Observation of $J/\psi\phi$ Structures Consistent with Exotic States from Amplitude Analysis of $B^+ \to J/\psi\phi K^+$ Decays

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The first full amplitude analysis of $B^+ \to J/\psi\phi K^+$ with $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ decays is performed with a data sample of 3 fb^{-1} of pp collision data collected at $\sqrt{s} = 7$ and 8 TeV with the LHCb detector. The data cannot be described by a model that contains only excited kaon states decaying into ϕK^+, and four $J/\psi\phi$ structures are observed, each with significance over 5 standard deviations. The quantum numbers of these structures are determined with significance of at least 4 standard deviations. The lightest has mass consistent with, but width much larger than, previous measurements of the claimed $X(4140)$ state.

There has been a great deal of experimental and theoretical interest in $J/\psi\phi$ mass structures in $B^+ \to J/\psi\phi K^+$ decays[1] since the CDF Collaboration presented 3.8σ evidence for a near-threshold $X(4140)$ mass peak, with width $\Gamma = 11.7$ MeV [1].[2] Much larger widths are expected for charmonium states at this mass because of open flavor decay channels [2], which should also make the kinematically suppressed $X \to J/\psi\phi$ decays undetectable. Therefore, it has been suggested that the $X(4140)$ peak could be a molecular state [3–9], a tetraquark state [10–14], a hybrid state [15,16] or a rescattering effect [17,18]. Subsequent measurements resulted in the confusing experimental situation summarized in Table I. Searches for the narrow $X(4140)$ in $B^+ \to J/\psi\phi K^+$ decays were negative in the Belle [19,20] (unpublished), LHCb [21] (0.37 fb^{-1}) and *BABAR* [22] experiments. The $X(4140)$ structure was, however, observed by the CMS [23] and D0 [24,25] collaborations.

In an unpublished update to their analysis [26], the CDF Collaboration presented 3.1σ evidence for a second relatively narrow $J/\psi\phi$ mass peak near 4274 MeV. A second peak was also observed by the CMS Collaboration at a mass which is higher by 3.2 standard deviations, but its statistical significance was not determined [23]. The Belle Collaboration obtained 3.2σ evidence for a narrow ($\Gamma = 13^{+18}_{-9} \pm 4$ MeV) $J/\psi\phi$ peak at $4350.6^{+4.6}_{-5.1} \pm 0.7$ MeV in two-photon collisions, which implies $J^{PC} = 0^{++}$ or 2^{++}, and found no signal for $X(4140)$ [27].

The $X(4140)$ and $X(4274)$ states are the only known candidates for four-quark systems that contain neither of the light u and d quarks. Their confirmation, and determination of their quantum numbers, would allow new insights into the binding mechanisms present in multiquark systems, and help improve understanding of QCD in the nonperturbative regime.

The data sample used in this work corresponds to an integrated luminosity of 3 fb^{-1} collected with the LHCb detector in pp collisions at center-of-mass energies 7 and 8 TeV. The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [28,29]. Thanks to the larger signal yield, corresponding to 4289 ± 151 reconstructed $B^+ \to J/\psi\phi K^+$ decays, the roughly uniform efficiency and the relatively low background across the entire $J/\psi\phi$ mass range, this data sample offers the best sensitivity to date, not only to probe for the previously claimed $J/\psi\phi$ structures, but also to inspect the high mass region for the first time. All previous analyses were based on naive $J/\psi\phi$ mass ($m_{J/\psi\phi}$) fits, with Breit-Wigner (BW) signal peaks on top of incoherent background described by *ad hoc* functional shapes (e.g. the three-body phase space distribution in $B^+ \to J/\psi\phi K^+$ decays). While the $m_{\phi K}$ distribution has been observed to be smooth, several resonant contributions from kaon excitations (denoted generically as K^*) are expected. It is important to prove that any $m_{J/\psi\phi}$ peaks are not merely reflections of K^* states. If genuine $J/\psi\phi$ states are present, it is crucial to determine their quantum numbers to aid their theoretical interpretation. Both of these tasks call for a proper amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays, in which the observed $m_{\phi K}$ and $m_{J/\psi\phi}$ masses are analyzed simultaneously with the distributions of decay angles, without which the resolution of different resonant contributions is difficult, if not impossible.

In this paper, results with a focus on $J/\psi\phi$ mass structures are presented from the first amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays. A detailed description of the analysis with more extensive discussion of the results on

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[1]Inclusion of charge-conjugate processes is implied.
[2]Units with $c = 1$ are used.

TABLE I. Previous results related to the $X(4140) \to J/\psi\phi$ mass peak. The number of reconstructed $B^+ \to J/\psi\phi K^+$ decays (N_B) is given if applicable. Significances (σ) correspond to numbers of standard deviations. Upper limits on the $X(4140)$ fraction of the total $B^+ \to J/\psi\phi K^+$ rate are at 90% confidence level. The statistical and systematic errors are added in quadrature and then used in the weights to calculate the averages, excluding unpublished results (shown in italics).

Experiment	N_B	Mass (MeV)	Width (MeV)	σ	Fraction (%)
CDF [1]	58	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8	
Belle [19]	*325*	*4143.0 fixed*	*11.7 fixed*	*1.9*	
CDF [26]	*115*	*$4143.4^{+2.9}_{-3.0} \pm 0.6$*	*$15.3^{+10.4}_{-6.1} \pm 2.5$*	*5.0*	*$15 \pm 4 \pm 2$*
LHCb [21]	346	4143.4 fixed	15.3 fixed	1.4	<7
CMS [23]	2480	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0	10 ± 3
D0 [24]	215	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.1	$21 \pm 8 \pm 4$
BABAR [22]	*189*	*4143.4 fixed*	*15.3 fixed*	*1.6*	*<13*
D0 [25]		*$4152.5 \pm 1.7^{+6.2}_{-5.4}$*	*$16.3 \pm 5.6 \pm 11.4$*	*4.7–5.7*	
Average		4147.1 ± 2.4	15.7 ± 6.3		

kaon spectroscopy can be found in Ref. [30]. The data selection is similar to that described in Ref. [21], with modifications [30] that increase the B^+ signal yield per unit luminosity by about 50% at the expense of larger background. A K^+K^- pair with mass within ± 15 MeV of the known ϕ mass [31] is accepted as a ϕ candidate. To avoid reconstruction ambiguities, we require that there be exactly one ϕ candidate per $J/\psi K^+K^-K^+$ combination, which reduces the B^+ yield by 3.2%. A fit to the mass distribution of $J/\psi\phi K^+$ candidates yields 4289 ± 151 $B^+ \to J/\psi\phi K^+$ events, with a background fraction (β) of 23% in the region used in the amplitude analysis (twice the B^+ mass resolution on each side of its peak). The non-ϕ $B^+ \to J/\psi K^+K^-K^+$ background is small (2.1%) and neglected in the amplitude model, but considered as a source of systematic uncertainty.

We first try to describe the data with kaon excitations alone. We construct an amplitude model ($\mathcal{M}$) using the helicity formalism [32–34] in which the six independent variables fully describing the $B^+ \to J/\psi K^{*+}$, $J/\psi \to \mu^+\mu^-$, $K^{*+} \to \phi K^+$, $\phi \to K^+K^-$ decay chain are $m_{\phi K}$, θ_{K^*}, $\theta_{J/\psi}$, θ_ϕ, $\Delta\phi_{K^*,J/\psi}$ and $\Delta\phi_{K^*,\phi}$, where θ denotes helicity angles, and $\Delta\phi$ angles between decay planes. The set of angles is denoted by Ω. The matrix element for a single K^{*+} resonance (j) with mass M_0^j and width Γ_0^j is assumed to factorize, $\mathcal{M}_{K^* \Delta\lambda_\mu}^j = R(m_{\phi K}|M_0^j,\Gamma_0^j)H_{\Delta\lambda_\mu}(\Omega|\{A^j\})$, where $R(m_{\phi K}|M_0^j,\Gamma_0^j)$ is a complex BW function and $H_{\Delta\lambda_\mu}(\Omega|\{A^j\})$ describes the angular correlations, with $\{A^j\}$ being a set of complex helicity couplings which are determined from the data (1–4 independent couplings depending on J^P), where $\Delta\lambda_\mu = \lambda_{\mu^+} - \lambda_{\mu^-}$, and λ denotes the helicity. The total matrix element sums coherently over all possible K^* resonances: $|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=\pm 1}|\sum_j \mathcal{M}_{\Delta\lambda_\mu}^{K^* j}|^2$. Detailed definitions of $R(m_{\phi K}|M_0^j,\Gamma_0^j)$ and of $H_{\Delta\lambda_\mu}(\Omega|\{A^j\})$ are given in Ref. [30]. The free parameters are determined

from the data by minimizing the unbinned six-dimensional (6D) negative log-likelihood ($-\ln\mathcal{L}$), where the probability density function (PDF) is proportional to $(1-\beta)|\mathcal{M}|^2$, multiplied by the detection efficiency, plus a background term. The signal PDF is normalized by summing over $B^+ \to J/\psi\phi K^+$ events generated [35,36] uniformly in decay phase space, followed by detector simulation [37] and data selection. This procedure accounts for the 6D efficiency in the reconstruction of the signal decays [30]. We use B^+ mass sidebands to obtain a 6D parametrization of the background PDF [30].

Past experiments on K^* states decaying to ϕK [38–40] had limited precision, gave somewhat inconsistent results, and provided evidence for only a few of the states expected from the quark model in the 1513–2182 MeV range probed in our data. We have used the predictions of the relativistic potential model by Godfrey and Isgur [41] (horizontal black lines in Fig. 2) as a guide to the quantum numbers of the K^{*+} states to be included in the amplitude model. The masses and widths of all states are left free; thus our fits do not depend on details of the predictions, nor on previous measurements. We also include a constant nonresonant amplitude with $J^P = 1^+$, since such ϕK^+ contributions can be produced, and can decay, in the S-wave. Allowing the magnitude of the nonresonant amplitude to vary with $m_{\phi K}$ does not improve fit qualities. While it is possible to describe the $m_{\phi K}$ and $m_{J/\psi K}$ distributions well with K^* contributions alone, the fit projections onto $m_{J/\psi\phi}$ do not provide an acceptable description of the data. For illustration we show in Fig. 1 the projection of a fit with the following composition: a nonresonant term plus candidates for two $2P_1$, two $1D_2$, and one of each of 1^3F_3, 1^3D_1, 3^3S_1, 3^1S_0, 2^3P_2, 1^3F_2, 1^3D_3 and 1^3F_4 states, labeled here with their intrinsic quantum numbers $n^{2S+1}L_J$ (n is the radial quantum number, S the total spin of the valence quarks, L the orbital angular momentum between quarks, and J the total angular momentum of the bound state). The fit
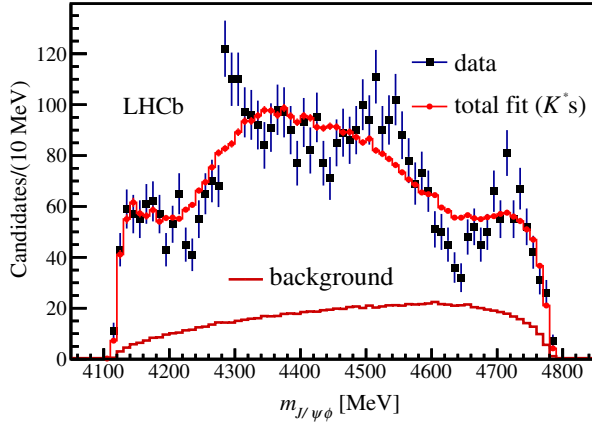
FIG. 1.   Distribution of $m_{J/\psi\phi}$ for the data and the fit results with a model containing only $K^{*+} \to \phi K^+$ contributions.
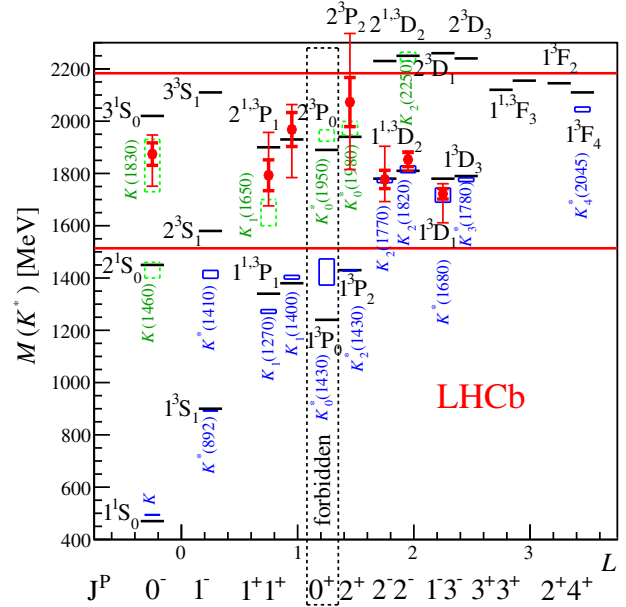

FIG. 2.   Masses of kaon excitations obtained in the default amplitude fit to the LHCb data, shown as red points with statistical (thicker bars) and total (thinner bars) errors, compared with the predictions by Godfrey and Isgur [41] (horizontal black lines) for the most likely spectroscopic interpretations labeled with $n^{2S+1}L_J$ (see the text). Experimentally established states are also shown with narrower solid blue boxes extending to $\pm 1\sigma$ in mass and labeled with their PDG names [31]. Unconfirmed states are shown with dashed green boxes. The long horizontal red lines indicate the ϕK mass range probed in $B^+ \to J/\psi\phi K^+$ decays. Decays of the 2^3P_0 state ($J^P = 0^+$) to ϕK^+ are forbidden.

contains 104 free parameters. The χ^2 value (144.9/68 bins) between the fit projection and the observed $m_{J/\psi\phi}$ distribution corresponds to a p-value below 10^{-7}. Adding even more resonances does not change the conclusion that non-K^* contributions are needed.

The matrix element for $B^+ \to XK^+$, $X \to J/\psi\phi$ decays can be parametrized using $m_{J/\psi\phi}$ and the θ_X, $\theta^X_{J/\psi}$, θ^X_ϕ, $\Delta\phi_{X,J/\psi}$, $\Delta\phi_{X,\phi}$ angles. The angles $\theta^X_{J/\psi}$ and θ^X_ϕ are not the same as in the K^* decay chain since J/ψ and ϕ are produced in decays of different particles. For the same reason, the muon helicity states are different between the two decay chains, and an azimuthal rotation by an angle α^X is needed to align them [30,42]. The parameters needed to characterize the X decay chain, including α^X, do not constitute new degrees of freedom since they can all be derived from $m_{\phi K}$ and Ω. We also consider possible contributions from $B^+ \to Z^+\phi$, $Z^+ \to J/\psi K^+$ decays, which can be parametrized in a similar way [30]. The total matrix element is obtained by summing all possible K^{*+} (j), X (k) and Z^+ (n) contributions: $|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu = \pm 1} |\sum_j \mathcal{M}^{K^*j}_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha^X}\sum_k \mathcal{M}^{Xk}_{\Delta\lambda_\mu} + e^{i\Delta\lambda_\mu\alpha^Z}\sum_n \mathcal{M}^{Zn}_{\Delta\lambda_\mu}|^2$.

We have explored adding X and Z^+ contributions of various quantum numbers to the fit models. Only X contributions lead to significant improvements in the description of the data. The default resonance model is summarized in Table II. It contains seven K^{*+} states (Fig. 2), four X states, and ϕK^+ and $J/\psi\phi$ nonresonant components. There are 98 free parameters in this fit. Additional K^{*+}, X or Z^+ states are not significant. Projections of the fit onto the mass variables are displayed in Fig. 3. The χ^2 value (71.5/68 bins) between the fit projection and the observed $m_{J/\psi\phi}$ distribution corresponds to a p-value of 22%, where the effective number of degrees of freedom has been obtained with simulations of pseudoexperiments generated from the default amplitude model. Projections onto angular variables, and onto masses in different regions of the Dalitz plot, can be found in Ref. [30].

The systematic uncertainties [30] are obtained from the sum in quadrature of the changes observed in the fit results when the K^{*+} and $X(4140)$ models are varied (the dominant errors); the BW amplitude parametrization is modified; only the left or right B^+ mass peak sidebands are used for the background parameterization; the ϕ mass selection is changed; the signal and background shapes are varied in the fit to $m_{J/\psi\phi K}$ which determines β; and the weights assigned to simulated events, in order to improve agreement with the data on B^+ production characteristics and detector efficiency, are removed.

The significance of each (non)resonant contribution is calculated from the change in log-likelihood between fits with and without the contribution included. The distribution of $\Delta(-2\ln\mathcal{L})$ between the two hypotheses should follow a χ^2 distribution with number of degrees of freedom equal to the number of free parameters in its parametrization (doubled when M_0 and Γ_0 are free parameters). The validity of this assumption has been verified using simulated pseudoexperiments. The significances of the X contributions are given after accounting for systematic uncertainties.

The K^{*+} composition of our amplitude model is in good agreement with the expectations for the $\bar{s}u$ states [41], and also in agreement with previous experimental results on K^*

TABLE II.   Results for significances, masses, widths and fit fractions (FF) of the components included in the default amplitude model. The first (second) errors are statistical (systematic). Possible interpretations in terms of kaon excitation levels are given for the resonant ϕK^+ fit components. Comparisons with the previously experimentally observed kaon excitations [31] and $X \to J/\psi\phi$ structures are also given.

| | | Fit results | | |
Contribution	Significance or Reference	M_0 (MeV)	Γ_0 (MeV)	FF %
All $K(1^+)$	8.0σ			$42 \pm 8^{+5}_{-9}$
$\mathrm{NR}_{\phi K}$				$16 \pm 13^{+35}_{-6}$
$K(1^+)2^1P_1$	7.6σ	$1793 \pm 59^{+153}_{-101}$	$365 \pm 157^{+138}_{-215}$	$12 \pm 10^{+17}_{-6}$
$K_1(1650)$	[31]	1650 ± 50	150 ± 50	
$K'(1^+)2^3P_1$	1.9σ	$1968 \pm 65^{+70}_{-172}$	$396 \pm 170^{+174}_{-178}$	$23 \pm 20^{+31}_{-29}$
All $K(2^-)$	5.6σ			$11 \pm 3^{+2}_{-5}$
$K(2^-)1^1D_2$	5.0σ	$1777 \pm 35^{+122}_{-77}$	$217 \pm 116^{+221}_{-154}$	
$K_2(1770)$	[31]	1773 ± 8	188 ± 14	
$K'(2^-)1^3D_2$	3.0σ	$1853 \pm 27^{+18}_{-35}$	$167 \pm 58^{+82}_{-72}$	
$K_2(1820)$	[31]	1816 ± 13	276 ± 35	
$K^*(1^-)1^3D_1$	8.5σ	$1722 \pm 20^{+33}_{-109}$	$354 \pm 75^{+140}_{-181}$	$6.7 \pm 1.9^{+3.2}_{-3.9}$
$K^*(1680)$	[31]	1717 ± 27	322 ± 110	
$K^*(2^+)2^3P_2$	5.4σ	$2073 \pm 94^{+245}_{-240}$	$678 \pm 311^{+1153}_{-559}$	$2.9 \pm 0.8^{+1.7}_{-0.7}$
$K_2^*(1980)$	[31]	1973 ± 26	373 ± 69	
$K(0^-)3^1S_0$	3.5σ	$1874 \pm 43^{+59}_{-115}$	$168 \pm 90^{+280}_{-104}$	$2.6 \pm 1.1^{+2.3}_{-1.8}$
$K(1830)$	[31]	~ 1830	~ 250	
All $X(1^+)$				$16 \pm 3^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.7}_{-2.0}$
Average form	Table I	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
CDF	[26]	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32^{+22}_{-15} \pm 8$	
CMS	[23]	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$	
All $X(0^+)$				$28 \pm 5 \pm 7$
$\mathrm{NR}_{J/\psi\phi}$	6.4σ			$46 \pm 11^{+11}_{-21}$
$X(4500)$	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$

states in this mass range [31] as illustrated in Fig. 2 and in Table II. Effects of adding extra insignificant K^{*+} resonances of various J^P, as well as of removing the least significant K^{*+} contributions, are included among the systematic variations of the fit amplitude. More detailed discussion of our results for kaon excitations can be found in Ref. [30].

A near-threshold $J/\psi\phi$ structure in our data is the most significant (8.4σ) exotic contribution to our model. We determine its quantum numbers to be $J^{PC} = 1^{++}$ at 5.7σ significance from the change in $-2\ln\mathcal{L}$ relative to other J^P assignments [43] including systematic variations. When fitted as a resonance, its mass ($4146.5 \pm 4.5^{+4.6}_{-2.8}$ MeV) is in excellent agreement with previous measurements for the $X(4140)$ state, although the width ($83 \pm 21^{+21}_{-14}$ MeV) is substantially larger. The upper limit previously set for production of a narrow ($\Gamma = 15.3$ MeV) $X(4140)$ state based on a small subset of our present data [21] does not

apply to such a broad resonance; thus the present results are consistent with our previous analysis. The statistical power of the present data sample is not sufficient to study its phase motion [44]. A model-dependent study discussed in Ref. [30] suggests that the $X(4140)$ structure may be affected by the nearby $D_s^{\pm}D_s^{*\mp}$ coupled-channel threshold. However, larger data samples will be required to resolve this issue.

We establish the existence of the $X(4274)$ structure with statistical significance of 6.0σ, at a mass of $4273.3 \pm 8.3^{+17.2}_{-3.6}$ MeV and a width of $56.2 \pm 10.9^{+8.4}_{-11.1}$ MeV. Its quantum numbers are determined to be $J^{PC} = 1^{++}$ at 5.8σ significance. Due to interference effects, the data peak above the pole mass, underlining the importance of proper amplitude analysis.

The high $J/\psi\phi$ mass region also shows structures that cannot be described in a model containing only K^{*+} states. These features are best described in our model by two $J^{PC} = 0^{++}$ resonances, $X(4500)$ (6.1σ) and $X(4700)$
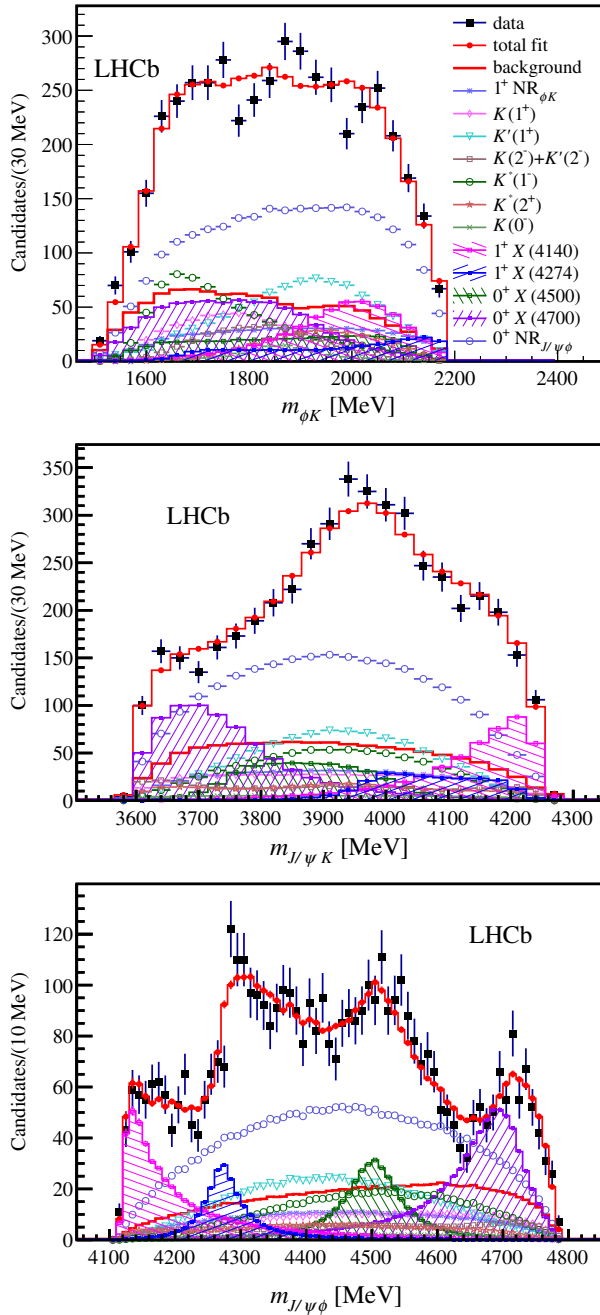
FIG. 3. Distributions of (top) ϕK^+, (middle) $J/\psi K^+$ and (bottom) $J/\psi\phi$ invariant masses for the $B^+ \to J/\psi\phi K^+$ candidates (black data points) compared with the results of the default amplitude fit containing eight $K^{*+} \to \phi K^+$ and five $X \to J/\psi\phi$ contributions. The total fit is given by the red points with error bars. Individual fit components are also shown.

(5.6σ), with parameters given in Table II. The resonances interfere with a nonresonant $J^{PC} = 0^{++} J/\psi\phi$ contribution that is also significant (6.4σ). The significances of the quantum number determinations for the high mass states are 4.0σ and 4.5σ, respectively.

In summary, we have performed the first amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays. We have obtained a

good description of the data in the 6D phase space composed of invariant masses and decay angles. The K^{*+} amplitude model extracted from our data is consistent with expectations from the quark model and from the previous experimental results on such resonances. We determine the J^{PC} quantum numbers of the $X(4140)$ structure to be 1^{++}. This has a large impact on its possible interpretations, in particular ruling out the 0^{++} or 2^{++} $D_s^{*+}D_s^{*-}$ molecular models [3–8]. The $X(4140)$ width is substantially larger than previously determined. The below-$J/\psi\phi$-threshold $D_s^{\pm}D_s^{*\mp}$ cusp [9,18] may have an impact on the $X(4140)$ structure, but more data will be required to address this issue, as discussed in more detail in the companion article [30]. The existence of the $X(4274)$ structure is established and its quantum numbers are determined to be 1^{++}. Molecular bound states or cusps cannot account for these J^{PC} values. A hybrid charmonium state would have 1^{-+} [15,16]. Some tetraquark models expected 0^{-+}, 1^{-+} [11] or 0^{++}, 2^{++} [12] state(s) in this mass range. A tetraquark model implemented by Stancu [10] not only correctly assigned 1^{++} to $X(4140)$, but also predicted a second 1^{++} state at a mass not much higher than the $X(4274)$ mass. Calculations by Anisovich *et al.* [13] based on the diquark tetraquark model predicted only one 1^{++} state at a somewhat higher mass. Lebed and Polosa [14] predicted the $X(4140)$ peak to be a 1^{++} tetraquark, although they expected the $X(4274)$ peak to be a 0^{-+} state in the same model. A lattice QCD calculation with diquark operators found no evidence for a 1^{++} tetraquark below 4.2 GeV [45].

The high $J/\psi\phi$ mass region is investigated for the first time with good sensitivity and shows very significant structures, which can be described as two 0^{++} resonances: $X(4500)$ and $X(4700)$. The work of Wang *et al.* [46] predicted a virtual 0^{++} $D_s^{*+}D_s^{*-}$ state at 4.48 ± 0.17 GeV. None of the observed $J/\psi\phi$ states is consistent with the state seen in two-photon collisions by the Belle Collaboration [27].

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