Abstract

A gluon resonance $G$ of mass below 1 TeV could be the origin of the $t\bar{t}$ forward-backward asymmetry observed at the Tevatron provided that new decay modes $G \rightarrow g\bar{Q}$, with $q$ a standard quark and $Q$ its massive excitation, make $G$ broad enough. We consider all the different cases, with $q$ the top, the bottom or a light quark and dominant decay modes $Q \rightarrow Wq'$ or $Q \rightarrow Zq$. We show that current experimental searches are unable to probe the model, but that minimal departures from these analyses can explore a large region of its parameter space for the current LHC luminosity. This includes the challenging case with the new quarks decaying mostly into light quark flavors. In some channels not only the heavy quark but also the massive gluon can be reconstructed, which would establish the origin of the $t\bar{t}$ asymmetry. Similar analyses can be applied to more general models with new massive gluons and vectorlike quarks.
1 Introduction

With over $10 \text{fb}^{-1}$ of recorded data at the Tevatron and more than $4 \text{fb}^{-1}$ at the Large Hadron Collider (LHC), physics beyond the standard model (SM) is currently being searched with a very important degree of detail. Until now no discovery has been reported by any experimental collaboration, and bounds on many extensions of the SM rise up to the TeV scale and sometimes higher. As an alternative, these results may just imply that the experimental signature of the new physics is peculiar and easy to miss despite being at relatively low scales, as preferred by naturalness arguments. In this article we take this approach to study the $t\bar{t}$ forward-backward (FB) asymmetry at the Tevatron [1], arguably the most intriguing departure from the SM predictions. We show that it can be explained by new physics below 1 TeV that could be difficult to see in the first round of experiments unless dedicated analyses are considered.

Due to the relatively large coupling of the top quark to the electroweak (EW) symmetry breaking sector, new physics stabilizing the latter could also appear in top-quark observables. This generic argument makes the $2-3 \sigma$ deviation versus the standard value in the Tevatron asymmetry specially interesting. Even if it is not statistically significant at the level of discovery, the consistency among different CDF and D0 measurements strengthens the case for new physics. However, any candidate responsible for the asymmetry has to be carefully disguised, as its large contribution there should not translate into any significant departure from the SM in other related observables. In particular, the $t\bar{t}$ total cross section, its invariant mass distribution, dijet production, same sign top production, or the $t\bar{t}$ charge asymmetry at the LHC are observables where correlated anomalies could be expected [2].

In a recent work [3] we have shown that an $s$–channel gluon resonance $G$ of relatively low mass ($M_G \lesssim 1$ TeV) could explain the large value of the asymmetry consistently with all the other observations. (See [4] for alternative explanations of the Tevatron asymmetry in terms of massive gluons and ways to discover them.) It should have small-close to axial couplings to the light quarks ($g_L^q \approx -g_R^q$) together with a large coupling to the right-handed top quark, features that are obtained in Higgsless models after imposing consistency with EW precision data [5]. The key ingredient would be a large gluon width, $\Gamma_G = (0.5-0.7)M_G$, provided by new decay modes of type $G \rightarrow Q\bar{q}, q\bar{Q}$, where $q$ is a standard quark and $Q$ a massive vectorlike excitation. In composite holographic models these fields can be understood as Kaluza-Klein modes of the standard quarks. The large gluon width in this framework requires a proper treatment of energy-dependent effects. In particular, a Breit-Wigner with constant width would offer a poor description of the gluon-mediated amplitude.
Instead, when a new channel

\[ q\bar{q} \to G \to Q\bar{q}, q\bar{Q} \]  

(1)

opens at \( \sqrt{s} = m_Q + m_q \) it contributes to \( \Gamma_G(s) \)

\[ \Gamma_G^{Qq}(\hat{s}) = \theta [\hat{s} - (m_q + m_Q)^2] \frac{g^2}{12\pi M_G} \left( 1 - \frac{(m_q + m_Q)^2}{\hat{s}} \right)^{\frac{1}{2}} \left( 1 - \frac{(m_q - m_Q)^2}{\hat{s}} \right)^{\frac{1}{2}} \times \]

\[ \left[ \left( 1 - \frac{m_q^2 + m_Q^2 + 6m_qm_Q}{2\hat{s}} - \frac{(m_Q^2 - m_q^2)^2}{2\hat{s}^2} \right) g_A^{Qq}^2 + \right. \]

\[ \left. \left( 1 - \frac{m_q^2 + m_Q^2 - 6m_qm_Q}{2\hat{s}} - \frac{(m_Q^2 - m_q^2)^2}{2\hat{s}^2} \right) g_V^{Qq} \right], \]  

(2)

where \( g_{V,A}^{Qq} = (g_R \pm g_L)/2 \) are the vector and axial coupling of the massive gluon to \( Q \) and \( q \), respectively. The large width will then reduce all gluon effects at \( \sqrt{s} > m_Q + m_q \) (like a peak in the \( t\bar{t} \) or the dijet distributions) while leaving unchanged lower energy effects (namely, the Tevatron FB asymmetry).

For this mechanism to properly explain the asymmetry we need \( 700 \text{ GeV} \lesssim M_G \lesssim 900 \text{ GeV} \) and \( 400 \text{ GeV} \lesssim m_Q \lesssim 700 \text{ GeV} \) [3]. The low masses of the gluon and the new quarks, together with the sizable couplings required to generate the large width, make the production of single new quarks mediated by the massive gluon a very attractive channel at the LHC. In this article we investigate its potential to probe this scenario. The signal there will depend strongly on the nature of the vectorlike quark involved. In section 2 we classify all the possibilities and introduce a benchmark model that provides contributions in all the different channels. In section 3 we study single vectorlike quark production involving the third generation, and in section 4 we discuss the channels with light flavors. In both cases we show that current analysis could easily miss the model, whereas specific searches would very likely reveal the mechanism responsible for the Tevatron asymmetry. Section 5 is devoted to our conclusions.

2 A benchmark model

In this section we introduce a benchmark model that successfully reproduces the Tevatron FB asymmetry with no conflict with other experimental tests. It contains simultaneously all possible decay channels and, therefore, allows us to perform a comprehensive study of the stealth gluon scenario. The model admits variations where one or several channels are suppressed while the others are enhanced in such a way that the total gluon width does not change significantly. We take \( M_G = 850 \) GeV, although similar setups can be obtained for
gluon masses as low as 700 GeV. We fix the couplings to $G$ of the SM quarks to

$$g_L^q = 0.3 g_s, \quad g_R^q = g_R^b = -0.3 g_s, \quad g_R^t = 4 g_s, \quad g_L^t = g_L^b = 0,$$

where $g_s$ is the strong coupling constant. For the vectorlike quarks, we will assume the presence of six fields, corresponding to the excitations of $t_R$, $b_R$ and the four light flavors $q_L$ (from now on we use $q$ and $Q$ just for the $(u, d, s, c)$ quarks and their excitations). We fix their masses to

$$M_T = 450 \text{ GeV}, \quad M_B = M_Q = 600 \text{ GeV},$$

and their flavor-changing couplings to the heavy gluon to

$$g_R^{Tt} = 4 g_s, \quad g_R^{Bb} = 3.5 g_s, \quad g_L^{Qq} = 3.5 g_s.$$

These values imply a total width $\Gamma_G \approx 0.7 M_G$ and the decay branching fractions

$$\text{BR}(G \to t\bar{t}) \approx 0.2, \quad \text{BR}(G \to T\bar{t}, tT) \approx 0.24,$$
$$\text{BR}(G \to B\bar{b}, b\bar{B}) \approx 0.11, \quad \text{BR}(G \to Q\bar{q}, q\bar{Q}) \approx 0.44.$$  

(6)

As we mentioned above, the benchmark model just defined has the advantage that all possible channels are present simultaneously. However, when studying the possible collider implications of this scenario we will also consider the extreme cases where all but one $G$ decay modes are absent:

- Extreme $T$ model: $g_R^{Tt} = 7.28 g_s, \quad g_R^{Bb} = g_L^{Qq} = 0,$
- Extreme $B$ model: $g_R^{Bb} = 9.36 g_s, \quad g_R^{Tt} = g_L^{Qq} = 0,$
- Extreme $Q$ model: $g_L^{Qq} = 4.68 g_s, \quad g_R^{Tt} = g_R^{Bb} = 0,$

and all the other couplings unchanged. In these cases the heavy gluon has a 20% branching ratio into $t\bar{t}$ and 80% into the new channel. Note that in some of these models the required coupling is unrealistically large. We just take them as limiting examples to get clear idea of the LHC reach for these signatures (realistic models should lie somewhere in between the benchmark and the extreme cases).

The new heavy quarks will then be produced through $G$ in the $s$–channel as $Q\bar{Q}$ pairs or as a single particle together with a standard quark, $Q\bar{q}$. Pair production will also receive the standard QCD contribution (in fact, due to the axial nature of the $G$ coupling to light quarks, the interference terms cancel and away from the resonance pair production is like in the SM). Single heavy-quark production, on the other hand, is unsuppressed and opens
kinematically at lower energies ($\sqrt{s} = m_q + m_Q \ll 2m_Q$), appearing as a very promising mechanism unexplored in previous literature. The vectorlike quarks will then decay in a model-dependent way, according to their electroweak quantum numbers and their mixing with the SM quarks. Assuming weak couplings, their width will be narrow, and a simple scaling allows to go from one model to another. To be definite we will take the branching ratios obtained in the large-mass limit of the usual Higgsless models,

$$\text{BR}(Q \to Wq') = \frac{2}{3}, \quad \text{BR}(Q \to Zq) = \frac{1}{3}. \quad (10)$$

Higgs decays can potentially lead to interesting signatures \cite{6} but we defer the corresponding analysis to future work. In this paragraph, we have denoted with $Q$ the six vectorlike quarks.

With these assumptions the final states produced in the $q\bar{q}$ collisions will be the following (the conjugated processes are not explicitly shown but are included in our analyses):

\((i)\) $W^+W^-b\bar{b}$, from

$$q\bar{q} \to G \to T\bar{t} \to (W^+b)W^-\bar{b} \quad (11)$$

and

$$q\bar{q} \to G \to B\bar{b} \to (W-t)\bar{b} \to (W^-W^+b)\bar{b}. \quad (12)$$

\((ii)\) $Zt\bar{t}$, from

$$q\bar{q} \to G \to T\bar{t} \to (Zt)\bar{t} \to (ZW^+b)W^-\bar{b}. \quad (13)$$
(iii) $Z\bar{b}b$, from
\[
q\bar{q} \rightarrow G \rightarrow B\bar{b} \rightarrow (Zb)\bar{b}.
\] (14)

(iv) $W+\text{jets}$, from
\[
q\bar{q} \rightarrow G \rightarrow Q\bar{q} \rightarrow (Wq')\bar{q}
\] (15)

(v) $Z+\text{jets}$, from
\[
q\bar{q} \rightarrow G \rightarrow Q\bar{q} \rightarrow (Zq)\bar{q}.
\] (16)

In the next two sections we show that these signals do not introduce observable anomalies in current LHC analyses, but that simple modifications in the reconstruction of the final state could very likely provide a signal. The impact of this scenario on top-quark physics at the Tevatron has been discussed in \[3\], where we name it as the stealth gluon model due to its ability to explain the FB asymmetry without introducing anomalies (peaks or tails) in the $t\bar{t}$ invariant mass distribution ($m_{t\bar{t}}$). In particular, it implies $A_{t\bar{t}}(m_{t\bar{t}} \leq 450 \text{ GeV}) = 0.12$ and $A_{t\bar{t}}(m_{t\bar{t}} \geq 450 \text{ GeV}) = 0.33$, values that are compatible with the D0 and CDF observations \[1\]. The $m_{t\bar{t}}$ distribution at the Tevatron is given in Fig. 1 where we compare the reconstruction as $t\bar{t}$ pairs of all the events giving $W^+W^-\bar{b}b$ in the benchmark model with the SM prediction. In our simulation we have followed the analysis in \[7\] and have generated the events with MADGRAPH/MADEVENT v4 \[8\] (with the matrix element properly modified to include the energy dependence of the width), using PYTHIA \[10\] for hadronization/showering effects and PGS4 \[11\] and DELPHES 1.9 \[12\] for detector simulation. We include in the figure the prediction in the extreme $T$ model (the prediction in the extreme $B$ model is similar, whereas in the extreme $Q$ model it is below the benchmark one). The deviations are never larger than $2.5 \sigma$ (assuming statistical errors only), and below $2 \sigma$ in all the bins for the benchmark and the extreme-$Q$ models.

3 Single $T$ and $B$ quark production at the LHC

3.1 $W^+W^-\bar{b}b$ channel

As described in the previous section, the new processes $q\bar{q} \rightarrow T\bar{t}, B\bar{b}$ followed by the charged-current decay of the heavy quark will result in the same $W^+W^-\bar{b}b$ final state as $t\bar{t}$ production. In our model this signal would add to the one from top-quark pairs produced through the massive gluon, and it is then necessary to check that these processes do not imply any observable excess in current analyses of $t\bar{t}$ production or fourth generation $T\bar{T}$ searches. Measurements of the $t\bar{t}$ mass invariant distribution at the LHC have been reported in \[13\].
We have simulated the analyses in the first two works of this reference and studied the effect of the channels

$$pp \to T\bar{t}, t\bar{T}, B\bar{b}, b\bar{B}$$

(17)

together with all the contributions to $t\bar{t}$ production. We show the result in Fig. 2 (we have followed the second Ref. in [13] for 0.2 fb$^{-1}$; the third reference uses the dilepton channel and a larger data set, implying a very similar sensitivity). In the plot we have assumed a 10% uncertainty in the $t\bar{t}$ prediction and allowed a normalization factor (within this 10%) to correctly reproduce the three bins around the peak at $m_{t\bar{t}} \approx 500$ GeV. We show the SM, the benchmark model (with statistical error bars) and the extreme $T$ model. The deviation in the extreme $B$ case is similar to the one in the extreme $T$ model, whereas the extreme $Q$ case is closer than the benchmark to the SM. The $\approx 20\%$ excess at $m_{t\bar{t}} = 600–900$ GeV in the extreme $T$ and $B$ models seems in the limit of being probed with the current LHC data. Increasing the luminosity to 4 fb$^{-1}$ we find 8 consecutive bins with differences above 3 $\sigma$ for the DELPHES simulation and 7 consecutive ones for the PGS simulation in the case of the extreme $T$ model. The benchmark and extreme $Q$ models are not as clear. For instance, using PGS we find 3 and 2 consecutive bins with departures larger than 3 $\sigma$ in these cases for a luminosity of 4 fb$^{-1}$ (in all our estimates we only include statistical errors). In summary, in our model one could expect a 10% excess relative to the SM prediction in all the $m_{t\bar{t}}$ bins below 1 TeV. These events are just $t\bar{t}$ pairs mediated by the heavy gluon $G$. In addition, the bins between 600–900 GeV could be increased an extra 15% with $T\bar{T}$ and/or $B\bar{b}$ events that are reconstructed as $t\bar{t}$ pairs.

Another LHC study sensitive to our model is the search for a fourth generation of quarks produced as $TT$ pairs [14]. We have reproduced the corresponding CMS analysis and plot our results in Fig. 3 for the muon channel with the published luminosity of 0.821 fb$^{-1}$. Our results are similar to the ones obtained for $t\bar{t}$ production. The benchmark and the extreme $Q$ models are not visible, whereas the extreme $T$ and $B$ models are starting to be probed by the data. We plot in Fig. 3 the SM, the benchmark and the extreme $T$ cases in solid blue, data points (with error bars), and dotted black, respectively. The left panel shows the $H_T$ distribution (defined in this case as the scalar sum of the $p_T$ of the jets, the charged lepton and the missing $E_T$), and the right panel gives the $T$ reconstructed mass in the events generated with our model(s) and with the SM. In both plots the number of standard events has been normalized by the same factor. We have also checked that pair production of $T$ quarks give in our model a negligible contribution, compatible with the bound obtained in [14]. Similarly, the recent search for pair production of vectorlike $T$ quarks decaying to $Zt$ [15] does not imply any restriction to our model.

Our results indicate that the model, proposed to explain the large FB Tevatron asymme-
try, is almost invisible in $t\bar{t} \rightarrow W^+W^- b\bar{b}$ searches. The reason for that is twofold. First, the large gluon width suppresses the number of $t\bar{t}$ events in the region $m_{t\bar{t}} = 600–900$ GeV, while its axial couplings to the light quarks does the same at lower and higher invariant masses. Second, $T\bar{T}$ or $B\bar{B}$ events are reconstructed as $t\bar{t}$ or $T\bar{T}$ pairs, resulting into a poorer fit and a wider spread. The key to isolate events of type $T\bar{T}$ would be to reconstruct them not like two objects with the same mass, but like a $t$ quark plus a $T$ quark of arbitrary mass. These events will only occur at large invariant masses, $m_{T\bar{T}} > m_T + m_t$, a region already accessible at the LHC with the current luminosity. Therefore, we can use the more stringent cuts used in the $T\bar{T}$ analysis of [14] (we use the muon channel). Actually, we will require the hardest jet to have $p_T \geq 200$ GeV instead of the 120 GeV of that reference. We will then identify just one 173 GeV $t$ quark (using a $\chi^2$ similar to the one used in the first reference of [13] and requiring $\chi^2 \leq 10$) and will plot the mass of the second one in events of invariant mass above 600 GeV (Fig. 4, left panel) for SM and extreme $T$ model simulations. We have normalized the plots to the recorded luminosity of 4 fb$^{-1}$. As it is apparent in the plot, we find three consecutive bins around $m_T = 450$ GeV departing more than three sigmas from the SM prediction even in the benchmark model. Counting the total excess $S$ of events versus the
Figure 3: $T\bar{T}$ search at the LHC for 0.821 fb$^{-1}$. Left panel: $H_T$ distribution. Right panel: $m_{\text{fit}}$ distribution. In both cases we show the predictions in the SM (solid blue), in the benchmark model (data points with statistical errors) and in the extreme $T$ case (dotted black). We include the contribution from $T\bar{t}, t\bar{T}$ and $B\bar{b}, bB$ when present.

standard background $B$ on the peak (three bins between 350 and 500 GeV) we get

$$\frac{S}{\sqrt{B}} \approx \begin{cases} 8, & \text{benchmark,} \\ 21, & \text{extreme } T. \end{cases}$$  \hspace{1cm} (18)$$

Thus, the extreme $T$ case would imply a stunning deviation in this kind of searches, and even the benchmark model could show evidence for new physics. With the large excess in the extreme $T$ model one can also try to reconstruct the massive gluon peak. In order to do that, we remove the total invariant mass cut and compute the total invariant mass $m_{T\bar{t}}$ for the events with a reconstructed $T$ mass above 350 GeV. The result is shown in Fig. 4 right panel. Although the SM and the new physics model peak in the same region, the factor of $\sim 3(2)$ excess in the extreme B (benchmark) model is quite evident.

The $B\bar{b}, bB \rightarrow W^+W^-\bar{b}\bar{b}$ channel is slightly different. Instead of producing two top-like objects, the heavy bottom decays into a $W$ plus a top that subsequently decays into another $W$ (with opposite charge) and a $b$. We will still follow the selection procedure in our previous analysis, with the cuts in [14] (muon channel) except for the cut on the $p_T$ of the hardest jet, that is moved from 120 GeV to 200 GeV and a $\chi^2 \leq 10$ (again we use a similar $\chi^2$ to the one used in the first reference of [13]) choosing the best configuration reconstructing a 173 GeV top quark, and will plot the invariant mass of this $t$ quark plus the extra $W$. The result is shown in Fig. 5 for the benchmark and the extreme $B$ models with two different cuts in the
Figure 4: Left panel: Reconstruction of $m_T$ at the LHC. Right panel: Reconstruction of $m_G$. In both cases we have normalized the distributions to 4 fb$^{-1}$ data and represent the results for the SM (solid blue), the benchmark model (data points with statistical errors) and the extreme $T$ case (dotted black). Details of the reconstruction method can be found in the text.

total invariant mass distribution and 4 fb$^{-1}$. In this case, our reconstruction of the $B$ quark is not as clear as the one of the $T$ quark, and more sophisticated analyses should be used to dig out the signal from the background. Nevertheless, we will see in the next section that the extreme $B$ model can be probed much more efficiently using the neutral decay of the $B$ quark.

3.2 $Zb\bar{b}$ channel

Let us now turn to the neutral decays of the heavy $T$ and $B$ quarks, starting with the $B\bar{b}, b\bar{B}$ channel into a $Zb\bar{b}$ final state. The SM irreducible background to this process is small ($\sigma(Zb\bar{b})$ with a leptonic $Z$ decay is around 2 pb), whereas the background from final states with larger cross sections like $Z+jets$ and $t\bar{t}$ can be reduced with a very simple set of cuts. To isolate the signal we will require two same-flavor opposite-sign leptons with $p_T \geq 25$ GeV and $|m_{l^+l^-} - m_Z| \leq 25$ GeV, and two $b$-tagged jets with $p_T \geq 20$ GeV and $|\eta| \leq 2.8$. We will also impose a veto on missing energy $E_T \leq 40$ GeV, to reduce the $t\bar{t}$

\[ ^1 \text{We have also checked that our model does not conflict with current searches of } H \to ZZ \to Zb\bar{b} \text{ [16] or measurements of } Z + b \text{ cross-section [17}. \]
Figure 5: Reconstruction of $m_B$ at the LHC for 4 fb$^{-1}$ in the SM (solid blue), the benchmark model (data points with errors) and the $B$ case (dotted black). We consider the cuts $m_{B\bar{b}} > 600$ GeV (left) and $m_{B\bar{b}} > 700$ GeV (right). Details of the reconstruction method can be found in the text.

background. With this selection we compute the invariant mass of the $Z$ and the hardest of the two $b$-jets (denoted by $b_h$), since the $b$ quark from the decay of the heavy $B$ is typically the hardest one. We plot the result in Fig. 6. In the left panel we show the $m_{Zb_h\bar{b}}$ invariant mass distribution in the SM, the benchmark model and the extreme $B$ case. It is clear that the distributions in the SM and the new model peak in very different regions. The benchmark model leads to too small a cross section and would require higher luminosity for discovery. The extreme $B$ model, however, shows a clear peak with a total number of $\approx 40$ events at $m_{Zb_h} \approx m_B = 600$ GeV, versus $\approx 3$ background events, implying a statistical significance of

$$\frac{S}{\sqrt{B}} \approx 21, \quad (Zb\bar{b} \text{ for extreme } B).$$

(19)

Given the presence of a distinct peak we can attempt to reconstruct the mass of the heavy gluon. In the right panel of Fig. 6 we show the total invariant mass of the three objects $Zb\bar{b}$ for the events passing the cuts. Due to the large width of the heavy gluon (the kinematical threshold prevents the full width to be apparent at energies below $\sim 600$ GeV) the number of events peaks slightly below $M_G = 850$ GeV, but the effect is clearly observable. The approximate statistical significance of the excess above 600 GeV is

$$\frac{S}{\sqrt{B}} \approx \frac{38}{\sqrt{5}} = 17, \quad (M_G \text{ peak in } Zb\bar{b} \text{ for extreme B}).$$

(20)
Figure 6: Left panel: reconstruction of $m_{Zb\bar{b}}$ at the LHC. Right panel: reconstruction of $m_{Zb\bar{b}}$ to show the heavy gluon mass. In both cases we have normalized the distributions to 4 fb$^{-1}$ of data and have represented the SM with thick solid blue line, the benchmark model with thin solid red line and the extreme $B$ case (data points with statistical errors).

The $Zb\bar{b}$ channel appears then as very promising even with the very simple cuts that we have used. In the extreme case the reconstruction of the $B$ quark and of the massive gluon at the 4 fb$^{-1}$ LHC could be correlated with the $t\bar{t}$ anomalies discussed in Section 3.1, disentangling the origin of the Tevatron FB asymmetry.

### 3.3 $Zt\bar{t}$ channel

The $Zt\bar{t}$ production channel resulting into a $ZW^+W^-b\bar{b}$ final state has also a very small SM background, but it is harder to reconstruct due to its large multiplicity. Instead of trying to reconstruct the $T$ mass, it is simpler to reconstruct the total final state in the search for the massive gluon. We do that requiring (i) three charged leptons with $p_T \geq 25$ GeV, and at least two of them with the same flavor and opposite sign reconstructing the $Z$ within 25 GeV; (ii) at least two $b$-tagged and at least two non-$b$-tagged jets with $p_T > 20$ and $|\eta| < 2.8$. We reconstruct the neutrino momentum using the on-shellness condition for a $W$ and take the two hardest jets and $b$-jets if there are more of them. The result is shown in Fig. 7. The extreme $T$ model shows a clear peak with $\approx 36$ events with no expected background events (the benchmark gives a weaker deviation). A more detailed analysis, trying to reconstruct both top quarks, would certainly help in the reconstruction of the heavy $T$ mass. Since the
Figure 7: Total invariant mass reconstruction for the $Zt\bar{t}$ channel in the SM (solid blue), benchmark (solid red) and extreme $T$ (data with statistical errors shown as a band) models for the $Ztt$ analysis described in the text for the LHC with 4 fb$^{-1}$.

The extreme $T$ model would also show up in the charged decay channel, a hint on the $T$ mass could be used in the reconstruction of this channel.

4 Light flavor excitations: $Wq'\bar{q}$ and $Zqq$

We have seen in previous sections that the production of single $T$ or $B$ quarks tend to introduce anomalies in current searches and could be seen if the reconstruction algorithms are slightly modified. However, $Q\bar{q}$ production is less apparent in these searches, being the best example of stealth new physics. We discuss in this section the best strategy to observe the extreme $Q$ model at the LHC. In the benchmark (extreme $Q$) model the production of heavy excitations $Q$ of the light flavors has a total cross section of 2.9 (5.4) pb at the 7 TeV LHC, resulting with a 2:1 ratio the final states $Wq'q$ and $Zqq$. The SM irreducible background is 17 nb for $W$ plus $\geq 1$ jets and 6 nb for $Z$ plus $\geq 1$ jets. Therefore, we need to impose stringent cuts to disentangle our signal from these large backgrounds. First of all, these extra $Q\bar{q}$ events will only appear at invariant masses above $m_Q = 600$ GeV, with the maximum at $\approx 700$ GeV. In addition, the jet from the decay of the heavy quark, with a $p_T \sim m_Q/2$, will be typically harder than the second jet. We should then impose an stringent cut on the hardest jet in order to reduce the SM backgrounds. In particular,
Figure 8: Left panel: transverse mass for the $Wj_h$ system in the $Wjj$ analysis described in the text for the SM (solid blue), benchmark model (data points with errors) and extreme Q model (dotted black). Right panel: Result of the fit of the $m_{Zj_h}$ distribution for the $Zjj$ analysis described in the text for the SM (solid blue), extreme Q model (data points with statistical errors) and the fit to both distributions (dotted black). Both plots are for the 7 TeV LHC with 4 fb$^{-1}$.

requiring a hardest jet with $p_T \geq 150$ GeV on top of the cuts defined in Ref. [18] reduces the $W+jets$ background to manageable levels. We show in Fig. 8 (left panel) the transverse mass distribution of the $W$ and the hardest jet. The signal does not seem significant in the benchmark model but may be observable in the extreme $Q$ case, with 6 bins departing more than 3 standard deviations from the expected background.

The neutral case is even more promising. Requiring two same-flavor, opposite-charge leptons with $p_T \geq 25$ GeV that reconstruct the $Z$ mass within 25 GeV, and two or more jets, with $p_T \geq 150$ GeV for one of them, and computing the invariant mass of the $Z$ and the hardest jet, we obtain the distribution in Fig. 8 (right panel). Although the benchmark model is still unobservable, there is a clear peak for the extreme model. We have fitted the signal plus background histogram to a Crystal Ball plus gaussian shape and obtained an excess of 170 events over the expected 540 background events in the region of two standard deviations around the center of the gaussian. This leads to a statistical significance of $7\sigma$ and a best fit of $m_{Q}^{\text{fit}} = 590$ GeV, very close to the actual heavy quark mass. This analysis is interesting as it gives a very clean signal for a model that is otherwise very difficult to find.
5 Summary and discussion

The Tevatron $A_t$ anomaly is a strong motivation for a search of correlated effects from new physics at the 7 TeV LHC. An explanation with physics above $\sim 1$ TeV seems disfavoured by data [2]. If it is below this energy, then a large width could be the key reason why it has escaped detection in the usual observables. In a recent work we proposed that a massive gluon with new decay modes $G \to Q\bar{q}$ would be a promising candidate, and here we have studied in some detail the consequences of these processes in current analyses and possible signals to be searched.

ATLAS and CMS are studying $t\bar{t}$ and $T\bar{T}$ production. We have shown that $T\bar{T}$ production could also be explored just by slightly changing the criteria of reconstruction. The channel $B\bar{b}$ provides the same $WWb\bar{b}$ signal and could also be studied there.

We have also discussed new channels that, if analyzed, could reveal single heavy quark production at the LHC. In particular, $Zq\bar{q}$ where the $Q$ quark is reconstructed with the $Z$ boson and the highest-energy jet looks promising. Other signals, like $Zb\bar{b}$ or $Zt\bar{t}$, are predicted here and have small SM backgrounds. The study of these channels is well motivated by holographic models. If the Tevatron anomaly is due to new quark interactions below the TeV, then they should be searched for at the LHC, since there seems to be few hideouts for the new physics beneath. We have focused our study on the region motivated by the Tevatron asymmetry but our analyses can be also applied to a wider range of couplings and quark and gluon masses.

Note added

During completion of this work we became aware of Refs. [19] in which similar ideas to the ones presented here are being investigated. See also [20].

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