Relating Direct CP Violation in D Decays and the Forward-Backward Asymmetry in $t\bar{t}$ Production

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The CDF and LHCb experiments have recently provided two intriguing hints for new physics: a large forward-backward asymmetry in $t\bar{t}$ production and a direct CP asymmetry in D decays of order of a percent. In both cases, flavor nonuniversal interactions are required in the up sector, raising the possibility that the two effects come from one and the same new physics source. We show that a minimal model, with an extra scalar doublet, previously suggested to explain the top data, gives—without any modifications or additions—a contribution to CP violation in charm decays that is of the right size.

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Introduction to ΔA_{CP}.—The Large Hadron Collider beauty (LHCb) experiment has announced evidence for direct CP violation in singly Cabibbo-suppressed D decays [1],

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11) \times 10^{-2}. \quad (1)$$

The updated world average for this asymmetry is [2] $\Delta A_{CP} = (-0.65 \pm 0.18) \times 10^{-2}$, which is more than 3.5σ away from zero. Here,

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}. \quad (2)$$

In ΔA_{CP}, that is the difference between asymmetries, effects of indirect CP violation cancel out [3]. (Due to different decay time acceptances between the K^+K^- and $\pi^+\pi^-$ modes, a small residual effect of indirect CP violation remains.) Thus, ΔA_{CP} is a manifestation of CP violation in decay.

The standard model (SM) contribution to the individual asymmetries is CKM (Cabibbo-Kobayashi-Maskawa)-suppressed by a factor of

$$I_{\rm CKM} \equiv 2\,{\rm Im}\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) \approx 1.2 \times 10^{-3} \quad (3)$$

and loop-suppressed by a factor of order $\alpha_s(m_c)/\pi \sim 0.1$. (For the numerical estimate of Eq. (3) we use [4] $|V_{cb}| = 0.041$, $|V_{ub}| = 0.0035$, $|V_{us}| = 0.23$, $|V_{cs}| = 0.97$, and $\sin\gamma = 0.93$.) While perhaps one cannot exclude an enhancement factor of order 30 from hadronic physics [5–13], in which case (1) will be accounted for by SM physics, this situation seems unlikely. It is thus interesting to find new physics that can contribute to ΔA_{CP} a factor of order 10 higher than the SM [2,3,14].

Introduction to $A_{\rm FB}^{t\bar{t}}$.—The Collider Detector at Fermilab (CDF) Collaboration has announced evidence for a large forward-backward $t\bar{t}$ production asymmetry for large invariant mass of the $t\bar{t}$ system [15]

$$A_h^{t\bar{t}} \equiv A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} \geq 450~{\rm GeV}) = +0.475 \pm 0.114, \quad (4)$$

to be compared with the SM prediction [16–18], $(A_h^{t\bar{t}})_{\rm SM} = +0.09 \pm 0.01$. Equation (4) updates (and is consistent with) previous CDF and D0 measurements of the inclusive asymmetry [19,20].

The source of the asymmetry must be in the quark process $u\bar{u} \to t\bar{t}$. The large effect is suggestive of interference between a tree-level exchange of a new boson with an electroweak-scale mass and the SM gluon-mediated amplitude (see Ref. [21] and references therein). Moreover, the couplings of the intermediate boson cannot be flavor universal.

It is interesting to note that both ΔA_{CP} and $A_{\rm FB}^{t\bar{t}}$ are related to flavor physics in the up sector. Could the two measurements be related to each other? In this Letter, we show that a mechanism previously studied to explain $A_{\rm FB}^{t\bar{t}}$ [22] *predicts* a new physics contribution to ΔA_{CP} that is quantitatively of the right size, namely, a factor of $\mathcal{O}(10–100)$ above the SM.

Scalar-mediated $A_{\rm FB}^{t\bar{t}}$.—In Ref. [22], we investigated (in collaboration with K. Blum) whether the large value reported by CDF for $A_{\rm FB}^{t\bar{t}}$ at large invariant mass $M_{t\bar{t}}$ can be accounted for by tree-level scalar exchange. We considered top-related measurements, flavor constraints, and electroweak precision measurements. We reached the following conclusions. Out of the eight possible scalar representations that are relevant to $A_{\rm FB}^{t\bar{t}}$, only the color-singlet weak-doublet

$$\Phi \sim (1,2)_{-1/2} = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \quad (5)$$

can enhance $A_h^{t\bar{t}}$ and remain consistent with the low bin $t\bar{t}$ asymmetry and the total and differential $t\bar{t}$ cross section. Roughly speaking, the relevant Yukawa coupling should be $\mathcal{O}(1)$, and the mass of the scalar should be below $\sim$130 GeV. (See also Refs. [23–26].) Two types of couplings of Φ can contribute to $u\bar{u} \to t\bar{t}$: (1) $X_{13}q_{L1}^\dagger \Phi t_R$ and

(2) $X_{31} q_{L3}^{\dagger} \Phi u_R$. There is no tension with the differential or total $t\bar{t}$ production cross section. Both couplings are constrained by flavor physics: (1) The X_{13} coupling is strongly constrained by $K^0 - \bar{K}^0$ and/or $D^0 - \bar{D}^0$ mixing and so cannot generate a large $A_h^{t\bar{t}}$. (2) The X_{31} coupling is not strongly constrained by neutral meson mixing or by R_b. If ϕ^- couples to the three left-handed down generations with CKM-like suppression $\mathcal{O}(V_{tq})$, then it contributes to the branching ratio of $\bar{B}^0 \to \pi^+ K^-$ more than 2 orders of magnitude above the experimental bounds. If, on the other hand, the X_{31} coupling is carefully aligned so that ϕ^- couples only to b_L (but not to s_L and d_L), then it can be large enough to explain $A_h^{t\bar{t}}$. Thus, the relevant Lagrangian terms for the new weak doublet field are given in the quark mass basis as follows [22]:

$$\mathcal{L}_{\Phi} = -V(\Phi) + 2\lambda[\phi^0 \bar{U}_{Li} V_{ib} u_R + \phi^- \bar{b}_L u_R + \text{H.c.}], \tag{6}$$

where $(U_L)_{1,2,3} = u_L, c_L, t_L$. Equation (6) assumes that the coupling $\lambda \Phi \bar{Q}_{L3} u_R$ is defined in the weak basis where the down-type Yukawa matrix is diagonal. The $\lambda V_{tb} \phi^0 \bar{t}_L u_R$ coupling accounts for the forward-backward asymmetry in $t\bar{t}$ production, with

$$|\lambda| \gtrsim 0.6, \qquad M_{\Phi} \lesssim 130 \text{ GeV}. \tag{7}$$

(For further details, see Ref. [22].)

Scalar-mediated ΔA_{CP}.—In addition to the coupling to $\bar{t}_L u_R$, the neutral scalar ϕ^0 couples u_R to the lighter two up-type quarks: $\lambda V_{cb} \phi^0 \bar{c}_L u_R + \lambda V_{ub} \phi^0 \bar{u}_L u_R$. Integrating out the ϕ^0 field, these couplings lead to the following effective four-quark coupling:

$$\frac{4|\lambda|^2}{m_{\phi^0}^2} V_{ub} V_{cb}^* (\bar{u}_R c_L)(\bar{u}_L u_R). \tag{8}$$

This operator contributes, via annihilation diagram ($c\bar{u} \to u\bar{u}$), to both $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$ decays. In the U-spin symmetry limit, the resulting asymmetries in the two modes are equal in magnitude and opposite in sign.

Thus, the expected size of ΔA_{CP} from the interference between the new physics (8) amplitude and the SM W-mediated tree amplitude is

$$\Delta A_{CP} = 2\sqrt{2}(G_0/G_F) I_{\text{CKM}} I_{\text{QCD}} \sim (2\text{–}7) \times 10^{-2} I_{\text{QCD}}. \tag{9}$$

The various factors in this equations are the following: The factor of 2 comes from the opposite sign asymmetries in the U-spin limit. G_0 is defined as $G_0 \equiv 4|\lambda|^2/m_{\phi^0}^2$. Equation (7) implies that $G_0/(G_F/\sqrt{2}) \sim 10\text{–}30$. I_{CKM} is the CKM suppression factor defined in Eq. (3). Its value is known to a good approximation, including the CP violating phase. I_{QCD} includes all the hadronic aspects of the decay: ratio of matrix elements, the price for annihilation (if any), U-spin violation, and the strong phase. Thus on one hand, all the electroweak parameters are well-known, but on the other hand, the hadronic physics introduces an order of magnitude uncertainty and further prevents us from predicting the sign of ΔA_{CP}.

Compared to the SM, the scalar contribution is tree level, and a loop suppression, naively of order $\alpha_s(m_c)/\pi \sim 0.1$, is avoided. Moreover, the contribution is enhanced by the requirement that $G_0 \gg G_F$ (to account for $A_{\text{FB}}^{t\bar{t}}$). It involves, however, annihilation, which introduces a suppression factor that is naively of order $f_D/m_D \sim 0.1$. The authors of Ref. [6] argue, on the basis of experimental data, that tree-level annihilation amplitudes are large and do not suffer $1/m_c$ suppression. In any case, it is plausible that hadronic physics, e.g., the strong phase, provides the mild suppression $I_{\text{QCD}} \sim 0.1\text{–}0.3$ that is necessary to make the theoretical prediction (9) consistent with the experimental result (1).

We conclude that our model predicts ΔA_{CP} of order of a percent.

Scalar-mediated ϵ'/ϵ.—The same Yukawa couplings of ϕ^0 that unavoidably contribute to direct CP violation in D decays also unavoidably contribute to direct CP violation in K decays. The former effect comes at tree level and modifies ΔA_{CP}. The latter effect comes via a box diagram, involving ϕ^0 and a W boson and modifies ϵ'/ϵ. This type of relation was pointed out in Ref. [2]. Their analysis cannot, however, be directly applied to our model, since it makes use of an effective Lagrangian with a scale of new physics that is similar to or higher than 1 TeV. Instead, we carried out a full calculation of the relevant box diagram.

We find that the couplings of Eq. (6) lead to the following effective four-quark coupling:

$$\frac{\sqrt{2}|\lambda|^2 G_F}{\pi^2} \frac{\ln x_{\phi}}{1 - x_{\phi}} V_{ud}^* V_{cs} V_{ub} V_{cb}^* (\bar{d}_L u_R)(\bar{u}_R s_L), \tag{10}$$

where $x_{\phi} \equiv m_{\phi^0}^2/m_W^2$. To estimate the contribution of this operator to ϵ'/ϵ, we use

$$\text{Re}\left(\frac{\epsilon'}{\epsilon}\right) = -\frac{\omega}{\sqrt{2}|\epsilon| \text{Re}A_0}\left(\text{Im}A_0 - \frac{1}{\omega}\text{Im}A_2\right). \tag{11}$$

We further use the recent lattice calculation of the relevant matrix element [27] and obtain, for the scalar-mediated contribution, $[\text{Im}A_2]^{\phi} = -(5.6 - 7.7) \times 10^{-12}$ GeV, a factor of 8–11 above the SM value [27], $[\text{Im}A_2]^{\text{SM}} = -(6.8 \pm 1.4) \times 10^{-13}$ GeV. Inserting these ranges into Eq. (11), we find $\text{Re}(\epsilon'/\epsilon)_{\phi} = -(6.3 \pm 2.3) \times 10^{-3}$, compared to [27] $\text{Re}(\epsilon'/\epsilon)_{\text{EWP}} = -(6.5 \pm 1.3) \times 10^{-4}$.

Our result for $\text{Im}A_2$ can be combined with the experimental results for $\text{Re}A_2$, $\text{Re}A_0$, and ϵ'/ϵ to obtain the unknown ratio

$$\frac{\text{Im}A_0}{\text{Re}A_0} = -(4\text{–}7) \times 10^{-4}, \tag{12}$$

which is a factor of about 3 above the value extracted within the standard model [27], $\frac{\text{Im}A_0}{\text{Re}A_0} = -(1.6 \pm 0.3) \times 10^{-4}$. Given the large hadronic uncertainties [28], such an enhancement cannot be used to exclude our model. Below we mention other ways in which the model can be tested. We note, however, that had it been possible to exclude the model based on ϵ'/ϵ, it would have led to the interesting result that there is no viable single scalar-mediated mechanism that can explain the large value of $A_h^{t\bar{t}}$.

Additional phenomenological aspects.—In this section, we assume throughout that Eq. (6) describes the full set of interactions of the scalar weak doublet with fermions and that ϕ^0 is a mass eigenstate. We postpone the discussion of additional couplings, beyond those that are required to explain $A_{\rm FB}^{t\bar{t}}$, to future work.

The scalar exchange contributes to $D^0 - \bar{D}^0$ mixing via box diagrams. Requiring that this contribution is not larger than the experimental constraint from Δm_D gives [22]

$$\frac{|\lambda|^4}{32\pi^2}\left(\frac{100\ \text{GeV}}{m_{\phi^0}}\right)^2 (V_{ub}V_{cb}^*)^2 < 7 \times 10^{-9}. \qquad (13)$$

Given that $|\lambda| = \mathcal{O}(1)$ and $m_{\phi^0} \approx 100$ GeV, the new contribution is a factor of order 100 below the experimental value, which is negligibly small for both Δm_D and indirect CP violation [29].

As concerns D decays, the operator (8) contributes to neither Cabibbo favored, nor doubly Cabibbo-suppressed decays. Thus it affects only the singly Cabibbo-suppressed decays. Given that it is suppressed by the fifth power of the Cabibbo angle, the effects on the rates of these decays is negligible, and it can be signalled only via CP violation.

We note that this model predicts a contribution to the CP asymmetry in both the $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ channels, and so measurements of the individual asymmetries by the LHCb Collaboration would be useful. Previous experiments and, in particular, the recent CDF result [30] lead to a world average of [31]

$$A_{CP}(K^+K^-) = -0.0023 \pm 0.0017,$$
$$A_{CP}(\pi^+\pi^-) = +0.0020 \pm 0.0022, \qquad (14)$$

consistent with the U-spin prediction of equal magnitudes and opposite signs.

The scalar exchange also contributes in principle to the LHC charge asymmetry in top pair production. We find that the parameter space of mass and coupling of the weak doublet relevant for explaining the $t\bar{t}$ forward-backward asymmetry and ΔA_{CP} is at present unconstrained by the CMS [32] and ATLAS [33] results at the 2σ level.

Since the required mass range for m_{ϕ^0} is 100–130 GeV, the question arises whether ϕ^0 can be discovered via present Higgs searches at ATLAS and CMS. Here the answer is, unfortunately, negative. The reason is that the leading two-body decay mode of ϕ^0 is $\phi^0 \to c\bar{u}$. The decay to $\gamma\gamma$ is generated only by an up-quark loop and is suppressed by a $|V_{ub}|$ factor. Furthermore, ϕ^0 does not couple to W^+W^-, ZZ, and $b\bar{b}$ and $\tau^+\tau^-$. Thus, none of the decay modes that are used in the search of the Higgs boson are useful to observe ϕ^0. The leading three-body decay mode of ϕ^0 is $\phi^0 \to u\bar{b}W$ via an off-shell top.

The coupling of the charged scalar ϕ^+ in Eq. (6) is to only the $\bar{b}u$ pair. Therefore, it does not contribute to B decays. It could be that Φ has couplings additional to those of Eq. (6). For example, if it couples to $\tau\nu$, then it can affect the $B \to \tau\nu$ decay. A discussion of additional couplings beyond those of Eq. (6) is postponed to future work.

Finally, as discussed in Ref. [22], the model predicts a large cross section for single top production and a large branching fraction of the top to the new scalar and light jets. A dedicated study is required in order to establish the applicability of existing measurements [34]. On the other hand, there is no observable effect on the production of same-sign tops, since that would require not only a $\phi^0\bar{t}_L u_R$ coupling, as in Eq. (6), but also a $\phi^0\bar{t}_R u_L$ coupling, which is absent in our model.

Conclusions.—Evidence for a large forward-backward asymmetry in $t\bar{t}$ production ($A_{\rm FB}^{t\bar{t}}$) has been observed by the CDF Collaboration. Evidence for direct CP violation in singly Cabibbo-suppressed D decays (ΔA_{CP}) has been observed by the LHCb Collaboration. Both effects are suggestive of new physics that has nonuniversal interactions in the up sector.

In previous work [22] it was found that, among the single scalar-mediated mechanisms that can explain $A_{\rm FB}^{t\bar{t}}$, only the t-channel exchange of a weak doublet, with a very special flavor structure, is consistent with the total and differential $t\bar{t}$ cross section, flavor constraints, and electroweak precision measurements. In this work we showed that the required flavor structure implies that the scalar *unavoidably* contributes at tree level to ΔA_{CP}. The relevant electroweak parameters are either directly measured or fixed by the top-related data, implying that, for a plausible range of the hadronic parameters, the scalar-mediated contribution is of the right size.

The model predicts large effects on ϵ'/ϵ, single top production, and top decays. It can be excluded based on better knowledge of the hadronic parameters in the calculation of ϵ'/ϵ or with a dedicated study of single top production and top decay that takes into account the special features of the model [34].

We find it intriguing that a single, highly constrained mechanism might simultaneously explain the two measurements. It motivates further study of possible experimental signatures and tests as well as a search for a theoretical framework that would give a natural explanation to the required flavor structure.

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