an incoherent sum over final-state μ^+ and μ^- helicities. All known K^{*+} resonances with masses below the upper kinematic limit ($1.593\ \mathrm{GeV}/c^2$) are considered in the baseline amplitude model. These comprise the $K_0^*(700)^+$ and $K_0^*(1430)^+$ mesons with $J = 0$, the $K^*(892)^+$ and $K^*(1410)^+$ mesons with $J = 1$, and the $K_2^*(1430)^+$ meson with $J = 2$. The masses and widths of these K^{*+} resonances are fixed to their known values [28], except for the dominant $K^*(892)^+$ state, whose mass and width are allowed to float in the amplitude fit with Gaussian constraints to the known values [28]. The amplitude is constructed using LS (orbital angular momentum and spin coupling) bases instead of helicity bases [44]. The relative momentum between the $\psi(2S)$ and K^{*+} meson in the B^+ rest frame is rather small, so only the amplitudes with the lowest possible orbital angular momentum between $\psi(2S)$ and K^{*+} mesons are considered in the baseline fit, except for $B^+ \to \psi(2S)K^*(892)^+$ amplitudes where all three possible contributions are included. The effects of including amplitudes with higher orbital angular momenta are considered as systematic uncertainties. Each amplitude is associated with a complex coupling, which is determined by the fit to data.

The K^{*+} resonances are modeled using relativistic Breit-Wigner amplitudes,

$$BW(m_{K\pi}|m_0, \Gamma_0) = \frac{1}{m_0^2 - m_{K\pi}^2 - i m_0 \Gamma(m_{K\pi})}, \tag{1}$$

where $\Gamma(m_{K\pi}) = \Gamma_0 (q/q_0)^{2L+1} (m_0/m_{K\pi}) B_L^2(q, q_0, d)$ is the mass-dependent width, and m_0 and Γ_0 are the mass and natural width of a K^{*+} resonance. The variable q refers to the momentum of the K_S^0 meson in the K^{*+} rest frame, and q_0 denotes the value evaluated at the resonance peak $m_{K\pi} = m_0$. The orbital angular momentum between K_S^0 and π^+ mesons, L, is fixed by the K^{*+} resonance spin. The Blatt-Weisskopf form factor is also applied to the relativistic Breit-Wigner amplitude, together with an orbital angular momentum suppression factor, to account for the effects of higher partial waves with nonzero orbital angular momentum. In the Blatt-Weisskopf form factor [45], $B_L(q, q_0, d)$, the radius $d = 3\ (\mathrm{GeV}/c)^{-1}$ is used for intermediate states and $d = 5\ (\mathrm{GeV}/c)^{-1}$ for the B^+ meson [12].

A weighted, unbinned maximum-likelihood fit is performed to the data in four kinematic variables, following the sFit technique [39–41], which removes the need of an explicit description of the background in the fit. In the fit, the efficiency dependence on kinematic variables is determined using simulated samples of the $B^+ \to \psi(2S)K_S^0\pi^+$ decay.

The background-subtracted invariant-mass distributions for $K_S^0\pi^+$ ($m_{K\pi}$), $\psi(2S)\pi^+$ ($m_{\psi\pi}$) and $\psi(2S)K_S^0$ ($m_{\psi K}$) pairs are shown in Fig. 1, together with the results of the fit considering only $B^+ \to \psi(2\mathrm{S})K^{*+}$ contributions. While the K^{*+} model can describe the $m_{K\pi}$ and $m_{\psi K}$ distributions well, the fit does not provide an adequate description of the $m_{\psi\pi}$ shape, especially in the range $4.2 < m_{\psi\pi} < 4.7\ \mathrm{GeV}/c^2$. Adding more K^{*+} resonances or nonresonant $K_S^0\pi^+$ contributions does not significantly improve the fit quality in this region.

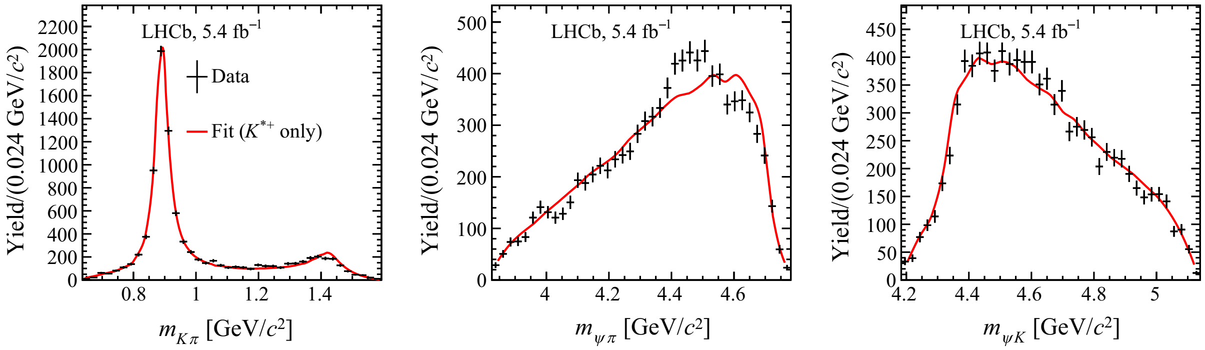

FIG. 1. Invariant-mass distributions of (left) the $K^0_S\pi^+$, (middle) $\psi(2S)\pi^+$, and (right) $\psi(2S)K^0_S$ pairs for background-subtracted data (black dots), together with projections of the results of an amplitude fit (red solid line) with only $B^+ \to \psi(2S)K^{*+}$ contributions.

The unidentified structure in the $m_{\psi\pi}$ spectrum (in the following referred to as structure X) is investigated by adding a $\psi(2S)\pi^+$ component to the K^{*+} amplitudes. In the coherent sum of the K^{*+} and $\psi(2S)\pi^+$ amplitudes, the muon helicity reference frames are aligned by applying a rotation that depends on the four independent variables $m_{K\pi}$, $\cos\theta_{K^*}$, $\cos\theta_\psi$ and ϕ [44]. A model-independent approach is employed to describe the X invariant-mass distribution, with a cubic spline interpolation of the amplitudes at six fixed $m_{\psi\pi}$ values chosen equidistantly in the range $[4.2, 4.7]$ GeV$/c^2$. The complex amplitudes at six fixed $m_{\psi\pi}$ values, with the orbital angular momentum between $\psi(2S)$ and π^+ fixed to zero, describe the data well. The projection of the fit on the $m_{\psi\pi}$ distribution is shown on the left side of Fig. 2. The corresponding amplitudes in the complex plane (the Argand diagram [46]) are presented on the right side of Fig. 2, revealing a circular phase shift as a function of $m_{\psi\pi}$ from lower to higher $\psi(2S)\pi^+$ masses, suggesting that the X structure is unlikely to be caused by statistical fluctuations in data. Counterclockwise evolution with mass is consistent with a resonant behavior but could also originate from other physical effects, such as triangle singularity [22,24].

Model-dependent approaches are used to extract the properties of the X structure. In the first model the structure is considered as a resonance, $T^+_{c\bar{c}}$, decaying into the $\psi(2S)\pi^+$ final state and with the mass distribution described by a relativistic Breit-Wigner function. The mass and width of the $T^+_{c\bar{c}}$ state are allowed to float, and only the lowest possible orbital angular momentum between the $\psi(2S)$ and π^+ mesons is considered in the baseline fit. A satisfactory description of data is achieved for the spin-parity $J^P(T^+_{c\bar{c}}) = 1^+$. The projection of the amplitude fit result onto the $\psi(2S)\pi^+$ invariant mass is shown by the red curve in Fig. 3. The $T^+_{c\bar{c}}$ mass and width are measured to be $M_{T^+_{c\bar{c}}} = 4.452 \pm 0.016^{+0.055}_{-0.033}$ GeV$/c^2$ and $\Gamma_{T^+_{c\bar{c}}} = 0.174 \pm 0.019^{+0.083}_{-0.020}$ GeV. The $T^+_{c\bar{c}}$ fit fraction in the $B^+ \to \psi(2S)K^0_S\pi^+$ decay is determined to be $f_{T^+_{c\bar{c}}} = (3.7 \pm 0.6^{+4.0}_{-0.7})\%$, where the first uncertainty is statistical and the second systematic. The fit fraction of a specific contribution is calculated as the integral of its amplitude squared over the full phase space divided by that of the total amplitude squared. The sources of systematic uncertainties are described below. The $T^+_{c\bar{c}}$ properties are consistent with those of the $T_{c\bar{c}1}(4430)^+$ structure observed

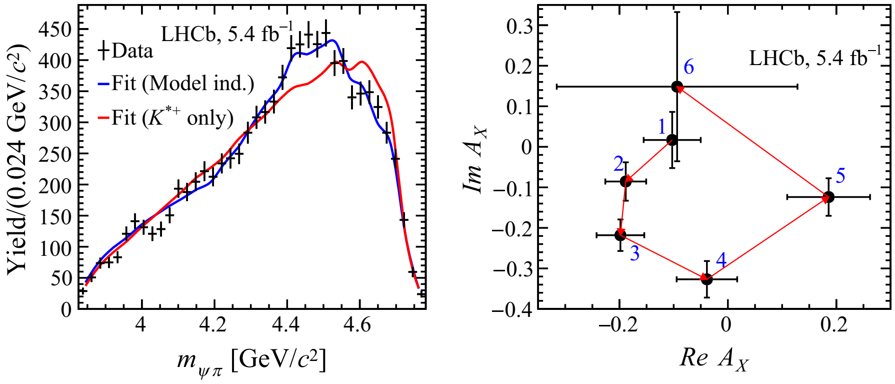

FIG. 2. Left: distribution of the $\psi(2S)\pi^+$ invariant-mass of background-subtracted data. The projections of the fit including (red) only K^{*+} resonances and (blue) a model-independent amplitude are also shown. Right: Argand diagram for the amplitude A_X, showing the complex amplitude values at six points. Each point corresponds to a different value of $m_{\psi\pi}$, which increases in the counterclockwise direction.

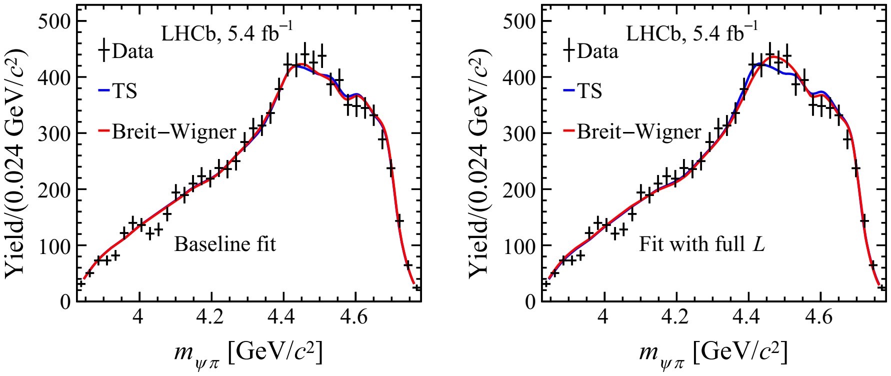

FIG. 3. Distribution of the $\psi(2S)\pi$ invariant-mass of background-subtracted data, with the projections of the fit including the relativistic Breit–Wigner parametrization (red) or the triangle singularity amplitude (blue) for the (left) baseline fit and (right) the fit with full orbital angular momenta.

in the $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decay [28]. The significance of the $T_{c\bar{c}}^+$ state is evaluated based on $2\Delta\ln L = 2\ln L_{T_{c\bar{c}}^+} - 2\ln L_{K^{*+}}$, where $L_{K^{*+}}$ and $L_{T_{c\bar{c}}^+}$ refer to the likelihood functions without and with the $T_{c\bar{c}}^+$ component, each evaluated at its maximum. The quantity $2\Delta\ln L$ follows a χ^2 distribution, with a number of degrees of freedom approximately twice the number of additional free parameters in the $T_{c\bar{c}}^+$ fit compared to the K^{*+}-only fit, after accounting for the look-elsewhere effect [12,47]. The statistical significance of the $T_{c\bar{c}}^+$ state with $J^P = 1^+$ is determined to be more than 16σ, and remains above 9σ after including systematic effects, which is obtained by the fit with the smallest $\Delta\ln L$ among all systematic sources.

The J^P assignment for the $T_{c\bar{c}}^+$ state is determined by comparing the likelihood values of the fits with different hypotheses. The 0^+ assignment is excluded due to parity conservation. The hypotheses 0^-, 1^-, 2^-, 2^+ are rejected relative to the 1^+ hypothesis with a significance of more than 6σ, 11σ, 7σ, 11σ, respectively, after accounting for the systematic uncertainty. Therefore, the $T_{c\bar{c}}^+$ spin-parity is unambiguously determined as $J^P = 1^+$, consistent with the quantum numbers of the $T_{c\bar{c}1}(4430)^+$ state observed in the $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decay [28]. Consequently, it is reasonable to conclude that the $T_{c\bar{c}}^+$ state in the $B^+ \to \psi(2S)K_S^0\pi^+$ decay corresponds to that observed in the $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decay [11,12,47], being produced by the decay processes related via isospin symmetry.

Various sources of systematic uncertainties are studied for the mass, width and fit fraction measurements of the $T_{c\bar{c}}^+$ state, including varying the masses and widths of K^{*+} resonances; adding a nonresonant $K_S^0\pi^+$ component with zero spin; including the low mass tails of $K^*(1680)^+$ and $K_3^*(1780)^+$ into the amplitude fit; parametrizing the $K_0^*(700)^+$ and $K_0^*(1430)^+$ states with the LASS model [48]; varying the Blatt-Weisskopf radius for both B^+ and intermediate states' decays between 3 and 5 $(\mathrm{GeV}/c)^{-1}$; allowing higher orbital angular momenta to contribute; extracting the signal projection weights using alternative signal or background models in the B^+ invariant-mass fit. The differences between the results of the baseline fit and alternative fits are taken as the systematic uncertainties. Based on previous measurements of $\psi(nS)\pi^+$ spectra [11–13,47], an additional $T_{c\bar{c}1}(4200)^+ \to \psi(2S)\pi^+$ or $T_{c\bar{c}0}(4240)^+ \to \psi(2S)\pi^+$ component is added to the amplitude with the $T_{c\bar{c}1}(4200)^+$ or $T_{c\bar{c}0}(4240)^+$ parameters fixed to their known values [28] as another source of systematic uncertainty. The significance of either the $T_{c\bar{c}}(4200)^+$ state or the $T_{c\bar{c}}(4240)^+$ state is determined to be 4σ. Among systematic uncertainties related to the K^{*+} modeling, which are not independent, only the maximum difference is retained and is combined with other sources to obtain the total systematic uncertainty.

In the model described above, the $T_{c\bar{c}1}(4430)^+$ state is assumed to decay only into the $\psi(2S)\pi^+$ final state. However, if the $T_{c\bar{c}1}(4430)^+$ has a molecular nature, it is expected to couple strongly to open-charm hadrons whose invariant-mass threshold lies near its mass. Notably, the $T_{c\bar{c}1}(4430)^+$ mass is close to the $\bar{D}_1^*(2600)^0D^+$ production threshold, and its spin-parity is consistent with an S-wave $\bar{D}_1^*(2600)^0D^+$ configuration. To account for this possibility, the amplitude model is modified, taking into account the effect that the opening of the $T_{c\bar{c}1}(4430)^+ \to \bar{D}_1^*(2600)^0D^+$ decay channel would have on the $T_{c\bar{c}1}(4430)^+ \to \psi(2S)\pi^+$ lineshape. Within this framework, the $T_{c\bar{c}1}(4430)^+$ resonance is modeled using the Flatté parametrization [49],

$$F = \frac{1}{m_f^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}, \tag{2}$$

where the positive parameters g_1 and g_2 represent the coupling strengths to the $\psi(2S)\pi^+$ and $\bar{D}_1^*(2600)^0D^+$ channels, respectively, and ρ_1 and ρ_2 are the corresponding phase-space factors, discussed further in the Supplemental Material [36]. The Flatté parametrization reduces to the relativistic Breit–Wigner parametrization for $g_2 = 0$.

The amplitude fit with the $T_{c\bar{c}1}(4430)^+$ state modeled with the Flatté parametrization yields $m_f = 4.452 \pm 0.022^{+0.103}_{-0.005}\ \mathrm{GeV}/c^2$, $g_1 = 1.58 \pm 0.17^{+0.05}_{-0.82}\ \mathrm{GeV}/c^2$, $g_2 = 0.00 \pm 1.78 \pm 2.81\ \mathrm{GeV}/c^2$ and the fit fraction $f = (3.7 \pm 0.6^{+3.7}_{-0.7})\%$. The upper limit for the relative decay strength $R \equiv |g_2/g_1|$ is determined to be $R < 6.8$ at the 95% confidence level, using a profile-likelihood scan. This constrains the coupling of $T_{c\bar{c}1}(4430)^+$ to the $\bar{D}^*_1(2600)^0 D^+$ final state.

Apart from dynamical interpretations, the origin of the X structure could be kinematical. Following the model in Ref. [24], a triangle singularity mechanism is tested, where the X structure in the $\psi(2S)\pi^+$ mass spectrum arises from the $\psi(4230)\pi^+ \to \psi(2S)\pi^+$ rescattering in the $B^+ \to \psi(4230)K^*(892)^+$, $K^*(892)^+ \to K^0_S\pi^+$ cascade decay, as shown in the Supplemental Material [36]. In such a triangle singularity mechanism, a relatively large $B^+ \to \psi(4230)K^*(892)^+$ branching fraction is implied. The $K^{*+}(892)^+\psi(4230)\pi^+$ triangle diagram develops a singularity in the S-matrix of $\psi(4230)\pi^+ \to \psi(2S)\pi^+$ transition when the intermediate states are simultaneously on shell. The amplitude for the triangle singularity is obtained through integration over the triangle diagram, and the $\psi(2S)\pi^+$ invariant-mass distribution is determined by the properties of the involved intermediate and final-state hadrons, leaving no free parameters apart from an overall complex coupling. The triangle singularity also exhibits a phase shift behavior as a function of the $\psi(2S)\pi^+$ invariant mass, very similar to that of the Breit-Wigner distribution. The result of the fit using the $K^*(892)^+\psi(4230)\pi^+$ triangle amplitude to model the X structure is shown in Fig. 3 projected onto the $\psi(2S)\pi^+$ invariant mass. The model provides a reasonable description of the data. The fit yields a fit fraction $f_X = (3.9 \pm 0.7^{+3.3}_{-0.1})\%$, consistent with that of the fit using the Breit-Wigner function. In some of the scenarios considered in the study of systematic uncertainties, the fit quality of the triangle contribution is reduced relative to that of the Breit-Wigner lineshape. For example, including higher orbital angular momenta between $\psi(2S)$ and K^{*+} mesons, the quality of the fit with the triangle amplitude is slightly worse than that with the Breit-Wigner lineshape for the X structure, as shown on the right of Fig. 3. Larger samples may help to distinguish the two models. An alternative triangle singularity model, described in Ref. [50], was also investigated. It features longer tails in the $m_{\psi\pi}$ distribution, and cannot provide a satisfactory description of data.

To summarize, a full amplitude analysis is performed to the $B^+ \to \psi(2S)K^0_S\pi^+$ decay using pp collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of $5.4\ \mathrm{fb}^{-1}$. With contributions of known K^{*+} resonances only, a discrepancy between data and the amplitude fit is observed, most obvious in the $\psi(2S)\pi^+$ invariant-mass distribution around $4.5\ \mathrm{GeV}/c^2$. The discrepancy is resolved by including a component in the $\psi(2S)\pi^+$ final state in the amplitude. A model-independent description of this component reveals a peaking structure with its complex phase evolving as a function of the $\psi(2S)\pi^+$ invariant mass. Modeling the structure with a Breit–Wigner function gives a measurement of its mass, width, spin-parity and fit fraction in $B^+ \to \psi(2S)K^0_S\pi^+$ decays of: $M_{T^+_{c\bar{c}}} = 4.452 \pm 0.016^{+0.055}_{-0.033}\ \mathrm{GeV}/c^2$, $\Gamma_{T^+_{c\bar{c}}} = 0.174 \pm 0.019^{+0.083}_{-0.020}\ \mathrm{GeV}$, $J^P = 1^+$, and $f_{T^+_{c\bar{c}}} = (3.7 \pm 0.6^{+4.0}_{-0.7})\%$. The results are consistent with the exotic candidate $T_{c\bar{c}1}(4430)^+$ reported by the Belle and LHCb collaborations in the $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decay. An additional fit is performed with a formalism that includes the possible $T_{c\bar{c}1}(4430)^+$ decay into the $\bar{D}^*_1(2600)^0 D^+$ final state. An upper limit is set on the coupling strength of the $T_{c\bar{c}1}(4430)^+ \to \bar{D}^*_1(2600)^0 D^+$ decay relative to that of the $T_{c\bar{c}1}(4430)^+ \to \psi(2S)\pi^+$ decay. A reasonable description of the $T_{c\bar{c}1}(4430)^+$ structure is also achieved using a kinematical model incorporating the singularity in the $\psi(4230)K^{*+}\pi^+$ triangle diagram [24].

This analysis reports the observation of the $T_{c\bar{c}1}(4430)^+$ structure in the $B^+ \to \psi(2S)K^0_S\pi^+$ decay, and is the first experimental investigation into the nature of the $T_{c\bar{c}1}(4430)^+$ structure using a hadronic molecule-motivated model and the amplitude of a triangle diagram with a full amplitude analysis. These results provide valuable insights into the nature of the $T_{c\bar{c}1}(4430)^+$ structure.

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: ARC (Australia); CAPES, CNPq, FAPERJ, and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMFTR, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICIU and AEI (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (USA). We acknowledge the computing resources provided by ARDC (Australia), CBPF (Brazil), CERN, IHEP and LZU (China), IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), Polish WLCG (Poland), IFIN-HH (Romania), PIC (Spain), CSCS (Switzerland), and GridPP (United Kingdom). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from the Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central

Universities, and the Science and Technology Program of Guangzhou (China); Minciencias (Colombia); EPLANET, Marie Skłodowska-Curie Actions, ERC and NextGenerationEU (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Alexander von Humboldt Foundation (Germany); ICSC (Italy); Severo Ochoa and María de Maeztu Units of Excellence, GVA, XuntaGal, GENCAT, InTalent-Inditex and Programa Atracción Talento CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

Data availability.

The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

---

[1] M. Gell-Mann, A schematic model of baryons and mesons, Phys. Lett. **8**, 214 (1964).

[2] F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, and B.-S. Zou, Hadronic molecules, Rev. Mod. Phys. **90**, 015004 (2018); **94**, 029901(E) (2022).

[3] H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, and S.-L. Zhu, An updated review of the new hadron states, Rep. Prog. Phys. **86**, 026201 (2023).

[4] Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu, and S.-L. Zhu, Pentaquark and tetraquark states, Prog. Part. Nucl. Phys. **107**, 237 (2019).

[5] S. L. Olsen, T. Skwarnicki, and D. Zieminska, Nonstandard heavy mesons and baryons: Experimental evidence, Rev. Mod. Phys. **90**, 015003 (2018).

[6] D. Johnson, I. Polyakov, T. Skwarnicki, and M. Wang, Exotic hadrons at LHCb, Annu. Rev. Nucl. Part. Sci. **74**, 583 (2024).

[7] N. Hüsken, E. S. Norella, and I. Polyakov, A brief guide to exotic hadrons, Mod. Phys. Lett. A **40**, 2530002 (2024).

[8] Z.-G. Wang, Review of the QCD sum rules for exotic states, Front. Phys. **21**, 016300 (2025).

[9] S. K. Choi *et al.* (Belle Collaboration), Observation of a resonancelike structure in the $\pi^{+-}\psi'$ mass distribution in exclusive $B \to K\pi^{+-}\psi'$ decays, Phys. Rev. Lett. **100**, 142001 (2008).

[10] R. Mizuk (Belle Collaboration), Dalitz analysis of $B \to K\pi^{+}\psi'$ decays and the $Z(4430)^{+}$, Phys. Rev. D **80**, 031104 (2009).

[11] K. Chilikin *et al.* (Belle Collaboration), Experimental constraints on the spin and parity of the $Z(4430)^{+}$, Phys. Rev. D **88**, 074026 (2013).

[12] R. Aaij *et al.* (LHCb Collaboration), Observation of the resonant character of the $Z(4430)^{-}$ state, Phys. Rev. Lett. **112**, 222002 (2014).

[13] A. Beiter, Amplitude analysis of B^0 decays to $J/\psi\pi^{-}K^{+}$ and $\psi(2S)\pi^{-}K^{+}$, Ph.D. thesis, Syracuse University, 2023.

[14] C. Meng and K.-T. Chao, $Z^{+}(4430)$ as a resonance in the $D_1(D_1')D^*$ channel, arXiv:0708.4222.

[15] X. Liu, Y.-R. Liu, W.-Z. Deng, and S.-L. Zhu, Is $Z^{+}(4430)$ a loosely bound molecular state?, Phys. Rev. D **77**, 034003 (2008).

[16] G.-J. Ding, W. Huang, J.-F. Liu, and M.-L. Yan, $Z^{+}(4430)$ and analogous heavy flavor molecules, Phys. Rev. D **79**, 034026 (2009).

[17] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, The $Z(4430)$ and a new paradigm for spin interactions in tetraquarks, Phys. Rev. D **89**, 114010 (2014).

[18] C. Deng, J. Ping, H. Huang, and F. Wang, Systematic study of Z_c^{+} family from a multiquark color flux-tube model, Phys. Rev. D **92**, 034027 (2015).

[19] Z.-G. Wang, Analysis of the $Z(4430)$ as the first radial excitation of the $Z_c(3900)$, Commun. Theor. Phys. **63**, 325 (2015).

[20] S. S. Agaev, K. Azizi, and H. Sundu, Treating $Z_c(3900)$ and $Z(4430)$ as the ground state and first radially excited tetraquarks, Phys. Rev. D **96**, 034026 (2017).

[21] S. Coleman and R. E. Norton, Singularities in the physical region, Nuovo Cimento **38**, 438 (1965).

[22] F.-K. Guo, X.-H. Liu, and S. Sakai, Threshold cusps and triangle singularities in hadronic reactions, Prog. Part. Nucl. Phys. **112**, 103757 (2020).

[23] M. Mikhasenko, Y. Wunderlich, A. Jackura, V. Mathieu, A. Pilloni, B. Ketzer, and A. P. Szczepaniak, Three-body scattering: Ladders and resonances, J. High Energy Phys. 08 (2019) 080.

[24] S. X. Nakamura and K. Tsushima, $Z_c(4430)$ and $Z_c(4200)$ as triangle singularities, Phys. Rev. D **100**, 051502 (2019).

[25] P. Bicudo, Tetraquarks and pentaquarks in lattice QCD with light and heavy quarks, Phys. Rep. **1039**, 1 (2023).

[26] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, J. Instrum. **3**, S08005 (2008).

[27] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, Int. J. Mod. Phys. **A30**, 1530022 (2015).

[28] S. Navas *et al.* (Particle Data Group), Review of particle physics, Phys. Rev. D **110**, 030001 (2024).

[29] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth International Group, Belmont, California, USA, 1984).

[30] Y. Freund and R. E. Schapire, A decision-theoretic generalization of on-line learning and an application to boosting, J. Comput. Syst. Sci. **55**, 119 (1997).

[31] H. Voss, A. Hoecker, J. Stelzer, and F. Tegenfeldt, TMVA—Toolkit for multivariate data analysis with ROOT, Proc. Sci. ACAT2007 (**2007**) 040.

[32] A. Hoecker *et al.*, TMVA 4—Toolkit for multivariate data analysis with ROOT. Users Guide, arXiv:physics/0703039.

[33] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to Pythia 8.1, Comput. Phys. Commun. **178**, 852 (2008).

[34] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[35] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, IEEE Trans. Nucl. Sci. **53**, 270 (2006).

[36] See Supplemental Material at http://link.aps.org/supplemental/10.1103/rcfs-ynh2 for additional derivations and figures.

[37] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.

[38] M. Pivk and F. R. Le Diberder, sPlot: A statistical tool to unfold data distributions, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005).

[39] H. Dembinski, M. Kenzie, C. Langenbruch, and M. Schmelling, Custom orthogonal weight functions (COWs) for event classification, Nucl. Instrum. Methods Phys. Res., Sect. A **1040**, 167270 (2022).

[40] Y. Xie, sFit: A method for background subtraction in maximum likelihood fit, arXiv:0905.0724.

[41] C. Langenbruch, Parameter uncertainties in weighted unbinned maximum likelihood fits, Eur. Phys. J. C **82**, 393 (2022).

[42] M. Jacob and G. C. Wick, On the general theory of collisions for particles with spin, Ann. Phys. (N.Y.) **7**, 404 (1959).

[43] S. J. Lindenbaum and R. M. Sternheimer, Isobaric nucleon model for pion production in nucleon-nucleon collisions, Phys. Rev. **105**, 1874 (1957).

[44] R. Aaij *et al.* (LHCb Collaboration), Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$ decays, Phys. Rev. Lett. **115**, 072001 (2015).

[45] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (Springer, New York, 1952).

[46] V. A. Alessandrini, P. G. O. Freund, R. Oehme, and E. J. Squires, Argand diagrams and resonances, Phys. Lett. **27B**, 456 (1968).

[47] R. Aaij *et al.* (LHCb Collaboration), Model-independent confirmation of the $Z(4430)^-$ state, Phys. Rev. D **92**, 112009 (2015).

[48] D. Aston *et al.*, A study of $K^-\pi^+$ scattering in the reaction $K^-p \to K^-\pi^+n$ at 11 GeV/c, Nucl. Phys. **B296**, 493 (1988).

[49] S. M. Flatté, Coupled-channel analysis of the $\pi\eta$ and $K\bar{K}$ systems near $K\bar{K}$ threshold, Phys. Lett. **63B**, 224 (1976).

[50] V. Gribov, *Strong Interactions of Hadrons at High Energies: Gribov Lectures on Theoretical Physics* (Oxford University Press, New York, 2009).

R. Aaij,[38] A. S. W. Abdelmotteleb,[57] C. Abellan Beteta,[51] F. Abudinén,[57] T. Ackernley,[61] A. A. Adefisoye,[69]
B. Adeva,[47] M. Adinolfi,[55] P. Adlarson,[85] C. Agapopoulou,[14] C. A. Aidala,[87] Z. Ajaltouni,[11] S. Akar,[11]
K. Akiba,[38] M. Akthar,[40] P. Albicocco,[28] J. Albrecht,[19,b] R. Aleksiejunas,[80] F. Alessio,[49] P. Alvarez Cartelle,[56]
R. Amalric,[16] S. Amato,[3] J. L. Amey,[55] Y. Amhis,[14] L. An,[6] L. Anderlini,[27] M. Andersson,[51] P. Andreola,[51]
M. Andreotti,[26] S. Andres Estrada,[84] A. Anelli,[31,49,c] D. Ao,[7] C. Arata,[12] F. Archilli,[37,d] Z. Areg,[69]
M. Argenton,[26] S. Arguedas Cuendis,[9,49] L. Arnone,[31,c] A. Artamonov,[44] M. Artuso,[69] E. Aslanides,[13]
R. Ataíde Da Silva,[50] M. Atzeni,[65] B. Audurier,[12] J. A. Authier,[15] D. Bacher,[64] I. Bachiller Perea,[50]
S. Bachmann,[22] M. Bachmayer,[50] J. J. Back,[57] P. Baladron Rodriguez,[47] V. Balagura,[15] A. Balboni,[26]
W. Baldini,[26] Z. Baldwin,[78] L. Balzani,[19] H. Bao,[7] J. Baptista de Souza Leite,[2] C. Barbero Pretel,[47,12]
M. Barbetti,[27] I. R. Barbosa,[70] R. J. Barlow,[63] M. Barnyakov,[25] S. Barsuk,[14] W. Barter,[59] J. Bartz,[69]
S. Bashir,[40] B. Batsukh,[5] P. B. Battista,[14] A. Bay,[50] A. Beck,[65] M. Becker,[19] F. Bedeschi,[35] I. B. Bediaga,[2]
N. A. Behling,[19] S. Belin,[47] A. Bellavista,[25] K. Belous,[44] I. Belov,[29] I. Belyaev,[36] G. Benane,[13]
G. Bencivenni,[28] E. Ben-Haim,[16] A. Berezhnoy,[44] R. Bernet,[51] S. Bernet Andres,[46] A. Bertolin,[33] F. Betti,[59]
J. Bex,[56] O. Bezshyyko,[86] J. Bhom,[41] M. S. Bieker,[18] N. V. Biesuz,[26] A. Biolchini,[38] M. Birch,[62]
F. C. R. Bishop,[10] A. Bitadze,[63] A. Bizzeti,[27,e] T. Blake,[57,f] F. Blanc,[50] J. E. Blank,[19] S. Blusk,[69]
V. Bocharnikov,[44] J. A. Boelhauve,[19] O. Boente Garcia,[15] T. Boettcher,[68] A. Bohare,[59] A. Boldyrev,[44]
C. S. Bolognani,[82] R. Bolzonella,[26,g] R. B. Bonacci,[1] N. Bondar,[44,49] A. Bordelius,[49] F. Borgato,[33,49]
S. Borghi,[63] M. Borsato,[31,c] J. T. Borsuk,[83] E. Bottalico,[61] S. A. Bouchiba,[50] M. Bovill,[64] T. J. V. Bowcock,[61]
A. Boyer,[49] C. Bozzi,[26] J. D. Brandenburg,[88] A. Brea Rodriguez,[50] N. Breer,[19] J. Brodzicka,[41]
A. Brossa Gonzalo,[47,a] J. Brown,[61] D. Brundu,[32] E. Buchanan,[59] M. Burgos Marcos,[82] A. T. Burke,[63] C. Burr,[49]
C. Buti,[27] J. S. Butter,[56] J. Buytaert,[49] W. Byczynski,[49] S. Cadeddu,[32] H. Cai,[75] Y. Cai,[5] A. Caillet,[16]
R. Calabrese,[26,g] S. Calderon Ramirez,[9] L. Calefice,[45] M. Calvi,[31,c] M. Calvo Gomez,[46]
P. Camargo Magalhaes,[2,h] J. I. Cambon Bouzas,[47] P. Campana,[28] A. F. Campoverde Quezada,[7] S. Capelli,[31]
M. Caporale,[25] L. Capriotti,[26] R. Caravaca-Mora,[9] A. Carbone,[25,i] L. Carcedo Salgado,[47] R. Cardinale,[29,j]
A. Cardini,[32] P. Carniti,[31] L. Carus,[22] A. Casais Vidal,[65] R. Caspary,[22] G. Casse,[61] M. Cattaneo,[49]

G. Cavallero,[26] V. Cavallini,[26,g] S. Celani,[49] I. Celestino,[35,k] S. Cesare,[30,l] A. J. Chadwick,[61] I. Chahrour,[87]
H. Chang,[4,m] M. Charles,[16] Ph. Charpentier,[49] E. Chatzianagnostou,[38] R. Cheaib,[79] M. Chefdeville,[10]
C. Chen,[56] J. Chen,[50] S. Chen,[5] Z. Chen,[7] A. Chen Hu,[62] M. Cherif,[12] A. Chernov,[41] S. Chernyshenko,[53]
X. Chiotopoulos,[82] V. Chobanova,[84] M. Chrzaszcz,[41] A. Chubykin,[44] V. Chulikov,[28,36,49] P. Ciambrone,[28]
X. Cid Vidal,[47] G. Ciezarek,[49] P. Cifra,[38] P. E. L. Clarke,[59] M. Clemencic,[49] H. V. Cliff,[56] J. Closier,[49]
C. Cocha Toapaxi,[22] V. Coco,[49] J. Cogan,[13] E. Cogneras,[11] L. Cojocariu,[43] S. Collaviti,[50] P. Collins,[49]
T. Colombo,[49] M. Colonna,[19] A. Comerma-Montells,[45] L. Congedo,[24] J. Connaughton,[57] A. Contu,[32]
N. Cooke,[60] G. Cordova,[35,k] C. Coronel,[66] I. Corredoira,[12] A. Correia,[16] G. Corti,[49] J. Cottee Meldrum,[55]
B. Couturier,[49] D. C. Craik,[51] M. Cruz Torres,[2,n] E. Curras Rivera,[50] R. Currie,[59] C. L. Da Silva,[68]
S. Dadabaev,[44] L. Dai,[72] X. Dai,[4] E. Dall'Occo,[49] J. Dalseno,[84] C. D'Ambrosio,[62] J. Daniel,[11] G. Darze,[3]
A. Davidson,[57] J. E. Davies,[63] O. De Aguiar Francisco,[63] C. De Angelis,[32,o] F. De Benedetti,[49] J. de Boer,[38]
K. De Bruyn,[81] S. De Capua,[63] M. De Cian,[63,49] U. De Freitas Carneiro Da Graca,[2,p] E. De Lucia,[28]
J. M. De Miranda,[2] L. De Paula,[3] M. De Serio,[24,q] P. De Simone,[28] F. De Vellis,[19] J. A. de Vries,[82]
F. Debernardis,[24] D. Decamp,[10] S. Dekkers,[1] L. Del Buono,[16] B. Delaney,[65] H.-P. Dembinski,[19] J. Deng,[8]
V. Denysenko,[51] O. Deschamps,[11] F. Dettori,[32,o] B. Dey,[79] P. Di Nezza,[28] I. Diachkov,[44] S. Didenko,[44]
S. Ding,[69] Y. Ding,[50] L. Dittmann,[22] V. Dobishuk,[53] A. D. Docheva,[60] A. Doheny,[57] C. Dong,[4,m]
A. M. Donohoe,[23] F. Dordei,[32] A. C. dos Reis,[2] A. D. Dowling,[69] L. Dreyfus,[13] W. Duan,[73] P. Duda,[83]
L. Dufour,[49] V. Duk,[34] P. Durante,[49] M. M. Duras,[83] J. M. Durham,[68] O. D. Durmus,[79] A. Dziurda,[41]
A. Dzyuba,[44] S. Easo,[58] E. Eckstein,[18] U. Egede,[1] A. Egorychev,[44] V. Egorychev,[44] S. Eisenhardt,[59]
E. Ejopu,[61] L. Eklund,[85] M. Elashri,[66] J. Ellbracht,[19] S. Ely,[62] A. Ene,[43] J. Eschle,[69] S. Esen,[22] T. Evans,[38]
F. Fabiano,[32] S. Faghih,[66] L. N. Falcao,[2] B. Fang,[7] R. Fantechi,[35] L. Fantini,[34,r] M. Faria,[50] K. Farmer,[59]
D. Fazzini,[31,c] L. Felkowski,[83] M. Feng,[5,7] M. Feo,[19] A. Fernandez Casani,[48] M. Fernandez Gomez,[47]
A. D. Fernez,[67] F. Ferrari,[25,i] F. Ferreira Rodrigues,[3] M. Ferrillo,[51] M. Ferro-Luzzi,[49] S. Filippov,[44] R. A. Fini,[24]
M. Fiorini,[26,g] M. Firlej,[40] K. L. Fischer,[64] D. S. Fitzgerald,[87] C. Fitzpatrick,[63] T. Fiutowski,[40] F. Fleuret,[15]
A. Fomin,[52] M. Fontana,[25] L. A. Foreman,[63] R. Forty,[49] D. Foulds-Holt,[59] V. Franco Lima,[3]
M. Franco Sevilla,[67] M. Frank,[49] E. Franzoso,[26,g] G. Frau,[63] C. Frei,[49] D. A. Friday,[63,49] J. Fu,[7]
Q. Führing,[19,56,b] T. Fulghesu,[13] G. Galati,[24] M. D. Galati,[38] A. Gallas Torreira,[47] D. Galli,[25,i] S. Gambetta,[59]
M. Gandelman,[3] P. Gandini,[30] B. Ganie,[63] H. Gao,[7] R. Gao,[64] T. Q. Gao,[56] Y. Gao,[8] Y. Gao,[6] Y. Gao,[8]
L. M. Garcia Martin,[50] P. Garcia Moreno,[45] J. García Pardiñas,[65] P. Gardner,[67] L. Garrido,[45] C. Gaspar,[49]
A. Gavrikov,[33] L. L. Gerken,[19] E. Gersabeck,[20] M. Gersabeck,[20] T. Gershon,[57] S. Ghizzo,[29,j]
Z. Ghorbanimoghaddam,[55] F. I. Giasemis,[16,s] V. Gibson,[56] H. K. Giemza,[42] A. L. Gilman,[66] M. Giovannetti,[28]
A. Gioventù,[45] L. Girardey,[63,58] M. A. Giza,[41] F. C. Glaser,[14,22] V. V. Gligorov,[16] C. Göbel,[70]
L. Golinka-Bezshyyko,[86] E. Golobardes,[46] D. Golubkov,[44] A. Golutvin,[62,49] S. Gomez Fernandez,[45]
W. Gomulka,[40] I. Gonçales Vaz,[49] F. Goncalves Abrantes,[64] M. Goncerz,[41] G. Gong,[4,m] J. A. Gooding,[19]
I. V. Gorelov,[44] C. Gotti,[31] E. Govorkova,[65] J. P. Grabowski,[30] L. A. Granado Cardoso,[49] E. Graugés,[45]
E. Graverini,[50,t] L. Grazette,[57] G. Graziani,[27] A. T. Grecu,[43] N. A. Grieser,[66] L. Grillo,[60] S. Gromov,[44]
C. Gu,[15] M. Guarise,[26] L. Guerry,[11] A.-K. Guseinov,[50] E. Gushchin,[44] Y. Guz,[6,49] T. Gys,[49] K. Habermann,[18]
T. Hadavizadeh,[1] C. Hadjivasiliou,[67] G. Haefeli,[50] C. Haen,[49] S. Haken,[56] G. Hallett,[57] P. M. Hamilton,[67]
J. Hammerich,[61] Q. Han,[33] X. Han,[22,49] S. Hansmann-Menzemer,[22] L. Hao,[7] N. Harnew,[64] T. H. Harris,[1]
M. Hartmann,[14] S. Hashmi,[40] J. He,[7,u] A. Hedes,[63] F. Hemmer,[49] C. Henderson,[66] R. Henderson,[14]
R. D. L. Henderson,[1] A. M. Hennequin,[49] K. Hennessy,[61] L. Henry,[50] J. Herd,[62] P. Herrero Gascon,[22]
J. Heuel,[17] A. Heyn,[13] A. Hicheur,[3] G. Hijano Mendizabal,[51] J. Horswill,[63] R. Hou,[8] Y. Hou,[11]
D. C. Houston,[60] N. Howarth,[61] W. Hu,[7] X. Hu,[4,m] W. Hulsbergen,[38] R. J. Hunter,[57] M. Hushchyn,[44]
D. Hutchcroft,[61] M. Idzik,[40] D. Ilin,[44] P. Ilten,[66] A. Iniukhin,[44] A. Iohner,[10] A. Ishteev,[44] K. Ivshin,[44]
H. Jage,[17] S. J. Jaimes Elles,[77,48,49] S. Jakobsen,[49] E. Jans,[38] B. K. Jashal,[48] A. Jawahery,[67] C. Jayaweera,[54]
V. Jevtic,[19] Z. Jia,[16] E. Jiang,[67] X. Jiang,[5,7] Y. Jiang,[7] Y. J. Jiang,[6] E. Jimenez Moya,[9] N. Jindal,[88] M. John,[64]
A. John Rubesh Rajan,[23] D. Johnson,[54] C. R. Jones,[56] S. Joshi,[42] B. Jost,[49] J. Juan Castella,[56] N. Jurik,[49]
I. Juszczak,[41] D. Kaminaris,[50] S. Kandybei,[52] M. Kane,[59] Y. Kang,[4,m] C. Kar,[11] M. Karacson,[49]
A. Kauniskangas,[50] J. W. Kautz,[66] M. K. Kazanecki,[41] F. Keizer,[49] M. Kenzie,[56] T. Ketel,[38] B. Khanji,[69]

A. Kharisova,[44] S. Kholodenko,[62,49] G. Khreich,[14] T. Kirn,[17] V. S. Kirsebom,[31,c] O. Kitouni,[65] S. Klaver,[39]
N. Kleijne,[35,k] D. K. Klekots,[86] K. Klimaszewski,[42] M. R. Kmiec,[42] T. Knospe,[19] R. Kolb,[22] S. Koliiev,[53]
L. Kolk,[19] A. Konoplyannikov,[6] P. Kopciewicz,[49] P. Koppenburg,[38] A. Korchin,[52] M. Korolev,[44] I. Kostiuk,[38]
O. Kot,[53] S. Kotriakhova,[26] E. Kowalczyk,[67] A. Kozachuk,[44] P. Kravchenko,[44] L. Kravchuk,[44] O. Kravcov,[80]
M. Kreps,[57] P. Krokovny,[44] W. Krupa,[69] W. Krzemien,[42] O. Kshyvanskyi,[53] S. Kubis,[83] M. Kucharczyk,[41]
V. Kudryavtsev,[44] E. Kulikova,[44] A. Kupsc,[85] V. Kushnir,[52] B. Kutsenko,[13] J. Kvapil,[68] I. Kyryllin,[52]
D. Lacarrere,[49] P. Laguarta Gonzalez,[45] A. Lai,[32] A. Lampis,[32] D. Lancierini,[62] C. Landesa Gomez,[47]
J. J. Lane,[1] G. Lanfranchi,[28] C. Langenbruch,[22] J. Langer,[19] T. Latham,[57] F. Lazzari,[35,49,t] C. Lazzeroni,[54]
R. Le Gac,[13] H. Lee,[61] R. Lefèvre,[11] A. Leflat,[44] S. Legotin,[44] M. Lehuraux,[57] E. Lemos Cid,[49] O. Leroy,[13]
T. Lesiak,[41] E. D. Lesser,[49] B. Leverington,[22] A. Li,[4,m] C. Li,[4,m] C. Li,[13] H. Li,[73] J. Li,[8] K. Li,[76] L. Li,[63]
M. Li,[8] P. Li,[7] P.-R. Li,[74] Q. Li,[5,7] T. Li,[72] T. Li,[73] Y. Li,[8] Y. Li,[5] Y. Li,[4] Z. Lian,[4,m] Q. Liang,[8] X. Liang,[69]
Z. Liang,[32] S. Libralon,[48] A. L. Lightbody,[12] C. Lin,[7] T. Lin,[58] R. Lindner,[49] H. Linton,[62] R. Litvinov,[32]
D. Liu,[8] F. L. Liu,[1] G. Liu,[73] K. Liu,[74] S. Liu,[5,7] W. Liu,[8] Y. Liu,[59] Y. Liu,[74] Y. L. Liu,[62]
G. Loachamin Ordonez,[70] A. Lobo Salvia,[45] A. Loi,[32] T. Long,[56] F. C. L. Lopes,[2,h] J. H. Lopes,[3]
A. Lopez Huertas,[45] C. Lopez Iribarnegaray,[47] S. López Soliño,[47] Q. Lu,[15] C. Lucarelli,[49] D. Lucchesi,[33,v]
M. Lucio Martinez,[48] Y. Luo,[6] A. Lupato,[33,w] E. Luppi,[26,g] K. Lynch,[23] X.-R. Lyu,[7] G. M. Ma,[4,m] H. Ma,[72]
S. Maccolini,[19] F. Machefert,[14] F. Maciuc,[43] B. Mack,[69] I. Mackay,[64] L. M. Mackey,[69] L. R. Madhan Mohan,[56]
M. J. Madurai,[54] D. Magdalinski,[38] D. Maisuzenko,[44] J. J. Malczewski,[41] S. Malde,[64] L. Malentacca,[49]
A. Malinin,[44] T. Maltsev,[44] G. Manca,[32,o] G. Mancinelli,[13] C. Mancuso,[14] R. Manera Escalero,[45]
F. M. Manganella,[37] D. Manuzzi,[25] D. Marangotto,[30,l] J. F. Marchand,[10] R. Marchevski,[50] U. Marconi,[25]
E. Mariani,[16] S. Mariani,[49] C. Marin Benito,[45] J. Marks,[22] A. M. Marshall,[55] L. Martel,[64] G. Martelli,[34]
G. Martellotti,[36] L. Martinazzoli,[49] M. Martinelli,[31,c] D. Martinez Gomez,[81] D. Martinez Santos,[84]
F. Martinez Vidal,[48] A. Martorell i Granollers,[46] A. Massafferri,[2] R. Matev,[49] A. Mathad,[49] V. Matiunin,[44]
C. Matteuzzi,[69] K. R. Mattioli,[15] A. Mauri,[62] E. Maurice,[15] J. Mauricio,[45] P. Mayencourt,[50] J. Mazorra de Cos,[48]
M. Mazurek,[42] M. McCann,[62] N. T. McHugh,[60] A. McNab,[63] R. McNulty,[23] B. Meadows,[66] G. Meier,[19]
D. Melnychuk,[42] D. Mendoza Granada,[16] P. Menendez Valdes Perez,[47] F. M. Meng,[4,m] M. Merk,[38,82]
A. Merli,[50,30] L. Meyer Garcia,[67] D. Miao,[5,7] H. Miao,[7] M. Mikhasenko,[78] D. A. Milanes,[77,x] A. Minotti,[31,c]
E. Minucci,[28] T. Miralles,[11] B. Mitreska,[63] D. S. Mitzel,[19] R. Mocanu,[43] A. Modak,[58] L. Moeser,[19]
R. D. Moise,[17] E. F. Molina Cardenas,[87] T. Mombächer,[49] M. Monk,[56] S. Monteil,[11] A. Morcillo Gomez,[47]
G. Morello,[28] M. J. Morello,[35,k] M. P. Morgenthaler,[22] A. Moro,[31,c] J. Moron,[40] W. Morren,[38] A. B. Morris,[49]
A. G. Morris,[13] R. Mountain,[69] H. Mu,[4,m] Z. M. Mu,[6] E. Muhammad,[57] F. Muheim,[59] M. Mulder,[81]
K. Müller,[51] F. Muñoz-Rojas,[9] R. Murta,[62] V. Mytrochenko,[52] P. Naik,[61] T. Nakada,[50] R. Nandakumar,[58]
T. Nanut,[49] I. Nasteva,[3] M. Needham,[59] E. Nekrasova,[44] N. Neri,[30,l] S. Neubert,[18] N. Neufeld,[49] P. Neustroev,[44]
J. Nicolini,[49] D. Nicotra,[82] E. M. Niel,[15] N. Nikitin,[44] L. Nisi,[19] Q. Niu,[74] P. Nogarolli,[3] P. Nogga,[18]
C. Normand,[55] J. Novoa Fernandez,[47] G. Nowak,[66] C. Nunez,[87] H. N. Nur,[60] A. Oblakowska-Mucha,[40]
V. Obraztsov,[44] T. Oeser,[17] A. Okhotnikov,[44] O. Okhrimenko,[53] R. Oldeman,[32,o] F. Oliva,[59,49] E. Olivart Pino,[45]
M. Olocco,[19] R. H. O'Neil,[49] J. S. Ordonez Soto,[11] D. Osthues,[19] J. M. Otalora Goicochea,[3] P. Owen,[51]
A. Oyanguren,[48] O. Ozcelik,[49] F. Paciolla,[35,y] A. Padee,[42] K. O. Padeken,[18] B. Pagare,[47] T. Pajero,[49]
A. Palano,[24] L. Palini,[30] M. Palutan,[28] C. Pan,[75] X. Pan,[4,m] S. Panebianco,[12] G. Panshin,[5] L. Paolucci,[63]
A. Papanestis,[58] M. Pappagallo,[24,q] L. L. Pappalardo,[26] C. Pappenheimer,[66] C. Parkes,[63] D. Parmar,[78]
G. Passaleva,[27] D. Passaro,[35,49,k] A. Pastore,[24] M. Patel,[62] J. Patoc,[64] C. Patrignani,[25,i] A. Paul,[69]
C. J. Pawley,[82] A. Pellegrino,[38] J. Peng,[5,7] X. Peng,[74] M. Pepe Altarelli,[28] S. Perazzini,[25] D. Pereima,[44]
H. Pereira Da Costa,[68] M. Pereira Martinez,[47] A. Pereiro Castro,[47] C. Perez,[46] P. Perret,[11] A. Perrevoort,[81]
A. Perro,[49,13] M. J. Peters,[66] K. Petridis,[55] A. Petrolini,[29,j] S. Pezzulo,[29,j] J. P. Pfaller,[66] H. Pham,[69] L. Pica,[35,k]
M. Piccini,[34] L. Piccolo,[32] B. Pietrzyk,[10] G. Pietrzyk,[14] R. N. Pilato,[61] D. Pinci,[36] F. Pisani,[49]
M. Pizzichemi,[31,49,c] V. M. Placinta,[43] M. Plo Casasus,[47] T. Poeschl,[49] F. Polci,[16] M. Poli Lener,[28]
A. Poluektov,[13] N. Polukhina,[44] I. Polyakov,[63] E. Polycarpo,[3] S. Ponce,[49] D. Popov,[7,49] S. Poslavskii,[44]
K. Prasanth,[59] C. Prouve,[84] D. Provenzano,[32,49,o] V. Pugatch,[53] A. Puicercus Gomez,[49] G. Punzi,[35,t]
J. R. Pybus,[68] Q. Q. Qian,[6] W. Qian,[7] N. Qin,[4,m] S. Qu,[4,m] R. Quagliani,[49] R. I. Rabadan Trejo,[57] R. Racz,[80]

J. H. Rademacker,[55] M. Rama,[35] M. Ramírez García,[87] V. Ramos De Oliveira,[70] M. Ramos Pernas,[57]
M. S. Rangel,[3] F. Ratnikov,[44] G. Raven,[39] M. Rebollo De Miguel,[48] F. Redi,[30,w] J. Reich,[55] F. Reiss,[20]
Z. Ren,[7] P. K. Resmi,[64] M. Ribalda Galvez,[45] R. Ribatti,[50] G. Ricart,[15,12] D. Riccardi,[35,k] S. Ricciardi,[58]
K. Richardson,[65] M. Richardson-Slipper,[56] F. Riehn,[19] K. Rinnert,[61] P. Robbe,[14,49] G. Robertson,[60]
E. Rodrigues,[61] A. Rodriguez Alvarez,[45] E. Rodriguez Fernandez,[47] J. A. Rodriguez Lopez,[77]
E. Rodriguez Rodriguez,[49] J. Roensch,[19] A. Rogachev,[44] A. Rogovskiy,[58] D. L. Rolf,[19] P. Roloff,[49]
V. Romanovskiy,[66] A. Romero Vidal,[47] G. Romolini,[26,49] F. Ronchetti,[50] T. Rong,[6] M. Rotondo,[28] S. R. Roy,[22]
M. S. Rudolph,[69] M. Ruiz Diaz,[22] R. A. Ruiz Fernandez,[47] J. Ruiz Vidal,[82] J. J. Saavedra-Arias,[9]
J. J. Saborido Silva,[47] S. E. R. Sacha Emile R.,[49] N. Sagidova,[44] D. Sahoo,[79] N. Sahoo,[54] B. Saitta,[32,o]
M. Salomoni,[31,49,c] I. Sanderswood,[48] R. Santacesaria,[36] C. Santamarina Rios,[47] M. Santimaria,[28] L. Santoro,[2]
E. Santovetti,[37] A. Saputi,[26,49] D. Saranin,[44] A. Sarnatskiy,[81] G. Sarpis,[49] M. Sarpis,[80] C. Satriano,[36,z]
A. Satta,[37] M. Saur,[74] D. Savrina,[44] H. Sazak,[17] F. Sborzacchi,[49,28] A. Scarabotto,[19] S. Schael,[17] S. Scherl,[61]
M. Schiller,[22] H. Schindler,[49] M. Schmelling,[21] B. Schmidt,[49] N. Schmidt,[68] S. Schmitt,[65] H. Schmitz,[18]
O. Schneider,[50] A. Schopper,[62] N. Schulte,[19] M. H. Schune,[14] G. Schwering,[17] B. Sciascia,[28] A. Sciuccati,[49]
G. Scriven,[82] I. Segal,[78] S. Sellam,[47] A. Semennikov,[44] T. Senger,[51] M. Senghi Soares,[39] A. Sergi,[29,j]
N. Serra,[51] L. Sestini,[27] A. Seuthe,[19] B. Sevilla Sanjuan,[46] Y. Shang,[6] D. M. Shangase,[87] M. Shapkin,[44]
R. S. Sharma,[69] I. Shchemerov,[44] L. Shchutska,[50] T. Shears,[61] L. Shekhtman,[44] Z. Shen,[38] S. Sheng,[5,7]
V. Shevchenko,[44] B. Shi,[7] Q. Shi,[7] W. S. Shi,[73] Y. Shimizu,[14] E. Shmanin,[25] R. Shorkin,[44] J. D. Shupperd,[69]
R. Silva Coutinho,[2] G. Simi,[33,v] S. Simone,[24,q] M. Singha,[79] N. Skidmore,[57] T. Skwarnicki,[69] M. W. Slater,[54]
E. Smith,[65] K. Smith,[68] M. Smith,[62] L. Soares Lavra,[59] M. D. Sokoloff,[66] F. J. P. Soler,[60] A. Solomin,[55]
A. Solovev,[44] K. Solovieva,[20] N. S. Sommerfeld,[18] R. Song,[1] Y. Song,[50] Y. Song,[4,m] Y. S. Song,[6]
F. L. Souza De Almeida,[45] B. Souza De Paula,[3] K. M. Sowa,[40] E. Spadaro Norella,[29,j] E. Spedicato,[25]
J. G. Speer,[19] P. Spradlin,[60] F. Stagni,[49] M. Stahl,[78] S. Stahl,[49] S. Stanislaus,[64] M. Stefaniak,[88] E. N. Stein,[49]
O. Steinkamp,[51] D. Strekalina,[44] Y. Su,[7] F. Suljik,[64] J. Sun,[32] J. Sun,[63] L. Sun,[75] D. Sundfeld,[2]
W. Sutcliffe,[51] V. Svintozelskyi,[48] K. Swientek,[40] F. Swystun,[56] A. Szabelski,[42] T. Szumlak,[40] Y. Tan,[4,m]
Y. Tang,[75] Y. T. Tang,[7] M. D. Tat,[22] J. A. Teijeiro Jimenez,[47] A. Terentev,[44] F. Terzuoli,[35,y] F. Teubert,[49]
E. Thomas,[49] D. J. D. Thompson,[54] A. R. Thomson-Strong,[59] H. Tilquin,[62] V. Tisserand,[11] S. T'Jampens,[10]
M. Tobin,[5,49] T. T. Todorov,[20] L. Tomassetti,[26,g] G. Tonani,[30] X. Tong,[6] T. Tork,[30] D. Torres Machado,[2]
L. Toscano,[19] D. Y. Tou,[4,m] C. Trippl,[46] G. Tuci,[22] N. Tuning,[38] L. H. Uecker,[22] A. Ukleja,[40]
D. J. Unverzagt,[22] A. Upadhyay,[49] B. Urbach,[59] A. Usachov,[38] A. Ustyuzhanin,[44] U. Uwer,[22] V. Vagnoni,[25,49]
V. Valcarce Cadenas,[47] G. Valenti,[25] N. Valls Canudas,[49] J. van Eldik,[49] H. Van Hecke,[68] E. van Herwijnen,[62]
C. B. Van Hulse,[47,aa] R. Van Laak,[50] M. van Veghel,[82] G. Vasquez,[51] R. Vazquez Gomez,[45]
P. Vazquez Regueiro,[47] C. Vázquez Sierra,[84] S. Vecchi,[26] J. Velilla Serna,[48] J. J. Velthuis,[55] M. Veltri,[27,bb]
A. Venkateswaran,[50] M. Verdoglia,[32] M. Vesterinen,[57] W. Vetens,[69] D. Vico Benet,[64] P. Vidrier Villalba,[45]
M. Vieites Diaz,[47,49] X. Vilasis-Cardona,[46] E. Vilella Figueras,[61] A. Villa,[25] P. Vincent,[16] B. Vivacqua,[3]
F. C. Volle,[54] D. vom Bruch,[13] N. Voropaev,[44] K. Vos,[82] C. Vrahas,[59] J. Wagner,[19] J. Walsh,[35] E. J. Walton,[1,57]
G. Wan,[6] A. Wang,[7] B. Wang,[5] C. Wang,[22] G. Wang,[8] H. Wang,[74] J. Wang,[6] J. Wang,[5] J. Wang,[4,m]
J. Wang,[75] M. Wang,[49] N. W. Wang,[7] R. Wang,[55] X. Wang,[8] X. Wang,[73] X. W. Wang,[62] Y. Wang,[76]
Y. Wang,[6] Y. H. Wang,[74] Z. Wang,[14] Z. Wang,[30] J. A. Ward,[57,1] M. Waterlaat,[49] N. K. Watson,[54]
D. Websdale,[62] Y. Wei,[6] Z. Weida,[7] J. Wendel,[84] B. D. C. Westhenry,[55] C. White,[56] M. Whitehead,[60]
E. Whiter,[54] A. R. Wiederhold,[63] D. Wiedner,[19] M. A. Wiegertjes,[38] C. Wild,[64] G. Wilkinson,[64,49]
M. K. Wilkinson,[66] M. Williams,[65] M. J. Williams,[49] M. R. J. Williams,[59] R. Williams,[56] S. Williams,[55]
Z. Williams,[55] F. F. Wilson,[58] M. Winn,[12] W. Wislicki,[42] M. Witek,[41] L. Witola,[19] T. Wolf,[22] E. Wood,[56]
G. Wormser,[14] S. A. Wotton,[56] H. Wu,[69] J. Wu,[8] X. Wu,[75] Y. Wu,[6,56] Z. Wu,[7] K. Wyllie,[49] S. Xian,[73]
Z. Xiang,[5] Y. Xie,[8] T. X. Xing,[30] A. Xu,[35,k] L. Xu,[4,m] L. Xu,[4,m] M. Xu,[49] Z. Xu,[49] Z. Xu,[7] Z. Xu,[5]
K. Yang,[62] X. Yang,[6] Y. Yang,[15] Y. Yang,[79] Z. Yang,[6] V. Yeroshenko,[14] H. Yeung,[63] H. Yin,[8] X. Yin,[7]
C. Y. Yu,[6] J. Yu,[72] X. Yuan,[5] Y Yuan,[5,7] E. Zaffaroni,[50] J. A. Zamora Saa,[71] M. Zavertyaev,[21] M. Zdybal,[41]
F. Zenesini,[25] C. Zeng,[5,7] M. Zeng,[4,m] C. Zhang,[6] D. Zhang,[8] J. Zhang,[7] L. Zhang,[4,m] R. Zhang,[8] S. Zhang,[64]
S. L. Zhang,[72] Y. Zhang,[6] Y. Z. Zhang,[4,m] Z. Zhang,[4,m] Y. Zhao,[22] A. Zhelezov,[22] S. Z. Zheng,[6]

X. Z. Zheng,[4,m] Y. Zheng,[7] T. Zhou,[6] X. Zhou,[8] Y. Zhou,[7] V. Zhovkovska,[57] L. Z. Zhu,[7] X. Zhu,[4,m] X. Zhu,[8]
Y. Zhu,[17] V. Zhukov,[17] J. Zhuo,[48] Q. Zou,[5,7] D. Zuliani,[33,v] and G. Zunica[28]

(LHCb Collaboration)

[1]*School of Physics and Astronomy, Monash University, Melbourne, Australia*
[2]*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[3]*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[4]*Department of Engineering Physics, Tsinghua University, Beijing, China*
[5]*Institute Of High Energy Physics (IHEP), Beijing, China*
[6]*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[7]*University of Chinese Academy of Sciences, Beijing, China*
[8]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[9]*Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica*
[10]*Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[11]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[12]*Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Saclay, France, Gif-Sur-Yvette, France*
[13]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[14]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[15]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[16]*Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), Sorbonne Université, CNRS/IN2P3, F-75005 Paris, France, Paris, France*
[17]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
[18]*Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
[19]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[20]*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[21]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[22]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[23]*School of Physics, University College Dublin, Dublin, Ireland*
[24]*INFN Sezione di Bari, Bari, Italy*
[25]*INFN Sezione di Bologna, Bologna, Italy*
[26]*INFN Sezione di Ferrara, Ferrara, Italy*
[27]*INFN Sezione di Firenze, Firenze, Italy*
[28]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[29]*INFN Sezione di Genova, Genova, Italy*
[30]*INFN Sezione di Milano, Milano, Italy*
[31]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[32]*INFN Sezione di Cagliari, Monserrato, Italy*
[33]*INFN Sezione di Padova, Padova, Italy*
[34]*INFN Sezione di Perugia, Perugia, Italy*
[35]*INFN Sezione di Pisa, Pisa, Italy*
[36]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[37]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[38]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[39]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[40]*AGH - University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[41]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[42]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[43]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[44]*Authors affiliated with an institute formerly covered by a cooperation agreement with CERN*
[45]*ICCUB, Universitat de Barcelona, Barcelona, Spain*
[46]*La Salle, Universitat Ramon Llull, Barcelona, Spain*
[47]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[48]*Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[49]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*

[50]*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[51]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[52]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[53]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[54]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[55]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[56]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[57]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[58]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[59]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[60]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[61]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[62]*Imperial College London, London, United Kingdom*
[63]*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[64]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[65]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[66]*University of Cincinnati, Cincinnati, Ohio, USA*
[67]*University of Maryland, College Park, Maryland, USA*
[68]*Los Alamos National Laboratory (LANL), Los Alamos, New Mexico, USA*
[69]*Syracuse University, Syracuse, New York, USA*
[70]*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil [associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil]*
[71]*Universidad Andres Bello, Santiago, Chile (associated with Physik-Institut, Universität Zürich, Zürich, Switzerland)*
[72]*School of Physics and Electronics, Hunan University, Changsha City, China (associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)*
[73]*Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China (associated with Department of Engineering Physics, Tsinghua University, Beijing, China)*
[74]*Lanzhou University, Lanzhou, China [associated with Institute Of High Energy Physics (IHEP), Beijing, China]*
[75]*School of Physics and Technology, Wuhan University, Wuhan, China (associated with Department of Engineering Physics, Tsinghua University, Beijing, China)*
[76]*Henan Normal University, Xinxiang, China (associated with Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)*
[77]*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia [associated with Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), Sorbonne Université, CNRS/IN2P3, F-75005 Paris, France, Paris, France]*
[78]*Ruhr Universitaet Bochum, Fakultaet f. Physik und Astronomie, Bochum, Germany (associated with Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany)*
[79]*Eotvos Lorand University, Budapest, Hungary [associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland]*
[80]*Faculty of Physics, Vilnius University, Vilnius, Lithuania (associated with Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany)*
[81]*Van Swinderen Institute, University of Groningen, Groningen, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
[82]*Universiteit Maastricht, Maastricht, Netherlands (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)*
[83]*Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland (associated with Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland)*
[84]*Universidade da Coruña, A Coruña, Spain (associated with La Salle, Universitat Ramon Llull, Barcelona, Spain)*
[85]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden (associated with School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)*

[86]*Taras Schevchenko University of Kyiv, Faculty of Physics, Kyiv,
Ukraine (associated with Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France)*
[87]*University of Michigan, Ann Arbor, Michigan,
USA (associated with Syracuse University, Syracuse, New York, USA)*
[88]*Ohio State University, Columbus, Ohio, USA [associated with Los Alamos National Laboratory (LANL),
Los Alamos, New Mexico, USA]*

[a] Deceased.

[b] Also at Lamarr Institute for Machine Learning and Artificial Intelligence, Dortmund, Germany.

[c] Also at Università degli Studi di Milano-Bicocca, Milano, Italy.

[d] Also at Università di Roma Tor Vergata, Roma, Italy.

[e] Also at Università di Modena e Reggio Emilia, Modena, Italy.

[f] Also at Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada.

[g] Also at Università di Ferrara, Ferrara, Italy.

[h] Also at Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil.

[i] Also at Università di Bologna, Bologna, Italy.

[j] Also at Università di Genova, Genova, Italy.

[k] Also at Scuola Normale Superiore, Pisa, Italy.

[l] Also at Università degli Studi di Milano, Milano, Italy.

[m] Also at Center for High Energy Physics, Tsinghua University, Beijing, China.

[n] Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras.

[o] Also at Università di Cagliari, Cagliari, Italy.

[p] Also at Centro Federal de Educacão Tecnológica Celso Suckow da Fonseca, Rio De Janeiro, Brazil.

[q] Also at Università di Bari, Bari, Italy.

[r] Also at Università di Perugia, Perugia, Italy.

[s] Also at LIP6, Sorbonne Université, Paris, France.

[t] Also at Università di Pisa, Pisa, Italy.

[u] Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.

[v] Also at Università di Padova, Padova, Italy.

[w] Also at Università di Bergamo, Bergamo, Italy.

[x] Also at Universidad de Ingeniería y Tecnología (UTEC), Lima, Peru.

[y] Also at Università di Siena, Siena, Italy.

[z] Also at Università della Basilicata, Potenza, Italy.

[aa] Also at Universidad de Alcalá, Alcalá de Henares, Spain.

[bb] Also at Università di Urbino, Urbino, Italy.