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Time-integrated measurements of the CKM angle γ/ϕ_3 in *BABAR*

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The most recent determinations of the CKM angle γ/ϕ_3 by the *BABAR* Collaboration, using time-integrated observables measured in charged $B \to D^{(*)}K^{(*)}$ decays, are presented. The measurements have been performed on the full sample of 468 million $B\overline{B}$ pairs collected by the *BABAR* detector at the SLAC PEP-II asymmetric-energy B factory in the years 1999-2007.

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1 Introduction

A theoretically clean measurement of the angle $\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$ (also denoted as ϕ_3 in the literature) can be obtained using *CP*-violating $B \to D^{(*)}K^{(*)}$ decays. The interference between the $b \to c\overline{u}s$ and $b \to u\overline{c}s$ tree amplitudes results in observables that depend on the relative weak phase γ, the magnitude ratio $r_B \equiv \left|\frac{A(b\to u)}{A(b\to c)}\right|$, and the relative strong phase δ_B between the two amplitudes. The hadronic parameters, r_B and δ_B, depend on the B decay under investigation; they can not be precisely calculated from theory, but can be extracted directly from data by simultaneously reconstructing several different D final states.

In this contribution we present the most recent γ determinations obtained by *BABAR*, based on the full sample ($\approx 468 \times 10^6$ $B^\pm$ decays) of charged B mesons produced in $e^+e^- \to \Upsilon(4S) \to B^+B^-$ and accumulated in the years 1999-2007. The following decays have been reconstructed: (i) $B^\pm \to D^{(*)}K^\pm$ and $B^\pm \to DK^{*\pm}(K^{*\pm} \to K^0_S\pi^\pm)$, with $D \to K^0_S h^+h^-$, $h = \pi, K$; (ii) $B^\pm \to DK^\pm$, with D decaying to *CP*-eigenstates f_{CP}; (iii) $B^\pm \to D^{(*)}K^\pm$, with D decaying to $K^\pm\pi^\mp$. The results are statistically limited, as the effects that are being searched for are tiny, since: (i) the branching fractions of the B meson decays considered here are on the order of 5×10^{-4} or lower; (ii) the branching fractions for $D^{(*)}$ decays, including secondary decays, range between $O(10^{-2})$ and $O(10^{-4})$; (iii) the interference between the $b \to c$ and $b \to u$ mediated B decay amplitudes is low, as the ratios r_B are around 0.1 due to CKM factors and the additional color-suppression of $A(b \to u)$.

The B decay final states are completely reconstructed, with efficiencies between 40% (for low-multiplicity, low-background decay modes) and 5% (for high-multiplicity decays). The selection is optimized to maximise the statistical sensitivity $S/\sqrt{S+B}$, where the number of expected signal (S) and background (B) events is estimated from simulated samples and data control samples. Signal B decays are distinguished from $B\overline{B}$ and continuum $q\overline{q}$ background by means of maximum likelihood fits to two variables exploiting the kinematic constraint from the known beam energies: the energy-substituted invariant mass $m_{\rm ES}\equiv\sqrt{E^{*2}_{\rm beam} - p^{*2}_B}$ and the energy difference $\Delta E \equiv E^*_B - E^*_{\rm beam}$. Additional continuum background discrimination is achieved by including in the likelihood a variable built, using multivariate analysis tools, from the combination (either a linear Fisher discriminant, $\mathcal{F}$, or a non-linear neural-network, NN) of several event-shape quantities. These variables distinguish spherical $B\overline{B}$ events from more jet-like $q\overline{q}$ events and exploit the different angular correlations in the two event categories. $B \to D^{(*)}\pi$ decays, which are 12 times more abundant than $B \to D^{(*)}K$ and are expected to show negligible *CP*-violating effects ($r_B \approx 0.01$ in such decays), are discriminated by means of the excellent pion and kaon identification provided by dE/dx measured in the charged particle tracking devices and by the radiation detected in the Cherenkov detector, and are used as control samples.

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2 Dalitz-plot method: $B^{\pm} \to D^{(*)}K^{(*)\pm}$, $D \to K^0_S h^+ h^-$

We reconstruct $B^{\pm}\to DK^{\pm}$, $D^*K^{\pm}$ ($D^*\to D\gamma$ and $D\pi^0$), and $DK^{*\pm}$ ($K^{*\pm}\to K^0_S\pi^{\pm}$) decays, followed by neutral D meson decays to the 3-body self-conjugate final states $K^0_S h^+ h^-$ ($h = \pi, K$) [1]. From an extended maximum likelihood fit to $m_{\rm ES}$, ΔE and $\mathcal{F}$ (Fig. 1) we determine the signal and background yields in each channel: we find 268 B candidates with $D \to K^0_S K^+ K^-$ and 1507 B candidates with $D \to K^0_S \pi^+\pi^-$.

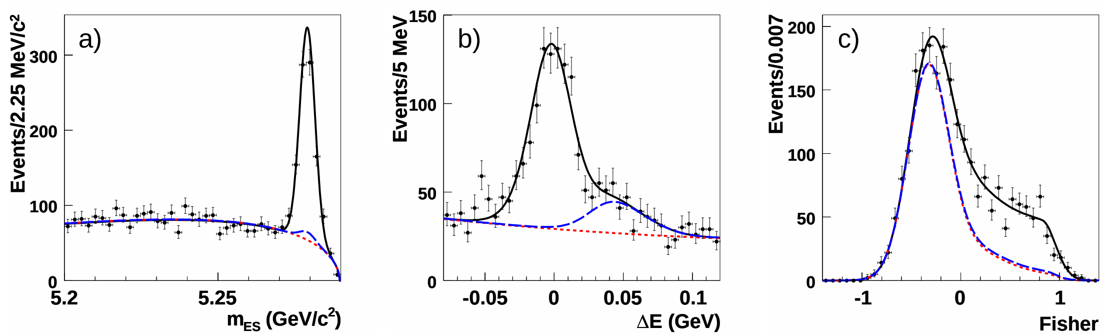

Figure 1: The $m_{\rm ES}$ (a), ΔE (b), and $\mathcal{F}$ (c) distributions for $B^{\pm}\to DK^{\pm}$, $D\to K^0_S\pi^+\pi^-$. for events in the signal region ($m_{\rm ES} > 5.272$ GeV/c^2, $|\Delta E| < 30$ MeV, and $\mathcal{F} > -0.1$), after all the selection criteria, except the one on the plotted variable, are applied. The curves represent the fit projections: signal plus background (solid black lines), $q\overline{q}+B\overline{B}$ background (dotted red lines), $q\overline{q} + B\overline{B} + B \to D\pi$ background (dashed blue lines).

Following the technique proposed in [2], from a fit to the Dalitz-plot distribution of the D daughters we determine 2D confidence regions for the variables $x_{\pm} \equiv r_B \cos(\delta_B \pm \gamma)$ and $y_{\pm} \equiv r_B \sin(\delta_B \pm \gamma)$ (Fig. 2). In the fit we model the D^0 and $\overline{D}^0$ decay amplitudes to $K^0_S h^+h^-$ as the coherent sum of a non-resonant part and several intermediate two-body decays that proceed through known $K^0_S h$ or h^+h^- resonances. The model is determined from large ($\approx 6.2\times 10^5$) and very pure ($\approx 99\%$) control samples of D mesons produced in $D^*\to D\pi$ decays [3]. The results for x and y are summarized in Table 1.

Parameter	$B^{\pm} \to DK^{\pm}$	$B^{\pm} \to D^*K^{\pm}$	$B^{\pm} \to DK^{*\pm}$
x_+	$-0.103 \pm 0.037 \pm 0.006 \pm 0.007$	$0.147 \pm 0.053 \pm 0.017 \pm 0.003$	$-0.151 \pm 0.083 \pm 0.029 \pm 0.006$
y_+	$-0.021 \pm 0.048 \pm 0.004 \pm 0.009$	$-0.032 \pm 0.077 \pm 0.008 \pm 0.006$	$0.045 \pm 0.106 \pm 0.036 \pm 0.008$
x_-	$0.060 \pm 0.039 \pm 0.007 \pm 0.006$	$-0.104 \pm 0.051 \pm 0.019 \pm 0.002$	$0.075 \pm 0.096 \pm 0.029 \pm 0.007$
y_-	$0.062 \pm 0.045 \pm 0.004 \pm 0.006$	$-0.052 \pm 0.063 \pm 0.009 \pm 0.007$	$0.127 \pm 0.095 \pm 0.027 \pm 0.006$

Table 1: Values of $x_{\pm}$ and $y_{\pm}$ measured with the Dalitz-plot analysis of $B^{\pm}\to D^{(*)}K^{(*)\pm}$

From the $(x_{\pm}, y_{\pm})$ confidence regions we determine, using a frequentist procedure, 1σ confidence intervals for γ, r_B and δ_B (Fig. 3). We obtain γ mod $180° = (68 \pm 14 \pm$

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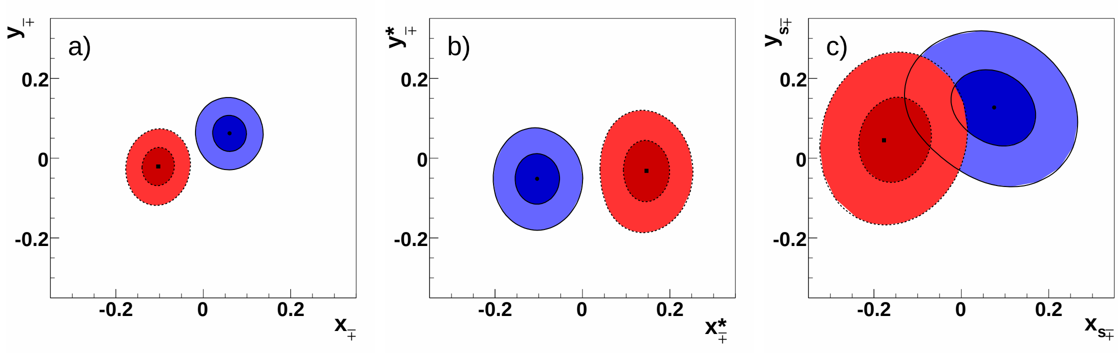

Figure 2: 1σ and 2σ contours in the $x_\pm, y_\pm$ planes for (a) $B \to DK$, (b) $B \to D^*K$ and (c) $B \to DK^*$, for B^- (solid lines) and B^+ (dotted lines) decays.

$4\pm3)^\circ$, where the three uncertainties are respectively the statistical, the experimental systematic and the Dalitz-model systematic ones. We find values of r_B around 0.1, confirming that interference is low in these channels: $r_B^{DK^\pm} = 0.096\pm0.029$; $r_B^{D^*K^\pm} = 0.133^{+0.042}_{-0.039}$; $kr_B^{DK^{*\pm}} = 0.149^{+0.066}_{-0.062}$ (k=0.9±0.1 takes into account the K^* finite width). We also measure the strong phases (modulo 180°): $\delta_B^{DK^\pm}$=$(119^{+19}_{-20})^\circ$; $\delta_B^{D^*K^\pm}$=$(-82\pm21)^\circ$; $\delta_B^{DK^{*\pm}}$=$(111\pm32)^\circ$. A 3.5σ evidence of direct CP violation is found from the distance between (x_+, y_+) and (x_-, y_-) (0 in absence of CPV) in the three B decay channels.

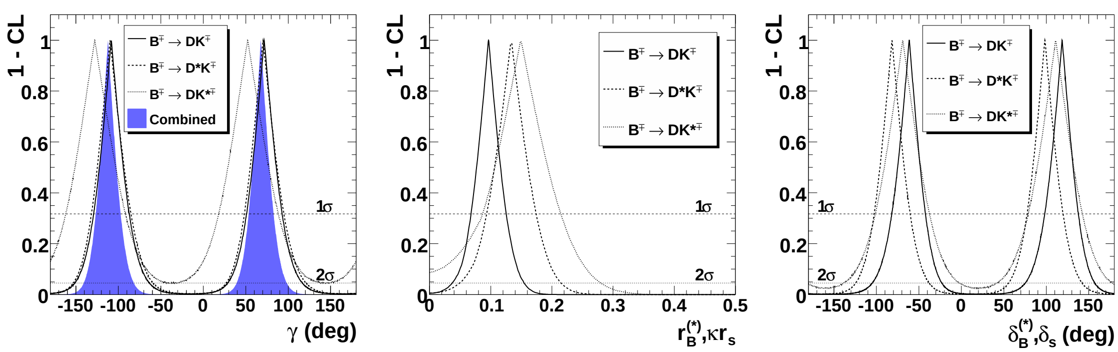

Figure 3: 1-confidence level (CL) as a function of γ (left), r_B (center) and δ_B (right) from the $B \to D^{(*)}K^{(*)}$ Dalitz-plot analysis.

3 GLW method: $B^\pm \to DK^{(*)\pm}$, $D \to f_{(\mathrm{CP})}$

We reconstruct $B^\pm \to DK^\pm$ decays, with D mesons decaying to non-CP ($D^0 \to K^-\pi^+$), CP-even (K^+K^-, $\pi^+\pi^-$) and CP-odd ($K^0_S\pi^0$, $K^0_S\phi$, $K^0_S\omega$) eigenstates [4].

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The partial decay rate charge asymmetries $A_{CP\pm}$ for CP-even and CP-odd D final states and the ratios $R_{CP\pm}$ of the charged-averaged B meson partial decay rates in CP and non-CP decays provide a set of four observables from which the three unknowns γ, r_B and δ_B can be extracted (with an 8-fold discrete ambiguity for the phases) [5].

The signal yields, from which the partial decay rates are determined, are obtained from maximum likelihood fits to $m_{\rm ES}$, ΔE and $\mathcal{F}$. An example is shown in Fig. 4. We identify about 500 $B^\pm \to DK^\pm$ decays with CP-even D final states and a similar amount of $B^\pm \to DK^\pm$ decays with CP-odd D final states. We measure $A_{CP+} = 0.25 \pm 0.06 \pm 0.02$ and and $A_{CP-} = -0.09 \pm 0.07 \pm 0.02$, respectively, where the first error is the statistical and the second is the systematic uncertainty. The parameter A_{CP+} is different from zero with a significance of 3.6 standard deviations, constituting evidence for direct CP violation. We also measure $R_{CP+} = 1.18 \pm 0.09 \pm 0.05$ and $R_{CP-} = 1.07 \pm 0.08 \pm 0.04$.

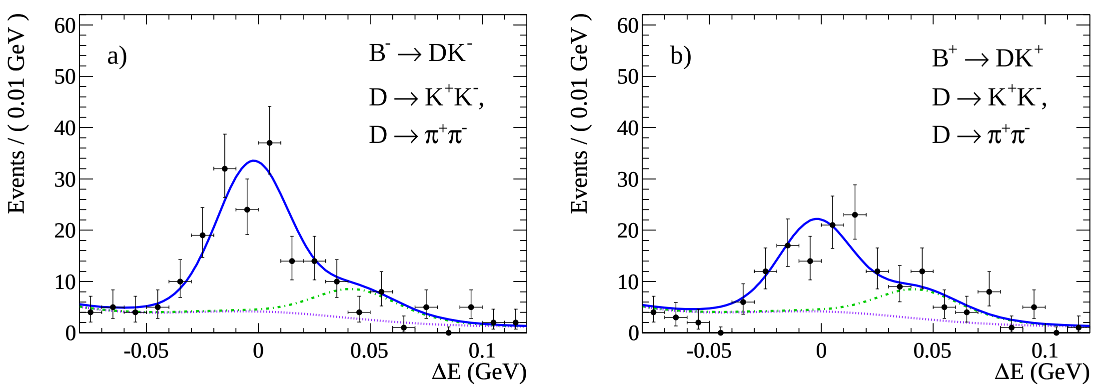

Figure 4: ΔE projections of the fits to the data: (a) $B^-{\to}D_{CP+}K^-$, (b) $B^+{\to}D_{CP+}K^+$. The curves are the full PDF (solid, blue), and $B{\to}D\pi$ (dash-dotted, green) stacked on the remaining backgrounds (dotted, purple). We require candidates to lie inside a signal-enriched region: $0.2 < \mathcal{F} < 1.5$, $5.275 < m_{\rm ES} < 5.285\,{\rm GeV}/c^2$, charged particle from the B passing kaon identification criteria.

Using a frequentist technique, including statistical and systematic uncertainties, we obtain $0.24 < r_B < 0.45$ ($0.06 < r_B < 0.51$) and, modulo 180°, $11.3° < \gamma < 22.7°$ or $80.9° < \gamma < 99.1°$ or $157.3° < \gamma < 168.7°$ ($7.0° < \gamma < 173.0°$) at the 68% (95%) confidence level (Fig. 5). To facilitate the combination of these measurements with the results of the Dalitz-plot analysis, we exclude the $D \to K_S^0\phi$, $\phi \to K^+K^-$ channel from this analysis – thus removing events common to the two measurements – and express our results in terms of the variables $x_\pm$ using $x_\pm = \frac{1}{4}\left[R_{CP+}(1 \mp A_{CP+}) - R_{CP-}(1 \mp A_{CP-})\right]$. We find: $x_+ = -0.057 \pm 0.039 \pm 0.015$ and $x_- = 0.132 \pm 0.042 \pm 0.018$, in good agreement with the results from the Dalitz-plot analysis.

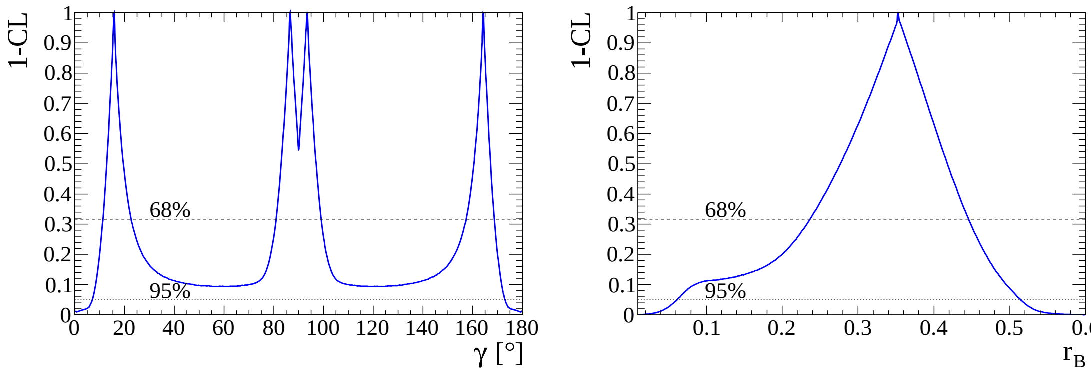

Figure 5: 1-CL as a function of γ mod 180° (left) and r_B (right) from the $B \to DK$ GLW study.

4 ADS method: $B^{\pm} \to D^{(*)}K^{\pm}$, $D \to K^{\pm}\pi^{\mp}$

We reconstruct $B^{\pm} \to DK^{\pm}$ and $D^*K^{\pm}$ ($D^* \to D\gamma$ and $D\pi^0$), followed by D decays to both the doubly-Cabibbo-suppressed D^0 final state $K^+\pi^-$ and the Cabibbo-allowed final state $K^-\pi^+$, which is used as normalization and control sample [6]. Final states with opposite-sign kaons are produced from the interference of the CKM favored B decay followed by the doubly Cabibbo-suppressed D decay and the CKM- and color- suppressed B decay followed by the Cabibbo-allowed D decay, and the CP asymmetries may be potentially very large. On the other hand, their overall branching fractions are very small ($O(10^{-7})$) and background suppression is crucial. The three branching fraction ratios (R_{ADS}) between B decays with opposite-sign and same-sign kaons and the three charge asymmetries (A_{ADS}) in B decays with opposite-sign kaons provide six observables that can be used, together with the measurements by c- and B-factories of the amplitude ratio r_D and the strong phase difference δ_D between the two D decay amplitudes, to determine γ (with a 4-fold discrete ambiguity) and the two sets of r_B, δ_B [7].

The yields are determined from fits to $m_{\rm ES}$ and NN (Fig. 6). We see indications of signals for the $B \to DK$ and $B \to D^*_{D\pi^0}K$ opposite-sign modes, with significances of 2.1σ and 2.2σ, respectively. The measured branching fration ratios are $R^{DK}_{ADS} = (1.1 \pm 0.5 \pm 0.2) \times 10^{-2}$ and $R^{D\pi^0K}_{ADS} = (1.8 \pm 0.9 \pm 0.4) \times 10^{-2}$. The CP asymmetries are large, $A^{DK}_{ADS} = -0.86 \pm 0.47\ ^{+0,12}_{-0.16}$ and $A^{D\pi^0K}_{ADS} = +0.77 \pm 0.35 \pm 0.12$. We see no evidence of opposite-sign $B \to D^*_{D\gamma}K$ decays, and measure $R^{D\gamma K}_{ADS} = (1.3 \pm 1.4 \pm 0.8) \times 10^{-2}$ and $A^{D\gamma K}_{ADS} = +0.36 \pm 0.94\ ^{+0.25}_{-0.41}$. From these results we infer $r_B^{DK^{\pm}} = 0.095^{+0.051}_{-0.041}$, $r_B^{D^*K^{\pm}} = 0.096^{+0.035}_{-0.051}$ and $54° < \gamma < 83°$ (Fig. 7).

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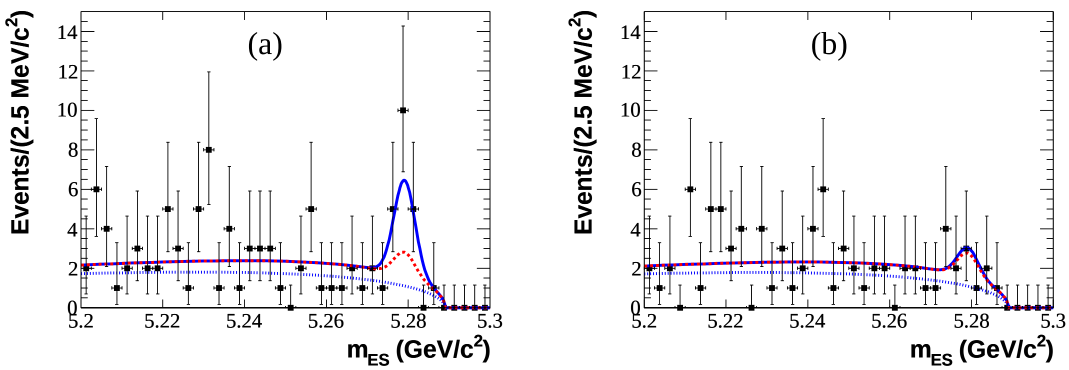

Figure 6: m_{ES} projection of the fit to the data for the $B^{\pm} \to DK^{\pm}$, $D \to K^{\mp}\pi^{\pm}$ decays, for samples enriched in signal ($NN > 0.94$), for (a) B^{+} and (b) B^{-} candidates. The curves represent the fit projections for signal plus background (solid), the sum of all background components (dashed), and the $q\overline{q}$ background only (dotted).

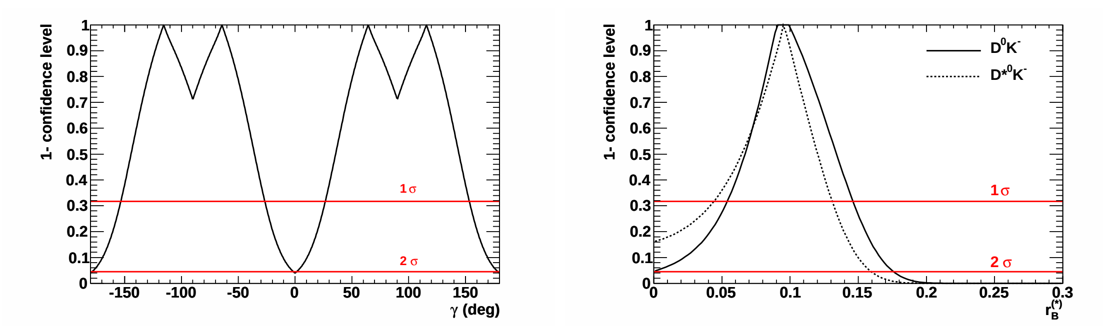

Figure 7: 1-CL as a function of γ (left) and r_B (right) from the $B \to D^{(*)}K$ ADS study.

5 Conclusion

The full *BABAR* dataset has been exploited to measure the CKM angle γ in several $B^{\pm} \to D^{(*)}K^{(*)\pm}$ decays using three alternative techniques. A coherent set of results on γ and on the hadronic parameters characterizing the B decay amplitudes has been obtained. The central value for γ, around $70°$, is consistent with indirect determinations from the CKM fits. We attained a precision on γ around $15°$, and confirm the theoretical expectations of significant suppression ($r_B \approx 0.1$) of the $b \to u$ mediated decay amplitud with respect to the $b \to c$ one. Finally, two direct CP violation evidences at the level of 3.5σ have been observed.

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