Ref.TH.3888-CERN

HEAVY COMPOSITE VECTOR BOSONS AND LOW-ENERGY WEAK INTERACTIONS

W. Buchmüller

CERN - Geneva

ABSTRACT

Models of quark-lepton substructure with composite W- and Z-bosons predict the existence of additional heavy vector bosons. We study a 15-plet of V-bosons which arise in a class of preon models with global Pati-Salam SU(4) invariance. An analysis of the weak interaction current-current Lagrangian yields the V-masses as functions of $\sin^2\theta_w$, M_W and M_Z . Furthermore, a non-vanishing C-parameter for neutral currents is predicted. The new vector bosons are expected to be heavier than ~ 500 GeV.

Ref.TH.3888-CERN
May 1984

Despite the recent discovery [1] of the W- and Z-bosons at the CERN $p\bar{p}$ collider with masses compatible with the standard model predictions it is still conceivable that the intermediate vector bosons are composite objects rather than elementary gauge particles. Composite W- and Z-bosons occur in preon models [2] of quarks and leptons whose substructure scale is related to the Fermi scale of weak interactions, $\Lambda_c \sim G_F^{-1/2} \sim 300$ GeV. Such models inevitably predict additional heavy vector bosons.

In a class of models the symmetry structure of the current-current Lagrangian of low-energy weak interactions is obtained by imposing on the preon Lagrangian the weak isospin SU(2) invariance and the Pati-Salam SU(4) invariance [3] in order to guarantee quark-lepton universality. In supersymmetric (SUSY) models this SU(2) $\times$ SU(4) symmetry is usually part of a U(6) invariance. These symmetry considerations concern the left-handed components of quarks and leptons. The weak interactions of the right-handed components can be understood as consequence of a dynamical γ -W³ mixing [4,5]. No additional right-handed currents have been observed so far. In the following we will therefore focus on the left-handed sector of one family only and consider right-handed particles, as in the Abbott-Farhi model [6], to be elementary as a first approximation.

As an example, let us consider the SUSY U(6) model of ref. [7]. Left-handed quarks and leptons ($i = 1, 2$; $a = 1, \dots, 4$; $\alpha = 1, \dots, 3$)

$$(f_L^{ia}) = (q_L^a, l_L) \quad , \quad q_L^a = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_L \quad , \quad l_L = \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L \quad , \quad (1)$$

transform as (2,4) with respect to SU(2) $\times$ SU(4). They are built from the scalar and fermionic components of the chiral supermultiplets $\chi_p^i = (\chi_p^i, \eta_{Lp}^i) \sim (2,1)$ and $\chi_p^a = (\chi_p^a, \eta_{Lp}^a) \sim (1,4)$,

$$f_L^{ia} = \frac{1}{\sqrt{2}} \varepsilon^{pq} (\chi_p^i \eta_{Lq}^a + \eta_{Lp}^i \chi_q^a) \quad , \quad (2)$$

where $p, q = 1, 2$ denote SU(2)_{HC} hypercolour indices. The isotriplet of W-bosons is given by

$$W_\mu^I = \bar{\eta}_{L,i}^I \chi_\mu^i (\frac{1}{2} \tau^I)_j^i \eta_{Lp}^j + i \chi_\mu^{*p} \overleftrightarrow{\partial}_\mu (\frac{1}{2} \tau^I)_j^i \chi_p^j + \dots \sim (3,1) \quad , \quad (3)$$

where τ^I , $I = 1, \dots, 3$, are the isospin matrices. In the model of ref. [7] it is conceivable [8], that due to the presence of scalar condensates the W-bosons are light compared to the hypercolour scale Λ_{HC} . This presumably implies the needed large γ - W^3 mixing [9,10] as well as the (approximate) validity of vector meson dominance [11,12] which leads to W- and Z-masses close to the standard model predictions.

Obviously, the model predicts further composite vector bosons,

$$W'_\mu = \frac{1}{2} \bar{\psi}_L^P \gamma_\mu \psi_L^i + \frac{i}{2} \chi^{*P} \overleftrightarrow{\partial}_\mu \chi^i + \dots \sim (1,1) \quad , \quad (4a)$$

$$V_\mu^A = \bar{\psi}_L^P \gamma_\mu (\frac{1}{2} \lambda^A)_b^a \psi_L^b + i \chi^{*P} \overleftrightarrow{\partial}_\mu (\frac{1}{2} \lambda^A)_b^a \chi^b + \dots \sim (1,15) \quad , \quad (4b)$$

$$V'_\mu = \frac{1}{2\sqrt{2}} \bar{\psi}_L^P \gamma_\mu \psi_L^a + \frac{i}{2\sqrt{2}} \chi^{*P} \overleftrightarrow{\partial}_\mu \chi^a + \dots \sim (1,1) \quad , \quad (4c)$$

where λ^A , $A = 1, \dots, 15$, are the SU(4) λ -matrices. The effective Lagrangian for the interaction of the vector bosons of eqs. (3) and (4) with quarks and leptons is determined by SU(2) $\times$ SU(4) invariance,

$$\mathcal{L}_{\text{eff}} = g_1 j_\mu^I W^{I\mu} + g_2 j_\mu^{(S)} W'^\mu + g_3 j_\mu^A V^{A\mu} + \frac{1}{\sqrt{2}} g_4 j_\mu^{(S)} V'^\mu \quad , \quad (5a)$$

with currents

$$\begin{aligned} j_\mu^I &= \bar{f}_{Li a} \gamma_\mu (\frac{1}{2} \tau^I)_j^i f_L^{j a} \quad , \\ j_\mu^{(S)} &= \frac{1}{2} \bar{f}_{Li a} \gamma_\mu f_L^{i a} \quad , \\ j_\mu^A &= \bar{f}_{Li a} \gamma_\mu (\frac{1}{2} \lambda^A)_b^a f_L^{i b} \quad . \end{aligned} \quad (5b)$$

The V-bosons contain a neutral colour octet V_8 , a colour triplet (antitriplet) $V_3 (V_{3^*})$ with charge 2/3 (-2/3) and a neutral V-boson, the analogue of the standard model B-boson, which couples to the hypercharge current, i.e. ($A' = 1, \dots, 8$),

$$j_\mu^A V^{\mu A} = \bar{q}_{L\alpha} \gamma_\mu \left(\frac{1}{2} \lambda^A \right)_\beta^\alpha q_L^\beta V_8^{\mu A} + \frac{1}{\sqrt{2}} \bar{q}_{L\alpha} \gamma_\mu l_L^\alpha V_3^{\mu A} + \frac{1}{\sqrt{2}} \bar{l}_L \gamma_\mu q_L^\alpha V_{3\alpha}^\mu + \sqrt{\frac{3}{2}} \left(\frac{1}{6} \bar{q}_L \gamma_\mu q_L - \frac{1}{2} \bar{l}_L \gamma_\mu l_L \right) V^\mu. \quad (6)$$

The exchange of the vector bosons in eq. (5a) yields an effective current-current Lagrangian. Using the property of SU(N) λ -matrices ($R = 1, \dots, N^2-1$),

$$\left(\frac{1}{2} \lambda^R \right)_n^m \left(\frac{1}{2} \lambda^R \right)_q^p = \frac{1}{2} \left(\delta_q^m \delta_n^p - \frac{1}{N} \delta_n^m \delta_q^p \right), \quad (7)$$

and the Fierz identity

$$\bar{\psi}_{L1} \gamma_\mu \psi_{L2} \bar{\psi}_{L3} \gamma^\mu \psi_{L4} = \bar{\psi}_{L1} \gamma_\mu \psi_{L4} \bar{\psi}_{L3} \gamma^\mu \psi_{L2}, \quad (8)$$

one easily proves [cf. (5b)]

$$j_\mu^A j^{\mu A} = j_\mu^I j^{\mu I} + \frac{1}{2} j_\mu^{(S)} j^{(S)\mu}, \quad (9)$$

and obtains the Lagrangian

$$\mathcal{L}_{\text{eff}}^{(q,l)} = -\frac{1}{2} \left(\frac{g_1^2}{M_1^2} + \frac{g_2^2}{M_2^2} \right) j_\mu^I j^{\mu I} - \frac{1}{4} \left(2 \frac{g_2^2}{M_2^2} + \frac{g_3^2}{M_3^2} + \frac{g_4^2}{M_4^2} \right) j_\mu^{(S)} j^{(S)\mu}, \quad (10)$$

where $M_1, \dots, M_4$ are the masses of W, W', V and V' .

This result is modified by the mixing of W^3 and V with the photon and the mixing of V_8 with the gluon (cf. Fig. 1). It is known [5,11] that a current-current Lagrangian due to the exchange of a vector boson, which couples to the current with strength g and mixes with the photon with strength λ , is modified as follows,

$$\begin{aligned} \mathcal{L}_{\text{eff}} &= -\frac{1}{2} \frac{g^2}{M^2} j_\mu j^\mu \\ &\rightarrow -\frac{1}{2} \frac{g^2}{M^2} \left(j_\mu - \frac{e}{g} \lambda j_\mu^{(E)} \right)^2, \end{aligned} \quad (11)$$

where e and $j_\mu^{(E)}$ are electromagnetic coupling and current. Equation (11) is valid to second order in e and g and to all orders in λ . Vector meson dominance [11,12]

of the electromagnetic form factor of the particles forming the current j_μ yields in addition $g\lambda = e$. The hypothesis of W^3 - and V - dominance implies (cf. Fig. 2)

$$g_1 \lambda_W = \sqrt{\frac{3}{2}} g_3 \lambda_V = e \quad ; \quad (12a)$$

a straightforward extension to the case of non-abelian gauge invariance (which has not yet been studied in detail) yields the relation (cf. Fig. 2)

$$g_3 \lambda'_V = g_s \quad , \quad (12b)$$

where g_s is the QCD coupling. The neutral bosons W' and V' are expected to mix very little with the photon because the expectation value of the charge operator vanishes for these states.

Equations (10) to (12) lead to the following effective Lagrangian for charged and neutral currents:

$$\begin{aligned} L_{CC} &= -\frac{1}{2} \left(\frac{g_1^2}{M_1^2} + \frac{g_3^2}{M_3^2} \right) j_\mu^+ j^{-\mu} \quad , \\ j_\mu^+ &= \bar{u}_L \gamma_\mu d_L + \bar{\nu}_L \gamma_\mu e_L \quad , \quad j_\mu^- = (j_\mu^+)^{\dagger} \quad ; \end{aligned} \quad (13a)$$

$$L_{NC} = L_{NC}^{(1)} + L_{NC}^{(2)} + L_{NC}^{(3)} \quad ;$$

$$L_{NC}^{(1)} = -\frac{1}{2} \left(\frac{g_1^2}{M_1^2} + \frac{g_3^2}{M_3^2} \right) \left[(j_\mu^3 - \sin^2 \theta_W j_\mu^{(e)})^2 + C (j_\mu^{(e)})^2 \right] \quad ,$$

$$\sin^2 \theta_W = \frac{1}{1+\varepsilon} \left(\lambda_W^2 - \frac{3}{2} \varepsilon \lambda_V^2 \right) \quad , \quad (13b)$$

$$C = \frac{\varepsilon}{1+\varepsilon} \left[-3 \lambda_V^2 \left(1 + \frac{1}{4} \lambda_V^2 \right) + (1+\varepsilon) \left(\sin^2 \theta_W + \frac{3}{2} \lambda_V^2 \right)^2 \right] \quad ,$$

$$\varepsilon = \frac{g_3^2}{M_3^2} \frac{M_1^2}{g_1^2} \quad ;$$

$$L_{NC}^{(2)} = \frac{g_3^2}{M_1^2} \lambda_V'^2 \left(1 - \frac{1}{2} \lambda_V'^2 \right) j_\mu^{A'} j^{A'\mu} \quad ; \quad (13c)$$

$$L_{NC}^{(1)} = -\frac{1}{4} \left(2 \frac{g_1^2}{M_1^2} + \frac{g_3^2}{M_3^2} + \frac{g_4^2}{M_4^2} \right) j_\mu^{(1)} j^{(1)\mu} ; \quad (13d)$$

$j_\mu^{A'}$ is the colour octet current of quarks [cf. eq. (6)].

The W^3 -, V - and V_8 -masses are also affected through the mixing with photon and gluon. The masses of charged vector bosons are unchanged: M_1 corresponds to $\hat{M}_W$, the W -mass at renormalization scale $\mu = 0$; M_3 is the mass of V_3 at $\mu = 0$. The γ - W^3 - V mixing matrix has been analysed by Kogerler and Schildknecht [11]. Their result yields for the masses $\hat{M}_Z$ and M_V at $\mu = 0$:

$$\frac{\hat{M}_Z^2}{\hat{M}_W^2} = \frac{1}{2\Delta} \left[1 - \lambda_V^2 + \frac{2}{3} \varepsilon \frac{\lambda_W^2}{\lambda_V^2} (1 - \lambda_W^2) - \frac{1}{\varepsilon} \left(\frac{4}{9} \frac{\lambda_W^4}{\lambda_V^4} (1 - \lambda_W^2)^2 - \frac{4}{3} \varepsilon \frac{\lambda_W^2}{\lambda_V^2} (\Delta - \lambda_W^2 \lambda_V^2) + \varepsilon^2 (1 - \lambda_V^2)^2 \right)^{\frac{1}{2}} \right] , \quad (14a)$$

$$\frac{M_V^2}{M_{V_3}^2} = \frac{1}{2\Delta} \left[1 - \lambda_W^2 + \frac{3}{2} \varepsilon \frac{\lambda_V^2}{\lambda_W^2} (1 - \lambda_V^2) + \left((1 - \lambda_W^2)^2 - 3 \varepsilon \frac{\lambda_V^2}{\lambda_W^2} (\Delta - \lambda_W^2 \lambda_V^2) + \frac{9}{4} \varepsilon^2 \frac{\lambda_V^4}{\lambda_W^4} (1 - \lambda_V^2)^2 \right)^{\frac{1}{2}} \right] , \quad (14b)$$

$$\Delta = 1 - \lambda_W^2 - \lambda_V^2$$

The mixing with the gluon gives for the mass of V_8

$$M_{V_8}^2 = \frac{M_{V_3}^2}{1 - \lambda_V^2} \quad (15)$$

What can we learn from eqs. (13) to (15) about the V -vector bosons? We have computed G_F , $\sin^2 \theta_W$, $\hat{M}_W$ and $\hat{M}_Z$ as functions of g_1 , M_1 , g_3 and M_3 . Thus, a measurement of the first four quantities can determine, in principle, the four input parameters and thereby the V -mass spectrum and the C -parameter.

Let us first consider three general features of the Lagrangian (13):

- i) Except for (13c), which affects only the experimentally not tested hadronic current interactions of u - and d -quarks, we have for the ratio of neutral-to-charged coupling strengths $\rho = 1$.
- ii) From (13) and:

$$\left(\frac{q_1^2}{M_1^2} + \frac{q_3^2}{M_3^2} \right) = 4 \sqrt{2} G_F \quad (16)$$

one obtains for the W-mass

$$\begin{aligned} \hat{M}_W^2 &= \frac{1+\varepsilon}{\lambda_W^2} \frac{\pi d_E}{\sqrt{2} G_F} \\ &< \frac{1}{\sin^2 \theta_W} \frac{\pi d_E}{\sqrt{2} G_F} = (M_W^0)^2, \end{aligned} \quad (17)$$

i.e., the W-mass is predicted to be smaller than the standard model prediction.

Due to the mixing of photon and V-boson, which couples to the hypercharge current, the C-parameter can be positive or negative contrary to cases discussed previously in the literature [4,13].

How light can the V-bosons be? From (12) and (16) one reads off

$$M_{V_3}^2 = \frac{2}{3} \frac{1+\varepsilon}{\varepsilon \lambda_V^2} \frac{\pi d_E}{\sqrt{2} G_F} \quad (18)$$

Experimental bounds on isoscalar weak interactions [14] suggest $\varepsilon < 0.10^*$ [cf. (10)]. Because of $M_V > M_W$ one expects $\lambda_V^2 < \lambda_W^2$, which leads to the lower bound $M_{V_3} > 220$ GeV. A substantially stronger constraint follows from the V_8 -dominance of the quark colour form factor. The consistency of the mixing scheme requires $\lambda_V'^2 < 1$ [cf. eq. (15)] and from eq. (12) one obtains

$$\lambda_V^2 < \frac{2}{3} \frac{d_E}{d_S} \approx 0.05, \quad (19)$$

where $\alpha_E = e^2/4\pi$, $\alpha_S = g_S^2/4\pi$ and $\alpha_S \left(Q^2 = (1000 \text{ GeV})^2 \right) \sim 0.10$. Together with $\varepsilon < 0.10$ this yields the lower bound

$$M_{V_3} > 450 \text{ GeV} \quad (20)$$

Given G_F and $\sin^2 \theta_W$, the V-masses are determined by the deviation of $\hat{M}_W$ and $\hat{M}_Z$ from the standard model predictions. The corresponding ratios

$$R_W \equiv \frac{\hat{M}_W^2}{(M_W^0)^2} = (1+\varepsilon) \frac{\sin^2 \theta_W}{\lambda_W^2}, \quad (21a)$$

*) Here we neglect contributions from the exchange of W' and V' . Including them raises the lower bound for V_3 .

$$R_Z \equiv \frac{\hat{M}_Z^2}{(\hat{M}_Z^0)^2} = \cos^2 \theta_w R_W \frac{\hat{M}_Z^2}{\hat{M}_W^2}, \quad (21b)$$

with M_W^0 given in (17) and $M_Z^0 = M_W^0 / \cos \theta_w$ are plotted in Fig. 3 as functions of ϵ , where we have assumed a mass shift due to radiative corrections as in the standard model, i.e., $\hat{M}_W/M_W = 0.943$ and $\hat{M}_Z/M_Z = 0.949$ [15]. In Fig. 3 we have chosen $\sin^2 \theta_w = 0.23$ and $\lambda_V^2 = 0.03$. The ratios R_W and R_Z are rather insensitive to $\sin^2 \theta_w$, a change $\Delta \sin^2 \theta_w = \pm 0.01$ corresponds to $|\Delta R/(R-1)| < 0.05$. A change $\Delta \lambda_V^2 = \pm 0.01$ implies $|\Delta R/(R-1)| < 0.3$. Figure 3 shows that a measurement of M_W and M_Z with an accuracy of at least 1% is needed in order to be sensitive to the effect of the V-bosons. Two numerical examples are given in the table.

Table

V masses and C-parameter
for different values of ϵ .
 $\lambda_V^2 = 0.03$, $\sin^2 \theta_w = 0.23$. All masses are given in GeV.

M_W	M_Z	ϵ	M_{V_3}	M_V	M_{V_8}	C
82.2	93.6	0.03	1030	1050	1660	-3.7×10^{-4}
81.8	94.1	0.09	610	620	980	-6.8×10^{-4}

Given ϵ and λ_V^2 the V-masses and the C-parameter are obtained from (12), (13), (14), (15) and (18). M_{V_3} and C are shown in Fig. 4 as functions of ϵ for $\lambda_V^2 = 0.03$. The values of C are about a factor of 30 below the sensitivity reached at PETRA and PEP [16].

We have studied the influence of a 15-plet of heavy vector bosons [17], which arise in preon models with global SU(4) invariance, on low-energy weak interactions. Theoretical consistency requires these new vector bosons to be heavier than ~ 500 GeV and consequently their effect on weak interaction parameters appears difficult to test in the near future. Nevertheless, these vector bosons may exist and masses above 500 GeV are expected for a compositeness scale $\Lambda_c \sim 300$ GeV. Our results appear to be rather restrictive compared to recent studies [18,19] of colour

octet W-bosons in the haplon model [20] for which masses much below 200 GeV are considered. We hope to extend our study to the case of more than one family in a future publication.

Acknowledgements

I would like to thank J. Ellis, F.M. Renard, D. Schildknecht and G. Veneziano for helpful discussions and J. Prentki for a careful reading of the manuscript.

REFERENCES

- [1] G. Arnison et al., Phys. Lett. 122B (1983) 103; 126B (1983) 398.
M. Banner et al., Phys. Lett. 122B (1983) 476; 129B (1983) 130.
- [2] For recent reviews and references, see R. Barbieri, *in* Proc. of the 1983 Int. Symp. on Lepton and Photon Interactions at High Energies, D.G. Cassel and D.L. Kreinick eds., (Ithaca, 1983); R.D. Peccei, *in* Proc. of the Int. Europhysics Conf. on High Energy Physics, J. Guy and C. Costain eds. (Brighton, 1983).
- [3] J.C. Pati and A. Salam, Phys. Rev. D10 (1974) 275.
- [4] J.D. Bjorken, Phys. Rev. D19 (1979) 335.
- [5] P.Q. Hung and J.J. Sakurai, Nucl. Phys. B143 (1978) 81.
- [6] L. Abbott and E. Farhi, Phys. Lett. 101B (1981) 69.
- [7] W. Buchmüller, R.D. Peccei and T. Yanagida, Nucl. Phys. B231 (1984) 53.
- [8] W. Buchmüller and M.G. Schmidt, in preparation.
- [9] P. Chen and J.J. Sakurai, Phys. Lett. 110B (1982) 481.
- [10] H. Fritzsch and G. Mandelbaum, Phys. Lett. 109B (1982) 224.
- [11] R. Kögerler and D. Schildknecht, CERN preprint TH.3231 (1982).
- [12] H. Fritzsch, R. Kögerler and D. Schildknecht, Phys. Lett. 114B (1982) 157.
- [13] E.H. de Groot and D. Schildknecht, Z. Phys. C10 (1981) 55.
- [14] J.E. Kim, P. Langacker, M. Levine and H.H. Williams, Rev. Mod. Phys. 53 (1981) 211.
- [15] W.J. Marciano and A. Sirlin, BNL preprint 33819 (1983).
- [16] For a review, see A. Böhm, *in* Proc. of the Int. Europhysics Conf. on High Energy Physics, J. Guy and C. Costain eds. (Brighton, 1983).
- [17] Implications of SU(4) invariance and vector meson dominance have been independently studied by B. Schrempp and F. Schrempp (Private communication at the Workshop on Quark and Lepton Structure, Erice, April 1983).

- [18] U. Baur and K.H. Streng, in preparation.
- [19] S. Narison, CERN preprint TH.3871 (1984).
- [20] H. Fritzsch and G. Mandelbaum, Phys. Lett. 102B (1981) 319.

Figure captions

- Fig. 1 : The mixings W^3 -photon, V-photon, V_8 -gluon.
- Fig. 2 : Vector meson dominance of electromagnetic and colour form factors of quarks and leptons.
- Fig. 3 : The ratios R_W and R_Z (see text) as functions of ϵ ; $\sin^2 \theta_W = 0.23$, $\lambda_V^2 = 0.03$.
- Fig. 4 : V_3 -vector boson mass and C parameter as functions of ϵ ; $\sin^2 \theta_W = 0.23$, $\lambda_V^2 = 0.03$.

FIG. 1

FIG. 2

FIG. 3

FIG. 4