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$Z \to b\bar{b}$ PROBABILITY AND ASYMMETRY IN A MODEL OF DYNAMICAL ELECTROWEAK SYMMETRY BREAKING

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The deviations from the Standard Model in the probability of $Z \to b\bar{b}$ decay and in the forward-backward asymmetry in the reaction $e^+e^- \to b\bar{b}$ are studied in the framework of the model of dynamical electroweak symmetry breaking, the basic point of which is the existence of a triple anomalous W-boson vertex in a region of momenta restricted by a cutoff Λ. We obtain a set of equations for additional terms in the $Wb\bar{t}$ vertex and apply its solution to the process $Z \to b\bar{b}$. We show that it is possible to obtain a consistent description both deviations, which is quite nontrivial because these effects are not simply correlated. The necessary value of the anomalous W interaction coupling, $\lambda = -0.22 \pm 0.01$, is consistent with existing limitations and leads to definite predictions, e.g., for pair W production in e^+e^- collisions at LEP200.

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It is well known that the Standard Model (SM) of the electroweak (EW) interaction is in very good shape in respect to experimental checks, the only dubious points consisting in two effects which are both connected with the $b\bar{b}$ final state. Namely, experiment gives for the probability ratio $R_b = 0.2178 \pm 0.0011$ as compared to the SM value 0.2158 and for the forward-backward asymmetry $A^b_{FB} = 0.0979 \pm 0.0023$ as compared to the SM value 0.1022 [1]. The relative discrepancies are as follows:

$$\Delta_b = \frac{R_b(\mathrm{exp}) - R_b(\mathrm{th})}{R_b(\mathrm{th})} = 0.009 \pm 0.005\,,$$
$$\Delta_{FB} = \frac{A^b_{FB}(\mathrm{exp}) - A^b_{FB}(\mathrm{th})}{A^b_{FB}(\mathrm{th})} = -0.042 \pm 0.023\,. \qquad (1)$$

In the present note we consider whether one can explain these deviations as something other than purely statistical fluctuations. Note that two independent deviations of 1.8 standard deviations each have a rather small probability of being a statistical fluctuation. For the present purpose we consider the version of EW theory in which the symmetry breaking is due to a self-consistent appearance of an additional triple gauge boson vertex in the region of small momenta [2, 3]. This vertex can be described by the following expression in momentum space, which, according to the approach taken, acts in a region limited by an effective cutoff Λ which is of the order of magnitude of a few TeV [4, 5]:

$$\Gamma^{abc}_{\mu\nu\rho}(p,q,k) = \epsilon^{abc}\,\frac{i\lambda g}{M_W^2}\,F(p^2,q^2,k^2)\,\Gamma_{\mu\nu\rho}(p,q,k)\,,$$
$$\Gamma_{\mu\nu\rho}(p,q,k) = g_{\mu\nu}(p_\rho(qk) - q_\rho(pk)) + g_{\nu\rho}(q_\mu(pk) - k_\mu(pq)) +$$
$$+\, g_{\rho\mu}(k_\nu(pq) - p_\nu(qk)) + k_\mu p_\nu q_\rho - q_\mu k_\nu p_\rho\,. \qquad (2)$$

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$$F(p^2,q^2,k^2) = \frac{\Lambda^6}{(\Lambda^2-p^2)(\Lambda^2-q^2)(\Lambda^2-k^2)}.$$

Note that this term, among others, is currently considered [6, 7] in the phenomenological analysis of possible gauge boson interactions. Vertex (2) leads to the generation of masses for the W and Z [2, 3], with $|\lambda|$ being a few tenths of a TeV and Λ being of the order of a few TeV. The mass generation for the t quark in this approach is connected with the other self-consistent vertex, having a Lorentz–Dirac structure of the anomalous magnetic moment of the t quark [3, 4]:

$$\Gamma^t_\mu(p,q,k) = \frac{ie\kappa}{2M_t} F(p^2,q^2,k^2)\,\sigma_{\mu\nu}\,k_\nu\,, \tag{3}$$

where $F(p^2,q^2,k^2)$ is the same form factor as in vertex (2), and k_ν is the photon momentum. The corresponding solution gives κ to be around unity, and an experimental limitation $|\kappa| \le 1$ is derived from the t production data in Ref. [4].

Adding anomalous vertices (2), (3) to the usual ones, we formulate equations for another anomalous vertex for the $\bar{t}Wb$ interaction. Let us look for it in the form

$$\Gamma^{tb}_\rho(p,q,k) = \frac{ig}{2M_t} F_m(p^2,k^2)\,\sigma_{\rho\omega}\,k_\omega\left(\xi_+(1+\gamma_5)+\xi_-(1-\gamma_5)\right), \tag{4}$$

where p and q are, respectively, the t-quark and b-quark momenta, k is the W momentum, and the form factor

$$F_m(p^2,k^2) = \frac{\Lambda^4}{(\Lambda^2-p^2)(\Lambda^2-k^2)}.$$

We assume that not only left-handed b quarks but possibly also right-handed ones take part in the interaction. Due to the gauge invariance there is, in addition to (4), a four-leg $\bar{t}\,b\,W^+W^0$ vertex

$$\Gamma^{tb}_{\mu\nu}(p,k_1,k_2) = \frac{i\,g^2}{2M_t} F(p,k_1^2,k_2^2)\,\sigma_{\mu\nu}\left(\xi_+(1+\gamma_5)+\xi_-(1-\gamma_5)\right); \tag{5}$$

where μ and ν are, respectively, the indices of W^+ and W^0, and p, k_1, and k_2 are the momenta of the t quark and of the same bosons, respectively.

We consider equations for vertex (4) in the one-loop approximation. This means that we take the following equation (written in a schematic form):

$$\begin{aligned}\Gamma^{tb} = \Gamma^{tb}_0 &+ \Big(\Gamma_0(bbA)\,\Gamma^{tb}\,\Gamma(WWA)\Big) + \Big(\Gamma_0(bbZ)\,\Gamma^{tb}\,\Gamma(WWZ)\Big) + \\ &+ \Big(\bar\Gamma^{tb}_0\,\Gamma^t\,\Gamma(WWA)\Big) + \Big(\Gamma^{tb}\,\Gamma^t\,\Gamma_0(WWA)\Big) + \Big(\Gamma^{tb}\,\Gamma^t\,\Gamma(WWA)\Big) + \\ &+ \Big(\Gamma^{tb}\,\Gamma_0(ttZ)\,\Gamma(WWZ)\Big) + \Big(\Gamma^{tb}\,\Gamma_0(ttA)\,\Gamma(WWA)\Big) + \\ &+ \Big(\Gamma^{tb}(WA)\,\Gamma(WWA)\Big) + \Big(\Gamma^{tb}(WZ)\,\Gamma(WWZ)\Big) + \Big(\Gamma^{tb}(WA)\,\Gamma^t\Big).\end{aligned} \tag{6}$$

Here a subscript zero means the corresponding SM vertex and, e.g., $\Gamma(WWA)$ means vertex (2) for the interaction of two W bosons and a photon (factor $\sin\theta_W$). The symbol $\Gamma^{tb}(..)$ means vertex (5) with the corresponding vector bosons. The new vertex

$$\bar\Gamma^{tb}_{0\alpha} = \frac{g}{2\sqrt{2}}\gamma_\alpha\left(\eta_+(1+\gamma_5)+\eta_-(1-\gamma_5)\right) \tag{7}$$

is introduced for the purpose of taking into account the contributions of loop diagrams to different matrix structures. We have of course the corresponding propagators between vertices and the usual momentum integration with a factor of $(2\pi)^{-4}$. All ten one-loop terms diverge quadratically if one neglects the form factors mentioned above. The integrations in loop diagrams (6) are performed with the use of Wick rotation in Euclidean momentum space. Taking the form factors into account, we obtain a finite result, which reads

$$\begin{aligned}
\eta_+ &= 1 - \frac{\sqrt{2}}{8}\kappa K \xi_+ \left(\frac{1}{4} + \frac{\lambda}{5\cos^2\theta_W}\right), \qquad \eta_- = -\frac{\sqrt{2}}{8}\kappa K \xi_- \left(\frac{1}{4} + \frac{\lambda}{5\cos^2\theta_W}\right),\\
\xi_+ &= -\frac{\lambda C \kappa \eta_+}{24\sqrt{2}\,F_1}, \qquad \xi_- = \frac{\lambda C K \kappa^2}{192\,F_2}\xi_- \left(\frac{1}{4} + \frac{\lambda}{5\cos^2\theta_W}\right),\\
F_1 &= 1 - \lambda C\left(\frac{\kappa}{40} - \frac{7}{48\sin^2\theta_W}\right), \qquad C = \frac{\alpha\Lambda^2}{\pi M_W^2},\\
F_2 &= 1 - \lambda C\left(\frac{\kappa}{40} - \frac{1}{8\sin^2\theta_W}\right), \qquad K = \frac{\alpha\Lambda^2}{\pi M_t^2}.
\end{aligned} \tag{8}$$

From set (8) one concludes that there can be two types of solutions. The first one could be called a trivial solution; that is, it corresponds to

$$\xi_- = 0. \tag{9}$$

However a non-zero solution may also exist, provided that the following condition is fulfilled:

$$\frac{\lambda\,\kappa^2 C K}{192 F_2}\left(\frac{1}{4} + \frac{\lambda}{5\cos^2\theta_W}\right) = 1. \tag{10}$$

This condition gives a relation among the parameters of the model. Namely, using formulas (8) and (10), we get

$$\begin{aligned}
\lambda &= 5\cos^2\theta_W\left(\frac{24}{\sin^2\theta_W} - \frac{24\,\kappa}{5} - \frac{\kappa^2 K}{4}\right)\frac{1-\sqrt{1+A}}{2\,\kappa^2 K},\\
A &= \frac{768\,\kappa^2 M_Z^2}{5M_t^2}\left(\frac{24}{\sin^2\theta_W} - \frac{24\,\kappa}{5} - \frac{\kappa^2 K}{4}\right)^{-2}, \qquad \xi_+ = -\sqrt{2}\,\kappa\sin^2\theta_W\,.
\end{aligned} \tag{11}$$

Now we use the relations obtained to evaluate the vertex $Z\bar{b}b$. We have for this vertex the symbolic one-loop representation

$$\begin{aligned}
\Gamma^b &= \Gamma^b_0 + \left(\Gamma^{tb}\,\Gamma^t_0\,\Gamma^{tb}\right) + \left(\Gamma^{tb}\,\Gamma_0(WWZ)\,\Gamma^{tb}\right) +\\
&+ \left(\Gamma^{tb}\,\Gamma(WWZ)\,\Gamma^{tb}\right) + \left(\Gamma^{tb}_0\,\Gamma(WWZ)\,\Gamma^{tb}\right) +\\
&+ \left(\Gamma^{tb}\,\Gamma(WWZ)\,\Gamma^{tb}_0\right) + \left(\Gamma^{tb}(WZ)\,\Gamma^{tb}\right) + \left(\Gamma^{tb}\Gamma^{tb}(WZ)\right).
\end{aligned} \tag{12}$$

Here the vertex Γ^b has the form

$$\Gamma^b_\rho = \frac{g}{2\cos\theta_W}\left(a\,\gamma_\rho + b\,\gamma_\rho\gamma_5 + c\,i\,\sigma_{\rho\mu}k_\mu\right). \tag{13}$$

Performing again the usual loop calculations, we have for the vertex

$$a = a_0 + a_1\,, \quad b = b_0 + b_1\,, \quad a_0 = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W\,, \quad b_0 = -\frac{1}{2}\,,$$

$$a_1 = \frac{\xi_+^2 K}{4}\left(-\frac{1}{3} + \left(\frac{\sin^{-2}\theta_W}{4} - \frac{1}{3}\right)R^2 - \cot^2\theta_W(1+R^2) + \sin^{-2}\theta_W(1+R^2)\frac{\lambda}{5}\right),$$

$$b_1 = \frac{\xi_+^2 K}{4}\left(-\frac{1}{3} - \left(\frac{\sin^{-2}\theta_W}{4} - \frac{1}{3}\right)R^2 - \cot^2\theta_W(1-R^2) + \sin^{-2}\theta_W(1-R^2)\frac{\lambda}{5}\right),$$

$$c = \frac{\lambda K M_t}{2M_W^2}\cot^2\theta_W\, R\left(\frac{\xi_+^2}{5} - \frac{\xi_+}{3\sqrt{2}}\right), \quad R = \frac{\xi_-}{\xi_+}. \tag{14}$$

Using vertex expression (13) and results (14), we obtain the following asymmetries Δ_b and Δ_{FB}, which we define as the relative differences of our results and the SM calculations, to be compared with the experimental numbers (1):

$$\Delta_b = \frac{1}{a_0^2+b_0^2}\left(2(a_0a_1+b_0b_1)+a_1^2+b_1^2+\frac{M_Z^2}{2}c^2\right), \quad \Delta_{FB} = \frac{\xi_1-\xi_2}{1+\xi_2},$$

$$\xi_1 = \frac{12(a_1b_0+a_0b_1+a_1b_1)}{3-4\sin^2\theta_W}, \tag{15}$$

$$\xi_2 = \frac{72(a_0a_1+b_0b_1)+36(a_1^2+b_1^2)+45c^2M_Z^2}{(3-4\sin^2\theta_W)^2+9}.$$

Let us compare results (15) with data (1). Let us first take solution (9), i.e., $R=0$. Then the signs of both deviations (1) are negative throughout the entire range of variation of our parameters. For example, for $K = 1.74$ (which corresponds to $\Lambda = 4.5$ TeV [4]; this is the value that we shall use in what follows), $\lambda = 0.5$, and $\xi_+ = 0.04$ we have

$$\Delta_b = -0.01; \qquad \Delta_{FB} = -0.0007.$$

Taking different values of the parameters, we become convinced that there is no way to obtain a comparatively large Δ_{FB} and a positive Δ_b, as the data (1) indicate.

Let us now turn to the nontrivial solutions (10). According to (11), for admissible values of κ, viz., $-1 < \kappa < 1$ (Ref. [4]), one has

$$-0.23 < \lambda < -0.21. \tag{16}$$

These numbers are in no way inconsistent with the experimental limitations [8, 9]. Relation (16) specifies λ to good accuracy. In addition to λ and K, which is already determined, we also have the parameters R and ξ_+. For the nontrivial solution $\xi_- \neq 0$ the ratio R is arbitrary. The parameter ξ_+ is connected with the effective anomalous magnetic moment κ of the t quark (10). Now we take $\lambda = -0.22$ and present in Table the dependence of deviations (1) on $|R|$ ($2.0 < |R| < 3.2$) and $\xi_+(-0.05 < \xi_+ < -0.03)$.

Δ_b (upper lines) and Δ_{FB} (lower lines) for different values of $|R|$ (rows) and ξ_+ (columns)

	-0.05	-0.045	-0.04	-0.035	-0.03
2.0	0.008	0.003	0.002	0.001	0.001
	-0.038	-0.031	-0.024	-0.018	-0.013
2.3	0.01	0.008	0.006	0.004	0.003
	-0.051	-0.041	-0.032	-0.024	-0.017
2.6	0.018	0.014	0.010	0.008	0.005
	-0.067	-0.053	-0.041	-0.031	-0.022
2.9	0.027	0.021	0.016	0.011	0.008
	-0.085	-0.067	-0.052	-0.039	-0.028
3.2	0.038	0.029	0.022	0.016	0.011
	-0.105	-0.083	-0.064	-0.048	-0.034

We see that quite acceptable numbers are concentrated around the main diagonal of the table. For example, for

$$|R| = 2.45, \qquad \xi_+ = -0.043 \tag{17}$$

the numbers hit precisely the center values of (1). We conclude that for the nontrivial solution (10) it is possible to obtain agreement with both numbers (1). This result is by no means obvious — we recall that for the trivial solution agreement is impossible. The important qualitative feature of our result is the presence of a large contribution of right-handed b quarks to the anomalous vertex (see (4), (7)). This modified vertex gives a number of predictions. For example, the t-quark width now reads

$$\Gamma_t = \Gamma_0\,(1 + \Delta), \tag{18}$$

$$\Gamma_0 = \frac{g^2\,(M_t^2 - M_W^2)^2\,(2M_W^2 + M_t^2)}{64\pi M_t^3 M_W^2},$$

$$\Delta = -\frac{6\sqrt{2}M_W^2\xi_+}{2M_W^2 + M_t^2} + \frac{K\,\beta\,\xi_+^2}{4\sin^2\theta_W} + \frac{2M_W^2(2M_t^2 + M_W^2)\,\xi_+^2(1+R^2)}{M_t^2(2M_W^2 + M_t^2)} +$$

$$+ \frac{3KM_W^2\beta\,\xi_+^3(1+R^2)}{2\sqrt{2}\sin^2\theta_W\,(2M_W^2 + M_t^2)} + \frac{K^2\beta^2\xi_+^4(1+R^2)}{64\sin^4\theta_W}, \tag{19}$$

$$\beta = \left(\frac{1}{4} + \frac{\lambda}{5\cos^2\theta_W}\right).$$

Here Γ_0 is the SM value, and if we take the parameter values (17), we find from (19) that $\Delta = 0.062$, i.e., more than a 6% effect is predicted for the t-quark width.

As to possible values for λ (16), this prediction could be checked at LEP200 [10], provided that the necessary integral luminosity is accumulated in the study of reaction $e^+ + e^- \to W^+ + W^-$.

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Note added in proof. The last experimental limitation $-0.31 < \lambda < 0.29$ [11], being consistent with our prediction (16), demonstrates, that the experimental accuracy approaches the necessary level.

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