

# $D^0$ - $\bar{D}^0$ mixing results from *BABAR* by analysis of $D^0 \rightarrow K^+\pi^-\pi^0$ Dalitz-plot regions

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We present a preliminary search for  $D^0$ - $\bar{D}^0$  mixing using the decays  $D^0 \rightarrow K^+\pi^-\pi^0$ , additionally presenting Dalitz-plot distributions and a measurement of the branching ratio for this mode. A new tagging technique is used to produce the doubly Cabibbo-suppressed Dalitz plot, which in turn is used to motivate the method used for the  $D$ -mixing search. We analyze  $230.4 \text{ fb}^{-1}$  of data collected from the *BABAR* detector at the PEP-II collider. Assuming  $CP$  conservation, we find  $R_M < 0.054\%$  with 95% confidence, and we estimate that the data are consistent with no mixing at a 4.5% confidence level. We present  $D$ -mixing results both with and without the assumption of  $CP$  conservation.

## 1. Introduction

Although  $K$  and  $B$  mixing are well established,  $D$  mixing has yet to be observed. As this particular mixing phenomenon is sensitive to new physics in a complementary manner to the  $K$  and  $B$  systems, it is an essential test of the completeness of the Standard Model. We present preliminary results of a new mixing analysis using the decays  $D^0 \rightarrow K^+\pi^-\pi^0$ , taking into account the resonant structure of the doubly Cabibbo-suppressed contributions. This is the first search for mixing using either this decay mode or this technique.

G. Burdman and I. Shipsey have written a thorough review of  $D$ -mixing predictions [1]; accurate predictions are difficult to obtain because of significant contributions from long-distance effects.

Using  $230.4 \text{ fb}^{-1}$  of data collected from the *BABAR* detector at the PEP-II collider, corresponding to approximately 300 million  $c\bar{c}$  events, we obtain a pure sample of  $D^0$  candidates by reconstructing the decays

$$\begin{aligned} D^{*+} &\rightarrow D^0\pi_s^+ \\ D^0 &\rightarrow K^\mp\pi^\pm\pi^0 \quad (+ \text{C.C.}). \end{aligned} \quad (1)$$

The flavor of the  $D^0$  candidate at production is carried by the charge of the associated  $\pi_s^\pm$ . The large sample of Cabibbo-favored (CF) decays  $D^0 \rightarrow K^-\pi^+\pi^0$  is used both as a means for reducing systematic uncertainties in the probability density functions (PDFs) used to describe the *wrong-sign* (WS) decays  $D^0 \rightarrow K^+\pi^-\pi^0$  and as a normalization mode when determining the WS decay rate.

We separate correctly reconstructed decays from background, and distinguish doubly Cabibbo-suppressed (DCS) contributions from CF mixed contributions, by means of an (unbinned) extended maximum likelihood fit. PDFs are fit to the three distributions  $\{m_{K\pi\pi^0}, \Delta m, t_{K\pi\pi^0}\}$ , where  $m_{K\pi\pi^0}$  is the invariant mass of the  $D^0$  candidate,  $\Delta m$  is the invariant mass difference between the  $D^{*+}$  and  $D^0$  candidates, and  $t_{K\pi\pi^0}$  is the candidate decay time.

## 2. $D^0 \rightarrow K^+\pi^-\pi^0$ Branching Ratio

In a nonleptonic search for  $D$  mixing, DCS contributions obscure signs of mixing in the final state. To the extent that the DCS rate is low for a particular mode compared to the corresponding CF rate, there is greater sensitivity to a potential mixing signal. The branching ratio

$$R = \frac{\Gamma(D^0 \rightarrow K^+\pi^-\pi^0)}{\Gamma(D^0 \rightarrow K^-\pi^+\pi^0)} \quad (2)$$

is measured using a maximum likelihood fit to the distributions  $\{m_{K\pi\pi^0}, \Delta m\}$ , and we find the preliminary result

$$R = (0.214 \pm 0.008 (\text{stat}) \pm 0.008 (\text{syst}))\%. \quad (3)$$

This result is consistent with that reported by the Belle Collaboration last year [2]. Comparing this to the corresponding branching ratio for the decay  $D^0 \rightarrow K^+\pi^-$  [3],

$$R(K\pi) = (0.362 \pm 0.029)\%, \quad (4)$$

we find that an analysis of  $D^0 \rightarrow K^+\pi^-\pi^0$  may in fact have more sensitivity to mixing than the standard analysis of the decays  $D^0 \rightarrow K^+\pi^-$ . We note that while the branching ratio in Eq. 3 may contain contributions from  $D$  mixing (known to be small), the level of these contributions cannot be determined without an analysis of the WS decay-time distribution.

## 3. Event-Level Tagging and DCS Resonance Contributions

Just as an analysis of the decay  $D^0 \rightarrow K^+\pi^-\pi^0$  may offer greater sensitivity to a mixing signal than that of  $D^0 \rightarrow K^+\pi^-$  because of the lower relative DCS contribution, regions of the decay phase space (*i.e.*, the Dalitz plot) may have greater sensitivity to mixing to the extent that the DCS contribution in those regions is relatively low. However, obtaining an accurate

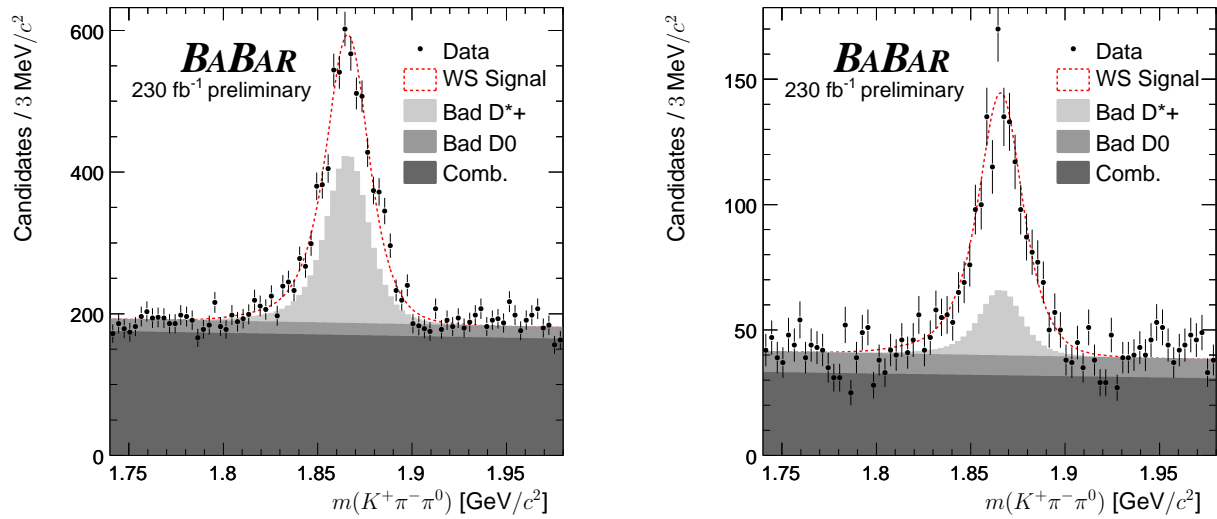


Figure 1: The  $m_{K\pi\pi^0}$  distribution with fitted PDFs overlaid for the WS data sample used to search for  $D$  mixing (left) and for the sample used to obtain the Dalitz-plot distributions (right). The sample on the right requires a second, event-level, flavor tag. Both distributions require  $0.1444 < \Delta m < 0.1464$  GeV/c<sup>2</sup>.

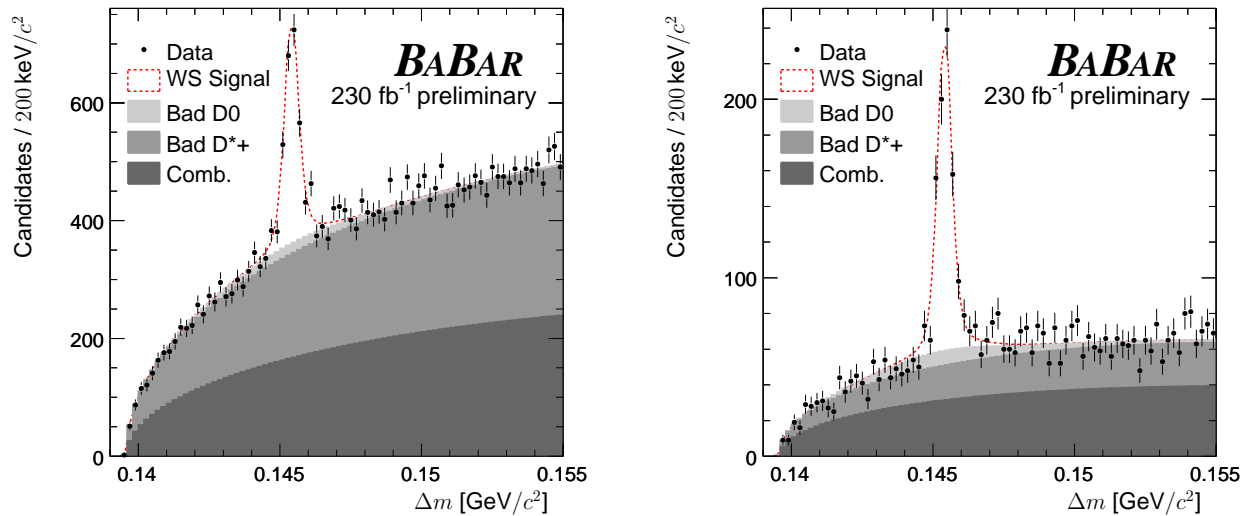


Figure 2: The  $\Delta m$  distribution with fitted PDFs overlaid for the WS data sample used to search for  $D$  mixing (left) and for the sample used to obtain the Dalitz-plot distributions (right). The sample on the right requires a second, event-level, flavor tag. Both distributions require  $1.85 < m_{K\pi\pi^0} < 1.88$  GeV/c<sup>2</sup>.

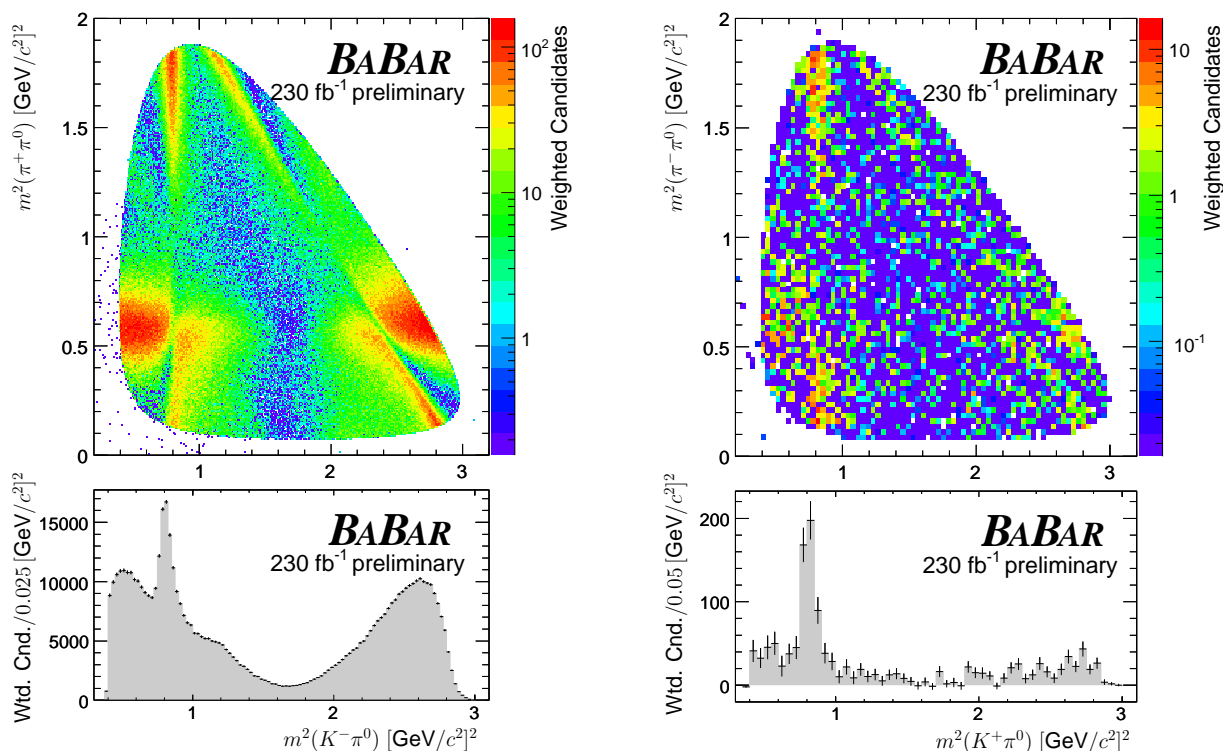


Figure 3: Dalitz plot and one-dimensional projection onto  $m_{K\pi^0}^2$  for the CF decay (left) and the DCS decay (right). A statistical background subtraction has been applied (*i.e.* candidates have been weighted), and distributions have been corrected for efficiency variations as a function of the Dalitz plot. The shaded histograms in the lower plots are projections of the Dalitz plots above them, with error bars superimposed. Candidates have been selected requiring the event-level tag.

distribution of events in the Dalitz plot is challenging because of the large number of background events still remaining after requiring event-selection criteria. In particular, a large component of the background is from real  $D^0$  decays having a misassociated  $\pi_s^\pm$ . Since this background is from real  $D^0 \rightarrow K^- \pi^+ \pi^0$  decays, it populates the Dalitz plot with structure that tends to obscure that of the signal. This peaking background is marked “Bad  $D^{*+}$ ” in Figs. 1 and 2.

To suppress peaking background from  $D^0 \rightarrow K^- \pi^+ \pi^0$  decays, we use an event-level tag in addition to the primary  $\pi_s^\pm$  flavor tag. This tag is determined by searching the event hemisphere opposite that in which the  $D^{*+}$  candidate is reconstructed for any of the following:  $K^\pm$ ,  $\pi_s^\mp$ ,  $e^\mp$ , or  $\mu^\mp$ . If the charge of one of these candidate is consistent with the hypothesis of hadronization and decay of a  $\bar{c}$  quark in that event hemisphere, then the event is tagged. The signal efficiency after applying this second, opposite-side, tag is 46.4%, while the peaking-background efficiency is 10.9%. The effect of

requiring this tag is shown in Figs. 1 and 2.

After requiring the opposite-side tag, correcting for efficiency variations as a function of the Dalitz plot, and performing a statistical background subtraction [4] based on a maximum likelihood fit to  $\{m_{K\pi\pi^0}, \Delta m\}$ , we obtain the Dalitz plots in Fig. 3. The CF Dalitz plot is qualitatively different from the WS Dalitz plot, which is assumed to contain primarily DCS contributions<sup>1</sup>. While CF decays proceed primarily through the resonance  $D^0 \rightarrow K^- \rho^+$ , DCS decays proceed primarily through the resonance  $D^0 \rightarrow K^{*+} \pi^-$ . We use this observation to maximize sensitivity to a potential  $D$ -mixing signal as described in the next Section.

<sup>1</sup>We assume that possible contributions from  $D$  mixing cannot be distinguished by eye in the Dalitz plots shown.

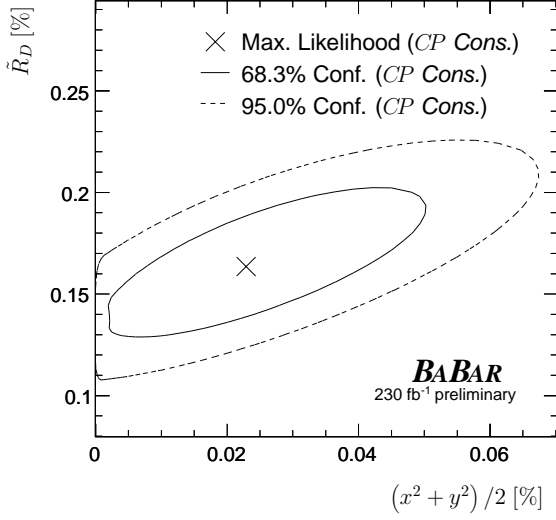


Figure 4: Contours of constant  $\Delta \log \mathcal{L} = 1.15, 3.0$  in terms of the doubly Cabibbo-suppressed rate and the integrated mixing rate. The upward slope of the contour indicates negative interference.

#### 4. Preliminary Results of a $D$ -mixing Search

The two mass eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad (5)$$

generated by mixing dynamics have different masses ( $m_{1,2}$ ) and widths ( $\Gamma_{1,2}$ ), and we parameterize the mixing process with the quantities

$$x \equiv 2 \frac{m_2 - m_1}{\Gamma_2 + \Gamma_1}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}. \quad (6)$$

If  $CP$  is not violated, then  $|p/q| = 1$ . For a multibody WS decay, the time-dependent decay rate, relative to a corresponding *right-sign* (RS) rate, is well approximated by

$$\frac{\Gamma_{\text{WS}}(t)}{\Gamma_{\text{RS}}(t)} = \tilde{R}_D + \alpha \tilde{y}' \sqrt{\tilde{R}_D} (\Gamma t) + \frac{\tilde{x}'^2 + \tilde{y}'^2}{4} (\Gamma t)^2 \quad (7)$$

$$0 \leq \alpha \leq 1,$$

where the tilde indicates quantities that have been integrated over the selected phase-space regions. Here,  $\tilde{R}_D$  is the integrated DCS branching ratio;  $\tilde{y}' = y \cos \tilde{\delta} - x \sin \tilde{\delta}$  and  $\tilde{x}' = x \cos \tilde{\delta} + y \sin \tilde{\delta}$ ,  $\tilde{\delta}$  is an unknown integrated strong-phase difference;  $\alpha$  is a suppression factor that accounts for strong-phase variation over the region; and  $\Gamma$  is the average width. The time-integrated mixing rate  $R_M = (\tilde{x}'^2 + \tilde{y}'^2)/2 = (x^2 + y^2)/2$  is independent of decay mode and should be consistent among mixing measurements.

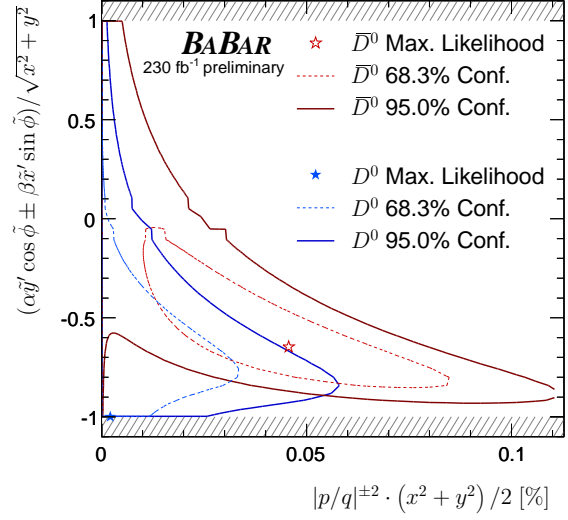


Figure 5: Contours of constant  $\Delta \log \mathcal{L} = 1.15, 3.0$  in terms of the normalized interference term and the integrated mixing rate, for the  $D^0$  and  $\bar{D}^0$  samples separately. The hatched regions are physically forbidden.

The necessity of the suppression factor  $\alpha$  can be understood as follows. Suppose the strong-phase difference between DCS decay and mixing is such that in a particular region of phase space there is positive interference, while in another region, there is negative interference. If one performs a mixing analysis considering the decay-time distributions of events in both phase-space regions simultaneously, then the combined decay-time distribution will have a suppressed interference effect relative to the mixing rate  $R_M$ , which is nonnegative and invariant across phase space.

In addition to our search for a  $CP$ -conserving mixing signal, we manifestly permit  $CP$  violation by fitting to the  $D^0 \rightarrow K^+\pi^-\pi^0$  and  $\bar{D}^0 \rightarrow K^-\pi^+\pi^0$  samples separately. We consider  $CP$  violation in the interference between the DCS channel and mixing, parameterized by an integrated weak-phase  $\phi$ , as well as  $CP$  violation in mixing, parameterized by  $|p/q|$ . We assume  $CP$  invariance in both the DCS and CF rates. The transformations

$$\alpha \tilde{y}' \rightarrow \left| \frac{p}{q} \right|^{\pm 1} (\alpha \tilde{y}' \cos \tilde{\phi} \pm \beta \tilde{x}' \sin \tilde{\phi}) \quad (8)$$

$$(x^2 + y^2) \rightarrow \left| \frac{p}{q} \right|^{\pm 2} (x^2 + y^2) \quad (9)$$

are applied to Eq. 7, using (+) for  $\Gamma(\bar{D}^0 \rightarrow K^-\pi^+\pi^0)/\Gamma(D^0 \rightarrow K^+\pi^-\pi^0)$  and (−) for the charge-conjugate ratio. The parameter  $\beta$  is analogous to  $\alpha$ .

Because decays with mixing will obey the CF-decay resonance structure, and we can qualitatively see the

Table I Preliminary signal-candidate yields determined by the two-dimensional fit to the  $\{m_{K\pi\pi^0}, \Delta m\}$  distributions for the WS and RS samples. Yields are shown for (a) the selected phase-space regions used in this analysis and (b) the entire allowed phase-space region. Uncertainties are those calculated from the fit, and no efficiency corrections have been applied.

	$D^0$ Cand.	$\bar{D}^0$ Cand.
(a) WS	$(3.84 \pm 0.36) \times 10^2$	$(3.79 \pm 0.36) \times 10^2$
RS	$(2.518 \pm 0.006) \times 10^5$	$(2.512 \pm 0.006) \times 10^5$
(b) WS	$(7.5 \pm 0.5) \times 10^2$	$(8.1 \pm 0.5) \times 10^2$
RS	$(3.648 \pm 0.007) \times 10^5$	$(3.646 \pm 0.007) \times 10^5$

differences between the CF and DCS Dalitz plots, we choose regions of the Dalitz plot to analyze in order to maximize sensitivity to a potential mixing signal. We do this by excluding events with two-body invariant masses in the ranges  $850 < m(K\pi) < 950 \text{ MeV}/c^2$  or  $850 < m(K\pi^0) < 950 \text{ MeV}/c^2$ . The signal yields before and after applying these selection criteria are listed in Table I.

We search for mixing in the WS decay-time distribution by constructing a three-dimensional PDF in  $\{m_{K\pi\pi^0}, \Delta m, t_{K\pi\pi^0}\}$ . The WS signal PDF in  $t_{K\pi\pi^0}$  is a function based on Eq. 7 convolved with three Gaussians. We fit the WS PDF to the  $t_{K\pi\pi^0}$  distribution allowing yields and shape parameters to vary.

The results of the decay-time fit, both with and without the assumption of  $CP$  conservation, are listed in Table II. The statistical uncertainty of a particular parameter is obtained by finding its extrema for  $\Delta \log \mathcal{L} = 0.5$ ; in finding the extrema, the likelihood is kept maximal by refitting the remaining parameters. Contours of constant  $\Delta \log \mathcal{L} = 1.15, 3.0$ , enclosing two-dimensional coverage probabilities of 68.3% and 95.0%, respectively, are shown in Figures 4 and 5. The likelihood is maximized when evaluating  $\Delta \log \mathcal{L}$  for a particular point in two-dimensions.

We note that  $\Delta \log \mathcal{L}$  as a function of the quantity  $\text{sign}(\alpha\tilde{y}') \times R_M$  is approximately parabolic. The two-sided interval  $-0.054\% < \text{sign}(\alpha\tilde{y}') \times R_M < 0.054\%$  contains 95% coverage probability; thus, we quote  $R_M < 0.054\%$  as our upper limit on the integrated mixing rate under the assumption of  $CP$  conservation.

A feature of  $\Delta \log \mathcal{L}$  in one dimension is that it changes behavior near  $R_M = 0$  because the interference parameters become unconstrained. Therefore, we estimate the consistency of the data with no mixing using a frequentist method. Generating 1000 simulated data sets with no mixing, each with 58,800 events representing signal and background in the quantities  $\{m_{K\pi\pi^0}, \Delta m, t_{K\pi\pi^0}\}$ , we find 4.5% of

simulated data sets have a fitted value of  $R_M$  greater than that in the observed data set. We conclude that the observed data are consistent with no mixing with 4.5% confidence.

Table II Preliminary mixing results assuming  $CP$  conservation ( $D^0$  and  $\bar{D}^0$  samples are not separated) and manifestly permitting  $CP$  violation ( $D^0$  and  $\bar{D}^0$  samples are fit separately). The first listed uncertainty is statistical, the second is systematic.  $\tilde{R}_D$  is not reported for the latter case because  $\pi_s^\pm$  efficiencies were not studied.

	$CP$ conserved	$CP$ violation allowed
$R_M$	$(0.023 \pm_{-0.014}^{+0.018} \pm 0.004)\%$	$(0.010 \pm_{-0.007}^{+0.022})\%$
$\tilde{R}_D$	$(0.164 \pm_{-0.022}^{+0.026} \pm 0.012)\%$	
$\alpha\tilde{y}'$	$-0.012 \pm_{-0.008}^{+0.006} \pm 0.002$	$\alpha\tilde{y}' \cos \tilde{\phi}$ $-0.012 \pm_{-0.007}^{+0.006}$
		$\beta\tilde{x}' \sin \tilde{\phi}$ $0.003 \pm_{-0.005}^{+0.002}$
		$ p/q $ $2.2 \pm_{-1.0}^{+1.9}$

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