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Phenomenology of one extra neutral Z.

C. VERZEGNASSI*

Laboratoire d'Annecy-le-Vieux de Physique des Particules,
IN2P3-CNRS, BP 110,
F-74941 Annecy-le-Vieux Cedex
FRANCE

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ABSTRACT

I review the main features and limits of present and future indirect searches of one extra neutral Z of general theoretical origin.

* On leave of absence from Dept. of Theor. Physics, Trieste, and INFN, Sezione di Trieste, Italy.

A characteristic feature of all the models of New Physics that propose an extension of the Standard Model via a gauge group of rank bigger than four is the appearance of (at least) one extra neutral vector boson. I will call "orthodox" Z' such an object, and ignore possible heavier neutral partners throughout this talk.

On the other hand, a number of proposals of a drastic replacement of the Standard Model symmetry breaking description (via mechanisms not involving the Higgs particle) also require the presence of (at least) one additional neutral Z. I will call "heretical" Z' such an object, ignoring again the possible existence of heavier partners.

The question of whether one extra neutral Z exists and the identification of its possible (orthodox? heretical?) nature is clearly a relevant one. To try to answer it, different methods can be followed. In practice, two realistic alternative possibilities exist at the moment i.e. :

a) direct production (at pp colliders);

b) indirect searches (from high precision measurements).

The main features and possibilities of direct production have been investigated long time ago[1)], and since excellent review papers already exist[2)] I will not insist on it here. Obviously, direct production is the clear-cut way of seeing a Z'. It also allows, in principle, to distinguish between different models looking e.g. at special angular distributions[3)], and therefore it represents an excellent experimental answer to the various theoretical proposals. Qualitatively, it should be able to cover a range of Z' mass (the relevant parameter in this case) up to a few (five, six...) GeV when the new giant colliders (LHC, SSC) become operative. This one order of magnitude improvement with respect to the existing[2)] collider limits (represented in Fig.(1)) can be viewed as a remarkable experimental achievement. Still, one should not forget that no strong theoretical reasons exist that prevent the existence of a Z' sufficiently heavy for not being produced in these future direct searches.

From this point of view, a very interesting possibility is that provided by indirect searches (via high precision measurements), since in principle these would be able to reveal the existence of a small mixing angle parameter even for a "too" heavy Z'. Such searches are being carried through right now and will continue to be performed in the next few years. Moreover, a number of very recent theoretical approaches has been proposed in this case, and I will try to summarize in this talk two particularly simple and efficient theoretical strategies. In order to be as self-contained as possible, I will also first recall a few notations and conventions.

If one extra U(1) is left as a relic of higher gauge symmetries, the associated vector boson Z_0' and the Z_0 associated with $SU(2)_L \times U(1)_Y$ are not, in general, good mass eigenstates i.e. a non diagonal mass matrix exists :

$$M_0^2 \equiv \begin{vmatrix} a & b \\ b & c \end{vmatrix} \tag{1}$$

and, although this is not a particularly convenient one, I will use the notation :

$$a \equiv M_0^2 \, ; \; c = M_0^{'2} . \tag{2}$$

The physical states Z, Z' are then defined as :

$$Z = \cos\theta_M \, Z_0 + \sin\theta_M \, Z_0^{'} \tag{3}$$

$$Z' = -\sin\theta_M \, Z_0 + \cos\theta_M \, Z_0^{'} \tag{4}$$

where θ_M is associated with the rotation that diagonalizes the mass matrix :

$$M^2 \equiv \begin{vmatrix} M_Z^2 & 0 \\ 0 & M_{Z'}^2 \end{vmatrix} \; ; \; M_{Z'}^2 > M_Z^2 \tag{5}$$

and

$$tg^2\,\theta_M = \frac{\left(M_0^2 - M_Z^2\right)}{\left(M_{Z'}^2 - M_0^2\right)} \tag{6}$$

The parameters θ_M , $M_{Z'}$ are not really independent ones since, in full generality, one can show that

$$tg\,\theta_M = \frac{x}{\sqrt{\left[\frac{1}{\varepsilon}-1\right]^2 - x^2 + \left[\frac{1}{\varepsilon} - 1\right]\sqrt{\left[\frac{1}{\varepsilon} - 1\right]^2 - 2x^2}}} \tag{7}$$

where $\varepsilon = M_Z^2/M_{Z'}^2$ and x is the model dependent parameter

$$x = \sqrt{2}\,\frac{b}{M_Z^2} \tag{8}$$

fixed by the unknown Higgs structure that determines the non diagonal elements in eq. (1).
From eq.(7) one sees that, when $\varepsilon \to 0$, θ_M goes to zero as well since in that case

$$| \, tg\,\theta_M \, | \underset{\varepsilon \to 0}{\simeq} \frac{|x|}{\sqrt{2}}\,\varepsilon . \tag{9}$$

However, the exact numerical value of x is very much model dependent, although in general it is of O(1). Thus, eq.(9) is almost never providing a quantitative relationship between θ_M and $M_{Z'}$. In practice, this is the reason why these parameters are usually considered as independent ones, with the only constraint that if one of the two becomes extremely small, the remaining one cannot possibly be large.

The modifications to the MSM predictions due to the existence of one extra neutral Z are of two kinds. The first one is due to the Z' exchange and contains (besides the Z' couplings that are fixed by the various models) the Z' mass. The second one is due to the shift of both the Z couplings and mass from those of the MSM Z_0. For the new couplings one usually writes

$$Z_{f\bar{f}} \simeq Z_{0f\bar{f}} \left[1 + O(\theta_M)\right] \tag{10}$$

where f is a generic fermion. The $O(\theta_M)$ term contains a coefficient that is fixed by the various models and multiplies θ_M (higher orders in the mixing angle are normally neglected since one already knows from previous measurements that θ_M is small).

The mass shift is usually taken into account by writing

$$M_0^2 = M_Z^2 \left[1 + \frac{M_0^2 - M_Z^2}{M_Z^2} \right] \equiv M_Z^2 \left[1 + \delta_\rho^{Z'} \right] \tag{11}$$

which allows to retain all the MSM expressions introducing the correction :

$$\delta_\rho^{Z'} = \frac{M_0^2 - M_Z^2}{M_Z^2} \equiv \left[\frac{M_{Z'}^2}{M_Z^2} - 1 \right] \sin^2 \theta_M \tag{12}$$

formally analogous to a redefinition (at tree level) of the ρ parameter. In practice, this corresponds to a replacement of the oblique correction to one loop to ρ :

$$\Delta_\rho(0) \simeq \frac{\alpha}{\pi} \frac{m_t^2}{M_Z^2} \tag{13}$$

with a new "block"

$$\nabla_\rho = \Delta_\rho(0) + \delta_\rho^{Z'} \tag{14}$$

as exhaustively discussed in several previous papers[4)].

If no extra charged W are requested by the model, an upper bound on $\delta_\rho^{Z'}$ can be provided by already existing data. In fact, one can write in this case the theoretical expression[4)] :

$$\xi \equiv \frac{M_W^2}{M_Z^2\, c_0^2} = 0.998 \pm 0.003 + \frac{3}{2}\nabla_\rho \qquad (15)$$

where $c_0^2 \simeq 0.769$. From a comparison with the latest CDF, UA2 analyses[5] one derives :

$$\nabla_\rho = 0.005 \pm 0.007\ . \qquad (16)$$

Using eqs.(13), (14) and the fact that $m_t \gtrsim 89$ GeV leads then to the bound (2 σ confidence level)

$$\delta_\rho^{Z'} \lesssim 0.016 \qquad (17)$$

that will be used throughout the forthcoming discussion.

A first simple possibility of looking for virtual effects of a Z' is provided by atomic parity violation (APV) and is illustrated in a recent paper[6]. The quantity that is measured in cesium atoms is conventionally defined as :

$$Q_W = 2\,[(2Z + N)\ C_{1u} + (Z + 2N)\ C_{1d}] \qquad (18)$$

where Z(N) are the number of protons (neutrons) in the nucleus and

$$C_{1q} = 2\, g_{Ae}\, g_{Vq}\ . \qquad (19)$$

The MSM prediction for Q_W is[7] :

$$Q_W^{MSM} \equiv Q_W^{(0)} = -\ 73.1 \pm 0.15 \qquad (20)$$

while the most recent experimental result is[8] :

$$Q_W^{exp} = -71.04 \pm 1.60 \pm 0.71 \qquad (21)$$

where the second error comes from atomic theory uncertainties. Thus :

$$\Delta Q_W \equiv Q_W^{exp} - Q_W^{(0)} = 2.06 \pm 1.75 \pm 0.71. \qquad (22)$$

If a Z' is present, its overall effect, represented graphically in Fig.(2), gives rise to the three effects previously discussed. The theoretical prediction for ΔQ_W eq.(22) would be in this case :

$$\Delta Q_W \equiv \Delta Q_W^{Z'} = \delta_\rho^{Z'} \; Q_W^{(0)} + \left[n_1\, \varepsilon + n_2\, \theta_M \right], \qquad \varepsilon = \frac{M_Z^2}{M_{Z'}^2} \tag{23}$$

where $n_{1,2}$ are fixed by the various models and small (e.g. $O(\theta_M{}^2)$) terms have been systematically neglected.

From eqs. (17), (22) (23) one derives informations of the kind quoted in ref.(6) i.e. :

$$-1.44 \le n_1\, \varepsilon + n_2\, \theta_M \le 6.87\ . \tag{24}$$

To derive bounds on ε, θ_M in a certain model (n_1, n_2 fixed) is now straightforward. One plots in the (ε, θ_M) plane the limiting curve of eq.(17) :

$$\delta_\rho^{Z'} \simeq \frac{\theta_M{}^2}{\varepsilon} = 0.016 \tag{25}$$

which separates the allowed region (above the curve) from the forbidden one. The bounds of eq.(24) then correspond to the region between two straight lines for every model. The intersections of the two regions sets the limits on θ_M and on $M_{Z'}$. This is represented graphically in Fig.(3) for a typical model (called $S^{(0)}$ in ref.(6)). As one sees, the bounds in this case would be[6] :

$$-0.006 \lesssim |\theta_M| \lesssim 0.045 \tag{26}$$

$$M_{Z'}(0) \gtrsim 274\ \text{GeV}. \tag{27}$$

This procedure can be repeated for any chosen model, leading to results that the authors of ref.(6) list in a table (for eleven specific cases) and that give typical bounds of a few hundred GeV for $M_{Z'}$ and of a few percent for θ_M. The interesting point is that future measurements of APV are foreseen with a much higher precision[9] which would lead to better bounds on both $M_{Z'}$ and on the mixing angle in the considered models.

In the previous example the Z' effect came from the simultaneous appearance of all the three parameters $M_{Z'}$, θ_M, $\delta\rho^{Z'} \simeq \theta_M^2/\varepsilon$. A simpler possibility is that of isolating the effects due to $M_{Z'}$ and θ_M.

This can be achieved via the high precision measurements that are being (and will be) performed at LEP1 and LEP2. More precisely, LEP1 would be able to isolate the θ_M effect, while LEP2 would identify effects due to $M_{Z'}$. This has been discussed in several previous papers[10,11,12], and I will only summarize here the main features and results.

The starting point is the observation that on Z resonance, since the Z' exchange graph does not survive, the contribution from $\delta_\rho^{Z'}$ can be washed out by a simple proper choice of observables that are completely free of the obscure ∇_ρ block[10]. For these "twiddled" observables, if only one extra neutral Z appears in addition to the MSM scheme, the deviations from the theoretical predictions can only be due to the θ_M effect, which provides an excellent and relatively unbiased way of measuring the mixing angle, and, also, of setting severe self-consistency tests allowing to identify (or forbid) various theoretical models[10,12].

Rather than insisting on the technical details of the method, I will illustrate with two simple and impressive examples how this technique works. With this aim, I consider the two "twiddled" quantities :

$$\tilde{\gamma}_e = \gamma_e - \frac{2}{3}\xi \tag{28}$$

$$\tilde{\gamma}_v = \gamma_v - \frac{2}{3}\xi \tag{29}$$

where

$$\gamma_e = \frac{9}{\alpha(M_Z)}\ \frac{\Gamma_e}{M_Z};\ \gamma_v = \frac{9}{2\alpha(M_Z)}\ \frac{\Gamma_v}{M_Z} \tag{30}$$

and ξ is defined by eq.(15). In eqs.(28), (29) the ∇_ρ contribution has been practically cancelled. Consequently, the theoretical predictions for these quantities in the MSM are remarkably stable, and read :

$$\tilde{\gamma}_e^{MSM} = 0.391 \pm 0.002 \tag{31}$$

$$\tilde{\gamma}_e^{MSM} = 0.384 \pm 0.002 \tag{32}$$

to be compared with the latest official experimental results[5,13], that give :

$$\tilde{\gamma}_e^{(exp)} = 0.394 \pm 0.010 \tag{33}$$

$$\tilde{\gamma}_v^{(exp)} = 0.352 \pm 0.034 \tag{34}$$

If a new neutral Z exists, it will change the theoretical predictions eqs.(31), (32). In "othodox" models this shift will be a linear function of θ_M, with coefficients fixed by the model. For example, in a (by now) "classical" case of a Z' of E_6 origin[14], the shifts will have the expressions :

$$\delta\tilde{\gamma}_e^{(E_6)} = \theta_M\left[\frac{-2}{\sqrt{6}}\cos\beta - \frac{\sqrt{10}}{3}\sin\beta\right] \tag{35}$$

$$\delta\tilde{\gamma}_v^{(E_6)} = \theta_M\left[\sqrt{\frac{3}{2}}\cos\beta + \sqrt{\frac{5}{18}}\sin\beta\right] \tag{36}$$

where $\cos\beta$ is the weight of the so called χ mode[14]. A comparison of eqs.(35), (36) with eqs.(31)-(34) provides immediate and relatively unbiased bounds on θ_M for every value of $\cos\beta$. Here I will only examine the case of two special models, corresponding to $\cos\beta = 1$ (χ model) and $\cos\beta = -\sqrt{\frac{3}{8}}$ ("$-\eta$" model) $\left(\sin\beta \equiv +\sqrt{1-\cos^2\beta}\right)$.

One easily sees that the available experimental data eqs.(33), (34) give the following information on θ_M :

a) in the χ model, θ_M must be contained into the interval

$$-0.018 \leq \theta_M \leq 0.010 \tag{37}$$

(at one standard deviation)

b) in the ($-\eta$) model, θ_M must be nearly positive and contained in the interval

$$-0.003 \leq \theta_M \leq 0.027 \tag{38}$$

(one standard deviation).

To derive bounds at higher confidence level is straightforward. For example, for the "$-\eta$" model, one would have at 2σ confidence level :

$$-0.03 \lesssim \theta_M \lesssim 0.06 \tag{39}$$

The general analysis for variable $\cos\beta$ can be easily performed[12]. It leads to curves that are the "daughters" of that given in ref.(12) from the March 1990 data shown in Fig.(4), giving the limits on θ_M at that time. These limits will finally be pushed, in case of negative searches, to the values shown in Fig.(5) for the E_6 case[12]. As one sees, the bounds for $|\theta_M|$ would be at the ~ 0.005 level. Thus, if LEP1 will not find such an orthodox Z' from mixing angle effects, it will set limits on θ_M that will safely allow to disregard systematically the mixing angle for future LEP2 (and, also, pp collider) $M_{Z'}$ searches. (Analogous conclusions would obtain for the case of a Z' of left-right symmetry origin[15], as shown in ref.(12)).

Analogous interesting, sometimes drastic, bounds can also be obtained for some examples of a Z' of "heretical" nature, in particular of composite Z origin[16]. Here I will only concentrate on the simple and particularly instructive case of the so called[16] Y, Y_L models. Although the real theoretical parameters in this cases are M_Y and λ_Y^2 (the analogue of $\sin^2\theta_W$) one can still define two quantities that formally correspond to the parameters θ_M and $\delta_\rho^{Z'}$ of the "orthodox" case. In particular,, one finds for the "twiddled" leptonic widths a Y, Y_L effect of the following form :

$$\delta\tilde{\gamma}_V(Y, Y_L) = \frac{1}{2}\,\frac{M_Z^2}{M_{Y,Y_L}^2} \tag{40}$$

where the λ_Y^2 parameter has completely disappeared. When compared with the experimental result eq.(34), this expression leads to the following conclusions for the models (one standard deviation) :

$$\frac{M_Z^2}{M_{Y,Y_L}^2} \leq 0.008 \tag{41}$$

i.e. $M_{Y,Y_L} \gtrsim 1$ TeV.

Again, one can produce predictions at different confidence level. At two standard deviations, for instance, one would derive the following conclusions :

$$\frac{M_Z^2}{M_{Y,Y_L}^2} \lesssim 0.08 \tag{42}$$

i.e. $M_{Y,Y_L} \gtrsim 300$ GeV.

An interesting possibility is to plot in the (Γ_ν, M_W) plane the curve that corresponds to the MSM prediction. From eqs. (29), (32) one sees that the curve is a parabola corresponding to the numerical equation :

$$\frac{\Gamma_\nu}{\text{MeV}} = [0.0164] \frac{M_W^2}{\text{GeV}^2} + [60.41 \pm 0.31] \tag{43}$$

Eq.(43) is represented graphically on Fig.(6). One sees that it can really be considered as a "parabola della morte" ("death" parabola) for various heretical models, since different cases are able to produce deviations either below or beyond the parabola, that provides therefore both bounds and consistency conditions at the same time. Thus, a measurement of the neutrino partial width could really be a "yes/no" test for several heretical proposals.

The previous examples have shown the potential information on a Z' that would be obtainable at LEP1. At LEP2, the Z' exchange would not be kinematically depressed and would lead to non trivial information on $M_{Z'}$ (with θ_M fixed from the previous LEP1 results). From the non observation of deviations in two realistic experimental quantities i.e. the forward-backward muon asymmetry A_{FB}^{μ} and the ratio $R \equiv \Gamma_h/\Gamma_\mu$ one would derive in the illustrative case of a Z' of E_6 origin the bounds shown in Fig.(7)[12) (that were already derivable form the detailed analysis of ref.(11) to which I defer for details). As one sees, LEP2 would be able to set a limit of order 1 GeV for the various models, leading to a significant improvement with respect to previous existing analyses[2,6)]. Note, also, that a 500 GeV e^+e^- collider would lead to limits of the order of a few TeV, comparable with those of the giant pp colliders.

CONCLUSIONS

The conclusions that emerge from this talk is that, at the end of the LEP and of the pp collider runs, negative searches of a Z' will force this particle to be characterized in general by a high (more than ~ 5-6 TeV) mass and by a miserable ($\lesssim$ 0.005) mixing angle in orthodox cases. From a practical point of view, the hopes of discovering such a heavy, unfriendly creature would begin to appear, least to say, mildly discouraging. On the other hand, these negative features might lead to severe restrictions on the candidate models and, possibly, to a deeper theoretical understanding of their origin.

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FIGURE CAPTIONS

Fig. 1 : Typical limits on $M_{Z'}$ from the existing collider data for the "orthodox" case of a Z' of E_6 origin, taken from ref.(2).

Fig. 2 : Z' effect in APV, from ref.(6).

Fig. 3 : Allowed region in the (ε, θ_M) plane from APV experiments for the special model $S^{(0)}$ of ref.(6).

Fig. 4 : Limits on θ_M versus $\cos\beta$ in the case of a Z' from E_6.
- - - - - previous limits
—— limits from present LEP results
hatched region : resulting allowed region.

Fig. 5 : Future limits from LEP1 on θ_M versus $\cos\beta$ in the case of a Z' from E_6 without (continuous line) and with (discontinuous line) a high luminosity phase.

Fig. 6 : Graphical representation of the MSM parabola relating Γ_ν to M_W as from eq.(41), for $M_W \simeq 80$ GeV.

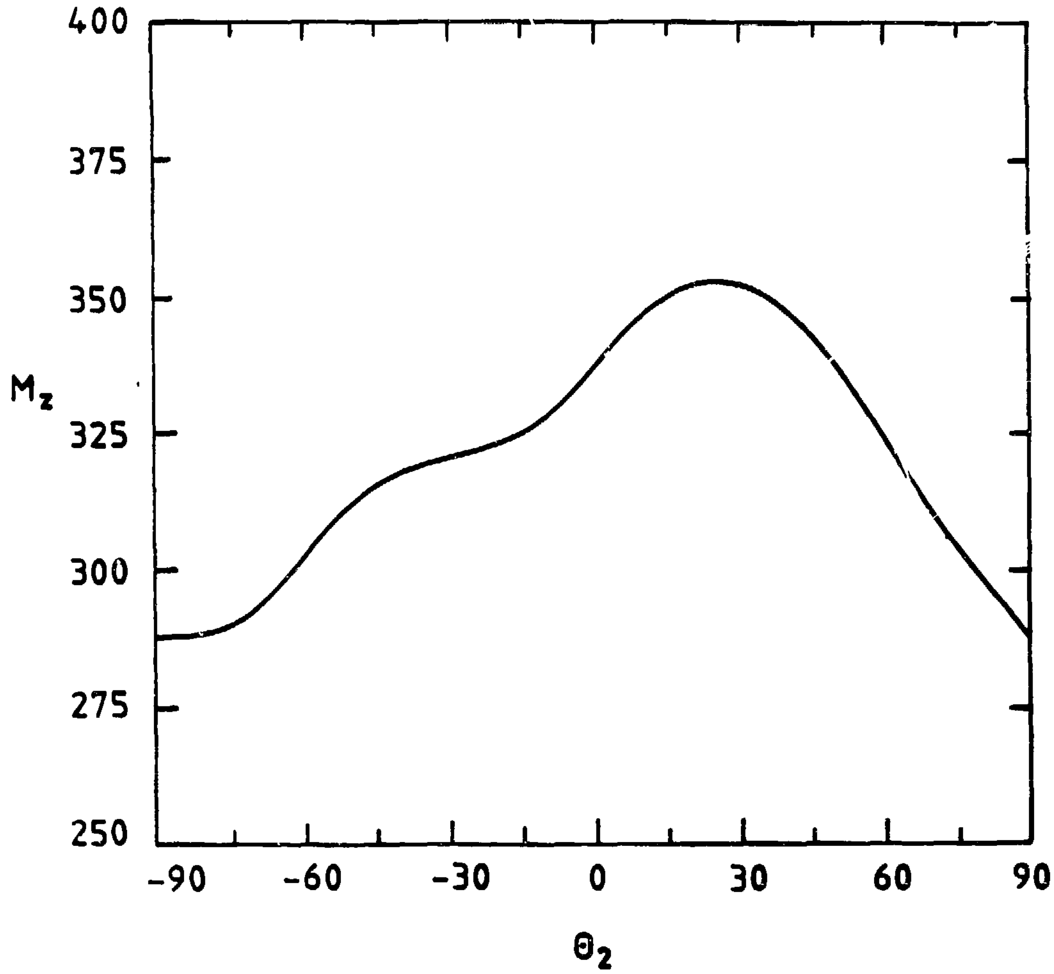
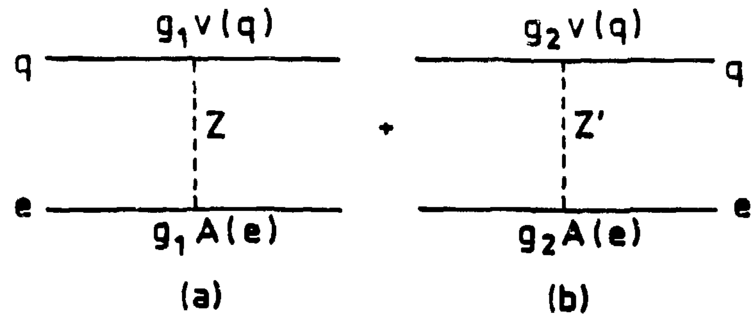
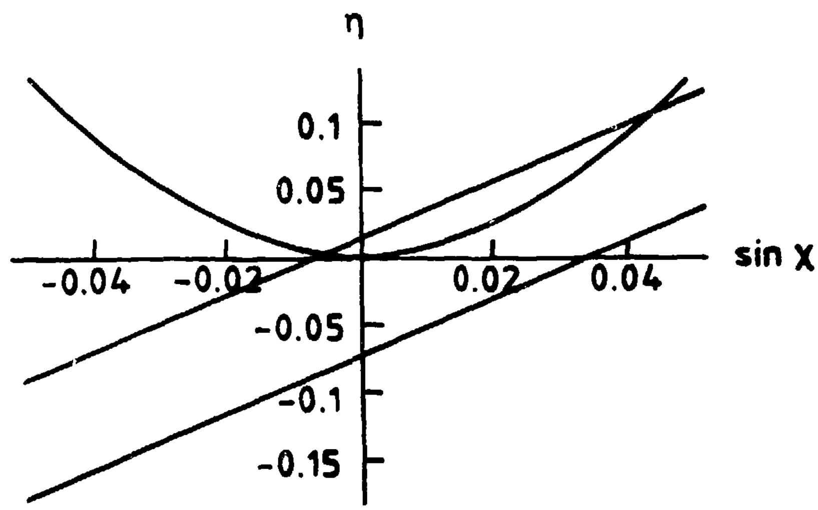


Fig. 1



$g_1 v(q)$
q
Z
e
$g_1 A(e)$
(a)
$g_2 v(q)$
q
Z'
e
$g_2 A(e)$
(b)

Fig. 2



η
0.1
0.05
-0.05
-0.1
-0.15
-0.04
-0.02
0.02
0.04
sin χ

Fig. 3

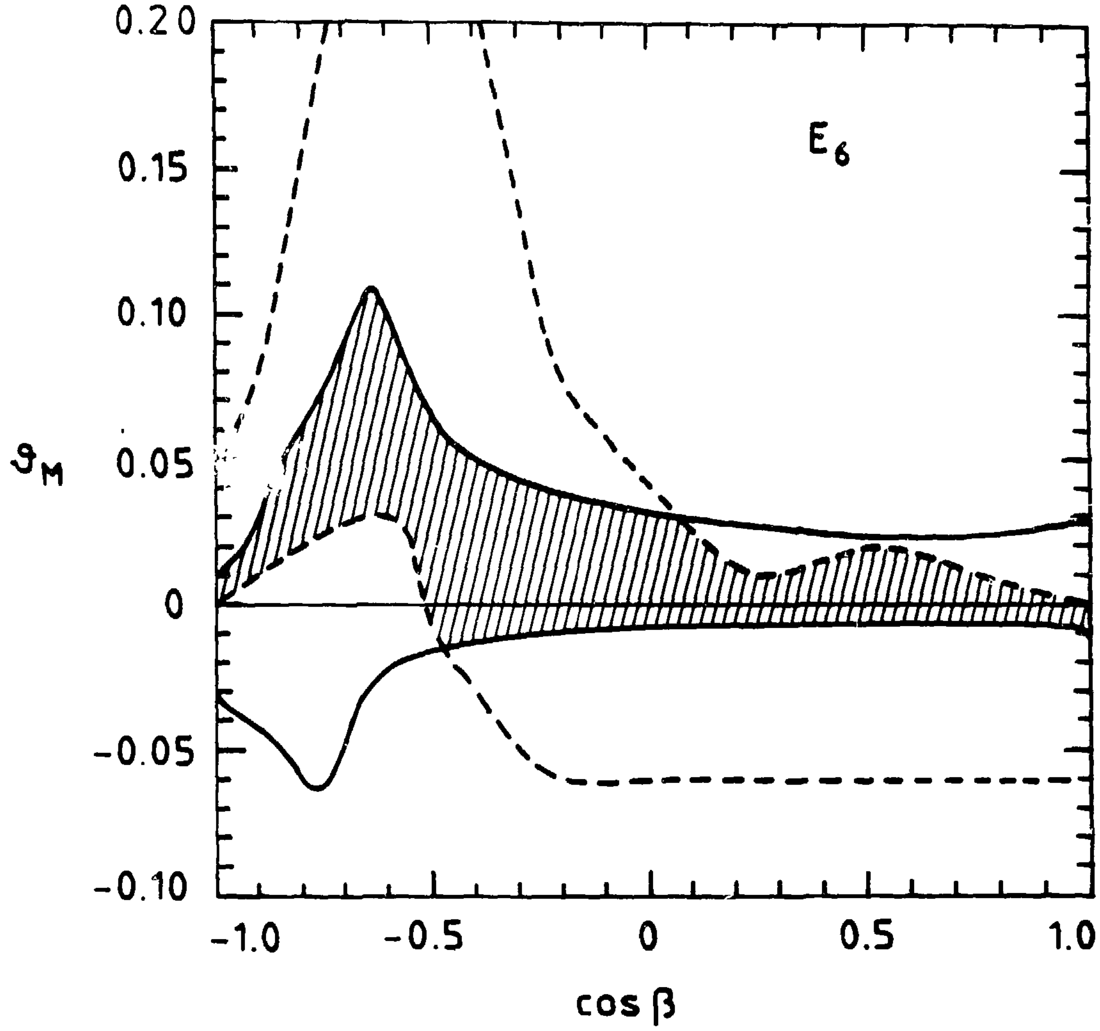


Fig. 4

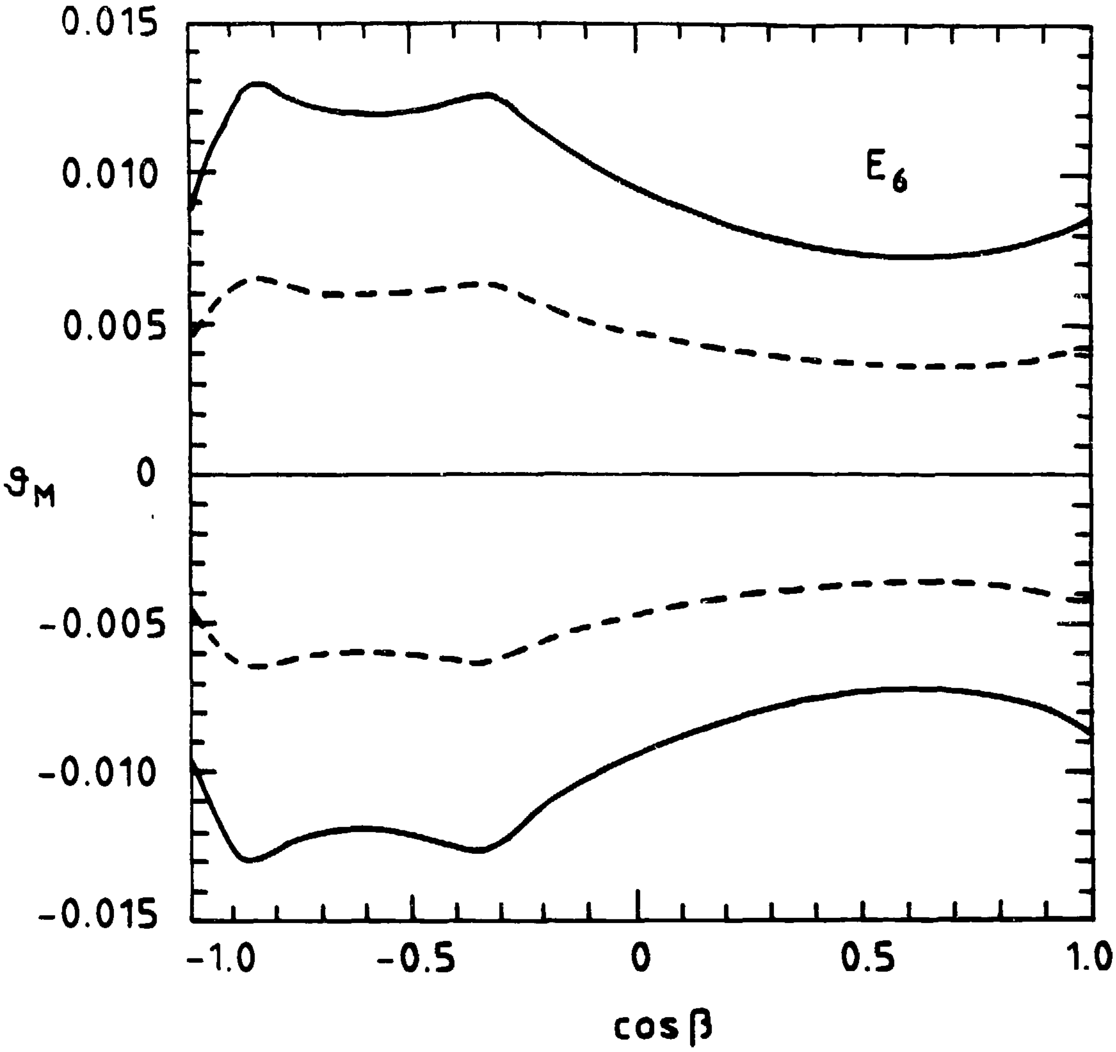


Fig. 5

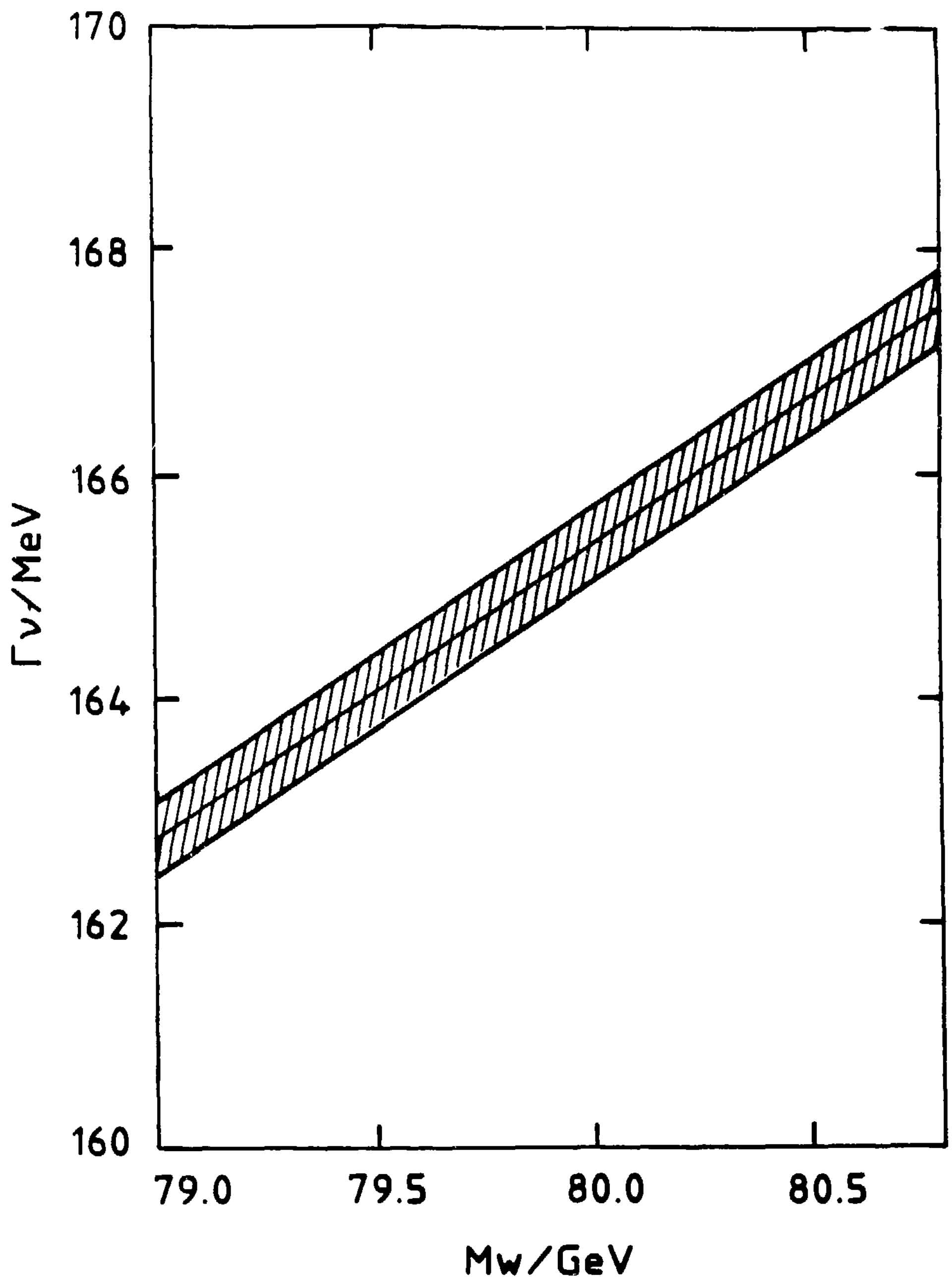
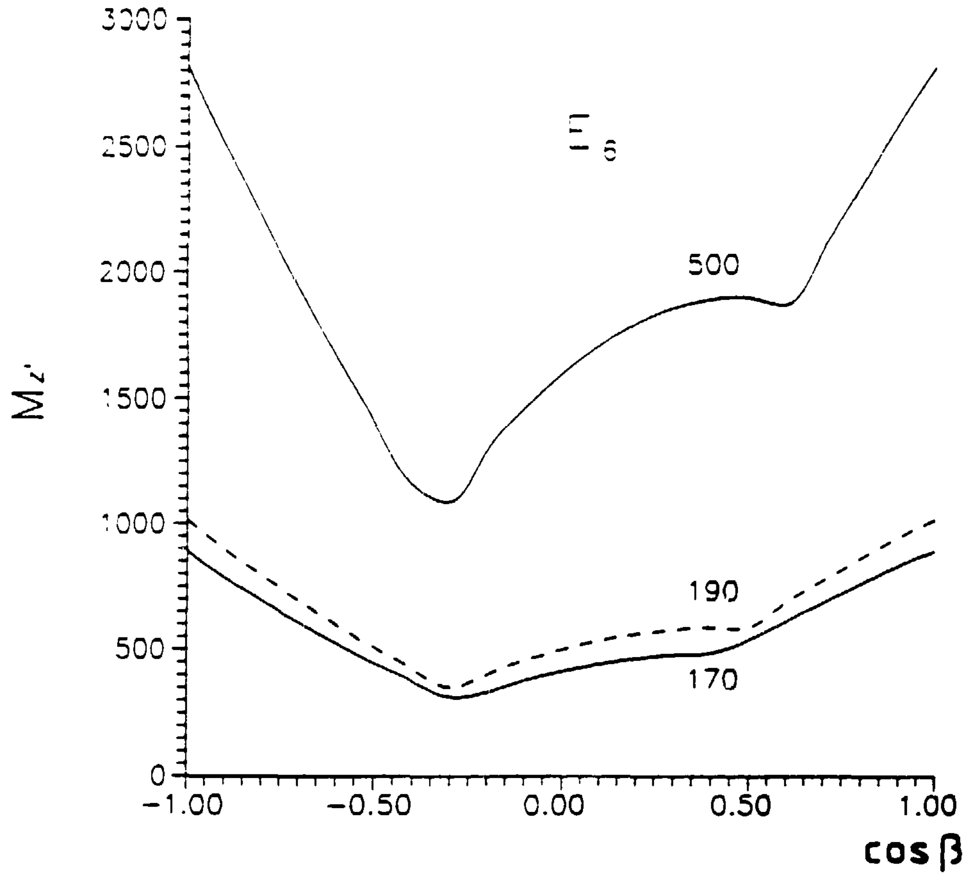


Fig. 6



3000
2500
2000
1500
1000
500
0
$M_{Z'}$
E_6
500
190
170
−1.00
−0.50
0.00
0.50
1.00
cos β

Fig. 7