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Heavy colored resonances in $t\bar{t} + \mathrm{jet}$ at the LHC

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Abstract

The LHC is the perfect environment for the study of new physics in the top quark sector. We study the possibility of detecting signals of heavy color-octet vector resonances, through the charge asymmetry, in $t\bar{t}$+jet events. Besides contributions with the $t\bar{t}$ pair in a color-singlet state, the asymmetry gets also contributions which are proportional to the color factor f^2_{abc}. This process is particularly interesting for extra-dimensional models, where the inclusive charge asymmetry generated by Kaluza-Klein excitations of the gluon vanishes at the tree level. We find that the statistical significance for the measurement of such an asymmetry is sizable for different values of the coupling constants and already at low energies.

1 Introduction

The physics of the top quark is one of the most promising research fields at hadronic colliders such as the Tevatron at Fermilab or the Large Hadron Collider (LHC) at CERN. Its huge mass compared with the other quarks, and of the same order as the Higgs boson vacuum expectation value, suggests that it can play an important role in the electroweak symmetry breaking. Since its discovery at Tevatron in 1995, it has been extensively studied and its properties have been measured with better and better precision. However, the optimal environment to perform top quark measurements is the LHC, due to its high energy reach (14 TeV center-of-mass energy at full activity). At the LHC a great amount of top-antitop quark pairs will be produced, thus allowing to develop analyses with high statistic. There, physics at the TeV scale will be widely explored, carrying to a better determination of the Standard Model (SM) as well as, possibly, discovery of new physics.

Several models predict the existence of heavy colored resonances decaying to top-antitop quark pairs, that in principle can be detected at the LHC, like axigluons [1] and colorons [2] or Kaluza–Klein excitations in extra dimensional models [3, 4, 5, 6, 7, 8]. So far, masses under roughly 1 TeV have been

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excluded by measurements performed at Tevatron [9, 10, 11, 12, 13]. The natural signature of such resonances is to find a peak in the invariant mass distribution of the top-antitop quark pair. However, asymmetries can be an alternative way of revealing these resonances. In QCD, a charge asymmetry appears in the differential distributions for top quarks and antiquarks at $\mathcal{O}(\alpha_S^3)$ [14]. It is generated mostly by $q\bar{q} \longrightarrow t\bar{t}(g)$ processes, through the diagrams shown in Figure 1. The contribution from $gq \longrightarrow t\bar{t}q$ is much smaller.

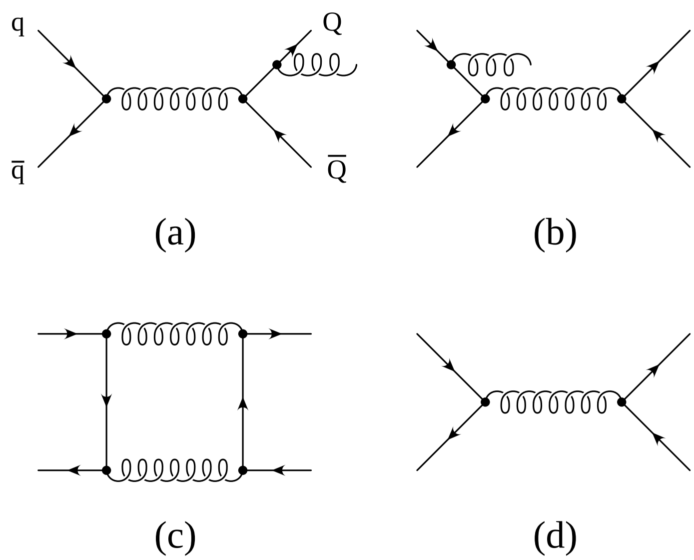

Figure 1: Origin of the QCD charge asymmetry.

The inclusive differential asymmetry at Tevatron is defined as:

$$A^{p\bar{p}}(\cos\theta) = \frac{N_t(\cos\theta) - N_{\bar{t}}(\cos\theta)}{N_t(\cos\theta) + N_{\bar{t}}(\cos\theta)}\,, \tag{1}$$

and is equivalent to a forward-backward asymmetry. This leads to an integrated asymmetry of $4-5\%$,with top quarks more abundant in the direction of the incoming proton [14, 15, 16, 17]. The latest measurement of the forward–backward asymmetry by CDF attests [18]:

$$A^{p\bar{p}} = 0.193 \pm 0.065_{\rm stat.} \pm 0.024_{\rm syst.}\,. \tag{2}$$

This 2σ discrepancy between data and theoretical prediction opens a window to the presence of new physics. Although it is too early to claim new physics there, because the statistical error of the measurement is rather large, this result clearly disfavours extra resonances with vanishing or negative contribution to the asymmetry, e.g. axigluons or colorons. As expected, this result has boosted a renovated interest in looking for new models that would account for this 2σ effect. In Ref. [19] we have considered, in a model independent way, heavy color-octet boson resonances with arbitrary vector and axial-vector couplings to quarks, and pointed out that the charge asymmetry can be a better way of revealing new resonances than the total cross section, also at the LHC. In Ref. [20], using the latest information from CDF on both the charge asymmetry and the invariant mass distribution [21], we have set constraints on the couplings between quarks and colored resonances as a function of its mass. We found that in the flavor-universal scenario, a large value of the vector coupling is necessary in order to obtain a positive charge asymmetry at the Tevatron. A positive charge asymmetry can also be obtained in flavor-non-universal scenarios where the light and the top quarks couple to the heavy resonance with strengths of opposite sign. A new model with this property has been constructed in [22]. Other flavor-universal axigluon-like models have been presented recently in [23, 24, 25]. The charge asymmetry in extra dimensional models has been analyzed in [26]. Different possibilities have also been explored in the t-channel: diquarks [27], Z'/W' exchange with large flavor violating coupling [28, 29], or scalar multiplets [30].

At the LHC, due to its symmetric configuration, the integrated asymmetry vanishes. Nevertheless, it is still possible to find a charge asymmetry in suitable defined kinematic regions. Selecting events in a given range of rapidity in the central region, the integrated central charge asymmetry can be defined [16, 19]:

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)} \, . \tag{3}$$

The central asymmetry $A_C(y_C)$ obviously vanishes if the whole rapidity spectrum is integrated, while a non-vanishing asymmetry can be obtained over a finite interval of rapidity.

The production of top quark pairs together with one jet is important at the LHC: the exclusive cross-section for this process can reach roughly half of the total inclusive cross-section calculated at next-to-leading order (NLO) [31]. The asymmetry produced in $t\bar{t}$+jet by the interference of initial- with final-state real gluon emission (Figures 1a and 1b) is, obviously, a tree level effect, and moreover, one of the main contributions to the inclusive asymmetry. In this paper we investigate the charge asymmetry in $t\bar{t}$+jet in the presence of a heavy color-octet vector resonance with different couplings to the quarks. We give the analytic form of the charge asymmetric contribution to the differential cross section, leaving the vector and axial-vector couplings as free parameters. We then concentrate on three different scenarios for such parameters and calculate the central charge asymmetry and its statistical significance at the LHC.

2 Charge asymmetry at the LHC

The LHC has already resumed its activity, after a one-year stop due to technical problems. It has started with an energy in the center-of-mass of a few TeV, in order to test the whole apparatus. In a second phase, the energy will rise to 7 TeV and subsequently to 10 TeV. Finally, the full 14 TeV energy will be reached. According to this planning, we have considered in our analysis both the center-of-mass energies of 7 and 10 TeV, in order to give predictions that can be tested in the first running period.

The SM predicts a charge asymmetry in $t\bar{t}$+jet already at tree level from $q\bar{q}$ events. This asymmetry is of similar size, but of opposite sign to the total $t\bar{t}$ inclusive asymmetry [14]. At the LHC, however, top quark production is dominated by gg fusion, which is charge symmetric. To reduce the contribution of these processes, and to enhance the asymmetry, it is necessary to perform a cut on the invariant mass of the top-antitop quark pair $m_{t\bar{t}}$. In Ref. [19] we found that for the central asymmetry in Eq. (3) values of the maximum rapidity around $y_C = 0.7$ maximize the statistical significance. Thus, in the following, we fix $y_C = 0.7$, and analyze the central asymmetry in the SM as a function of the cut on $m_{t\bar{t}}$. The additional jet is defined by using the k_T algorithm [33], with minimum transverse momentum $p_T = 20$ GeV and the jet parameter $R = 0.5$. In Figure 2 we show the results for center-of-mass energies of 7 and 10 TeV. We find that the asymmetry is positive and of the order of few percents (Fig. 2, left plots). As expected, at 7 TeV the asymmetry is higher than at 10 TeV, for the same value of $m_{t\bar{t}}^{\min}$, because the $q\bar{q}$ component is larger. The right plots in Fig. 2 show the luminosity that would be needed in order to have a statistical

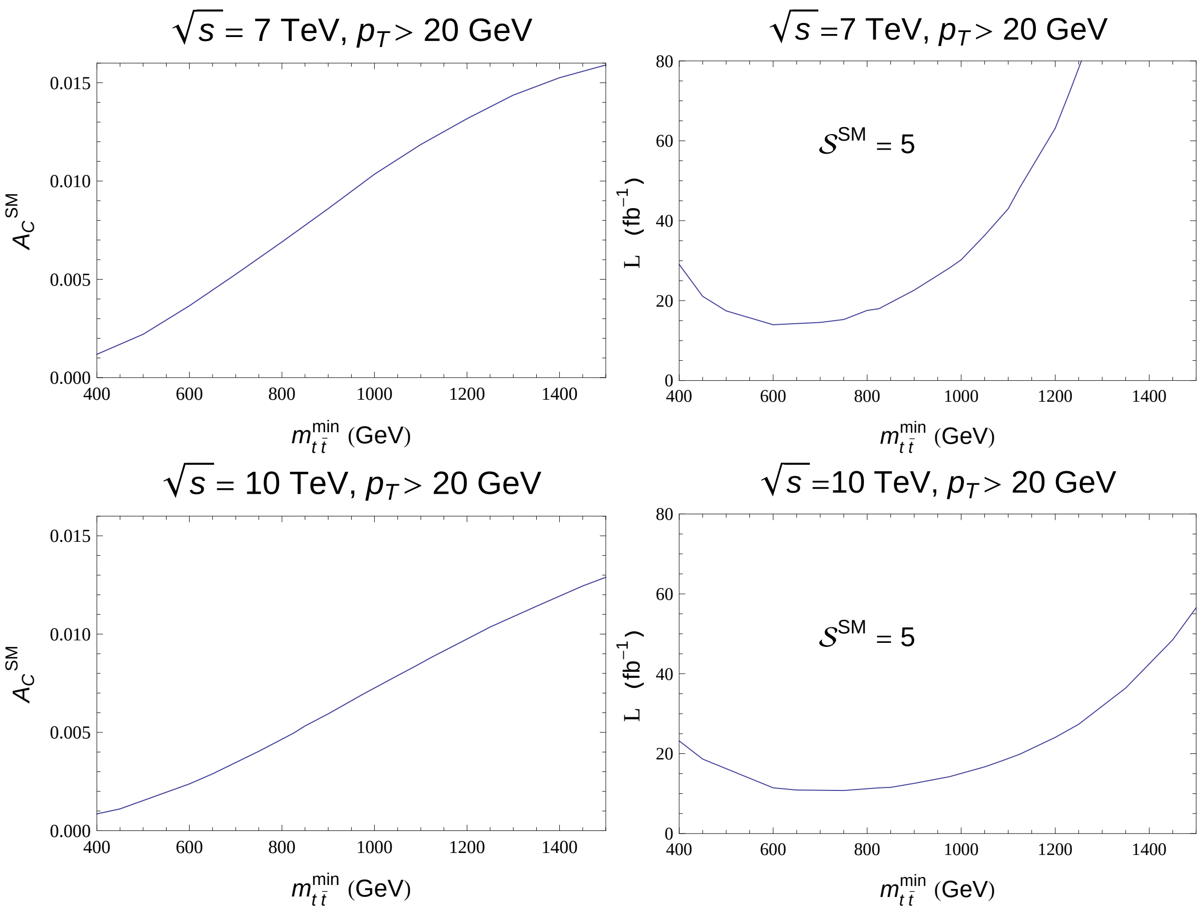

Figure 2: Central charge asymmetry and luminosity at the LHC from QCD, as a function of the cut $m_{t\bar{t}}^{\rm min}$ for $\sqrt{s} = 7$ TeV and 10 TeV.

significance equal to 5. The statistical significance $\mathcal{S}^{\rm SM}$ of the measurement, defined as the number of standard deviations of which the asymmetry differs from zero, can be written in the following way:

$$\mathcal{S}^{\rm SM} = \frac{A_C^{\rm SM}}{\sqrt{1-(A_C^{\rm SM})^2}} \sqrt{(\sigma_t + \sigma_{\bar{t}})^{\rm SM}\,\mathcal{L}} \simeq \frac{N_t - N_{\bar{t}}}{\sqrt{N_t + N_{\bar{t}}}} \,, \tag{4}$$

where $\mathcal{L}$ is the total integrated luminosity. From Fig. 2 we see that there is a minimum in the required luminosity for low values of $m_{t\bar{t}}^{\rm min}$. Before that minimum, $\mathcal{L}$ increases since the corresponding asymmetry approaches zero, while after the minimum, it increases because the number of events decreases. In conclusion, in the SM, with few tens of fb^{-1} it would be possible to have a sizable significance for low values of $m_{t\bar{t}}^{\rm min}$. We should mention that we have not considered experimental efficiencies, therefore this number should be seen only as a lower limit. In a realistic analysis, much higher luminosities will be required to perform that measurement. However, we are interested here in showing the position of the minimum as a function of $m_{t\bar{t}}^{\rm min}$.

As in Ref. [20], we consider now a toy model where a color-octet vector resonance can couple differently to light and top quarks. The vector and axial-vector couplings are denoted by $g_V^{q(t)}$ and $g_A^{q(t)}$, respectively, where the index q indicates the light quarks and the index t the top quarks. In Appendix A we list the expression for the asymmetric contribution to the $t\bar{t}$+jet differential cross section. It is interesting to stress that, contrary to the SM, where top quarks contribute to the asymmetry only when they are in a color-singlet state (color factor equal to d_{abc}^2), we find also color-octet contributions proportional to the color factor f_{abc}^2. We consider now three different scenarios. A large part of the parameter space for flavor-universal couplings is disfavored because the inclusive asymmetry in that case is negative [20]. In particular, axigluons such as originally introduced [1], i. e. with $g_V^{q(t)} = 0$, $g_A^{q(t)} = 1$, would be forbidden. Yet, it is possible to generate a positive inclusive asymmetry if the lighter quarks and the top quarks couple with different sign. Thus, as a first case, we examine a ”modified axigluon”, with $g_V^{q(t)} = 0$ and $g_A^t = -g_A^q = 1$. In the flavor-universal scenario, the only possibility that is still allowed at the 95% C.L. is the one where g_V takes high values and g_A is constrained accordingly as a function of the resonance mass. So we choose as a second scenario $g_V^{q(t)} = 1.8$ and $g_A^{q(t)} = 0.7$. In the third scenario we focus on a Kaluza–Klein gluon excitation in a basic Randall–Sundrum model: $g_V^q = -0.2$, $g_V^t = 2.5$, $g_A^q = 0$, $g_A^t = 1.5$, as presented, for instance, in [7]. Since the axial coupling for the light quarks is zero, the inclusive central charge asymmetry vanishes at tree level. Thus, it is necessary to look at the hard emission process, where it becomes different from zero. Accordingly, the inclusive charge asymmetry will get also non-vanishing loop contributions.

The results for the asymmetry and the minimal luminosity to achieve a statistical significance of 5 are shown in the Figures 3 and 4. We have chosen $m_G = 1.5$ TeV as a reference mass for the resonance. As in the pure QCD case, the maximal rapidity of $y_C = 0.7$ is optimal to enhance the statistical significance, which is defined as:

$$\mathcal{S} = \frac{A_C - A_C^{\rm SM}}{\sqrt{1-(A_C^{\rm SM})^2}} \sqrt{(\sigma_t + \sigma_{\bar{t}})^{\rm SM} \mathcal{L}} \,. \tag{5}$$

As expected, in the three models the asymmetry is slightly higher for $\sqrt{s} = 7$ TeV. The luminosity required to have a fixed significance has a minimum for low values of $m_{t\bar{t}}^{\rm min}$, at around one half the mass of the resonance, for all the scenarios. In the flavor-universal case, we found that this minimum value is reached with even softer cuts. We find also that in this scenario the needed luminosity is lower than in the other two cases, and almost of about one order of magnitude less. A few hundreds of pb^{-1} at relatively low values of $m_{t\bar{t}}^{\rm min}$ would allow a measurement in the first times of the LHC running. The Kaluza-Klein model shows an asymmetry of opposite sign compared to the other two cases. This can be an interesting way for distinguishing it from the other models. In Figs. 3 and 4 we also show the color-singlet contribution to the asymmetry. In the modified axigluon scenario, it has opposite sign compared with the total asymmetry. In the flavor-universal scenario it is about one half of the asymmetry. In the Kaluza-Klein model, the color-octet contribution is almost zero.

3 Conclusions

We have explored the central charge asymmetry in $t\bar{t} + {\rm jet}$ at the LHC. It receives contributions from top quark pairs both in a color-octet and in a color-singlet state. We have set a lower limit on the luminosity needed in order to have a statistical significance equal to 5 for three different scenarios at $\sqrt{s} = 7$ and 10 TeV. We have found that, in the flavor-universal case, this lower bound is around a few hundreds of pb^{-1}, while for the other scenarios few ${\rm fb}^{-1}$ are required. These values depend, of course, on the resonance mass. For the three choices of the parameters that we have considered, the minimum of the required luminosity is reached for relatively low values of $m_{t\bar{t}}^{\rm min}$. This is a non-trivial result as very boosted top quarks are difficult to distinguish from jets initiated by light quarks.

NLO calculations of $t\bar{t}$+jet [32] in the SM show that the exclusive asymmetry is almost completely washed out at Tevatron. Although there is no reason why we should find the same behavior if a heavy resonance exists, it would be interesting to extend this analysis at NLO, and to combine it with a realistic estimation of experimental efficiencies. From our analysis, the measurement of the charge asymmetry from $t\bar{t}$+jet events at the LHC seems promising, although challenging. Experimental analysis from the Tevatron with more statistics will also constrain further those resonances in the near future.

Aknowledgements

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A Asymmetric contribution to the $t\bar{t} + \mathrm{jet}$ cross section

The tree level cross section for $t\bar{t}$ production in the presence of a heavy resonance with arbitrary vector and axial-vector couplings to quarks, and the decay width of the resonance can be found in Ref. [19]. We define the propagator of the heavy resonance as:

$$G(s) = \frac{1}{s - m_G^2 + i\, m_G\, \Gamma_G} \, . \tag{6}$$

The charge asymmetric piece of the hard gluon radiation process

$$q(p_1) + \bar{q}(p_2) \to Q(p_3) + \bar{Q}(p_4) + g(p_5) \, , \tag{7}$$

defined as:

$$d\sigma_A^{q\bar{q}} \equiv \frac{1}{2} \left[d\sigma(q\bar{q} \to QX) - d\sigma(q\bar{q} \to \bar{Q}X) \right] \, , \tag{8}$$

is given by:

$$\begin{aligned}
\frac{d\sigma_A^{q\bar{q},hard}}{dy_{35}\, dy_{45}\, d\Omega} \;=\; & \frac{\alpha_s^3\, \hat{s}}{4\pi} \Bigg[\frac{d_1}{\hat{s}\, \hat{s}_{34}} + \left(g_V^q\, g_V^t\, d_1 - g_A^q\, g_A^t\, f_1 \right) \mathrm{Re} \left\{ \frac{G(\hat{s}_{34})}{\hat{s}} + \frac{G(\hat{s})}{\hat{s}_{34}} \right\} \\
& - \; 2\, g_A^q\, g_A^t\, f_2\, \frac{\mathrm{Re}\{G(\hat{s})\}}{\hat{s}_{34}} + \left(g_V^q\, g_A^t\, f_3 + g_A^q\, g_V^t\, d_3 \right) \mathrm{Im} \left\{ \frac{G(\hat{s}_{34})}{\hat{s}} - \frac{G(\hat{s})}{\hat{s}_{34}} \right\} \\
& + \; \left[\left((g_V^q)^2 + (g_A^q)^2 \right) \left((g_V^t)^2\, d_1 + (g_A^t)^2\, d_2 \right) - 4\, g_V^q\, g_A^q\, g_V^t\, g_A^t\, (f_1 + f_2) \right] \mathrm{Re}\{G(\hat{s})^\dagger G(\hat{s}_{34})\} \\
& + \; 2 \left[\left((g_V^q)^2 + (g_A^q)^2 \right) g_V^t\, g_A^t\, f_3 + g_V^q\, g_A^q\, \left((g_V^t)^2\, d_3 + (g_A^t)^2\, d_4 \right) \right] \mathrm{Im}\{G(\hat{s})^\dagger G(\hat{s}_{34})\} \Bigg] \\
& - \; (3 \leftrightarrow 4)
\end{aligned} \tag{9}$$

where

$$\mathrm{Re}\{G(\hat{s})\} = \frac{\hat{s} - m_G^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \, , \qquad \mathrm{Im}\{G(\hat{s})\} = \frac{m_G\, \Gamma_G}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \, ,$$

$$
\begin{aligned}
\mathrm{Re}\{G(\hat{s})^\dagger G(\hat{s}_{34})\} &= \frac{(\hat{s}-m_G^2)(\hat{s}-m_G^2)+m_G^2\Gamma_G^2}{[(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2]\,[(\hat{s}_{34}-m_G^2)^2+m_G^2\Gamma_G^2]}\;, \\
\mathrm{Im}\{G(\hat{s})^\dagger G(\hat{s}_{34})\} &= \frac{(\hat{s}-\hat{s}_{34})\,m_G^2\,\Gamma_G^2}{[(\hat{s}-m_G^2)^2+m_G^2\Gamma_G^2]\,[(\hat{s}_{34}-m_G^2)^2+m_G^2\Gamma_G^2]}\;,
\end{aligned} \tag{10}
$$

and

$$
\begin{aligned}
d_1 &= \frac{c_1}{y_{35}}\left[\left(\frac{y_{13}}{y_{15}}-\frac{y_{23}}{y_{25}}\right)\left(y_{13}^2+y_{14}^2+y_{23}^2+y_{24}^2+2m^2\left(y_{34}+2m^2+y_{12}\right)\right)+4m^2\left(y_{24}-y_{14}\right)\right]\;, \\
d_2 &= \frac{c_1}{y_{35}}\left[\left(\frac{y_{13}}{y_{15}}-\frac{y_{23}}{y_{25}}\right)\left(y_{13}^2+y_{14}^2+y_{23}^2+y_{24}^2-2m^2\left(y_{34}+2m^2+y_{12}\right)\right)+4m^2\left(y_{13}-y_{23}\right)\right]\;, \\
d_3 &= \frac{c_1}{y_{35}}\left[\frac{y_{13}^2+y_{14}^2-y_{23}^2-y_{24}^2-2m^2(y_{15}-y_{25})}{y_{15}\,y_{25}}\right]\frac{4}{\hat{s}^2}\,\epsilon^{p_1\,p_2\,p_3\,p_4}\;, \\
d_4 &= \frac{c_1}{y_{35}}\left[\frac{y_{13}^2+y_{14}^2-y_{23}^2-y_{24}^2+2m^2(y_{15}-y_{25})}{y_{15}\,y_{25}}\right]\frac{4}{\hat{s}^2}\,\epsilon^{p_1\,p_2\,p_3\,p_4}\;, \\
f_1 &= \frac{c_2}{y_{35}}\Bigg[\left(\frac{y_{23}}{y_{25}}-\frac{y_{13}}{y_{15}}\right)\left(y_{13}^2+y_{14}^2+y_{23}^2+y_{24}^2\right) \\
&+ 4\left(\frac{(y_{13}+y_{15})y_{24}(y_{13}-y_{35})}{y_{15}}-\frac{(y_{23}+y_{25})y_{14}(y_{23}-y_{35})}{y_{25}}\right)\Bigg]\;, \\
f_2 &= \frac{c_2}{y_{35}}\left[2m^2\left(y_{15}-y_{25}\right)\right]\;, \\
f_3 &= \frac{c_2}{y_{35}}\left[\frac{y_{13}^2+y_{14}^2-y_{23}^2-y_{24}^2}{y_{15}\,y_{25}}\right]\frac{4}{\hat{s}^2}\,\epsilon^{p_1\,p_2\,p_3\,p_4}\;,
\end{aligned} \tag{11}
$$

with

$$
y_{ij} = \frac{2p_i\cdot p_j}{\hat{s}}\;. \tag{12}
$$

The colour factor are $c_1 = \frac{d_{abc}^2}{16N_C^2}$, and $c_2 = \frac{f_{abc}^2}{16N_C^2}$, with $N_C = 3$, $d_{abc}^2 = 2C_F(N_C^2-4) = 40/3$ and $f_{abc}^2 = 2C_F N_C^2 = 24$.

The charge asymmetric contribution of the flavor excitation process

$$
q(p_1)+g(p_2)\to Q(p_3)+\bar{Q}(p_4)+q(p_5)\;, \tag{13}
$$

defined as:

$$
d\sigma_A^{q\bar{q}} \equiv \frac{1}{2}\left[d\sigma(qg\to QX)-d\sigma(qg\to\bar{Q}X)\right]\;, \tag{14}
$$

is infrared finite and can be obtained just by crossing of the momenta $(2\leftrightarrow 5)$ from Eq. (9).

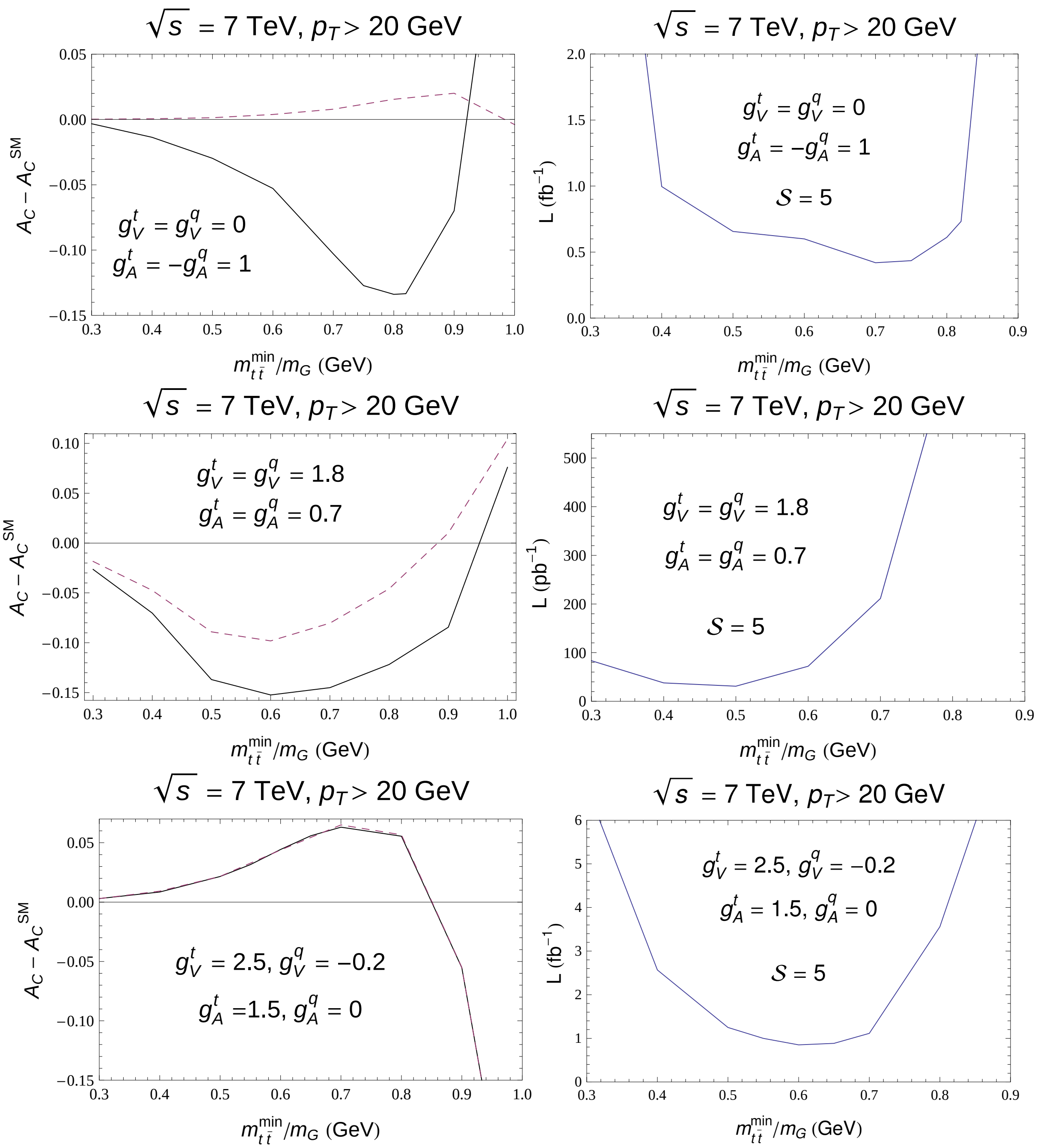

Figure 3: Central charge asymmetry and luminosity to obtain a statistical significance $\mathcal{S} = 5$ at the LHC, as a function of $m_{t\bar{t}}^{\min}$ for $\sqrt{s} = 7$ TeV. The dashed line represent the contribution of the d_{abc}^2 terms. $m_G = 1.5$ TeV.

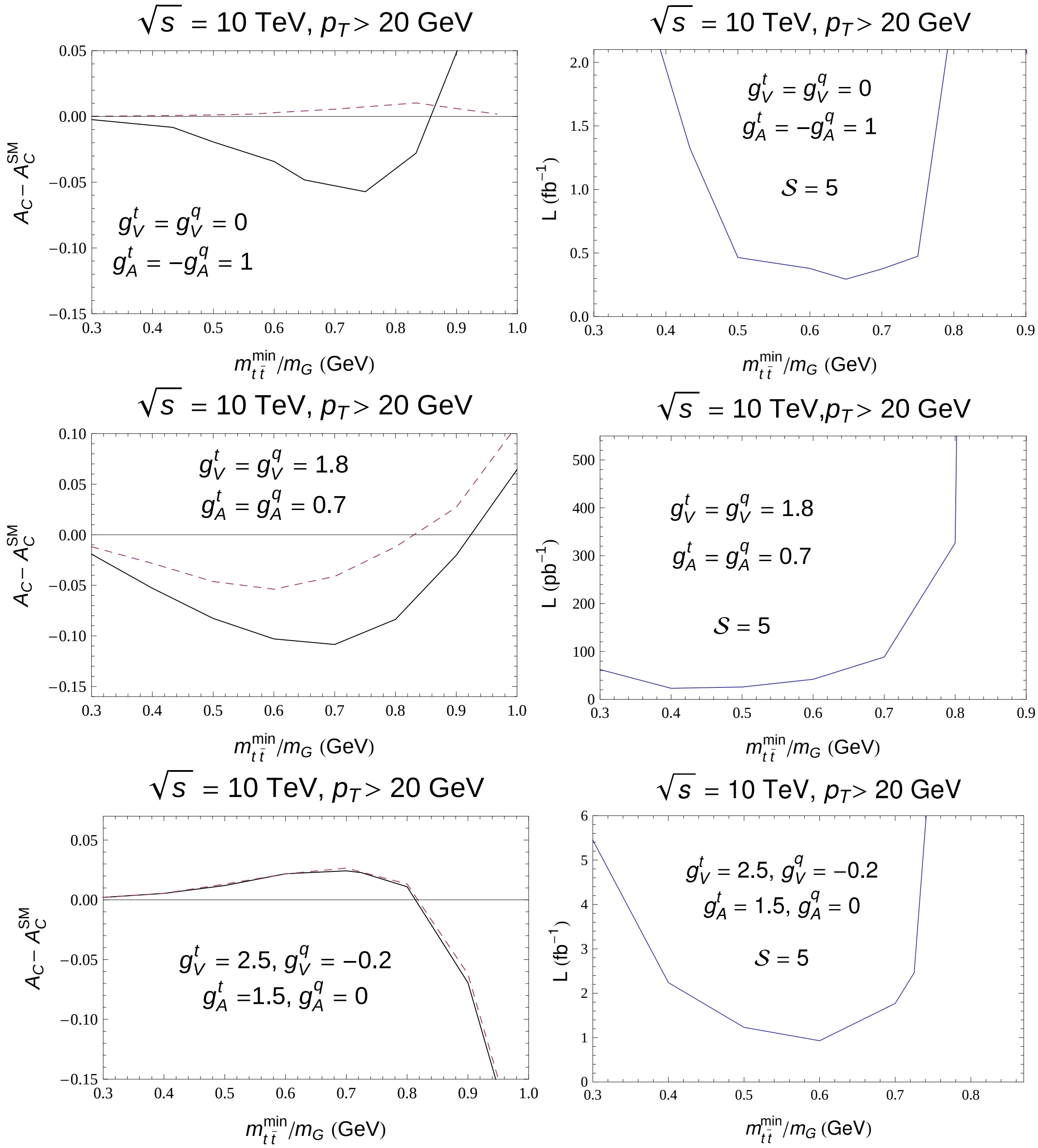

Figure 4: Central charge asymmetry and luminosity to obtain a statistical significance $\mathcal{S} = 5$ at the LHC, as a function of $m_{t\bar{t}}^{\rm min}$ for $\sqrt{s} = 10$ TeV. The dashed line represent the contribution of the d_{abc}^2 terms. $m_G = 1.5$ TeV.

References

[1] J. C. Pati and A. Salam, Phys. Lett. B **58** (1975) 333; L. J. Hall and A. E. Nelson, Phys. Lett. B **153** (1985) 430; P. H. Frampton and S. L. Glashow, Phys. Lett. B **190** (1987) 157; Phys. Rev. Lett. **58** (1987) 2168; J. Bagger, C. Schmidt and S. King, Phys. Rev. D **37** (1988) 1188; F. Cuypers, Z. Phys. C **48** (1990) 639.

[2] C. T. Hill, Phys. Lett. B **266** (1991) 419; C. T. Hill and S. J. Parke, Phys. Rev. D **49** (1994) 4454; R. S. Chivukula, A. G. Cohen and E. H. Simmons, Phys. Lett. B **380** (1996) 92.

[3] T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin (Math. Phys.) **1921** (1921) 966; O. Klein, Z. Phys. **37** (1926) 895 [Surveys High Energ. Phys. **5** (1986) 241].

[4] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 3370.

[5] D. A. Dicus, C. D. McMullen and S. Nandi, Phys. Rev. D **65** (2002) 076007.

[6] K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D **77** (2008) 015003; K. Agashe, A. Falkowski, I. Low and G. Servant, JHEP **0804** (2008) 027.

[7] B. Lillie, L. Randall and L. T. Wang, JHEP **0709** (2007) 074; B. Lillie, J. Shu and T. M. P. Tait, Phys. Rev. D **76** (2007) 115016.

[8] A. Djouadi, G. Moreau and R. K. Singh, Nucl. Phys. B **797** (2008) 1.

[9] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **79**, 112002 (2009).

[10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 041801 (2009).

[11] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **77**, 051102 (2008); Y. Oksuzian *et al.* [CDF Collaboration], Conf. Note 9844 (June 2009).

[12] D0 Collaboration, Conf. Note 5882 (March 2009).

[13] C. Wang *et al.* [CDF Collaboration], Public Note 9730 (April 2009); A. Boveia *et al.* [CDF Collaboration], Public Note 9640 (January 2009).

[14] J. H. Kühn and G. Rodrigo, Phys. Rev. D **59** (1999) 054017; Phys. Rev. Lett. **81** (1998) 49.

[15] M. T. Bowen, S. D. Ellis and D. Rainwater, Phys. Rev. D **73** (2006) 014008.

[16] O. Antuñano, J. H. Kühn and G. Rodrigo, Phys. Rev. D **77** (2008) 014003; G. Rodrigo, PoS **RADCOR2007** (2008) 010.

[17] L. G. Almeida, G. Sterman and W. Vogelsang, Phys. Rev. D **78** (2008) 014008.

[18] G. L. Strycker *et al.* [CDF Collaboration], Conf. Note 9724 (March 2009).

[19] P. Ferrario and G. Rodrigo, Phys. Rev. D **78** (2008) 094018; J. Phys. Conf. Ser. **171**, 012091 (2009).

[20] P. Ferrario and G. Rodrigo, Phys. Rev. D **80** (2009) 051701.

[21] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. 102 (2009) 222003.

[22] P. H. Frampton, arXiv:0910.0307 [hep-ph]; P. H. Frampton, J. Shu and K. Wang, arXiv:0911.2955 [hep-ph].

[23] C. D. Carone, J. Erlich and M. Sher, Phys. Rev. D **78** (2008) 015001.

[24] M. V. Martynov and A. D. Smirnov, Mod. Phys. Lett. A **24** (2009) 1897.

[25] A. R. Zerwekh, arXiv:0908.3116 [hep-ph].

[26] A. Djouadi, G. Moreau, F. Richard and R. K. Singh, arXiv:0906.0604 [hep-ph].

[27] A. Arhrib, R. Benbrik and C. H. Chen, arXiv:0911.4875 [hep-ph].

[28] S. Jung, H. Murayama, A. Pierce and J. D. Wells, arXiv:0907.4112 [hep-ph].

[29] K. Cheung, W. Y. Keung and T. C. Yuan, arXiv:0908.2589 [hep-ph].

[30] J. Shu, T. M. P. Tait and K. Wang, arXiv:0911.3237 [hep-ph].

[31] S. Dittmaier, P. Uwer and S. Weinzierl, Eur. Phys. J. C **59**, 625 (2009)

[32] S. Dittmaier, P. Uwer and S. Weinzierl, Phys. Rev. Lett. **98**, 262002 (2007).

[33] S. Catani, Y. L. Dokshitzer and B. R. Webber, Phys. Lett. B **285**, 291 (1992).