CERN-TH.5646/90
UAB-FT-236/90
IEM-FT-16/90

$M_{Z'}$ mass bounds from neutrino-hadron neutral current data and a precise M_Z measurement *

F. del Aguila, [†]

Departamento de Física Teórica
Universidad Autónoma de Barcelona, Bellaterra
E-08193 Barcelona. Spain

J. M. Moreno

Instituto de Estructura de la Materia
Serrano 119, E-28006 Madrid. Spain

and M. Quirós [‡]

CERN - Geneva

Abstract

We study the constraints on the minimal (gauge) extension of the standard model from $\nu - q$ neutral current data. Using α, G_μ and M_Z (with the present accuracy) as input parameters, we find that previous bounds on $M_{Z'}$ are strengthened by a factor ~ 2 ($M_{Z'} > 555 \text{ GeV}$ (90% c.l.) for $m_t > 77 \text{ GeV}$ and $m_H < 1 \text{ TeV}$, for the simplest model).

*Work partly supported by CICYT under contract AEN88-0040

[†]Electronic mail: ifteagu@ebccuab1.BITNET

[‡]On leave from Instituto de Estructura de la Materia, Serrano 119, E-28006 Madrid. Spain

The standard model of electroweak interactions[1-3] is being tested by high precision experiments at large colliders (Tevatron and SLC and LEP). The high accuracy of the measurements makes it necessary to include radiative corrections[3-6]. They are certainly a key ingredient when discussing the new physics provided by extensions of the standard model as, for instance, that provided by an additional neutral gauge boson. This possible (gauge) extension of the standard model is well motivated theoretically (grand unification[7], superstrings[8], ...), is easy to detect at large pp colliders [9-11], and can leave tracks at e^+e^- colliders if the new Z' gets mixed with the standard Z boson[3,12].

The minimal standard model can be fixed by the electromagnetic fine structure constant, α , the Fermi constant, G_F , and the electroweak mixing angle, $s_W^2 \equiv \sin^2 \theta_W$ (once the top and Higgs masses m_t and m_H are known). The high precision of recent Z mass (M_Z) measurements makes it convenient, however, to replace s_W^2 by M_Z , as an independent parameter. Doing so, s_W^2 becomes a well-known function of the other parameters. Then, the analysis of precise data whose dependence is mainly on the electroweak mixing angle, allows for a strong test of the minimal standard model and its possible extensions. In this letter we use recent analyses of the ν - q neutral current data to bound the mass of a new neutral gauge boson.

Any bound on new physics depends on the particular extension considered. Here we concentrate on the minimal gauge extension of the standard model. The addition of a new (non-trivial) $U(1)$ always demands the existence of new fermions in order to cancel the new gauge anomalies. The minimal and simplest case results from the addition of only one extra fermion per family, to be identified with the right-handed neutrino ν_L^c [13]. The extra hypercharge is then fixed,

$$fermion - type : \begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_L^c \quad d_L^c \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad e_L^c \quad \nu_L^c \quad (1)$$

$$\sqrt{\frac{8}{3}} Y^c : \quad \frac{1}{3} \quad \frac{1}{3} \quad \frac{1}{3} \quad -\frac{2}{3} \quad -\frac{2}{3} \quad \frac{1}{3} \quad 1$$

This is the class of models obtained in superstring-inspired models with large intermediate scales[14]. (The general parametrization of the new gauge interaction has been given in detail some time ago[10]. In particular, this class contains the neutral gauge sector of the left-right models[15].) The lightness of the left-handed neutrinos and the efficient decoupling of ν_L^c can be ensured by the addition of one new fermion N , completely neutral, per family. This will combine with ν_L^c to form a heavy Dirac particle[16]. (We assume that the model is non-supersymmetric at low energy.) Existing calculations including radiative corrections within the standard model can be safely applied. Any other gauge extension requires a discussion, usually overlooked, of the necessary, abundant extra matter.

The neutral (lowest order) gauge-fermion lagrangian for a general $SU(2)_L \times U(1)_Y \times U(1)_{Y^c}$ model reads[10]:

$$\begin{aligned} L_{NC} &= e J_{EM}^\mu A_\mu + \frac{e}{s_W c_W} J_Z^\mu Z_\mu + \frac{e}{c_W} J_{Z'}^\mu Z'_\mu, \\ J_{EM} &= J_1 + \sqrt{\frac{2}{3}} J_2, \\ J_Z &= c_3 J_{Z^0} - s_3 J_{Z'^0}, \\ J_{Z'} &= s_3 J_{Z^0} + c_3 J_{Z'^0} \\ (J_{Z^0} &= J_1 - s_W^2 J_{EM}, \\ J_{Z'^0} &= \sqrt{\frac{2}{3}} [s_1 c_1 (\lambda - \frac{1}{\lambda}) J_2 - (s_1^2 \lambda + \frac{c_1^2}{\lambda}) J_e]), \end{aligned} \quad (2)$$

where $e = \sqrt{4\pi\alpha}$ and $c_W^2 = 1 - s_W^2$. $J_{EM}(J_1)$ is the usual electric (isospin) current corresponding to $Q_{EM}(T_3^L)$, whereas J_e is the current corresponding to Y^c in Eq. (1) and $\lambda \geq 1$ and $\theta_1 \in [-\pi/2, \pi/2]$ (with $s_1(c_1) = \sin(\theta_1(\cos\theta_1))$) are the two new (arbitrary) gauge couplings. $c_3(s_3) = \sin\theta_3(\cos\theta_3)$ gives the $Z^0 Z'$ mixing and is a function of the former parameters[17],

$$s_3 = \frac{s_W M_W^2 \gamma}{c_W^2 \sqrt{(M_{Z'}^2 - \frac{M_W^2}{c_W^2})(M_{Z'}^2 - M_Z^2)}}, \quad (3)$$

where M_W is the W mass and

$$\gamma = -s_1 c_1 \left(\lambda - \frac{1}{\lambda} \right) - \sqrt{\frac{2}{3}} \left(s_1^2 \lambda + c_1^2 \frac{1}{\lambda} \right). \quad (4)$$

Hence, in this minimal extension three new parameters, $\lambda, \theta_1, M_{Z'}$, must be added to the set of independent ones, α, G_μ [18] and (combining all the errors in quadrature) [19]

$$M_{Z'} = 91.10 \pm 0.04 \text{ GeV} \quad (5)$$

(plus m_t and m_H), in the standard model. The analysis will be performed for the two popular cases [11, 18]: $(\chi) \lambda = 1$ (and, hence, independent of θ_1), which is the simplest possibility; and (LR) $\lambda = \sqrt{\frac{3}{2}} \frac{\sqrt{1-2s_W^2}}{s_W} \simeq 1.877$, $\theta_1 = \arcsin \sqrt{\frac{2}{3}}$, which give the neutral sector of a left-right model.

The $\nu - q$ neutral current data are summarized in four couplings [20],

$$\begin{aligned} u_L^2 &= 0.1208 \pm 0.0115 \\ d_L^2 &= 0.1786 \pm 0.0123 \\ u_R^2 &= 0.0253 \pm 0.0081 \\ d_R^2 &= 0.0051 \pm 0.0083 \end{aligned} \quad (6)$$

(where the total errors, with a (symmetric) correlation matrix

$$r = \begin{pmatrix} 1 & -0.945 & -0.405 & 0.405 \\ & 1 & 0.366 & -0.502 \\ & & 1 & -0.861 \\ & & & 1 \end{pmatrix}, \quad (7)$$

combine experimental and theoretical ones). Other $\nu - q$ analyses [21] give compatible results. In the following analysis we include one-loop radiative corrections within the minimal standard model and the tree-level contributions from the new gauge interaction (this approximation is valid in the limit $M_{Z'}^2 \ll M_Z^2$) [22] and will be

justified by the final, numerical results). The couplings in Eq. (6) are predicted to be:

$$\begin{aligned} u_L &= \rho [2\nu_L^Z (c_3 u_L^Z(r.c.) - s_3 u_L^Z(r.c.)) + \frac{1}{2\pi c_W^2 s_W^2} a_{BL} (c_W^2 + \frac{1}{3}s_W^2) + \frac{M_{Z'}^2}{M_Z^2} 2\nu_L^Z (s_3 u_L^Z + c_3 d_L^Z)], \\ d_L &= \rho [2\nu_L^Z (c_3 d_L^Z(r.c.) - s_3 d_L^Z(r.c.)) + \frac{1}{2\pi c_W^2 s_W^2} a_{BL} (c_W^2 - \frac{1}{3}s_W^2) + \frac{M_{Z'}^2}{M_Z^2} 2\nu_L^Z (s_3 d_L^Z + c_3 d_L^Z)], \\ u_R &= \rho [2\nu_R^Z (c_3 u_R^Z(r.c.) - s_3 u_R^Z(r.c.)) + \frac{1}{20\pi c_W^2} + \frac{M_{Z'}^2}{M_Z^2} 2\nu_R^Z (s_3 u_R^Z + c_3 u_R^Z)], \\ d_R &= \rho [2\nu_R^Z (c_3 d_R^Z(r.c.) - s_3 d_R^Z(r.c.)) + \frac{1}{10\pi c_W^2} + \frac{M_{Z'}^2}{M_Z^2} 2\nu_R^Z (s_3 d_R^Z + c_3 d_R^Z)], \end{aligned} \quad (8)$$

where

$$\rho = \frac{M_W^2}{c_W^2 M_Z^2} \quad (9)$$

and different from 1 in general,

$$a_{BL} = -\frac{(\frac{3}{16} - \frac{2}{3}s_W^2 + \frac{4}{15}s_W^4)}{c_W^2}, \quad (10)$$

and

$$\begin{aligned} u_L^Z(r.c.) &= \rho_{NC}^{(\nu, h)} [\frac{1}{2} - \frac{2}{3}\kappa_{NC}^{(\nu, h)} (q^2) s_W^2], \\ d_L^Z(r.c.) &= \rho_{NC}^{(\nu, h)} [-\frac{1}{2} + \frac{1}{3}\kappa_{NC}^{(\nu, h)} (q^2) s_W^2], \\ u_R^Z(r.c.) &= -\rho_{NC}^{(\nu, h)} \kappa_{NC}^{(\nu, h)} (q^2) \frac{2}{3} s_W^2, \\ d_R^Z(r.c.) &= \rho_{NC}^{(\nu, h)} \kappa_{NC}^{(\nu, h)} (q^2) \frac{1}{3} s_W^2 \end{aligned} \quad (11)$$

(see Ref. [6] for notation and for the explicit dependence of the radiative correction factors $\rho_{NC}^{(\nu, h)}, \kappa_{NC}^{(\nu, h)}$ on $m_{t,H}$), $u_L^Z, \dots = u_L^Z(r.c.)|_{\rho_{NC}^{(\nu, h)} = \kappa_{NC}^{(\nu, h)} = 1, \dots}$,

$$\begin{aligned} u_L^Z &= d_L^Z = s_W [\frac{1}{6} s_1 c_1 (\lambda - \frac{1}{\lambda}) - \sqrt{\frac{1}{24}} (s_1^2 \lambda + \frac{c_1^2}{\lambda})], \\ u_R^Z &= s_W [\frac{2}{3} s_1 c_1 (\lambda - \frac{1}{\lambda}) + \sqrt{\frac{1}{24}} (s_1^2 \lambda + \frac{c_1^2}{\lambda})], \\ d_R^Z &= -s_W [\frac{1}{3} s_1 c_1 (\lambda - \frac{1}{\lambda}) + \sqrt{\frac{3}{8}} (s_1^2 \lambda + \frac{c_1^2}{\lambda})], \\ \nu_L^Z &= c_3 \frac{1}{2} - s_3 s_W [-\frac{1}{2} s_1 c_1 (\lambda - \frac{1}{\lambda}) + \sqrt{\frac{3}{8}} (s_1^2 \lambda + \frac{c_1^2}{\lambda})], \\ \nu_R^Z &= s_3 \frac{1}{2} + c_3 s_W [-\frac{1}{2} s_1 c_1 (\lambda - \frac{1}{\lambda}) + \sqrt{\frac{3}{8}} (s_1^2 \lambda + \frac{c_1^2}{\lambda})]. \end{aligned} \quad (12)$$

M_W^2 and s_W^2 in Eqs. (4,9-11) are now definite functions of the conveniently chosen independent parameters. They are calculated using the usual expression (including radiative corrections, Δr [5])

$$M_W^2 = \frac{\pi \alpha}{\sqrt{2} G_\mu s_W^2} \frac{1}{1 - \Delta r} \equiv \frac{\beta^2}{s_W^2} \quad (13)$$

and the generalization of $\rho = 1$ in the minimal standard model to the case of an extra gauge interaction[17,22,23]

$$M_Z^2 = \frac{M_W^2}{c_W^2} + \frac{s_W^2 \gamma^2 \frac{M_W^2}{c_W^2}}{c_W^2 - M_{Z'}^2}, \quad (14)$$

which follows from the diagonalization of the massive neutral gauge boson mass matrix. Solving the resulting quartic equation, we find

$$s_W^2 = \frac{1}{2} + \frac{-\sqrt{x-a_1} + \sqrt{x-a_1-2(x-\sqrt{x^2-4a_3})}}{2}, \quad (15)$$

where

$$\begin{aligned} x &= \frac{a_1}{3} + \sqrt[3]{B + \sqrt{C^3 + B^2}} + \sqrt[3]{B - \sqrt{C^3 + B^2}}, \\ B &= \frac{2c_W^3 + 27c_W^2 - 72a_1a_3}{54}, \\ C &= -\frac{a_1^3 + 12a_3}{9}, \\ a_1 &= -\frac{1}{2} + \frac{\beta^2(M_Z^2 + M_{Z'}^2)}{M_Z^2 M_{Z'}^2}, \\ a_2 &= \frac{\beta^4 \gamma^2}{M_Z^2 M_{Z'}^2}, \\ a_3 &= \frac{1}{16} + \frac{\beta^4(1+\gamma^2/2) - \beta^2(M_Z^2 + M_{Z'}^2)/4}{M_Z^2 M_{Z'}^2}, \end{aligned} \quad (16)$$

whereas M_W^2 is given by the Eq. (13) itself, after replacing s_W^2 by its expression in Eq. (15).

Armed with the previous Eqs. (8-16) we can study the χ^2 function for the couplings in Eqs. (6,7). In the Figure we plot the allowed region (90%*c.l.*) for models χ , LR above. The main point is that $M_{Z'}$ is banished by neutral current data to large values, making its contributions very small. This implies that the relatively small variations of the radiative corrections with m_H amplify in an appreciable shift of the preferred region in the Figure. The lowest bound is obtained for the largest m_H value, which we fix equal to 1 TeV. For comparison we plot the allowed region for $m_H = 20$ GeV, too. On the contrary, the $M_{Z'}$ bound diminishes with m_t . Then the lowest limit corresponds to the present m_t lower bound of 77 GeV[24]. To summarize:

$$\begin{aligned} \chi : \quad & M_{Z'} > 555 \text{ GeV}, \quad (90\%c.l.) \quad (m_t > 77 \text{ GeV}, \quad m_H < 1 \text{ TeV}), \\ LR : \quad & M_{Z'} > 795 \text{ GeV}, \quad (90\%c.l.) \quad (m_t > 77 \text{ GeV}, \quad m_H < 1 \text{ TeV}). \end{aligned} \quad (17)$$

The variation of the limits on $M_{Z'}$ in the Figure is $\sim 1-2\%$ for the extreme M_Z values in Eq. (5).

The improvement of the previous $M_{Z'}$ limits[11,21] is mainly due to the precise M_Z value and the subsequent change of ρ in the presence of an extra gauge interaction, as given by Eq.(14). As stated above, the $\nu - q$ data already imply negligible Z' contributions, and then that the inclusion in our analysis of the remaining experimental constraints (which appear to agree with the minimal standard model) should not change appreciably the bounds. A discussion of these constraints, as well as of the entire λ, θ_1 class of models, is presented elsewhere.

Acknowledgements

We thank A. Casas and J. Terrón for helping us with computing.

Figure Caption

Allowed region (90%*c.l.*) in the $m_t - M_{Z'}$ plane for models χ and LR in the text. The direct m_t limit of 77 GeV is also plotted.

References

- [1] S. L. Glashow, *Nucl. Phys.* **22** (1961) 579; A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No.8)*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968); S. Weinberg, *Phys. Rev. Lett.* **19** (1967) 1264; S. L. Glashow, J. Iliopoulos and L. Maiani, *Phys. Rev. D* **2** (1970) 1285.
- [2] Proceedings of the Workshop on *Physics at LEP*, eds. J. Ellis and R. Peccei, CERN report 86-02.
- [3] Proceedings of the Workshop on *Z Physics at LEP*, eds. G. Altarelli, R. Kleiss and C. Verzegnassi, CERN report 89-08.
- [4] G. Passarino and M. Veltman, *Nucl. Phys.* **B160** (1979) 151; M. Consoli, *Nucl. Phys.* **B160** (1979) 208; F. Antonelli et al., *Nucl. Phys.* **B183** (1981) 195; J. F. Wheeler and C. H. Llewellyn Smith, *Nucl. Phys.* **B208** (1982) 27; B. W. Lynn and R. G. Stuart, *Nucl. Phys.* **B253** (1985) 216; for other references, see: *Radiative Corrections in $SU(2) \times U(1)$* , Eds. B. W. Lynn and J. F. Wheeler (World Scientific, Singapore, 1984); for a recent review, see: W. F. L. Hollik, DESY preprint, DESY 88-188 (1988).
- [5] A. Sirlin, *Phys. Rev. D* **22** (1980) 971.
- [6] W. J. Marciano and A. Sirlin, *Phys. Rev. D* **22** (1980) 2695.
- [7] G. G. Ross, *Grand Unified Theories* (The Benjamin/Cummings Publishing Company, 1985) and references therein.
- [8] M. Green, J. Schwarz and E. Witten, *Superstring Theory* (Cambridge U.P., Cambridge, 1987) and references therein.
- [9] E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, *Rev. Mod. Phys.* **56** (1984) 579; (E) **58** (1986) 1065, and references therein; P. Langacker, R. W. Robinett and J. L. Rosner *Phys. Rev. D* **30** (1984) 1470.
- [10] F. del Aguila, M. Quirós and F. Zwirner, *Nucl. Phys.* **B287** (1987) 419.
- [11] F. del Aguila, J. M. Moreno and M. Quirós, *Phys. Rev. D* **41** (1990), to appear.
- [12] M. Cvetič and B. W. Lynn, *Phys. Rev. D* **35** (1987) 51; V. Barger, J. L. Hewett and T. G. Rizzo, University of Wisconsin-Madison preprint, MAD/PH/514 (1989).
- [13] J. A. Minahan, P. Ramond and R. C. Warner, University of Florida preprint, UFIFT-HEP-89-16, June, 1989.
- [14] E. Witten, *Nucl. Phys.* **B258** (1985) 75; M. Dine, V. Kaplunovsky, M. Mangano, C. Nappi and N. Seiberg, *ibid* **B259** (1985) 549; S. Cecotti, J.-P. Derendinger, S. Ferrara, L. Girardello and M. Roncadelli, *Phys. Lett.* **156B** (1985) 318; J. Breit, B. Ovrut and G. Segre, *ibid* **158B** (1985) 33; S. M. Barr, *Phys. Rev. Lett.* **55** (1985) 2778; F. del Aguila, G. Blair, M. Daniel and G. G. Ross *Nucl. Phys.* **B272** (1986) 413; V. Barger, N. G. Deshpande and K. Whisnant, *ibid* **56** (1986) 30; D. London and J. Rosner, *Phys. Rev. D* **34** (1986) 1530; see also, F. Zwirner, *Int. J. Mod. Phys. A* **3** (1988) 49; J. L. Hewett and T. G. Rizzo, *Phys. Rep.* **183C**(1989) 193.
- [15] A. De Rújula, H. Georgi and S. L. Glashow, *Ann. Phys. (NY)* **109** (1977) 242, 258; R. N. Mohapatra and D. P. Sidler, *Phys. Rev. Lett.* **38** (1977) 665.
- [16] E. Witten, *Nucl. Phys.* **B268** (1986) 79; R. Mohapatra and J. W. F. Valle, *Phys. Rev. D* **34** (1986) 1642.
- [17] F. del Aguila, M. Quirós and F. Zwirner, *Nucl. Phys.* **B284** (1987) 530.

[18] Particle Data Group, *Review of Particle Properties*, *Phys. Lett.* **204B** (1988) 1 and references therein.

[19] L3 Collaboration, B. Adeva et al., *Phys. Lett.* **231B** (1989) 509; ALEPH Collaboration, B. Decamp et al., *ibid* **231B** (1989) 519; OPAL Collaboration, M. Z. Akrawy et al. *ibid* **231B** (1989) 530; DELPHI Collaboration, P. Aarnio et al., *ibid* **231B** (1989) 539; Mark II Collaboration, G. S. Abrams et al., *Phys. Rev. Lett.* **63** (1989) 724, 2173; CDF Collaboration, F. Abe et al., *Phys. Rev. Lett.* **63** (1989) 720; UA2 Collaboration, J. M. Gaillard, in the Proceedings of the *International Europhysics Conference on High-Energy Physics*, Madrid, September 6-13, 1989.

[20] G. L. Fogli and D. Haidt, *Z. Phys.* **C40** (1988) 379; G. L. Fogli, *ibid.* **C43**(1989) 229 and references therein.

[21] U. Amaldi et al., *Phys. Rev.* **D36** (1987) 1385; G. Costa et al., *Nucl. Phys.* **B297** (1988) 244.

[22] G. Degrossi and A. Sirlin, *Phys. Rev.* **D40** (1989) 3066.

[23] L. S. Durkin and P. Langacker, *Phys. Lett.* **166B** (1986) 436.

[24] CDF Collaboration, F. Abe et al., *Phys. Rev. Lett.* **64** (1990) 142.