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Mass dependent top forward–backward asymmetry in the effective Lagrangian approach: Addendum to “Model independent analysis of the forward–backward asymmetry of top quark production at the Tevatron”

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ABSTRACT

Recently the CDF and the D0 Collaborations presented the data on the top forward–backward (FB) asymmetry $A_{\rm FB}$ as functions of $M_{t\bar{t}}$ and $\Delta y \equiv y_t - y_{\bar{t}}$. We study these observables in the effective Lagrangian approach with dimension-6 $q\bar{q}t\bar{t}$ contact interactions, and compare with the CDF and D0 data. When we stay within the validity region of the effective Lagrangian approach, the mass dependent top FB asymmetry turns out to be smaller than the CDF data, more than 2-σ away. If this discrepancy remains in the future data with better statistics, it would imply that the effective Lagrangian approach is not adequate for the top FB asymmetry, and a new physics scale around a few hundred GeV in the t- or u-channel may be responsible for the observed top FB asymmetry.

1. Introduction

The top forward–backward (FB) asymmetry ($A_{\rm FB}$) measured at the Tevatron has been an interesting subject, since it may indicate a new physics around the corner. For the last few years, only the integrated $A_{\rm FB}$ was reported. The most recent updated number from the CDF Collaboration is [1]

$$A_{\rm FB}({\rm CDF}) = 0.158 \pm 0.074 \tag{1}$$

in the $t\bar{t}$ rest frame, whereas the SM prediction [2] based on MCFM is 0.058 ± 0.009 [3]. In our previous papers [4,5], we used the integrated FB asymmetry in order to extract information on the possible new physics scenarios and could discriminate a class of models from another, in the limit where new physics scale is beyond the reach of the Tevatron.

Early January this year, the CDF Collaboration reported new data on the $A_{\rm FB}$ as functions of $M_{t\bar{t}}$ and $\Delta y \equiv y_t - y_{\bar{t}}$ using the lepton + jets channel [1], and $A_{\rm FB}$ as a function of Δy in the dilepton channel [6], see Table 1. These new data sets enable us to perform more detailed study on the subject. In particular, the data with lower/higher $M_{t\bar{t}}$ and Δy are presented, as tabulated in Table 1 along with the MCFM predictions. These numbers are obtained at the parton level for the final $t\bar{t}$ state, and can be compared with the theoretical predictions at the parton level. These new data stimulated a number of new papers on the top FB asymmetry at the Tevatron, especially paying attention to the large FB asymmetry at large $M_{t\bar{t}}$ and Δy.

Table 1
CDF data on the top FB asymmetry for lower/higher $M_{t\bar{t}}$ and Δy, compared with the SM predictions based on the MCFM, after unfolding the effects of detector resolution and acceptance [1,6].

FB asymmetry	Data	Predictions
$A_{\rm FB}(M_{t\bar{t}} < 450\ {\rm GeV})$	-0.116 ± 0.153	0.040 ± 0.006
$A_{\rm FB}(M_{t\bar{t}} > 450\ {\rm GeV})$	0.475 ± 0.112	0.088 ± 0.013
$A_{\rm FB}(\lvert\Delta y\rvert < 1.0)$	0.026 ± 0.118	0.039 ± 0.006
$A_{\rm FB}(\lvert\Delta y\rvert > 1.0)$	0.611 ± 0.256	0.123 ± 0.018

The D0 Collaboration also reported recently a new result based on the lepton + jets channel [7]:

$$A_{\rm FB}({\rm D0}) = 0.196 \pm 0.065 \tag{2}$$

after unfolding the effects of detector resolution and acceptance. The reconstructed values of $A_{\rm FB}$ with two-bin analysis in $M_{t\bar{t}}$ show the flatter and smaller asymmetry than the CDF data, see Table 2. But they are at the reconstructed level and cannot be compared directly to the theoretical predictions.

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Table 2
D0 data on the top FB asymmetry for lower/higher $M_{t\bar{t}}$ and Δy, compared with the SM predictions based on the MC@NLO, before unfolding the effects of detector resolution and acceptance [7].

FB asymmetry	Data	Predictions
$A_{\mathrm{FB}}(M_{t\bar{t}} < 450\ \mathrm{GeV})$	0.078 ± 0.048	0.013 ± 0.006
$A_{\mathrm{FB}}(M_{t\bar{t}} > 450\ \mathrm{GeV})$	0.115 ± 0.060	0.043 ± 0.013
$A_{\mathrm{FB}}(\lvert\Delta y\rvert < 1.0)$	0.061 ± 0.041	0.014 ± 0.006
$A_{\mathrm{FB}}(\lvert\Delta y\rvert > 1.0)$	0.213 ± 0.097	0.063 ± 0.016

In this Addendum to Ref. [4], we present the predictions for the A_{FB} as functions of $M_{t\bar{t}}$ and $\Delta y \equiv y_t - y_{\bar{t}}$ within the effective Lagrangian approach with dim-6 contact interactions for $q\bar{q} \to t\bar{t}$ [4,5]:

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} \bigl[C_{8q}^{AB} \bigl(\bar{q}_A T^a \gamma_\mu q_A\bigr)\bigl(\bar{t}_B T^a \gamma^\mu t_B\bigr)\bigr]. \tag{3}$$

And we compare the predictions with the recent CDF data. We will use Eq. (1) in order to fix the effective couplings $C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}$ and $C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$ and predict the $M_{t\bar{t}}$ and Δy dependent A_{FB} for those C_i's within 1-σ range. We found that $C_1(1\ \mathrm{TeV}/\Lambda)^2$ and $-C_2(1\ \mathrm{TeV}/\Lambda)^2$ take values between ~ -0.5 and ~ 2.5, see Fig. 1 in Ref. [5] for updated results.

Since our approach adopted here is based on nonrenormalizable dim-6 operators, care should be exercised when we make predictions and compare with data.

Purpose of this Addendum is three-fold.

- We reiterate the basic philosophy of using the effective Lagrangian approach for the top FB asymmetry, making a recall of the old electroweak physics in the FB asymmetry in $e^+e^- \to \mu^+\mu^-$ at PETRA with $\sqrt{s} \simeq 34\ \mathrm{GeV} \ll M_Z$.[1] Also it is emphasized that care should be exercised when the effective Lagrangian approach is used for phenomenology at hadron colliders.
- At present, the FB asymmetry alone does not select a particular new physics scenario uniquely, beyond the earlier study on the subject. The reason is rather simple. $A_{\mathrm{FB}}(M_{t\bar{t}})$ will vary as a function of $M_{t\bar{t}}$, unless it is constant. So it should increase or decrease, with either positive or negative slope and curvature, that determine the shape of $A_{\mathrm{FB}}(M_{t\bar{t}})$. However it is bounded between -1 and $+1$, and $A_{\mathrm{FB}}(M_{t\bar{t}})$ cannot increase or decrease indefinitely. The shape should change at some scale $M_{t\bar{t}}$, which would be related with the mass scale of new physics that comes into $q\bar{q} \to t\bar{t}$ and modifies the top FB asymmetry at the Tevatron.
- If the measured $A_{\mathrm{FB}}(M_{t\bar{t}})$ changes its shape and decreases at some scale after unfolding, it would indicate that our approach based on the dim-6 effective Lagrangian is not a good one. One has to include explicitly the new resonances that contribute to the top FB asymmetry, and redo the analysis. The sign of $A_{\mathrm{FB}}(M_{t\bar{t}})$ can be still useful when we choose some models.

2. Old wisdom from electroweak interaction: $e^+e^- \to \mu^+\mu^-$ at PETRA

First of all, we wish to state our philosophy of model independent analysis using the effective Lagrangian up to dim-6 operators involving $q\bar{q}$ and $t\bar{t}$. It is needless to emphasize our approach could be relevant in case that the new particle is too heavy to be directly produced at the Tevatron or even at the LHC. It is instructive to recall the past history where new P- and C-violating neutral current (Z^0) effects were first observed through the interference effect well below the Z^0 mass scale.

The first example is the SLAC experiment on the polarized electron scattering on the nucleus target [8]. The difference between the $e_L N$ and $e_R N$ was attributed to the interference between the P-conserving QED photon exchange and the P-violating Z^0 exchange.

The second example is the FB asymmetry of the muon in $e^+e^- \to \mu^+\mu^-$ measured at PETRA [9], the CM energy of which was $\sqrt{s} \simeq 34$ GeV, far below the Z^0 pole mass. Still one can observe a clear FB asymmetry due to the interference between photon and Z^0 exchange diagrams. In Refs. [4,5], we assumed that physics behind the top FB asymmetry at the Tevatron might be similar to physics behind the second example from PETRA. As long as the new physics coupling is as strong as QCD interaction and it violates P- and C-symmetries, then there could be a large A_{FB} asymmetry.

Far below the Z^0 pole mass ($s \ll M_Z^2$), one can approximate $A_{FB}(s)$ as [10]

$$A_{\mathrm{FB}}(s) \simeq -\frac{3G_F}{\sqrt{2}} \frac{s}{4\pi\alpha} (g_L - g_R)^2 \equiv k G_F s, \tag{4}$$

which is negative definite, a generic feature of the new vector boson with universal couplings to the initial and the final fermions and antifermions. (Recall that one needs different couplings of axigluon to light quarks and top, opposite in the sign, in order to produce a positive A_{FB}.) The PETRA measurement of $A_{\mathrm{FB}}(s)$ in the region far below the Z^0 pole is that the $A_{\mathrm{FB}}(1200\ \mathrm{GeV}^2) \simeq -0.1$, which can be translated into

$$k = -7.18,$$

compared with the SM prediction: $k = -5.78$. Note that we can get the rough size of k (or $(g_L - g_R)^2/M_Z^2$) only from the interference term between the QED photon and the Z^0 boson exchanges in the limit $s \to 0$ (near threshold), if $s \ll M_Z^2$.

In the upper frame of Fig. 1, we show the normalized angular distribution of $e^+e^- \to \mu^+\mu^-$ at PETRA ($\sqrt{s} \simeq 34.6$ GeV), along with the pure QED contribution in dashed curve. We can clearly observe that there can be a large FB asymmetry due to the interference between the pure QED amplitude through γ exchange and the P- and C-violating Z^0 exchange amplitude, even if the CM energy is far below the Z^0 pole mass.

In the lower frame of Fig. 1, we plot the FB asymmetry at low energy (still far below M_Z), and show that the behavior is almost linear in s. Therefore the effective Lagrangian approach should be adequate in this regime.

Note that the shape of the $A_{\mathrm{FB}}(s)$ changes when $\sqrt{s}$ becomes close to M_Z within Γ_Z. Well below the Z^0 resonance, the shape is almost monotonically decreasing function of $\sqrt{s}$ without much structure.

We expect that basically the same thing could happen in $q\bar{q} \to t\bar{t}$. However the situation becomes more subtle in hadron colliders compared to $e^+e^- \to \mu^+\mu^-$ at the PETRA for two reasons.

First, the parton level CM energy $\sqrt{\hat{s}}$ is no longer fixed for $t\bar{t}$ productions at hadron colliders such as Tevatron or LHC. Therefore the shape of $A_{\mathrm{FB}}(\hat{s})$ will be distorted from the linear behavior in $\hat{s}$, after one convolutes over the Parton Distribution Functions (PDFs). This part is rather straightforward to include in the analysis.

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[1] This was described in the talks by one of the authors at Blois 2010, ICHEP2010, CDF Collaboration Seminar in 2010, and KEKPH 2011, etc. See, for example, http://confs.obspm.fr/Blois2010/Ko.pdf or http://indico.cern.ch/getFile.py/access?contribId=326&sessionId=51&resId=0&materialId=slides&confId=73513.

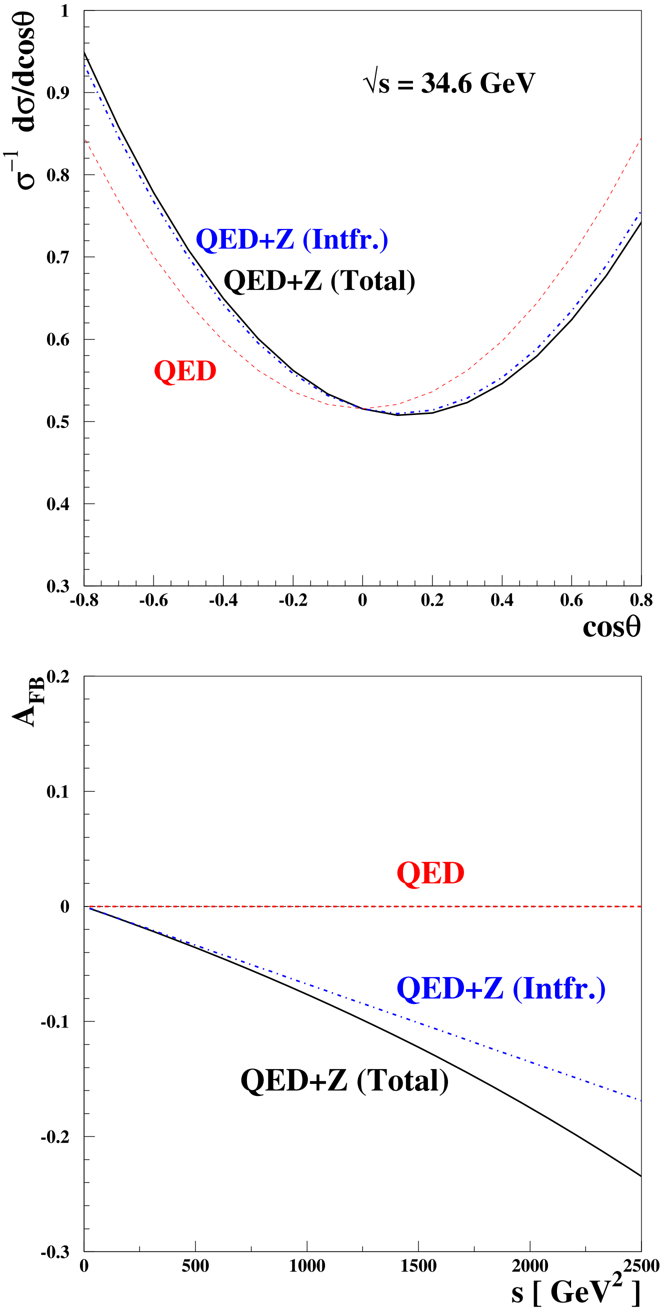

Fig. 1. (Upper) The normalized angular distribution of $e^+e^- \to \mu^+\mu^-$ at PETRA ($\sqrt{s} \simeq 34.6$ GeV), and (lower) the integrated A_{FB} as functions of s up to $s = 2500\ \text{GeV}^2$. The dashed (red in the web version) curves are for the symmetric QED case. The dash-dotted (blue in the web version) curves include only the interference between the diagrams mediated by γ and Z^0 bosons. The full QED + Z prediction is represented by the solid (black) curves.

Second part is the issue of breakdown of perturbative unitarity at some high energy scale $\hat{s}_{\text{unit}}$, which would be roughly $\sim \text{Min}(\Lambda^2/C_1, \Lambda^2/C_2)$. Again, the situation is not that simple since the parton level CM energy $\hat{s}$ is not fixed at hadron colliders. The scale where perturbative unitarity is violated is a function of $\hat{s}$, which has a range at hadron colliders. There is no good way to implement the cutoff energy scale where perturbative unitarity is violated at hadron colliders. This is in sharp contrast with the Fermi theory of weak interactions in terms of dimensionful coupling G_F. When one describes the νe elastic scattering for example, perturbative unitarity will be broken near $\sqrt{s} \sim G_F^{-1/2}$.

One possible way to address the issue of perturbative unitarity might be to include some form factors with new mass parameters. For example, one can make the replacement:

$$(C_1 \pm C_2) \to (C_1 \pm C_2)/\left(1 - \hat{s}/M_{\text{res}}^2\right)^n \qquad (5)$$

with some exponent $n = 1$ or 2, etc. However there is no unique way to do this, and we could introduce the form factors in t- or u-channel. This arbitrariness will change the predictions for $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$ and other distributions. Our standing position is that it would be better to work with explicit models instead with effective Lagrangian approach, if tree-level unitarity breaks down within the energy scale we work at.

3. The case for $q\bar{q} \to t\bar{t}$: predictions for A_{FB} as functions of $M_{t\bar{t}}$ and Δy

Now we consider the process $q\bar{q} \to t\bar{t}$ in the presence of the dim-6 operators. We refer to Ref. [4] for the explicit expression of the amplitude squared in terms of the couplings $C_{1,2}$. The mass dependent FB asymmetry at the parton level ($\hat{A}_{\text{FB}}$) is given by

$$\hat{A}_{\text{FB}}(M_{t\bar{t}}) = \frac{\hat{\beta}_t \frac{\hat{s}}{\Lambda^2}(C_1 - C_2)}{\frac{8}{3}[1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)] + \frac{16\hat{s}}{3m_t^2}[1 + \frac{\hat{s}}{2\Lambda^2}(C_1 + C_2)]}$$
$$\simeq \frac{3\hat{\beta}_t \frac{\hat{s}}{\Lambda^2}(C_1 - C_2)}{8 + 16\frac{\hat{s}}{m_t^2}}. \qquad (6)$$

In any case, the whole point is that the FB asymmetry near the threshold is approximately linear in $\hat{s}$ modulated by $\hat{\beta}_t = \sqrt{1 - 4m_t^2/\hat{s}}$ with a small slope parameter that could have either sign depending on $(C_1 - C_2)$, namely the underlying new physics affecting $q\bar{q} \to t\bar{t}$. The point is that near threshold behavior is almost linear in $\hat{s}$ modulo $\propto \hat{\beta}_t$, and not so much determined by underlying dynamics except for the single overall scale which is nothing but the slope of the asymmetry. There would be many different underlying new physics that might predict more or less the same value for this single overall scale. Therefore it is not possible to conclude that some scenarios are favored to others, beyond the level stated in Ref. [4]. Additional information from the same sign top pair production can help to distinguish one model from another.

If the $A_{\text{FB}}(M_{t\bar{t}})$ shows some nontrivial structure like wiggles or it changes the shape, one can say more about the underlying physics, e.g., the mass scale of new physics to some extent. Otherwise it is not easy to figure out the nature of underlying new physics for the top FB asymmetry.

As our general analysis indicates, more physical observables will be helpful to diagnose the underlying new physics that might affect the top FB asymmetry, such as the (FB) spin–spin correlation [4], the (FB) longitudinal top polarization [5], etc. These new observables proposed in our previous works provide information on the underlying physics that are qualitatively different from that contained in the more common $t\bar{t}$ cross section and the integrated top FB asymmetry.

Secondly, in Ref. [4], we concluded that the A_{FB} from the Tevatron may favor some scenarios. And we try to draw some conclusions about possible new physics scenarios that might explain the observed A_{FB}. Using the integrated top FB asymmetry equation (1), we can determine C_1 and C_2. Most models considered in Ref. [4]

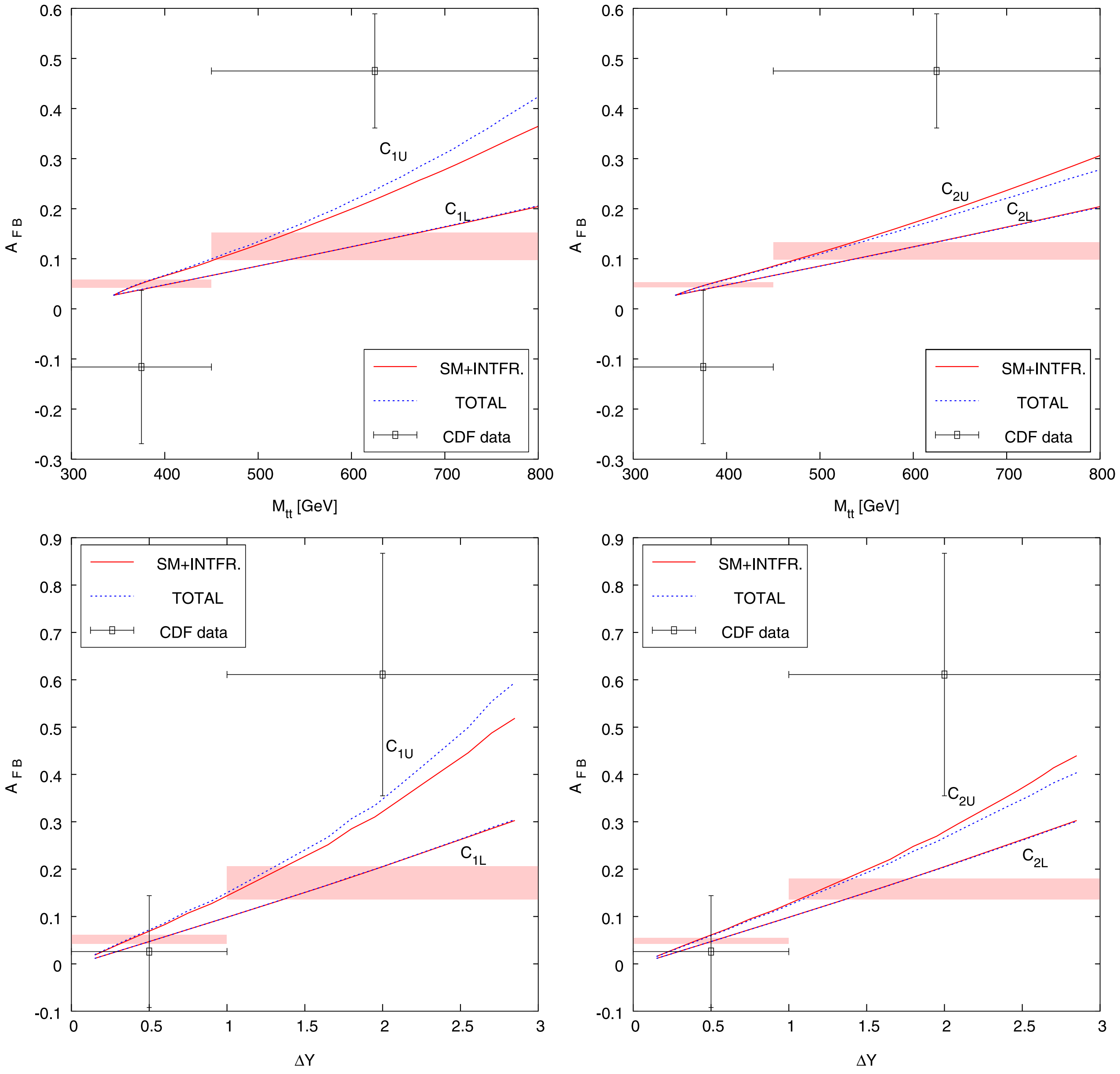

Fig. 2. Top FB asymmetry as functions of $M_{t\bar{t}}$ (upper) and Δy (lower). In the left frames we are taking C_1 in the range between $C_{1L} = 0.15$ and $C_{1U} = 0.97$ with $C_2 = 0$. In the right frames, we vary C_2 in the range between $C_{2L} = -0.15$ and $C_{2U} = -0.67$ with $C_1 = 0$. We have taken $\Lambda = 1$ TeV in both cases. In each frame, the two bands are for A_{FB} in the lower and higher $M_{t\bar{t}}$ or Δy bins varying C_1 (left) and C_2 (right) in the ranges delimited by $C_{1L,1U}$ and $C_{2L,2U}$, respectively, and the dots for the CDF data with errors. In the solid (red in the web version) lines, we include only the SM contribution and the one from the interference between the SM and NP amplitudes while the effects of $(\mathrm{NP})^2$ term have been added in the dotted (blue in the web version) lines.

predict that only one of C_1 or C_2 is nonzero. In order to simplify the discussions, we extract C_1 assuming $C_2 = 0$, and vice versa[2]:

$$(C_1, C_2) = (0.15 \sim 0.97, 0) \quad \text{or}$$
$$(C_1, C_2) = (0, -0.67 \sim -0.15), \tag{7}$$

taking $\Lambda = 1$ TeV. For these two different cases with the 1-σ allowed range, we show the predictions on A_{FB} as functions of $M_{t\bar{t}}$ and $\Delta y \equiv y_t - y_{\bar{t}}$ in Fig. 2. Note that A_{FB} increases monotonically in both cases as anticipated in earlier discussions. In order to check the validity of the effective Lagrangian approach, we also show the plots with the $(\mathrm{NP})^2$ contributions added to the interference terms between the SM and the NP amplitudes in the dotted lines in each frame. The differences between the two cases are too small to be discernible in the cases denoted by C_{1L} and C_{2L}, while they are well below the $\sim$20% level for the cases of C_{1U} and C_{2U} over the whole regions of $M_{t\bar{t}}$ and Δy. Therefore, we can conclude that the effective Lagrangian approach for these two choices of C_i's may be a good approximation. We also show our predictions for the two-bins in the $M_{t\bar{t}}$ and Δy by the horizontal bands, and the CDF data [1] by the dots together with the error bars. Our prediction

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[2] Recently QCD corrections to the dim-6 operators describing $q\bar{q} \to t\bar{t}$ have been calculated, and the effective couplings C_1 and C_2 have been determined using the mass dependent top FB asymmetry [11]. The size of QCD corrections is about 10%, but the resulting effective coupling is $\sim$3 times larger than our values. This difference in C_i's is another sign that we don't have a consistent description for the integrated and the mass dependent top FB asymmetries within the effective Lagrangian approach. We would like to note that the values obtained in Ref. [11] is too large for the effective Lagrangian description to be a good approximation. The effects of $(\mathrm{NP})^2$ term are too large compared with those of the interference term.

based on the effective Lagrangian approach is away from the CDF data more than 2-σ, although the experimental uncertainties are quite large at present. If this discrepancy in the mass dependent FB asymmetry remains even if more data is accumulated and analyzed and the central value of the integrated top FB asymmetry is more or less the same as the current value equation (1), it would indicate that the effective Lagrangian approach may not give a proper description for the top FB asymmetry at the Tevatron.[3] In such a case, it is very likely that the mass dependent (or Δy dependent) FB asymmetry shows nonlinear behavior, changing the shape.

4. Implications for the model building

Finally, we wish to note that the current CDF and D0 data do not favor any particular type of new physics scenario.[4] New color octet vector boson with both vector and axial vector couplings to both light quarks and top quark can do the job. Also t-channel exchanges of W' or Z' with flavor changing, or u-channel color antisextet scalar exchange are also fine. Whichever the final solution may be, all the solutions have a common feature of flavor dependent interactions in order to explain the top FB asymmetry measured at the Tevatron. It seems to be very challenging to construct realistic flavor models which can explain the top $A_{\rm FB}$ without conflict with stringent constraints from flavor changing neutral current (FCNC) processes (especially from the down-quark sector).

Since there are a few phenomenologically acceptable models with nontrivial flavor dependent interactions, it would be interesting to make them mathematically consistent and realistic, in the sense that the model is anomaly free, renormalizable and equipped with all the necessary fields necessary for realistic Yukawa couplings. For example, if we consider a leptophobic $U(1)'$ which is anomalous, we have to include extra fermions in order to cancel all the gauge anomalies. If there are any colored or charged stable particles, we may have to add extra fields in order to have those particles decay. Furthermore, if $U(1)'$ is chiral, then one has to introduce new $U(1)'$-charged Higgs doublets in order to allow renormalizable Yukawa couplings for the SM quarks. Recently such a model has been constructed in Ref. [20], where the $U(1)'$ flavor models for a light Z' with nonzero coupling to $t_R - u_R$ of Ref. [15] was implemented with additional $U(1)'$ charged Higgs doublets. These new Higgs doublets make contributions to the top FB asymmetry as well as the same sign top pair productions, and make the light Z' scenario for the top FB asymmetry still safe from the same sign top pair production. Also the model has a natural housing for the CDF Wjj excess through $p\bar{p} \to H^\pm \to W^\pm Z'$ followed by $Z' \to jj$. See Ref. [20] for more details.

5. Conclusion

In this Addendum, we make predictions for $A_{\rm FB}$ as functions of $M_{t\bar{t}}$ and Δy assuming that the new physics effects could be described by dim-6 contact interactions [4,5], and compared with the recent data from the CDF Collaboration. Since our predictions are made at the parton level for the final state, we can compare with the two bin analysis with the unfolded data of Ref. [1]. And it is not possible to compare them directly with the full $M_{t\bar{t}}$ dependence of $A_{\rm FB}$ presented in Ref. [7]. Still we can talk about the general tendency of $A_{\rm FB}(M_{t\bar{t}})$ and $A_{\rm FB}(\Delta y)$. Unlike some recent claims, we cannot draw definite conclusions about which type of new physics model is favored by the data, beyond the level of our previous works [4,5]. In particular, it is still viable that the new particle mass is high enough and it cannot be produced directly at the Tevatron. If we remind the old PETRA data on the muon FB asymmetry measured at $\sqrt{s} = 34$ GeV which is far below the new particle mass ($M_Z = 91$ GeV), it is conceivable that the new physics scale that is relevant to the Tevatron top FB asymmetry could be in fact very large (with the order of a few TeV), and thus unlikely to be produced even at the LHC. In such case, our effective Lagrangian becomes very powerful, and one can get deep information about the chiral structure of the new physics using the total cross sections, $A_{\rm FB}$ (differential or integrated), and the (anti)top longitudinal polarizations [5].

Note added in proof

While we were finishing this work, we became to be aware of new estimates of the SM contributions to the top FB asymmetry [21,22], which is significantly larger than the previous prediction. If these new estimates are confirmed, the tension between the SM prediction and the data would be weaker, and the new physics contributions will be significantly smaller. Then the effective Lagrangian approach proposed in Refs. [4,5] will become more relevant than before.

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[3] It is interesting to note that our predictions obtained from the total $A_{\rm FB}$(CDF) equation (1) by the use of the effective Lagrangian approach are more consistent with the flatter D0 two-bin data though we could not use the not-yet-unfolded D0 data in our analysis.

[4] For some earlier consideration of particular new physics scenarios for the top $A_{\rm FB}$, we refer to, for example, Refs. [12–19].