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Constraining heavy colored resonances from top-antitop quark events

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Recent measurements of the top quark charge asymmetry at Tevatron disfavor the existence of flavor universal axigluons and colorons at 2σ. In this letter we explore the possibility of reconciling the data with these models and use the charge asymmetry and the invariant mass distribution of top-antitop quark pair events to constrain the mass and couplings of massive color-octet gauge bosons decaying to top quarks.

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The top quark, being the heaviest known elementary particle, plays a fundamental role in many extensions of the Standard Model (SM) and in alternative mechanisms for electroweak symmetry breaking (EWSB). Since its discovery in 1995 at Tevatron, many properties of the top quark, such as mass and total cross section, have been measured with high precision [1], also allowing for limits to be set on physics beyond the SM. Because the production cross section of top quarks is about 50 to 100 times larger at LHC than at Tevatron, the LHC will produce, even with early data, more top-antitop quark pairs than the Tevatron during its whole life – 200 pb^{-1} of integrated luminosity at 10 TeV center of mass energy are expected to be collected by the end of 2010 – offering new opportunities to probe new physics in the top quark sector.

In this paper, we shall set bounds on the mass and couplings of heavy colored gauge bosons decaying to top quarks by analyzing recent measurements of the top-antitop quark pair invariant mass distribution [2] and the charge asymmetry (or forward-backward asymmetry) [3, 4, 5]. Particularly interesting is the fact that the uncertainty of both measurements is still statistically dominated, which opens the possibility for further improvements in the near future even before the start of the LHC.

Several models predict the existence of new electroweak W' and Z' gauge bosons, color-octet gauge bosons, or gravitons that should be detectable in top-antitop quark events, particularly in those models where the coupling of the new gauge bosons to the third generation is enhanced with respect to the lighter fermions. The most stringent lower bounds on the mass of such new states are about 800 GeV for the W' and Z' [6, 7, 8, 9], 1.2 TeV for axigluons and flavor-universal colorons [6], and 600 GeV for gravitons [10]. Electroweak precision measurements rise the exclusion mass region of the Z' to above 3 TeV in Randall-Sundrum scenarios [11]. Those limits, however, should be taken with care as they depend on the given model adopted to set that bounds, although the numbers quoted above are quite similar across different analysis.

We are interested in color-octet gauge bosons which couple to quarks with a nonvanishing axial-vector coupling. Those states appear, for example, in chiral color models [12] where the SM color group have been extended to $SU(3)_R \otimes SU(3)_L$, and the symmetry breaking to the diagonal $SU(3)_C$ generates the massive axigluon, which couples to quarks with a pure axial-vector structure and the same strength as QCD. Chiral color models also require the existence of extra fermions to cancel anomalies, and extra Higgs bosons to break the enlarged gauge symmetry. We will assume that it is always possible to set them arbitrarily heavy. Those models can also be generalized by considering different coupling constants associated with each $SU(3)$ component [13, 14], thus generating both vector and axial-vector couplings of the axigluon to quarks.

We shall not stick here to a particular model, but will analyze the most general scenario where the heavy resonance interacts with quarks with arbitrary vector g_V and axial-vector g_A strength relative to the strong coupling g_S. We also assume that there is no direct coupling of a single resonance to an even number of gluons, and therefore the production of top quarks is driven by $q\bar{q}$ events. This choice is motivated by different implementations of models predicting the existence of extra color-octet gauge bosons. For example, the asymmetric chiral color model [13] allows the existence of three axigluon vertices, which are forbidden in the usual chiral color model by parity [12], but exclude gluon-gluon-axigluon vertices as well. Models in extra warped dimensions, where Kaluza-Klein (KK) modes can be single produced, have been constructed [15], but in the conventional and more extended extra dimensional models, a single KK gauge field does not couple to two SM gauge bosons at leading order by orthonormality of field profiles [16].

The Born cross-section for $q\bar{q}$ annihilation into top quarks in the presence of a color-octet vector resonance

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reads

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2\,\frac{T_F C_F}{N_C}\,\frac{\pi\beta}{2\hat{s}}\,\Big\{1+c^2+4m^2 + \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2}\,\big[g_V^q\,g_V^t\,(1+c^2+4m^2) + 2\,g_A^q\,g_A^t\,c\big] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2}\,\big[\big((g_V^q)^2+(g_A^q)^2\big) \times \big((g_V^t)^2(1+c^2+4m^2)+(g_A^t)^2(1+c^2-4m^2)\big) + 8\,g_V^q\,g_A^q\,g_V^t\,g_A^t\,c\big]\Big\}\;, \quad (1)$$

where $\hat{\theta}$ is the polar angle of the top quark with respect to the incoming quark in the center of mass rest frame, $\hat{s}$ is the squared partonic invariant mass, $T_F = 1/2$, $N_C = 3$ and $C_F = 4/3$ are color factors, $\beta = \sqrt{1-4m^2}$ is the velocity of the top quark, with $m = m_t/\sqrt{\hat{s}}$, and $c = \beta\cos\hat{\theta}$. The parameters $g_V^q(g_V^t)$ and $g_A^q(g_A^t)$ represent, respectively, the vector and axial-vector couplings of the excited gluons to the light quarks (top quarks). Color-octet resonances are naturally broad:

$$\frac{\Gamma_G}{m_G} \approx \frac{\alpha_S\,T_F}{3}\sum_{i=q,t}\big((g_V^i)^2+(g_A^i)^2\big) \approx \mathcal{O}(10\%)\;. \quad (2)$$

The terms in Eq. (1) that are odd in c generate a charge asymmetry, namely a difference in the differential distribution of top versus antitop quarks. At Tevatron, this charge asymmetry is equivalent to a forward-backward asymmetry as a consequence of charge conjugation symmetry. CP violation arising from electric or chromoelectric dipole moments of the top quark do not contribute to the asymmetry, unless the asymmetry is defined through the decay products. Only the terms in Eq. (1) that are even in c contribute to the top-antitop quark invariant mass distribution.

At leading order in QCD, there is no charge asymmetry; the differential distributions of top and antitop quarks are identical. But due to higher order radiative corrections a charge asymmetry is generated at $\mathcal{O}(\alpha_S^3)$ in $q\bar{q}$ events, and top quarks become more abundant in the direction of the incoming light quarks. The QCD prediction for Tevatron is [17, 18, 19]

$$A^{p\bar{p}} = \frac{N_t(y\geq 0)-N_{\bar{t}}(y\geq 0)}{N_t(y\geq 0)+N_{\bar{t}}(y\geq 0)} = 0.051(6)\;, \quad (3)$$

where y denotes the rapidity. This also includes a small mixed QCD-electroweak contribution. The charge asymmetry can also be defined through $\Delta y = y_t - y_{\bar{t}}$, which is equivalent to evaluate the asymmetry in the $t\bar{t}$ rest frame because Δy is invariant under boosts. In that frame the asymmetry is about 50% larger [17]: $A^{t\bar{t}} = 0.078(9)$. Although one can enlarge the uncertainty of the QCD asymmetry to a conservative 30% in order to account for higher order corrections, the result in Eq. (3) has been proven to be stable to threshold resummations [20], which shift the central value only by one per mille. Whether one prefers to quote a more conservative theoretical prediction for the asymmetry or not, is not relevant at the moment, as the present uncertainty of the experimental measurement (see below) is of the same order as the size of the QCD prediction. In the following, we will use therefore the result in Eq. (3) as reference number.

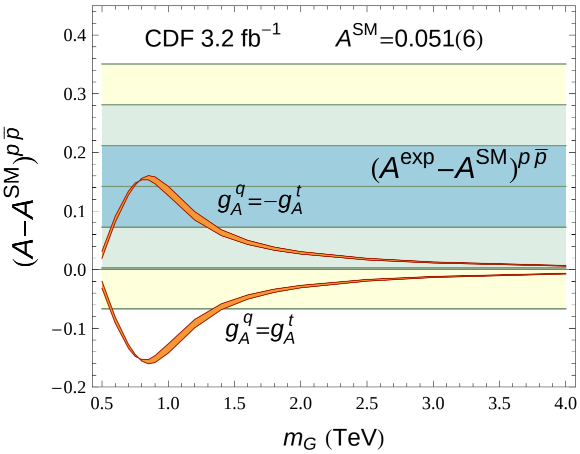

FIG. 1: Comparison of the axigluon contribution to the top quark charge asymmetry with the 1σ, 2σ, and 3σ contours as a function of the axigluon mass. We also consider the case $g_A^q = -g_A^t = 1$.

At Tevatron, CDF and D0 have recently measured the charge (or forward-backward) asymmetry with top-antitop quark events [3, 4, 5]. The measurement has been performed both in the $p\bar{p}$ rest frame [3, 4, 5] and in the $t\bar{t}$ rest frame [4]. The most recent measurement in the laboratory frame with 3.2 fb^{-1} is [3]

$$A^{p\bar{p}} = 0.193 \pm 0.065_{\,\mathrm{stat.}} \pm 0.024_{\,\mathrm{syst.}}\;, \quad (4)$$

to be compared with the one year old result: $A^{p\bar{p}} = 0.17 \pm 0.07_{\,\mathrm{stat.}} \pm 0.04_{\,\mathrm{syst.}}$, with 1.9 fb^{-1} [4]. The uncertainty of both measurements is still large, but systematic errors have been improved considerably from one measurement to another, and statistical errors have decreased accordingly. Moreover, it turns out to be quite interesting that the uncertainty is still statistically dominated, and hence significant improvements should be expected in the near future. Indeed, we shall see that the new measurement have a larger impact in constraining heavy resonances than the older one. Comparing Eq. (3) with Eq. (4), we can deduce that heavy resonances giving rise to a vanishing or negative charge asymmetry are disfavored at 2σ (see Fig. 1). This is the case of colorons ($g_A = 0$) and normal axigluons ($g_V = 0, g_A = 1$). At 3σ one can also exclude axigluon masses below 1.4 TeV. In comparison with 2008, where at 2σ there was still a sizable room for a negative contribution to the asymmetry [21], the situation has changed dramatically.

Now We explore whether it is still possible to reconcile the axigluon with the measurement of the charge asymmetry. A positive asymmetry can be generated if the term from the squared amplitude of the massive color-octet in Eq. (1), which is proportional to $8g_V^q g_A^q g_V^t g_A^t c$, dominates over the term of the interference, that is proportional to $2g_A^q g_A^t c$. This is possible if the vector couplings are large enough [22]. However, although the total cross section might still be compatible with the SM prediction in that case, because the contribution of the excited gluon is suppressed by powers of its mass, the top-antitop quark invariant mass distribution might be enhanced considerably, due to the factor

$$\left((g_V^q)^2 + (g_A^q)^2\right)\left((g_V^t)^2 + (g_A^t)^2\right) \ , \tag{5}$$

particularly for high values of the top-antitop quark invariant mass. The top-antitop quark invariant mass distribution has been measured very recently [2]. The last bin

$$\frac{d\sigma}{dM_{t\bar{t}}}(0.8-1.4 \text{ TeV}) \ = \ 0.068 \pm 0.032_{\text{stat.}} \pm 0.015_{\text{syst.}} \pm 0.004_{\text{lumi.}} \ (\text{fb GeV}^{-1}) \tag{6}$$

is, for the reasons explained above, the most sensible to extra contributions beyond the SM at the TeV scale.

As in Ref. [22], we consider the flavor-universal scenario where light and top quarks share the same vector g_V and axial-vector g_A coupling to the massive color-octet gauge boson and evaluate the size of the charge asymmetry for different values of the couplings and the mass. Then, we set the limits on the parameter space that are compatible with the newest experimental value (Eq. (4)), after subtracting the theoretical QCD prediction (Eq. (3)). We do the same exercise with the top-antitop quark invariant mass distribution in the interval 800 GeV$< M_{t\bar{t}} <$ 1.4 TeV (Eq. (6)). Within 1σ we allow the invariant mass distribution in that bin to be enhanced by 50%. The charge asymmetry and the invariant mass distribution probe different combinations of the vector and axial-vector couplings; therefore by combining both limits (we do not perform a global fit), one can constrain complementary regions of the parameter space. Similar analyses have also been performed recently in warped extra dimensional models [23] and in the asymmetric chiral color model [24].

Our results are shown in Fig. 2, where, for a given value of the mass of the color-octet we provide the allowed region at 95% C.L. in the $g_V - g_A$ plane. The solid lines are obtained from the charge asymmetry, while the dashed lines are derived from the last bin of the invariant mass distribution. The allowed regions are quite constrained; indeed at 90% C.L., we do not find any overlapping region for any value of the color-octet mass, and future experimental measurements with higher statistics can shrink significantly, or even exclude completely the allowed regions. With the most recent experimental values we find, in particular, that the asymmetric chiral color model ($g_V = \cot 2\theta, g_A = 1/\sin 2\theta$, or $g_V = \sqrt{g_A^2 - 1}$) is disfavored.

Another possibility to generate a positive charge asymmetry is to couple the third generation of quarks and the lighter quarks with axial-vector couplings of opposite sign: $g_A^q = -g_A^t$. From Eq. (1) it is obvious that the actual sign of these couplings is irrelevant; only their relative sign is important because the asymmetric contributions to the differential cross section are proportional to their product. Chiral color models with nonuniversal flavor couplings were already considered in the pioneering works [12]. Our approach here is, nevertheless, purely phenomenological, and building a realistic model in that scenario is beyond the scope of this paper. The results for the axigluon case with $g_A^q = -g_A^t = 1$ are presented in Fig. 1. That scenario is compatible with the experimental data for any mass within 2σ. The most general case is shown in Fig. 3. From Fig. 3 and for $|g_A| < 2$, we find that, independently of the resonance mass, the

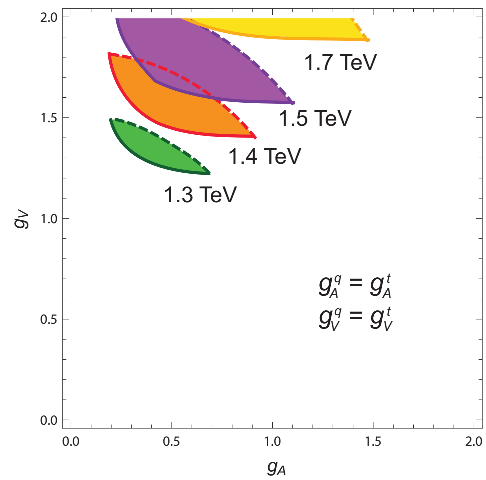

FIG. 2: Contours at 95% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass for flavor-universal couplings.

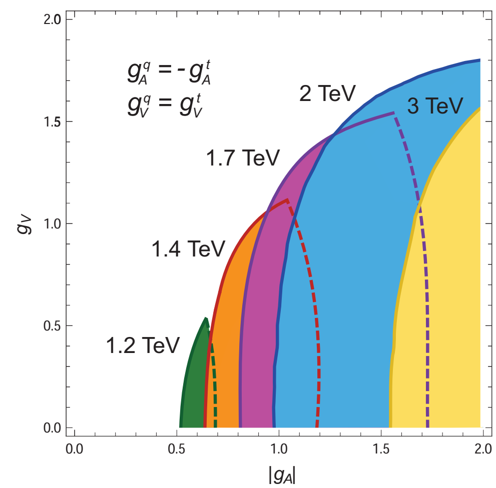

FIG. 3: Contours at 90% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass and $g_A^q = -g_A^t$.

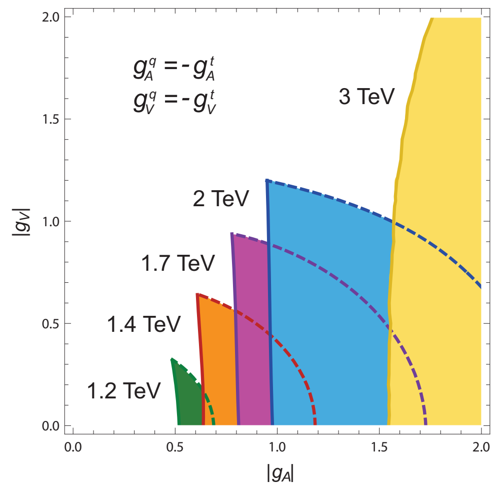

FIG. 4: Contours at 90% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass and $g_V^q = -g_V^t$, $g_A^q = -g_A^t$.

region about

$$(|g_V| - 2.3)^2 + |g_A|^2 \gtrsim 1.8^2 \tag{7}$$

is excluded at 90% C.L. Furthermore, for fixed values of the vector and axial-vector couplings the charge asymmetry sets a lower limit on the mass of the color-octet, while an upper bound can be set thanks to the invariant mass distribution, e.g. for $|g_A| = 1$, we find that at 90% C.L.

$$1.33 \text{ TeV} < m_G < 2 \text{ TeV} . \tag{8}$$

Finally, we have also considered the case $g_V^q = -g_V^t$ and $g_A^q = -g_A^t$. Our results are presented in Fig. 4. Obviously, for $g_V = 0$, we obtain the same result as in Fig. 3.

In conclusion, recent measurements of the charge asymmetry and the invariant mass distribution in top-antitop quark pair events allow for constraining the mass and couplings of hypothetic color-octet resonances decaying to top quarks with masses at the TeV scale. In the flavor-universal scenario, the allowed parameter space is quite constrained because the most recent measurements disfavor at 2σ vanishing or negative values of the charge asymmetry. In the flavor nonuniversal case, it is still possible to reconcile the experimental data with the existence of such resonances, and already a significant region of the parameter space can be excluded. In view of the significant progress over the last year from the experimental side, we expect that new results from Tevatron will further constrain efficiently the parameter space even before the start of the LHC, which is the natural place to discover those heavy resonances. At the LHC, there is no forward-backward asymmetry, obviously, but a sizeable charge asymmetry can be obtained by selecting events in the central region [22].

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