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We report inclusive and exclusive measurements for χ_{c1} and χ_{c2} production in B decays. We measure $\mathcal{B}(B \to \chi_{c1}X)= (3.03 \pm 0.05(\mathrm{stat}) \pm 0.24(\mathrm{syst})) \times 10^{-3}$ and $\mathcal{B}(B \to \chi_{c2}X)= (0.70 \pm 0.06(\mathrm{stat}) \pm 0.10(\mathrm{syst})) \times 10^{-3}$. For the first time, χ_{c2} production in exclusive B decays in the modes $B^0 \to \chi_{c2}\pi^-K^+$ and $B^+ \to \chi_{c2}\pi^+\pi^-K^+$ has been observed, along with first evidence for the $B^+ \to \chi_{c2}\pi^+K^0_S$ decay mode. For χ_{c1} production, we report the first observation in the $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^0 \to \chi_{c1}\pi^+\pi^-K^0_S$ and $B^0 \to \chi_{c1}\pi^0\pi^-K^+$ decay modes. Using these decay modes, we observe a difference in the production mechanism of χ_{c2} in comparison to χ_{c1} in B decays. In addition, we report searches for $X(3872)$ and $\chi_{c1}(2P)$ in the $B^+ \to (\chi_{c1}\pi^+\pi^-)K^+$ decay mode. The reported results use 772×10^6 $B\overline{B}$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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I. INTRODUCTION

Belle reported the first observation of χ_{c2} production in B meson decays with an inclusive measurement [1]. The $\chi_{cJ}(J = 1, 2)$ [2] momentum distributions in the $\Upsilon(4S)$ rest frame (CM frame) indicate that most of the χ_{c2} mesons come from non-two-body B decays [1, 3]. Still, there have been only a few searches for exclusive B decays with a χ_{c2} in the final state, $B^+ \to \chi_{c2}K^+$ [4] and $B^0 \to \chi_{c2}K^*(892)^0$ [5–7]. The $B^+ \to \chi_{c2}K^{(*)}$ decays are found to be highly suppressed with respect to the similar χ_{c1} processes [8]. The suppression can be explained in the framework of the factorization in two-body B decays [9], where χ_{c2} production is allowed only when one takes into account final state interactions. Due to angular momentum conservation, $J^{PC} = 0^{-+}$, 1^{--} and 1^{++} are favored while 0^{++}, 2^{++}, 2^{--} and so on are suppressed.

A study of the multi-body B decay modes with χ_{c1} and χ_{c2} in the final state is important to understand the detailed dynamics of B meson decays. Further, one can search for charmonium/charmonium-like exotic states in one of the intermediate final states such as $\chi_{cJ}\pi$ and $\chi_{cJ}\pi\pi$. For example, looking at the $\chi_{c1}\pi^+\pi^-$ invariant mass spectrum in $B \to \chi_{c1}\pi^+\pi^-K$ decays, one can search for $\chi_{c1}(2P)$ and/or $X(3872)$. The quantum numbers of the narrow exotic resonance $X(3872)$ have been determined to be $J^{PC} = 1^{++}$ [10–12]. One plausible interpretation is an admixture of a $D^0\bar{D}^{*0}$ molecule and a conventional charmonium with the same J^{PC}, the yet-unseen $\chi_{c1}(2P)$ [13]. The $\chi_{c1}(2P)$ component may have a substantial decay rate to $\chi_{c1}\pi^+\pi^-$ because of no obvious conflict in quantum numbers and observations of di-pion transitions between χ_{bJ} states in the bottomonium system. In case that $X(3872)$ is not a mixed state and hence $\chi_{c1}(2P)$ is a physically observable state, its decay to $\chi_{c1}\pi^+\pi^-$ would still be expected. Its mass is predicted to be about 3920 MeV/c^2, assuming that it lies between $\chi_{c2}(2P)$ and the $X(3915)$ that is interpreted as $\chi_{c0}(2P)$ by PDG [8].

Using the $\chi_{cJ} \to J/\psi\gamma$ modes, we report on the inclusive branching fractions ($\mathcal{B}$) of $B \to \chi_{cJ}X$ decays and the exclusive reconstruction of multi-body B decays to χ_{cJ} in order to search for still-undiscovered intermediate states.

II. DATA SAMPLE AND DETECTOR

We use a data sample of 772×10^6 $B\bar{B}$ events collected with the Belle detector [14] at the KEKB asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance [15]. The Belle detector is a large-solid-angle spectrometer, which includes a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of 8736 CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect K_L^0 mesons and identify muons (KLM). The detector is described in detail elsewhere [14]. Two inner detector configurations were used. A first sample of 152×10^6 $B\bar{B}$ events was collected with a 2.0 cm radius beam-pipe and a 3-layer SVD, while the remaining 620×10^6 $B\bar{B}$ pairs were collected with a 1.5 cm radius beam pipe, a 4-layer silicon detector and modified CDC (the cathode part of the CDC replaced by a compact small cell-type drift chamber) [16].

III. EVENT SELECTION

We reconstruct inclusive χ_{cJ} from B decays. To suppress continuum background, we exploit the $\Upsilon(4S)$ decay topology. For the events passing the Belle standard hadronic event selection [17], we require the ratio of the second to zeroth Fox-Wolfram moment [18] to be less than 0.5. Charged tracks are required to originate from the vicinity of the interaction point (IP): the distance of closest approach to the IP is required to be within 3.5 cm along the beam direction and within 1.0 cm in the transverse plane. Photons are reconstructed from the energy deposition in the ECL by requiring no matching with any extrapolated charged track. To further avoid photons coming from neutral hadrons, we reject the photon candidate if the ratio of the energy deposited in the central array of 3×3 ECL cells to that deposited in the enclosing array of 5×5 cells is less than 0.85.

We use EVTGEN [19] with QED final state radiation by PHOTOS [20] for the generation of Monte-Carlo (MC) simulation events. A GEANT-based [21] MC simulation is used to model the response of the detector and determine the efficiency of the signal reconstruction.

The J/ψ meson is reconstructed via its decays to $\ell^+\ell^-$ ($\ell = e$ or μ) and selected by the invariant mass $M_{\ell\ell}$. For the di-muon mode, $M_{\ell\ell}$ is given by the invariant mass $M_{\mu^+\mu^-}$; for the di-electron mode, the four-momenta of all photons within 50 mrad with respect to the original direction of the e^+ or e^- tracks are included in $M_{\ell\ell} \equiv M_{e^+e^-(\gamma)}$ to reduce the radiative tail. The reconstructed invariant mass of the J/ψ candidates is required to satisfy 2.95 GeV/c^2 $< M_{e^+e^-(\gamma)} <$ 3.13 GeV/c^2 or 3.03 GeV/c^2 $< M_{\mu^+\mu^-} <$ 3.13 GeV/c^2. For the selected J/ψ candidates, a vertex-constrained fit is applied to the charged tracks and then a mass-constrained fit is performed to improve its momentum resolution. The χ_{c1} and χ_{c2} candidates are reconstructed by combining a J/ψ candidate with a photon having an energy larger than 100 MeV.

IV. INCLUSIVE B DECAYS TO χ_{cJ}

A. Branching fraction measurement

To reduce combinatorial background coming from $\pi^0 \to \gamma\gamma$, we use a likelihood function that distinguishes an isolated photon from π^0 decays using the photon-pair invariant mass, the photon laboratory-frame energy, and the laboratory-frame polar angle with respect to the beam direction [22]. We reject both photons of a pair whose π^0 likelihood probability is larger than 0.3. Applying this cut, combinatorial background is reduced by 56.9% (59.1%) with a signal loss of 26.5% (39.9%) for χ_{c2} (χ_{c1}).

To identify the signal, we use the distribution of the $J/\psi\gamma$ invariant mass $M_{J/\psi\gamma}$ and extract the signal yield from a binned maximum likelihood fit. The signal of χ_{cJ} is described by a double-sided Crystal Ball function [23, 24], which accommodates the tails of the mass distribution. The function's left (right) side tail parameters n_l (n_r) and α_l (α_r) are fixed to the values obtained from MC simulated events. For $B \to \chi_{c1}X$, all other shape parameters are floated in the fit whereas, for $B \to \chi_{c2}X$, they are fixed using the mass difference ($m_{\chi_{c2}} - m_{\chi_{c1}}$) from Ref. [8] and the resolution ratio between χ_{c1} and χ_{c2}, $\sigma_{\chi_{c2}}/\sigma_{\chi_{c1}}$, determined from MC simulations. The combinatorial background component is modeled with a third-order Chebyshev polynomial.

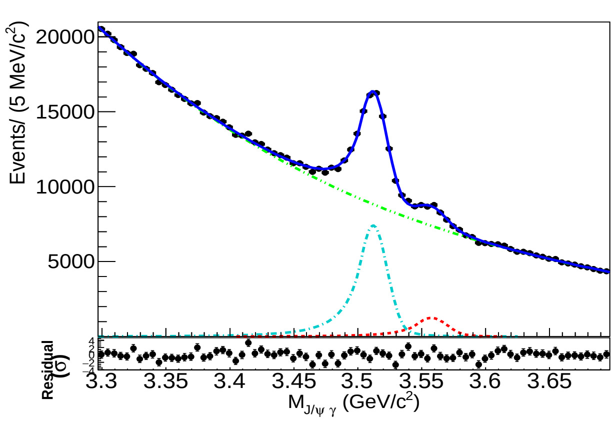

FIG. 1: (color online) $M_{J/\psi\gamma}$ distribution of the $B \to \chi_{cJ}(\to J/\psi(\to \ell^+\ell^-)\gamma)X$ decays in data. The curves show the signal (cyan dash-dotted for χ_{c1} and red dashed for χ_{c2}) and the background component (green dash-double-dotted for combinatorial) as well as the overall fit (blue solid). The lower plot shows the pull of the residuals with respect to the fit.

Figure 1 shows the fit of the $M_{J/\psi\gamma}$ distribution for $\chi_{c1}X$ and $\chi_{c2}X$ decays in the range of [3.297, 3.697] GeV/c^2. The fit returns a reduced χ^2 of 1.3 with a p-value of 0.0123 and a yield of 51353 ± 614 events for the χ_{c1} and 9651 ± 446 events for the χ_{c2}, where the errors are statistical.

The reconstruction efficiencies for the inclusive $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ decays are estimated to be 24.2% and 25.9%, respectively. The efficiency is estimated using simulated multi-body B decays, $B \to \chi_{cJ}K(n\pi)$, where the number of pions n varies from 0 to 4 over the entire $p^*_{\chi_{cJ}}$ range; it is averaged with proper weighting according to the distribution of $p^*_{\chi_{cJ}}$ in data.

We use the 2014 world-average values [8] for secondary daughter branching fractions $\mathcal{B}(J/\psi \to l^+l^-) = (11.932 \pm 0.004)\%$, $\mathcal{B}(\chi_{c1} \to J/\psi\gamma) = (33.9 \pm 1.2)\%$, and $\mathcal{B}(\chi_{c2} \to J/\psi\gamma) = (19.2 \pm 0.7)\%$.

We use the 89 fb^{-1} off-resonance data sample taken at 60 MeV below the $\Upsilon(4S)$ resonance to estimate the contribution of χ_{cJ} particles that do not arise from B meson decays. From the fit to the $M_{J/\psi\gamma}$ distribution for that sample, we obtain 139 ± 38 (92 ± 38) signal events for χ_{c1} (χ_{c2}), corresponding to 1098 ± 300 (727 ± 300) signal events for $\chi_{c1}X$ ($\chi_{c2}X$) after proper scaling to the integrated luminosity at the $\Upsilon(4S)$ resonance. The scaled χ_{c1} and χ_{c2} continuum yields are subtracted from the on-resonance yields.

One also expects a contribution from "feed-down" $B \to \chi_{cJ}X$ decays where the χ_{cJ} is from the cascade $B \to \psi'X \to \chi_{cJ}\gamma X$. To determine the rate for direct decays to the χ_{cJ} states, we subtract this feed-down contribution, which is estimated using $\mathcal{B}(B \to \psi'X)$ and $\mathcal{B}(\psi' \to \chi_{cJ}\gamma)$ from Ref. [8].

The sources and estimates of the systematic uncertainties are summarized in Table I. A correction for small differences in the signal detection efficiency between MC and data has been applied for the lepton identification requirements. Uncertainties in these corrections are included in the systematic error. The $e^+e^- \to e^+e^-\ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ ($\ell = e$ or μ) samples are used to estimate the lepton identification correction. The uncertainty of the probability density function (PDF) shapes are obtained by varying all fixed parameters by $\pm 1\sigma$, fitting with different binning, and using a fourth-order polynomial for the background, then adding the changes in the yield in quadrature to get the systematic uncertainty. We perform a fit to the data by including the χ_{c0} component and find its statistical significance to be 1.7σ. We further add the signal yield difference for χ_{c1} or χ_{c2} with respect to the original fit to the PDF systematic uncertainty. Based on this, we get an uncertainty of 3.1% (7.9%) for $B \to \chi_{c1}X$ ($B \to \chi_{c2}X$). The uncertainties due to the secondary branching fractions are also taken into account. The uncertainty on the track finding efficiency is found to be 0.35% per track by comparing the data and MC for $D^* \to D^0\pi$ decay, where $D^0 \to \pi^+\pi^-K^0_S$ and $K^0_S \to \pi^+\pi^-$ here one of the π is allowed not to be reconstructed explicitly. For $N_{B\bar{B}}$, systematic uncertainty is estimated to be 1.4%. The uncertainty on the photon identification is estimated to be 2.0% from sample of radiative Bhabha events. The systematic uncertainty associated with the difference of the π^0 veto between data and MC is estimated to be 1.2% from a study of the $B^\pm \to \chi_{c1}(\to J/\psi\gamma)K^\pm$ sample. The potential bias to extract signal yields of the χ_{cJ} is estimated by the MC from variation of the efficiency for the different decay modes bin by bin in the $p^*_{\chi_{cJ}}$ distribution. The efficiency change due to the unknown χ_{cJ} polarization is estimated using the $B^0 \to \chi_{c1}K^{*0}$ signal MC samples by varying the polarization over the allowed range. The sum of these two effects is 4.0%.

We measure the feed-down-contaminated branching fractions $\mathcal{B}(B \to \chi_{c1}X)$ and $\mathcal{B}(B \to \chi_{c2}X)$ to be $(3.33\pm0.05\pm0.24)\times10^{-3}$ and $(0.98\pm0.06\pm0.10)\times10^{-3}$, respectively, where the first (second) error is statistical (systematic). After subtracting the feed-down contribution, we obtain the pure inclusive branching fractions $\mathcal{B}(B \to \chi_{c1}X) = (3.03 \pm 0.05 \pm 0.24) \times 10^{-3}$ and $\mathcal{B}(B \to \chi_{c2}X) = (0.70 \pm 0.06 \pm 0.10) \times 10^{-3}$. In both cases, the systematic uncertainty dominates. We estimate the inclusive branching fractions according to the formula:

$$\mathcal{B}(B \to \chi_{cJ}X) = \frac{N_{\rm sig} - N_{\rm off}}{\epsilon \times N_B \times \mathcal{B}(\chi_{cJ} \to J/\psi\gamma) \times \mathcal{B}(J/\psi \to \ell^+\ell^-)} - \mathcal{B}(B \to \psi' X) \times \mathcal{B}(\psi' \to \chi_{cJ}\gamma)$$

Here, $N_{\rm sig}$ is the obtained signal yield, $N_{\rm off}$ is the estimated off-resonance contribution, ϵ is the reconstruction efficiency, N_B is the number of B mesons in the data sample and $\mathcal{B}$ is the branching fraction for the particular mode taken from [8].

TABLE I: Summary of systematic uncertainties in the $B \to \chi_{cJ}X$ branching fraction.

	Uncertainty (%)	
Source	$B \to \chi_{c1}X$	$B \to \chi_{c2}X$
Lepton identification	2.3	2.3
PDF uncertainty	3.1	7.9
Secondary $\mathcal{B}$	3.6	3.7
Tracking efficiency	0.7	0.7
$N_{B\bar{B}}$	1.4	1.4
Photon efficiency	2.0	2.0
π^0 veto	1.2	1.2
$B \to \chi_{cJ}X$ modeling	4.0	4.0
ψ' feed-down	1.0	3.0
Total	7.3	10.7

The ratio $\mathcal{R}_\mathcal{B} \equiv \mathcal{B}(B \to \chi_{c2}X)/\mathcal{B}(B \to \chi_{c1}X)$ is $(23.1 \pm 2.0 \pm 2.1)$%. Here, most of the systematics cancel except for the PDF uncertainty (4.5%), secondary $\mathcal{B}$ (4.7%), unknown polarization (5.6%), and feed-down (2.1%).

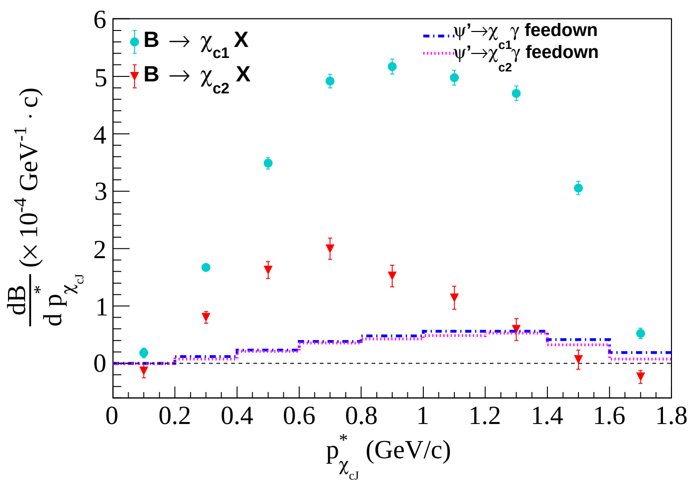

FIG. 2: (color online) Differential branching fractions $D\mathcal{B}(B \to \chi_{c1}X)$ with cyan circles (●) and $D\mathcal{B}(B \to \chi_{c2}X)$ with red triangles (▼) in each bin of $p^*_{\chi_{cJ}}$ extracted from the maximum likelihood (ML) fits performed with the ΔM distribution of the data sample for $B \to \chi_{cJ}(\to J/\psi\gamma)X$ after continuum suppression but without feed-down subtraction. The ψ' feed-down component (estimated from the MC simulation using ψ' momentum distribution presented in Ref. [3]) is shown by blue dash-dotted (magenta dotted) line for χ_{c1} (χ_{c2}). The uncertainties in these plots are statistical only.

B. $p^*_{\chi_{cJ}}$ distribution

The distribution of the χ_{cJ} momentum in the e^+e^- center-of-mass frame, $p^*_{\chi_{cJ}}$, provides valuable insight into the production mechanism of the χ_{cJ}. To obtain the $p^*_{\chi_{cJ}}$ distribution, we fit the $M_{J/\psi\gamma}$ distribution in bins of $p^*_{\chi_{cJ}}$. We fix all of the signal parameters to the values obtained from the fit to the total and the resolution in each bin to the value obtained from the signal MC after MC/data correction. The background shape and normalization are floated in all fits. The fitted χ_{c1} and χ_{c2} yields are converted into differential branching fractions ($D\mathcal{B}$) after subtraction of the continuum contribution in each bin, estimated from the continuum data. In the absence of reliable bin by bin estimation of the feed-down contribution, we do not apply feed-down subtraction here. Efficiency corrections are applied to each bin. Figure 2 shows the resulting distributions of $D\mathcal{B}$ in bins of $p^*_{\chi_{cJ}}$. Suppression of the two-body decay of χ_{c2} is visible in the $p^*_{\chi_{cJ}}$ distribution. Most of the χ_{c2} production comes from three- or higher-body decays.

V. EXCLUSIVE RECONSTRUCTION

To further understand χ_{c1} and χ_{c2} production in B decays, we reconstruct the following exclusive B decays: $B^0 \to \chi_{cJ}\pi^- K^+$, $B^+ \to \chi_{cJ}\pi^+ K^0_S$, $B^+ \to \chi_{cJ}\pi^0 K^+$, $B^+ \to \chi_{cJ}\pi^+\pi^- K^+$, $B^0 \to \chi_{cJ}\pi^+\pi^- K^0_S$ and $B^0 \to \chi_{cJ}\pi^-\pi^0 K^+$ [25].

The χ_{c1} and χ_{c2} candidates are reconstructed as in the inclusive study except for a looser criterion to reduce the $\pi^0 \to \gamma\gamma$ background, requiring the π^0 likelihood probability to be less than 0.8. Applying this cut, the combinatorial background is reduced by 30-35% with a signal loss of 6-11% depending upon the mode of interest. The reconstructed invariant mass of the χ_{c1} (χ_{c2}) is required to satisfy 3.467 GeV/c^2 $< M_{J/\psi\gamma} <$ 3.535 GeV/c^2 (3.535 GeV/c^2 $< M_{J/\psi\gamma} <$ 3.579 GeV/c^2). The selected mass windows correspond to $[-4.5\sigma, +2.8\sigma]$ for χ_{c1} and $[-1.5\sigma, +3.0\sigma]$ for χ_{c2} around their nominal mass. A mass-constrained fit is applied to the selected χ_{c1} and χ_{c2} candidates.

The combined information from the CDC, TOF and ACC is used to identify charged kaons and pions based on the K/π likelihood ratio, $R_K = \mathcal{L}_K/(\mathcal{L}_K+\mathcal{L}_\pi)$, where $\mathcal{L}_K$ and $\mathcal{L}_\pi$ are likelihood values for the kaon and pion hypotheses, respectively. A track is identified as a kaon if R_K is greater than 0.6; otherwise, it is classified as a pion. The kaon (pion) identification efficiency lies in the range of $87-94\%$ $(94-97\%)$ while the probability of misidentifying a pion (kaon) as a kaon (pion) is $6.8-10.4\%$ $(6.5-7.0\%)$, depending on the momentum range of kaons and pions. To ensure that tracks with low transverse momentum (p_T) with respect to the beam axis are included only once as they can curl up and result in duplicate tracks, criteria similar to those of Refs. [26, 27] are used: duplicated tracks for charged pions with $p_T <$ 0.25 GeV/c often appear as the track pair having $\cos\theta_{\rm open} > 0.95$ ($\cos\theta_{\rm open} < -0.95$) for same (opposite) charged tracks, where $\theta_{\rm open}$ is the angle between the two tracks. Among those, when the difference between the absolute value of the momentum of the two tracks is less than 0.1 GeV/c, it is treated as a duplicate pair. Of the two such tracks, the one having the closest approach to the IP is retained.

K^0_S mesons are reconstructed by combining two oppositely charged pions with an invariant mass $M_{\pi^+\pi^-}$ lying between 482 and 514 MeV/c^2 ($\pm 6\sigma$ around the nominal mass of the K^0_S). The selected candidates are required to satisfy the quality criteria described in Ref. [28]. Pairs of photons are combined to form π^0 candidates within the mass range 120 MeV/c^2 $< M_{\gamma\gamma} <$ 150 MeV/c^2 ($\pm 3\sigma$ around the nominal mass of π^0). To reduce combinatorial background, the $\pi^0 \to \gamma\gamma$ candidates are also required to have an energy balance parameter $|E_1 - E_2|/(E_1 + E_2)$ smaller than 0.8, where E_1 (E_2) is the energy of the first (second) photon in the laboratory frame. For each selected π^0 candidate, a mass-constrained fit is performed to improve its momentum resolution.

To identify the B meson, two kinematic variables are used: the beam-constrained mass $M_{\rm bc}$ and the energy difference ΔE. The former is defined as $\sqrt{E^2_{\rm beam}/c^2 - (\sum_i \vec{p}_i)^2}/c$ and the latter as $\sum_i E_i - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy in the CM frame and p_i (E_i) is the momentum (energy) of the i-th daughter particle in the CM frame; the summation is over all final-state particles used for reconstruction. We reject candidates having $M_{\rm bc}$ less than 5.27 GeV/c^2 or $|\Delta E| >$ 120 MeV. In case of multiple B candidates, we use a statistic χ^2, defined as:

$$\chi^2 = \chi^2_V + \chi^2_N + (\frac{M_{\chi_{cJ}} - m_{\chi_{cJ}}}{\sigma_{\chi_{cJ}}})^2 + (\frac{M_{\rm bc} - m_B}{\sigma_{M_{\rm bc}}})^2,$$

where χ^2_V is the reduced χ^2 returned by the vertex fit of all charged tracks, χ^2_N is the reduced χ^2 for the K^0_S or π^0 mass-constrained fit, $M_{\chi_{cJ}}$ is the reconstructed mass of χ_{cJ}, and $m_{\chi_{cJ}}$ and m_B are the nominal masses of the χ_{cJ} and B mesons, respectively. The resolution $\sigma_{M_{\rm bc}}$ of $M_{\rm bc}$, estimated from the fit to data, is 3 MeV/c^2. The resolution $\sigma_{\chi_{c1}}$ ($\sigma_{\chi_{c2}}$) of χ_{c1} (χ_{c2}), is taken to be 9.5 MeV (10.5 MeV) from the inclusive measurements. The B candidate with the lowest χ^2 value is retained. The procedure to select the most probable B candidate is called best candidate selection (BCS). After the reconstruction, mean of 1.1-2.7 B candidates per event is found, depending on the decay mode, and the BCS chooses the true candidate 75-98% of the time.

We extract the signal yield from an unbinned extended maximum likelihood (UML) fit to the ΔE variable. The signal PDF is modeled by the sum of two Gaussians unless otherwise explicitly mentioned. The parameters of the wider Gaussian are fixed from MC simulations while the mean and the width of the core Gaussian are treated according to the B decay mode. For the $B \to \chi_{c1}X$ decay modes, the parameters of the core Gaussian are floated unless otherwise stated. For $B \to \chi_{c2}X$, the core Gaussian is fixed after a data/MC correction estimated from the $B \to \chi_{c1}X$ decay mode; otherwise, a correction from the other decay mode is implemented.

To study the background from events with a J/ψ, we use a large MC-simulated $B \to J/\psi X$ sample corresponding to 100 times the integrated luminosity of the data sample. The non-J/ψ (non-χ_{cJ}) background is studied using $M_{\ell\ell}$ ($M_{J/\psi\gamma}$) sidebands in data. For $B \to \chi_{c1}X$, no significant peaking background is found. However, in the $B \to \chi_{c2}X$ modes, there can be a contamination from $B \to \chi_{c1}X$ because of its larger branching fraction.We call this effect $B \to \chi_{c1}X$ cross-feed. Since we apply a mass-constrained fit for $\chi_{c2} \to J/\psi\gamma$ candidates, this cross-feed tends to cluster around $\Delta E = +50$ MeV. This peaking background is parameterized by a Gaussian whose yield and parameters are fixed from the signal MC study after applying a MC/data correction estimated from the $B \to \chi_{c1}X$ decay mode. The flat background in all decay modes is modeled with a Chebyshev first-

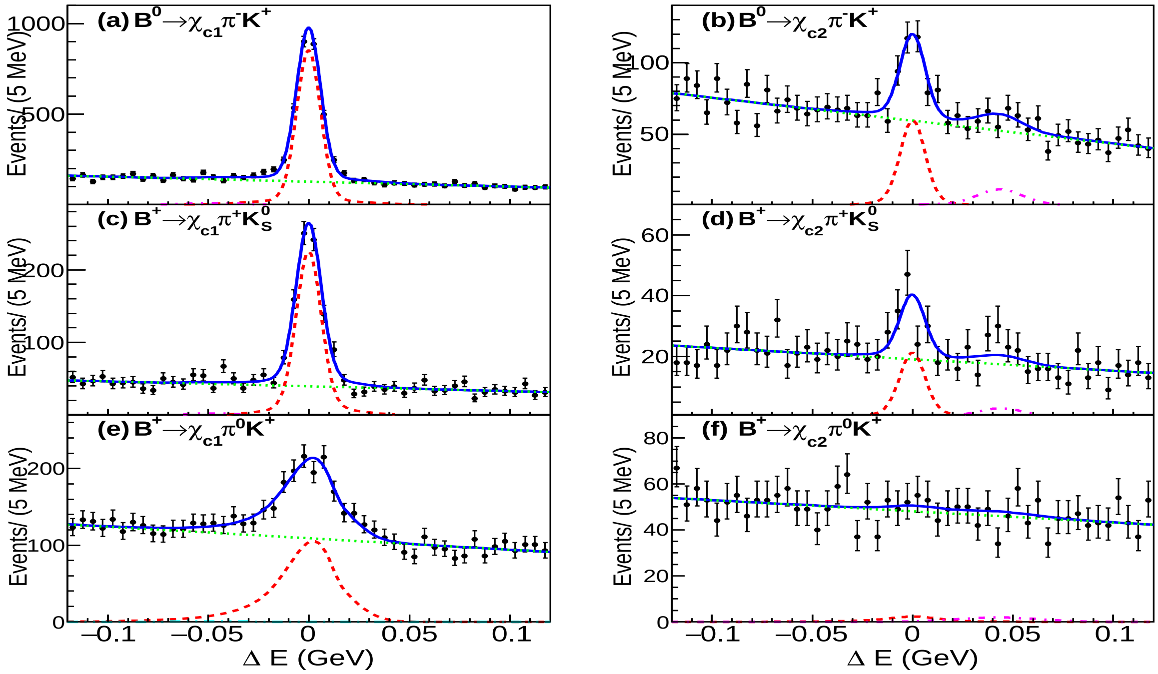

FIG. 3: (color online) ΔE distribution for the (a) $B^0 \to \chi_{c1}\pi^- K^+$, (b) $B^0 \to \chi_{c2}\pi^- K^+$, (c) $B^+ \to \chi_{c1}\pi^+ K^0_S$, (d) $B^+ \to \chi_{c2}\pi^+ K^0_S$, (e) $B^+ \to \chi_{c1}\pi^0 K^+$, and (f) $B^+ \to \chi_{c2}\pi^0 K^+$ decay modes. The curves show the signal (red dashed), the peaking background (magenta dash-dotted) and the background component (green dotted for combinatorial) as well as the overall fit (blue solid).

order polynomial unless otherwise explicitly mentioned. For the $B \to \chi_{c1} X$ decay modes, the PDF comprises the signal PDF and a flat background; for $B \to \chi_{c2} X$ decay modes, the PDF comprises the signal PDF, the $B \to \chi_{c1} X$ cross-feed and a flat background.

To understand the intermediate states, we examine the background-subtracted $M_{\chi_{cJ}\pi}$, $M_{K\pi}$, $M_{\chi_{cJ}\pi\pi}$, $M_{K\pi\pi}$, and $M_{\pi\pi}$ distributions for the decay mode of interest. We perform a UML fit to the ΔE distribution and use the ${}_s\mathcal{P}lot$ formalism [29] to project signal events in the distribution.

The efficiency (ϵ) for each decay mode is estimated using MC simulation generated over the whole phase space. In the absence of information regarding the intermediate state and a proper model for each decay mode, we divide the sample according to the $M_{Kn\pi}$ and $M_{\chi_{cJ}n\pi}$ distributions, where $n \in \{1, 2\}$ is the number of pions, so that each bin indexed by i has equal statistics. The efficiency estimated in each bin (ϵ_i) using MC simulation is then weighted by the signal yield of the bin to provide the final efficiency $\epsilon = \sum_i w_i \epsilon_i$, where w_i = yield in i-th bin / total yield. In decay modes having no significant signal, the efficiency is simply estimated using MC simulation generated over the whole phase space as distribution is unknown. We calibrate this efficiency by the difference between MC simulation and data, as described later. The so-estimated efficiency for the decay mode of interest lies between 4.3% and 18.0%, depending upon the final states used for the reconstruction.

A. $B \to \chi_{cJ}\pi K$

To study χ_{cJ} production in three-body B decays, we use charged and neutral kaons and pions to reconstruct the B decay mode of interest: $B^0 \to \chi_{cJ}\pi^- K^+$, $B^+ \to \chi_{cJ}\pi^+ K^0_S$ and $B^+ \to \chi_{cJ}\pi^0 K^+$. The signal is identified using kinematic requirements on ΔE and $M_{\rm bc}$. Among the events containing B candidates, 10%, 16% and 22% have multiple candidates in the $B^0 \to \chi_{cJ}\pi^- K^+$, $B^+ \to \chi_{cJ}\pi^+ K^0_S$ and $B^+ \to \chi_{cJ}\pi^0 K^+$ modes, respectively. The aforementioned BCS procedure is used to select the B candidate in such events.

The UML fit to the ΔE distribution for the $B^0 \to \chi_{cJ}\pi^- K^+$ and $B^+ \to \chi_{cJ}\pi^+ K^0_S$ decay modes is shown in Fig. 3 (a)-(d). For $B^+ \to \chi_{cJ}\pi^0 K^+$ decays, the signal is modeled by the sum of a Gaussian and a logarithmic Gaussian [30]. For $B^+ \to \chi_{c1}\pi^0 K^+$ decays, the mean and width of the core Gaussian are floated and the remaining parameters are fixed according to MC; for $B^+ \to \chi_{c2}\pi^0 K^+$ decays, all parameters are fixed after applying the data/MC correction estimated from the $B^+ \to \chi_{c1}\pi^0 K^+$ decay mode. No peaking background is expected in the $B^+ \to \chi_{c1}\pi^0 K^+$ decay mode while, in $B^+ \to \chi_{c2}\pi^0 K^+$, feed-down from $B^+ \to \chi_{c1}\pi^0 K^+$ is expected and is modeled by a Gaussian PDF (whose yield and all parameters are fixed from MC simulation study). The rest of the background is combinatorial and modeled using a first-order Chebyshev polynomial. The fit to the ΔE distribution for $B^+ \to \chi_{cJ}\pi^0 K^+$ is shown in Fig. 3

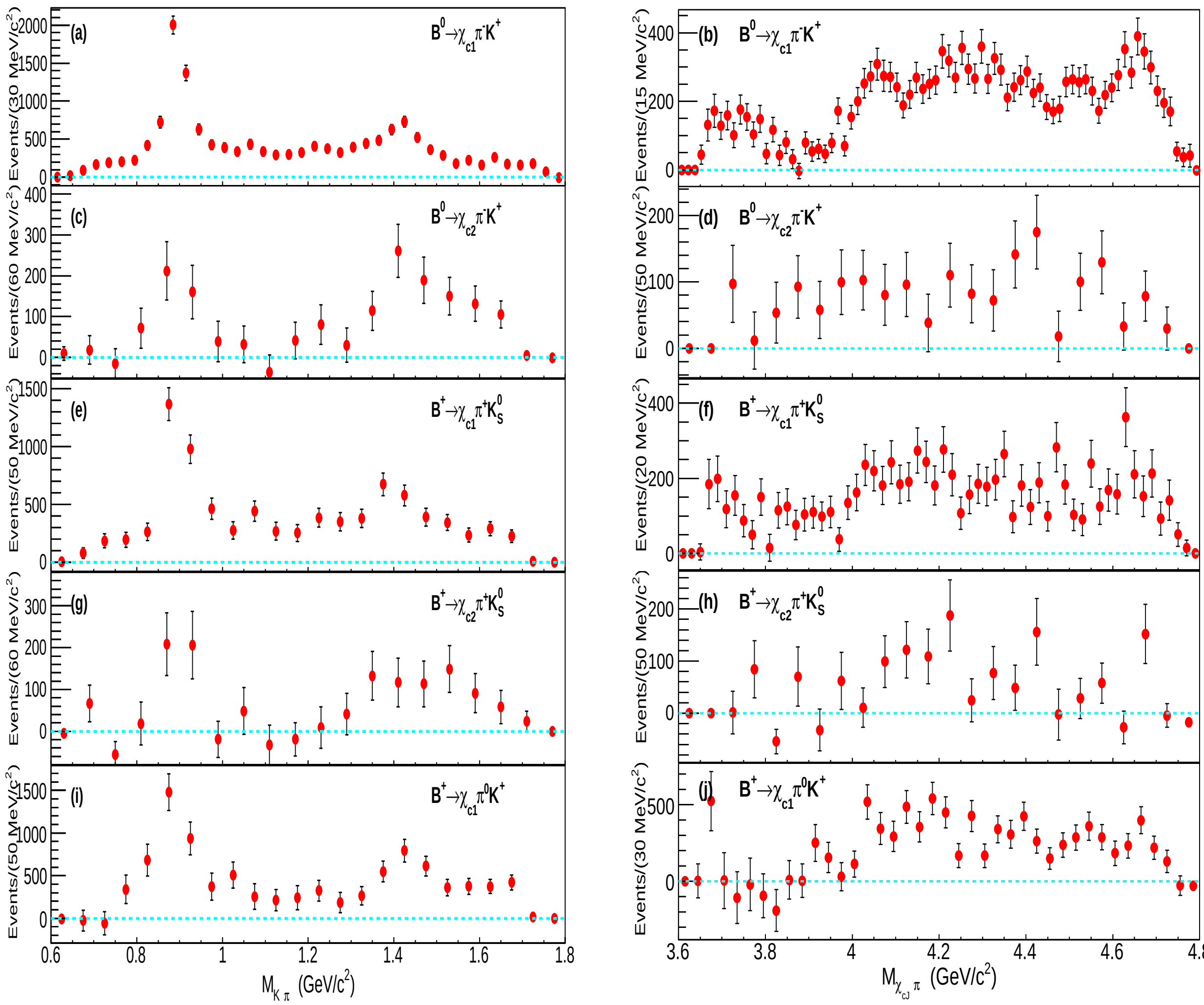

FIG. 4: (color online) Background subtracted efficiency corrected ${}_s\mathcal{P}lot$ $M_{K\pi}$ and $M_{\chi_{cJ}\pi}$ distributions for the (a and b) $B^0\to\chi_{c1}\pi^-K^+$, (c and d) $B^0\to\chi_{c2}\pi^-K^+$, (e and f) $B^+\to\chi_{c1}\pi^+K^0_S$, (g and h) $B^+\to\chi_{c2}\pi^+K^0_S$ and (i and j) $B^+\to\chi_{c1}\pi^0K^+$ decay modes.

(e) and (f).

We obtain 2774 ± 66 (206 ± 25), 770 ± 35 (76 ± 15) and 803 ± 70 (17.5 ± 28.4) signal events for the $B^0\to\chi_{c1}\pi^-K^+$ ($B^0\to\chi_{c2}\pi^-K^+$), $B^+\to\chi_{c1}\pi^+K^0_S$ ($B^+\to\chi_{c2}\pi^+K^0_S$) and $B^+\to\chi_{c1}\pi^0K^+$ ($B^+\to\chi_{c2}\pi^0K^+$) decay modes having a significance of 67σ (8.7σ), 34σ (4.6σ) and 16σ (0.4σ), respectively. The significance is estimated using the value of $-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})$, where $\mathcal{L}_{\rm max}$ ($\mathcal{L}_0$) denotes the likelihood value when the yield is allowed to vary (is set to zero). The systematic uncertainty, which is described below, is included in the significance calculation [31]. We make the first observation of the $B^0\to\chi_{c2}\pi^-K^+$ decay mode along with the first evidence for a $B^+\to\chi_{c2}\pi^+K^0_S$ decay. We estimate the branching fractions according to the formula $\mathcal{B}=Y/(\epsilon\times\mathcal{B}_s\times N_{B\bar{B}})$; here Y is the yield, ϵ is the reconstruction efficiency, $\mathcal{B}_s$ is the secondary branching fraction taken from Ref. [8], and $N_{B\bar{B}}$ is the number of $B\bar{B}$ mesons in the data sample. Equal production of neutral and charged B meson pairs in the $\Upsilon(4S)$ decay is assumed. Table II summarizes the results.

The $K^*(892)$ is found to be a major contribution in the $B\to\chi_{c1}\pi K$ decay modes as seen from Fig. 4 (a), (e) and (i); in $B\to\chi_{c2}\pi K$ decays, the $K^*(892)$ component is less prominent and a cluster of events around $M_{K^\pm\pi^\mp}=1.4$ GeV/c^2 shows a relatively large contribution. Our study suggests that the $B\to\chi_{c2}K^*(892)$ mechanism does not dominate the $B\to\chi_{c2}\pi K$ decay, in marked contrast to the χ_{c1} case. Until now, the previous measurements of χ_{c2} [6, 7] were limited to $B^0\to\chi_{c2}K^*(892)^0$ only and so were not able to observe three-body B decays. From this study, one may posit that the production mechanism of the χ_{c2} from B mesons is different in three-body decays for the $B\to\chi_{c1}\pi K$ case. As shown in Fig. 4 (b) and (f), the $M_{\chi_{c1}\pi^\pm}$ distributions are similar to those obtained by a previous Belle study [32] in which a Dalitz

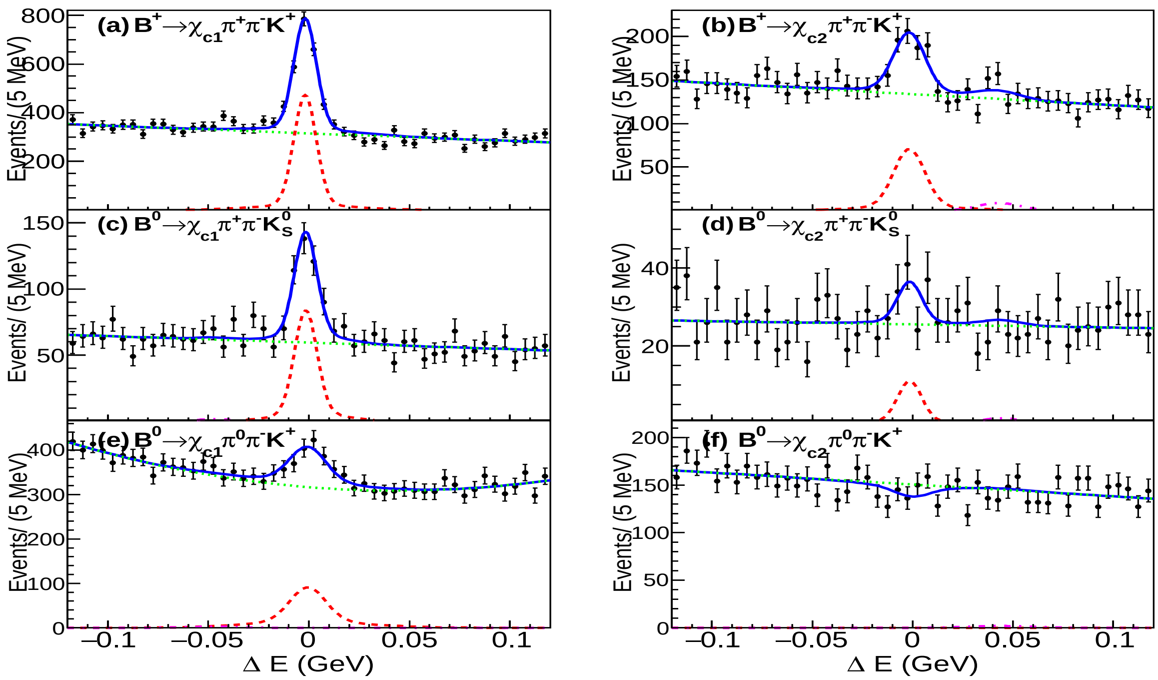

FIG. 5: (color online) ΔE distributions for the (a) $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, (b) $B^+ \to \chi_{c2}\pi^+\pi^-K^+$, (c) $B^0 \to \chi_{c1}\pi^+\pi^-K^0_S$, (d) $B^0 \to \chi_{c2}\pi^+\pi^-K^0_S$, (e) $B^0 \to \chi_{c1}\pi^0\pi^-K^+$ and (f) $B^0 \to \chi_{c2}\pi^0\pi^-K^+$ decay modes. The curves show the signal (red dashed), peaking background (magenta dash-dotted) and the background component (green dotted for combinatorial) as well as the overall fit (blue solid).

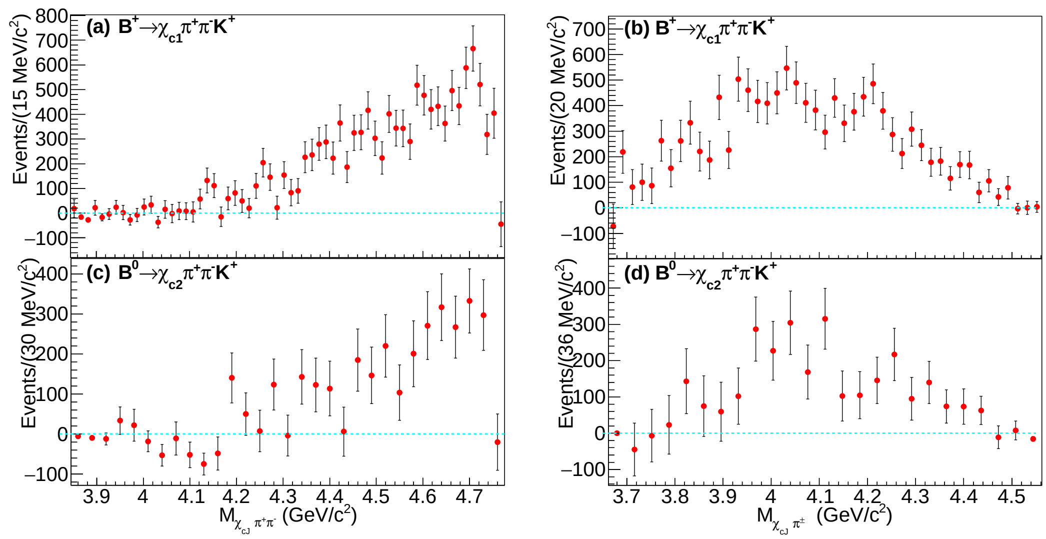

FIG. 6: (color online) Background subtracted efficiency corrected $_s\mathcal{P}lot$ (a) $M_{\chi_{c1}\pi^+\pi^-}$, (b) $M_{\chi_{c1}\pi^\pm}$, (c) $M_{\chi_{c2}\pi^+\pi^-}$ and (d) $M_{\chi_{c2}\pi^\pm}$ distributions for the $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$ decay modes.

analysis suggested two charged Z states decaying into $\chi_{c1}\pi^+$. Also, the $M_{\chi_{c1}\pi^0}$ distribution in Fig. 4 (j) shows a similar behavior as seen in the charged $M_{\chi_{c1}\pi^\pm}$ distribution. However, due to limited statistics, no noticeable feature in the $M_{\chi_{c2}\pi^+}$ spectrum is seen as shown in the corresponding Fig. 4 (d) and (h).

In decay modes where we find no significant signal, we determine a 90% C.L. upper limit (U.L.) on its branching fraction with a frequentist method that uses ensembles of pseudo-experiments. For a given signal yield, 10000 sets of signal and background events are generated according to their PDFs and fits are performed. The U.L. is de-

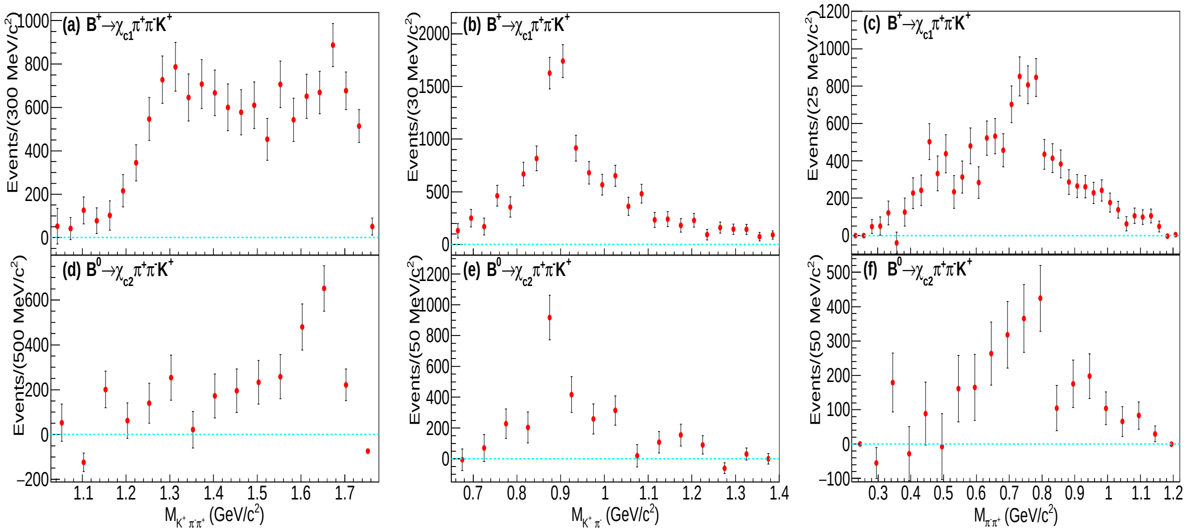

FIG. 7: (color online) Background subtracted efficiency corrected $_s\mathcal{P}lot$ (a and d) $M_{K^+\pi^+\pi^-}$, (b and e) $M_{K^+\pi^-}$ and (c and f) $M_{\pi^+\pi^-}$ distributions for $B^+ \to \chi_{c1}\pi^+\pi^-K^+$ decay (upper) and $B^+ \to \chi_{c2}\pi^+\pi^-K^+$ decay (lower), respectively.

termined from the fraction of samples that give a yield larger than that of data.

B. $B \to \chi_{cJ}\pi\pi K$

Each χ_{cJ} candidate is combined with a pair of oppositely charged pions (or a charged-neutral pair) and a kaon (either $K^\pm$ or K^0_S) to reconstruct the B decays of interest: $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$, $B^0 \to \chi_{cJ}\pi^+\pi^-K^0_S$ and $B^0 \to \chi_{cJ}\pi^-\pi^0K^+$ decay modes. Of the selected B candidates, identified by the ΔE and $M_{\rm bc}$ requirement, 35%, 35% and 50% have multiple candidates in the $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$, $B^0 \to \chi_{cJ}\pi^+\pi^-K^0_S$ and $B^0 \to \chi_{cJ}\pi^-\pi^0K^+$ decay modes, respectively. In case of multiple B candidates, the aforementioned BCS is used to select a single B candidate in the event.

The signal yield is extracted from a 1D UML fit to the ΔE distribution as shown in Fig. 5. We get 1502 ± 70 (269 ± 34), 268 ± 30 (37.8 ± 14.2) and 545 ± 81 (-76.7 ± 42.0) signal events with a 19.2σ (8.4σ), 7.1σ (1.8σ) and 6.5σ (null) significance for the $B^+ \to \chi_{c1}\pi^+\pi^-K^+$ ($B^+ \to \chi_{c2}\pi^+\pi^-K^+$), $B^0 \to \chi_{c1}\pi^+\pi^-K^0_S$ ($B^0 \to \chi_{c2}\pi^+\pi^-K^0_S$) and $B^0 \to \chi_{c1}\pi^-\pi^0K^+$ ($B^0 \to \chi_{c2}\pi^-\pi^0K^+$) decay modes, respectively. For the first time, we observe the $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^+ \to \chi_{c2}\pi^+\pi^-K^+$, $B^0 \to \chi_{c1}\pi^+\pi^-K^0_S$, and $B^0 \to \chi_{c1}\pi^-\pi^0K^+$ decay modes. Table II summarizes the fit results.

In order to understand the dynamics of the production of χ_{cJ} in four-body B decays, we examine the background-subtracted $_s\mathcal{P}lot$ distribution of $M_{\chi_{cJ}\pi\pi}$, $M_{\chi_{cJ}\pi^\pm}$, $M_{K\pi\pi}$, $M_{K^+\pi^-}$, and $M_{\pi^+\pi^-}$, which are shown in Figs. 6 and 7 for the $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$ decay mode. No narrow resonance can be seen in the $M_{\chi_{cJ}\pi^+\pi^-}$ and $M_{\chi_{cJ}\pi^\pm}$ distributions with the current statistics. There seems to be an enhancement of signal events around 4.1-4.2 GeV$/c^2$ in $M_{\chi_{cJ}\pi\pi}$ that is due to cross-feed; the same effect is seen in our $B \to J/\psi X$ MC sample that is used to study the background. Higher K^* resonances are seen in the $M_{K^+\pi^-\pi^+}$ and $M_{K^+\pi^-}$ distributions shown in Fig. 7 similar to the ones seen in the $B^+ \to J/\psi\pi^+\pi^-K^+$ decay mode [27]. There is a peaking structure near 1680 MeV$/c^2$ due to the $K^*(1680)^+$. Further, a $K^*(892)^0$ peak is found in $M_{K^+\pi^-}$. Here again, the contrast between $B^+ \to \chi_{c2}\pi^+\pi^-K^+$ decays and those to χ_{c1} is apparent: the decays to χ_{c2} mostly include higher K^* resonances. Figures 7 (e) and (f) show the $M_{\pi^+\pi^-}$ distributions for the $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$ decay mode, which suggest a contribution from ρ as an intermediate state.

Search for $X(3872)$ and $\chi_{c1}(2P)$

To search for the $X(3872) \to \chi_{c1}\pi^+\pi^-$, we investigate the signal in the $M_{\chi_{c1}\pi^+\pi^-}$ distribution within the signal-enhanced window of -20 MeV $< \Delta E <$ 20 MeV for $B^+ \to \chi_{c1}\pi^+\pi^-K^+$ candidates. In the absence of any significant peak as shown in Fig. 8, we count the number of events within the $\pm 3\sigma$ window and find no events. Therefore, we use 2.6 events as the upper limit of the signal yield based on the Feldman and Cousins approach [33] including systematic uncertainty of the detection efficiency. Using 5.6% as the corrected efficiency for $B^+ \to X(3872)(\to \chi_{c1}\pi^+\pi^-)K^+$ estimated from signal MC, we obtain $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \chi_{c1}\pi^+\pi^-) < 1.5 \times 10^{-6}$ (90% C.L.).

The $\chi_{c1}(2P)$ signal in the $M_{\chi_{c1}\pi\pi}$ spectrum is described by a PDF composed as the convolution of a Breit-Wigner function with a Gaussian. As a plausible as-

TABLE II: Summary of the results. Signal yield (Y) from the fit, significance ($\mathcal{S}$) with systematics included, corrected efficiency (ϵ) and measured $\mathcal{B}$. For $\mathcal{B}$, the first (second) error is statistical (systematic). Here, in the neutral B decay case, the $K^0_S \to \pi^+\pi^-$ branching fraction is included in the efficiency (ϵ) but the factor of 2 (for $K^0 \to K^0_S$ or K^0_L) is taken into account separately. $\mathcal{R}_{\mathcal{B}}$ is the ratio of $\mathcal{B}(B \to \chi_{c2}X)$ to $\mathcal{B}(B \to \chi_{c1}X)$, where X is the same set of particles accompanying the χ_{c1} (χ_{c2}) in the final states.

Decay	Yield (Y)	$\mathcal{S}(\sigma)$	$\epsilon(\%)$	$\mathcal{B}$ (10^{-4})	$\mathcal{R}_{\mathcal{B}}$
$B^0 \to \chi_{cJ}\pi^- K^+$					0.14 ± 0.02
χ_{c1}	2774 ± 66	66.7	17.9	$4.97 \pm 0.12 \pm 0.28$	
χ_{c2}	206 ± 25	8.7	16.2	$0.72 \pm 0.09 \pm 0.05$	
$B^+ \to \chi_{cJ}\pi^+ K^0$					0.20 ± 0.04
χ_{c1}	770 ± 35	33.7	8.6	$5.75 \pm 0.26 \pm 0.32$	
χ_{c2}	76.4 ± 14.7	4.6	7.5	$1.16 \pm 0.22 \pm 0.12$	
$B^+ \to \chi_{cJ}\pi^0 K^+$					< 0.21
χ_{c1}	803 ± 70	15.6	7.8	$3.29 \pm 0.29 \pm 0.19$	
χ_{c2}	17.5 ± 28.4	0.4	7.0	< 0.62	
$B^+ \to \chi_{cJ}\pi^+\pi^- K^+$					0.36 ± 0.05
χ_{c1}	1502 ± 70	19.2	12.8	$3.74 \pm 0.18 \pm 0.24$	
χ_{c2}	269 ± 34	8.4	11.4	$1.34 \pm 0.17 \pm 0.09$	
$B^0 \to \chi_{cJ}\pi^+\pi^- K^0$					< 0.61
χ_{c1}	268 ± 30	7.1	5.4	$3.16 \pm 0.35 \pm 0.32$	
χ_{c2}	37.8 ± 14.2	1.8	4.8	< 1.70	
$B^0 \to \chi_{cJ}\pi^-\pi^0 K^+$					< 0.25
χ_{c1}	545 ± 81	6.5	5.0	$3.52 \pm 0.52 \pm 0.24$	
χ_{c2}	-76.7 ± 42.0	—	4.3	< 0.74	

sumption for the $\chi_{c1}(2P)$ state, its mass and width are fixed at 3920 MeV/c^2 and 20 MeV, assuming the PDG interpretation of $X(3915)$=$\chi_{c0}(2P)$ and the property of $\chi_{c2}(2P)$ [8]. The width of the Gaussian is fixed to 2 MeV, corresponding to the detector resolution in the mass estimation obtained from MC simulated samples. The fit (shown in Fig. 8) results in a signal yield of 12.2 ± 9.1 events, which translates to 30.3 events at the 90% confidence level. A product branching fraction upper limit is extracted, including statistical and systematic uncertainties and the 8.9% reconstruction efficiency: $\mathcal{B}(B^+ \to \chi_{c1}(2P)K^+) \times \mathcal{B}(\chi_{c1}(2P) \to \chi_{c1}(1P)\pi^+\pi^-) < 1.1 \times 10^{-5}$ (90% C.L.).

Table III summarizes our search for $X(3872)$ and $\chi_{c1}(2P)$ in the $B^+ \to (\chi_{c1}\pi^+\pi^-)K^+$ decay mode.

TABLE III: U.L. for $B^+ \to X(\to \chi_{c1}\pi^+\pi^-)K^+$; here X stands for $X(3872)$ and the assumed $\chi_{c1}(2P)$. The upper limit at (90% C.L.) includes the systematics ($N^{U.L.}$), corrected efficiency (ϵ) and product of branching fractions $\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to \chi_{c1}\pi^+\pi^-)$ ($\mathcal{B}^{U.L.}$).

Mode	$Y^{U.L.}$	ϵ (%)	$\mathcal{B}^{U.L.}$ ($\times 10^{-5}$)
$X(3872)$	< 2.6	5.6	< 0.15
$\chi_{c1}(2P)$	< 30.3	8.9	< 1.10

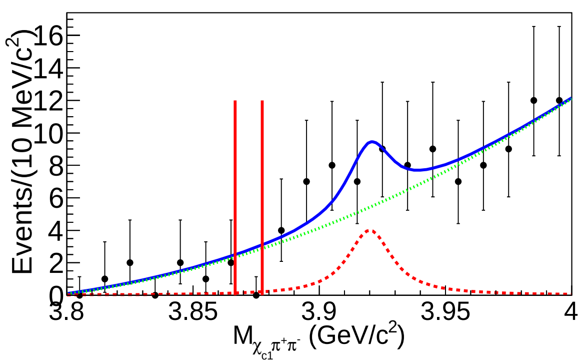

FIG. 8: (color online) The $\chi_{c1}\pi^+\pi^-$ invariant mass spectrum for $B^+ \to \chi_{c1}\pi^+\pi^- K^+$ candidates. Two vertical red lines show the $\pm 3\sigma$ window to search for $X(3872) \to \chi_{c1}\pi^+\pi^-$. The curves show the $\chi_{c1}(2P)$ signal (red dashed) and the background (green dotted) and the overall fit (blue solid).

C. Systematics

Table IV summarizes the systematic for each mode. Corrections for small differences in the signal detection efficiency between MC and data have been applied for the lepton and kaon identification requirements, as was done in the inclusive study. In addition to the items commonly affecting the inclusive branching fractions measurements, we consider the following systematic uncertainty sources. In Belle, dedicated $D^{*+} \to D^0(K^-\pi^+)\pi^+$ samples are used to estimate the kaon (pion) identification efficiency correction. To estimate the correction and residual systematic uncertainty for K_S^0 reconstruction, $D^{*+} \to D^0(\to K_S^0\pi^+\pi^-)\pi^+$ samples are used. For π^0, the efficiency correction and systematic uncertainty are estimated from a sample of $\tau^- \to \pi^+\pi^0\nu_\tau$ decays. The errors on the PDF shapes are obtained by varying all fixed parameters by $\pm1\sigma$ and taking the change in the yield as the systematic uncertainty.

D. Discussion on Exclusive decays

Table II summarizes the studied exclusive decays of B to $\chi_{cJ}X$ decays. For the first time, we observe the $B^0 \to \chi_{c2}\pi^-K^+$, $B^+ \to \chi_{c2}\pi^+K_S^0$, $B^+ \to \chi_{c2}\pi^+\pi^-K^+$, $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^0 \to \chi_{c1}\pi^+\pi^-K^0$ and $B^0 \to \chi_{c1}\pi^-\pi^0K^+$ decay modes. We find that in three-body decays the χ_{c2} is more likely to be produced in association with higher K^* resonances; in contrast, decays to χ_{c1} are accompanied predominantly by the $K^*(892)$. The same phenomenon is observed in the four-body production of χ_{c2} and χ_{c1} from B decays. No strong hint for any narrow resonance (less than 5 MeV width) is seen in the $M_{\chi_{cJ}\pi}$ and $M_{\chi_{cJ}\pi\pi}$ distributions. If one adds the measured branching fraction in this paper (excluding the obtained U.L.), we obtain $\mathcal{B}(B \to \chi_{c1}n\pi K)$ with $n \in \{1,2\}$ to be $(1.75\pm0.08)\times10^{-3}$, which corresponds to a $(58\pm5)\%$ fraction of the measured $\mathcal{B}(B \to \chi_{c1}X)$. Using $\mathcal{B}(B^+ \to \chi_{c1}K^+)$ [8], this accounts for $(74\pm6)\%$ of B mesons decaying into $\chi_{c1}X$. Similarly, $\mathcal{B}(B \to \chi_{c2}n\pi K)$ with $n \in \{1,2\}$ is $(0.23\pm0.02)\times10^{-3}$, corresponding to $(32\pm5)\%$ of the inclusive $\mathcal{B}(B \to \chi_{c2}X)$. For the treatment of the uncertainty, no correlation is assumed and the uncertainty is the sum of the systematic and statistical uncertainties in quadrature.

VI. SUMMARY

We measured the feed-down-contaminated $\mathcal{B}(B \to \chi_{c1}X)$ and $\mathcal{B}(B \to \chi_{c2}X)$ of $(3.33\pm0.05\pm0.24)\times10^{-3}$ and $(0.98\pm0.06\pm0.10)\times10^{-3}$, respectively, where the first (second) error is statistical (systematic). After subtracting the ψ' feed-down contributions, we find the pure inclusive branching fractions $\mathcal{B}(B \to \chi_{c1}X)$ and $\mathcal{B}(B \to \chi_{c2}X)$ of $(3.03\pm0.05\pm0.24)\times10^{-3}$ and $(0.70\pm0.06\pm0.10)\times10^{-3}$, respectively. Here, the systematic uncertainty dominates. For inclusive production of χ_{cJ}, we measure the ratio $\mathcal{B}(B \to \chi_{c2}X)/\mathcal{B}(B \to \chi_{c1}X)$ of $(23.1\pm2.0\pm2.1)\%$. We observe the $B^0 \to \chi_{c2}\pi^-K^+$ decay mode for the first time, with 206 ± 25 signal events and a significance of 8.7σ, along with evidence for the $B^+ \to \chi_{c2}\pi^+K_S^0$ decay mode, with 76 ± 15 signal events and a significance of 4.6σ. In four-body decays, we observe the $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^0 \to \chi_{c1}\pi^+\pi^-K_S^0$, and $B^0 \to \chi_{c1}\pi^0\pi^-K^+$ decay modes for the first time and report on measurements of their branching fractions. We find that χ_{c2} production, in contrast with χ_{c1}, increases with a higher number of multi-body B decays: $\mathcal{R_B}$ for $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$ decay (0.36 ± 0.05) is almost twice that measured in the $B^0 \to \chi_{cJ}\pi^-K^+$ decay mode (0.20 ± 0.04). We observe that the χ_{c2} is more often accompanied by higher K^* resonances, in contrast to the χ_{c1} that is dominantly produced with the lower K^* resonance. All previous studies [6, 7] were limited to $K^*(892)^0$, while our study suggests that χ_{c2} is preferentially produced with higher K^* resonances. Clearly, to study χ_{c2} production in B decays, it is important to avoid considering solely the lower K^* resonances. Suppression in two-body B decays is found to be due to the factorization hypothesis [9]. In our search for $X(3872) \to \chi_{c1}\pi^+\pi^-$ and $\chi_{c1}(2P)$, we determine an U.L. on the product of branching fractions $\mathcal{B}(B^+ \to X(3872)K^+)\times(X(3872) \to \chi_{c1}\pi^+\pi^-)$ $[\mathcal{B}(B^+ \to \chi_{c1}(2P)K^+)\times(\chi_{c1}(2P) \to \chi_{c1}\pi^+\pi^-)] < 1.5\times10^{-6}$ $[1.1\times10^{-5}]$ at the 90% C.L. The negative result for our searches is compatible with the interpretation of $X(3872)$ as an admixture state of a $D^0\bar{D}^{*0}$ molecule and a $\chi_{c1}(2P)$ charmonium state.

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TABLE IV: Summary of systematic uncertainties on the $B \to \chi_{cJ} X$ branching fraction. Uncertainty on lepton identification (ℓ), kaon identification (K), pion identification (π), tracking, gamma identification (γ id), K_S^0 reconstruction, π^0 reconstruction, π^0 veto, uncertainty in the secondary branching fractions, PDFs used to extract signal yield and uncertainty on the $N_{B\bar{B}}$.

	Uncertainty (%)												
Mode	ℓ	K	π	Tracking	γ id	Secondary $\mathcal{B}$	K_S^0	π^0	π^0 veto	ϵ	PDF	$N_{B\bar{B}}$	Total
$B^0 \to \chi_{cJ}\pi^- K^+$													
χ_{c1}	2.1	1.0	1.0	1.4	2.0	3.6	—	—	1.2	1.0	1.4	1.4	5.6
χ_{c2}	2.1	1.0	1.0	1.4	2.0	3.7	—	—	1.2	2.4	3.2	1.4	6.7
$B^+ \to \chi_{cJ}\pi^+ K^0$													
χ_{c1}	2.1	—	1.0	1.8	2.0	3.6	0.7	—	1.2	1.0	0.7	1.4	5.5
χ_{c2}	2.1	—	1.1	1.8	2.0	3.7	0.7	—	1.2	2.2	9.1	1.4	10.8
$B^+ \to \chi_{cJ}\pi^0 K^+$													
χ_{c1}	2.1	1.0	—	1.1	2.0	3.6	—	2.2	1.2	1.0	1.7	1.4	5.9
χ_{c2}	2.1	1.0	—	1.1	2.0	3.7	—	2.2	1.2	2.4	191	1.4	191.1
$B^+ \to \chi_{cJ}\pi^+\pi^- K^+$													
χ_{c1}	2.1	1.1	2.3	1.8	2.0	3.6	—	—	1.2	1.0	2.6	1.4	6.5
χ_{c2}	2.1	1.2	2.3	1.8	2.0	3.7	—	—	1.2	2.2	2.0	1.4	6.6
$B^0 \to \chi_{cJ}\pi^+\pi^- K^0$													
χ_{c1}	2.1	—	2.3	2.1	2.0	3.6	0.7	—	1.2	1.0	8.1	1.4	10.1
χ_{c2}	2.1	—	2.3	2.1	2.0	3.7	0.7	—	1.2	2.3	31.5	1.4	32.1
$B^0 \to \chi_{cJ}\pi^-\pi^0 K^+$													
χ_{c1}	2.1	1.1	1.1	1.4	2.0	3.6	—	2.2	1.2	1.1	3.6	1.4	6.9
χ_{c2}	2.1	1.2	1.1	1.4	2.0	3.7	—	2.2	1.2	2.9	**	1.4	7.5

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[1] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 011803 (2002).

[2] Hereinafter, χ_{cJ} refers to either χ_{c1} or χ_{c2}, depending on which is reconstructed.

[3] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. D **67**, 032002 (2003).

[4] V. Bhardwaj *et al.* (Belle Collaboration), Phys. Rev. Lett. **107**, 091803 (2011).

[5] N. Soni *et al.* (Belle Collaboration), Phys. Lett. B **634**, 155 (2006).

[6] B. Aubert *et al.* (Babar Collaboration), Phys. Rev. Lett. **102**, 132001 (2009).

[7] R. Aaij *et al.* (LHCb Collaboration), Nucl. Phys. B **874**, 663 (2013).

[8] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[9] J.H. Kühn, S. Nussinov and R. Rückl, Z. Physik C, **5**, 117 (1980); G.T. Bodwin, E. Braaten, T.C. Yuan and G.P. Lepage, Phys. Rev. D **46**, 3703(R) (1992).

[10] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 132002 (2007).

[11] S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).

[12] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 222001 (2013).

[13] E. Braaten and M. Kusunoki, Phys. Rev. D **69**, 074005 (2004); Y.-B. Dong, A. Faessler, T. Gutsche and V. E. Lyubovitskij, Phys. Rev. D **77**, 094013 (2008).

[14] A. Abashian *et al.* (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 117 (2002); also see detector section in J. Brodzicka *et al.*, Prog. Theor. Exp. Phys. 04D001 (2012).

[15] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A **499**, 1 (2003), and other papers included in this Volume; T. Abe *et al.*, Prog. Theor. Exp. Phys. 03A001 (2013) and following articles up to 03A011.

[16] Z. Natkaniec *et al.* (Belle SVD2 Group), Nucl. Instrum. Methods Phys. Res., Sect. A **560**, 1 (2006).

[17] K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **67**, 032003 (2003).

[18] G.C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[19] D.J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).

[20] E. Barberio and Z. Wąs, Comput. Phys. Commun. **79**, 291 (1994).

[21] R. Brun *et al.*, GEANT3.21, CERN Report DD/EE/84-1 (1984).

[22] P. Koppenburg *et al.* (Belle Collaboration), Phys. Rev. Lett. **93**, 061803 (2004).

[23] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, Krakow, 1986; DESY Internal Report No. DESY F31-86-02, 1986.

[24] The double-sided Crystal Ball function is defined as :
$$
\begin{aligned}
f(x) = {} & N_0\,(n_l/|\alpha_l|)^{n_l}\exp\left(-|\alpha_l|^2/2\right)\times \\
& \qquad [n_l/|\alpha_l| - |\alpha_l| - (x-\mu)/\sigma]^{-n_l}\,, \\
& \text{if } (x-\mu)/\sigma \le -\alpha_l \\
= {} & N_0\,(n_r/|\alpha_r|)^{n_r}\exp\left(-|\alpha_r|^2/2\right)\times \\
& \qquad [n_r/|\alpha_r| - |\alpha_r| + (x-\mu)/\sigma]^{-n_r}\,, \\
& \text{if } (x-\mu)/\sigma \ge \alpha_r \\
= {} & N_0\exp\left[-(x-\mu)^2/(2\sigma^2)\right], \quad \text{otherwise.}
\end{aligned}
$$
Here N_0 is the normalization, σ is the standard deviation, μ is the mean, n_l (n_r), α_l (α_r) are shape parameters for left (right) tail.

[25] Charge-conjugate and neutral modes are included throughout the paper unless stated otherwise.

[26] H. Kakuno, Ph.D. thesis, Tokyo Institute of Technology (2003), http://belle.kek.jp/belle/theses/doctor/kakuno03/kakuno_thesis.ps.gz.

[27] H. Guler *et al.* (Belle Collaboration), Phys. Rev. D **83**, 032005 (2011).

[28] K.-F. Chen *et al.* (Belle Collaboration), Phys. Rev. D **72**, 012004 (2005).

[29] M. Pivk and F.R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A **555**, 356 (2005).

[30] The logarithmic Gaussian is parameterized as: $f(x) = N_0/c\times\,\exp -\{\ln[(\epsilon - x)/(\epsilon - x_p)]\}^2/(2\sigma_0^2)$ where $\epsilon = \sigma/a + x_p$, $c = \sqrt{2\pi}\sigma_0(\epsilon - x)$ and $\sigma_0 = (\ln(a\sqrt{2\ln 2} + \sqrt{1+2a^2\ln 2})/\sqrt{2\ln 2}$. Here, N_0 is the normalization, σ is the standard deviation, x_p is the mean and a is the asymmetry.

[31] R.D. Cousins and V.L. Highland, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 331 (1992).

[32] R. Mizuk *et al.* (Belle Collaboration), Phys. Rev. D **78**, 072004 (2008).

[33] G.J. Feldman and R.D. Cousins, Phys. Rev. D **57**, 3873 (1998).