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ATOMIC PARITY VIOLATION IN EXTENDED GAUGE MODELS AND LATEST CDF AND LEP DATA ^{*)}

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ABSTRACT

Possible allowed deviations in atomic parity violation from new gauge bosons in extra U(1) models and left-right models are estimated on the basis of the present electroweak data, particularly the latest LEP and CDF limits. The theoretical expectation for the shift in the weak charge is written as the sum of a term proportional to the ρ -value deviation, a term proportional to the $Z - Z'$ mixing angle, and a term surviving also for zero mixing. For the Cesium atom, constraints on $M_{Z'}$ and on the $Z - Z'$ mixing result in strong restrictions on the allowed deviations from the standard model prediction. In specific models atomic parity is already capable of putting interesting limitations without any assumption about the Higgs structure (for instance $M_{Z'} \geq 360 \text{ GeV}$ in extra U(1) models with $\theta_2 = 90^\circ$). The expected accuracy increase in atomic parity data will allow for more stringent conclusions.

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1. Introduction

The current uncertainty of about 2.5% (experimental uncertainty [1] plus the uncertainty of theoretical atomic calculations [2]) in atomic parity violation already provides for an excellent test for the electroweak theory in the limit of low energy. The experimental results in Cesium [3,4,1] have gone through a remarkable increase in accuracy, always remaining in essential agreement. Atomic theory calculations have also increased in precision by an almost comparable amount. New ideas and proposals have recently been advanced which substantiate the hope for further progress in this field. Hopefully the uncertainty will be reduced below 1% by further work both in atomic theory and in experiment, so that atomic parity violation will become an additional source of information on the still unknown parameters of the standard model and on possible physics beyond the standard model (SM).

The aim of the present note is to analyze the deviations from the SM predictions in atomic parity violation, due to the presence of an extra neutral gauge vector boson. We will mostly use the existing restrictions from different areas of neutral current precision experiments to explore the allowed range of deviations for the models considered.

The parity violating electron-nucleus effects for axially-coupled electron and vector-coupled quarks are described through the so-called weak charge of the nucleus, $Q_W(Z, N)$, which expresses the coherent effect of the weak charges of the $(2Z + N)$ u-quarks and of the $(Z + 2N)$ d-quarks in a (Z, N) nucleus. The precise measurement of this charge might play an important role in discriminating among different new physics effects (if any). For instance, in technicolour models, with self-energy corrections evaluated in one-loop technifermion approximation, Q_W receives a negative contribution, whose size is proportional both to the number of technicolours and of technidoublets [5]. Other models of strong electroweak breaking may allow for some more freedom depending on their parameters [6]. Our analysis is devoted to a characterization of Q_W in models with an extra, low energy $U(1)$ factor, and in left-right models.

A large freedom is however available in constructing models with new gauge vector bosons, and, to build a common basis to the discussion, it has become customary to fix the attention on some particular models, and in particular to two classes of models: models with one extra $U(1)$, contained in E_6 [7], and left-right-symmetric models [8]. One basis for such types of considerations is the possibility that, when some original high symmetry, unifying different interactions, is broken down to low energies, for some breaking pattern, an additional group factor (a $U(1)$ or an $SU(2)$) survives down to the low energies, besides the $SU(2) \times U(1)$ structure. But, independently of the theoretical

standpoint, one may consider the reference to a limited set of particular models as a very convenient common convention to parametrize possible deviations.

The models we consider with an extra $U(1)$ [7] have an additional gauge boson coupled to a new additive quantum number. The electric charge retains its original form in terms of T_{3L} and Y . In the physical basis one has the photon, and two mass eigenstates Z and Z' from diagonalization of the mass matrix for the unphysical Z_0 , coupled to $J_{3L} - \sin^2 \theta J_{em}$, and Z'_0 , coupled to the new quantum number. In addition it is assumed that the extra $U(1)$ originates from the breaking of a unifying E_6 structure. This requires specification of an angle θ_2 (*), which defines the choice of the extra $U(1)$ within the linear space defined by the two independent colour neutral $U(1)$ of E_6 which lie outside $SU(2)_L \times U(1)$. Particular choices of θ_2 have retained some attention in the literature. They correspond to the following choices for θ_2 : $\theta_2 = 0$ (model called A [9] or η [10,11]), $\theta_2 = 52.24^\circ$ (called B [9] or χ [10,12,13]), $\theta_2 = -52.24^\circ$ (called C [9]).

Left-right symmetric models [8] assume a gauge group $SU(2)_L \times SU(2)_R \times U(1)$, with $U(1)$ generated by $B - L$. The electric charge is $T_{3L} + T_{3R} + B - L$, allowing for the identification of the photon field through a first orthogonal transformation which defines a particular basis Z_{0L} and Z_{0R} , from which by subsequent rotation one obtains the massive physical bosons Z, Z' . In addition there will be physical charged massive W and W' , which are a linear combination of W_L and W_R . Additional specifications on the models are contained in the text.

We shall write the deviation, δQ_W , of the weak charge Q_W , from its standard model prediction (including radiative corrections), as a sum of three pieces. The first piece is proportional to a shift in the ρ value, originating from the mixing between the two neutral gauge bosons, and the second piece is directly proportional to the mixing angle. The last piece is proportional to $M_Z^2/M_{Z'}^2$, and does not vanish for zero mixing. From this structure of the δQ_W , also common to other low energy neutral current measurements, one sees immediately a complementary aspect in the information it provides when compared with the tests made at the Z pole, essentially with LEP data. For all those tests the deviations depend entirely on the existence of a mixing angle and vanish for a Z' which is unmixed.

In the following sections, we will present a short derivation of δQ_W , to clarify the different origin of the three terms mentioned above. Then we will let the parameters vary within the range presently allowed by the experimental data collected in other sectors of electroweak interactions, such as the CDF Z' direct search and the LEP data.

(*) We adopt the definition of the θ_2 angle of ref. [9].

The peculiar structure of δQ_W together with the constraints on the parameter space will result in a characterization of the deviations coming from a Z' which may show up in future atomic parity violation experiments.

2. Weak Charge Q_W in models with an extra $U(1)$

Basic to the analysis of the experiments on parity violation in atoms is the electron-quark effective Lagrangian:

$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} (\bar{e} \gamma_\mu \gamma_5 e) (C_{1u} \bar{u} \gamma^\mu u + C_{1d} \bar{d} \gamma^\mu d) \quad (2.1)$$

The parity violating effect for the vector-coupled electrons and axially-coupled quarks is strongly suppressed because of the smaller vector coupling of electrons in the standard model and because of its dependence on spins rather than charges. We shall not discuss this effect, which is very small in a heavy atom, and presents a difficult problem when trying to determine the hadronic axial couplings because of contaminations from nuclear parity violation (expressed by anapole moment).

The experimental results are usually quoted in terms of the related so-called weak charge Q_W :

$$Q_W = -2[C_{1u}(2Z + N) + C_{1d}(Z + 2N)] \quad (2.2)$$

where Z and N are the number of protons and neutrons, respectively, of the atom considered.

In extensions of the standard model by an extra $U(1)$, Q_W will deviate from its standard model expression by the quantity δQ_W . After the precise determination of M_Z at LEP it is convenient to choose as independent physical parameters α , G_F and M_Z . We shall express δQ_W for such a choice of the physical parameters and we will see that it consists of the sum of three terms (see eq. 2.16): one proportional to the shift $\Delta\rho_M$ of the ρ parameter originated from $Z_0 - Z'_0$ mixing, one proportional to the mixing angle ξ , and a third one proportional to the squared mass ratio $M_Z^2/M_{Z'}^2$. All these contributions are supposed to be small, so that their higher orders may be neglected.

For the sake of self-consistency, we will briefly sketch the derivation of the expression for Q_W in SM extensions with an extra $U(1)$. As starting point we consider the Lagrangian:

$$\mathcal{L} = \frac{1}{2} z_0^T M^2 z_0 + z_0^T j \quad (2.3)$$

where

$$\begin{aligned} z_0 &= \begin{pmatrix} Z_0 \\ Z'_0 \end{pmatrix} \\ j &= \begin{pmatrix} J \\ J' \end{pmatrix} \end{aligned} \quad (2.4)$$

$$\begin{aligned} J_\mu &= \frac{g}{\cos\theta} \sum_f (v_f \bar{f} \gamma^\mu f + a_f \bar{f} \gamma^\mu \gamma_5 f) \\ J'_\mu &= \frac{\tilde{g}}{\sin\theta} \sum_f (v'_f \bar{f} \gamma^\mu f + a'_f \bar{f} \gamma^\mu \gamma_5 f) \end{aligned} \quad (2.5)$$

In eq. (2.3) M^2 is the square-mass matrix for the neutral sector (Z_0, Z'_0) , before diagonalization. In eq. (2.5) f represents the generic fermion, g and $\tilde{g}$ are the gauge coupling constants associated to $SU(2)_L$ and to the extra $U(1)$, and $\cos\theta$ is defined, at tree-level, through the relation:

$$\sin\theta = \frac{e}{g} \quad (2.6)$$

The expressions of the vector and axial-vector couplings v_f, v'_f, a_f and a'_f relevant to our analysis are given in table I. In eq. (2.3) we have deliberately omitted the kinetic energy for Z_0 and Z'_0 , negligible in the energy range of atomic experiments. The mass eigenstate z :

$$z = \begin{pmatrix} Z \\ Z' \end{pmatrix} \quad (2.7)$$

will be rotated with respect to the interaction eigenstates z_0 via the orthogonal transformation:

$$z = O z_0 \quad (2.8)$$

where:

$$O = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \quad (2.9)$$

The square mass-matrix $M_z^2 = O M^2 O^T$ is diagonal and its eigenvalues will be denoted by $M_Z^2, M_{Z'}^2$.

It is important to note that, due to the $Z_0 - Z'_0$ mixing specified by the matrix (2.9), the $\rho = 1 + \Delta\rho$ parameter, defined by the relation

$$\frac{M_W^2}{\rho M_Z^2} = \cos^2\theta \quad (2.10)$$

receives a positive contribution $\Delta\rho_M$ given by [14,15]:

$$\Delta\rho_M = \sin^2\xi \left(\frac{M_{Z'}^2}{M_Z^2} - 1 \right) \quad (2.11)$$

The quantity $\Delta\rho_M$ adds to the other possible terms contributing to the ρ parameter, such as $\Delta\rho_T = 3G_F m_\tau^2/8\pi^2\sqrt{2}$ coming from the leading electroweak radiative correction. The modification to the ρ parameter given in eq. (2.11) affects the relation between the $\sin\theta$ defined in eq. (2.6) and the basic electroweak parameters α , G_F , and M_Z . By writing the relation (2.6) in the form:

$$\sin^2\theta \cos^2\theta = \frac{\mu^2}{\rho M_Z^2} \quad (2.12)$$

with $\mu^2 = \pi\alpha/\sqrt{2}G_F$, and by solving eq. (2.12) in $\sin^2\theta$, one finds that a shift $\Delta\rho_M$ in the value of the ρ parameter produces a shift $\delta(\sin^2\theta)$, already at the tree level, given by:

$$\delta(\sin^2\theta) \simeq -\frac{\sin^2\theta \cos^2\theta}{\cos 2\theta} \Delta\rho_M \quad (2.13)$$

This modification of $\sin^2\theta$ must be appropriately taken into account in evaluating the deviation δQ_W of Q_W from the SM predictions.

Due to the absence of the kinetic energy terms, the Lagrangian $\mathcal{L}$ of eq. (2.3) is equivalent to the effective, four-fermion Lagrangian $\mathcal{L}'$ given by:

$$\mathcal{L}' = -\frac{1}{2} j^T O^T M_d^{-2} O j \quad (2.14)$$

By isolating in the expression of the currents (J, J') the relevant electron and quark terms we can identify the coefficients C_{1u} and C_{1d} of eq. (2.1). We obtain:

$$\begin{aligned} C_{1u,d} = & -8\rho \left[(\cos^2\xi + \sin^2\xi \frac{M_Z^2}{M_{Z'}^2}) a_e v_{u,d} + \right. \\ & + \frac{\tilde{g}}{g'} \cos\xi \sin\xi (1 - \frac{M_Z^2}{M_{Z'}^2}) (a_e v'_{u,d} + a'_e v_{u,d}) + \\ & \left. + \frac{\tilde{g}^2}{g'^2} (\sin^2\xi + \cos^2\xi \frac{M_Z^2}{M_{Z'}^2}) a'_e v'_{u,d} \right] \end{aligned} \quad (2.15)$$

The SM expressions for $C_{1u,d}$ can be obtained from those of eq. (2.15) in the limit $M_{Z'} \rightarrow \infty$ and $\xi \rightarrow 0$.

We are interested in the deviation $\delta Q_W = Q_W - Q_W^{\text{SM}}$ with respect to the Standard Model predictions. In view of further applications, we expand the expressions of $C_{1u,d}$ in equation (2.15) keeping only the terms of first order in ξ or $M_Z^2/M_{Z'}^2$, (assuming that these quantities are of the same order). The approximation adopted here is justified, as we will see, by the smallness of the phenomenologically allowed values for ξ and $M_Z^2/M_{Z'}^2$. We also assume $\tilde{g} = g'$, which is approximately realized for models embedded in a grand unification scheme.

We finally obtain:

$$\begin{aligned} \delta Q_W = & +16 \left\{ \frac{1}{16} \left[\left(1 + 4 \frac{\sin^4\theta}{\cos 2\theta} \right) Z - N \right] \Delta\rho_M + \right. \\ & + [(2Z + N)(a_e v'_u + a'_e v_u) + (Z + 2N)(a_e v'_d + a'_e v_d)] \xi + \\ & \left. + [(2Z + N)a'_e v'_u + (Z + 2N)a'_e v'_d] \frac{M_Z^2}{M_{Z'}^2} \right\} \end{aligned} \quad (2.16)$$

We notice that the first term of the left-hand side of eq. (2.16) is proportional to $\Delta\rho_M$ (which here is assumed to be of the same order as ξ and $M_Z^2/M_{Z'}^2$). This term receives two independent contributions. The first one comes from the overall ρ factor on the right-hand side of eq. (2.15), representing the different normalization of the neutral current effective Lagrangian with respect to the charged current one. The second one is precisely due to the difference quoted in eq. (2.13) between the $\sin^2\theta$ in the considered class of models and the $\sin^2\theta$ of the SM. We stress the fact that the appearance of the second contribution reflects the choice of α , G_F and M_Z as independent parameters, so that, in the various models considered, $\sin^2\theta$ has to be treated as a derived quantity. The choice of M_Z as third fundamental parameter of the electroweak interaction has become extremely convenient after the very precise measurement of M_Z at LEP, and, in this sense, our presentation updates the previous analysis of parity violation in atoms in the context of extra $U(1)$ extensions of the SM [9,10], where $\sin^2\theta$ was preferred as third electroweak independent parameter.

It is remarkable that, for the isotope 133 of the Cesium atom, the sum of the two separate contributions to the $\Delta\rho_M$ term of eq. (2.16) almost cancels. Indeed, assuming $\sin^2\theta = 0.232$, one can rewrite the $\Delta\rho_M$ part of δQ_W in the form:

$$(\delta Q_W)_{\Delta\rho_M} = [77.09(Z - 55) + (78 - N) - 0.91] \Delta\rho_M \quad (2.17)$$

Therefore, for the isotope ^{133}Cs , one ends up with $-0.91\Delta\rho_M$. This small $\Delta\rho_M$ dependence of $Q_W(^{133}\text{Cs})$ just reflects the small dependence on ρ pointed out in ref. [5]

For vanishing mixing only the third term of eq. (2.16) survives, since $\Delta\rho_M$ also vanishes in that limit (see eq. 2.11).

3. Expectations for δQ_W

In this section we will estimate the range of δQ_W which is compatible with the present bounds on $\Delta\rho_M$, ξ and $M_{Z'}$. Laboratory limits on $M_{Z'}$ come from overall fits to the neutral current data [9,10,16,17], as well from direct search in hadron colliders [18]. Here we have considered the CDF results, as translated for the extra $U(1)$ models

and the LR model in ref [19]. The lower limits on $M_{Z'}$ used in the analysis are quoted for convenience in Table II.

The parameter $\Delta\rho_M$ can be directly constrained from the ratio $M_W/M_{Z'}$ measured by CDF, UA2 and UA1 and the value of $M_{Z'}$ measured at LEP [20]. Also LEP data on Z widths and asymmetries provide a constraint on $\Delta\rho_M$. Deviations from SM predictions in LEP I observables, coming from an extra $U(1)$ gauge symmetry factor, depend in general on $\Delta\rho_M$ and ξ [14], the Z' exchange term being completely negligible on the Z pole. The results of a recent fit [21] of the available LEP data [22] gives the 90 % CL upper bound:

$$\Delta\rho_M \leq 0.010 - 0.003 \left[\frac{m_t(\text{GeV})}{100} \right]^2 \quad (3.1)$$

The allowed range for the mixing angle ξ can be derived both from the low energy neutral current data and from LEP data. For the models whose extra $U(1)$ is contained in E_6 , we use the results of a recent fit of LEP data [21], quoted in Table II. For the LR model we use [21]: $-0.0069 \leq \xi \leq 0.0135$. We also note that the upper bound on $\Delta\rho_M$ given in eq. (3.1), together with the (model dependent) lower bound on $M_{Z'}$, also given in Table II, results, through eq. (2.11), in an upper bound on $|\xi|$, which we have included in our analysis.

The results for the models parametrized by θ_2 are shown, versus θ_2 , in fig. 1. The region inside the continuous line corresponds to any choice of parameters compatible with the above-mentioned constraints, when a top mass of 100 GeV is assumed. For comparison, the dotted lines were obtained by turning off the mixing, that is by setting to zero ξ and $\Delta\rho$. The dotted line may also be thought to represent the situation of a top quark with mass equal to about 180 GeV, saturating the bound given in eq. (3.1). In this case there is no room available for the mixing effects and only the Z' exchange contribution is effective. From fig. 1 we see that positive deviations are always allowed, with a maximum ranging from about 1 to about 9. Negative deviations are only allowed in a specific range of the θ_2 interval; moreover they can reach at most a value of about -3, and they require a substantial contribution from the mixing. Comparing the continuous and the dotted lines, one sees that the mixing terms (those proportional to $\Delta\rho_M$ and ξ) are more important for lower top masses, as could be expected on the basis of eq. (3.1) which shows how the limit on $\Delta\rho_M$ becomes more and more active for growing m_t .

Although in some range of the θ_2 angle and for low top masses the mixing effects considerably enhance the range of δQ_W represented by the dotted line in fig. 1, the constraints on $\Delta\rho_M$ and ξ coming from LEP data are so stringent that we are not far from a situation in which they can be neglected with respect to the direct Z' exchange.

In that case the size of largest negative deviations is further reduced to about -1.

For the LR model the allowed range of δQ_W is found to be, for both $m_t = 100$ GeV and $m_t = 200$ GeV, $-0.1 \leq \delta Q_W \leq 4.8$.

Finally we wish to compare the expectations we have found in this paper to the present experimental determination of Q_W [1,2]:

$$Q_W(^{133}\text{Cs}) = -71.04 \pm 1.58 \pm 0.88 \quad (3.2)$$

where the first error is experimental and the second comes from atomic theory. From the SM predictions (for a Higgs mass of 100 GeV) [5]:

$$Q_W(^{133}\text{Cs}) = -73.20 \pm 0.13 \quad (3.3)$$

including hadronic-loop uncertainty, one can estimate:

$$\delta Q_W = 2.16 \pm 1.81 \quad (3.4)$$

where the quoted error has been obtained by adding in quadrature the errors quoted in eqs. (3.2) and (3.3). Fig. 1 shows the 90 % CL band corresponding to eq. (3.4).

While this band is compatible with the limitations we find, fig. 1 suggests that eq. (3.4) might be used to improve the present bounds on $M_{Z'}$ [23]. For instance, at $\theta_2 = 90^\circ$ and ignoring mixing effects, we find:

$$M_{Z'} \geq 360 \text{ GeV} \quad (3.5)$$

It should be stressed that such a limit is obtained without any specific assumption about the Higgs sector.

4. Conclusions

The deviation δQ_W of the weak charge Q_W from its standard model value, in extensions of the standard model gauge group introducing a massive Z' , can be written as a sum of three terms; one proportional to the ρ -value shift $\Delta\rho_M$ due to $Z - Z'$ mixing, one proportional to the mixing angle ξ , and one proportional to $M_{Z'}^2/M_{Z'}^2$. Present data provide for bounds for $M_{Z'}$, $\Delta\rho_M$ and ξ , for given top mass, which translate into bounds for δQ_W . We have considered extensions of the standard model of the type extra- $U(1)$ contained in E_6 , and a left-right symmetric extension. In the extra- $U(1)$ models an undetermined angle θ_2 characterizes the choice of the extra $U(1)$ within the E_6 generators. Study of the allowed region for δQ_W shows that positive δQ_W may be

possible, based on the collection of present electroweak data, for all choices of θ_2 , limited to values from 2 to 9, while negative δQ_W down to -3 at most are possible only in some θ_2 -interval. The importance of $Z - Z'$ mixing in these considerations is relevant for the smaller values of the top mass. Negative values of δQ_W below -1 are only possible if mixing is present. For the left-right extensions, δQ_W is allowed to take positive values up to about 4.8.

Radiative corrections have been taken into account in our analysis and are responsible for the top mass dependence. Large values of m_t leave less room for the mixing contribution. Eventually for a m_t of about 180 GeV, no mixing is allowed. The figure 1 refers to $m_t \approx 100 \text{ GeV}$. For the considered left-right extension we find less dependence on m_t . Present data on δQ_W represented in fig. 1 by a straight band are still compatible with the limitations we find. Already the present situation allows an improvement of the bounds on $M_{Z'}$ at least in some specific case. For instance at $\theta_2 = 90^\circ$ we find $M_{Z'} \geq 360 \text{ GeV}$. Future atomic parity experiments are hoped to reduce the present overall accuracy of 2.5% to something of the order of 1% or less. This, accompanied by more precise electroweak data, may turn out to severe limitations on certain models. On a speculative ground, a significative positive δQ_W , while disfavoured by technicolour models at one-loop level, could still be accommodated by a class of extra $U(1)$ models.

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TABLE CAPTIONS

- Table I - Vector and axial-vector coupling constants relevant for the determination of C_{1u} and C_{1d} for the SM, models with an extra $U(1)$ contained in E_6 and the left-right model. $s_\theta = \sin \theta$, $c_2 = \sin \theta_2$ and $c_3 = \cos \theta_2$.
- Table II - Lower and upper bounds on ξ from the overall fit of electroweak data of ref. [21] and lower bound on $M_{Z'}$ (in GeV) from direct Z' searches at CDF, taken from ref. [19].

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Table I

SM	Extra-U(1)	LR
$a_e = \frac{1}{4}$	$a'_e = \frac{s_\theta^2}{4} \left(-\frac{1}{3}c_2 + \sqrt{\frac{5}{3}}s_2 \right)$	$a'_e = -\frac{\sqrt{c_{2\theta}}}{4}$
$v_u = \frac{1}{4} - \frac{2}{3}s_\theta^2$	$v'_u = 0$	$v'_u = \frac{1}{2\sqrt{c_{2\theta}}} \left(\frac{1}{2} - \frac{4}{3}s_\theta^2 \right)$
$v_d = -\frac{1}{4} + \frac{1}{3}s_\theta^2$	$v'_d = \frac{s_\theta^2}{4} \left(c_2 + \sqrt{\frac{5}{3}}s_2 \right)$	$v'_d = \frac{1}{2\sqrt{c_{2\theta}}} \left(-\frac{1}{2} + \frac{2}{3}s_\theta^2 \right)$

Table II

θ_2	-90	-70	-50	-30	-10	10	30	50	70	90
ξ_{low}	-0.0076	-0.0075	-0.0083	-0.0104	-0.0156	-0.0249	-0.0198	-0.0147	-0.0125	-0.0119
ξ_{up}	0.0119	0.0126	0.0151	0.0209	0.0322	0.0316	0.0178	0.0113	0.0086	0.0076
$M_{Z'}$	288	292	312	320	327	347	352	337	310	288

FIGURE CAPTION

Fig. 1 - Range of δQ_W allowed by the constraints from the present CDF and LEP data, versus θ_2 which specifies the extra U(1) gauge model embedded in E_6 . The continuous line refers to $m_{top} = 100$ GeV. The dotted line is obtained by neglecting the contribution from the $Z - Z'$ mixing. The horizontal band reproduces the present experimental determination (at 90% CL) of δQ_W [5].

Fig. 1