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$\sin 2\beta + \gamma$ MEASUREMENTS

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I report on the most recent measurements done to constrain $\sin(2\beta+\gamma)$ with neutral B mesons. Direct measurements of $2\beta+\gamma$ will provide a precise test of the standard model predictions with higher statistics. Present constraints come from studies of $B \rightarrow D^{(*)\pm}\pi^{\mp}/\rho^{\mp}$ decays done by *BABAR* and Belle collaborations with full and inclusive techniques to reconstruct B mesons. $B \rightarrow D^{0(*)}K^{0}$ decays are also very promising but statistics are too low to give any constraint at the moment.

1 Introduction

The Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] provides an explanation of CP violation and is under experimental investigation, aimed at constraining its parameters. A crucial part of this program is the measurement of the least known angle of the Unitarity Triangle related to the CKM matrix $\gamma = \arg\left(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right)$. While the measurement of $\sin 2\beta$ is now a precision measurement [2,3], the constraints on the other two angles [a] α and γ, are still limited by statistics and/or by theoretical uncertainties. $B \rightarrow D^{*\mp}h^{\pm}$ decays (where h is a meson made of u and d quarks : π or ρ) can be used [4] to constrain $\sin(2\beta+\gamma)$. As β is well known from $b \rightarrow c\bar{c}s$ decays, a constraint on the angle γ follows. The goal is to check if the standard model explanation of CP violation is a complete description, or whether additional factors come into play.

[a] *BABAR* convention is to call α, β and γ the angles of the UT. They respectively correspond to angles ϕ_2, ϕ_1 and ϕ_3 used by the Belle collaboration. As a member of the *BABAR* collaboration, I use α, β and γ.

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2 Sensitivity to $\sin(2\beta+\gamma)$

$B^0 \to D^{(*)\pm}h^{\mp}$ decays can occur either directly through a Cabbibo-favoured decay (CFD) or through mixing followed by doubly-Cabbibo-suppressed decay (DCSD), as shown in Fig. 1. I call A_c (resp. A_u) the amplitude of the CFD (resp. DSCD) decay.

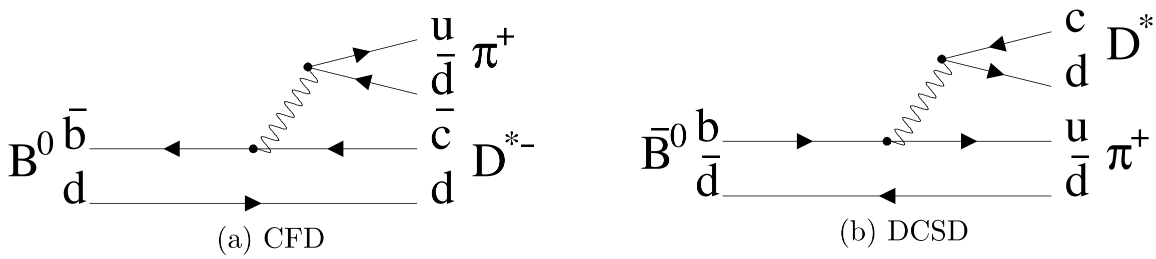

Figure 1: Feynman diagrams for the Cabibbo-favored decay $B^0 \to D^{*-}\pi^+$ (a), corresponding to the decay amplitude A_c, and the Cabibbo-suppressed decay $\overline{B}^0 \to D^{*-}\pi^+$ (b), whose amplitude is A_u.

The difference of the weak phases of the 2 diagrams is equal to γ and the interference from B^0 $\overline{B}^0$ mixing adds a sensitivity on 2β. The time-dependent decay rates of $B^0/\overline{B}^0 \to D^{(*)\pm}h^{\mp}$ are given by [5]

$$\begin{aligned}
P(B^0 \to D^{(*)+}h^-) &= \frac{1}{8\tau_{B^0}}e^{-|\Delta t|/\tau_{B^0}}\left[1 - C\cos(\Delta m\Delta t) + S^+\sin(\Delta m\Delta t)\right],\\
P(B^0 \to D^{(*)-}h^+) &= \frac{1}{8\tau_{B^0}}e^{-|\Delta t|/\tau_{B^0}}\left[1 + C\cos(\Delta m\Delta t) + S^-\sin(\Delta m\Delta t)\right],\\
P(\bar{B}^0 \to D^{(*)+}h^-) &= \frac{1}{8\tau_{B^0}}e^{-|\Delta t|/\tau_{B^0}}\left[1 + C\cos(\Delta m\Delta t) - S^+\sin(\Delta m\Delta t)\right],\\
P(\bar{B}^0 \to D^{(*)-}h^+) &= \frac{1}{8\tau_{B^0}}e^{-|\Delta t|/\tau_{B^0}}\left[1 - C\cos(\Delta m\Delta t) - S^-\sin(\Delta m\Delta t)\right],
\end{aligned} \tag{1}$$

where Δt is the difference between the time of the decay and the time at which the flavour of the B meson is tagged, τ_{B^0} is the B^0 lifetime, Δm is the $B\bar{B}$ mixing parameter. The parameters C and $S^{\pm}$ are given by

$$C \equiv \frac{1 - r^2_{D^{(*)}h}}{1 + r^2_{D^{(*)}h}}, \qquad S^{\pm} \equiv \frac{2r_{D^{(*)}h}}{1 + r^2_{D^{(*)}h}}\sin(2\beta+\gamma\pm\delta_{D^{(*)}h}). \tag{2}$$

$\delta_{D^{(*)}h}$ is the strong phase difference between A_u and A_c, and $r_{D^{(*)}h} = |A_u/A_c|$. Since A_u is doubly CKM-suppressed with respect to A_c, one expects [7] $r_{D^{(*)}h} \approx \left|\frac{V_{ub}V^*_{cd}}{V^*_{cb}V_{ud}}\right| = 0.02$, but this has not yet been measured. Therefore, we neglect terms of $\mathcal{O}\left(r^2_{D^{(*)}h}\right)$. Hence $C = 1$ and we can measure $S^{\pm}$ instead of $\sin(2\beta+\gamma)$. *CP* violation is expected to be very small but high branching ratios $\mathcal{B}(B^0 \to D^{(*)+}h^-)$ guarantee high statistics and pure datasets.

$r_{D^{(*)}h}$ are too small to be extracted from the measurement of C with the current statistics. They can however be determined from the ratios of the branching fractions $\mathcal{B}(B^0\to D_s^{(*)+}\pi^-)/\mathcal{B}(B^0\to D^{(*)-}\pi^+)$ and $\mathcal{B}(B^0\to D_s^{(*)+}\rho^-)/\mathcal{B}(B^0\to D^{(*)-}\rho^+)$ [8,9,10], assuming $SU(3)$ symmetry and neglecting contributions from annihilation diagrams:

$$r_{D\pi} = 0.020 \pm 0.003, \qquad r_{D^*\pi} = 0.015 \pm 0.005, \qquad r_{D\rho} = 0.003 \pm 0.006. \tag{3}$$

These numbers do not take into account the theoretical errors coming from the fact that factorization is assumed and that exchange and annihilation diagrams are neglected.

3 Analyses strategies

There are two strategies to study *CP* violation in $B \to D^{(*)\pm}h^{\mp}$ decays : a full or a partial reconstruction of the B candidate.

In the first case all particles from high branching fraction D meson decay modes like $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$ and $K^-\pi^+\pi^+\pi^-$, are reconstructed and the D candidate is combined with a high momentum pion or ρ candidate. The D^* is reconstructed by combining the D^0 candidate with a slow π.

The partial reconstruction of the $B \to D^{*\pm}\pi^{\mp}$ channel only uses the high momentum pion from the B and the slow pion from the D^* to look for a "missing D^0". Backgrounds are higher but statistics are also ~ 10 times higher.

4 *CP* violation on the tag-side

BABAR and Belle are installed on the PEP-II and KEKB electron-positron colliders which produce the $\Upsilon(4S)$ resonance with a boost. The $\Upsilon(4S)$ decays in to a $B\bar{B}$ pair, evolving coherently in space (see Eq. 1). The boost is big enough to consider that the B's fly along the beam axis and their difference of length of the flight can be used to estimate their difference of time of flight Δt.

To use Eq. 1, we need to know the flavour of the B at $\Delta t = 0$. The decay products of the other B in the event are used to tag the flavour since, at this time , the flavour of the reconstructed B and the tagged B are opposite. Charged leptons, pions, and kaons that are not associated with the reconstructed $D^{(*)}h$ decays are used to identify the flavour of the tagged B meson.

While the flavour is reliably tagged when leptons are used, hadronic tags using kaons from $D^{(*)}h$ are affected by the *CP* asymmetry we want to measure. This usually negligible effect is here of the order of the signal [11], because the expected asymmetries are very small.

To avoid this effect, *BABAR* uses a different parameterisation:

$$\begin{aligned} a^{D^{(*)}h} &= 2r^{D^{(*)}h}\sin(2\beta+\gamma)\cos\delta^{D^{(*)}h}\,, \\ b_i &= 2r'_i\sin(2\beta+\gamma)\cos\delta'_i\,, \\ c_i^{D^{(*)}h} &= 2\cos(2\beta+\gamma)(r^{D^{(*)}h}\sin\delta^{D^{(*)}h} - r'_i\sin\delta'_i)\,. \end{aligned} \quad (4)$$

Here r'_i (δ'_i) is, for each tagging category, the effective amplitude (phase) used to parameterise the tag side interference. This parametrisation has the advantage that the a parameter doesn't depend on tagging category. On the other hand, the c parameter can only be estimated with lepton tagged events. The b parameter characterises *CP* violation on the tag side and does not contribute to the interpretation.

5 Analyses results

5.1 Exclusive results (Belle)

This study [12] uses a dataset of 152 millions $B^0\bar{B}^0$ pairs, collected with the Belle detector [13] at the KEKB collider [14].

Belle measures $S^{\pm}$. *CP* violation for kaon tagged B is considered as a systematic effect and estimated using a $D^*l\nu$ control sample. The distributions of Δt for the $D^*\pi$ selected data for the four data samples (Eq. 1) are shown on figure 2.

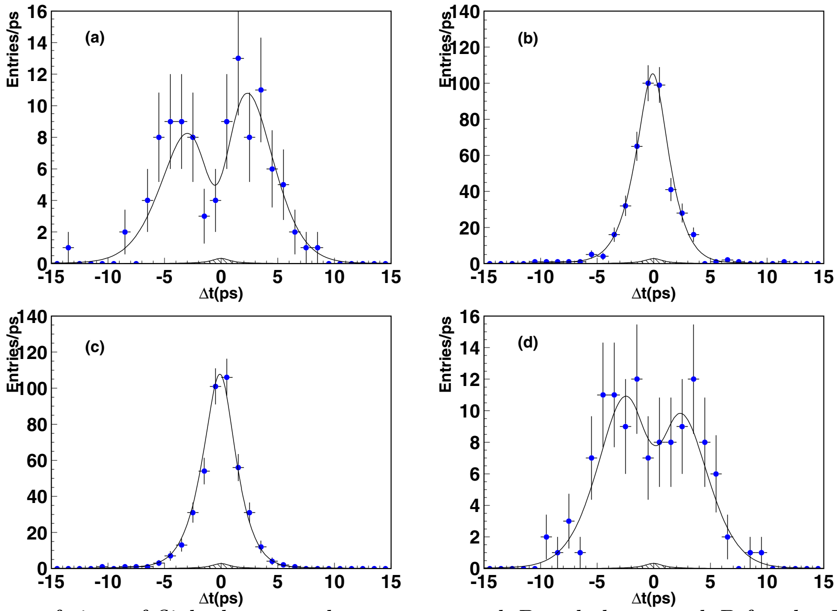

Figure 2: Difference of time of flight between the reconstructed B and the tagged B for the $D^*\pi$ selected data for (a) $B^0 \to D^{*+}\pi^-$, (b) $B^0 \to D^{*-}\pi^+$, (c) $\bar{B}^0 \to D^{*+}\pi^-$, (d) $\bar{B}^0 \to D^{*-}\pi^+$. The curves show the fit results for the entire event sample, hatched regions indicate the backgrounds.

The final results are[b]:

$$
\begin{aligned}
2r_{D^*\pi}\sin(2\beta+\gamma+\delta_{D^*\pi}) &= 0.109 \pm 0.057 \pm 0.019, \\
2r_{D^*\pi}\sin(2\beta+\gamma-\delta_{D^*\pi}) &= 0.011 \pm 0.057 \pm 0.019, \\
2r_{D\pi}\sin(2\beta+\gamma+\delta_{D\pi}) &= 0.087 \pm 0.054 \pm 0.018, \\
2r_{D\pi}\sin(2\beta+\gamma-\delta_{D\pi}) &= 0.037 \pm 0.052 \pm 0.018.
\end{aligned}
$$

The authors also express the results $|2r_{D^*\pi}\sin(2\beta+\gamma)| = 0.060 \pm 0.040(\text{stat}) \pm 0.019(\text{sys})$ and $|2r_{D\pi}\sin(2\beta+\gamma)| = 0.061 \pm 0.037(\text{stat}) \pm 0.018(\text{sys})$ after neglecting strong phases [6,5].

5.2 Exclusive results (BABAR)

This measurement [15] is based on 110 million $\Upsilon(4S) \to B\overline{B}$ decays collected from the *BABAR* detector [16] at the PEP-II asymmetric-energy B factory at SLAC. The analysis was performed for $B \to D^*\pi$, $B \to D\pi$ and $B \to D\rho$. We defined the beam-energy substituted mass of a B meson as $m_{\rm ES} \equiv \sqrt{E^{*2}_{beam} - {p^*_B}^2}$, where in the $\Upsilon(4S)$ rest frame, E^*_{beam} is the beam energy and p^*_B is the reconstructed B momentum. Distributions of $m_{\rm ES}$ are represented on figure 3 for the signal. Signal and background are discriminated by two kinematic variables:

Finally, the results are:

$$
\begin{aligned}
a^{D\pi} &= -0.032 \pm 0.031 \pm 0.020 \quad , \quad c^{D\pi}_{lep} = -0.059 \pm 0.055 \pm 0.033 \\
a^{D^*\pi} &= -0.049 \pm 0.031 \pm 0.020 \quad , \quad c^{D^*\pi}_{lep} = +0.044 \pm 0.054 \pm 0.033 \\
a^{D\rho} &= -0.005 \pm 0.044 \pm 0.021 \quad , \quad c^{D\rho}_{lep} = -0.147 \pm 0.074 \pm 0.035.
\end{aligned}
$$

The a parameters are measured with all tagging categories while the c parameters are measured only with lepton tagged events.

[b]The first and second errors are statistical and systematic. This convention is kept throughout this paper.

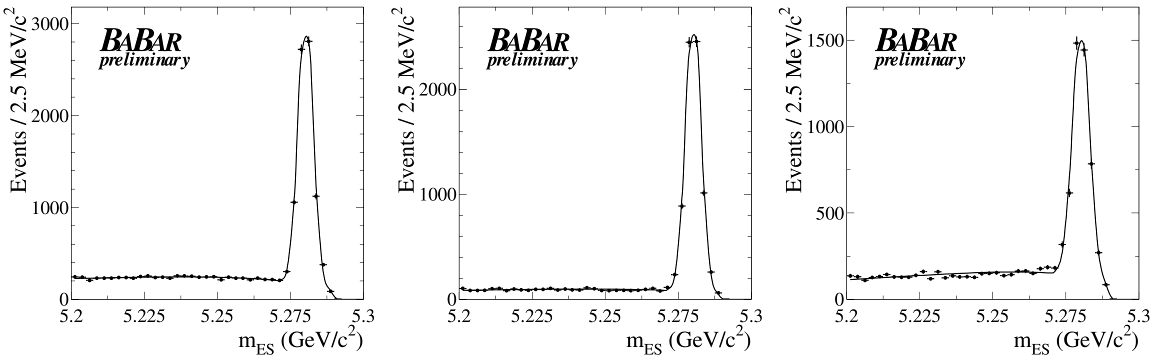

Figure 3: $m_{\rm ES}$ distributions in the signal region for, from left to right, the $B^0 \to D^{\pm}\pi^{\mp}$, $B^0 \to D^{*\pm}\pi^{\mp}$ and $B^0 \to D^{\pm}\rho^{\mp}$ sample for the events with tagging information. A fit to a Gaussian plus a threshold function is overlaid. $m_{\rm ES}$ is defined in the text.

5.3 Inclusive results (Belle)

This measurement [17] is based on a 140 fb^{-1} data sample, which contains 152 million $B\overline{B}$ pairs, collected from the Belle detector. The analysis uses only lepton tags, therefore no *CP* violation is expected from tagging. For $B \to D^*\pi$, the form of the distributions of Δt are shown on figure 4.

The results are

$$
\begin{aligned}
S^+ &= 0.035 \pm 0.041 \pm 0.018, \\
S^- &= 0.025 \pm 0.041 \pm 0.018.
\end{aligned}
$$

5.4 Inclusive results (BABAR)

This measurement [18] uses 232 million $B\overline{B}$ events recorded by the *BABAR* experiment using the PEP-II e^+e^- storage ring. Distributions of Δt are represented on figure 5.

$$a_{D^*\pi} = -0.034 \pm 0.014 \pm 0.009 \tag{5}$$
$$c^{\ell}_{D^*\pi} = -0.019 \pm 0.022 \pm 0.013, \tag{6}$$

The authors of the analysis also provide an interpretation of their results. They use a frequentist approach detailed in their paper and adding a theoretical error of 30% on the $r_{D^*\pi}$ coefficient determined by equation 3 and obtain a limit : $|\sin(2\beta+\gamma)| > 0.62(0.35)$ at 68 (90)% CL. Confidence levels are shown on the right of figure 5 in 1 dimension in $|\sin(2\beta+\gamma)|$ and in the $\bar{\rho} - \bar{\eta}$ plane.

6 Final results and conclusions

Figure 6 summarises previous results [20]. The results are statistically limited. A bayesian interpretation [19] of the combined results can be seen on Fig. 7. This gives a limit of $|\sin(2\beta+\gamma)| > 0.74$ at 68% CL.

The analyses on $\sin(2\beta+\gamma)$ are still an active experimental physics area. New results from $B^0 \to D^0\ K^0$ decays will contribute soon.

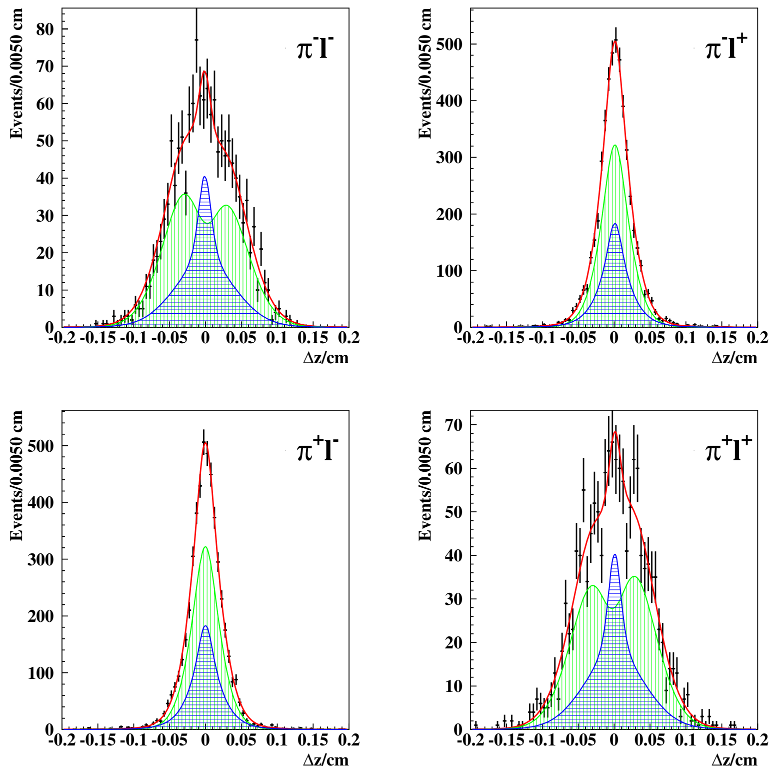

Figure 4: Difference of time of flight between the reconstructed B and the tagged B for the $D^*\pi$ selected data for (a) $B^0 \to D^{*+}\pi^-$, (b) $B^0 \to D^{*-}\pi^+$, (c) $\bar{B}^0 \to D^{*+}\pi^-$, (d) $\bar{B}^0 \to D^{*-}\pi^+$. The curves show the fit results for the entire event sample. The signal component is shown as the vertically hatched area. The horizontally hatched area indicates the background contribution.

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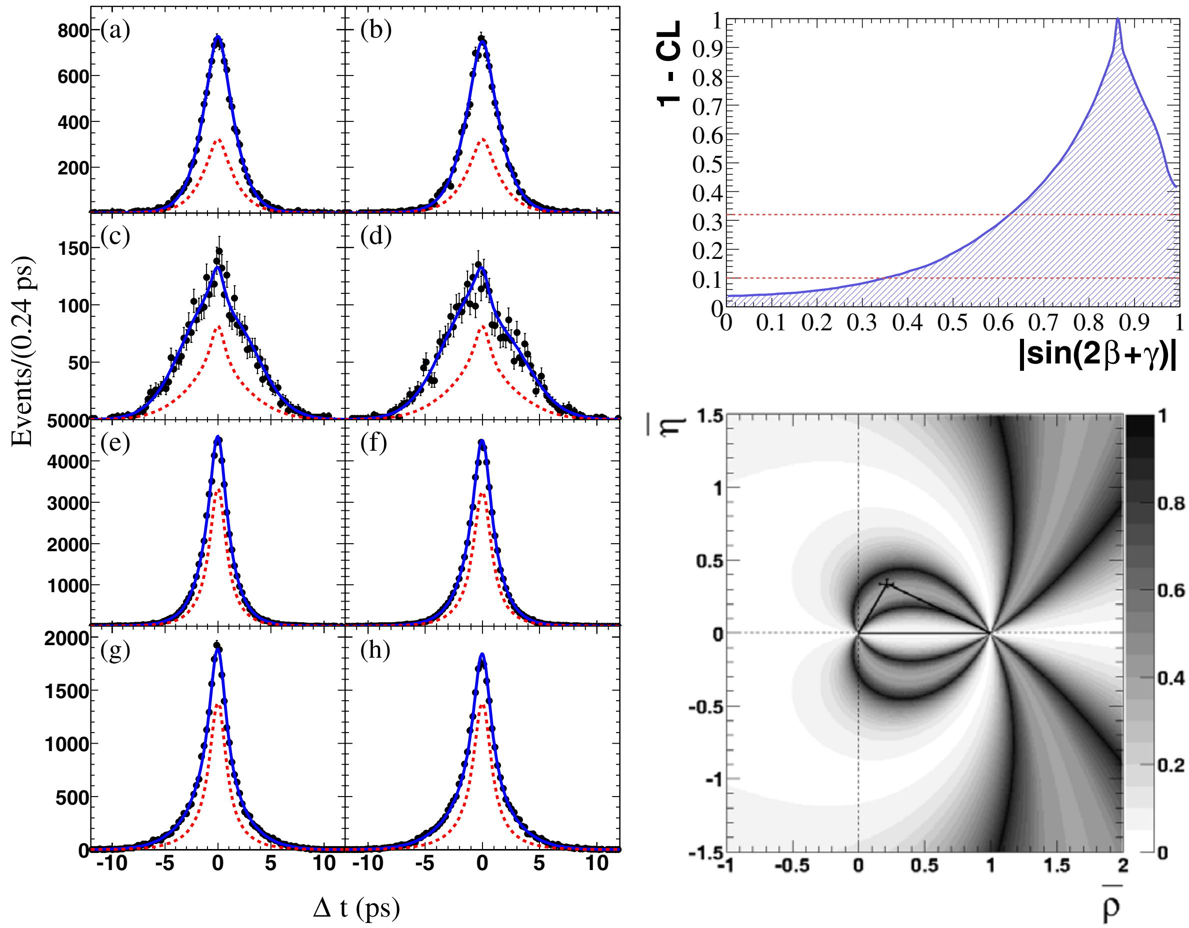

Figure 5: (left) Δt distributions for the lepton-tagged (a-d) and kaon-tagged (e-h) events separated according to the tagged flavor of $B_{\rm tag}$ and whether they were found to be mixed or unmixed: a,e) B^0 unmixed, b,f) $\overline{B}^0$ unmixed, c,g) B^0 mixed, d,h) $\overline{B}^0$ mixed. The solid curves show the PDF, calculated with the parameters obtained by the fit. The PDF for the total background is shown by the dashed curves. (top right) The shaded region denotes the allowed range of $|\sin(2\beta+\gamma)|$ for each confidence level. The horizontal lines show, from top to bottom, the 68% and 90% CL. (bottom right) The confidence level is represented in the $\bar{\rho}-\bar{\eta}$ plane.

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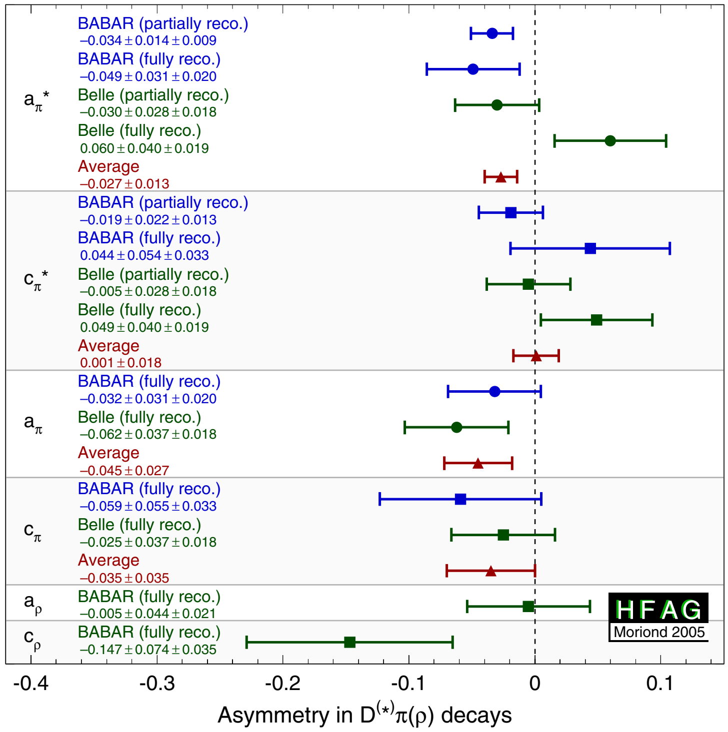

Figure 6: Compilation of the $B \to D^{(*)\pm} h^{\mp}$ results.

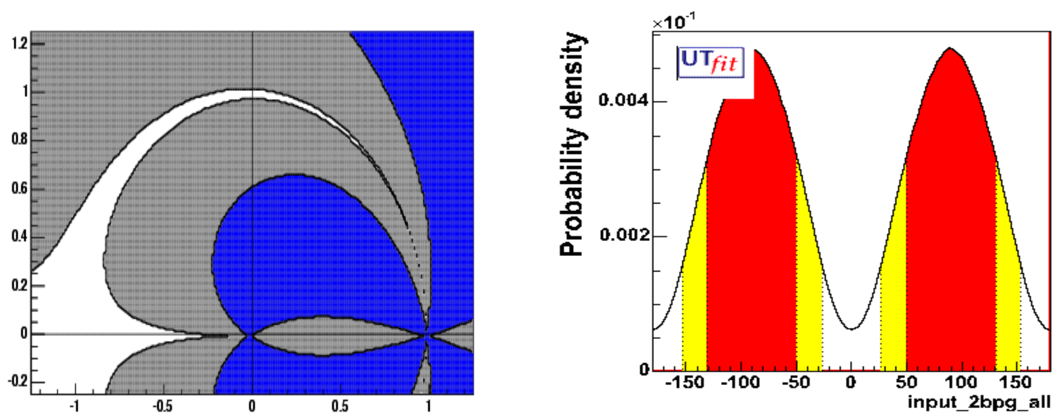

Figure 7: Exclusion level coming from the actual constraints on $\sin(2\beta + \gamma)$.