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Model independent analysis of the forward-backward asymmetry of top quark production at the Tevatron

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We perform a model independent analysis on $q\bar{q} \to t\,\bar{t}$ using an effective lagrangian with dim-6 four-quark operators, and derive necessary conditions on new physics that are consistent with the $t\bar{t}$ production cross section and the forward-backward (FB) asymmetry ($A_{\rm FB}$) measured at the Tevatron. We also propose a new FB spin-spin correlation that is strongly correlated with the $A_{\rm FB}$, and discuss possible new physics scenarios that could generate such dim-6 operators.

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1. Introduction

The $A_{\rm FB}$ of the top quark is one of the interesting observables related with top quark. Within the Standard Model (SM), this asymmetry vanishes at leading order in QCD because of C symmetry. At next-to-leading order $[O(\alpha_s^3)]$, a nonzero $A_{\rm FB}$ can develop from the interference between the Born amplitude and two-gluon intermediate state, as well as the gluon bremsstrahlung and gluon-(anti)quark scattering into $t\bar{t}$, with the prediction $A_{\rm FB} \sim 0.078$ [1]. The measured asymmetry has been off the SM prediction by 2σ for the last few years, albeit a large experimental uncertainties. The measurement in the $t\bar{t}$ rest frame before this meeting was [2]

$$A_{\rm FB} \equiv \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)} = (0.24 \pm 0.13 \pm 0.04) \tag{1.1}$$

with θ being the polar angle of the top quark with respect to the incoming proton in the $\bar{t}$ rest frame. This $\sim 2\sigma$ deviation stimulated some speculations on new physics scenarios [3, 4].

On the other hand, search for a new resonance decaying into $\bar{t}$ pair has been carried out at the Tevatron. As of now, there is no clear signal for such a new resonance [2]. Therefore, in this talk, I assume that a new physics scale relevant to $A_{\rm FB}$ is large enough so that production of a new particle is beyond the reach of the Tevatron [4], which makes a key difference between our work and other literatures on this subject [3] Then it is adequate to integrate out the heavy fields, and use the resulting effective lagrangian approach in order to study new physics effects on $\sigma_{t\bar{t}}$ and $A_{\rm FB}$. 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. A similar approach was adopted for the dijet production to constrain the composite scale of light quarks, and we are proposing the same analysis for the $t\bar{t}$ system.

2. Model independent analysis

Our starting point is the effective lagrangian with dimension-6 operators relevant to the $\bar{t}$ production at the Tevatron:

$$\mathscr{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} \left[C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A)(\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A)(\bar{t}_B T^a \gamma^\mu t_B) \right] \tag{2.1}$$

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.

It is straightforward to calculate the amplitude for $q(p_1) + \bar{q}(p_2) \to t(p_3) + \bar{t}(p_4)$ using the above effective lagrangian and the SM. The squared amplitude summed (averaged) over the final (initial) spins and colors is given by

$$\begin{aligned} \overline{|\mathscr{M}|^2} \simeq {} & \frac{4 g_s^4}{9 \hat{s}^2} \left\{ 2 m_t^2 \hat{s} \left[1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_{\hat{\theta}}^2 \right. \\ & \left. + \frac{\hat{s}^2}{2} \left[\left(1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right) (1 + c_{\hat{\theta}}^2) + \hat{\beta}_t \left(\frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_{\hat{\theta}} \right] \right\} \end{aligned} \tag{2.2}$$

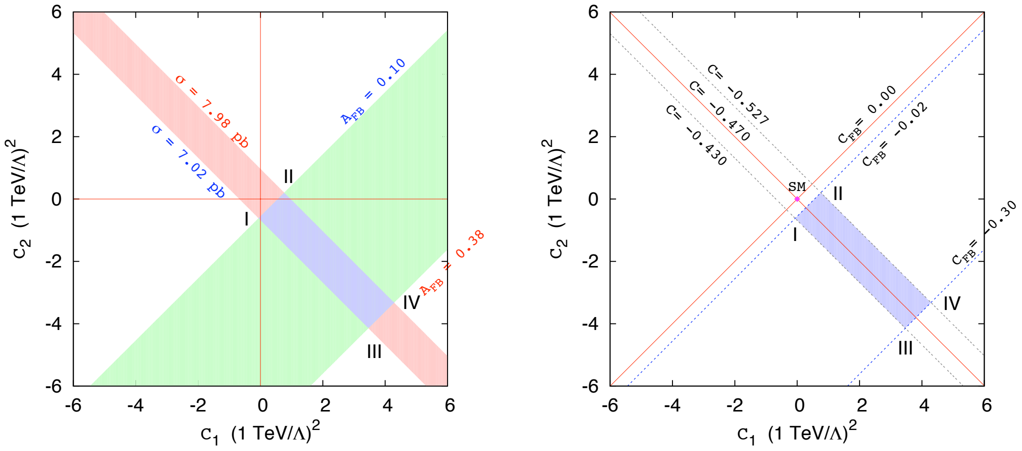

Figure 1: (a) The region in (C_1, C_2) plane that is consistent with the Tevatron data at the 1σ level: $\sigma_{t\bar{t}} = (7.50 \pm 0.48)$ pb and $A_{\rm FB} = (0.24 \pm 0.13 \pm 0.04)$. (b) the spin-spin correlations C and C_{FB}.

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 [5]. In Fig. 1, we show the allowed region in the (C_1, C_2) plane that is consistent with the Tevatron data at the 1σ level. The allowed region is around $0 \lesssim C_1 \lesssim 4$ and $-4 \lesssim C_2 \lesssim +0.5$. The negative sign of C_2 is preferred at the 1 σ level.

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 [6, 5]:

$$C = \frac{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) - \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L + t_R\bar{t}_R) + \sigma(t_L\bar{t}_R + t_R\bar{t}_L)}. \tag{2.3}$$

Since new physics must have chiral couplings both to light quarks and top quark, the spin-spin correlation defined above will be affected. From Eq. (2.3), it is clear the spin-spin correlation Eq. (4) is sensitive to $(C_1 + C_2)$, since the linear term in $\cos\hat{\theta}$ does not contribute to the correlation C after integration over $\cos\hat{\theta}$. On the other hand, if one considers the forward and the backward regions separately, the spin-spin correlation would depend on $(C_1 - C_2)$ and will be closely correlated with $A_{\rm FB}$. Therefore we propose a new spin-spin FB asymmetry C_{FB} defined as

$$C_{FB} \equiv C(\cos\theta \geq 0) - C(\cos\theta \leq 0), \tag{2.4}$$

where $C(\cos\theta \geq 0 (\leq 0))$ implies the cross sections in the numerator of Eq. (4) are obtained for the forward (backward) region: $\cos\theta \geq 0 (\leq 0)$. In Fig. 1 (b), we show the contour plots for the C and C_{FB} in the (C_1, C_2) plane along with the SM prediction at LO. There is a clear correlation between

C_{FB} and A_{FB} in Fig. 1, which 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.

3. Explicit Models

So far, we considered dim-6 four-quark operators that could affect the $t\bar{t}$ productions at the Tevatron, and found the necessary conditions for accommodating $A_{\rm FB}$. In Ref. [4], we also considered the explict models with new particles with various spins and colors that could affect $A_{\rm FB}$. We found that the four types of exchanges of V_8, $\tilde{V}_8$, $\tilde{S}_1$, and $S_{13}^{\alpha\beta}$ could give rise to the large positive $A_{\rm FB}$ at the 1-σ level (see Table I of Ref. [4] for more details). It would be interesting to search for new vector or scalar particles that satisfy the above conditions at LHC. For more quantitative discussions, we have to study the full amplitude without integrating out new heavy particles, the detailed study of which will be presented in the future work [5].

4. Conclusions

In this talk, I presented a model independent study of $t\bar{t}$ production cross section and $A_{\rm FB}$ at the Tevatron using dimension-6 contact interactions. We derived conditions for the couplings of four-quark operators that could generate the FB asymmetry observed at the Tevatron [Fig. 1]. Then we considered the $s-$, $t-$ and $u-$channel exchanges of spin-0 and spin-1 particles whose color quantum number is either singlet, octet, triplet or sextet. Our results in Fig. 1 encode the necessary conditions for the underlying new physics in a compact and an effective way, when those new particles are too heavy to be produced at the Tevatron but still affect $A_{\rm FB}$. 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, and anticipate rich phenomenology at colliders as well as at low energy. Detailed study of these issues will be discussed in the future publications [5].

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