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Evidence of a $J/\psi K_{\mathrm{S}}^{0}$ Structure in $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ Decays

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

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An amplitude analysis of $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ decays is performed using proton-proton collision data, corresponding to an integrated luminosity of 9 fb^{-1}, collected with the LHCb detector at center-of-mass energies of 7, 8, and 13 TeV. Evidence with a significance of 4.0 standard deviations of a structure in the $J/\psi K_{\mathrm{S}}^{0}$ system, named $T_{\psi s1}^{\theta}(4000)^{0}$, is seen, with its mass and width measured to be $3991_{-10}^{+12}{}_{-17}^{+9}$ $\mathrm{MeV}/\mathrm{c}^{2}$ and $105_{-25}^{+29}{}_{-23}^{+17}$ MeV, respectively, where the first uncertainty is statistical and the second systematic. The $T_{\psi s1}^{\theta}(4000)^{0}$ state is likely to be the isospin partner of the $T_{\psi s1}^{\theta}(4000)^{+}$ state, previously observed in the $J/\psi K^{+}$ system of the $B^{+} \to J/\psi\phi K^{+}$ decay. When isospin symmetry for the charged and neutral $T_{\psi s1}^{\theta}(4000)$ states is assumed, the signal significance increases to 5.4 standard deviations.

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Hadrons formed by more than three quarks, namely exotic hadrons, can have complex color and flavor structures, and studies of the structures shed light on the nature of the strong interaction. Since the discovery of the $\chi_{c1}(3872)$ [1], several states compatible with a four or five quark composition have been observed [2], including the fully charmed tetraquark states [3–5] and the pentaquark states [6,7]. In 2020, the BESIII Collaboration reported the observation of the $Z_{cs}(3985)^{+}$ state in the $D_{s}^{+}\bar{D}^{*0}$ and $D_{s}^{*+}\bar{D}^{0}$ mass spectra [8]. (Charge conjugation is implied throughout the Letter unless specified otherwise.) Two similar states, $T_{\psi s1}^{\theta}(4000)^{+}$ and $T_{\psi s1}(4220)^{+}$, were observed in $B^{+} \to J/\psi\phi K^{+}$ decays by the LHCb experiment [9,10]. The observations of the $T_{\psi s1}^{\theta}(4000)^{+}$, $T_{\psi s1}(4220)^{+}$, and $Z_{cs}(3985)^{+}$ states have stimulated many theoretical studies to interpret their internal structures, such as hadronic molecules [12], compact tetraquarks [13], or threshold effects [14].

Searching for $T_{\psi s}^{0}$, the isospin partner of the $T_{\psi s}^{+}$, is an important step in identifying the full SU(3) nonet that involves these states. The quark contents for the $T_{\psi s}^{+}$ and $T_{\psi s}^{0}$ states are $c\bar{c}u\bar{s}$ and $c\bar{c}d\bar{s}$, respectively. Recently, the BESIII experiment reported evidence for the $Z_{cs}(3985)^{0}$ state ($c\bar{c}d\bar{s}$) in the $D_{s}^{+}D^{*-}$ and $D_{s}^{*+}D^{-}$ mass spectra [15]. The $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ decay [16–18] is the ideal candidate to search for such $T_{\psi s}^{0}$ states. The quark level processes of the $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ decay are similar to those of the $B^{+} \to J/\psi\phi K^{+}$ decay, as shown in Figs. 1(c) and 1(d) of Ref. [17], and the two decays are related by isospin symmetry.

In this Letter, evidence of a $J/\psi K_{\mathrm{S}}^{0}$ structure is reported by making use of an amplitude analysis of $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ decays. The analysis is based on proton-proton (pp) collision data, collected with the LHCb detector at center-of-mass energies of 7, 8, and 13 TeV, corresponding to integrated luminosities of 1, 2, and 6 fb^{-1}, respectively.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [19,20]. Simulated samples of the signal decays are used to estimate the effect of reconstruction and event selections. The samples are generated with PYTHIA [21], EvtGen [22], and the GEANT4 toolkit [23] as described in Ref. [24].

For the $B^{0} \to J/\psi\phi K_{\mathrm{S}}^{0}$ decays, the J/ψ, ϕ, and K_{S}^{0} candidates are reconstructed by combining two oppositely charged muons, kaons, and pions, respectively, forming vertices detached from any primary vertex (PV). The B^{0} candidate is reconstructed by combining the J/ψ, ϕ, and K_{S}^{0} candidates, and the resulting decay vertex must be of high quality. In order to improve the resolution of the mass of the B^{0} candidates (referred to as $m_{J/\psi\phi K_{\mathrm{S}}^{0}}$), a kinematic constraint [25] is applied, where the momenta of the final-state particles are recalculated constraining the masses of the J/ψ and K_{S}^{0} candidates to their nominal values, and the momentum of B^{0} candidate pointing back to its associated PV. The associated PV is the one with the smallest impact parameter χ^{2}, defined as the difference in the vertex fit χ^{2} of a given PV with and without the particle under consideration.

The B^{0} candidates are selected by a multivariate classifier based on a multilayer perceptron [26,27].

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

The selection is similar to that used in Ref. [9], with the additional requirement on the significance of the flight distance of the K^0_S from the B^0 decay vertex. Only candidates with the mass of the K^+K^- system within ± 15 MeV around the nominal ϕ mass [2] are kept, where the mass resolution is about 0.7 MeV. (Natural units with $\hbar = c = 1$ are used throughout the Letter.) The multivariate classifier uses 11 variables related to the decay-chain topology, particle transverse momentum, vertex fit quality, and charged particle identification information. The selection criterion on the classifier response is chosen by maximizing the figure of merit, $\mathcal{S}^2/(\mathcal{S}+\mathcal{B})^{3/2}$ [28], where $\mathcal{S}$ and $\mathcal{B}$ are the yields of signal and background in the signal region, respectively. The signal region in $m_{J/\psi\phi K^0_\mathrm{S}}$ is defined to be ± 15 MeV around the nominal B^0 mass [2].

An extended maximum-likelihood fit is performed to the reconstructed B^0 mass, as is shown in Fig. 1(a). The B^0 signal is described by a Hypatia function [29] and the background is described by an exponential function. The B^0 yield is measured to be 1866 ± 47 in the signal region. The fraction of combinatorial background in the signal region is 6%. Roughly 4% of the B^0 yield corresponds to peaking background $B^0 \to J/\psi K^+K^-K^0_\mathrm{S}$ decays without an intermediate ϕ meson (referred to as non-ϕ). The non-ϕ contribution is neglected in the default amplitude model and is considered as a source of systematic uncertainty. A further kinematic fit is performed to improve the momentum resolution of the final-state particles by constraining the measured B^0 mass to its nominal value. Figure 1(b) shows the distribution of $m^2_{J/\psi K^0_\mathrm{S}}$ versus $m^2_{J/\psi\phi}$ for candidates in the signal region.

An amplitude fit is performed to study the intermediate states. The $B^0 \to J/\psi\phi K^0_\mathrm{S}$ sample size is small, while the intermediate contributions are complicated, making the fit difficult to converge. In order to solve this difficulty, a simultaneous fit is performed to the $B^0 \to J/\psi\phi K^0_\mathrm{S}$ sample and the $B^+ \to J/\psi\phi K^+$ sample in Ref. [9], where the amplitudes in the two decay modes are related through isospin symmetry. The likelihood for the B^0 decay is given by

$$\mathcal{L}(\vec{\omega}) = \prod_i [(1-\beta)\mathcal{P}_\mathrm{sig}(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i|\vec{\omega}) + \beta\mathcal{P}_\mathrm{bkg}(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i)], \tag{1}$$

where $\mathcal{P}_\mathrm{sig}(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i|\vec{\omega})$ and $\mathcal{P}_\mathrm{bkg}(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i)$ refer to the probability density functions (PDFs) for the signal and background components, respectively. The superscript i refers to the ith candidate. The fraction of combinatorial background, β, is fixed to 6%. The likelihood of the B^+ decay is similar to Eq. (1), and is described in detail in Ref. [30]. The decay kinematics are described by a mass, chosen to be $m_{\phi K^0_\mathrm{S}}$, and five angular variables $\vec{\Omega}$ as defined below. The signal PDF is proportional to the incoherent sum of the squared matrix elements for different final-state muon helicities $(\lambda_{\mu^+}, \lambda_{\mu^-})$, and depends on the set of fit parameters, $\vec{\omega}$, which includes masses, widths, and helicity couplings of intermediate states contributing to $B^0 \to J/\psi\phi K^0_\mathrm{S}$ decays,

$$\mathcal{P}_\mathrm{sig}(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i|\vec{\omega}) = \frac{1}{I(\vec{\omega})} \sum_{\lambda_{\mu^+}\lambda_{\mu^-}} \sum_f |\mathcal{M}_f(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i|\vec{\omega})|^2 \times \Phi(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i)\epsilon(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i). \tag{2}$$

The term $\Phi(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i)$ represents the phase-space density, the term $\epsilon(m^i_{\phi K^0_\mathrm{S}}, \vec{\Omega}^i)$ represents the efficiency, and the term $I(\vec{\omega})$ is a normalization factor. The efficiency is obtained from simulated samples. Since the $B^0 \to J/\psi\phi K^0_\mathrm{S}$ decay is a self-charge-conjugated mode, the data sample contains both B^0 and $\bar{B}^0$ decays with unknown b flavor. Therefore, the signal PDF for the neutral B decay averages B^0 and $\bar{B}^0$ contributions, where the flavor of B candidates is denoted as f in Eq. (2).

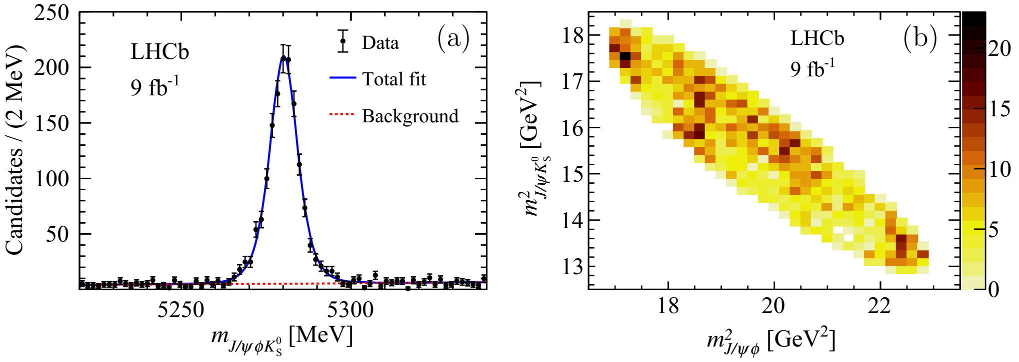

FIG. 1. (a) Invariant-mass distribution of selected B^0 candidates and corresponding fit result. (b) Distribution of $m^2_{J/\psi K^0_\mathrm{S}}$ versus $m^2_{J/\psi\phi}$ for candidates in the ± 15 MeV region around the nominal B^0 mass.

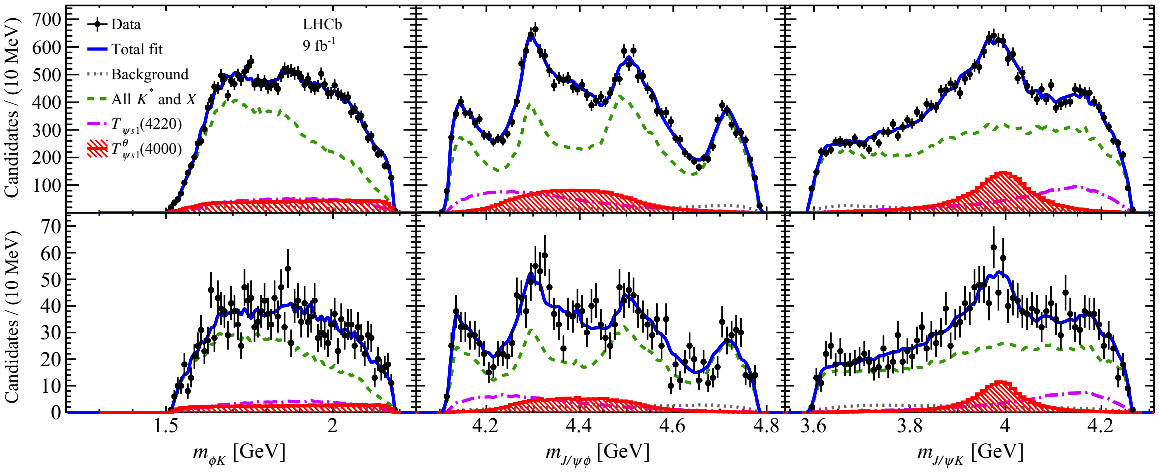

FIG. 2. Distributions of (left) $m_{\phi K}$, (middle) $m_{J/\psi\phi}$, and (right) $m_{J/\psi K}$, overlaid with the corresponding projections of the default fit model. The upper and lower rows correspond to the $B^+ \to J/\psi\phi K^+$ and $B^0 \to J/\psi\phi K^0_S$ decays, respectively.

The matrix element $\mathcal{M}_f(m^i_{\phi K^0_S}, \vec{\Omega}^i|\vec{\omega})$ is constructed based on the helicity formalism [31]. Three interfering decay sequences are considered: $B^0 \to (K^* \to \phi K^0_S)J/\psi$, $B^0 \to (X \to J/\psi\phi)K^0_S$, and $B^0 \to (T_{\psi s1} \to J/\psi K^0_S)\phi$. (The K^* denotes any excited K state. The X denotes $\chi_{c0,1}$, η_{c2}, and $T^{\eta}_{\psi\phi 1}$ states.) The decay sequences can be described by $m_{\phi K^0_S}$ and $\vec{\Omega} \equiv (\theta_{K^*}, \theta_{J/\psi}, \theta_{\phi}, \Delta\varphi_{K^* J/\psi}, \Delta\varphi_{K^*\phi})$, where the θ_{K^*}, $\theta_{J/\psi}$, and θ_{ϕ} are the helicity angles of the ϕ, μ, and K^+ particles in the K^*, J/ψ, and ϕ rest frames, respectively. The angles between the K^* and J/ψ decay planes, and between the K^* and ϕ decay planes in the B rest frame, are denoted as $\Delta\varphi_{K^* J/\psi}$, and $\Delta\varphi_{K^*\phi}$, respectively. The background PDF $\mathcal{P}_{\rm bkg}(m^i_{\phi K^0_S}, \vec{\Omega}^i)$ is determined from studying the candidates in the sideband of the $m_{J/\psi\phi K^0_S}$ distribution with the methods outlined in Ref. [30].

The default model is taken from Ref. [9] and is composed of nine K^* components, seven X components, and two $T_{\psi s1}$ states [$T^{\theta}_{\psi s1}(4000)$ and $T_{\psi s1}(4220)$], and one $J/\psi\phi$ nonresonant component (NR). Relativistic Breit–Wigner (RBW) functions are used to model the line shapes of these resonances. The amplitudes of the B^0 and the B^+ decays are formed by intermediate states that are either identical (namely X) or isospin partners (K^* or $T_{\psi s1}$). Under the assumption of isospin symmetry, the mass, width, and helicity couplings for all the components except for the $T^{\theta}_{\psi s1}(4000)$ states are constrained to be identical. In order to test the significance of the $T^{\theta}_{\psi s1}(4000)^0$ signal without prior knowledge of its properties, a fit is performed with the masses, widths, and helicity couplings of $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$ states allowed to vary independently. In an alternative model, isospin symmetry is imposed for the $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$ components. The parameters for the $T_{\psi s1}(4220)^0$ state are always constrained to be identical to the $T_{\psi s1}(4220)^+$ state due to the limited size of the B^0 sample.

Figure 2 shows the ϕK, $J/\psi\phi$, and $J/\psi K$ mass distributions and the corresponding fit projections of the default model for the two B decay modes. Table I summarizes measurements of the mass, width, and fit fraction of the $T^{\theta}_{\psi s1}(4000)^0$ state, and the mass difference between the $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$ states, defined as $\Delta M \equiv M_{T^{\theta}_{\psi s1}(4000)^0} - M_{T^{\theta}_{\psi s1}(4000)^+}$. The fit value of ΔM is zero within uncertainties, consistent with the two states being isospin partners. The fit fraction of each component is defined as the integral of the signal PDF divided by the $I(\vec{\omega})$ term. All the fit parameters, including mass, width, and helicity couplings of the intermediate states, of the default model in this analysis are consistent with the corresponding parameters of the default model for the $B^+ \to J/\psi\phi K^+$ decay in Ref. [9].

The estimated systematic uncertainties on the mass, width, and fit fraction of the $T^{\theta}_{\psi s1}(4000)^0$ state, and on ΔM are summarized in Table II. Both the background PDF and efficiency function are described by an expansion with Legendre polynomials and a spherical harmonic function instead of interpolation. The Blatt-Weisskopf hadron size is varied between 1.5 and 4.5 GeV^{-1} from the default value 3 GeV^{-1}. The Flatté model [32] is used for the line shape of the $X(4140)$ state instead of the RBW function to account

TABLE I. Results for the $T^{\theta}_{\psi s1}(4000)^0$ state from the default model. The first uncertainty is statistical and the second systematic.

State	Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
$T^{\theta}_{\psi s1}(4000)^0$	$3991^{+12}_{-10}{}^{+9}_{-17}$	$105^{+29}_{-25}{}^{+17}_{-23}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$	$-12^{+11}_{-10}{}^{+6}_{-4}$

TABLE II. Systematic uncertainties associated to the mass, width, and fit fraction of the $T^{\theta}_{\psi s1}(4000)^0$ state, and the mass difference between the $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$ states.

Source	Mass (MeV)	Width (MeV)	Fit fraction (%)	ΔM (MeV)
Efficiency and background models	$+10.46$	$+1.91$	-0.06	$+1.02$
Hadron radius	${}^{+0.29}_{-1.92}$	${}^{+2.33}_{-5.85}$	${}^{+0.05}_{-0.39}$	${}^{+0.92}_{-1.68}$
$X(4140)$ Flatté model	$+0.61$	-3.47	-0.31	-0.18
$J/\psi\phi$ NR representation	$+1.72$	$+1.46$	$+0.38$	$+0.12$
Simplified K-matrix model	-7.30	-17.54	-1.73	-3.38
RBW widths	$+1.90$	-3.41	-0.56	$+1.70$
Spin parity of the $T_{\psi s1}(4220)$ state	-16.32	-17.76	-2.33	-1.48
Non-ϕ contribution	$+5.52$	$+7.98$	$+0.92$	$+5.49$
Additional 1^+ $J/\psi\phi$ NR	$+0.80$	-3.66	$+0.18$	-1.28
Additional 2^+ $J/\psi\phi$ NR	$+7.66$	$+2.57$	$+2.52$	$+0.92$
Extended model	-6.36	-2.54	-0.20	-2.98
Additional X state	-5.58	$+0.27$	$+0.34$	-1.48
Fit fraction constraint	$+0.07$	$+1.94$	-0.48	-0.45
Impact parameter χ^2 modeling	$+1.00$	-2.49	-0.22	$+0.72$
Finite simulation sample size	$+2.90$	$+11.20$	$+1.33$	$+2.17$
Fixed mass and width of K^* states	-0.58	-1.30	-0.43	-0.58
Samples to construct the $\mathcal{P}_{\rm bkg}$	${}^{+1.06}_{-1.38}$	${}^{+6.38}_{-7.25}$	${}^{+0.54}_{-0.59}$	${}^{+0.52}_{-0.68}$
Background fraction uncertainty	${}^{+0.37}_{-0.45}$	${}^{+1.38}_{-1.55}$	${}^{+0.06}_{-0.07}$	${}^{+0.22}_{-0.38}$
Final	${}^{+8.46}_{-16.71}$	${}^{+17.09}_{-23.33}$	${}^{+3.00}_{-2.84}$	${}^{+6.04}_{-4.23}$

for the possible additional decay channel $D_s^{*+}D_s^-$. The $J/\psi\phi$ NR shape is changed from constant to be a linear function of $m_{J/\psi\phi}$. The K^* states are described by a simplified one-channel K-matrix model [2] instead of a sum of RBW functions. The mass-dependent widths in the RBW function for the K^* resonances are calculated using the decay with the largest branching fraction, $K^* \to K\pi$ or $K^* \to K^*(892)\pi$, instead of using the $K^* \to \phi K$ decay. The spin parity of the $T_{\psi s1}(4220)$ state is changed from the default 1^+ to 1^- to account for its ambiguity between 1^+ and 1^- [9]. The uncertainty originating from the neglected non-ϕ contribution is evaluated by narrowing the ϕ mass window from ± 15 to ± 8 MeV. An additional $J/\psi\phi$ NR contribution with the spin parity equal to 1^+ or 2^+ is included. An extended model with more K^* states is also studied, which includes all the K^* resonances that are within the allowed phase space, as predicted in Ref. [33]. Possible additional X states, with spins ranging from 0 to 2, are checked based on the extended model. The total fit fraction of the default model is 165.2%, which indicates that the interference between the decay amplitudes is large. An alternative fit constraining the total fit fraction to be smaller than 140%, corresponding to a reduction by 3 times its uncertainty, is performed. The final positive (negative) systematic uncertainty is taken as the maximal positive (negative) deviation from the model uncertainties above summed in quadrature with the uncertainty from other sources. These other sources of systematic uncertainty include mismodeling of the impact parameter χ^2 of B candidates, the finite size of the simulated samples, the fixed masses and widths of the known K^* states, the choice of the data sample used to construct the background PDF model, and the uncertainty on the background fraction.

The significance of the $T^{\theta}_{\psi s1}(4000)^0$ state is evaluated with a likelihood ratio test. The test statistic is defined as $t \equiv -2\ln[\mathcal{L}(H_0)/\mathcal{L}(H_1)]$, with H_1 and H_0 denoting the default model with and without the $T^{\theta}_{\psi s1}(4000)^0$ state. Here, the term $\mathcal{L}$ represents the likelihood of the B^0 decay. Five thousand pseudoexperiments are generated with the H_0 model, where the parameters of the model are fixed to the values determined from data. The sample size of each pseudoexperiment follows a Poisson distribution with its mean being equal to the number of candidates in the data sample. A fit is performed to each pseudoexperiment with the H_0 and H_1 models to determine the test statistic t. The t value from these pseudoexperiments should follow a χ^2 distribution, where the number of degrees of freedom is a freely varying parameter. Using the resulting χ^2 distribution, the probability of $t > t_{\rm data}$ is taken as the p value. The corresponding significance is estimated to be 4.9σ, decreasing to 4.0σ after including systematic uncertainties, which provides evidence for the $T^{\theta}_{\psi s1}(4000)^0$ state. The significance for the $T^{\theta}_{\psi s1}(4000)^0$ state is taken as the smallest significance found when varying the sources of systematic uncertainty.

The significance is also evaluated assuming isospin symmetry for the $T^{\theta}_{\psi s1}(4000)$ states, where the test statistic is defined as $t' \equiv -2\ln[\mathcal{L}(H_0)/\mathcal{L}(H'_1)]$, with $\mathcal{L}$ denoting the total likelihood of the B^+ and B^0 decays. The corresponding fit parameters for the $T^{\theta}_{\psi s1}(4000)^+$ and $T^{\theta}_{\psi s1}(4000)^0$ states, including mass, width, and helicity couplings, are constrained to be equal between the two states in the H'_1 model. A fit is performed to the t' distribution from the pseudoexperiments with a Gaussian function. The Gaussian function rather than a χ^2 distribution is used here because the number of degrees of freedom of the H_0 and H'_1 models is equal. The significance is estimated to be 7.2σ and decreases to 5.4σ after accounting for systematic uncertainties.

In conclusion, an amplitude analysis of the $B^0 \to J/\psi\phi K^0_{\mathrm{S}}$ decay is performed. Evidence of a $J/\psi K^0_S$ structure, denoted the $T^{\theta}_{\psi s1}(4000)^0$ state, is obtained with a significance of 4.0σ. The mass and width of this state are measured to be

$$M(T^{\theta}_{\psi s1}(4000)^0) = 3991^{+12}_{-10}{}^{+9}_{-17}\ \mathrm{MeV},$$
$$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = 105^{+29}_{-25}{}^{+17}_{-23}\ \mathrm{MeV},$$

where the first uncertainty is statistical and the second systematic. The mass difference between the $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$ states is measured to be

$$\Delta M = -12^{+11}_{-10}{}^{+6}_{-4}\ \mathrm{MeV},$$

which is consistent with the two states being isospin partners. With isospin symmetry imposed for the $T^{\theta}_{\psi s1}(4000)$ states, the significance of the $T^{\theta}_{\psi s1}(4000)^0$ structure is measured to be 5.4σ.

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R. A. Ruiz Fernandez,[40] J. Ruiz Vidal,[41] A. Ryzhikov,[38] J. Ryzka,[34] J. J. Saborido Silva,[40] N. Sagidova,[38]
N. Sahoo,[47] B. Saitta,[27,k] M. Salomoni,[42] C. Sanchez Gras,[32] I. Sanderswood,[41] R. Santacesaria,[30]

C. Santamarina Rios,[40] M. Santimaria,[23] E. Santovetti,[31,b] D. Saranin,[38] G. Sarpis,[14] M. Sarpis,[70] A. Sarti,[30] C. Satriano,[30,t] A. Satta,[31] M. Saur,[15] D. Savrina,[38] H. Sazak,[9] L. G. Scantlebury Smead,[57] A. Scarabotto,[13] S. Schael,[14] S. Scherl,[54] M. Schiller,[53] H. Schindler,[42] M. Schmelling,[16] B. Schmidt,[42] S. Schmitt,[14] O. Schneider,[43] A. Schopper,[42] M. Schubiger,[32] S. Schulte,[43] M. H. Schune,[11] R. Schwemmer,[42] B. Sciascia,[23] A. Sciuccati,[42] S. Sellam,[40] A. Semennikov,[38] M. Senghi Soares,[33] A. Sergi,[24,h] N. Serra,[44] L. Sestini,[28] A. Seuthe,[15] Y. Shang,[5] D. M. Shangase,[78] M. Shapkin,[38] I. Shchemerov,[38] L. Shchutska,[43] T. Shears,[54] L. Shekhtman,[38] Z. Shen,[5] S. Sheng,[4,6] V. Shevchenko,[38] B. Shi,[6] E. B. Shields,[26,f] Y. Shimizu,[11] E. Shmanin,[38] R. Shorkin,[38] J. D. Shupperd,[62] B. G. Siddi,[21,e] R. Silva Coutinho,[62] G. Simi,[28] S. Simone,[19,j] M. Singla,[63] N. Skidmore,[56] R. Skuza,[17] T. Skwarnicki,[62] M. W. Slater,[47] J. C. Smallwood,[57] J. G. Smeaton,[49] E. Smith,[44] K. Smith,[61] M. Smith,[55] A. Snoch,[32] L. Soares Lavra,[9] M. D. Sokoloff,[59] F. J. P. Soler,[53] A. Solomin,[38,48] A. Solovev,[38] I. Solovyev,[38] R. Song,[63] F. L. Souza De Almeida,[2] B. Souza De Paula,[2] B. Spaan,[15,a] E. Spadaro Norella,[25,p] E. Spedicato,[20] E. Spiridenkov,[38] P. Spradlin,[53] V. Sriskaran,[42] F. Stagni,[42] M. Stahl,[42] S. Stahl,[42] S. Stanislaus,[57] E. N. Stein,[42] O. Steinkamp,[44] O. Stenyakin,[38] H. Stevens,[15] S. Stone,[62,a] D. Strekalina,[38] Y. Su,[6] F. Suljik,[57] J. Sun,[27] L. Sun,[68] Y. Sun,[60] P. Svihra,[56] P. N. Swallow,[47] K. Swientek,[34] A. Szabelski,[36] T. Szumlak,[34] M. Szymanski,[42] Y. Tan,[3] S. Taneja,[56] M. D. Tat,[57] A. Terentev,[44] F. Teubert,[42] E. Thomas,[42] D. J. D. Thompson,[47] K. A. Thomson,[54] H. Tilquin,[55] V. Tisserand,[9] S. T'Jampens,[8] M. Tobin,[4] L. Tomassetti,[21,e] G. Tonani,[25,p] X. Tong,[5] D. Torres Machado,[1] D. Y. Tou,[3] S. M. Trilov,[48] C. Trippl,[43] G. Tuci,[6] N. Tuning,[32] A. Ukleja,[36] D. J. Unverzagt,[17] A. Usachov,[33] A. Ustyuzhanin,[38] U. Uwer,[17] A. Vagner,[38] V. Vagnoni,[20] A. Valassi,[42] G. Valenti,[20] N. Valls Canudas,[76] M. Van Dijk,[43] H. Van Hecke,[61] E. van Herwijnen,[55] C. B. Van Hulse,[40,u] M. van Veghel,[32] R. Vazquez Gomez,[39] P. Vazquez Regueiro,[40] C. Vázquez Sierra,[42] S. Vecchi,[21] J. J. Velthuis,[48] M. Veltri,[22,v] A. Venkateswaran,[43] M. Veronesi,[32] M. Vesterinen,[50] D. Vieira,[59] M. Vieites Diaz,[43] X. Vilasis-Cardona,[76] E. Vilella Figueras,[54] A. Villa,[20] P. Vincent,[13] F. C. Volle,[11] D. vom Bruch,[10] A. Vorobyev,[38] V. Vorobyev,[38] N. Voropaev,[38] K. Vos,[74] C. Vrahas,[52] J. Walsh,[29] E. J. Walton,[63] G. Wan,[5] C. Wang,[17] G. Wang,[7] J. Wang,[5] J. Wang,[4] J. Wang,[3] J. Wang,[68] M. Wang,[25] R. Wang,[48] X. Wang,[66] Y. Wang,[7] Z. Wang,[44] Z. Wang,[3] Z. Wang,[6] J. A. Ward,[50,63] N. K. Watson,[47] D. Websdale,[55] Y. Wei,[5] B. D. C. Westhenry,[48] D. J. White,[56] M. Whitehead,[53] A. R. Wiederhold,[50] D. Wiedner,[15] G. Wilkinson,[57] M. K. Wilkinson,[59] I. Williams,[49] M. Williams,[58] M. R. J. Williams,[52] R. Williams,[49] F. F. Wilson,[51] W. Wislicki,[36] M. Witek,[35] L. Witola,[17] C. P. Wong,[61] G. Wormser,[11] S. A. Wotton,[49] H. Wu,[62] J. Wu,[7] K. Wyllie,[42] Z. Xiang,[6] Y. Xie,[7] A. Xu,[5] J. Xu,[6] L. Xu,[3] L. Xu,[3] M. Xu,[50] Q. Xu,[6] Z. Xu,[9] Z. Xu,[6] D. Yang,[3] S. Yang,[6] X. Yang,[5] Y. Yang,[6] Z. Yang,[5] Z. Yang,[60] L. E. Yeomans,[54] V. Yeroshenko,[11] H. Yeung,[56] H. Yin,[7] J. Yu,[65] X. Yuan,[62] E. Zaffaroni,[43] M. Zavertyaev,[16] M. Zdybal,[35] M. Zeng,[3] C. Zhang,[5] D. Zhang,[7] L. Zhang,[3] S. Zhang,[65] S. Zhang,[5] Y. Zhang,[5] Y. Zhang,[57] Y. Zhao,[17] A. Zharkova,[38] A. Zhelezov,[17] Y. Zheng,[6] T. Zhou,[5] X. Zhou,[6] Y. Zhou,[6] V. Zhovkovska,[11] X. Zhu,[3] X. Zhu,[7] Z. Zhu,[6] V. Zhukov,[14,38] Q. Zou,[4,6] S. Zucchelli,[20,g] D. Zuliani,[28] and G. Zunica[56]

(LHCb Collaboration)

[1]*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[2]*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[3]*Center for High Energy Physics, Tsinghua University, Beijing, China*
[4]*Institute of High Energy Physics (IHEP), Beijing, China*
[5]*School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[6]*University of Chinese Academy of Sciences, Beijing, China*
[7]*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
[8]*Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
[9]*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[10]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[11]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
[12]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
[13]*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
[14]*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*

[15]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[16]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[17]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[18]*School of Physics, University College Dublin, Dublin, Ireland*
[19]*INFN Sezione di Bari, Bari, Italy*
[20]*INFN Sezione di Bologna, Bologna, Italy*
[21]*INFN Sezione di Ferrara, Ferrara, Italy*
[22]*INFN Sezione di Firenze, Firenze, Italy*
[23]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[24]*INFN Sezione di Genova, Genova, Italy*
[25]*INFN Sezione di Milano, Milano, Italy*
[26]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[27]*INFN Sezione di Cagliari, Monserrato, Italy*
[28]*Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*
[29]*INFN Sezione di Pisa, Pisa, Italy*
[30]*INFN Sezione di Roma La Sapienza, Roma, Italy*
[31]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[32]*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
[33]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
[34]*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[35]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[36]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[37]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[38]*Affiliated with an institute covered by a cooperation agreement with CERN*
[39]*ICCUB, Universitat de Barcelona, Barcelona, Spain*
[40]*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
[41]*Instituto de Fisica Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
[42]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[43]*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[44]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[45]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[46]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[47]*University of Birmingham, Birmingham, United Kingdom*
[48]*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[49]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[50]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[51]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[52]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[53]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[54]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[55]*Imperial College London, London, United Kingdom*
[56]*Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[57]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[58]*Massachusetts Institute of Technology, Cambridge, 02139 Massachusetts, USA*
[59]*University of Cincinnati, Cincinnati, 45221 Ohio, USA*
[60]*University of Maryland, College Park, 20742 Maryland, USA*
[61]*Los Alamos National Laboratory (LANL), Los Alamos, 87545 New Mexico, USA*
[62]*Syracuse University, Syracuse, 13244 New York, USA*
[63]*School of Physics and Astronomy, Monash University, Melbourne, Australia*
(associated with Institution Department of Physics, University of Warwick, Coventry, United Kingdom)
[64]*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil*
(associated with Institution Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
[65]*Physics and Micro Electronic College, Hunan University, Changsha City, China*
(associated with Institution Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China)
[66]*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 Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
[67]*Lanzhou University, Lanzhou, China*
(associated with Institution Institute Of High Energy Physics (IHEP), Beijing, China)

[68]*School of Physics and Technology, Wuhan University, Wuhan, China*
(associated with Institution Center for High Energy Physics, Tsinghua University, Beijing, China)
[69]*Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia*
(associated with Institution LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France)
[70]*Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
(associated with Institution Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
[71]*Eotvos Lorand University, Budapest, Hungary*
(associated with Institution European Organization for Nuclear Research (CERN), Geneva, Switzerland)
[72]*INFN Sezione di Perugia, Perugia, Italy*
(associated with Institution INFN Sezione di Ferrara, Ferrara, Italy)
[73]*Van Swinderen Institute, University of Groningen, Groningen, Netherlands*
(associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[74]*Universiteit Maastricht, Maastricht, Netherlands*
(associated with Institution Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands)
[75]*Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland*
(associated with Institution Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland)
[76]*DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
(associated with Institution ICCUB, Universitat de Barcelona, Barcelona, Spain)
[77]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*
(associated with Institution School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom)
[78]*University of Michigan, Ann Arbor, 48109 Michigan, USA*
(associated with Institution Syracuse University, Syracuse, New York, USA)

[a] Deceased.
[b] Also at Università di Roma Tor Vergata, Roma, Italy.
[c] Also at Università di Firenze, Firenze, Italy.
[d] Also at Scuola Normale Superiore, Pisa, Italy.
[e] Also at Università di Ferrara, Ferrara, Italy.
[f] Also at Università di Milano Bicocca, Milano, Italy.
[g] Also at Università di Bologna, Bologna, Italy.
[h] Also at Università di Genova, Genova, Italy.
[i] Also at Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras.
[j] Also at Università di Bari, Bari, Italy.
[k] Also at Università di Cagliari, Cagliari, Italy.
[l] Also at Università di Perugia, Perugia, Italy.
[m] Also at Universidade de Brasília, Brasília, Brazil.
[n] Also at Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China.
[o] Also at Università di Pisa, Pisa, Italy.
[p] Also at Università degli Studi di Milano, Milano, Italy.
[q] Also at Central South University, Changsha, China.
[r] Also at Università di Padova, Padova, Italy.
[s] Also at Excellence Cluster ORIGINS, Munich, Germany.
[t] Also at Università della Basilicata, Potenza, Italy.
[u] Also at Universidad de Alcalá, Alcalá de Henares, Spain.
[v] Also at Università di Urbino, Urbino, Italy.