Search for the Anomalous Interactions of Up-Type Heavy Quarks in $\gamma\gamma$ collision at the LHC

M. Köksal* and S.C. İnan†

Department of Physics, Cumhuriyet University, 58140, Sivas, Turkey

Abstract

We investigate the anomalous interactions of heavy up-type quark $t'$ in a $\gamma\gamma$ collision at the LHC. We have obtained 95% confidence level (C.L.) limit of $t'q\gamma$ ($q = u, c$) anomalous coupling by taking into account three forward detector acceptances; $0.0015 < \xi < 0.15, 0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. 

*mkoksal@cumhuriyet.edu.tr
†sceminan@cumhuriyet.edu.tr
I. INTRODUCTION

The Standard Model (SM) ensures a conspicuously successful description of high energy physics at an energy scale of up to a few hundred GeV. However, the number of fermion families is arbitrary in the SM. The only limitation on number of fermion families comes from asymptotic freedom $N \leq 8$. We should use at least three fermion families to obtain CP violation [1] in the SM. CP violation could explain the matter-antimatter asymmetry in the universe. The SM with three families is not enough to show the real magnitude for matter-antimatter asymmetry of universe. However, this problem can be solved when the number of family reaches four [2]. Also, the existence of three or four families is equally consistent with the updated electroweak precision data [3, 4]. The possible discovery of the fourth SM family may help to respond to some unanswered questions about electroweak symmetry breaking [5, 7], fermions mass and mixing pattern [8–10], and flavor structure of the SM [11–14].

Higgs boson is a theoretical particle that is suggested by the SM. Many experiments were conducted so far to detect Higgs boson. A boson consistent with this boson was a detected in 2012, but it may take quite time to demonstrate certainly whether this particle is indeed a Higgs boson. If the lately surveyed 125 GeV boson is Higgs boson of the SM [15, 16], the presence of the fourth family would be disfavoured [17, 19]. Besides, a theory with extended Higgs sector beyond the SM [20] can still include a fourth fermion family even though the 125 GeV boson is one of the forecasted extended Higgs bosons. Moreover, the other models estimate the presence of a heavy quark as a partner to the top quark [21, 22]. Current bounds on the masses of the fourth SM fermion families are given follows; $m_{t'} > 670$ GeV [23], $m_{b'} > 611$ GeV [24], $m_{l'} > 100.8$ GeV, $m_{\nu'} > 90.3(80.5)$ GeV for Dirac (Majorana) neutrinos [25]. When we analyze our results we have taken into account LHC limits in $\sqrt{s} = 7$ TeV. For this purpose, we have assumed $t'$ mass to be greater than its current experimental limits. The fourth SM quarks would be produced abundantly in pairs at the LHC via the strong interaction for masses below $O(1$ TeV) [26, 29], with fairly large cross sections. The exact designation of their properties can ensure important advantage in the determination of new physics which is established upon high energy scales. Moreover, we can expect a crucial addition from anomalous interactions for production of fourth family quarks. These interactions have been investigated at lepton colliders at lepton colliders.
γe colliders, ep colliders, and hadron colliders.

The LHC has high energetic proton-proton collisions with high luminosity. It provides high statistics data. We expect that this collider will answer many open questions in particle physics. Research of exclusive production of proton-proton interactions opens a new field of surveying high energy photon-induced reactions such as photon-photon and photon-proton interactions. ATLAS and CMS Collaborations established a program of forward physics with new detectors located in a region almost 100 m- 400 m from the central detectors. These detectors are called very forward detectors. They can detect intact protons which are scattered after the collisions. Very forward detectors can label intact protons with some momentum fraction loss given the formula \( \xi = (|\vec{p}'| - |\vec{p}'|)/|\vec{p}| \). Here \( \vec{p}' \) is the momentum of intact scattered proton and \( \vec{p} \) is the momentum of incoming proton. ATLAS Forward Physics Collaboration (AFP) proposed an acceptance of \( 0.0015 < \xi < 0.15 \) for the forward detectors. Two types of measurements will be planned to examine with high precision using the AFP: first, exploratory physics (anomalous couplings between \( \gamma \) and \( W \) or \( Z \) bosons, exclusive production, etc.) and second, standard QCD physics (double Pomeron exchange, exclusive production in the jet channel, single diffraction, \( \gamma\gamma \) physics, etc.). These studies will develop the HERA and Tevatron measurements to the LHC kinematical region. Also, CMS-TOTEM forward detector scenario has acceptance regions \( 0.1 < \xi < 0.5 \) and \( 0.0015 < \xi < 0.5 \). The TOTEM experiment at the LHC is concentrated on the studies of the total proton-proton cross-section, the elastic \( pp \) scattering, and all classes of diffractive phenomena. Detectors housed in Roman Pots which can be moved close to the outgoing proton beams allow to trigger on elastic and diffractive protons and to determine their parameters like the momentum loss and the transverse momentum transfer. Moreover, charged particle detectors in the forward domains can detect nearly all inelastic events. Together with the CMS detector, a large solid angle is covered enabling precise studies. The forward detectors of ATLAS and CMS were not built in the first phase of the LHC. However, the CMS forward detectors were commissioned in 2009. The first measurement of the forward energy flow has been carried out and forward jets at \( |\eta| > 3 \) have been analyzed for the first time at Hadron Colliders. Also, two photon reactions \( pp \rightarrow p\gamma\gamma p \rightarrow p\mu^-\mu^+p \), \( pp \rightarrow p\gamma\gamma p \rightarrow pe^-e^+p \) were examined with the help of forward detectors by the CMS Collaboration in 2012. On the other hand, AFP Collaboration has not yet installed the forward detectors. The forward detectors are planned to be built 210 m away from
the central detectors in 2013. Additionally, 420 m additional detectors will be installed if physics motivates it later [58]. Forward detectors allow to determine high energy photon-photon process. This process occurred by two almost real photons with low virtuality emitted from protons. The proton structure does not spoil in this process due to low virtuality of photons. Therefore, intact scattered protons after the collision can be detected by the aid of the forward detectors. Searching new physics via photon-induced reactions have been studied in earlier works [59–69].

Photon-photon interaction can be explained by equivalent photon approximation [70, 71]. Emitted photons by protons are produced an $X$ object via $pp \rightarrow p\gamma\gamma p \rightarrow pXp$ process. The cross section of this process can be found by

$$d\sigma = \int \frac{dL_{\gamma\gamma}}{dW}d\hat{\sigma}_{\gamma\gamma \rightarrow X}(W)dW$$  \hspace{1cm} (1)$$

where $W$ is the invariant mass of the two photon system, $\hat{\sigma}_{\gamma\gamma \rightarrow X}$ is the cross section for subprocess $\gamma\gamma \rightarrow X$ and $\frac{dL_{\gamma\gamma}}{dW}$ is the luminosity spectrum of photon-photon collisions. $\frac{dL_{\gamma\gamma}}{dW}$ can be given as follows [63]:

$$\frac{dL_{\gamma\gamma}}{dW} = \int_{Q_{\gamma\gamma}}^{Q_{\gamma\gamma}} dQ_{1}^{2} \int_{y_{\gamma\gamma}}^{y_{\gamma\gamma}} dy \frac{W}{2y} f_1 \left( \frac{W^2}{4y}, Q_1^2 \right) f_2 (y, Q_2^2)$$  \hspace{1cm} (2)$$

with

$$y_{\gamma\gamma} = \text{MAX}(W^2/(4\xi_{\gamma\gamma}E, \xi_{\gamma\gamma}E)), y_{\gamma\gamma} = \xi_{\gamma\gamma}E, Q_{\gamma\gamma}^2 = 2GeV^2$$  \hspace{1cm} (3)$$

here $f_1$ and $f_2$ are functions of equivalent photon energy spectrum. The photon spectrum with energy $E_\gamma$ and virtuality $Q^2$ is given by the following [70]:

$$f = \frac{dN}{dE_\gamma dQ^2} = \frac{1}{\pi E_\gamma Q^2} \left[ (1 - E_\gamma/E)(1 - Q_{\min}^2/Q^2) F_E + \frac{E_\gamma^2}{2E^2} F_M \right]$$  \hspace{1cm} (4)$$

where

$$Q_{\min}^2 = \frac{m_p^2 E_\gamma^2}{E(E - E_\gamma)}, F_E = \frac{4m_p G_E^2}{4m_p^2 + Q^2}, G_E^2 = \frac{G_M^2}{\mu_p^2} = \left( 1 + \frac{Q^2}{Q_0^2} \right)^{-4}, F_M = G_M^2, Q_0^2 = 0.71GeV^2.$$  \hspace{1cm} (5)
The terms in above equations are the following: $E$ is the energy of the proton beam which is related to the photon energy by $E_\gamma = \xi E$, $m_p$ is the mass of the proton, $F_M$ is function of the magnetic form factor, $F_E$ is function of the electric form factor and $\mu_p^2 = 7.78$ is the magnetic moment of the proton.

In this study, we have examined the anomalous interaction of up-type $t'$ quark via the $pp \rightarrow p\gamma\gamma p \rightarrow p\bar{q}q'p$ ($q = u, c$) process by considering three forward detector acceptances; $0.0015 < \xi < 0.15, 0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$.

II. ANOMALOUS INTERACTION OF $t'$ QUARK

The fourth family $t'$ quark can interact with the ordinary quarks $q_i$ via SM gauge bosons ($\gamma, g, Z^0, W^\pm$). The lagrangian of this interaction is expressed by

$$
L = -g_e Q_i \bar{t}' \gamma^\mu t' A_\mu - g_s \bar{t}' T^a \gamma^\mu t' G^a_\mu - \frac{g_Z}{2} \bar{t}' \gamma^\mu (g_V - g_A \gamma^5) t' Z^0_\mu - \frac{g_e}{2\sqrt{2} \sin \theta_W} V_{t'q_i} \bar{t}' \gamma^\mu (1 - \gamma^5) q_i W^\pm_\mu + h.c.
$$

where $g_e$ is the electromagnetic coupling constant, $g_s$ is the strong coupling constant, $g_Z$ is the weak neutral current coupling constant, $g_A$ and $g_V$ are the vector and axial-vector type couplings of the neutral weak current with $t'$ quark, $T_a$ are the Gell-Mann matrices, $Q_{t'}$ is the electric charge of fourth family $t'$ quark. The vector fields $A_\mu$, $G_\mu$, $Z^0_\mu$ and $W^\pm_\mu$ represent photon, gluon, $Z^0$-boson and $W^\pm$-boson, respectively. Finally, the $V_{t'q_i}(Q_i = d, b, s, b')$ are the elements of the extended CKM mixing matrix. In [19] they found that the maximum value of the fourth generation quark mass is $\sim 300$ GeV for a Higgs boson mass of $\sim 125$ GeV, which is already in conflict with bounds from direct searches. Therefore, we have considered that $t'$ is a heavy quark instead of fourth generation quark. The $t'$ quark is heavier than the top quark. It is accepted as the heaviest particle, and it is couple the flavor changing neutral currents, leading to an enhancement in the resonance processes at the LHC. The interaction Lagrangian for the anomalous interactions between the fourth family $t'$ quark, ordinary quarks $u, c, t$ and the gauge bosons $\gamma, g, Z$ is given as follows:
\[ L = \sum_{q_i=u,c,t} \frac{\kappa^q_i}{\Lambda} Q_{q_i} g_{\gamma q_i} \sigma_{\mu\nu} q_i F_{\mu\nu} + \]
\[ + \sum_{q_i=u,c,t} \frac{\kappa^Z_i}{\Lambda} g_{\gamma q_i} \sigma_{\mu\nu} q_i Z_{\mu\nu} + \]
\[ + \sum_{q_i=u,c,t} \frac{\kappa^g_i}{\Lambda} g_{\gamma q_i} T_a q_i G_{\mu\nu}^a + h.c. \quad (7) \]

where \( \kappa_\gamma, \kappa_Z \) and \( \kappa_g \) are the anomalous couplings with photon, \( Z \) boson and gluon, respectively. \( \Lambda \) is a new physics cutoff and \( \sigma_{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2 \); \( F_{\mu\nu}, Z_{\mu\nu} \) and \( G_{\mu\nu}^a \) are the field stress tensor of the photon, \( Z \) boson and gluons, respectively. Jets that originate from light quarks (\( u, d, \) and \( s \)) differ from heavy quarks (\( c \) and \( b \)) in the final state at the LHC. Therefore, anomalous \( \kappa_\gamma u \) coupling can be distinguished from \( \kappa_\gamma c \) coupling via the process \( \gamma\gamma \to q\bar{q} \), if anomalous couplings \( \kappa_\gamma u \) are not equal to \( \kappa_\gamma c \). It can be understood that the bound on product \( \kappa_\gamma u \times \kappa_\gamma c \) through the process \( \gamma\gamma \to u\bar{c} \) can be also examined. However, we consider that \( \kappa_\gamma u \) is equal to \( \kappa_\gamma c \) in our paper. For the fourth family leptons \( \ell' \gamma \) coupling was calculated in the literature for the photon-photon fusion at the LHC[72]. Also, \( b'q\gamma \) coupling can be examined through the process \( \gamma\gamma \to q\bar{q} \) (\( q = d, s \)). But study of the \( b'd\gamma \) and \( b's\gamma \) couplings is difficult for this process since \( d \) and \( s \) quarks cannot be distinguished from each other.

Using interaction Lagrangian in (7) anomalous decay widths of \( t' \) quarks can be obtained as follows:

\[ \Gamma(t' \to q\gamma) = \frac{2\kappa_\gamma^2}{\Lambda} \alpha_e Q_{q_i}^2 m_{t'}^3. \quad (8) \]

where \( m_{t'} \) is the mass of the fourth family \( t' \) quark and \( \alpha_e \) is the electromagnetic coupling constant.

The subprocess \( \gamma\gamma \to q\bar{q} \) consists of \( t \) and \( u \) channel tree-level SM diagrams. Additionally, there are two Feynman diagrams containing \( t' \) quark propagators in \( t \) and \( u \) channels. The whole polarization summed amplitude square of this process has been calculated as follows:

\[ |M|^2 = 8g_{\gamma q_i}^4 Q_{q_i}^4 \left( \frac{t}{u} + \frac{u}{t} \right) - 64g_{\gamma q_i}^4 Q_{q_i}^4 \left( \frac{\kappa_\gamma}{\Lambda} \right)^2 \left( \frac{u^2}{u-m_{t'}^2} + \frac{t^2}{t-m_{t'}^2} \right) \]
\[ + 128g_{\gamma q_i}^4 Q_{q_i}^4 \left( \frac{\kappa_\gamma}{\Lambda} \right)^4 \left[ \frac{2stu_{t'}^2}{(u-m_{t'}^2)(t-m_{t'}^2)} + (tu + m_{t'}^2) \left( \frac{u^2}{(u-m_{t'}^2)^2} + \frac{t^2}{(t-m_{t'}^2)^2} \right) \right] \quad (9) \]
where $s$, $t$ and $u$ are the Mandelstam variables and we omit the mass of ordinary quark ($q_i = u, c$). We have supposed $\sqrt{s} = 14$ TeV to be center of mass energy of the proton-proton system during calculations.

The leading order background process comes from QCD induced reactions (pomeron exchange). Pomerons emitted from incoming protons can interact with each other, and they can occur at the same final state. However, survival probability for a pomeron exchange is quite smaller than survival probability of induced photons. Therefore, pomeron background is expected to have minor effect on sensitivity bounds [73, 74].

In Figure (1), we have plotted the SM and total cross sections of $pp \rightarrow pq\bar{q}p$ ($q = u, c$) process as a function $p_{t,\text{min}}$ ($p_t$ cut) transverse momentum of final state quarks for three forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. Here $m_t$ and $\kappa_*/\Lambda$ is taken to be 700 GeV, $1$ TeV$^{-1}$, respectively. From these figures, we see that the SM and total cross sections can be distinguished from each other at large values of the $p_t$ cut. Then, it can be understood that imposing higher values of $p_t$ cut can reduce the SM background. These cuts allow to obtaining better sensitivity bounds.

In this motivation, we show the SM event numbers of $pp \rightarrow pq\bar{q}p$ for different values of $p_t$ cut and luminosities in Tables 1, 2, and 3 for acceptance regions $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$, respectively. During statistical analysis we use two different techniques. In the first approach we apply cuts on the $p_t$ of the final state quarks to suppress the SM cross section. We make the number of SM event smaller than 0.5. Then it is very appropriate to set bounds on the couplings using a Poisson distribution since the number of SM events with these cuts is small enough. From our calculations, $p_t$ cuts are obtained as 380 GeV and 452 GeV for two acceptance regions $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ in order to be less than 0.5 the number of SM event, respectively. Since the invariant mass of the final state quarks for $0.1 < \xi < 0.5$ is greater than 1400 GeV, the SM cross section is very small. Hence, it does not need a high $p_t$ cut for $0.1 < \xi < 0.5$ acceptance region.

Moreover, ATLAS and CMS have central detectors with a pseudorapidity $|\eta| < 2.5$ for the tracking system at the LHC. Therefore, for all of the calculations in this paper, we also apply $|\eta| < 2.5$ cut. The parameter plane $m_t - \kappa_*/\Lambda$ is plotted at 95% C.L. using Poisson analyze for the three different acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$ in Figure 2. In Figures 2(a) and 2(b), we use the different $p_t$ values for every acceptance span to obtain less than 0.5 event number of SM: a) $p_t = 380$ GeV for acceptance span...
0.0015 < \xi < 0.15, b) \p_t = 452 \text{ GeV} \text{ for acceptance span } 0.0015 < \xi < 0.5 \text{ as mentioned above. In Figure 2(c), we applied a } \p_t \text{ cut of } \p_t = 50 \text{ GeV} \text{ for acceptance span } 0.1 < \xi < 0.5 \text{ for detection of the final state quarks in central detectors.}

Second analyze technique, we have used to one parameter \( \chi^2 \) analyze when the SM event number larger than 10. The \( \chi^2 \) function is given as follows:

\[
\chi^2 = \left( \frac{\sigma_{SM} - \sigma_{NP}}{\sigma_{SM} \delta} \right)^2
\]

where \( \sigma_{SM} \) is the cross section of SM, \( \sigma_{NP} \) is the cross section containing new physics effects and \( \delta = \frac{1}{\sqrt{N_{SM}}} \) is the statistical error. In Figure 3, the parameter plane of \( m_{t'} - \kappa_\gamma/\Lambda \) is plotted at 95\% C.L. using \( \chi^2 \) analyse for the two different acceptances 0.0015 < \xi < 0.15, 0.0015 < \xi < 0.5. For the 0.1 < \xi < 0.5 acceptance region we cannot use \( \chi^2 \) analysis due to SM event number being smaller than 10 as seen from Table 3. We have found from Figure 3 that 0.0015 < \xi < 0.5 acceptance region provides more restrictive limit than 0.0015 < \xi < 0.15 acceptance region because new physics effect comes from high energy region.

III. CONCLUSIONS

Forward detector equipments at the LHC can discern intact scattered protons after the collision. Hence, we can distinguish exclusive photon-photon processes with respect to deep inelastic scattering which damages the proton structure. Since photon-photon interaction has very clean environment, it is important to examine new physics for a given detector acceptance region through photon-induced reactions. Moreover, this interaction can isolate to \( \kappa_\gamma \) coupling from the other gauge boson couplings. In these motivations, we have researched the anomalous interaction of \( t' \) quark via \( pp \rightarrow p\gamma\gamma p \rightarrow pXp \) process at the LHC to investigate anomalous \( t'q\gamma \) coupling. Our results show that the sensitivity of the anomalous \( \kappa_\gamma/\Lambda = 0.85 \text{ TeV}^{-1} \) coupling can be reached at \( \sqrt{s} = 14 \text{ TeV} \) and \( L_{int} = 100 \text{ fb}^{-1} \) for the \( m_{t'} = 650 \text{ GeV} \), the acceptance span 0.0015 < \xi < 0.5. As a result, the exclusive \( pp \rightarrow p\gamma\gamma p \rightarrow pq\bar{q}p \) reaction at the LHC offers us an important opportunity to probe anomalous couplings of \( t' \) quark.
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FIG. 1: The SM and total cross sections of $pp \to pq\bar{q}p$ ($q = u, c$) process as a function transverse momentum cut ($p_{t,\text{min}}$) on the final state quarks for three forward detector acceptances: $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$ and $0.1 < \xi < 0.5$. $m_t$ and $\kappa_\gamma/\Lambda$ is taken to be 700 GeV, 1 TeV$^{-1}$, respectively.

TABLE I: The SM event numbers of $pp \to pq\bar{q}p$ process for different values of $p_t$ transverse momentums and luminosities. Here acceptance span is taken to be $0.0015 < \xi < 0.15$.

| $p_{t,\text{min}}$(GeV) | 50 fb$^{-1}$ | 100 fb$^{-1}$ | 200 fb$^{-1}$ |
|--------------------------|-------------|--------------|--------------|
| 50                       | 206.75      | 413.5        | 827          |
| 100                      | 24.46       | 48.94        | 97.87        |
| 150                      | 5.97        | 11.95        | 23.89        |
| 200                      | 2.02        | 4.05         | 8.11         |
| 300                      | 0.37        | 0.75         | 1.51         |
| 400                      | 0.096       | 0.19         | 0.382        |
FIG. 2: The parameter plane of $m_{t'}$ and $\kappa_{\gamma}/\Lambda$ at 95% C.L. using Poisson analysis for three different luminosities: 50, 100 and 200 fb$^{-1}$. In (a) and (b), we use the different $p_t$ values for every acceptance region to obtain less than 0.5 event number of SM: (a) $p_t = 380$ GeV for acceptance region $0.0015 < \xi < 0.15$; (b) $p_t = 452$ GeV for acceptance region $0.0015 < \xi < 0.15$. In (c), we applied a $p_t$ cut of $p_t = 50$ GeV for acceptance region $0.1 < \xi < 0.5$.

TABLE II: The SM event numbers of $pp \rightarrow p\bar{q}q\bar{p}$ process for different values of $p_t$ transverse momentums and luminosities. Here acceptance span is taken to be $0.0015 < \xi < 0.5$.

| $p_{t,\text{min}}$(GeV) | 50fb$^{-1}$ | 100fb$^{-1}$ | 200fb$^{-1}$ |
|--------------------------|-------------|-------------|-------------|
| 50                       | 224.8       | 449.6       | 899.2       |
| 100                      | 29.2        | 58.4        | 116.6       |
| 150                      | 7.8         | 15.6        | 31.3        |
| 200                      | 2.9         | 5.8         | 11.6        |
| 300                      | 0.65        | 1.3         | 2.6         |
| 400                      | 0.21        | 0.42        | 0.83        |
| 500                      | 0.08        | 0.16        | 0.32        |
FIG. 3: The parameter plane of $m_t$ and $\kappa_\gamma/\Lambda$ for the two different acceptances: $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ at 95% C.L. using $\chi^2$ analysis. Here, $p_{t,\text{min}}$ transverse momentum cuts are taken to be 50, 100, and 150 GeV, respectively.

TABLE III: The SM event numbers of $pp \rightarrow pq\bar{q}p$ process for different values of $p_t$ transverse momentums and luminosities. Here acceptance span is taken to be $0.1 < \xi < 0.5$.

| $p_{t,\text{min}}$(GeV) | 50$fb^{-1}$ | 100$fb^{-1}$ | 200$fb^{-1}$ |
|-------------------------|-------------|--------------|--------------|
| 50                      | 0.06        | 0.12         | 0.24         |
| 100                     | 0.057       | 0.115        | 0.23         |
| 150                     | 0.05        | 0.1          | 0.2          |