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CP violation in D^0 decays

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We report on the search for CP violation in D^0 decays that has been performed at the B-factories in recent years. After a brief presentation of the phenomenology of CP violation in D decays, a summary of the experimental techniques and the related analyses are shown. Finally we report on the most recent analysis on the search fot CP violation using T-odd correlations in the four-body D^0 decays and compare with all the experimental results.

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1. The Physics

In Standard Model, *CP* violation arises from Kobayashi-Maskawa phase in Cabibbo-Kobayashi-Maskawa quark mixing matrix [1, 2]. Theoretical attempts to predict the effect of *CP* violation in singly Cabibbo suppressed charmed decays have been made in the past [3], obtaining an upper limit of 0.1% not excluding even 1% effects. The authors of reference [3] suggest that this limit can be lowered by at least one order of magnitude by oscillations, which have been recently observed [4, 5].

CP violation in charm decays can be exploited by many New Physics models [6, 7] both at tree and one-loop level; among these the latter expect a *CP* violation asymmetry of the order of 10^{-2}, which is now the level of experimental sensitivity [8].

There are many factors which help in the search for *CP* violation in *D* decays at the *B*-factories:

- $e^+e^- \to c\bar{c}$ cross section is about 25% of the total at the energy of the $\Upsilon(4S)$.
- The $B-\bar{B}$ background can be easily separated from the $c\bar{c}$ contribution by the request to the center of mass momentum of the *D* meson to be greater than $2.5\,\mathrm{GeV}/c$.
- Finally the D^0 flavor can be obtained from the charge of the slow pion by mean of the reconstruction of the decay $D^{*+} \to D^0\,\pi^+$ [9] (D^* tag). This results also in a high purity of the reconstructed sample.

There is anyway a drawback represented by the electroweak forward-backward (FB) asymmetry introduced by the interference between the electromagnetic and weak $e^+e^- \to c\bar{c}$ production processes that makes the ratio $N_c/N_{\bar{c}}$ depending upon the quarks production angle in the e^+e^- rest frame.

2. Experimental Techniques and Related Measurements

Four types of experimental techniques have been used to search for *CP* violation in D^0 decays:

- direct *CP* violation;
- Dalitz plot analysis;
- time dependent analysis;
- *T*-odd correlations.

2.1 Direct *CP* violation

The search for direct *CP* violation is made by looking for asymmetries in the production of D^0 and $\bar{D}^0$ mesons in a given final state. The observable is simply:

$$A_{CP} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}},$$

where N_D is the number of reconstructed *D* decays.

This measurement can be biased by the previously mentioned FB asymmetry. In order to account for this effect, two solutions have been found:

- estimate the FB asymmetry itself;
- normalize N_D to the number of events reconstructed using the same procedure to the corresponding Cabibbo favored decay channel. The Cabibbo favored decay channel is indeed subjected to the same FB asymmetry but should not show any *CP* asymmetry.

At the *B*-factories, the first analysis of this kind has been done by Belle using about 2000 $D^0 \to K^+ \pi^- \pi^0$ and 1700 $D^0 \to K^+ \pi^- \pi^+ \pi^-$ decays [10]. These decays are doubly Cabibbo suppressed and are identified through the D^* tag and the kaon charge. In order to account for FB asymmetry effect, the asymmetry 2.1 is computed using $R_D = N_{DCS}/N_{CF}$, i.e. the ratio of the doubly Cabibbo suppressed over the Cabibbo favored decay channels.

$$A_{CP} = \frac{R_{D^0} - R_{\bar{D}^0}}{R_{D^0} + R_{\bar{D}^0}}. \tag{2.1}$$

The number of events for each decay channel has been measured through a two dimensional fit to D and Δm mass spectrum . The results are

$$A_{CP}^{K\pi\pi} = (-1.8 \pm 4.4)\%$$
$$A_{CP}^{K\pi\pi\pi} = (-0.6 \pm 5.3)\%,$$

where the systematic error is not quoted since it is less than 1%.

A more complete analysis looked to the two-body singly Cabibbo suppressed D^0 decay channels into two hadrons ($D^0 \to h^+h^-$, $h = \pi$, K). A_{CP} can be considered as the sum of direct and indirect *CP* violation contributions:

$$A_{CP} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} = A_{CP,dir} + A_{CP,ind},$$

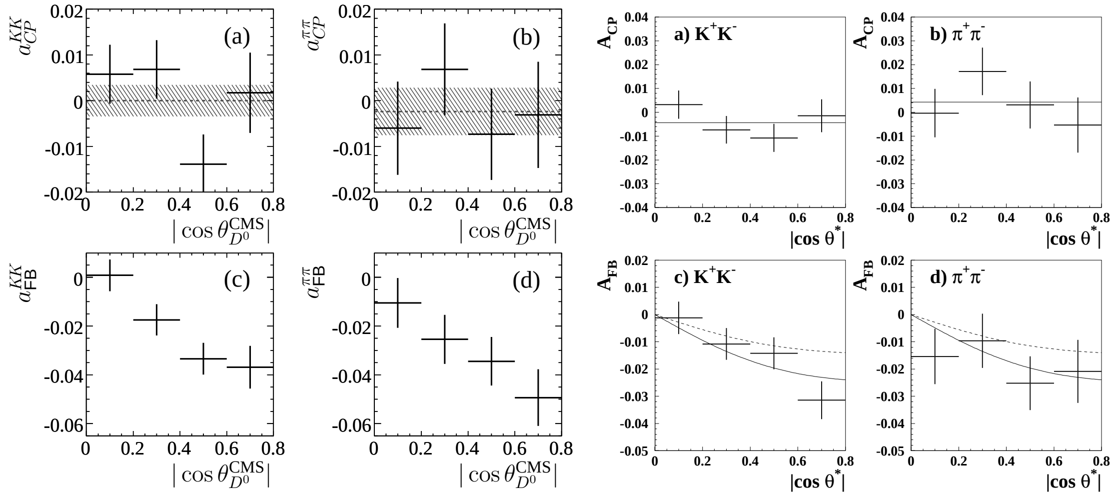
where $A_{CP,ind}$ can be evaluated from the corresponding mixing analysis. Other asymmetries in $A_{CP,dir}$ are due to FB asymmetry and soft pion reconstruction asymmetry.

The bias to A_{CP} introduced by the soft pion reconstruction is removed by mapping the asymmetry in the plane $\cos\theta_{\pi_s}$ (polar angle in the lab frame) vs p_{π_s} using $D^0 \to K^- \pi^+$ tagged and untagged data. The plane is divided into nine regions to obtain the weighting factors to correct $D^0 \to h^+h^-$ yields.

The asymmetry between D^0 and $\bar{D}^0$ is measured in bins of $\cos\theta^*_D$ (being θ^*_D the D production angle in the center of mass system). Since the FB asymmetry component is asymmetric upon the production angle, the symmetric part is the *CP* violation observable we need:

$$a^{\pm}(\cos\theta^*_D) = \frac{N_{D^0}(\pm|\cos\theta^*_D|) - N_{\bar{D}^0}(\pm|\cos\theta^*_D|)}{N_{D^0}(\pm|\cos\theta^*_D|) + N_{\bar{D}^0}(\pm|\cos\theta^*_D|)},$$
$$A_{CP} = \frac{a^+(\cos\theta^*_D) + a^-(\cos\theta^*_D)}{2},$$
$$A_{FB} = \frac{a^+(\cos\theta^*_D) - a^-(\cos\theta^*_D)}{2}.$$

A_{CP} is then measured applying a χ^2 fit over bins of $\cos\theta^*_D$.



(**A**) *BABAR* (**B**) Belle

Figure 1: A_{CP} for (a) $D^0 \to K^+ K^-$ and (b) $D^0 \to \pi^+\pi^-$. The corresponding A_{FB} are shown in (c) and (d). Plots on the left are from *BABAR* **(A)**, plots on the right are from Belle **(B)**.

The first measurement has been performed by *BABAR* [11] using about $1.5(6.6) \times 10^6$ tagged (untagged) $D^0 \to K^- \pi^+$, 1.3×10^5 $D^0 \to K^+ K^-$ and 6.4×10^4 $D^0 \to \pi^+ \pi^-$ decays. The results are

$$A_{CP}^{KK} = (0.0 \pm 3.4_{\text{stat}} \pm 1.3_{\text{syst}}) \times 10^{-3},$$
$$A_{CP}^{\pi\pi} = (-2.4 \pm 5.2_{\text{stat}} \pm 2.2_{\text{syst}}) \times 10^{-3},$$

where the main contribution to systematic error comes from soft pion asymmetry evaluation. The same analysis performed by Belle [12] with similar statistically significant samples obtained:

$$A_{CP}^{KK} = (-4.3 \pm 3.0_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{-3},$$
$$A_{CP}^{\pi\pi} = (4.3 \pm 5.2_{\text{stat}} \pm 1.2_{\text{syst}}) \times 10^{-3}.$$

The main contribution to the systematic uncertainties is from soft pion asymmetry evaluation. The only difference among the two analyses is that the number of events is evaluated using a one dimensional fit to D^0 mass spectrum in Belle, while *BABAR* performed a two dimensional fit to D^0 and $\Delta m = m_{D^*} - m_{D^0}$ mass spectra. The results are compared also in Fig. 1.

2.2 Dalitz plot analysis

A Dalitz plot analysis can be used to measure asymmetries in the distribution of the events on the Dalitz plot, in the angular moments, in the amplitudes (model dependent) or in integrated yields.

The latter has been exploited by Belle in 2.4×10^3 $D^0 \to \pi^+ \pi^- \pi^0$ decays [13]. Monte Carlo events have been used to develop a fitting model which takes into account peaking backgrounds from other D^0 decay modes. The resulting asymmetry is:

$$A_{CP} = (0.43 \pm 0.41_{\text{stat}} \pm 1.30_{\text{syst}})\%.$$

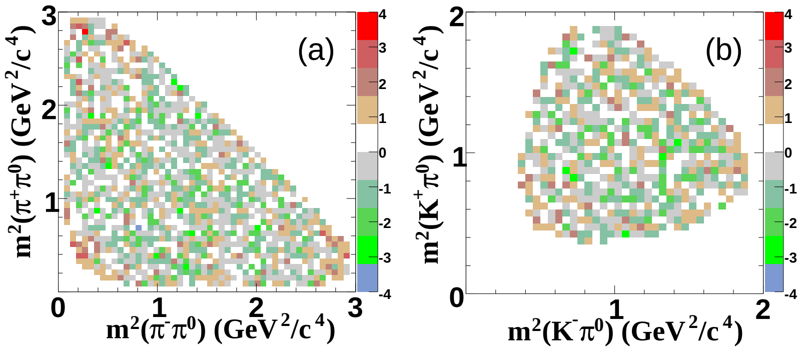


Figure 2: Normalized residuals between D^0 and $\bar{D}^0$ evaluated for (a) $D^0 \to \pi^+ \pi^- \pi^0$ and (b) $D^0 \to K^+ K^- \pi^0$.

The main contributions to systematic uncertainties are due to the tracking efficiency corrections and the fit model.

A complete Dalitz plot analysis of high statistics samples of $D^0 \to \pi^+ \pi^- \pi^0$ (8.2×10^4 events) and $D^0 \to K^+ K^- \pi^0$ (1.1×10^4 events) has been performed by BABAR [14]. The analysis searched for asymmetries in the Dalitz plot comparing bin-per-bin the D^0 and $\bar{D}^0$ two-dimensional Dalitz plot. In order to estimate the amount of the asymmetry a confidence level for the "no CP violation" hypothesis has been evaluated from the normalized residuals between D^0 and $\bar{D}^0$

$$\Delta = \frac{N_{\bar{D}^0} - R\cdot N_{D^0}}{\sqrt{\sigma^2_{N_{\bar{D}^0}} + R^2\cdot\sigma^2_{N_{D^0}}}},$$

where R is the efficiency corrected $N_{\bar{D}^0}/N_{D^0}$ ratio. The χ^2 is defined as

$$\chi^2/\nu = \left(\sum_{i=1}^{\nu}\Delta_i^2\right)/\nu,$$

being ν the number of Dalitz plot elements. The confidence level for the no CP violation hypothesis is evaluated from the resulting one-sided gaussian. The normalized residuals evaluated on the two Dalitz plots are shown in Fig. 2. The resulting confidence level for no CP violation hypothesis is 32.8% for $D^0 \to \pi^+ \pi^- \pi^0$ and 16.6% for $D^0 \to K^+ K^- \pi^0$.

In a similar way a confidence level has been evaluated to search for asymmetries in the angular moments. The two-body invariant masses from the three-body D^0 decays are weighted by the Legendre polynomials. The normalized residuals of the difference between D^0 and $\bar{D}^0$ are used to compute a confidence level for the no CP violation hypothesis (see Table 1).

In order to check for asymmetries in the amplitudes a full Dalitz plot analysis has been performed separately on the D^0 and $\bar{D}^0$ samples, A comparison of amplitudes, phases and fractions for each resonance contributing to the three-body decays gives asymmetries consistent with zero.

The integrated asymmetries have been evaluated as a function of $\cos\theta^{CM}_{D^0}$ as shown in Fig. 3.

Table 1: Confidence level of the no *CP* violation hypothesis for the asymmetry in the angular moments

particles combination	$\pi^+\pi^-$	$\pi^+\,\pi^0$	$K^+\,K^-$	$K^+\,\pi^0$
C. L. (no *CPV*)	28.2%	28.4%	63.1%	23.8%

The a_{CP} average values are:

$$A_{CP}^{\pi\pi\pi^0} = (-0.31 \pm 0.41_{\text{stat}} \pm 0.17_{\text{syst}})\%$$
$$A_{CP}^{KK\pi^0} = (1.00 \pm 1.67_{\text{stat}} \pm 0.25_{\text{syst}})\%,$$

again consistent with zero.

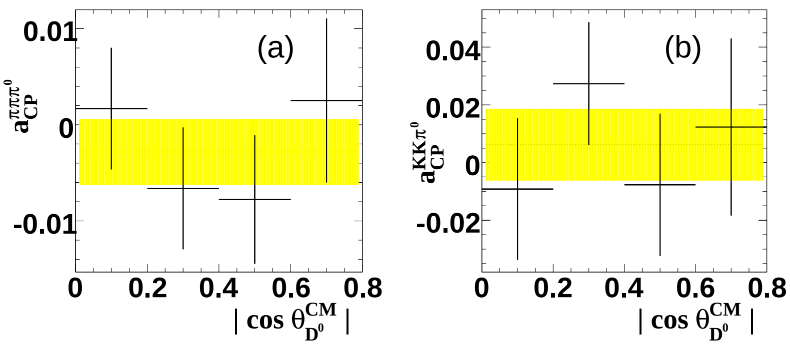


Figure 3: Phase space integrated asymmetry between D^0 and $\bar{D}^0$ in bins of $\cos\theta^*$ evaluated for (a) $D^0 \to \pi^+\,\pi^-\,\pi^0$ and (b) $D^0 \to K^+\,K^-\,\pi^0$.

2.3 Time Dependent Analysis

The time dependent analysis of D^0 decays is strictly related to mixing, in fact the D^0 mixing affects the decay times as follows:

$$\tau_{hh}^{+} = \tau_{K\pi}\left[1 + r_m\left(y\cos\phi_f - x\sin\phi_f\right)\right]^{-1} \tag{2.2}$$
$$\tau_{hh}^{-} = \tau_{K\pi}\left[1 + r_m^{-1}\left(y\cos\phi_f - x\sin\phi_f\right)\right]^{-1}, \tag{2.3}$$

where $h = K,\ \pi$. The definitions of the mixing parameters x, y, r_m and ϕ_f can be found in ref. [15]. Defining

$$\tau_{hh} = \frac{\tau_{hh}^{+} + \tau_{hh}^{-}}{2} \qquad A_\tau = \frac{\tau_{hh}^{+} - \tau_{hh}^{-}}{\tau_{hh}^{+} + \tau_{hh}^{-}},$$

one can measure

$$\Delta Y = \frac{\tau_{K\pi}}{\tau_{hh}} A_\tau,$$

which is a probe for *CP* violation in decay times, since in the Standard Model we have $(r_m = 1, \phi_f = 0) \Longleftrightarrow (A_\tau = 0, \Delta Y = 0)$.

An analysis of this kind has been made by Belle [16] on a D^* tagged sample of 1.2×10^6 $D^0 \to K^-\pi^+$, 1.1×10^5 $D^0 \to K^+K^-$ and 4.9×10^4 $D^0 \to \pi^+\pi^-$ decays. The D^0 lifetime has been measured as $t = m_{D^0}\vec{L}\cdot\vec{p}/p^2$, where $\vec{L}$ is the D^0 decay length and $\vec{p}$ its momentum. The asymmetry parameter is $A_\Gamma = -A_\tau$ and they obtained

$$A_\Gamma^{KK} = (0.15 \pm 0.35_{\text{stat}})\%,$$
$$A_\Gamma^{\pi\pi} = (-0.28 \pm 0.57_{\text{stat}})\%.$$

Combining the two results

$$A_\Gamma = (0.01 \pm 0.30_{\text{stat}} \pm 0.15_{\text{syst}})\%,$$

where the systematic error comes mainly from the background parametrization, however it is reduced by the fact that many contributions cancel in lifetime ratio.

The same analysis performed by BABAR [17] on a sample of events statistically similar to that one from Belle reports

$$\Delta Y^{KK} = (-0.40 \pm 0.44_{\text{stat}} \pm 0.12_{\text{syst}})\%,$$
$$\Delta Y^{\pi\pi} = (0.05 \pm 0.64_{\text{stat}} \pm 0.32_{\text{syst}})\%.$$

Combining the results from the two decay channels

$$\Delta Y = (-0.26 \pm 0.36_{\text{stat}} \pm 0.08_{\text{syst}})\%,$$

where the main contribution to systematic error is from signal model.

2.4 *T*-odd correlations

The most recent search for *CP* violation at the *B*-factories has been performed by BABAR using the technique of the *T*-odd correlations. The analysis search for *CP* violation in the decay $D^0 \to K^+K^-\pi^+\pi^-$ using a kinematic triple product correlation of the form $C_T = \vec{p}_{K^+}\cdot(\vec{p}_{\pi^+}\times\vec{p}_{\pi^-})$, where each $\vec{p}_i$ is a momentum vector of one of the particles in the decay.

The product is odd under time-reversal (T) and, assuming the *CPT* theorem, T-violation is a signal for *CP*-violation. Strong interaction dynamics can produce a non-zero value of the A_T asymmetry,

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \tag{2.4}$$

where Γ is the decay rate for the process, even if the weak phases are zero.

Defining as $\overline{A}_T$ the T-odd asymmetry measured in the *CP*-conjugate decay process,

$$\overline{A}_T \equiv \frac{\Gamma(-\overline{C}_T > 0) - \Gamma(-\overline{C}_T < 0)}{\Gamma(-\overline{C}_T > 0) + \Gamma(-\overline{C}_T < 0)}, \tag{2.5}$$

we can construct:

$$\mathcal{A}_T = \frac{1}{2}(A_T - \overline{A_T}), \tag{2.6}$$

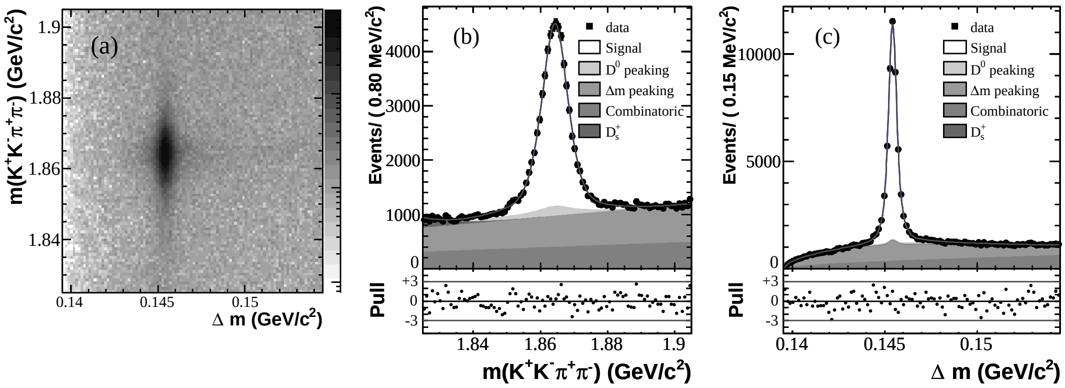


Figure 4: (a) $m(K^+K^-\pi^+\pi^-)$ vs Δm for the total sample; (b) $m(K^+K^-\pi^+\pi^-)$ and (c) Δm projections with curves from the fit results. Shaded areas indicate the different contributions. The fit residuals, represented by the pulls, are also shown under each contribution.

which is a true T-violating signal [18, 19, 20].

At least four particles are required in the final state so that the three used to define the triple product are independent [21] of each other. A D^0 singly Cabibbo suppressed decay having relatively high branching fractions and four different particles in the final state, therefore suitable for this type of analysis is $D^0 \to K^+ K^- \pi^+ \pi^-$.

The analysis made by BABAR [22] makes use of about 47,000 $D^0 \to K^+ K^- \pi^+ \pi^-$ decays and performs a two dimensional fit to the $m(K^+K^-\pi^+\pi^-)$ vs Δm distribution. The fit is performed simultaneously on the full data set split in four samples, depending on D^0 flavor and the value of C_T.

The results from the fit are shown in Figs. 4, 5 and give

$$A_T = \left(-68.5 \pm 7.3_{\text{stat}} \pm 5.8_{\text{syst}}\right) \times 10^{-3}$$
$$\bar{A}_T = \left(-70.5 \pm 7.3_{\text{stat}} \pm 3.9_{\text{syst}}\right) \times 10^{-3}$$

from which

$$\mathcal{A}_T = \left(1.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}\right) \times 10^{-3},$$

where the systematic error is dominated by the particle identification and the D^0 center of mass momentum cut.

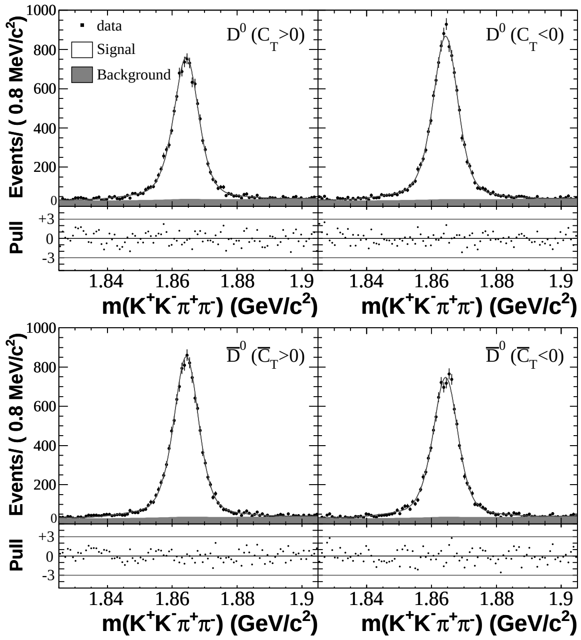


Figure 5: Fit projections onto the $m(K^+K^-\pi^+\pi^-)$ for the four different C_T subsamples with a cut on Δm. The shaded areas indicate the total backgrounds.

3. Conclusion

Charm decays provide a powerful probe for non Standard Model processes involving *CP* violation. Fig. 6 summarizes the searches for *CP* violation at *B*-factories in D^0 decays. At moment no evidence for *CP* violation is found with sensitivities which reach 0.5%, in order of magnitude of the higher Standard Model predictions.

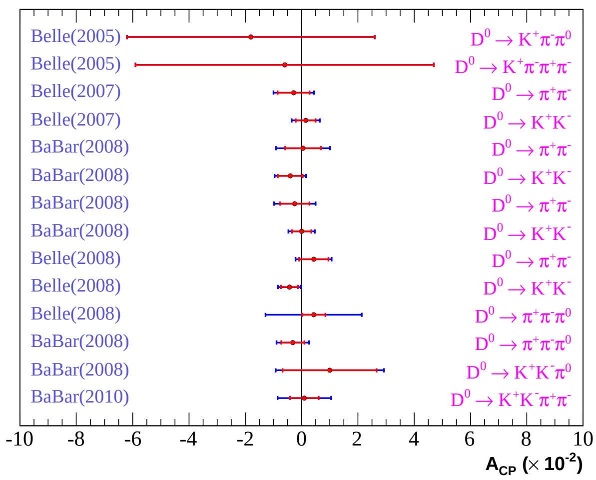


Figure 6: Summary of the searches for *CP* violation at *B*-factories in D^0 decays.

These results constrain the possible effects of New Physics in this observable [6]. Sensitivity improvements are expected in the next few years at the proposed Super *B* Factories or at LHCb.

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