Doubling of Weak Gauge Bosons in an Extension of the Standard Model

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The standard SU(2)⊗U(1) model is extended to include two W and two Z bosons without changing the structure of its low-energy phenomenology. The experimental implications of this model regarding the existence of a light W and a light Z are discussed.

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The success of the standard SU(2)⊗U(1) model[1] in explaining all of weak-interaction phenomena at presently available energies is now well established.[2] However, to the extent that the W and Z gauge bosons and the Higgs boson are yet to be discovered, the model is not completely tested. In fact, predictions at low energies can be essentially the same as in the standard model for a large class of models[3,4] with two or more Z's. Recently, the phenomenology of a specific model with two Z's has been discussed.[4,5] In this Letter we discuss a similar model[6,7] with double the number of charged and neutral gauge bosons of the standard model. The model has the remarkable property that the relative strength of the neutral-current coupling to the charged-current coupling at low energies is still naturally the same as in the standard model. At high eneriges, the salient feature of this model is the existence of a W_1, which is lighter than the W, as well as a Z_1, which is lighter than the Z.

We consider the gauge group SU(2)⊗U(1)⊗SU(2)′ with couplings g_0, $\frac{1}{2}g_1$, and g_2, respectively. All quarks and leptons transform as in the standard model, with respect to the SU(2)⊗U(1) subgroup only. In addition to the usual Higgs doublet $\varphi=(\varphi^+, \varphi^0)$ in the representation $(\frac{1}{2}, 1, 0)$, let there be a Higgs quartet $\eta=(\eta^+, \eta_1^0, \eta_2^0, \eta^-)$ in the representation $(\frac{1}{2}, 0, \frac{1}{2})$. The spontaneous breakdown of the SU(2)⊗U(1)⊗SU(2)′ symmetry to U(1) occurs with $\langle\varphi^0\rangle=v$ and $\langle\eta_1^0\rangle=\langle\eta_2^0\rangle=v'$. This pattern of symmetry breaking can be guaranteed with the imposition of a discrete symmetry in the Higgs potential; the details will be given elsewhere. Then there are five basic parameters in this model, namely, g_0, g_1, g_2, v, and v', and all gauge-boson masses and interactions are expressible in terms of them. A straightforward calculation[7] shows that

$$e^2=g_0^2g_1^2g_2^2[g_0^2g_2^2+g_1^2(g_0^2+g_2^2)]^{-1}, \tag{1}$$

$$G_F/\sqrt{2}=1/4v^2, \tag{2}$$

and

$$\sin^2\theta_W=g_1^2(g_0^2+g_2^2)[g_0^2g_2^2+g_1^2(g_0^2+g_2^2)]^{-1}, \tag{3}$$

where the expression for $\sin^2\theta_W$ is deduced by comparison with the effective Lagrangian of the standard model at low energies. With these experimental constraints, two free parameters remain to determine the four gauge-boson masses. Eliminating these free parameters, two equalities are obtainted[6,7]:

$$M_{W_1}M_{W_2}=M_{Z_1}M_{Z_2}\cos\theta_W, \tag{4}$$

$$M_{W_1}^2+M_{W_2}^2+M_W^2\tan^2\theta_W=M_{Z_1}^2+M_{Z_2}^2. \tag{5}$$

Furthermore, several mass inequalities can be derived. The masses bracket the W and Z masses of the standard model:

$$M_{W_1}<M_W<M_{W_2}, \quad M_{Z_1}<M_Z<M_{Z_2}, \tag{6}$$

where $M_W=eG_F^{-1/2}/(2^{5/4}\sin\theta_W)$ and $M_Z=M_W/\cos\theta_W$. The masses are ordered in the sequence

$$M_{W_1}<M_{Z_1}<M_{W_2}<M_{Z_2} \tag{7}$$

and satisfy the constraints

$$M_{Z_1}\cos\theta_W<M_{W_1}<M_{Z_1}, \quad M_{Z_2}\cos\theta_W<M_{W_2}<M_{Z_2}. \tag{8}$$

Since $\cos\theta_W\simeq 0.88$ (from $\sin^2\theta_W=0.23$), the mass of W_1 is close to that of Z_1 and the mass of W_2 is similar to that of Z_2.

The gauge bosons W_1 and W_2 are coupled to the left-handed charged current

$$j_\mu^{(+)} = \bar{\nu}\gamma_\mu[\tfrac{1}{2}(1-\gamma_5)]e + \bar{u}\gamma_\mu[\tfrac{1}{2}(1-\gamma_5)]d + \cdots \tag{9}$$

according to

$$\mathcal{H}_{CC} = (4G_F/\sqrt{2})^{1/2}\left\{\frac{M_{W_1}^2}{M_W}\left(\frac{M_{W_2}^2 - M_W^2}{M_{W_2}^2 - M_{W_1}^2}\right)^{1/2} W_{1\mu}^+ + \frac{M_{W_2}^2}{M_W}\left(\frac{M_W^2 - M_{W_1}^2}{M_{W_2}^2 - M_{W_1}^2}\right)^{1/2} W_{2\mu}^+\right\} j_\mu^{(+)} + \text{H.c.} \tag{10}$$

The gauge bosons Z_1 and Z_2 are coupled to the currents

$$j_\mu^{(3)} = \tfrac{1}{2}\bar{\nu}\gamma_\mu[\tfrac{1}{2}(1-\gamma_5)]\nu - \tfrac{1}{2}\bar{e}\gamma_\mu[\tfrac{1}{2}(1-\gamma_5)]e + \tfrac{1}{2}\bar{u}[\tfrac{1}{2}(1-\gamma_5)]u - \tfrac{1}{2}\bar{d}[\tfrac{1}{2}(1-\gamma_5)]d + \cdots \tag{11}$$

and

$$j_\mu^{\text{em}} = -\bar{e}\gamma_\mu e + \tfrac{2}{3}\bar{u}\gamma_\mu u - \tfrac{1}{3}\bar{d}\gamma_\mu d + \cdots \tag{12}$$

according to

$$\mathcal{H}_{NC} = (8G_F/\sqrt{2})^{1/2}\left\{\frac{M_{Z_1}^2}{M_Z}\left(\frac{M_{Z_2}^2 - M_Z^2}{M_{Z_2}^2 - M_{Z_1}^2}\right)^{1/2} Z_{1\mu}\left[j_\mu^{(3)} - \frac{M_Z^2 x_W}{M_{Z_1}^2} j_\mu^{\text{em}}\right] + \frac{M_{Z_2}^2}{M_Z}\left(\frac{M_Z^2 - M_{Z_1}^2}{M_{Z_2}^2 - M_{Z_1}^2}\right)^{1/2} Z_{2\mu}\left[j_\mu^{(3)} - \frac{M_Z^2 x_W}{M_{Z_2}^2} j_\mu^{\text{em}}\right]\right\}, \tag{13}$$

where $x_W \equiv \sin^2\theta_W$. At low energies, the effective current-current interactions are given by

$$\mathcal{H}_{CC}^{\text{eff}} = (4G_F/\sqrt{2})\, j_\mu^{(+)} j_\mu^{(-)} \tag{14}$$

and

$$\mathcal{H}_{NC}^{\text{eff}} = (8G_F/\sqrt{2})[(j_\mu^{(3)} - x_W j_\mu^{\text{em}})^2 + C(j_\mu^{\text{em}})^2], \tag{15}$$

where

$$C \equiv x_W^2(M_{Z_2}^2 - M_Z^2)(M_Z^2 - M_{Z_1}^2)/(M_{Z_1}^2 M_{Z_2}^2). \tag{16}$$

These interactions are of the same form as in the standard model, except that the C term is absent there. In the SU(2) ⊗ U(1) ⊗ U(1)′ model of De Groot, Gounaris, and Schidknecht[4] and De Groot, Schildknecht, and Gounaris[5] the corresponding $\mathcal{H}_{NC}^{\text{eff}}$ has the form of Eq. (15), but with a factor of $(1-x_W)^2$ in C in place of x_W^2.

The additional $(j_\mu^{\text{em}})^2$ term of Eq. (15) is not stringently tested because it has to compete with the much stronger electromagnetic interaction at these energies. In fact, the only low-energy experimental constraint that might be of value is from the muon anomalous magnetic moment $a_\mu = \frac{1}{2}(g_\mu - 2)$. By using Eqs. (14) and (15), and the results of Leveille and of Darby and Grammer,[8] we find

$$a_\mu = a_\mu^{\text{sm}} + \sqrt{2}\, G_F m_\mu^2 C/3\pi^2, \tag{17}$$

where a_μ^{sm} is the value of a_μ in the standard model. The discrepancy between the latest experimental value[9] for a_μ and the theoretical electromagnetic contributions through eighth order[10] is $(4 \pm 22) \times 10^{-9}$. The value of a_μ^{sm} is about 2×10^{-9}, and hence Eqs. (16) and (17) can be used to set a lower limit on M_{Z_1} for given M_{Z_2}. When one allows for 1 standard deviation from the mean experimental value, the resulting bound on M_{Z_1} is not very restrictive: See Fig. 1.

In e^+e^- collisions, the two neutral gauge bosons Z_1 and Z_2 can be discovered as resonances. If the Z_1 is sufficiently light, its width will be quite narrow. For example, with $M_{Z_1} = 45$ GeV and $M_{Z_2} = 100$ GeV, Γ_{Z_1} is about 39 MeV, which is about a factor of 50 narrower than the 2.2-GeV width expected of the Z in the standard model. The integrated Z-resonance contributions to the hadronic cross section are

$$\int d(\sqrt{s})\,\sigma(e^+e^- \to Z \to \text{hadrons}) = 6\pi^2 B_\mu B_h \Gamma_Z/m_Z^2. \tag{18}$$

The branching fractions $B_\mu = \Gamma(Z \to \mu\mu)/\Gamma$ and $B_h = \Gamma(Z \to \text{hadrons})/\Gamma$ of Z_1 (or Z_2) depend only on its own mass. Calculations of B_μ and B_h based on six leptons and six quarks are shown in Fig. 2;

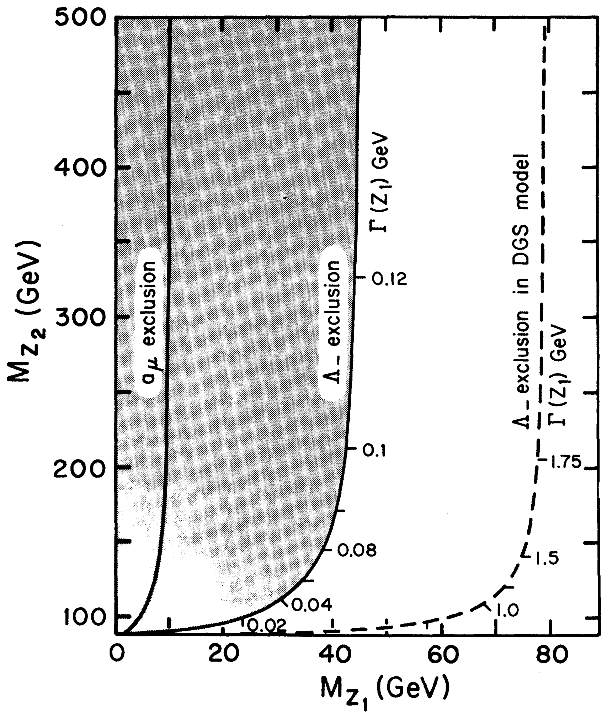

FIG. 1. Excluded regions (shaded areas) for Z_1 and Z_2 masses from (i) the muon anomalous moment a_μ (with allowance for 1 standard deviation from the mean experimental value), and (ii) the QED cutoff parameter Λ_- of $e^+e^- \to \mu^+\mu^-$ measurements. The dashed curve denotes the boundary of the corresponding Λ_- excluded region for the model of Refs. 4 and 5.

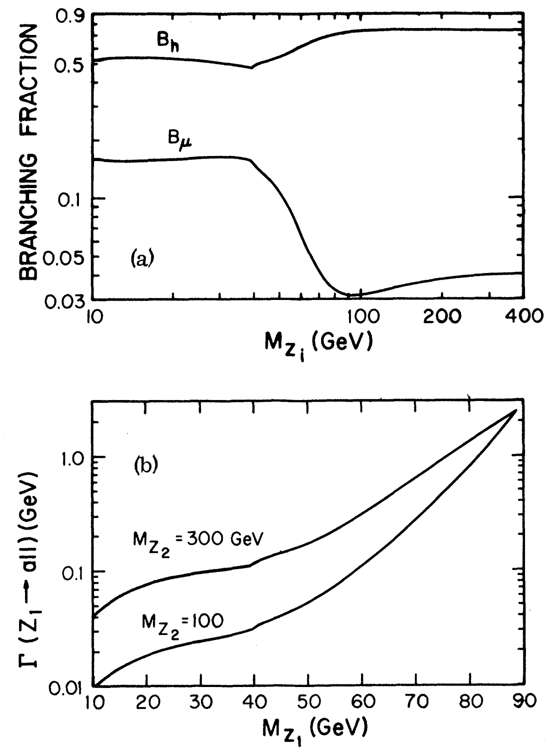

FIG. 2. (a) Branching fractions into $\mu^+\mu^-$ (B_μ) and hadrons (B_h) of the Z_1 or Z_2 boson vs its mass and (b) total width of the Z_1 boson vs its mass.

these results are insensitive to the precise mass of the t quark. The signal for Z_1 production in e^+e^- collisions is large and would have been detected at PETRA[11] if $M_{Z_1} < 32$ GeV.

Limits on deviations from quantum electrodynamics (QED) of the $e^+e^- \to \mu^+\mu^-$ cross section also provide a lower bound[5] on M_{Z_1} for given M_{Z_2}. The deviations $\Delta\sigma$ of the measured cross sections from the QED value σ are parametrized by cutoff parameters $\Lambda_\mp$ as[13]

$$-2s/\Lambda_-^2 \leq \Delta\sigma/\sigma \leq 2s/\Lambda_+^2. \qquad (19)$$

Assuming that the weak contribution saturates the lower bound in Eq. (19), we have

$$C \leq \pi\alpha/\sqrt{2}G_F\Lambda_-^2 - (\tfrac{1}{4} - x_W)^2. \qquad (20)$$

The corresponding restriction on the Z_1, Z_2 masses with[13] $\Lambda_- = 97$ GeV are shown in Fig. 1.

To detect the presence of M_{W_1}, let us consider first neutrino-nucleon deep-inelastic scattering. Instead of the usual $(1 - q^2 M_W^{-2})^{-1}$ propagator fac-

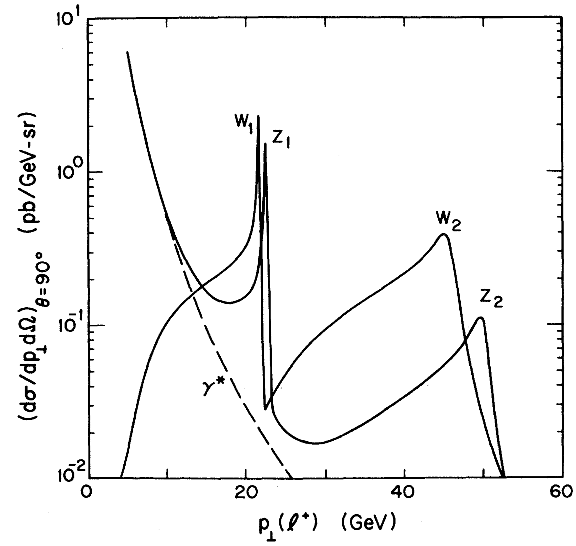

FIG. 3. Predicted transverse momentum spectrum of the lepton (l^+) resulting from $W_{1,2}^+$ and $Z_{1,2}$ production in $\bar{p}p$ collisions at c.m. energy $\sqrt{s} = 540$ GeV. The QED background from the Drell-Yan process is represented by the dashed line.

tor, we now have, using Eq. (10),

$$\frac{1-q^2(M_{W_1}{}^{-2}+M_{W_2}{}^{-2}-M_W{}^{-2})}{(1-q^2M_{W_1}{}^{-2})(1-q^2M_{W_2}{}^{-2})},$$

which reduces to $1+q^2M_W{}^{-2}$ for small q^2 and has therefore an identical cutoff parameter as in the standard model. Hence neutrino experiments, even at moderately high energies are not able to supply much information on W_1. However, restrictions on the mass range on Z_1 also limit the mass of W_1 through Eq. (8).

The only real hope to see the effect of W_1 (or W_2) is to produce it in pp or $\bar{p}p$ collisions. In Fig. 3, we show the $\bar{p}p$ differential cross section for observing a high-transverse-momentum e^+ or μ^+ from virtual γ, $W_{1,2}{}^+$, and $Z_{1,2}$ production at $\sqrt{s}$ = 540 GeV. These calculations are based[14] on the Drell-Yan model, with quantum chromodynamics parton distributions from Owens and Reya.[15] In this illustration $M_{W_1}=43$ GeV, $M_{Z_1}=45$ GeV, M_{W_2} = 91 GeV, and $M_{Z_2}=100$ GeV. Notice that the single-lepton signal from W_1 (or Z_1) production is significantly above the γ^* background, even if M_{W_1} is as small as 30 GeV.

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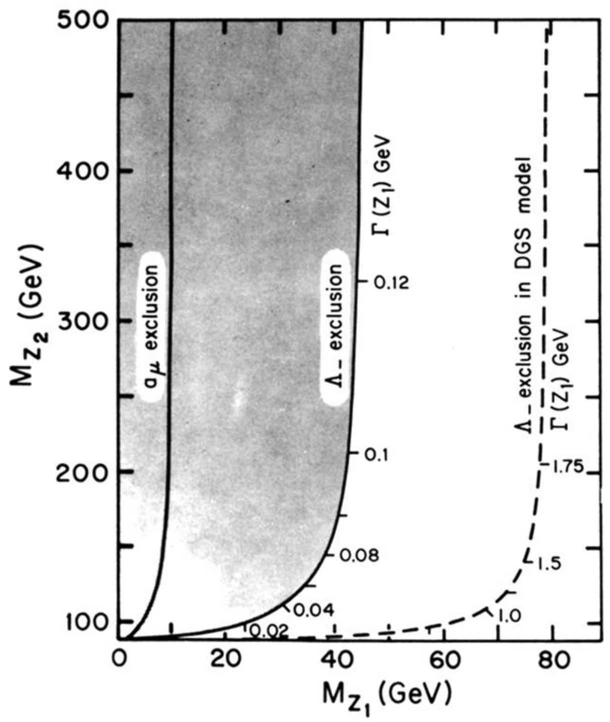

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