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Search for $ZZ\gamma$ and $Z\gamma\gamma$ couplings at the LHC

İ. Şahin [1,*], A.A.Billur[2]

[1] *Department of Physics, Bulent Ecevit University, 67100 Zonguldak, Turkey*
[2] *Department of Physics, Cumhuriyet University, 58140 Sivas, Turkey*

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Abstract. We study the possibility for the process $pp \to p\gamma p \to pZqX$ with anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings in a model independent effective Lagrangian approach at the LHC. We find 95% confidence level bounds on the h_i^V ($i = 1, ..4$, $V = Z, \gamma$) anomalous coupling parameters for two detector acceptances $0.0015 < \xi < 0.15$, $0.0015 < \xi < 0.5$ and various values of the integrated luminosity at the $\sqrt{s} = 14$ TeV. It is shown that the reaction $pp \to p\gamma p \to pZqX$ can improve the sensitivity limits on the couplings compared to results of LEP, Tevatron and current CMS limits.

1. INTRODUCTION

Electroweak interactions are understood very well in standard model (SM) and this model has been so far quite successful below the electroweak scale with high precision. Although the vector boson self-interactions are fully described by the $SU_L(2) \times U_Y(1)$ gauge theory structure of the SM, self coupling of the Z boson and the photon at the tree level is forbidden due to lack of the electric charge of the Z boson. Neutral gauge boson self-couplings are permitted with loop diagrams in the SM but this corrections are below the current experimental sensitivity. The $ZZ\gamma$ and $Z\gamma\gamma$ couplings of the neutral bosons could not be obtained with a good precision up to now. Therefore trilinear couplings of gauge bosons are extremely important to test the standard model.

The terms of effective Lagrangian can be obtained from the high energy theory and parametrize all possible effects at low energies. The vertex function derived from the effective Lagragian can be written as [1,2,3],

$$\begin{aligned} ig_e\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, P) = ig_e\frac{p_V^2 - m_V^2}{m_Z^2}\{h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \\ \frac{h_2^V}{m_Z^2}P^\alpha(P.q_2 g^{\mu\beta} - q_2^\mu P^\beta) \\ +h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} + \\ \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\} \end{aligned} \tag{1.1}$$

* Corresponding author. Email addresses: inancsahin@karaelmas.edu.tr, abillur@cumhuriyet.edu.tr

Table 1: 95% C.L. experimental sensitivity bounds of the trilinear couplings h_3^V and h_4^V $(V = Z, \gamma)$. For LEP we showed all combined data from ALEPH, OPAL, L3, DELPHI collaborations.

	$h_3^\gamma(\times 10^{-3})$	$h_4^\gamma(\times 10^{-4})$	$h_3^Z(\times 10^{-3})$	$h_4^Z(\times 10^{-4})$
D0	-1.4;1.4	-0.26;0.26	-1.3;1.3	-0.24;0.24
CDF	-22;22	-9 ;9	-22;22	-9;9
LEP	-49;-8	-20;340	-200;70	-500;1200
CMS	-70;70	-5 ;6	-50;60	-5;5

where m_Z is the Z boson mass and $g_e = \sqrt{4\pi\alpha_e}$, h_1^V, h_2^V $(V = Z, \gamma)$ are dimension-six and dimension-eight CP violating couplings, h_3^V, h_4^V are dimension-six and dimension-eight CP conserving couplings respectively. All couplings h_i^V vanish in the SM at the tree level. $ZZ\gamma$ and $Z\gamma\gamma$ couplings go to zero according to tree level unitarity condition at high energies. Due to this condition these couplings can be defined as form factors below:

$$h_i(\hat{s}) = \frac{h_{i0}^V}{\left(1 + \dfrac{\hat{s}}{\Lambda^2}\right)^n} \tag{1.2}$$

where for $i = 1, 3$; n is 3 and $i = 2, 4$; n is 4. In this paper we assume that new physics scale Λ is much bigger than the center of mass energy thefore we ignore the energy dependence of the anomalous couplings and all other couplings of the SM particles have been assumed to be valid. The $Z\gamma\gamma$ vertex is vanish if the two photons are on the mass shell due to the Yang's theorem [4]. Anomalous couplings $ZZ\gamma$ and $Z\gamma\gamma$ have been discussed in the literature previously [5-14].

Experimental results on the couplings h_3^V, h_4^V $(V = \gamma, Z)$ from different colliders have shown in Table 1. [15-18]. There are bounds come from two colliders for CP violating couplings $h_{1,2}^V$. The first one is from LEP combined results $-0.13 < h_1^Z < 0.13$, $-0.078 < h_2^Z < 0.071$, $-0.056 < h_1^\gamma < 0.055$, $-0.045 < h_2^\gamma < 0.025$ [18] and second one is from D0 collaboration $|h_1^\gamma| < 1,20.10^{-3}$, $|h_2^\gamma| < 2.4.10^{-5}$, $|h_1^Z| < 1,17.10^{-3}$ and $|h_2^Z| < 2.4.10^{-5}$ [19]. In Table 1 it was seen that D0 collaboration has the best limits on anomalous couplings because of they used collected data between 2002 and 2010 and we have taken the most stringent limits of these.

Photon induced reactions with photon-photon and photon-proton collisions have cleaner final states than the processes involving strong interactions. These type of collisions could be investigated at various colliders. To give a few examples of, $p\bar{p} \to p\gamma\gamma\bar{p} \to pe^+e^-\bar{p}$ [20-22], $p\bar{p} \to p\gamma\gamma\bar{p} \to p\mu^+\mu^-\bar{p}$ [23-28] by CDF collaboration at the Tevatron, $ep \to epX$ in ep collisions, pair production in relativistic heavy ion collisions [29-32], $pp \to p + e^+e^-p$ exclusive production at CMS at $\sqrt{s} = 7$ TeV [33]. Experimental results show that, LHC can be considered as in additon to proton-proton collider, photon-photon and photon-proton collider. Up to now, photon-induced reactions have been studied phenomenologically at the LHC with different models [34-48].

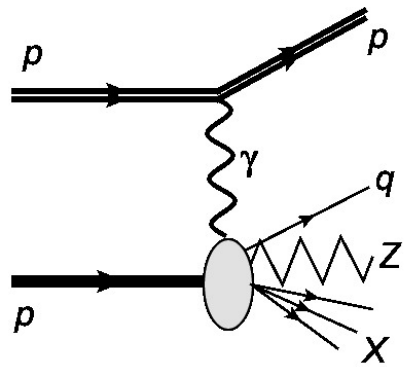

Figure 1: Schematic diagram for the reaction $pp \to p\gamma p \to pZqX$.

2. γp collision at the LHC

The quasi-real photon which is emitted by the intact proton can collide other proton through deep inelastic scattering and produce a final state of ZqX (Fig.1). The realised photon spectrum can be identified by the equivalent photon spectrum (EPA). In this case protons remain intact and their momenta can be measured experimentally by means of forward detectors probing with the central detectors. The proton, which transferred its energy to the photon, escapes from the central detectors. Quasi-real photon is scattered with small angles from the beam pipe therefore transverse momentum of the quasi-real photon is very small. This process is useful in photon-induced reactions due to the restoring the kinematics of the initial state. There are plans for forward detectors at 220 m and 420 m from the interaction point made by ATLAS and CMS collaborations. Intact protons can be detected with the energy fraction loss $\xi = E_{loss}/E_{beam}$ by the forward detectors. ATLAS Forward Physics (AFP) and CMS collaborations envisaged that $0.0015 < \xi < 0.15$ range for the energy fraction loss experimentally [49,50], CMS-TOTEM collaboration has $0.0015 < \xi < 0.5$ forward detector scenerio [51,52]. Forward detectors to be closer to the interaction point provides higher ξ. Soft and hard diffraction, low-x dynamics, high energy photon-induced reactions, large rapdity gaps between forward jets, and luminosity monitoring are the examples of topics which are aimed to explore at the forward detectors that are planned to built in the near future [53-69].

Equivalent photon spectrum of virtuality Q^2 and photon energy E_γ quasi-real photons $Q^2/E_\gamma^2\ ll1$ is given by the following formula [70-72];

$$\frac{dN_\gamma}{dE_\gamma dQ^2} = \frac{\alpha}{\pi}\frac{1}{E_\gamma Q^2}[(1-\frac{E_\gamma}{E})(1-\frac{Q^2_{min}}{Q^2})F_E + \frac{E_\gamma^2}{2E^2}F_M] \tag{2.1}$$

where

$$Q^2_{min} = \frac{m_p^2 E_\gamma^2}{E(E-E_\gamma)}, \quad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2} \tag{2.2}$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = (1+\frac{Q^2}{Q_0^2})^{-4}, \quad F_M = G_M^2, \quad Q_0^2 = 0.71\text{GeV}^2 \tag{2.3}$$

here E is the energy of proton beam and m_p is mass of the proton, F_E, F_M are electromagnetic moments which makes proton different from the pointlike particle and $\mu_p^2 = 7.78$ is magnetic moment of the proton. If we integrate this spectrum over Q^2 we obtain;

$$dN(E_\gamma) = \frac{\alpha}{\pi}\frac{dE_\gamma}{E_\gamma}\left(1-\frac{E_\gamma}{E}\right)\left[\varphi\left(\frac{Q^2_{max}}{Q^2_0}\right)-\varphi\left(\frac{Q^2_{min}}{Q^2_0}\right)\right] \tag{2.4}$$

here the function φ is defined as follows

$$\varphi(x) = (1+ay)\left[-ln(1+x^{-1})+\sum_{k=1}^{3}\frac{1}{k(1+x)^k})\right]+\frac{(1-b)y}{4x(1+x)^3}+c\left(1+\frac{y}{4}\right) \times\left[ln\frac{1+x-b}{1+x}+\sum_{k=1}^{3}\frac{b^k}{k(1+x)^k}\right] \tag{2.5}$$

where

$$y = \frac{E_\gamma^2}{E(E-E_\gamma)}, \quad a = \frac{1}{4}(1+\mu_p^2)+\frac{4m_p^2}{Q_0^2} \approx 7.16$$

$$b = 1-\frac{4m_p^2}{Q_0^2} \approx -3.96, \quad c = \frac{\mu_p^2-1}{b^4} \approx 0.028. \tag{2.6}$$

The contribution to the integral above the $Q^2_{max} = 2$ GeV ^{2} is negligible therefore we take this value during the calculations.

3. Details of the Calculation of Sensitivity limits

There are four tree level Feynman diagrams including Standard Model and anomalous couplings of the neutral gauge bosons for the subprocess $\gamma q \to Zq$ (Fig.2). Due to the internal structure of the proton different subprocesses can be considered in γp collision. In this work we have taken into account 10 different subprocesses;

$$\begin{array}{ll} \text{(i)}\ \gamma u \to Zu & \text{(vi)}\ \gamma\bar{u} \to Z\bar{u} \\ \text{(ii)}\ \gamma d \to Zd & \text{(vii)}\ \gamma\bar{d} \to Z\bar{d} \\ \text{(iii)}\ \gamma s \to Zs & \text{(viii)}\ \gamma\bar{s} \to Z\bar{s} \\ \text{(iv)}\ \gamma c \to Zc & \text{(ix)}\ \gamma\bar{c} \to Z\bar{c} \\ \text{(v)}\ \gamma b \to Zb & \text{(x)}\ \gamma\bar{b} \to Z\bar{b} \end{array} \tag{3.1}$$

The total cross section for the process $pp \to p\gamma p \to pZq(\bar{q})X$ can be obtained by integrating the cross section for the subprocesses over the photon and quark distributions:

$$\sigma\left(pp \to p\gamma p \to pZq(\bar{q})X\right) = \int_{\xi_{1\ min}}^{\xi_{1\ max}} dx_1 \int_0^1 dx_2 \left(\frac{dN_\gamma}{dx_1}\right)\left(\frac{dN_{q(\bar{q})}}{dx_2}\right) \left[\hat{\sigma}_{\gamma q(\bar{q})\to Zq(\bar{q})}(\hat{s})\right] \tag{3.2}$$

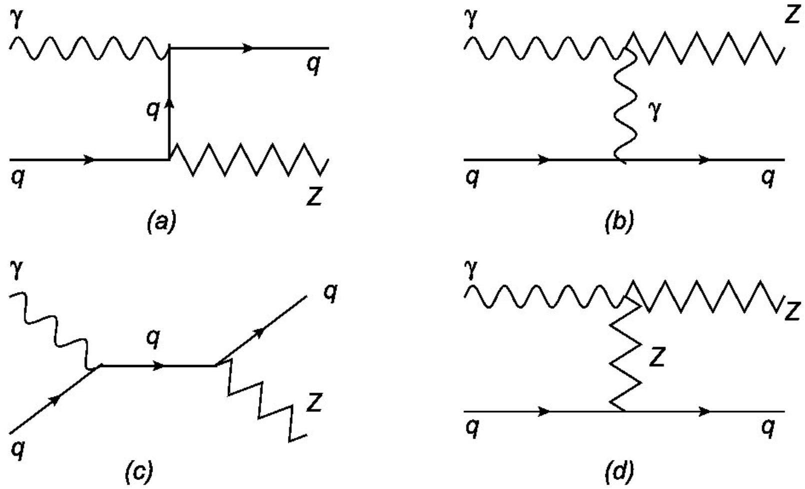

Figure 2: Tree level Feynman diagrams for the reaction $\gamma q \to Zq$.

In this formula, $\frac{dN_{q(\bar{q})}}{dx_2}$ is the quark (anti-quark) distribution function and during the total cross section calculations we have used Martin, Stirling, Thorne and Watt distribution functions [73].

One-parameter χ^2 analysis was used for the calculation of the sensitivity limits of the anomalous couplings. χ^2 function can be defined as;

$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma(h_i^Z, h_i^\gamma)}{\sigma_{SM}\ \delta} \right)^2 \tag{3.3}$$

where $i = 1, 2, 3, 4$ and $\delta = \frac{1}{\sqrt{N}}$ is the statistical error. The expected number of events can be calculated as N =S$\times\sigma_{SM} \times L_{int} \times$ BR$(Z \to l\bar{l})$ where $l = e$ or μ and for the S is the survival probability and we have considered 0.7 [74,75]. For the leptonic decay channel of the Z boson we have BR$(Z \to l\bar{l})$=$\Gamma(Z \to l\bar{l})/\Gamma_{total}$. In our calculations we discussed only electrons and muons for the final state leptons. ATLAS and CMS detector pseudorapidity parameter $|\eta| < 2.5$ are taken into consideration for final state leptons and quarks.

From Fig.3 to Fig.10 we have depicted that the limits for the anomalous couplings for the two detector acceptances $0.0015 < \xi < 0.15$ and $0.0015 < \xi < 0.5$ versus the integrated luminosity. As expected, limits on anomalous couplings are narrowing with the increasing integrated luminosity values. It can be seen from figures anomalous couplings h_2^V and h_4^V are more sensitive than h_1^V and h_3^V $(V = \gamma, Z)$ due to the h_2^V and h_4^V coulings are dimension eight operators and the h_1^V, h_3^V are dimension six operators. Our limits in $0.0015 < \xi < 0.5$ detector acceptance region with 200 fb^{-1} luminosity on h_2^Z is almost six times and on h_2^γ is five times better than D0 limits. In addition h_4^γ and h_4^Z limits are approximately six times better than D0 limits. Limits on h_1^V and h_3^V are slightly worse than D0 due to the energy dependence of these couplings are weaker than the others. The region $0.0015 < \xi < 0.15$ has more narrow energy range than the $0.0015 < \xi < 0.5$ and therefore the our limits on the anomalous couplings are worse than the limits in the $0.0015 < \xi < 0.5$ case.

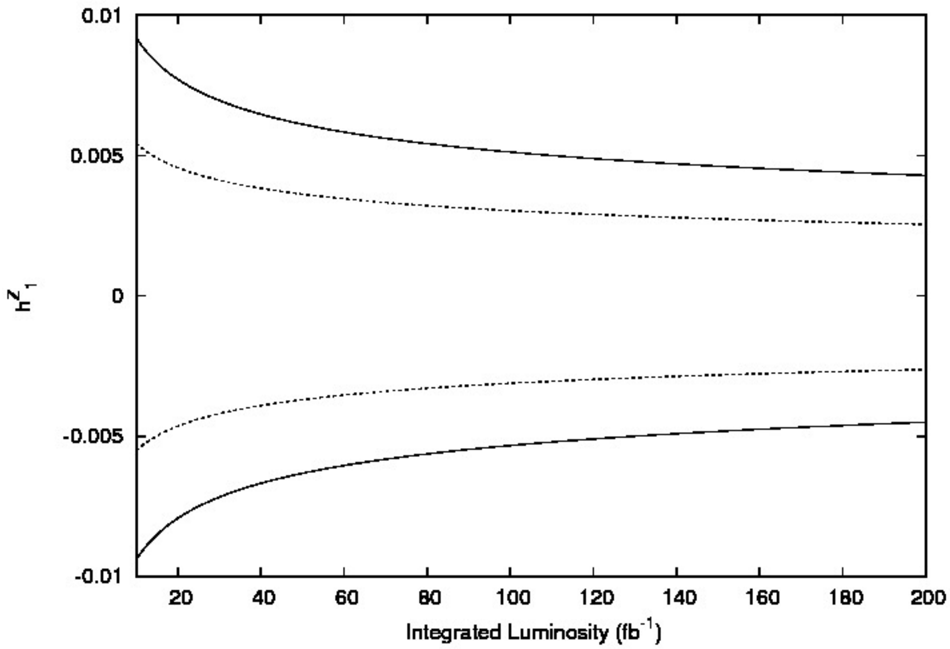

Figure 3: Ninety-five percent C.L. sensitivity bounds of the coupling h_1^Z for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

4. Conclusions

Photon-induced reactions which have been planned by the ATLAS and CMS collaborations give us a chance to examine new interactions at the LHC. In this paper anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings have been investigated in γp collision. The Zq production can be occured via the $pp \to p\gamma p \to pZqX$ reaction at the LHC and we have considered Z bosons decay only electrons and muons. Our limits on the couplings h_2^V, h_4^V are much better and h_1^V, h_3^V are slightly worse than current experimental limits.

From the figures Fig.3-Fig.5 and Fig.4-Fig.6 we observe that limits on the anomalous couplings h_1^Z-h_3^Z and h_2^Z-h_4^Z are almost same due to the cross sections of the subprocesses depending on these couplings. In these amplitudes of the cross sections only cross-terms of the anomalous couplings are different and these terms give small contibution to the process. The similar argument can be made for the h_1^γ-h_3^γ and h_2^γ-h_4^γ couplings from the figures Fig.7-Fig.9 and Fig.8-Fig.10.

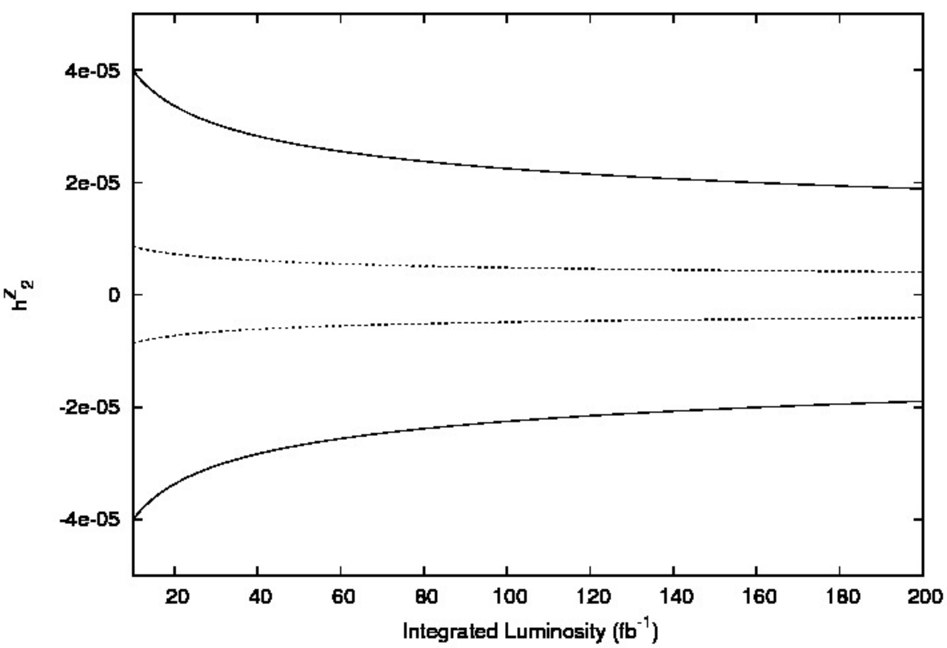

Figure 4: Ninety-five percent C.L. sensitivity bounds of the coupling h_2^Z for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

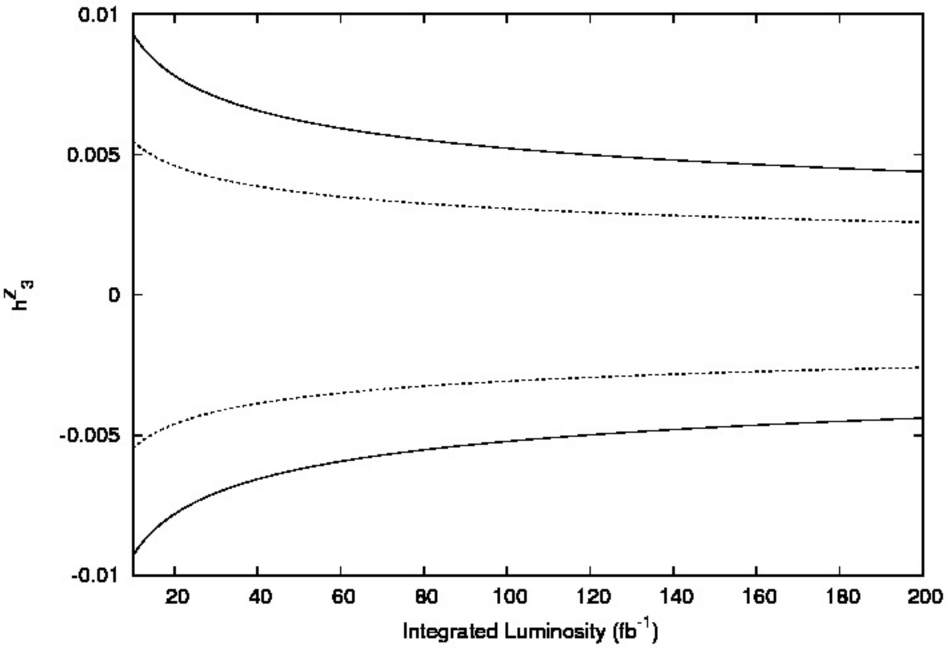

Figure 5: Ninety-five percent C.L. sensitivity bounds of the coupling h_3^Z for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

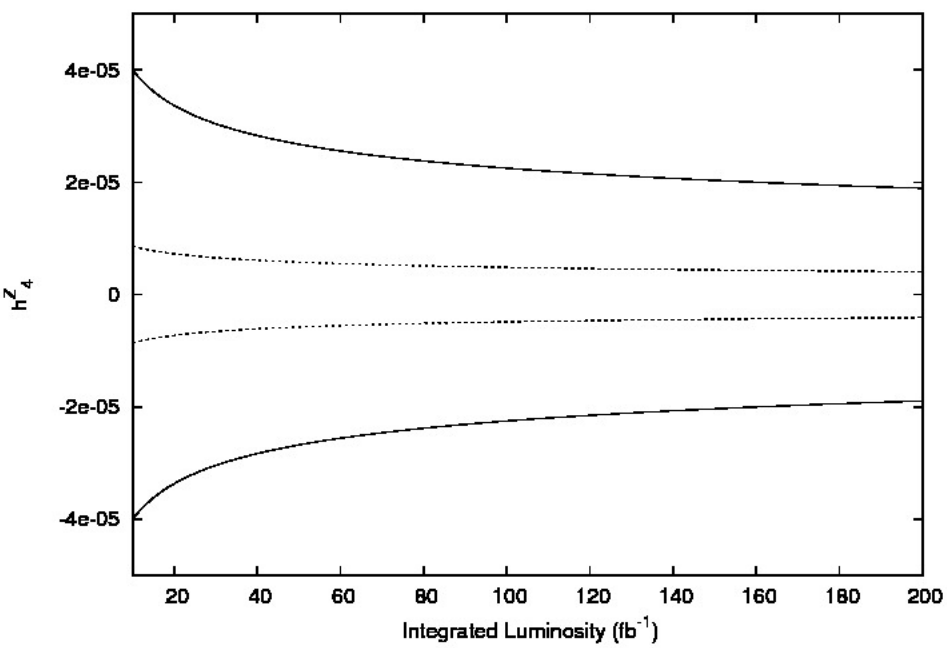

Figure 6: Ninety-five percent C.L. sensitivity bounds of the coupling h_4^Z for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

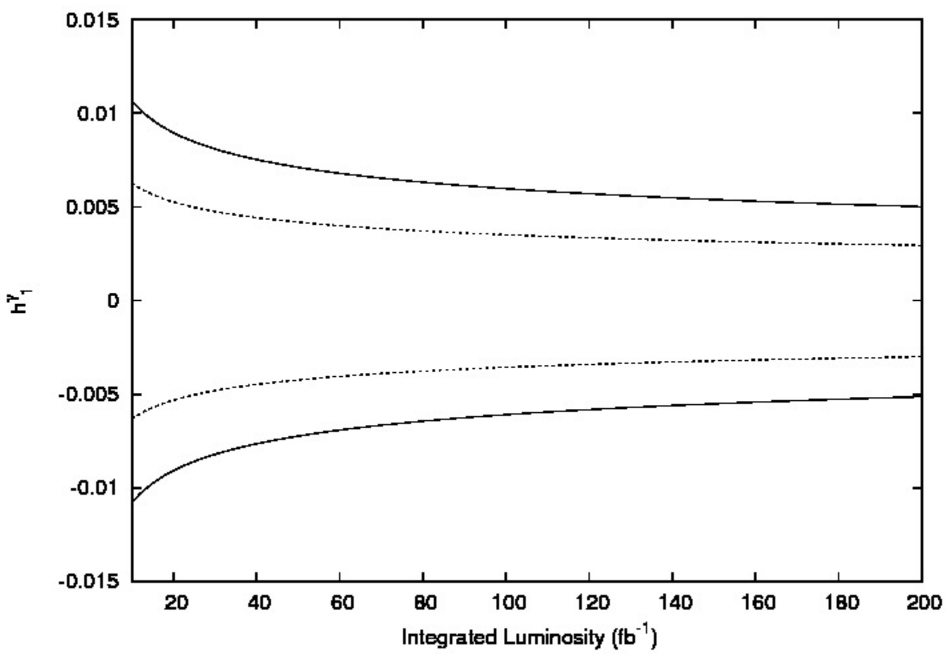

Figure 7: Ninety-five percent C.L. sensitivity bounds of the coupling h_1^γ for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

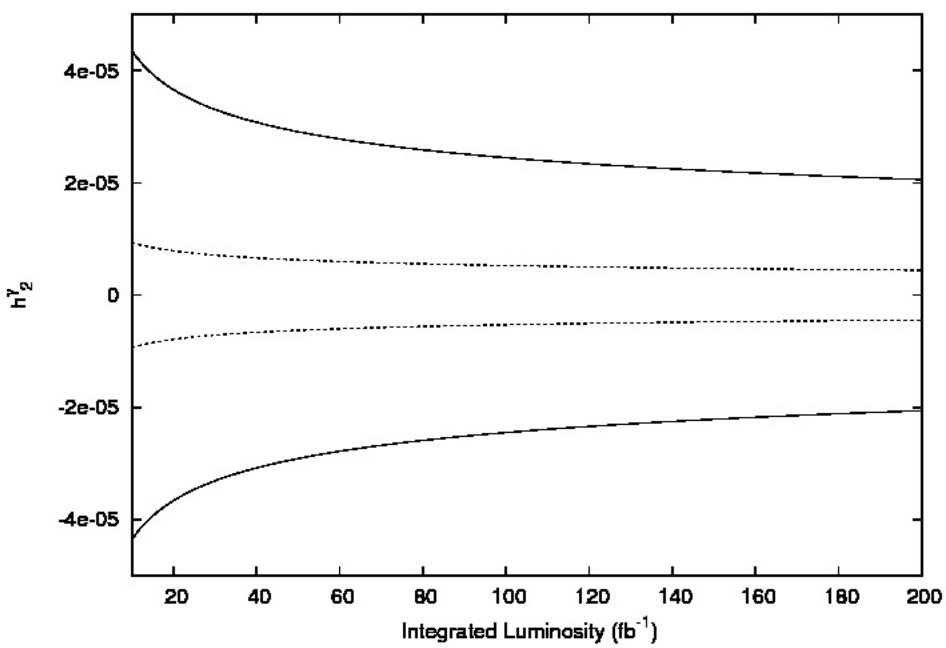

Figure 8: Ninety-five percent C.L. sensitivity bounds of the coupling h_2^γ for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

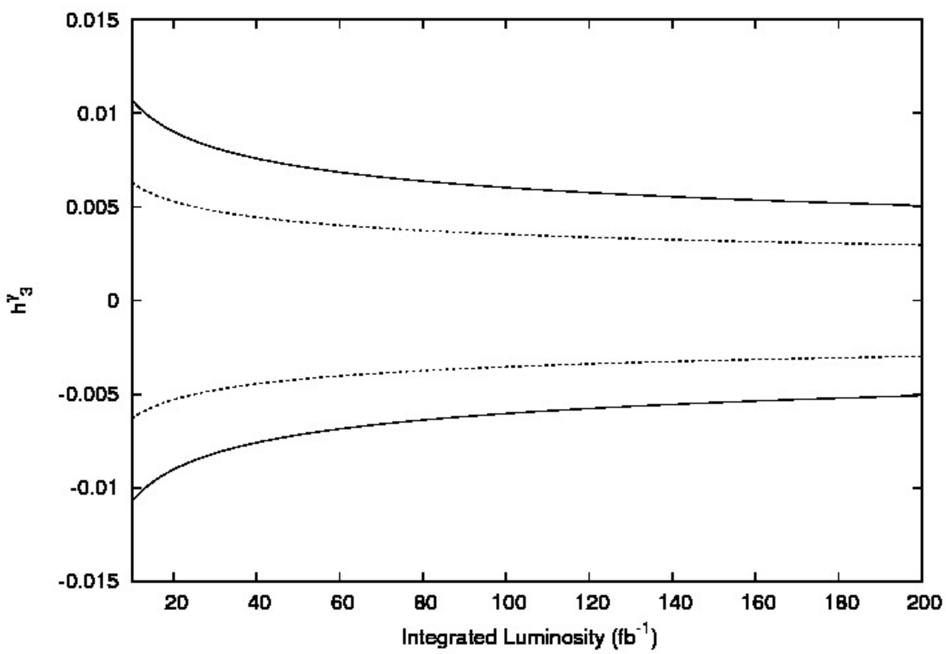

Figure 9: Ninety-five percent C.L. sensitivity bounds of the coupling h_3^γ for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

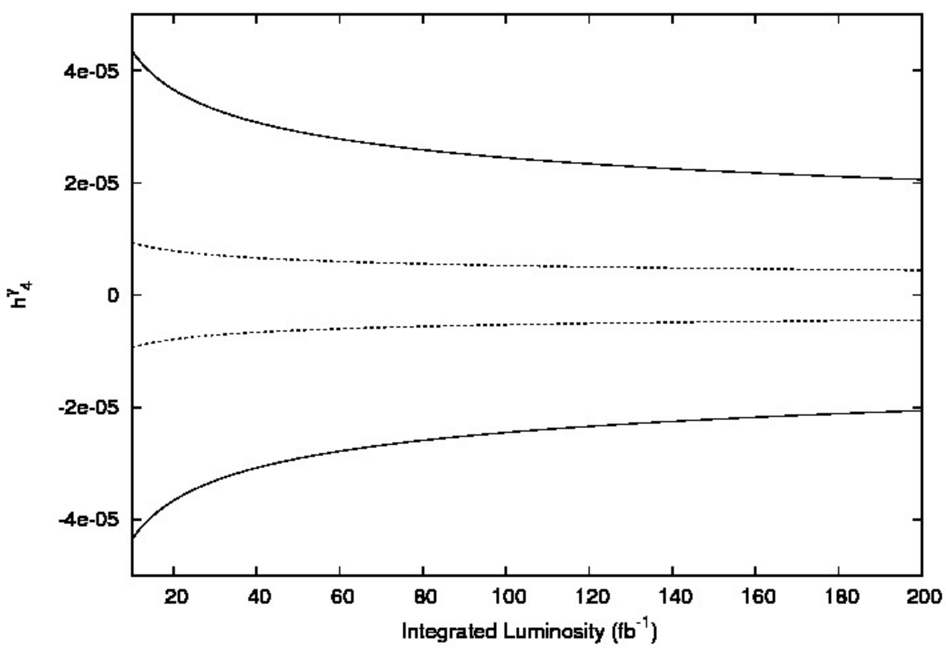

Figure 10: Ninety-five percent C.L. sensitivity bounds of the coupling h_4^γ for $0.0015 < \xi < 0.5$ (dashed curves) and $0.0015 < \xi < 0.15$ (solid curves) forward detector acceptances as a function of the intagrated LHC luminosities. The center-of-mass energy of the proton-proton system is taken to be $\sqrt{s} = 14$ TeV.

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