On mass limit for chiral color symmetry $G'$-boson from Tevatron data on $t\bar{t}$ production

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Abstract

The contributions of $G'$-boson predicted by the chiral color symmetry of quarks to the cross section $\sigma_{t\bar{t}}$ and to the forward-backward asymmetry $A_{FB}$ of $t\bar{t}$ production at the Tevatron are calculated with account of the difference of the strengths of the $\bar{q}qG$ and $\bar{q}qG'$ interactions. The results are analysed in dependence on two free parameters of the model, the mixing angle $\theta_{G'}$ and $G'$ mass $m_{G'}$. The $G'$-boson contributions to $\sigma_{t\bar{t}}$ and $A_{FB}$ are shown to be consistent with the Tevatron data on $\sigma_{t\bar{t}}$ and $A_{FB}$, the allowed region in the $m_{G'} - \theta_{G'}$ plane is discussed and around $m_{G'} = 1.2\, TeV$, $\theta_{G'} = 14^\circ$ the region of $1\sigma$ consistency is found.

Keywords: Beyond the SM; chiral color symmetry; axigluon; massive color octet; $G'$-boson; top quark physics.
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The Standard Model (SM) of electroweak and strong interactions based on the gauge symmetry group

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

is now the reliable theoretical basis for description of interactions of quarks and leptons and gauge fields at the energies of order of hundreds GeV. At the same time the SM leaves some questions within itself open and seems to be only a first step in our understanding the fundamental interactions at more high energies and the investigations of the possible extentions of the SM is one of the aims of the modern elementary particle physics. The simplest extentions of the SM (such as two Higgs models, models based on supersymmetry, left-right symmetry, four color quark-lepton symmetry or models implying the four fermion generation, etc.) predict the new physics effects at one or a few TeV energies and are most interesting now in anticipation of the new results from the LHC which will allow the investigations of new physics effects at the TeV energy scale with very large statistics [1].

One of such simple extentions of the SM can be based on the idea of the originally chiral character of $SU_c(3)$ color symmetry of quarks. i.e on the gauge group of the chiral color symmetry

$$G_c = SU_L(3) \times SU_R(3) \rightarrow SU_c(3),$$

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which is assumed to be valid at high energies and is broken to usual QCD $SU_c(3)$ at low energy scale. Such chiral color theories \[2\,\textnormal{[5]}\] in addition to the usual massless gluon $G_\mu$ predict in the simplest case of $g_L = g_R$ the existence of a new color-octet gauge boson, the axigluon $G_A$ with mass $m_{G_A}$. The axigluon couples to quarks with an axial vector structure with the strong interaction coupling constant $\alpha_s$ and has a width $\Gamma_{G_A} \approx 0.1 m_{G_A}$ \[6\]. Since it is the colored gauge particle with axial vector coupling to quarks, the axigluon should give rise to the increase of the hadronic cross section as well as the appearance of a spin-1 resonance in $t\bar{t}$ invariant mass distribution \[7\] and of a forward-backward asymmetry of order $\alpha_s^2$ \[8\] in the $t\bar{t}$ production. The lower mass limit for the axigluon from the Tevatron data have been found in ref. \[8\,\textnormal{[9]}\]. The massive color octet with arbitrary vector– and axial-vector–quark coupling constants has been considered phenomenologically with analysys of mass limits for this octet in dependence on its coupling constants in ref. \[10\].

The color octet as the gauge boson $G'$ induced by the chiral color symmetry in general case of $g_L \neq g_R$ was considered firstly in ref. \[11\] and then with analysys of its phenomenology at the Tevatron and LHC in ref. \[12\]. The model has two free parameters, $G'$-boson mass $m_{G'}$ and the $G^L - G^R$ mixing angle $\theta_G$, $tg \theta_G = g_R/g_L$. Using the CDF data on cross section \[13\] and forward-backward asymmetry \[14\] of the $t\bar{t}$ production at the Tevatron

$$\sigma_{t\bar{t}} = 7.0 \pm 0.3 (\text{stat}) \pm 0.4 (\text{lumi}) \text{pb}, \quad (3)$$

$$A_{FB}^{pp} = 0.17 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (sys)} \quad (4)$$

the $m_{G'} - \theta_G$ region simultaneously compatible with data \[3\] and \[11\] within 2$sigma$ was found \[12\] with assuming the same values of $\alpha_s$ in $\bar{q}qG$ and $\bar{q}qG'$ interactions.

The SM predictions for $\sigma_{t\bar{t}}$ and $A_{FB}^{pp}$ have been discussed in refs. \[15\,\textnormal{[17]}\] and \[9\,\textnormal{[18]}\,\textnormal{[20]}\] respectively and we quote here the next SM predictions for $\sigma_{t\bar{t}}$ \[15\] and $A_{FB}^{pp}$ \[9\]

$$\sigma_{t\bar{t}}^{SM} = 7.35 \pm 0.38 \text{ (scale)} \pm 0.49 \text{ (PDFs)} [\text{CTEQ6.5}] \text{pb} \quad (5)$$

$$7.93 \pm 0.34 \text{ (scale)} \pm 0.20 \text{ (PDFs)} [\text{MRST2006nnlo}] \text{pb},$$

$$A_{FB}^{SM} (p\bar{p} \to t\bar{t}) = 0.051(6). \quad (6)$$

The first and second values in \[5\] were obtained in NLO+NLL approximation with $m_t = 171 \text{ GeV}$ and correspond to the different choises of the parton distribution functions (CTEQ6.5 and MRST2006nnlo respectively). As seen the experimental and theoretical values of $\sigma_{t\bar{t}}$ \[3\,\textnormal{[5]}\] are compatible within the experimental and theoretical errors whereas the experimental value of $A_{FB}^{pp}$ \[14\] exceeds the corresponding theoretical prediction \[6\]. This deviation is not so large with account of the experimental errors nevertheless this circumstance induces the discussion of this situation in the literature \[21\,\textnormal{[33]}\].

At the present time the CDF data on cross section \[34\] and forward-backward asymmetry \[35\] of the $t\bar{t}$ production at the Tevatron are updated as

$$\sigma_{t\bar{t}} = 7.5 \pm 0.31 (\text{stat}) \pm 0.34 (\text{syst}) \pm 0.15 (\text{lumi}) \text{pb} (= 7.5 \pm 0.48 \text{ pb}), \quad (7)$$

$$A_{FB}^{pp} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (sys)} (= 0.193 \pm 0.069) \quad (8)$$

so that the difference between the central value in \[8\] and the SM prediction \[6\] exceeds now 2$sigma$ and the gauge $G'$-boson \[12\] could look as disfavoured \[21\]. In this situation it is reasonable to analyse the contributions of the gauge $G'$-boson into cross section and forward-backward asymmetry of the $t\bar{t}$ production at the Tevatron more carefully, with the more correct account of the strength of the $\bar{q}qG'$ interaction.
In the present paper we calculate the contributions of the gauge $G'$-boson to the cross section and to the forward-backward asymmetry of the $Q\bar{Q}$ production in $p\bar{p}$ collisions with account of the running coupling constant $\alpha_s(M_{\text{chc}})$ at the mass scale of the chiral color symmetry breaking $M_{\text{chc}}$. We compare the results with the Tevatron data \cite{7, 8} and discuss the corresponding allowed $m_{G'}-\theta_G$ region of the free parameters of the model.

The interaction of the $G'$-boson with quarks can be written as

$$\mathcal{L}_{G'q\bar{q}} = g_{st}(M_{\text{chc}}) \bar{q} \gamma^\mu (v + a \gamma^5) G'_\mu q$$ \hspace{1cm} (9)$$

where $g_{st}(M_{\text{chc}})$ is the strong interaction coupling constant at the mass scale $M_{\text{chc}}$ of the chiral color symmetry breaking and $v$ and $a$ are the phenomenological vector and axial-vector coupling constants. The gauge symmetry \cite{2} gives for $v$ and $a$ the expressions

$$v = \frac{c_G^2 - s_G^2}{2s_G c_G} = \cot(2\theta_G), \hspace{1cm} a = \frac{1}{2s_G c_G} = 1/ \sin(2\theta_G).$$ \hspace{1cm} (10)$$

where

$$s_G = \sin \theta_G = \frac{g_R}{\sqrt{(g_L)^2 + (g_R)^2}}, \hspace{1cm} c_G = \cos \theta_G = \frac{g_L}{\sqrt{(g_L)^2 + (g_R)^2}}.$$ \hspace{1cm} (11)$$

$\theta_G$ is $G^L-G^R$ mixing angle, $g_L$ and $g_R$ are the gauge coupling constants satisfying the relation

$$\frac{g_L g_R}{\sqrt{(g_L)^2 + (g_R)^2}} = g_{st}(M_{\text{chc}}).$$ \hspace{1cm} (12)$$

The differential partonic cross section of the process $q\bar{q} \rightarrow Q\bar{Q}$ considering the $G'$-boson and gluon contributions within the tree approximation with account of the difference of the strengths of the $\bar{q}q$- and $q\bar{q}$-$G'$ interactions has the form

$$\frac{d\sigma(q\bar{q} \rightarrow G' Q\bar{Q})}{d \cos \hat{\theta}} = \frac{\pi \beta}{9\hat{s}} \left\{ \alpha_s^2(\mu) f^{(+)} + \frac{\alpha_s(\mu) \alpha_s(M_{\text{chc}})}{(\hat{s} - m_{G'}^2)^2 + m_{G'}^2 \Gamma_{G'}^2} \left[ v^2 f^{(+)} + 2a^2 \beta c \right] + \frac{\alpha_s^2(M_{\text{chc}}) \hat{s}^2}{(\hat{s} - m_{G'}^2)^2 + m_{G'}^2 \Gamma_{G'}^2} \left[ (v^2 + a^2) (v^2 f^{(+)} + a^2 f^{(-)}) + 8a^2 v^2 \beta c \right] \right\},$$ \hspace{1cm} (13)$$

where $f^{(\pm)} = (1 + \beta^2 c^2 \pm 4m_Q^2/\hat{s})$, $c = \cos \hat{\theta}$, $\hat{\theta}$ is the scattering angle of $Q$-quark in the parton center of mass frame, $\hat{s}$ is the invariant mass of $Q\bar{Q}$ system, $\beta = \sqrt{1 - 4m_Q^2/\hat{s}}$, $M_{\text{chc}}$ is the mass scale of the chiral color symmetry breaking and $\mu$ is a typical scale of the process.

The corresponding to \cite{13} total cross section takes the form

$$\sigma(q\bar{q} \rightarrow G' Q\bar{Q}) = \frac{4\pi \beta}{27\hat{s}} \left\{ \alpha_s^2(\mu) (3 - \beta^2) + \frac{2\alpha_s(\mu) \alpha_s(M_{\text{chc}})}{(\hat{s} - m_{G'}^2)^2 + \Gamma_{G'}^2 m_{G'}^2} \left[ v^2 \hat{s}(\hat{s} - m_{G'}^2)(3 - \beta^2) + \frac{\alpha_s^2(M_{\text{chc}}) \hat{s}^2}{(\hat{s} - m_{G'}^2)^2 + \Gamma_{G'}^2 m_{G'}^2} \left[ v^4 (3 - \beta^2) + v^2 a^2 (3 + \beta^2) + 2a^2 \beta c \right] \right\},$$ \hspace{1cm} (14)$$

The entering into \cite{13}, \cite{14} hadronic width $\Gamma_{G'}$ of the $G'$-boson is known \cite{10, 12}. Its magnitude is proportional to $\alpha_s = \alpha_s(M_{\text{chc}})$ and for example at $M_{\text{chc}} = 1.2$ TeV we obtain the next estimations for the relative width of $G'$-boson

$$\frac{\Gamma_{G'}/m_{G'}}{0.08, 0.14, 0.33, 0.60, 1.37}$$ \hspace{1cm} (15)
for $\theta_G = 45^\circ$, 30$^\circ$, 20$^\circ$, 15$^\circ$, 10$^\circ$ respectively.

As is known the $G'$-boson in tree approximation does not contribute to the partonic process $gg \rightarrow Q\bar{Q}$ of gluon fusion and the differential and total SM cross sections of this process are well known and defined by $\alpha_s(\mu)$.

The $G'$-boson can generate, at tree-level, a forward-backward asymmetry through the interference of $q\bar{q} \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ amplitudes [9, 36, 37]. From (13) we obtain the forward-backward difference in the $q\bar{q} \rightarrow Q\bar{Q}$ cross section in the form

$$
\Delta_{FB}(q\bar{q} \rightarrow Q\bar{Q}) = \sigma(q\bar{q} \rightarrow Q\bar{Q}, \cos \theta > 0) - \sigma(q\bar{q} \rightarrow Q\bar{Q}, \cos \theta < 0) =
\frac{4\pi^2 \alpha^2}{9} \left( \frac{\alpha_s(\mu) \alpha_s(M_{chc}) (\hat{s} - m_{G'}^2) + 2\alpha_s^2(M_{chc}) v^2 \hat{s}}{(\hat{s} - m_{G'}^2)^2 + m_{G'}^2 \Gamma_{G'}^2} \right)
$$

(16)

which can give rise to the corresponding forward-backward asymmetry $A_{FB}^{p\bar{p}}$ of $t\bar{t}$-pair production in $p\bar{p}$ collisions at the Tevatron. Notice that the first term in (13) describing the SM contribution in the differential parton cross section in tree approximation does not contribute in the forward-backward difference (16) and in the forward-backward asymmetry $A_{FB}^{p\bar{p}}$ as well.

We have calculated the cross section $\sigma(p\bar{p} \rightarrow t\bar{t})$ of $t\bar{t}$-pair production in $p\bar{p}$-collisions at the Tevatron energy using the total parton cross section of quark-antiquark annihilation (14), the total SM parton cross section of the gluon fusion $gg \rightarrow Q\bar{Q}$ and the parton densities AL’03 [38] (NLO, fixed-flavor-number, $Q^2 = m_t^2$) with the appropriate K-factor $K = 1.24$ [39]. Here and below we believe $\mu^2 = Q^2$, $M_{chc} = m_{G'}$.

With the same parton densities we have calculated and analysed the forward-backward asymmetry $A_{FB}^{p\bar{p}}$ in the form

$$
A_{FB}^{p\bar{p}} = A_{FB}^{G'} + A_{FB}^{SM},
$$

(17)

where $A_{FB}^{G'}$ is the corresponding $G'$ boson contribution which has been calculated using the differential parton cross section (13) (one can use also the expression (16)) and $A_{FB}^{SM}$ is the SM prediction for $A_{FB}^{p\bar{p}}$ for which we have used the value (6) of ref. [9].

We have analysed the results of calculations in dependence on $m_{G'}$ and $\theta_G$ in comparison with the data [7], [8]. The Fig.1 shows the regions in the $m_{G'} - \theta_G$ plane which are simultaneously consistent with the data (7) and (8) within 1$\sigma$ (dark region), 2$\sigma$ (grey region) and 3$\sigma$ (light-grey region). As seen from the Fig.1 for

$$
m_{G'} > 1.02 TeV
$$

(18)
in the $m_{G'} - \theta_G$ plane there is the region which is consistent with the data (7), (8) within 1$\sigma$. For example, for the masses

$$
\begin{align*}
a) & \ m_{G'} = 1.02 \ TeV, \quad b) \ m_{G'} = 1.2 \ TeV, \quad c) \ m_{G'} = 1.4 \ TeV
\end{align*}
$$

(19)

with the appropriate values of $\theta_G$ ($\theta_G = 19^\circ$, $\theta_G = 14^\circ$, $\theta_G = 11^\circ$ respectively, these points are marked in Fig.1 by crosses) we obtain for $\sigma_{t\bar{t}}$, $A_{FB}^{p\bar{p}}$ the values

$$
\begin{align*}
a) & \ \sigma_{t\bar{t}} = 7.98 \ pb, \quad A_{FB}^{p\bar{p}} = 0.158 \ (0.107), \quad (20) \\
b) & \ \sigma_{t\bar{t}} = 7.61 \ pb, \quad A_{FB}^{p\bar{p}} = 0.154 \ (0.103), \quad (21) \\
c) & \ \sigma_{t\bar{t}} = 7.57 \ pb, \quad A_{FB}^{p\bar{p}} = 0.141 \ (0.090), \quad (22)
\end{align*}
$$

which are consistent with the data (7), (8) within 1$\sigma$ (in parentheses we show for comparison the $G'$-boson contributions in $A_{FB}^{p\bar{p}}$ defined by (16), without the SM contribution (6)).
So, the $G'$-boson induced by the chiral color symmetry (2) in general case of $g_L \neq g_R$ is consistent with the data (7), (8) and can reduce the difference between the experimental and SM values (8), (6) of the forward-backward asymmetry $A_{FB}^{pp}$ in the $t\bar{t}$ production at the Tevatron.

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 cross section $\sigma_{t\bar{t}}$ and to the forward-backward asymmetry $A_{FB}^{pp}$ of $t\bar{t}$ production at the Tevatron are calculated with account of the difference of the strengths of the $\bar{q}qG$ and $\bar{q}qG'$ interactions by using the running coupling constants $\alpha_s(\mu)$ and $\alpha_s(M_{\text{chc}})$ at the typical mass scale of the process $\mu$ and at the mass scale of the chiral color symmetry breaking $M_{\text{chc}}$ respectively. The results are analysed in dependence on two free parameters of the model, the mixing angle $\theta_G$ and $G'$ mass $m_{G'}$, in comparison with the Tevatron data on $\sigma_{t\bar{t}}$ and $A_{FB}^{pp}$. The $G'$-boson contributions to $\sigma_{t\bar{t}}$ and $A_{FB}^{pp}$ are shown to be consistent with these data, the allowed region in the $m_{G'} - \theta_G$ plane is discussed and it is shown that for $m_{G'} > 1.02 \text{TeV}$, $\theta_G < 19^\circ$ there is the region in the $m_{G'} - \theta_G$ plane with $1\sigma$ consistency.

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Figure captions

Fig. 1. The $m_G - \theta_G$ regions consistent with CDF data on cross section $\sigma_{\bar{t}t}$ and forward-backward asymmetry $A_{FB}^{\bar{t}t}$ in $t\bar{t}$ production within 1\(\sigma\) (dark region), 2\(\sigma\) (grey region) and 3\(\sigma\) (light-grey region).
Figure 1: