Top-quark forward-backward asymmetry from a color-octet *t*-channel resonance

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We consider new physics contributions to the top-quark forward-backward asymmetry from a neutral V_8^0 or charged V_8^+ color-octet vector exchanged in the *t* channel. We study the phenomenological constraints on these particles arising from the Tevatron and LHC7 measurements and compare them with those on their color-singlet counterparts Z' and W'. We find that the color octets fare better than the singlets in that they generate a lower A_C, a lower high-invariant mass cross section at LHC7 and a lower same sign top-pair cross section. However, they also generate a lower A_{FB} than their color-singlet counterparts.

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I. INTRODUCTION

The forward-backward asymmetry was first observed in top-quark pair production at the Tevatron D0 experiment, $A_{\text{FB}} = (19.6 \pm 6.5)\%$ [1], to be larger than the standard model (SM) expectation of around 6% [2,3]. Although this effect is only at the two standard deviation level, it remains a hint at possible new physics after improved measurements and calculations.

Since the first D0 result, the asymmetry measurement has been repeated by both D0 and CDF with increased luminosity with the latest CDF result being obtained with 9.4 fb^{-1} [4]. The corresponding theoretical predictions have been improved to beyond next-to-leading order (NLO) [5] with the observation remaining about 2 sigma above the SM prediction. This situation has produced a large number of papers exploring the possibility of a new physics explanation for the deviation. Among the first possibilities considered was an axigluon [6–14] for which a window in the light mass region remains a viable option [15]. Many other models have been discussed in this context, including extra dimensions [16–18]; composite models [19,20]; models with Z' bosons [21–31]; models with W' (or both) bosons [32–38]; and models with extra scalars [39–47]. Model independent analyses in terms of effective operators also exist [48–56], as well as studies that compare different models and study the implications for observables at the LHC [57–68].

A recent comparison of models has found that it is very hard for simple models (those consisting of the exchange of one new particle) to satisfy all existing constraints from cross sections and asymmetries at the Tevatron and at the LHC [69]. Amongst these simple models there is one case that has not been studied in detail before, new vector

color-octet particles exchanged in the *t* channel. Our purpose in this paper is to consider this case, comparing our results to the color-singlet counterparts Z' and W'. More complicated models considered before in Ref. [46] include color-octet vectors that can be exchanged in the *t* channel. But this particular effect exists in isolation within that model only for the charged vector case. Reference [70] also presented a catalog of possible resonances contributing to A_{FB}, of which a neutral color-octet vector in the *t* channel is a possibility. Neither one of these papers presents a comprehensive study of the effect of color-octet resonances in the *t* channel, which we do in this paper at the MadGraph5 level.

II. OBSERVABLES

The original discrepancy with the SM prediction was observed at the Tevatron in the top-quark forward-backward asymmetry

$$A_{\text{FB}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad (1)$$

where $\Delta y = y_t - y_{\bar{t}}$ is the difference between the rapidities of the top quark and antiquark with the *z* axis taken along the proton direction. This asymmetry is equivalent to the top-quark forward-backward asymmetry in the top-quark production angle in the $t\bar{t}$ rest frame. The asymmetry has now been measured repeatedly by both D0 and CDF [1,4,71–73] with results that have been consistently above the SM expectation. Within the SM, the asymmetry originates through QCD interference effects at order $\mathcal{O}(\alpha_s^3)$. It was first predicted by Kuhn and Rodrigo [2,3,74–77] and has been revisited several times since then [78–81], including beyond NLO analysis [5]. For our study we will use the latest CDF results available [4], as well as the theory prediction quoted by CDF as obtained using the NLO event generator POWHEG,

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$$A_{\text{FB}} = (16.4 \pm 4.7)\%$$

$$A_{\text{FB}} = (6.6 \pm 2.0)\% \text{ POWHEG.} \qquad (2)$$

We will assume that potential new physics contributions are small, as supported by the agreement between theory and experiment for the $t\bar{t}$ production cross section, for example. In this case any new physics contributions to the asymmetry can be treated at leading order and simply added to the SM result. The numbers in Eq. (2) then allow for a new physics contribution to the asymmetry, adding all errors in quadrature,

$$0.05 < A_{\text{FB}}^{\text{new}} < 0.15. \qquad (3)$$

In addition to the integrated (over $t\bar{t}$ invariant mass) forward-backward asymmetry, the Tevatron experiments have also measured an approximately linear dependence of A_{FB} on m_{tt}. As a second observable to constrain new physics scenarios we adopt the high invariant mass asymmetry as reported by CDF and the corresponding theoretical prediction quoted by them in Ref. [4],

$$A_{\text{FB}}(M_{t\bar{t}} \geq 450 \text{ GeV}) = (29.5 \pm 5.8 \pm 3.3)\%$$

$$A_{\text{FB}}(M_{t\bar{t}} \geq 450 \text{ GeV}) = (10.0 \pm 3.0)\% \text{ POWHEG.} \qquad (4)$$

Again this leaves room for a new physics contribution after adding all errors in quadrature,

$$0.12 < A_{\text{FB}}^{\text{new}}(M_{t\bar{t}} \geq 450 \text{ GeV}) < 0.27. \qquad (5)$$

The total $t\bar{t}$ production cross section can also provide a powerful constraint on new physics given the good agreement between the measured and SM predicted values. The combined D0 and CDF results are given in Ref. [82] which also quotes the corresponding SM result at NNLO + NNLL QCD based on Ref. [83] for $m_t = 172.5$ GeV,

$$\sigma = 7.35^{+0.28}_{-0.33} \text{ pb SM}$$

$$\sigma = (7.60 \pm 0.41) \text{ pb D0-CDF combination} \qquad (6)$$

Adding all errors in quadrature, this allows a new physics contribution to the $p\bar{p} \to t\bar{t}$ cross section at Tevatron energies:

$$\sigma - \sigma_{\text{SM}} = (0.25 \pm 0.5) \text{ pb.} \qquad (7)$$

As first noted in Refs. [2,3], it is possible to define a related charge asymmetry for proton-proton colliders. Taking advantage of the larger average valence quark momentum than the average antiquark momentum in a proton, one of the observables that has been proposed for the LHC is a charge asymmetry defined by

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \qquad (8)$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$. This asymmetry has been measured both by CMS and ATLAS with somewhat different results, but in agreement with the SM. The CMS result compared to its SM prediction is [84]

$$A_C = 0.004 \pm 0.010 \pm 0.012$$

$$A_C = 0.0115 \pm 0.0006 \text{ SM here POWHEG} \qquad (9)$$

where the first error is statistical and the second systematic. If we again add all errors in quadrature, this leaves room for a new physics contribution to the charge asymmetry

$$-0.023 < A_C^{\text{new}} < 0.008. \qquad (10)$$

The corresponding result from ATLAS [85] is

$$A_C = 0.057 \pm 0.024 \pm 0.015$$

$$A_C = 0.006 \pm 0.002 \text{ SM here} \qquad (11)$$

which allows a new physics contribution

$$0.023 < A_C^{\text{new}} < 0.08. \qquad (12)$$

Other related asymmetries have been proposed and measured at the LHC but we will only use A_C for the reconstructed $t\bar{t}$ pair in this paper. As with the Tevatron, the total cross section also places severe constraints on potential new physics. The theoretical [83], ATLAS [86] and CMS [87] numbers for 7 TeV collisions at the LHC are respectively given by

$$\sigma = 172 \text{ pb SM}$$

$$\sigma = (177 \pm 3^{+8}_{-7} \pm 7) \text{ pb ATLAS}$$

$$\sigma = (161.9 \pm 2.5^{+5.1}_{-5.0} \pm 3.6) \text{ pb CMS.} \qquad (13)$$

The theory uncertainties from scale dependence and parton distribution functions are estimated at about 3% each. The CMS and ATLAS uncertainties quoted correspond to statistical, systematic and luminosity in that order. Adding all errors in quadrature and using the ATLAS result allows a new physics contribution to the cross section

$$\sigma - \sigma_{\text{SM}} \leq 18 \text{ pb.} \qquad (14)$$

The CMS result, being below the SM prediction, would constrain new physics contributions to the cross section much more severely; our results using Eq. (14) would be in agreement with the CMS result at about the 3σ level.

In addition to the total cross section, it has been pointed out that the high tail cross section at the LHC provides

another constraint on new physics [64,65]. In Ref. [88] ATLAS reported that in the combined lepton plus jets channels at 7 TeV with 2.05 fb^{-1} the high mass tail cross section

$$\frac{\sigma(pp \to t\bar{t})(m_{t\bar{t}} > 950 \text{ GeV})}{\sigma(pp \to t\bar{t})} = (1.2 \pm 0.5)\%, \quad (15)$$

about 1σ below the theoretical prediction. This has been converted into a 99% C.L. upper limit $\sigma/\sigma_{\text{SM}} \leq 1.3$ in this mass bin in Ref. [69]. The CMS result is a bit higher than the ATLAS result but uses different binning [89].

Finally, for the case of a neutral new particle such as a Z', it is known that there is a strong constraint from same charge top-pair production at the LHC [25–27]. The experimental limit from LHC7 at 95% C.L. for the inclusive cross section from ATLAS is

$$\sigma(pp \to tt) < 4 \text{ pb} \quad (16)$$

and the limit from CMS is weaker [90].

III. VECTOR COLOR OCTETS IN THE t CHANNEL

As already mentioned, our aim in this paper is to complete the picture of simple new physics contributions to the top-quark forward-backward asymmetry by considering the t-channel exchange of spin one color-octet resonances. These resonances may arise, for example, in technicolor models as color-octet neutral or charged technirhos [91–93]. The origin of these resonances, however, is not relevant for our phenomenological analysis which will simply follow from the effective Lagrangian

$$\mathcal{L} = -\frac{g_{W_R}}{2}\bar{t}\gamma_\mu T_a(1+\gamma_5)d V_8^{+\mu} - \frac{g_{Z_R}}{2}\bar{t}\gamma_\mu T_a(1+\gamma_5)u V_8^{0\mu}$$
$$+ \text{H.c.} \quad (17)$$

The form chosen is of course motivated by the existing studies of Z' and W' contributions. In particular the flavor structure is chosen to maximize the contribution to the A_{FB}, as is the use of right-handed couplings. We will find it useful to compare our results to those of Z' and W' models in the form

$$\mathcal{L} = -\frac{g_{W_R}}{2}\bar{t}\gamma_\mu(1+\gamma_5)d V^{+\mu} - \frac{g_{Z_R}}{2}\bar{t}\gamma_\mu(1+\gamma_5)u V^{0\mu}$$
$$+ \text{H.c.} \quad (18)$$

It is interesting to note that a recent study of new physics contributions to A_{FB} in terms of effective four-fermion operators arising from s-channel exchanges of new particles finds that color-octet structures provide a better fit to the data [94]. That analysis does not cover our model of Eq. (17) because the color structure arising from the t-channel exchange of the new vectors does not appear

in their basis of effective operators. Our analysis of the new physics contributions will only be at leading order, thus ignoring interference between the new physics and NLO SM where the color structure could play an important role. It nevertheless differs from the color-singlet structure of Z' and W' models as in Eq. (18) because the different color structure gives a different sign to the interference terms in the differential cross section. Explicitly, the terms corresponding to the parton level process $q\bar{q} \to t\bar{t}$ including the dominant SM gluon exchange amplitude and the exchange of a t-channel $V^{0,+}$ color octet or singlet are given by

$$\frac{d\sigma}{dt} = C_{f1}\frac{g_s^4}{8\pi s^4}(2sm_t^2 + (t-m_t^2)^2 + (u-m_t^2)^2)$$
$$+ C_{f3}\frac{g_V^4}{16\pi s^2(t-m_V^2)^2}((u-m_t^2)^2(L_V^4 + R_V^4)$$
$$- 2L_V^2 R_V^2 s(t+u))$$
$$- C_{f2}\frac{g_V^2 g_s^2}{8\pi s^3(t-m_V^2)}((u-m_t^2)^2 + m_t^2 s)(L_V^2 + R_V^2))$$

$$(19)$$

where g_V and m_V refer to either g_{W_R} and m_{W_R} or to g_{Z_R} and m_{Z_R}. For purely right-handed couplings as in Eqs. (17) or (18) $R_V = 1$ and $L_V = 0$. The color factors for the case of color-singlet resonances are given by

$$2C_{f1} = C_{f2} = \frac{4}{9}, \qquad C_{f3} = 1; \quad (20)$$

and for color-octet resonances by

$$C_{f1} = C_{f3} = \frac{2}{9}, \qquad C_{f2} = -\frac{2}{27}. \quad (21)$$

The different color factors are responsible for the different weights of the new physics contributions, including a possible sign change.

IV. NUMERICAL RESULTS

For our numerical study we implement the Lagrangian of Eqs. (17) and Eq. (18) into MadGraph5 [95] with the aid of FeynRules [96]. We use the resulting model universal FeynRules output file to generate top-quark pair events for different values of couplings and masses in a range that roughly reproduces the new contribution to A_{FB} as in Eq. (3). We study the different observables discussed above for these ranges and compare the cases of color-octet and color-singlet resonances. Finally we fit the numerical results for the case of $m_V = 500$ GeV to obtain approximate expressions for cross sections and asymmetries in terms of the new couplings. The results of this fit are presented in the Appendix.

In Fig. 1 we plot the deviation in the Tevatron $t\bar{t}$ cross section from its SM value as a function of A_{FB}^{new} for one resonance at a time. The range we show is limited by the charged color octet V_8^+ which does not produce a very large A_{FB}, the points shown corresponding to $1.4 < g_{W_R} < 2$. To obtain a similar asymmetry with V_8^0 we show the range $0.8 < g_{Z_R} < 1.2$. The correlation between cross section and asymmetry exhibited in Fig. 1 for the color octets shows

that A_{FB} cannot be much larger than about 7% if the cross section is to remain within the 1σ range of Eq. (7). In the same figure we show in the right panel the case of color-singlet resonances using the ranges $0.5 < g_{W_R} < 2$ and $1.15 < g_{Z_R} < 1.4$. The color singlets allow much larger asymmetries due to the relatively larger color factor in the interference term in Eq. (19). The corresponding cross sections are also lower for the singlet as there is destructive
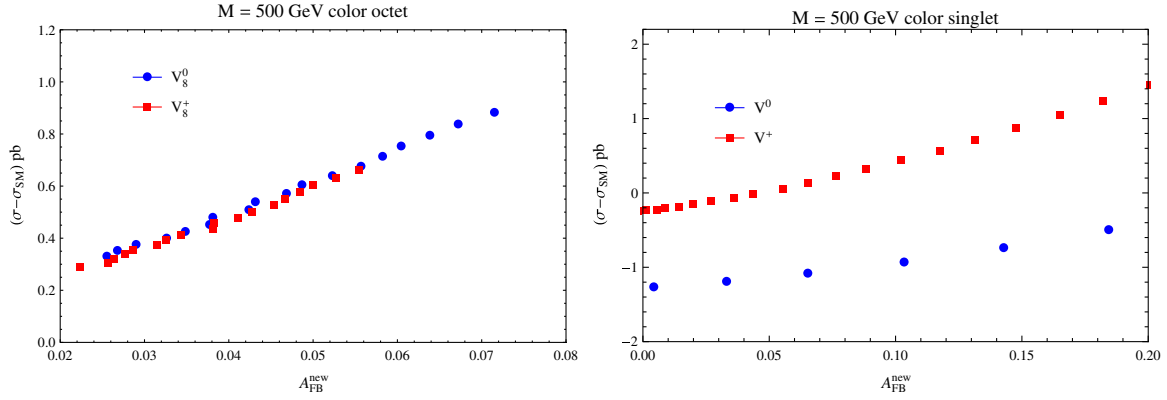

FIG. 1 (color online).   Deviation in the Tevatron cross section from its SM value as a function of A_{FB}^{new} for one resonance at a time.
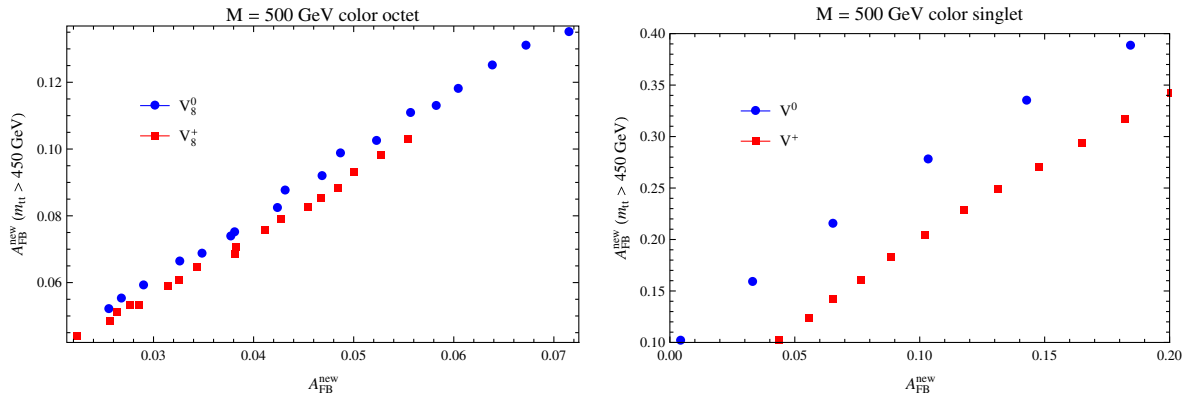

FIG. 2 (color online). $A_{FB}^{new}(m_{t\bar{t}} > 450 \text{ GeV})$ as a function of A_{FB}^{new} for one resonance at a time.
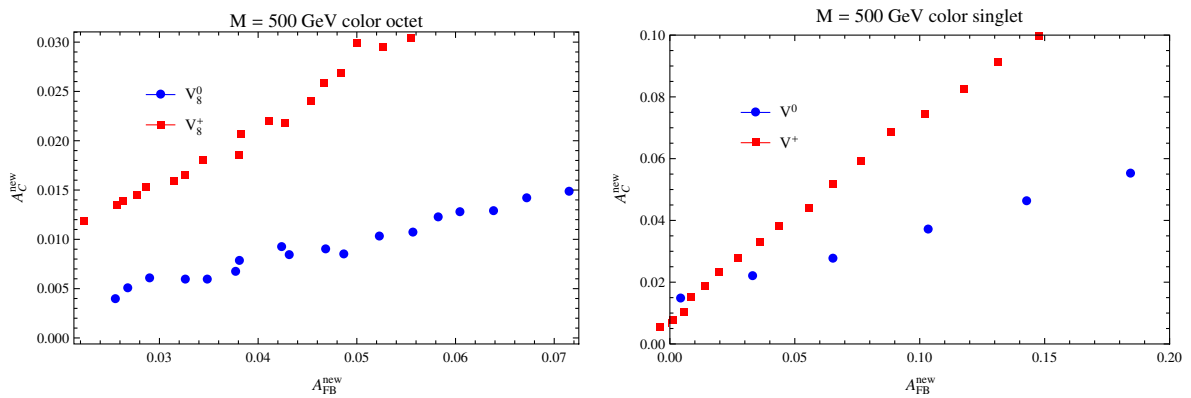

FIG. 3 (color online). A_C^{new} as a function of A_{FB}^{new} for one resonance at a time.
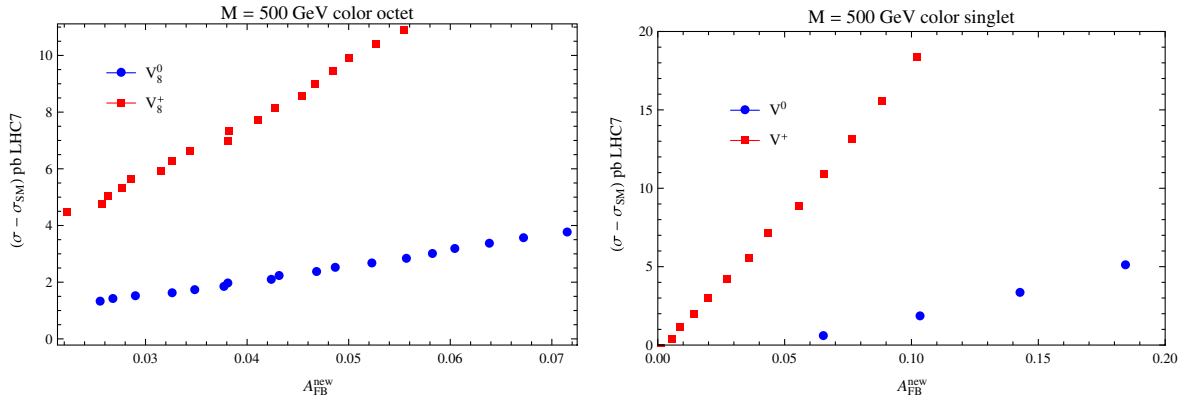
FIG. 4 (color online).   Deviation in the LHC7 cross section from its SM value as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time.
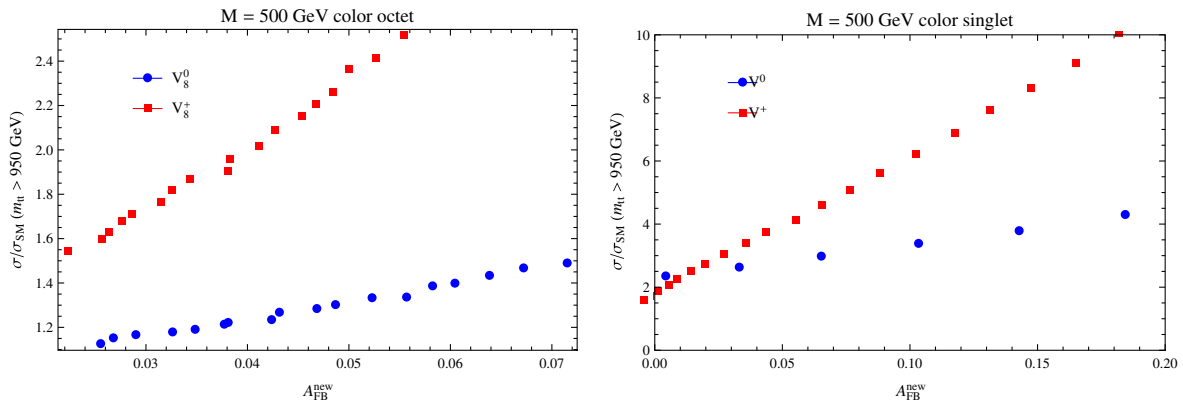

FIG. 5 (color online).   High invariant mass cross section at LHC7 as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time.

interference with the SM. In fact all the points shown in Fig. 1 for V^0 (color singlet) have a cross section below the 1σ bound of Eq. (7).

In Fig. 2 we plot the high invariant mass Tevatron asymmetry $A_{\text{FB}}^{\text{new}}(m_{t\bar{t}} > 450 \text{ GeV})$ as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time using the same couplings as in Fig. 1. The results indicate that the color-octet resonances

FIG. 6 (color online). $\sigma(pp \to tt)$ at LHC7 for the neutral bosons of mass 500 GeV.

can only reproduce the lower ends of the 1σ ranges of Eqs. (3) and (5). The right panel, corresponding to the color singlets, corroborates that a Z' tends to overpredict the high invariant mass asymmetry [63].

In Fig. 3 we plot the charge asymmetry A_C^{new} for LHC7 as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time with the same couplings used in Fig. 1. The correlation between these two observables is such that a neutral boson is preferred over a charged boson by the measured A_C. In fact, the tighter CMS constraint from Eq. (10) at the 1σ level only allows the neutral color octet. The panel on the right, again for the color singlets, corroborates that current LHC data disfavor a W' as it overpredicts A_C [63,69].

In Fig. 4 we plot the deviation in the LHC7 cross section from its SM value as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time with the same couplings used in Fig. 1. All the points shown satisfy the 1σ range from Eq. (14) obtained from the ATLAS result but the W' and its color-octet counterpart V_8^+ give the largest cross sections, possibly in conflict with the CMS measurement.

In Fig. 5 we plot the high invariant mass cross section at LHC7 as a function of $A_{\text{FB}}^{\text{new}}$ for one resonance at a time using the same couplings as in Fig. 1. Again the neutral resonances
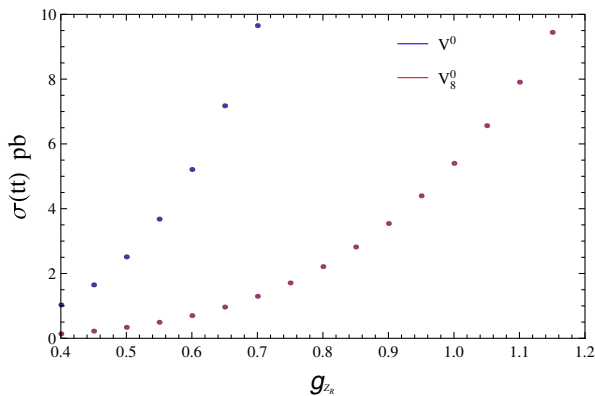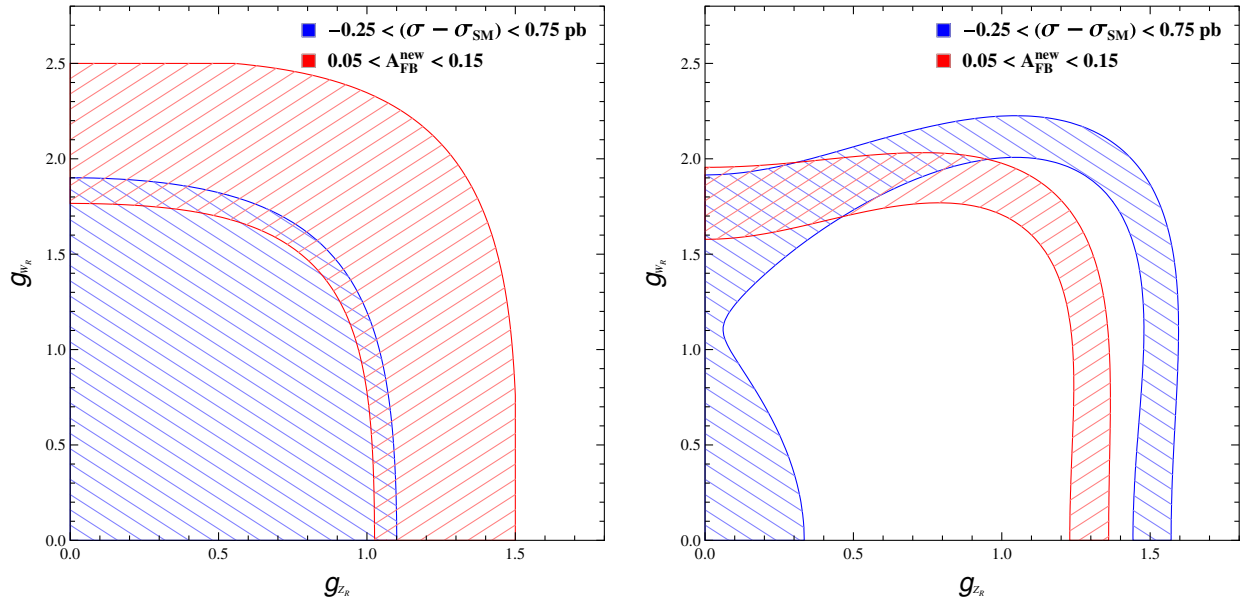
FIG. 7 (color online).   Color-octet (left panel) vs color-singlet (right panel) parameter space for couplings allowed by the Tevatron cross section and forward-backward asymmetry.

fare better than the charged ones and the color octet much better than the color singlet in a comparison with Eq. (15).

Finally in Fig. 6 we show the cross section for double top-quark production, $\sigma(pp \to tt)$, at LHC7 for the neutral bosons of mass 500 GeV. The figure indicates that the color singlet Z' quickly runs into trouble with the ATLAS limit on this process, Eq. (16), but the color octet fares better.

We now turn to the question of whether there is an optimal region in parameter space to satisfy all the constraints. To this end we use the approximate fits presented in the Appendix to produce Figs. 7, 8 and 9 where we compare the allowed regions in the $g_{W_R} - g_{Z_R}$ plane for the different observables discussed above. Figure 7 shows a cross section and an asymmetry at the Tevatron that are
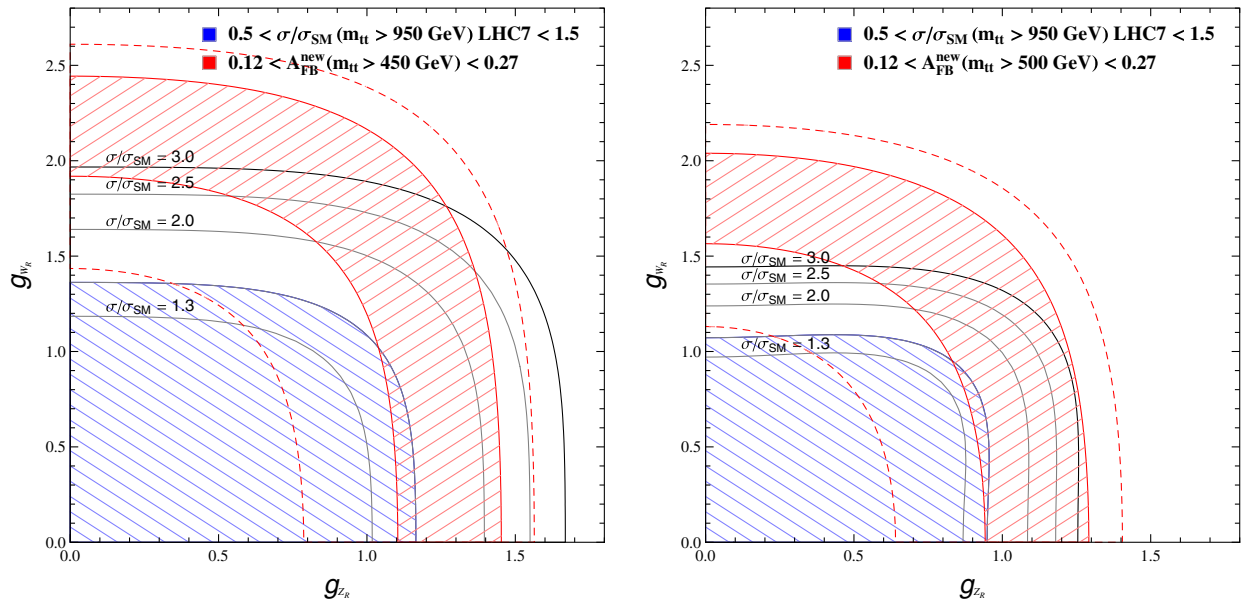

FIG. 8 (color online).   Color-octet (left panel) vs color-singlet (right panel) parameter space for couplings allowed by the high invariant mass LHC7 cross section and high invariant mass Tevatron forward-backward asymmetry. The black lines are contours for higher values of $\sigma(m_{t\bar{t}} > 950$ GeV) at LHC7 than allowed by the current ATLAS measurement. The dashed red lines illustrate the 2σ contour for $A_{FB}^{new}(m_{t\bar{t}} > 450$ GeV).
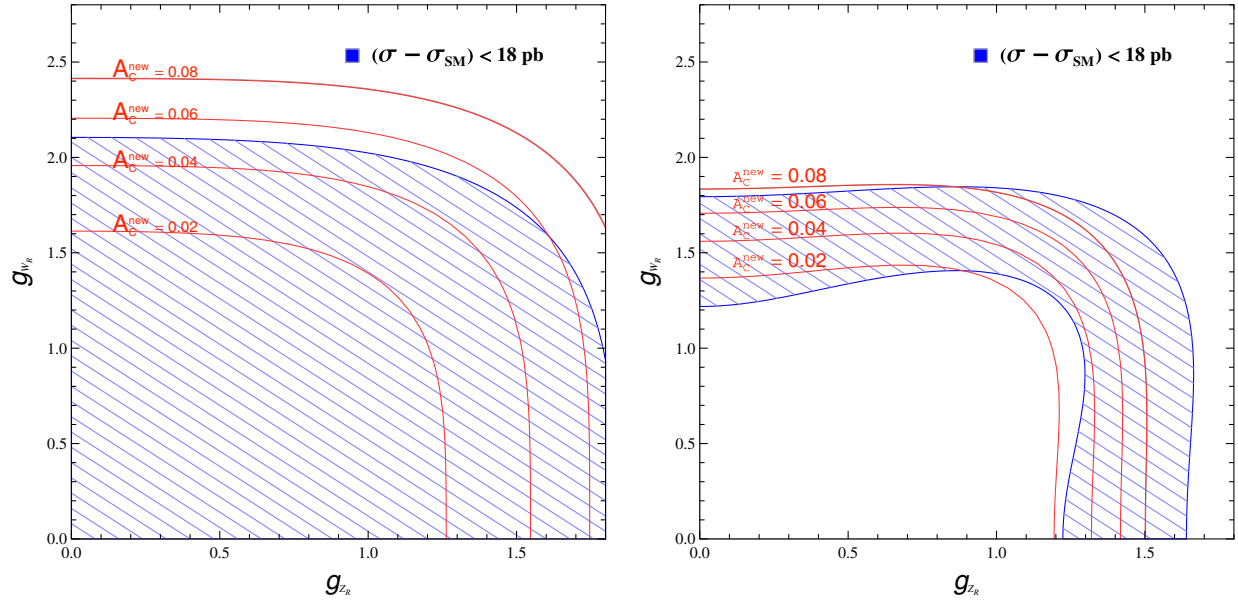
FIG. 9 (color online).   Color-octet (left panel) vs color-singlet (right panel) parameter space for couplings allowed by the LHC7 cross section and charge asymmetry.

compatible at the 1-sigma level with a narrow band of parameter space for the color octet. The new physics required to increase the asymmetry also increases the cross section and the two are compatible only for the lower end of the 1σ range for A_{FB}^{new}. This situation is different from the color singlet where there is destructive interference between the SM and the new physics.

In Fig. 8 we examine the effect of the high invariant mass observables. The 99% C.L. upper limit $\sigma/\sigma_{SM}(m_{t\bar{t}} > 950 \text{ GeV}) \leq 1.3$ from ATLAS quoted in Ref. [69] rules out both the color-singlet and color-octet resonances as explanations for A_{FB}. We also show in the figure the boundaries corresponding to $\sigma/\sigma_{SM}(m_{t\bar{t}} > 950 \text{ GeV}) = 2.0$, 2.5, and 3.0 to indicate what would be necessary to be compatible with the current 1σ range for $A_{FB}^{new}(m_{t\bar{t}} > 450 \text{ GeV})$. Of course, a lower value of this high invariant mass asymmetry (at the 2-sigma level for example) also opens up the allowed parameter space as indicated by the dashed red lines in the figure.

In Fig. 9 we consider the constraints from the charge asymmetry and cross section at LHC7. We have indicated several contours for A_C^{new} to compare with the different results found by ATLAS and CMS.

For our numerical study we have used a mass of 500 GeV for the new color-octet boson as an illustration. But we also generated similar samples for 600 GeV and smaller samples for masses ranging between 400 GeV and 1 TeV. For all cases we found that the correlations between the different observables are very similar to those exhibited in Figs. 1–5. The value of A_{FB} for masses higher than 500 GeV that is obtained when keeping the couplings fixed gets smaller with increasing mass. For a mass of 600 GeV, for example, the range of A_{FB} shown in Figs. 1–5 can be

covered by increasing the couplings used by about 0.2 in each case. For heavier bosons this becomes harder to do as couplings would move into nonperturbative regimes. By the time masses reach 1 TeV it is only possible to generate very small values of A_{FB}. We also simulated events for the benchmark point ($m_V = 300$ GeV) for the model "Vector field VII_O" of Ref. [46] (corresponding to our V_8^+), as well as for the points in Table IV, model C8 V of Ref. [70] (corresponding to our V_8^0) and we are in rough agreement in these cases.

V. CONCLUSION

We have studied the effect from a neutral V_8^0 or charged V_8^+ color-octet vector exchanged in the t channel on the top-quark forward-backward asymmetry. We find that they can modestly increase the SM value of A_{FB}, to within the 1σ range from the Tevatron measurement. The color octets fare better than the color singlets when confronted with other constraints. In particular they generate a lower A_C, a lower high invariant mass cross section at LHC7 and a lower same sign top-pair cross section. We have studied the correlations between the different observables for a mass of 500 GeV and the corresponding parameter space that is still allowed. We find that this type of new physics is still consistent with the measurements at the 2-sigma level.

ACKNOWLEDGMENTS

Ref. [46] and to Moira Gresham for clarifications on Ref. [70].

APPENDIX: APPROXIMATE RESULTS FOR $m_V = 500$ GeV

We generated samples of 1×10^6 events for at least 40 points in g_{W_R}, g_{Z_R} parameter space with resonance masses of 500 GeV and widths of 50 GeV (although the

precise value of the width is not important for t-channel resonances). Using these points we performed a fit to a quartic polynomial in these couplings (of the form that occurs in an analytic calculation) to obtain approximate expressions for the different observables. These expressions were then used in our exploration of parameter space. The results of these fits for color-octet resonances and for Tevatron observables are

$$\sigma(p\bar{p} \to t\bar{t}) \approx (6.06 + 0.325g_{Z_R}^2 + 0.245g_{Z_R}^4 + 0.074g_{W_R}^2 + 0.037g_{W_R}^4) \text{ pb}$$

$$\sigma \cdot A_{\text{FB}} = (0.012 + 0.132g_{Z_R}^2 + 0.176g_{Z_R}^4 + 0.028g_{W_R}^2 + 0.025g_{W_R}^4) \text{ pb}$$

$$A_{\text{FB}}(M_{t\bar{t}} \geq 450 \text{ GeV}) = (58.2g_{Z_R}^2 + 33.0g_{Z_R}^4 + 12.2g_{W_R}^2 + 5.5g_{W_R}^4) \times 10^{-3}$$

Note that for the case of A_{FB} (but not for A_{FB} at high invariant mass) our fit is for A_{FB} times the cross section. The constant term in this expression is the electroweak contribution in the SM as calculated by MadGraph 5. For color-octet resonances and LHC observables at a 7 TeV energy we obtain

$$\sigma(pp \to t\bar{t}) \approx (96.33 + 1.115g_{Z_R}^2 + 1.245g_{Z_R}^4 + 0.877g_{W_R}^2 + 0.719g_{W_R}^4) \text{ pb}$$

$$\sigma \cdot A_C = (0.1 + 0.261g_{Z_R}^2 + 0.632g_{Z_R}^4 + 0.040g_{W_R}^2 + 0.290g_{W_R}^4) \text{ pb}$$

$$\sigma(pp \to t\bar{t})(M_{t\bar{t}} \geq 950 \text{ GeV}) = (1.2 + 0.042g_{Z_R}^2 + 0.294g_{Z_R}^4 + 0.050g_{W_R}^2 + 0.147g_{W_R}^4) \text{ pb}.$$

The results of our fits for color-singlet resonances and for Tevatron observables are

$$\sigma(p\bar{p} \to t\bar{t}) \approx (6.06 - 2.423g_{Z_R}^2 + 1.106g_{Z_R}^4 - 0.407g_{W_R}^2 + 0.167g_{W_R}^4) \text{ pb}$$

$$\sigma \cdot A_{\text{FB}} = (0.012 - 1.046g_{Z_R}^2 + 0.800g_{Z_R}^4 - 0.158g_{W_R}^2 + 0.113g_{W_R}^4) \text{ pb}$$

$$A_{\text{FB}}(M_{t\bar{t}} \geq 450 \text{ GeV}) = (104.8g_{Z_R}^2 + 34.1g_{Z_R}^4 + 26.2g_{W_R}^2 + 9.3g_{W_R}^4) \times 10^{-3.}$$

For color-singlet resonances and LHC observables at a 7 TeV energy we obtain

$$\sigma(pp \to t\bar{t}) \approx (96.33 - 8.40g_{Z_R}^2 + 5.61g_{Z_R}^4 - 4.79g_{W_R}^2 + 3.22g_{W_R}^4) \text{ pb}$$

$$\sigma \cdot A_C = (0.1 - 2.82g_{Z_R}^2 + 2.92g_{Z_R}^4 - 1.10g_{W_R}^2 + 1.15g_{W_R}^4) \text{ pb}$$

$$\sigma(pp \to t\bar{t})(M_{t\bar{t}} \geq 950 \text{ GeV}) = (1.2 - 0.482g_{Z_R}^2 + 1.28g_{Z_R}^4 - 0.254g_{W_R}^2 + 0.675g_{W_R}^4) \text{ pb}.$$

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