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Full Text

Preamble

Probing Topcolor-Assisted Technicolor from Top Charge Asymmetry and Triple-Top Production at the LHC

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Abstract

In a topcolor-assisted technicolor model (TC2) with large FCNC top quark couplings, we study its correlated contributions to the top quark forward-backward asymmetry (A_{FB}) at the Tevatron, the top charge asymmetry (A_C) and the triple-top production at the LHC. Under current constraints on the top quark from the LHC and Tevatron (such as the total and differential production rates), we scan the parameter space of such a TC2 model. We find that in the allowed parameter space the TC2 model can explain the Tevatron measured A_{FB} at the 2σ level, but meanwhile significantly enhance A_C at the LHC. Such enhanced A_C , albeit currently allowed by the LHC measurement at 2σ level, will serve as a test of TC2 with the improvement of measurement precision at the LHC.

Then with all the constraints (including the requirement to explain A_{FB} at 2σ level and satisfying the current LHC measurement of A_C at 2σ level), we find that the TC2 model can induce sizable triple-top production at the 14 TeV LHC (the production rate can maximally reach 16 pb). Due to the low SM backgrounds, the triple-top production can also be a good probe for TC2 model, complementary to A_C .

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Introduction

As the heaviest particle observed so far, the top quark is speculated to play an important role in probing new physics beyond the Standard Model (SM) [?]. Since its discovery, many of the top quark properties have been firmly established, and most measurements agree well with the SM predictions, except for the top quark forward-backward asymmetry A_{FB} reported at the Tevatron [?, ?]. The CDF Collaboration measured A_{FB} based on an integrated luminosity of 5.3 fb^{-1} and obtained $A_{FB} = 15.0 \pm 5.5\%$ [?], which is larger than the SM prediction $0.056(7)$ [?, ?]. Such an anomaly has been attempted to be explained in various new physics models [?, ?, ?, ?, ?], such as models with Z' [?, ?, ?], W' [?, ?], and exotic scalars [?, ?]. In these models, new flavor-changing interactions are usually invoked and lead to other phenomenologies, such as like-sign top pair production [?, ?, ?] and single top production [?, ?, ?], which can be tested at the LHC.

As a concrete dynamical electroweak symmetry breaking model, topcolor-assisted technicolor (TC2) has recently been found capable of accounting for the top quark forward-backward asymmetry [?]. In TC2 [?, ?, ?, ?, ?], electroweak symmetry breaking (EWSB) is mainly driven by the technicolor interaction. All ordinary quark and lepton masses, including a very small portion of the top quark mass, are provided by extended technicolor, while the topcolor interactions give rise to the main part of the top quark mass and also make small contributions to EWSB. As is well known, the topcolor interactions are non-universal [?, ?, ?] and thus cause tree-level flavor-changing neutral-current (FCNC) interactions for the top quark. These new FCNC

interactions between the up quark and top quark can contribute to A_{FB} in $t\bar{t}$ production at the Tevatron through t -channel mediation by new scalars (top-pion, top-Higgs) and vector bosons (top-rho) at tree level [?]. With such contributions, the discrepancy between the experimental result and the SM prediction for A_{FB} can be significantly reduced.

On the other hand, we note that any attempts to solve the A_{FB} problem must satisfy other experimental measurements on the top quark, such as recent LHC measurements on the $t\bar{t}$ total cross section [?], the differential cross section [?, ?], and like-sign top pair production [?]. The LHC has also performed measurements on the top charge asymmetry [?, ?], which is considered a direct test of the anomalous A_{FB} at the LHC [?, ?]. In our analysis, we consider all current constraints from the LHC and Tevatron and examine the correlation between A_{FB} at the Tevatron and A_C at the LHC.

Furthermore, we note that the FCNC interactions in the TC2 model will inevitably induce triple-top ($t\bar{t}t + \bar{t}t\bar{t}$) production at tree level. Therefore, we study the TC2 contribution to triple-top production at the LHC with $\sqrt{s} = 14$ TeV while requiring TC2 to explain the A_{FB} anomaly. In the SM, triple-top can be produced in association with a W boson or a jet at leading order, and the production rates are very small [?]. Pure triple-top production (without a W or a jet) is forbidden by the GIM mechanism at tree level and highly suppressed by the non-diagonal elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix at one-loop level. In contrast, in TC2, due to large couplings between the top quark and new scalars and vector bosons, pure triple-top can be copiously produced and may be accessible at the LHC. Therefore, triple-top production may provide a new way to test the TC2 model at the LHC.

This paper is organized as follows. In Sec. II, we briefly outline the relevant features of the TC2 model. Then in Sec. III we work in TC2, present the correlation between A_{FB} and A_C , and discuss the triple-top production and its kinematical distributions. Finally, we draw our conclusion in Sec. IV.

II. The TC2 Model

Technicolor is a dynamical theory for electroweak symmetry breaking through the condensation of fermion bilinears in the vacuum. It can provide a natural way to explain the weak scale but has difficulty generating fermion masses, particularly the heavy top quark mass. On the other hand, topcolor can produce the large top quark mass but provides an incomplete explanation of EWSB. To overcome these difficulties, the topcolor-assisted technicolor model (TC2) combining the technicolor interaction with the topcolor interaction was proposed [?, ?, ?, ?, ?]. In this model, there are a number of pseudo-Goldstone bosons (PGBs) at the weak scale, such as the neutral top-pion π_t . These PGBs can induce tree-level top quark FCNC interactions arising from the top quark mass term [?]. In addition, the new strong interactions can greatly enhance the flavor-conserving top quark interaction with π_t . Therefore, these new interactions can

not only affect top pair production through t -channel at tree level and s -channel at loop level, but also lead to sizable triple-top production.

The relevant interactions are given by [?]:

$$\mathcal{L}_{\pi_t} = ig_{tt\pi_t}(\pi_t \bar{t} \gamma_5 t) + ig_{tu\pi_t}(\pi_t \bar{t}_L u_R) + ig_{tc\pi_t}(\pi_t \bar{t}_L c_R) + \text{h.c.}$$

Here $g_{ij\pi_t} = m_t/f_\pi U_{ij}^R$, where U_{ij}^R is the rotation matrix that transforms the weak eigenstates of the right-handed up-type quarks to their mass eigenstates, and f_π is the vacuum value of the top condensate, which is about 60 GeV in the NJL model. However, indirect constraints from $Z \rightarrow b\bar{b}$ require that f_π be larger than 100 GeV [?, ?, ?].

In addition, the TC2 model also predicts a CP-even scalar called the top-Higgs (h_t). Since the top-Higgs and neutral top-pion are respectively the real and imaginary parts of one complex scalar in the linear sigma model, the couplings of the top quark with the top-Higgs are given by [?]:

$$\mathcal{L}_{h_t} = g_{tth_t}(h_t \bar{t} t) + g_{tuh_t}(h_t \bar{t}_L u_R) + g_{tch_t}(h_t \bar{t}_L c_R) + \text{h.c.}$$

where g_{ijh_t} is the coupling of h_t to the up-type quarks and $g_{ijh_t} = g_{ij\pi_t}$. In our study, we also consider the lightest vector excitation of the top condensate, the top-rho, whose coupling to $t\bar{t}$ is assumed to be a free parameter [?]. After rotating the up-type quarks to the mass eigenstates, we can obtain the FCNC interactions between the top quark and top-rho [?]:

$$\mathcal{L}_\rho = g_{tt\rho} \rho^\mu \bar{t} \gamma_\mu t + g_{tc\rho} \rho^\mu \bar{t}_R \gamma_\mu c_R + g_{tu\rho} \rho^\mu \bar{t}_R \gamma_\mu u_R + \text{h.c.}$$

where $g_{ij\rho}$ is the coupling of top-rho to the quarks. Due to the larger masses for higher excited states of the $t\bar{t}$ condensate, we will not discuss them for the purpose of solving the A_{FB} problem.

As discussed in [?], a sizable $u_R - t_R$ mixing does not conflict with low-energy flavor physics constraints (such as $D - \bar{D}$ mixing and $B - \bar{B}$ mixing) given that other flavor mixings are suppressed. In our analysis, we assume only a large $g_{tu\pi_t}/h_t/\rho$ and $g_{tc\pi_t}/h_t/\rho = 0$ for simplicity [?]. Since the masses of top-Higgs and top-pion cannot be calculated from the theory, we take them as free parameters and further assume they are equal to avoid constraints from like-sign top pair production at the LHC and Tevatron. For the excited state top-rho, it is reasonable to set its mass above the ground state top-Higgs [?].

Although current LHC and Tevatron data through WW and ZZ channels have excluded a heavy mass range for the SM Higgs [?, ?], these constraints are not applicable to the TC2 scalars (top-pion and top-Higgs) because they are responsible for only a small part of EWSB. For the top-pion, parity conservation forbids couplings of $\pi_t WW$ or $\pi_t ZZ$, while for the top-Higgs, its couplings to the electroweak gauge bosons W and Z at tree level are suppressed by a factor of f_π/v_w compared with SM Higgs couplings [?] ($v_w = 174$ GeV is the electroweak vev).

III. Numerical Results and Discussions

In our calculations we take the SM parameters as [?]: $m_t = 175$ GeV, $m_Z = 91.19$ GeV, $\sin^2 \theta_W = 0.2228$, $\alpha = 1/128$. We use the parton distribution function CTEQ10L [?] with renormalization scale and factorization scale $\mu_R = \mu_F = 2m_t$ for $t\bar{t}$ production and $\mu_R = \mu_F = 3m_t$ for triple-top production. We scan the parameters in the following ranges:

$$200 \text{ GeV} < m_{\pi_t/h_t} < 500 \text{ GeV}, \quad 500 \text{ GeV} < m_\rho < 800 \text{ GeV}$$

$$1.2 < (g_{tt\pi_t}, g_{tth_t}, g_{tt\rho}) < 3.3, \quad 0.5 < (g_{tu\pi_t}, g_{tuh_t}, g_{tu\rho}) < 1.2$$

Here the upper bounds on the flavor-conserving couplings are based on the requirement of perturbativity, and the lower bounds are taken from [?], which are obtained from considerations of explaining A_{FB} while avoiding large same-sign top production.

In our study, we consider the following constraints from the LHC and Tevatron:

- (i) **The $t\bar{t}$ cross sections:** At Tevatron, based on 4.6 fb^{-1} luminosity data, the $t\bar{t}$ total cross section measured by CDF Collaboration is $\sigma_{t\bar{t}}^{\text{exp}} = 7.50 \pm 0.31_{\text{stat}} \pm 0.34_{\text{syst}} \pm 0.48_{\text{lumi}}$ pb [?], which is in good agreement with the SM prediction $\sigma(t\bar{t}) = 7.5^{+0.5}_{-0.15}$ pb [?]. Combining errors in quadrature, we get $\sigma_{t\bar{t}}^{\text{exp}} = 7.50 \pm 0.7$ pb. At LHC, CMS Collaboration has recently reported combined results corresponding to an integrated luminosity between 0.8 fb^{-1} and 1.1 fb^{-1} , which is $\sigma_{t\bar{t}}^{\text{exp}} = 165.8 \pm 2.2_{\text{stat}} \pm 10.6_{\text{syst}} \pm 7.8_{\text{lumi}}$ pb [?]. This is consistent with the SM prediction $\sigma(t\bar{t}) = 167^{+10+15}_{-17-13}$ pb [?]. In our calculations, we require the theoretical prediction (the SM value plus new physics effects) for the $t\bar{t}$ cross section to agree with experimental data at the 2σ level.
- (ii) **The $t\bar{t}$ invariant mass distribution:** Since new TC2 particles contribute to $t\bar{t}$ production through t -channel, they may distort the $t\bar{t}$ invariant mass distribution. At Tevatron, we use data from CDF Collaboration [?] and require the new physics contribution in each bin to lie within the 2σ range. At LHC, the high $t\bar{t}$ invariant mass distribution has been used to exclude heavy resonances with strong couplings to $t\bar{t}$, such as KK-gluon and axigluon [?, ?]. In our model, besides t -channel contributions, the top-pion and top-Higgs can contribute to $t\bar{t}$ production through s -channel via gluon fusion at loop level. We find they can maximally enhance the differential cross section by about 9%, which is still within the allowed range of experimental data [?].
- (iii) **Top+jet resonance in $t\bar{t}$ +jets events at Tevatron:** The new FCNC interactions will also cause single top production t (or \bar{t}) + X with X decaying to \bar{t} (or t) + jet. CDF Collaboration has recently searched for a t (or \bar{t})+jet resonance in $t\bar{t}$ +jet events and set an upper limit of 0.61 pb for $m_X = 200$ GeV and 0.02 pb for $m_X = 800$ GeV [?]. For our model,

when $m_X > 2m_t$, the new decay mode $X \rightarrow t\bar{t}$ will be dominant. Thus the main constraint on our model is in the mass range $m_X < 2m_t$.

- (iv) **The like-sign top pair production:** Although the mass degeneracy of top-pion and top-Higgs can partially evade like-sign top constraints, the top-rho can also contribute to $t\bar{t}$ production. At Tevatron, CDF Collaboration has performed an exclusive search for $t\bar{t}$ production and given an upper bound on the $t\bar{t}$ rate: $\sigma_{t\bar{t}} \leq 500$ fb [?]. At LHC, CMS Collaboration has recently published results of $t\bar{t}$ search for the light Z' model and given an upper bound of 0.67 pb on the $t\bar{t}$ production rate [?].

A. A_{FB} and A_C in TC2

In a given model, the prediction for A_{FB} at the Tevatron should be correlated to the prediction for $A_C(t\bar{t})$ at the LHC. However, while the Tevatron observed an anomaly in A_{FB} , the LHC measurement of $A_C(t\bar{t})$ is in agreement with the SM prediction [?, ?]. Recently, with an integrated luminosity of 1.09 fb^{-1} , the CMS result is $A_C^{\text{exp}}(t\bar{t}) = 0.0130 \pm 0.030_{\text{stat}}^{+0.010}_{-0.019}$ (syst.) [?], which is consistent with its SM prediction $A_C^{\text{SM}}(t\bar{t}) = 0.011(11)$ [?]. A similar result is also reported by ATLAS Collaboration but with larger uncertainty [?]. Therefore, we use the CMS result in our analysis.

[Figure 1: see original paper] shows scatter plots of the scanned parameter space projected on the plane of A_{FB} (Tevatron) versus A_C (LHC). The dots (red) and crosses (green) denote respectively the survived samples with and without the constraints (i-iv). The horizontal dashed lines (blue) show the 1σ and 2σ upper limits from the LHC data of A_C , while the vertical dashed lines (red) show the 1σ and 2σ regions from the Tevatron data of A_{FB} .

We first scan over the parameter space of TC2 and then calculate A_{FB} and A_C in this space. In [Figure 1: see original paper], we project the parameter space onto the plane of A_{FB} versus A_C . From this figure we can see the correlation between A_{FB} and A_C . Generically, the value of A_C at the LHC is proportional to the value of A_{FB} at the Tevatron because the produced top (anti-top) quark is inclined to go along (against) the valence quark direction in $t\bar{t}$ production [?]. In the TC2 model there are two new contributions to A_{FB} : one from the scalars (top-pion and top-Higgs) and the other from the vector boson top-rho. Both contribute to $t\bar{t}$ production through t -channel, which, due to the Rutherford singularity, can maximally increase the value of A_{FB} to 13.6%. However, with only the scalars' contribution, A_{FB} cannot be enhanced effectively because of spin correlation between top and anti-top quarks [?]. Thus, the vector boson top-rho plays an important role in generating a large A_{FB} . We also note that although the value of A_C becomes larger with increasing A_{FB} , most samples are still within the 2σ range of the experimental value. However, from the red dots which denote the parameter space surviving all constraints (i-iv), we can see that most parameter space has been excluded due to new like-sign top experimental results at CMS.

[Figure 2: see original paper] shows scatter plots of the survived samples: the crosses (green) are allowed by Tevatron constraints while the dots (red) are allowed by all constraints from both Tevatron and LHC. To demonstrate how strong the current LHC constraints are, we display two sets of samples in [Figure 2: see original paper]: one set (denoted by dots) allowed by all constraints from Tevatron and LHC, and the other set (denoted by crosses) allowed by Tevatron constraints but not by LHC constraints. Note that here the Tevatron constraints include the requirement that the theoretical value of A_{FB} agrees with experimental data at the 2σ level. We see that current LHC constraints are already quite stringent, able to exclude much of the parameter space allowed by Tevatron. The figure shows that LHC constraints exclude the region with large FCNC coupling $g_{tu\rho}$ (> 0.55) and light top-rho mass m_ρ (< 730 GeV). The reason is that a large $g_{tu\rho}$ and light top-rho mass may lead to a large production rate of like-sign top pair, which is not allowed by the LHC bound.

B. TC2 Contribution to Triple-Top Production at the LHC

In the TC2 model, both the FCNC couplings and flavor-conserving couplings are large, which will induce sizable triple-top production at the LHC. The main contributions are from the t -channel diagrams, as shown in [Figure 3: see original paper].

[Figure 4: see original paper] shows scatter plots of the TC2 parameter space surviving all constraints (the Tevatron constraints include the requirement that the theoretical value of A_{FB} agrees with experimental data at the 2σ level, and the LHC constraints include A_C at 2σ level), displaying the triple-top production rate at the LHC with $\sqrt{s} = 14$ TeV. The dots (red) show results with the top-rho contribution, and the crosses (green) denote the cross section without the top-rho contribution.

Since the triple-top process involves an extra free parameter $g_{t\bar{t}\rho}$, we generate its values randomly. Other parameters in the calculation are required to satisfy experimental constraints (i-iv) and solve A_{FB} at the 2σ level. The TC2 prediction for the triple-top production rate at the LHC is shown in [Figure 4: see original paper]. From this figure we see that the triple-top production cross section at the LHC (14 TeV) can maximally reach 12 pb without the top-rho contribution and 16 pb with the top-rho contribution, which may be detectable with proper reconstruction techniques [?, ?, ?]. It should be noted that since triple-top production involves an extra coupling $g_{t\bar{t}\rho}$ which does not appear in $t\bar{t}$ production, the correlation between the triple-top production rate and A_{FB} or A_C is weak.

To provide more information about triple-top production, we display some kinematical distributions of final states using Madgraph5 [?, ?]. For illustration, we take a point in the allowed parameter space which gives the largest cross section:

$$g_{tu\pi} = 1.176, \quad g_{tt\pi} = 2.39, \quad g_{tu\rho} = 0.50, \quad g_{tt\rho} = 3.136, \quad m_\pi = 588.12 \text{ GeV}, \quad m_\rho = 732.87 \text{ GeV}.$$

For this parameter set, some kinematical distributions of the cross section are shown in [Figure 5: see original paper]. From the left panel of [Figure 5: see original paper] we see a peak at about $H_T = 500$ GeV which is higher than usual SM processes. From the middle panel we see that the distribution is peaked at large $\Delta R_{t\bar{t}}$ near π , indicating that the top and anti-top quarks from the on-shell top-rho tend to go in opposite directions. From the right panel we see a peak near the mass of top-pion or top-Higgs (588 GeV) in the $t\bar{t}$ invariant mass distribution (from the parent top-pion or top-higgs), caused by on-shell decay of a top-pion or top-Higgs. It should be noted that there is not a peak around the mass of top-rho (732 GeV) due to the large decay width of the top-rho. All these features may be helpful for detecting the triple-top signal at the LHC.

IV. Conclusion

In the TC2 model we studied its correlated contributions to A_{FB} at the Tevatron, A_C and triple-top production at the LHC. Under current constraints on the top quark from the LHC and Tevatron (such as total and differential production rates), we scanned the parameter space of the TC2 model. We found that in the allowed parameter space the TC2 model can explain the Tevatron measured A_{FB} at 2σ level, but meanwhile significantly enhance A_C at the LHC. Such enhanced A_C , albeit currently allowed by the LHC measurement at 2σ level, will serve as a test of TC2 with improved measurement precision at the LHC.

Then with all constraints (including the requirement to explain A_{FB} at 2σ level and satisfying the current LHC measurement of A_C at 2σ level), we found that the TC2 model can induce sizable triple-top production at the 14 TeV LHC (the production rate can maximally reach 16 pb). Due to the low SM backgrounds, triple-top production can also be a good probe for the TC2 model, complementary to A_C .

V. Note Added

After we finished our manuscript, the CMS Collaboration published a search for events with three or more isolated leptons in pp collisions at $\sqrt{s} = 7$ TeV with an integrated luminosity of 4.98 fb^{-1} [?]. Since our triple-top production can also give a final state with three leptons, this search may be relevant to our study. We calculated the triple-top production for $\sqrt{s} = 7$ TeV (8 TeV) and found that the production rate can maximally reach 2 pb (3 pb), which, without any cuts, can give tri-lepton events below 200 (300). We checked that such a number of events is allowed by the CMS results.

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[1] For top quark reviews, see, e.g., W. Bernreuther, *J. Phys. G* **35**, 083001 (2008); D. Chakraborty, J. Konigsberg, and D. Rainwater, *Ann. Rev. Nucl. Part. Sci.* **53**, 301 (2003); E. H. Simmons, hep-ph/0211335; C.-P. Yuan, hep-ph/0203088; S. Willenbrock, hep-ph/0211067; M. Beneke et al., hep-ph/0003033; T. Han, arXiv:0804.3178.

[2] T. Aaltonen et al. [The CDF Collaboration], *Phys. Rev. D* **83**, 112003 (2011).

[3] V. M. Abazov et al. [The D0 Collaboration], arXiv:1107.4995.

[4] J. H. Kuhn and G. Rodrigo, *JHEP* **1201**, 063 (2012); W. Hollik and D. Pagani, arXiv:1107.2606 [hep-ph].

[5] Q.-H. Cao et al., *Phys. Rev. D* **81**, 114004 (2010); G. Rodrigo and P. Ferrario, *Nuovo Cim. C* **33**, 04 (2010); M. I. Gresham, I. W. Kim and K. M. Zurek, *Phys. Rev. D* **83**, 114027 (2011); J. F. Kamenik et al., arXiv:1107.5257 [hep-ph]; S. Westhoff, arXiv:1108.3341 [hep-ph]; J. A. Aguilar-Saavedra, arXiv:1202.2382 [hep-ph].

[6] D. W. Jung et al., *Phys. Lett. B* **691**, 238 (2010); arXiv:1012.0102; C. Zhang and S. Willenbrock, arXiv:1008.3869; J. A. Aguilar-Saavedra, *Nucl. Phys. B* **843**, 638 (2011); *Nucl. Phys. B* **812**, 181 (2009); C. Degrande et al., arXiv:1010.6304; K. Blum et al., arXiv:1102.3133; C. Delaunay et al., arXiv:1103.2297; J. A. Aguilar-Saavedra and M. Perez-Victoria, *Phys. Rev. D* **84**, 115013 (2011); D. Y. Shao et al., arXiv:1107.4012; S. S. Biswal et al., arXiv:1201.3668 [hep-ph].

[7] S. Jung et al., *Phys. Rev. D* **81**, 015004 (2010); S. Jung et al., *Phys. Rev. D* **83**, 114039 (2011); J. Cao et al., *Phys. Rev. D* **81**, 014016 (2010); J. Cao et al., *Phys. Rev. D* **83**, 034024 (2011); I. Dorsner et al., *Phys. Rev. D* **81**, 055009 (2010); B. Xiao et al., *Phys. Rev. D* **82**, 034026 (2010); B. Bhattacherjee et al., *Phys. Rev. D* **83**, 091501 (2011); K. M. Patel and P. Sharma, *JHEP* **1104**, 085 (2011); M. R. Buckley et al., *Phys. Rev. D* **83**, 115013 (2011); E. R. Barreto et al., *Phys. Rev. D* **83**, 054006 (2011); arXiv:1104.1497; A. Rajaraman et al., arXiv:1104.0947; M. I. Gresham et al., arXiv:1107.4364; M. Duraisamy et al., arXiv:1106.5982; B. Grinstein et al., arXiv:1108.4027; D. Kahawala et al., arXiv:1108.3301; P. Ko et al., arXiv:1108.4005; M. Frank et al., arXiv:1108.0998; F. Larios and M. A. Perez, *Phys. Rev. D* **85**, 017503 (2012).

[8] K. Cheung et al., *Phys. Lett. B* **682**, 287 (2009); K. Cheung and T. C. Yuan, *Phys. Rev. D* **83**, 074006 (2011); V. Barger et al., *Phys. Rev. D* **81**, 113009 (2010); *Phys. Lett. B* **698**, 243 (2011); K. Yan et al., *Phys. Rev. D* **85**, 034020 (2012); S. Knapen et al., arXiv:1111.5857 [hep-ph]; C. Spethmann, arXiv:1111.6576 [hep-ph]; K. S. Babu et al., *Nucl. Phys. B* **858**, 468 (2012); J. N. Ng and P. T. Winslow, *JHEP* **1202**, 140 (2012); K. Kolodziej, arXiv:1110.2103 [hep-ph].

- [9] J. Shu, T. M. P. Tait and K. Wang, Phys. Rev. D 81, 034012 (2010).
- [10] A. Arhrib et al., Phys. Rev. D 82, 034034 (2010); Z. Ligeti et al., JHEP 1106, 109 (2011); K. Blum et al., arXiv:1107.4350; L. Wang et al., arXiv:1111.4771 [hep-ph].
- [11] S. K. Gupta, arXiv:1011.4960 [hep-ph]; J. Cao et al., arXiv:1101.4456; E. L. Berger et al., Phys. Rev. Lett. 106, 201801 (2011); arXiv:1109.3202; J. A. Aguilar-Saavedra and M. Perez-Victoria, Phys. Lett. B 701, 93 (2011); C. Degrande et al., Phys. Lett. B 703, 306 (2011).
- [12] J. Cao et al., Phys. Rev. D 85, 014025 (2012).
- [13] N. Craig, C. Kilic and M. J. Strassler, Phys. Rev. D 84, 035012 (2011); F. Penunuri, F. Larios, A. O. Bouzas, Phys. Rev. D 83, 077501 (2011); S. Jung et al., Phys. Rev. D 84, 091502 (2011); E. L. Berger et al., E. L. Berger, Q. -H. Cao, J. -H. Yu and C. -P. Yuan, Phys. Rev. D 84, 095026 (2011).
- [14] Y. Cui, Z. Han and M. D. Schwartz, JHEP 1107, 127 (2011).
- [15] C. T. Hill, Phys. Lett. B 345, 483 (1995); K. Lane and E. Eichten, Phys. Lett. B 352, 382 (1995), Phys. Lett. B 433, 96 (1998); G. Cvetič, Rev. Mod. Phys. 71, 513 (1999); E. Malkawi and C. P. Yuan, Phys. Rev. D 61, 015007 (2000), Phys. Lett. B 385, 304 (1996); C. T. Hill and E. H. Simmons, Phys. Rept. 381, 235 (2003) [Erratum-ibid. 390, 553 (2004)].
- [16] V. A. Miransky et al., Phys. Lett. B 221, 177 (1989); W. A. Bardeen et al., Phys. Rev. D 41, 1647 (1990); C. T. Hill, Phys. Lett. B 266, 419 (1991).
- [17] <http://cdsweb.cern.ch/record/1401250>
- [18] <http://cdsweb.cern.ch/record/1369186/files/ATLAS-CONF-2011-095>; CMS Collaboration, arXiv:1107.4771 [hep-ex].
- [19] <http://cdsweb.cern.ch/record/1422425>
- [20] <http://cdsweb.cern.ch/record/1434376>
- [21] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 709, 28 (2012).
- [22] <http://cdsweb.cern.ch/record/1372916/files/ATLAS-CONF-2011-106>
- [23] J. L. Hewett et al., arXiv:1103.4618; J. A. Aguilar-Saavedra and M. Perez-Victoria, arXiv:1105.4606 [hep-ph]; arXiv:1107.0841 [hep-ph]; arXiv:1107.2120 [hep-ph]; J. A. Aguilar-Saavedra, A. Juste and F. Rubbo, arXiv:1109.3710 [hep-ph]; J. F. Arguin, M. Freytsis and Z. Ligeti, arXiv:1107.4090 [hep-ph].
- [24] V. Barger, W. -Y. Keung and B. Yencho, Phys. Lett. B 687, 70 (2010).
- [25] G. Buchalla, G. Burdman, C.T. Hill and D. Kominis, Phys. Rev. D 53, 5185 (1996); H. -J. He and C. P. Yuan, Phys. Rev. Lett. 83, 28 (1999); G. Burdman, Phys. Rev. Lett. 83, 2888 (1999); G. Burdman, K. D. Lane and T. Rador, Phys. Lett. B 514, 41 (2001); P. J. Fox, Z. Ligeti, M. Papucci, G. Perez and M. D. Schwartz, Phys. Rev. D 78, 054008 (2008).

- [26] C. T. Hill and X. -m. Zhang, Phys. Rev. D 51, 3563 (1995); G. Buchalla and D. Kominis, Phys. Lett. B 403, 101 (1996); F. Braam, M. Flossdorf, R. S. Chivukula, S. Di Chiara and E. H. Simmons, Phys. Rev. D 77, 055005 (2008).
- [27] R. S. Chivukula et al., Nucl. Phys. B 343, 554 (1990)
- [28] [ATLAS Collaboration], arXiv:1202.1408 [hep-ex]; S. Chatrchyan et al. [CMS Collaboration], arXiv:1202.1488 [hep-ex].
- [29] C. Amsler et al., Particle Data Group, Phys. Lett. B 667, 1 (2008).
- [30] J. Pumplin et al., Phys. Rev. D 82, 074024 (2010).
- [31] CDF results from <http://www-cdf.fnal.gov/>; V. M. Abazov et. al. [D0 Collaborations], arXiv:0903.5525 [hep-ex].
- [32] M. Cacciari, S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, JHEP 0809, 127 (2008) [arXiv:0804.2800 [hep-ph]].
- [33] V. Ahrens, M. Neubert, B. D. Pecjak, A. Ferroglia and L. L. Yang, Phys. Lett. B 703, 135 (2011).
- [34] T. Aaltonen et al. [CDF Collaboration], arXiv:1108.0101 [hep-ex].
- [35] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 102, 222003 (2009) [arXiv:0903.2850 [hep-ex]].
- [36] http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf_10776_ttj.pdf
- [37] <http://cdsweb.cern.ch/record/1369205/files/TOP-11-014-pas>
- [38] B. S. Acharya et al., arXiv:0901.3367 [hep-ph].
- [39] J. A. Aguilar-Saavedra and J. Santiago, Phys. Rev. D 85, 034021 (2012).
- [40] F. Maltoni and T. Stelzer, JHEP 0302, 027 (2003); J. Alwall et al., JHEP 0709, 028 (2007); J. Alwall et al., JHEP 1106, 128 (2011).
- [41] S. Chatrchyan et al. [CMS Collaboration], CMS-SUS-11-013.

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