

Charge asymmetries of top quarks: a window to new physics at hadron colliders

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Abstract.

With the next start of LHC, a huge production of top quarks is expected. There are several models that predict the existence of heavy colored resonances decaying to top quarks in the TeV energy range. A peak in the differential cross section could reveal the existence of such a resonance, but this is experimentally challenging, because it requires selecting data samples where top and antitop quarks are highly boosted. Nonetheless, the production of such resonances might generate a sizable charge asymmetry of top versus antitop quarks. We consider a toy model with general flavour independent couplings of the resonance to quarks, of both vector and axial-vector kind. The charge asymmetry turns out to be a more powerful observable to detect new physics than the differential cross section, because its highest statistical significance is achieved with data samples of top-antitop quark pairs of low invariant masses.

1. Introduction

The CERN Large Hadron Collider (LHC) will start-up very soon colliding protons to protons. The full $\sqrt{s} = 14$ TeV design energy run will operate with an initial low luminosity of $\mathcal{L} = 10^{33} \text{cm}^{-2} \text{s}^{-1}$ (equivalent to $10 \text{fb}^{-1}/\text{year}$ integrated luminosity) and then it will pass to a second phase of $\mathcal{L} = 100 \text{fb}^{-1}/\text{year}$. The production cross section of top-antitop quark pairs at LHC is about 430pb at 10TeV , and 950pb at 14TeV [1]. The LHC will produce even in the first phase of operation a sample of $t\bar{t}$ -pairs equivalent to the sample already collected at Tevatron during its whole life, and millions of top-antitop quark pairs in the next runs. This will allow not only to measure better some of the properties of the top quark, such as mass and cross section, but also to explore with unprecedented huge statistics the existence of new physics at the TeV energy scale in the top quark sector.

At leading order in the strong coupling α_s the differential distributions of top and antitop quarks are identical. This feature changes, however, due to higher order corrections [2], which predict at $\mathcal{O}(\alpha_s^3)$ a charge asymmetry of top versus antitop quarks. The inclusive charge asymmetry receives contributions from two reactions: radiative corrections to quark-antiquark annihilation (Fig. 1) and interference between different amplitudes contributing to gluon-quark scattering $gq \rightarrow t\bar{t}q$ and $g\bar{q} \rightarrow t\bar{t}\bar{q}$. The latter contribution is, in general, much smaller than the former. Gluon-gluon fusion remains charge symmetric. At Tevatron, this asymmetry is equivalent to a forward-backward asymmetry and QCD predicts that the size of the inclusive charge asymmetry is 5 to 8% [2, 3, 4], with top quarks (antitop quarks) more abundant in the direction of the incoming proton (antiproton). This is in agreement with the experimental data [5, 6], but more statistic is needed to reduce the errors.

At LHC, the total forward-backward asymmetry vanishes trivially because the proton-proton initial state is symmetric. Nevertheless, a charge asymmetry is still visible in suitably defined distributions [2].

Top quark production at LHC is dominated by gluon-gluon fusion (84 % at 10 TeV, and 90 % at 14 TeV), which is charge symmetric under higher order corrections. The charge antisymmetric contributions to top quark production are thus screened at LHC due to the prevalence of gluon-gluon fusion. This is the main handicap for that measurement. The amount of events initiated by gluon-gluon collisions can nevertheless be suppressed with respect to the $q\bar{q}$ and $gq(\bar{q})$ processes, the source of the charge asymmetry, by introducing a lower cut on the invariant mass of the top-antitop quark system $m_{t\bar{t}}$; this eliminates the region of lower longitudinal momentum fraction of the colliding partons, where the gluon density is much larger than the quark densities. The charge asymmetry of the selected data samples is then enhanced, although at the price of lowering the statistics. This is, in principle, not a problem at LHC, where the high luminosity will compensate by far this reduction.

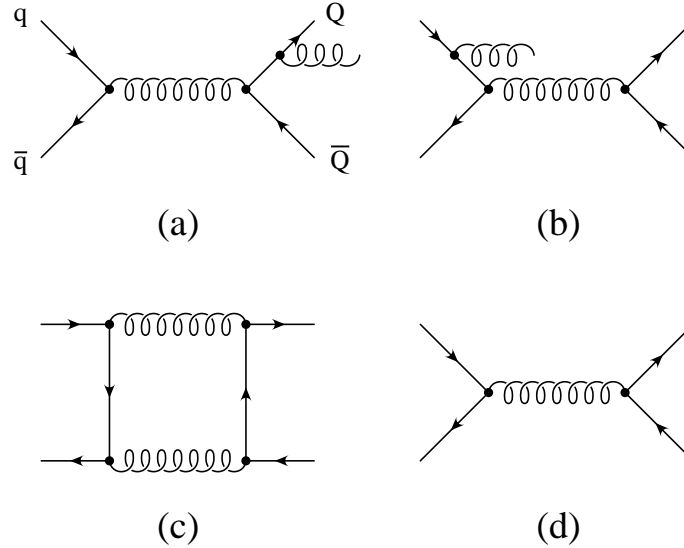


Figure 1. Origin of the QCD charge asymmetry in hadroproduction of heavy quarks: interference of final-state (a) with initial-state (b) gluon bremsstrahlung, plus interference of the double virtual gluon exchange (c) with the Born diagram (d). Only representative diagrams are shown.

Several models predict the existence of heavy colored resonances decaying to top quarks that might be observed at the LHC [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. Those resonances will appear as a peak in the invariant mass distribution of the top-antitop quark pair located at the mass of the new resonance.

Some of those exotic gauge bosons, such as the axigluons [7, 8], might generate at tree-level a charge asymmetry too, through the interference with the $q\bar{q} \rightarrow t\bar{t}$ Standard Model (SM) amplitude [3, 9, 10]. Gluon-gluon fusion to top quarks stays, at first order, unaltered by the presence of new interactions because a pair of gluons do not couple to a single extra resonance in this kind of models [8, 13].

To discover those resonances, hence, it is necessary to select top-antitop quark events with large invariant masses; i.e. in the vicinity of the mass of the new resonance. A sizable charge asymmetry can also be obtained only if gluon-gluon fusion is sufficiently suppressed, that is at large values of $m_{t\bar{t}}$. Because the top quarks of those data samples will be produced highly boosted, they will be observed as a single monojet. The standard reconstruction algorithms that are based on the reconstruction of the decay products, however, loose efficiency very rapidly at high transverse momentum. For $p_T > 400$ GeV new identification techniques are necessary. This has motivated many recent investigations [19, 20, 21, 22] aimed at distinguishing top quark jets from the light quark QCD background by exploiting the jet substructure, without identifying the decay products.

In our work [23] we find that for a measurement at LHC of the top quark charge asymmetry it is not necessary to select events with very large invariant masses of the top-antitop quark pairs. We show that the highest statistical significance occurs with moderate selection cuts. Indeed, we find that the measurement of the charge asymmetry induced by QCD is better suited in the region of low top-antitop quark pair invariant masses. The higher statistics in this region compensates the smallness of the charge asymmetry. We also investigate the charge asymmetry generated by the exchange of a heavy color-octet resonance. We study the scenario where the massive extra gauge boson have arbitrary flavour independent vector and axial-vector couplings to quarks. This includes the case of the axigluon that we have already analyzed in Ref. [3].

2. QCD induced charge asymmetry at LHC

Top quark production at LHC is forward-backward symmetric in the laboratory frame as a consequence of the symmetric colliding proton-proton initial state. The charge asymmetry can be studied nevertheless by selecting appropriately chosen kinematic regions. The production cross section of top quarks is, however, dominated by gluon-gluon fusion and thus the charge asymmetry generated from the $q\bar{q}$ and gq ($g\bar{q}$) reactions is small in most of the kinematic phase-space.

Nonetheless, QCD predicts at LHC a slight preference for centrally produced antitop quarks, with top quarks more abundant at very large positive and negative rapidities [2]. The difference between the single particle inclusive distributions of t and \bar{t} quarks can be understood easily. Due to the proton composition in terms of quarks, production of $t\bar{t}(g)$ is dominated by initial quarks with large momentum fraction and antiquarks with small momentum fraction. QCD predicts that top (antitop) quarks are preferentially emitted in the direction of the incoming quarks (antiquarks) in the partonic rest frame as shown in Fig. 2 (left graphs). The boost into the laboratory frame "squeezes" the top mainly in the forward and backward directions, while antitops are left more abundant in the central region (see Fig. 2, right graphs).

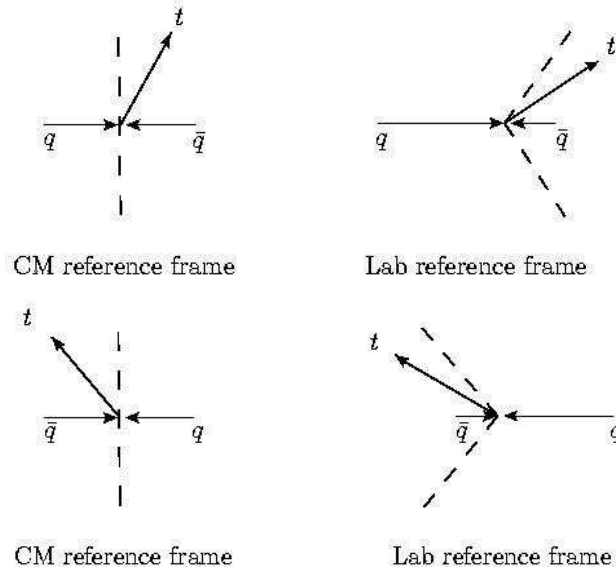


Figure 2. Boost from the center-of-mass quark-antiquark reference frame to the laboratory frame.

We select events in a given range of rapidity y and define the integrated charge asymmetry in the central region as [3]:

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}. \quad (1)$$

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. Since more antitop quarks are present in the central region (low y), we expect the asymmetry to be negative. We also perform a cut on the invariant mass of the top-antitop quark pair, $m_{t\bar{t}} > m_{t\bar{t}}^{\min}$, because that region of the phase space is more sensitive to the quark-antiquark induced events rather than the gluon-gluon ones, so that the asymmetry is enhanced. The main virtue of the central asymmetry is that it vanishes exactly for parity-conserving processes.

In Fig. 3 (left plot) we show the central charge asymmetry at 14 TeV as a function of the maximum rapidity y_C for two different values of the cut on the invariant mass of the top-antitop quark pair $m_{t\bar{t}} > 500$ GeV, and 1 TeV, respectively. As expected, the central charge asymmetry is negative, is larger for larger values of the cut $m_{t\bar{t}}^{\min}$, and vanishes for large values of y_C . We also show in Fig. 3 (right plot) the corresponding statistical significance \mathcal{S} of the measurement, defined as

$$\mathcal{S}^{\text{SM}} = A_C^{\text{SM}} \sqrt{(\sigma_t + \sigma_{\bar{t}})^{\text{SM}} \mathcal{L}} = \frac{N_t - N_{\bar{t}}}{\sqrt{N_t + N_{\bar{t}}}}, \quad (2)$$

where \mathcal{L} denotes the total integrated luminosity for which we take $\mathcal{L} = 10 \text{ fb}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$, accordingly to the first LHC schedule. The maximum significance is reached at $y_C = 1$ for $m_{t\bar{t}} > 500$ GeV, and at $y_C = 0.7$ for $m_{t\bar{t}} > 1 \text{ TeV}$. Surprisingly, although the size of the asymmetry is greater for the larger value of $m_{t\bar{t}}^{\min}$, its statistical significance is higher for the lower cut. This is a very interesting feature because softer top and antitop quarks should be identified more easily than the very highly boosted ones.

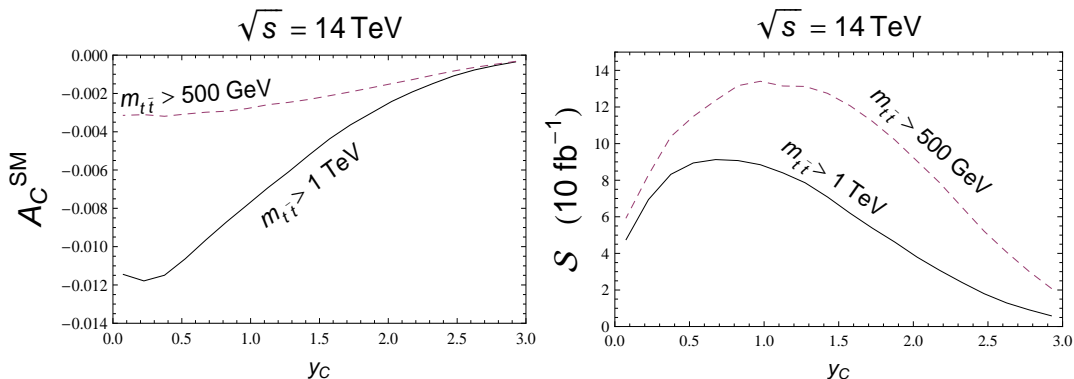


Figure 3. Central charge asymmetry at LHC as predicted by QCD, as a function of the maximum rapidity y_C (left plot), and corresponding statistical significance (right plot), for two different cuts on the top-antitop quark pair invariant mass.

We now fix the value of the maximum rapidity to $y_C = 0.7$ and study the size of the asymmetry and its statistical significance as a function of $m_{t\bar{t}}^{\min}$. Our results are shown in Fig. 4 for $\sqrt{s} = 14 \text{ TeV}$ and $\mathcal{L} = 10 \text{ fb}^{-1}$. We find that the asymmetry increases for larger values of $m_{t\bar{t}}^{\min}$, while the statistical significance is larger without introducing any selection cut. Note that the size of the asymmetry decreases again above $m_{t\bar{t}}^{\min} = 2.5 \text{ TeV}$ because in that region the $gq(\bar{q})$ events compensate the asymmetry generated by the $q\bar{q}$ events; their contributions are of opposite sign. Although we have not taken into account experimental efficiencies, we can conclude that 10 fb^{-1} of data at the design energy of the LHC seems to be enough for a clear measurement of the QCD asymmetry.

3. Charge asymmetry of color-octet resonances at LHC

We study here the charge asymmetry produced at LHC by the decay of a color-octet resonance G to top quarks, in the scenario where the vector g_V^q and axial-vector g_A^q couplings are flavour independent. We

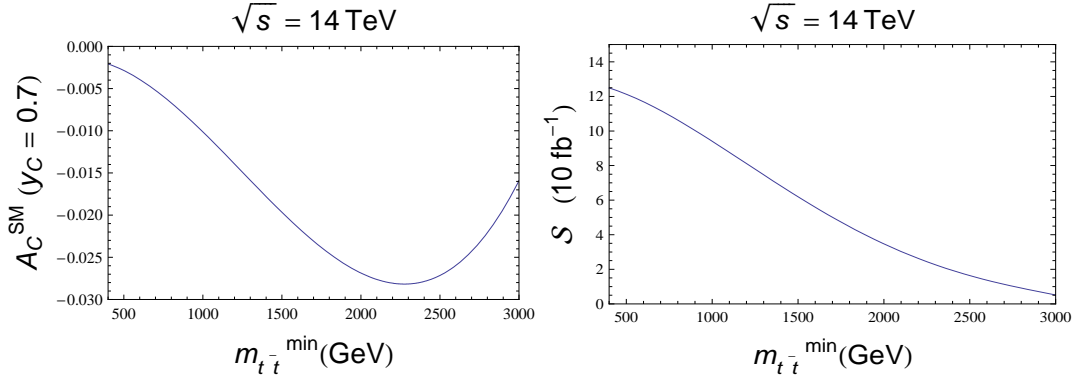


Figure 4. Central charge asymmetry and statistical significance at LHC from QCD, as a function of the cut $m_{t\bar{t}}^{\min}$, for $y_C = 0.7$.

evaluate the central asymmetry in Eq. (1), and its statistical significance, defined as [16]

$$\mathcal{S}^G = \frac{A_C^{G+SM} - A_C^{SM}}{\sqrt{1 - (A_C^{SM})^2}} \sqrt{(\sigma_t + \sigma_{\bar{t}})^{SM} \mathcal{L}}, \quad (3)$$

for different values of the couplings and the kinematical cuts.

The corresponding differential cross section is given in Eq. (A.1) of the Appendix. The charge asymmetry is built up from the two contributions of the differential partonic cross section that are odd in the polar angle. The first one arises from the interference with the gluon amplitude, and is proportional to the product of the axial-vector couplings of the light and the top quarks. This contribution, provided that the product of couplings is positive, is negative in the forward direction for invariant masses of the top-antitop quark pair below the resonance mass, and changes sign above. At LHC, because of the boost into the laboratory frame (cf. discussion in Section 2), this means that a positive central asymmetry is found for values of the cut in the invariant mass of the top-antitop quark pair below the mass of the resonance and a negative asymmetry above. This means that the asymmetry has to vanish at a certain intermediate value of that cut, close to and below the resonance mass.

The second contribution, arising from the squared amplitude of the heavy resonance, although always positive for positive couplings, is suppressed with respect to the contribution of the interference term by two powers of the resonance mass. For large values of the vector couplings, however, it might compensate the interference contribution, then leading to a positive contribution in the forward region.

In summary, we expect to find two maxima in the statistical significance as a function of $m_{t\bar{t}}^{\min}/m_G$. Starting from the threshold, where the asymmetry is small because gluon-gluon fusion dominates there, the size of the central asymmetry will grow by increasing $m_{t\bar{t}}^{\min}$, as the quark-antiquark annihilation process becomes more and more important. Since the asymmetry induced by the excited gluon will vanish at a certain critical point, its statistical significance will do as well, and will reach a maximum at an intermediate value between that critical point and the threshold. Above the critical point, the asymmetry becomes negative and its statistical significance increases again, until the event yield becomes too small. A second maximum in the statistical significance will be generated there. For certain values of the vector couplings, however, the contribution from the squared amplitude of the exotic resonance is greater than the interference term. In this case, the central asymmetry generated by the exotic resonance will be negative exclusively, and we will find only one maximum in the statistical significance.

In our first analysis we shall determine the value of the maximum rapidity y_C that maximizes the statistical significance. We fix the resonance mass at 1.5 TeV, and impose two different cuts on the invariant mass of the top-antitop quark pair, namely $m_{t\bar{t}} > 700$ GeV and $m_{t\bar{t}} > 1.5$ TeV. We choose

as an example the axigluon case: $g_V^{q(t)} = 0$, $g_A^{q(t)} = 1$. In Fig 5, we present the results obtained for the central asymmetry and the statistical significance at 14 TeV centre-of-mass energy. We notice that the central asymmetry suffers a change of sign by passing from the lower cut to the higher one. This means that it will vanish for a given value of the cut, thus making the statistical significance vanishing also.

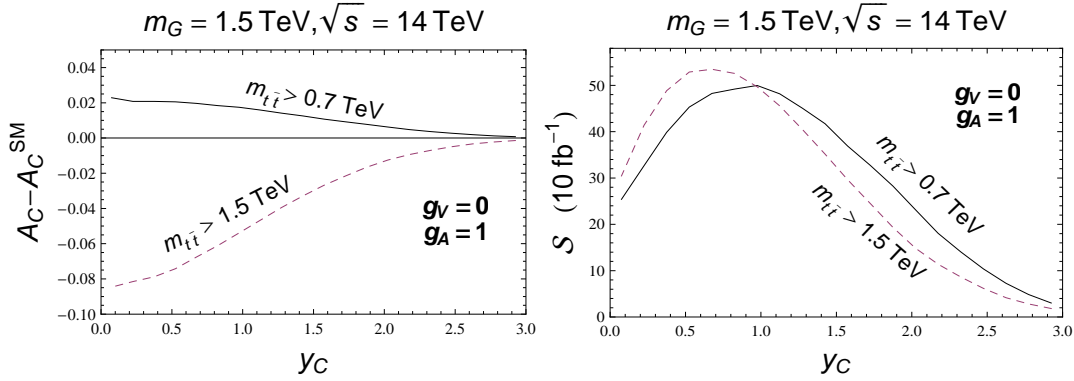


Figure 5. Central charge asymmetry (left plot) and statistical significance (right plot) at LHC as a function of the maximum rapidity, for two different cuts on the top-antitop quark invariant mass. The axigluon case is shown.

By looking at the corresponding significance we find that $y_C = 0.7$ is a good choice for any value of the couplings. Thus, we use this value to find the best cut for the top-antitop quark pair invariant mass. In order to do that, we choose several values of the parameters and we study the trend of the significance as a function of $m_{t\bar{t}}^{\text{min}}/m_G$. We show again the results for the axigluon case, in Fig 6. The optimal cuts depend, of course, on the values of the vector and axial-vector couplings, but either $m_{t\bar{t}}^{\text{min}}/m_G = 0.5$ or $m_{t\bar{t}}^{\text{min}}/m_G = 0.8$ provide a reasonable statistical significance for almost all the combinations of the couplings. This is an important result, because it means that a relatively low cut – at about half of the mass of the resonance or even below – is enough to have a good statistical significance, and a clear signal from the measurement of the charge asymmetry.

We now fix $m_{t\bar{t}}^{\text{min}}/m_G = 0.5$ and $m_{t\bar{t}}^{\text{min}}/m_G = 0.8$, and we study how the central asymmetry and its statistical significance vary as a function of the vector and the axial-vector couplings, for a given value of the resonance mass. These choices, for which we have found the best statistical significances, are of course arbitrary and are not necessarily the best for all the values of the vector and axial-vector couplings. For illustrative purposes are, however, good representatives. We have chosen $m_G = 1.5, 2$ and 3 TeV . The results in the (g_V, g_A) plane are presented in Fig 7. It is possible to see that the pattern of the size of the asymmetry is quite similar independently of the value of the resonance mass; it depends mostly on the ratio $m_{t\bar{t}}^{\text{min}}/m_G$. A sizable asymmetry is found whatever the value of the resonance mass is. The statistical significance, as expected, decreases with higher resonance masses.

4. Conclusions

We have analyzed at LHC the charge asymmetry of top-antitop quark pair production in QCD and through the exchange of a color-octet heavy boson with flavor independent coupling to quarks.

This is an observable that is very sensitive to new physics. We have studied the statistical significance of the measurement of such an asymmetry, and we have found that it is possible to tune the selection cuts in order to find a sensible significance. The maximum of the statistical significance for the measurement of the asymmetry as predicted by QCD is obtained without introducing any cut in the invariant mass of the top-antitop quark pair, even if the asymmetry is smaller in this case.

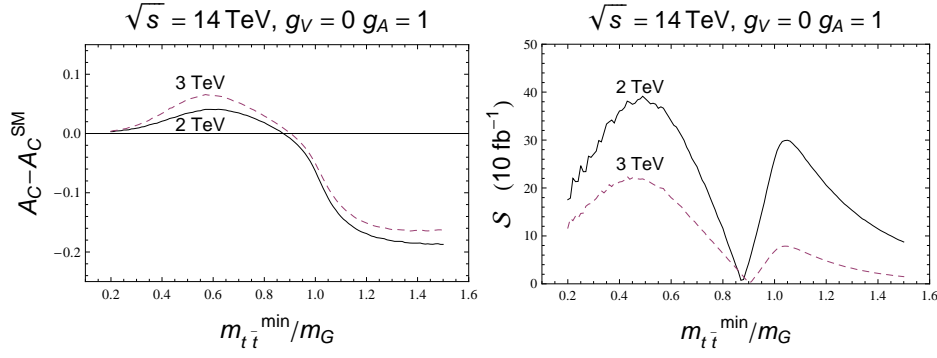


Figure 6. Central asymmetry and statistical significance at LHC, for $g_V = 0$, $g_A = 1$, as a function of the cut on the top-antitop quark pair invariant mass for $m_G = 2$ and 3 TeV.

When a heavy resonance is considered, one or two maxima in the significance spectrum are found, depending on the size of the couplings. The position of the peaks depends on the ratio $m_{t\bar{t}}^{\min}/m_G$ and not on the resonance mass. One of the peaks can be located at an energy scale as low as one half of the resonance mass, or even below. Data samples of top and antitop quarks that are not too energetic can then be used to detect or exclude the existence of this kind of resonances.

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Appendix

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

$$\begin{aligned}
\frac{d\sigma^{q\bar{q}\rightarrow t\bar{t}}}{d\cos\hat{\theta}} &= \alpha_s^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \left(1 + c^2 + 4m^2 + \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[g_V^q g_V^t (1 + c^2 + 4m^2) + 2g_A^q g_A^t c \right] \right. \\
&+ \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[\left((g_V^q)^2 + (g_A^q)^2 \right) \left((g_V^t)^2 (1 + c^2 + 4m^2) \right. \right. \\
&\left. \left. + (g_A^t)^2 (1 + c^2 - 4m^2) \right) + 8g_V^q g_A^q g_V^t g_A^t c \right] \Bigg), \tag{A.1}
\end{aligned}$$

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 the 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 $g_V^q(g_V^t)$, $g_A^q(g_A^t)$ represent the vector and vector-axial couplings among the excited gluons and the light quarks (top quarks).

There are two terms in Eq. (A.1) that are odd in the polar angle and therefore there are two contributions to the charge asymmetry. The first one arises from the interference of the SM amplitude with the resonance amplitude, and the second one from the square of the resonance amplitude. The former depends on the axial-vector couplings only, while the latter is proportional to both the vector and the axial-vector couplings. For large values of the resonance mass, the second term is suppressed, and

the charge asymmetry will depend mostly on the value of the axial-vector couplings, and residually on the vector couplings. The decay width is given by:

$$\Gamma_G \equiv \sum_q \Gamma(G \rightarrow q\bar{q}) \approx \frac{\alpha_s m_G T_F}{3} \left[\sum_q \left((g_V^q)^2 + (g_A^q)^2 \right) + \sqrt{1 - \frac{4m_t^2}{m_G^2}} \left((g_V^t)^2 \left(1 + \frac{2m_t^2}{m_G^2} \right) + (g_A^t)^2 \left(1 - \frac{4m_t^2}{m_G^2} \right) \right) \right]. \quad (\text{A.2})$$

We assume that the Born gluon-gluon fusion cross-section is the same as in the SM:

$$\frac{d\sigma^{gg \rightarrow t\bar{t}}}{d \cos \hat{\theta}} = \alpha_s^2 \frac{\pi\beta}{2\hat{s}} \left(\frac{1}{N_C(1-c^2)} - \frac{T_F}{2C_F} \right) \left(1 + c^2 + 8m^2 - \frac{32m^4}{1-c^2} \right). \quad (\text{A.3})$$

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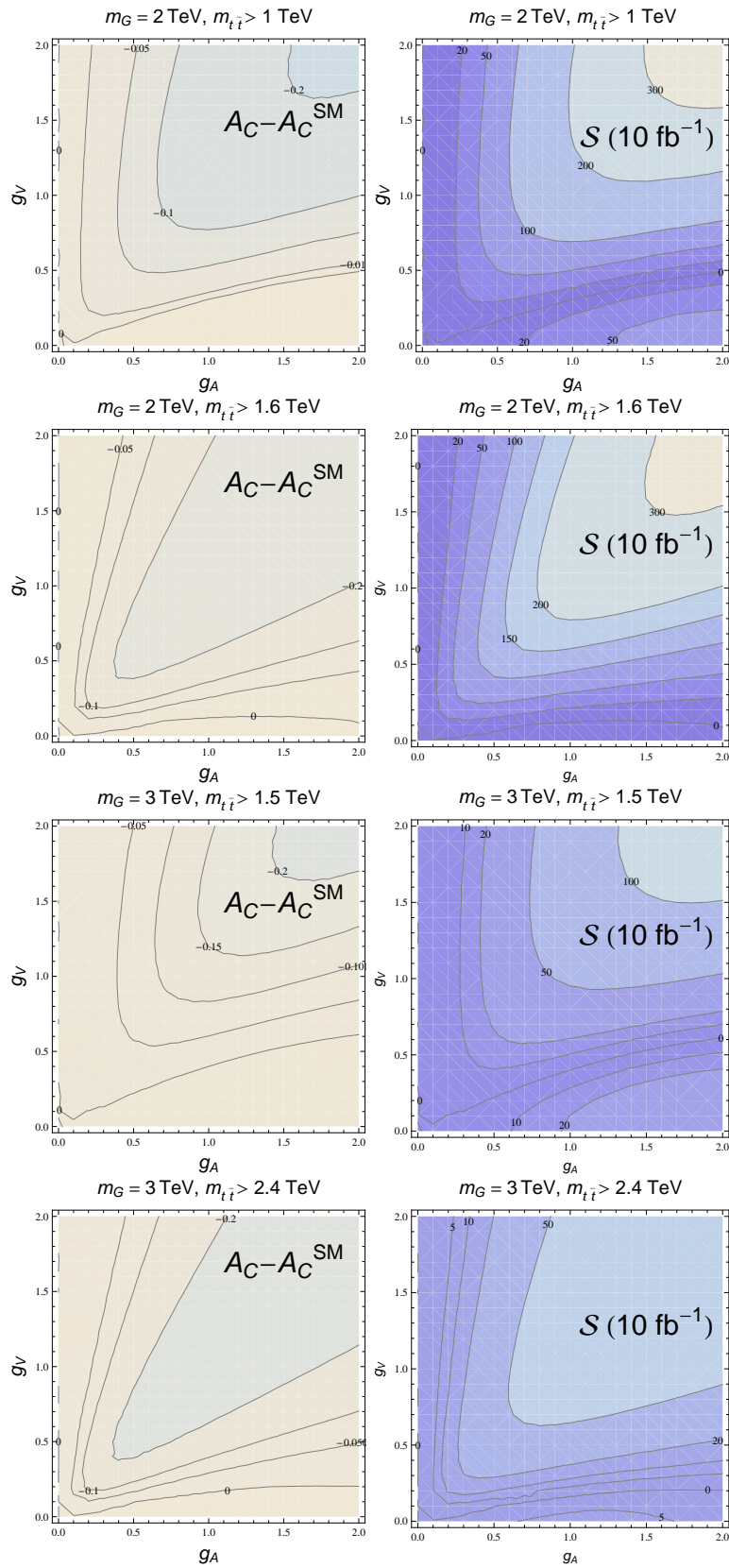


Figure 7. Central charge asymmetry and statistical significance at LHC for 14 TeV energy in the $g_A - g_V$ plane, for different values of the resonance mass and the cut on the top-antitop quark pair invariant mass.