The chiral color symmetry of quarks and $G'$-boson contributions to charge asymmetry in $tt\bar{t}$-production at the LHC and Tevatron

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Abstract

The contributions of $G'$-boson predicted by the chiral color symmetry of quarks to the charge asymmetry $A_C(pp \rightarrow t\bar{t})$ in $tt\bar{t}$ production at the LHC and to the forward-backward asymmetry $A_{FB}(p\bar{p} \rightarrow t\bar{t})$ in $tt\bar{t}$ production at the Tevatron are calculated and analysed in dependence on two free parameters of the model, the $G'$ mass $m_{G'}$ and mixing angle $\theta_{G'}$. The $m_{G'} - \theta_{G'}$ regions of $1\sigma$ consistency with the CMS data on the cross section $\sigma(pp \rightarrow t\bar{t})$ and on the charge asymmetry $A_C(pp \rightarrow t\bar{t})$ are found and compared with those resulted from the CDF data on the cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ and on the forward-backward asymmetry $A_{FB}(p\bar{p} \rightarrow t\bar{t})$ of $tt\bar{t}$ production at the Tevatron with account of the current SM predictions for $A_{FB}(p\bar{p} \rightarrow t\bar{t})$.

Keywords: New physics; chiral color symmetry; axigluon; massive color octet; $G'$-boson; top quark physics; forward-backward asymmetry; charge asymmetry.

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The Standard Model (SM) of electroweak and strong interactions based on the gauge symmetry group

$$G_{SM} = SU_e(3) \times SU_L(2) \times U(1)$$

(1)

describes well the interactions of quarks and leptons and gauge fields at the energies of order of hundreds GeV and is still consistent with all the experimental data, including the current experimental data from LHC. After discovery of the Higgs-like boson $H$ with mass $m_H \approx 126$ GeV the investigations of the propeties of this boson as well as the further search for the possible effects of new physics are the main goals of the experiments at the LHC. There many models predicting new physics effects at the LHC (such as two Higgs models, models with the fourth fermion generation, models based on supersymmetry, left-right symmetry, four color quark-lepton symmetry, etc.) and the unobservation of these effects at the LHC will set the new limits on the parameter of these models.

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One of such models which also can be verified at the LHC is based on the idea of the originally chiral character of $SU_c(3)$ color symmetry of quarks i.e on the gauge group of

$$G_c = SU_L(3) \times SU_R(3) \xrightarrow{M_{cch}} SU_c(3)$$

which is assumed to be valid at high energies and is broken to usual QCD $SU_c(3)$ at some low energy scale $M_{cch}$. It would be of interest to know the lower limit on this energy scale of the chiral color symmetry breaking which is achieved now at the LHC.

The immediate consequence of the chiral color symmetry of quarks is the prediction of a new gauge particle – the axigluon $G^A$ (in particular case of $g_L = g_R$ [1–4]) or $G'$-boson (in more general case of $g_L \neq g_R$ [5–8]). The $G'$-boson is the color octet massive gauge particle with vector and axial-vector couplings to quarks of order $g_{st}$ defined by the gauge group (2). As a result, the $G'$-boson can give rise to the increase of the cross section and to the charge asymmetry of $t\bar{t}$ production at the LHC as well as to the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron. The possible effect of $G'$-boson on the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron has been considered in refs. [6–8]. The other possible explanations of the large forward-backward asymmetry in $t\bar{t}$ production at the Tevatron are also known and discussed in a large number of papers, see for instance recent papers [9–17] and the references therein.

The charge asymmetry in $t\bar{t}$ production at the LHC has been measured by CMS [18–20] and ATLAS [21, 22] Collaborations in agreement (within experimental errors) with SM predictions. For the further analysys we use the CMS data on cross section $\sigma_{tt}$ [23] and charge asymmetry $A_C$ [19] in the $t\bar{t}$ production at the LHC

$$\sigma_{tt} = 165.8 \pm 2.2 \text{(stat.)} \pm 10.6 \text{(syst.)} \pm 7.8 \text{(lumi.)} \text{pb} (= 165.8 \pm 13.3 \text{pb}),$$

$$A_C = 0.004 \pm 0.010 \text{(stat.)} \pm 0.012 \text{(syst.)} (= 0.004 \pm 0.015)$$

and the SM predictions for $\sigma_{tt}$ [24] and $A_C$ [25]

$$\sigma_{tt}^{\text{NNLOapprox}} = 163^{+11}_{-10} \text{pb},$$

$$A_C^{\text{SM}} = 0.0115 \pm 0.0006.$$

In the present paper we calculate the contributions of the gauge $G'$-boson to the cross section and to the charge asymmetry in the $t\bar{t}$ production at the LHC. We compare the results with the CMS data [3], [4] and discuss the corresponding allowed region of the free parameters of the model in comparision with that resulted from Tevatron data on the forward-backward asymmetry.

The interaction of the $G'$-boson with quarks defined by gauge chiral color symmetry group (2) can be written as

$$\mathcal{L}_{G'qq} = \bar{q} \gamma^\mu (g_V + g_A \gamma_5) G'_\mu q = g_{st}(M_{cch}) \bar{q} \gamma^\mu (v + a \gamma_5) G'_\mu q$$

where $G'_\mu = G'_\mu t_i, t_i, i = 1, 2, ..., 8$ are the generators of $SU_c(3)$ group,

$$g_{st}(M_{cch}) = \frac{g_L g_R}{\sqrt{(g_L)^2 + (g_R)^2}}$$

is the strong interaction coupling constant at the mass scale $M_{cch}$ of the chiral color symmetry breaking and the vector and axial-vector coupling constants $v$ and $a$ are defined by one parameter, the $G^L - G^R$ mixing angle $\theta_G$ as

$$v = \frac{c_G^2 - s_G^2}{2 s_G c_G} = \cot(2\theta_G), \quad a = \frac{1}{2 s_G c_G} = 1/\sin(2\theta_G),$$

where $c_G = \cos(\theta_G)$ and $s_G = \sin(\theta_G)$.
$s_G = \sin \theta_G$, $c_G = \cos \theta_G$, $tg \theta_G = g_R/g_L$, $g_L$, $g_R$ are the gauge coupling constants of the chiral color group \((2)\). As a result the gauge chiral color symmetry model has two free parameters, $G'$-boson mass $m_{G'}$ and the $G^L - G^R$ mixing angle $\theta_G$.

In the parton process $q\bar{q} \rightarrow t\bar{t}$ of $t\bar{t}$ production in $q\bar{q}$ collisions the momenta of initial quarks in collinear limit can be written as

$$p_q = \{\varepsilon_q, 0, 0, p_{qz}\}, \quad p_{\bar{q}} = \{\varepsilon_{\bar{q}}, 0, 0, p_{\bar{q}z}\}$$

with $\hat{s} = (p_q + p_{\bar{q}})^2$.

The momenta of the final $t$- and $\bar{t}$-quarks can be expressed in terms of their rapidities $y_t$, $y_{\bar{t}}$ and of the transversal momentum $p_{\perp x}$, $p_{\perp y}$ as

$$p_t = \left\{ \sqrt{p_{\perp}^2 + m_t^2} \cosh y_t, p_{\perp x}, p_{\perp y}, \sqrt{p_{\perp}^2 + m_t^2} \sinh y_t \right\},$$

$$p_{\bar{t}} = \left\{ \sqrt{p_{\perp}^2 + m_{\bar{t}}^2} \cosh y_{\bar{t}}, -p_{\perp x}, -p_{\perp y}, \sqrt{p_{\perp}^2 + m_{\bar{t}}^2} \sinh y_{\bar{t}} \right\},$$

where

$$y_i = \frac{1}{2} \ln \left( \frac{\varepsilon_i + p_{iz}}{\varepsilon_i - p_{iz}} \right), \quad i = t, \bar{t}$$

are the rapidities of $t$- and $\bar{t}$-quarks.

Below instead of the rapidities we use the variables

$$Y = y_t + y_{\bar{t}}, \quad z = y_t^2 - y_{\bar{t}}^2$$

(one often uses the variable $\Delta|y| = |y_t| - |y_{\bar{t}}|$ instead of the variable $z$ but the variable $z$ is more convinient for mathematical manipulations).

The conservation of the 4-momentum fixes for $Y$ and $p_{\perp}$ the values

$$\bar{Y} = \ln \left( \frac{\varepsilon_q + \varepsilon_\bar{q} + p_{qz} + p_{\bar{q}z}}{\varepsilon_q + \varepsilon_\bar{q} - (p_{qz} + p_{\bar{q}z})} \right), \quad p_{\perp}^2 + m_t^2 = \frac{\hat{s}}{4\cosh^2(z/2\bar{Y})}$$

whereas $z$ varies in interval

$$-z_0 \leq z \leq z_0, \quad z_0 = \bar{Y}\Delta y_0, \quad \text{th}(\Delta y_0/2) = \sqrt{1 - 4m_t^2/\hat{s}} \equiv \beta.$$

The total parton cross section of the process $q\bar{q} \xrightarrow{g,G'} t\bar{t}$ with account of the $G'$-boson for $m_q^2 \ll m_t^2$, $\hat{s}$ can be written as

$$\sigma(q\bar{q} \xrightarrow{g,G'} t\bar{t}) = \sigma_{SM}(q\bar{q} \rightarrow t\bar{t}) + \Delta\sigma_{LO}(q\bar{q} \rightarrow t\bar{t})$$

where $\sigma_{SM}(q\bar{q} \rightarrow t\bar{t})$ is the total parton cross section in the SM and

$$\Delta\sigma_{LO}(q\bar{q} \rightarrow t\bar{t}) = \frac{4\pi\beta}{27} \left\{ \frac{2\alpha_s(\mu)\alpha_s(M_{tch})}{\sin^2 \theta_W} \frac{v^2(\hat{s} - m_{G'}^2)(3 - \beta^2)}{(\hat{s} - m_{G'}^2)^2 + \Gamma_{G'}^2 m_{G'}^2} + \frac{\alpha_s^2(M_{tch})}{\sin^4 \theta_W} \frac{v^2(3 - \beta^2) + 2a^2\beta^2}{(\hat{s} - m_{G'}^2)^2 + \Gamma_{G'}^2 m_{G'}^2} \right\}$$

(7)

is the contribution induced by the $G'$-boson in tree approximation, $\mu$ is a typical energy scale of the process.
We define the charge difference of the parton cross sections of the process $q\bar{q} \rightarrow t\bar{t}$ as
\[
\Delta_C(q\bar{q} \rightarrow t\bar{t}) = \sigma(q\bar{q} \rightarrow t\bar{t}, z > 0) - \sigma(q\bar{q} \rightarrow t\bar{t}, z < 0).
\]  

We have found the $G'$-boson contribution of tree approximation to the charge difference of the process $q\bar{q} \xrightarrow{g, G'} t\bar{t}$ for $m_q^2 \ll m_t^2$, $\hat{s}$ in the form
\[
\Delta_C^G(q\bar{q} \xrightarrow{g, G'} t\bar{t}) = \Delta(\hat{s}) \frac{\nabla}{|Y|} \chi(p_q, p_{\bar{q}})
\]  
where
\[
\Delta(\hat{s}) = \frac{4\pi \beta^2 a^2}{9} \alpha_s(\mu) \alpha_s(M) \Delta G^2 (\hat{s} - m^2_G) + 2\alpha_s^2(M) \eta^2 \hat{s}
\]  
and
\[
\chi(p_q, p_{\bar{q}}) = (p_{q_2} \varepsilon_q - p_{\bar{q}_2} \varepsilon_{\bar{q}})/(p_q p_{\bar{q}})
\]
is the antisymmetric under permutation $q \leftrightarrow \bar{q}$ function of the momenta of the initial quark and antiquark.

As concerns the process $gg \rightarrow t\bar{t}$ of $t\bar{t}$ production in gluon fusion the $G'$-boson does not contribute to this process in tree approximation.

The total cross section of $t\bar{t}$-production in pp-collisions can be expressed in terms of the parton cross sections $\sigma(ij \rightarrow t\bar{t})$ and the parton distribution functions $f_i(x_1), f_j(x_2)$ in the usual way
\[
\sigma(pp \rightarrow t\bar{t}) = \sum_{i,j} \int \int f_i(x_1) f_j(x_2) \sigma(ij \rightarrow t\bar{t}) dx_1 dx_2, \quad (i, j = q_k, \bar{q}_k, g).
\]

The parton cross sections $\sigma(ij \rightarrow t\bar{t})$ can be written as the sum of the SM cross sections $\sigma_{SM}(ij \rightarrow t\bar{t})$ and the contributions $\Delta\sigma_{LO}^G(ij \rightarrow t\bar{t})$ induced in tree approximation by the $G'$-boson
\[
\sigma(ij \rightarrow t\bar{t}) = \sigma_{SM}(ij \rightarrow t\bar{t}) + \Delta\sigma_{LO}^G(ij \rightarrow t\bar{t}).
\]

The SM cross sections $\sigma_{SM}(ij \rightarrow t\bar{t})$ can be written as the expansion
\[
\sigma_{SM}(ij \rightarrow t\bar{t}) = a_s^2 \left[ \sigma_{SM}^{(0)}(ij \rightarrow t\bar{t}) + a_s \sigma_{SM}^{(1)}(ij \rightarrow t\bar{t}) + a_s^2 \sigma_{SM}^{(2)}(ij \rightarrow t\bar{t}) \right] + O(a_s^3), \quad a_s = \alpha_s/\pi
\]
where $a_s^2 \sigma_{SM}^{(0)}(ij \rightarrow t\bar{t})$ are the well known SM cross sections of tree approximation for $i = q_k(\bar{q}_k)g, j = \bar{q}_k(q_k)g$ and for the perturbation corrections we have used the expressions $\sigma_{SM}^{(1)}(ij \rightarrow t\bar{t})$, $\sigma_{SM}^{(2)}(ij \rightarrow t\bar{t})$ of ref. [20].

For the $G'$-boson contributions $\Delta\sigma_{LO}^G(ij \rightarrow t\bar{t})$ we use the expressions (7)
\[
\Delta\sigma_{LO}^G(ij \rightarrow t\bar{t}) = \Delta\sigma_{LO}^G(qk \bar{q}_k \rightarrow t\bar{t}) \quad \text{for} \quad i = q_k(\bar{q}_k), j = \bar{q}_k(q_k).
\]

As a result we obtain the total cross section (12) as the sum
\[
\sigma(pp \rightarrow t\bar{t}) = \sigma_{SM}(pp \rightarrow t\bar{t}) + \Delta\sigma_{LO}^G(pp \rightarrow t\bar{t})
\]
(13)
of the SM cross section $\sigma^{SM}(pp \to t\bar{t})$ and the contribution $\Delta\sigma^{G'}_{LO}(pp \to t\bar{t})$ induced in tree approximation by the $G'$-boson.

The charge difference of the parton cross section \[\Delta_c(pp \to t\bar{t})\] results in the corresponding charge difference $\Delta_c(pp \to t\bar{t})$ of the $t\bar{t}$-production in $pp$-collisions. One usually uses the charge asymmetry in the $t\bar{t}$-production which we define as

$$A_c(pp \to t\bar{t}) = \frac{\sigma(pp \to t\bar{t}, z > 0) - \sigma(pp \to t\bar{t}, z < 0)}{\sigma(pp \to t\bar{t})} \equiv \frac{\Delta_c(pp \to t\bar{t})}{\sigma(pp \to t\bar{t})}$$

(this definition coincides with the definition with use of the variable $\Delta|y|$ instead of $z$).

With account the $G'$-boson the charge asymmetry $A_c(pp \to t\bar{t})$ can be written as the sum

$$A_c(pp \to t\bar{t}) = A_{c}^{SM}(pp \to t\bar{t}) + A_{c}^{G'}(pp \to t\bar{t})$$

(14)
of the charge asymmetry $A_{c}^{SM}(pp \to t\bar{t})$ in the SM and of the contribution induced by the $G'$-boson

$$A_{c}^{G'}(pp \to t\bar{t}) = \frac{\Delta_{c}^{G'}(pp \to t\bar{t})}{\sigma(pp \to t\bar{t})}$$

(15)

where $\Delta_{c}^{G'}(pp \to t\bar{t})$ is the contribution of the leading order to the charge difference $\Delta_{c}(pp \to t\bar{t})$ from the $G'$-boson.

The contribution of the $G'$-boson to the charge difference in the leading order has been calculated with account of (9), (10), (11) as

$$\Delta_{c}^{G'}(pp \to t\bar{t}) = 2 \int \int_{D_1} F_{\Delta c}^{pp}(x_1, x_2) \Delta(x_1 x_2 s) dx_1 dx_2$$

(16)

where $\Delta(x_1 x_2 s)$ is defined by (10) with $s = x_1 x_2 s$, $s = (P_1 + P_2)^2$, $P_1, P_2$ are the momenta of the colliding protons. The integration in (16) is performed over the region

$$D_1 : \frac{x_0^2}{x_1} \leq x_2 \leq x_1, \quad x_0 \leq x_1 \leq 1, \quad x_0^2 = 4m_t^2/s$$

and the function $F_{\Delta c}^{pp}(x_1, x_2)$ is defined by the parton distribution functions of quarks and antiquarks as

$$F_{\Delta c}^{pp}(x_1, x_2) = \sum_k \left[ f_{q_k}^{p}(x_1) f_{q_k}^{p}(x_2) - f_{q_k}^{p}(x_1) f_{q_k}^{p}(x_2) \right].$$

(17)

The function (17) is antisymmetric under permutation $x_1 \leftrightarrow x_2$ and is nonzero because of difference of the parton distribution functions of the (valence) quarks and (see) antiquarks in proton (the minus sign appears due to the antisymmetric function (11), for $m_q^2, m_{\bar{q}}^2 \ll s$ this function takes the values $\sigma(p_q, p_{\bar{q}}) = \pm 1$ in dependence on whether the quark flies along the positive direction of $z$-axis (hence the antiquark flies in the opposite direction) or vice versa).

We have calculated and analysed the cross section (13) and the charge asymmetry (14) in $t\bar{t}$-production in $pp$-collisions. For numerical calculations we use the parton cross sections with $\mu = \mu_R = m_t$ and the parton distribution functions MSTW2008 [27] with $\mu_F = m_t$.

For $\sigma^{SM}(pp \to t\bar{t})$ as a result of calculation we have obtained the value $\sigma^{SM}(pp \to t\bar{t}) = 162_{-13.6}^{+7.8} pb$ in agreement with CMS experimental value [3] and with SM prediction [5].

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The $G'$-boson contribution $\Delta \sigma_{LO}^{G'} (pp \rightarrow t\bar{t})$ to the cross section \((13)\) has been calculated by using the formulas \((7), (12)\) and occurs to be of a few pb in a reasonable $m_{G'} - \theta_G$ region.

For the SM contribution $A_C^{SM} (pp \rightarrow t\bar{t})$ to the charge asymmetry we have used the value \((6)\). The $G'$-boson contribution $A_C^{G'} (pp \rightarrow t\bar{t})$ to the charge asymmetry \((14)\) has been calculated by using the formulas \((15), (16), (17)\).

The $G'$-boson contributions $A_C^{G'} (pp \rightarrow t\bar{t})$ to the charge asymmetry in $t\bar{t}$ production at the LHC are shown in the Fig. 1 as the functions of the $G'$-boson mass $m_{G'}$ in dependence on the mixing angle $\theta_G$, \((\sqrt{s} = 7 \text{ TeV})\). The dashed horizontal lines indicate the experimental values \((4)\) of the charge asymmetry and the corresponding experimental errors of $1\sigma$ and the solid horizontal line indicates the SM prediction \((6)\).

![Figure 1](image)

Figure 1: The $G'$-boson contributions $A_C^{G'} (pp \rightarrow t\bar{t})$ to the charge asymmetry in $t\bar{t}$ production at the LHC as the functions of the $G'$-boson mass $m_{G'}$ in dependence on the mixing angle $\theta_G$, \((\sqrt{s} = 7 \text{ TeV})\).

As seen from the Fig.1, for the $G'$-boson masses of order or larger 1 TeV and for the appropriate mixing angles the $G'$-boson contributions $A_C^{G'} (pp \rightarrow t\bar{t})$ to the charge asymmetry with account of the SM contribution \((6)\) can be in agreement with CMS experimental value \((4)\).

The regions in $m_{G'} - \theta_G$ plane which are consistent within $1\sigma$ with CMS data on the cross section $\sigma(pp \rightarrow t\bar{t})$ \((3)\) and on the charge asymmetry $A_C (pp \rightarrow t\bar{t})$ \((11)\) are shown in the Fig.2, \((\sqrt{s} = 7 \text{ TeV})\). The curves \((a)\) and \((b)\) show the lower bounds of the $1\sigma$ consistency regions resulted from the cross section \((3)\) and from the charge asymmetry \((11)\) respectively. As seen from the Fig.2, the the $G'$-boson with masses

$$m_{G'} > 1.0 - 1.7 \text{ TeV} \quad (18)$$

for $\theta_G = 45^\circ - 15^\circ$ respectively is consistent within $1\sigma$ with the CMS data \((3), (11)\).
The $m_{G^'} - \theta_G$ regions consistent within 1$\sigma$ with CMS data (a) on the cross section $\sigma(pp \to t\bar{t})$ and (b) on the charge asymmetry $A_C(pp \to t\bar{t})$ of $t\bar{t}$ production at the LHC, ($\sqrt{s} = 7$ TeV) and with CDF data on the cross section $\sigma(p\bar{p} \to t\bar{t})$ and on the forward-backward asymmetry $A_{FB}(p\bar{p} \to t\bar{t})$ of $t\bar{t}$ production at the Tevatron for c) $A_{FB}^{SM}(p\bar{p} \to t\bar{t}) = 8.7\%$, d) $A_{FB}^{SM}(p\bar{p} \to t\bar{t}) = 12.5\%$.

It should be noted however that $G'$-boson can have also the mass bounds from another sources. For example, $G'$-boson interacts also with the light quarks and could manifest itself as the peak in the light quark dijet production. The unobservation of such peak at the LHC gives the corresponding lower bound on $G'$-boson mass which can be more stringent than those resulting from $t\bar{t}$ production. Nevertheless the bounds on $G'$-boson mass \cite{18} obtained in this paper from the $t\bar{t}$ production are interesting as independent ones.

The $G'$-boson gives rise also to the charge asymmetry in $p\bar{p} \to t\bar{t}$ process, which results in the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron defined as

$$A_{FB}(p\bar{p} \to t\bar{t}) = \frac{\sigma(p\bar{p} \to t\bar{t}, \Delta y > 0) - \sigma(p\bar{p} \to t\bar{t}, \Delta y < 0)}{\sigma(p\bar{p} \to t\bar{t})} \equiv \frac{\Delta_{FB}(p\bar{p} \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})}$$ \hspace{1cm} (19)

where $\Delta y = y_t - y_{\bar{t}}$ is related to the scattering angle $\hat{\theta}$ of $t$-quark in the parton center of mass frame as $\text{th}(\Delta y/2) = \beta \cos \hat{\theta}$.

The region in $m_{G^'} - \theta_G$ plane which is simultaneously consistent within 1$\sigma$ with CMS data on the cross section $\sigma(pp \to t\bar{t})$ and on the charge asymmetry $A_C(pp \to t\bar{t})$ should be compared with the regions which are consistent within 1$\sigma$ with experimental data on the cross section $\sigma(p\bar{p} \to t\bar{t})$ and on the forward-backward asymmetry $A_{FB}(p\bar{p} \to t\bar{t})$ in $t\bar{t}$ production at the Tevatron.

At the parton level the $G'$-boson gives rise to the forward-backward difference

$$\Delta_{FB}(q\bar{q} \to t\bar{t}) = \sigma(q\bar{q} \to t\bar{t}, \Delta y > 0) - \sigma(q\bar{q} \to t\bar{t}, \Delta y < 0)$$

of $t\bar{t}$ production in the form

$$\Delta^G_{FB}(q\bar{q} \xrightarrow{g, G'} t\bar{t}) = \Delta(\hat{s}) \mathcal{K}(p_q, p_{\bar{q}})$$ \hspace{1cm} (20)
where $\Delta(s)$ and $\propto(p_q,p_{\bar{q}})$ are given by equations (10), (11).

With account of (20) the $G'$-boson contribution $\Delta_{\text{FB}}(p\bar{p} \rightarrow t\bar{t})$ to the forward-backward difference $\Delta_{\text{FB}}(p\bar{p} \rightarrow t\bar{t})$ in the leading order can be expressed in terms of the parton distribution functions of quarks and antiquarks in proton and antiproton as

$$\Delta_{\text{FB}}^{G'}(p\bar{p} \rightarrow t\bar{t}) = 2 \int \int D_1 F_{\Delta_{\text{FB}}}(x_1,x_2) \Delta(x_1 x_2 s) dx_1 dx_2 \quad (21)$$

where

$$F_{\Delta_{\text{FB}}}(x_1,x_2) = \sum_k \left[ f_{q_k}^p(x_1) f_{\bar{q}_k}^p(x_2) - f_{\bar{q}_k}^p(x_1) f_{q_k}^p(x_2) \right]. \quad (22)$$

Because of the relations $f_{q_k}^p(x) = f_{\bar{q}_k}^p(x)$, the function $F_{\Delta_{\text{FB}}}(x_1,x_2)$ is symmetric under permutation $x_1 \leftrightarrow x_2$. From (19), (21) we obtain the $G'$-boson contribution $A_{\text{FB}}^{G'}(p\bar{p} \rightarrow t\bar{t})$ to the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron in the form

$$A_{\text{FB}}^{G'}(p\bar{p} \rightarrow t\bar{t}) = \frac{\Delta_{\text{FB}}^{G'}(p\bar{p} \rightarrow t\bar{t})}{\sigma(p\bar{p} \rightarrow t\bar{t})}. \quad (23)$$

For the further comparison we use below the CDF data on $t\bar{t}$-production at the Tevatron

$$\sigma_{t\bar{t}}(p\bar{p} \rightarrow t\bar{t}) = 7.5 \pm 0.48 \text{ pb} \quad (24),$$
$$A_{t\bar{t}}^\text{FB}(p\bar{p} \rightarrow t\bar{t}) = 0.164 \pm 0.045 \quad (25),$$

and the current SM predictions

$$\sigma_{t\bar{t}}^{\text{NNLOapprox}}(p\bar{p} \rightarrow t\bar{t}) = 7.08 \pm 0.36 \text{ pb} \quad (26),$$
$$A_{t\bar{t}}^\text{FB}(p\bar{p} \rightarrow t\bar{t}) = 0.087(10) \quad (27),$$
$$A_{t\bar{t}}^\text{FB}(p\bar{p} \rightarrow t\bar{t}) = 0.125 \quad (28).$$

It should be noted that the SM value (27) of the forward-backward asymmetry is about $1.7\sigma$ below the experimental value (25) whereas the SM value (28) is consistent with (25) within $1\sigma$.

We have calculated the contributions of $G'$-boson to the cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ and to the forward-backward asymmetry $A_{\text{FB}}(p\bar{p} \rightarrow t\bar{t})$ in $t\bar{t}$ production at the Tevatron and have analysed them with account of the SM contributions (26), (27), (28) in comparison with the experimental data (24), (25). We have found the regions in $m_{G'}-\theta_G$ plane which are consistent within $1\sigma$ with CDF data (24), (25) with account of the SM predictions for the cross section (26) and for the forward-backward asymmetry (27) or (28).

The $G'$-boson contributions $A_{\text{FB}}^{G'}(p\bar{p} \rightarrow t\bar{t})$ to the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron are shown in the Fig. 3 as the functions of the $G'$-boson mass $m_{G'}$ for the mixing angles $a) \theta_G = 45^\circ$, $b) \theta_G = 30^\circ$, $c) \theta_G = 15^\circ$. The dashed horizontal lines indicate the experimental value (25) and the corresponding experimental errors of $1\sigma$ and the solid horizontal lines indicate the SM predictions (27), (28).

The $m_{G'}-\theta_G$ regions consistent within $1\sigma$ with CDF data on the cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ and on the forward-backward asymmetry $A_{\text{FB}}(p\bar{p} \rightarrow t\bar{t})$ in $t\bar{t}$ production at the Tevatron are shown in the Fig. 2 for the SM prediction (27) by dotted curve $c$ and for the SM prediction (28) by dashed curve $d$.
As seen from the Fig.3, the $G'$-boson contribution $A_{FB}^{G'}(p\bar{p} \rightarrow t\bar{t})$ to the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron for $\theta_{G} = 45^\circ$ (axigluon) is negative for all the $G'$-boson masses but for $\theta_{G} \sim 15^\circ - 20^\circ$ it can be positive and for the $m_{G'} \sim 1.2$ TeV could improve the agreement of the SM prediction (27) and the experimental value (25) to 1σ (the dotted region c) in the Fig.2). But, as seen from the Fig.2, the lower mass limit for $G'$-boson resulted from CMS data (4) on the charge asymmetry in $t\bar{t}$ production at the LHC (the curve b) exceeds the $G'$-mass region c) of 1σ consistency of the data (25) and the SM prediction (27) of the forward-backward asymmetry in $t\bar{t}$ production at the Tevatron. For $m_{G'} > 1.3$ TeV the $G'$-boson contributions $A_{FB}^{G'}(p\bar{p} \rightarrow t\bar{t})$, as also seen from the Fig.3, are negative and for $m_{G'} \gtrsim 5$ TeV become sufficiently small.

For the SM prediction (28) the region of 1σ consistency of the data (25) with the SM prediction (28) near $m_{G'} \sim 1.2$ TeV in the Fig.2 is slightly larger but still is below the curve b). But in this case there appears the allowed region of large $G'$-boson masses with lower limis of order $m_{G'} = 3.5 - 6.0$ TeV (right dashed curve d)). So, as seen from the Fig.2, in the case of the SM prediction (28) the $G'$-boson with masses

$$m_{G'} > 3.5 - 6.0 \text{ TeV} \tag{29}$$

for $\theta_{G} = 45^\circ - 15^\circ$ respectively is consistent within 1σ with the CDF data (24), (25) as well as with CMS data (3), (4). It should be noted, that in the region of the masses and mixing angles (29) the $G'$-boson contribution to the charge asymmetry in $t\bar{t}$ production at the LHC, as seen from the Fig.1, becomes small and is of order of $-0.1\%$.

In conclusion, we summarize the results found in this work.

The contributions of $G'$-boson predicted by the chiral color symmetry of quarks to the charge asymmetry $A_{C}(pp \rightarrow t\bar{t})$ in $t\bar{t}$ production at the LHC and to the forward-backward asymmetry $A_{FB}(p\bar{p} \rightarrow t\bar{t})$ in $t\bar{t}$ production at the Tevatron are calculated and analysed in dependence on two free parameters of the model, the $G'$ mass $m_{G'}$ and mixing angle $\theta_{G}$. 
The $m_{G'} - \theta_G$ regions of $1\sigma$ consistency with the CMS data on the cross section $\sigma(pp \to t\bar{t})$ and on the charge asymmetry $A_C(pp \to t\bar{t})$ are found and compared with those resulted from the CDF data on the cross section $\sigma(p\bar{p} \to t\bar{t})$ and on the forward-backward asymmetry $A_{FB}(p\bar{p} \to t\bar{t})$ of $t\bar{t}$ production at the Tevatron with account of the current SM predictions for $A_{FB}(p\bar{p} \to t\bar{t})$.

It is shown that in the case of the SM prediction (27) the $m_{G'} - \theta_G$ region of $1\sigma$ consistency with the CMS data on the charge asymmetry $A_C(pp \to t\bar{t})$ exceeds that resulted from the CDF data on the forward-backward asymmetry $A_{FB}(p\bar{p} \to t\bar{t})$ in $t\bar{t}$ production at the Tevatron.

In the case of the SM prediction (28) the $G'$-boson with masses $m_{G'} > 3.5 - 6.0$ TeV for $\theta_G = 45^\circ - 15^\circ$ is shown to be consistent within $1\sigma$ with the CDF data on $\sigma(p\bar{p} \to t\bar{t})$, $A_{FB}(p\bar{p} \to t\bar{t})$ and with the CMS data on $\sigma(pp \to t\bar{t})$, $A_C(pp \to t\bar{t})$ simultaneously.

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