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The $SU(2)_c$ -symmetric W and Higgs Interactions at e^+e^- Linear Colliders†

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Abstract

We study the main signatures of the two possible $SU(2)_c$ conserving New Physics (NP) interactions $\lambda_W \mathcal{O}_W$ and $d \mathcal{O}_{UW}$, in the e^+e^- , $\gamma\gamma$ and γe collisions, which are accessible at a high energy e^+e^- linear collider. Ways to disentangle and separately measure the couplings λ_W and d are studied, and their discovery limits in e^+e^- colliders with c.m. energies of 0.5, 1 and 2 TeV are estimated. We find that a 2 TeV e^+e^- collider should be more sensitive to such NP interactions, than a hadronic collider like LHC.

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High energy e^+e^- linear colliders should offer interesting possibilities for realizing very accurate tests of electroweak interactions. Various such projects have been studied [1] with total center of mass energies ranging from 0.5 to 2 TeV. The expected luminosities should be larger than $10^{33} \text{cm}^{-2} \text{sec}^{-1}$, which ensures a one year run integrated luminosity of at least 10fb^{-1} . With these characteristics, the physics possibilities appear to be very rich [2]. In particular, very interesting tests of the bosonic sector of the electroweak interactions, *i.e.* of the gauge and Higgs boson dynamics could be performed.

The potential of the process $e^+e^- \rightarrow W^+W^-$ for testing the pure gauge sector has already been carefully studied [3]. It has been found that very accurate tests of the 3-gauge boson interactions can be performed in a rather general case for the γWW and ZWW couplings contributing to this process [4]. The very high energy e^+e^- colliders offer additional possibilities though, due to the occurrence of the quasireal boson-boson scattering processes [5]. It is these later processes that we address to in the present paper. However, the high invariant boson pair masses, which are required in order to realize significant NP tests, are largely cut by the boson distribution functions inside the electron. This disadvantage has been recently overcome though, by using laser induced high energy photon beams [6]. It has been found that the use of laser beams allows the realization of real photon-photon and photon-electron collisions reaching c.m. energies of about 80% and 90% respectively, of the e^+e^- energy, while retaining an acceptable luminosity.

The boson-boson collisions offer many new options for testing the pure bosonic sector, since they test not only the 3-gauge boson couplings, but also couplings involving four gauge bosons and/or the physical Higgs. The cleanest case is certainly offered by the $\gamma\gamma$ collisions, where in contrast to the e^+e^- ones, no ambiguity associated with fermionic interactions appears. Photon-electron collisions further enrich such a study by giving access to γW and γZ collisions at the price of introducing the W and Z distribution functions inside the electron, which reduce the rates by one to two orders of magnitude at large invariant masses. Such photon and electron experiments are certainly cleaner than the experiments at a proton-proton supercollider [7, 8], where somewhat larger energies at the subprocess level can be reached, but the background is considerably larger.

A general study of the boson-boson amplitudes with all possible types of couplings has not been done, since it would be very complicated. Only studies with a limited number of anomalous gauge boson or Higgs interactions have been performed up to now [9]. An appealing way of limiting the number of interactions is by invoking a physical principle which restricts the effective operators describing the New Physics (NP) relics at the present "low" energies of up to a few TeV [11, 10, 8]. Such a physical principle is amply motivated by the precision tests realized at the Z peak and at lower energies, which show no departure from Standard Model (SM) predictions for the neutral to charged current ratio ρ and the fermionic couplings. Motivated by these, it is natural to assume that the NP effective operators are invariant under custodial $SU(2)_c$ transformations. Under this assumption, no anomalous fermion-boson couplings can appear, and strong limitations on the possible anomalous gauge boson and Higgs interactions are imposed. Thus, it has been found that the only allowed NP operators with dimension up to 6, are $\mathcal{O}_W$ with a

coupling called λ_W , and $\mathcal{O}_{UW}$ with a coupling called d [10, 8]. $\mathcal{O}_W$ only involves gauge bosons, whereas $\mathcal{O}_{UW}$ contains both gauge and Higgs bosons. The theoretical basis of this assumption is most completely presented in [11]. It has already been found that at a high energy leptonic linear collider, the process $e^+e^- \rightarrow W^+W^-$ is sensitive to the λ_W coupling down to values smaller than 10^{-2} for e^+e^- energies above 0.5 TeV [3]. The d coupling cannot be tested by this process, however. At LHC a constraint on λ_W of a similar order of magnitude is expected, while $\mathcal{O}_{UW}$ can also be studied there using the vector boson fusion processes which lead to a d sensitivity of the order of 10^{-1} [12].

We now turn to the boson-boson processes available at a leptonic linear collider, and discuss their sensitivity to $\mathcal{O}_W$ and $\mathcal{O}_{UW}$.

The four-gauge-boson amplitudes for $V_1V_2 \rightarrow V_3V_4$, containing Standard Model (SM) effects at the tree level as well as contributions from the anomalous operator $\mathcal{O}_W$, have been calculated in [13, 14, 8]. Simple and accurate high energy analytic expressions for these amplitudes, including also the $\mathcal{O}_{UW}$ contributions, have been given in [12]. These expressions should considerably facilitate the analysis of the experimental search of such new interactions, and have already been used to derive the unitarity restrictions on the couplings λ_W and d [11]. It turns out that these restrictions are about as strong as the ones presently derived on the basis of the LEP1 precision measurements at the 1 loop level [15]. Thus the allowed coupling strengths for which the perturbative treatment of the amplitudes is acceptable, is known.

The processes accessible to $\gamma\gamma$ collisions are $\gamma\gamma \rightarrow W^+W^-$, $\gamma\gamma \rightarrow ZZ$, $\gamma\gamma \rightarrow \gamma Z$, and $\gamma\gamma \rightarrow \gamma\gamma$. In order to calculate the corresponding cross sections we first need the $\gamma\gamma$ flux induced by using laser beams at a linear e^+e^- collider. Taking the laser and $e^\pm$ beams to be unpolarized, we get the spectral $\gamma\gamma$ luminosity [6]

$$\frac{d\mathcal{L}_{\gamma\gamma}(y)}{dy} = 2y \int_{\frac{\tau}{x_{max}}}^{x_{max}} \frac{dx}{x} f_{\gamma/e}^{laser}(x) f_{\gamma/e}^{laser}\left(\frac{\tau}{x}\right) , \quad (1)$$

where

$$y \equiv \sqrt{\tau} \equiv \sqrt{\frac{s_{\gamma\gamma}}{s_{ee}}} \quad (2)$$

is the ratio of the $\gamma\gamma$ c.m. energy to the e^+e^- one. The photon distribution $f_{\gamma/e}^{laser}(x)$, obtained by Compton scattering the laser on the electrons, is given by

$$f_{\gamma/e}^{laser}(x) = \frac{1}{D(\xi)} \left(1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right) , \quad (3)$$

where x is the fraction of the incident $e^\pm$ energy carried by the backscattered photon, and

$$D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \text{Ln}(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2} , \quad (4)$$

with $\xi = 2(1 + \sqrt{2}) \simeq 4.8$, $x_{max} = \frac{\xi}{1+\xi} \simeq 0.82$ [16, 17].

The cross section for the various $\gamma\gamma$ processes in laser induced collisions at an e^+e^- collider are then expressed as

$$\frac{d\sigma}{dy} = \frac{d\mathcal{L}_{\gamma\gamma}}{dy} \sigma_{\gamma\gamma}(s_{\gamma\gamma}) \quad , \quad (5)$$

while the correspondingly expected number of events per year is

$$\frac{dN}{dy} = \bar{\mathcal{L}}_{ee} \frac{d\sigma}{dy} \quad , \quad (6)$$

where $\bar{\mathcal{L}}_{ee}$ is the integrated e^+e^- annual luminosity taken to be $10fb^{-1}year^{-1}$. It will also be useful to discuss the number of events for which the invariant mass of the boson pair is larger than a certain value (say 1TeV), which according to (2) corresponds to $y \geq y_0$ (with say $y_0 = 1TeV/\sqrt{s_{ee}}$). For this we have

$$N(> 1TeV) = \int_{y_0}^{y_{max}} dy \frac{dN}{dy} \quad , \quad (7)$$

where the use of (1,2) leads to $y_{max} = x_{max} \simeq 0.82$. In order to increase the sensitivity of the quantities in (5) and (6) on the non-standard couplings, an angular cut is applied to the subprocess of the form $|\cos(\theta)| < z_0$, where θ is the subprocess c.m. scattering angle. Illustrations are always given for $z_0 = 0.9$, if not otherwise specified. A discussion of the influence of this cut will be given below.

The results are shown in Fig.1a in the case of a 2 TeV e^+e^- linear collider ($E_e = 1TeV$). As it is indicated there, only the process $\gamma\gamma \rightarrow W^+W^-$ receives a standard tree level contribution. As for the case of hadronic colliders [8, 12], large departures from the SM result due to anomalous contributions with $\lambda_W = \pm 0.01$ or $d = \pm 0.1$ appear for vector boson invariant masses larger than 1TeV. The other three processes in Fig.1a receive neither SM nor any λ_W contributions at tree level. Such contributions can only arise at the one loop level for these processes. On the other hand the operator $\mathcal{O}_{UW}$ does contribute at the tree level, and the result is shown in Fig.1a. Its contribution is particularly strong for $\gamma\gamma \rightarrow ZZ$, because of the standard Higgs-ZZ coupling. Consequently this process can be used to produce interesting constraints on d at large ZZ invariant masses.

We now turn to the electron-photon collisions which may be used to study not only the aforementioned $\gamma\gamma$ amplitudes, but also the processes $\gamma W^- \rightarrow \gamma W^-$, $\gamma W^- \rightarrow ZW^-$, $\gamma Z \rightarrow W^+W^-$, $\gamma Z \rightarrow \gamma\gamma$, $\gamma Z \rightarrow \gamma Z$, and $\gamma Z \rightarrow ZZ$. The corresponding cross sections involve the distribution functions for quasi-real γ , W or Z with various helicities, inside an unpolarized electron beam. To leading order at high energy, x being the fraction of the incident electron's energy E_e carried by the vector boson V, these distributions are [18] :

$$f_{V/e}^{(+)}(x) = \frac{\alpha}{4\pi} \frac{[(a_e + b_e)^2 + (1-x)^2(a_e - b_e)^2]}{x} \mathbf{L} \quad , \quad (8)$$

$$f_{V/e}^{(-)}(x) = \frac{\alpha}{4\pi} \frac{[(a_e - b_e)^2 + (1-x)^2(a_e + b_e)^2]}{x} \mathbf{L} \quad , \quad (9)$$

$$f_{V/e}^{(L)}(x) = \frac{\alpha}{\pi} (a_e^2 + b_e^2) \frac{(1-x)}{x} \quad , \quad (10)$$

where ($V = \gamma, W, Z$), the upper index (+, -, L) denotes the vector boson helicity,

$$\mathbf{L} = \text{Ln} \left(\frac{4E_e^2}{\frac{m_e^2 x^2}{1-x} + M_V^2} \right) \quad , \quad (11)$$

and

$$a_e = \frac{-1 + 4s_W^2}{4s_W c_W} \quad , \quad b_e = \frac{-1}{4s_W c_W} \quad , \quad (12)$$

for $V = Z$, while $a_e = b_e = 1/(2\sqrt{2}s_W)$ for W , and ($a_e = -1$, $b_e = 0$) for γ .

These simple expressions are only valid for $x \gg \frac{M_V}{E_e}$. For low values of x they are affected by threshold effects. We shall not discuss them because we are in fact only interested in the domain with a large γV invariant mass where the sensitivity to the NP interactions is the strongest. We shall also only consider the relative departure from the SM predictions due to NP and not really the precise absolute value of these predictions.

The corresponding cross section for a definite initial state vector boson V colliding with a laser induced photon is given by

$$\frac{d\sigma}{dy} = 2y \sum_{i=+,-,L} \mathcal{L}_{\gamma V}^{(i)}(\tau) \sigma_{\gamma V}^{(i)}(s_{\gamma V}) \quad , \quad (13)$$

where instead of (2) we now define

$$y \equiv \sqrt{\tau} = \sqrt{\frac{s_{\gamma V}}{s_{ee}}} \quad , \quad (14)$$

and the above threshold requirements imply that our calculations are reliable only for

$$\tau \gg \max \left(\frac{M_V^2}{s_{ee}} \quad , \quad \frac{(M_{V_3} + M_{V_4})^2}{s_{ee}} \right) \quad , \quad (15)$$

M_{V_3}, M_{V_4} being the masses of the final state bosons.

The intermediate γV luminosity in (13) is defined as

$$\mathcal{L}_{\gamma V}^{(i)}(\tau) = \int_{\tau}^{x_{\max}} \frac{dx}{x} f_{\gamma/e}^{\text{laser}}(x) f_{V/e}^{(i)} \left(\frac{\tau}{x} \right) \quad , \quad (16)$$

where as in (8-10), the upper index i denotes the vector boson helicity. Using the same annual integrated e^+e^- luminosity as in (6), the number of events is given by

$$\frac{dN}{dy} = \bar{\mathcal{L}}_{ee} \frac{d\sigma}{dy} \quad . \quad (17)$$

In the numerical applications below we use the same angular cut $z_0 = 0.9$ in the subprocess cross sections, as in the laser induced $\gamma\gamma$ case. The results for neutral channels at $2E_e = 2TeV$, where contributions from $\gamma\gamma$ and γZ initial states have been added, are presented in Fig.1b. Their features are similar to those in Fig.1a, but the rates are reduced by a factor 10^{-1} to 10^{-2} , as $y = \sqrt{\tau}$ runs from 0.4 to 0.8. The expected number of events is nevertheless sufficiently large for these collisions to be useful for λ_W and d studies.

The cross sections for the charged channels contributing to γW^- and ZW^- production are shown in Fig.2. Standard tree level contributions do exist for these channels, and the rates are just slightly lower than those for W^+W^- presented in Fig.1b. There exist new and interesting features in these processes, as compared to those discussed for hadronic colliders [8, 12]. These have to do with the response of the cross sections to the anomalous couplings λ_W and d . The λ_W effect is similar to the one in $\gamma\gamma \rightarrow W^+W^-$ and it always increases the cross section. On the contrary, the $\mathcal{O}_{UW}$ contribution to these channels reduces the cross section for $|d| \sim 0.1$, independently of the sign of the coupling d . This must be due to the dominance of the interference between the d^2 and SM terms, for such d values. However, the effect depends also on the angular cut chosen. In Fig.2 we use $z_0 = 0.9$ for which the $\mathcal{O}_{UW}$ effect for $|d| = 0.1$, is negative. When z_0 is smaller, or when $|d|$ is larger, so that the dominant contribution to the cross section comes from the squared anomalous part, (and not from the interference between the d^2 and the SM terms), then the global d effect becomes positive. This behaviour, presented in Fig.3, provides a remarkable way of disentangling the λ_W and d effects. Finally in Fig.4 we give the production cross section ratios W^-Z/W^+W^- and $W^-\gamma/W^+W^-$, which should further help the disentangling of the $\mathcal{O}_W$ and $\mathcal{O}_{UW}$ effects.

We now turn to the study of how these results vary when the e^+e^- energy decreases down to 0.5 or 1 TeV, assuming the same annual integrated luminosity of $10fb^{-1}$. The main difference comes from the fact that the sensitivity to anomalous λ_W and d couplings strongly depends on the vector pair invariant mass, which is now accordingly reduced. We can roughly summarize the results as follows.

In $\gamma\gamma \rightarrow W^+W^-$, we shall ask for a 10% accuracy on the number of events in the large $\sqrt{\tau}$ domain (*i.e.* $\sqrt{\tau} \geq 0.4$). As we see from Fig.1, this number of events is sufficiently large to make the statistical uncertainty negligible, even after taking into account that one W may be detected leptonically and the other through a hadronic mode. We suppose therefore that the main uncertainty will come from the photon-photon luminosity and the background rejection. Assuming that only one of $\mathcal{O}_W$ and $\mathcal{O}_{UW}$ acts at a time, one obtains the lower bounds on the $|\lambda_W|$ and $|d|$ values respectively, to which this reaction is sensitive. These bounds, termed "sensitivity", are given in Table 1.

Table 1: Sensitivity of $\gamma\gamma$ processes to λ_W and d			
$2E_e$ (TeV)	$ \lambda_W $	$ d $ from W^+W^-	$ d $ from ZZ
0.5	0.08	0.3	0.25
1	0.02	0.15	0.07
2	0.006	0.05	0.02

The process $\gamma\gamma \rightarrow ZZ$ requires a much more detailed study, as in the standard picture it first occurs through 1 loop diagrams. An analysis of this process within SM has been recently done in [19]. The result strongly depends on the values of the Higgs and top mass, and it appears to be of the order of 10^{-2} times the SM prediction for $\gamma\gamma \rightarrow W^+W^-$, as one would guess for such a high order process. We thus obtain that $d\sigma(\gamma\gamma \rightarrow ZZ)/dy \sim 10^{-4}nb$ in SM. After taking into account the branching ratios for one Z to decay to leptons and the other to hadrons, this implies that about 100 observable events are expected in the SM case. Because of this small number of events and additional theoretical uncertainties, we shall only make a rough estimate of the d sensitivity, by demanding that the $d\mathcal{O}_{UW}$ and SM contributions are comparable to each other, so that the actual and the SM cross sections are similar within a factor of two. In this case one gets the $\mathcal{O}_{UW}$ sensitivity given in the last column of Table 1. Thus, the process $\gamma\gamma \rightarrow ZZ$ at high energy can be as important as the process $\gamma\gamma \rightarrow WW$, in testing the presence of the d coupling.

Because of the suppressed boson distribution functions inside the electron, the photon-electron processes for a neutral final state cannot compete with the $\gamma\gamma$ ones, at lower energies. The processes involving γW and ZW production though, may still be useful for disentangling λ_W from d , using the opposite signs of their effects shown in Fig.2. Asking again for a 10% maximum discrepancy on the number of events from the SM prediction, the disentangling is possible down to the limiting values from $\gamma\gamma \rightarrow W^+W^-$ quoted in Table 1.

Let us now discuss the implications of the results presented above. We consider two different scenarios.

1) One uses all processes available including the fermionic ones, assuming that basic fermion-boson couplings keep their standard forms and values. This is a very strong assumption for the level of accuracy that one can reach here (better than 10^{-2}). Precision tests at LEP1 support this assumption in the case of Z couplings, but new phenomena may appear at higher energies for both Z and W couplings. This assumption is at the basis of the principle of $SU(2)_c$ conservation for NP phenomena [8, 12], which allows only the $\mathcal{O}_W$ and $\mathcal{O}_{UW}$ interactions. One can then start from the fermionic process $e^+e^- \rightarrow W^+W^-$ in order to constrain λ_W first, since the process $\gamma e \rightarrow W\nu$ is known to give weaker limits, [13]. Thus, from $e^+e^- \rightarrow W^+W^-$ one can exclude λ_W down to values of a few 10^{-3} , using for a 2 TeV collider the scaling laws established in [3]. Having established this, we can subsequently turn to constraining d , for which the best processes are the photon-photon ones. According to Table 1, $\gamma\gamma \rightarrow W^+W^-$ allows to limit d down to 0.3 and 0.05 for energies of 0.5 and 2 TeV respectively, while $\gamma\gamma \rightarrow ZZ$ can further improve these bounds, especially if high energies are available. Photon-electron collisions can also be used to confirm the absence of anomalous effects, but they cannot improve them.

2) In a more conservative scenario one may decide to establish bounds on λ_W and d , by solely using the bosonic sector. The fermionic processes like *e.g.* $e^+e^- \rightarrow W^+W^-$ and $\gamma e \rightarrow W\nu$ could be affected by different unknown phenomena concerning the purely fermionic sector (heavy leptons,...), and are now not considered. The elements to be used in such a case are the process $\gamma\gamma \rightarrow W^+W^-$ (see Fig.1a) which is affected in a similar way by both couplings; while $\gamma\gamma \rightarrow ZZ, Z\gamma, \gamma\gamma$ receive only d contributions and can provide a signal for this coupling. The disentangling of the λ_W and d contributions may then occur in two different ways. First, the sign of the departure from the SM predictions for $\gamma W \rightarrow \gamma W, ZW$, as the angular cut is varied, may help revealing the nature of the signal (Fig. 3). The ratios WZ/WW and $W\gamma/WW$ may subsequently confirm the presence of d and provide a measurement of its size. The absence of an effect in these various observables ($WW, ZZ, ZW, \gamma W$) would allow to conclude that $|\lambda_W|$ and $|d|$ have values smaller than the ones quoted in Table 1.

These results mean that interesting improvements in the tests of the bosonic sector of the electroweak interactions can be expected from these processes. With the photon flux expected from laser backscattering, real $\gamma\gamma$ collisions constitute a very powerful tool for a sensible test of $SU(2)_c$ -symmetric W and H interactions. This is especially true in the case of a 2 TeV collider. The level of sensitivity (0.006) to λ_W is comparable and complementary to the one expected from $e^+e^- \rightarrow W^+W^-$, which is usually considered as the best way to constrain 3 boson couplings. This is the level where the SM weak radiative corrections lie, and is one order of magnitude better than the LEP2 limits and two orders better than LEP1 ones. Moreover, these limits are considerably less ambiguous than the ones achievable at LHC. They also lie in a region where our calculations are reliable, since they are much below the unitarity bounds [11].

The corresponding limits on d are obviously worse than those on λ_W , because they involve weaker Higgs exchange processes. They are closer to the unitarity limits. Nevertheless, they can easily reach a value of 0.05, which is better than the LHC expectation, since (apart from the smaller hadronic background) there exists no competition from fermionic processes there. Furthermore, a careful experimental study of the neutral channels $\gamma\gamma \rightarrow ZZ, Z\gamma, \gamma\gamma$, together with a theoretical study of the corresponding one loop SM predictions, could notably decrease these limits.

At lower energies (0.5 TeV) the sensitivity to λ_W from $\gamma\gamma$ collisions is not competitive to the one expected from $e^+e^- \rightarrow W^+W^-$, and the interest is mainly limited to the case of the anomalous W-Higgs interaction $d\mathcal{O}_{\nu W}$, which cannot be reached in this last process. Nevertheless, in order to exclude scenarios in which the e^+e^- channel could be affected by other types of effects, photon-photon and photon-electron collisions can be considered as valuable in providing consistency checks of the bosonic sector.

As compared to real photon-photon collisions, photon-W and photon-Z processes available from laser photon-electron collisions, especially at low energy, suffer from the reduction of the rates due to the boson distribution functions inside the electron. In spite of that, they bring essential information for the disentangling of the different types of anomalous interactions. For these processes the highest possible luminosity would be greatly profitable.

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Figure Captions

Fig.1 Cross sections for W^+W^- , ZZ , γZ , $\gamma\gamma$ production (a) in $\gamma\gamma$ collisions, (b) in γe collisions, for a 2 TeV e^+e^- linear collider. Standard prediction (solid line), with $\lambda_W \mathcal{O}_W$ ($\lambda_W = 0.01$, dashed line), with $d\mathcal{O}_{UW}$ ($d = \pm 0.1$, long dashed line), (the case $\lambda_W = -0.01$ coincides with the case of $d\mathcal{O}_{UW}$). The number of events per year expected with an integrated luminosity of $10 fb^{-1}$ is also indicated.

Fig.2 Cross sections for W^-Z , $W^-\gamma$ production in γe collisions. Standard prediction (solid line), with $\lambda_W \mathcal{O}_W$ ($\lambda_W = \pm 0.01$, dashed line), with $d\mathcal{O}_{UW}$ ($d = \pm 0.1$, long dashed line).

Fig.3 Cross sections for W^-Z production in γe collisions for $M_{W-Z} \geq 1TeV$ at variable angular cut z_0 . Standard prediction (solid line), with $\lambda_W \mathcal{O}_W$ ($\lambda_W = \pm 0.01$ dashed line, $\lambda_W = \pm 0.02$ short dashed line), with $d\mathcal{O}_{UW}$ ($d = \pm 0.1$, long dashed line, $d = \pm 0.2$, very long dashed line).

Fig.4 Ratios of cross sections W^-Z/W^+W^- and $W^-\gamma/W^+W^-$ in γe collisions. Standard prediction (solid line), with $\lambda_W \mathcal{O}_W$ ($\lambda_W = 0.01$ dashed line, $\lambda_W = -0.01$ short dashed line), with $d\mathcal{O}_{UW}$ ($d = \pm 0.1$, long dashed line).

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Fig. 4