LETTERS TO THE EDITOR

PAIR PRODUCTION W BOSONS IN $SU(2)_L \times SU(2)_R \times U(1)$ MODEL

By O. M. Boyarkin

University of Grodno, Ogheshko Street 22, 230023 Grodno, USSR

(Received July 26, 1989; revised version received January 11, 1990)

The differential and total cross sections of process $e^+e^- \to W_i^\dagger W_k$ are calculated in analytical form for the $SU(2)_L \times SU(2)_R \times U(1)$ model ($i, k = 1, 2$).

PACS numbers: 25.80.+f

The standard electroweak spontaneously broken gauge theory based on $SU(2)_L \times U(1)$ (SM) has been extremely successful in describing the known weak interaction experiments. However, there still exists a possibility that the correct electroweak gauge group is larger than $SU(2)_L \times U(1)$ but contains the latter as a subgroup. There may be an example of left-right symmetric (LRS) gauge theories based on $SU(2)_L \times SU(2)_R \times U(1)$ [1]. A LRS theory is attractive since it allows spontaneous breakdown of parity. Its gauge group can appear as intermerdiate gauge structure within a grand unified theory. It is known that the trilinear boson couplings (TBC) are fixed by the choice of group symmetry. In LRS theory TBC are different from those of SM. The deviations from SM prediction will produce observable signatures in quark-antiquark annihilation into $W^+ W^-$, $W^\pm \gamma$ at hadron colliders. However, a particularly clean process for probing TBC is the process

$$e^+e^- \to W^+W^- \tag{1}$$

which will be accessible at CERNs LEP II.

Many papers (see [2] having detailed references) are devoted to cross section calculation of process (1). But the cross section is known in analytical form only in SM, and in the theory based on $SU(2)_L \times U(1) \times U'(1)$ gauge group [3]. All other cases have only numerical results. In this paper we find analytical expressions for differential and total cross sections of process (1) in LRS theory proposed in [4]. In this theory the neutral current Lagrangian for electrons is

$$\mathscr{L} = -ie\bar{\psi}\gamma_\mu\left[A_\mu - \frac{1}{2\sin\theta_0}\sum_{i=1}^{2}(P_i\gamma_5+2V_i\sin\theta_0\operatorname{ctg}2\theta_0)Z_{i\mu}\right]\psi, \tag{2}$$

where $P_1 = V_2 = \cos\theta_N$, $-P_2 = V_1 = \sin\theta_N$, θ_N is the mixing angle of the neutral bosons. The photon and the neutral $Z_{1,2}$ bosons can be written in terms of W_3^L and W_3^R and the U(1) gauge boson B as

$$\begin{bmatrix} Z_1 \\ A \\ Z_2 \end{bmatrix} = \begin{bmatrix} \dfrac{\cos\theta_N+\sin\theta_N\cos\theta_0}{\sqrt{2}} & -\sin\theta_N\sin\theta_0 & \dfrac{-\cos\theta_N+\sin\theta_N\cos\theta_0}{\sqrt{2}} \\ \dfrac{\sin\theta_0}{\sqrt{2}} & \cos\theta_0 & \dfrac{\sin\theta_0}{\sqrt{2}} \\ \dfrac{-\sin\theta_N+\cos\theta_N\cos\theta_0}{\sqrt{2}} & -\cos\theta_N\sin\theta_0 & \dfrac{\sin\theta_N+\cos\theta_N\cos\theta_0}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} W_3^L \\ B \\ W_3^R \end{bmatrix}. \tag{3}$$

The charged-current Lagrangian is

$$\mathscr{L}_{\text{C.C.}} = \frac{ig}{2\sqrt{2}}\bar{\psi}\gamma_\mu[(1+\gamma_5)W_\mu^L+(1-\gamma_5)W_\mu^R]\nu_e, \tag{4}$$

where $g = \sqrt{2}\,e/\sin\theta_0$. The mass eigenstates W_1 and W_2 are

$$W_{1\mu} = W_\mu^L\cos\theta_C - W_\mu^R\sin\theta_C,$$

$$W_{2\mu} = W_\mu^L\sin\theta_C + W_\mu^R\cos\theta_C. \tag{5}$$

Now, after straightforward (though somewhat tedious) calculations we obtain the following expression for the Lagrangian interaction describing the TBC

$$\mathscr{L}_{W\gamma Z} = -\frac{ie}{2}\left[W_{j\mu\nu}^*\left(\delta_{ij}A_\nu + \frac{1}{\sin\theta_0}\varrho_{ji}^{(l)}Z_{l\nu}\right)\right.$$

$$\left. + W_{j\nu}^*\left(\delta_{ji}A_{\nu\mu} + \frac{1}{\sin\theta_0}\varrho_{ji}^{(l)}Z_{l\nu\mu}\right)\right]W_{i\mu}, \tag{6}$$

where $j, i, l = 1, 2$,

$$\varrho_{ii}^{(1)} = \sin\theta_N\cos\theta_0 + (-1)^{i+1}\cos\theta_N\cos 2\theta_C,$$

$$\varrho_{ii}^{(2)} = \cos\theta_N\cos\theta_0 - (-1)^{i+1}\sin\theta_N\cos 2\theta_C,$$

$$\varrho_{12}^{(1)} = \varrho_{21}^{(1)} = \cos\theta_N\sin 2\theta_C,$$

$$\varrho_{12}^{(2)} = \varrho_{21}^{(2)} = -\sin\theta_N\sin 2\theta_C. \tag{7}$$

This theory reduces to the SM for $\varepsilon \ll 1 (\varepsilon = m_{Z_1}^2/m_{Z_2}^2)$ and $\sin^2\theta_0 = 2^0 \sin^2\theta_W$ with corrections of order ε [5]. From the expression (6) if tollows that in the LRS theory the weak dipole (μ_Z) and connected with them quadrupole (Q_Z) moments are different from those in SM while there is still $\mu_\gamma = (\mu_\gamma)_{SM}$. We have

$$\mu_{Z_l}^{(W_iW_j)} = \frac{e\varrho_{ij}^{(l)}}{2m_i \sin\theta_0} \quad \text{and} \quad Q_{Z_l}^{(W_iW_j)} = \frac{-e\varrho_{ij}^{(l)}}{m_i^2 \sin\theta_0} \quad \text{where } m_{W_i} = m_i.$$

We remind that the the angles θ_N, θ_C, θ_0 are defined by the vacuum expectation values of Higgs-fields.

It is convenient to begin the cross section of process (1) calculations for the case $e^+e^- \to W_1^+W_2^-$ (for this process the one-photon channel is closed). For the differential cross section of unpolarized particles we obtain the following expression (in the center-of-mass system)

$$d\sigma^{(12)} = \frac{\alpha^2\beta}{8x^2 s} \sum_{k,n} M_{kn} d\Omega, \tag{8}$$

where $k, n = Z_1, Z_2, \nu$, $x = \sin^2\theta_0$, $s = (p_{W_1}^+ + p_{W_2}^-)^2$, $t = (p_{W_1}^+ - p_e^+)^2$,

$$\beta = 2|\vec{p}_{W_1}^{\,+}|/\sqrt{s}, \qquad \varphi = \sphericalangle\,(\vec{p}_{W_1}^{\,+}\,\hat{,}\,\vec{p}_e^{\,+}), \qquad \kappa = 2\sin\theta_0 \operatorname{ctg} 2\theta_0,$$

$$M_{Z_iZ_i} = \frac{\varrho_{12}^{(i)}\varrho_{12}^{(j)}(P_iP_j + V_iV_j\kappa^2)s^2}{4(-s+m_{Z_i}^2)(-s+m_{Z_j}^2)} N_1(m_1, m_2),$$

$$M_{Z_i\nu} = \frac{\varrho_{12}^{(i)} P_i s \sin 2\theta_C}{8(-s+m_{Z_i}^2)} N_2(m_1, m_2),$$

$$M_{\nu\nu} = \tfrac{1}{2}\sin^2 2\theta_C N_3(m_1, m_2),$$

$$N_1(m_1, m_2) = \beta^2 \sin^2\varphi \left[\left(\frac{s}{2m_1m_2}\right)^2 - \frac{m_1^2+m_2^2}{4m_1^2m_2^2}(2s - m_1^2 - m_2^2) + 2\right]$$

$$+4\frac{m_1^2+m_2^2}{m_1^2m_2^2}\left(\frac{s}{2} - m_1^2 - \frac{2}{2}\right) + 4\frac{(m_1^4 - m_2^4)(m_1^2 - m_2^2)}{sm_1^2m_2^2},$$

$$N_2(m_1, m_2) = \tfrac{1}{2}\beta^2 \sin^2\varphi \left[\left(\frac{s}{m_1m_2}\right)^2 - 4\frac{s}{t} - \frac{s(m_1^2+m_2^2)}{m_1^2m_2^2}\right]$$

$$+4\frac{m_1^2+m_2^2}{m_1^2m_2^2}(s - m_1^2 - m_2^2) + 8\frac{m_1^2+m_2^2}{t},$$

$$N_3(m_1, m_2) = \tfrac{1}{2}\beta^2 \sin^2\varphi \left[\left(\frac{s}{2m_1m_2}\right)^2 + \left(\frac{s}{t}\right)^2\right] + \frac{s(m_1^2+m_2^2)}{m_1^2m_2^2}.$$

The expressions for the total cross section $\sigma_T^{(12)}$ follows from (8) by replacement $N_{1,2,3} \to 2\pi D_{1,2,3}$ where

$$D_1(m_1, m_2) = \tfrac{1}{3}\beta^2\left(\frac{s}{m_1 m_2}\right)^2 + \frac{s(m_1^2+m_2^2)}{m_1^2 m_2^2}\Bigg) 4 - \tfrac{2}{3}\beta^2 - 8\,\frac{m_1^2+m_2^2}{s}\Bigg)$$

$$+\tfrac{1}{3}\beta^2\left[8+\frac{(m_1^2+m_2^2)^2}{m_1^2 m_2^2}\right]+4\,\frac{(m_1^4-m_2^4)(m_1^2-m_2^2)}{s m_1^2 m_2^2},$$

$$D_2(m_1, m_2) = \tfrac{2}{3}\beta^2\left(\frac{s}{m_1 m_2}\right)^2 - \tfrac{2}{3}\beta^2\,\frac{s(m_1^2+m_2^2)}{m_1^2 m_2^2}$$

$$+8\,\frac{m_1^2+m_2^2}{m_1^2 m_2^2}(s-m_1^2-m_2^2)+8\,\frac{s-m_1^2-m_2^2}{s}$$

$$+\frac{4L}{\beta s}\left[\frac{\beta^2 s^2-(s-m_1^2-m_2^2)^2}{s}-4(m_1^2+m_2^2)\right],$$

$$D_3(m_1, m_2) = \tfrac{1}{6}\beta^2\left(\frac{s}{m_1 m_2}\right)^2 + 2\,\frac{s(m_1^2+m_2^2)}{m_1^2 m_2^2} + 4L\left(\frac{s-m_1^2-m_2^2}{\beta s}\right) - 8,$$

$$L = \ln\left|\frac{2p\sqrt{s}+s-m_1^2-m_2^2}{-2p\sqrt{s}+s-m_1^2-m_2^2}\right|, \qquad p = |\vec{p}_{W_1}^{\,+}|.$$

From the expression for $\sigma_T^{(12)}$ we can see that the linar and constant terms (in s) cancel out so that unitary bound is not a problem, i.e. $(s \to \infty)$ $\sigma_T^{(12)} \sim \dfrac{\ln s}{s}$.

For the differential cross section of processes $e^+e^- \to W_i^+W_i^-$ we obtain the following expression

$$d\sigma^{(ii)} = \frac{\alpha^2\beta}{8x^2 s}\sum_{k,n} M_{k,n}^{(ii)}\,d\Omega, \tag{9}$$

where

$$k, n = Z_1, Z_2, \gamma, \nu,$$

$$M_{Z_j Z_l}^{(ii)} = \frac{\varrho_{ii}^{(j)}\varrho_{ii}^{(l)}(P_j P_l + V_j V_l \kappa^2)s^2}{4(-s+m_{Z_j}^2)(-s+m_{Z_l}^2)}\,N_1(m_i, m_i),$$

$$M_{\gamma\gamma}^{(ii)} = x^2 N_1(m_i, m_i), \qquad M_{\nu\gamma}^{(ii)} = -\tfrac{1}{4}\,x N_2(m_i, m_i),$$

$$M_{Z_j\gamma}^{(ii)} = \frac{\varrho_{ii}^{(j)}(P_j\cos 2\theta_C + V_j\kappa)s}{8(-s+m_{Z_j}^2)}\,N_2(m_i, m_i),$$

$$M^{(ii)}_{\gamma\gamma} = (1-\tfrac{1}{2}\sin^2 2\theta_C)N_3(m_i, m_i),$$

$$M^{(ii)}_{Z_j\gamma} = \frac{-\varrho^{(j)}_{ii}V_j\kappa s}{2(-s+m^2_{Z_j})}N_1(m_i, m_i).$$

The total cross section $\sigma^{(ii)}_T$ can be obtained from (9) by substitution $N_{1,2,3}(m_i, m_i) \to 2\pi D_{1,2,3}(m_i, m_i)$. From the expressions for $\sigma^{(11)}_T$ and $\sigma^{(22)}_T$ we see that each of them does not contradict the unitary bounds.

REFERENCES

[1] J. C. Pati, A. Salam, *Phys. Rev.* **D10**, 275 (1974); R. Mohapatra, J. C. Pati, *Phys. Rev.* **D11**, 566 (1975).
[2] K. Hagiwara, R. Peccei, D. Zeppenfeld, K. Hikasa, *Nucl. Phys.* **B282**, 253 (1987).
[3] T. G. Rizzo, *Phys. Rev.* **D36**, 713 (1987).
[4] D. P. Sidhu, *Phys. Rev.* **D22**, 1158 (1980).
[5] M. Cvetic, B. W. Lynn, *Phys. Rev.* **D35**, 51 (1987).