Cumhuriyet Üniversitesi Fen Fakültesi
Fen Bilimleri Dergisi (CFD), Cilt 37, No. 4 (2016)
ISSN: 1300-1949

Cumhuriyet University Faculty of Science
Science Journal (CSJ), Vol. 37, No. 4 (2016)
ISSN: 1300-1949

http://dx.doi.org/10.17776/csj.79028

Probing the Anomalous $tq\gamma$ Couplings in $\gamma\gamma$ Collisions at the LHC

Murat KÖKSAL, Ahmet Alper BİLLUR

Departman of Physics, Cumhuriyet University, Faculty of Science, TR-58140 Sivas, Turkey

Received: 18.10.2016; Accepted: 02.11.2016

Abstract. γγ processes at the LHC provide an important opportunity to study of the new physics beyond the Standard Model due to the absence of the remnants of both proton beams. For this reason, we examine the sensitivity on the anomalous $\kappa_{tq\gamma}$ couplings through the process $pp \to p\gamma\gamma p \to pt\bar{q}p \to pW(\to l_{\nu l})b\bar{q}p$ $(q = u, c\ ;\ l = e,\ \mu)$ at the LHC in a model independent way through effective lagrangian approach. We show that the most stringent limits on anomalous coupling parameters at $\sqrt{s} = 14$ TeV 200 fb^{-1} is $\kappa_{tq\gamma} =\ 0.007$.

Keywords: LHC, top quark, anomalous coupling

LHC'de $\gamma\gamma$ Çarpışmalarında Anomal $tq\gamma$ Bağlaşımlarının Araştırılması

Özet. LHC'de γγ süreçleri, iki proton demetinin kalıntılarının olmaması sebebiyle Standart Model ötesi fiziğin incelenmesi için önemli bir fırsat sağlar. Bu nedenle, efektif lagranjiyen yaklaşımından geçerek model bağımsız bir yolla $pp \to p\gamma\gamma p \to pt\bar{q}p \to pW(\to l_{\nu l})b\bar{q}p$ $(q = u, c\ ;\ l = e,\ \mu)$ süreci aracılığıyla anomal $\kappa_{tq\gamma}$ bağlaşımları üzerine duyarlılığı inceliyoruz. 200 fb^{-1} is $\sqrt{S} = 14$ TeV anomal bağlaşım parametreleri üzerine en sınırlayıcı limit $\kappa_{tq\gamma} =\ 0.007$ olarak elde edileceğini gösteriyoruz.

Anahtar Kelimeler: LHC, üst kuark, anomal bağlaşım

I. INTRODUCTION

The top quark, which was discovered at the Tevatron in 1995 [1], completed the three family structure of the Standard Model (SM) of particle physics and therefore opened the new area of the top quark interactions. Top quarks are produced either singly via the weak interaction or in pairs dominantly via the strong interaction at hadron colliders [2-6]. Therefore, examination of its decay and production allows to determine the features of these forces of the SM with a great precision. On the other hand, any possible deviations from the SM top quark interactions will be a signal of the new physics beyond the SM. One of the top quark anomalous interactions is Flavour Changing Neutral Current (FCNC). The FCNC decays of the top quark are very suppressed at tree level in the SM by the Glashow- Iliopoulos-Maiani (GIM) mechanism [7]. However, these interactions are generated through many different models; the two-Higgs doublet model with or without avour-conservation [8{14], the littlest Higgs model [15, 16], the quark-singlet model [17-19], supersymmetry with R-parity violation [20], the minimal supersymmetric model [22{28], extra dimension models [29-31] or the topcolor-assisted technicolor model [32-34].

* Corresponding author. *Email address:* mkoksal@cumhuriyet.edu.tr

Up to now, the anomalous FCNC interactions of the top quark were experimentally examined at Tevatron [35, 36, 38, 39], LEP [40-44], and the LHC [45-48] colliders. The bounds on the anomalous interactions of the photon with the top quark are given as follows

$$\kappa_{tu\gamma} < 0.12 \tag{1}$$

presented by ZEUS collabaration [77], and

$$BR(t \to \upsilon\gamma) + BR(t \to c\gamma) < 3.2\% \tag{2}$$

supplied by CDF collobaration [36].

The most stringent experimental bounds recently have been obtained at 95% C.L. by the CMS Collaboration as follows [37]

$$BR(t \to \upsilon\gamma) + BR(t \to c\gamma) = 0.198\% \tag{3}$$

In this work, we have studied anomalous $\kappa_{tq\gamma}$ couplings via $pp \to p\gamma\gamma p \to pt\overline{q}p$ $(q = u, c)$ process at the LHC. The exclusive $pp \to pXp$ reaction has a clean environment due to absence of the proton remnants. ATLAS and CMS collaborations have a plan of forward physics with new detectors placed in a region nearly 220m-400m from the interaction point to detect particles not detected by the central detectors with a pseudorapidity coverage $|\eta|$<2.5 [51, 52]. These detectors can determine intact scattered protons in a range of $\xi_{min} < \xi < \xi_{max}$. Here ξ is the acceptance of the forward detectors. It is given by $\xi = \left(|\vec{p}| - |\vec{p'}|\right)/|\vec{p}|$, where $\vec{p}$ and $\vec{p'}$ are momentums of incoming protons and intact protons, respectively. ATLAS Forward Physics collaboration suggested an acceptance of 0.0015 < ξ < 0.15 [51, 52]. CMS –TOTEM forward detector scenario spans 0.0015 < ξ < 0.50.1 < ξ < 0.5 [53, 54]. Thanks to these forward detectors possible to observe high energy photon-photon processes. Photon-photon processes have been described by equivalent photon approximation. In this approximation, emitted photons which have a low virtuality are scattered very small angles from the beam pipe. Because of the emitted almost real photons have a low virtuality they do not spoil the proton structure. Hence, unspoil protons after the collision can be detected by forward detectors. By means of interacting two photons can produced an object X through $pp \to p\gamma\gamma p \to pXp$ process. Cross section of this process can be given by integrating the cross section for the subprocess $\gamma\gamma \to X$ over the effective photon luminosity $\frac{dL^{\gamma\gamma}}{dW}$

$$d\sigma = \int \frac{dL^{\gamma\gamma}}{dW} d\hat{\sigma}_{\gamma\gamma\to X}(W)dW \tag{4}$$

where W is the invariant mass of the two photon system $W = 2E\sqrt{\xi_1\xi_2}$. The effective photon luminosity is defined by

$$\frac{dL^{\gamma\gamma}}{dW} = \int_{Q^2_{1,min}}^{Q^2_{max}} dQ_1^2 \int_{Q^2_{2,min}}^{Q^2_{max}} dQ_2^2 \int_{y_{min}}^{y_{max}} dy \frac{W}{2y} f_1\left(\frac{W^2}{4y}, Q_1^2\right) f_2\left(y, Q_2^2\right) \tag{5}$$

with

$$y_{min} = MAX(W^2/(4\xi_{max}E), \xi_{min}E), y_{max} = \xi_{max}E, Q^2_{max} = 2GeV^2 \quad (6)$$

Here y is the energy of one of the emitted photons from the proton f_1 and f_2 are the functions of the equivalent photon spectrum. The photon spectrum with energy E_γ and virtuality Q^2 is defined by

$$f = \frac{dN}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}[(1-\frac{E_\gamma}{E})(1-\frac{Q^2_{min}}{Q^2})F_E + \frac{E^2_\gamma}{2E^2}F_M] \quad (7)$$

where E is the energy of the proton, E_γ is the energy of the photon, F_E and F_M are the electric and magnetic form factors of the proton, respectively. Also,

$$Q^2_{min} = \frac{m^2_p E^2_\gamma}{(E(E-E_\gamma))}, F_E = \frac{4m^2_p G^2_E + Q^2 G^2_M}{4m^2_p + Q^2} \quad (8)$$

$$G^2_E = \frac{G^2_M}{\mu^2_p} = (1+\frac{Q^2}{Q^2_0})^{-4}, F_M = G^2_M, Q^2_0 = 0.71GeV^2 \quad (9)$$

where m_p is the mass of the proton and $\mu^2_p = 7.78$ is the magnetic moment of the proton.

The Large Hadron Collider (LHC) which produces very high energetic proton-proton collisions provides high statistics data at high energies. However, proton-proton interactions have very large backgrounds coming from strong interactions. On the other hand, the photon-photon reactions are a pure QED processes because of absent of the proton remnants. Therefore, a signicant amount of backgrounds of these processes can be reduced. Also, photon-photon interactions occur greater energies than that of any existing collider. The physical potential of photon-photon processes were examined previously in the hadron-hadron collisions [55-73] and ep collisions [74-76] in the literature.

II. MODEL INDEPENDENT ANALYSIS OF ANOMALOUS $tq\gamma$ INTERACTION

The effective Lagrangian involving the FCNC interactions of the top quark can be given in a model independent way by the following formula [77, 78]

$$L = \sum_{q=u,c} g_e e_t \bar{t}\frac{i\sigma_{\mu\nu}p^\nu}{\Lambda}\kappa_{tq\gamma} q A^\mu \quad (10)$$

where $\kappa_{tq\gamma}$ defines magnitude of the anomalous $tq\gamma$ vertice, Λ is the new physics scale which is conventionally set to the mass of the top quark, $\sigma_{\mu\nu} = (\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)/2$, $g_e = \sqrt{4\pi\alpha}, e_t$ is the top quartk electric charge, and p is the momentum of the photon.

Also, using of interaction Lagrangian in Eq. (11), anomalous decay width of top quark can be easily obtained as follows

$$\Gamma(t \to q\gamma) = \frac{g_e^2 \kappa_{tq\gamma}^2 m_t^3}{8\pi\Lambda^2} \quad (q = u, c) \tag{11}$$

where we omit masses of the u and c quarks in above equation. Due to the dominant decay mode of top quark is $t \to bW$, the branching ratio of anomalous $t \to q\gamma$ decay generally is given by the following formula.

$$BR(t \to q\gamma) = \frac{\Gamma(t \to q\gamma)}{\Gamma(t \to bW)} \tag{12}$$

Therefore, using the equations (1) and (10), we can be obtained the magnitude for upper bounds of anomalous coupling provided by CDF collobaration as follows

$$\kappa_{tq\gamma} = 0.088. \tag{13}$$

In the existence of the effective Lagrangian in Eq. (8), Feynman diagrams of the $\gamma\gamma \to t\bar{q}$ $(q = u, c)$ subprocess where contains anomalous coupling are presented in Fig.1. The squared amplitudes can be given in terms of Mandelstam variables by the formulas:

$$|M_1|^2 = -\frac{8e_t^4 \kappa^2 g_e^2}{\Lambda^2 (t - m_t^2)^2} t(m_t^4 - (4t + u)m_t^2 + t(t + u)), \tag{14}$$

$$|M_2|^2 = |M_1(t \leftrightarrow u)|^2, \tag{15}$$

$$|M_3|^2 = \frac{8e_t^4 \kappa^2 g_e^2 (t - m_t^2)(m_t^2 - t - u)}{\Lambda^2 t}, \tag{16}$$

$$|M_4|^2 = |M_3(t \leftrightarrow u)|^2, \tag{17}$$

$$2Re(M_1^\dagger M_2) = \frac{4e_t^4 \kappa^2 g_e^2}{\Lambda^2 (t - m_t^2)(u - m_t^2)} (3(t + u)m_t^4 - (3t + u)(t + 3u)m_t^2 + tu(t + u)), \tag{18}$$

$$2Re(M_1^\dagger M_3) = -\frac{4e_t^4\kappa^2 g_e^2}{\Lambda^2(t-m_t^2)}(6m_t^4 - (11t+3u)m_t^2 + t(5t+u)), \tag{19}$$

$$2Re(M_1^\dagger M_4) = -\frac{16e_t^4\kappa^2 g_e^2 m_t^2 t(u-m_t^2)}{\Lambda^2 u(t-m_t^2)}, \tag{20}$$

$$2Re(M_2^\dagger M_3) = 2Re(M_1^\dagger M_4)^2(t \leftrightarrow u), \tag{21}$$

$$2Re(M_2^\dagger M_4) = 2Re(M_1^\dagger M_3)^2(t \leftrightarrow u), \tag{22}$$

$$2Re(M_3^\dagger M_4)^2 = \frac{4e_t^4\kappa^2 g_e^2(t+u)}{\Lambda^2} \tag{23}$$

where Mandelstam variables are described as $t = (P_{\gamma-}P_{\bar{t}})^2, u = (P_{\gamma-}P_q)^2$ and $s + t + u = m_t^2,\ g_e$ is the electromagnetic coupling constant.

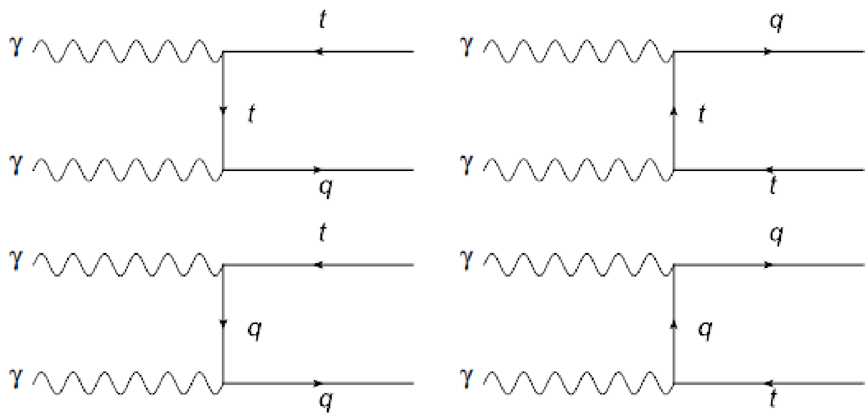

Fig. 1: Tree-Level Feynman diagrams for the $\gamma\gamma \rightarrow \bar{t}q$ subprocess ($q = u, c$)

We consider two different situation to compare our work with results of the CDF and ZEUS collaborations. Firstly, we calculate the magnitude for upper limit of the $\kappa_{tu\gamma}$ coupling which is found by the ZEUS collobaration. In Fig.2, we plot the integrated total cross-section of $pp \rightarrow p\gamma\gamma p \rightarrow p\bar{t}up$ process for the forward detector acceptances 0.0015<ξ<0.15, 0.0015<ξ<0.5 and 0.1<ξ<0.5 We see from this gure that the cross sections of acceptance ranges 0.0015<ξ<0.15 and

0.0015<ξ<0.5 are more sensitive to $\kappa_{tu\gamma}$ coupling than the cross section of acceptance range 0.1<ξ<0.5 In this work, we apply a Poisson distribution since there are no SM backgrounds for the $\gamma\gamma \to t\bar{q}$ subprocess. Therefore, we estimate the sensitivity to the $\kappa_{tu\gamma}$ coupling for various values of integrated luminosities and $\sqrt{s} = 14$ TeV. The expected number of events has been calculated considering the hadronic decay channel of the top quark as the signal $N = BR(t \to W^+ b \to q\bar{q}b)\sigma_{SM} L_{int} S$ where S=0.9 is the survival probability factor [94, 95]. CMS and ATLAS have central detectors with a pseudorapidity coverage $|\eta| < 2.5$. Therefore, we consider an acceptance window of $|\eta| < 2.5$ for final-state quarks. Branching ratios appearing in the number of events are defined as $BR = \Gamma/\Gamma_{Total}$ where Γ_{Total} is the full width and Γ_{Total} is the decay rate for the corresponding channel with a cut of for final decay products.

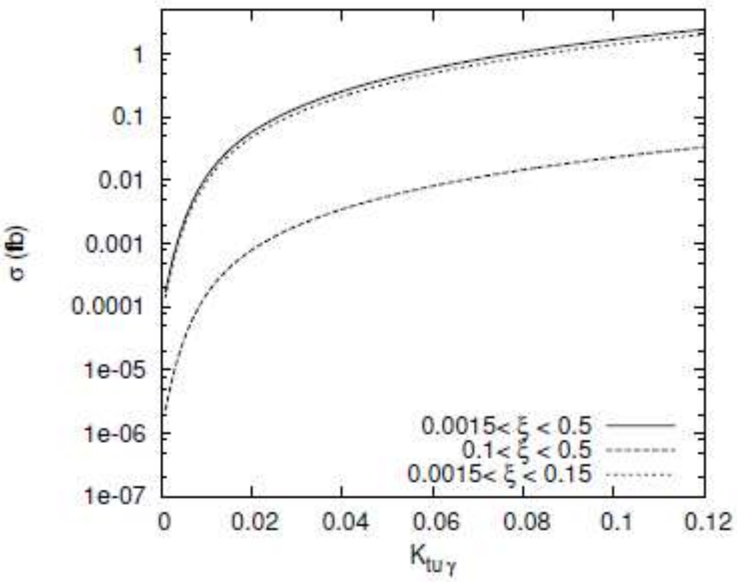

Fig. 2: The total cross sections of the $pp \to p\gamma\gamma p \to p\bar{t}up$ process as a function of $\kappa_{tu\gamma}$ coupling for three forward detector acceptances: 0.0015<ξ<0.5, 0.0015<ξ<0.15 and 0.1<ξ<0.5.

There are 13 Feynman diagrams for the process $\gamma\gamma \to W^+ bq\ (q = u, c)$ is the SM. The contributions from these are very small because of *Wbq* vertex in each diagram and this vertex contains small CKM value. Since the total cross section is order of 10^{-6} pb we use Poisson analysis for the determining FCNC couplings of the top quark. Upper bounds of number of events N_{up} at the 95% confidence level can be obtained as follows [96, 97]

$$\sum_{k=0}^{N_{obs}} P_{Poisson}(N_{up}; k) = 0.05. \qquad (24)$$

In Table (1), we show 95% confidence level sensitivity limits of the $\kappa_{tu\gamma}$ coupling for various LHC luminosities and for the three forward detector acceptances: 0.1<ξ<0.5, 0.0015<ξ<0.5 and

0.0015<ξ<0.15. We see from Table 1 that the best bounds for the $\kappa_{tu\gamma}$ coupling is 0.01 for forward detector acceptance 0.0015<ξ<0.5 and $L_{int} = 200\ fb^{-1}$.

Table 1 95% confidence level sensitivity bounds of the $\kappa_{tu\gamma}$ coupling for various LHC luminosities and forward detector acceptances of 0.1<ξ<0.5, 0.0015<ξ<0.5 and 0.0015<ξ<0.15. The center of mass energy of the proton-proton system to be $\sqrt{s} = 14$ TeV.

$L_{int}(fb^{-1})$	$0.1 < \xi < 0.5$	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$
10	0.38	0.044	0.049
30	0.22	0.026	0.028
50	0.17	0.02	0.022
100	0.12	0.014	0.016
130	0.11	0.013	0.014
160	0.095	0.011	0.012
200	0.085	0.01	0.011

Secondly, we estimate the magnitude for upper limit of the $\kappa_{tq\gamma}$ coupling which is obtained by the CDF collobaration. In Fig.3, we show the integrated total cross-section of $pp \rightarrow p\gamma\gamma p \rightarrow p\bar{t}qp$ process for the forward detector acceptances 0.0015<ξ<0.15, 0.0015<ξ<0.5 and 0.1<ξ<0.5 The explanation for Fig (3) is same with Fig.2. Finally, we find 95% confidence level sensitivity limits of the $\kappa_{tq\gamma}$ coupling for various LHC luminosities and forward detector acceptances of 0.0015<ξ<0.5, 0.0015<ξ<0.15 and 0.1<ξ<0.5 We obtain the most sensitivity limit $\kappa_{tq\gamma} = 0.098$ for forward detector acceptance 0.0015<ξ<0.5 and $L_{int} = 200\ fb^{-1}$ as shown in Table 2.

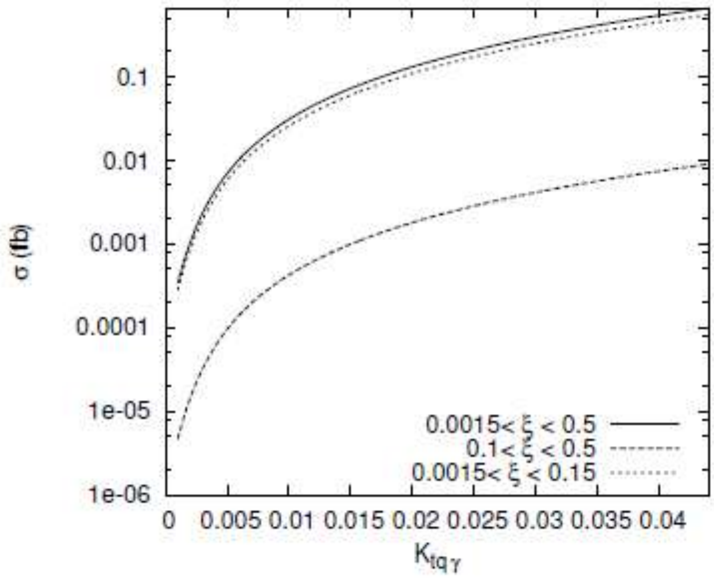

Fig. 3: The total cross sections of $pp \rightarrow p\gamma\gamma p \rightarrow p\bar{t}qp$ process as a function of $\kappa_{tq\gamma}$ coupling for three forward detector acceptances: 0.0015<ξ<0.5, 0.0015<ξ<0.15 and 0.1<ξ<0.5.

Table 2. 95% confidence level sensitivity bounds of the $\kappa_{tq\gamma}$ coupling for various LHC luminosities and forward detector acceptances of 0.1<ξ<0.5, 0.0015<ξ<0.5 and 0.0015<ξ<0.15 The center of mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

$L_{int}(fb^{-1})$	$0.1 < \xi < 0.5$	$0.0015 < \xi < 0.5$	$0.0015 < \xi < 0.15$
10	0.27	0.031	0.035
30	0.16	0.018	0.02
50	0.12	0.014	0.016
100	0.085	0.01	0.011
130	0.078	0.0092	0.01
160	0.067	0.0078	0.008
200	0.06	0.007	0.078

III. CONCLUSIONS

Forward detector equipments at the LHC determine the high energy photon-photon processes at centre-of-mass energies never reached before. These processes is generated by two almost real photons emitted from protons. The emitted photons do not spoil the proton structure. Therefore photon-photon interactions have very clean environments. Furthermore, detection of the intact scattered protons in the forward detectors allows us to reconstruct almost real photons momenta. In this work we have analyzed anomalous top quark photon couplings in a model independent way by means of the effective Lagrangian approach in the $pp \to p\gamma\gamma p \to p\bar{t}qp$ process. The bounds on $\kappa_{tu\gamma}$ and $\kappa_{tq\gamma}$ severely depend on values of the integrated luminosity and forward detector acceptance. Our limits on the anomalous $\kappa_{tu\gamma}$ and $\kappa_{tq\gamma}$ couplings are better than the bounds from experimental constraints at the CDF and ZEUS collaborations. On the other hand, we can see for forward detector acceptance of 0.0015<ξ<0.5 that our sensitivities on $\kappa_{tq\gamma}$ can set more stringent sensitive by one order of magnitude with respect to the best sensitivity derived at the CMS. For acceptances 0.0015<ξ<0.15 and 0.1<ξ<0.5 we observed that the best sensitivities obtained on anomalous couplings at the same order with those reported from the current experimental bounds. As a result, the LHC provides us an important opportunity to investigate the anomalous interactions of top quark as photon collider.

REFERENCES

1. F. Abe et al., CDF collobaration, Phys. Rev. Lett. 73, (1994) 225.
2. ATLAS Collaboration, Phys. Lett. B 707 (2012) 459.
3. CMS Collaboration, Phys. Rev. D 84 (2011) 092004.
4. T. Aaltonen, et al., Phys. Rev. Lett. 103 (2009) 092002.
5. D0 Collaboration, Phys. Lett. B 705 (2011) 313.
6. CMS Collaboration, Phys. Rev. Lett. 107 (2011) 091802.

7. S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2 (1970) 1285.
8. T. P. Cheng and M. Sher, Phys. Rev. D 35 (1987) 3484.
9. B. Grzadkowski, J. F. Gunion, and P. Krawczyk, Phys. Lett. B 268 (1991) 106.
10. I.Baum, G. Eilam and S.Bar-Shalom, Phys. Rev. D 77 (2008) 113008.
11. M. E. Luke and M. J. Savage, Phys. Lett. B 307 (1993) 387.
12. D. Atwood, L. Reina, and A. Soni, Phys. Rev. D 53 (1996) 1199.
13. D. Atwood, L. Reina, and A. Soni, Phys. Rev. D 55 (1997) 3156.
14. S. Bejar, J. Guasch, and J. Sola, Nucl. Phys. B 600 (2001) 21.
15. S. Fajfer, and J. F. Kamenik, JHEP 0712 (2007) 074.
16. H. H. Sheng, Phys. Rev. D 75 (2007) 094010.
17. J. A. Aguilar-Saavedra and B. M. Nobre, Phys. Lett. B 553 (2003) 251.
18. F. del Aguila, J. A. Aguilar-Saavedra, and R. Miquel, Phys. Rev. Lett. 82 (1999) 1628.
19. J. A. Aguilar-Saavedra, Phys. Rev. D 67 (2003) 035003. Erratum-ibid. D 69 (2004) 099901.
20. J. M. Yang, B.-L. Young, and X. Zhang, Phys. Rev. D 58 (1998) 055001.
21. J. J. Cao et al., Phys. Rev. D 79 (2009) 054003.
22. C. S. Li, R. J. Oakes, and J. M. Yang, Phys. Rev. D 49 (1994) 293. Erratumibid. D56:3156,1997.
23. G. M. de Divitiis, R. Petronzio, and L. Silvestrini, Nucl. Phys. B 504 (1997) 45.
24. J. L. Lopez, D. V. Nanopoulos and R. Rangarajan, Phys. Rev. D 56 (1997) 3100.
25. J. Guasch and J. Sola, Nucl. Phys. B562 (1999) 3.
26. D. Delepine and S. Khalil, Phys. Lett. B 599 (2004) 62.
27. J. J. Liu, C. S. Li, L. L. Yang, and L. G. Jin, Phys. Lett. B 599 (2004) 92.
28. J. J. Cao et al., Phys. Rev. D 75 (2007) 075021.
29. G. P. K. Agashe and A. Soni, Phys. Rev.D 71 (2005) 016002.
30. G. P. K. Agashe and A. Soni, Phys. Rev. D 75 (2007) 015002.
31. G. A. Gonzalez-Sprinberg, R. Martinez and J. A. Rodriguez, Eur.Phys.J. C 51 (2007) 919-926.
32. G. Lu, F. Yin, X. Wang, and L. Wan, Phys. Rev. D 68 (2003) 015002.
33. J. J. Cao et al., Phys. Rev. D 76 (2007) 014004.
34. H.-J. Zhang, Phys. Rev. D 77 (2008) 057501.
35. T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 102, (2009) 151801.
36. F. Abe et al., CDF Collaboration, Phys. Rev. Lett. 80 (1998) 2525.
37. CMS Collaboration, CMS-PAS-TOP-14-003.
38. M. Abazov et al., D0 Collaboration, Phys. Lett. B 701 (2011) 313.
39. T. Aaltonen et al., CDF Collaboration, Phys. Rev. Lett. 101, (2009) 192002.
40. Heister et al., ALEPH Collaboration, Phys. Lett. B 543 (2002) 173.
41. J. Abdallah et al., DELPHI Collaboration, Phys. Lett. B 590 (2004) 21.
42. G. Abbiendi et al., OPAL Collaboration, Phys. Lett. B 521 (2001) 181.
43. P. Achard et al., L3 Collaboration, Phys. Lett. B 549 (2002) 290.

44. The LEP Exotica WG, LEP Exotica WG 2001-01.
45. ATLAS Collaboration, Phys. Lett. B 712 (2012) 351.
46. ATLAS Collaboration, arXiv:1206.0257.
47. G. Aad et al., ATLAS Collaboration, JHEP 1209, (2012) 139.
48. CMS Collaboration, Phys. Lett. B 718 (2013) 1252.
49. Abe F. et al. [CDF Collaboration], Phys. Rev. Lett. 80 2525-2530 (1998).
50. Carvalho J. et al. [ATLAS Collaboration], Eur. Phys. J. C 52 999-1019 (2007).
51. Royon C. et al. (RP220 Collaboration), arXiv:0706.1796 [hep-ex].
52. Albrow M.G. et al. (FP420 R and D Collaboration), JINST 4 T10001 (2009), arXiv:0806.0302 [hep-ex].
53. Avati V. and Osterberg K., Report No. CERN-TOTEM-NOTE-2005-002, 2006.
54. Kepka O. and Royon C. Phys. Rev. D 78 073005 (2008).
55. Aaltonen T. et al. (CDF Collaboration), Phys. Rev. Lett. 99 242002 (2007).
56. Aaltonen T. et al. (CDF Run II Collaboration), Phys. Rev. D 77 052004 (2008).
57. Aaltonen T. et al. (CDF Collaboration), Phys. Rev. Lett. 102 242001 (2009).
58. Abulencia A. et al. (CDF Collaboration), Phys. Rev. Lett. 98 112001 (2007).
59. Aaltonen T. et al. (CDF Collaboration), Phys. Rev. Lett. 102 222002 (2009).
60. Lietti S. M., Natale A. A., Roldao C. G. and Rosenfeld R., Phys. Lett. B 497 (2001) 243.
61. Piotrzkowski K., Phys. Rev. D 63 071502(R) (2001).
62. Khoze V. A., Martin A. D., Orava R. and Ryskin M. G., Eur. Phys. J. C 19 313 (2001).
63. Kepka O. and Royon C., Phys. Rev. D 78 073005 (2008).
64. Chapon E., Royon C. and Kepka O., Phys. Rev. D 81 (2010) 074003.
65. Atag S., I_nan S. C. and S_ahin I., Phys. Rev. D 80 (2009) 075009.
66. S_ah_n _I. and _Inan S. C., JHEP 09 (2009) 069.
67. Atag S., _Inan S. C. and S_ahin _I., JHEP 09 (2010) 042.
68. Inan S. C., Phys. Rev. D 81 (2010) 115002.
69. Atag S. and Billur A. A., JHEP 11 (2010) 060.
70. Şahin İ. and Billur A. A., Phys. Rev. D 83 (2011) 035011.
71. Şahin İ Phys. Rev. D 85 (2012) 033002.
72. Şahin İ. and S_ahin B., Phys. Rev. D 86 (2012) 115001.
73. Şahin İ and K• oksal M., JHEP 03 (2011) 100.
74. Aktas A. et al., Phys. Lett. B 583 (2004) 428.
75. Aktas A. et al., Eur. Phys. J. C 31 (2003) 17.
76. Aaron F. D. et al., Eur. Phys. J. C 71 (2011) 1578.
77. ZEUS Collaboration, Phys. Lett. B, 708 (2012) 27-36.
78. T. Han and J.L. Hewett, Phys. Rev. D 60 (1999) 074015.
79. Li X.-Q. et al., JHEP 1108 (2011) 075.

80. Ashimova A. A. and Slabospitsky S. R., Phys. Lett. B 668 (2008) 282285.
81. Etesami S. M. and Najafabadi M. M., Phys. Rev. D 81 (2010) 117502.
82. Çakir O. et al., Eur. Phys. J. C 70 (2010) 295-303.
83. Çakir O. J. Phys. G, 29 (2003) 1181-1192.
84. Çakir I. T. et al., Phys. Lett. B 685 (2010) 170-173.
85. Liao Q.-L. et al., arxiv: 1304.1303.
86. Coimbra R. et al., Eur.Phys.J. C 72 (2012) 2222.
87. Li X.-Q. et al., JHEP 1203 (2012) 018.
88. Zhang Y. et al., Phys.Rev. D 83 (2011) 094003.
89. Zhang Y. et al., Phys. Rev. Lett. 102 (2009) 072001.
90. Najafabadi M. M. and Tazik N. Commun. Theor. Phys. 52 (2009) 662-664.
91. Larios F. et al., Phys.Rev. D 72 (2005) 057504.
92. Kidonakis N. and Belyaev A., JHEP 0312 (2003) 004.
93. Cordero-Cid A. et al., Phys.Rev. D 70 (2004) 074003.
94. Khoze V. A., Martin A. D. and Ryskin M. G., Eur.Phys. J. C 23 (2002) 311.
95. Kepka O. and Royon C., Phys. Rev. D 78 (2008) 073005.
96. Favereau de Jeneret J. de, Lemaitre V., Liu Y., Ovyn S., Pierzchala T., Piotrzkowski K., X. Rouby, N. Schul and M. Vander Donckt, arXiv:0908.2020 [hep-ph].
97. Pierzchala T. and Piotrzkowski K., Nucl. Phys. Proc. Suppl. 179-180 (2008) 257.