CDF Note 10784

Improved Measurement of the Difference between Time–Integrated CP Asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ Decays at CDF

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We report an updated search for CP violation in $D^0 \to h^+h^-$ ($h = K, \pi$) decays using the full CDF Run II dataset collected by the trigger on displaced tracks. We use the strong $D^{*+} \to D^0\pi^+$ decay ("D^* tag") to identify the flavor of the charmed meson at production time and measure the difference in CP asymmetries between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, $\Delta A_{\rm CP} = A_{\rm CP}(K^+K^-) - A_{\rm CP}(\pi^+\pi^-)$. This quantity is maximally sensitive to the presence of direct CP violation and highly suppresses systematic uncertainties from instrumental asymmetries. Using 550 000 $D^0 \to \pi^+\pi^-$ and 1.21 million $D^0 \to K^+K^-$ decays, we determine $\Delta A_{\rm CP} = \left[-0.62 \pm 0.21\ ({\rm stat}) \pm 0.10\ ({\rm syst})\right]\%$, which is the single most precise measurement to date and is inconsistent with no CP violation at the 2.7σ level, confirming the analogous result from LHCb.

Preliminary Result for Winter 2012 Conferences

I. INTRODUCTION AND MOTIVATION

Time–integrated CP asymmetries of singly–Cabibbo–suppressed transitions such as $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$, collectively referred as $D^0 \to h^+h^-$ in the following, are powerful probes of new physics. Contributions to these decays from "penguin" amplitudes are negligible in the Standard Model (SM), but the presence of new interactions could enhance the size of CP violation with respect to the SM expectation. Any asymmetry significantly larger than 1%, as expected in the CKM hierarchy, is believed to indicate new physics contributions [1].

In a previous analysis that used only $5.9\,\mathrm{fb}^{-1}$ of integrated luminosity, we measured the time–integrated CP asymmetries in $D^0 \to h^+h^-$ decays to be [3]:

$$A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = \big(+0.22 \pm 0.24\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})\big)\%, \tag{1}$$

$$A_{\mathrm{CP}}(D^0 \to K^+K^-) = \big(-0.24 \pm 0.22\ (\mathrm{stat}) \pm 0.09\ (\mathrm{syst})\big)\%, \tag{2}$$

in agreement with CP conservation.

Each of these asymmetries, owing to the slow mixing rate of charm mesons, is to first order the linear combination of a direct, $A_{\mathrm{CP}}^{\mathrm{dir}}$, and an indirect, $A_{\mathrm{CP}}^{\mathrm{ind}}$, term through a coefficient that is the mean proper decay time of D^0 candidates, $\langle t\rangle$, in units of D^0 lifetime ($\tau \approx 0.4$ ps):

$$A_{\mathrm{CP}}(h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)} \approx A_{\mathrm{CP}}^{\mathrm{dir}}(h^+h^-) + \frac{\langle t(h^+h^-)\rangle}{\tau} A_{\mathrm{CP}}^{\mathrm{ind}}.$$

Assuming that no large weak phases contribute in the decay amplitudes, $A_{\mathrm{CP}}^{\mathrm{ind}}$ is independent of the final state, thus a useful comparison with theory predictions is achieved by calculating the difference between the asymmetries observed in the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays,

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-) = \Delta A_{\mathrm{CP}}^{\mathrm{dir}} + \frac{\Delta\langle t\rangle}{\tau}\ A_{\mathrm{CP}}^{\mathrm{ind}}.$$

Since the difference in decay–time acceptance is small, $\Delta\langle t\rangle = \langle t(K^+K^-)\rangle - \langle t(\pi^+\pi^-)\rangle = 0.26 \pm 0.01\,\tau$, most of the indirect CP–violating asymmetry cancels in the subtraction, hence ΔA_{CP} approximates the difference in direct CP–violating asymmetries of the two decays, $\Delta A_{\mathrm{CP}}^{\mathrm{dir}} = A_{\mathrm{CP}}^{\mathrm{dir}}(K^+K^-) - A_{\mathrm{CP}}^{\mathrm{dir}}(\pi^+\pi^-)$. Using the observed asymmetries from eqs. (1) and (2), we found [3]

$$\Delta A_{\mathrm{CP}}(h^+h^-) = \big(-0.46 \pm 0.31\ (\mathrm{stat}) \pm 0.12\ (\mathrm{syst})\big)\%. \tag{3}$$

in $5.9\,\mathrm{fb}^{-1}$.

Recently, the LHCb collaboration presented a measurement of ΔA_{CP} using $0.62\,\mathrm{fb}^{-1}$ of the data collected in 2011 [4], whose result is

$$\Delta A_{\mathrm{CP}}(h^+h^-) = \big(-0.82 \pm 0.21\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})\big)\%, \tag{4}$$

which deviates by 3.5σ from zero. This is the first evidence of CP violation in the charm sector, with a size that may be suggestive of beyond–SM contributions.

An independent confirmation of this measurement is crucial to establish the effect and improve the precision on its size. The sample of hadronic charm decays collected by the CDF displaced-track trigger is the only one currently available in which this can be attained with sufficient precision. Building upon the techniques used in our previous analysis of individual asymmetries, we report a measurement of difference of asymmetries that uses the full dataset collected in Run II.

We measure ΔA_{CP} through the difference of the uncorrected "raw" asymmetries, A, observed in the D^*-tagged $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ samples as

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-) = A(KK^*) - A(\pi\pi^*). \tag{5}$$

We optimize the selection criteria specifically for the measurement of $\Delta A_{\mathrm{CP}}(h^+h^-)$ and use the full dataset collected by the CDF triggers on displaced vertices from February 2002 through September 2011, consisting of about $9.7\,\mathrm{fb}^{-1}$ of integrated luminosity.

Tracks	Units	Requirement
Total silicon hits	–	≥ 3
Axial COT hits	–	≥ 10
Stereo COT hits	–	≥ 10
Total COT hits	–	≥ 30
p_T	GeV/c	> 2
$\vert\eta\vert$	–	< 1.2
Impact parameter	μm	[100, 1000]
D^0 candidates		
Product of charges	e^2	-1
Transverse decay length	μm	> 200
Scalar sum of p_T	GeV/c	> 4.5
χ^2 of the 3D vertex fit	–	< 30
χ^2_{xy} of the 2D vertex fit	–	< 15
Azimuthal separation	degrees	$[2^\circ,\ 90^\circ]$
$M(h^+h^-)$	MeV/c^2	$[m_{D^0} - 24,\ m_{D^0} + 24]$
Soft pion for D^* candidates		
Silicon hits	–	≥ 1
COT hits	–	≥ 30
p_T	MeV/c	> 400
$\vert\eta\vert$	–	< 1.2
Impact parameter	μm	< 600
$\vert z_0\vert$ from primary vertex	cm	< 1.5
$M(D^0\pi_s)$	GeV/c^2	< 2.02

Table I: Summary of the selection requirements for D^*–tagged $D^0 \to h^+h^-$ decays.

II. DETECTOR AND TRIGGER

The CDF II detector [2] is a magnetic spectrometer surrounded by calorimeters and muon detectors. It identifies the decay point of particles with 15 μm resolution in the transverse plane using six layers of double-sided silicon-microstrip sensors at radii between 2.5 and 22 cm from the beam. A 96-layer drift chamber extending radially from 40 to 140 cm from the beam provides excellent momentum resolution, resulting in about 8 MeV/c^2 mass resolution for two body charm decays. A three-level online selection (trigger) selects events enriched in decays of long-lived particles by exploiting the presence of tracks not originated in the primary $p\bar{p}$ interaction point and measuring their impact parameter (minimal distance from the beam) with offline-like 30 μm resolution. The trigger requires the presence of two charged particles with transverse momenta greater than 2 GeV/c, impact parameters greater than 100 microns and basic cuts on azimuthal separation and scalar sum of momenta.

III. MEASUREMENT

Using the track pairs that fired the trigger we reconstruct signals consistent with the desired $\pi^+\pi^-$ or K^+K^- decay of a neutral charmed meson (D^0 or $\overline{D}^0$). No particle identification information is used. Then we associate a low–momentum charged particle to the charm candidate to construct a D^{*+} (or D^{*-}) candidate. The flavor of the charmed meson is unambiguously determined from the charge of the pion in the strong $D^{*+} \to D^0\pi^+$ (or $D^{*-} \to \overline{D}^0\pi^-$) decay.

The offline selection criteria (Tab. I) have been optimized toward the precision measurement of ΔA_{CP}. The selection has been loosened since the difference of asymmetries is much less sensitive to instrumental effects than the individual asymmetries, allowing for a more inclusive selection. For example, the measurement of ΔA_{CP} is insensitive to the presence of secondary D decays (any asymmetry induced by D mesons from B decays cancels in the subtraction), thus we dropped any requirement on the D^0 impact parameter. The h^+h^- mass is required to lie within 24 MeV/c^2 of the known D^0 mass. A tiny fraction of multiple candidates per event is found and removed as in the previous analysis. Because instrumental asymmetries depend on kinematic properties, the cancellation of spurious asymmetries is realized accurately only if the kinematic distributions across the two samples are the same. We therefore equalize

Source	$\Delta A_{\rm CP}$ [%]
Approximations in the suppression of detector-induced effects	0.009
Shapes assumed in fits	0.020
Charge-dependent mass distributions	0.100
Asymmetries from residual backgrounds	0.013
Total	0.103

Table II: Summary of the most significant systematic uncertainties. The total uncertainty is the sum in quadrature of all the contributions.

the kinematic distributions between K^+K^- and $\pi^+\pi^-$ samples that show some differences.

We determine the number of decays independently for D^0 and $\overline{D}^0$ candidates with a binned fit to the $D^0\pi_s$–mass distribution of positive and negative D^* decays. The fit minimizes a combined χ^2 quantity, defined as $\chi^2_{\rm tot} = \chi^2_+ + \chi^2_-$, where χ^2_+ and χ^2_- are the individual chi-squared for the two distributions. The functional form of the mass shape for both signals is fixed in the fit to the one extracted from 12.5 million D^*–tagged $D^0 \to K^-\pi^+$ decays.

The fits projections are shown in Fig. 1. We reconstruct approximately 550 000 D^*–tagged $D^0 \to \pi^+\pi^-$ decays and 1.21 million D^*–tagged $D^0 \to K^+K^-$ decays and measure the following event yield asymmetries:

$$A(\pi\pi^*) = (-1.71 \pm 0.15)\%,$$
$$A(KK^*) = (-2.33 \pm 0.14)\%.$$

yielding $\Delta A_{\rm CP} = \big[-0.62 \pm 0.21\ (\text{stat})\big]\%$.

As a consistency check, we repeated the measurement in the independent subsample of candidates which pass the new selection criteria but were not selected in the sample used in Ref. [3]. The corresponding result is $\Delta A_{\rm CP} = (-0.74 \pm 0.27)\%$, which is statistically compatible with the orthogonal result of (3).

IV. SYSTEMATIC UNCERTAINTIES

A few residual sources of systematic uncertainties can impact the results, despite the large degree of suppression provided by the difference: approximations in the suppression of detector–induced asymmetries; assumptions and approximations in fits, which include specific choice of analytic shapes, differences between distributions associated with charm and anticharm decays, and contamination from unaccounted backgrounds; and, finally, assumptions and limitations of kinematic reweighting.

We follow the same procedure used in our previous measurement to evaluate systematic uncertainties (Tab. II): most of these are evaluated by modifying the fit functions to include systematic variations and repeating the fits to data; the differences between results of modified fits and the central one are used as systematic uncertainties. The largest contribution comes from the small differences between $D^0\pi_s$–mass distributions of positive and negative D^* candidates, which impacts at first order the observed asymmetry. We ascribe it to possible differences in tracking resolutions between low-momentum positive and negative particles. To determine a systematic uncertainty, we repeat the fit in several configurations where various combinations of signal and background parameters are independently determined for positive and negative D^* candidates. The largest variation on $\Delta A_{\rm CP}$ with respect to the central fit, 0.100%, is used as systematic uncertainty. Assuming the individual systematic uncertainties independent and summing in quadrature, we obtain a total systematic uncertainty of 0.103% on the observed difference between CP–violating asymmetries of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays.

V. FINAL RESULT AND CONCLUSIONS

We report the measurement of the difference between time–integrated CP–violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays using the full Run II dataset collected by the CDF trigger on displaced tracks, which corresponds to about $9.7\,\text{fb}^{-1}$ of integrated luminosity. The final result is

$$\Delta A_{\rm CP} = \big[-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})\big]\%,$$

which is inconsistent with CP conservation at the 2.7σ level, thus providing a solid confirmation of the effect observed by LHCb (Eq. (4) [4]). This is the most precise determination of this quantity to date and supersedes the previous result of [3] shown in Eq. (3).

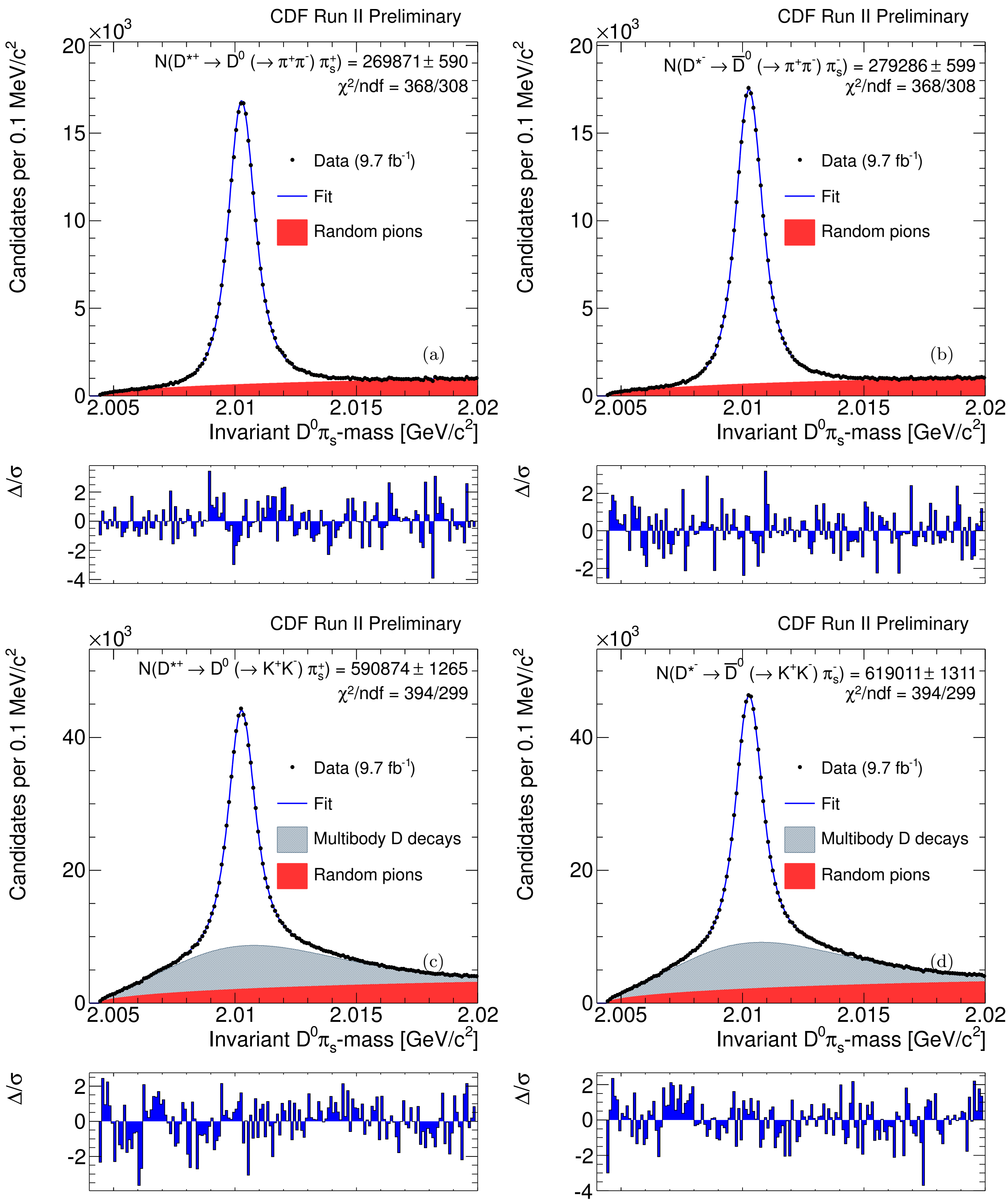

Figure 1: Projections of the combined fit on data for tagged $D^0 \to \pi^+\pi^-$ (a)-(b) and tagged $D^0 \to K^-K^+$ (c)-(d) decays. Charm decays on the left and anticharm on the right.

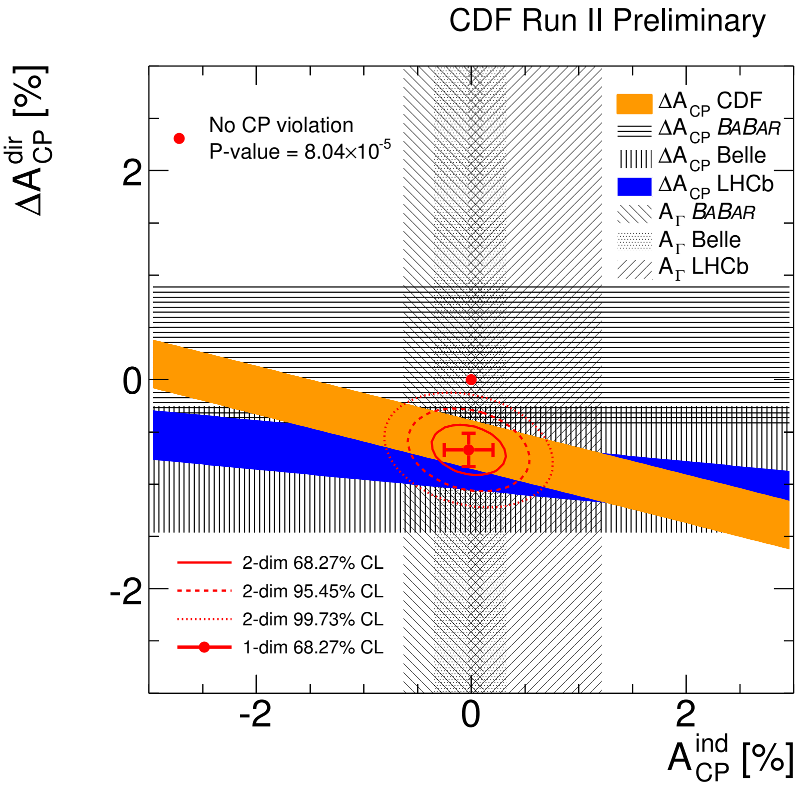

Figure 2: Representation of the measurements of differences between CP–violating asymmetries in the plane ($A^{\rm ind}_{\rm CP}$, $\Delta A^{\rm dir}_{\rm CP}$) [5].

The observed CP–violating asymmetry describes a straight line in the plane ($A^{\rm ind}_{\rm CP}$, $\Delta A^{\rm dir}_{\rm CP}$) with angular coefficient $-\langle\Delta t\rangle/\tau$. Using the observed values of 2.4τ (2.65τ) for the $D^0 \to \pi^+\pi^-$ ($D^0 \to K^-K^+$) as resulting from the proper-decay time bias of the displaced track trigger, we graphically compare our result with the no–CP violation point and previous measurements in Fig. 2. The combination of the present result with the LHCb measurements, assuming Gaussian, fully uncorrelated uncertainties, yields $\Delta A^{\rm dir}_{\rm CP} = (-0.67 \pm 0.16)\%$ and $A^{\rm ind}_{\rm CP} = (-0.02 \pm 0.22)\%$, which deviates by approximately 3.8σ from the no–CP violation hypothesis.

The measurement of $\Delta A_{\rm CP}$ from the subsample of events which were not used in the past iteration of the analysis is combined with Eqs. 1 and 2 to obtain a more precise determination of the single asymmetries in the two D^0 decay channels. Fig. 3 graphically shows such combination, which yields

$$A_{\rm CP}(D^0 \to \pi^+\pi^-) = \big(+0.31 \pm 0.22\big)\%, \tag{6}$$
$$A_{\rm CP}(D^0 \to K^+K^-) = \big(-0.32 \pm 0.21\big)\%, \tag{7}$$

with a correlation between the two asymmetries of 0.412. The results of Eqs. 6 and 7, whose uncertanties include both the statistical and the systematic component, improve and supersede the previous corresponding results of Ref. [3].

[1] A. Lenz and M. Bobrowski, arXiv:1011.5608; D.-S. Du, *Eur. Phys. J.* **C 50** (2007) 579; Y. Grossman, A. Kagan and Y. Nir, *Phys. Rev.* **D 75** (2006) 036008; I. I. Y. Bigi, arXiv:0902.3048; S. Bianco et al., Riv. Nuovo Cim. 26 N7, 1 (2003); Z.-Z. Xing, *Phys. Rev.* **D 55** (1997) 196.
[2] D. Acosta *et al.* [CDF Collaboration], *Phys. Rev.* **D 71** (2005) 032001.
[3] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev.* **D 85** (2012) 012009.
[4] R. Aaij *et al.* [LHCb Collaboration], *Phys. Rev. Lett.* **108** (2012) 111602.
[5] D. Asner *et al.*, arXiv:1010.1589 and online updates at `http://www.slac.stanford.edu/xorg/hfag`.

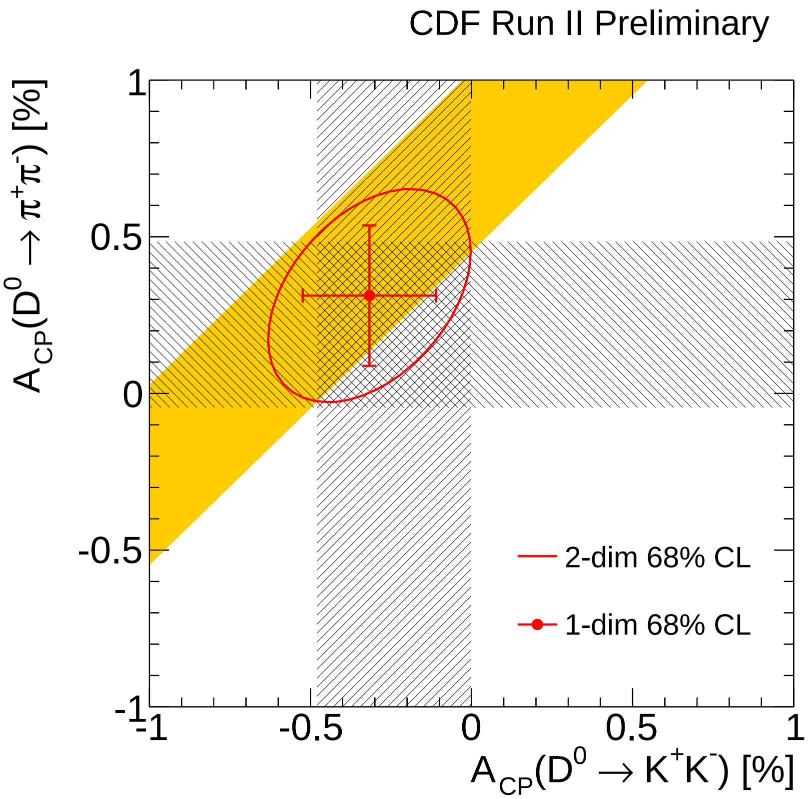

Figure 3: Combination of the measured values of $A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$ and $A_{\mathrm{CP}}(D^0 \to K^+K^-)$ from Ref. [3] (dashed bands) and the result of ΔA_{CP} from the subsample of events which have been added in this updated analysis but were not used in Ref. [3] (orange band).