PHYSICAL REVIEW D **78,** 094018 (2008)

# Massive color-octet bosons and the charge asymmetries of top quarks at hadron colliders

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(Received 1 October 2008; published 20 November 2008)

Several models predict the existence of heavy colored resonances decaying to top quarks in the TeV energy range that might be discovered at the CERN LHC. In some of those models, moreover, a sizable charge asymmetry of top versus antitop quarks might be generated. The detection of these exotic resonances, however, requires selecting data samples where the top and the antitop quarks are highly boosted, which is experimentally very challenging. We asses that the measurement of the top quark charge asymmetry at the LHC is very sensitive to the existence of excited states of the gluon with axial-vector couplings to quarks. We use a toy model with general flavor independent couplings, and show that a signal can be detected with relatively not too energetic top and antitop quarks. We also compare the results with the asymmetry predicted by QCD, and show that its highest statistical significance is achieved with data samples of top-antitop quark pairs of low invariant masses.

DOI: 10.1103/PhysRevD.78.094018 PACS numbers: 14.65.Ha, 11.30.Er, 12.10.Dm

## I. INTRODUCTION

The CERN Large Hadron Collider (LHC) will start-up very soon colliding protons to protons. In a first run, at a center of mass energy of $\sqrt{s} = 10$ TeV, about 20 $\mathrm{pb}^{-1}$ of data are expected to be collected. The next run will operate at the full $\sqrt{s} = 14$ TeV design energy with an initial low luminosity of $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (equivalent to 10 $\mathrm{fb}^{-1}$/year integrated luminosity).[1] The production cross section of top-antitop quark pairs at LHC is about 430 pb at 10 TeV, and 950 pb at 14 TeV [1]. The LHC will produce 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 run at 14 TeV. This will allow us not only to better measure 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 $\alpha_s$ 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. A similar effect leads also to a strange-antistrange quark asymmetry, $s(x) \neq \bar{s}(x)$, through next-to-next-to-leading (NNLO) evolution of parton densities [3]. At Tevatron, the charge asymmetry is equivalent to a forward–backward asymmetry because the top and the antitop single inclusive distributions are related by $N_{\bar{t}}(\cos\theta) = N_t(-\cos\theta)$ through $CP$ invariance of QCD. 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 $gq \to t\bar{t}q$ and $g\bar{q} \to t\bar{t}\,\bar{q}$. The latter contribution is, in general, much smaller than the former. Gluon-gluon fusion, which represents only 15% of all the events at Tevatron, remains charge symmetric. QCD predicts that the size of the inclusive charge asymmetry is 5% to 8% [2,4,5], with top quarks (antitop quarks) more abundant in the direction of the incoming proton (antiproton). The prediction for the charge asymmetry is, furthermore, robust with respect to the higher-order perturbative corrections generated by threshold resummation [6]. The forward-backward asymmetry of the exclusive process $p\bar{p} \to t\bar{t}+$ jet receives, however, large higher-order corrections [7].

At LHC, the total forward-backward asymmetry vanishes trivially because the proton-proton initial state is

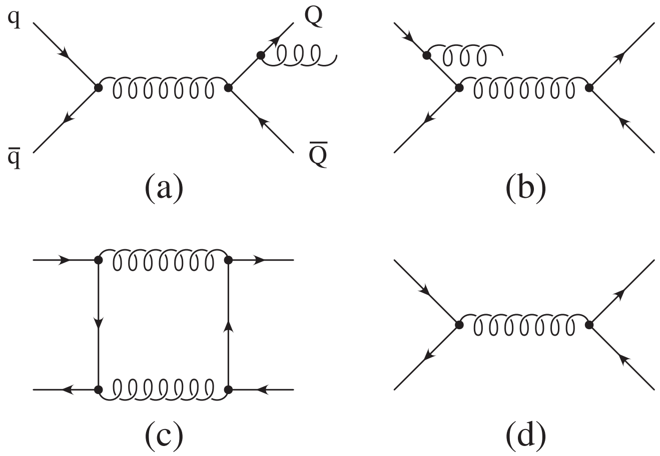

FIG. 1. Origin of the QCD charge asymmetry in hadro production of heavy quarks: interference of final-state (a) with initial-state (b) gluon bremsstrahlung, plus interference of the double virtual gluon exchange (c) with the Born diagram (d). Only representative diagrams are shown.

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[1] After a successful steering of the first beam, the start of LHC has been rescheduled to spring 2009. We perform our analysis on the basis of the original plans.

symmetric. Nevertheless, a charge asymmetry is still visible in suitably defined distributions [2]. In contrast with Tevatron, 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.

Several models predict the existence of heavy colored resonances decaying to top quarks that might be observed at the LHC [8–21]. 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. Colored resonances are fairly broad: $\Gamma_G/m_G = \mathcal{O}(\alpha_s) \sim 10\%$. Present lower bounds on their mass are about 1 TeV. The latest exclusion limit by CDF [22] at 95% C.L. is $260\ \text{GeV} < m_G < 1.250\ \text{TeV}$ for axigluons and flavor-universal colorons [with $\cot\theta = 1$ mixing of the two $SU(3)$].

Some of those exotic gauge bosons, such as the axigluons [8,9], might also generate at tree level a charge asymmetry through the interference with the $q\bar{q} \to t\bar{t}$ standard model (SM) amplitude [4,10,11]. 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 model [9,14].

To discover those resonances, hence, it is necessary to select top-antitop quark pair 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, i.e. 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 [23–26] aimed at distinguishing top quark jets from the light quark QCD background by exploiting the jet substructure, without identifying the decay products.

In this paper, we argue that for a measurement of the top quark charge asymmetry at LHC 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 flavor independent vector and axial-vector couplings to quarks. This includes the case of the axigluon that we have already analyzed in Ref. [4]. We first show the constraints that the recent measurements at Tevatron of the forward-backward or charge asymmetries impose over the parameter space, and then extend the analysis to LHC. We show that the selection cuts can be tuned such that the maximum statistical significance is obtained with a cut on the invariant mass of the top-antitop quark pair at roughly half of the mass of the heavy resonance. Because of this fact the measurement of the charge asymmetry has potentially a better sensitivity to higher masses of the exotic resonances than the direct measurement of the dijet distribution.

The outline of the paper is as follows. In Sec. II, we review the most recent measurements of the top quark charge asymmetries at Tevatron, and compare the QCD prediction for the asymmetries with the charge asymmetry generated by the exchange of a color-octet boson with flavor independent vector and axial-vector couplings to quarks. In Sec. III, we evaluate at the LHC the top quark charge asymmetry, as predicted by QCD, in a given finite interval of rapidity, and study its size and statistical significance as a function of the cut in the invariant mass of the top-antitop quark pair. In Sec. IV, we extend to the LHC the analysis of the charge asymmetry in the toy model used for Tevatron, and show that a detection of those resonances is possible with relatively low cuts on the invariant mass of the top-antitop quark pair at values much smaller than the resonance mass.

## II. TOP QUARK CHARGE ASYMMETRY AT TEVATRON

The forward-backward asymmetry of top quarks has already been measured at Tevatron [27–31]. The latest CDF analysis [27], based on 1.9 fb$^{-1}$ integrated luminosity, provides two different measurements in the lepton + jets channel. The first measurement is made in the laboratory frame, and gives

$$A_{\text{FB}}^{p\bar{p}} = \frac{N_t(\cos\theta > 0) - N_t(\cos\theta < 0)}{N_t(\cos\theta > 0) + N_t(\cos\theta < 0)} = 0.17 \pm 0.07(\text{stat}) \pm 0.04(\text{sys}), \quad (1)$$

where $\theta$ is the angle between the top quark and the proton beam. The second measurement exploits the Lorentz invariance of the difference between the $t$ and $\bar{t}$ rapidities, $\Delta y = y_t - y_{\bar{t}}$, which at LO is related to the top quark production angle $\alpha$ in the $t\bar{t}$ rest frame by [30]:

$$\Delta y = 2\tanh^{-1}(\beta \cos\alpha), \tag{2}$$

where $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$ is the top quark velocity. The asymmetry in this variable is

$$\begin{aligned} A_{\rm FB}^{t\bar{t}} &= \frac{N_{\rm ev.}(\Delta y > 0) - N_{\rm ev.}(\Delta y < 0)}{N_{\rm ev.}(\Delta y > 0) + N_{\rm ev.}(\Delta y < 0)} \\ &= 0.24 \pm 0.13({\rm stat}) \pm 0.04({\rm sys}). \end{aligned} \tag{3}$$

The measurement at D0 [28] with 0.9 fb$^{-1}$ integrated luminosity gives for the uncorrected asymmetry

$$A_{\rm FB}^{\rm obs} = 0.12 \pm 0.08({\rm stat}) \pm 0.01({\rm sys}). \tag{4}$$

Like CDF, this analysis uses $y_t - y_{\bar{t}}$ as sensitive variable. In Ref. [28], upper limits on $t\bar{t} + X$ production via a $Z'$ resonance are also provided. Measurements of the exclusive asymmetry of the four- and five-jet samples are also given by both experiments [27,28].

The corresponding theoretical predictions are [4]

$$\mathcal{A} = \frac{N_t(y \geq 0) - N_{\bar{t}}(y \geq 0)}{N_t(y \geq 0) + N_{\bar{t}}(y \geq 0)} = 0.051(6), \tag{5}$$

for the inclusive charge asymmetry, or forward-backward asymmetry ($\mathcal{A} = A_{\rm FB}^{p\bar{p}}$), and

$$\mathcal{A}_Y = \frac{\int dY(N_{\rm ev.}(y_t > y_{\bar{t}}) - N_{\rm ev.}(y_t < y_{\bar{t}}))}{\int dY(N_{\rm ev.}(y_t > y_{\bar{t}}) + N_{\rm ev.}(y_t < y_{\bar{t}}))} = 0.078(9), \tag{6}$$

for the integrated pair asymmetry, which is defined through the average rapidity $Y = \frac{1}{2}(y_t + y_{\bar{t}})$. The differential pair asymmetry is almost flat in the average rapidity, and amounts to about 7% for any value of $Y$. The corresponding integrated asymmetry is equivalent to the integrated forward-backward asymmetry in the $t\bar{t}$ rest frame: $\mathcal{A}_Y = A_{\rm FB}^{t\bar{t}}$. The pair asymmetry is larger than the forward-backward asymmetry $\mathcal{A}$ because events where both $t$ and $\bar{t}$ are produced with positive and negative rapidities in the laboratory frame do not contribute to the integrated forward-backward asymmetry, while they do contribute to the pair asymmetry. The experimental measurements of the top quark asymmetry in Eq. (1) and (3), although compatible with the corresponding theoretical predictions in Eq. (5) and (6), respectively, are still statistically dominated.

We shall consider in the following the production of heavy color-octet boson resonances decaying to top-antitop quark pairs with arbitrary vector and axial-vector couplings to quarks. The corresponding differential cross section is given in Eq. (A1) 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. This leads at Tevatron to a preference for the emission of the top quarks in the direction of the incoming light antiquarks (antiprotons) in most of the kinematic phase space, and then to a negative forward-backward asymmetry. 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 couplings, however, it might compensate the interference contribution, then leading to a positive forward-backward asymmetry, because it is enhanced by the product of the vector couplings. Indeed, for

$$\hat{s} = s' \equiv \frac{m_G^2}{1 + 2g_V^q g_V^t}, \tag{7}$$

the two odd terms cancel to each other, and above that value the contribution to the forward-backward asymmetry becomes positive.

To simplify our analysis we consider that the vector and axial-vector couplings, which are normalized to the strong coupling $\alpha_s$, are flavor independent: $g_V^q = g_V^t = g_V$ and $g_A^q = g_A^t = g_A$, where $q$ labels the coupling of the excited gluon to light quarks, and $t$ to top quarks. The axigluon of chiral color theories [8,9], for example, is given by $g_V = 0$ and $g_A = 1$. We study how the production cross section and the charge asymmetry vary depending on the vector and axial-vector couplings, which we take in the range [0, 2]. Within this range the perturbative expansion is still reliable. Moreover, in the flavor independent scenario the sign of the couplings is not relevant.

Results for the difference between the production cross section of the excited gluon and the SM prediction in the $(g_V, g_A)$ plane are presented in Fig. 2 for different values of the resonance mass. In all our analysis, we use the MRST 2004 parton distribution functions [32], and we set the renormalization and factorization scales to $\mu = m_t$, with $m_t = 170.9 \pm 1.1({\rm stat}) \pm 1.5({\rm sys})$ GeV [33]. For comparison, we also over impose in Fig. 2 the 1, 2, and 3 sigma contours obtained from the experimental measurement $\sigma_{t\bar{t}} = 7.3 \pm 0.9$ (pb) [34], and the SM prediction $\sigma_{t\bar{t}}^{\rm NLO} = 6.7 \pm 0.8$ (pb) [35]. Similar plots are presented in Fig. 3 and 4 for the forward-backward asymmetry and pair asymmetry, respectively. The sigma contours are calculated from the experimental measurement in Eq. (1) and from the theoretical prediction in Eq. (5) for the forward-backward asymmetry, and from Eq. (3) and (6) for the pair asymmetry. At 90% C.L. the plots of the production

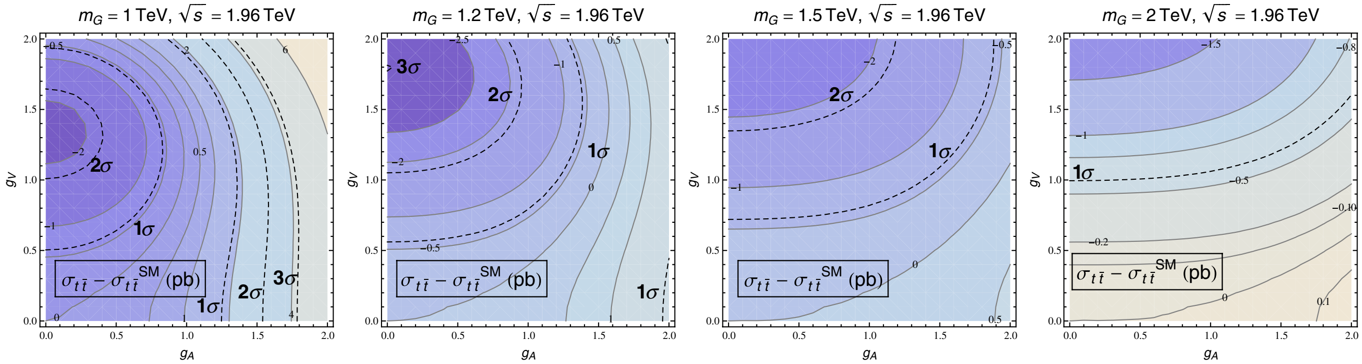

FIG. 2 (color online). Top quark cross section at Tevatron in the bidimensional $g_V$-$g_A$ plane for different values of the resonance mass.

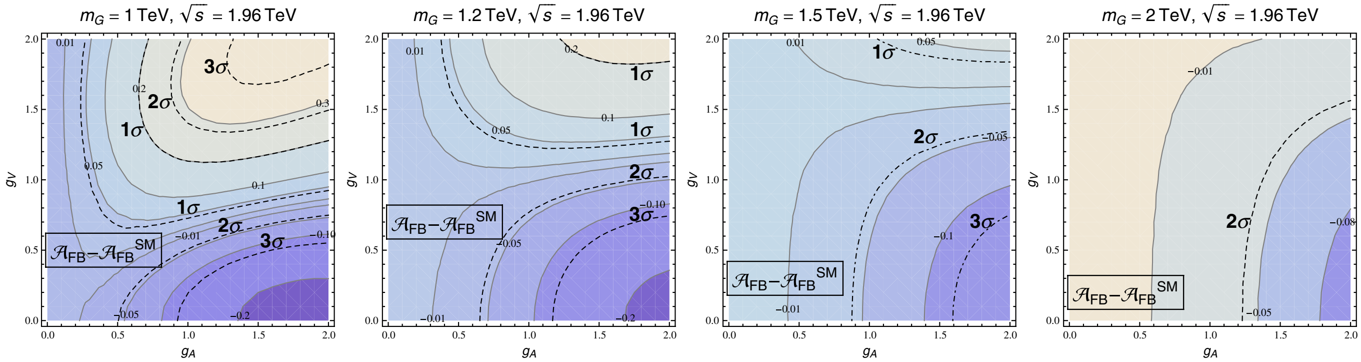

FIG. 3 (color online). Forward-backward asymmetry at Tevatron in the bidimensional $g_V$-$g_A$ plane for different values of the resonance mass.

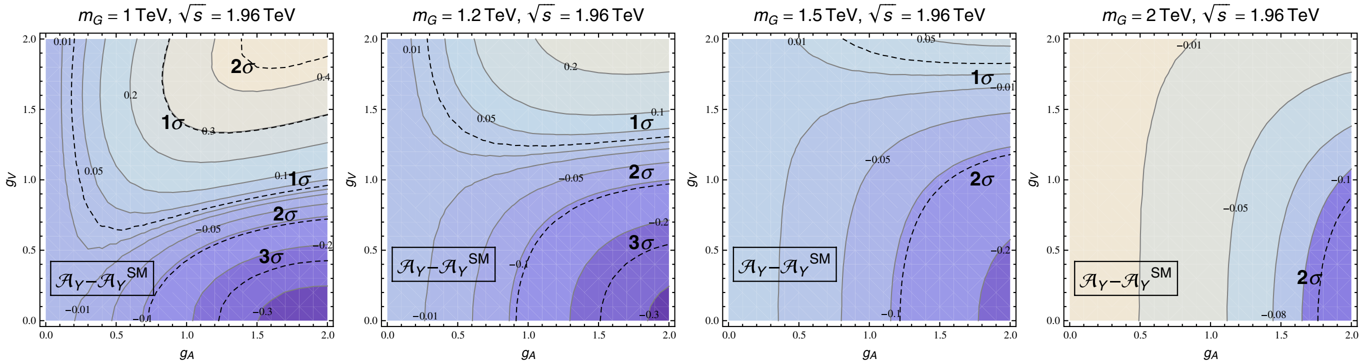

FIG. 4 (color online). Pair asymmetry at Tevatron in the bidimensional $g_V$-$g_A$ plane for different values of the resonance mass.

cross section and the asymmetries exclude complementary regions of the parameter space. While the production cross section excludes the corner with large vector couplings $g_V$ and low axial-vector coupling $g_A$, the forward-backward and the pair asymmetry exclude the corners with higher axial-vector couplings and either low or high vector couplings. This is not surprising because the terms of the differential cross section in Eq. (A1) that are even in the polar angle contribute exclusively to the integrated cross section, while the odd terms contribute to the charge asymmetry only, and they are proportional to different combinations of the vector and axial-vector couplings. The exclusion regions are, as expected, smaller for higher values of the resonance mass.

## III. 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. Production of $t\bar{t}(g)$ is dominated by initial quarks with large momentum fraction and antiquarks with small momentum fraction, while QCD predicts that top (antitop) quarks are preferentially emitted into the direction of the incoming quarks (antiquarks) in the partonic rest frame. Because of the boost into the laboratory frame the top quarks are then produced dominantly in the forward and backward directions, while antiquarks are more abundant in the central region.

We select events in a given range of rapidity and define the integrated charge asymmetry in the central region as [4]:

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}. \tag{8}$$

The central asymmetry $A_C(y_C)$ obviously vanishes if the whole rapidity spectrum is integrated, while a nonvanishing asymmetry can be obtained over a finite interval of rapidity. 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. 5 (left plots), we show the central charge asymmetry at $\sqrt{s} = 10$ TeV and 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

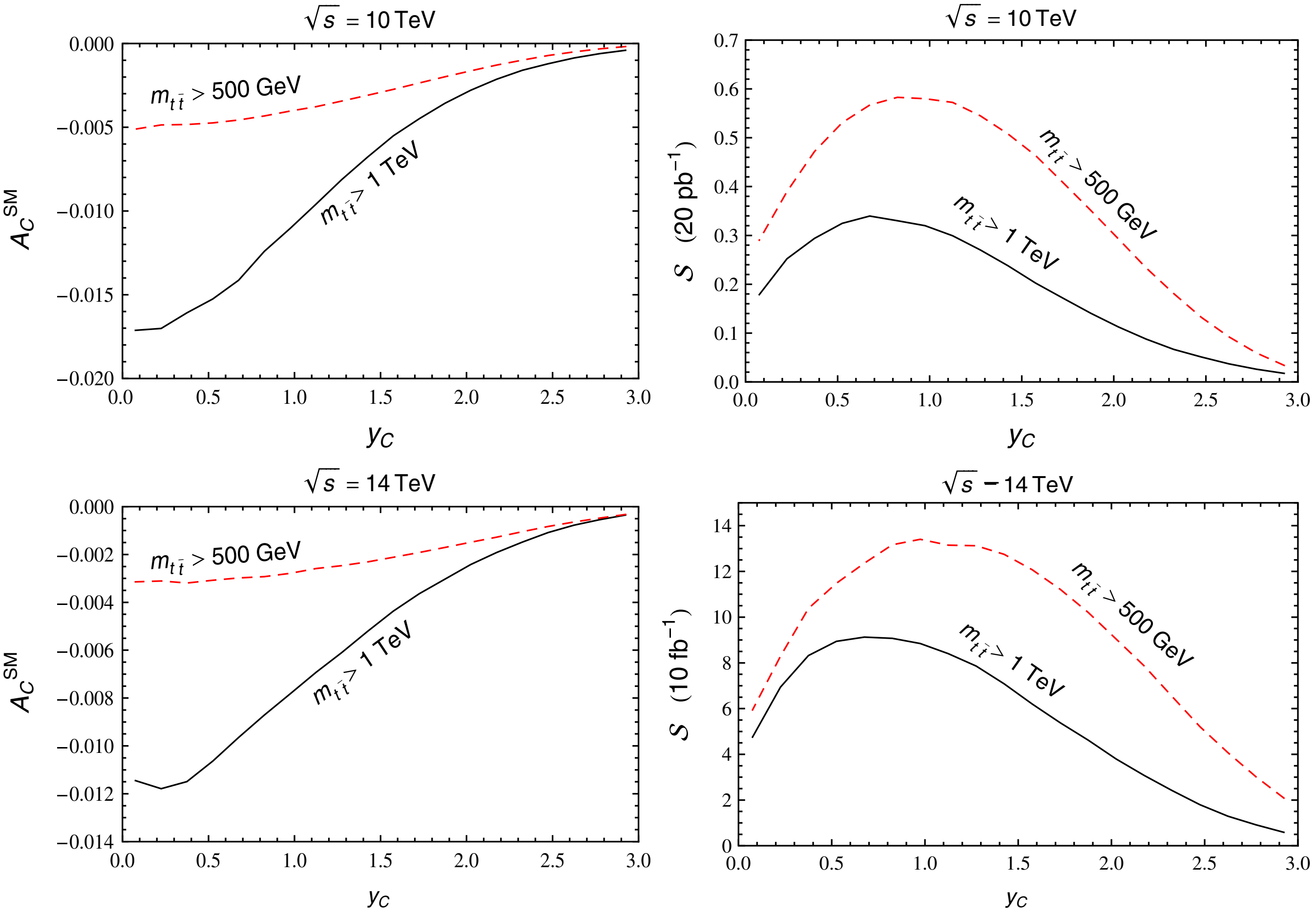

FIG. 5 (color online). Central charge asymmetry at LHC as predicted by QCD, as a function of the maximum rapidity $y_C$ (left plots), and corresponding statistical significance (right plots), for two different cuts on the top-antitop quark pair invariant mass.

$m_{t\bar{t}} > 500$ 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. 5 (right plots) the corresponding statistical significance $\mathcal{S}$ of the measurement, defined as

$$\mathcal{S}^{\rm SM} = A_C^{\rm SM}\sqrt{(\sigma_t + \sigma_{\bar{t}})^{\rm SM}\mathcal{L}} = \frac{N_t - N_{\bar{t}}}{\sqrt{N_t + N_{\bar{t}}}}, \tag{9}$$

where $\mathcal{L}$ denotes the total integrated luminosity for which we take $\mathcal{L} = 20\ \text{pb}^{-1}$ at $\sqrt{s} = 10$ TeV and $\mathcal{L} = 10\ \text{fb}^{-1}$ at $\sqrt{s} = 14$ TeV. The maximum significance is reached for both running energies at $y_C = 1$ for $m_{t\bar{t}} > 500$ GeV, and $y_C = 0.7$ for $m_{t\bar{t}} > 1$ 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. The statistical significance for the run at $\sqrt{s} = 10$ TeV is, however, rather small.

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. 6 for $\sqrt{s} = 10$ TeV and $\mathcal{L} = 20\ \text{pb}^{-1}$ and in Fig. 7 for $\sqrt{s} = 14$ TeV and $\mathcal{L} = 10\ \text{fb}^{-1}$. We also compare the results with and without introducing a cut in the transverse momenta of the heavy quarks: $p_T > 100$ GeV. The latter cut produces a significant effect only at very large values of the invariant mass $m_{t\bar{t}}^{\min}$, above 2 TeV, where the statistical significance is, however, small. In all cases, 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 $m_{t\bar{t}}^{\min} = 2.5$ 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. The statistical significance for the initial run at $\sqrt{s} = 10$ TeV is again too small. Although we have not taken into account experimental efficiencies, we can conclude that 10 $\text{fb}^{-1}$ of data at the design energy of the LHC seems to be enough for a clear measurement of the QCD asymmetry.

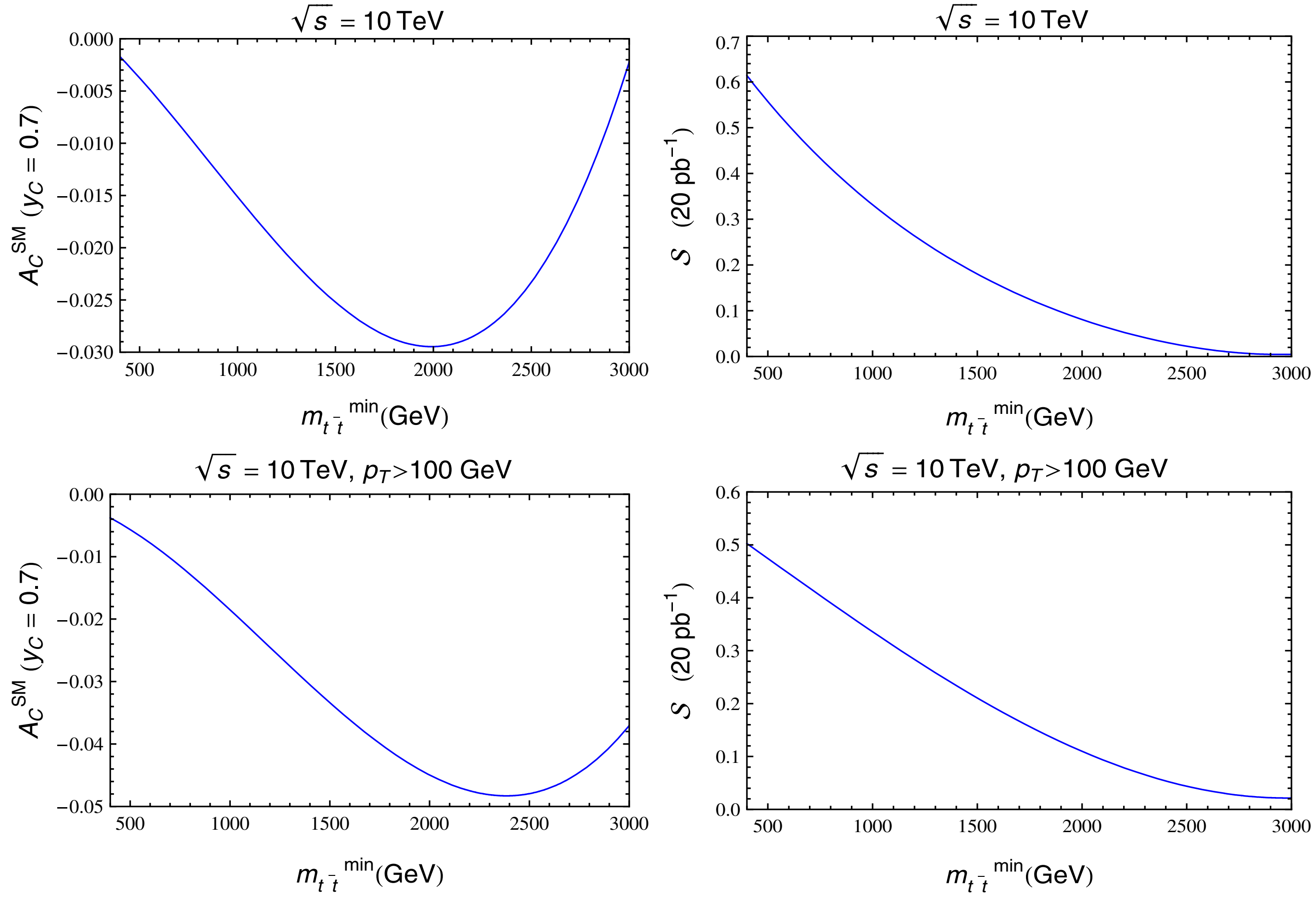

FIG. 6 (color online). Central charge asymmetry and statistical significance at LHC from QCD, as a function of the cut $m_{t\bar{t}}^{\min}$, for 10 TeV energy.

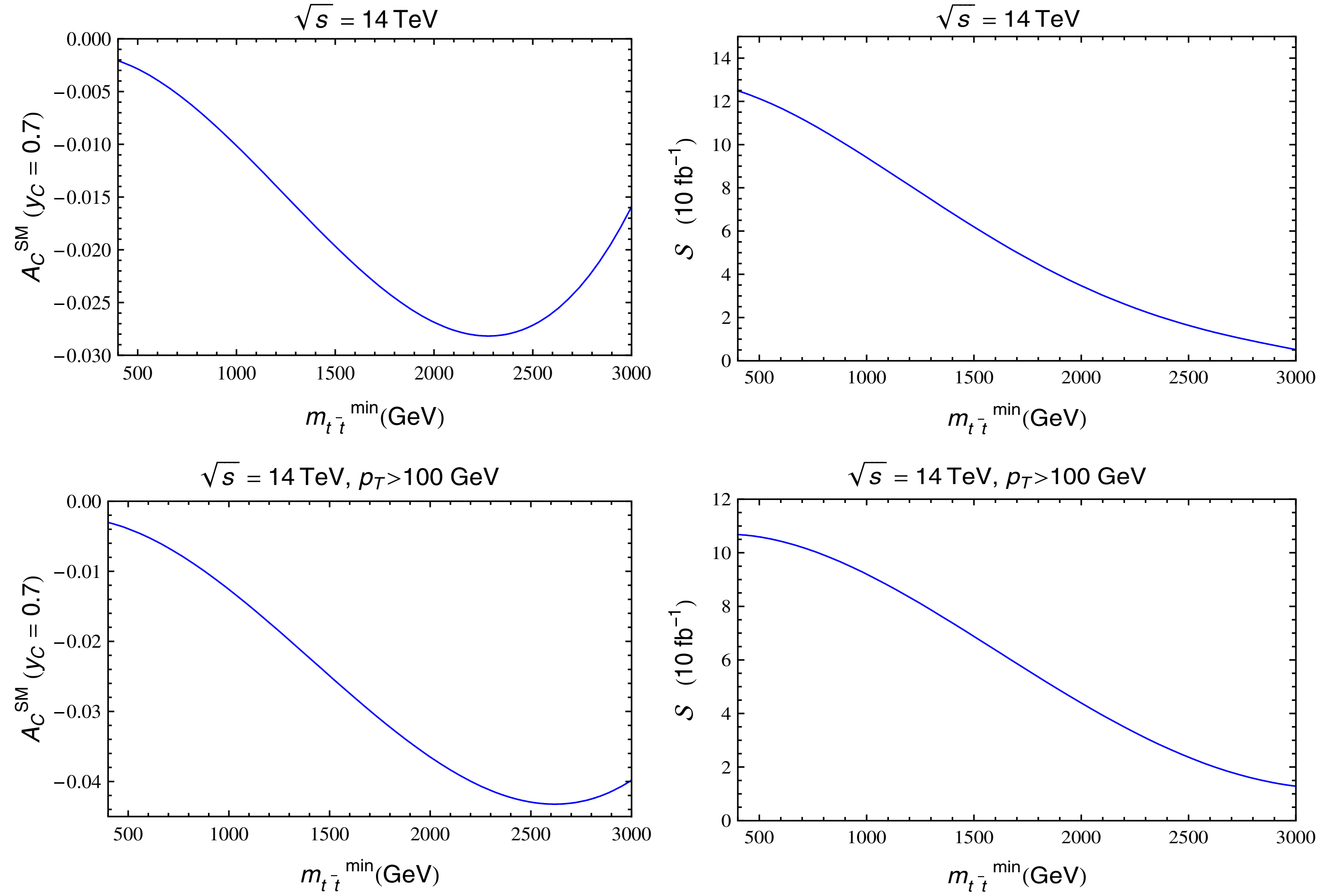

FIG. 7 (color online). Central charge asymmetry and statistical significance at LHC from QCD, as a function of the cut $m_{t\bar{t}}^{\min}$, for 14 TeV energy.

## IV. CHARGE ASYMMETRY OF COLOR-OCTET RESONANCES AT LHC

Like for Tevatron in Sec. II, we study here the charge asymmetry produced at LHC by the decay to top quarks of a color-octet resonance, in the scenario where the vector $g_V^{q(t)}$ and axial-vector $g_A^{q(t)}$ couplings are flavor independent. We evaluate the central asymmetry in Eq. (8), and its statistical significance, defined as

$$\mathcal{S}^{\mathrm{G}} = \frac{A_C^{\mathrm{G+SM}} - A_C^{\mathrm{SM}}}{\sqrt{1-(A_C^{\mathrm{SM}})^2}}\sqrt{(\sigma_t+\sigma_{\bar{t}})^{\mathrm{SM}}\mathcal{L}} \simeq \frac{(N_t - N_{\bar{t}})^{\mathrm{G}}}{\sqrt{(N_t+N_{\bar{t}})^{\mathrm{G+SM}}}}, \tag{10}$$

for different values of the couplings and the kinematical cuts.

We should mention that in the most popular models of warped extra dimensions the Kaluza-Klein excitations of the gluon couple identically to the left-handed and the right-handed light quarks, and these couplings are different only for the third generation [15–18]. A charge asymmetry, or correspondingly a central asymmetry, can not be generated in this kind of model by the production mechanism. An asymmetry will arise, however, if the polarization of the top quarks is analyzed [18], which also determines the angular distribution of its decay products. The polarization asymmetry [15], or the angular distribution [16,18] of the positron in the rest frame of the top quark along the direction of the boost is sensitive to the couplings of the top quark to the Kaluza-Klein excitations. The analysis of the decay products is, however, beyond the scope of this paper. The scenario presented here includes, however, the extra-dimensional model presented in [20] as a particular subcase.

When a heavy color-octet boson resonance is produced, considerations similar to those in Sec. II lead to predict a positive central asymmetry 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 is true as far as the interference term has a greater relevance than the squared amplitude of the exotic resonance. If this is the case, a higher number of antitop quarks will be emitted in the direction of the incoming quarks, and once the boost into the laboratory frame is performed (cf. discussion in Sec. III), a higher number of top quarks will be found in the central region, so that the central asymmetry is positive. Since for high values of the cut the sign of the interference term changes, the asymmetry will become negative, and then it has to vanish at a certain intermediate value of that cut, close to and below the resonance mass.

Under these conditions, 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 the gluon-gluon fusion process 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 critical partonic invariant mass defined in Eq. (7) can be located at a rather low scale. 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 two different combinations of the vector and axial-vector couplings $g_V$ and $g_A$. In Figs. 8 and 9, we present the results obtained for the central asymmetry and the statistical significance for $g_V = 0$, $g_A = 1$, and $g_V = g_A = 1$ for both values of the center-of-mass energy, 10 and 14 TeV, respectively. We notice that for the first choice of the parameters, namely $g_V = 0$, $g_A = 1$, the central asymmetry suffers a change of sign by passing from the lower cut to the higher one. This means

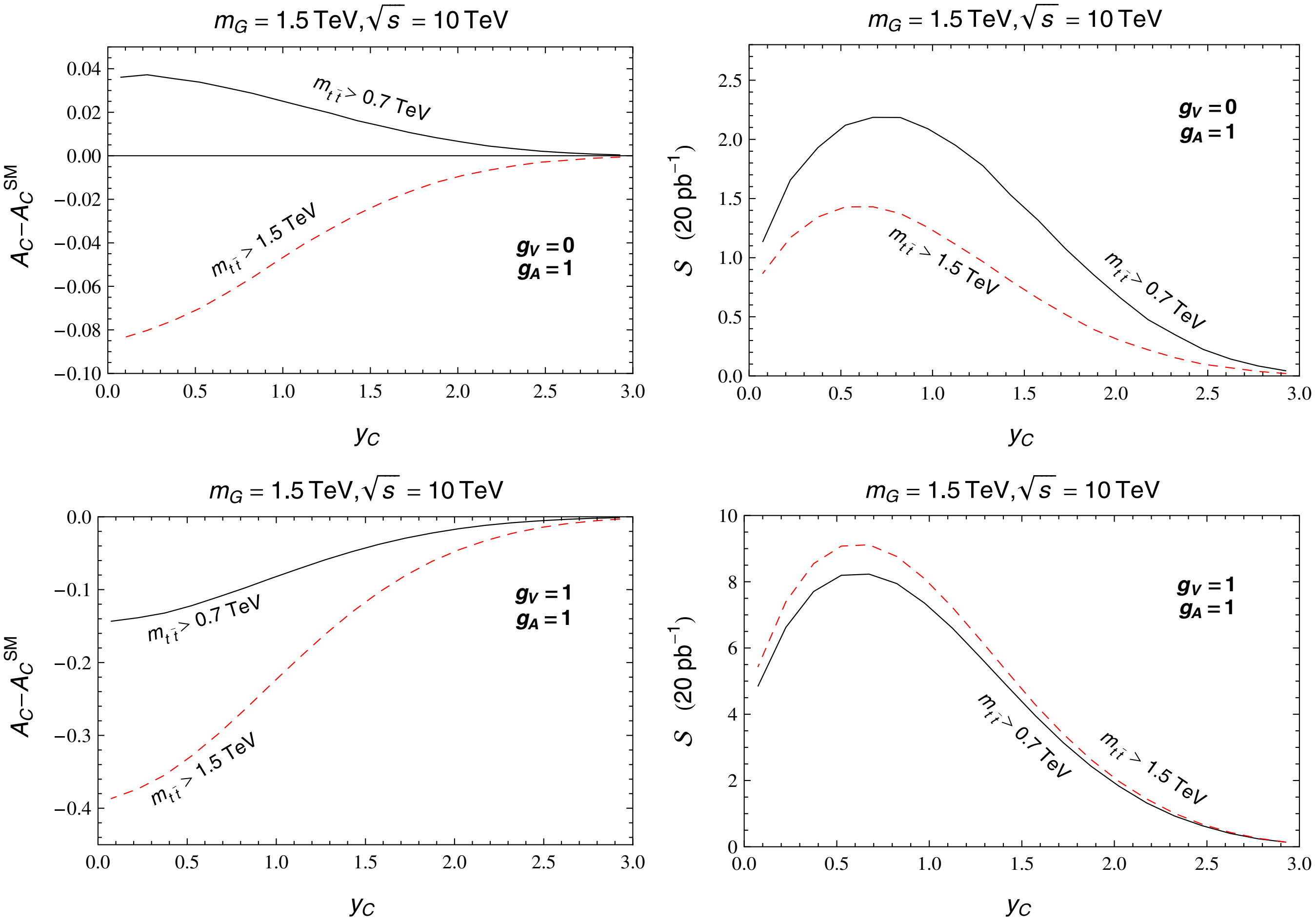

FIG. 8 (color online). Central charge asymmetry (left plots) and statistical significance (right plots) at LHC as a function of the maximum rapidity, for 10 TeV energy and two different cuts on the top-antitop quark invariant mass. Two different sets of couplings are shown.

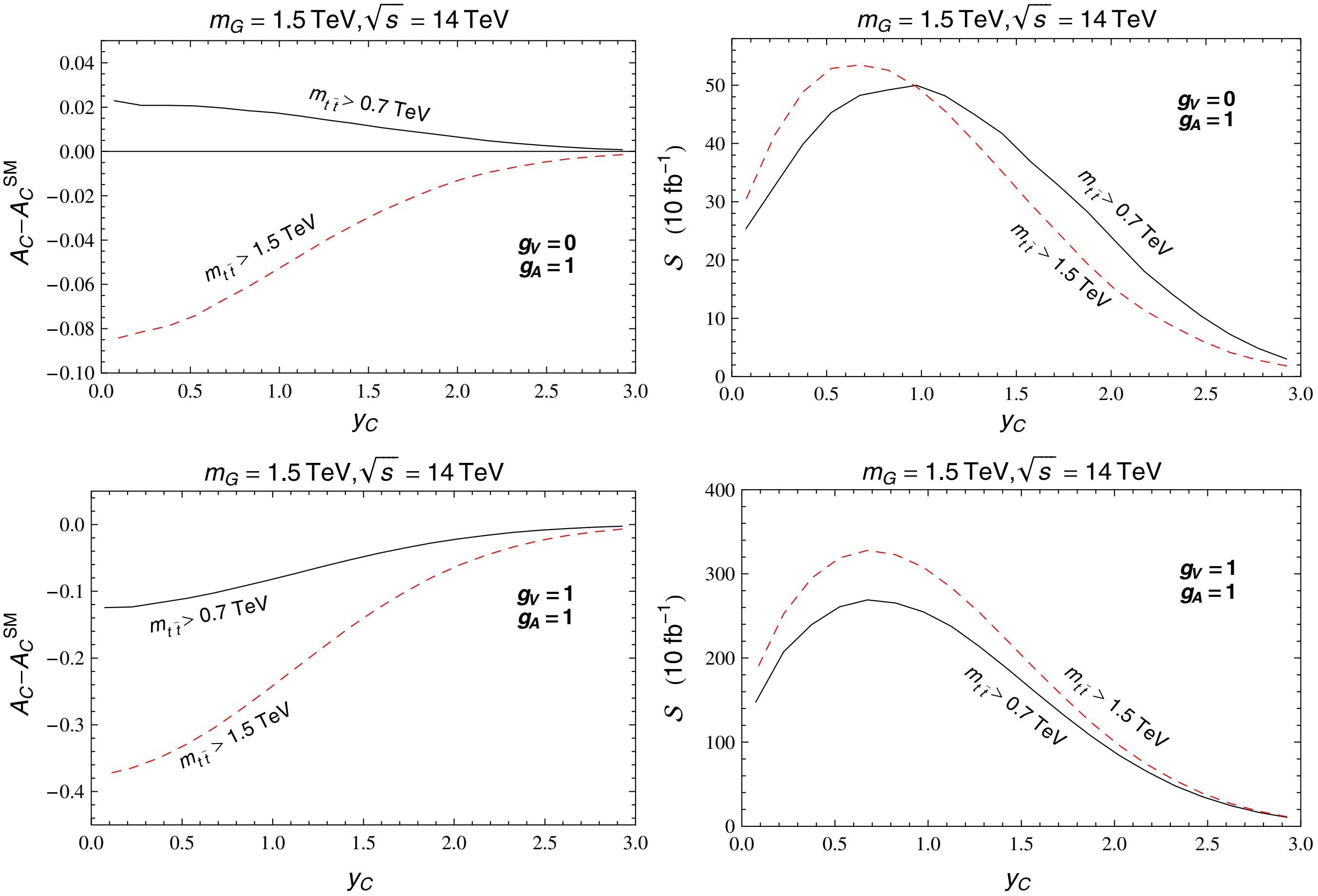

FIG. 9 (color online). Central charge asymmetry (left plots) and statistical significance (right plots) at LHC as a function of the maximum rapidity, for 10 TeV energy and two different cuts on the top-antitop quark invariant mass. Two different sets of couplings are shown.

that it will vanish for a given value of the cut, thus making the statistical significance vanish also.

By looking at the corresponding significance we find that $y_C = 0.7$ is a good choice in all cases. 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 $m_{t\bar{t}}^{\min}/m_G$. The results are shown in Figs. 10 and 11. The optimal cuts depend, of course, on the values of the vector and axial-vector couplings, but either $m_{t\bar{t}}^{\min}/m_G = 0.5$ or $m_{t\bar{t}}^{\min}/m_G = 0.8$ 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 $m_{t\bar{t}}^{\min}/m_G = 0.5$ and $m_{t\bar{t}}^{\min}/m_G = 0.8$, 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 they are, however, good representatives. We have chosen $m_G = 1.5$, 2, and 3 TeV. The results are presented in Figs. 12 and 13 in the $(g_V, g_A)$ plane for $\sqrt{s} = 10$ TeV and 14 TeV, respectively. 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 $m_{t\bar{t}}^{\min}/m_G$. A sizable asymmetry is found whatever the value of the resonance mass is. The statistical significance, as expected, decreases with the increasing of the resonance mass.

## V. CONCLUSIONS

We have analyzed the charge asymmetry in a top-antitop quark pair production through the exchange of color-octet heavy boson with flavor independent coupling to quarks. We have considered the experimental setups of Tevatron and LHC, studying different observables, and we have found that a sizable asymmetry can be found in both.

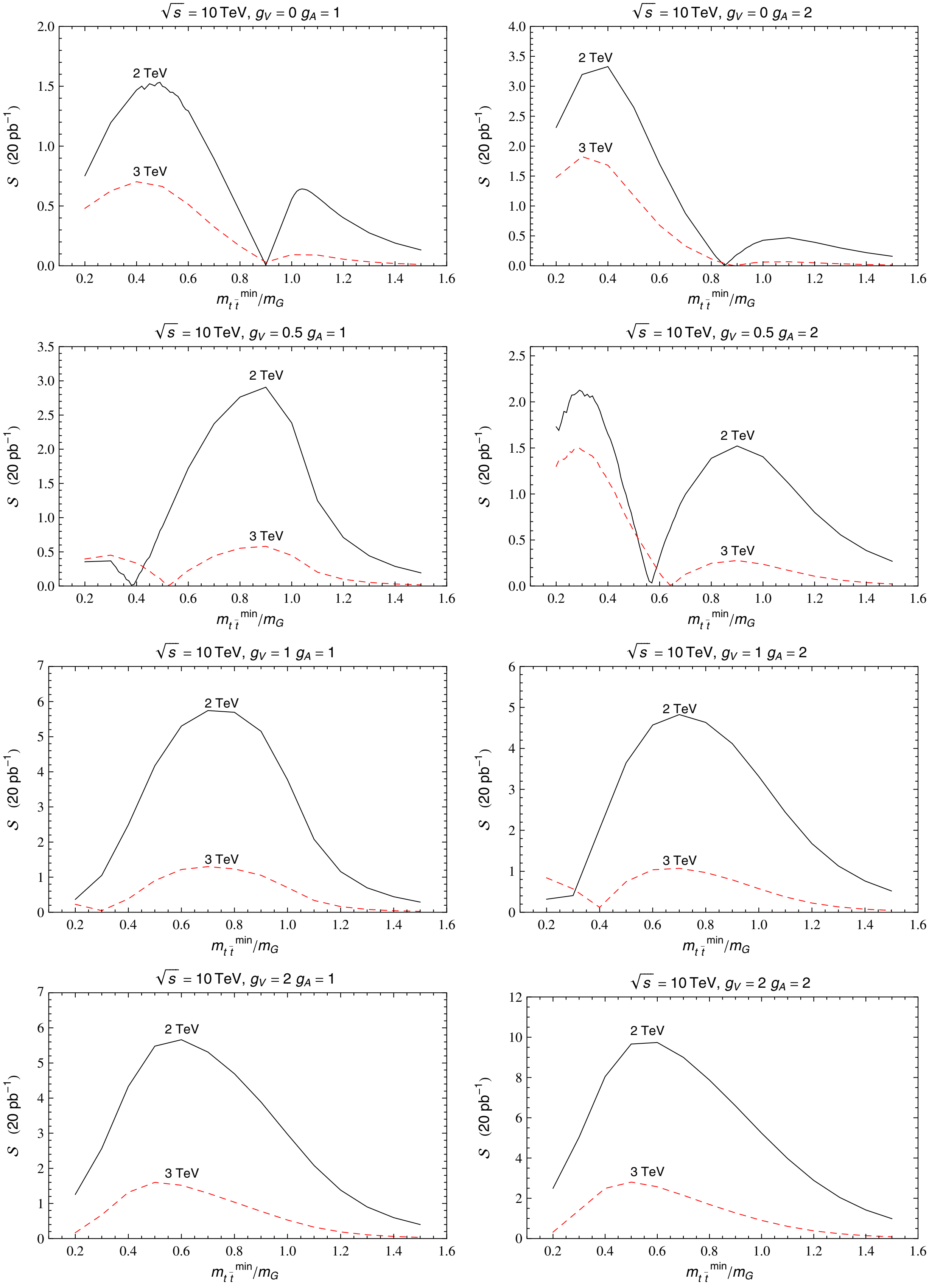

FIG. 10 (color online). Statistical significance at LHC for 10 TeV energy and different sets of $g_A$, $g_V$ as a function of the cut on the top-antitop quark pair invariant mass for $m_G = 2$ and 3 TeV.

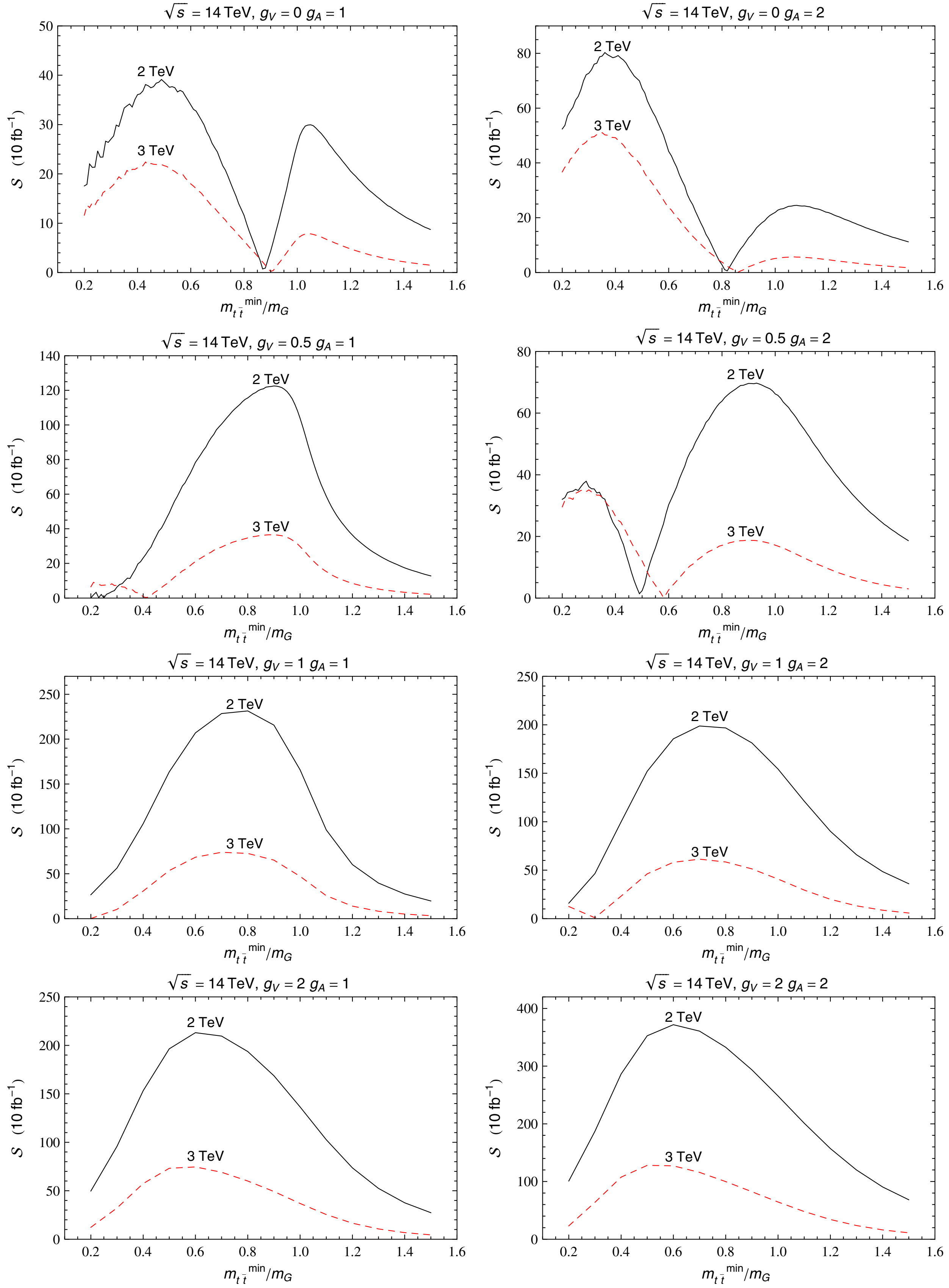

FIG. 11 (color online). Statistical significance at LHC for 14 TeV energy and different sets of $g_A$, $g_V$ as a function of the cut on the top-antitop quark pair invariant mass for $m_G = 2$ and 3 TeV.

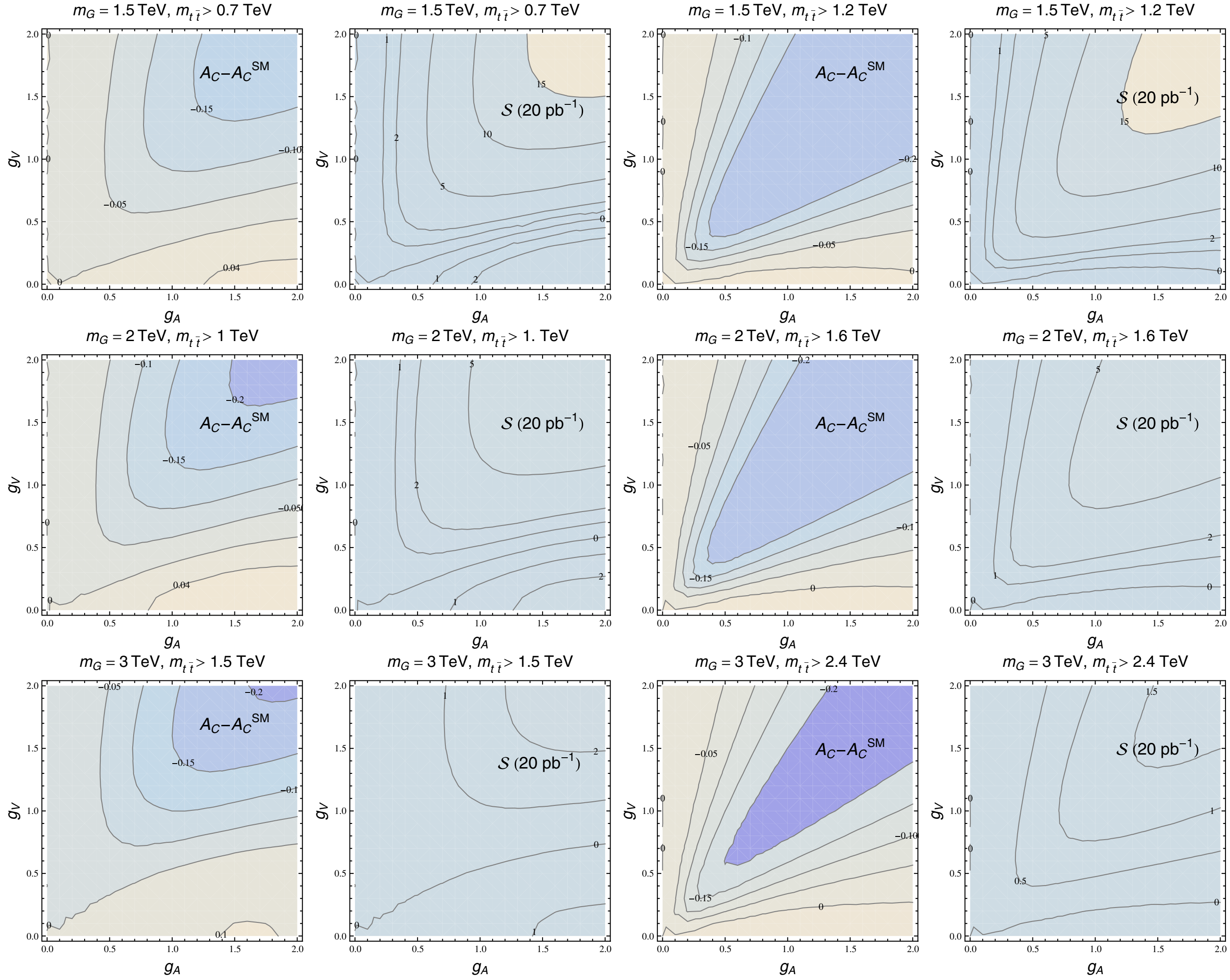

FIG. 12 (color online). Central charge asymmetry and statistical significance at LHC in the $g_A$-$g_V$ plane for 10 TeV energy, for different values of the resonance mass and the cut on the top-antitop quark pair invariant mass.

At Tevatron, the forward-backward asymmetry and the pair asymmetry, together with the total cross section exclude complementary corners of the parameter space. At the LHC, the central charge asymmetry 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.

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.

## ACKNOWLEDGMENTS

We thank S. Cabrera, C. Carone, J. H. Kühn, M. Sehr, and M. Vos for very useful discussions. The work of P. F. is supported by the Consejo Superior de Investigaciones Científicas (CSIC). This work is also partially supported by the Ministerio de Ciencia e Innovación under Grant No. FPA2007-60323, by CPAN (Grant No. CSD2007-00042), by the Generalitat Valenciana under Grant No. PROMETEO/2008/069, and by the European Commission MRTN FLAVIAnet under Contract No. MRTN-CT-2006-035482.

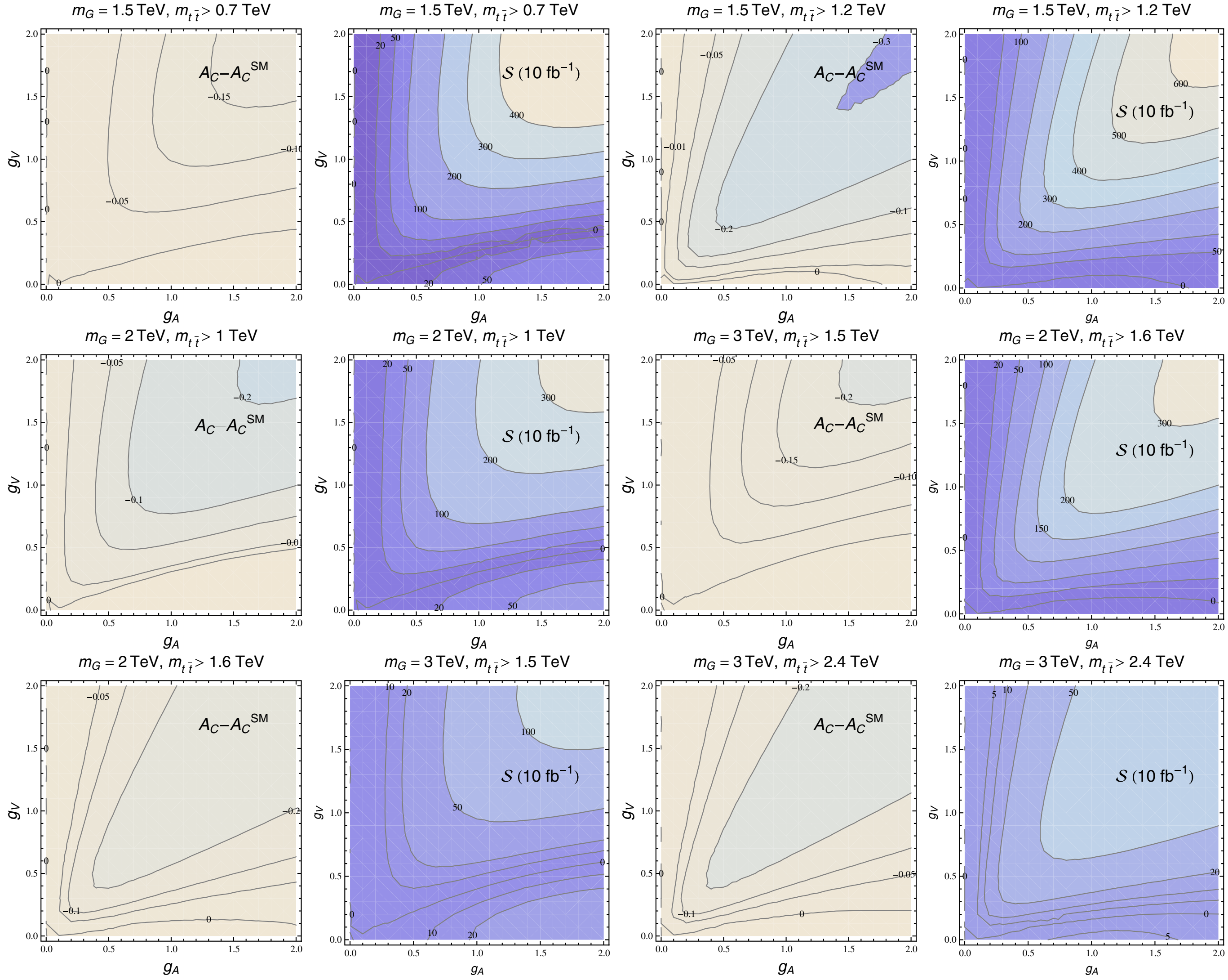

FIG. 13 (color online). Central charge asymmetry and statistical significance at LHC in the $g_A$-$g_V$ plane for 14 TeV energy, for different values of the resonance mass and the cut on the top-antitop quark pair invariant mass.

## APPENDIX: BORN CROSS SECTION

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

$$\begin{aligned}\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_s^2 \frac{T_F C_F}{N_C}\frac{\pi\beta}{2\hat{s}}\bigg(&1 + c^2 + 4m^2 \\ &+ \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2}[g_V^q g_V^t(1+c^2+4m^2) \\ &+ 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} \\ &\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1+c^2+4m^2) \\ &+ (g_A^t)^2(1+c^2-4m^2)) + 8g_V^q g_A^q g_V^t g_A^t c]\bigg),\end{aligned} \tag{A1}$$

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, $\beta = \sqrt{1\text{–}4m^2}$ 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. (A1) 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 squared 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

$$\begin{aligned}\Gamma_G &\equiv \sum_q \Gamma(G \to q\bar{q}) \\ &\approx \frac{\alpha_s m_G T_F}{3}\biggl[\sum_q ((g_V^q)^2 + (g_A^q)^2) \\ &\quad + \sqrt{1 - \frac{4m_t^2}{m_G^2}}\biggl((g_V^t)^2\biggl(1 + \frac{2m_t^2}{m_G^2}\biggr) + (g_A^t)^2\biggl(1 - \frac{4m_t^2}{m_G^2}\biggr)\biggr)\biggr]. \end{aligned} \tag{A2}$$

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

$$\begin{aligned}\frac{d\sigma^{gg\to t\bar{t}}}{d\cos\hat{\theta}} &= \alpha_s^2 \frac{\pi\beta}{2\hat{s}}\left(\frac{1}{N_C(1-c^2)} - \frac{T_F}{2C_F}\right) \\ &\quad \times \left(1 + c^2 + 8m^2 - \frac{32m^4}{1-c^2}\right). \end{aligned} \tag{A3}$$

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