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Measurement of mixing-induced CP violation Using Partial Reconstruction of $\bar{B}^0 \rightarrow D^{*+} X \ell^- \bar{\nu}_\ell$ and Kaon Tag.

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We present a new measurement of CP violation induced by B^0 $\overline{B}^0$ oscillations, based on the full data set collected by the *BABAR* experiment at the PEPII collider. We apply an original technique to a sample of about 5 million $\overline{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ decays reconstructed with partial reconstruction of the D^{*+} meson. The charged lepton identifies the flavor of the first B meson at its decay time, the flavor of the other B is determined by Kaon tagging. We determine the parameter $\delta_{CP} = 1-|q/p| = (0.29 \pm 0.84^{+1.61}_{-1.78}) \times 10^{-3}$. The precision of this measurement is comparable to that obtained by B-factories with dilepton samples.

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INTRODUCTION

The two mass eigenstates of the neutral B meson system, carrying mass m_L and m_H, are expressed in terms of the flavor eigenstates, B^0 and $\overline{B}^0$, as:

$$\begin{aligned} |B_L\rangle &= p|B^0\rangle + q|\overline{B}^0\rangle \\ |B_H\rangle &= p|B^0\rangle - q|\overline{B}^0\rangle. \end{aligned}$$

Any deviation from unity of the ratio $|q/p|$ would imply that the mass eigenstates are not CP eigenstates, which would result in the so-called CP violation in mixing. The value of $|q/p|$ is computed in terms of the off diagonal matrix elements. In the Standard Model, a number very next to unity is expected: one of the most recent theoretical calculations [1], including NLO QCD corrections, predicts:

$$\delta_{CP} = 1 - |q/p| = -(2.96 \pm 0.67) \times 10^{-4}.$$

A sizeable deviation from unity would be a clear proof of New Physics beyond the Standard Model.

If CP is violated in Mixing, the probability of a B^0 to oscillate to a $\overline{B}^0$ is different from the probability of a $\overline{B}^0$ to oscillate to a B^0 and thus we expect to observe a different number of B^0B^0 events with respect to $\overline{B}^0\overline{B}^0$. A value different from 0 is then expected for the asymmetry, defined as:

$$\mathcal{A}_{CP} = \frac{N(B^0B^0) - N(\overline{B}^0\overline{B}^0)}{N(B^0B^0) + N(\overline{B}^0\overline{B}^0)} \simeq 2\delta_{CP}, \tag{1}$$

where we neglet background and detector related charge asymmetries in lepton identification.

The Belle [2] and *BABAR* [3] Collaborations presented results based on the analysis of events with two identified leptons (dilepton events). The $D\emptyset$ Collaboration [4], using a dimuon sample, obtained a more precise measurement, which however includes contributions from B^0 and B_s mixing. They observe a deviation larger than three standard deviations from the SM expectation. An analysis of the muon impact parameters attributes the effect to B_s mesons. A recent measurement of LHCb [5] based on the reconstruction of $\bar{B}_s \rightarrow D_s^{(*)+}\ell\bar{\nu}_\ell$ decays is compatible both with the SM and with $D\emptyset$.

The dilepton measurements benefit from the large amount of events which can be selected at B-factories or at hadron colliders. They however rely on the use of control samples to subtract the charge asymmetric background from hadron to lepton misidentification or light hadron decay, and to compute the charge dependent lepton identification asymmetry which may produce a fake signal. These systematic uncertanties constitute a severe limitation to the precision of the measurement.

We present here a new kind of measurement. We partially reconstruct $\overline{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ decays by identifying only the charged lepton and the low momentum pion (π_s) from the $D^{*+} \rightarrow D^0\pi_s$ decays. A state decaying as a B^0 ($\overline{B}^0$) meson produces a positive (negative) charge lepton. Neglecting higher order terms, the observed asymmetry between the number of positive-charge and negative-charge leptons is therefore:

$$A_\ell \simeq \mathcal{A}_{r\ell} + \mathcal{A}_{CP}\chi_d, \tag{2}$$

where $\chi_d = 0.1862 \pm 0.0023$ [6] is the integrated mixing probability for B^0 mesons, and $\mathcal{A}_{r\ell}$ is the charge asymmetry in the reconstruction of $\overline{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ decays.

We use Kaons from the decays of the other B^0 to tag its flavor (K_T). A state decaying as a B^0 ($\overline{B}^0$) meson results most often in a $K^+(K^-)$. If mixing takes place, the ℓ and the K have then the same electric charge. In the same approximations as before, the observed asymmetry in the rate of mixed events is:

$$A_T = \frac{N(\ell^+K_T^+) - N(\ell^-K_T^-)}{N(\ell^+K_T^+) + N(\ell^-K_T^-)} \simeq \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}, \tag{3}$$

where $\mathcal{A}_K$ is the charge asymmetry in K reconstruction. A Kaon with the same charge as the ℓ might also come from the Cabibbo Favored (CF) decays of the D^0 meson produced with the lepton from the partially reconstructed side (K_R). The asymmetry observed for these events is then:

$$A_R = \frac{N(\ell^+K_R^+) - N(\ell^-K_R^-)}{N(\ell^+K_R^+) + N(\ell^-K_R^-)} \simeq \mathcal{A}_{r\ell} + \mathcal{A}_K + \mathcal{A}_{CP}\chi_d \quad (4)$$

Equations 2,3, and 4 can be inverted to extract $\mathcal{A}_{CP}$ and the detector induced asymmetries. It is not possible to distinguish in each event a K_T from a K_R. They are separated on statistical basis, using kinematics features and proper time difference information. We perform a multidimensional binned-likelihood fit to determine, together with the asymmetries, several other factors which would be otherwise sources of systematic uncertainty.

The *BABAR* detector is described briefly in the next section. Event selection, sample composition and B-flavor tagging is then described in Sec.. The measurement of $\mathcal{A}_{CP}$ is described in Sec., the discussion of the systematic uncertainties follows in Sec., while we summarize the results and draw our conclusions in Sec..

THE *BABAR* DETECTOR

The data sample used in this analysis consists of an integrated luminosity to $425.7\,\mathrm{fb}^{-1}$, corresponding to 468 million $B\overline{B}$ pairs, collected at the $\Upsilon(4S)$ resonance (on-resonance) and $45\,\mathrm{fb}^{-1}$ collected 40 MeV below the resonance (off-resonance) by the *BABAR* detector. The off-resonance events are used to describe the non-$B\overline{B}$ (continuum) background. A simulated sample of $B\overline{B}$ events with integrated luminosity equivalent to approximately three times the size of the data sample is also used.

A detailed description of the *BABAR* detector and the algorithms used for charged and neutral particle reconstruction and identification is provided elsewhere [7]. High-momentum particles are reconstructed by matching hits in the silicon vertex tracker (SVT) with track elements in the drift chamber (DCH). Lower momentum tracks, which do not leave signals on many wires in the DCH due to the bending induced by the 1.5 T solenoid field, are reconstructed solely in the SVT. Charged hadron identification is performed by combining the measurements of the energy deposition in the SVT and in the DCH with the information from a Cherenkov detector (DIRC). Electrons are identified by the ratio of the energy deposited in the calorimeter (EMC) to the track momentum, the transverse profile of the shower, the energy loss in the DCH, and the Cherenkov angle in the DIRC. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron. Muon candidates are required to have a path length and hit distribution in the IFR and energy deposition in the EMC consistent with that expected for a minimum-ionizing particle.

EVENT SELECTION AND KAON TAGGING

We preselect a sample of hadronic events with at least four charged tracks. To reduce continuum background, we require that the ratio of the 2^{nd} to the 0^{th} order Fox-Wolfram [8] variables be less than 0.6. We then select a sample of partially reconstructed B mesons in the channel $\overline{B}^0 \to D^{*+}X\ell^-\bar{\nu}_\ell$, by retaining events containing a charged lepton ($\ell = e,\,\mu$) and a low momentum pion (soft pion, π_s^+) from the decay $D^{*+} \to D^0\pi_s^+$. The lepton momentum [9] must be in the range $1.4 < p_{\ell^-} < 2.3\,\mathrm{GeV}/c$ and the soft pion candidate must satisfy $60 < p_{\pi_s^+} < 190\,\mathrm{MeV}/c$. The two tracks must be consistent with originating from a common vertex, constrained to the beam-spot in the plane transverse to the beam axis. Finally, we combine p_{ℓ^-}, $p_{\pi_s^+}$ and the probability from the vertex fit into a likelihood ratio variable (η), optimized to reject $B\overline{B}$ background. If more than a combination is found in an event, we keep the one with the largest value of η.

Using conservation of momentum and energy, the invariant mass squared of the undetected neutrino is calculated as $\mathcal{M}_\nu{}^2 \equiv (E_{\mathrm{beam}} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$, where E_{beam} is half the total center-of-mass energy and E_ℓ (E_{D^*}) and $\vec{p}_\ell$ ($\vec{p}_{D^*}$) are the energy and momentum of the lepton (the D^* meson). Since the magnitude of the B meson momentum, p_B, is sufficiently small compared to p_ℓ and p_{D^*}, we set $p_B = 0$. As a consequence of the limited phase space available in the D^{*+} decay, the soft pion is emitted nearly at rest in the D^{*+} rest frame. The D^{*+} four-momentum can therefore be computed by approximating its direction as that of the soft pion, and parameterizing its momentum as a linear function of the soft-pion momentum. We select pairs of tracks with opposite electric charge for our signal ($\ell^\mp\pi_s{}^\pm$) and we use same-charge pairs ($\ell^\pm\pi_s{}^\pm$) for background studies.

Several processes where D^{*+} and ℓ^- originate from the same B-meson produce a peak near zero in the $\mathcal{M}_\nu{}^2$ distribution. The peaking signal consists of (a) $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays (primary); (b) $\overline{B}^0 \to D^{*+}(\mathrm{n}\pi)\ell^-\bar{\nu}_\ell$ (D^{**}) , (c) $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$, $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$. The main source of peaking background is due to charged-B decays to excited resonant or non resonant charm excitations, $B^+ \to D^{*+}(\mathrm{n}\pi)\ell^-\bar{\nu}_\ell$, or to τ leptons, fake lepton $B \to D^{*+}h^-X$, where the hadron ($h = \pi, K, D$) is erroneously identified as, or decays to, a charged lepton (fake-lepton). We also include radiative events, where photons with energy above 1 MeV are emitted by any charged particle, as described by PHOTOS [10] in our simulation. We define the signal region $\mathcal{M}_\nu{}^2 > -2\ \mathrm{GeV}^2/c^4$, and the sideband $-10 < \mathcal{M}_\nu{}^2 < -4\ \mathrm{GeV}^2/c^4$.

Light quark (continuum) events and random combinations of a low momentum pion and an opposite charge lepton from combinatorial $B\overline{B}$ events, contribute to the non-peaking background. We determine the number of signal events in our sample with a minimum χ^2 fit to the ${\mathcal{M}_\nu}^2$ distribution in the interval $-10 < {\mathcal{M}_\nu}^2 < 2.5$ GeV^2/c^4. In the fit, the continuum contribution is obtained from off-peak events, normalized by the on-peak to off-peak luminosity ratio, the other contributions are taken from the simulation. The amount of events from combinatorial $B\overline{B}$ background, primary decays and D^{**} are allowed to vary in the fit, while the other peaking contributions (few percent) are fixed to the simulation expectations, rescaled by the luminosities ratios. The amount of B^0 mesons in the sample is then obtained assuming that 2/3 of the fitted amount of D^{**} events are produced by B^+ decays, as suggested by simple isospin considerations. A total of $(5945 \pm 7) \cdot 10^3$ peaking events are found; in the full range peaking events account for about 30% of the sample, continuum background for about 15%. The result of the fit is displayed in Fig.1

We select kaons from all the charged tracks with momentum larger than 0.2 GeV/c using a standard algorithm which combines DIRC informations with the measurements of the energy losses in the SVT and DCH. True kaons are identified with 86% efficiency and 3.4% pion mis-identification rate. Kaons may be produced from the decay of the D^0 from the partially reconstructed B^0 (K_R), or in any step of the decay of the other B (K_T).

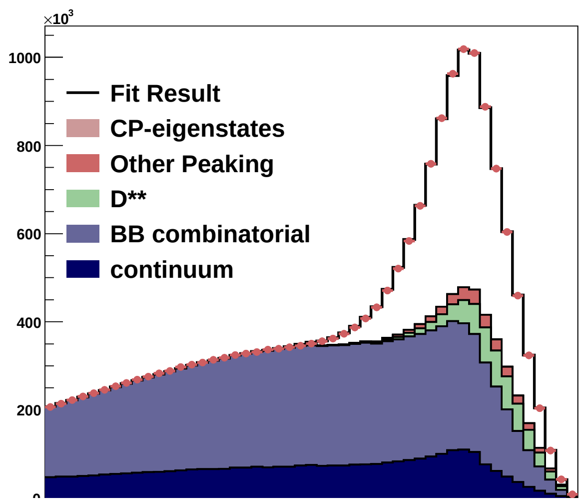

FIG. 1: ${\mathcal{M}_\nu}^2$ distribution for the data, points with error bars, and the fitted contributions from signal, peaking background, $B\overline{B}$ combinatorial and rescaled off-peak events (continuous line overlied).

We exploit the relation between the charge of the lepton and that of the K_T to tag mixing. When an oscillation takes place, a K_T from a Cabibbo Favored (CF) decay has the same electric charge as the ℓ. Equal-charge combinations are also observed from Cabibbo Supressed (CS) K_T production in unmixed events, and from CF K_R production. Unmixed CF K_T, mixed CS K_T, and CS K_R, result in opposite-charge combinations. Fake kaons contribute both to equal and opposite charge events with comparable rates.

We distinguish K_T from K_R using proper-time difference information. We define $\Delta Z = Z_{rec} - Z_{tag}$, where Z_{rec} is the projection along the beam direction of the B_{rec} decay point, and Z_{tag} is the projection along the same direction of the intersection of the K track trajectory with the beam-spot. In the boost approximation [11] we measure the proper-time-difference between the two B mesons using the relation $\Delta t = \Delta Z/(\beta\gamma c)$, where the parameters β, γ expressing the Lorentz Boost from the Laboratory to the $\Upsilon(4S)$ rest frame, are determined run by run from PEPII settings. We reject events if the error $\sigma(\Delta t)$ exceeds 3 ps.

Due to the short lifetime and small boost of the D^0 meson, small values of Δt are expected for the K_R. Much larger values are instead expected for CF mixed K_T, due to the long period of the B^0 oscillation (about six times the B^0 lifetime). By fitting the Δt distribution for equal and opposite charge ℓ-K combinations, we also compute the contamination from CS K_T decays.

To improve the separation between K_T and K_R, we also exploit kinematics. The ℓ and the D^{*+} are emitted at large angles in the rest frame of the decaying B^0: therefore the angle $\theta_{\ell K}$ between the ℓ and the K_R has values close to π, and $\cos(\theta_{\ell K})$ close to -1. The corresponding distribution for the K_T is instead uniform.

If more than a Kaon is found in an event, we consider each $\ell - K$ combination in turn. We use parameterized simulations (toys) to verify the effect of this choice on the computation of the statistical uncertainty.

EXTRACTION OF δ_{CP}

The measurement proceeds in two steps.

We first measure the sample composition of the eight tagged samples divided by lepton kind, lepton charge and K charge, with the fit to ${\mathcal{M}_\nu}^2$ described above. We also fit the four inclusive lepton samples to determine the charge asymmetries at the reconstruction stage (see eq. 2).

The results of the first stage are used in the second stage, where we fit simultaneously the $\cos\theta_{\ell K}$ and Δt distributions in the eight tagged samples. The individual $\cos\theta_{\ell K}$ shapes are obtained from the histograms of the simulated distributions for $B\overline{B}$ events, separately for K_T and K_R events. Off-peaks events are interpolated to parameterize the continuum distribution. The Δt distributions for K_T $B\overline{B}$ events are parameterized as the convolutions of the theoretical distributions with the resolution function: $\mathcal{G}_i(\Delta t) = \int_{-\infty}^{+\infty} \mathcal{F}_i(\Delta t'|\vec{\Theta})\mathcal{R}(\Delta t, \Delta t')d(\Delta t')$, where $\Delta t'$ is the actual difference between the times of decay of the two mesons and $\vec{\Theta}$ is the vector of the physical parameters.

B^+ decays are parameterized by an exponential function, $\mathcal{F}_{B^+} = \Gamma_+ e^{-|\Gamma_+ \Delta t'|}$, where the B^+ partial decay width is computed as the inverse of the lifetime $\Gamma_+^{-1} = \tau_+ = (1.641 \pm 0.008)$ ps.

B^0 decays are described by the following expressions:

$$
\begin{aligned}
\mathcal{F}_{\bar{B^0}B^0}(\Delta t') &= \mathcal{E}(\Delta t')\Bigg[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2) + \left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d \Delta t') - \left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t')\Bigg] \quad (5)\\
\mathcal{F}_{B^0\bar{B^0}}(\Delta t') &= \mathcal{E}(\Delta t')\Bigg[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2) + \left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d \Delta t') + \left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t')\Bigg]\\
\mathcal{F}_{\bar{B^0}\bar{B^0}}(\Delta t') &= \mathcal{E}(\Delta t')\Bigg[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2) - \left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d \Delta t') - \left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t')\Bigg]\left|\frac{q}{p}\right|^2\\
\mathcal{F}_{B^0B^0}(\Delta t') &= \mathcal{E}(\Delta t')\Bigg[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t'/2) - \left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d \Delta t') + \left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t')\Bigg]\left|\frac{p}{q}\right|^2\\
\mathcal{E}(\Delta t') &= \frac{\Gamma_0}{2(1+r'^2)} e^{-\Gamma_0|\Delta t'|},
\end{aligned}
$$

where the first index refers to the flavor of the B_{rec} at decay time and the second to the B_{tag}. $\Gamma_0 = {\tau_{B^0}}^{-1}$ is the average width of the two B^0 mass eigenstates, $\Delta\Gamma$ the width difference, r' a tiny (O %) parameter resulting from the interference of CF and Doubly Cabibbo Suppressed (DCS) decays in the B_{tag} side, b and c two parameters expressing the CP violation arising from that interference [12]. In the Standard Model $b = 2r' sin(2\beta+\gamma) cos\delta'$, $c = -2r' cos(2\beta+\gamma) sin\delta'$, where β and γ are angles of the Unitary Triangle [13], and δ' is a strong phase. Besides $|q/p|$, also Δm_d, τ_{B^0}, r', b, and c are determined as effective parameters to reduce the systematic uncertainty. The value of $\Delta\Gamma$ is instead fixed to zero, and then varied within its allowed range when computing the systematic uncertainty.

When the K_T comes from the decay of the B^0 meson to a CP-egeinstate (as, for instance $B^0 \to D^{(*)}D^{(*)}$), a different expression applies:

$$\mathcal{F}_{CPe}(\Delta t') = \frac{\Gamma_0}{4} e^{-\Gamma_0|\Delta t'|}(1 \pm S sin(\Delta m_d \Delta t') \pm C cos(\Delta m_d \Delta t'),$$

where the sign + is used if the B_{rec} decays as a B^0 and the sign - otherwise. We take the values of S and C, and the fraction of these events in each sample (about 1%) from the simulation.

The resolution function $\mathcal{R}(\Delta t, \Delta t')$ accounts for the experimental uncertainties in the measurement of Δt, for the smearing due to the boost approximation, and for the displacement of the K_T production point from the B_{tag} decay position due to the motion of the charm meson. It consists of the superposition of several Gaussian functions convoluted with exponentials. We use a different set of parameters for peaking and for combinatoric events.

To describe the Δt distributions for K_R events, $\mathcal{G}_{K_R}(\Delta t)$, we select a sub-sample of data containing less than 5% K_T decays, and we use the background subtracted histograms in our likelihood. As an alternative, we apply the same selection to the simulation and we correct the Δt distribution predicted by the Monte Carlo by the ratio of the histograms extracted from data and simulated events. Simulation shows that the distributions so obtained are unbiased.

We take the average of the two δ_{CP} determinations obtained with the two different strategies as our nominal result.

Continuum events ($\mathcal{G}_{cnt}(\Delta t)$) are represented by a decaying exponential, convoluted with a resolution function similar to that used for B-events. The effective lifetime and resolution parameters are determined by fitting simultaneously the off-peak data.

The two-dimensional PDFs are computed as the product of the Δt and $\cos(\theta_{\ell K})$ functions.

We perform a binned maximum likelihood fit. Events belonging to each of the four categories are grouped in 100 Δt bin, 25 $\sigma(\Delta t)$ bins, 4 $\cos\theta_{\ell,K}$ bins, and 5 ${\mathcal{M}_\nu}^2$ bins. We further split data in five bins of K momentum, p_K, to account for the dependencies of several parameters, describing the Δt resolution function, the $\cos(\theta_{\ell K})$ distributions, the fractions of K_T events, etc., observed in the simulation.

The rate of events in each bin $(\vec{j})$ and per each tagged sample are then expressed as the sum of the predicted contributions from peaking events, $B\overline{B}$ combinatorial and continuum:

$$
\begin{aligned}
\mathcal{N}_{\ell K}(\vec{j}) &= \mathcal{N}[(1 - f_{B^+} - f_{CPe} - f_{cmb} - f_{cnt})\mathcal{G}_{B^0}(\vec{j}) \quad (6)\\
&+ f_{B^+}\mathcal{G}_{B^+}(\vec{j}) + f_{CPe}\mathcal{G}_{CPe}(\vec{j})\\
&+ f^0_{cmb}\mathcal{G}_{B^0,cmb}(\vec{j}) + f^+_{cmb}\mathcal{G}_{B^+,cmb}(\vec{j}) + f_{cnt}\mathcal{G}_{cont}(\vec{j})]
\end{aligned}
$$

where the fractions of peaking B^+ (f_{B^+}), CP eigenstates (f_{CPe}), combinatoric $B\overline{B}$ (f_{cmb}), and continuum (f_{cnt}) events in each ${\mathcal{M}_\nu}^2$ interval is computed from the results of the first stage. The amounts of B^0 (f^0_{cmb}) and of B^+ events ($f^+_{cmb} = f_{cmb} - f^0_{cmb}$) in the combinatoric background are assumed from the simulation.

Accounting for mistags and K_R events, the peaking B^0 contributions to the equal-charge samples are:

$$
\begin{aligned}
\mathcal{G}_{\ell^+K^+}(\vec{j}) &= (1+\mathcal{A}_{r\ell})(1+\mathcal{A}_K) \\
&\quad \{(1-f^{++}_{K_R})[(1-\omega^+)\mathcal{G}_{B^0B^0} + \omega^-\mathcal{G}_{B^0\bar{B}^0}(\vec{j})] \\
&+ f^{++}_{K_R}(1-\omega'^+)\mathcal{G}_{K_R}(\vec{j})(1+\bar{\chi_d}\mathcal{A}_{CP})\ \} \\
\mathcal{G}_{\ell^-K^-}(\vec{j}) &= (1-\mathcal{A}_{r\ell})(1-\mathcal{A}_K) \\
&\quad \{(1-f^{--}_{K_R})[(1-\omega^-)\mathcal{G}_{\bar{B}^0\bar{B}^0} + \omega^+\mathcal{G}_{\bar{B}^0B^0}(\vec{j})] \\
&+ f^{--}_{K_R}(1-\omega'^-)\mathcal{G}_{K_R}(\vec{j})(1-\bar{\chi_d}\mathcal{A}_{CP})\ \}
\end{aligned}
$$

where the reconstruction asymmetries are computed separately for the e and μ samples. We allow for different mistags probabilities for K_T ($\omega^\pm$) and K_R ($\omega'^\pm$), because the former come from a mixture of D mesons, while the others are produced by D^0 decays only.

The parameters $f^{\pm\pm}_{K_R}(p_k)$ describe the fractions of K_R tags in each sample. All these parameters depend of the Kaon momentum. We let the fit determine the values of the $f^{\pm\pm}_{K_R}$ parameters in every p_k bin.

A total of 171 parameters are determined in the fit.

Fit Validation

Several test are performed to validate our result.

We first analyze simulated events as the data, considering first only B^0 signal and adding step by step all the other samples. At any stage, the fit reproduces the generated values of $|q/p|$ (zero), and of the other most significant parameters ($\mathcal{A}_{r\ell}$,$\mathcal{A}_K$, Δm_d, and τ_{B^0}).

We then repeat the test, randomly rejecting B^0 or $\bar{B}^0$ events in order to produce samples of simulated events with $\delta_{CP} = \pm 0.005, \pm 0.01, \pm 0.025$. Also in this case the generated values are well reproduced by the fit.

By removing events we also vary artificially $\mathcal{A}_{r\ell}$ or $\mathcal{A}_K$, testing values in the range of $\pm 10\%$. In each case the input values are correctly determined, and an unbiased value of $|q/p|$ is always obtained.

Parameterized simulations (toys) are used to check the estimate of the result and its statistical uncertainty. We perform 173 pseudo-experiments, each with the same amount of events as the data. We obtain a value of the likelihood larger than the data one in 23% of the cases.

The distribution of the results is described by a Gaussian function with a central value biased by -3.6×10^{-4} ($0.4\,\sigma$) wrt the nominal result. We quote this discrepancy as a systematic error related to the analysis bias.

The pull distribution is described by a Gaussian function, with a central value -0.48 ± 0.11 and RMS width of 1.44 ± 0.08. The statistical uncertainty is therefore somewhat underestimated. However, by fitting the likelihood profile near the minimum with a parabola, we obtain an estimation of the statistical uncertainty in good agreement with the RMS width of the distribution of the pseudo-experiments results. Therefore we assume the likelihood profile determination as the statistical uncertainty of our result.

SYSTEMATIC UNCERTAINTIES AND CONSISTENCY CHECKS

We consider several sources of systematic uncertainties. We vary each quantity by its uncertainty, as discussed below, we repeat the measurement, and we consider the variation of the result as the corresponding systematic uncertainty; we then add in quadrature all the contributions to compute the overall systematic error.

Peaking Sample Composition: we vary the sample composition in the second stage fit by the statistical uncertainties obtained at the first stage; the corresponding variation is added in quadratuture to the systematic uncertainty. We then vary the fraction of B^0 to B^+ in the D^{**} peaking sample in the range $50 \pm 25\%$ to account for (large) violation of isospin symmetry. The fraction of the peaking contributions fixed to the simulation expectations is varied by $\pm 20\%$. Finally we conservatively vary the fraction of CP-eigenstates by $\pm 50\%$.

$B\overline{B}$ combinatoric sample composition: the fraction of B^+ and B^0 in the $B\overline{B}$ combinatorial background is determined by the simulation. A difference between B^+ and B^0 is expected when mixing takes place and the the lepton is coupled to the tag side π_s from $\bar{B}^0 \to D^{*+}X$ decay. We then vary the fraction of B^0 to B^+ events in the combinatorial sample by $\pm 4.5\%$, which corresponds to the error in the inclusive branching fraction $\bar{B}^0 \to D^{*+}X$.

Δt resolution model: we perform a fit by leaving free all the parameters describing the resolution function and we quote the difference wrt the nominal one as systematic error.

K_R fraction: we vary the fraction of $B^+ \to K_RX$ to $B^0 \to K_RX$ by $\pm 6.8\%$, which corresponds to the uncertainty on the fraction $\frac{BR(D^{*0}\to K^-X)}{BR(D^{*+}\to K^-X)}$.

K_R Δt distribution: we use half the difference between the results obtained using the two different strategies to describe the Δt distribution as systematic uncertainty.

Fit bias: we add the statistical error on the validation test we performed with the detailed simulation and the difference between the nominal result and the central value of the pseudo-experiments ones.

CP eigenstates description: we vary the S and C parameters describing the CP-eigenstates by their statistical uncertainty as obtained from simulation.

Physical parameters: we repeat the fit imposing the value of $\Delta\Gamma$ to 0.02 ps^{-1} instead of zero. The lifetime of

TABLE I: Breakdown of the main systematic uncertainties affecting our result.

Source	$\Delta\lvert q/p\rvert$
Peaking Sample Composition	$^{+1.17}_{-1.50} \times 10^{-3}$
Combinatoric Sample Composition	$\pm 0.39 \times 10^{-3}$
Δt Resolution Model	$+0.60 \times 10^{-3}$
K_R fraction	$\pm 0.11 \times 10^{-3}$
K_R Δt distribution	$\pm 0.65 \times 10^{-3}$
Fit Bias	$^{+0.46}_{-0.58} \times 10^{-3}$
CP-eigenstate description	–
Physical Parameters	$+0.28 \times 10^{-3}$
Total	$^{+1.61}_{-1.78} \times 10^{-3}$

TABLE II: Results: second column, fit to the data; third, fit to simulated events; last: values of the parameters in the simulation at generation stage.

Parameter	Fit to the data	Fit to the simulation	MC truth
δ_{CP}	$(0.29 \pm 0.84) \times 10^{-3}$	$(0.35 \pm 0.46) \times 10^{-3}$	0
$\mathcal{A}_{re}$	0.0030 ± 0.0004	0.0097 ± 0.0002	
$\mathcal{A}_{r\mu}$	0.0031 ± 0.0005	0.0084 ± 0.0003	
$\mathcal{A}_{K}$	0.0137 ± 0.0003	0.0147 ± 0.0001	
τ_{B^0}	1.5535 ± 0.0019	1.5668 ± 0.0012	1.540
Δm_d	0.5085 ± 0.0009	0.4826 ± 0.0006	0.489

the B^0 and B^+ mesons and the Δm_d are floated in the fit. In alternative, we check the effect of fixing each in turn to the world average.

By adding in quadrature all the contributions described above we compute the overall systematic uncertainty of $^{+1.60}_{-1.78} \times 10^{-3}$. Table I summarizes all the systematic uncertainties described above.

RESULTS

We perform a blind analysis: the value of $|q/p|$ is kept masked untill the study of the systematic uncertainties is completed and all the consistency checks are succesfully accomplished; the values of all the other fit parameters, instead, are not masked.

After unblinding we find: $\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84) \times 10^{-3}$.

Figures 2 and 3 show the fit projections for Δt and $\cos\theta_{\ell K}$, respectively.

We report on Tab. II the fit results for the most significant parameters. The value of Δm_d is well consistent with the world average, while the value of τ_{B^0} is slightly larger than expected, an effect also observed in the simulation. By fixing its value to the world average, the $|q/p|$

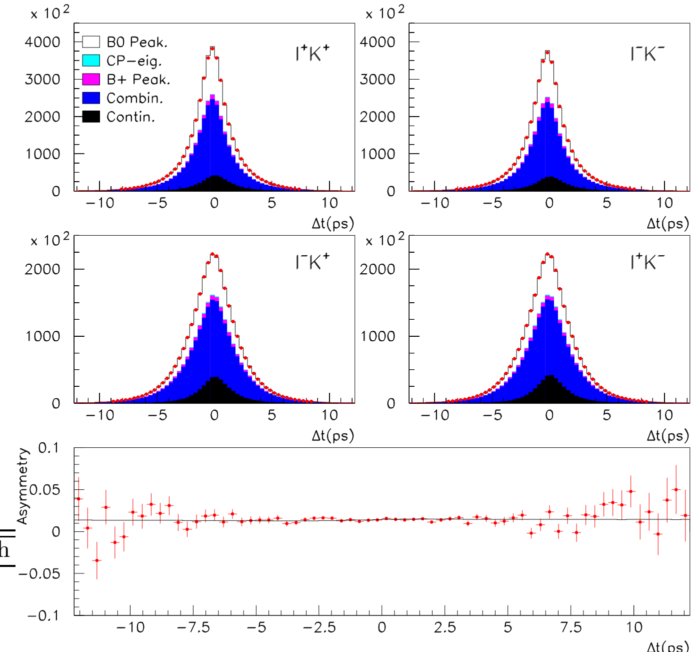

FIG. 2: Δt distribution for the data, point with error bars, and the fitted contributions from signal, peaking B^+ background, CP-eigenstates, $B\overline{B}$ combinatorial and continuum events. Top left plot: ℓ^+K^+. Top right plot: ℓ^-K^-. Central left plot: ℓ^-K^+ events. Central right plot: ℓ^+K^- events . Bottom plot: Raw asymmetry between ℓ^+K^+ and ℓ^-K^- events.

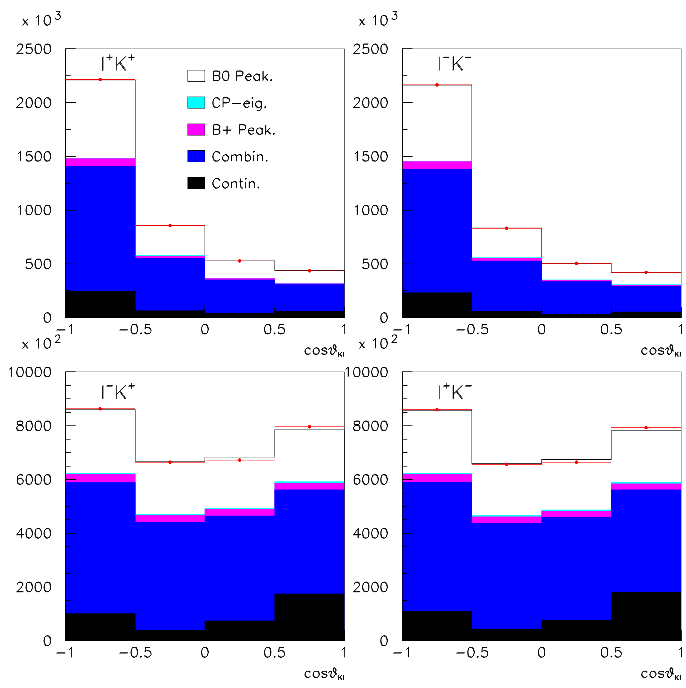

FIG. 3: $\cos\theta_{\ell K}$ distribution for the data, point with error bars and the fitted contributions from signal, CP-eigenstates, peaking B^+ background, $B\overline{B}$ combinatorial and continuum events. Top left plot: ℓ^+K^+. Top right plot: ℓ^-K^-. Central left plot: ℓ^-K^+ events. Central right plot: ℓ^+K^- events.

result increases by 0.18×10^{-3}. This effect is taken into account in the systematic error computation.

A sizable asymmetry is observed at the reconstruction stage, for both e and μ, and at the K tagging stage, as also observed in the simulation. This hints that the main sources of charge asymmetry are due to the reconstruction of the π_s and the K .

CONCLUSIONS

We present a new precise measurement of the parameter governing CP violation in B^0 $\overline{B}^0$ oscillations. With a tecnicque based on partial $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ reconstruction and K tagging we find

$$\delta_{CP} = (0.29 \pm 0.84^{+1.61}_{-1.78}) \times 10^{-3},$$

where the first uncertainty is statistical and the second is systematic. The corresponding value of the dilepton asymmetry,

$$\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.32}_{-0.36})\%,$$

is well consistent with and more precise than the results from dilepton measurements. No deviation is observed from the SM expectation [14].

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