Light axigluon and single top production at the \textit{LHC}

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Abstract

The light axigluon model can explain the Tevatron $t\bar{t}$ forward-backward asymmetry and at the same time satisfy the constraints from the electroweak precision measurement and the \textit{ATLAS} and \textit{CMS} data, which induces the flavor changing ($FC$) couplings of axigluon with the \textit{SM} and new quarks. We investigate the effects of these $FC$ couplings on the $s$- and $t$-channel single top productions at the \textit{LHC} and the $FC$ decays $Z \to b\bar{s} + b\bar{s}$, $t \to c\gamma$ and $cg$. Our numerical results show that the light axigluon can give significantly contributions to single top production and the rare top decays $t \to c\gamma$ and $cg$.

Key words: light axigluon, $FC$ couplings, single top production, rare top decays

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1. Introduction

The standard model (SM) of particle physics has been proven to be extremely successful describing collider experimented data so far. Even the discovery of a Higgs-like particle [1, 2] has confirmed the validity of the SM at the Fermi scale. However, the SM suffers from a key theoretical drawback, the so-called “hierarchy” problem, which means that it could be a low-energy effective theory valid only up to some cut-off energy scale Λ, about TeV scale. So new physics beyond the SM would be in an energy range accessible at the LHC and might be discovered in coming years, although, at the moment, there is not any collider hint of new physics at the LHC.

There are various new physics models extending the gauge group of the strong interaction sector give rise to massive color-octet vector boson, for example, the topcolor models [3] and chiral color models [4]. Other examples include the extra dimensional models [5] and technicolor [6], which predict the existence of the Kaluza-Klein (KK) gluons and technirhos, respectively. Among these color-octet vector bosons, the new particles with axial-vector couplings to the SM quarks are called ”axigluons”, which might explain the anomalous forward-backward asymmetry (FBA) in the t$\bar{t}$ production observed at the Tevatron [7]. So far, there has been a significant amount of works to explain the t$\bar{t}$ FBA via axigluons, for example see [8, 9, 10, 11, 12, 13]. Furthermore, the light axigluon A with a mass $M_A$ in the range from 100GeV to 400GeV can explain the t$\bar{t}$ FBA and satisfy the constraints from the ATLAS and CMS data [14, 15], as long as its decay width is large and its couplings to the SM quarks are relatively small [9, 10, 11, 12].

Top quark physics is expected to be a window to any new physics beyond the electroweak scale. At LHC energies, top quark is copiously produced both in pair and single productions, which allows for an unprecedented precision in the study of top observables, such as its couplings and rare decays [16]. At hadron colliders, single top quark production is an important process in probing the mechanism of electroweak symmetry breaking (EWSB), providing informations complementary to those that can be obtained from top pair production [17]. Single top production is also very sensitive to new physics effects,
whose strength can be assessed by precise measurement of the production cross section.

Single top production at hadron colliders has been observed in three channels: s-channel, t-channel [18, 19] and tW associated production channel [20], which accord with the SM predictions within experimental uncertainties. ATLAS and CMS collaborations have started searching for the new physics effects on single top production.

Inspired by the solution of the light axigluon to the $t\bar{t}$ FBA, some axigluon-mediated phenomena are studied in this paper. We consider the contributions of the light axigluon with flavor changing ($FC$) couplings to the SM and new quarks to the $FC$ decays $Z \rightarrow b\bar{s}$, the $s$- and $t$-channel single top productions, and rare top decays $t \rightarrow c\gamma$ and $cg$ in the context of the light axigluon model proposed by Tavares and Schmaltz [10]. The constraints on this new physics model from the electroweak precision observables and the relevant data given by hadron colliders are taken into account in our numerical calculations.

The rest of this paper is organized as follows: After reviewing the basic ingredients of the light axigluon model, in section 2, we calculate the contributions of the light axigluon to the $FC$ decays $Z \rightarrow b\bar{s}$ and $b\bar{s}$. Corrections of the light axigluon to the cross sections of the $s$- and $t$-channel single top productions at the LHC are studied in section 3. The branching ratios of the rare top decays $t \rightarrow c\gamma$ and $cg$ induced by light axigluon exchange are given in section 4. Section 5 is devoted to simple summary.

2. Light axigluon and the $FC$ decays $Z \rightarrow b\bar{s}$ and $b\bar{s}$

The light axigluon model [10] is based on the gauge group $G = SU(3)_1 \times SU(3)_2 \times SU(2) \times U(1)_Y$, where $SU(2) \times U(1)_Y$ is the conventional electroweak group and the extended gauge group $SU(3)_1 \times SU(3)_2$ is spontaneously broken to the QCD gauge group $SU(3)_C$ by the vacuum expectation value (VEV) of a bifundamental scalar $\phi$. This breaking pattern yields two mass eigenstates of color-octet gauge bosons. One is massless particle, which can be identified with the SM gluon, and the other is massive particle, which is called the light axigluon $A$. For its couplings to the SM quarks, there are the
vector coupling \( g_V \approx 0 \) and the axial-vector coupling \( g_A \neq 0 \) in the case of assuming approximately parity symmetry. In order to cancel the gauge anomaly, the extra up- and down-type quarks are introduced into this model, and the lepton sector is exactly same as that of the SM. To explain the \( t \overline{t} FBA \), the axigluon \( A \) should have mass below 450\( \text{GeV} \), while should be broad with \( \Gamma_A/M_A \sim 10 \sim 20\% \), where \( \Gamma_A \) and \( M_A \) represent its total decay width and mass, respectively.

In the original light axigluon model [10], the authors assume the existence of an exact global symmetry of the axigluon couplings, and thus the light axigluon only has flavor universal couplings to the SM quarks. In fact, this global symmetry is only approximate and there is mixing between new and ordinary quarks, which can induce flavor changing neutral currents (FCNCs) at tree level [21]. The new and ordinary quarks have same \( SU(2) \times U(1) \) charge, their mixing does not give rise to the FC Z couplings at tree level. The new scalars can not induce FCNCs, thus the non-universal axigluon couplings are the main source of FCNC for this model.

In this paper we will not assume the existence of an exact global symmetry of the axigluon couplings, which allows FC couplings of the axigluons to the SM quarks. If one assumes that these FC couplings are only axial-vector couplings, which are similar with their flavor conserving couplings to the SM quarks, then the axial-vector couplings of the light axigluon to the SM quarks can be general given by the Lagrangian

\[
\mathcal{L} \supset g_s \overline{u}_i \gamma_\mu \gamma_5 (g_A^{u_i} \delta_{ij} + \varepsilon_{ij}^{u}) u_j A^\mu + \overline{d}_i \gamma_\mu \gamma_5 ((g_A^{d_i} \delta_{ij} + \varepsilon_{ij}^{d}) d_j A^\mu),
\]  

where \( A^\mu \) is the light axigluon, \( g_s \) is the QCD coupling constant, \( u_i \) and \( d_i \) are the SM up- and down-type quarks, respectively. In above equation, we have neglected the color and spinor indices. \( g_A^{u_i} \) and \( g_A^{d_i} \) are the flavor independent coupling constants and there are \( g_A^{u_i} = g_A^{d_i} = g_A^q \) [10]. The FC coupling constants \( \varepsilon_{ij}^{u} \) and \( \varepsilon_{ij}^{d} \), which arise from flavor symmetry breaking of new and light quarks, are given by the matrices

\[
\varepsilon_u = \begin{pmatrix}
0 & g^{uc} & g^{ut} \\
(g^{uc})^* & 0 & g^{ct}
\end{pmatrix},
\varepsilon_d = \begin{pmatrix}
0 & g^{ds} & g^{db} \\
(g^{ds})^* & 0 & g^{bs}
\end{pmatrix}.
\]  

(2)

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The couplings of the axigluon to a pair of ordinary quarks and to the corresponding partners have opposite sign. So, in order to get suppressed couplings of the ordinary quarks to the axigluon, the extra quarks and the SM quarks should have mixing [10, 12, 22]. The mixing can be obtained by adding a Yukawa coupling involving a scalar field $\phi$ in addition to the quark field of $Q'$. After the spontaneous breakdown of $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_C$ induced by the VEV for $\phi$, the new quarks from the line combinations of $Q'$ and $Q$ get masses, while their orthogonal combinations correspond to the SM quarks remain massless, which get masses from the SM Higgs VEV via Yukawa couplings. In the mass eigenstates, the mixing couplings of the axigluon to ordinary and new quarks, which are assumed to be axial-vector couplings, can be general written as

$$L' \supset g_s g^A_{mix} \left[ \overline{U} H_i \gamma_\mu \gamma_5 (\bar{\epsilon}^i_H u) u_j A^\mu + \overline{D} H_i \gamma_\mu \gamma_5 (\bar{\epsilon}^i_H d) d_j A^\mu \right].$$

(3)

$U_{Hi}$ and $D_{Hi}$ represent the up-type and down-type new quarks, respectively. For the mixing coupling constant $g^A_{mix}$, there is the relation $(g^A_{mix})^2 + (g^q_A)^2 = 1$. For the two matrices $\epsilon_{Hu}$ and $\epsilon_{Hd}$, they are related through the SM CKM matrix: $\epsilon^+_H u \epsilon_{Hd} = V_{CKM}$, which is similar with the case for the mixing between the T-odd and T-even quarks in the LHT model [23]. In this paper, we assume that both $\epsilon_{Hu}$ and $\epsilon_{Hd}$ are nearly equal to the identity matrix, which provides us with a set of minimal flavor mixing scenarios.

We take as examples two simple cases:

Case I $\epsilon_{Hu} = I$, $\epsilon_{Hd} = V_{CKM}$,

Case II $\epsilon_{Hd} = I$, $\epsilon_{Hu} = V_{CKM}$.

In case I, the mixing coupling $g^Q_A$ has no contributions to $D^0 - \overline{D^0}$ mixing, while contributes to $B^0_q - \overline{B^0_q}$ and $K^0 - \overline{K^0}$ mixings. For case II, it is obvious that the mixing coupling $g^Q_A$ can only contribute to $D^0 - \overline{D^0}$ mixing. Reference [21] has obtained the constraints on the mixing matrix $\epsilon_d$ by using the available data from neutral meson mixings, such as $B^0_q - \overline{B^0_q}$, $K^0 - \overline{K^0}$ and $D^0 - \overline{D^0}$ mixings. Taking into account of these constants, in this section, we calculate the branching ratios of the FC decays $Z \rightarrow b \bar{s}$ and $b \overline{\sigma}$ given by axigluon exchange as shown in Fig.1. The self-energy diagrams Fig.1(b) and (c) contribute a finite field renormalization and the individual diagrams are finite.
To fulfill the broad width of the axigluon, the first and second generation new quarks should be degenerate and lighter than the axigluon, while the third generation new quarks must be heavier [10]. So we think that the contributions of the third generation new quarks to the $FC$ decays $Z \rightarrow \overline{b}s(b\overline{s})$ decouple and only consider the contributions of the first and second generation new quarks. In our numerical estimation, we will take $M_{D_{H1}} = M_{D_{H2}} = M_H = 0.2M_A$. In this case, one can safely neglect the phase space suppression effect for the axigluon decaying to one new quark and one ordinary quark and there should be $\Gamma_A/M_A \sim 10 \sim 20\%$.

Figure 1: One-loop Feynman diagrams for the $FC$ decay $Z \rightarrow \overline{b}s$ induced by light axigluon exchange.

The light axigluon model predicts the existence of new scalar, which also has the mixing couplings to new and ordinary quarks. However, it can not induce $FC$ couplings at tree level and thus in this paper we neglect the effects of the new scalar on the $FC$ processes $Z \rightarrow \overline{b}s$ and $b\overline{s}$.

The corrections of color-octet gauge boson to the $Zb\overline{b}$ coupling are firstly studied by Ref.[25] in the context of topcolor models, which contain only the leading-logarithmic contributions. The full one-loop results for the corrections of the axigluon to the $Zb\overline{b}$ coupling are given in Refs.[11, 12] in the case of neglecting the bottom quark mass. Ref.[12] have further computed the contributions from new quarks and new scalar to the $Zb\overline{b}$ coupling and find that the two kinds of contributions have opposite sign and the effect of new scalar is much smaller than that of new quarks. Following Refs.[11, 12], we can straightforwardly calculate the contributions of the light axigluon model to the $FC$
couplings $Zb\bar{s}$ and $Zb\bar{s}$. Then, the effective $Zb\bar{s}$ coupling can be written as

$$g_{Zbs}^{P} = \frac{\alpha_{s}}{3\pi} g_{Zbb}^{P} \kappa(x_{z}) + (g_{A}^{mix})^{2} \kappa(x_{z}, x_{h})(\varepsilon_{Hd}^{*}\varepsilon_{Hd} + \varepsilon_{Hd}^{22}\varepsilon_{Hd})],$$

where $P = L$ and $R$. $g_{Zbb}^{P}$ and $g_{Zbb}^{P}$ represent the couplings of the gauge boson $Z$ and axigluon $A$ to the bottom quark pairs, respectively. The explicit expressions of the factors $\kappa(x_{z})$ and $\kappa(x_{z}, x_{h})$ have been given in Ref.[12]. Since the couplings of the axigluon to pair of ordinary quarks and pair of new quarks are flavor universal and the new and ordinary quarks have same $SU(2) \times U(1)$ charge, in above equation we have added the contributions of the ordinary quarks $b$ and $s$, and taken

$$g_{L}^{Zbb} = g_{L}^{ZD_{i}D_{i}} = \frac{e}{4S_{W}C_{W}} \left(1 - 2\frac{2}{3}S_{W}^{2}\right), \quad g_{R}^{Zbb} = g_{R}^{ZD_{i}D_{i}} = -\frac{e}{4S_{W}C_{W}} \cdot \frac{2}{3}S_{W}^{2},$$

where $i = 1$ and 2, $S_{W} = \sin \theta_{W}$ and $C_{W} = \cos \theta_{W}$, $\theta_{W}$ is the Weinberg angle. The FC coupling $g_{Zbb}^{P}$ can contribute to $B_{s}^{0} - \overline{B_{s}^{0}}$ mixing at tree level and its upper bound has been obtained by Ref.[21] as $|g_{L}^{bs}| = |g_{R}^{bs}| = |g_{A}^{bs}| \leq 1.83 \times 10^{-3}$. In fact, for the case I, the new quarks can also generate contributions to $B_{s}^{0} - \overline{B_{s}^{0}}$ mixing via box diagrams that contain the light axigluon and new quark. However, the contributions from box diagrams are suppressed with respect to axigluon tree-level contributions by a loop factor $1/(16\pi^{2})$ and two additional mixing matrix elements $\varepsilon_{Hd}^{3}$ and $\varepsilon_{Hd}^{22}$. Therefore they cannot compete with the latter and are negligible. As numerical estimation, we will take $g_{L}^{bs} = 1.83 \times 10^{-3}$, $g_{R}^{bs} = -g_{A}^{bs} = g_{A}^{q}$.

In the SM, the FC decay $Z \rightarrow \overline{t}s + b\bar{s}$ originates from one loop diagrams with branching ratio $\sim 3 \times 10^{-8}$ [26]. For future linear collider (ILC), the expected sensitivity to the branching ratios of rare $Z$ decays can be improved from $10^{-5}$ at the LEP to $10^{-8}$ at the Giga $Z$ [27]. The new physics effects might be detectable via $Z \rightarrow bs$ if it indeed affects this decay. A lot of theoretical studies involving the FC decay $Z \rightarrow bs$ have been given within some popular models beyond the SM, where its branching ratio can be significantly enhanced [28].

Using the effective couplings $g_{L}^{Zbs}$ and $g_{R}^{Zbs}$ given by Eq.(4), we can easily calculate the partial width $\Gamma(Z \rightarrow \overline{t}s + b\bar{s})$. The numerical results for the branching ratio $Br(Z \rightarrow$
Figure 2: Variation of the branching ratio $Br(Z \to \bar{b}s + b\bar{s})$ with the axigluon mass $M_A$ for $g^b_A = 1.83 \times 10^{-3}$, $\varepsilon_{Hd} = V_{CKM}$ and three values of the coupling parameter $g^q_A$.

$\bar{b}s + b\bar{s}) = \Gamma(Z \to \bar{b}s + b\bar{s})/\Gamma_{total}$ are shown in Fig.2, in which we have taken the SM input parameters as: $\alpha_s(m_Z) = 0.118$, $S^2_W = 0.231$, $\Gamma_{total} = 2.4945 GeV$, and $M_Z = 91.1875 GeV$ [29]. If the light axigluon can explain the $t\bar{t}$ FBA and at the same time satisfy the constraints from the electroweak precision observables and the relevant data given by hadron colliders, its mass should be in the range of $100 GeV \sim 400 GeV$, its total decay width $\Gamma^A_t = (0.1 \sim 0.2)M_A$ and the flavor conserving coupling $g^f_A$ might be in the range of $0.3 \sim 0.5$ [9, 10, 11, 12]. In our numerical estimation we have considered the effects of the axigluon width and taken $\Gamma^A_t = 0.1M_A$. For the mixing between the SM and new quarks, we have taken case I and assumed $M_H = 0.2M_A$. One can see from Fig.2 that, in most of the parameter space, the value of the branching ratio $Br(Z \to \bar{b}s + b\bar{s})$ is smaller than $1 \times 10^{-8}$, which is still below the SM prediction. So considering the constraints of $B^0_s - \bar{B}^0_s$ mixing on the FC coupling $g^{bs}_A$, the contribution of the light axigluon to the
rare decays $Z \to \bar{b}s$ and $b\bar{s}$ is very difficult to be detected in near future. Certainly, if we assume $\varepsilon_{Hd} \neq V_{CKM}$, the numerical results should have some changes.

3. The FC couplings of the light axigluon $A$ and single top production at the LHC

![Feynman diagrams](image)

Figure 3: Leading order Feynman diagrams for $t\bar{b}$ and $t\bar{t}$ production contributed by the FC couplings $g^A_{tq}$, in which $q = u, c$, $q' = d, s, b$, and $q'' = d, s$.

In the SM, single top production dominantly occurs through electroweak processes, which are customary divided into three production channels: t-channel exchange of a space-like W boson, s-channel production and decay of a time-like W boson, and associated production of a top quark and an on-shell W boson. These partonic processes have their own distinct kinematics and do not interfere with each other. Both at Tevatron and the LHC, the t-channel process is dominant one, which in five flavor (5F) scheme proceeds via the partonic processes $qb \to q't$ and $q\bar{b} \to q'\bar{t}$ for single top production, and $q\bar{b} \to q\bar{t}$ and $q'\bar{b} \to q't$ for single antitop production. The s-channel partonic processes are $qq' \to t\bar{b}$ and $q\bar{q}' \to t\bar{t}$ for single top and antitop productions, respectively. The contributions of charged and neutral color-octet vector bosons to top pairs and single top production has been studied in Refs.[13, 30]. In this section we will consider the corrections of the light axigluon to the s- and t-channel single top productions via the FC couplings $g^A_{tq}$ with
\( q = u \) or \( c \). The relevant Feynman diagrams are shown in Fig.3.

For the partonic process \( q\bar{b} \rightarrow t\bar{b} \) as shown in Fig.3 (a), the differential cross section with respect to emerging angle of the single top quark \( \cos \theta_t \) can be written as

\[
\frac{d\sigma(t\bar{b})}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^{tb})^2}{9\hat{s}} P_t[\hat{s}(\hat{s} - m_t^2) + \hat{t}(\hat{t} - m_t^2)].
\] (6)

The partonic process \( q\bar{q} \rightarrow t\bar{q} \) is composed of the s- and t-channel diagrams corresponding to Fig.3 (b) and 3 (c). Its differential cross section is given by

\[
\frac{d\sigma(t\bar{q})}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^{tq})^2}{9\hat{s}} \left\{ P_s[\hat{u}(\hat{u} - m_t^2) + \hat{t}(\hat{t} - m_t^2)] + \frac{P_sP_t}{3}(\hat{s} - M_A^2)(\hat{t} - M_A^2)\hat{u}(\hat{u} - m_t^2) + P_t[\hat{s}(\hat{s} - m_t^2) + \hat{u}(\hat{u} - m_t^2)] \right\}.
\] (7)

The differential cross section of the t+u channel partonic process \( qq \rightarrow t+q \) can be written as

\[
\frac{d\sigma(tq)}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^{tq})^2}{9\hat{s}} \left\{ P_s[\hat{u}(\hat{u} - m_t^2) + \hat{t}(\hat{t} - m_t^2)] + \frac{P_sP_t}{3}(\hat{s} - M_A^2)(\hat{t} - M_A^2)\hat{s}(\hat{s} - m_t^2) + P_u[\hat{t}(\hat{t} - m_t^2) + \hat{s}(\hat{s} - m_t^2)] \right\}.
\] (8)

The differential cross section for the s-channel partonic \( q'q' \rightarrow t\bar{q} \) as shown in Fig.3 (e) is given by

\[
\frac{d\sigma_s(t\bar{q})}{d\cos\theta_t} = \frac{2\pi\alpha_s^2\beta(g_A^{tq})^2(g_A^{tq})^2}{9\hat{s}} P_s[\hat{u}(\hat{u} - m_t^2) + \hat{t}(\hat{t} - m_t^2)].
\] (9)

The explicit expression of the differential cross section for the t-channel \( qq'' \rightarrow t\bar{q}'' \) is same as that for the process \( q\bar{b} \rightarrow t\bar{b} \), as long as replace the initial state b quark by the quark \( q'' \) (d or s). In above equations, \( \beta = 1 - \frac{m_t^2}{\hat{s}}, \ \hat{s}, \ \hat{t}, \ \text{and} \ \hat{u} \) are the usual Mandelstam variables,

\[
P_i = \frac{1}{(\hat{i} - M_A^2)^2 + M_A^2\Gamma_A^2} \quad \text{with} \quad i = \hat{s}, \ \hat{t}, \ \text{or} \ \hat{u}.
\] (10)

Using above equations we can calculate the cross sections of \( tb \) and \( tj \) production at the LHC induced by the light axigluon with the FC coupling \( g_A^{tq} \). In our numerical
calculations, we use the leading order parton distribution function of CTEQ6L1 [31] and choose the factorization and renormalization scales to be $\mu_f = \mu_r = m_t/2$ with $m_t = 173$GeV. Our numerical results are added $t\bar{b}$ and $\bar{t}b$ for the process $pp \rightarrow t\bar{b}$, and similar for $tj$ production with $j = u, c, d,$ and $s$. It is obvious that the production cross sections depend on the mass parameter $M_A$, the coupling parameters $g_{tq}^A$ and $g_{q}^A$, where we have taken $g_{tA}^u = g_{tA}^d$ and the flavor conserving coupling $g_{tA}^q$ being flavor universal.

![Graph](image-url)

Figure 4: In the case of $\delta\sigma^s/\sigma_{SM}^s = 10\%$, the FC coupling $g_{tA}^q$ as function of the axigluon mass $M_A$ for $g_{tA}^A = 0.3$(solid line), 0.4(dashed line) and 0.5(dotted line).

In the $SM$, single top production at hadron colliders was first considered in Ref.[32]. Now the production cross sections for the s- and t-channels have been calculated up to next-to-next-to leading logarithm ($NNLL$) accuracy [33]: $\sigma_s = 1.04 \pm 4\% \, pb$ and $\sigma_t = 2.26 \pm 5\% \, pb$ at Tevatron with the centre-of-mass (c.m.) energy $\sqrt{s} = 1.96 TeV$ and $\sigma_s = 12 \pm 6\% \, pb$ and $\sigma_t = 243 \pm 4\% \, pb$ at the $LHC$ with $\sqrt{s} = 14 TeV$. The s- and t-channel cross sections have been measured at Tevatron by $CDF$ and $DO$ collaborations and the measurement precision can reach 18% [18]. The measurement precision for the
t-channel cross section at the 8TeV LHC reported by ATLAS and CMS is about 15% [19]. It will be enhanced in coming years. For example, Ref.[34] has shown that the cross section of the t-channel single top production at the 14TeV LHC can be measured with a precision of 5%.

Figure 5: In the case of $\delta \sigma^t/\sigma_{SM}^t = 10\%$, the FC coupling $g_{A}^{tq}$ as function of the axigluon mass $M_A$ for $g_{A}^{t}=0.3$(solid line), 0.4(dashed line) and 0.5(dotted line).

From above discussions we can see that the theoretical error of the SM NNLO cross section at the 14TeV LHC for the s- and t-channel productions could be as large as 5%, the same amount of the expected precision at the 14TeV LHC. So if the relative correction of the light axigluon to the single top production cross section is larger than 10%, the 14TeV LHC should detect this correction effect. In Fig.4 and Fig.5 we demand that $\delta \sigma^s/\sigma_{SM}^s = 10\%$ and $\delta \sigma^t/\sigma_{SM}^t = 10\%$, where $\sigma_{SM}^s$ and $\sigma_{SM}^t$ are the SM NNLO predictions for the s- and t-channel single top production cross sections at the LHC with $\sqrt{s} = 14$TeV, $\delta \sigma^s$ and $\delta \sigma^t$ are induced by the light axigluon $A$, and plot the FC coupling $g_{A}^{tq}$ as a function of the mass parameter $M_A$ for different values of the flavor
conserving $g_A^q$. In our numerical calculation, we have taken the central values for $\sigma_{SM}^s$ and $\sigma_{SM}^t$. From these figures one can see that the contributions of the light axigluon to the production cross sections of the processes $pp \to tb + X$ and $pp \to tj + X$ increase as the coupling parameters $g_A^{tq}$ and $g_A^q$ increasing, while decrease as $M_A$ increasing. For $100 GeV \leq M_A \leq 400 GeV$ and $0.3 \leq g_A^q \leq 0.5$, the values of FC coupling $g_A^{tq}$ are in the ranges of $0.017 \sim 0.163$ and $0.024 \sim 0.139$ for $\delta\sigma^s/\sigma_{SM}^s = 10\%$ and $\delta\sigma^t/\sigma_{SM}^t = 10\%$, respectively. We expect that, in near future, the LHC can authenticate this correction effect on single top production or at least give constraint on the FC coupling $g_A^{tq}$.

4. The light axigluon and the rare top decays $t \to c\gamma$ and $cg$

It is well known that in the SM the rare top decays $t \to qV$ ($q = u, c$ and $V = \gamma, g, Z$) mediated by FCNCs are highly GIM suppressed with branching ratios of $Br(t \to cV) \sim 10^{-14} \sim 10^{-12}$ [35], which are far below the detectable level of current or near future experiments. However, some new physics models can enhance these branching ratios significantly [36]. So rare top decays offer an opportunity to test the SM and search for new physics effects. Any positive signal of rare top decay processes would clearly indicate new physics beyond the SM.

![Feynman diagrams for the rare top decays](image)

Figure 6: Feynman diagrams for the rare top decays $t \to c\gamma$ and $cg$ coming from the FC coupling $g_A^{tq}$, in which $i = 1$ and 2.

On the experimental side, rare top decays are being searched for at Tevatron [37] and LHC [38, 39]. ATLAS collaboration has set upper limit on the branching ratio $Br(t \to cg) < 2.7 \times 10^{-4}$ at 95\% C.L. [39]. The sensitivity of ATLAS to the branching
ratio $Br(t \to c\gamma)$ is expected to be of the order of $10^{-4}$ \cite{40}.

From discussions given in above sections we can see that the light axigluon with $FC$ couplings can contribute rare top decays. In this section we will calculate the branching ratios $Br(t \to c\gamma)$ and $Br(t \to cg)$ induced by the light axigluon. The relevant Feynman diagrams are shown in Fig.6. In this section, we also assume that the contributions of the third generation new quarks to the rare top decays $t \to c\gamma$ and $t \to cg$ decouple. Compared to the $FC$ couplings of the light axigluon $A$ to the new quarks and the $SM$ quarks, the $FC$ couplings of the scalar $\phi$ to the new quarks and the $SM$ quarks arise at higher order, their $FC$ effects are much smaller than those induced by the axigluon $A$. Thus, in this section, we neglect the contributions of the scalar $\phi$ to the rare top decays $t \to c\gamma$ and $t \to cg$ as done for $Z \to bs$ in section 2.

Considering electromagnetic gauge invariance, the amplitude of the rare decay $t \to c\gamma$ can be general written as

$$M(t \to c\gamma) = i\overline{u}(P_c)\sigma^{\mu\nu}q_{\nu}(A_\gamma + B_\gamma\gamma_5)u(P_t)\varepsilon_\mu^*(q),$$

(11)

where $q = P_t - P_c$ is the photon momentum and $\varepsilon$ is its polarization vector, in which $P_t$ and $P_c$ represent the momenta of top and charm quarks, respectively. A similar structure is valid for $t \to cg$ with form factors $A_g$ and $B_g$. For the light axigluon $A$ with zero vector couplings to the $SM$ and new quarks i.e. $g_V^{tg} \approx 0$, $g_V^{QHq} \approx 0$ and $g_V^{q} \approx 0$ \cite{10,12}, there are $A_\gamma \neq 0$, $A_g \neq 0$ and $B_\gamma = 0$, $B_g = 0$. Recently, Ref.\cite{41} has calculated the contributions of color-singlet gauge bosons predicted by the 331 models to the rare top decay $t \to c\gamma$ and give the explicit expressions for the relevant form factors. In this paper we will use LoopTools \cite{42} to obtain our numerical results.

Using Eq.(11), the partial widths of $t \to c\gamma$ and $t \to cg$ contributed by the light axigluon can be written as

$$\Gamma(t \to c\gamma) = \frac{m_t^3}{8\pi}(1 - \frac{m_c^2}{m_t^2})^3|A_\gamma|^2,$$

(12)

$$\Gamma(t \to cg) = C_F\frac{m_t^3}{8\pi}(1 - \frac{m_c^2}{m_t^2})^3|A_g|^2,$$

(13)
Figure 7: The branching ratio $Br(t \rightarrow c\gamma)$ as a function of the axigluon mass $M_A$ for three values of the flavor conserving coupling $g_A^q$.

where $C_F = 4/3$ is a color factor.

To obtain numerical results, we have assumed that the top total decay width is dominated by the decay $t \rightarrow Wb$. The FC coupling $g_A^{tc}$ is determined by the parameters $g_A^q$ and $M_A$ via the relation $\delta\sigma_t/\sigma_{SM} = 10\%$. For calculation the contributions of the first and second generation new quarks, we take the case II: $\varepsilon_{Hd} = I, \varepsilon_{Hu} = V_{CKM}$ and assume $M_H = 0.2M_A$. In Fig.7 and Fig.8 we plot the branching ratios $Br(t \rightarrow c\gamma)$ and $Br(t \rightarrow cg)$ as functions of the axigluon mass $M_A$ for three values of the flavor conserving coupling $g_A^q$. One can see from these figures that the light axigluon $A$ can indeed enhance the branching ratios $Br(t \rightarrow c\gamma)$ and $Br(t \rightarrow cg)$. For $0.3 \leq g_A^q \leq 0.5$ and $100GeV \leq M_A \leq 400GeV$, the values of $Br(t \rightarrow c\gamma)$ and $Br(t \rightarrow cg)$ are in the ranges of $4.8 \times 10^{-9} \sim 5.9 \times 10^{-8}$ and $1.1 \times 10^{-8} \sim 1.3 \times 10^{-6}$, respectively. Replacing the FC couplings $g_A^{tc}$ and $g_A^{Uc}$ by $g_A^{tu}$ and $g_A^{Uu}$, we can easily calculate the contributions of the light axigluon $A$ to the rare top decays $t \rightarrow w\gamma$ and $ug$. 

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5. Conclusions

The light axigluon $A$ with a mass $M_A$ in the range from 100GeV to 400GeV predicted by the light axigluon model [10] can explain the $t\bar{t}$ FBA and satisfy the constraints from the ATLAS and CMS data, as long as its decay width is large and its couplings to the SM quarks are relatively small. In order to get suppressed couplings of the light axigluon $A$ to the SM quarks, the new quarks and the SM quarks should have mixing, which can induce the FC couplings to the new quarks and the SM quarks. Furthermore, to fulfill the broad width of the axigluon, the new quarks, at least the first and second generation new quarks, are lighter than the light axigluon. In this paper, we assume the flavor conserving axigluon couplings are universal and pure axial vector-like, and investigate some FC phenomena mediated by the light axigluon.

The contributions of the light axigluon model to the FC decays $Z \rightarrow \bar{b}s, \bar{b}\tau$ and $t \rightarrow c\gamma, cg$ mainly come from the FC quark- quark- axigluon coupling $g_{A}^{qq'}$ and the FC
quark–new quark–axigluon coupling $g_A^{QH}$. Considering the constraints of meson mixing on the FC coupling $g_A^{qG}$ and assuming that both $\varepsilon_{Hu}$ and $\varepsilon_{Hd}$ are nearly equal to the identity matrices and satisfy the relation $\varepsilon_{Hu}^T \varepsilon_{Hd} = V_{CKM}$ to give the value of $g_A^{QH}$, we calculate the branching ratios $Br(Z \to b\bar{s} + b\bar{s})$, $Br(t \to c\gamma)$ and $Br(t \to cg)$ in the context of the light axigluon model. Our numerical results show that, in most of parameter space, the value of the branching ratio $Br(Z \to b\bar{s} + b\bar{s})$ is smaller than $1 \times 10^{-8}$, which is still below the SM prediction. Compared to the SM predictions, the branching ratios $Br(t \to c\gamma)$ and $Br(t \to cg)$ can be significantly enhanced in the light axigluon model, while are still lower than the corresponding current experimental upper limits.

It is well known that single top production is very sensitive to new physics beyond the $SM$, whose effects can be assessed by precise measurement of the production cross section. In this paper, we study the correction effects of the light axigluon $A$ to the s- and t-channel single top productions at the $LHC$. We find that, in near future, the $LHC$ should observe this correction effect with reasonable values for the FC coupling $g_A^{qG}$ or at least give constraint on the FC coupling $g_A^{qG}$. If one demands $\delta\sigma^s/\sigma_{SM}^{s} = 10\%$ and $\delta\sigma^t/\sigma_{SM}^{t} = 10\%$, the values of the FC coupling $g_A^{qG}$ should be in the ranges of $0.017 \sim 0.163$ and $0.024 \sim 0.139$, respectively.

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