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Effects of an anomalous W–boson weak electric dipole moment in $f_i\overline{f}_j \rightarrow W^{\pm}Z^0(\gamma)$

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ABSTRACT. We study the high-energy production process $f_i\overline{f}_j \rightarrow W^{\pm}Z^0(\gamma)$ allowing for gauge boson compositeness through an anomalous W^-–boson weak-electric dipole moment parameter $\widetilde{\kappa}_z$. We give the angular differential and total cross-section for different values of $\widetilde{\kappa}_z$, and compare with the corresponding results coming from an anomalous weak-magnetic dipole moment κ_z.

RESUMEN. Estudiamos el proceso de producción $f_i\overline{f}_j \rightarrow W^{\pm}Z^0(\gamma)$ incluyendo un momento dipolar débil-eléctrico, $\widetilde{\kappa}_z$, en el contexto de modelos compuestos. Se presentan las secciones transversales diferencial y total para diferentes valores del parámetro $\widetilde{\kappa}_z$. Los resultados son comparados con las correspondientes secciones transversales que involucran al momento dipolar débil magnético κ_z.

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1. INTRODUCTION

The standard model of electroweak unification (SM) has surpassed all the experimental test up to now. One of the few aspects to be tested is the study of the WWV vertex. If the propierties of interaction between $W^{\pm}$ with γ and Z^0 are different (beyond radiative corrections) from those predicted by the standard model, the composite nature of $W^{\pm}$ (and Z^0) will show in the near future after the new acelerators start to take data. This compositeness can be described by possible anomalous multipole moments of this boson.

In particular, the presence of a weak electric dipole moment, the analogous to the electric dipole moment in QED, is a direct source of CP violation in the weak interactions.

In this paper we introduce anomalous WWV couplings to study the pair production reaction $f_i\overline{f}_j \rightarrow W^{\pm}Z^0(\gamma)$, where f_i and $\overline{f}_j$ are two members of an SU(2) doublet.

We consider an anomalous weak-magnetic moment κ_z and an anomalous weak-electric dipole moment $\widetilde{\kappa}_z$ of the W boson.Two approaches to introduce this anomalous parameters have been developed in the literature: the effective Lagrangian method [1, 2], and composite models [3]. The first one includes all operators respecting the symmetry of the SM. Then, their effects is to determine the renormalization group-running of the effective couplings. Within this approach, dimension six operators are responsible of κ_z and $\widetilde{\kappa}_z$, which in turn are of $O(v^2/\Lambda^2)$, with v the Higgs vacuum expectation value, and Λ the energy scale of new physics represented by the six dimension operators. Thus, if we assume $v = 250$ GeV, and $\Lambda = 1000$ GeV, κ_z and $\widetilde{\kappa}_z$ are $O(10^{-2})$. The second approach, assumes that the terms in the Lagrangian beyond SM respects Lorentz covariance (and the U(1) symmetry for the case $V = \gamma$). So, the properties of the W boson are due to internal structure, and are given by some parameters like κ_z and $\widetilde{\kappa}_z$, to be determined by experiment. Bounds on κ_z and $\widetilde{\kappa}_z$ from their contributions to the weak dipole moments of fermions [2] yields $|\kappa_z| \leq 1$, and $|\widetilde{\kappa}_z| \leq 10^{-3}$ (this last bound depends on the assumption that any dynamics beyond the standard model must respect the local gauge symmetry of the latter, above the weak symmetry-breaking scale, which in turns entails a relation among $\widetilde{\kappa_z}$ and the analogous γWW parameter $\widetilde{\kappa}_\gamma$: $\widetilde{\kappa_z} = -\sin^2\theta_W\,\widetilde{\kappa}_\gamma$).

With this in mind we have calculated the angular differential cross-section and total cross-section of the reaction $f_i\overline{f}_j \to W^\pm Z^0$, complementing previous results [4], and including the limit $M_Z = 0$ in order to embrace the reaction $f_i\overline{f}_j \to W^\pm\gamma$ [5]. In the following sections we present our results.

2. ANOMALOUS WEAK-MAGNETIC AND WEAK-ELECTRIC DIPOLE MOMENTS OF THE W-BOSON

If we only assume Lorentz covariance (and U(1)-gauge symmetry for the photon case) the WWV vertex can be writen as

$$\begin{aligned}\Gamma^{\mu\alpha\beta}(k,p_1,p_2)\Big|_{WWV} &= g_V\left[(2p_1+p_2)^\mu g^{\alpha\beta} - (2p_2+p_1)^\beta g^{\alpha\mu} - (p_1-p_2)^\alpha g^{\beta\mu}\right]\\ &\quad - g_{WWV}\,\kappa_V\left(p_2^\beta g^{\mu\alpha} - p_2^\alpha g^{\mu\beta}\right)\\ &\quad - g_{WWV}\,\widetilde{\kappa}_V\,\varepsilon^{\alpha\beta\mu\sigma}p_{2\sigma},\end{aligned} \tag{1}$$

where k, p_1 and p_2 are four-momenta for the $W(k = p_1 + p_2)$, $W(p_1)$, and $V(p_2)$, respectively. In (1), κ_V and $\widetilde{\kappa}_V$ parametrize the anomalous weak-magnetic and weak-electric dipole moments of the W boson, with values $\kappa_z = 1$, $\widetilde{\kappa_z} = 0$ in SM.

The diagrams contributing to the process $f_i\overline{f}_j \to W^\pm V$ are depicted in Figs. 1a to c.

The corresponding total amplitude is

$$M = \overline{v}(k_2)\,T_{\mu\nu}\,u(k_1)\,\varepsilon^\mu(p_1)\,\varepsilon^\nu(p_2), \tag{2}$$

where

$$\begin{aligned}T_{\mu\nu} &= iG^{ij}_{V-A}(1+\gamma_5)\left\{\frac{e_z}{s-M_W^2}(\not p_2 - \not p_1)g_{\mu\nu} + (2p_1+p_2)_\nu\gamma_\mu\right.\\ &\quad \left. - (p_1+2p_2)_\mu\gamma_\nu\Big] - g^i\frac{\gamma_\mu \not\ell_2\gamma_\nu}{u} - g^j\frac{\gamma_\nu\not\ell_1\gamma_\mu}{u}\right\}\\ &\quad + iG^{ij}_{V-A}\frac{(\kappa_z-1)e_z}{s-M_W^2}(1+\gamma_5)(\not p_2\,g_{\mu\nu} - p_{2\mu}\,\gamma_\nu)\\ &\quad + iG^{ij}_{V-A}\frac{\widetilde{\kappa_z}e_z}{s-M_W^2}(1+\gamma_5)\gamma^\beta\varepsilon_{\beta\mu\nu\alpha}p_2^\alpha.\end{aligned} \tag{3}$$

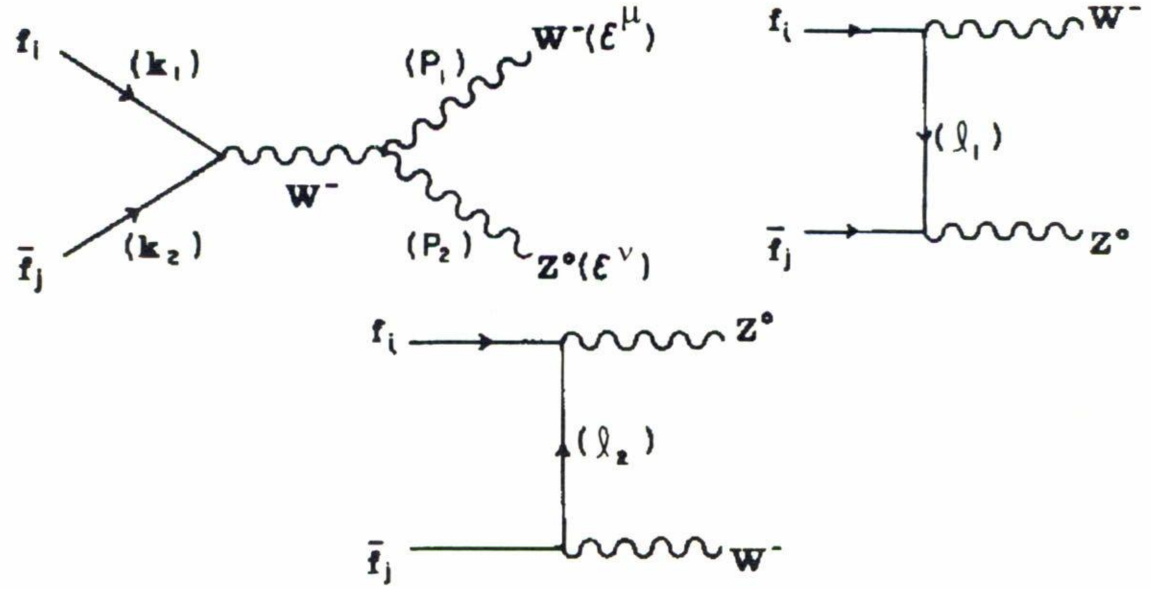


FIGURE 1. a–c. Feynman diagrams for $f_i\overline{f}_j \to W^{\pm}Z^0$. With p_1, p_2, k_1 and k_2 the 4–momenta of the particles ($p_1^2 = M_W^2, p_2^2 = M_Z^2$). Here $s = (k_1+k_2)^2$, $t = \ell_1^2 = (k_1-p_1)^2$ and $u = \ell_2^2 = (k_1-p_2)^2$. $\varepsilon^{\mu}(p_1)$ and $\varepsilon^{\nu}(p_2)$ are the $W^{\pm}$ and Z^0–polarization 4–vectors, respectively.

Here $e_z = e\cot\theta_{\rm W}$, e is the charge of the positron, $\theta_{\rm W}$ is the Weinberg angle and the parameters g^i, g^j and G^{ij}_{V-A} are given in Table I.

The Mandelstam variables s, t, u have been used. If fermion masses are neglected they fulfill $s+t+u = M_W^2 + M_V^2$. In order to exhibit an interesting property of (2), for the case $M_V = 0$, we rewrite the SM contribution in Eq. (3) in the form [6]

$$
\begin{aligned}
T_{\mu\nu} = {} & iG^{ij}_{V-A}(1+\gamma_5)\left\{\frac{ut}{s-M_W^2}\left[\frac{g^i}{u}+\frac{g^j}{t}\right]\left[\frac{\gamma_\nu \not{\ell}_1 \gamma_\mu}{t}+\frac{\gamma_\mu \not{\ell}_2 \gamma_\nu}{u}\right]\right. \\
& \left. -\frac{M_V^2}{s-M_W^2}\left(g^j\frac{\gamma_\nu \not{\ell}_1 \gamma_\mu}{t}+g^i\frac{\gamma_\mu \not{\ell}_2 \gamma_\nu}{u}\right)\right\} \\
& + iG^{ij}_{V-A}\frac{(\kappa_z-1)e_z}{s-M_W^2}(1+\gamma_5)(\not{p}_2\, g_{\mu\nu} - p_{2\mu}\,\gamma_\nu) \\
& + iG^{ij}_{V-A}\frac{\widetilde{\kappa}_z\, e_z}{s-M_W^2}(1+\gamma_5)\gamma^{\beta}\varepsilon_{\beta\mu\nu\alpha}p_2^{\alpha}.
\end{aligned}
\tag{4}
$$

Equation (4) shows that, when $M_V = 0$ (the $W^{\pm}\gamma$ final state case), the amplitude for SM vanishes for the kinematic region

$$
\frac{g^i}{u} = -\frac{g^j}{t},
\tag{5}
$$

TABLE I. Parameters g^i, g^j and G^{ij}_{V-A} for different particles. With $\xi = \sin\theta_{\rm W}$, $\theta_{\rm C}$ is Cabbibo angle and $G_{\rm F}$ is Fermi constant.

j^1	g^i	g^j	G^{ij}_{V-A}
$\nu_e{}^e$	$2^{1/4}M_Z\sqrt{G_{\rm F}}(-1+2\xi^2)$	$2^{1/4}M_Z\sqrt{G_{\rm F}}$	$2^{-1/4}M_W\sqrt{G_{\rm F}}$
$u^{d,s}$	$2^{1/4}M_Z\sqrt{G_{\rm F}}(-1+\frac{2}{3}\xi^2)$	$2^{1/4}M_Z\sqrt{G_{\rm F}}(1-\frac{4}{3}\xi^2)$	$2^{-1/4}M_W\sqrt{G_{\rm F}}(\cos\theta_{\rm C}, \mathrm{sen}\,\theta_{\rm C})$
$c^{d,s}$	$2^{1/4}M_Z\sqrt{G_{\rm F}}(-1+\frac{2}{3}\xi^2)$	$2^{1/4}M_Z\sqrt{G_{\rm F}}(1-\frac{4}{3}\xi^2)$	$2^{-1/4}M_W\sqrt{G_{\rm F}}(-\sin\theta_{\rm C}, \cos\theta_{\rm C})$

with $g^i = Q_i$ and $g^j = Q_j$ the electric charges of the fermions f_i and f_j, respectively. Equation (5) is known as the radiation amplitude zero condition. We can see that for the same condition (5), Eq. (4) reduces to

$$
\begin{aligned}
T_{\mu\nu} = {} & iG^{ij}_{V-A}(1+\gamma_5)\frac{M_z^2}{s-M_W^2}\frac{g^i}{u}[\gamma_\nu \not{\epsilon}_1\gamma_\mu - \gamma_\mu \not{\epsilon}_2 \gamma_\nu] \\
& + iG^{ij}_{V-A}\frac{(\kappa_z-1)e_z}{s-M_W^2}(1+\gamma_5)(\not{p}_2\, g_{\mu\nu} - p_{2\mu}\,\gamma_\nu) \\
& + iG^{ij}_{V-A}\frac{\widetilde{\kappa}_z\, e_z}{s-M_W^2}(1+\gamma_5)\gamma^\beta \varepsilon_{\beta\mu\nu\alpha}\, p_2^\alpha .
\end{aligned}
\tag{6}
$$

3. DIFFERENTIAL AND TOTAL CROSS-SECTIONS

Squaring the total amplitude in Eq. (2), summing and averaging over initial spins and summing over final polarization boson vectors, we obtain for the differential cross-section

$$
\begin{aligned}
\frac{d\sigma}{dt} = {} & \left(1+\delta_{j\nu_e}\right)\frac{4\pi\alpha^2}{s^2}\left[\frac{G^{ij}_{V-A}}{e}\right]^2 \Bigg\{ \left[\frac{se_z/e}{s-M_W^2}\right]^2 A(s,t,u) \\
& + \frac{2se_z/e}{s-M_W^2}\left[-\frac{g^j}{e}I(s,t,u) + \frac{g^i}{e}I(s,u,t)\right] \\
& + \left[\frac{g^i-g^j}{e}\right]^2 E(s,t,u) + \left[\frac{g^i}{e}\right]^2\left[\frac{ut+M_W^2M_z^2}{u^2}\right] \\
& + \left[\frac{g^j}{e}\right]^2\left[\frac{ut-M_W^2M_z^2}{t^2}\right] + 2\left[\frac{g^i\,g^j}{e^2}\right]\frac{s\left(M_W^2+M_Z^2\right)}{ut}\Bigg\} \\
& + (1+\delta_{j\nu_e})\frac{4\pi\alpha^2}{s^2}\left[\frac{G^{ij}_{V-A}}{e}\right]^2 \Bigg\{ (\kappa_z-1)^2\left[\frac{se_z/e}{2\left(s-M_W^2\right)}\right]^2 A'(s,t,u)
\end{aligned}
$$

$$+ (\kappa_z - 1)\left[\frac{se_z/e}{s - M_W^2}\right]^2 B(s,t,u)$$

$$\left. - (\kappa_z - 1)\frac{se_z/e}{s - M_W^2}\left[\frac{g^i}{e}I'(s,u,t) - \frac{g^j}{e}I'(s,t,u)\right]\right\}$$

$$+ (1 + \delta_{j\nu_e})\,\frac{4\pi\alpha^2}{s^2}\left[\frac{G^{ij}_{V-A}}{e}\right]^2\left[\frac{\widetilde{\kappa}_z\, e_z/e}{2\left(s - M_W^2\right)}\right]^2 A''(s,t,u). \tag{7}$$

The functions $A(s,t,u)$, $I(s,t,u), \ldots,$ to $I'(s,t,u)$ were given in Ref. [4], the new contribution $A''(s,t,u)$ is given by

$$A'' = A' - \left[\frac{ut}{M_Z^2 M_W^2} - 1\right]\frac{M_Z^4}{s^2} + \frac{2M_W^2\, s + t^2}{s^2} - \frac{s\beta^2}{M_W^2}. \tag{8}$$

We have plotted Eq. (7) as a function of $\cos\theta$, where θ is the c.m. angle between one of the fermions and the W^+, and for $\sqrt{s} = 250$ GeV. For example, for $e^-\overline{\nu}_e \longrightarrow W^-Z^0$ we got the plots in Figs. 2a-b, for various values of κ_z (with $\widetilde{\kappa}_z = 0$), and for values of $\widetilde{\kappa}_z$ (with $\kappa_z = 1$), assuming no cancellations among κ_z and $\widetilde{\kappa}_z$ contributions. There, we see that the contribution coming from κ_z, tends to increase the standard model result, while that coming from $\widetilde{\kappa}_z$ tends to decrease it.

Integrating Eq. (7) we obtain the total cross-section

$$\sigma = (1 + \delta_{j\nu_e})\,\frac{4\pi\alpha^2}{s^2}\left[\frac{G^{ij}_{V-A}}{e}\right]^2\left\{\frac{s^3\beta}{24M_W^2\, M_Z^2}\left(\frac{se_z/e}{s - M_W^2} + \frac{g^i - g^j}{e}\right)^2\right.$$

$$\times\left[1 + \frac{10\left(M_W^2 + M_Z^2\right)}{s} + \frac{M_W^4 + 10M_W^2\, M_Z^2 + M_Z^4}{s^2}\right]$$

$$- \frac{s^2\beta}{24M_W^2\, M_Z^2}\,\frac{2e_z/e}{s - M_W^2}\left(\frac{g^i - g^j}{e}\right)\left(M_W^2 + M_Z^2\right)$$

$$\times\left[1 + \frac{10\left(M_W^2 + M_Z^2\right)}{s} + \frac{M_W^4 + 10M_W^2\, M_Z^2 + M_Z^4}{s^2}\right]$$

$$- \frac{s\beta}{2}\left[\left(\frac{g^i - g^j}{e}\right)^2 + \left(\frac{2g^i}{e}\right)^2 + \left(\frac{2g^j}{e}\right)^2\right]$$

$$- \left(\frac{g^i - g^j}{e}\right)\frac{4e_z/e}{s - M_W^2}\left(M_W^2 + M_Z^2\right)\left(1 + \frac{M_W^2 M_Z^2}{s\left(M_W^2 + M_Z^2\right)}\right)\ln L$$

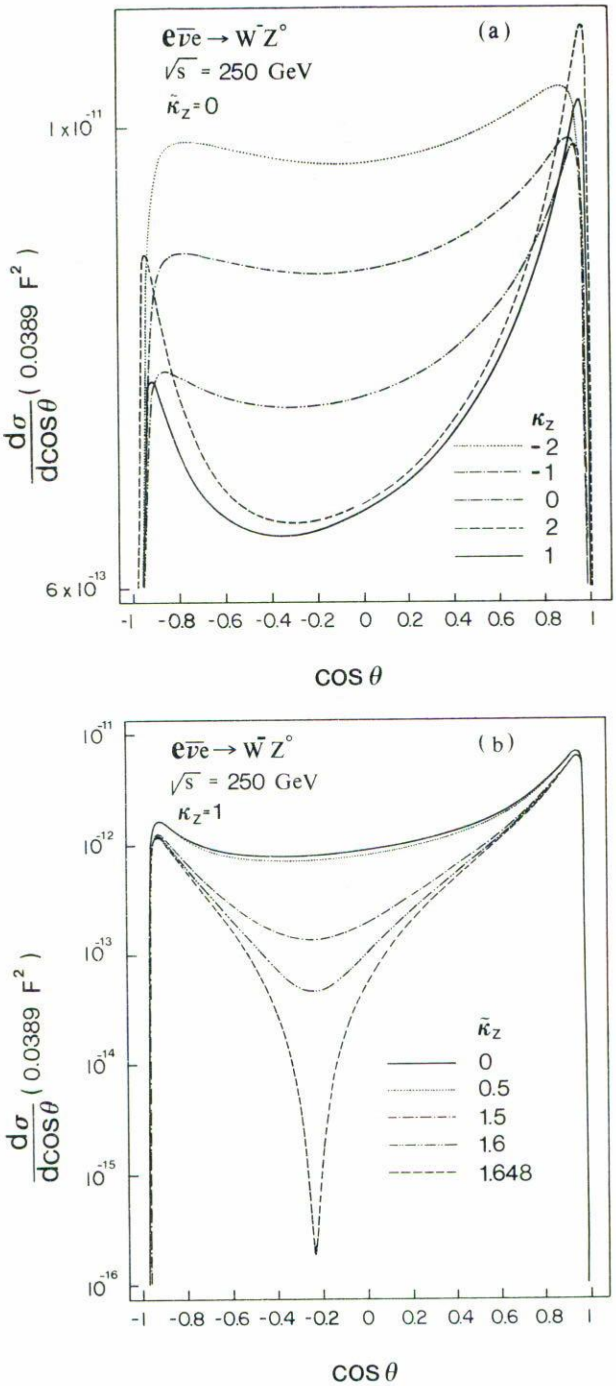


FIGURE 2. Angular differential cross-section for the reaction $e^-\overline{\nu}_e \longrightarrow W^-Z^0$. (a) Curves for $\kappa_z = -2, -1, 0, 1, 2$, and $\widetilde{\kappa}_z = 0$ (b) curves for $\widetilde{\kappa}_z = 0, 0.5, 1.5, 1.6, 1.648$, and $\kappa_z = 1$. Here θ is the c.m. angle between e^- and W^-, and $\sqrt{s} = 250$ GeV.

$$+ \left[\left(\frac{g^i}{e}\right)^2 + \left(\frac{g^j}{e}\right)^2\right] 2s \left[1 - \frac{M_W^2 + M_Z^2}{s}\right] \ln L$$

$$+ 2\left(\frac{g^i g^j}{e^2}\right) s(M_W^2 + M_Z^2) \frac{4 \ln L}{s - \left(M_W^2 + M_Z^2\right)} \Bigg\}$$

$$+ (1 + \delta_{j\nu_e}) \frac{4\pi\alpha^2}{s^2} \left[\frac{G_{V-A}^{ij}}{e}\right]^2 \Bigg\{ (\kappa_z - 1)^2 \left[\frac{s e_z/e}{s - M_W^2}\right] \frac{s\beta^3}{24 M_W^2} \left[2M_W^2 + M_Z^2 + s\right]$$

$$+ (\kappa_z - 1) \left[\frac{s e_z/e}{s - M_W^2}\right]^2 \frac{s\beta^3}{12 M_W^2} \left[5M_W^2 + M_Z^2 + 5s\right].$$

$$- (\kappa_z - 1) \left(\frac{g^i - g^j}{e}\right) \frac{s e_z/e}{s - M_W^2} \left[\frac{s^2\beta^3}{12 M_W^2} + \frac{\beta}{2M_W^2}\left(M_W^2 + M_Z^2 - s\right)\left(M_W^2 + s\right)\right.$$

$$\left. + \frac{2M_Z^2}{s}\left(M_W^2 + s\right) \ln L \right\}$$

$$+ (1 + \delta_{j\nu_e}) \frac{4\pi\alpha^2}{s^2} \left[\frac{G_{V-A}^{ij}}{e}\right]^2 \left(\frac{\widetilde{\kappa}_z e_z/e}{2\left(s - M_W^2\right)}\right)^2 \frac{1}{4} \Bigg\{ M_Z^2 \left(2s - M_W^2 - M_Z^2\right) \beta s$$

$$+ \frac{\beta s^2}{2M_W^2} \left(s - M_W^2 - M_Z^2\right)^2 \left(\frac{2M_W^2 + M_Z^2}{s\left(s - M_W^2 + M_Z^2\right)^2} + 1\right) + \frac{1}{8}\left(\frac{s}{M_W^2} - 2\right)$$

$$\times \left[\left(s - M_W^2 - M_Z^2\right) \left[\left(\beta s - s + M_W^2 + M_Z^2\right)^2 - \left(\beta s + s - M_W^2 - M_Z^2\right)^2\right]\right.$$

$$\left. + \frac{\left(\beta s - s + M_W^2 + M_Z^2\right)^3}{3} + \frac{\left(\beta s + s - M_W^2 - M_Z^2\right)^3}{3}\right]\Bigg\}. \qquad (9)$$

Here we have corrected some misprints in Ref. [4]. Graphs for the reaction $e^- \overline{\nu}_e \longrightarrow W^- Z^0$ are given in Figs. 3a–b. Again, we note that the κ_z contribution tends to increase, in general, the SM result, but the $\widetilde{\kappa}_z$ tends to decrease it. In Figs. 4a–b we have plotted Eq. (7) and Eq. (9) for $\kappa_z = 2$ and $\widetilde{\kappa}_z = 0.5$, and noted that, as asserted above, both contributions could cancel each other. Thus, in a real situation, when both contributions are present, their contributions could cancel each other.

As Fig. 3a shows, curves grows rapidly as κ_z grows negatively then unitarity must restrict the values of negative κ_z to $\kappa_z > -2$.

For $M_V = 0$, we have the plots in Fig. 5 for $e^- \overline{\nu}_e \longrightarrow W^- \gamma$, with the same total energy as in Fig. 2. Here we note the presence of the radiation amplitude zero for $\cos\theta = 1$ in both figures. Also we note that the anomalous couplings give contributions quite different

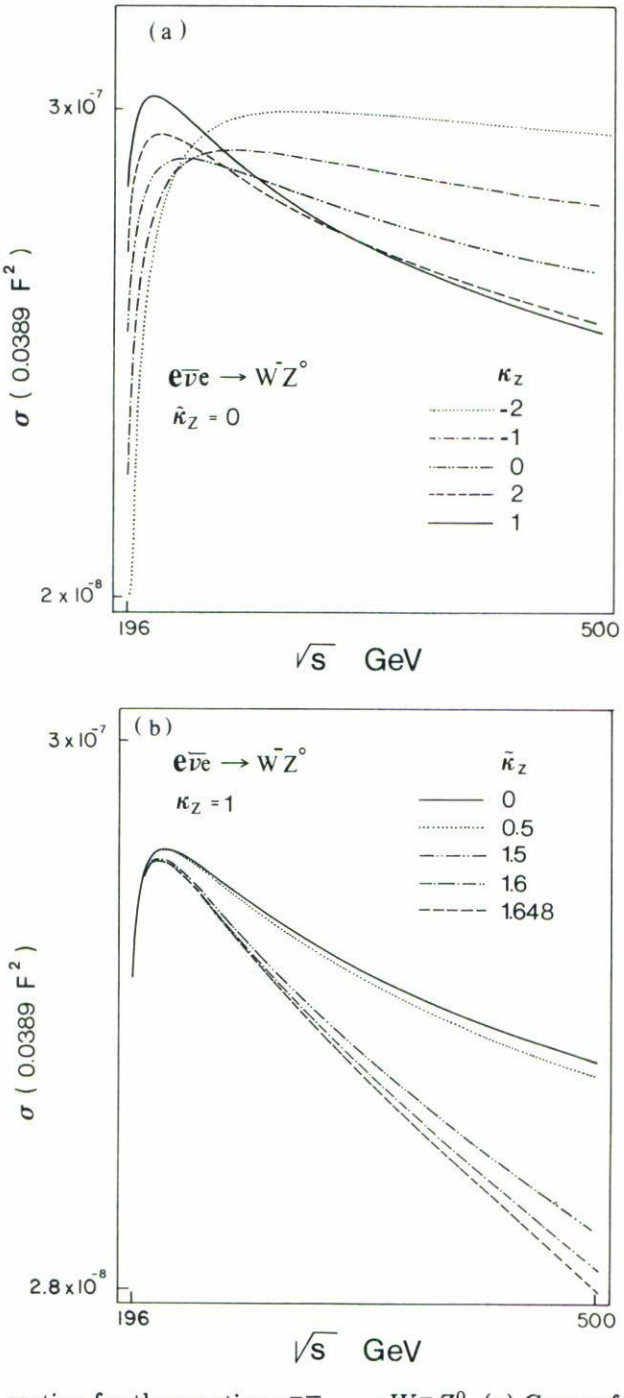


FIGURE 3. Total cross-section for the reaction $e^-\overline{\nu}_e \longrightarrow W^-Z^0$. (a) Curves for $\kappa_z = -2, -1, 0, 1, 2$, and $\widetilde{\kappa}_z = 0$ (b) curves for $\widetilde{\kappa}_z = 0, 0.5, 1.5, 1.6, 1.648$, and $\kappa_z = 1$ are shown as function of $\sqrt{s}$.

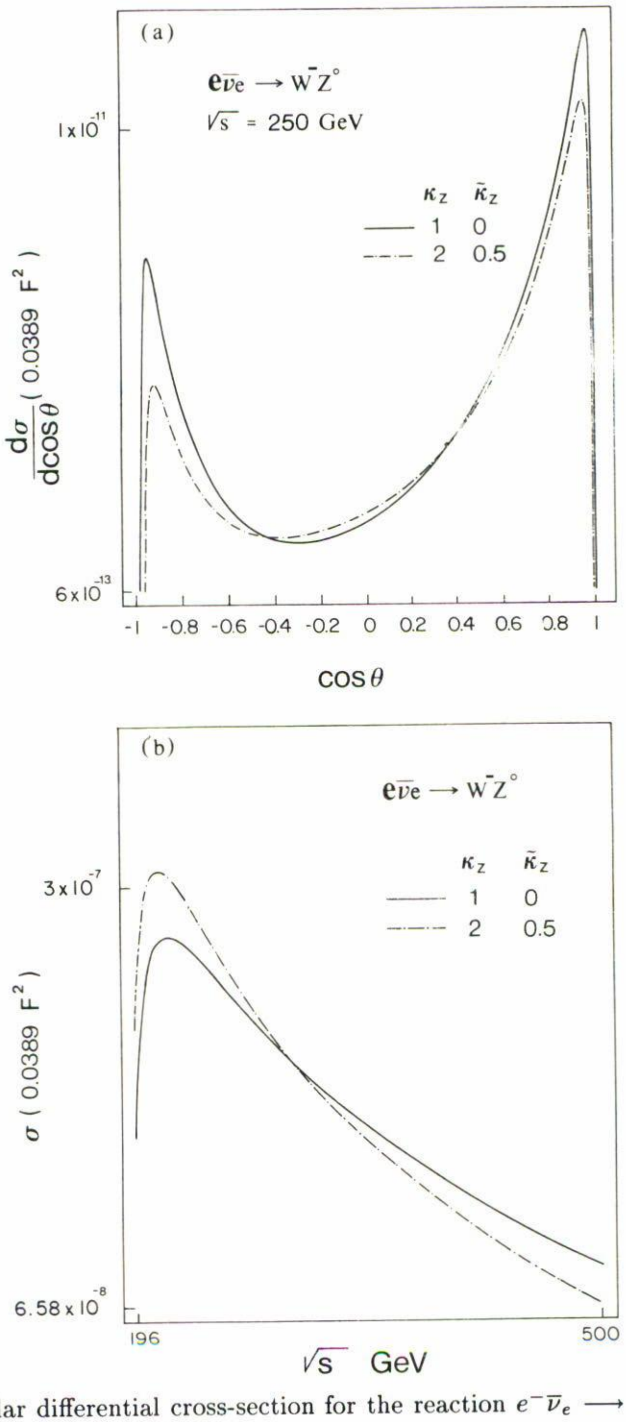
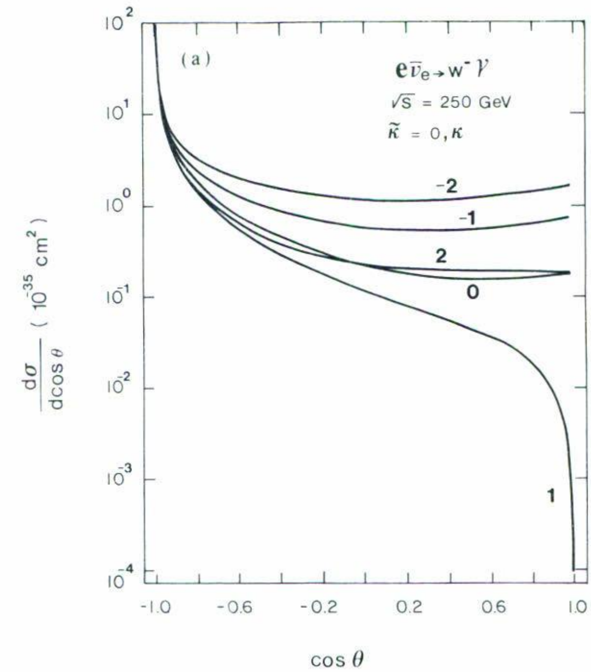


FIGURE 4. (a) Angular differential cross-section for the reaction $e^-\overline{\nu}_e \longrightarrow W^-Z^0$, and (b) total cross-section for $\kappa_z = 2$, and $\widetilde{\kappa}_z = 0.5$.



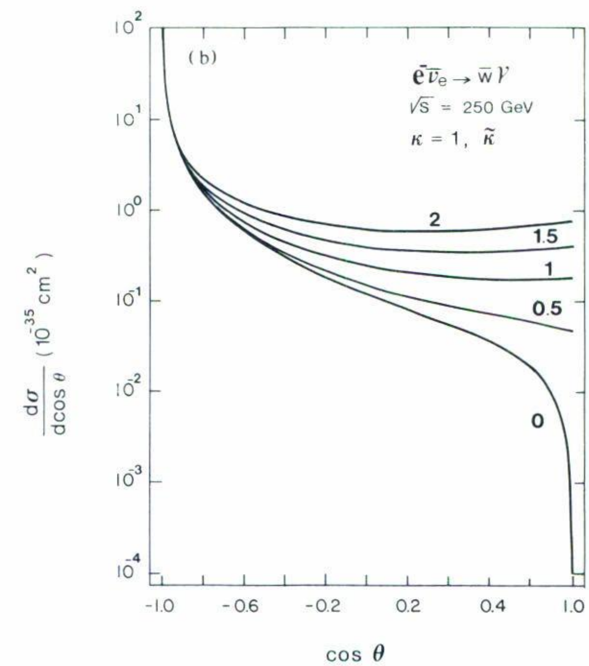


FIGURE 5. Angular differential cross-section for the reaction $e^-\overline{\nu}_e \longrightarrow W^-\gamma$. (a) Curves for $\kappa_\gamma = -2, -1, 0, 1, 2$, and $\widetilde{\kappa}_\gamma = 0$, and (b) curves for $\widetilde{\kappa}_\gamma = 0, 0.5, 1, 1.5, 2$, and $\kappa_\gamma = 1$. Here θ is the c.m. angle between e^- and W^-, and $\sqrt{s} = 250$ GeV.

to the SM contribution in a wide range of values of the angular variable, which can be useful to test experimentaly the vertex under consideration.

4. CONCLUSION

We have studied the pair bosons production process $f_i\overline{f}_j \longrightarrow W^{\pm}V$ ($V = Z^0$ or γ), and showed that the SM contribution can be written in a way that exhibits an approximate zero for $V = Z^0$, and an exact zero for $V = \gamma$. Anomalous coupling spoil this approximate zero. We have considered the anomalous coupling $\widetilde{\kappa}_z$ (or $\widetilde{\kappa}_\gamma$), a coupling associated to (weak)-electric dipole moment, and compared its contributions to the contributions from the anomalous coupling κ_z (or κ_γ), which is associated to the (weak)-magnetic dipole moment.

In this paper we presented results for the angular differential and total cross-sections, and we have noted clear deviations from the SM results, for the range of values of $\widetilde{\kappa}_z$ (or $\widetilde{\kappa}_\gamma$) considered here.

It has been argumented [6] that the reaction with final state WZ is a better place to look for this approximate zero than the final state $W\gamma$, since in the first one the approximate zero is located at $\cos\theta = -0.3$, while in the second one is at the kinematical boundary $\cos\theta \cong 1$.

Our results can be applied to quarks in the initial state also. This in turn can be used to study process as $p\overline{p} \longrightarrow WZX$, where p ($\overline{p}$) is a proton (antiproton).

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