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Effective field theory for top physics

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Summary. — We study the top forward-backward asymmetry (FBA $\equiv A_{\mathrm{FB}}$) reported by CDF and D0 Collaborations in the effective Lagrangian approach. Using dimension-6 effective Largrangians for $q\bar{q} \to t\bar{t}$, we study the $t\bar{t}$ production cross section and the A_{FB}, and a few observables: the FB spin-spin correlation that is strongly correlated with the A_{FB}, and longitudinal top polarization as a new probe of chiral structures for possible new physics scenarios.

PACS 14.65.Ha – Top quarks.
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1. – Introduction

Top quark is the heaviest particle observed so far, and could be sensitive to the underlying physics of electroweak symmetry breaking. So far there is no clear deviation from the SM predictions, possibly except for the A_{FB} observed at the Tevatron

$$A_{\mathrm{FB}}(\mathrm{CDF}) = (0.158 \pm 0.074), \qquad A_{\mathrm{FB}}(\mathrm{D0}) = (0.196 \pm 0.065), \tag{1}$$

compared with the SM prediction $A_{\mathrm{FB}} \sim 0.078$ [1]. This $\sim$ 1–2σ deviation and the mass-dependent A_{FB} might be due to some new physics. On the other hand, search for a new resonance decaying into $t\bar{t}$ pair has been carried out at the Tevatron. As of now, there is no clear signal for such a new resonance. And the $t\bar{t}$ production cross section is well described by the SM. Therefore, in this paper, I will consider the case where a new physics scale relevant to A_{FB} is large enough so that production of a new particle is beyond the reach of the Tevatron [2-4]. Then it is adequate to integrate out the heavy fields, and use the resulting effective Lagrangian in order to study new physics effects on $\sigma_{t\bar{t}}$ and A_{FB} in a model independent way. At the Tevatron, the $t\bar{t}$ production is dominated by $q\bar{q} \to t\bar{t}$, and it would be sufficient to consider dimension-6 four-quark operators (the so-called contact interaction terms) to describe the new physics effects on the $t\bar{t}$ production at the Tevatron. Note that a similar approach was adopted for the dijet production to constrain the composite scale of light quarks for long time. Before proceeding to the main topics of this paper, let us recall that similar approaches were taken in refs. [5-7]. Also, there are effective field theory approaches for the same-sign top pair production [8].

2. – Effective field theory for top physics and new physical observables

Our starting point is the effective Lagrangian with dimension-6 operators relevant to the $t\bar{t}$ production at the Tevatron [2]

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} \left[C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A)(\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A)(\bar{t}_B T^a \gamma^\mu t_B) \right], \tag{2}$$

where $T^a = \lambda^a/2$, $\{A, B\} = \{L, R\}$, and $L, R \equiv (1 \mp \gamma_5)/2$ with $q = (u, d)^T, (c, s)^T$. Using this effective Lagrangian, we calculate the cross section up to $O(1/\Lambda^2)$, keeping only the interference term between the SM and new physics contributions.

We make one comment: the chromomagnetic operators of dim-5 would be generated at one loop level, whereas the $q\bar{q} \to t\bar{t}$ operators can be induced at tree level. Therefore the chromomagnetic operators will be suppressed further by $g_s/(4\pi)^2 \times$ (*loop function*), compared with the dim-6 operators we consider in this paper. Therefore we will ignore chromomagnetic operators in this paper. (See refs. [5-7] for the discussion on this operator.)

Neglecting the transverse polarizations, the squared amplitude summed (averaged) over the final (initial) colors is given by

$$\overline{|\mathcal{M}|^2} = \frac{g_s^4}{\hat{s}^2} \left\{ \mathcal{D}_0 + \mathcal{D}_1 (P_L + \bar{P}_L) + \mathcal{D}_2 (P_L - \bar{P}_L) + \mathcal{D}_3 P_L \bar{P}_L \right\}, \tag{3}$$

where P_L and $\bar{P}_L$ are the longitudinal polarizations of t and $\bar{t}$ [3].

The unpolarized coefficient $\mathcal{D}_0$ leads to the total cross section $\sigma_{t\bar{t}}$ and the forward-backward asymmetry $A_{\rm FB}$. On the other hand, the coefficient $\mathcal{D}_3$ gives the spin-spin correlations C and $C_{\rm FB}$ considered and suggested before

$$\begin{aligned} \mathcal{D}_0 \simeq \frac{4}{9} \Bigg\{ & 2 m_t^2 \hat{s} \left[1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_{\hat{\theta}}^2 \\ & + \frac{\hat{s}^2}{2} \left[\left(1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right) (1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_{\hat{\theta}} \right] \Bigg\}, \end{aligned} \tag{4}$$

where $\hat{s} = (p_1 + p_2)^2$, $\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}$, and $s_{\hat{\theta}} \equiv \sin\hat{\theta}$ and $c_{\hat{\theta}} \equiv \cos\hat{\theta}$, with $\hat{\theta}$ being the polar angle between the incoming quark and the outgoing top quark in the $t\bar{t}$ rest frame. And the couplings are defined as: $C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}$ and $C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$. Since we have kept only up to the interference terms, there are no contributions from the color-singlet operators with coupling C_{1q}^{AB}. The term linear in $\cos\hat{\theta}$ could generate the forward-backward asymmetry which is proportional to $\Delta C \equiv (C_1 - C_2)$. Note that both light quark and top quark should have chiral couplings to the new physics in order to generate $A_{\rm FB}$ at the tree level (namely $\Delta C \neq 0$). This parity violation, if large, could be observed in the nonzero (anti)top spin polarization [3]. The allowed region in the (C_1, C_2) plane that is consistent with the Tevatron data at the 1σ level is around $0.15 \lesssim C_1 \lesssim 0.97$ and $-0.67 \lesssim C_2 \lesssim -0.15$ for $\Lambda = 1\,\text{TeV}$. The positive C_1 and the negative C_2 are preferred at the 1σ level [2, 3].

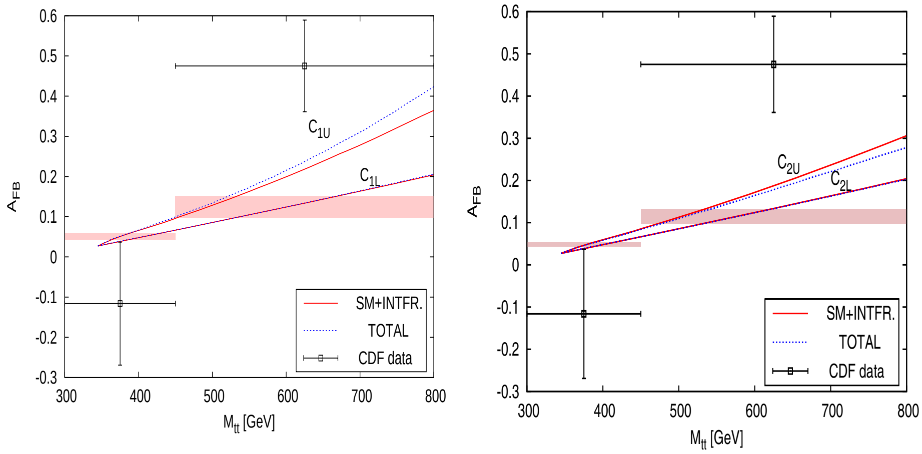

Fig. 1. – (Color online) Top FB asymmetry as functions of $M_{t\bar{t}}$. In the left frames we are taking C_1 in the range between $C_{1L} = 0.15$ and $C_{1U} = 0.97$ with $C_2 = 0$. In the right frames, we vary C_2 in the range between $C_{2L} = -0.15$ and $C_{2U} = -0.67$ with $C_1 = 0$. In each frame, the two bands are for $A_{\rm FB}$ in the lower and higher $M_{t\bar{t}}$ 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) lines, we include only the SM contribution and the one from the interference beween the SM and NP amplitudes while the effects of $(NP)^2$ term have been added in the dotted (blue) lines.

Another interesting observable which is sensitive to the chiral structure of new physics affecting $q\bar{q} \to t\bar{t}$ is the top quark spin-spin correlation [2]

$$C = \frac{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) - \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) + \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}\,. \tag{5}$$

Since new physics must have chiral couplings both to light quarks and top quark, the spin-spin correlation defined above will be affected. In ref. [2], we proposed a new spin-spin FB asymmetry C_{FB} defined as $C_{FB} \equiv C(\cos\theta \geq 0) - C(\cos\theta \leq 0)$, where $C(\cos\theta \geq 0(\leq 0))$ implies that the cross sections in the numerator of eq. (5) are obtained for the forward (backward) region: $\cos\theta \geq 0(\leq 0)$. In ref. [2], it was noticed that there is a clear strong correlation between C_{FB} and A_{FB}. This correlation must be observed in the future measurements if the $A_{\rm FB}$ anomaly is real and a new particle is too heavy to be produced at the Tevatron.

One can also make predictions of the $A_{\rm FB}$ as functions of $M_{t\bar{t}}$ [9], which are shown in fig. 1. Our results based on the effective Lagrangian approach are significantly smaller than the CDF and D0 data. If this deviation is confirmed in the future analysis, it would imply that the effective Lagrangian approach is not adequate to describe the top FB asymmetry at the Tevatron, and one has to consider various explicit models one by one, and investigate which model describes all the data in a consistent way.

The other P-violating coefficient $\mathcal{D}_2$ could be observable at the Tevatron, revealing genuine features of new physics responsible for $A_{\rm FB}$. Explicitly, we have obtained

$$\mathcal{D}_2 \simeq \frac{\hat{s}}{9\,\Lambda^2}\left[(C_1' + C_2')\hat{\beta}_t(1 + c_{\hat{\theta}}^2) + (C_1' - C_2')(5 - 3\hat{\beta}_t^2)c_{\hat{\theta}}\right], \tag{6}$$

with $C_1' \equiv C_{8q}^{RR} - C_{8q}^{LL}$, $C_2' \equiv C_{8q}^{LR} - C_{8q}^{RL}$. Therefore $\mathcal{D}_2$ will provide additional information on the chiral structure of new physics in $q\bar{q} \to t\bar{t}$. For definiteness, we consider the two new observables

$$D \equiv \frac{\sigma(t_R\bar{t}_L) - \sigma(t_L\bar{t}_R)}{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) + \sigma(t_L\bar{t}_R) + \sigma(t_R\bar{t}_L)}\,, \tag{7a}$$

$$D_{\rm FB} \equiv D(\cos\hat{\theta} \geq 0) - D(\cos\hat{\theta} \leq 0), \tag{7b}$$

which involve the sum and difference of the coefficients C_1' and C_2', respectively. We found that $|D|$ and $|D_{\rm FB}|$ could be as large as 0.1 in the region $|C_{1,2}'\,(1\,{\rm TeV}/\Lambda)^2| \lesssim 1$ [3]. Note that there are no experimental constraints on the D and $D_{\rm FB}$ observables yet.

3. – Possible underlying physics?

Now we study specific new physics that could generate the relevant dim-6 operators with corresponding Wilson coefficients (please refer to refs. [2,3] for the definitions of the interaction Lagrangians). It is impossible to exhaust all the possibilities, and we consider the following interactions of quarks with spin-1 flavor-conserving (FC) color-octet V_{8A}^a vectors, spin-1 flavor-violating (FV) color-singlet $\tilde{V}_{1A}$ and color-octet $\tilde{V}_{8A}^a$ vectors, and spin-0 FV color-singlet $\tilde{S}_1$ and color-octet $\tilde{S}_{8A}^a$ scalars ($A = L, R$). After integrating out the heavy vector and scalar fields, we obtain the Wilson coefficients C_{8q}^{AB} with $A, B = L, R$, explicit expressions of which could be found in refs. [2,3].

TABLE I. – *New particle exchanges and the signs of induced couplings C^{AB} $(A, B = R, L)$, $C_1 - C_2$, $C_1' + C_2'$, and $C_1' - C_2'$.*

Resonance	C^{RR}	C^{LL}	C^{LR}	C^{RL}	$C_1 - C_2$	$C_1' + C_2'$	$C_1' - C_2'$	$A_{\rm FB}$
$\tilde{V}_{1R}$	$-$	0	0	0	$-$	$-$	$-$	$\times$
$\tilde{V}_{1L}$	0	$-$	0	0	$-$	$+$	$+$	$\times$
$\tilde{V}_{8R}$	$+$	0	0	0	$+$	$+$	$+$	$\surd$
$\tilde{V}_{8L}$	0	$+$	0	0	$+$	$-$	$-$	$\surd$
$\tilde{S}_{1R}$	0	0	0	$-$	$+$	$+$	$-$	$\surd$
$\tilde{S}_{1L}$	0	0	$-$	0	$+$	$-$	$+$	$\surd$
$\tilde{S}_{8R}$	0	0	0	$+$	$-$	$-$	$+$	$\times$
$\tilde{S}_{8L}$	0	0	$+$	0	$-$	$+$	$-$	$\times$
S_2^α	$-$	0	0	0	$-$	$-$	$-$	$\times$
$S_{13}^{\alpha\beta}$	$+$	0	0	0	$+$	$+$	$+$	$\surd$
V_{8R}	$\pm$	0	0	0	$\pm$	$\pm$	$\pm$	$\surd(+)$or$\times(-)$
V_{8L}	0	$\pm$	0	0	$\pm$	$\mp$	$\mp$	$\surd(+)$or$\times(-)$
V_{8R}, V_{8L}	indef.	indef.	indef.	indef.	indef.	indef.	indef.	indef.

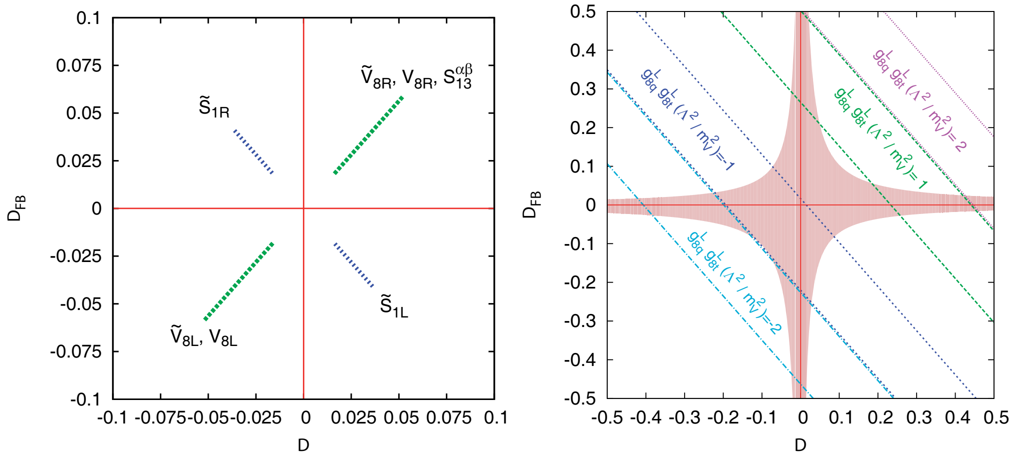

Fig. 2. – (Color online) (a) The predictions for D and D_{FB} of the models under consideration, being consistent with the $\sigma_{t\bar{t}}$ and A_{FB} measurements at the 1-σ level. We assume that only one resonance exists or dominates. (b) The predictions for D and D_{FB}, being consistent with the $\sigma_{t\bar{t}}$ and A_{FB} measurements at the 1-σ level, for several values of $g^L_{8q} g^L_{8t}\,(1\,\mathrm{TeV}/m_{V8})^2 = +2$ (magenta), $+1$ (green), -1 (blue), and -1 (sky blue), from the upper-right corner to the lower-left one. The general model with flavor-conserving color-octet V_{8R} and V_{8L} vectors is considered.

Let us first consider the FV cases. Among the FV interactions with vector or scalar bosons, $\tilde{V}_{8R,8L}$, $\tilde{S}_{1R,1L}$, and $S^{\alpha\beta}_{13}$ can give the correct sign for $(C_1 - C_2) \propto A_{\mathrm{FB}}$ [2]. But one cannot discriminate one model from another only with the A_{FB} measurement. From table I, we observe that each of the four cases with $\tilde{V}_{8R}$, $\tilde{V}_{8L}$, $\tilde{S}_{1R}$, and $\tilde{S}_{1L}$ gives a different sign combination of $C'_1 + C'_2$ and $C'_1 - C'_2$. In fig. 2, we show the prediction of each model for D and D_{FB} varying the model parameters which are consistent with the current measurements of $\sigma_{t\bar{t}}$ and A_{FB} at the 1-σ level. We observe that D and D_{FB} take the same $(+,+)$ and $(-,-)$ signs for $\tilde{V}_{8R}$ and $\tilde{V}_{8L}$, respectively, while they take different $(+,-)$ and $(-,+)$ signs for $\tilde{S}_{1L}$ and $\tilde{S}_{1R}$, respectively. The color-sextet scalar $S^{\alpha\beta}_{13}$ gives the same $(+,+)$ sign as the $\tilde{V}_{8R}$ case. Therefore, a simple sign measurement of D and D_{FB} can endow us with the model-discriminating power.

Unlike the FV cases, the FC color-octet vectors can always accommodate the positive sign of $(C_1 - C_2)$. For the case of V_{8R} (V_{8L}), the couplings g^R_{8q} (g^L_{8q}) and g^R_{8t} (g^L_{8t}) must have different signs to accommodate the positive A_{FB}. In fig. 2, we also show the predictions of the model with V_{8R} or V_{8L} vector for D and D_{FB}.

4. – Beyond the effective field theory: the case of light Z'

Before closing this paper, let me make a few comments on the new physics scenarios with spin-1 objects, such as axigluon, Z', W' or $SU(3)_{u_R}$ flavor gauge bosons. Whenever these new spin-1 particles have chiral couplings to the SM quarks, it is important to extend the SM Higgs sector too, in order that we can write (renormalizable) Yukawa couplings for all the SM fermions. One has to introduce new Higgs doublets that are charged under new gauge group, and they can affect the top FBA and the same-sign top pair production rate in general. Also the new Higgs doublets can contribute to the Wjj

signals. These points were first noticed in refs. [10, 11], and was presented by Chaehyun Yu in the poster session [12] at this workshop. It is important to make sure that all the minimal ingredients for the minimal consistent model are included before one starts phenomenological analysis.

5. – Conclusions

In this paper, we considered the $t\bar{t}$ productions at the Tevatron using dimension-6 contact interactions relevant to $q\bar{q} \to t\bar{t}$, mainly concentrating on the top FBA, (FB) spin-spin correlation, and the P-odd longitudinal (anti)top polarization of P_L and $\bar{P}_L$. The P-odd top-quark longitudinal polarization observables Both P_L and $\bar{P}_L$ can be nonzero in many new physics scenarios for the top FBA, in sharp contrast to the case of pure QCD, and can give another important clue for the chiral structure of new physics, which is completely independent of $\sigma_{t\bar{t}}$ or A_{FB}. Our results in table I and fig. 2 encode the predictions for the P-odd observables corresponding to the polarization difference $(P_L - \bar{P}_L)$ in various new physics scenarios in a compact and an effective way, when those new particles are too heavy to be produced at the Tevatron but still affect A_{FB}. If these new particles could be produced directly at the Tevatron or at the LHC, we cannot use the effective Lagrangian any more. We have to study specific models case by case including the new particles explicitly, and anticipate rich phenomenology at colliders as well as at low energy [13].

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