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CP violation and suppressed B_s decays at CDF

J. D. Lewis
Fermi National Accelerator Laboratory - Batavia, IL, USA

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Summary. — The study of heavy-quark decays continues to have wide interest as a possible avenue for the discovery of physics beyond the standard model. With data samples as large as $6\,\text{fb}^{-1}$, the CDF Collaboration is exploring new channels that will extend the reach of measurements in probing the CKM mechanism of CP violation. Several new measurements are presented.

PACS `12.15.Ff` – Quark and lepton masses and mixing.
PACS `14.40.Lb` – Charmed mesons ($|C| > 0$, $B = 0$).
PACS `14.40.Nd` – Bottom mesons ($|B| > 0$).

1. – Measurement of the branching fraction of $B_s^0 \to J/\psi\, f_0(980)$

Because the standard model phase is predicted to be small in B_s mixing [1], the study of B_s decays remains an important avenue to search for indications of new physics. Thus far measurements have been restricted to the decay mode $B_s^0 \to J/\psi\,\phi, \phi \to K^+K^-$ [2,3] which not only requires tagging the flavor of the b quark at production, but also requires an angular analysis to disentangle the contributions of the CP even and odd contributions in the decay to two vector mesons. These fits over decay-time and angular variables can also yield measurements of the difference in the lifetimes of the two B_s eigenstates. The decay mode $B_s^0 \to J/\psi\, f_0(980)$ provides new information in several important ways [4]. Because the f_0 is a scalar, this decay mode can be used to study CP violation without the need of an angular analysis. Also, the suppressed decay $B_s^0 \to J/\psi\, f_0(980), f_0(980) \to K^+K^-$ may yield an S-wave contribution that would pollute the fit in $J/\psi\,\phi$ analysis. Finally, as a pure $CP = -1$ decay, $B_s^0 \to J/\psi\, f_0(980)$ can provide a direct measurement of $1/\Gamma_H$, the lifetime of the heavier B_s mass eigenstate.

A convenient way to normalize the branching fraction is to measure it relative to the more copious $B_s^0 \to J/\psi\,\phi$ decay mode:

$$R_{f_0/\phi} = \frac{\mathcal{B}(B_s^0 \to J/\psi\, f_0(980))}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)}\,\frac{\mathcal{B}(f_0(980) \to \pi^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)}\,, \tag{1}$$

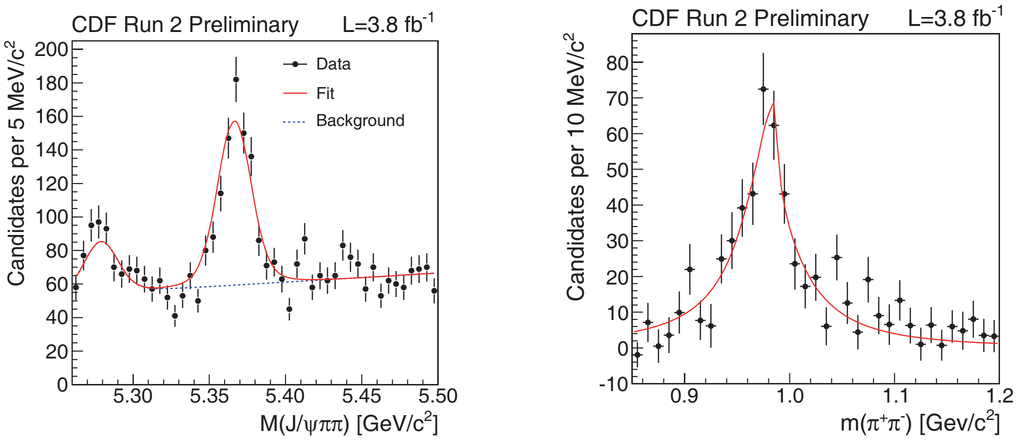

Fig. 1. – Fit of the mass distribution for the yield of $B_s^0 \to J/\psi\, f_0(980), f_0 \to \pi^+\pi^-$.

which is predicted to be in the range 0.1 to 0.5 [4-6]. LHCb has recently reported the first observation of this decay mode with a significance exceeding 12σ and measured $R_{f_0/\phi} = 0.252^{+0.046}_{-0.032}{}^{+0.027}_{-0.033}$ [7]. Belle has also observed the decay in data taken at the $\Upsilon(5S)$ resonance at found $\mathcal{B}(B_s^0 \to J/\psi\, f_0(980), f_0 \to \pi^+\pi^-) = (1.16^{+0.31}_{-0.19}{}^{+0.15}_{-0.17}{}^{+0.26}_{-0.18}) \times 10^{-4}$ [8].

CDF has searched for the $B_s^0 \to J/\psi\, f_0(980), f_0 \to \pi^+\pi^-$ in $3.8\,\text{fb}^{-1}$ of $p\bar{p}$ collision data and has measured $R_{f_0/\phi}$ with substantially improved precision [9]. The analysis begins with a sample of pairs of opposite-charge muon candidates found in the pseudorapidity range $|\eta| < 1$ with transverse momentum $p_T > 1.5\,\text{GeV}/c$ that are selected by the trigger if they have masses in the range $2.7 < M_{\mu\mu} < 4\,\text{GeV}/c^2$. In a kinematic fit, the pairs are required to originate from a common point and to have a mass consistent with a J/ψ. These J/ψ candidates are then combined with two additional charged-particle tracks that are assumed to be pions. The pion pair must have a mass in the range $0.85 < M_{\pi\pi} < 1.2\,\text{GeV}/c^2$ to be considered as an f_0 candidate, and a kinematic fit of the B candidate is performed. A neural network algorithm (NN) is used to purify the sample. The quantities used include kinematic variables, the displacement and quality of the reconstructed decay point, and quality of the muon identification. Monte Carlo (MC) simulations of $J/\psi\, f_0(980)$ events are used for the signal in the NN training, while the background is taken from events in the data with a B_s candidate mass in the range 5.45–5.55 GeV/c^2. The normalization $B_s^0 \to J/\psi\,\phi$ sample is identified in a similar way with the substitution of a pair of tracks assumed to be kaons instead of pions. The mass is the KK pair is required to be within $10\,\text{MeV}/c^2$ of the ϕ pole mass. The same NN selection is used for the normalization and signal modes, and the relative efficiency is determined in simulations. In the simulation of the signal, the dipion mass spectrum is modeled using a Flattè distribution using parameters measured by BES [10].

The yield is found using an unbinned maximum likelihood fit for the B candidate mass in the range 5.26 to $5.5\,\text{GeV}/c^2$ which avoids physics backgrounds such as improperly reconstructed $B^0 \to J/\psi\, K^{*0}$. Physics backgrounds such as $J/\psi\,\rho$ decays are included in the fit. The signal shape is two Gausssians with parameters determined in simulations. The mass distribution with a projection of the fit is shown in fig. 1. The yield is 571 ± 37 events in the signal and 2302 ± 49 in the normalization channel. Figure 1 also shows

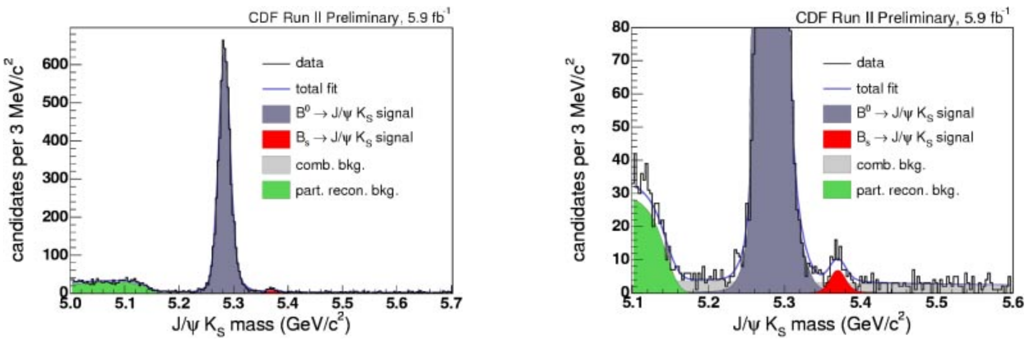

Fig. 2. – Fit of the mass distribution for the yield of $B_s^0 \to J/\psi\, K_S^0, K_S^0 \to \pi^+\pi^-$. The full distribution showing the dominant B^0 peak is shown on the left, while in the zoomed-in view on the right, the B_s^0 signal is visible.

the dipion mass distribution when selecting events consistent with the B_s mass and performing a sideband subtraction. A fit to the Flattè distribution is overlaid, showing that the signal is quite consistent with the f_0 hypothesis. Projections of the helicity angle of the $J/\psi \to \mu^+\mu^-$ and $f_0 \to \pi^+\pi^-$ are also consistent with the decay of a pseudoscalar to a vector and a scalar particle. The principal systematic uncertainties are from the relative efficiency, the shape of the background, and the mass resolution scale. When all uncertainties are included the ratio of branching fractions is: $R_{f_0/\phi} = 0.292 \pm 0.020 \pm 0.017$.

2. – Measurement of the branching fraction of $B_s^0 \to J/\psi\, K_S^0$

The decay $B_s^0 \to J/\psi\, K_S^0$ is also a CP-odd final state and thus has much the same interest as $J/\psi\, f_0$. However, the former is Cabibbo suppressed; therefore, one expects a ratio of branching fractions

$$R_{K_S^0} = \frac{\mathcal{B}(B_s^0 \to J/\psi\, K_S^0)}{\mathcal{B}(B^0 \to J/\psi\, K_S^0)} \simeq 0.05. \tag{2}$$

CDF has observed this decay mode [11] in a $5.9\,\text{fb}^{-1}$ data sample. The principal differences in the experimental technique compared to the $J/\psi\, f_0$ search are that reconstruction must account for the $K_S^0 \to \pi^+\pi^-$ decay length, the signal sample is a tail on the mass distribution of the normalization sample, and the relative yield is derived in a single mass fit. The combinatorial background is again suppressed using a NN with a Monte Carlo simulation for the signal sample and data from the upper sideband as the background sample for the training. The MC is also used to derive a signal shape distribution for the fit where the mass peak and a width scale factor are set by the dominant B^0 mode, and the B_s peak uses the same shape parameters with the known [12] mass splitting (see fig. 2).

A binned log-likelihood fit including the combinatorial backgrounds and background from partially reconstructed b hadrons yields 64 ± 14 $B_s^0 \to J/\psi\, K_S^0$ decays. To determine the significance, the null hypothesis is tested with the fit repeated without a B_s contribution. The difference in $-2\ln\mathcal{L}$ is interpreted as $\Delta\chi^2$ yielding a probability of background fluctuation of 4×10^{-13} or a significance of 7.2σ. The ratio of yields

$N(B_s^0 \to J/\psi\, K_S^0)/N(B^0 \to J/\psi\, K_S^0) = 0.0108 \pm 0.0019$ can be multiplied by the ratio of efficiencies found from the MC and the ratio of production abundances of B_s^0 and B^0 to result in $R_{K_S^0} = 0.041 \pm 0.007(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.005(\text{frag.})$, in good agreement with expectations.

3. – Measurement of the time-integrated mixing parameter $\bar{\chi}$

The measurement in the previous section has a large uncertainty from the fragmentation fraction f_s/f_d, the ratio of production fractions of B_s^0 and B^0 mesons. Several different types of measurements can contribute to the extraction of f_s/f_d: in semileptonic decays, one can assume $SU(3)$ (*e.g.*, $\Gamma(B^+ \to \bar{D}^0\mu^+\nu) = \Gamma(B^0 \to D^-\mu^+\nu) = \Gamma(B_s^0 \to D_s^-\mu^+\nu)$), and use the yields in various partially reconstructed decay modes to extract the production fractions; with theoretical input on the ratios of branching fractions of decays with similar topology, the yields in exclusive hadronic decays can be used; and the time-average mixing parameter $\bar{\chi} = f_d\chi_d + f_s\chi_s$ provides additional constraints since the mixing parameter χ_d is known from the B factories at the $\Upsilon(4S)$ and $\chi_s \simeq 0.5$ since B_s mixing is nearly maximal.

There is significant tension in existing measurements of $\bar{\chi}$ and f_s/f_d, with the LEP average of $\bar{\chi} = 0.1259 \pm 0.0042$ [13] and a recent measurement from D0 of $\bar{\chi} = 0.132 \pm 0.007 \pm 0.024$ [14], while CDF in Run 1A found $\bar{\chi} = 0.152 \pm 0.007 \pm 0.011$. Similarly, the averages for the relative fractions [15] are $f_s/f_d = 0.363 \pm 0.047$ from Tevatron measurements and $f_s/f_d = 0.256 \pm 0.024$ for measurements taken at the Z. While this difference could be an indication of a difference in the fragmentation properties of b quarks in the two environments, precise measurements from the Tevatron are required to understand if the difference is significant.

$\bar{\chi}$ is measured from the ratio of same-sign to opposite-sign dileptons

$$R = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^-)} \tag{3}$$

after correcting for other sources of dileptons such as fakes, charmonium, and sequential $b \to c \to \ell$ decays. The new CDF measurement [16] uses a $1.4\,\text{fb}^{-1}$ sample of dimuons with $p_T > 3\,\text{GeV}/c$ and $|\eta| < 0.6$ that have traversed about 8 hadronic interaction lengths of material. In addition, to exclude pairs from a single B decay, the pair mass is required to exceed $5\,\text{GeV}/c^2$. Muons can come from several sources: bottom hadron decays, charm hadron decays, or fakes. The fakes in turn can be from prompt particles or from heavy-flavor decays. The different sources can be distinguished statistically on the basis of the impact parameter distribution of the muons. This method has been used previously to measure the correlated $b\bar{b}$ cross section [17]. The analysis uses a two-dimensional binned fit to the distribution of the impact parameters of the two muons. The templates are derived from MC as are constraints on heavy-flavor fakes ($b, c \to K\pi \to \mu$). The fake rates for kaons and pions to yield reconstructed muons are derived from $D^0 \to K^-\pi^+$ decays in an independently triggered data sample.

The event selection for this analysis is significantly more stringent than for the Run 1 measurement with tight cuts on the quality of the track reconstruction in the silicon detector, including the requirement of a hit in the innermost layer which is 1.7 cm from the beam. This last requirement removes a background of tracks with large impact parameter that was not accounted for in earlier fits using the template method. Figure 3 shows projections of the fits onto a single axis for the $\mu^+\mu^-$, $\mu^+\mu^+$, and $\mu^-\mu^-$ samples. The raw

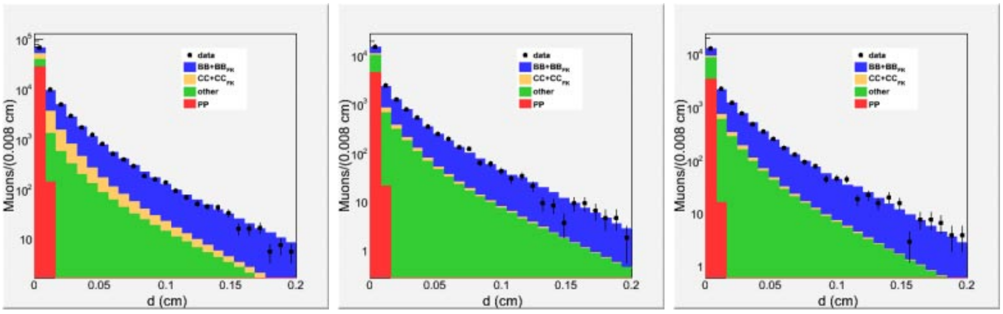

Fig. 3. – Fit of templates to the two-dimensional impact parameter distributions for $\mu^+\mu^-$ (left), $\mu^+\mu^+$ (center), and $\mu^-\mu^-$ (right) events.

value of the asymmetry is $R_{\mu\mu,raw} = 0.472\pm0.011\pm0.007$ where the dominant systematic uncertainty is due to the fake muon contributions. There are many sources of like-sign dimuons in the $b\bar{b} \to \mu\mu$ sample including b semileptonic decay, $b \to c \to \mu$ sequential decays, $b \to \psi \to \mu\mu$ decays, and hadron fakes. Only the first component should be included in a the determination of $\bar{\chi}$. MC results are used to correct for the other contributions to yield the final result $\bar{\chi} = 0.126\pm0.008$. The systematic uncertainty on the indirect muon contributions in b decays is included in the total uncertainty. This result is now quite close to the LEP and D0 values. While this may hint that the fragmentation process may not be very different in the two environments, better determination of the b baryon fraction will be required to make a definitive statement.

4. – Measurement of branching fractions and CP asymmetries in $B^\pm \to D^0 h^\pm$ decays

The CKM angle $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ is the least well-known element of the unitarity triangle and is challenging to determine from experiment. The ADS method [18] is one of several techniques that have been proposed. It takes advantage of the interference between two doubly Cabibbo-suppressed decay chains. In one, a color-allowed $b \to c+\bar{u}s(d)$ decay is followed by a doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ decay, and in the other, a color-suppressed $b \to u+\bar{c}s(d)$ transition is followed by a Cabibbo-favored $\bar{D}^0 \to K^+\pi^-$ decay. There are two ADS observables:

$$R_{ADS} = \frac{\mathcal{B}(B^- \to [K^+\pi^-]_{D^0}K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_{D^0}K^+)}{\mathcal{B}(B^- \to [K^-\pi^+]_{D^0}K^-) + \mathcal{B}(B^+ \to [K^+\pi^-]_{D^0}K^+)}\,, \tag{4}$$

$$A_{ADS} = \frac{\mathcal{B}(B^- \to [K^+\pi^-]_{D^0}K^-) - \mathcal{B}(B^+ \to [K^-\pi^+]_{D^0}K^+)}{\mathcal{B}(B^- \to [K^+\pi^-]_{D^0}K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_{D^0}K^+)}\,. \tag{5}$$

R_{ADS} is the ratio of fraction of doubly-Cabibbo-suppressed (DCS) decays to Cabibbo-favored (CF) decays, and A_{ADS} is the asymmetry between B^+ and B^- for decays in the DCS modes. The relationship between γ and the observables can be found in ref. [18]. Similar observables are defined with a pion in the final state instead of the kaon.

The CDF analysis [19] uses $5\,\text{fb}^{-1}$ of data collected with the displaced secondary vertex trigger. The selection is optimized using the CF hypothesis to minimize combinatorial background using cuts on kinematics, candidate isolation, and decay lengths.

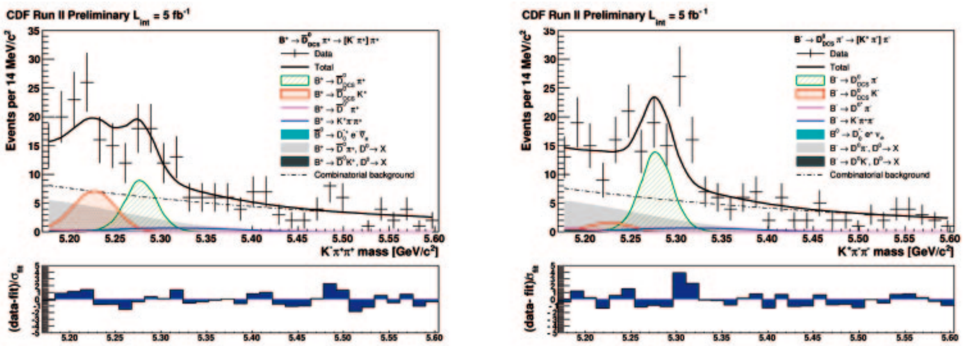

Fig. 4. – Mass distributions of DCS decays $B^+ \to [K^-\pi^+]_{D^0}h^+$ (left) and $B^- \to [K^+\pi^-]_{D^0}h^-$ (right). The curves show projections of the fit that include D^0K and $D^0\pi$ signal contribution as well as backgrounds from random combinations and physics sources such as partially reconstructed B decays.

Candidates that are consistent with a D^0 reconstructed both in the CF and DCS mode are rejected. Specific ionization ($\mathrm{d}E/\mathrm{d}x$) is used to reject $D^0 \to \pi^+\pi^-$ decays. Events are reconstructed according to both the CF and DCS $B^- \to D^0\pi^-$ hypotheses. The sample also includes $B^- \to D^0K^-$ decays which will populate a secondary peak in the mass distribution shifted below the B mass. The numbers of CF and DCS events in the B^+ and B^- samples are determined in a joint fit over the CF and DCS sets of candidates that includes the candidate ($K\pi\pi$) mass as well as $\mathrm{d}E/\mathrm{d}x$ to distinguish between D^0K and $D^0\pi$ decays. Figure 4 shows the DCS mass distributions with projections of the fit overlaid. The signal shape is common to CF and DCS candidates so there is little uncertainty in the shape for the DCS candidates. The fit includes contributions from combinatorial backgrounds as well as partially reconstructed B decays and other physics backgrounds. The ADS observables are determined directly from the yields after including a small correction for the difference in nuclear interaction probabilities for K^+ and K^-. The observed values are

$$R_{ADS}(K) = 0.022 \pm 0.008 \pm 0.008, \tag{6}$$

$$R_{ADS}(\pi) = 0.0041 \pm 0.0008 \pm 0.0004, \tag{7}$$

$$A_{ADS}(K) = -0.63 \pm 0.40 \pm 0.23, \tag{8}$$

$$A_{ADS}(\pi) = 0.22 \pm 0.18 \pm 0.06. \tag{9}$$

The systematic uncertainties arise from the fit model, physics background, and $\mathrm{d}E/\mathrm{d}x$ model. These are the first measurements of ADS observables at a hadron collider, and they are consistent and competative with measurements from Belle [20] and BaBar [21].

5. – Measurement of CP violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays

The the time-integrated CP-violating asymmetry in the Cabibbo-suppressed decays $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ offers a strong probe for physics beyond the standard model. The B decays $B^0 \to K^+K^-$ and $\pi^+\pi^-$ have large asymmetries because the $b \to u$ transition as a complex CKM phase at order λ^3; however, charm transitions are real up to $O(\lambda^5)$. Therefore, a significant asymmetry would be the result of a new process. The

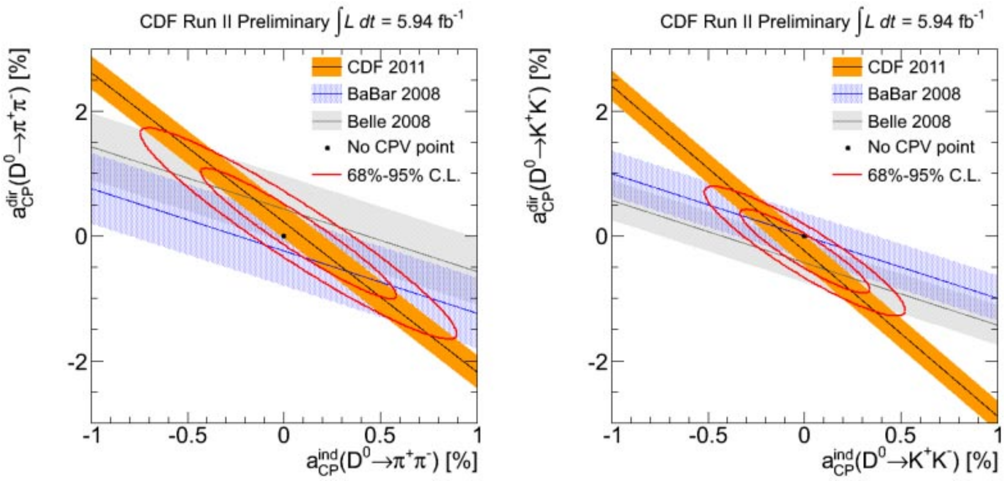

Fig. 5. – Allowed region for a_{CP}^{Indirect} and a_{CP}^{Direct} from CDF for $D^0 \to \pi^+\pi^-$ (left) and $D^0 \to K^+K^-$ (right) decays shown in comparison to results from Belle and BaBar. The ellipses show the 68% and 95% CL allowed regions from combining the result.

asymmetry is the difference between the rates of decay of D^0 mesons to a particular final state compared to that for a $\bar{D}^0$ to the same final state:

$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)}. \tag{10}$$

Both direct CP violation and mixing-induced CP violation are possible. Because charm mixing is slow, to first order the time-integrated asymmetry can be expressed as

$$A_{CP} = a_{CP}^{\text{Direct}} + \int_0^\infty A_{CP}(t)D(t)\text{d}t \approx a_{CP}^{\text{Direct}} + a_{CP}^{\text{Indirect}}\frac{\langle t\rangle}{\tau}, \tag{11}$$

where $D(t)$ is the observed distribution of proper decay times. Therefore, experiments that are sensitive to different regions of proper decay time will have differing sensitivity to the direct and indirect components.

In a $5.9\,\text{fb}^{-1}$ sample collected with a displaced-decay trigger, CDF has measured asymmetries in both the KK and $\pi\pi$ channels [22]. The flavor of the D^0 at production is tagged using $D^{*+} \to D^0\pi^+$ decays where the charge of the pion tags the flavor: π^+ for D^0 and π^- for $\bar{D}^0$. The observed asymmetry for D^*-tagged h^+h^- events is $A_{obs}(h^+h^-, \pi_S) = A_{CP}(h^+h^-) + \delta(\pi_S)$ where A_{obs} is the observed asymmetry, A_{CP} is the true asymmetry, and $\delta(\pi_S)$ is the detection asymmetry for the tagging soft pion. That detector asymmetry can be found from events with a D^* tag and Cabibbo-favored $D^0 \to K^-\pi^+$ decays where the flavor of the decay is known: $A_{obs}(K^-\pi^+, \pi_S) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+) + \delta(\pi_S)$ which also includes intrinsic and detector asymmetries from the D decay mode. These in turn can be measured from inclusive $D^0 \to K^-\pi^+$ decays where the asymmetry is $A_{obs}(K^-\pi^+) = A_{CP}(K^-\pi^+) + \delta(K^-\pi^+)$. These three equations are solved to find

$$A_{CP}(h^+h^-) = A_{obs}(h^+h^-, \pi_S) - A_{obs}(K^-\pi^+, \pi_S) + A_{obs}(K^-\pi^+). \tag{12}$$

This method relies on several fairly weak assumptions. First, it is assumed that there is no production asymmetry for D^{*+} and D^{*-} which should be the case for the charge symmetric $p\bar{p}$ initial state. The soft pion efficiency is assumed to be independent of the D decay mode, and there is assumed to be no variation in acceptance as a function of rapidity. Both of these latter assumptions are verified with data. Fits to the mass distributions give yields of 106421 ± 361 $\pi^+\pi^-\pi_S^+$, 110447 ± 368 $\pi^+\pi^-\pi_S^-$, 232520 ± 759 $K^+K^-\pi_S^+$, and 243575 ± 778 $K^+K^-\pi_S^-$ events. The measured asymmetries are

$$A_{CP}(D^0 \to \pi^+\pi^-) = +0.22 \pm 0.24 \pm 0.11\%, \tag{13}$$

$$A_{CP}(D^0 \to K^+K^-) = -0.24 \pm 0.22 \pm 0.10\%, \tag{14}$$

where the dominant systematic uncertainty comes from allowing changes in the signal shape for the oppositely tagged samples. As described in eq. (11), these asymmetries depend on the actual experiment and correspond to a joint limit in the $(a_{CP}^{\text{Indirect}}, a_{CP}^{\text{Direct}})$ plane. Those limits are shown in fig. 5 along with limits from Belle [23] and BaBar [24]. The CDF limits are the most stringent to date. The slopes CDF and B-factory measurements are different as a result of the different lifetime distributions of the samples, thus the results can be combined to yield the elliptical limit regions shown on the figure. All of the results are consistent with the point showing no CP violation.

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