

# 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  $B^0 \bar{B}^0$  oscillations, based on the full data set collected by the BABAR experiment at the PEP-II collider. We select a sample of about 5 million  $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$  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  $\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$ .

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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  $\bar{B}^0$ , as  $|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$ . Any deviation from unity of the ratio  $|q/p|$  would imply that the mass eigenstates are not CP eigenstates (“mixing-induced CP violation”). The Standard Model prediction, including NLO QCD corrections, is  $\delta_{CP} = 1 - |q/p| = -(2.96 \pm 0.67) \times 10^{-4}$  [1]. A sizeable deviation from unity would be a clear evidence of New Physics beyond the Standard Model.

If CP is violated in Mixing, the probability of a  $B^0$  to oscillate to a  $\bar{B}^0$  is different from the probability of a  $\bar{B}^0$  to oscillate to a  $B^0$  and thus we expect to observe a sizeable value for the asymmetry:

$$\mathcal{A}_{CP} = \frac{N(B^0 B^0) - N(\bar{B}^0 \bar{B}^0)}{N(B^0 B^0) + N(\bar{B}^0 \bar{B}^0)} \simeq 2\delta_{CP}. \quad (1)$$

$B$ -factories [2], [3] and hadron collider experiments have published results where the  $B$  mesons are tagged by their semileptonic decays. The  $D\theta$  Collaboration observes a large deviation from the SM, which is however attributed to  $B_s$  meson oscillation [4]. LHCb preliminary result is in fact compatible both with the SM and with  $D\theta$  [5].

These 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 uncertainties constitute a severe limitation to the precision of the measurement.

We present here a new kind of measurement. We partially reconstruct  $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$  decays (hereafter  $B_R$ ) by identifying only the charged lepton and the low momentum pion ( $\pi_s$ ) from the  $D^{*+} \rightarrow D^0 \pi_s$  decays. A

state decaying as a  $B^0$  ( $\bar{B}^0$ ) 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:

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

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  $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$  decays.

We use kaons from the decays of the other  $B^0$  ( $B_T$ ) to tag its flavor ( $K_T$ ). A state decaying as a  $B^0$  ( $\bar{B}^0$ ) meson results most often in a  $K^+$  ( $K^-$ ). If mixing takes place, the  $\ell$  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:

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

where  $\mathcal{A}_K$  is the charge asymmetry in kaon reconstruction. A kaon with the same charge as the  $\ell$  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:

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

Eq. 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 multi-dimensional binned-likelihood fit to determine, together with the asymmetries, several other factors which would be otherwise sources of systematic uncertainty.

The data sample used in this analysis consists of an integrated luminosity to  $425.7 \text{ fb}^{-1}$ , corresponding to 468 million  $B\bar{B}$  pairs, collected at the  $\Upsilon(4S)$  resonance by the

BABAR detector. A detailed description of the BABAR detector and the algorithms used for charged and neutral particle reconstruction and identification is provided elsewhere [7]. A sample of  $45 \text{ fb}^{-1}$  collected 40 MeV below the resonance are used to describe the non- $B\bar{B}$  (continuum) background. A simulated sample of  $B\bar{B}$  events with integrated luminosity equivalent to approximately three times the size of the data sample is also used.

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

Using conservation of momentum and energy, the invariant mass squared of the undetected neutrino is calculated as  $\mathcal{M}_\nu^2 \equiv (E_{\text{beam}} - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$ , where  $E_{\text{beam}}$  is half the total center-of-mass energy and  $E_\ell$  ( $E_{D^*}$ ) 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  $p_\ell$  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  $\ell^-$  originate from the same  $B$ -meson produce a peak near zero in the  $\mathcal{M}_\nu^2$  distribution. The peaking signal consists of (a)  $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$  decays (primary); (b)  $\bar{B}^0 \rightarrow D^{*+} (n\pi) \ell^- \bar{\nu}_\ell$  ( $D^{**}$ ), (c)  $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ ,  $\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau$ . The main source of peaking background is due to charged- $B$  decays to excited resonant or non resonant charm excitations,  $B^+ \rightarrow D^{*+} (n\pi) \ell^- \bar{\nu}_\ell$ , or to  $\tau$  leptons, fake lepton  $B \rightarrow D^{*+} h^- X$ , 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  $\mathcal{M}_\nu^2 > -2 \text{ GeV}^2/c^4$ , and the sideband  $-10 < \mathcal{M}_\nu^2 < -4 \text{ GeV}^2/c^4$ .

Light quark (continuum) events and random combinations of a low momentum pion and an opposite charge lepton from combinatorial  $B\bar{B}$  events, contribute to the non-peaking background. We determine the number of signal events in our sample with a minimum  $\chi^2$  fit to the  $\mathcal{M}_\nu^2$  distribution in the interval  $-10 < \mathcal{M}_\nu^2 < 2.5 \text{ GeV}^2/c^4$ . 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  $B\bar{B}$  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.

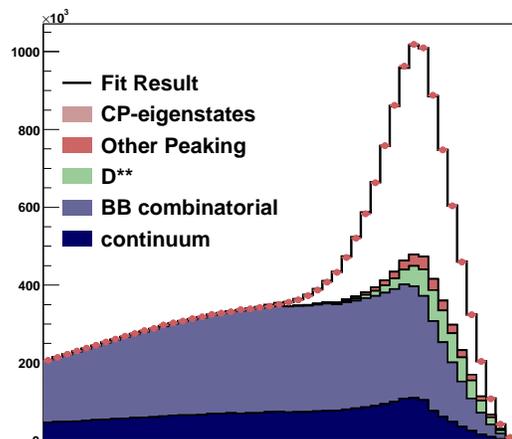


FIG. 1:  $\mathcal{M}_\nu^2$  distribution for the data, points with error bars, and the fitted contributions from signal, peaking background,  $B\bar{B}$  combinatorial and rescaled off-peak events (continuous line overlaid).

We select kaons from all the charged tracks with momentum larger than 0.2 GeV/c combining informations from the Cherenkov detector with the measurements of the energy losses in the trackers. 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  $B$  ( $K_T$ ). 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 charge as the  $\ell$ . Equal-charge combinations are also observed from Cabibbo Suppressed (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 com-

binations. 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  $\Delta Z = Z_R - Z_T$ , where  $Z_R$  is the projection along the beam direction of the  $B_R$  decay point, and  $Z_T$  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  $\beta, \gamma$  expressing the Lorentz Boost from the Laboratory to the  $\Upsilon(4S)$  rest frame, are determined run by run from PEP-II 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  $\Delta t$  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  $\Delta t$  distribution for equal and opposite charge  $\ell$ - $K$  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  $\ell$  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  $\ell$  and the  $K_R$  has values close to  $\pi$ , and  $\cos(\theta_{\ell K})$  close to  $-1$ . The corresponding distribution for the  $K_T$  is uniform.

If more than a Kaon is found in an event, we consider each combination in turn. We use parameterized sim-

ulations (toys) to verify the effect of this choice on the computation of the statistical uncertainty.

The measurement proceeds in two steps. We first measure the sample composition of the eight tagged samples defined by lepton type, 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  $\Delta t$  distributions in the eight tagged samples. The individual  $\cos\theta_{\ell K}$  shapes are obtained from the histograms of the simulated distributions for  $B\bar{B}$  events, separately for  $K_T$  and  $K_R$  events. Off-peak events are interpolated to parameterize the continuum distribution. The  $\Delta t$  distributions for  $K_T B\bar{B}$  events are parameterized as the convolutions of the theoretical distributions  $\mathcal{F}_i(\Delta t|\vec{\Theta})$  with the resolution function  $\mathcal{R}(\Delta t, \Delta t')$ :  $\mathcal{G}_i(\Delta t) = \int_{-\infty}^{+\infty} \mathcal{F}_i(\Delta t'|\vec{\Theta})\mathcal{R}(\Delta t, \Delta t')d(\Delta t')$ , 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:

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

where the first index refers to the flavor of the  $B_R$  at decay time and the second to the  $B_T$ .  $\Gamma_0 = \tau_{B^0}^{-1}$  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  $B_T$  side,  $b$  and  $c$  two parameters expressing the  $CP$  violation arising from that interference [12]. In the SM  $b = 2r' \sin(2\beta + \gamma) \cos\delta'$ ,

$c = -2r' \cos(2\beta + \gamma) \sin\delta'$ , where  $\beta$  and  $\gamma$  are angles of the Unitary Triangle [13], and  $\delta'$  is a strong phase. Besides  $|q/p|$ , also  $\Delta m_d$ ,  $\tau_{B^0}$ ,  $r'$ ,  $b$ , 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  $CP$ -eigenstate (for instance  $B^0 \rightarrow D^{(*)}D^{(*)}$ ), 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  $B_R$  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 accounts for the experimental uncertainties in the measurement of  $\Delta t$ , for the smearing due to the boost approximation, and for the displacement of the  $K_T$  production point from the  $B_T$  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  $\Delta t$  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  $\Delta t$  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  $\delta_{CP}$  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 result is obtained with a binned maximum likelihood fit to a two-dimensional PDF obtained as a product of the  $\Delta t$  and  $\cos(\theta_{\ell K})$  functions. Events belonging to each of the four categories are grouped in 100  $\Delta t$  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  $\Delta t$  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,  $B\bar{B}$  combinatorial and continuum, where the fractions of peaking,  $CP$  eigenstates, combinatoric  $B\bar{B}$ , and continuum events in each  $\mathcal{M}_\nu^2$  interval is fixed to the results of the first stage. The amounts of  $B^0$  and of  $B^+$  events 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:

$$\mathcal{G}_{\ell^\pm K^\pm}(\vec{j}) = (1 \pm \mathcal{A}_{r\ell})(1 \pm \mathcal{A}_K) \{ (1 - f_{K_R}^{\pm\pm}) [(1 - \omega^\pm) \mathcal{G}_{B^0 B^0 / \bar{B}^0 \bar{B}^0}(\vec{j}) + \omega^\mp \mathcal{G}_{B^0 \bar{B}^0 / \bar{B}^0 B^0}(\vec{j})] f_{K_R}^{\pm\pm} (1 - \omega'^\pm) \mathcal{G}_{K_R}(\vec{j}) (1 \pm \chi_d \mathcal{A}_{CP}) \}$$

where the reconstruction asymmetries are computed separately for the  $e$  and  $\mu$  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  $f_{K_R}^{\pm\pm}(p_k)$  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  $f_{K_R}^{\pm\pm}$  parameters in every  $p_k$  bin. A total of 171 parameters are determined in the fit.

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  $\delta_{CP}(\text{zero})$ , and of the other most significant parameters ( $\mathcal{A}_{r\ell}, \mathcal{A}_K, \Delta m_d$ , and  $\tau_{B^0}$ ).

We then repeat the test, randomly rejecting  $B^0$  or  $\bar{B}^0$  events in order to produce samples of simulated events with  $\delta_{CP} = \pm 0.005, \pm 0.01, \pm 0.025$ . 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  $-3.6 \times 10^{-4}$  ( $0.4 \sigma$ ) 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  $-0.48 \pm 0.11$  and RMS width of  $1.44 \pm 0.08$ . 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.

For the systematic uncertainty, we vary each quantity under consideration, as discussed below, and we repeat the fit. The variation of the result is considered 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. We 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  $\pm 50\%$ .

*$B\bar{B}$  combinatoric sample composition:* the fraction of  $B^+$  and  $B^0$  in the  $B\bar{B}$  combinatorial background is determined by the simulation. A difference between  $B^+$  and  $B^0$  is expected when mixing takes place and the lepton is coupled to the tag side  $\pi_s$  from  $\bar{B}^0 \rightarrow D^{*+}X$  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  $\bar{B}^0 \rightarrow D^{*+}X$ .

*$\Delta t$  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  $B^+ \rightarrow K_R X$  to  $B^0 \rightarrow K_R X$  by  $\pm 6.8\%$ , which corresponds to the uncertainty on the ratio  $\frac{BR(D^{*0} \rightarrow K^- X)}{BR(D^{*+} \rightarrow K^- X)}$ .

*$K_R$   $\Delta t$  distribution:* we use half the difference between the results obtained using the two different strategies to describe the  $\Delta t$  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  $0.02 \text{ ps}^{-1}$  instead of zero. The lifetime of the  $B^0$  and  $B^+$  mesons and the  $\Delta m_d$  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  $^{+1.78}_{-1.61} \times 10^{-3}$ .

We perform a blind analysis: the value of  $|q/p|$  is kept masked until the study of the systematic uncertainties is completed and all the consistency checks are successfully accomplished; the values of all the other fit parameters, instead, are not masked. After unblinding we find:  $\delta_{CP} = 1 - |q/p| = (0.29 \pm 0.84) \times 10^{-3}$ . The value of  $\Delta m_d (= 0.5085 \pm 0.0009)$  is consistent with the world average, while the value of  $\tau_{B^0} (= 1554 \pm 0.002)$  is slightly larger than expected, an effect also observed in the simulation. By fixing its value to the world average, the  $|q/p|$  result increases by  $0.18 \times 10^{-3}$ . This effect is taken into

account in the systematic error computation. A sizable asymmetry is observed at the reconstruction stage, for both  $e$  ( $30 \pm 4 \times 10^{-4}$ ) and  $\mu$  ( $31 \pm 5 \times 10^{-4}$ ), and at the  $K$  tagging stage ( $1.37 \pm 0.03\%$ ).

Fig. 2 and 3 show the fit projections for  $\Delta t$  and  $\cos\theta_{\ell K}$ , respectively.

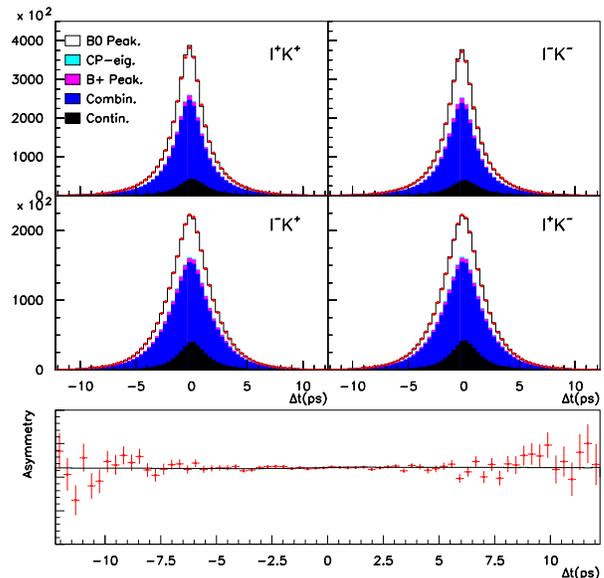


FIG. 2:  $\Delta t$  distribution for the data, point with error bars, and the fitted contributions from signal, peaking  $B^+$  background,  $CP$ -eigenstates,  $B\bar{B}$  combinatorial and continuum events. Top left plot:  $\ell^+K^+$ . Top right plot:  $\ell^-K^-$ . Central left plot:  $\ell^-K^+$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

In summary, we present a new precise measurement of the parameter governing  $CP$  violation in  $B^0 \bar{B}^0$  oscillations. With a partial  $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell$  reconstruction and  $K$  tagging we find  $\delta_{CP} = (0.29 \pm 0.84^{+1.78}_{-1.61}) \times 10^{-3}$ , and  $\mathcal{A}_{CP} = (0.06 \pm 0.17^{+0.36}_{-0.32})\%$ . These results are consistent with and more precise than the  $B$ -factories results from dilepton measurements. No deviation is observed from the SM expectation.

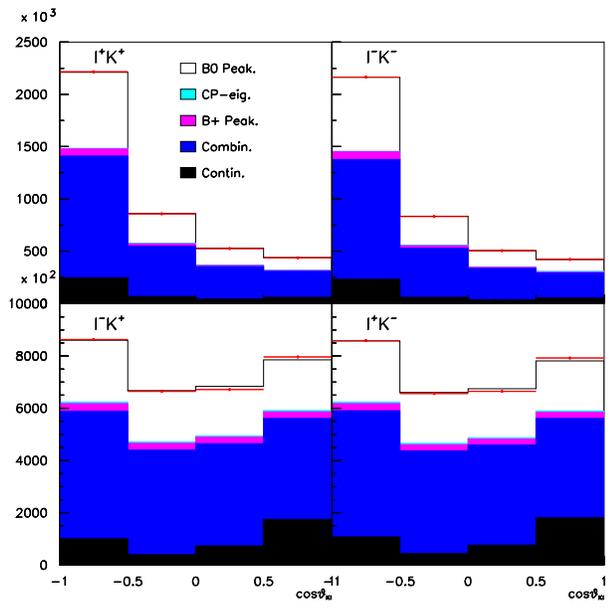


FIG. 3:  $\cos\theta_{\ell K}$  distribution for the data, point with error bars and the fitted contributions from signal,  $CP$ -eigenstates, peaking  $B^+$  background,  $B\bar{B}$  combinatorial and continuum events. Top left plot:  $\ell^+ K^+$ . Top right plot:  $\ell^- K^-$ . Central left plot: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

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