Top-pair forward-backward asymmetry from loops of new strongly coupled quarks

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Top Pair Forward-Backward Asymmetry from Loops of New Strongly Coupled Quarks

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We examine loop-mediated effects of new heavy quarks $Q = (t', b')$ on $t\bar{t}$ production at hadron colliders, using a phenomenological model with flavor off-diagonal couplings of charged and neutral scalars $\phi = (\phi^{\pm}, \phi^0)$ to Q. We show that an invariant-mass-dependent asymmetry, in the $t\bar{t}$ center of mass, consistent with those recently reported by the CDF collaboration can be obtained for quark masses around 350–500 GeV, scalar masses of order 100–200 GeV, and modest to strong Yukawa couplings. The requisite strong interactions suggest a non-perturbative electroweak symmetry breaking mechanism and composite states at the weak scale. A typical prediction of this framework is that the new heavy quarks decay dominantly into $t\,\phi$ final states.

Introduction: The CDF collaboration has recently reported [1] an asymmetry in $t\bar{t}$ production that suggests a departure from the predictions of the Standard Model (SM) [2]. In the $t\bar{t}$ rest frame, the CDF data yield $A^{t\bar{t}}_{\rm CDF} = 0.158 \pm 0.075$, with combined statistical and systematic uncertainties; the next-to-leading order QCD prediction is 0.058 ± 0.009. The data display a significant dependence on the invariant mass of the $t\bar{t}$ pair:

$$\begin{aligned} A^{t\bar{t}}_{\rm CDF}(M_{t\bar{t}} < 450\ \text{GeV}) &= -0.116 \pm 0.153, \\ A^{t\bar{t}}_{\rm CDF}(M_{t\bar{t}} > 450\ \text{GeV}) &= 0.475 \pm 0.114, \end{aligned} \tag{1}$$

where the SM predictions given by MCFM [3] are 0.04 ± 0.006 and 0.088 ± 0.013, respectively. When cuts are imposed on the difference of rapidities $\Delta y \equiv y_t - y_{\bar{t}}$, the $t\bar{t}$ rest frame asymmetry is found to be

$$\begin{aligned} A^{t\bar{t}}_{\rm CDF}(|\Delta y| < 1) &= 0.026 \pm 0.118, \\ A^{t\bar{t}}_{\rm CDF}(|\Delta y| \geq 1) &= 0.611 \pm 0.256, \end{aligned} \tag{2}$$

while the MCFM predictions are 0.039 ± 0.006 and 0.123 ± 0.008, respectively. Indications of an asymmetry in $t\bar{t}$ were also reported earlier by the Tevatron experiments [4–6].

In the past few months, the D0 collaboration [7] has also announced its results for this asymmetry using 5.4 fb^{-1} of data. For the inclusive asymmetry they find $A^{t\bar{t}}_{\rm D0} = (19.6 \pm 6.5)\%$, which is somewhat more significant than the corresponding CDF result above. However, D0 does not report any significant enhancement in the high-mass region at the"reconstruction level", given by $(11.5 \pm 6.0)\%$. This should be compared with the corresponding CDF number $(26.6 \pm 6.0)\%$ (errors added in quadrature). We note that these two numbers are roughly consistent within 1.8σ. Since the D0 collaboration has not provided the "unfolded" parton-level asymmetry, a direct comparison with the CDF value in the high mass region from Eq. (1) is not reliably possible. However, assuming an unfolding procedure for the D0 result similar to that of CDF, we may assume that a roughly 2σ consistency between the two results would obtain. In what follows, we address the above CDF results directly, as they require a larger effect. This makes our treatment more conservative, in terms of what we would demand from our model. In any event, we will only consider a 2σ consistency with the CDF central values, which therefore should also accommodate smaller central values of the D0 data.

Together, these results have attracted a great deal of attention, and a variety of theoretical ideas have been proposed to explain these measurements [8–10]. The main challenge faced by any such attempt is to account for a substantial asymmetry while maintaining consistency with other measured quantities, such as the $t\bar{t}$ total cross section, that do not show significant departure from the predictions of the SM.

In this Letter, we provide a simple phenomenological model that can explain the general features of the most recent CDF results, while staying consistent with current experimental constraints. We mainly postulate that heavy quarks $Q = (t', b')$ with charges $(+2/3, -1/3)$, respectively, have rather strong flavor-changing interactions with the top quark (t) and also some flavor-changing coupling with the up and down quarks (u, d) through Yukawa couplings to charged and neutral scalar particles $\phi = (\phi^{\pm}, \phi^0)$. The new physics appears in loops through box graphs and can interfere with the leading QCD process, $q\bar{q} \to g \to t\bar{t}$. This interference can generate a significant forward-backward asymmetry in $t\bar{t}$ production with a dependence on $M_{t\bar{t}}$ and Δy consistent with the experimental results. At the same time, we will show that the relevant parameter space in our model provides sufficient freedom to avoid any significant deviation from existing bounds.

A typical prediction of our model is that Q will dominantly decay into $t\,\phi$; we will mention some other properties of Q in this model later on. In what follows, we only consider a minimal model, for simplicity. However, the SM augmented by a fourth generation would be a natural context for our requisite setup, though it should be clear that the (t', b') in our model are *not* typical heavier replicas of the SM (t, b). For example, our model typically predicts bW or $b'W$ to be sub-dominant decay modes of t', with important ramifications for t' searches.

The Model: We propose a simple model, guided only by the requirements of producing the desired level of $t\bar{t}$ asymmetry while avoiding significant conflict with other data. We will assume the existence of two new heavy quarks t' and b', with a common mass m_Q, and of a real scalar ϕ^0 and charged scalars $\phi^{\pm}$, with a common mass m_ϕ. In a minimal model, we only need to assume that scalars couple t' and b' with u, d, and t in order to generate asymmetries consistent with those in Eqs. (1) and (2). The new interactions are given by

$$\mathcal{L} \supset \lambda_{ut'}\phi^0 \bar{u}t' + \lambda_{ub'}\phi^+ \bar{u}b' + \lambda_{dt'}\phi^- \bar{d}t' + \lambda_{db'}\phi^0 \bar{d}b' + \lambda_{tt'}\phi^0 \bar{t}t' + \lambda_{tb'}\phi^+ \bar{t}b' + \text{H.C.}, \quad (3)$$

where the λ_{ij} are coupling constants which will be chosen to generate the needed asymmetry. In most of our discussion, we will assume that $\lambda_{qt'} = \lambda_{qb'} \equiv \lambda_q$ for $q = u, d, t$, although this need not be the case.

We will later require $\lambda_q \lambda_t \gtrsim 5$ for $q = u$ or d, which implies at least one strong Yukawa coupling. Of course, misalignment with the mass basis would typically mean that interactions with other quarks are naturally present. Thus, it is fair to assume other smaller flavor-changing or diagonal couplings to light quarks for $(\phi^0, \phi^{\pm})$, allowing them to have prompt decays into jets. However, the above interactions suffice to illustrate our main idea. In this paper, we will not dwell on the possible flavor structure of these interactions or their ramifications, as those would depend on the detailed form of the underlying physics, which is outside the scope of our discussion. We note also that we do not assume that t' and b' have the same chiral structure as the SM quarks, and hence our simple model does not necessarily give rise to gauge anomalies. For simplicity, we have assumed vectorlike couplings in Eq. (3), although other structures are possible as well.

Results: The model encoded in the Lagrangian (3) allows for new one-loop contributions to $t\bar{t}$ production in the color-octet channel. Graphs corresponding to these processes are presented in Figs. 1 and 2; these contributions interfere with the leading-order s-channel gluon exchange graph of QCD. We find that the box graphs in Fig. 1 give rise to an additional positive asymmetry, consistent with CDF observations. The size of the effect depends on the values of the couplings $\lambda_u, \lambda_d, \lambda_t$, and on the masses m_Q and m_ϕ. The vertex corrections shown in Fig. 2 are analogous to the vertex correction involving the SM Higgs boson [11]. They do not produce an asymmetry, but they do give a contribution to the cross section comparable to that of the box graphs, and are therefore included in our computation. We also include the tree-level SM process $gg \to t\bar{t}$, which contributes about 5% of the total cross section. Here, we note that squares of box diagram amplitudes are not included in our computations, since the quantitative accuracy we aim for in this work does not merit such an extensive analysis. Given the size of the couplings that we will consider later, such contributions may not be negligible, in principle. However, we expect the freedom in the choice of parameters afforded by our phenomenological model would allow reaching quantitatively similar conclusions, even if the omitted terms were included in our analysis. Our approach is justified as we will only attempt to obtain consistency with the CDF results at the 2σ level and we mainly want to illustrate how new physics loop contributions can be important in accounting for the reported $t\bar{t}$ asymmetries.

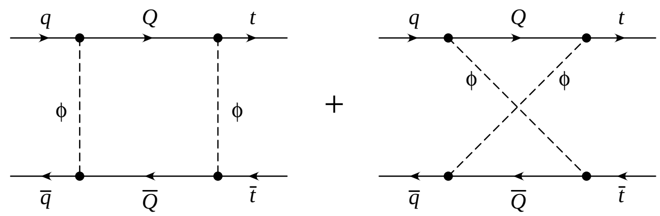

FIG. 1: New physics contributions to $t\bar{t}$ production in the color-octet channel from the interactions in Eq. (3).

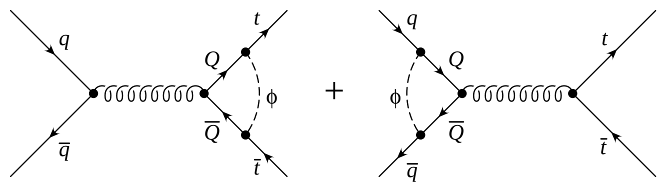

FIG. 2: Vertex corrections to $q\bar{q} \to g \to t\bar{t}$. There are also corrections due to self-energy insertions on the external legs.

The amplitudes appearing in the interference of the box graphs in Fig. 1 with the SM graph were calculated by hand and checked with QGRAF [12] and FORM [13]. The resulting expressions must be integrated over the two-body phase space and the Feynman parameters introduced in the loop integration, and convolved with parton distribution functions (PDFs). These integrations were performed numerically using the CUBA library [14] and the CT10 PDFs [15]. After ultraviolet divergences have been cancelled analytically, the vertex corrections can be integrated in the same way. As a check, we set the masses and couplings equal to those used in Ref. [11], and found agreement with the results therein.

In Fig. 3, for several sets of Yukawa couplings, we show the values of m_Q and m_ϕ that yield the inclusive asymmetry reported by CDF, as well as the asymmetries involving cuts on $M_{t\bar{t}}$ and Δy, each within 2σ, without changing the total $t\bar{t}$ cross section by more than 30%. The shaded region corresponds to $(\lambda_u, \lambda_d, \lambda_t) = (1, 2, 6)$, the hatched region to $(0, 3.5, 4.5)$, and the cross-hatched region to $(1, 3, 5)$.

Here, we would like to add some comments about the perturbative validity of our calculations, given that the Yukawa couplings we are considering are rather large. Let us consider the case with $(\lambda_u, \lambda_d, \lambda_t) = (1, 3, 5)$ as an example; similar considerations apply to our other choices in Fig. 3. The leading order at which our new physics contributes to the asymmetry is at the one-loop level, proportional to $\lambda_d^2 \lambda_t^2/(16\pi^2) \sim 1.4$. Hence, it may appear that our choices of parameters have rendered a perturbative treatment invalid. However, we note that the use of a perturbative calculation only requires that higher-order terms have decreasing magnitude. The two-loop correction is in fact suppressed by a factor which is, at worst, proportional to $\lambda_t^2/(16\pi^2) \sim 0.2$. Hence, we see that higher-order amplitudes tend to be sufficiently smaller than our leading-order (one-loop) terms, and a perturbative approach should yield fair estimates.

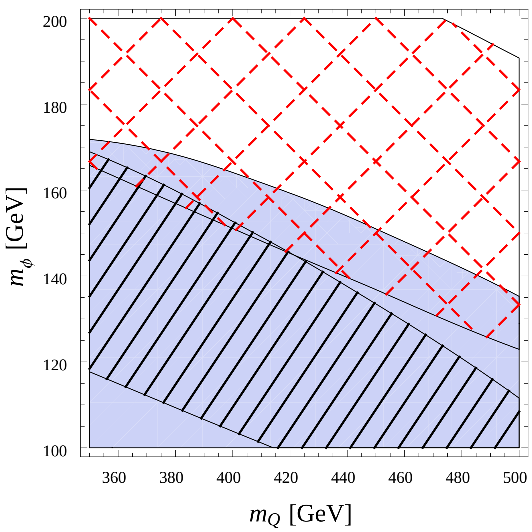

FIG. 3: Regions of parameter space that yield 2σ agreement with the CDF results [1], as well as agreement with the $t\bar{t}$ total cross section within 30%, for $(\lambda_u, \lambda_d, \lambda_t) = (1, 2, 6)$ (shaded), for $(\lambda_u, \lambda_d, \lambda_t) = (0, 3.5, 4.5)$ (hatched) and for $(\lambda_u, \lambda_d, \lambda_t) = (1, 3, 5)$ (cross-hatched).

Our results in Fig. 3 are presented for $350\,\text{GeV} \leq m_Q \leq 500\,\text{GeV}$ and $100\,\text{GeV} \leq m_\phi \leq 200\,\text{GeV}$. The current limits on heavy fourth-generation quarks [16–19] depend on assumptions about their dominant decay modes [20]. The most stringent bounds, obtained by the CMS collaboration, apply to t' quarks that decay into bW, excluding $m_{t'} < 450$ GeV at 95% confidence level [19]. We note that if ϕ can decay into light quarks, such bounds may not immediately apply to our t' particle. To see this, note that given the decay chain $t' \to t\phi \to bW\bar{q}_i q_j$, for $\lambda_t \gg \lambda_{u,d}$, the decay products of our t' state include 2 extra jets. Also, if the Yukawa couplings involving light quarks are not too small, there may be a significant branching fraction for *e. g.* $t' \to d\phi^+ \to 3j$, which could also help us evade heavy-quark exclusions. Similar considerations also apply to the decays of b'. As for the ϕ particles, with small couplings to pairs of light quarks and leptons, as may be assumed in our minimal construct, the bounds on m_ϕ are generally not very restrictive. Hence, we expect that a significant part of the favorable parameter space presented in Fig. 3 is currently allowed. However, a more precise determination of the allowed parameter space in our model requires a more detailed analysis of the current data, taking account of the main decay channels and their associated background and systematics, which is outside the scope of this work.

In Fig. 4, we plot the (parton-level) asymmetry as a function of $M_{t\bar{t}}$ for several values of the model parameters. We have computed this observable using the same bins as in Fig. 10 of Ref. [1]. The solid and dotted curves correspond to two sets of masses and couplings from the hatched region of Fig. 3, while the dashed curve corresponds to a set from the shaded region. We can see that this observable is quite sensitive to the choice of masses and couplings, and hence can be used to discriminate among various realizations of our model.

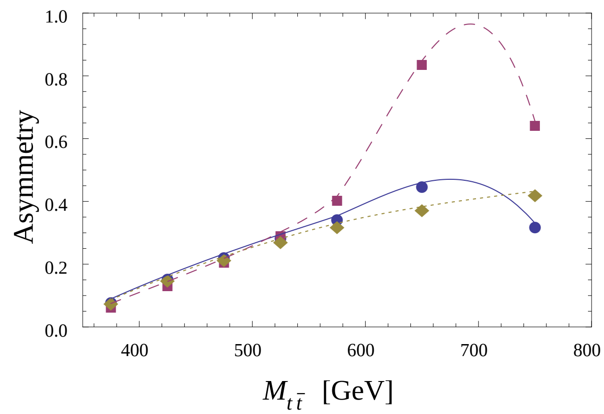

FIG. 4: Asymmetry as a function of the invariant mass $M_{t\bar{t}}$ for $(m_Q, m_\phi, \lambda_u, \lambda_d, \lambda_t) = (380\,\text{GeV}, 140\,\text{GeV}, 0, 3.5, 4.5)$ (solid), $(380\,\text{GeV}, 140\,\text{GeV}, 1, 2, 6)$ (dashed), and $(440\,\text{GeV}, 120\,\text{GeV}, 0, 3.5, 4.5)$ (dotted).

We also show the asymmetry as a function of $|\Delta y|$, for the same values of the parameters, in Fig. 5. We consistently see an enhanced asymmetry when $|\Delta y| > 1$, but this observable appears to have less discriminating power than $M_{t\bar{t}}$.

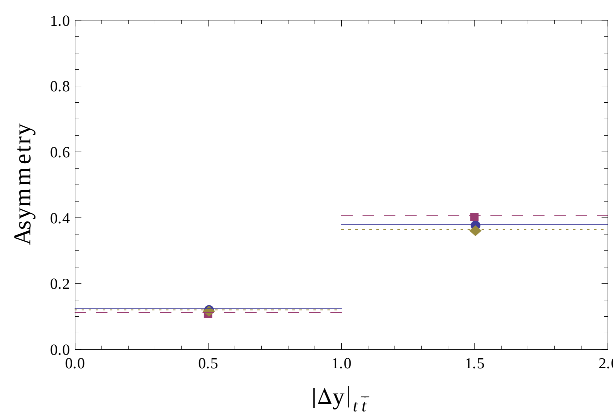

FIG. 5: Asymmetry as a function of the rapidity separation $|\Delta y|$ for $(m_Q, m_\phi, \lambda_u, \lambda_d, \lambda_t) = (380\,\text{GeV}, 140\,\text{GeV}, 0, 3.5, 4.5)$ (solid), $(380\,\text{GeV}, 140\,\text{GeV}, 1, 2, 6)$ (dashed), and $(440\,\text{GeV}, 120\,\text{GeV}, 0, 3.5, 4.5)$ (dotted).

Discussion: The above results imply that the likely underlying physics for our model is a dynamical theory

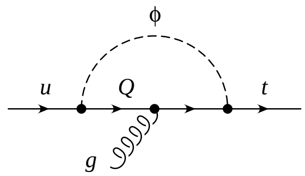

FIG. 6: Flavor-changing vertex $g\,t\,u$ from the interactions in Eq. (3); there are other diagrams where the gluon is replaced with another vector boson, such as the photon.

of electroweak symmetry breaking, giving rise to composite states with strong couplings [21]. Hence, in a more detailed picture, ϕ, for example, could be a composite state [10]. An obvious prediction for our model is the discovery of the heavy quarks t' and b'. Such particles will naturally fit within a four-generation version of the SM, but may also arise in other ways, for example due to non-trivial weak-scale dynamics. Regardless of the exact nature of physics above the weak scale, our model gives rise to some interesting predictions, despite its austere structure, as outlined below.

The model presented here allows for same-sign top pair production. The CMS collaboration has studied such processes [22] in the context of the model in Ref. [23] and has constrained the coefficient of the relevant dimension-6 operator generated by Z' exchange to be roughly less than 1.4 TeV^{-2}. Our model will also lead to such a dimension-6 operator, but with a different structure, whose coefficient we estimate to be of order

$$c_{tt} \sim \frac{(\lambda_u \lambda_t)^2}{16\pi^2\, m_{t'}^2}\,. \tag{4}$$

For values of parameters in Fig. 3 that yield the desired asymmetries, we find $c_{tt} \lesssim 1.4$ TeV^{-2} for $m_Q \gtrsim 400$ GeV, which does not impose a severe constraint on our fiducial parameter space. Note that $c_{tt} = 0$ for choices of parameters (hatched region in Fig. 3) such that $\lambda_u = 0$. Hence, we expect that the typical parameter space relevant to the CDF top pair asymmetry will not be excluded by the current bounds.

Note that due to the flavor structure of our model, which does not include couplings to strange, charm, or bottom quarks, we do not expect significant constraints from flavor physics. In a more complete framework one would expect that some such couplings may be present, but they should be sufficiently suppressed compared to λ_q, to maintain consistency with existing limits. For a valid analysis, we have only considered $\lambda_q \lesssim 4\pi$. The values of λ_q in Fig. 3 require Q to have strong couplings to t, and less strong couplings to lighter quarks. Such a hierarchy of couplings may arise in models where the top quark is at least partially composite. Here, as mentioned before, we generally expect that the most dominant decay mode of Q will be $Q \to t\,\phi(\to jj)$ [24], which is an important input for t' searches at the Tevatron and the LHC.

Loop-level processes would allow for single-top production or flavor-changing decays of the top quark [25], through the diagram in Fig. 6. The effective flavor-changing vertex in this diagram is expected to have a size

$$\lambda_{tu} \sim g_s \frac{\lambda_u \lambda_t}{16\pi^2} \frac{m_t}{m_Q}, \tag{5}$$

which yields $\lambda_{tu} \lesssim 0.02$ for $\lambda_u \lambda_t \lesssim 6$ and $m_Q \gtrsim 350$ GeV. Thus we can expect a significant cross section for the unorthodox single-top process $gu \to t$, where the top is not accompanied by a jet in the final state. The SM s- and t-channel single-top processes always produce another quark along with the top, and the single-top measurements at the Tevatron [26] have required this additional jet in their event selection. QCD corrections to the process in Fig. 6 can generate a $t+j$ final state, and thus there may be tension between our model and the Tevatron measurements. However, the single-top rate in our model can be reduced in two ways. First, we can relax the assumption that $\lambda_{ut'} = \lambda_{ub'}$; if these couplings have opposite signs, there is a cancellation between the diagram involving a virtual t' and ϕ^0 and the one with b' and ϕ^+. Changing the relative sign of $\lambda_{ut'}$ and $\lambda_{ub'}$ has no effect on the $t\bar{t}$ cross section and asymmetry, which depend only on the squares of these two couplings. Second, if the magnitude of the coupling λ_u decreases, the rate for single top (and also that for same-sign tops) decreases along with it. Figure 3 shows that it is possible to generate the desired asymmetry even with $\lambda_u = 0$, and thus avoid running afoul of single-top constraints.

We also mention that the $qQ\phi$ vertices in our model can lead to a measurable forward-backward asymmetry in t' and b' pair production, through the t-channel exchange of a ϕ scalar; a similar mechanism has been used to explain the $t\bar{t}$ forward-backward asymmetry [27]. Due to the expected large mass of t' and b', such measurements would perhaps be more feasible at the LHC. However, since the LHC is a pp collider, establishing an asymmetry in t' and b' pair production would require additional kinematic considerations [28].

Conclusions: We have proposed that flavor-changing couplings of new heavy quarks $Q = (t', b')$ to the SM u, d, and t quarks and new scalars $\phi = (\phi^\pm, \phi^0)$ can generate, at the one-loop level, an asymmetry in top pair production, similar to that reported by the CDF collaboration [1]. We discussed how various existing constraints can be satisfied within our framework. The simple model we propose can yield the desired phenomenology with ϕ in the 100–200 GeV mass range and a Q of mass about 350–500 GeV [29]. We also showed that information about the model parameters can be extracted by measuring the asymmetry as a function of $M_{t\bar{t}}$.

A model with four SM-like generations can provide a possible realization of our proposal. The strong couplings of the new particles suggest a dynamical mechanism for electroweak symmetry breaking, leading to composite states. Assuming large couplings for the $tQ\phi$ vertex, as may be expected for composite heavy flavors, generally implies that the most dominant decay mode of Q would be $t\,\phi$ [24]. The scalars ϕ likely have smaller, but nonzero, couplings to the remaining quarks, in which case they would mainly decay into two jets. In the case of a typical fourth generation b' this can be mimicked by $b' \to tW$ with $W \to jj$. However, in typical four-generation models, the most likely t' decay modes are $b'W$ and bW, which lead to different final states. Hence, current limits on the mass of t' do not immediately apply to the t' proposed in our model. In any event, we expect the LHC to be able to discover our proposed heavy quarks and test their properties, including asymmetries in their pair production.

Acknowledgments

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