The Measurement of β by Belle and *BABAR*

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We describe recent results on the measurement of the *CP* violation parameter β from the Belle and *BABAR* experiments. Having established *CP* violation in B decays, a number of distinct approaches have been utilized to search for deviations from the Standard Model expectation of *CP* violation in decays sensitive to sin2β either at tree level of via penguin diagrams. New results from studies of $B \to (c\bar{c})K$, $B \to D^{(*)\pm}D^{\mp}$, $B \to D^{(*)}\pi^0$ and $B \to \eta' K$ decays include the first significant deviation from sin$2\beta = 0$ observed in charmless B decays.

The presence of *CP* violation in B-meson decays is well established. Initial measurements of $B \to J/\psi\, K^0_S$ and related $B \to (c\bar{c})K$ decays by the Belle and *BABAR* experiments demonstrated that the Cabibbo Kobayashi Maskawa matrix [1] within the Standard Model of electroweak physics provides the dominant mechanism for this *CP* violation.

In $B \to (c\bar{c})K$ decays, *CP* violation in the Standard Model arises from the interference of decay and mixing amplitudes. The measurement of this effect requires the determination of both the B decay time difference, Δt and flavor tag (B^0 or $\overline{B}^0$) of the decaying B meson. While B mesons are just below threshold at the $\Upsilon(4S)$, the KEK and PEP-II accelerators utilize a boosted center of mass, which enables the measurement of Δt with good resolution.

Flavor tagging relies upon distinctive features of B^0 decays, in particular the correlation of high momentum leptons as well as kaon charge with the flavor of the decaying B meson. Excellent particle identification capabilities allow for efficient detection of electrons, muons, and kaons. Sophisticated algorithms developed by each experiment allow for an effective tagging efficiency of approximately 30%. Both vertex resolution and tagging performance are measured directly on the data.

Given sufficient Δt resolution and flavor tagging capability, *CP* violation parameters are determined through a time-dependent analysis. For the decays studied here, the decay rate $f_+(f_-)$ when the tagging meson is a $B^0(\overline{B}^0)$ is given in terms of a complex parameter λ by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d \Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d \Delta t)\right], \quad (1)$$

where $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay times of the reconstructed B meson $B_{\rm rec}$ and the tagging B meson $B_{\rm tag}$, τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}^0$ oscillation frequency. The *CP* asymmetry is then written

$$A_{CP}(\Delta t) \equiv \frac{f_+ - f_-}{f_+ + f_-} = S\sin(\Delta m_d\,\Delta t) - C\cos(\Delta m_d\,\Delta t), \quad (2)$$

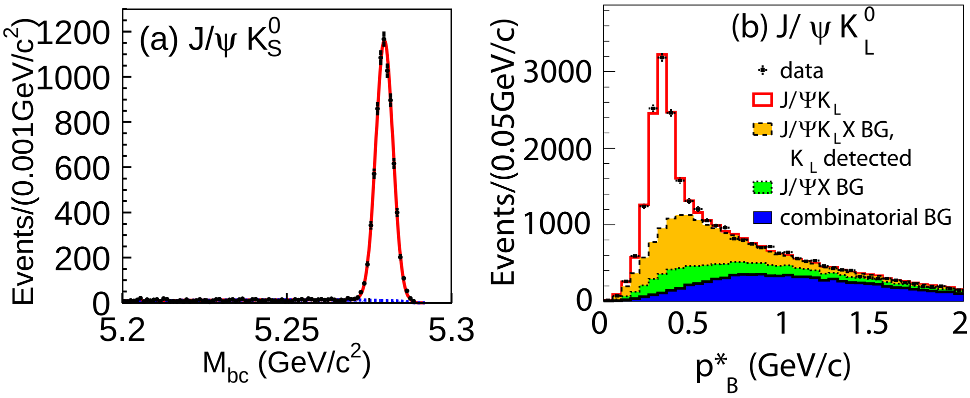

Figure 1: Event samples from the Belle analysis of $B \to J/\psi\, K^0_S$ (left) and $B \to J/\psi\, K^0_L$ (right). The points are the data, the sum of histograms shows the fit result, and the shaded histograms indicate the measured background level.

where we have used the approximation that $\Delta\Gamma = 0$. In the modes described here, $S = -\eta_f \sin 2\beta$ and $C = 0$, where η_f is the *CP* eigenvalue of the final state, in the Standard Model. We will quote results in terms of $\sin 2\beta_{eff} \equiv -\eta_f S$.

The large data samples collected by both the *B*-Factory experiments have subsequently allowed for the precise measurement of *CP* violation in $B \to (c\bar{c})K$ decays, as well as signs of physics beyond the Standard Model. Decay modes that are sensitive to the angle $\beta \equiv \arg\left[-V_{\rm cd}V^*_{\rm cb}/V_{\rm td}V^*_{\rm tb}\right]$ include $b \to c\bar{c}s$ decays, $b \to c\bar{c}d$ decays, and penguin-diagram dominated decays ($b \to d\bar{d}s$ and $b \to s\bar{s}s$).

In this contribution, we summarize a number of new results presented at this conference.

1 The Measurement of $\sin 2\beta$ with $B \to (c\bar{c})K$ decays

The most precise measurement of $\sin 2\beta$ is made using $B \to (c\bar{c})K$ decays, including the channels $J/\psi\, K^0_S$, $J/\psi\, K^0_L$, and for the *BABAR* analysis $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$. Most recent results from Belle and *BABAR* for these channels utilize approximately 535 million and 384 million $B\bar{B}$ events, respectively. The event samples from the Belle analysis are illustrated in Fig. 1. A total of nearly 25000 signal events are reconstructed in the two analysis. Modes with a K^0_S are identified with a very high signal to noise. However, the $J/\psi\, K^0_L$ mode is more challenging as the K^0_L is identified only via hadronic interactions in the calorimeter or detectors in the magnet flux return. Nevertheless, the $J/\psi\, K^0_L$ channel contributes substantially to the final *CP* result.

Figure 2 shows the Δt distribution and raw asymmetry from the *BABAR* analysis. The characteristic $\sin(\Delta m_d \Delta t)$ distribution is apparent, as is the opposite *CP* asymmetry between the $\eta_f = -1$ and $\eta_f = +1$ channels. The results for S are [2,3,4]:

$$\begin{aligned}
\sin 2\beta_{eff} &= 0.714 \pm 0.032 \pm 0.018 \ (BABAR), \\
\sin 2\beta_{eff} &= 0.642 \pm 0.031 \pm 0.017 \ (\text{Belle}), \\
\sin 2\beta_{eff} &= 0.678 \pm 0.026 \ (\text{Average}). \qquad (3)
\end{aligned}$$

These measurements remain limited by their statistical precision, and the interpretation of these measurements in terms of $\sin 2\beta$ also does not introduce significant uncertainty [5]. Also shown in Fig. 2 is a mode by mode breakdown of *CP* results presented for the first time by the *BABAR* experiment, including systematic uncertainties. No significant deviation from the average $\sin 2\beta_{eff}$ is observed. Additionally, both experiments fit for direct *CP* violation. No evidence is found, and the average result is $C = 0.002 \pm 0.021$.

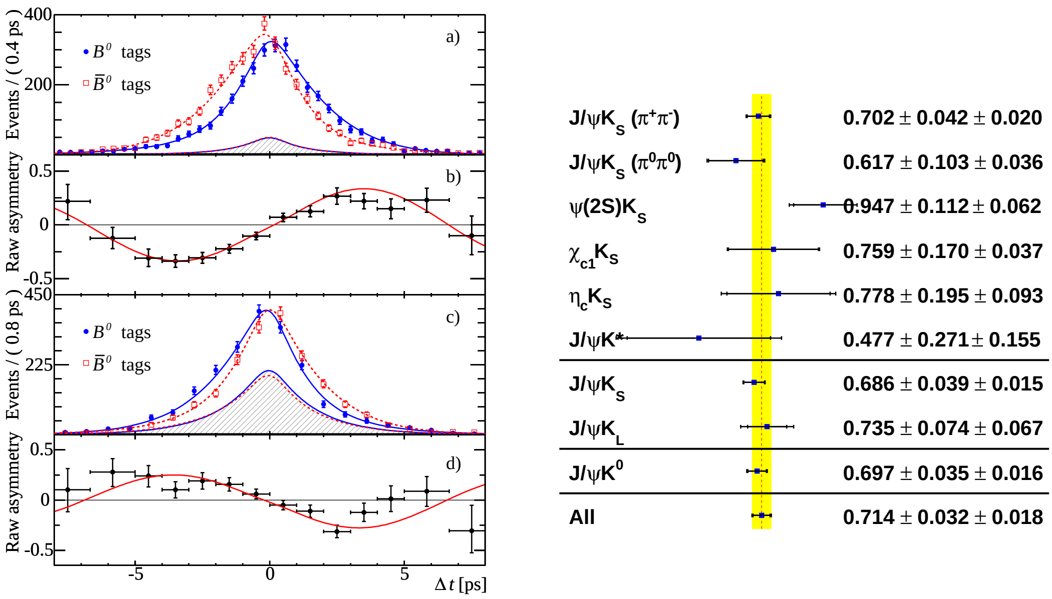

Figure 2: Distributions of Δt and raw asymmetries from the *BABAR* analysis for $\eta_f = -1$ (left,top) and $\eta_f = 1$ (left,bottom) and tabulation (right) of results for sin2β for each decay channel included in *BABAR* the $B \to (c\bar{c})K$ analysis. For the Δt and raw asymetry distributions, the points show the data and the curves show the projection of the likelihood fit.

2 *CP* violation in $B \to D^+D^-$ and $B \to D^{*+}D^-$ decays

CP violation in $B \to D^{(*)}D^{(*)}$ decays is related to sin2β if contributions from penguin diagrams are neglected. In the Standard Model, these contributions are expected to be only a few percent [6], so a significant deviation of S (C) from sin2β (0) would be a strong indication of new physics contributions via penguin diagrams. Both Belle and *BABAR* have measured $B \to D^{*+}D^{*-}$ to have *CP* violation in agreement with expectations.

Here, new results are summarized from both experiments on $B \to D^+D^-$, which has a lower branching fraction than $B \to D^{*+}D^{*-}$. The flavor-tagged Δt distributions for each experiment are shown in Fig. 3. As is apparent, the experiments determine rather different results for *CP* parameters based on their data samples.

The Belle experiment observes *CP* violation at the 4.1σ level and determines

$$\begin{aligned} \sin 2\beta_{eff} &= 1.13 \pm 0.37 \pm 0.09, \\ C &= -0.91 \pm 0.23 \pm 0.06, \end{aligned} \tag{4}$$

where the direct *CP* coefficient is significantly different from expectations. This is evident from the asymmetry shown in number of events the B^0 and $\overline{B}^0$ Δt distributions. The *BABAR* experiment instead determines

$$\begin{aligned} \sin 2\beta_{eff} &= 0.54 \pm 0.34 \pm 0.06, \\ C &= 0.11 \pm 0.22 \pm 0.07, \end{aligned} \tag{5}$$

where C is consistent with the Standard Model expectation (0). The Belle and *BABAR* result in approximately 3σ apart, thus further analysis is required to resolve the issue of direct *CP*-violation effects in $B \to D^+D^-$.

In addition, *BABAR* has recently updated results on $B \to D^{*\pm}D^{\mp}$, which is not a *CP* eigenstate. Here, The $D^{*+}D^-$ and $D^{*-}D^+$ decay modes are analyzed separately. In the absence of

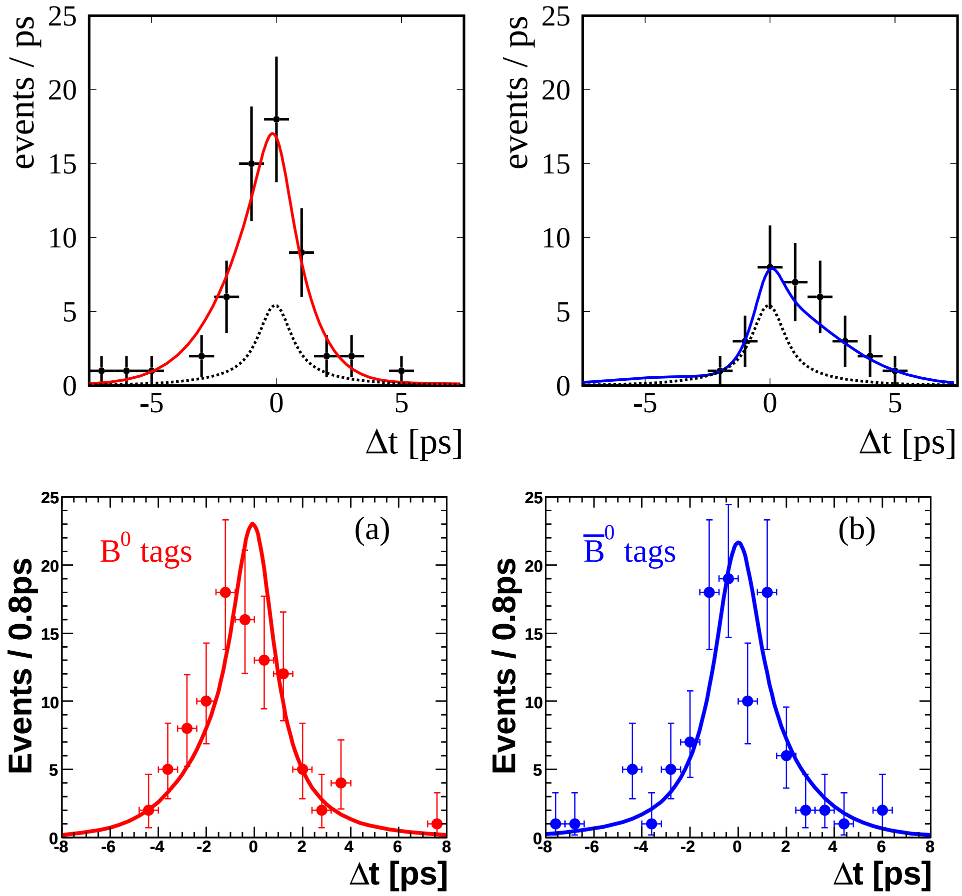

Figure 3: Distributions of B^0 tagged (left) and $\overline{B}^0$ tagged $B \to D^+D^-$ events from the Belle (top) and *BABAR*(bottom) analyses. The points show the data and the solid lines show the fit result.

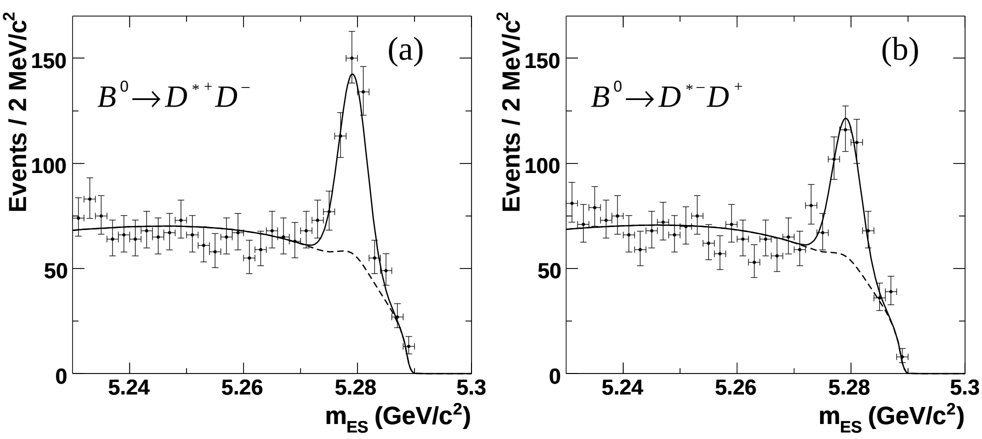

Figure 4: Signal distributions for $B \to D^{*+}D^-$ (left) and $B \to D^{*-}D^+$ from *BABAR*. The points are the data and the curves show the total fit result as well as the background contribution.

CP violation, $S_{D^{*+}D^-} = -S_{D^{*-}D^+}$ and $C_{D^{*+}D^-} = -C_{D^{*-}D^+}$. Figure 4 shows the signal samples for these modes, where *BABAR* determines

$$\begin{aligned} S_{D^{*+}D^-} &= -0.79 \pm 0.21 \pm 0.06, \\ C_{D^{*+}D^-} &= 0.18 \pm 0.15 \pm 0.06, \\ S_{D^{*-}D^+} &= -0.44 \pm 0.22 \pm 0.04, \\ C_{D^{*-}D^+} &= 0.23 \pm 0.15 \pm 0.04. \end{aligned} \quad (6)$$

Here, $S_{D^{*+}D^-} + S_{D^{*-}D^+}$ is significantly different from 0, a first indication of *CP* violation in these decay modes.

3 Measurement of *CP* violation in $B^0 \to D^0\pi^0$ and related channels

CP violation has been previously measured in $B^0 \to D^0\pi^0$ and related color-suppressed channels utilizing the $D^0 \to K^0_S\pi^+\pi^-$ final state and a Dalitz plot analysis. Here, new results are presented using other *CP* eigenstate decays of the D^0 including $D^0 \to \pi + \pi^-$, $D^0 \to K^+K^-$, and $D^0 \to K^0_S\omega$. Loop diagrams do not contribute to these decays, however *R*-parity-violating supersymmetrric processes [9] could enter at tree level in these decays. With a small interpretation uncertainty in the Standard Model, a significant deviation of $\sin2\beta_{eff}$ from $\sin2\beta$ in these decays would be a sign of new physics.

A total of 340 signal events are observed and the time-dependent analysis finds

$$\begin{aligned} \sin2\beta_{eff} &= 0.56 \pm 0.23 \pm 0.05 \\ C &= -0.23 \pm 0.16 \pm 0.04 \end{aligned} \quad (7)$$

These results [10] are in good agreement with Standard Model expectations. Figure 5 shows the Δt distributions and raw asymmetries for the reconstructed *CP* odd and even events.

4 Charmless B decay measurements of $\sin2\beta$

Unlike the $b \to c\bar{c}s$ amplitude dominated decays described above, *CP* violation in decays to charmless final states proceed via a single loop (penguin) amplitude. For modes such as $B \to \eta' K$ and $B \to \phi K$, this amplitude has the same relative phase β with respect to $B^0\overline{B}^0$ mixing and are thus sensitive to the same *CP*-violation parameter $\sin2\beta$ in the Standard Model.

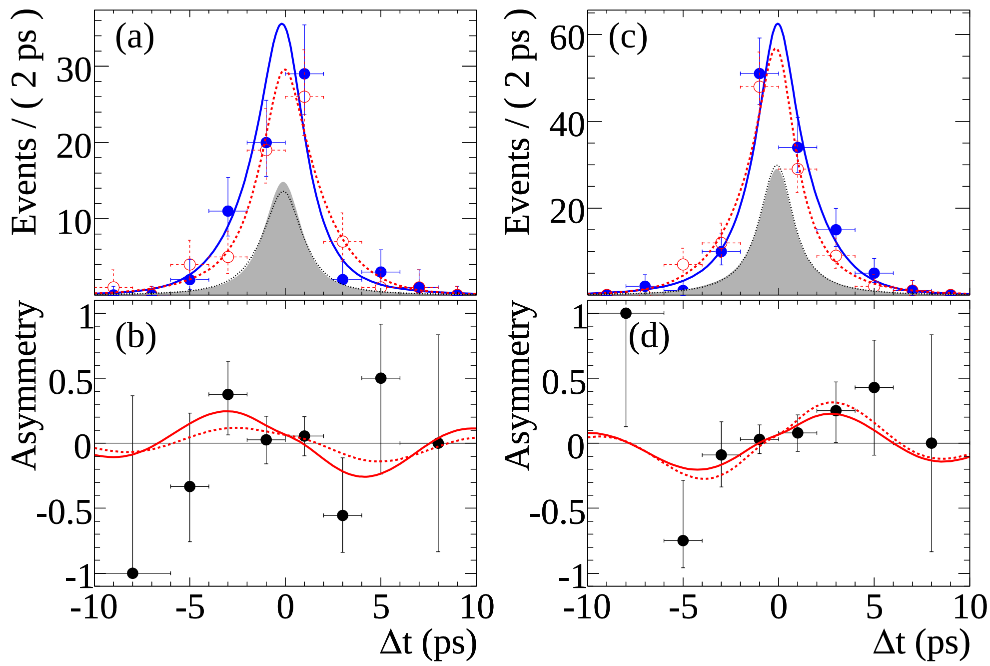

Figure 5: Plots on Δt (top) and raw asymmetries (bottom) for $\eta_f = -1$ (left) and $\eta_f = 1$ (right) modes in the *BABAR* $B \to D^{(*)}h^0$ analysis. In each case the points with error bars show the data and the lines show the fit projections. In the Δt distributions the two lines show the B^0 and $\overline{B}^0$ tagged events. In the raw asymmetries, the solid line shows the combined fit result, while the dashed line shows the $\eta_f = -1$ (left) or $\eta_f = 1$ (right) fit alone.

In these decays additional amplitudes, such as new physics processes contributing in the loop diagram, may give a sizable contribution to the observed *CP*-violation effect. A measurement of sin2β in charmless decays that differs significantly from that in $b \to c\bar{c}s$ decays would be an indication of beyond the Standard Model physics. Theoretical estimates [12] indicate that higher order Standard Model contributions are generally small and tend to increase the value of sin$2\beta_{eff}$ in these modes.

Analysis results from Belle and *BABAR* indicate a possible deviation between sin2β measured in $B \to (c\bar{c})K$ decays as described above and $b \to s\bar{s}s$ decays. Here we describe the first measurements [2,11] of sin$2\beta_{eff}$ in charmless B decays that conclusively differ from sin$2\beta_{eff} = 0$.

In these measurements, both $B \to \eta' K^0_S$ and $B \to \eta' K^0_L$ final states are used. The η' is reconstructed in its $\eta\pi^+\pi^-$ and $\rho^0\gamma$ decay modes. Combined, the analysis reconstruct more than 3000 signal events. Figure 6 shows the corresponding *BABAR* event samples.

Using these events, *BABAR* and Belle apply the same time-dependent analysis techniques as used in the $b \to c$ analysis above and determine

$$
\begin{aligned}
\sin 2\beta_{eff} &= 0.58 \pm 0.10 \pm 0.03 \ (BABAR), \\
C &= -0.16 \pm 0.07 \pm 0.03 \ (BABAR), \\
\sin 2\beta_{eff} &= 0.64 \pm 0.10 \pm 0.04 \ (\text{Belle}), \\
C &= 0.01 \pm 0.07 \pm 0.05 \ (\text{Belle}),
\end{aligned} \tag{8}
$$

both measuring sin$2\beta_{eff}$ to differ from 0 with greater than 5σ significance. No significant direct *CP* violation is observed in this mode. The Δt distribution for $B \to \eta' K$ from the Belle analysis is shown in Fig. 7.

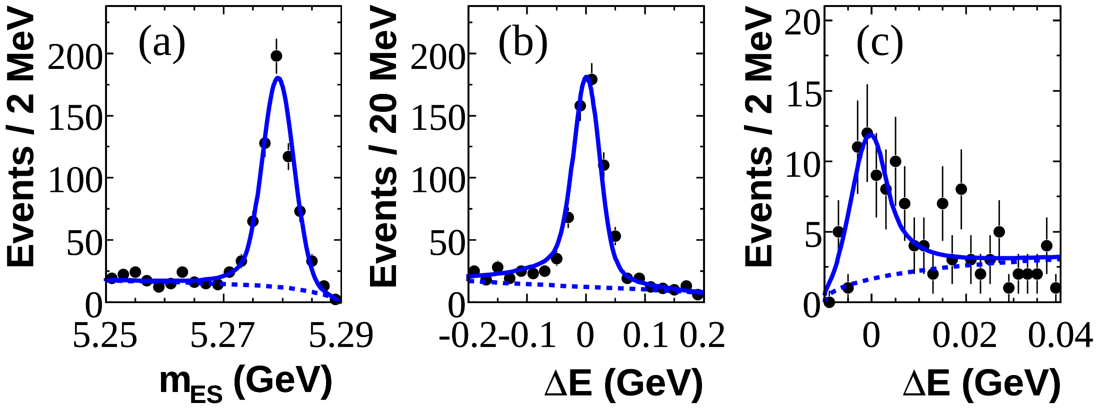

Figure 6: Event samples from the *BABAR* analysis of $B \to \eta' K^0_S$ (left and middle) and $B \to \eta' K^0_L$ (right). In each case, the points with error bars are the data, the dashed line illustrates the determined background level, and the solid line shows the total fit result.

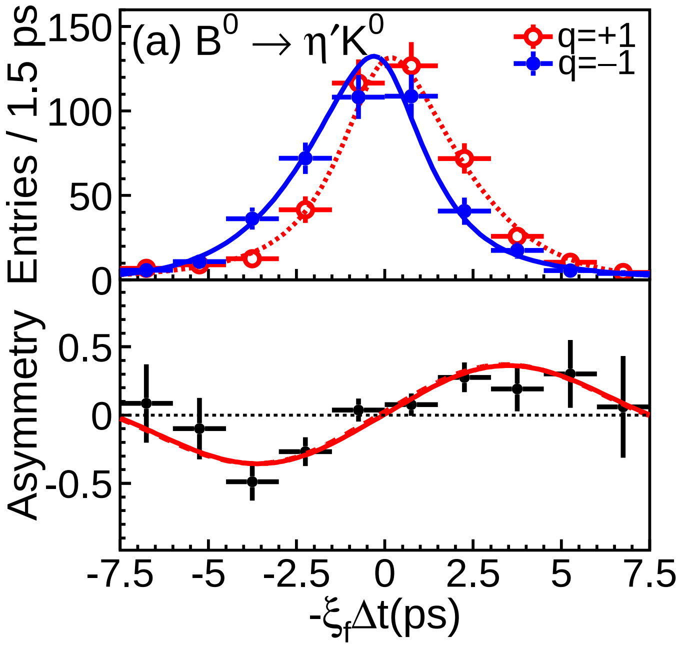

Figure 7: Δt for B^0 and $\overline{B}^0$ events (top) and raw asymmetry (bottom) distributions from the Belle analysis of $B \to \eta' K$. The distributions for $B \to \eta' K^0_L$ have been flipped to account for the opposite η_f with respect to the $B \to \eta' K^0_S$ channel.

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