CP VIOLATION BEYOND STANDARD MODEL*

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The study of CP violation in systems where it is expected to be suppressed and in systems where it is expected to be approximately the same as in the "golden" $b \to c\bar{c}s$ transitions, provides an excellent laboratory for the search for physics beyond the Standard Model. Hadronic $b \to s\bar{q}q$ decays, radiative $b \to s\gamma$ events, charm and tau decays are selected from the samples of events collected by the BaBar and Belle detectors by means of several strategies. Standard Model tests are performed through measurements of $B^0 \to K^0_{\rm S}K^0_{\rm S}K^0_{\rm S}$ and $B^0 \to \phi K^0_{\rm S}\gamma$ time-dependent CP asymmetries, $D^+_{(s)} \to K^+K^0_{\rm S}\pi^+\pi^-$ T-odd correlations, $D^+ \to \phi\pi^+$ time-integrated CP asymmetry and $\tau^- \to \pi^-K^0_{\rm S}\nu_\tau$ decay-rate CP asymmetry. Limits on the charged Higgs boson couplings in the multi-Higgs-doublet scenario are obtained from the study of the relevant angular distributions in $\tau^- \to \pi^-K^0_{\rm S}\nu_\tau$ decays.

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1. Introduction

In the Standard Model, the observed CP symmetry violation in the quark sector is accounted for by a single complex phase $i\eta$ in the three-generation Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix [1, 2]. In this framework, over the past ten years, the BaBar and Belle collaborations have measured very precisely the CP asymmetries in the proper-time distribution of the tree-dominated "golden" neutral B decays to charmonium final states, providing a direct determination of $\sin(2\beta) = 0.679 \pm 0.020$ [3], where

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$\beta = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$. However, there may be other CP violating sources beyond the Standard Model. Contributions from new heavy particles in the loops may induce sizable deviations from the expectations. CP violating effects induced by new physics can be searched in systems where the Standard Model CP asymmetries are expected to be approximately the same as in the $b \to c\bar{c}s$ transitions, like in the case of $b \to s\bar{q}q$ $(q = d, s)$ decays, or in systems where they are expected to be suppressed, as in the radiative $b \to s\gamma$ decays, B^0 mixing, charm and tau sectors.

The neutral B_q^0 $(q = d, s)$ mesons mix with their antiparticles leading to oscillations between the mass eigenstates. The time evolution of the neutral mesons doublet is governed by an effective Hamiltonian, from which the physical eigenstates with defined masses and widths are obtained

$$\left|B_q^{L,H}\right\rangle = \frac{1}{\sqrt{1+|q/p|_q^2}}\left(|B_q\rangle \pm (q/p)_q \left|\bar{B}_q\right\rangle\right) ,$$

where $m^H > m^L$ and $\Gamma^L > \Gamma^H$. If $|q/p|_q = 1$, $|B_q^{L,H}\rangle$ would be also CP eigenstates. The time-independent CP violation asymmetry in the B_q^0 mixing is defined as

$$A_{\mathrm{CP}}^q = \frac{\mathrm{Prob}\left(\bar{B}_q^0(t=0) \to B_q^0(t)\right) - \mathrm{Prob}\left(B_q^0(t=0) \to \bar{B}_q^0(t)\right)}{\mathrm{Prob}\left(\bar{B}_q^0(t=0) \to B_q^0(t)\right) + \mathrm{Prob}\left(B_q^0(t=0) \to \bar{B}_q^0(t)\right)} = \frac{1-|q/p|_q^4}{1+|q/p|_q^4} .$$

Experiments at hadron colliders measure a combination of the B_d^0 and B_s^0 CP parameters, $A_{\mathrm{SL}}^b = C_d A_{\mathrm{SL}}^d + C_s A_{\mathrm{SL}}^s$, where the $C_{d,s}$ coefficients depend on the $B_{d,s}^0$ production rates and mixing probabilities. Standard Model predicts [4] $A_{\mathrm{SL}}^d = (-4.8_{-1.2}^{+1.0}) \times 10^{-4}$, $A_{\mathrm{SL}}^s = (2.06 \pm 0.57) \times 10^{-5}$ and $A_{\mathrm{SL}}^b = (-2.8_{-0.6}^{+0.5}) \times 10^{-4}$, respectively. New particle exchange in the B_q^0 box diagrams could enhance A_{SL} to values within the reach of the current precision of the experiments.

In charmless hadronic $b \to s\bar{q}q$ $(q = d, s)$ penguin transitions, the time-dependent CP asymmetry of B^0 decays to a CP eigenstate f is described in terms of a mixing induced CP violation parameter, S_f, and a direct CP violation one, C_f

$$A_{\mathrm{CP}}(t) = \frac{\mathrm{BR}\left(\bar{B}^0(t) \to f\right) - \mathrm{BR}\left(B^0(t) \to f\right)}{\mathrm{BR}\left(\bar{B}^0(t) \to f\right) + \mathrm{BR}\left(B^0(t) \to f\right)} = S_f \sin(\Delta m t) - C_f \cos(\Delta m t) , \tag{1}$$

where $\Delta m = m^H - m^L$ is the mass difference between the two B^0 physical eigenstates. In this class of transitions, the decay amplitude is dominated by a single weak-phase term as in the $b \to c\bar{c}s$ transitions, therefore, the

CP parameters are predicted to be $S_f \sim -\eta_f \sin(2\beta)$ and $C_f \sim 0$, where $\eta_f = 1$ (-1) for CP-even (odd) final states. Final state interactions and additional $b \to u$ tree diagrams contributions, depending on the decay mode, could modify the "effective" $\sin(2\beta_{\rm eff})$ measured in this class of decays with respect to $\sin(2\beta)$ [5, 6, 7]. Penguin $b \to s\bar{q}q$ transitions are dominated by loop diagrams and are thus sensitive to new physics effects at large energy scales which can reflect in large corrections to $\beta_{\rm eff}$ or give $C_f \neq 0$ [8].

Flavor Changing Neutral Current $b \to s\gamma$ transitions occur via one-loop radiative penguin diagrams. Recent NNLL order computations give $\mathrm{BR}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ [9] for photons with $E_\gamma >$1.6 GeV in the B rest frame. The emitted photons in $b \to s\gamma$ ($\bar{b} \to \bar{s}\gamma$) are expected to be predominantly left-handed (right-handed) with the same weak phase, therefore, the time-dependent CP asymmetry is predicted to be suppressed by the quark mass ratio $(2m_s/m_b)$. The expected mixing induced and direct CP parameters are predicted to be $S \sim O(3\%)$ and $C \sim -0.6\%$, respectively [10, 11]. Contributions from non Standard Model heavy particles in the loop can cause a sizable deviation from the predicted rate. Both photon helicities can contribute to the process and hence the CP asymmetries can be modified via right-handed currents.

Within the Standard Model, CP violation in charm decay amplitudes is predicted to be very small, due to the suppression of the CP violating complex phase contribution in the relevant CKM matrix elements involved in the transitions. CP violation in D decays is described in terms of two contributions: an indirect CP violation component, $a_{\rm CP}^{\rm ind}$, and a direct CP violation one, $a_{\rm CP}^{\rm dir}(f)$, depending on the final state f. The first term accounts for CP violation in D^0 mixing and in the interference between mixing and decay, it is universal among CP eigenstates and is expected to be only $O(10^{-3})$. The second one is predicted to be negligible in Cabibbo-Favored and in Doubly-Cabibbo-Suppressed decays [12] and largest $(O(10^{-3}) \div O(10^{-4}))$ in Singly-Cabibbo-Suppressed decays [13]. Both direct and indirect CP violation contributions could be enhanced by new physics up to $O(10^{-2})$ through loop diagrams.

In the Standard Model and in many of its extensions, direct CP violation is predicted to be negligible in τ decays. However, CP violation in the K^0 sector leads to a non-zero CP asymmetry in the rates of hadronic τ decays with $K_{\rm S}^0$ in the final state [14, 15]. The decay rate asymmetry is predicted to be

$$A_Q = \frac{\Gamma\left(\tau^+ \to \pi^+ K_{\rm S}^0 \bar{\nu_\tau}\right) - \Gamma\left(\tau^- \to \pi^- K_{\rm S}^0 \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_{\rm S}^0 \bar{\nu_\tau}\right) + \Gamma\left(\tau^- \to \pi^- K_{\rm S}^0 \nu_\tau\right)} = (0.33 \pm 0.01)\% \qquad (2)$$

for decay times comparable to the $K_{\rm S}^0$ lifetime. New physics effect could significantly modify A_Q with respect to the Standard Model expectations. Charged Higgs boson exchange in the multi-Higgs-doublet scenario reflects in a difference between the τ^+ and τ^- decay angular distributions.

2. B meson system measurements

2.1. BaBar $B^0 \to K^0_S K^0_S K^0_S$ time-dependent CP asymmetry

The B^0 decay in the pure CP-even eigenstate $K^0_S K^0_S K^0_S$ final state is theoretically and experimentally very clean, characterized by a predicted difference $\sin(2\beta_{\rm eff}) - \sin(2\beta) = 0.06$ with negligible theoretical error, and a favorable signal-to-noise ratio [16, 17].

From 426 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance, $B^0 \to K^0_S K^0_S K^0_S$ decays are reconstructed from either three $K^0_S \to \pi^+\pi^-$ candidates, or from two $K^0_S \to \pi^+\pi^-$ and one $K^0_S \to \pi^0\pi^0$, where the π^0 candidates are formed from pairs of photons [18]. Events are selected exploiting informations about the K^0_S vertex quality, the invariant mass of the pion pairs, the K^0_S flight length and the electromagnetic shower profile. Combinatorial background is limited with a cut on the angle between the K^0_S flight direction and its momentum vector. The dominant background from continuum events is suppressed by means of a neural network using event shape variables and trained on off-resonance data. The signal efficiency is determined to be respectively $\epsilon = 6.7\%$ and $\epsilon = 3.1\%$ for the $3K^0_S(\pi^+\pi^-)$ and the $2K^0_S(\pi^+\pi^-)K^0_S(\pi^0\pi^0)$ modes from a Monte Carlo generated using the results of a Dalitz–Plot amplitude analysis. Signal events are selected based on the energy-substituted mass $m_{\rm ES} = \sqrt{E^{*2}_{\rm beam} - \vec{p}_B^{\,*2}}$ and the energy difference $\Delta E = E^*_B - E^*_{\rm beam}$, where the asterisk denotes the $\Upsilon(4S)$ frame. The time-dependent CP asymmetry (see Eq. (1)) is a function of the proper time difference $\Delta t = t_{\rm CP} - t_{\rm tag}$ between the fully reconstructed $B^0 \to 3K^0_S$ decay ($B_{\rm CP}$) and the other B meson decay in the event ($B_{\rm tag}$), which is partially reconstructed. The observed rate depends on the flavor of the $B_{\rm tag}$ meson which is obtained using an algorithm which combines several different signatures, as charges, momenta and decay angles of charged particles in the event. The Δt resolution is described by a sum of three Gaussians determined on simulation.

The signal yield and the CP parameters $S_{3K^0_S}$ and $C_{3K^0_S}$ are obtained from a simultaneous unbinned extended maximum likelihood fit to $m_{\rm ES}$, ΔE, Δt and the neural network output. The total PDF is the sum of the contributions due to signal, continuum and a residual 2% $b\bar{b}$ background, described by the simulation.

The fit result for the time-dependent CP violation parameters is

$$
\begin{aligned}
S_{3K^0_S} &= -0.94^{+0.24}_{-0.21}({\rm stat}) \pm 0.06({\rm syst})\,, \\
C_{3K^0_S} &= -0.17 \pm 0.18({\rm stat}) \pm 0.24({\rm syst})\,,
\end{aligned}
$$

where the systematic errors are dominated by the Δt resolution and the fit bias. This result is in agreement within one-standard deviation with those measured in the tree-dominated modes $b \to c\bar{c}s$, as expected in the Standard Model.

2.2. Summary of sin$(2\beta_{eff})$ *from* $b \to s\bar{q}q$ *transitions*

Figure 1 shows the available measurements of the time-dependent CP asymmetries obtained using $b \to s\bar{q}q$ penguin transitions. The direct comparison of the $b \to c\bar{c}s$ results with a naive s-penguin average, performed neglecting the correlations of the experimental systematic uncertainties between the individual modes, gives a 0.8σ difference with a confidence level of 40% [3].

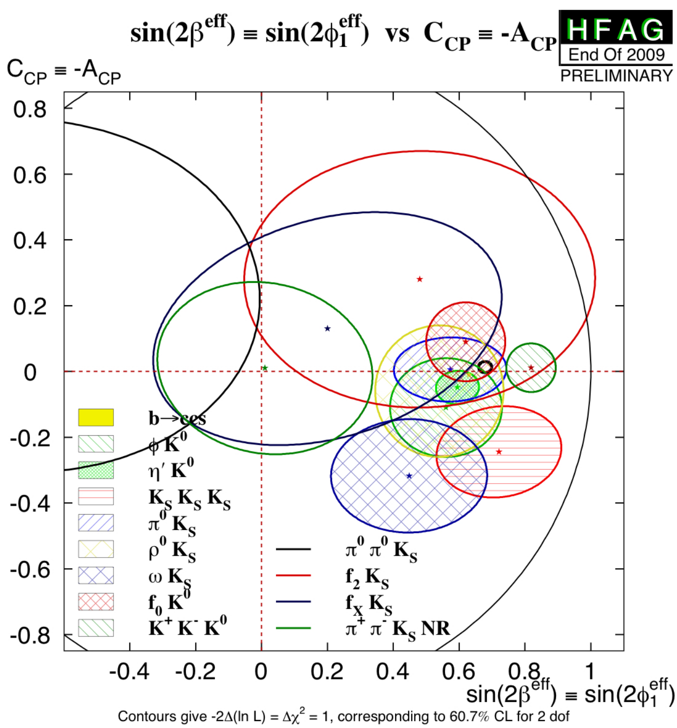

Fig. 1. Comparison of the time-dependent CP asymmetry results from penguin $b \to q\bar{q}s$ transitions with the average of the $b \to c\bar{c}s$ ones in the $(\sin(2\beta_{\rm eff}), C)$ plane [3].

2.3. Belle first observation of radiative $B^0 \to \phi K^0_S\gamma$ decays and measurement of their time-dependent CP asymmetry

From 711 fb^{-1} of data, signal candidates are reconstructed in the $\phi \to K^+K^-$ and $K^0_S \to \pi^+\pi^-$ modes in events with an energetic photon with 1.4 GeV$< E_\gamma <$3.4 GeV [19]. Background from π^0 and η decays into photons is reduced using a likelihood ratio algorithm exploiting electromagnetic shower shape and $\gamma\gamma$ invariant mass informations. B candidates are eventually identified by means of m_{ES} and ΔE. The dominant background from continuum is suppressed by a likelihood ratio procedure exploiting kinematical and topological variables. Peaking background from $D\pi$, $D\eta$ and $D\rho$ is vetoed by rejecting ϕK^0_S combinations compatible with the D meson mass. Non-resonant $K^+K^-K\gamma$ events are estimated from the ϕ mass side-band in data.

The signal yield is extracted using an extended unbinned maximum likelihood fit to the two-dimensional $(m_{\mathrm{ES}}, \Delta E)$ distribution. The shape of the signal component is described by a Crystal Ball line shape for ΔE and a Gaussian for m_{ES}. Continuum background shape parameters are floated in the fit; the other background shapes are fixed to the simulation and adjusted using a $K^*(K^+\pi^-)\gamma$ control sample. The fit yields a signal of 37 ± 8 $B^0 \to \phi K^0_S\gamma$ events with a significance of 5.4σ, taking into account both statistical and systematic uncertainties. Using a signal efficiency $\epsilon = 10.0 \pm 0.1(\mathrm{stat})\%$, the branching ratio $B(B^0 \to \phi K^0_S\gamma) = (2.74 \pm 0.60(\mathrm{stat}) \pm 0.32(\mathrm{syst})) \times 10^{-6}$ is obtained, where the systematic uncertainties are dominated by the non-resonant background yield, the K^0_S reconstruction and the photon selection efficiency. The projections of the fit results onto ΔE and m_{ES} are shown in Fig. 2.

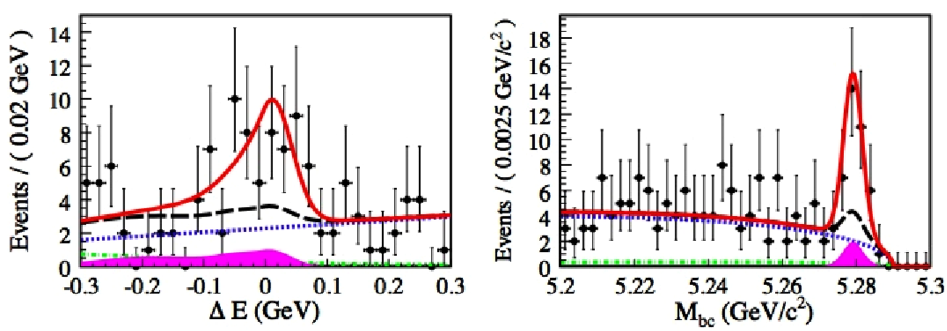

Fig. 2. ΔE and m_{ES} projections. The curves show the total fit function (solid/red), total background function (long-dashed black), continuum component (dotted/blue), the $b \to c$ component (dash-dotted/green) and the non-resonant component (filled/magenta histogram).

The CP violation parameters are obtained by means of a likelihood fit to the $\Delta t = t_{\rm CP} - t_{\rm tag}$ distribution for B^0 and $\bar{B}^0$ tags, where the B meson flavor is determined in several different tagging categories, depending on the mistagging probability. Only the CP parameters are floated in the fit. The shape of the Δt continuum background is determined from the signal side-bands and the fitting technique is checked on control samples. The fit gives

$$\begin{aligned} S_{\phi K^0_{\rm S}} &= 0.74^{+0.72}_{-1.05}({\rm stat})^{+0.10}_{-0.24}({\rm syst})\,, \\ C_{\phi K^0_{\rm S}} &= -0.35 \pm 0.58({\rm stat})^{+0.23}_{-0.10}({\rm syst}) \end{aligned}$$

in agreement with the Standard Model predictions. Systematic errors are dominated by vertex reconstruction, Δt resolution function and fit bias.

Figure 3 shows the Δt distributions and raw asymmetry for events with good tagging quality.

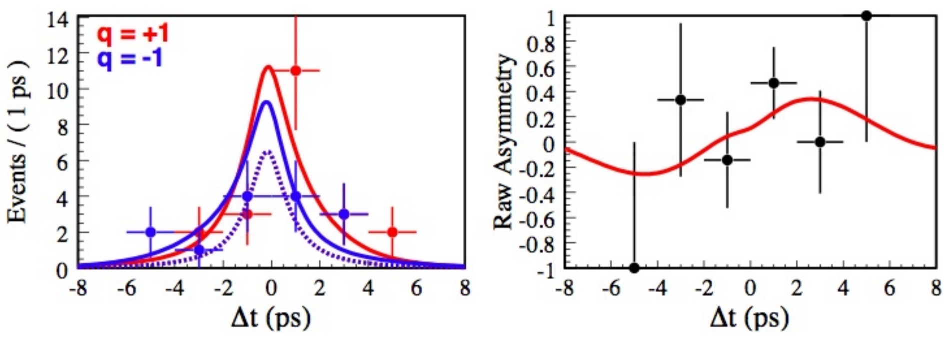

Fig. 3. Δt distributions for $q = +1$ (B^0) and $q = -1$ ($\bar{B}^0$) tags (left) and the raw asymmetry (right). The dashed curves are the sum of backgrounds while the solid curves are the sum of signal and backgrounds.

2.4. Summary of $b \to s\gamma$ CP asymmetries

Figure 4 shows the available measurements of the time-dependent CP asymmetry parameters S and C obtained using $b \to s\gamma$ radiative penguin transitions. The precision of the various measurements does not allow to reveal any discrepancy with respect to the Standard Model expectations.

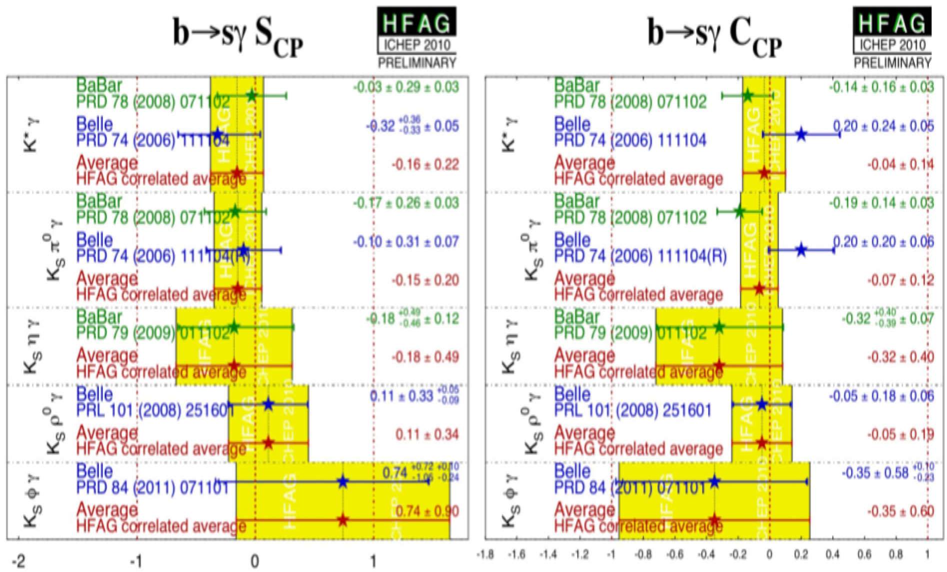

Fig. 4. Summary of the time-dependent CP asymmetry results from penguin radiative $b \to s\gamma$ transitions [3].

2.5. *Summary of CP violation in the B^0 mixing*

The Heavy Flavor Averaging Group combination of the $\Upsilon(4S)$ measurements of the semileptonic CP violation asymmetry in the B_d^0 mixing gives $A_{\rm SL}^d = -0.0047 \pm 0.0046$ [20], in agreement with the Standard Model prediction. Figure 5 shows the comparison of $A_{\rm SL}^d$ with the recent measurements

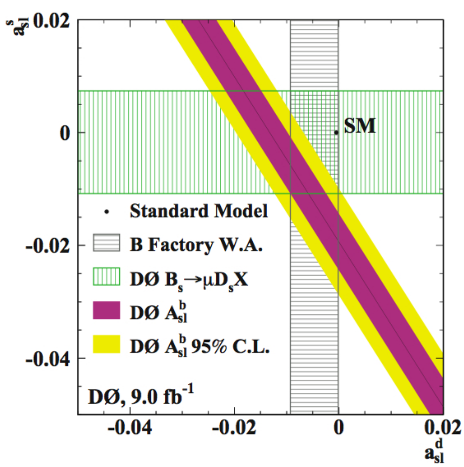

Fig. 5. Summary of the measurements of the CP violation asymmetry in the $B_{d,s}^0$ mixing in the $(A_{\rm SL}^d, A_{\rm SL}^s)$ plane. The Standard Model expectation is reported for comparison.

of the charge asymmetry of like-sign dimuons in B^0 semileptonic decays, A^b_{SL}, and of the CP asymmetry in $B^0_s \to \mu D_s X$ decays, A^s_{SL}, from the D0 Collaboration.

The recent D0 measurement $A^b_{\mathrm{SL}} = (-0.787 \pm 0.172(\mathrm{stat}) \pm 0.093(\mathrm{syst}))\%$ differs by 3.9σ from the Standard Model predictions [21]. New results from Beauty Factories and LHCb will be available soon and hopefully will help in understanding the apparent tension.

3. D meson system measurements

Singly-Cabibbo-Suppressed modes with gluonic penguin are very promising to search for direct CP violation from the interference between tree and penguin amplitudes.

3.1. BaBar $D^+_{(s)} \to K^+ K^0_{\mathrm{S}} \pi^+ \pi^-$ T-odd correlations

From 520 fb^{-1} of data, Singly-Cabibbo-Suppressed $D^+ \to K^+ K^0_{\mathrm{S}} \pi^+ \pi^-$ and Cabibbo-Favored $D^+_s \to K^+ K^0_{\mathrm{S}} \pi^+ \pi^-$ events are reconstructed using $K^0_{\mathrm{S}} \to \pi^+\pi^-$ candidates surviving cuts on $\pi^+\pi^-$ vertex quality, $m(\pi^+\pi^-)$ and K^0_{S} decay length [22]. Signal events are selected by means of a likelihood ratio algorithm exploiting the D meson transverse decay length and vertex probability. Combinatorial background from B decays is suppressed by means of a cut on the D meson candidate momentum. Charm background from $D^{*+} \to \pi^+ D^0 (K^0_{\mathrm{S}} K^+ \pi^-)$ and $D^+ \to K^+ K^0_{\mathrm{S}} K^0_{\mathrm{S}} (\pi^+\pi^-)$, characterized by the same topology of signal events, is removed by means of $m(D^*) - m(D^0)$ and $m(\pi^+\pi^-)$ requirements. It is not possible to remove the background from $D^+ \to K^0_{\mathrm{S}} \pi^+\pi^+\pi^-$ and $\Lambda^+_c \to p K^0_{\mathrm{S}} \pi^+\pi^-$ without biasing the signal mass distribution. Simulation, however, shows that this background does not affect the signal yield extraction.

The kinematic triple product $C_{\mathrm{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$, defined using the vector momenta of the final state particles in the D^+_s rest frame, is odd under time reversal. Under assumption of CPT invariance, time reversal violation is equivalent to CP violation. T-odd correlations are studied by measuring the asymmetry

$$A_{\mathrm{T}} = \frac{\Gamma(C_{\mathrm{T}} > 0) - \Gamma(C_{\mathrm{T}} < 0)}{\Gamma(C_{\mathrm{T}} > 0) + \Gamma(C_{\mathrm{T}} < 0)}\,,$$

where Γ is the decay rate of the process under study. However, final state interactions could produce $A_{\mathrm{T}} \neq 0$ due to strong phases effects [23]. Using the T-odd asymmetry measured in the CP conjugate process, $\bar{A}_{\mathrm{T}}$, the final state interactions contributions are removed in the asymmetry

$$\mathcal{A}_{\mathrm{T}} = \tfrac{1}{2}\left(A_{\mathrm{T}} - \bar{A}_{\mathrm{T}}\right)$$

which characterizes T violation in the weak decay processes [24, 25, 26].

The selected events are grouped in four categories according to the $D_{(s)}$ meson charge and the sign of the $C_{\rm T}$ variable. Signal yields and CP asymmetries are obtained from a simultaneous fit to the mass spectra of the different subsamples, sharing the same shape parameters, floated in the fit. The fit gives

$$\begin{aligned} \mathcal{A}_{\rm T}\left(D^+\right) &= (-12.0 \pm 10.0(\text{stat}) \pm 4.6(\text{syst})) \times 10^{-3}\,, \\ \mathcal{A}_{\rm T}\left(D_s^+\right) &= (-13.6 \pm 7.7(\text{stat}) \pm 3.4(\text{syst})) \times 10^{-3} \end{aligned}$$

consistent with zero both for Singly-Cabibbo-Suppressed $D^+ \to K^+K^0_{\rm S}\pi^+\pi^-$ and Cabibbo-Favored $D_s^+ \to K^+K^0_{\rm S}\pi^+\pi^-$ decays. Systematic errors are dominated by asymmetries in the detector response, likelihood ratio event selection and particle identification.

3.2. Belle $D^+ \to \phi\pi^+$ time-integrated CP asymmetry

From 955 fb^{-1} of data, Singly-Cabibbo-Suppressed $D^+ \to \phi\pi^+$ and Cabibbo-Favored $D_s^+ \to \phi\pi^+$ events are reconstructed using $\phi \to K^+K^-$ decays with K and π candidates surviving proton and lepton vetoes [27]. The dominant combinatorial background from B decays is reduced exploiting the K^+K^- invariant mass, the D meson and pion momenta and the helicity angle between the K^- and the D^+ candidates directions in the ϕ rest frame.

The measured time-integrated asymmetry

$$A_{\rm rec}^{D^+_{(s)}\to\phi\pi^+} = \frac{\mathit{\Gamma}\left(D^+_{(s)} \to \phi\pi^+\right) - \mathit{\Gamma}\left(D^-_{(s)} \to \phi\pi^-\right)}{\mathit{\Gamma}\left(D^+_{(s)} \to \phi\pi^+\right) + \mathit{\Gamma}\left(D^-_{(s)} \to \phi\pi^-\right)}$$

is the sum of several contributions: the intrinsic asymmetry, $A_{\rm CP}$, the forward–backward production asymmetry of $c\bar{c}$ events, that can be described as an odd function of the cosine of the $D_{(s)}$ meson production polar angle in the center-of-mass frame, and the K and π charge asymmetries due to detector efficiency effects. Cabibbo-Favored $D_s^+ \to \phi\pi^+$ decays are expected to have negligible $A_{\rm CP}$, therefore, the no-CP contributions are suppressed in the difference $\Delta A_{\rm rec} = A_{\rm rec}^{D^+} - A_{\rm rec}^{D_s^+}$.

The signal yields are obtained from a binned maximum likelihood fit to the $K^+K^-\pi^+$ invariant mass in bins of the three-dimensional phase space $(\cos\theta^*, p_\pi, \cos\theta_\pi)$, where the variables are, respectively, the polar angle of the $D_{(s)}$ meson in the center-of-mass reference frame, the pion momentum and its polar angle in the laboratory frame. The value of the $D_{(s)}$ meson masses and widths are floated in the fit together with the parameters describing the background shape. From the fitted yields in 3D bins the asymmetry difference $\Delta A_{\rm rec}$ is computed. The difference in the momentum spectrum distributions of K candidates from D and D_s decays reflects in a difference of $\sim O(0.1\%)$ between the charge asymmetry of the K efficiency in the two samples. $\Delta A_{\rm rec}$ is, therefore, corrected to take into account this effect. Finally, $A_{\rm CP}^{D^+\to\phi\pi^+}$ is extracted by adding the corrected asymmetry difference in opposite bins of $\cos\theta^*$

$$A_{\rm CP}^{D^+\to\phi\pi^+}(|\cos\theta^*|) = \frac{\Delta A_{\rm rec}^{\rm cor}(\cos\theta^*) + \Delta A_{\rm rec}^{\rm cor}(-\cos\theta^*)}{2}.$$

The average over the full θ^* range gives

$$A_{\rm CP}^{D^+\to\phi\pi^+} = (0.5 \pm 0.28({\rm stat}) \pm 0.05({\rm syst}))\%\,,$$

where the dominant systematic uncertainties come from the K charge asymmetry correction, the 3D phase space binning, the signal and the background parameterization. The result shows no evidence for CP violation and agrees with Standard Model predictions.

3.3. Summary of CP violation in D^0 decays

The time-integrated CP asymmetry in D^0 meson decays to a final state f is defined as

$$A_{\rm CP}(f) = \frac{\Gamma\left(D^0\to f\right) - \Gamma\left(\bar{D}^0\to\bar{f}\right)}{\Gamma\left(D^0\to f\right) + \Gamma\left(\bar{D}^0\to\bar{f}\right)} = a_{\rm CP}^{\rm dir}(f) + \frac{\langle t\rangle}{\tau}a_{\rm CP}^{\rm ind}\,,$$

where $a_{\rm CP}^{\rm dir}(f)$ and $a_{\rm CP}^{\rm ind}$ are the direct and indirect CP asymmetry components, $\langle t\rangle$ is the average decay time in the sample, and τ is the D^0 lifetime. The level of agreement for the no-CP violation hypothesis can be extracted by means of a combination of the direct and indirect CP asymmetries, using as input the following observables

$$\begin{aligned}\Delta A_{\rm CP} &= A_{\rm CP}\left(K^+K^-\right) - A_{\rm CP}\left(\pi^+\pi^-\right) = \Delta a_{\rm CP}^{\rm dir} + \frac{\Delta\langle t\rangle}{\tau}a_{\rm CP}^{\rm ind}\,,\\ A_\Gamma &= \frac{\tau\left(\bar{D}^0\to K^+K^-\right) - \tau\left(D^0\to K^+K^-\right)}{\tau\left(\bar{D}^0\to K^+K^-\right) + \tau(D^0\to K^+K^-)} = -a_{\rm CP}^{\rm ind}\,,\end{aligned}$$

where differences between quantities for $D^0\to K^+K^-$ and $D^0\to\pi^+\pi^-$ are denoted by Δ. The direct and the indirect CP asymmetry components are constrained by $\Delta A_{\rm CP}$ and A_Γ, respectively. A recent LHCb measurement of the difference in time-integrated CP asymmetry between $D^0\to K^-K^+$ and $D^0\to\pi^-\pi^+$ differs from the hypothesis of CP conservation by 3.5 standard deviations [28].

From a fit to all the available measurements of A_Γ, $A_{\rm CP}(K^+K^-)$, $A_{\rm CP}(\pi^+\pi^-)$ and $\Delta A_{\rm CP}$, the following results are obtained

$$\begin{aligned} a_{\rm CP}^{\rm ind} &= (-0.019 \pm 0.232)\%\,, \\ \Delta a_{\rm CP}^{\rm dir} &= (-0.645 \pm 0.180)\% \end{aligned}$$

with a confidence level of 0.128% for data to be consistent with the no-CP violation hypothesis [3]. Figure 6 shows the summary of the various measurements and the result of the fit. The no-CP violation hypothesis is reported for comparison.

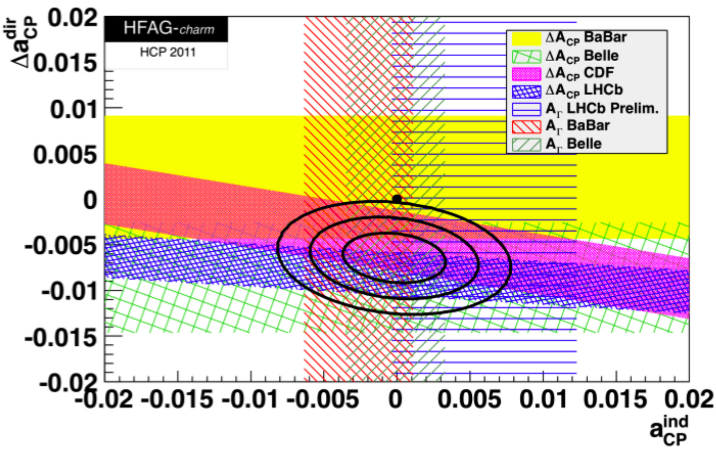

Fig. 6. Measurements of A_Γ and $\Delta A_{\rm CP}$ in the $(a_{\rm CP}^{\rm ind}, \Delta a_{\rm CP}^{\rm dir})$ plane. The point of no-CP violation is shown as a filled circle, and the two-dimensional 68% C.L., 95% C.L. and 99.7% C.L. regions are plotted as ellipses.

4. τ lepton system measurements

4.1. BaBar $\tau^- \to \pi^- K_{\rm S}^0 \nu$ CP asymmetry

In the center-of-mass frame, events are divided into two hemispheres using the plane perpendicular to the direction of the thrust axis. From 476 fb^{-1} of data, $\tau^+\tau^-$ events are selected with a $K_{\rm S}^0 \to \pi^+\pi^-$ candidate and a single prompt track in one hemisphere and one prompt electron or muon with opposite charge in the other hemisphere [29]. Signal events are selected by means of two likelihood ratio algorithms using topological and kinematical variables to distinguish $\tau^+\tau^-$ from $q\bar{q}$ decays. The dominant background from Bhabha, $\mu^+\mu^-$ events and continuum is suppressed exploiting the value of the thrust variable, the $\pi^- K^0_S$ invariant mass and the momentum of the single prompt track. Residual background from $\tau \to K K^0_S \nu$ and $\tau \to K^0 \bar{K}^0 \nu$ decays is estimated on simulation and corrected using the likelihood ratio side-bands in the data.

After the subtraction of continuum and τ decays with no K^0_S in the final state, the raw charge asymmetries (see Eq. (2)) are obtained for the electron and muon samples separately

$$\begin{aligned} A_Q(e - \text{tag}) &= (-0.32 \pm 0.23)\% \,, \\ A_Q(\mu - \text{tag}) &= (-0.05 \pm 0.27)\% \,, \end{aligned}$$

where the errors are statistical. No significant decay rate asymmetries from selection criteria and detector response are found both in dedicated real and simulated $\tau \to h^+ h^- h^+ \nu$ data samples and in the background event sample rejected from the analysis.

The raw decay rate asymmetry is modified by the different nuclear interaction cross sections of the K^0_S and $\bar{K}^0_S$ with the detector material, which can be related to the K^{+-}-nucleon cross sections via isospin symmetry. The raw A_Q asymmetries are corrected on an event-by-event basis in terms of the momentum and the polar angle of the K^0_S in the laboratory frame [30]. Taking into account a further residual charge asymmetry due to background τ decays in K^0_S final states, the first measurement of A_Q is obtained

$$A_Q = (-0.45 \pm 0.24(\text{stat}) \pm 0.11(\text{syst}))\% \,,$$

where the dominant systematic uncertainties come from the selection bias, the background subtraction and the $K^0_S/\bar{K}^0_S$ nuclear interaction.

The interference between the K^0_S and K^0_L intermediate amplitudes plays an important role [31], and therefore the decay-rate asymmetry depends on the reconstruction efficiency as function of the K^0_S decay time. After correcting for this effect, the decay rate is predicted to be $A_Q^{\text{expected}} = (0.36 \pm 0.01)\%$. The BaBar result is, therefore, 3.1 standard deviations from the Standard Model expectation.

4.2. Belle $\tau^- \to \pi^- K^0_S \nu$ CP asymmetry

From 699 fb^{-1} of data, $\tau^+\tau^-$ events are selected with a $K^0_S \to \pi^+\pi^-$ candidate and a single prompt track in one hemisphere and one prompt electron, muon or pion with opposite charge in the other hemisphere [32]. Event hemispheres are defined as in the BaBar analysis. Background from π^0 decays is suppressed by rejecting events with photons in the K^0_S hemisphere. Continuum background is reduced exploiting the thrust value and the number of photons in the opposite hemisphere. Contamination due to

$\tau^- \to \pi^-\pi^+\pi^-\nu$ events is estimated in real data using the $K^0_{\rm S}$ invariant mass side-bands. The residual background, dominated by $\tau^- \to K^0_{\rm L}K^0_{\rm S}\pi^-\nu$, $\tau^- \to K^0_{\rm S}\pi^-\pi^0\nu$ and continuum decays is estimated on simulation to be $f_{\rm BKG} = (22.1 \pm 3.6)\%$.

CP asymmetry is extracted from the study of two angular distributions in the $K^0_{\rm S}\pi^-$ reference frame. The relevant quantities are the angle β between the directions of the e^+e^- center-of-mass and the $K^0_{\rm S}$, and the angle ψ between the directions of the e^+e^- center-of-mass and the τ.

The exchange of a charged scalar Higgs boson in multi-Higgs-doublet scenario can be parameterized in terms of a modified scalar form factor and a dimensionless complex coupling constant $\eta_{\rm S}$. This effect reflects in a difference between the average values of the distribution of $\cos\beta\cos\psi$ for τ^+ and τ^- decays in bin i of the $m^2(K^0_{\rm S}\pi)$ distribution [33]

$$A^i_{\rm CP} = \langle\cos\beta\cos\psi\rangle^i_{\tau^-} - \langle\cos\beta\cos\psi\rangle^i_{\tau^+} = c_i{\rm Im}(\eta_{\rm S})\,,$$

where c_i are linearity constants.

Possible sources of artificial CP violation, as forward–backward production asymmetry of $e^+e^- \to \tau^+\tau^-$ events and detector induced differences between the π^+ and π^- reconstruction efficiency, are determined on a $\tau^\pm \to \pi^\mp\pi^+\pi^-\nu$ control sample in terms of the three pions system momentum and polar angle. These effects are found to be $\Delta A_{\rm CP}(A_{\rm FB}) \sim O(10^{-4})$ and $\Delta A_{\rm CP}(A_{\rm detector}) \sim O(10^{-3})$, respectively. Figure 7 shows the measured CP asymmetry after background subtraction in bin of $W = m(K^0_{\rm S}\pi)$. For comparison, the predicted CP symmetry is shown for ${\rm Im}(\eta_{\rm S}) = 0.1$ and

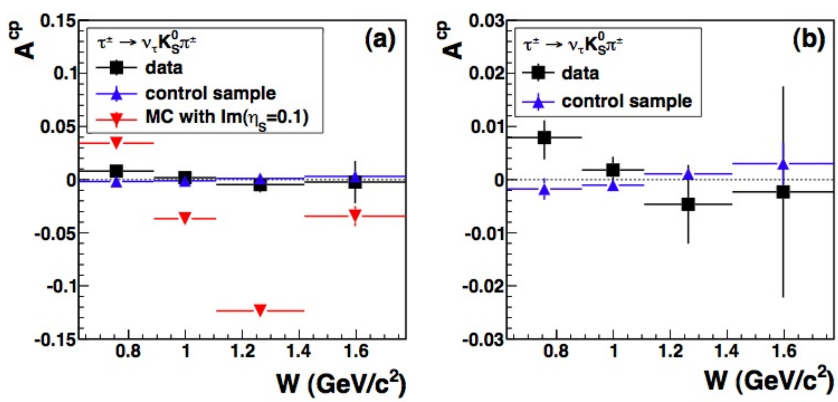

Fig. 7. (a) Measured CP violation asymmetry after background subtraction (squares). The CP asymmetry measured in the $\tau^\pm \to \pi^\mp\pi^+\pi^-\nu$ control sample is indicated by the triangles (blue). The inverted triangles (red) show the expected asymmetry for ${\rm Im}(\eta_{\rm S}) = 0.1$ and ${\rm Re}(\eta_{\rm S}) = 0$. (b) Expanded view.

$\mathrm{Re}(\eta_{\mathrm{S}}) = 0$. The measured values of A_{CP} reflect in the range of limits on the CP violation parameter $\mathrm{Im}(\eta_{\mathrm{S}}) < (0.012–0.026)$ at 90% confidence level, depending on the parameterization of the modified scalar form factor.

5. Conclusions

Measurement of CP violation asymmetries, in systems where they are expected to be suppressed and in systems, where they are expected to be approximately the same as in the neutral B decays to charmonium final states, provides an optimal chance to search for physics beyond the Standard Model. Almost all the results are in agreement with the expectations. In the near future, the study of CP violation asymmetries at the LHC and at the high intensity B factories will offer the opportunity to improve the experimental techniques, perform very stringent Standard Model tests and, hopefully, to discover or to understand new physics.

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