

## Measurements of $CP$ -Violating Asymmetries in the Decay $B^0 \rightarrow K^+ K^- K^0$

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We analyze the decay  $B^0 \rightarrow K^+K^-K^0$  using 383 million  $B\bar{B}$  events collected by the BABAR detector at SLAC to extract  $CP$  violation parameter values over the Dalitz plot. Combining all  $K^+K^-K^0$  events, we find  $A_{CP} = -0.015 \pm 0.077 \pm 0.053$  and  $\beta_{eff} = 0.352 \pm 0.076 \pm 0.026$  rad, corresponding to a  $CP$  violation significance of  $4.8\sigma$ . A second solution near  $\pi/2 - \beta_{eff}$  is disfavored with a significance of  $4.5\sigma$ . We also report  $A_{CP}$  and  $\beta_{eff}$  separately for decays to  $\phi(1020)K^0$ ,  $f_0(980)K^0$ , and  $K^+K^-K^0$  with  $m_{K^+K^-} > 1.1$  GeV/ $c^2$ .

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In the Standard Model (SM), the phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] is the sole source of  $CP$  violation in the quark sector. Due to interference between decays with and without mixing, this phase yields observable time-dependent  $CP$  asymmetries in  $B^0$  meson decays. In particular, significant  $CP$  asymmetries in  $b \rightarrow s\bar{s}s$  decays, such as  $B^0 \rightarrow K^+K^-K^0$  [2], are expected [3, 4]. Deviations from the predicted  $CP$  asymmetry behavior for  $B^0 \rightarrow K^+K^-K^0$  are expected to depend weakly on Dalitz plot (DP) position [5, 6]. Since the  $b \rightarrow s\bar{s}s$  amplitude is dominated by loop contributions, heavy virtual particles beyond the SM might contribute significantly [6, 7]. This sensitivity motivates measurements of  $CP$  asymmetries in multiple  $b \rightarrow s\bar{s}s$  decays [3, 8–10].

Previous measurements of  $CP$  asymmetries in  $B^0 \rightarrow K^+K^-K^0$  have been performed separately for events with  $K^+K^-$  invariant mass ( $m_{K^+K^-}$ ) in the  $\phi$  mass [11] region, and for events excluding the  $\phi$  region, neglecting interference effects among intermediate states [3, 8, 10]. In this Letter we describe a time-dependent Dalitz plot analysis of  $B^0 \rightarrow K^+K^-K^0$  decay from which we extract the values of the  $CP$  violation parameters  $A_{CP}$  and  $\beta_{eff}$  by taking into account the complex amplitudes describing the entire  $B^0$  and  $\bar{B}^0$  Dalitz plots. We first extract the values of the parameters of the amplitude model, and measure the average  $CP$  asymmetry in  $B^0 \rightarrow K^+K^-K^0$  decay over the entire Dalitz plot. Using this model, we then measure the  $CP$  asymmetries for the  $\phi K^0$  and  $f_0 K^0$  decay channels, from a “low-mass” analysis of events with  $m_{K^+K^-} < 1.1$  GeV/ $c^2$ . Finally, we perform a “high-mass” analysis to determine the average  $CP$  asymmetry for events with  $m_{K^+K^-} > 1.1$  GeV/ $c^2$ .

The data sample for this analysis was collected with the BABAR detector [12] at the PEP-II asymmetric-energy  $e^+e^-$  collider at SLAC. Approximately 383 million  $B\bar{B}$  pairs recorded at the  $\Upsilon(4S)$  resonance were used.

We reconstruct  $B^0 \rightarrow K^+K^-K^0$  decays by combining two oppositely-charged kaon candidates with a  $K^0$  reconstructed as  $K_s^0 \rightarrow \pi^+\pi^-$  ( $B_{(+,-)}^0$ ) [13],  $K_s^0 \rightarrow \pi^0\pi^0$  ( $B_{(00)}^0$ ), or  $K_L^0$  ( $B_{(L)}^0$ ). Each  $K_s^0 \rightarrow \pi^0\pi^0$  candidate is formed from two  $\pi^0 \rightarrow \gamma\gamma$  candidates. Each photon has  $E_\gamma > 50$  MeV and transverse shower shape consistent with an electromagnetic shower. Both  $\pi^0$  candidates satisfy  $100 < m_{\gamma\gamma} < 155$  MeV/ $c^2$  and yield an invariant mass  $m_{\pi^0\pi^0}$  in the range  $-20 < m_{\pi^0\pi^0} - m_{K_s^0} < 30$  MeV/ $c^2$ . A  $K_L^0$  candidate is defined by an unassociated energy de-

posit in the electromagnetic calorimeter or an isolated signal in the Instrumented Flux Return [8].

For each fully reconstructed  $B^0$  meson ( $B_{CP}$ ), we use the remaining tracks in the event to reconstruct the decay vertex of the other  $B$  meson ( $B_{tag}$ ), and to identify its flavor  $q_{tag}$  [4]. For each event we calculate the difference  $\Delta t \equiv t_{CP} - t_{tag}$  between the proper decay times of the  $B_{CP}$  and  $B_{tag}$  mesons, and its uncertainty  $\sigma_{\Delta t}$ .

We characterize  $B_{(+,-)}^0$  and  $B_{(00)}^0$  candidates using two kinematic variables: the beam-energy-substituted mass  $m_{ES}$  and the energy difference  $\Delta E$  [8]. The signal region (SR) is defined as  $m_{ES} > 5.26$  GeV/ $c^2$ , and  $|\Delta E| < 0.06$  GeV for  $B_{(+,-)}^0$ , or  $-0.120 < \Delta E < 0.06$  GeV for  $B_{(00)}^0$ . For  $B_{(L)}^0$  the SR is defined by  $-0.01 < \Delta E < 0.03$  GeV [8], and the missing momentum for the entire event is required to be consistent with the calculated  $K_L^0$  laboratory momentum.

The main source of background is continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events. We use event-shape variables to exploit the jet-like structure of these events in order to remove much of this background [8].

We perform an unbinned maximum likelihood fit to the selected  $K^+K^-K^0$  events using the likelihood function defined in Ref. [8]. The probability density function (PDF),  $\mathcal{P}_i$ , is given by

$$\mathcal{P}_i \equiv \mathcal{P}(m_{ES}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}_{Low} \cdot \mathcal{P}_{DP}(m_{K^+K^-}, \cos\theta_H, \Delta t, q_{tag}) \otimes \mathcal{R}(\Delta t, \sigma_{\Delta t}), \quad (1)$$

where  $i = (\text{signal, continuum, } B\bar{B} \text{ background})$ , and  $\mathcal{R}$  is the  $\Delta t$  resolution function [4]. For  $B_{(L)}^0$ ,  $\mathcal{P}(m_{ES})$  is not used.  $\mathcal{P}_{Low}$  is a supplementary PDF used only in the low-mass fit, which depends on the event-shape variables and, for  $B_{(L)}^0$  only, the missing momentum in the event [8]. We characterize  $B^0$  ( $\bar{B}^0$ ) events on the Dalitz plot in terms of  $m_{K^+K^-}$  and  $\cos\theta_H$ , the cosine of the helicity angle between the  $K^+$  ( $K^-$ ) and the  $K^0$  ( $\bar{K}^0$ ) in the rest frame of the  $K^+K^-$  system. The Dalitz plot PDF for signal events is

$$\mathcal{P}_{DP} = d\Gamma \cdot \varepsilon(m_{K^+K^-}, \cos\theta_H) \cdot |J|, \quad (2)$$

where  $d\Gamma$  is the time- and flavor-dependent decay rate over the Dalitz plot,  $\varepsilon$  is the efficiency, and  $J$  is the Jacobian of the transformation to our choice of Dalitz plot coordinates.

The time- and flavor-dependent decay rate is

$$\frac{d\Gamma}{d\Delta t} \propto \frac{e^{-|\Delta t|/\tau}}{2\tau} \times \left[ |\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2 + q_{\text{tag}} 2\text{Im}(\xi \bar{\mathcal{A}} \mathcal{A}^*) \sin \Delta m_d \Delta t - q_{\text{tag}} (|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2) \cos \Delta m_d \Delta t \right], \quad (3)$$

where  $\tau$  and  $\Delta m_d$  are the lifetime and mixing frequency of the  $B^0$  meson, respectively [14]. The parameter  $\xi = \eta_{CP} e^{-2i\beta}$ , where  $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$  and  $V_{qq'}$  are CKM matrix elements [1]. The  $CP$  eigenvalue  $\eta_{CP} = 1$  ( $-1$ ) for the  $K_S^0$  ( $K_L^0$ ) mode. We define the amplitude  $\overleftarrow{\mathcal{A}}$  for  $\overleftarrow{B}^0$  decay as a sum of isobar amplitudes [14],

$$\overleftarrow{\mathcal{A}}(m_{K^+K^-}, \cos \theta_H) = \sum_r \overleftarrow{\mathcal{A}}_r \quad (4)$$

$$= \sum_r c_r (1 \mp b_r) e^{i(\varphi_r \mp \delta_r)} \cdot f_r(m_{K^+K^-}, \cos \theta_H),$$

where the minus signs are associated with the  $\overleftarrow{\mathcal{A}}$ , the parameters  $c_r$  and  $\varphi_r$  are the magnitude and phase of the amplitude of component  $r$ , and we allow for different isobar coefficients for  $B^0$  and  $\overleftarrow{B}^0$  decays through the asymmetry parameters  $b_r$  and  $\delta_r$ .

Our isobar model includes resonant amplitudes  $\phi$ ,  $f_0$ ,  $\chi_{c0}(1P)$ , and  $X_0(1550)$  [15, 16]; non-resonant terms; and incoherent terms for  $B^0$  decay to  $D^-K^+$  and  $D_s^-K^+$ . For each resonant term, the function  $f_r = F_r \times T_r \times Z_r$  describes the dynamical properties, where  $F_r$  is the Blatt-Weisskopf centrifugal barrier factor for the resonance decay vertex [17],  $T_r$  is the resonant mass-lineshape, and  $Z_r$  describes the angular distribution in the decay [18]. The barrier factor  $F_r = 1/\sqrt{1+(Rq)^2}$  [17] for the  $\phi$ , where  $\vec{q}$  is the  $K^+$  momentum in the  $\phi$  rest frame and  $R = 1.5 \text{ GeV}^{-1}$ ;  $F_r = 1$  for the scalar resonances. For  $\phi$  decay  $Z_r \sim \vec{q} \cdot \vec{p}$ , where  $\vec{p}$  is the momentum of the  $K^0$  in the  $\phi$  rest frame, while  $Z_r = 1$  for the scalar decays. We describe the  $\phi$ ,  $X_0(1550)$ , and  $\chi_{c0}(1P)$  with relativistic Breit-Wigner lineshapes [14]. For the  $\phi$  and  $\chi_{c0}(1P)$  parameters we use average measurements [14]. For the  $X_0(1550)$  resonance, we use parameters from our analysis of the  $B^+ \rightarrow K^+K^-K^+$  decay [15]. The  $f_0$  resonance is described by a coupled-channel amplitude [19], with the parameter values of Ref. [20].

We include three non-resonant amplitudes parameterized as  $f_{NR,k} = \exp(-\alpha m_k^2)$ , where the parameter  $\alpha = 0.14 \pm 0.01 \text{ c}^4/\text{GeV}^2$  is taken from measurements of  $B^+ \rightarrow K^+K^-K^+$  decays with larger signal samples [15, 16]. We include a complex isobar coefficient for each component  $k = (K^+K^-, K^+K^0, K^-K^0)$ .

Continuum background PDFs for  $B^0 \rightarrow K^+K^-K_S^0$  are modeled using events in the region  $5.2 < m_{ES} < 5.26 \text{ GeV}/c^2$ . The region  $0.02 < \Delta E < 0.04 \text{ GeV}$  is used for  $B_{(L)}^0$ . Samples of simulated  $B\bar{B}$  events are used to define  $B\bar{B}$  background PDFs. We use two-dimensional

histogram PDFs to model the Dalitz plot distributions for continuum and  $B\bar{B}$  backgrounds.

We compute the  $CP$  asymmetry parameters for component  $r$  from the asymmetries in amplitude ( $b_r$ ) and phase ( $\delta_r$ ) given in Eq. (4). The rate asymmetry is

$$A_{CP,r} = \frac{|\bar{\mathcal{A}}_r|^2 - |\mathcal{A}_r|^2}{|\bar{\mathcal{A}}_r|^2 + |\mathcal{A}_r|^2} = \frac{-2b_r}{1 + b_r^2}, \quad (5)$$

and  $\beta_{\text{eff},r} = \beta + \delta_r$  is the phase asymmetry.

The selection criteria yield 3266  $B_{(+,-)}^0$ , 1611  $B_{(00)}^0$ , and 27513  $B_{(L)}^0$  candidates which we fit to obtain the event yields, the isobar coefficients of the Dalitz plot model, and the  $CP$  asymmetry parameters averaged over the Dalitz plot. The parameters  $b_r$  and  $\delta_r$  are constrained to be the same for all model components, so in this case  $A_{CP,r} = A_{CP}$  and  $\beta_{\text{eff},r} = \beta_{\text{eff}}$ . We find  $947 \pm 37 B_{(+,-)}^0$ ,  $144 \pm 17 B_{(00)}^0$ , and  $770 \pm 71 B_{(L)}^0$  signal events. Isobar coefficients and fractions are reported in Table I, and  $CP$  asymmetry results are summarized in Table II. The fraction  $\mathcal{F}_r$  for resonance  $r$  is computed as in Ref. [15]. The sum of the fractions is greater than one due to interference. Note that there is a  $\pm\pi$  rad ambiguity in the  $\chi_{c0}(1P)K^0$  phase.

TABLE I: The isobar amplitudes  $c_r$ , phases  $\varphi_r$ , and fractions  $\mathcal{F}_r$  from the fit to the full  $K^+K^-K^0$  Dalitz plot. The three NR components are combined for the fraction calculation. Errors are statistical only.

Isobar Mode	Amplitude $c_r$	Phase $\varphi_r$ (rad)	$\mathcal{F}_r$ (%)
$\phi K^0$	$0.0085 \pm 0.0010$	$-0.016 \pm 0.234$	$12.5 \pm 1.3$
$f_0 K^0$	$0.622 \pm 0.046$	$-0.14 \pm 0.14$	$40.2 \pm 9.6$
$X_0(1550)K^0$	$0.114 \pm 0.018$	$-0.47 \pm 0.20$	$4.1 \pm 1.3$
$(K^+K^-)_{NR}K^0$	1 (fixed)	0 (fixed)	
$(K^+K^0)_{NR}K^-$	$0.33 \pm 0.07$	$1.95 \pm 0.27$	$112.0 \pm 14.9$
$(K^-K^0)_{NR}K^+$	$0.31 \pm 0.08$	$-1.34 \pm 0.37$	
$\chi_{c0}(1P)K^0$	$0.0306 \pm 0.0049$	$_{-2.33}^{0.81} \pm 0.54$	$3.0 \pm 1.2$
$D^-K^+$	$1.11 \pm 0.17$		$3.6 \pm 1.5$
$D_s^-K^+$	$0.76 \pm 0.14$		$1.8 \pm 0.6$

In Fig. 1, we plot twice the change in the negative logarithm of the likelihood as a function of  $\beta_{\text{eff}}$ . We find that the  $CP$ -conserving case of  $\beta_{\text{eff}} = 0$  is excluded at  $4.8\sigma$  ( $5.1\sigma$ ), including statistical and systematic errors (statistical errors only). Also, the interference between  $CP$ -even and  $CP$ -odd amplitudes leads to the exclusion of the  $\beta_{\text{eff}}$  solution near  $\pi/2 - \beta$  at  $4.5\sigma$  ( $4.6\sigma$ ).

We also measure  $CP$  asymmetry parameters for events with  $m_{K^+K^-} < 1.1 \text{ GeV}/c^2$ . In this region, we find 1359  $B_{(+,-)}^0$ , 348  $B_{(00)}^0$ , and 7481  $B_{(L)}^0$  candidates. The fit yields  $282 \pm 20$ ,  $37 \pm 9$  and  $266 \pm 36$  signal events, respectively. The most significant contributions in this region are from  $\phi K^0$  and  $f_0 K^0$  decays, with a smaller contribution from the low-mass tail from non-resonant decays. In this fit we vary the amplitude asymmetries  $b_r$  and  $\delta_r$  for the  $\phi$  and  $f_0$ , while the other components are fixed to the SM

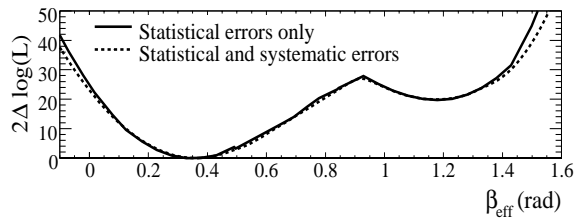


FIG. 1: The change in twice the negative log likelihood as a function of  $\beta_{\text{eff}}$  for the fit to the whole Dalitz plot.

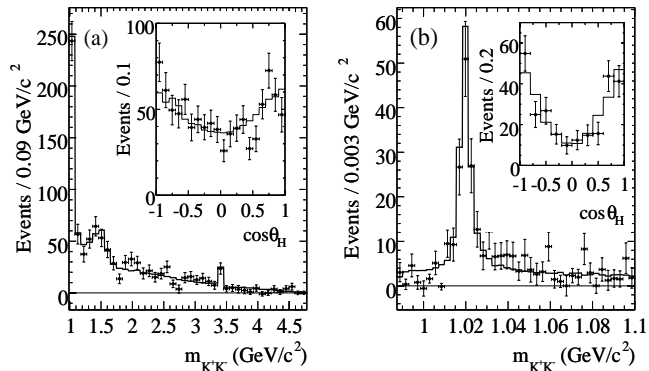


FIG. 2: The distributions of  $m_{K+K^-}$  for signal-weighted [23]  $B_{(+-)}^0$  data in (a) the entire DP and (b) the low-mass region. Insets show distributions of  $\cos\theta_H$ . The histograms are projections of the fit function for the corresponding result.

expectations of  $\beta_{\text{eff}} = 0.370$  rad and  $A_{CP} = 0$  [21]. We also vary the isobar coefficient for the  $\phi$ , while fixing the others to the results from the whole DP fit. There are two solutions with likelihood difference of only  $\Delta \log L = 0.1$ . Solution (1) is consistent with the SM, while in Solu-

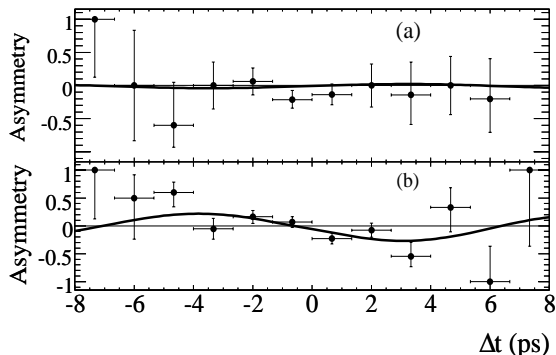


FIG. 3: The raw asymmetry between  $B^0$ - and  $\bar{B}^0$ -tagged signal-weighted [23] events for  $B_{(+-)}^0$ , in (a) the low-mass region and (b) the high-mass region. The curves are projections of the corresponding fit results.

tion (2)  $\beta_{\text{eff}}$  for the  $f_0$  differs significantly from the SM value (Table II). The solutions also differ significantly in the values of the  $\phi$  isobar coefficient. There is also a mathematical ambiguity of  $\pm\pi$  rad on  $\beta_{\text{eff}}$  for the  $\phi$ , with a corresponding change of  $\pm\pi$  rad in the solution for  $\varphi_\phi$ . This unresolvable ambiguity is present for both solutions. The fit correlation between  $\delta_r$  for the  $\phi$  and that for the  $f_0$  is 0.71 [22].

Finally, we perform a fit to extract the average  $CP$  asymmetry parameters in the high-mass region. In the 2384  $B_{(+-)}^0$ , 1406  $B_{(00)}^0$ , and 20032  $B_{(L)}^0$  selected events with  $m_{K+K^-} > 1.1$   $\text{GeV}/c^2$ , we find signal yields of  $673 \pm 31$ ,  $87 \pm 14$  and  $462 \pm 56$  events, respectively; the  $CP$  asymmetry results are shown in Table II. Based on the change in the likelihood, we find that for this fit the  $CP$ -conserving case of  $\beta_{\text{eff}} = 0$  is excluded at  $5.1\sigma$ , including statistical and systematic errors.

Figure 2 shows distributions of the Dalitz plot variables  $m_{K+K^-}$  and  $\cos\theta_H$  obtained using the background-subtraction method described in [23]. Figure 3 shows the  $\Delta t$ -dependent asymmetry between  $B^0$ - and  $\bar{B}^0$ -tagged events.

TABLE II: The  $CP$ -asymmetries for  $B^0 \rightarrow K^+K^-K^0$  for the entire DP, in the high-mass region, and for  $\phi K^0$  and  $f_0 K^0$  in the low-mass region. The first errors are statistical and the second are systematic. The solutions (1) and (2) from the low-mass fit are discussed in the text.

	$A_{CP}$	$\beta_{\text{eff}}$ (rad)
Whole DP	$-0.015 \pm 0.077 \pm 0.053$	$0.352 \pm 0.076 \pm 0.026$
High-mass	$-0.054 \pm 0.102 \pm 0.060$	$0.436 \pm 0.087^{+0.055}_{-0.031}$
(1) $\phi K^0$	$-0.08 \pm 0.18 \pm 0.04$	$0.11 \pm 0.14 \pm 0.06$
(1) $f_0 K^0$	$0.41 \pm 0.23 \pm 0.07$	$0.14 \pm 0.15 \pm 0.05$
(2) $\phi K^0$	$-0.11 \pm 0.18$	$0.10 \pm 0.13$
(2) $f_0 K^0$	$-0.20 \pm 0.31$	$3.09 \pm 0.19$

Systematic errors on the  $CP$ -asymmetry parameters are listed in Table III. The fit bias uncertainty includes effects of detector resolution and possible correlations among the fit variables determined from full-detector simulations. We also account for uncertainties on isobar model parameters and for different  $X_0(1550)$  parameters [16]. Other uncertainties, including those due to fixed PDF parameters, and possible  $CP$  asymmetries in the  $B\bar{B}$  background are also taken into account [8, 24]. As a cross-check, we perform the analysis using  $B_{(+-)}^0$  alone and find  $A_{CP} = -0.061 \pm 0.088$  (stat),  $\beta_{\text{eff}} = 0.357 \pm 0.080$  (stat) in the fit to the whole DP; low- and high-mass results are also consistent with the results in Table II.

In summary, in a sample of 383 million  $B\bar{B}$  meson pairs we simultaneously analyze the Dalitz plot distribution and measure the time-dependent  $CP$  asymmetries for  $B^0 \rightarrow K^+K^-K^0$  decays. The values of  $\beta_{\text{eff}}$  and  $A_{CP}$  are consistent with the SM expectations of  $\beta \simeq 0.370$  rad,  $A_{CP} \simeq 0$  [21]. The significance of  $CP$

TABLE III: A summary of the systematic errors on the  $CP$  asymmetry parameter values.

Source	Whole DP		High-mass		$\phi K^0$		$f_0 K^0$	
	$A_{CP}$	$\beta_{eff}$	$A_{CP}$	$\beta_{eff}$	$A_{CP}$	$\beta_{eff}$	$A_{CP}$	$\beta_{eff}$
Fit Bias	0.003	0.001	0.014	0.008	0.03	0.06	0.06	0.03
Isobar model	0.004	0.009	0.025	$^{+0.051}_{-0.024}$	0.00	0.01	0.01	0.03
Other	0.052	0.024	0.053	0.018	0.02	0.01	0.03	0.02
Total	0.053	0.026	0.060	$^{+0.055}_{-0.031}$	0.04	0.06	0.07	0.05

violation is  $4.8\sigma$ , and we reject the solution near  $\pi/2 - \beta$  at  $4.5\sigma$ . In a fit to the low-mass region of the Dalitz plot, we measure  $CP$  asymmetries for the decays  $B^0 \rightarrow \phi K^0$  and  $B^0 \rightarrow f_0 K^0$ , where we find  $\beta_{eff}$  lower than the SM expectation by about  $2\sigma$ . The  $CP$  parameters in the high-mass region are compatible with SM expectations, and we observe  $CP$  violation at the level of  $5.1\sigma$ .

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