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Measurements of *CP*-Violating Asymmetries in $B^0 \to a_1^{\pm}(1260)\,\pi^{\mp}$ Decays

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We present measurements of *CP*-violating asymmetries in the decays $B^0 \to a_1^{\pm}(1260)\,\pi^{\mp}$ with $a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$. The data sample corresponds to 384×10^6 $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric *B*-factory at SLAC. We measure the time- and flavor-integrated charge asymmetry $\mathcal{A}_{CP}^{a_1\pi} = -0.07 \pm 0.07 \pm 0.02$, the mixing-induced *CP* violation parameter $S_{a_1\pi} = 0.37 \pm 0.21 \pm 0.07$, the direct *CP* violation parameter $C_{a_1\pi} = -0.10 \pm 0.15 \pm 0.09$, and the parameters $\Delta C_{a_1\pi} = 0.26 \pm 0.15 \pm 0.07$ and $\Delta S_{a_1\pi} = -0.14 \pm 0.21 \pm 0.06$. From these measured quantities we extract the angle $\alpha_{\rm eff} = 78.6^{\circ} \pm 7.3^{\circ}$.

I. INTRODUCTION

The angle $\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$ of the unitarity triangle of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] has recently been measured by the *BABAR* and Belle Collaborations from time-dependent *CP* asymmetries in the $\bar{b} \to \bar{u}u\bar{d}$ dominated B^0 decays to $\pi^+\pi^-$ [2], $\rho^{\pm}\pi^{\mp}$ [3], and $\rho^+\rho^-$ [4]. In all these rare B decays the presence of additional loop (penguin) contributions with a different weak phase than the $\bar{b} \to \bar{u}u\bar{d}$ tree amplitudes complicates the extraction of the angle α. Theoretical uncertainties [5] and available experimental data samples limit the current precision on this measurement. Therefore a new and independent measurement of the angle α in another B decay mode is important to increase the precision of the measurement.

The decays $B^0 \to a_1^{\pm}\pi^{\mp}$ [6] proceed dominantly through the $\bar{b} \to \bar{u}u\bar{d}$ process in the same way as the previously studied modes and can be used to measure the time-dependent *CP* asymmetries and extract the angle α [7]. The observation of these B^0 decay modes has been recently reported by the *BABAR* collaboration [8].

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II. ANALYSIS METHOD

A. Strategy in the Measurement of α in the Decays $B^0(\overline{B}^0) \to a_1^{\pm}\pi^{\mp}$.

In these proceedings we report the measurements of the *CP*-violating asymmetries in the decays $B^0 \to a_1^{\pm}\pi^{\mp}$ with $a_1{}^{\pm} \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$ [9]. These asymmetries may be then used to extract the angle α. As mentioned in the introduction, this extraction is complicated by the presence of penguin contributions. We might overcome these complications using isospin symmetry [10] or a time-dependent Dalitz plot analysis [11] or approximate SU(3) flavor symmetry [12]. The state $a_1^{\pm}\pi^{\mp}$, like $\rho^{\pm}\pi^{\mp}$, is not a *CP* eigenstate and four flavor-charge configurations must be considered ($B^0(\overline{B}^0) \to a_1^{\pm}\pi^{\mp}$). Symmetry applications are similar in the $B^0 \to \rho^{\pm}\pi^{\mp}$ and $B^0 \to a_1^{\pm}\pi^{\mp}$ decay modes. A full isospin analysis [10] requires the precise measurement of the branching fractions and asymmetries in the five modes $B^0 \to a_1^{+}\pi^{-}$, $a_1^{-}\pi^{+}$, $a_1^{0}\pi^{0}$, $B^+ \to a_1^{+}\pi^{0}$, $a_1^{0}\pi^{+}$ and in the five charge conjugate modes. Currently only the first two decay modes (and the corresponding two charge conjugate modes) have been studied experimentally [8]. However, even measuring all the ten branching fractions and the time-dependent *CP* asymmetries in the three B^0 decay modes, this isospin method for the extraction of the angle α is not feasible at the present statistics because of the inaccuracy expected on the measured experimental quantities.

As pointed out in Ref. [11] the angle α may be extracted without ambiguity with a time-dependent analysis on the Dalitz plot . This method has been recently applied to the decay $B^0 \to \pi^+\pi^-\pi^0$ [13]. It could be applied to the decay $B^0 \to \pi^+\pi^-\pi^0\pi^0$ with contributions from $a_1^{+}\pi^{-}$, $a_1^{-}\pi^{+}$, $a_1^{0}\pi^{0}$, $\rho^+\rho^-$ amplitudes or to the decay $B^0 \to \pi^+\pi^-\pi^+\pi^-$ with contributions from $a_1^{+}\pi^{-}$, $a_1^{-}\pi^{+}$, and $\rho^0\rho^0$ amplitudes. Such analyses would be difficult because of the four particles in the final state, uncertainties in the a_1 meson parameters and lineshape, the small number of signal events and the large expected background. With current data samples this approach seems impractical. It could be considered in the next years when more data will be available.

The BaBar analysis presented in these proceedings follows a quasi-two-body approximation. The decays $B^0(\overline{B}^0) \to a_1^{\pm}\pi^{\mp}$ have been reconstructed with $a_1^{\pm} \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$ (all charged particles in final state). The other sub-decay modes with $a_1^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ could be used to enhance statistics but they have low reconstruction efficiency and large background. Details on the reconstraction and handling of the a_1 meson can be found in Ref. [8]. From a time-dependent *CP* analysis we extract an effective angle $\alpha_{\rm eff}$ which is an approximate measure of the angle α [14]. These two angles coincide in the limit of vanishing penguin contributions. Details on this approach for the decays $B^0 \to a_1^{\pm}\pi^{\mp}$ can be found in Ref.[15]. Applying flavor SU(3) symmetry one can determine an upper bound on $\Delta\alpha = |\alpha - \alpha_{\rm eff}|$, using the ratio of *CP*-averaged rates involving SU(3) related decays (in the axial-vector nonet 1^{++}): $B^0 \to a_1^{+}K^{-}$, $B^0 \to K_1^{+}(1270)\pi^{-}$, $B^0 \to K_1^{+}(1400)\pi^{-}$ or $B^+ \to a_1^{+}K^{0}$, $B^+ \to K_1^{0}(1270)\pi^{+}$, $B^+ \to K_1^{0}(1400)\pi^{+}$.

B. Time-Dependence

From a candidate $B\overline{B}$ pair we reconstruct a B^0 decaying into the final state $f = a_1\pi$ ($B^0_{a_1\pi}$). We also reconstruct the vertex of the other B meson ($B^0_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{a_1\pi} - t_{\rm tag}$ of the proper decay times of the reconstructed and tag B mesons, respectively, is obtained from the measured distance between the $B^0_{a_1\pi}$ and $B^0_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. The Δt distributions are given [15] by:

$$
\begin{aligned}
F_{Q_{\rm tag}}^{a_1^{\pm}\pi^{\mp}}(\Delta t) = (1 \pm \mathcal{A}_{CP}^{a_1\pi})\frac{e^{-|\Delta t|/\tau}}{4\tau}\Big\{1 - Q_{\rm tag}\Delta w + \\
Q_{\rm tag}(1-2w)\Big[(S_{a_1\pi} \pm \Delta S_{a_1\pi})\sin(\Delta m_d \Delta t) - \\
(C_{a_1\pi} \pm \Delta C_{a_1\pi})\cos(\Delta m_d \Delta t)\Big]\Big\} ,
\end{aligned}
\tag{1}
$$

where $Q_{\rm tag} = +1(-1)$ when the tagging meson $B^0_{\rm tag}$ is a $B^0(\overline{B}^0)$, τ is the mean B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\overline{B}^0$ or vice versa. The time- and flavor-integrated charge asymmetry $\mathcal{A}_{CP}^{a_1\pi}$ measures direct *CP* violation. The quantities $S_{a_1\pi}$ and $C_{a_1\pi}$ parameterize the mixing-induced *CP* violation related to the angle α, and flavor-dependent direct *CP* violation, respectively. The parameter $\Delta C_{a_1\pi}$ describes the asymmetry between the rates $\Gamma(B^0 \to a_1^{+}\pi^{-}) + \Gamma(\overline{B}^0 \to a_1^{-}\pi^{+})$ and $\Gamma(B^0 \to a_1^{-}\pi^{+}) + \Gamma(\overline{B}^0 \to a_1^{+}\pi^{-})$, while $\Delta S_{a_1\pi}$ is related to the strong phase difference between the amplitudes contributing to $B^0 \to a_1^{\pm}\pi^{\mp}$ decays. The parameters $\Delta C_{a_1\pi}$ and $\Delta S_{a_1\pi}$ are insensitive to *CP* violation.

A measurable angle $\alpha_{\rm eff}$ can be defined [15] as:

$$\alpha_{\rm eff} = \frac{1}{4}\Bigg[\arcsin\left(\frac{S_{a_1\pi}+\Delta S_{a_1\pi}}{\sqrt{1-(C_{a_1\pi}+\Delta C_{a_1\pi})^2}}\right)+ \arcsin\left(\frac{S_{a_1\pi}-\Delta S_{a_1\pi}}{\sqrt{1-(C_{a_1\pi}-\Delta C_{a_1\pi})^2}}\right)\Bigg] \tag{2}$$

To resolve discrete ambiguities in $\alpha_{\rm eff}$, the relative strong phase of the tree amplitudes of the B^0 decays to $a_1^-\pi^+$ and $a_1^+\pi^-$ has been assumed much smaller than 90° [15], as predicted by QCD factorization [16] and valid to leading order in $1/m_b$ [17] . With this assumption $\alpha_{\rm eff}$ can be determined from formula 2 up to four-fold discrete ambiguity.

Charge-flavor specific branching fractions can be obtained through the relation [14]:

$$\mathcal{B}_{a_1^q\pi^{-q}}(Q_{\rm tag},q) = \frac{1}{2}(1+q\,\mathcal{A}_{CP}^{a_1\pi})(1+ Q_{\rm tag}(C_{a_1\pi}+q\,\Delta C_{a_1\pi}))\,\mathcal{B}_{a_1\pi}^{\pm\mp} \tag{3}$$

with q the charge of the a_1 meson and $\mathcal{B}_{a_1\pi}^{\pm\mp}$ the measured branching fraction [8] where the final states $a_1^+\pi^-$ and $a_1^-\pi^+$ are summed and intial states (B flavors) are averaged.

III. THE *BABAR* DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- collider. An integrated luminosity of 349 fb^{-1}, corresponding to 384 ± 4 million $B\overline{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance ("on-resonance") at a center-of-mass (CM) energy $\sqrt{s} = 10.58$ GeV. An additional 37 fb^{-1} were taken about 40 MeV below this energy ("off-resonance") for the study of continuum background in which a charm or lighter quark pair is produced . A detailed description of the *BABAR* detector is given in Ref. [18]. Track and vertex reconstruction is based on a silicon vertex tracker (SVT) and a drift chamber (DCH). Photons are reconstructed in an electromagnetic calorimeter (EMC). The internally reflected Cherenkov light together with the energy loss (dE/dx) in the SVT and DCH are used for particle identification. Muons are primarily identified by the use of the instrumented flux return of the solenoid.

IV. EVENT SELECTION AND BACKGROUND SUPPRESSION

Full Monte Carlo (MC) simulations of the signal decay modes, continuum, and $B\overline{B}$ backgrounds are used to establish the event selection criteria. The MC signal events are simulated as B^0 decays to $a_1\pi$ with $a_1 \to \rho\pi$.

In the reconstruction of these decays we require $0.87 < m_{a_1} < 1.8$ GeV and $0.51 < m_\rho < 1.1$ GeV. We impose several PID requirements to ensure the identity of the signal pions. A B candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = \sqrt{(s/2+\mathbf{p}_0\cdot\mathbf{p}_B)^2/E_0^2-\mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the laboratory frame, respectively, and the asterisk denotes the CM frame. The resolutions in $m_{\rm ES}$ and in ΔE are about 3.0 MeV and 20 MeV respectively. We require $|\Delta E| \leq 0.1$ GeV and $5.25 \leq m_{\rm ES} \leq 5.29$ GeV.

To reject continuum background, we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the CM frame. We require $|\cos\theta_T| < 0.65$ To suppress further combinatorial background we require that the absolute value of the cosine of the angle between the direction of the π meson from $a_1 \to \rho\pi$ with respect to the flight direction of the B in the a_1 meson rest frame is required to be less than 0.85. We discriminate further against $q\bar{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines several variables [8].

We use MC simulations of $B^0\overline{B}^0$ and B^+B^- decays to look for $B\overline{B}$ backgrounds. Neutral and charged D mesons may contribute to background through particle mis-identification or mis-reconstruction. We remove any combinations of the decay products, including possible additional π^0, with invariant mass consistent with nominal mass values for $D^\pm \to K^\mp\pi^\pm\pi^\pm$ or $K_S^0\,\pi^\pm$ and $D^0 \to K^\mp\pi^\pm$ or $K^\mp\pi^\pm\pi^0$. The decay mode $B^0 \to a_2^\pm(1320)\,\pi^\mp$ has the same final-state particles as the signal. We improve the discrimination against this decay with an angular variable $\mathcal{H}$, defined as the cosine of the angle between the normal to the plane of the 3π resonance and the flight direction of the primary pion from B meson evaluated in the 3π resonance rest frame. We require $|\mathcal{H}| < 0.62$.

V. THE MAXIMUM LIKELIHOOD FIT

We obtain the *CP* parameters and signal yield from an unbinned extended maximum likelihood (ML) fit with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, m_{a_1}, $\mathcal{H}$, and Δt. We have six fit components in the likelihood: signal, charm and charmless $B\overline{B}$ background, $B^0 \to a_2^{\pm}(1320)\,\pi^{\mp}$, continuum $q\bar{q}$ background, and non-resonant $\rho\pi\pi$. The flavor-tagging algorithm uses six mutually exclusive categories [9].

The total probability density function (PDF) for the component j and tagging category c in the event i, $\mathcal{P}^i_{j,c}$, is written as a product of the PDFs of the discriminating variables used in the fit. The factored form of the PDF is a good approximation since linear correlations among observables are below 10%. The systematic uncertainty from residual correlations is taken into account in the fit bias. We write the extended likelihood function for all events as

$$\mathcal{L} = \prod_c \exp\left(-n_c\right) \prod_i^{N_c} \left[\sum_j n_j f_{j,c} \mathcal{P}^i_{j,c} \right] , \tag{4}$$

where n_j is the yield of events of component j, $f_{j,c}$ is the fraction of events of component j for each category c, $n_c = \sum_j f_{j,c} n_j$ is the number of events found by the fitter for category c, and N_c is the number of events of category c in the sample. We fix $f_{j,c}$ to $f_{B_{\rm flav},c}$, the values measured with a large sample of fully reconstructed B^0 decays into flavor eigenstates ($B_{\rm flav}$ sample) [19], for the signal, $\rho\pi\pi$, and $B^0 \to a_2^{\pm}(1320)\,\pi^{\mp}$ fit components. We fix $f_{j,c}$ to values obtained with MC events for the charmless and charm fit components and allow it to vary for the $q\bar{q}$ component.

We test and calibrate the fitting procedure by applying it to ensembles of simulated $q\bar{q}$ experiments drawn from the PDF, into which we have embedded the expected number of signal, charmless, $B^0 \to a_2^{\pm}(1320)\,\pi^{\mp}$, charm, and $\rho\pi\pi$ events randomly extracted from the fully simulated MC samples. The measured quantities $S_{a_1\pi}$, $C_{a_1\pi}$, $\Delta S_{a_1\pi}$, $\Delta C_{a_1\pi}$, and $\mathcal{A}_{CP}^{a_1\pi}$ have been corrected for the fit biases and a systematic uncertainty equal to half of the bias found in MC simulations is assigned on the final results.

In the fit there are 35 free parameters, including $S_{a_1\pi}$, $C_{a_1\pi}$, $\Delta S_{a_1\pi}$, $\Delta C_{a_1\pi}$, the charge asymmetries for signal and continuum background, five yields, the signal a_1 width, eleven parameters determining the shape of the combinatorial background, and 12 tagging efficiencies for the continuum.

VI. RESULTS

The maximum likelihood fit to a sample of 29300 events results in a signal yield of 608 ± 53, of which 461 ± 46 have their flavor identified.

Figure 1 shows distributions of $m_{\rm ES}$ and ΔE, enhanced in signal content by requirements on the signal-to-continuum likelihood ratios using all discriminating variables other than the one plotted.

Figure 2 gives the Δt projections and asymmetry for flavor tagged events selected as for Fig. 1.

We have studied systematic uncertainties arising from several sources: variation of the signal PDF shape parameters within their errors; modeling of the signal Δt distribution; tagging efficiency and mistag rates determined from the $B_{\rm flav}$ sample; uncertainties in Δm_d and τ [21]; uncertainty in the fit bias; uncertainty due to *CP* violation present in the $B\overline{B}$ background, the $a_2^{\pm}(1320)\,\pi^{\mp}$ *CP* violation; uncertainty due to the interference between $B^0 \to a_1^{\pm}\pi^{\mp}$ and other 4π final states; doubly-Cabibbo-suppressed (DCS) $b \to \bar{u}c\bar{d}$ amplitude for some tag-side B decays [22]; SVT alignment; and the particle identification algorithm. We allow for a *CP* asymmetry up to 20% in B decays to charmless final states, and up to 50% in B decays to $a_2(1320)\pi$. The total systematic error (%) on the fit parameters $S_{a_1\pi}$, $C_{a_1\pi}$, $\Delta S_{a_1\pi}$, $\Delta C_{a_1\pi}$, and $\mathcal{A}_{CP}^{a_1\pi}$ are 7.0, 8.5, 6.4, 7.1, and 1.6 respectively.

We measure $S_{a_1\pi} = 0.37 \pm 0.21 \pm 0.07$, $\Delta S_{a_1\pi} = -0.14 \pm 0.21 \pm 0.06$, $C_{a_1\pi} = -0.10 \pm 0.15 \pm 0.09$, $\Delta C_{a_1\pi} = 0.26 \pm 0.15 \pm 0.07$, $\mathcal{A}_{CP}^{a_1\pi} = -0.07 \pm 0.07 \pm 0.02$. Linear correlations between these fit parameters are small.

Using the measured fit parameters in formula 2, we extract the angle $\alpha_{\rm eff}$ and one of the four solutions, $\alpha_{\rm eff} = 78.6^\circ \pm 7.3^\circ$, is compatible with the result of SM-based fits. Using the published branching fraction [8] and adding statistical and systematic errors in quadrature, we derive from relation 3 the following values for the flavor-charge branching fractions (in units of 10^{-6}): $\mathcal{B}(B^0 \to a_1^+\pi^-) = 17.9 \pm 4.8$, $\mathcal{B}(B^0 \to a_1^-\pi^+) = 11.4 \pm 4.7$, $\mathcal{B}(\overline{B}^0 \to a_1^+\pi^-) = 13.0 \pm 4.3$, and $\mathcal{B}(\overline{B}^0 \to a_1^-\pi^+) = 24.2 \pm 5.8$. The average of the branching fractions in the decays $B^0 \to a_1^+\pi^-$ and $\overline{B}^0 \to a_1^-\pi^+$, where the a_1 meson is emitted by the W boson, is larger than that in the decays $B^0 \to a_1^-\pi^+$ and $\overline{B}^0 \to a_1^+\pi^-$, where the a_1 meson originates from the spectator interaction. This behaviour is in agreement with expectations based on form factor arguments.

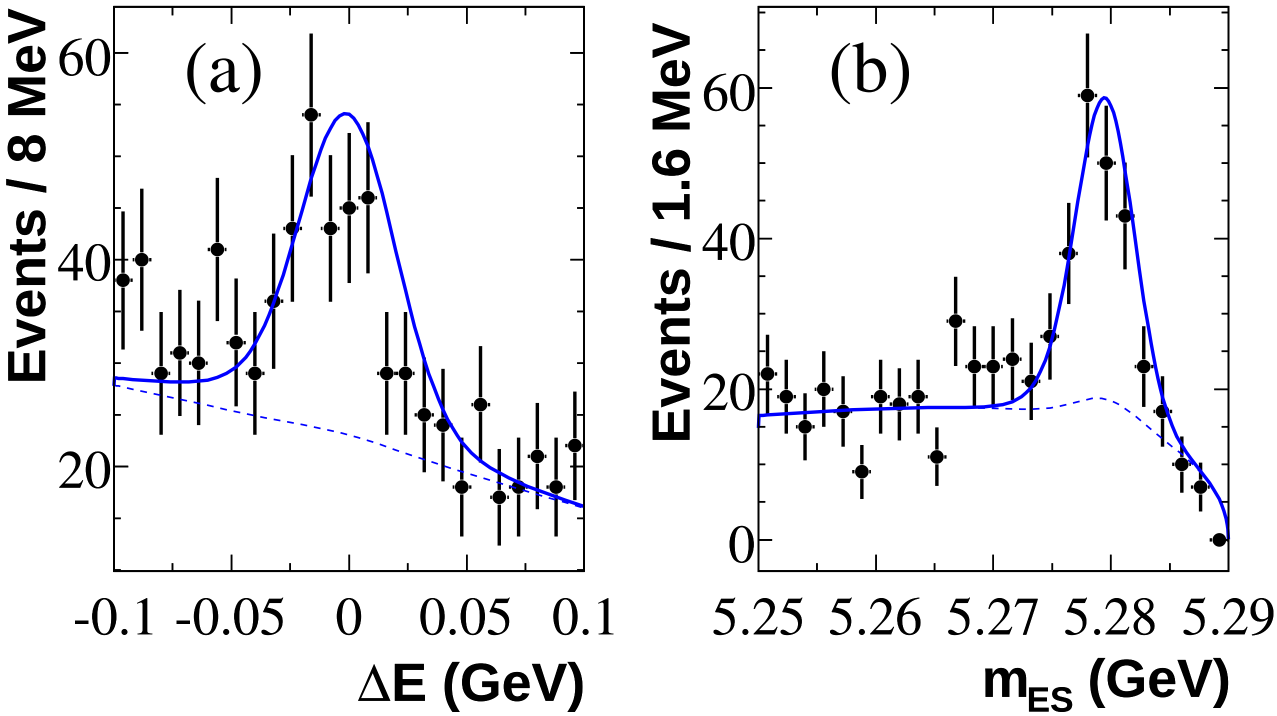

FIG. 1: Projections of a) ΔE, b) $m_{\rm ES}$. Points represent on-resonance data, dotted lines the sum of all backgrounds, and solid lines the full fit function.

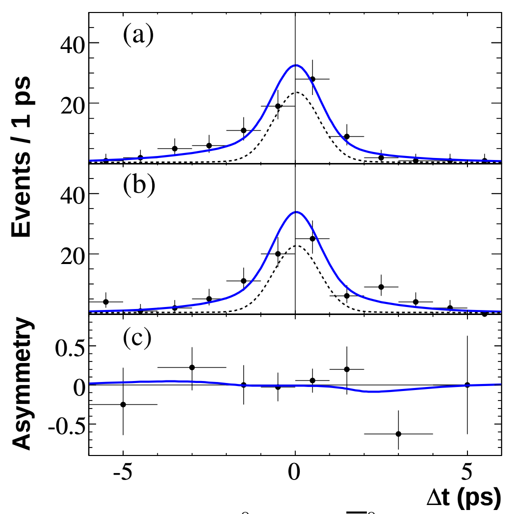

FIG. 2: Projections onto Δt of the data (points) for a) B^0 and b) $\overline{B}^0$ tags, showing the fit function (solid line), and the background function (dotted line), and c) the asymmetry between B^0 and $\overline{B}^0$ tags.

VII. SUMMARY

In summary, we measure in the $B^0(\overline{B}^0) \to a_1^{\pm}\pi^{\mp}$ decays the charge asymmetry $\mathcal{A}_{CP}^{a_1\pi} = -0.07 \pm 0.07 \pm 0.02$, the mixing-induced CP violation parameter $S_{a_1\pi} = 0.37 \pm 0.21 \pm 0.07$, the direct CP violation parameter $C_{a_1\pi} = -0.10 \pm 0.15 \pm 0.09$, and the parameters $\Delta C_{a_1\pi} = 0.26 \pm 0.15 \pm 0.07$ and $\Delta S_{a_1\pi} = -0.14 \pm 0.21 \pm 0.06$. From these measured quantities we extract the angle $\alpha_{\rm eff} = 78.6^\circ \pm 7.3^\circ$ and the following values for the flavor-charge branching fractions (in units of 10^{-6}): $\mathcal{B}(B^0 \to a_1^+\pi^-) = 17.9 \pm 4.8$, $\mathcal{B}(B^0 \to a_1^-\pi^+) = 11.4 \pm 4.7$, $\mathcal{B}(\overline{B}^0 \to a_1^+\pi^-) = 13.0 \pm 4.3$, and $\mathcal{B}(\overline{B}^0 \to a_1^-\pi^+) = 24.2 \pm 5.8$. Once the measurements of branching fractions for SU(3)-related decays become available, an upper bound on $\Delta\alpha$ will provide a constraint on the angle α.

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