Conclusions from CDF Results on CP Violation in $D^0 \rightarrow \pi^+\pi^-$, $K^+K^-$ and Future Tasks

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Abstract

Within the Standard Model (SM) one predicts both direct and indirect CP violation in $D^0 \rightarrow \pi^+\pi^-$, $K^+K^-$ transitions, although the effects are tiny: Indirect CP asymmetry cannot exceed $\mathcal{O}(10^{-4})$, probably even $\mathcal{O}(10^{-5})$; direct effects are estimated at not larger than $10^{-4}$. At B factories direct and indirect asymmetries have been studied with $\langle t \rangle/\tau_{D^0} \approx 1$; no CP asymmetry was found with an upper bound of about 1%. CDF has shown intriguing data on CP violation in $D^0 \rightarrow \pi^+\pi^- [K^+K^-]$ with $\langle t \rangle/\tau_{D^0} \approx 2.4$. Also, CDF has not seen any CP violation. For direct CP asymmetry, CDF has a sensitivity similar to the combination of the B factories, yet for indirect CP violation it yields a significantly smaller sensitivity of $a_{\text{CP}}^{\text{ind}} = (-0.01 \pm 0.06_{\text{stat}} \pm 0.05_{\text{syst}})\%$ due to it being based on longer decay times. New Physics models (NP) like Little Higgs Models with T-Parity (LHT) can produce an indirect CP asymmetry up to 1%; CDF’s findings thus cover the upper range of realistic NP predictions $\sim 0.1 - 1\%$. One hopes that LHCb and a Super-Flavour Factory will probe the lower range down to $\sim 0.01\%$. Such non-ad-hoc NP like LHT cannot enhance direct CP violation significantly over the SM level in $D^0 \rightarrow \pi^+\pi^-$, $K^+K^-$ and $D^\pm \rightarrow \pi^\pm K^+K^-$ transitions, but others might well do so.
1 Introduction

The existence of hadrons with charm as a strong stable quantum number was predicted by some courageous theorists to keep the analogy between quark and lepton families, reproduce the observed suppression of strangeness changing neutral currents and even save the renormalization of the Standard Model (SM). They also fell in the expected mass range and showed the predicted preference for decaying to strange hadrons with non-strange hadrons being suppressed by $\sim \sin\theta_C$. At that time most of the community saw little hope of finding manifestations of New Physics (NP) in charm transitions. Only a few physicists have advocated the search of NP in charm decays despite these successes of the SM, mainly because SM weak phenomenology is so ‘dull’ with very slow $D^0 - \bar{D}^0$ oscillation, little CP violation and with rare decays dominated by Long Distance (LD) dynamics.

Some possible hints of New Physics (NP) have appeared in charm physics. Compelling evidence for $D^0 - \bar{D}^0$ oscillations has been presented by Belle, BaBar and CDF [1]. The HFAG has combined the results allowing for CP violation [2]:

$$x_D = \frac{\Delta M_D}{\Gamma_D} = (0.63^{+0.19}_{-0.20})\% \quad , \quad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D} = (0.75 \pm 0.12)\% \quad (1)$$

$$\left| \frac{q}{p} \right| = 0.91^{+0.18}_{-0.16} \quad , \quad \phi = (-10.2^{+9.4}_{-8.9})^\circ \quad (2)$$

Oscillations happen if $x_D \neq 0$ and/or $y_D \neq 0$; indirect CP violation needs oscillations with $|q/p| \neq 1$ and/or $\phi \neq 0$.

The observation of $D^0 - \bar{D}^0$ oscillations seems established, while the relative size of $x_D$ and $y_D$ is not clear yet. Before these experimental results in 2007, most authors had argued that the SM predicts $x_D, y_D \leq 10^{-4}$ — yet not all. In 1998, $x_D, y_D \leq 10^{-2}$ was listed, admittedly as a conservative SM bound [3], together with a question: How can one rule out that the SM can not produce $10^{-6} \leq r_D \leq 10^{-4}$ (corresponding to $x_D, y_D \sim 10^{-3} - 10^{-2}$). In 2000 and 2003, an SM prediction obtained from an operator product expansion (OPE) yielded $x_D, y_D \sim \mathcal{O}(10^{-3})$ [4]; later a more sophisticated OPE analysis was done with similar results [5]. Alternatively in 2001 and 2004, an SM prediction on $D^0 - \bar{D}^0$ oscillations was based on $SU(3)$ breaking mostly in the phase space for $y_D$ and then from a dispersion relation for $x_D$ [6].

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1 Up to date results can be found in the HFAG website.
While the present experimental results on \( x_D \) and \( y_D \) can be accommodated within some available theoretical SM estimates — and no non-zero CP asymmetry has been seen yet — the observation of \( D^0 - \bar{D}^0 \) oscillations has ‘wetted’ the appetite on thinking of NP in charm decays. The authors of Refs. [7, 8, 9] suggest that NP could make a noticeable impact on charm decays. In particular in [9] such has been analyzed, if future data confirm that \( x_D \) indeed falls in the range of 0.5% and 1%. While SM long distance dynamics could accommodate a value in that range, it could not be ruled out that NP could contribute half or quarter value of \( x_D \) considering the reasonable theoretical uncertainty in the predictions from long distance dynamics. Yet indirect CP violation in \( D^0 - \bar{D}^0 \) oscillations would provide us a clear signature for the manifestation of NP dynamics.

In neutral \( K \) and \( B_d \) decays CP violation has been observed for more than 45 years: since 1964 and 1999 indirect and direct asymmetries have been established in \( K_L \) transitions, and since 2001 (and later) in \( B_d \) decays. They are (at least mostly) in agreement with SM flavour dynamics. No such asymmetries have been found in up-type — \( u, c \) and \( t \) — quark transitions. CP asymmetries cannot be as large in \( D \) decays as in \( B \) ones, the former cannot be even close to the latter. Yet observable CP violations are less suppressed for SM dynamics for charm than for \( up \) or \( top \) quarks; the same conclusion is likely to hold for charm forces in NP scenarios.

In the next section we sketch SM CP phenomenology for charm and in Sect.3 explain the conclusions from CDF’s data on CP violation in \( D^0 \rightarrow \pi^+\pi^-/K^+K^- \) about restricting the parameter space of viable models of NP in a non-trivial way; in Sect.4 we discuss signals about a class of NP in CP violation, mostly of Little Higgs Models with T-parity, and future tasks before our outlook in Sect.5.

2 CP Violation for \( D \) Decays in SM Dynamics

SM flavour dynamics (with six quarks) create direct and indirect CP violation in \( D \) transitions, but only with a small magnitude. Furthermore the theoretical predictions suffer from sizable uncertainties as discussed below.

There are three portals through which CP violation can enter in observable ways in two- and three-body final states:

1. |\( q \)\| \( p \)|: in ‘wrong-charged’ semi-leptonic decays of neutral \( D \) mesons, \( D^0 - \bar{D}^0 \) oscillations are the only source in the SM. One finds a time independent asymmetry

\[
A_{SL}^{CP}(D^0 \rightarrow l^−X) = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} . \tag{3}
\]

The rate into wrong-charged leptons is time-dependent and tiny since it is given by \((x_D^2 + y_D^2)/2\) irrespective of what dynamics generate \( x_D \) and \( y_D \). Within the SM this manifestation of indirect CP violation is also tiny:

\[
A_{SL}^{CP}(D^0 \rightarrow l^-X)|_{SM} = \mathcal{O}(10^{-3}) . \tag{4}
\]

2. Direct CP asymmetries in non-leptonic decays can surface in \( \Gamma(D \rightarrow f) \neq \Gamma(\bar{D} \rightarrow \bar{f}) \) in a time-independent way for different final states.

3. ‘Tertium datur’: there is a third portal in non-leptonic \( D^0 \) decays where CP violation can occur as given by

\[
\text{Im} \left( \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow \bar{f})} \right) \cdot \sin \Delta M_D t
\]

where for simplicity \( f \) is assumed to be a CP eigenstate. CP violation affects \( q/p \) in \( \Delta C = 2 \) dynamics and \( T(\bar{D}^0 \rightarrow \bar{f})/T(D^0 \rightarrow f) \) in \( \Delta C = 1 \) forces; the latter will create a difference between different final states like for \( \pi^+\pi^- \) vs. \( K^+K^- \).

As discussed below these three classes are not zero in the SM, but tiny and suffer large theoretical and experimental uncertainties in SM predictions.
2.1 SM Indirect CP Violation in Non-leptonic Charm Decays

Indirect CP effects for \( D^0 \) in non-leptonic decays can have time-dependence due to oscillations parametrized by \( x_D = \Delta M_D / \Gamma_{D^0} \) and \( y_D = \Delta \Gamma_{D^0} / 2 \Gamma_{D^0} \); the indirect CP violating parameter can be approximated by implementing \( x_D, y_D \ll 1 \) applied to the leading \( D^0 \rightarrow K_S \phi \), where direct CP violation is very unlikely:

\[
a^{\text{ind}}_{NL}(D^0 \rightarrow K_S \phi; t) = \frac{\Gamma(D^0 \rightarrow K_S \phi; t) - \Gamma(D^0 \rightarrow K_S \phi; t)}{\Gamma(D^0 \rightarrow K_S \phi; t) + \Gamma(D^0 \rightarrow K_S \phi; t)} \approx \frac{t}{\tau_{D^0}} \left[ y_D \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) \cos 2\phi - x_D \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \sin 2\phi \right]; \tag{5}\]

\( y_D \) and \( x_D \) could be as \('large\)' as 0.01 - but also close to 0.005 or less, in particular for one of the two. The theoretical SM estimates for \( x_D \) and \( y_D \) are hardly more than guesses and the theoretical uncertainties there are even larger than the experimental ones, since the SM predictions depend strongly on our theoretical treatment of LD dynamics for \( x_D \) and \( y_D \) (or its lack thereof) and our treatment of the extraction of the CKM phase as it enters charm decays \([4, 9]\):

\[
\sin 2\phi \sim 10^{-3} \tag{6}\]

\[
a^{\text{ind}}_{NL}(t)|_{\text{SM}} \leq \text{several} \cdot 10^{-5} \cdot \frac{t}{\tau_{D^0}}, \tag{7}\]

where the oscillation’s strength expressed through \( y_D \) and \( x_D \) — or its weakness — has been incorporated in this number. It depends sensitively on non-perturbative parameters \([4]\) that are somewhat larger than one would assume if not suggested by experimental values for \( x_D \) and \( y_D \). For later discussion we mention that at the same time NP could naturally create a value for \( x_D \approx 0.01 \), yet \( y_D \) would be unlikely to be sensitive to NP. Using the experimental values of \( |q_D / p_D| \) and \( \phi \) stated in Eq.(2) one gets

\[
|a^{\text{ind}}_{NL}(t)|_{\text{exp}} \leq 1\%. \tag{8}\]

2.2 On Time Evolution with Indirect CP Asymmetries

As expressed in Eq.(5) one calculates the difference over the sum of partial rates. However one measures the BR\((D^0 \rightarrow f)\) vs. BR\((\bar{D}^0 \rightarrow f)\); i.e., \( \Gamma(D^0 \rightarrow f) / \Gamma_{D^0} \) vs. \( \Gamma(\bar{D}^0 \rightarrow f) / \Gamma_{\bar{D}^0} \). If oscillation happens to have \( \Delta M_D \neq 0 \), yet \( \Delta \Gamma_D = 0 \), there is only one time scale, namely given by \( \Gamma_D = \Gamma_{D^0} \). However in the general case one has \( \Delta \Gamma_D \neq 0 \). Therefore the two mass eigenstates have two different lifetimes, and the two flavour eigenstates \( D^0 \) and \( \bar{D}^0 \) represent different combinations of \( D_1 \) and \( D_2 \):

\[
\Gamma(D^0(t) \rightarrow f) \propto \frac{1}{2} \cdot |T(D^0 \rightarrow f)|^2 \cdot G_f(t),
\]

\[
G_f(t) = Ae^{-\Gamma t} + Be^{-\Gamma_2 t} + (C \cos \Delta \Gamma t + D \sin \Delta \Gamma t) e^{-\Gamma t}, \tag{9}\]

\[
\Gamma(\bar{D}^0(t) \rightarrow f) \propto \frac{1}{2} \cdot |T(\bar{D}^0 \rightarrow f)|^2 \cdot \bar{G}_f(t),
\]

\[
\bar{G}_f(t) = \bar{A}e^{-\Gamma_1 t} + Be^{-\Gamma_2 t} + (\bar{C} \cos \Delta \Gamma t + \bar{D} \sin \Delta \Gamma t) e^{-\Gamma t}, \tag{10}\]

with \( \Gamma = (\Gamma_1 + \Gamma_2)/2 \). The general expressions are given by

\[
A = \frac{1}{2} \left( 1 + \left| \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right|^2 \right) + \text{Re} \left( \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right), \tag{11}\]

\[
B = \frac{1}{2} \left( 1 + \left| \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right|^2 \right) - \text{Re} \left( \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right), \tag{12}\]

\[
C = 1 - \left| \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right|^2, \quad D = -2\text{Im} \left( \frac{q}{p} \frac{T(D^0 \rightarrow f)}{T(\bar{D}^0 \rightarrow f)} \right), \tag{13}\]
\[
\begin{align*}
\bar{A} &= \frac{1}{2} \left( 1 + \left| \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right|^2 \right) + \Re \left( \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right) \\
\bar{B} &= \frac{1}{2} \left( 1 + \left| \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right|^2 \right) - \Re \left( \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right) \\
\bar{C} &= 1 - \left| \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right|^2, \quad \bar{D} = -2 \text{Im} \left( \frac{p}{q} \frac{T(D^0 \to f)}{T(D^0 \to f)} \right)
\end{align*}
\]
With this we find through first order in $y_D$, $x_D$:

$$R = \frac{\Gamma_{\text{calib}}(D^0 \rightarrow f) - \Gamma_{\text{calib}}(\bar{D}^0 \rightarrow f)}{\Gamma_{\text{calib}}(D^0 \rightarrow f) + \Gamma_{\text{calib}}(\bar{D}^0 \rightarrow f)} = \frac{e^{\tilde{\Phi} t} \left( G_f(t) - \bar{G}_f(t) \right)}{e^{\tilde{\Phi} t} \left( G_f(t) + \bar{G}_f(t) \right)} + O(y_D^2)$$

(28)

with

$$e^{\tilde{\Phi} t} G_f(t) = 2\tilde{\Gamma} t \left( 1 - y_D \left[ \frac{q}{p} \cos 2\tilde{\phi} - x_D \frac{q}{p} \sin 2\tilde{\phi} \right] \right)$$

(29)

$$e^{\tilde{\Phi} t} \bar{G}_f(t) = 2\tilde{\Gamma} t \left( 1 - y_D \left[ \frac{p}{q} \cos 2\tilde{\phi} + x_D \frac{p}{q} \sin 2\tilde{\phi} \right] \right);$$

(30)

thus

$$R \simeq -\tilde{\Gamma} t \left[ y_D \cos 2\tilde{\phi} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) + x_D \sin 2\tilde{\phi} \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) \right].$$

(31)

If $D^0 - \bar{D}^0$ oscillations show $y_D$ to be measurable, one has two different lifetimes of the two mass eigenstates $D_1$ and $D_2$. Yet for $y_D \ll 1$, the ansatz used by CDF applies for indirect CP asymmetries in non-leptonic transitions holds to first order in $y_D$:

$$A_{\text{indir., CPV}} \simeq \frac{\langle t \rangle}{\tilde{\tau}} a_{\text{indir., CPV}} = \langle t \rangle \frac{(\Gamma_1 + \Gamma_2)}{2} a_{\text{indir., CPV}}$$

(32)

The same conclusions hold when direct CP violation can surface in $D^0 \rightarrow \pi^+\pi^-, K^+K^-$.

### 2.3 Direct CP Violation

Purely direct CP asymmetries need two amplitudes $A_{1,2}$ with non-zero weak phase $\Delta \phi$ and strong phases $\Delta \alpha$; thus they exhibit direct time-independent asymmetries:

$$a_{D \rightarrow f}^{\text{dir}} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = \frac{-2|A_1||A_2| \sin \Delta \alpha \times \sin \Delta \phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos \Delta \alpha \times \cos \Delta \phi}$$

(33)

The strong phases $\Delta \alpha$ mostly come from LD dynamics as do a large part of the two $|A_{1,2}|$, of which we do not have good quantitative theoretical control. There is a large uncertainty already within the SM.

Nevertheless Cabibbo-suppressed non-leptonic decays of charm mesons $D \rightarrow f$ contain the needed ingredients, namely two amplitudes with different weak and in general strong phases. Fortunately for $D^0 \rightarrow \pi^+\pi^-$ decays they can be obtained from other measurements, namely comparing branching ratios of $D^0 \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ and $D^0 \rightarrow \pi^+\pi^0$.

Such direct CP asymmetries have been quoted in the literature as SM predictions for Cabibbo suppressed non-leptonic $D$ decays of about $10^{-4}$ or less for the final state $\pi^+\pi^-$:

$$a_{D^0 \rightarrow \pi^+\pi^-; \text{SM}} \leq 10^{-4}.$$  

(34)

Our current calculations confirm this and we can reproduce numbers very close to the upper limit mentioned above. For direct charm asymmetries it can occur in the form of Penguin diagrams like for $B$ transitions. For $B$ decays they are well defined, since the leading contribution — like for $b \rightarrow tW \rightarrow d$ — is given by a local operator because $m_t \gg m_b$. Yet for charm decays the leading diagram for $c \rightarrow sW \rightarrow u$ looks like a Penguin graph, but does not represent a local operator, since $m_s < m_c$. Therefore one has to allow for even larger uncertainties than usual. Therefore we want to address explicitly the uncertainties in the SM predictions.

#### 2.3.1 Revisiting Direct CP Asymmetries in $D \rightarrow hh$ within the SM

SM contributions to direct CP asymmetries in $D \rightarrow hh$ come primarily from the tree level current-current and gluonic penguins operators. The latter, even though loop suppressed, get enhanced in the matrix elements due to a factor of $\sim m_s^2/m_b^2$ for $D^0 \rightarrow \pi^+\pi^-$; it is smaller in $D^0 \rightarrow K^+K^-$. The ansatz applied to
\( B \to \pi K, \pi \pi \) decays [10] has been extended to Cabibbo-suppressed \( D \) decays in Ref.[11]. These calculations of amplitudes include current-current, the gluonic penguin and the electric dipole operators. In our preparation to include LHT contributions in \( D \to hh \), we had to take this calculation a step further. The reasons for our labour will be evident when we discuss LHT contributions to \( a_{FP}^{D_0} \) in Sect.4.2. The details of this calculation shall not be discussed in this paper, but will be elucidated on in a future work. We shall only list the salient features of this calculation here. One has to keep in mind that non-perturbative effects are much less under theoretical control in \( D \to hh \) than for \( B \to hh \).

- We include twelve \( \Delta C = 1 \) operators pertinent to the process: two current-current, four gluon penguins, four electroweak penguins, an electric dipole and a chromomagnetic dipole operator.
- All calculations are done in next-to-leading order in \( \alpha_s \).
- A renormalization scale of \( \mu = 1 \) GeV was chosen.
- Only a limited set of hadronic non-perturbative parameters have been included which are necessary for inclusion of all the operators mentioned above.
- Both hard gluon exchange contributions involving spectator quarks and weak annihilation contribution have been ignored.

The SM predictions of \( D \to hh \) decay rates reach within about a factor of two of the experimental values; this is about as much as one can expect considering the theoretical uncertainties.

3 CDF’s CP Searches in \( D^0 \) Decays

The two factories at Belle and BaBar have established \( D^0 - \bar{D}^0 \) oscillations and have searched data for direct and indirect CP asymmetries; no positive signals have been found for \( \langle t \rangle \simeq \tau_{D^0} \) in \( D^0 \to \pi \pi^- \), \( K^+ K^- \) averaged by Belle/BaBar:

\[
\langle A_{\text{CP}}^{\text{BF}}(D^0 \to \pi^+ \pi^-) \rangle = a_{\text{CP}}^{\text{ind}} + a_{\text{CP}}^{\text{dir}} = (+0.11 \pm 0.39)\% \quad (35)
\]

\[
\langle A_{\text{CP}}^{\text{BF}}(D^0 \to K^+ K^-) \rangle = a_{\text{CP}}^{\text{ind}} + a_{\text{CP}}^{\text{dir}} = (-0.24 \pm 0.24)\% . \quad (36)
\]

CDF has now shown data on CP asymmetry in \( D^0 \to \pi^+ \pi^- , K^+ K^- \) [12]:

\[
\langle A_{\text{CP}}^{\text{CDF}}(D^0 \to \pi^+ \pi^-) \rangle = (+0.22 \pm 0.24_{\text{stat}} \pm 0.11_{\text{syst}})\% \quad (37)
\]

\[
\langle A_{\text{CP}}^{\text{CDF}}(D^0 \to K^+ K^-) \rangle = (-0.24 \pm 0.22_{\text{stat}} \pm 0.10_{\text{syst}})\% . \quad (38)
\]

CDF’s data has exhibited an overall similar sensitivity as the average of the two \( B \) factories. It shows that neither Belle/BaBar nor CDF data have the sensitivity to get even close to the level of the SM predictions around \( 10^{-4} \) or less for direct and indirect CP violation.

One important feature of CDF’s data is their acceptance for \( D^0 \) decays at significantly larger times than at the \( B \) factories, namely \( \langle t \rangle = (2.40 \pm 0.03)\tau_{D^0} \simeq (2.65 \pm 0.03)\tau_{D^0} \) for \( D^0 \to \pi^+ \pi^- [K^+ K^-] \); therefore

\[
\langle A_{\text{CP}}^{\text{CDF}}(D^0 \to \pi^+ \pi^-) \rangle \simeq a_{\text{CP}}^{\text{dir}}(\pi^+ \pi^-) + 2.40 \times a_{\text{CP}}^{\text{ind}} \quad (39)
\]

\[
\langle A_{\text{CP}}^{\text{CDF}}(D^0 \to K^+ K^-) \rangle \simeq a_{\text{CP}}^{\text{dir}}(K^+ K^-) + 2.65 \times a_{\text{CP}}^{\text{ind}} . \quad (40)
\]

As a moderate input from theory, as explained in Sect.4, NP models can generate a much larger impact on indirect CP violation, but hardly any for a direct CP asymmetry. Assuming \( a_{\text{CP}}^{\text{dir}} = 0 \), CDF finds a much larger sensitivity for indirect CP violation than Belle/BaBar:

\[
a_{\text{CP}}^{\text{ind}}(D^0 \to \pi^+ \pi^-)|_{\text{CDF}} = (+0.09 \pm 0.10_{\text{stat}} \pm 0.05_{\text{syst}})\% \quad (41)
\]

\[
a_{\text{CP}}^{\text{ind}}(D^0 \to K^+ K^-)|_{\text{CDF}} = (-0.09 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}})\% \quad (42)
\]

\[
a_{\text{CP}}^{\text{ind}}(D^0 \to \pi^+ \pi^-/K^+ K^-)|_{\text{CDF}} = (-0.01 \pm 0.06_{\text{stat}} \pm 0.05_{\text{syst}})\% \quad (43)
\]

or

\[
|a_{\text{CP}}^{\text{ind}}(D^0 \to \pi^+ \pi^-/K^+ K^-)|_{\text{CDF}} < 0.14\% \text{ at } 95\% \text{ CL } . \quad (44)
\]

As explained below, the experimental values of \( x_D, y_D, |q/p| \) and \( \phi_D \) tell us that \( |a_{\text{CP}}^{\text{ind}}| \leq 1\% \) at best. Non-ad-hoc NP models can produce such values. Belle and BaBar bounds can barely enter that regime – but CDF bounds can enter the upper part of the regime.
4 CP Violation due to New Physics

Charm dynamics have been viewed as a signature success of the SM going back to its discovery. Yet few authors have seen charm decays as a chance to find NP due to the SM’s dullness in its weak phenomenology. To say it differently: while contributions from NP will not be large or even sizable, they will not have to deal with a ‘background’ from SM’s phenomenology.

NP’s impacts on weak charm dynamics are often discussed in isolation of other flavours and in an ad-hoc model fashion. Instead we want to discuss scenarios that are primarily motivated by the weak-electric phase transition; yet they can have implications for flavour dynamics. More specifically, we consider the Littlest Higgs Models with T-Parity designed to deal with the ‘little hierarchy’ problem: interestingly they do not represent ‘Minimal Flavour Violation’ models in $K$, $B$ and $D$ decays; i.e., one can find non-SM predictions in rare decays and CP asymmetries.

As mentioned before, LHT can have a large impact on $\Delta C = 2$ dynamics which is sketched below. Therefore we have next analyzed LHT’s impact on $\Delta C = 1$ dynamics in $D^0 \rightarrow \gamma\gamma/\mu^+\mu^-$ [13] and $D \rightarrow l^+l^-X$ [14]. The results are that LHT models hardly have any noticeable impact. Significant enhancement over SM contribution can be seen only in forward-backward (FB) asymmetries. However, large $O(10\%)$ asymmetry can only be seen in the CP asymmetry of the FB asymmetry while the pure FB asymmetry is limited to $O(1\%)$ [14].

In the analysis to follow on direct CP violation from NP models like LHT, we continue to use the same parameter set as has been used in the previous works; details can be found in [13, 14]. This parameter set was also used in the earlier analysis of indirect CP violation and $D^0 - \bar{D}^0$ oscillation in [?].

4.1 Indirect CP Violation on $D^0 \rightarrow h^+h^-$ from LHT Models

As shown in Ref.[?], for some regions in parameter space LHT can produce

$$|a_{\text{CP}}^{\text{ind,LHT}}| \leq 1\%$$  \hspace{1cm} (45)

assuming that LHT generates most of the observed $D^0 - \bar{D}^0$ oscillations (otherwise less). In such a scenario one gets $|\sin\phi_{\text{weak},NP}|$ up to unity and therefore a large CP asymmetry in wrong-charge leptons, larger by at least two orders of magnitudes than the SM.

The combination of Belle/BaBar results just enters the regime of Eq.(45). Yet CDF’s data, Eq.(43), establish a very non-trivial upper bound of about 0.2\% from an interesting class of NP models motivated outside of flavour dynamics. LHT-like models [13] could generate a signal for indirect CP violation ‘just around the corner’ for future measurements.

4.2 Direct CP Violation in LHT Models

Like in the SM, direct CP asymmetries in non-leptonic $D$ decays are generated from the interference of the SM tree level diagrams with one-loop diagrams from NP. In the LHT all the one-loop $\Delta C = 1$ diagrams are local operators as the internal states are very heavy — unlike for the SM. However, a closer analysis shows that LHT models cannot produce a larger enhancement to SM direct CP asymmetries unlike for the case of indirect CP violation; it will be evident from the following line of argument. Before plunging into the next few paragraphs, it is recommended for the enthusiastic reader to follow the scaling arguments that have been presented in [14] as that will be vital to our argument.

Firstly, enhancement to direct CP violation over the SM is expected from LHT-like models because of two reasons: (i) the presence of large phases in the new mixing matrices and (ii) presence of heavy mirror quarks which can produce effects akin to what has so commonly been seen due to the existence of top in the SM. However, this has to compete with the breaking scale suppression of $\frac{1}{M} (v^2/f^2)$ that the LHT loop functions will have relative to the SM loop functions, a factor of the $O(10^{-3})$.

In the SM the leading contribution is from the tree level current-current operator and the power enhanced gluon penguins. However, in the LHT the scenario is different. To begin with, due to T parity, there are no tree level contributions. The loop contributions can be divided into three types:
• gluon penguin operators (GPOs);
• electroweak penguin operators (EPOs);
• chromomagnetic and electric dipole penguin operators (CDPs).

The GPOs scale as $\log(x)$. Here $x$ is the square of the ratio between the mass of the internal fermion to the mass of the internal gauge boson that exist as virtual states in the loop. In the SM $x \sim O(10^{-7} - 10^{-2})$. In the LHT $x \sim O(1)$. Hence from both SM and LHT GPOs receive the same contribution from loop functions. However, the LHT functions are suppressed by breaking scale as noted before. This results in very tiny contributions to the GPOs from LHT.

For the EPOs, the loop functions scale as $x$ or $x \log(x)$. Hence, EPOs receive much larger enhancement from LHT than GPOs. Despite the fact that EPOs come with a relatively smaller coupling of $\alpha$ compared to the $\alpha_s$ present in the GPOs, the huge enhancement due to the loop functions compensate for this. However at this point the unitarity of the mixing matrices also becomes important. Since the masses of the mirror quarks are not too hierarchical, the suppression from the unitarity of the mass mixing matrix is significant. It results in a comparable, but not significantly larger enhancement to either the SM decay rate or the CP violating parameter. Of course, the CP violating parameter sees more enhancement than the decay rate as it probes the phases in the new mixing matrices which are large.

The CDPs also scale as $x$ but asymptotically reach a constant value for large $x$. They do show the possibility of getting large contributions from the LHT flavour sector. However, CDPs are both $\alpha_s/4\pi$ (or $\alpha/4\pi$) and colour suppressed. Hence contributions from them are not very significant.

All of this is quite contrary to what is seen in the SM and hence it is very easy to overlook the EPO contribution from NP. However, in any NP scenario which limits the presence of tree level processes, large enhancements of direct CP violation are not possible. We see at most an enhancement factor of two to $a_{\text{CP}}^{\text{dir}}$ for the unconstrained set and $O(10\%)$ enhancement for the constrained set as seen in fig. 1 for $D^0 \to \pi^+\pi^-$ and somewhat less for $D^0 \to K^+K^-$.\footnote{cf \cite{13, 14} for details of the parameter sets.}

One can understand with little work that NP cannot generate a large enhancement in direct CP asymmetries as it might happen for indirect CP violation. However some theorists have allowed sizable CP asymmetries like one of authors of this paper. Yet a class of NP models of which LHT models are a prominent example shows no sizable enhancements. However, this close-to-zero result is due to several subtle features of NP models and the impact of QCD radiative corrections. One of the authors of this paper, in spite of being pleased with the knowledge gained, might despair that the absence of any sizable effect might make his work a waste of efforts on his side. Yet the other two authors (not having spent a lot of time on those tough calculations) consider even a zero result relevant for theory, if it implies subtle arguments like the scaling of NP contributions and the impact of QCD radiative corrections.
4.3 Future Tasks
Asymmetries from indirect CP violation have to be the same in $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ (and $D^0 \rightarrow K_{S0}$). If those asymmetries are different, they need a source for direct CP violation in $\Delta C = 1$ processes — and LHT-like models would become unlikely candidates for NP.

5 Summary
The existence of charm and the features of its dynamics have been seen — correctly so — as a great success of our understanding of the SM. Nevertheless we should probe weak charm decays for manifestations of NP — in particular in studies of CP violation in different areas. The SM generates small (although non-zero) asymmetries in wrong-charge semi-leptonic and in non-leptonic transitions, while NP models can produce much more sizable asymmetries than the SM. They are large relative to the SM effect, but not in absolute size; therefore the data have only now achieved the necessary sensitivities.

The case of whether the SM can produce the observed values for $x_D$ (and $y_D$) or whether NP is needed, has not been decided due to theoretical and experimental uncertainties. However the previous data on indirect CP violation in $D^0$ transitions had hardly entered the regime where non-ad-hoc NP models like LHT can generate observed effects. The CDF data implies a very non-trivial bound of 0.14 % (at 95% CL) for $|a_{CP}^{\text{ind}}(D^0 \rightarrow hh)|$. It also means that a manifestation of NP might be ‘around the corner’ for future data.

The pessimism about direct CP asymmetries derived from LHT-like NP models does not mean that searches for direct CP violation in $D$ decays are useless. Experimentalists should get the theorists’ betting line, which can reduce the number of possible culprits — but then probe CP invariance in $D \rightarrow 3h, 4h$.

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