Effective field theory for top physics

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Summary. — We study the top forward-backward asymmetry (FBA \( \equiv A_{FB} \)) reported by CDF and D0 Collaborations in the effective lagrangian approach. Using dimension-6 effective lagrangians 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.

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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:

\[
A_{FB}(CDF) = (0.158 \pm 0.074), \quad A_{FB}(D0) = (0.196 \pm 0.065),
\]

compared with the SM prediction \( A_{FB} \sim 0.078 \) [1]. This \( \sim 1 - 2\sigma \) 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 talk, 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, 3, 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 talk, let us recall that similar approaches were taken...
in Refs. [5, 6, 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]:

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

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 $g_s/(4\pi)^2 \times (\text{loop function})$, compared with the dim-6 operators we consider in this talk. Therefore we will ignore chromomagnetic operators in this talk. (See Ref. [5, 6, 7] for the discussion on this operator.)

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

$$|\mathcal{M}|^2 = \frac{g^4}{s^2} \left\{ D_0 + D_1(P_L + \tilde{P}_L) + D_2(P_L - \tilde{P}_L) + D_3 P_L \tilde{P}_L \right\}$$

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

The unpolarized coefficient $D_0$ leads to the total cross section $\sigma_{tt}$ and the forward-backward asymmetry $A_{FB}$. On the other hand, the coefficient $D_3$ gives the spin-spin correlations $C$ and $C_{FB}$ considered and suggested before.

$$D_0 \approx \frac{4}{9} \left\{ 2m_t^2 \hat{s} \left[ 1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_\theta^2 + \frac{s_\theta^2}{2} \left[ 1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] (1 + c_\theta^2) + \hat{\beta}_t \left( \frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_\theta \right\}$$

where $\hat{s} = (p_1 + p_2)^2$, $\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}$, and $s_\theta \equiv \sin \hat{\theta}$ and $c_\theta \equiv \cos \hat{\theta}$ 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 $\Delta C \equiv \langle C_1 - C_2 \rangle$. Note that both light quark and top quark should have chiral couplings to the new physics in order to generate $A_{FB}$ 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 $1\sigma$ level is around...
Fig. 1. – 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 $A_{FB}$ 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 between the SM and NP amplitudes while the effects of $(NP)^2$ term have been added in the dotted (blue) lines.

\[
0.15 \lesssim C_1 \lesssim 0.97 \quad \text{and} \quad -0.67 \lesssim C_2 \lesssim -0.15 \quad \text{for} \quad \Lambda = 1 \text{ TeV.} \quad \text{The positive} \quad C_1 \quad \text{and the negative} \quad C_2 \quad \text{are preferred at the 1} \sigma \text{ level} \quad [2, 3].
\]

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

\[
C = \frac{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) - \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}{\sigma(t_Lt_L + t_Rt_R) + \sigma(t_Lt_R + t_Rt_L)}.
\]

(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 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 $A_{FB}$ anomaly is real and a new particle is too heavy to be produced at the Tevatron.

One can also make predictions of the $A_{FB}$ as functions of $M_{t\bar{t}}$ [9], which are shown in Fig. 2. Our results based on the effective lagrangian approach is 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 $D_2$ could be observable at the Tevatron, revealing
genuine features of new physics responsible for $A_{FB}$. Explicitly, we have obtained

$$D_2 \simeq \frac{\hat{s}}{9 \Lambda^2} \left[ (C'_1 + C'_2) \hat{\theta} (1 + c_d^2) + (C'_1 - C'_2) (5 - 3 \hat{\theta}^2) c_d \right]$$

with $C'_1 \equiv C'_{8q}^{RR} - C'_{8q}^{LL}$, $C'_2 \equiv C_{8q}^{LR} - C_{8q}^{RL}$. Therefore $D_2$ will provide additional information on the chiral structure of new physics in $q \bar{q} \rightarrow t \bar{t}$. For definiteness, we consider the two new observables:

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

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

which involve the sum and difference of the coefficients $C'_1$ and $C'_2$, respectively. We found that $|D|$ and $|D_{FB}|$ could be as large as 0.1 in the region $|C'_{1,2} (1 \text{ TeV/}\Lambda)^2| \lesssim 1$ [3]. Note that there are no experimental constraints on the $D$ and $D_{FB}$ 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] 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 $V_{8q}$ vectors, spin-1 flavor-violating (FV) color-singlet $V_{8A}$ vectors, spin-0 FV color-singlet $\bar{S}_1$ and color-octet $\bar{S}_{8A}$ scalars ($A = L, R$). After integrating out the heavy vector and scalar fields, we obtain the Wilson coefficients $C_{AB}^{8q}$ with $A, B = L, R$, explicit expressions of which could be found in Refs. [2, 3].

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 $S_{13}$ can give the correct sign for $(C_1 - C_2) \propto A_{FB}$ [2]. But one can not 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-$\sigma$ 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 the different $(+, -)$ and $(-, +)$ signs for $\tilde{S}_{1L}$ and $\tilde{S}_{1R}$, respectively. The color-octet scalar $S_{13}$ 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 $V_{8R}$ ($\tilde{V}_{8L}$), the couplings $g_{8q}^R$ ($g_{8L}^R$) and $g_{8R}^A$ ($g_{8L}^A$) 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 talk, let me make a few comments on the new physics scenarios with spin-1 objects, such as axigluon, $Z'$, $W'$ or $SU(3)_{uR}$ flavor gauge bosons. Whenever these new spin-1 particles have chiral couplings to the SM quarks, it is important to
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 $\tilde{V}$ | $C^{RR}$ | $C^{LL}$ | $C^{LR}$ | $C^{RL}$ | $C_1 - C_2$ | $C'_1 + C'_2$ | $C'_1 - C'_2$ | $A_{FB}$ |
|------------------------|---------|---------|---------|---------|-------------|-------------|-------------|--------|
| $\tilde{V}_{1R}$       | −       | 0       | 0       | 0       | −           | −           | −           | ×      |
| $\tilde{V}_{1L}$       | 0       | −       | 0       | 0       | −           | +           | +           | ×      |
| $\tilde{V}_{2R}$       | +       | 0       | 0       | 0       | +           | +           | +           | √      |
| $\tilde{V}_{2L}$       | 0       | +       | 0       | 0       | +           | −           | −           | ×      |
| $\tilde{S}_{1R}$       | 0       | 0       | 0       | −       | +           | +           | −           | √      |
| $\tilde{S}_{1L}$       | 0       | 0       | −       | 0       | +           | −           | +           | √      |
| $\tilde{S}_{2R}$       | 0       | 0       | 0       | +       | −           | −           | +           | ×      |
| $\tilde{S}_{2L}$       | 0       | 0       | +       | 0       | −           | +           | −           | ×      |
| $V_{8R}$               | ±       | 0       | 0       | 0       | ±           | ±           | ±           | √ (+) or × (−) |
| $V_{8L}$               | 0       | ±       | 0       | 0       | ±           | †           | †           | √ (+) or × (−) |
| $V_{8R}, V_{8L}$       | indef.  | indef.  | indef.  | indef.  | indef.      | indef.      | indef.      | indef. |

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 $W_{jj}$ 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 talk, we considered the $t\bar{t}$ productions at the Tevatron using dimension-6 contact interactions relevant to $q\bar{q} \rightarrow t\bar{t}$, 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
Fig. 2. – (a) The predictions for $D$ and $D_{FB}$ of the models under consideration, being consistent with the $\sigma_{\ell\ell}$ and $A_{FB}$ measurements at the 1-$\sigma$ level. We assume only one resonance exists or dominates. (b) The predictions for $D$ and $D_{FB}$, being consistent with the $\sigma_{\ell\ell}$ and $A_{FB}$ measurements at the 1-$\sigma$ level, for several values of $g_{L}^{q}g_{L}^{t}(1\text{ TeV}/m_{V})^{2} = +2$ (magenta), $+1$ (green), $-1$ (blue), and $-2$ (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.

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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