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MANIFESTATIONS OF HEAVY EXTRA NEUTRAL E_6 GAUGE BOSONS IN $e^+e^- \to W^+W^-$ at LEP II

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Abstract

We have studied the manifestations of a new neutral gauge boson (Z') with $M_{Z'} > \sqrt{s}$, which might exist in E_6 models, in the process $e^+e^- \to W^+W^-$ at LEP II. We have found that the differential cross section is quite sensitive to the existence of a heavy Z'. In particular, $d\sigma/d\cos\theta$ should show the effect of heavier Z' bosons with $M_{Z'} > 350\ GeV$ as an enhanced effect due to the $Z - Z'$ mixing.

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Recently there has been renewed interest [1-4] in the possibility of producing two-gauge boson final states in both e^+e^- and in hadron colliders. In the Standard Model (SM), such processes can be used as direct tests of non-abelian gauge boson self-couplings. In scenarios with extended gauge and scalar sectors, such as E_6 superstring-inspired models [5], the production and decay of new neutral gauge bosons (Z') into such final states can probe $Z - Z'$ mixing as well as trilinear gauge boson couplings.

In this paper we shall discuss the angular distribution of W pairs produced at the CERN e^+e^- collider LEP II ($\sqrt{s} = 200\ GeV$) in the process

$$e^+ + e^- \to W^+ + W^-, \tag{1}$$

in particular the deviations that can be expected from the SM, and how these could be enhanced by the mechanism of $Z - Z'$ mixing for larger values of the Z' mass. We shall assume that the mass of this particle is higher than the maximum machine energy $\sqrt{s} = 200\ GeV$, so that only indirect Z' evidence can be looked for. We anticipate that, although our investigation will be performed for all values $M_{Z'} > 200\ GeV$, we shall be particularly interested to the range $M_{Z'} > 350\ GeV$, where Z' effects to reaction (1) turn out to be most significant, and which might be difficult to probe directly even at the TEVATRON Collider experiments [6]. Having high luminosity ($L = 5 \cdot 10^{31} cm^{-2} sec^{-1}$), and being in the clean environment of e^+e^-, LEP II will undoubtedly give us a lot of useful information on the physics beyond the SM. For definiteness we will consider in what follows only one class of extended electroweak theories, namely that originating from the breaking of E_6 in superstring-inspired models [5] via the chain

$$\begin{aligned} E_6 \to SO(10) \times U(1)_\Psi \to SU(5) \times U(1)_\chi \times U(1)_\Psi \\ \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\alpha. \end{aligned} \tag{2}$$

From the phenomenological point of view this class of models represents quite a natural scheme, in the context of grand unification, where to accomodate both the SM and an extra Z' gauge boson.

We define the physical Z_1 and Z_2 states in terms of the gauge Z and Z' ones:

$$\begin{aligned} Z_1 &= Z \cos\Phi + Z' \sin\Phi \\ Z_2 &= -Z \sin\Phi + Z' \cos\Phi. \end{aligned} \tag{3}$$

The lightest extra Z' boson will be a linear combination of the generators of the two additional $U(1)$'s: $Z' = Z_\Psi \cos\alpha + Z_\chi \sin\alpha$. Specific choices of α correspond to different symmetry breaking patterns which can be related to different subgroup chains, so that the angle α characterizes the direction of the Z'-related generator in the E_6 group space. If E_6 is broken to a rank-6 group the mixing angle α is in general unconstrained, while in the case E_6 is broken to a rank-5 group at the unification scale in superstring theories α is uniquely determined and has the value $\alpha = \arctan\sqrt{3/5} = 37.8^\circ$ (Z_η). The values $\alpha = 0^\circ$, $\alpha = 90^\circ$ correspond to pure Z_Ψ and Z_χ. There is also the special value $\alpha = \arctan(-\sqrt{5/3}) = 127.8^\circ$ (Z_I), corresponding to an extra $SU(2)$ group at electroweak energies [5]. Note that all the conclusions valid for the χ model would also apply to the left-right symmetric model with $g_R^2 \simeq \frac{1}{2}g_L^2$ [7,8].

The mixing angle Φ is constrained by existing data, and such constraints critically depend on the value of α [9-14]. The situation could be roughly summarized by saying that in general $|\Phi|$ should be limited to the range $|\Phi| \leq 0.05$, although for some values of α the constraints from the LEP data could be even more severe [14]. However, in the case of the η model, the experimental constraint is much weaker, because the effects of mixing and of Z_η exchange tend to cancel each other for large negative mixing angles, so that $|\Phi| \leq 0.1$ could be allowed.

To discuss the influence of the extra Z_2 boson on the process (1), we separately consider the effects of the indirect modification of the SM couplings to the ordinary Z boson (mainly that of the e^+e^-, and to a much smaller extent that of the W^+W^- pairs) due to $Z - Z'$ mixing, and the direct contribution to the cross section from the virtual Z_2 exchange diagram. We refer to them as the mixing effect and as the virtual effect respectively, although clearly the latter also implicitly depends on the $Z - Z'$ mixing which generates the (W^+W^-Z') couplings [15-18].

Starting with the mixing effect, it physically corresponds to the case where the Z_2 bosons are heavy enough that one can neglect their (virtual) propagator contribution. In this situation the process (1) is described (in the Born approximation) by the same three diagrams as it is in the SM [19-21]: the t-channel ν exchange and the the s-channel exchanges of neutral gauge bosons γ and Z_1. Thus, to evaluate the effects of the Z_2 boson, we can use the formulae presented in Ref.[20] in the tree-level approximation to the SM, and make the following replacements of the electron couplings [8]:

$$\begin{aligned} v \to v_1 &= v\cos\Phi + cv'\sin\Phi \simeq v + cv'\Phi \\ a \to a_1 &= a\cos\Phi + ca'\sin\Phi \simeq a + ca'\Phi, \end{aligned} \tag{5}$$

where

$$v = -\frac{1}{2} + 2\sin^2\theta_W, \quad a = -\frac{1}{2}, \quad c = 2\sqrt{\frac{5}{3}}\sin\theta_W,$$
$$v' = -\frac{\sin\alpha}{\sqrt{10}}, \quad a' = \frac{\cos\alpha}{2\sqrt{6}} - \frac{\sin\alpha}{2\sqrt{10}} \tag{6}$$

The relative contribution of the Z_2 boson to the differential cross section of process (1) is defined as:

$$\delta_W = \frac{\frac{d\sigma}{d\cos\theta} - \frac{d\sigma^{SM}}{d\cos\theta}}{\frac{d\sigma^{SM}}{d\cos\theta}} \tag{7}$$

(θ being the angle between the e^- and the W^- momenta). Evidently, the contributions to the numerator of Eq.(7) are due to the presence of the "modified" Z_1 boson exchange diagrams:

$$\delta_W = \frac{\Delta\bar{\sigma}_{\gamma Z}}{\bar{\sigma}^{SM}} + \frac{\Delta\bar{\sigma}_{\nu Z}}{\bar{\sigma}^{SM}} + \frac{\Delta\bar{\sigma}_{ZZ}}{\bar{\sigma}^{SM}}, \tag{8}$$

where we use the following notation:

$$\bar{\sigma}^{SM}_{ij} = \frac{d\sigma^{SM}_{ij}}{d\cos\theta}, \qquad \Delta\bar{\sigma}_{\gamma Z} = \bar{\sigma}_{\gamma Z_1} - \bar{\sigma}^{SM}_{\gamma Z}$$
$$\Delta\bar{\sigma}_{\nu Z} = \bar{\sigma}_{\nu Z_1} - \bar{\sigma}^{SM}_{\nu Z}, \qquad \Delta\bar{\sigma}_{ZZ} = \bar{\sigma}_{Z_1 Z_1} - \bar{\sigma}^{SM}_{ZZ}. \tag{9}$$

The modification to the (ZW^+W^-) vertex is negligible in practice as it is proportional to $\cos\Phi$.

Following Ref.[20], we take into account that

$$\bar{\sigma}_{\gamma Z} \propto v, \quad \bar{\sigma}_{\nu Z} \propto v + a, \quad \bar{\sigma}_{ZZ} \propto v^2 + a^2, \tag{10}$$

and similarly

$$\bar{\sigma}_{\gamma Z_1} \propto v_1, \quad \bar{\sigma}_{\nu Z_1} \propto v_1 + a_1, \quad \bar{\sigma}_{Z_1 Z_1} \propto v_1^2 + a_1^2. \tag{10'}$$

Replacing Eqs.(9) and (10-10') into Eq.(8), we can express δ_W as follows:

$$\delta_W = c\left[\left(\frac{v'}{v}\right) R^{SM}_{\gamma Z} + \left(\frac{v' + a'}{v + a}\right) R^{SM}_{\nu Z} + 2\left(\frac{vv' + aa'}{v^2 + a^2}\right) R^{SM}_{ZZ}\right]\Phi, \tag{11}$$

where $R^{SM}_{ij} = \frac{\bar{\sigma}^{SM}_{ij}}{\bar{\sigma}^{SM}}$ are the contributions to the differential cross section of process (1) in the SM, coming from the individual diagrams as well as from the interference terms. For brevity we omit the explicit form of the various R^{SM}_{ij}, and limit ourselves to represent their behaviour with the scattering angle θ in Fig.(1). One we can see that the effect is maximal in the backward direction $\cos\theta = -1$ ($\sqrt{s} = 200\ GeV$), and moreover that in this region the $\nu - Z$ and the $Z - Z$ contributions are by themselves several times greater than the differential cross section as given by the sum of all contributions.

We now evaluate numerically Eq.(11) in the Ψ, η and χ models. One finds, at $\cos\theta = -1$ and $\sin^2\theta_W = 0.23$, $M_{Z_1} = 91.1\ GeV$, $M_W = 80\ GeV$:

$$\delta_W = \Phi \begin{cases} +0.80 & (\Psi) \\ -0.95 & (\eta) \\ -2.52 & (\chi) \end{cases} \tag{12}$$

(for the model I the result is similar to that for the model χ).

Eq.(12) shows the sensitivity of δ_W on the mixing angle Φ and on the various models. This is even more explicitly displayed in Fig.(2), which essentially shows the dependence of δ_W at $\cos\theta = -1$ on the various values of α.

Concerning the angular behaviour of $|\delta_W|$, it is found to have a maximum at $\cos\theta = -1$, where however the cross section is smallest, and to be smaller than the maximum at $\cos\theta = 1$, where the cross section is largest. To discuss the size of this mixing effect, taking into account the θ dependence and the experimental conditions available at LEP II, we can define as an example the ratio:

$$r = \frac{\Delta\bar{\sigma}}{\delta\bar{\sigma}}, \tag{13}$$

where $\Delta\bar{\sigma}$ is the numerator of Eq.(7) and $\delta\bar{\sigma}$ is the statistical uncertainty obtainable on the measured differential cross section. Assuming an integrated luminosity of 500 pb^{-1} in one year run, with $\frac{d\sigma}{d\cos\theta} \simeq 1.5\ pb$ at $\cos\theta = -1$ one may expect a sample of about 750 events in that direction, sufficient for 3.5% measurement. Conversely, with $\frac{d\sigma}{d\cos\theta} \simeq 40\ pb$ at $\cos\theta = 1$, 0.7% measurements should be possible in the forward region. In Fig.(3) is represented the behaviour of r as a function of $\cos\theta$ in the case of the η model, for two choices of the mixing angle Φ compatible with the present experimental limits. Since we are obviously interested in $r > 1$, the most favorable region to look for deviations from the SM is the backward direction. Another point to be noticed is that r changes sign around $\cos\theta \simeq 0.7$: this makes the total cross section (integrated over $\cos\theta$) less convenient to search for this kind of effect, since there is a cancellation. Analogous results are found for the other models considered here.

Coming now to the second effect mentioned at the beginning, the virtual one, this turns out to somewhat decrease the mixing effect discussed above, by an amount which depends on the value of M_{Z_2}. This is due to the fact that the two contributions have opposite signs, and consequently show a partial cancellation. The resulting values (mixing plus virtual contributions) of δ_W at $\cos\theta = -1$ are represented as a function of M_{Z_2} in Fig.(4). The increasing behaviour reflects the above mentioned cancellation, which becomes less and less effective as being suppressed for increasing M_{Z_2} by the propagator effect, so that in principle the curve should flatten to the pure mixing contribution for infinite M_{Z_2}. However, we should keep in mind, in this regard, that the curves in Fig.(4) should not be naively extrapolated to the asymptotic values of M_{Z_2}, because the maximum allowed values of $|\Phi|$ also depend on M_{Z_2} [13].

Fig.(4) qualitatively shows that the reaction (1) at LEP II should be sensitive to values of the Z_2 mass larger than (say) 300 GeV, in the optimistic case in which the mixing angle Φ takes the maximum values presently allowed for the various models. In particular, Z_2 boson effects would be clearly seen, within the assumed statistical uncertainty, for the η (χ) models at $|\Phi| \approx 0.1$ (0.05) and $M_{Z_2} \geq 300\ GeV$, and also at $|\Phi| \geq 0.03$ (0.015) for $M_{Z_2} \geq 450\ GeV$.

The range $M_{Z_2} < 350\ GeV$ should be more conveniently probed either at the TEVATRON Collider or by $e^+e^- \to f\bar{f}$ at LEP II [22-24]. In fact the latter reaction is mostly sensitive to the virtual propagator effect rather than to the mixing angle Φ, and in that sense it can be considered as complementary to the process (1).

In summary, the angular distribution of the final W bosons in reaction (1) at LEP II should allow to test $Z - Z'$ mixing in E_6 extensions of the SM, by the enhancement mechanism discussed above. In particular, it might be useful in order to improve the bounds on the mixing angle, especially for the upper range of Z_2 masses considered in Fig.(4). The enhancement mechanism noted here, based on the dominance of individual contributions to the cross section, could play an interesting role also in other kinds of physical effects beyond the Standard Model.

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Figure captions

Fig.(1) : The ratios R_{ij}^{SM} of Eq.(11) as a function of $\cos\theta$ at $\sqrt{s} = 200\ GeV$: R_{ZZ}^{SM} (1); $R_{\nu Z}^{SM}$ (2); $R_{\gamma Z}^{SM}$ (3); $R_{ZZ}^{SM} + R_{\nu Z}^{SM} + R_{\gamma Z}^{SM}$ (4).

Fig.(2) : δ_W (Eq.(11)) as a function of the mixing angle Φ at $\cos\theta = -1$, $\sqrt{s} = 200\ GeV$ for the Ψ (1), η (2), χ (3) and I (4) models.

Fig.(3) : r (Eq.(13)) as a function of $\cos\theta$ for the η model at $\sqrt{s} = 200\ GeV$, $\Phi = -0.1$ (1) and $\Phi = -0.05$ (2).

Fig.(4) : δ_W as a function of M_{Z_2} at $\cos\theta = -1$, $\sqrt{s} = 200\ GeV$, for the χ model with $\Phi = -0.05$ (1), $\Phi = -0.01$ (2) and for the η model with $\Phi = -0.1$ (3), $\Phi = -0.05$ (4).

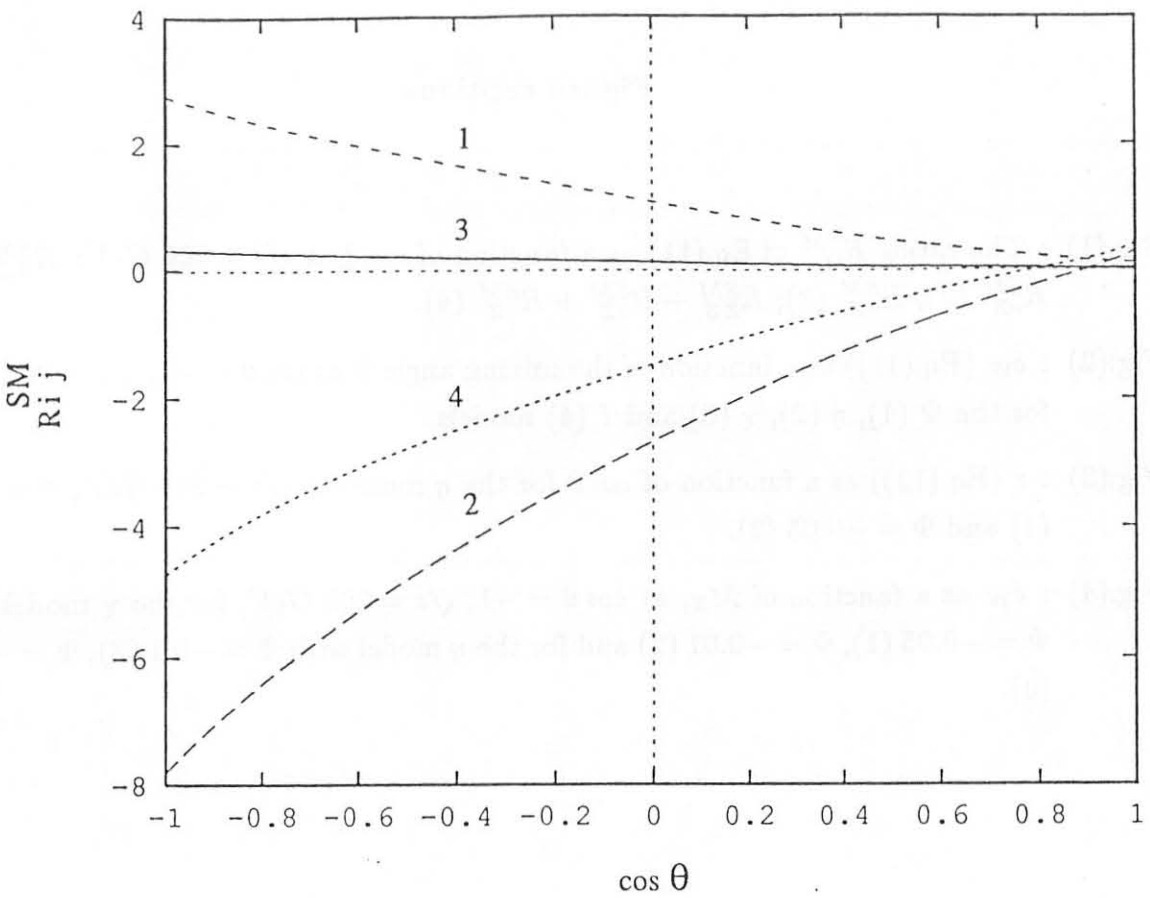

4
2
0
-2
-4
-6
-8
SM
Ri j
1
3
4
2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos θ

Fig. - 1

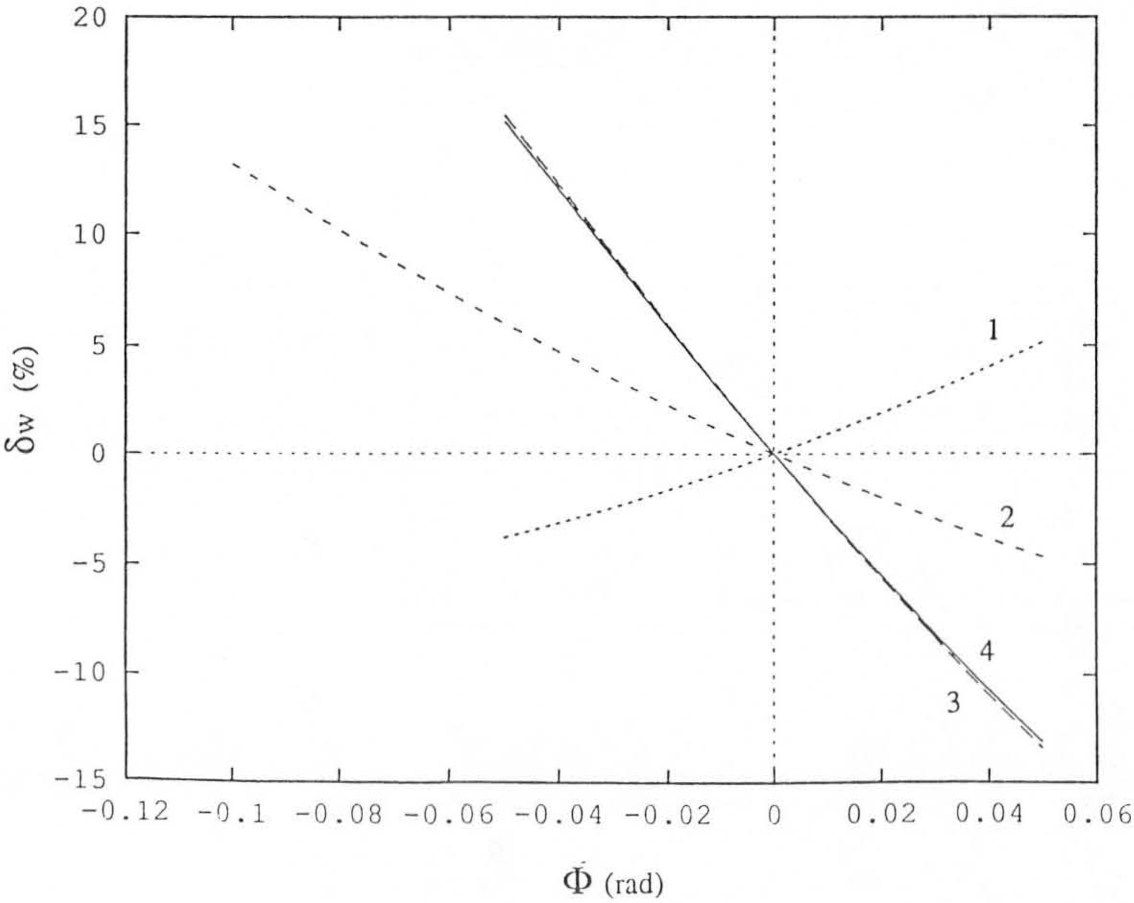
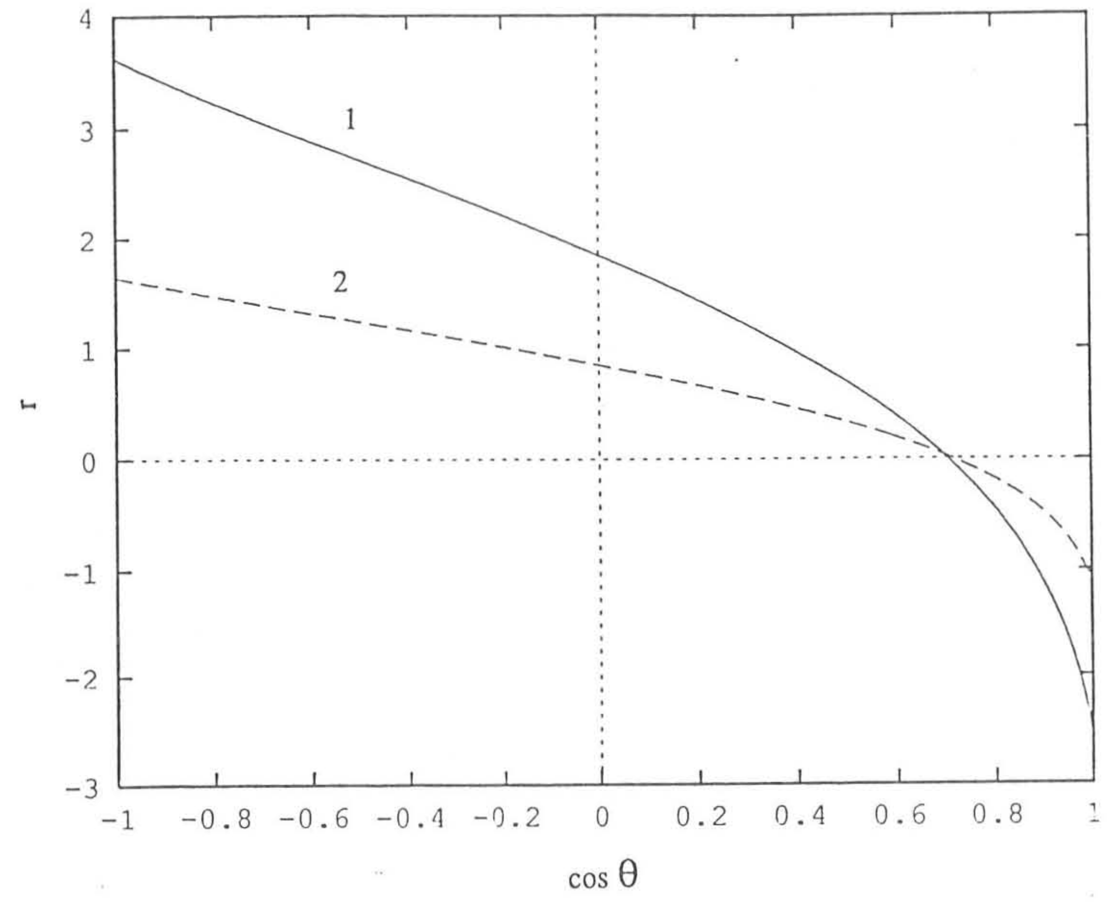
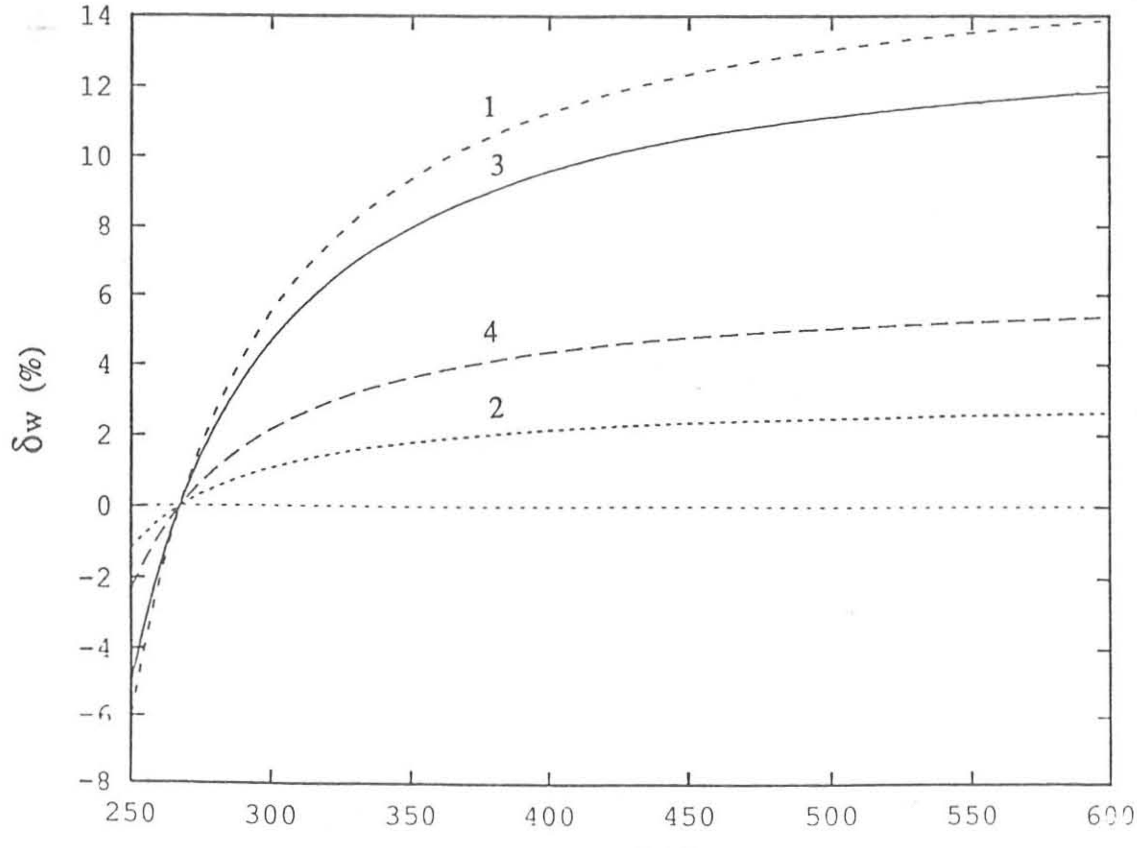

20
15
10
5
0
-5
-10
-15
δw (%)
1
2
4
3
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
Φ (rad)

Fig. - 2



4
3
2
1
0
-1
-2
-3
r
1
2
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos θ

Fig. - 3



14
12
10
8
6
4
2
0
-2
-4
-6
-8
δw (%)
1
3
4
2
250
300
350
400
450
500
550
600
M_{Z_2} (GeV)

Fig. - 4