Four tops and the $t\bar{t}$ forward-backward asymmetry

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New colour octet vectors below the TeV scale could explain the anomalous $t\bar{t}$ forward-backward asymmetry observed at the Tevatron experiments, while being consistent with the current LHC data. These models generally lead to four-top final states at the LHC at observable levels. We compute the four-top production cross section at the LHC in a model with a massive colour octet vector as a function its mass, its width and its coupling to the top quark. Octet masses in the vicinity of the $t\bar{t}$ threshold are generally excluded by present limits on the production of same-sign dileptons and trileptons. Masses above 650 GeV are allowed, quite independently of the couplings, but they can be probed with the luminosity of 5 fb^{-1} already collected at the LHC, up to around 800 GeV. The four-top production cross section is increased by a factor ~ 2 with $\sqrt{s} = 8$ TeV and by up to almost two orders of magnitude with $\sqrt{s} = 14$ TeV, thus greatly increasing the reach for massive gluons after the LHC energy upgrade.

Due to its large mass, the top quark is expected to play a relevant role in the discovery of new physics beyond the Standard Model (SM). The first hint of such new physics could be already available in the form of the anomalously large $t\bar{t}$ forward-backward (FB) asymmetry observed at both Tevatron experiments [1, 2]. The fact that neither the Tevatron nor the Large Hadron Collider (LHC) have observed any other anomaly in top or jet physics sets strong constraints on possible explanations in terms of new physics [3–5]. One of the few surviving explanations, compatible with the present measurements of the $t\bar{t}$ invariant mass spectrum [6] and the charge asymmetry at the LHC [7, 8], is a relatively light colour octet vector boson (called here 'gluon' for brevity) with mass $M \lesssim 1$ TeV and with suppressed axial-vector couplings to the light quarks and sizeable axial-vector couplings to top quarks [9–17]. The axial coupling ensures cancelation of the interference terms between the SM and new physics contribution [18–20] in symmetric observables while preserving the contribution to the asymmetry. Masses around 1 TeV require large couplings to the top quark and a large gluon width, usually with extra decay channels [11]. Masses close to the $t\bar{t}$ threshold can easily hide in the large SM $t\bar{t}$ background, although they may also need extra decay channels to be invisible [12]. Masses lighter than the $t\bar{t}$ threshold can do with smaller couplings and are essentially invisible in symmetric observables [14].

In this paper we consider an alternative, yet unexplored probe of these models. The massive gluon is a colour octect vector resonance, thus its couplings to SM gluons are fixed by gauge invariance. Due to the relatively low masses relevant for the FB asymmetry, pair production of such objects with subsequent decay in two top pairs can receive a fairly large cross section, which is further increased by non-resonant contributions and by single gluon resonant production, especially if the coupling of the new gluon to the top quark is sizeable. (See [21–25] for preliminary studies of colour octet pair production at hadron colliders followed by top decays.) Four-top final states have a very small background in the SM but are difficult to reconstruct completely (see for instance section 12 of [26] and [27]). Here we show that simpler searches, based on production of same-sign dileptons and trileptons, are enough to probe and constrain models of light gluons as an explanation of the $t\bar{t}$ asymmetry. Specifically, to estimate the present limits on four-top production at the LHC we use (i) a supersymmetry-motivated search [28]; (ii) a search for fourth generation b' quarks [29], both performed by the CMS Collaboration. The present analysis is of course relevant to any model with color octect vector resonances that couple strongly to the top quark and not only to the ones attempting to explain the top FB asymmetry.

Let us consider a new massive gluon G. Its couplings to SM gluons are fixed by gauge invariance whereas the ones to fermions $g_i^{V,A}$ are in principle free. The relevant Lagrangian is

$$\begin{aligned}\mathcal{L}^G &= -\frac{1}{2} D_\mu G^a_\nu \Big(D^\mu G^{a\,\nu} - D^\nu G^{a\,\mu} \Big) + \frac{1}{2} M^2 G^a_\mu G^{a\,\mu} \\ &\quad + \bar{\psi}_i \gamma^\mu G^a_\mu \frac{\lambda^a}{2} \Big[g_i^V + g_i^A \gamma_5 \Big] \psi_i , \qquad (1)\end{aligned}$$

where i is a flavor index, λ^a are the Gell-Mann matrices and

$$D_\mu G^a_\nu \equiv \partial_\mu G^a_\nu + g_s f^{abc} g^b_\mu G^c_\nu$$

is the SM covariant derivative, with $a = 1, \ldots, 8$, g^a_μ the SM gluons, f^{abc} the SU(3) structure constants and g_s the strong coupling constant. In order to contribute to the $t\bar{t}$ asymmetry, G must have non-vanishing couplings to the top and first generation quarks, being the FB asymmetry in $q\bar{q} \to t\bar{t}$ proportional to the product $g_q^A g_t^A$, with $q = u, d$. Searches for dijet resonances typically constrain g_q^A (as well as the vector coupling) to be relatively small, the precise bound depending on the gluon mass M (see for instance [10, 14]). This implies that the axial coupling to the top must be of order unity or even larger, in order to generate a sizeable asymmetry. For gluon masses above the $t\bar{t}$ threshold, $M \geq 2m_t$, pair production of massive gluons followed by decays into top pairs is a large source of four-top final states, see Fig. 1 (left). Non-resonant diagrams such as the one depicted in the right panel, in which the new gluons are not produced on-shell, are also important for larger values of the gluon coupling to the top quark, and dominate both below the $t\bar{t}$ threshold and at large gluon masses.

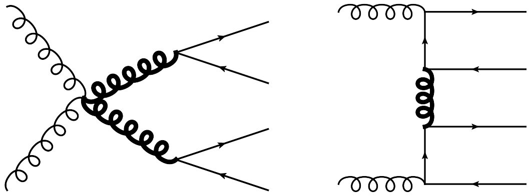

FIG. 1: Sample diagrams for resonant (left) and non-resonant (right) contribution to four-top production in the presence of new heavy gluons. The thick line corresponds to the massive gluon.

Given the fact that $g_q^{A,V} \ll g_t^A$, the cross section for four-top final states is essentially independent of the coupling to light quarks. For definiteness, we take a purely axial coupling $g_q \equiv g_q^A = 0.2$ to light quarks, which is around the upper limit for a wide range of heavy gluon masses [14], and a right-handed one $g_t/2 \equiv g_t^A = g_t^V$ to the top quark, as preferred by B physics constraints [32]. (Setting g_q to zero the four-top cross section found is nearly identical in all mass range, except for a slightly steeper rise at the $M \sim 2m_t$ threshold.) The coupling to the second generation is also constrained to be small by dijet production and has even a smaller effect on our results. For simplicity, it is set to zero. On the other hand, the four-top cross section depends on the gluon mass and its coupling to the top quark. In case that additional new particles exist, the four-top cross section near and above the $t\bar{t}$ threshold also depends on the partial width for gluon decays into these new particles.

In order to test the sensitivity of existing analyses to four-top production, we have implemented our model in `MADGRAPH 5` [33] using `FeynRules` [34]. The matrix element generated by `MADGRAPH` has been implemented in `Protos` [35] for an efficient exploration of the model parameter space and computation of four-top production cross sections. We have generated events for different configurations of gluon masses and couplings for pp collisions at a centre of mass (CM) energy $\sqrt{s} = 7$ TeV and passed them through `PYTHIA` [36] and `PGS4` [37]. All our simulations are performed at leading order. For the same-sign dilepton final state we have applied the selection and kinematical cuts in Ref. [28] and found that the analysis most sensitive to four-top production is the one requiring

- two same-sign leptons $\ell^\pm \ell^\pm$, $\ell = e, \mu$ with pseudorapidity $|\eta| < 2.4$. Electrons must have transverse momentum $p_T > 10$ GeV and for muons $p_T > 5$ GeV is required.
- $H_T \geq 400$ GeV, where H_T is the scalar sum of the p_T of all jets. Only those with $p_T > 40$ GeV and $|\eta| < 2.5$ are considered here.
- Missing energy $\not{E}_T \geq 50$ GeV.

The global efficiency of these cuts for our four-top signal, including the same-sign dilepton branching ratio, is approximately of 2% for a wide range of heavy gluon masses. (Requiring $H_T \geq 200$ GeV and $\not{E}_T \geq 120$ GeV results in an efficiency only slightly smaller.) With this selection, the CMS Collaboration measures 7 events with an integrated luminosity $L = 0.98$ fb^{-1}, for a SM background prediction of 5.3 ± 2.4 [28]. For the trilepton channel we ask for

- three leptons $\ell = e, \mu$ with $p_T > 20$ GeV and $|\eta| < 2.4$; same-flavour opposite-charge pairs are required to be outside a window $|M_Z - m_{ll}| < 10$ GeV (m_{ll} is the invariant mass of the two leptons).
- Two jets with $p_T > 25$ GeV and $|\eta| < 2.4$, at least one b-tagged.
- The scalar sum $H_T + \sum_\ell p_T^\ell + \not{E}_T \geq 50$ must be larger than 500 GeV.

With such cuts the efficiency for our four-top signal is of 0.6%. With this selection, the CMS Collaboration measures one event with a luminosity $L = 1.16$ fb^{-1}, for an expected SM background of 0.16 ± 0.09 [29].

Upper bounds on four-top production can be obtained from either of these channels, as well as from their combination, using the modified frequentist likelihood method [30, 31]. These limits are evaluated using 10^6 pseudo-experiments of the expected signal and background samples. Statistical uncertainty effects are implemented assuming Gaussian distributions [30]. The obtained 95% CL bound on four-top production are

$$\begin{aligned} \sigma_{4t} &\leq 0.50 \text{ pb} && (2l)\,, \\ \sigma_{4t} &\leq 0.70 \text{ pb} && (3l)\,, \\ \sigma_{4t} &\leq 0.36 \text{ pb} && (\text{combined})\,. \end{aligned} \tag{2}$$

As we have mentioned, the four-top cross section crucially depends on whether the new gluon can decay to additional non-SM particles. Thus, a detailed discussion of the heavy gluon width is compulsory. Let us denote by Γ_0 the partial width of the gluon to SM particles. Below the $M \sim 2m_t$ threshold, Γ_0 receives the largest contribution from decays $G \to u\bar{u}, d\bar{d}$, with a smaller one from four-body decays $G \to W^+ b W^- \bar{b}$. (At any rate, for masses $M \leq 320$ GeV the four-top cross section is practically independent of Γ, as we will explicitly see below.) Above this threshold, Γ_0 is largely dominated by on-shell decays to $t\bar{t}$. This is clearly seen in Fig. 2, in which we plot Γ_0 as a function of M, for five values of the coupling to the top quark $g_t = 1, 2, 3, 4, 5$.

We consider in first place models in which the new gluon only decays to SM particles, that is, $\Gamma = \Gamma_0$.

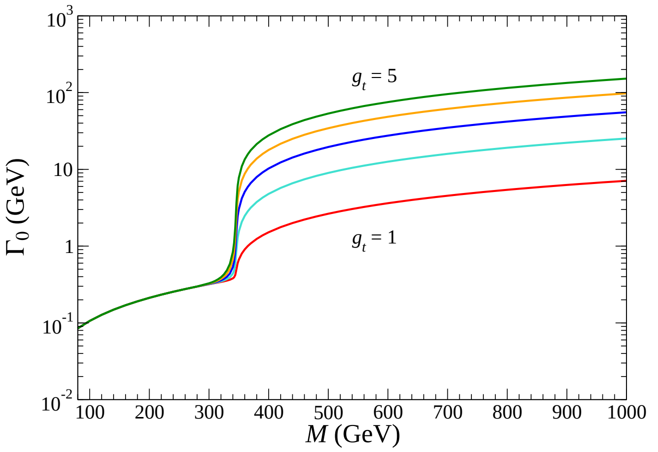

FIG. 2: Partial width of the heavy gluon to SM final states. The five lines, from bottom to top, correspond to $g_t = 1, 2, 3, 4, 5$.

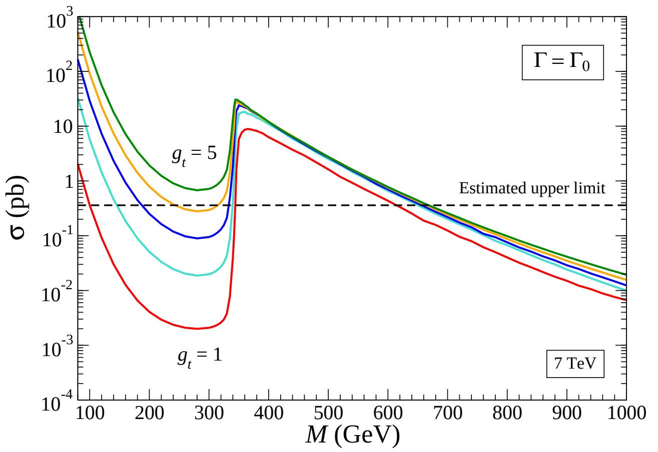

FIG. 3: Four-top cross section for $\Gamma = \Gamma_0$ (decays to SM particles only) for the LHC with $\sqrt{s} = 7$ TeV. The five lines, from bottom to top, correspond to $g_t = 1, 2, 3, 4, 5$.

The four-top cross section is shown in Fig. 3 for $g_t = 1, 2, 3, 4, 5$. Clearly, for $M \geq 2m_t$ the four-top cross section receives a boost from diagrams corresponding to on-shell production of two gluons with subsequent decay to $t\bar{t}$. Still, for these masses the contribution of non-resonant diagrams (and diagrams with a single on-shell gluon production) is important, as it can be found out by the different cross sections for the several g_t values considered. (Clearly, the cross section for on-shell production of two gluons with subsequent decay to $t\bar{t}$ is independent of g_t, as long as $G \to t\bar{t}$ is the dominant decay channel.) From this plot we can learn that models with gluon masses $M = 350 - 650$ GeV are quite generally excluded, unless there is an extra enhancement of the width by decay to non-SM particles. As soon as the limits on four-top production at LHC get more stringent, with dedicated analyses and the use of the full 5 fb^{-1} dataset, larger masses will be excluded. For example, an upper limit $\sigma_{4t} < 0.1$ pb (slightly better than a naive $1/\sqrt{L}$ rescaling) seems likely, especially bearing in mind the possibility of combination with the semileptonic channel. Such limit will allow to probe gluon masses up to $M \sim 800$ GeV.

Realistic models explaining the FB asymmetry with a new gluon above the $t\bar{t}$ threshold often require new particles to enhance the gluon width, $\Gamma > \Gamma_0$, so as to make the resonance invisible in the $t\bar{t}$ invariant mass spectrum [11, 14]. In this case, the four top cross section decreases by a factor $R \sim (\Gamma_0/\Gamma)^2$, but not exactly equal to this ratio of widths because of the contributions from diagrams with non-resonant G exchange. We plot in Fig. 4 the ratio of cross sections for different gluon total widths,

$$R_\Gamma = \frac{\sigma_{4t}|_\Gamma}{\sigma_{4t}|_{\Gamma_0}} \,, \tag{3}$$

for $\Gamma = 2\Gamma_0, 4\Gamma_0$. We only consider $g_t = 4, 5$, since these heavy gluon masses require a large top coupling to generate the FB asymmetry. We observe that this ratio deviates from $(\Gamma_0/\Gamma)^2$ both at threshold and at high M, due precisely to the sizeable contributions from non-doubly-resonant diagrams. Note also that in our simulations we have considered the fixed width approximation. For very large widths its full energy dependence must be taken into account, which reduces the suppression with respect to the one depicted in Fig. 4 [11]. Thus, although the enlarged gluon width required in realistic models of the FB asymmetry with gluon masses above threshold tend to reduce the constraints, they do not remove them completely. Furthermore, we will see below that once the LHC energy is upgraded, the dramatic increase in the production cross section will be enough to impose stringent constraints even with enlarged widths.

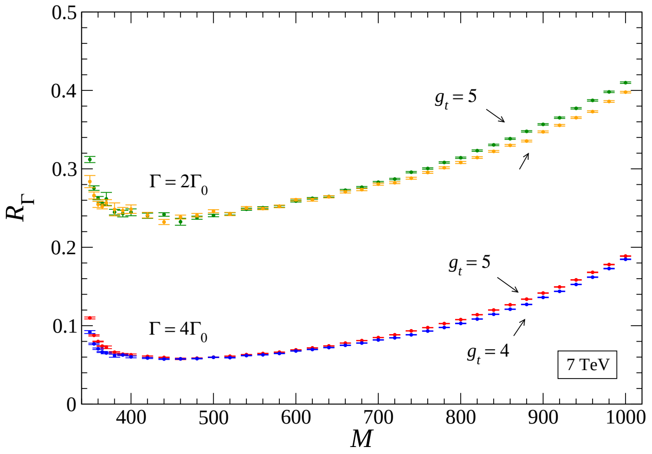

FIG. 4: Ratio R_Γ in Eq. (3) between cross sections for different values of the gluon total width Γ, for $M \geq 2m_t$. The error bars represent the Monte Carlo uncertainty.

Models with new gluons of masses $M \sim 300$ GeV under the $t\bar{t}$ threshold can generate sizeable asymmetries with g_t of order unity [14]. In this case, four-top production is well below the present and foreseeable limits. Still, one may consider a width enhancement from decay to particles lighter than the top quark [16]. We show in Fig. 5 the four-top cross section in this case, for width enhancements $\Gamma = \Gamma_0 + 0.1M$ and $\Gamma = \Gamma_0 + 0.25M$. In both cases the cross section for masses $M \leq 300$ GeV is unchanged by the extra width, so models with very light colour octets [15] may already be compromised by limits on four-top production. On the other hand, four-top production close to threshold is largely suppressed, a fact which is expected since the extra width $0.1M$, $0.25M$ to non-SM states is orders of magnitude larger than $\Gamma(G \to t\bar{t})$, see Fig. 2. Besides, achieving such a width enhancement may not be natural and/or may require too large couplings to the new particles. At any rate, an extra gluon width may hide the four-top signal but gives rise to other new final states from the decay of the heavy gluons, which have to be considered when discussing the viability of any model.

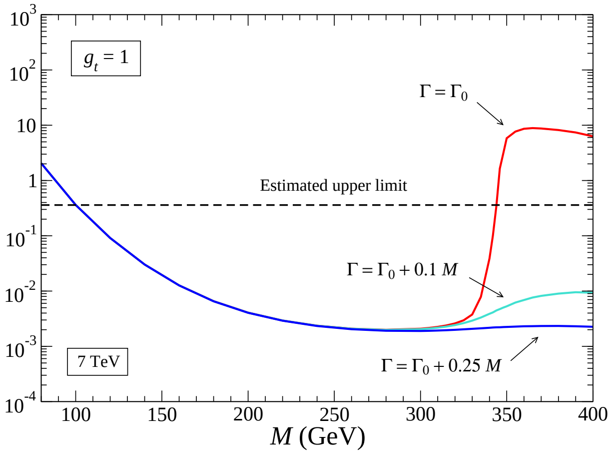

FIG. 5: Four-top cross section for new gluons below and slightly above the $t\bar{t}$ threshold, for $g_t = 1$, with and without an extra width enhancement.

Let us now consider the effect of the foreseen LHC energy upgrade. If the CM energy is increased to 8 TeV we obtain a factor of $2-2.3$ increase in the four-top production cross section, thus partially compensating the supression due to an enlarged gluon width (see Fig. 4). A much more dramatic increase of the signal cross section is obtained for $\sqrt{s} = 14$ TeV, as we show in Fig. 6. The four-top production cross section in enhanced by one to almost two orders of magnitude, depending on the gluon mass, with respect to the one at $\sqrt{s} = 7$ TeV. Although the backgrounds also grow at this energy we can anticipate a very good sensitivity to four-top production. For example, the lowest point in Fig. 6 has a cross section of 52 fb while an estimated 5 σ observation limit of 45 fb is expected with 100 fb^{-1} of integrated luminosity [22]. Moreover, the production cross section at the $t\bar{t}$ threshold is almost four orders of magnitude larger than the expected observation limit. Thus, even with a strong suppresion due to an enlarged width, models with a light gluon below the TeV scale are expected to be probed at the LHC.

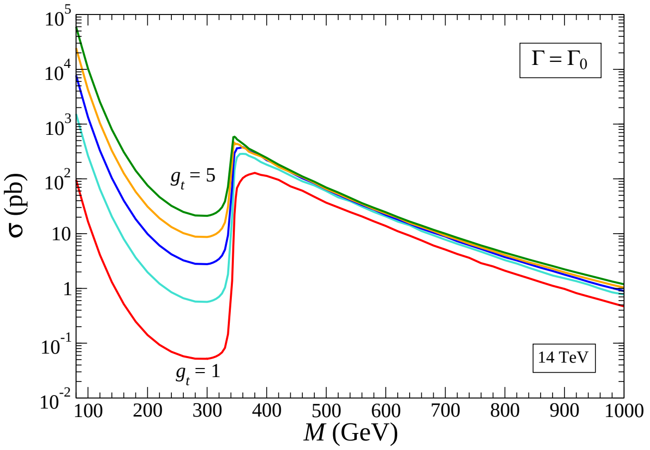

FIG. 6: Four-top cross section for $\Gamma = \Gamma_0$ (decays to SM particles only) for the LHC with $\sqrt{s} = 14$ TeV. The five lines, from bottom to top, correspond to $g_t = 1, 2, 3, 4, 5$.

In summary, in this paper we have considered four-top production in models explaining the Tevatron $t\bar{t}$ asymmetry with new 'light' gluons. Pair production of these particles followed by decays into top pairs is a new, potentially large, source of four-top final states. In order to cover all the relevant parameter space, we have studied the four-top production cross section as a function of the gluon mass and its coupling to the top. We have also considered some examples of scenarios where the heavy gluon width is increased by decays to additional non-SM particles. Our main results are summarized in Figs. 3, 4 and 5 for the 7 TeV LHC and Fig. 6 for the 14 TeV LHC. The large four-top cross sections found in a large part of the parameter space, and their small SM backgrounds, make this channel a very promising probe of this class of models, capable to reach gluon masses up to 800 GeV with the luminosity already collected at the LHC. An LHC energy upgrade to 8 (14) TeV implies an increase in the four-top production cross section by a factor of ~ 2 (10-500), thus improving dramatically the reach in these models.

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