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W boson weak electric dipole moment in $pp(p\overline{p}) \to W^{\pm} Z^0 X$

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We introduce an anomalous weak electric dipole moment of the W boson to study the process $pp(p\overline{p}) \to W^{\pm}Z^0X$. We compute the invariant mass spectrum of the WZ pair, and the total cross-section production.

Keywords: W boson, total cross-section production

Estudiamos el proceso de producción de bosones $pp(p\overline{p}) \to W^{\pm}Z^0X$ introduciendo un momento dipolar débil eléctrico anómalo del bosón W. Presentamos resultados para el espectro de masa invariante del par WZ, y la sección total de producción.

Descriptores: bosón W, sección total de producción

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1. Introduction

In a previous paper [1] we studied the effects of a possible anomalous W boson (weak)-electric dipole moment $\widetilde{\kappa}_V$ in $f_i\overline{f}_j \to WV$, where f_i and f_j are two members of an SU(2) doublet of elementary fermions in the standard model of electroweak unification (SM), and V is a photon or a neutral Z boson. We showed that the angular differential and the total cross-sections are sensitive to $\widetilde{\kappa}_V$ and that they are of the same order of magnitude than those contributions coming from the anomalous W boson (weak) magnetic dipole moment κ_V. The purpose of this paper is to report results for the effects of $\widetilde{\kappa}_V$ on the invariant mass of the WV pair and on the total cross-section in the hadronic reactions $pp\,(p\overline{p}) \to WZX$, where $p(\overline{p})$ is a proton (antiproton), and X denotes a final state hadron. We shall show that similar results as in [1] are obtained here.

To calculate the mass spectrum of the WV pair produced in pp or $p\overline{p}$ reactions, we write the angular differential cross-section at the quark level, $q_i\overline{q}_j$. If θ is the angle of the W boson with respect to quark q_i, we can write $t = a + bz$, where $a = -s(1-\varepsilon)/2$, $b = s\beta/2$, $z = \cos\theta$, and $\varepsilon = (M_W^2 + M_V^2)/s$, $\beta = \sqrt{(1-\varepsilon)^2 - 4M_W^2 M_V^2/s^2}$. Then, splitting in the sum of two terms, the angular differential cross-section at the quark level is given by

$$\frac{d\sigma(q_i\overline{q}_j \to WV)}{dz} = \left(\frac{d\sigma}{dz}\right)_{\text{SM}} + \left(\frac{d\sigma}{dz}\right)_{\text{NSM}}, \tag{1a}$$

with

$$\left(\frac{d\sigma}{dz}\right)_{\text{SM}} = \frac{2\pi\alpha^2\beta}{3s}\left(\frac{G^{ij}}{e}\right)^2 \Bigg\{ \left(\frac{se_V/e}{s-M_W^2}\right)^2 A(s,z) + \frac{2se_V/e}{s-M_W^2}\left[-\frac{g^j}{e}I(s,z,b) + \frac{g^i}{e}I(s,z,-b)\right] + \left(\frac{g^i-g^j}{e}\right)^2 E(s,z)$$
$$+ \left(\frac{g^i}{e}\right)^2 \frac{a^2 - b^2z^2 - M_W^2M_V^2}{(a-bz)^2} + \left(\frac{g^j}{e}\right)^2 \frac{a^2 - b^2z^2 - M_W^2M_V^2}{(a+bz)^2} + 2\left(\frac{g^ig^j}{e^2}\right)\frac{s(M_W^2 + M_V^2)}{a^2 - b^2z^2}\Bigg\}, \tag{1b}$$

the SM contribution,

$$\left(\frac{d\sigma}{dz}\right)_{\text{NSM}} = \frac{2\pi\alpha^2\beta}{3s}\left(\frac{G^{ij}}{e}\right)^2 \Bigg\{ (\kappa_V - 1)^2 \left[\frac{se_V/e}{2(s-M_w^2)}\right]^2 A_1(s,z)$$
$$+ (\kappa_V - 1)\frac{se_V/e}{s-M_w^2}\left[B(s,z) + \frac{g^j}{e}I_1(s,z,b) - \frac{g^i}{e}I_1(s,z,-b)\right] + \frac{3}{2}\widetilde{\kappa}_V^2\left[\frac{se_V/e}{2(s-M_w^2)}\right]^2 A_2(s,z)\Bigg\}, \tag{1c}$$

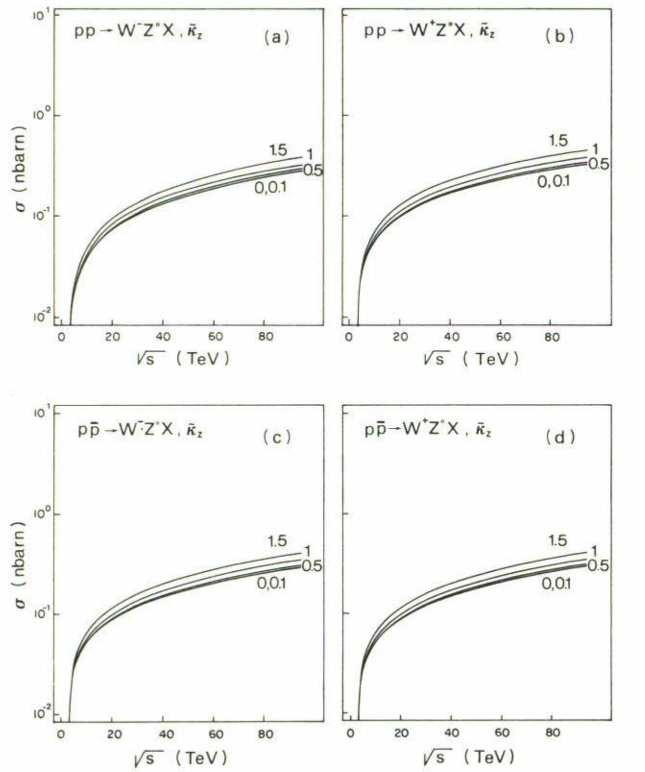

Figure 1. Invariant mass spectrum of the WZ pair for (a) $pp \to W^-Z^0X$, (b) $pp \to W^+Z^0X$, (c) $p\overline{p} \to W^-Z^0X$, and (d) $p\overline{p} \to W^+Z^0X$. We use $|Y| \leq 2.5$, and the center of mass energy is $\sqrt{S} = 20\ TeV$. Labels on curves denote values of $\widetilde{\kappa}_Z$.

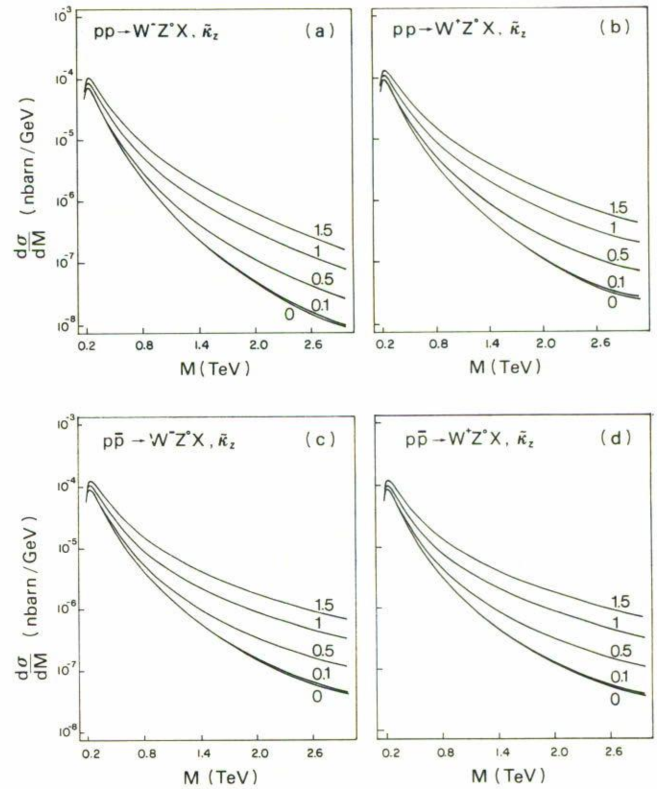

Figure 2. Total cross-section as a function of $\sqrt{S}$ for (a) $pp \to W^-Z^0X$, (b) $pp \to W^+Z^0X$, (c) $p\overline{p} \to W^-Z^0X$, and (d) $p\overline{p} \to W^+Z^0X$. Labels on curves denote values of $\widetilde{\kappa}_Z$.

for the non-standard model contribution. In Appendix A we give all the functions and parameters appearing in Eqs. (1a) to (1c).

The invariant mass of the WV pair ($V = \gamma$ or Z) is defined by $M = \sqrt{(p_1+p_2)^2}$, with $p_1^2 = M_W^2$, and $p_2^2 = M_V^2$. Denoting by $\sqrt{S}$ the total energy in the $pp(p\overline{p})$ center of mass reference system, we have that 0.2 TeV $\leq M \leq \sqrt{S}$. Then the differential cross-section for $pp(p\overline{p}) \to WZX$ is given by [2]

$$\frac{d\sigma(ab \to WZX)}{dM} = \frac{2M}{S}\sum_{i,j}\int_{-Y}^{Y} dy_b\Big[f_i^{(a)}(x_a, M^2)f_{\overline{j}}^{(b)}(x_b, M^2) + f_{\overline{j}}^{(a)}(x_a, M^2)f_i^{(b)}(x_b, M^2)\Big]\int_{-z_0}^{z_0} dz\frac{d\sigma(q_i\overline{q}_j \to WV)}{dz}. \tag{2}$$

Here $f_i^{(a)}(x_a, M^2)$ is the quark q_i distribution function inside hadron a, $f_{\overline{j}}^{(b)}(x_b, M^2)$ the corresponding one for quark q_j inside hadron b; $s = \tau S$, where τ is the scale factor defined by $x_{a,b} = e^{\pm y_b}\sqrt{\tau}$. The integration over y_b is performed assuming an interval $(Y, -Y)$, where Y is the so-called rapidity cut.

Integration in the variable z in Eq. (2) can be done analitically, but the one in y_b is performed numerically, since the quark distributions functions, given in Appendix B, are quite complicated. The results are shown in Fig. 1 for the case $V = Z$; we have used the Set 1 of Duke-Owens [3] for the distribution functions, and considered contributions from valence and sea u, d, c, and s quarks only. Fig. 1 shows that the contributions from $\widetilde{\kappa}_Z$ are similar than those coming from κ_Z, in the same interval of values [4].

Integrating Eq. (2) over M yields the total cross-section, and as a function of $\sqrt{S}$ is plotted in Fig. 2 for $2 \leq \sqrt{S} \leq 100$ in TeV, and $|Y| \leq 2.5$. Here again our results for $\widetilde{\kappa}_Z$ are similar to those coming from κ_Z.

In summary, in this work we have complemented previous results by us, for the posible effects of an anomalous (weak) electric dipole moment of the W boson. From the above results we observe that the contributions from $\widetilde{\kappa}_V$ are of the same order of magnitude than the corresponding results for κ_V, when both are in the range $(-2, 2)$. A final coment on this range of values is as follows. The origin of $\widetilde{\kappa}_V$ is related to the violation of the CP symmetry, and in the SM this comes from the interactions of the W boson with the quarks. Then a term like $\widetilde{\kappa}_V$ arise via radiative corrections, starting at the three-loop level [5], which means a very small value. Since κ_V is related to a CP-even property of the W boson, radiative corrections to its value at tree-level ($\kappa_V = 1$)start contributing from the one-loop level, leading to a value bigger than $\widetilde{\kappa}_V$. Then, within SM, the contributions from $\widetilde{\kappa}_V$ are suppressed compared to the contributions from κ_V for the kind of observables computed in this work [6]. A different situation occurs in the minimal supersymmetric SM, where the W boson could have a non-vanishing electric dipole moment through a one loop diagram mediated by the heavy massive charginos and neutralinos [7]. In composite models the situation can be less restrictive, since as is shown in [8] for κ_V, simple model calculations give a significative enhancement of one or two orders of magnitude for the radiative corrections. Thus, if the W boson turn out to be non-elementary, one can expect a $\widetilde{\kappa}_V$ of the order 10^{-1} and its contributions be not much supressed. Nevertheless, as we have shown in this work, only if $\widetilde{\kappa}_V$ is as big as in Figs. 1 and 2 its contributions are competitive regarding to the physical observables considered here. For smaller values of $\widetilde{\kappa}_V$ it is required a very great accumulation of data than is expected from the experiments now running in the Tevatron, and in the analogous experiments at LEP collider. As we have commented above a different situation emerges when we study the helicity amplitudes at the elementary fermion level [6].

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Appendix A

The various functions appearing in Eqs. (1b)–(1c) are:

$$A(s,z)=(c_0-1)\left[\left(\frac{1-\varepsilon}{2}\right)^2+\frac{2M_W^2M_V^2}{s^2}\right]+\frac{s^2\varepsilon}{M_W^2M_V^2}\left[\frac{1}{2}-\varepsilon+\frac{(M_W^2-M_V^2)^2}{2s^2}\right]+c_2\left[\left(\frac{1-\varepsilon}{2}\right)^2+\frac{2M_W^2M_V^2}{s^2}\right]z^2, \quad (A.1)$$

$$I(s,z,b)=\left(\frac{c_0-1}{4}+\frac{s^2\varepsilon}{2M_W^2M_V^2}+\frac{1}{2}\right)(1-\varepsilon)+\frac{\beta}{2}z+\frac{c_2(1-\varepsilon)}{4}z^2+\frac{s^2\varepsilon+M_W^2M_V^2}{s(a+bz)}, \quad (A.2)$$

$$E(s,z)=\frac{s^2\varepsilon}{2M_W^2M_V^2}+\frac{c_0-1}{4}\frac{c_2}{4}z^2, \quad (A.3)$$

$$A_1(s,z)=\frac{s\beta^2}{2M_W^2}+\frac{(2M_W^2-M_V^2+s)M_V^2}{2s^2}(c_0-1+c_2z^2), \quad (A.4)$$

$$B(s,z)=A_1(s,z)+\frac{(M_W^2-M_V^2+s)M_V^2}{2s^2}(c_0-1+c_2z^2), \quad (A.5)$$

$$I_1(s,z)=-\frac{s(1-\varepsilon)}{2M_W^2}+\frac{s\beta^2}{8M_W^2}\left(1+\frac{2M_W^2}{a+bz}\right)(1-z^2)-\frac{M_V^2}{a+bz}, \quad (A.6)$$

$$A_2(s,z)=\frac{1}{2}A_1(s,z)+\frac{M_V^4+2M_W^2s}{2s^2}-\frac{s\beta^2}{2M_W^2}+M_W^2M_V^2-s^2 2M_W^2M_V^2s^2a^2+\frac{\beta}{2s}z+\frac{\beta^2(s^2+M_W^2M_V^2)}{4M_W^2M_V^2}z^2, \quad (A.7)$$

and

$$c_0=\frac{s^2(1-\varepsilon)^2}{4M_W^2M_V^2}, \qquad c_2=1-c_0. \quad (A.8)$$

Appendix B

To evaluate Eq. (2) we use the following set of valence quark distribution functions:

$$u_v+d_v=N_{ud}\,x^{\eta_1-1}(1-x)^{\eta_2}(1+\gamma_{ud}\,x), \quad (B.1)$$

$$d_v=N_{ud}\,x^{\eta_3-1}(1-x)^{\eta_4}(1+\gamma_d\,x), \quad (B.2)$$

where

$$N_{ud}=3\left\{B(\eta_1,\eta_2+1)\left[1+\frac{\gamma_{ud}\,\eta_1}{(1+\eta_1+\eta_2)}\right]\right\}^{-1}, \quad (B.3)$$

$$N_d=\left\{B(\eta_3,\eta_4+1)\left[1+\frac{\gamma_d\,\eta_3}{(1+\eta_3+\eta_4)}\right]\right\}^{-1}. \quad (B.4)$$

B(x,y) is the Euler beta function. The sea quark distribution function are:

$$u_s = \overline{u}_s = d_s = \overline{d}_s = s_s = \overline{s}_s = \left(\tfrac{1}{6}\right) A_s x^{a-1}(1-x)^b \times (1 + \alpha x + \beta x^2 + \gamma x^3), \quad \text{(B.5)}$$

$$c_s = \overline{c}_s = A_c x^{a'-1}(1-x)^{b'} \times (1 + \alpha' x + \beta' x^2 + \gamma' x^3). \quad \text{(B.6)}$$

Here η_i $(i = 1,2,3,4)$, γ_{ud}, γ_d, A_s, A_c, a, b, a', b', α, β, γ, α', β', and γ' are functions of

$$r = \ln\left[\ln\left(\frac{M^2}{\Lambda^2}\right) \Big/ \ln\left(\frac{Q_0^2}{\Lambda^2}\right)\right], \quad \text{(B.7)}$$

where $\Lambda^2 = 0.04\ \text{GeV}^2$, and $Q_0^2 = 4.0\ \text{GeV}^2$. In Eq. (2) z_0 is related to y_b by

$$z_0 = \min\left[\beta_W^{-1} \tanh(Y - y_b), 1\right],$$

with

$$\beta_W = \beta\left[1 + \frac{M_W^2 - M_V^2}{s}\right]^{-1}.$$

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