Bounds on the $Z\gamma Z$ anomalous couplings from radiative ep scattering at the Very Large Hadron Collider

Y. A. Coutinho,* A. J. Ramalho,† R. Walsh,‡ and S. Wulck§
Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil
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We analyze the prospects of probing anomalous $Z\gamma Z$ couplings at the proposed ep mode of the Very Large Hadron Collider (VLHC), by means of the process $e^- + p \rightarrow e^- + \gamma + X$. The 95% C.L. limits for the form factors that describe the $Z\gamma Z$ vertex are calculated for the ep collider of the VLHC, both in its low- and high-field options, and for the current energies and luminosities of the DESY HERA ep collider. The sensitivity of the VLHC ep collider to the form factor scale Λ is briefly discussed.

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I. INTRODUCTION

The interactions among vector gauge bosons continue to attract the attention of both theorists and experimentalists. In the standard model these interactions are determined by an underlying non-Abelian gauge symmetry, and at the lowest order of perturbation theory are described by trilinear vertices. Experimental high energy physicists have searched [1] for signals of possible deviations of these couplings from the standard model structure, either in their form or strength. These nonstandard signals, if detected, would point to new physics. Anomalous vertices are an important ingredient in some extended models that allow for composite vector bosons or gauge vector bosons strongly interacting with each other [2]. Current experimental results are consistent with the standard model expectations, allowing that limits be set on the various parameters which characterize the anomalous interactions. However, experimental studies of the vector gauge boson self-interactions are at an early stage, especially those in which only neutral vector bosons are involved [3]. A considerable effort will be made to increase statistics and improve the sensitivity of the observables to the anomalous couplings at the energies of the next generation of colliders.

The Very Large Hadron Collider (VLHC) program [4] allows for two different ep collider designs: the low- and high-field options. In the low-field version ep collisions would be produced by an 80 GeV electron ring and a 3 TeV proton booster ($\sqrt{s}=1$ TeV), with a luminosity of 0.26 $(\text{nb s})^{-1}$, while in the high-field option one could reach a center-of-mass energy $\sqrt{s}=6.32$ TeV and a luminosity of 0.14 $(\text{nb s})^{-1}$ with the collision of a 200 GeV electron beam with a 50 TeV proton beam. This paper presents an analysis of the effects of anomalous $Z\gamma Z$ couplings in radiative ep scattering, considering these VLHC parameters and also those of the DESY ep collider HERA for comparison. For the sake of simplicity we ignore a possible $Z\gamma\gamma$ vertex. The analysis of the $Z\gamma\gamma$ vertex presented in Ref. [5] indicates that limits that can be set on the neutral gauge boson anomalous vertices at HERA are expected to be not very restrictive, even considering the planned upgrade of the machine.

II. $Z\gamma Z$ TRILINEAR GAUGE BOSON VERTEX

The most general trilinear $Z\gamma Z$ vertex, for an on-shell photon, consistent with Lorentz and gauge invariance, is described by four anomalous couplings h_i^Z $(i=1\ldots4)$:

$$V_{Z\gamma Z}^{\alpha\beta\mu}(k,p,q)=ie\frac{q^2-k^2}{M_Z^2}\Bigg\{h_1^Z(p^\mu g^{\alpha\beta}-p^\alpha g^{\mu\beta}) + \frac{h_2^Z}{M_Z^2}[q^\alpha(q\cdot p g^{\mu\beta}-p^\mu q^\beta) - k^\mu(k\cdot p g^{\alpha\beta}-p^\alpha k^\beta)]+h_3^Z(\varepsilon^{\mu\alpha\beta\rho}p_\rho) + \frac{h_4^Z}{M_Z^2}(\varepsilon^{\mu\beta\rho\sigma}q^\alpha q_\rho p_\sigma-\varepsilon^{\alpha\beta\rho\sigma}k^\mu k_\rho p_\sigma)\Bigg\}. \tag{1}$$

Terms proportional to k^α or q^μ are neglected since the two virtual Z bosons couple to massless fermions. Equation (1) is consistent with the results obtained in Ref. [6]. The index assignments and momentum flow are given in Fig. 1. h_1^Z and h_2^Z are P even and violate CP, whereas h_3^Z and h_4^Z conserve CP. In the standard model all four couplings h_i^Z vanish at tree level. In order to restore unitarity at high energies, the anomalous couplings must be taken as form factors $h_i^Z(k^2,q^2,p^2)$ that vanish as k^2, q^2 or p^2 become very large.

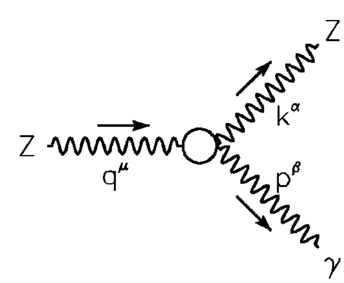

FIG. 1. Neutral boson trilinear vertex.

*Electronic address: yara@if.ufrj.br
†Electronic address: ramalho@if.ufrj.br
‡Electronic address: walsh@if.ufrj.br
§Electronic address: steniow@if.ufrj.br

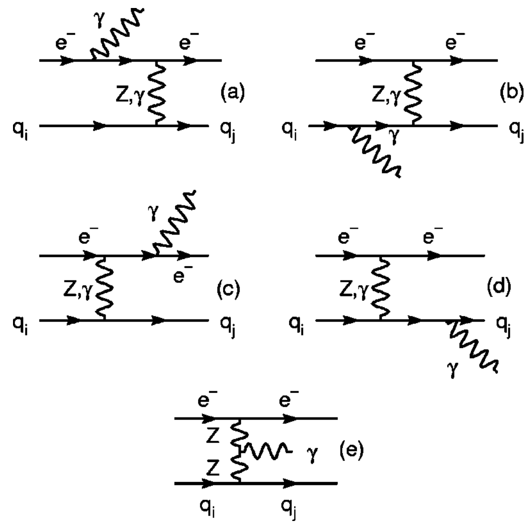

FIG. 2. Feynman diagrams for the parton subprocesses in radiative ep scattering.

For the process we are considering, with an on-shell photon in the final state, it suffices to model the form factors in a dipolelike form:

$$h_i^Z(q^2,k^2)=\frac{h_{i0}^Z}{\left(1-\dfrac{q^2+k^2}{\Lambda^2}\right)^n}, \quad i=1\ldots 4, \tag{2}$$

where h_{i0}^Z represent their values at low energies, and Λ is a large energy scale, around which new physics would become important. In this paper we take $n=2$ for $h_{1,3}^Z(k^2,q^2)$ and $n=3$ for $h_{2,4}^Z(k^2,q^2)$. With this dependence of the form factors $h_i^Z(q^2,k^2)$ on the invariants k^2 and q^2, the Bose symmetry of the two Z lines is manifest in each of the four terms of Eq. (1).

III. MONTE CARLO SIMULATION

At the parton level, radiative neutral current scattering $e^-+p\rightarrow e^-+\gamma+X$ proceeds via the Feynman diagrams (a)–(d) in Fig. 2. Diagram (e) accounts for the anomalous $Z\gamma Z$ interaction, and as such is not present in the standard model. The corresponding graphs with antiquarks replacing quarks were also taken into account in the simulation, but are not shown in Fig. 2. Because of the large number of Feynman diagrams, it is more convenient to write the associated helicity amplitudes in a form suitable for numerical evaluation. We only considered two quark families, setting all quark masses equal to zero throughout. CTEQ5M1 parton distribution functions [7] were used to calculate all cross sections, with the square of the center of mass energy for the parton subprocess chosen for evolution scale. The signal of interest consists of an electron, a photon and a jet produced by the scattered quark. No attempt was made to incorporate fragmentation and hadronization effects in the simulation, the jet was identified with the scattered quark itself. A $p_T>20$ GeV cut was imposed on the transverse momenta of the electron, photon and jet, along with angular cuts $|\cos\theta|<0.99$ on the angles of the photon and the electron with respect to the direction of the proton. These cuts hopefully simulate the acceptance of VLHC detectors, eliminating events in which the final-state particles would be lost in the beam pipe. In addition, we also imposed isolation cuts $R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}>0.5$ on the jet-photon and electron-photon separations in the pseudorapidity-azimuthal angle planes. These cuts insure that the photon is well separated from the electron and from the jet, and control collinear singularities.

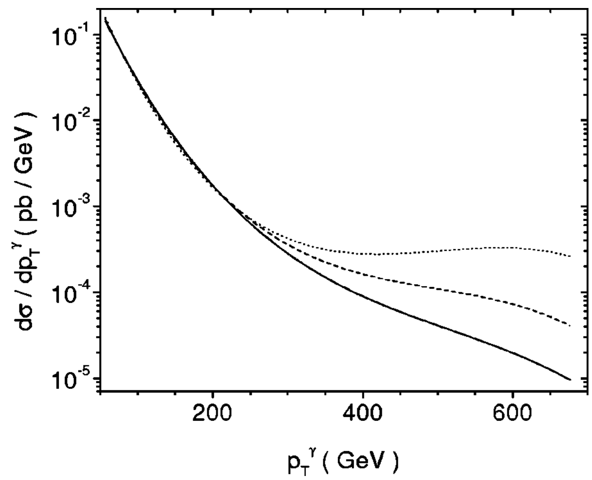

FIG. 3. Transverse momentum distribution for the photon, with an input scale $\Lambda=1$ TeV. The solid curve represents the standard model prediction, while the dashed and dotted lines correspond to the presence of anomalous couplings $h_{30}^Z=0.05$ and $h_{40}^Z=0.005$, respectively.

IV. DISTRIBUTIONS AND RESULTS

In order to determine the most sensitive observables to the presence of anomalous $Z\gamma Z$ couplings, we examined several one- and two-dimensional differential distributions, such as distributions in energy, transverse momentum, invariant masses, rapidity of the electron, photon or jet. The most sensitive distribution turned out to be the photon transverse momentum distribution $d\sigma/p_T^\gamma$. Figure 3 shows the photon transverse momentum spectrum for the standard model and for two values of the anomalous couplings. Photon emission from the massless fermion lines leads to infrared singularities in the cross section, which explain the strong peak at small values of p_T^γ. This photon radiation from fermion lines does not occur in the diagram with the $Z\gamma Z$ vertex, and no sensitivity is lost by imposing a $p_T^\gamma>20$ GeV cut on the photon transverse momentum. On the other hand, Fig. 3 shows that the presence of anomalous $Z\gamma Z$ couplings enhances the event rates at large values of p_T^γ. At HERA energies, only large values of the anomalous couplings can produce sizable deviations from the standard model p_T^γ spectrum, whereas in the environment of the VLHC, as higher values of transverse momentum become available for the photon, even small values of the anomalous couplings can lead to considerable deviations from the standard model rates.

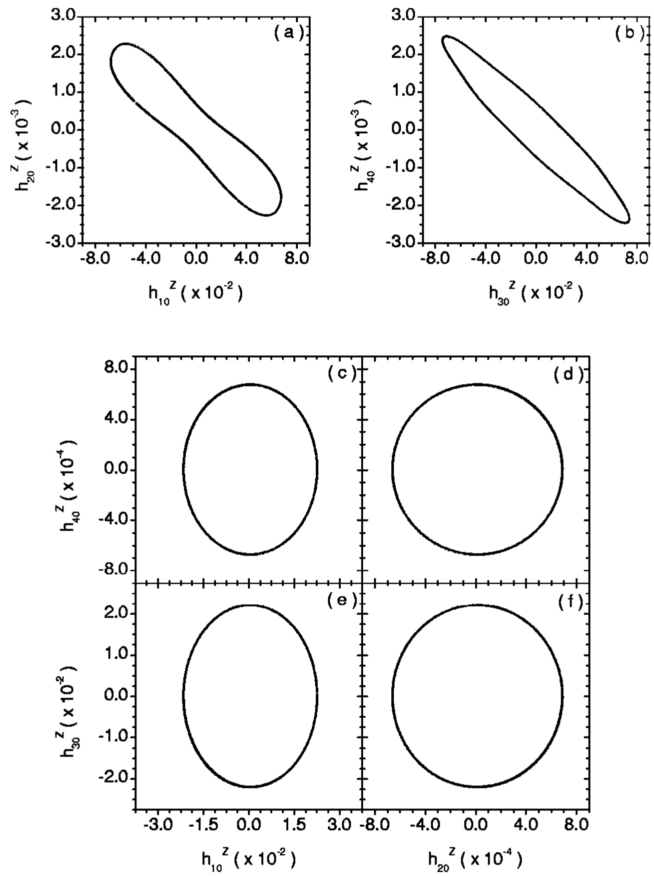

FIG. 4. 95% C.L. contours for each pair of form factor (h_{i0}^Z, h_{j0}^Z) ($i,j=1\ldots4$, $j>i$), for a form factor scale $\Lambda=1$ TeV.

Starting from the $d\sigma/dp_T^\gamma$ spectra, we performed a χ^2 analysis to determine the 95% confidence level limits for the h_{i0}^Z form factors. The p_T^γ kinematical range was divided into $n_B=5$ bins, and the χ^2 function was defined as

$$\chi^2=\sum_{i=1}^{n_B}\left(\frac{N_i^{SM}-N_i^{AN}}{\Delta N_i^{SM}}\right)^2, \tag{3}$$

where N_i^{SM} represents the number of events predicted by the standard model in the i^{th} bin, N_i^{AN} the number of events in the i^{th} bin considering anomalous couplings, and $\Delta N_i^{SM}=\sqrt{N_i^{SM}+(N_i^{SM}\delta)^2}$ the associated total error obtained by adding the statistical and systematic errors in quadrature. The numbers of events were calculated for an annual integrated luminosity of 4.42 fb^{-1} for the high-field ep collider and 8.20 fb^{-1} for the low-field option. The systematic error for a single measurement was taken to be $\delta=5\%$. Each form factor pair (h_{0i}^Z, h_{0j}^Z) was varied over a 81 point rectangular grid in the $h_{0i}^Z\times h_{0j}^Z$ plane ($i,j=1\ldots4$, $j>i$), while keeping all the remaining form factors equal to zero. The resulting 95% C.L. contour plots are displayed in Figs. 4(a)–4(f), for a form factor scale $\Lambda=1$ TeV. The corresponding correlated limits and correlation coefficients are given in Table I. Correlations are rather strong for pairs of form factors of the same CP parity. On the other hand, form factors of opposite CP parity are found to be nearly uncorrelated, suggesting that it may be possible to disentangle CP-conserving from CP-violating effects. We also calculated one-degree of freedom 95% C. L. limits for the form factors by varying one form factor at a time. These limits are listed in Table II. For the sake of comparison, we also show the corresponding bounds at HERA ($\sqrt{s}=314$ GeV, integrated luminosity of 200 pb^{-1}) and at the low-field version ep collider of the VLHC. Because of the different conventions adopted in the literature, it is not a simple matter to compare bounds on the $Z\gamma Z$ couplings obtained by the various sources. Generally speaking, experimental bounds on the form factors h_{i0}^Z obtained at the current energies and luminosities of the CERN e^+e^- collider LEP and Fermilab Tevatron are in the range 10^{-1}–10^{-2} [3]. Theoretical estimates for $Z\gamma Z$ anomalous couplings using Next Linear Collider (NLC) [8] and CERN Large Hadron Collider (LHC) [1] parameters point to limits of the order of 10^{-3}–10^{-4}.

TABLE I. Correlated 95% C.L. limits on the form factors pairs (h_{i0}^Z, h_{j0}^Z) ($i,j=1\ldots4, j>i$), for an input scale $\Lambda=1$ TeV, and corresponding correlation coefficients.

Parameter	Negative limit	Positive limit	Correlation coefficient
h_{10}^Z	-6.8×10^{-2}	$+6.8\times10^{-2}$	-0.88
h_{20}^Z	-2.3×10^{-3}	$+2.3\times10^{-3}$	
h_{30}^Z	-7.4×10^{-2}	$+7.4\times10^{-2}$	-0.95
h_{40}^Z	-2.5×10^{-3}	$+2.5\times10^{-3}$	
h_{10}^Z	-2.2×10^{-2}	$+2.3\times10^{-2}$	-4.4×10^{-3}
h_{30}^Z	-2.2×10^{-2}	$+2.2\times10^{-2}$	
h_{10}^Z	-2.2×10^{-2}	$+2.3\times10^{-2}$	-2.7×10^{-3}
h_{40}^Z	-6.8×10^{-4}	$+6.8\times10^{-4}$	
h_{20}^Z	-6.7×10^{-4}	$+6.9\times10^{-4}$	-4.4×10^{-3}
h_{30}^Z	-2.2×10^{-2}	$+2.2\times10^{-2}$	
h_{20}^Z	-6.6×10^{-4}	$+6.9\times10^{-4}$	-2.8×10^{-3}
h_{40}^Z	-6.8×10^{-4}	$+6.8\times10^{-4}$	

TABLE II. One-degree-of-freedom bounds on the form factors, for an input scale $\Lambda=1$ TeV. (a) and (b) give the predictions for the high-field and low-field modes of the VLHC ep collider, respectively, while (c) shows the predictions for the HERA collider.

	Parameter	Negative limit	Positive limit
(a)	h_{10}^Z	-1.9×10^{-2}	$+2.0\times10^{-2}$
	h_{20}^Z	-5.9×10^{-4}	$+6.2\times10^{-4}$
	h_{30}^Z	-2.0×10^{-2}	$+2.0\times10^{-2}$
	h_{40}^Z	-6.0×10^{-4}	$+6.1\times10^{-4}$
(b)	h_{10}^Z	-2.6×10^{-1}	$+2.7\times10^{-1}$
	h_{20}^Z	-3.2×10^{-2}	$+3.2\times10^{-2}$
	h_{30}^Z	-2.8×10^{-1}	$+2.8\times10^{-1}$
	h_{40}^Z	-3.2×10^{-2}	$+3.2\times10^{-2}$
(c)	h_{10}^Z	-23.5	$+24.1$
	h_{20}^Z	-19.6	$+19.6$
	h_{30}^Z	-23.9	$+23.7$
	h_{40}^Z	-19.8	$+19.5$

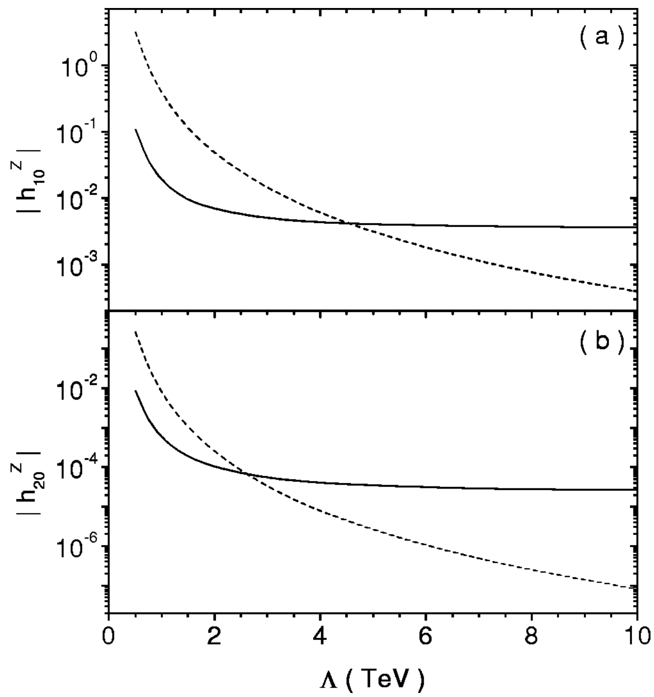

FIG. 5. Dependence of the form factor bounds for $|h_{10}^Z|$ (a) and $|h_{20}^Z|$ (b) on the scale Λ. The dashed lines display the respective partial wave unitarity bounds.

The bounds on the anomalous couplings extracted from the Monte Carlo simulation depend on the parametrization of the form factors. Here we discuss this dependence of the bounds on the form factor scale Λ. Figure 5 illustrates the bounds on $|h_{10}^Z|$ and $|h_{20}^Z|$ as functions of Λ, for the high-field ep collider of the VLHC. The dashed lines show the corresponding partial wave unitarity bounds [9]. Curves for $|h_{30}^Z|$ and $|h_{40}^Z|$ are not shown, since they are similar to those of $|h_{10}^Z|$ and $|h_{20}^Z|$ respectively. It can be seen that the bounds on the anomalous couplings initially fall with Λ, then become essentially constant. From the experimental point of view, one can expect the VLHC to be insensitive to any further increase in the scale Λ once this asymptotic limit is reached. In the case of h_{10}^Z this asymptotic behavior sets in at $\Lambda \sim 4.5$ TeV, which also corresponds to the beginning of S matrix unitarity violation. In the case of h_{20}^Z, however, unitarity is violated around $\Lambda \sim 2.6$ TeV, long before the value $\Lambda \sim 8$ TeV of maximum machine sensitivity is reached.

V. CONCLUSIONS

We have shown that the ep collider proposed for the VLHC could play an important role in the task of detecting (or excluding) an eventual nonstandard $Z\gamma Z$ coupling, which would be strong indication of new physics. In radiative ep scattering it is possible to test the trilinear $Z\gamma Z$ vertex in a kinematical regime in which the two Z lines are spacelike, complementing the usual s-channel processes of e^+e^- and pp colliders. Moreover, our calculations suggest that, as far as the investigation of the structure of a nonstandard $Z\gamma Z$ vertex is concerned, an ep collider at the VLHC facility would be competitive with the next generation of linear colliders (NLC) and the CERN hadron collider LHC.

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