Measurement of CP Violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ Decays at CDF

The CDF Collaboration
URL `http://www-cdf.fnal.gov`

(Dated: January 24, 2011)

We report a measurement of CP–violating asymmetry in the Cabibbo-suppressed $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays reconstructed in about 5.94 fb^{-1} of CDF data. We use the strong $D^{\star +} \to D^0\pi^+$ decay ("$D^\star$ tag") to identify the flavor of the charmed meson at production time and exploit CP-conserving strong $c\bar{c}$ pair-production in $p\bar{p}$ collisions. Higher statistic samples of Cabibbo-favored $D^0 \to K^-\pi^+$ decays with and without $D^\star$ tag are used to highly suppress systematic uncertainties due to detector effects. The results,

$$A_{\rm CP}(D^0 \to \pi^+\pi^-) = \left[+0.22 \pm 0.24\ (stat.) \pm 0.11\ (syst.)\right]\%$$
$$A_{\rm CP}(D^0 \to K^+K^-) = \left[-0.24 \pm 0.22\ (stat.) \pm 0.10\ (syst.)\right]\%,$$

are the world's most precise measurements to date and they are fully consistent with no CP violation.

I. INTRODUCTION AND MOTIVATION

Time integrated CP-violating asymmetries of singly-Cabibbo suppressed transitions as $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ are powerful probes of new physics (NP). Contribution to these decays from "penguin" amplitudes are negligible in the Standard Model (SM), but presence of NP particles could enhance the size of CP-violation with respect to the SM expectation. Any asymmetry significantly larger than few 1%, as expected in the CKM hierarchy, may unambiguously indicate new physics contributions [1]. We present a measurement of time-integrated CP violating asymmetry in the Cabibbo-suppressed $D^0 \to h^+h^-$ decays (where $h = \pi$ or K):

$$A_{\mathrm{CP}}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}. \tag{1}$$

Both direct and mixing-induced CP violation contribute to the asymmetry. The latter source produces a time-dependent asymmetry, whose expression when neutral charmed mesons decay into CP eigenstates is [1]

$$A_{\mathrm{CP}}(t) \approx \frac{\eta_{CP}}{2}\,\frac{t}{\tau}\left[y\left(\left|\frac{p}{q}\right| - \left|\frac{q}{p}\right|\right)\cos(\varphi) + x\left(\left|\frac{p}{q}\right| + \left|\frac{q}{p}\right|\right)\sin(\varphi)\right], \tag{2}$$

that persists when integrated over time. In eq. (2) η_{CP} is the CP-parity of the decay final state, x, y, p and q are the usual parameters used to describe flavored mesons mixing, φ is the weak CP violating phase and t/τ the proper decay time in unit of D^0 lifetime ($\tau \approx 0.5$ ps). The measured integrated asymmetry, owing to the slow mixing rate of charm mesons, reduces at first order to a sum of two terms:

$$A_{\mathrm{CP}} = a_{\mathrm{CP}}^{\mathrm{dir}} + \int_0^\infty A_{\mathrm{CP}}(t)D(t)dt \approx a_{\mathrm{CP}}^{\mathrm{dir}} + \frac{\langle t\rangle}{\tau}a_{\mathrm{CP}}^{\mathrm{ind}}. \tag{3}$$

The first term arises from direct and the second one from mixing-induced CP violation. The integration in eq. (3) is performed over the observed distribution of proper decay time, $D(t)$. Since the value of $\langle t\rangle$ depends strongly on $D(t)$, different values of A_{CP} could be observed in different experimental environments because of different sensitivities to $a_{\mathrm{CP}}^{\mathrm{dir}}$ or $a_{\mathrm{CP}}^{\mathrm{ind}}$. Since the trigger used in this analysis imposes requirements on minimum impact parameters of the D^0 decay particles, our sample is enriched of higher-valued proper decay time candidates with respect to B-factory experiments. This makes the present measurement more sensitive to mixing-induced CP violation and the combination of the two helps to isolate the two different contributions as we will describe later in the text.

II. DETECTOR AND TRIGGER

The CDF II detector [2] is a magnetic spectrometer surrounded by calorimeters and muon detectors. It provides a determination of 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, yielding approximately 8 MeV/c^2 mass resolution for two body charm decays. A three-level trigger system selects events enriched in decays of long-lived particles by exploiting the presence of displaced tracks in the event and measuring their impact parameter with offline-like 30 μm resolution. The trigger requires 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. ANALYSIS OVERVIEW

We updated and improved an early Run II analysis [3], using an event sample collected with the displaced-track trigger from March 2001 to January 2010 that corresponds at about 5.94 fb^{-1} of integrated luminosity.

We measure the asymmetry in singly-Cabibbo suppressed $D^0 \to h^+h^-$ decays from $D^\star$ through fits of the $D^0\pi^+$ and $\overline{D}^0\pi^-$ distributions. The observed asymmetry includes a possible tiny contribution from actual CP violation, diluted in much larger effects from instrumental charge-asymmetries. Indeed the layout of the main tracker detector, the drift chamber, is intrinsically charge-asymmetric due to a 35° tilt angle of the cells from the radial direction [2], thus different detection efficiencies for positive and negative low-momentum tracks induce an instrumental asymmetry in the number of reconstructed $D^\star$-tagged D^0 and $\overline{D}^0$ mesons. Other possible asymmetries may originate in slightly different performance of pattern-reconstruction and track-fitting algorithms for negative and positive particles. The combined effect of these is a net asymmetry in the range of a few percents, as shown in fig. 1. This must be corrected to better than one permille to match the expected statistical precision of the present measurement.

We exploit a fully data-driven method that uses higher statistic samples of $D^\star$-tagged (indicated with an asterisk) and untagged Cabibbo-favored $D^0 \to K^-\pi^+$ decays to correct for all detector effects thus suppressing systematic uncertainties to below the statistical ones. The uncorrected "raw" asymmetries [5] in the three samples can be written as a sum of several (assumed small) contributions:

$$\begin{aligned} A_{\mathrm{CP}}^{\mathrm{raw}}(hh^\star) &= A_{\mathrm{CP}}(hh) + \delta(\pi_s)^{hh^\star} \\ A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi^\star) &= A_{\mathrm{CP}}(K\pi) + \delta(\pi_s)^{K\pi^\star} + \delta(K\pi)^{K\pi^\star} \\ A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi) &= A_{\mathrm{CP}}(K\pi) + \delta(K\pi)^{K\pi}, \end{aligned} \tag{4}$$

where

- $A_{\mathrm{CP}}(hh)$ and $A_{\mathrm{CP}}(K\pi)$ are the actual physical asymmetries defined by eq. (1);
- $\delta(\pi_s)^{hh^\star}$ is the instrumental asymmetry in reconstructing a positive or negative soft pion associated to a h^+h^- charm decay. This is mainly induced by charge-asymmetric track-reconstruction efficiency at low transverse momentum.
- $\delta(\pi_s)^{K\pi^\star}$ is the instrumental asymmetry in reconstructing a positive or negative soft pion associated to a $K^+\pi^-$ or $K^-\pi^+$ charm decay. This is mainly induced by charge-asymmetric track-reconstruction efficiency at low transverse momentum.
- $\delta(K\pi)^{K\pi}$ and $\delta(K\pi)^{K\pi^\star}$ are the instrumental asymmetries in reconstructing a $K^+\pi^-$ or a $K^-\pi^+$ charm decay respectively for the untagged and the $D^{\star +}$–tagged case. These are mainly due to the difference in interaction cross-section with matter between positive and negative kaons. Smaller effect are due to charge-curvature asymmetries in track triggering and reconstruction.

The physical asymmetry is extracted by subtracting the instrumental effects through the combination:

$$A_{\mathrm{CP}}(hh) = A_{\mathrm{CP}}^{\mathrm{raw}}(hh^\star) - A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi^\star) + A_{\mathrm{CP}}^{\mathrm{raw}}(K\pi) \tag{5}$$

The cancellation provided by this formula relies on some basic assumptions:

- $p\bar{p}$ strong interactions are charge symmetric, i.e. primary D^0 and $\overline{D}^0$ mesons are produced in equal number and so primary $D^{\star +}$ and $D^{\star -}$ mesons;
- small charge asymmetries in D^0 and $\overline{D}^0$ production as a function of η could be caused by beam drag effects. This asymmetry is constrained to change sign for opposite η thus the net effect cancel out as long as the distribution of our decays are symmetric in η that is true at first order;
- the detection efficiency for the $D^\star$ can be expressed as the product of the efficiency for the soft pion times the efficiency for the D^0 final state.
- kinematic distributions should be equal across samples. Any instrumental effect can vary as a function of a number of kinematic variables or environmental conditions in the detector, but if the kinematic distributions of soft pions are consistent in $K\pi^\star$ and $hh^\star$ samples, and the distributions of D^0 decay products are consistent in $K\pi^\star$ and $K\pi$ samples, then $\delta(\pi_s)^{hh^\star} \approx \delta(\pi_s)^{K\pi^\star}$ and $\delta(K\pi)^{K\pi^\star} \approx \delta(K\pi)^{K\pi}$. This condition was verified in the analysis by inspecting a large set of kinematic distributions and applying small corrections (reweigh) when needed.

IV. MEASUREMENT

Using the track pairs that fired the trigger we reconstruct signals consistent with the desired two-body decays (h^+h^- or $K^-\pi^+$ or $K^+\pi^-$) of a neutral charmed meson (D^0 or $\overline{D}^0$). To remove most part of non-promptly produced charmed mesons we also require the unsigned impact parameter of the D^0 candidate not to exceed 100 μm. Then we associate a low-momentum charged particle to the meson candidate to construct a $D^{\star +}$ (or $D^{\star -}$) candidate. The flavor of the charmed meson is determined from the charge of the pion in the strong $D^{\star +} \to D^0\pi^+$ (or $D^{\star -} \to \overline{D}^0\pi^-$)

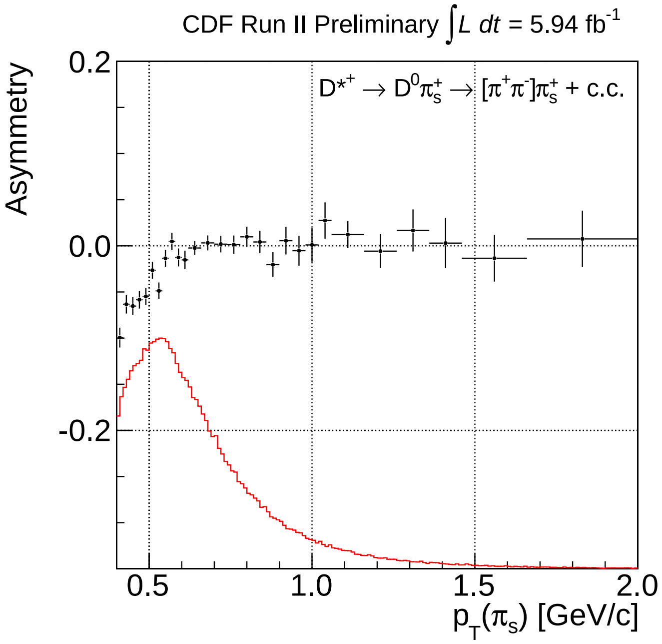

Figure 1: Soft pion charge asymmetry as a function of transverse momentum for a clean sample of $D^\star \rightarrow D^0\pi_s$ candidates with $D^0 \rightarrow \pi^+\pi^-$. In red the transverse momentum spectrum is shown.

decay. The offline requirements applied to select the decays of interest are summarized in tab. I. Additional sample-specific mass requirements are used for the two tagged samples: we ask the two-body invariant mass ($M(K\pi)$ for the $D^0 \rightarrow K\pi$ case and $M(hh)$, for the $D^0 \rightarrow hh$ case) to lie within 24 MeV/c^2 of the nominal D^0 mass.

We reconstruct approximately 215,000 $D^\star$–tagged $D^0 \rightarrow \pi^+\pi^-$ decays, 476,000 $D^\star$–tagged $D^0 \rightarrow K^+K^-$ decays, 5 million $D^\star$–tagged $D^0 \rightarrow \pi^+K^-$ decays and 29 million $D^0 \rightarrow \pi^+K^-$ decays where no tag was required. The much larger statistics of $D^0 \rightarrow \pi^+K^-$ channels, used for correction of instrumental asymmetries, with respect to the signal sample ensures smaller systematic uncertainties than statistical ones on the final result. Figs. 2 (a)-(c) show the $D^0\pi_s$-mass distribution for the three tagged samples. A clean $D^\star$ peak is visible superimposed to different background components according to the specific D^0 decay modes: for the $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ cases the background is mainly due to random pions associated to a real D^0 candidate while for the $D^0 \rightarrow K^+K^-$ case there is also a substantial contribution from partially-reconstructed multi-body charged and neutral charm decays (mainly $D^{\star +} \rightarrow D^0\pi_s^+ \rightarrow [K^-\pi^+\pi^0]\pi_s^+$ where the neutral pion is not reconstructed) that forms a broader bump underneath the signal peak. Fig. 2 (d) shows instead the invariant $K^-\pi^+$-mass for the untagged sample. Here the narrow peak comes from $D^0 \rightarrow K^-\pi^+$ decays while the broader distribution with mean value around the nominal D^0 mass are $\overline{D}^0 \rightarrow K^+\pi^-$ candidates reconstructed with the swapped mass assignment. The two smaller peaks, one on the left (low masses) of the narrow peak, the other on the right (high masses), are respectively the $D^0 \rightarrow K^+K^-$ and the $D^0 \rightarrow \pi^+\pi^-$ components. Two different background contributions are also visible. At higher masses than the signal it's evident the combinatorial background, which contributes almost uniformly in all mass range. At lower masses a significant shoulder due to the multi-body decays component is also visible.

The technique for suppressing detector-induced asymmetries in soft pion reconstruction requires kinematics across the three samples to be the same. Small differences between D^0 final state distributions when a soft pions is or is not reconstructed and soft pion distributions associated to decays in different D^0 final states ($K\pi$ or hh) may be induced by trigger and reconstruction biases. We checked for them and reweighed the tagged $D^0 \rightarrow h^+h^-$ (untagged $D^0 \rightarrow K^-\pi^+$) distributions to the tagged $D^0 \rightarrow K^-\pi^+$ ones when necessary.

We extract independent signal yields for D^0 and $\overline{D}^0$ candidates without using particle identification in the analysis. In the three $D^\star$-tagged samples this is done using the charge of the soft pion. In the untagged $D^0 \rightarrow K^-\pi^+$ sample we randomly divided the sample in two indipendent subsamples similar in size. In each subsample we calculate the mass of each candidate with a specific mass assignments: $K^-\pi^+$ in the first subsample and $K^+\pi^-$ in the second one. So in one sample the $D^0 \rightarrow K^-\pi^+$ signal is correctly reconstructed and appears as a narrow peak, overlapping a broader peak of the misreconstructed $\overline{D}^0 \rightarrow K^+\pi^-$ component. The viceversa applies the other sample. The yield asymmetry is extracted by fitting the number of candidates populating the two narrow peaks.

We determine the yields by performing a binned fit to the $D^0\pi_s$-mass ($K\pi$-mass) distribution combining positive

Tracks	Units	Requirement
Axial silicon hits	–	≥ 3
90° silicon hits	–	≥ 2
Small angle stereo silicon hits	–	≥ 1
Axial COT SL hits	–	≥ 10
Stereo COT SL hits	–	≥ 10
Total COT hits	–	≥ 40
p_T	GeV/c	> 2.2
$\lvert\eta\rvert$	–	< 1.0
Impact parameter	μm	$[100,\ 1000]$

D^0 candididate	Units	Requirement
Product of charges	e^2	-1
Transverse decay length	μm	> 200
Scalar sum of p_T	GeV/c	> 4.5
Impact parameter	μm	< 100
χ^2 of the 3D vertex fit	–	< 30
χ^2_{xy} of the 2D vertex fit	–	< 15
$\lvert\eta\rvert$	–	< 1
Azimuthal separation	degrees	$[2^\circ,\ 90^\circ]$
$M(\pi\pi)$	GeV/c^2	$[1.8,\ 2.4]$

Soft pion for $D^\star$ candidates	Units	Requirement
Silicon hits	–	≥ 1
COT hits	–	≥ 30
p_T	MeV/c	> 400
$\lvert\eta\rvert$	–	< 1
Impact parameter	μm	< 600
$\lvert z_0\rvert$ from primary vertex	cm	< 1.5
$M(D^0\pi_s)$	GeV/c^2	< 2.02

Table I: Summary of the selection cuts for $D^\star$-tagged and untagged $D^0 \to h^+h'^-$ decays.

and negative decays of the tagged (untagged) sample. The fit minimizes a combined χ^2 quantity, defined as

$$\chi^2_{\text{tot}} = \chi^2_+ + \chi^2_-,$$

where χ^2_+ and χ^2_- are the individual chi-squared for the two distributions. The fits projections are shown in fig. 3 for the two Cabibbo-suppressed decays samples and in fig. 3 for the Cabibbo-favored ones, the resulting raw asymmetries are

$$\begin{aligned} A^{\text{raw}}_{\text{CP}}(\pi\pi^\star) &= (-1.86 \pm 0.23)\%, \\ A^{\text{raw}}_{\text{CP}}(KK^\star) &= (-2.32 \pm 0.21)\%, \\ A^{\text{raw}}_{\text{CP}}(K\pi^\star) &= (-2.91 \pm 0.05)\%, \\ A^{\text{raw}}_{\text{CP}}(K\pi) &= (-0.83 \pm 0.03)\%. \end{aligned}$$

V. SYSTEMATIC UNCERTAINTIES

The analysis technique has been extensively tested on Monte Carlo simulation using samples simulated with a wide range of physical and detector asymmetries to verify that the cancellation works regardless of the specific configuration. These studies confirm the validity of our approach and provide a quantitative estimate of possible asymmetries induced by higher order detector effect that may not get fully cancelled or effects of non factorization of $K\pi$ and π_s reconstruction efficiencies. This upper limit is used as systematic uncertainty and amount to 0.009%.

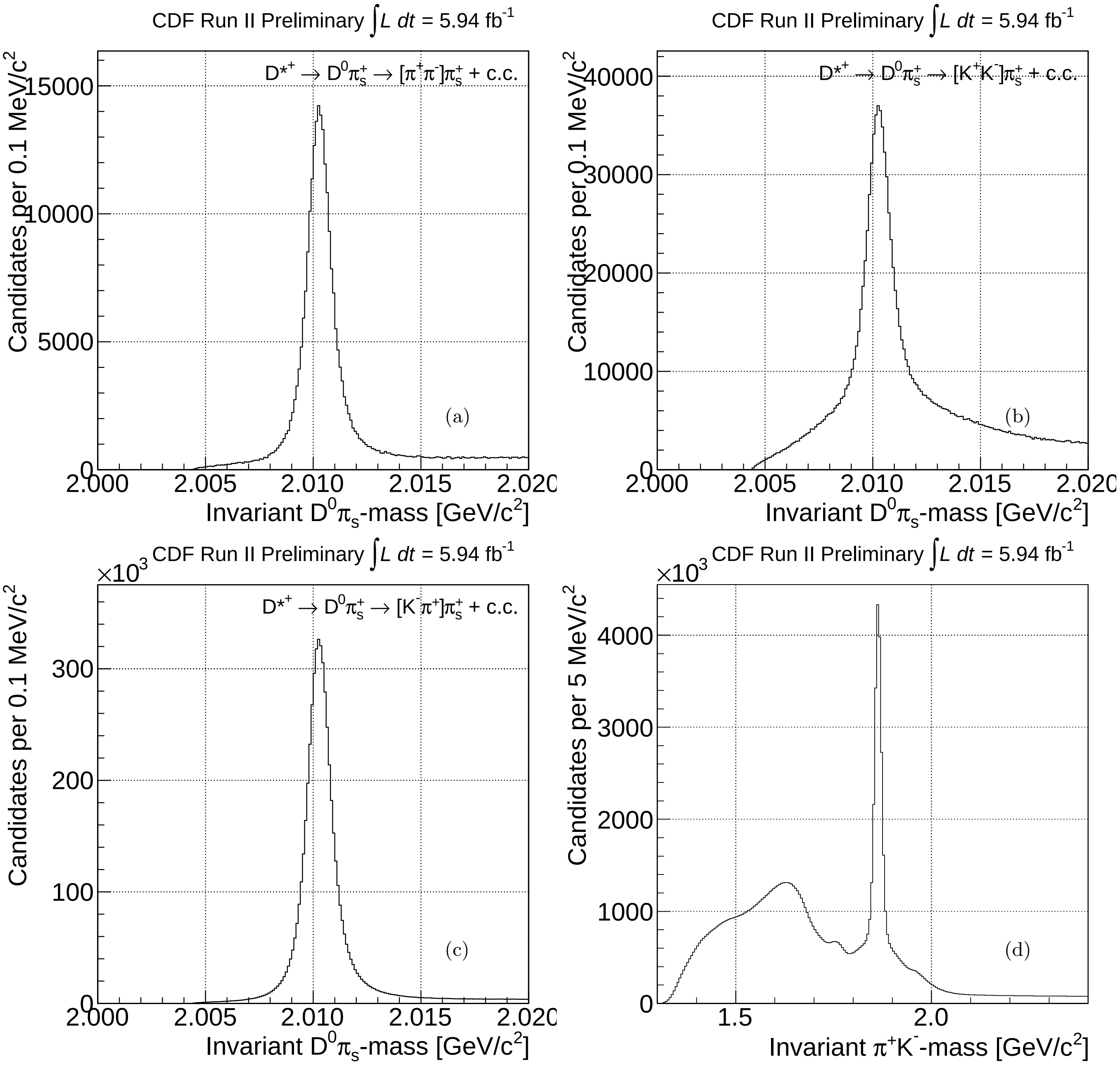

Figure 2: Invariant $D^0\pi_s$-mass distributions for the tagged $D^0 \to \pi^+\pi^-$ (a), $D^0 \to K^+K^-$ (b) and $D^0 \to K^-\pi^+$ samples (c). Invariant $K^-\pi^+$-mass for the untagged sample (d).

We evaluate all other systematic uncertainties from data. In most cases, this implied varying slightly the shape of the functional forms used in fits, repeating the fit on data, and using the difference between the results of these and the central fit as a systematic uncertainty. This overestimates the size of the systematic effects because it introduces an additional statistical source of fluctuation in the results. But we can comfortably afford that given the large event samples size involved.

Small differences between $D^0\pi_s$-mass distributions of positive and negative $D^\star$ candidates selected in their $D^0(\to K\pi)\pi$ decay are present. This may be due to possible small differences in tracking resolutions between positive and negative tracks at low momentum. These effects impact at first order the observed asymmetry. Non-significant differencies are observed in the $K\pi$-mass distributions of the untagged $D^0 \to K\pi$ sample. To evaluate an associated systematic uncertainty we repeated the fits after fixing signal shapes to be the same and/or leaving background shapes to vary independently for positive and negative $D^\star$ candidates. The maximum observed variations are used

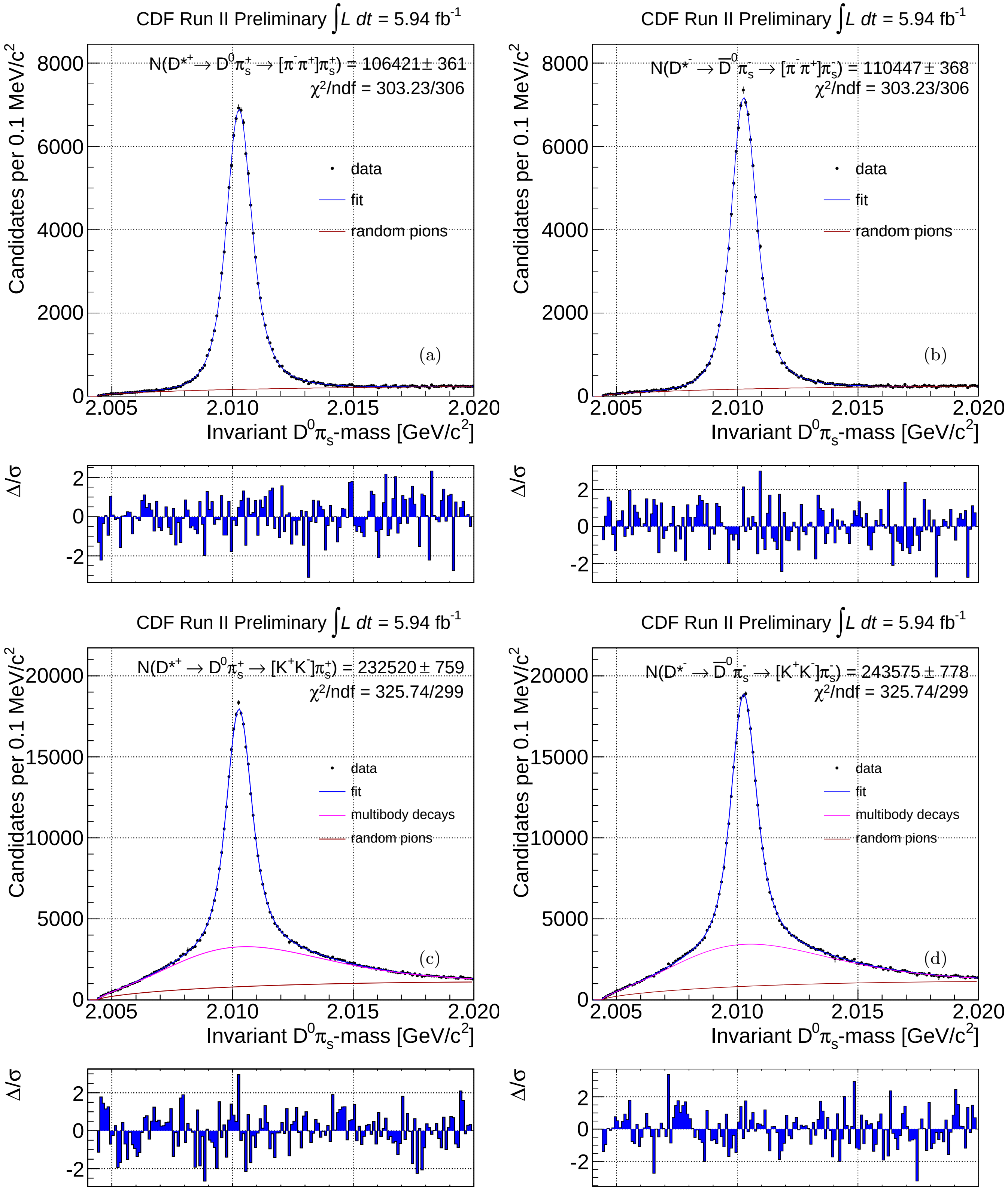

Figure 3: Projections of the combined fit on data for tagged $D^0 \to \pi^+\pi^-$ (a)-(b) and tagged $D^0 \to K^-K^+$ (c)-(d) decays. Charm decays on the left and anticharm on the right.

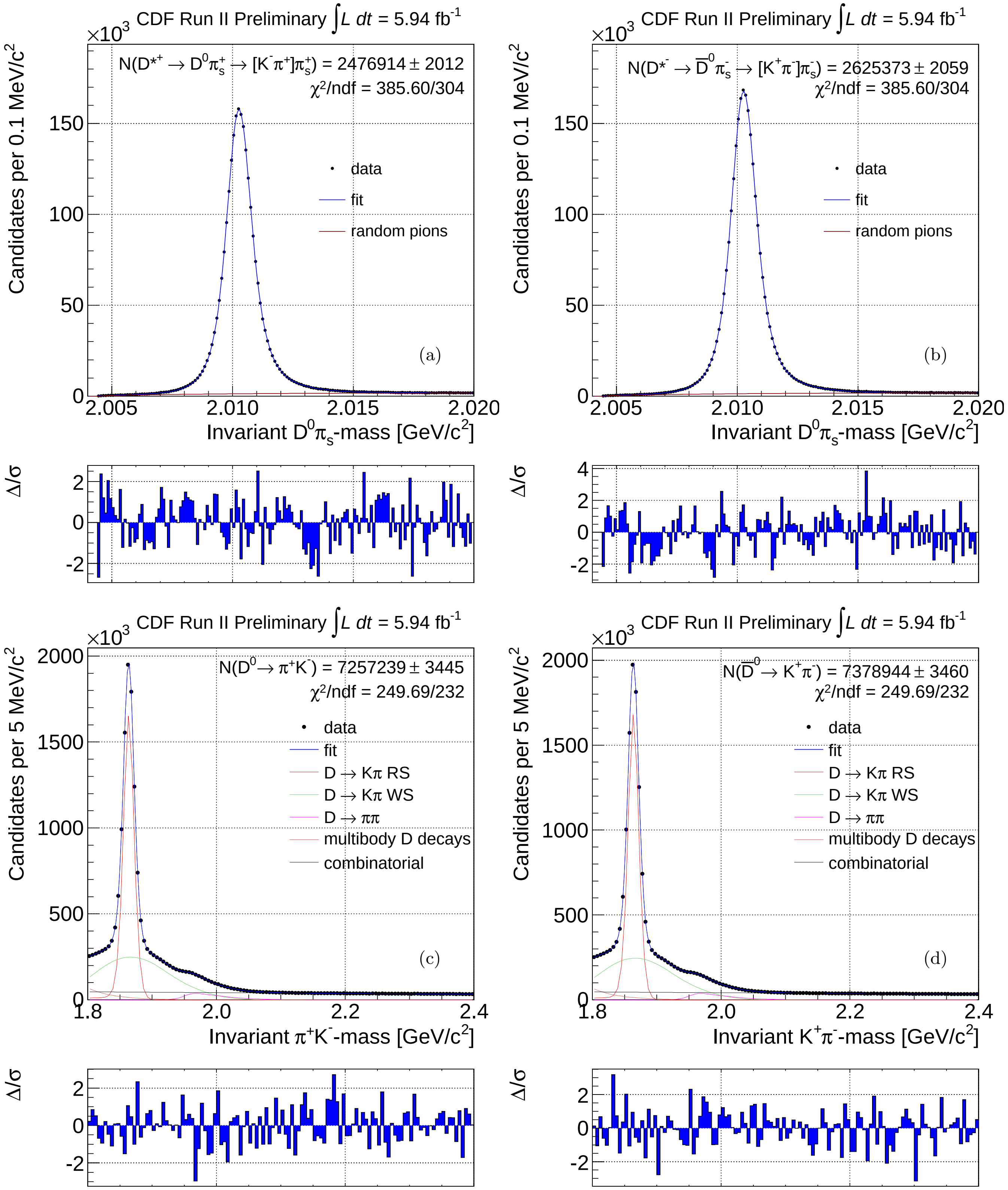

Figure 4: Projections of the combined fit on data for tagged $D^0 \to K^-\pi^+$ (a)-(b) and untagged $D^0 \to K^-\pi^+$ (c)-(d) decays. $K^-\pi^+$ on the left and $K^+\pi^-$ on the right.

Source of systematic uncertainty	Variation on $A_{\rm CP}(\pi\pi)$	Variation on $A_{\rm CP}(KK)$
Approximations in the method	0.009%	0.009%
Beam drag effects	0.004%	0.004%
Contamination of non-prompt D^0s	0.034%	0.034%
Shapes used in fits	0.010%	0.058%
Shapes charge differences	0.098%	0.052%
Asymmetries from non-subtracted backgrounds	0.018%	0.045%
Imperfect sample reweighing	0.0005%	0.0005%
Sum in quadrature	0.105%	0.097%

Table II: Summary of systematic uncertainties.

as systematic uncertainties.

A contamination by charm mesons produced in b–hadron decays could affect the asymmetry measurement in case CP–violating asymmetries in B decays induce an asymmetric source of charm and anti-charm mesons. These effect may be sizable for a single exclusive mode, but are expected to average to very small values for inclusive $B \to D^0/D^\star X$ decays. In the analysis we exclude the majority of non-primary charm contributions by applying an upper threshold on the D^0 candidate impact parameter. However, a fit to the impact parameter distribution determines a residual 16.6% fraction of charm from B in our sample. To assess the effect of these events we repeat the measurement using only charm mesons with large impact parameters, enriched in b–hadron decays. The observed asymmetry is

$$A_{\rm CP}(B \to D^0/D^\star X) = (-0.21 \pm 0.20)\%.$$

The uncertainty on this number, and the fraction of the non-prompt contribution that survives the D^0 impact parameter cut, is used to asses a conservative estimate of the systematic uncertainty caused by the non-prompt contamination in our samples.

Tab. II summarizes the set of all systematic uncertainties considered in the measurement. Assuming they are independent and summing in quadrature we obtain a total systematic uncertainty on our final $A_{\rm CP}(\pi\pi)$ ($A_{\rm CP}(KK)$) measurement of 0.11% (0.10%), approximately half of the statistical uncertainty.

VI. FINAL RESULT AND CONCLUSIONS

We report the measurement of the CP asymmetry in the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays using 5.94 fb^{-1} of data collected by the CDF displaced track trigger. The final results are

$$\begin{aligned} A_{\rm CP}(D^0 \to \pi^+\pi^-) &= \left[+0.22 \pm 0.24\ (stat.) \pm 0.11\ (syst.)\right]\% \qquad \text{and} \\ A_{\rm CP}(D^0 \to K^+K^-) &= \left[-0.24 \pm 0.22\ (stat.) \pm 0.10\ (syst.)\right]\%, \end{aligned}$$

which are consistent with CP conservation and also with the SM predictions.

To disentangle the independent contributions of direct and indirect CP violation in $D^0 \to h^+h^-$ decays, an analysis where the time evolution of charm decays is studied is needed. Nevertheless some interesting conclusions could be derived either comparing our result with B-factories measurements or making some theoretical assumptions.

The observed asymmetry is at first order the linear combination of a direct, $a_{\rm CP}^{\rm dir}$, and an indirect, $a_{\rm CP}^{\rm ind}$, CP violating asymmetry through a coefficient that is the mean proper decay time of D^0 candidates in the data sample (see eq. (3),). Fig. 5 shows a fit to the mean proper decay time distribution of our tagged $D^0 \to \pi^+\pi^-$ ($D^0 \to K^+K^-$) sample, the resulting mean value is 2.40 ± 0.03 (2.65 ± 0.03) times the D^0 lifetime. Our measurement therefore describes a straight band in the plane ($a_{\rm CP}^{\rm ind}, a_{\rm CP}^{\rm dir}$) with angular coefficient -2.40 (-2.65). The same holds for B-factories' measurements, with angular coefficient -1 [4], due to their unbiased acceptance in charm decay time. The three measurements in the plane ($a_{\rm CP}^{\rm ind}, a_{\rm CP}^{\rm dir}$) are shown in fig. 6, where the bands are 1σ wide and the red curves represent the 68% and 95% CL limits of the combined result assuming Gaussian uncertainties.

If we assume no direct CP violation in the charm sector eq. (3) simplifies to

$$A_{\rm CP} \approx \frac{\langle t \rangle}{\tau} a_{\rm CP}^{\rm ind}$$

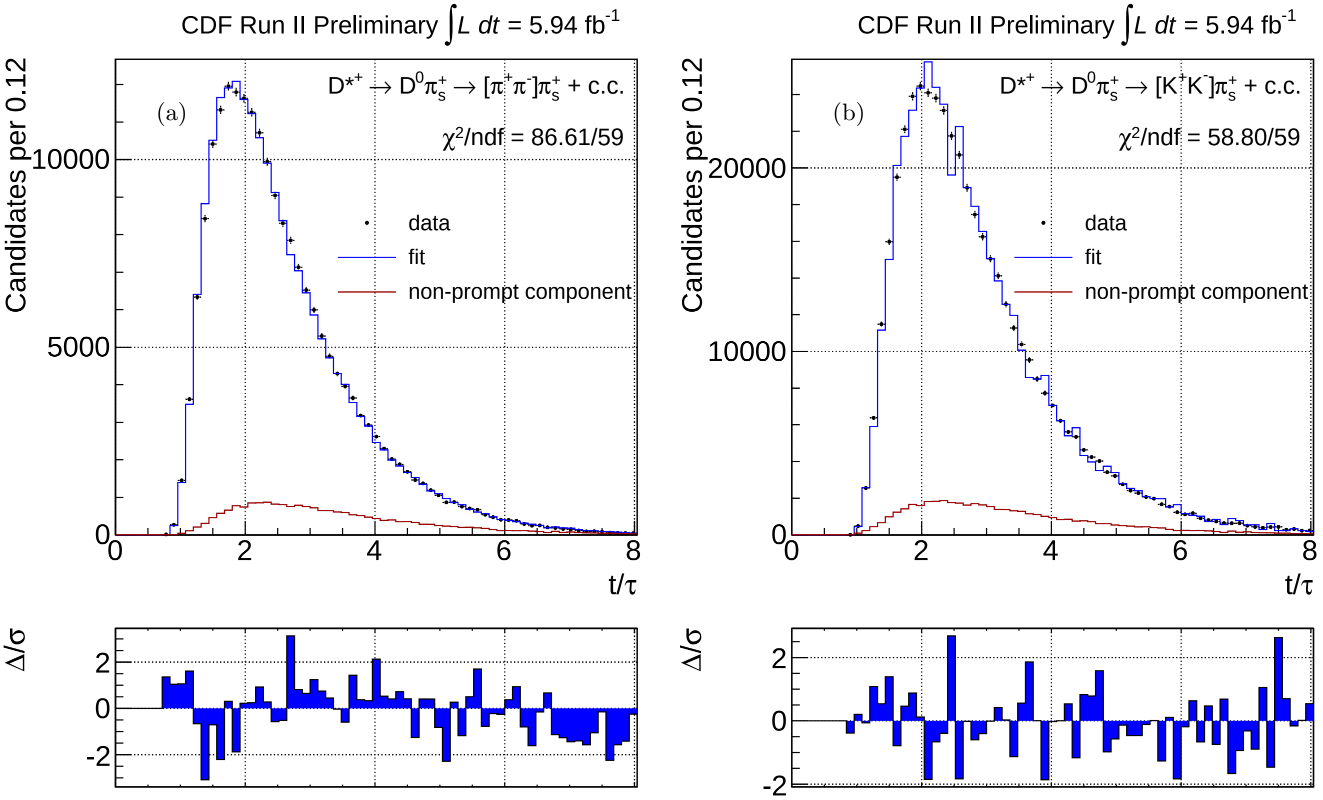

Figure 5: Fit to the proper decay time (in units of D^0 lifetime) distribution of sideband-subtracted tagged $D^0 \to \pi\pi$ (a) and $D^0 \to K^-K^+$ data (b). In red the residual component from non promptly-produced charmed mesons is highligthed.

so these measurements imply

$$a_{\mathrm{CP}}^{\mathrm{ind}}(D^0 \to \pi^+\pi^-) = \left[+0.09 \pm 0.10\ (stat.) \pm 0.05\ (syst.)\right]\% \quad \text{and}$$
$$a_{\mathrm{CP}}^{\mathrm{ind}}(D^0 \to K^+K^-) = \left[-0.09 \pm 0.08\ (stat.) \pm 0.04\ (syst.)\right]\%,$$

For the $D^0 \to \pi^+\pi^-$ ($D^0 \to K^+K^-$) case that means the range $[-0.124, 0.307]\%$ ($[-0.269, 0.088]\%$) covers $a_{\mathrm{CP}}^{\mathrm{ind}}$ at the 95% CL. Note that, since $\langle t \rangle/\tau$ in our sample is greater than in B-factories ones, this range is more than five (three) times tighter than the ones obtained using B-factories measurements, as shown in figs. 7 (a)-(b).

If we assume that there is no direct CP violation in both $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays, $a_{\mathrm{CP}}^{\mathrm{ind}}(D^0 \to \pi^+\pi^-)$ and $a_{\mathrm{CP}}^{\mathrm{ind}}(D^0 \to K^+K^-)$ represent two indipendent measurements of the CP violation in D^0 mixing, we can then average them and obtain an even more precise result:

$$a_{\mathrm{CP}}^{\mathrm{ind}} = \left[-0.01 \pm 0.06\ (stat.) \pm 0.05\ (syst.)\right]\%,$$

where we treated the systematic errors as fully correlated between the two measurements.

Conversely, assuming $a_{\mathrm{CP}}^{\mathrm{ind}} = 0$, our numbers are directly comparable to other measurements in different experimental configurations. In this case, figs. 7 (c)-(d), our statistical uncertainties are still more precise than the best B-factories measurements, and also systematic uncertainties are smaller.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa

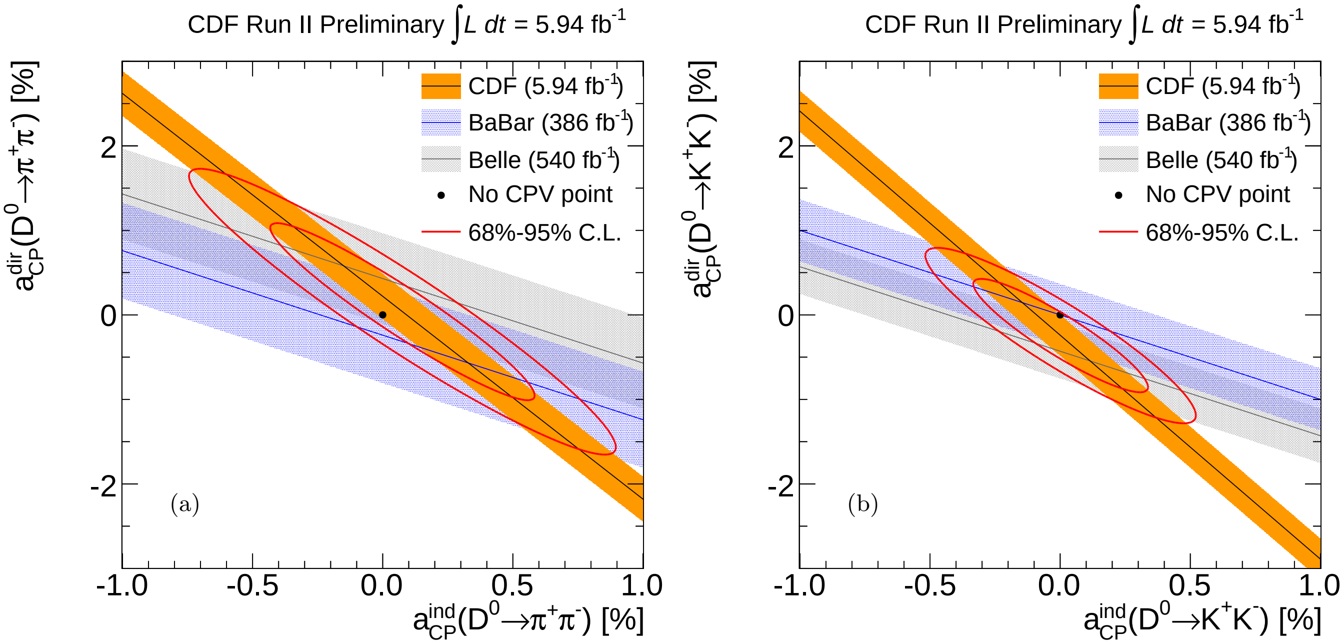

Figure 6: Comparison of our measurements of the CP asymmetry in the $D^0 \to \pi^+\pi^-$ (a) and $D^0 \to K^+K^-$ (b) decays with current best results from B-factories in the parameter space $(a_{\rm CP}^{\rm ind}, a_{\rm CP}^{\rm dir})$.

Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

---

[1] A. Lenz and M. Bobrowski, "Standard Model Predictions for D^0-Oscillations and CP-Violation", talk at the 4th International Workshop on Charm Physics, Beijing (China), 21-24 Oct 2010 [arXiv:1011.5608]; D.-S. Du, "CP Violation for Neutral Charmed Meson Decays into CP Eigenstates", *Eur. Phys. J.* **C 50** (2007) 579; Y. Grossman, A. Kagan and Y. Nir, "New Physics and CP Violation in Singly Cabibbo Suppressed D Decays", *Phys. Rev.* **D 75** (2006) 036008; I. I. Y. Bigi, "Could Charm 'Third-time' Be the Real Charm? A Manifesto", [arXiv:0902.3048]; S. Bianco et al. "A Cicerone for the Physics of Charm", Riv. Nuovo Cim. 26 N7, 1 (2003); Z.-Z. Xing,"$D^0 - \overline{D}^0$ Mixing and CP Violation in Neutral D-Meson Decays", *Phys. Rev.* **D 55** (1997) 196.

[2] CDF Collaboration, "Measurement of the J/ψ meson and b-hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV", *Phys. Rev.* **D 71** (2005) 032001.

[3] CDF Collaboration, "Measurement of Partial Widths and Search for Direct CP Violation in D^0 Meson Decays to K^+K^- and $\pi^+\pi^-$", *Phys. Rev. Lett.* **94** (2005) 122001.

[4] BaBar Collaboration, "Search for CP violation in the decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$", *Phys. Rev. Lett.* **100** (2008) 061803; Belle Collaboration, "Measurement of CP asymmetry in Cabibbo suppressed D^0 decays", *Phys. Lett.* **B 670** (2008) 190.

[5] "Raw" are the observed asymmetries in signal yields,

$$A_{\rm CP}^{\rm raw}(D^0 \to f) = \frac{N_{\rm obs}(D^0 \to f) - N_{\rm obs}(\overline{D}^0 \to \bar{f})}{N_{\rm obs}(D^0 \to f) + N_{\rm obs}(\overline{D}^0 \to \bar{f})},$$

before any correction for instrumental effects has been applied.

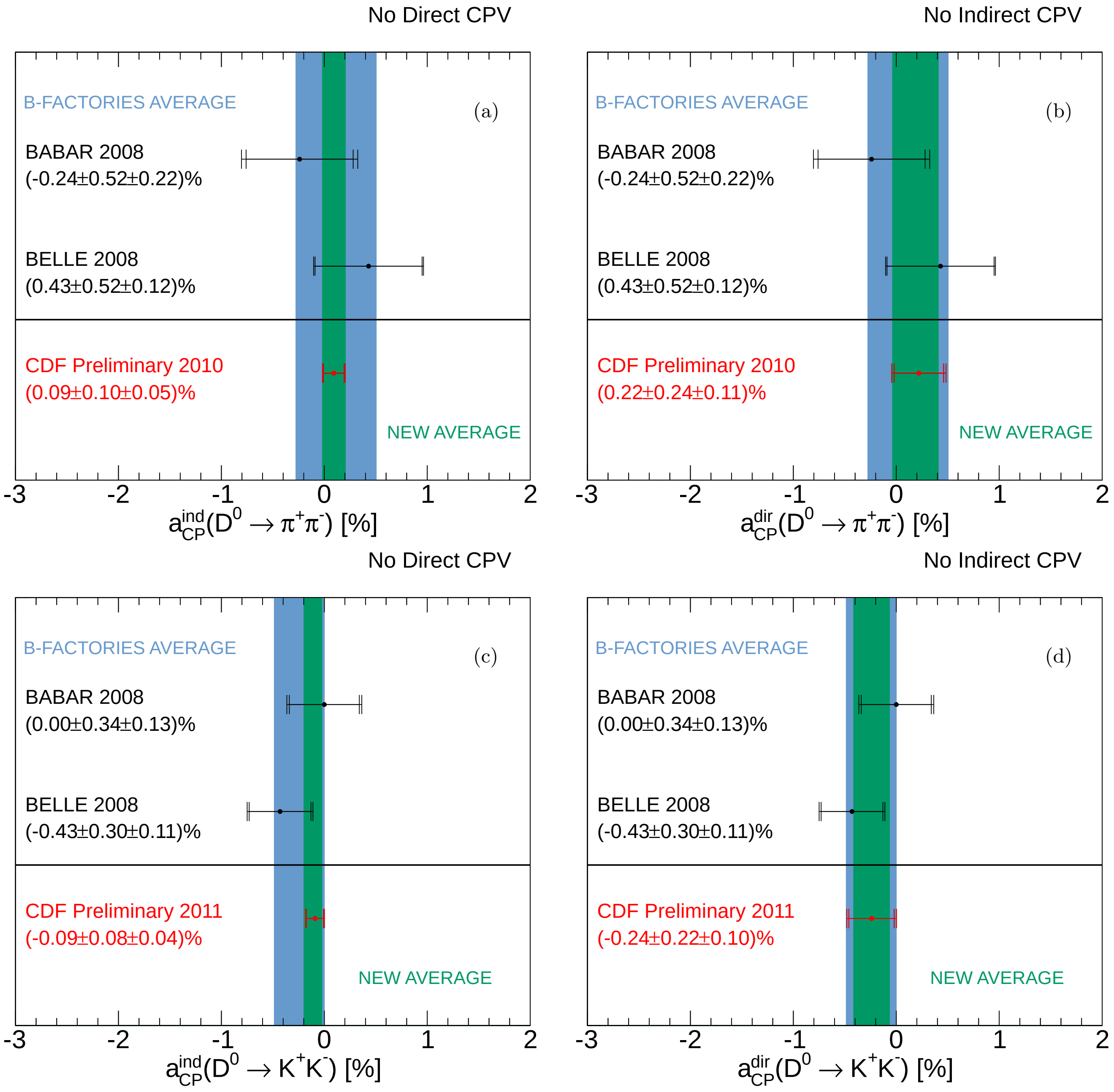

Figure 7: Comparison of our measurements with B-factories experiments assuming no direct (a)-(c) or indirect (b)-(d) CP violation. In each plot the 1σ band of the average between B-factories measurements is represented in blue, while in green we report the new average computed including also these preliminary results.