

Gauge Kinetic Mixing and Leptophobic Z' in E_6 and $SO(10)$ *

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Abstract

We examine the influence of gauge kinetic mixing on the couplings of a TeV scale Z' in both E_6 and $SO(10)$ models. The strength of such mixing, which arises due to the existence of incomplete matter representations at low scale, can be described by a single parameter, δ . The value of this parameter can significantly influence the ability of both hadron and lepton colliders to detect a Z' using conventional search techniques. In addition, $\delta \neq 0$ also adds to the complexities involved in separating E_6 Z' models from those arising from alternative scenarios. Employing a reasonable set of assumptions we have determined the allowed range for this parameter within a wide class of models via an RGE analysis. In particular, given the requirements of Standard Model gauge coupling unification, anomaly freedom and perturbativity up to the GUT scale, we demonstrate that the necessary condition for exact leptophobia in η type E_6 models, $\delta = -1/3$, is impossible to achieve in this scenario. Furthermore we show that the allowed range for δ is rather restricted for arbitrary values of the mixing between the $U(1)_\chi$ and $U(1)_\psi$ type couplings. The $SO(10)$ Z' model χ is discussed as a separate case since it requires special attention.

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1 Introduction

Though the Standard Model(SM) does an excellent job at describing precision electroweak data[1] there are many reasons to believe that new physics must exist at a scale not far above that which is currently being probed at colliders. The minimal supersymmetric extension of the SM, the MSSM, provides a setting for addressing a number of important questions left unanswered by the SM framework. Although convenient for many analyses due to its relative simplicity, no one truly expects that the MSSM will represent the actual version of SUSY realized by nature at low energies. Perhaps one of the simplest and well motivated extensions of the MSSM scenario is the enlargement of the SM gauge group, $SU(3)_C \times SU(2)_L \times U(1)_Y$, by additional $SU(2)$ or $U(1)$ factors. From the GUT or string point of view, the presence at low energies, ~ 1 TeV, of an additional neutral gauge boson, Z' , associated with a $U(1)'$ seems reasonably likely[2]. At a high energy scale, such a Z' could arise naturally from, for example, the breaking of real or ersatz GUT such as $SO(10)$ or E_6 via patterns such as $SO(10) \rightarrow SU(5) \times U(1)_\chi$ or $E_6 \rightarrow SO(10) \times U(1)_\psi$, with some linear combination of the $U(1)$'s surviving unbroken down to the TeV scale.

If such particles are indeed present they must either be reasonably massive, have small mixings with the SM Z , and/or have ‘unlucky’ combinations of fermionic couplings in order to avoid direct searches at the Tevatron[3] and potential conflict with precision electroweak data[4]. One ‘unlucky’ set of couplings that has gotten much attention in the literature is the condition know as leptophobia[5], *i.e.*, where the Z' does not couple to SM leptons. In such a situation the Z' avoids traditional collider searches since it cannot be produced in Drell-Yan collisions and it does not perturb any of the leptonic coupling data collected at LEP through asymmetry measurements or the value of A_{LR} obtained by SLD. To discover such a Z' at the Tevatron or LHC would require the observation of a bump in the dijet

mass spectrum, a difficult prospect due to large QCD backgrounds[6] and finite jet energy resolution. In the absence of mixing with the SM Z , the Z' would also not be produced at future lepton colliders except via loops.

As is easily demonstrated, the condition of leptophobia does not exist in *conventional* $SO(10)$ or E_6 models[7] where the fermionic couplings are essentially determined by group theory, the choice of embedding and, in the E_6 case, by the value of a mixing angle θ . Interestingly, in the flipped (non- $SO(10)$ unified) $SU(5) \times U(1)_X$ [8] model, leptophobia is possible if one assumes that leptons do not carry X quantum numbers (*i.e.*, only the three $\mathbf{10}$'s carries a non-zero X charge) and one allows the X charge assignments to be generation dependent in order to cancel anomalies. If we also demand that the Z' couplings be at least approximately flavor diagonal in order to avoid problems associated with flavor changing neutral currents then there is no leptophobic Z' case in this scheme as well. Of course it is always possible to directly construct leptophobic Z' models with generation independent couplings following a purely phenomenological approach[9] but it is not clear how such models are embedded in a larger framework.

In a recent series of papers, Babu, Kolda and March-Russell[10] discussed the possibility of constructing a leptophobic Z' model within E_6 -type models through the dynamical effects associated gauge boson kinetic mixing(KM)[11] which occurs naturally at some level in almost all realistic GUT or string models. KM essentially arises due to the existence of incomplete GUT representations at the low energy scale. For example, such a situation is seen to occur even in the MSSM where the usual two Higgs doublet superfields are low energy survivors associated with part of a pair of $\mathbf{5} + \bar{\mathbf{5}}$'s at the high scale. While the Higgs doublet components are light the remaining dangerous, color triplet isosinglet pieces are forced phenomenologically to remain heavy by proton decay constraints. Even if KM is naturally absent at the high scale, the partitioning of any of the multiplets will drive KM to

be non-zero at the TeV scale via the renormalization group equations(RGEs). If there are enough low energy survivors from split multiplets with the correct quantum numbers, Babu *et al.* showed that the effects of KM on the Z' couplings can be sufficiently large to obtain leptophobic conditions.

The purpose of the present paper is to make a broad survey of models associated with new $U(1)$ factors arising from E_6 and $SO(10)$ and to ascertain quantitatively the impact of KM on the corresponding Z' couplings. Clearly if leptophobia is indeed possible a Z' may be missed by present and future collider searches. We will show, subject to a reasonable set of assumptions, that the values of the parameters necessary for *complete* leptophobia, *i.e.*, identically zero vector and axial vector leptonic couplings, cannot be achieved in these models. We also show that although KM has dramatic consequences for the Z' couplings in these scenarios it will still remain possible to discover the Z' at both hadron and lepton colliders via their leptonic couplings. In addition we will show that it will still be possible to distinguish a Z' originating from E_6 (including KM) from, *e.g.*, a Z' originating from the Left-Right Symmetric Model[12] once the Z' couplings are measured with reasonable accuracy at future hadron and lepton colliders. For the Z' arising in $SO(10)$ we will show that ambiguities in identification remain unless the Z' is directly produced at a lepton collider.

This paper is organized as follows: in Section 2 we set up our notation and review the essentials of kinetic mixing and Z' couplings in general E_6 models which incorporate KM. The possibilities associated with alternative fermion embedding schemes are discussed. We explicitly show how the search reaches for such a Z' would be altered by an arbitrary amount of KM at both the Tevatron and LHC. We also show the KM impact on the couplings themselves and the possible confusion that can arise when trying to determine the model from which the Z' originated if KM effects were allowed to be arbitrarily large. The basic formulae needed in our later analysis are also supplied here at the one-loop level. In Section

3 we discuss our model building assumptions and numerically analyze the resulting 68 E_6 models and 134 $SO(10)$ models to which these assumptions naturally lead. We demonstrate that exact leptophobia does not occur in any of these models even though the overall effects of KM can be numerically substantial. The resulting allowed range of couplings are determined in all cases. The influence of kinetic mixing on the Z' search reaches of the Tevatron and LHC within these models is also examined in detail as are a number of issues relating to Z' identification. A summary and discussion as well as our conclusions can be found in Section 4.

2 Notation, Background and Review of Kinetic Mixing

Consider the Lagrangian for the electroweak part of the SM with the addition of a new $U(1)$ field which is decomposed in the following manner:

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{int} + \mathcal{L}_{SB} + \mathcal{L}_{SUSY}, \quad (1)$$

where the most general form of \mathcal{L}_{kin} is given by

$$\mathcal{L}_{kin} = -\frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}\tilde{B}^{\mu\nu}\tilde{B}_{\mu\nu} - \frac{\sin\chi}{2}\tilde{B}_{\mu\nu}\tilde{Z}'^{\mu\nu}, \quad (2)$$

with W^a , \tilde{B} and \tilde{Z}' representing the usual $SU(2)_L$, $U(1)_Y$ and $U(1)'$ fields, with the index ‘a’ labelling the weak isospin. Note that the term proportional to $\sin\chi$ which directly couples the \tilde{B} and \tilde{Z}' fields is not forbidden by either $U(1)_Y$ or $U(1)'$ gauge invariance and corresponds to gauge kinetic mixing. In this basis the interaction terms for fermions can be written as

$$\mathcal{L}_{int} = -\bar{\psi}\gamma^\mu[g_L T^a W_\mu^a + \tilde{g}_Y Y \tilde{B}_\mu + \tilde{g}_{Q'} Q' \tilde{Z}'_\mu]\psi. \quad (3)$$

The parts of the Lagrangian describing symmetry breaking and the interactions of the SUSY partners are contained in terms $\mathcal{L}_{SB} + \mathcal{L}_{SUSY}$ and will not directly concern us here. We can

remove the off-diagonal coupling of the \tilde{B} and \tilde{Z}' in the kinetic energy by making the field transformations:

$$\begin{aligned}\tilde{B}_\mu &= B_\mu - \tan \chi Z'_\mu, \\ \tilde{Z}'_\mu &= \frac{Z'_\mu}{\cos \chi}.\end{aligned}\tag{4}$$

This diagonalizes the kinetic terms in \mathcal{L}_{kin} and, making the corresponding transformation in the couplings:

$$\begin{aligned}g_Y &= \tilde{g}_Y, \\ g_{Q'} &= \frac{\tilde{g}_{Q'}}{\cos \chi}, \\ g_{YQ'} &= -\tilde{g}_Y \tan \chi,\end{aligned}\tag{5}$$

allows the interaction term in the Lagrangian to be written in a more familiar form. The couplings are assumed to be ‘GUT’ normalized in this basis since we will assume that complete representations exist at the high scale. Using the SM notation and normalization conventions, *i. e.*, $Y \rightarrow \sqrt{\frac{3}{5}}Y_{SM}$ and $g_Y \rightarrow \sqrt{\frac{5}{3}}g'$ such that $Q_{em} = T_{3L} + Y_{SM}$, we obtain the more traditional appearing result

$$\mathcal{L}_{int} = -\bar{\psi}\gamma^\mu[g_L T^a W_\mu^a + g' Y_{SM} B_\mu + g_{Q'}(Q' + \sqrt{\frac{3}{5}}\delta Y_{SM})Z'_\mu]\psi,\tag{6}$$

where $\delta \equiv g_{YQ'}/g_{Q'}$ and we immediately recognize the usual SM weak isospin and hypercharge coupling terms. Note that $\delta \neq 0$ requires $g_{YQ'} \neq 0$. Of course, for our purposes we must remember that all of the couplings in this term run with energy and are thus to be evaluated at the EW or TeV scale to make contact with experiment. Furthermore, recalling that $g_{Q'}$ is GUT normalized, the Z' piece of this interaction can also be re-written to conform

to more conventional[7, 13] notation, *i.e.*,

$$\mathcal{L}(Z')_{int} = -\lambda \frac{g_L}{c_w} \sqrt{\frac{5x_w}{3}} \bar{\psi} \gamma^\mu (Q' + \sqrt{\frac{3}{5}} \delta Y_{SM}) \psi Z'_\mu, \quad (7)$$

with as usual $x_w = \sin^2 \theta_w = e^2/g_L^2$, $c_w = \cos \theta_w$ and $\lambda = g_{Q'}/g_Y$. Note that in this notation $\delta \cdot \lambda = -\tan \chi$. Assuming for our purposes that the Z' arises from the symmetry breaking chain $E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow SM \times U(1)_\theta$, one obtains $Q' = Q_\psi \cos \theta - Q_\chi \sin \theta$, where θ is the familiar E_6 mixing angle and the $Q_{\psi,\chi,\eta}$, the last being the appropriate combination for model η which corresponds to $\theta = \tan^{-1} \sqrt{3/5} \simeq 37.76^\circ$, are given in Table 1 assuming the conventional particle embeddings. (In the $SO(10)$ case to be discussed later we simply set $\theta = -\pi/2$ which corresponds to the χ model.)

Particle	$SU(3)_c$	$2\sqrt{6}Q_\psi$	$2\sqrt{10}Q_\chi$	$2\sqrt{15}Q_\eta$	Y
$Q = (u, d)^T$	3	1	-1	2	1/6
$L = (\nu, e)^T$	1	1	3	-1	-1/2
u^c	$\bar{\mathbf{3}}$	1	-1	2	-2/3
d^c	$\bar{\mathbf{3}}$	1	3	-1	1/3
e^c	1	1	-1	2	1
ν^c	1	1	-5	5	0
$H = (N, E)^T$	1	-2	-2	-1	-1/2
$H^c = (N^c, E^c)^T$	1	-2	2	-4	1/2
h	3	-2	2	-4	-1/3
h^c	$\bar{\mathbf{3}}$	-2	-2	-1	1/3
S^c	1	4	0	5	0

Table 1: Quantum numbers of the particles contained in the **27** representation of E_6 ; standard particle embeddings are assumed and all fields are taken to be left-handed.

As we will see below, the a priori unknown parameters δ and λ are directly calculable

for any value of θ from an RGE analysis within the framework of a given model with fixed matter content assuming high scale coupling unification. Allowing both of these parameters to vary freely clearly leads to significant modifications of the potential Z' couplings. However, as was noted by Babu *et al.*, if we do indeed treat them as free parameters one finds that for conventional particle embeddings with $\delta = -1/3$ and $\theta = \tan^{-1} \sqrt{3/5}$, *i.e.*, the couplings of model η , both the vector and axial vector leptonic couplings of the Z' vanish for all values of λ and leptophobia is obtained. A quick analysis shows that this choice of parameters is *unique*. In alternative embeddings leptophobia is also possible but its location in the model parameter space is modified. In the case of the flipped $SU(5)$ -type model [8], the roles played by the pairs (u^c, e^c) and (d^c, ν^c) are interchanged, so that the lepton's right-handed couplings are modified. Similarly, in the alternative embedding scheme of Ma[14], the fields (L, d^c, ν^c) are interchanged with (H, h^c, S^c) , which also leads to leptonic coupling changes, this time for the left-handed couplings. Of course we can also imagine both interchanges being made simultaneously leading to a fourth set of possible leptonic couplings. In each of these cases a unique point in the $\theta - \delta$ parameter space leads to leptophobia; these are summarized in Table 2. Note that both the standard and the alternative embedding due to Ma lead to the same required values of the parameters in order to achieve leptophobia. This is not too surprising as model η couplings are invariant under the particle interchange associated with Ma's model. In all cases we see that the required magnitude of δ to achieve leptophobia is reasonably large. We also note from this Table that the $SO(10)$ -inspired χ model can never be even approximately leptophobic independently of how the particles are embedded.

To get an idea of the potential impact of leptophobia, and $\delta \neq 0$ in general, we show in Fig. 1 the search reaches for an E_6 Z' , assuming the canonical particle embedding and assuming that the Z' decays only to SM particles, at both the Tevatron Run II and the LHC; we take the value $\lambda = 1$ and use the CTEQ4M parton densities[15]. (For other

Embedding	$\tan \theta$	δ
Standard	$\sqrt{3/5}$	$-1/3$
Flipped	$\sqrt{15}$	$-\sqrt{10}/3$
Ma	$\sqrt{3/5}$	$-1/3$
Both	$\sqrt{5/27}$	$-\sqrt{5/12}$

Table 2: Values of the parameters θ and δ for which exact leptophobia is obtained for the various embedding schemes discussed in the text.

values of λ near unity the mass reaches scale approximately as $\Delta M \simeq 180 \log(\lambda)$ GeV and $\Delta M \simeq 660 \log(\lambda)$ GeV at TeV II and LHC, respectively.) In both cases the reach is roughly θ and δ independent ($\simeq 850$ GeV and $\simeq 4200$ GeV for TeV II and the LHC, respectively) except near the leptophobic region where it falls off quite dramatically forming a hole in the mass reach. It is clear that the conventional Z' searches will fail in this region and that the dijet method would need to be employed to find the Z' .

Arbitrarily large values of δ can also lead to possible confusion when Z' couplings are extracted at, *e.g.*, future lepton colliders. It is well known that when KM is absent sufficient data on Z' couplings can be extracted at such machines, even below the Z' production threshold, so that the Z' 's model of origin can be identified[16, 13]. When $\delta \neq 0$, the allowed ranges of the various vector and axial vector fermionic couplings in E_6 models is greatly extended in comparison to the more conventional case creating overlaps with the corresponding coupling values anticipated in other models. This result is shown explicitly in Fig. 2 for both leptonic and b quark couplings, these being the ones most easily measured. Here the E_6 case with and without KM is compared to the predictions of the Left-Right Model[12], Ma's Alternative model[14], the Un-unified Model[17] as well as to the reference case of a Z' with SM couplings. In the KM case it has been assumed for simplicity that $\lambda = 1$

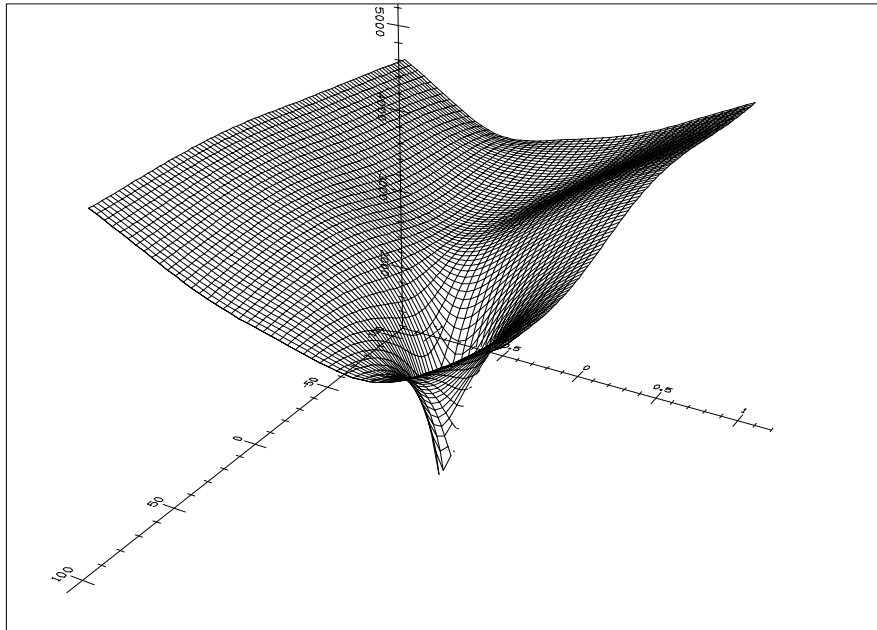
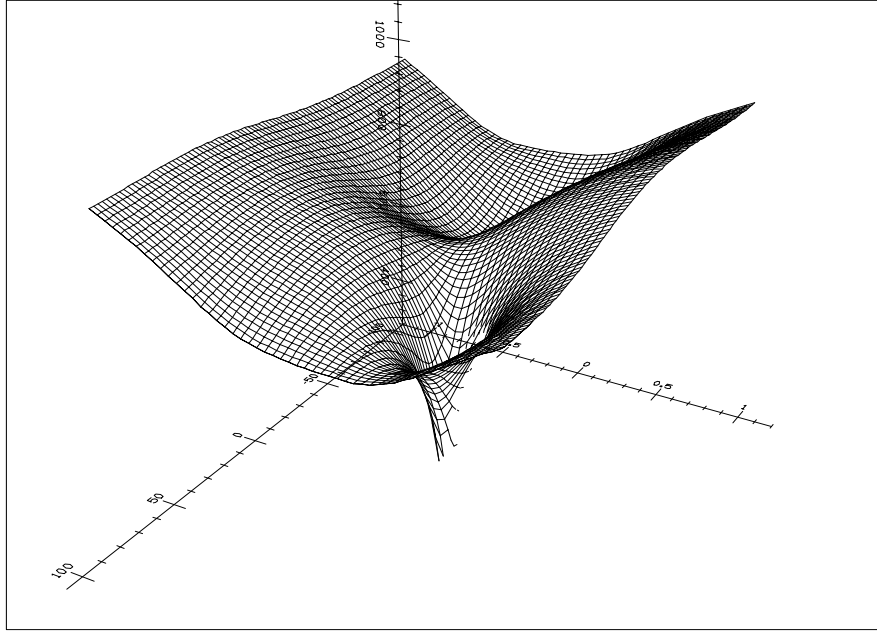


Figure 1: Search reaches for the E_6 Z' at (top) the Tevatron($2 fb^{-1}$) and(bottom) LHC($100 fb^{-1}$) in GeV as functions of θ (left axis) and δ (right axis) assuming no exotic decay modes. The leptophobic hole is evident in both cases. The sign of δ has been reversed in these plots for ease of viewing and $\lambda = 1$ has been assumed.

and δ is confined to the range $-1/2 \leq \delta \leq 1/2$. One sees immediately that the presence of KM leads to potential mis-identification of the Z' even when precise measurements of the couplings are available. Though not shown, similar effects would be observed in u -quark type couplings. Clearly, if the range of δ is increased and/or λ were allowed to vary from unity by as small a value as say 25%, the size of the E_6 coupling region would dramatically increase and the Z' mis-identification potential would rise dramatically. Note that the $SO(10)$ inspired χ model in the absence of KM corresponds to the point of contact of the solid and dashed curves, *i.e.*, the non-KM E_6 and LRM cases, in both the coupling planes. In this case the Z' in the non-KM χ model has the same couplings as does the Z' in the LRM with $\kappa^2 = (g_R/g_L)^2 = \frac{5}{3} \frac{x_w}{(1-x_w)}$, with $g_{L,R}$ being the gauge coupling associated with the $SU(2)_{L,R}$ group factor. From this analysis it is clear that apart from the specific problems of leptophobia it is very important to determine what the allowed ranges of both δ and λ are in realistic E_6 and $SO(10)$ models.

In order to constrain the low scale values of both λ and δ for a given model we must first perform an RGE analysis. The coupled RGEs for g_Y , $g_{Q'}$ and $g_{YQ'}$ at one-loop are given in our notation by[10]

$$\begin{aligned} \frac{dg_Y^2}{dt} &= \frac{(g_Y^2)^2}{8\pi^2} B_{YY}, \\ \frac{dg_{Q'}^2}{dt} &= \frac{g_{Q'}^2}{8\pi^2} [g_{Q'}^2 B_{Q'Q'} + g_{YQ'}^2 B_{YY} + 2g_{Q'} g_{YQ'} B_{YQ'}], \\ \frac{dg_{YQ'}^2}{dt} &= \frac{1}{8\pi^2} [g_{Q'}^2 g_{YQ'}^2 B_{Q'Q'} + g_{YQ'}^4 B_{YY} + 2g_Y^2 g_{YQ'}^2 B_{YY} + 2g_Y^2 g_{Q'} g_{YQ'} B_{YQ'} + 2g_{Q'} g_{YQ'}^3 B_{YQ'}], \end{aligned} \tag{8}$$

where $B_{ij} = Tr(Q_i Q_j)$, with the trace extending over the full low energy matter spectrum. In particular, $B_{YY} = \beta_Y = \frac{3}{5} Tr(Y^2)$ is the conventional GUT normalized beta function for the $U(1)_Y$ coupling. At the high (GUT or string) scale where complete multiplets are present

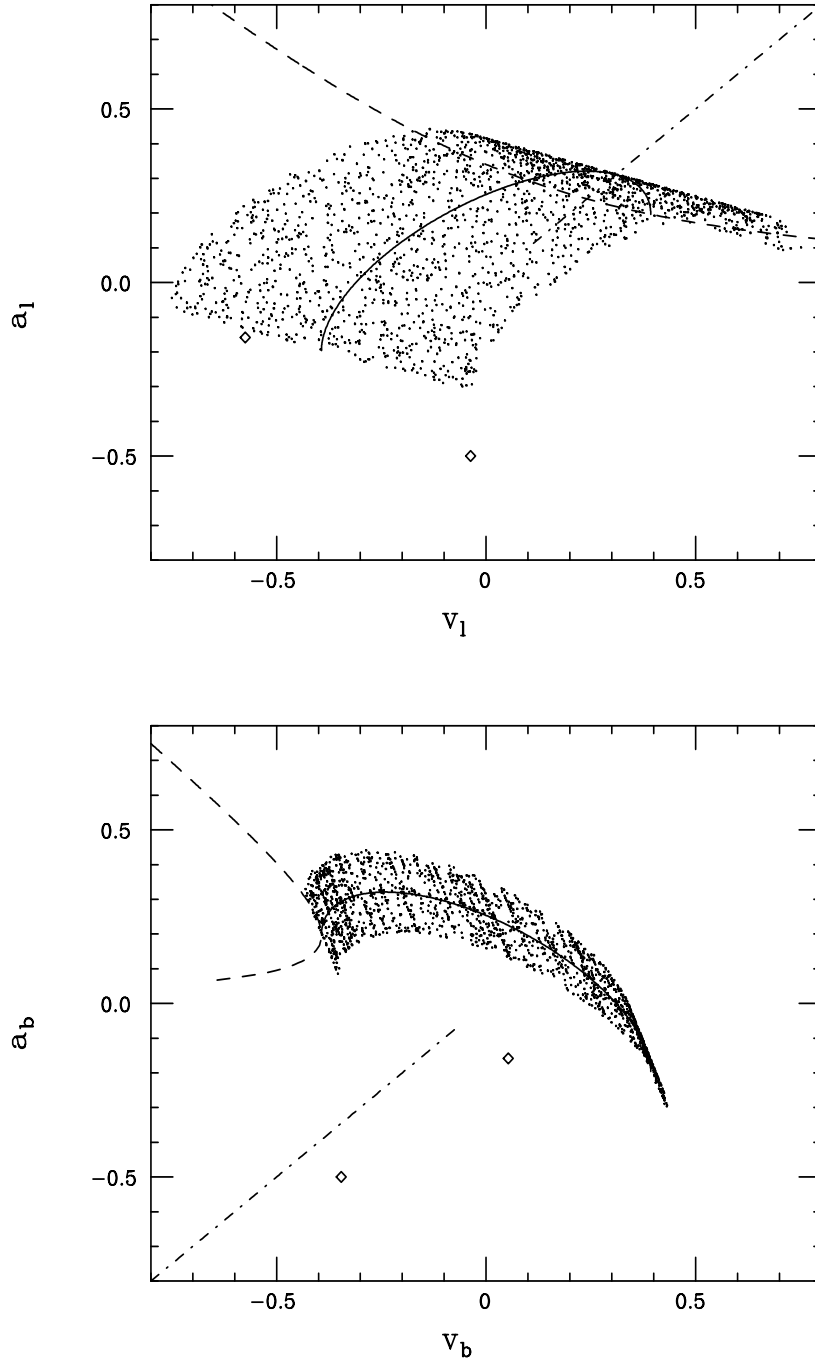


Figure 2: Vector and axial vector couplings for leptons(top) and b -quarks(bottom) in various Z' models: the E_6 model with no KM(solid), the Left-Right Model(dashed), and the Unified Model(dash-dot), as well as the case of a heavy SM Z' and the Alternative Model of Ma(labeled by the two diamonds.) The points are the predicted values in E_6 with KM assuming $-1/2 \leq \delta \leq 1/2$ and $\lambda = 1$. For $\lambda \neq 1$ the predicted coupling region scales appropriately.

one finds that $B_{YQ'} = 0$, identically, so that $g_{YQ'}$, and hence, $\delta = g_{YQ'}/g_{Q'}=0$. Below the high scale we imagine that at least some *incomplete* matter multiplets survive to low energies rendering $\delta \neq 0$ via RGE evolution. The quantum numbers of these survivors will tell us the specific value of δ . It is important to stress that $B_{YQ'}$ receives no contributions from complete multiplets or from SM singlets.

Since gauge invariance tells us that there is no mixing between the $SU(3)_C$, $SU(2)_L$ and either of the $U(1)$ gauge fields, the one-loop RGEs for both the $g_{L,s}$ couplings take their conventional forms and can be trivially analytically integrated. Writing $L = \log(M_U/M_Z)$, these two equations can be combined as usual from which we obtain

$$\begin{aligned} L &= \frac{2\pi(\alpha_s^{-1} - x_w\alpha^{-1})}{\beta_s - \beta_L}, \\ \alpha_U^{-1} &= \frac{\beta_s x_w \alpha^{-1} - \beta_L \alpha_s^{-1}}{\beta_s - \beta_L}, \end{aligned} \tag{9}$$

with α_U being the common unification coupling. Further, integration of the hypercharge RGE yields the usual result

$$g_Y^{-2}(t) = \frac{\alpha_U^{-1}}{4\pi} \left[1 + \frac{\alpha_U}{2\pi} B_{YY}(t_U - t) \right], \tag{10}$$

where $t_U \sim \log M_U$ and the unification boundary condition has been imposed.

Since $\delta = g_{YQ'}/g_{Q'}$, and the solution for $g_Y^2(t)$ is known, we can combine the last two of the RGEs above to obtain

$$\begin{aligned} \frac{d\delta}{dt} &= \frac{1}{g_{Q'}} \frac{dg_{YQ'}}{dt} - \frac{g_{YQ'}}{g_{Q'}^2} \frac{dg_{Q'}}{dt}, \\ &= \frac{g_Y^2}{8\pi^2} [B_{YQ'} + \delta B_{YY}]. \end{aligned} \tag{11}$$

This can now be directly integrated with the result

$$\delta(t) = -\frac{B_{YQ'}}{B_{YY}} \left[1 - \left[1 + \frac{\alpha_U B_{YY} (t_U - t)}{2\pi} \right]^{-1} \right], \quad (12)$$

where we have imposed the boundary condition that $\delta(t)$ vanishes at the GUT scale M_U since we assume that complete multiplets exist there. The weak scale parameter δ relevant for the Z' couplings is obtained when we set $t \sim \log M_Z$ so that $t_u - t = \log(M_U/M_Z) = L$ in the expression above. Note that δ grows as the value of $B_{YQ'}$ increases. From this expression it is obvious that we need to have as many split multiplets as possible at low energies in order to enhance the value of δ . Knowing $\delta(t)$ then allows us to re-write the RGE for $g_{Q'}^2$ as

$$\frac{dg_{Q'}^2}{dt} = \frac{(g_{Q'}^2)^2}{8\pi^2} [B_{Q'Q'} + 2\delta(t)B_{YQ'} + \delta^2(t)B_{YY}], \quad (13)$$

which also can be integrated analytically. Defining the combination $z = \alpha_U B_{YY} L / 2\pi$ we find

$$g_{Q'}^{-2}(M_Z) = \frac{\alpha_U^{-1}}{4\pi} + \frac{B_{Q'Q'} L}{8\pi^2} \left[1 - \frac{B_{YQ'}^2}{B_{YY} B_{Q'Q'}} \frac{z}{1+z} \right], \quad (14)$$

from which the coupling strength parameter λ can be immediately calculated. We are now set to examine the values of δ and λ that can arise in a given model.

3 Models and Results

In order to proceed we must consider how the low energy particle content of our models is to be chosen. These will follow from the following set of basic model building assumptions:

- The SM gauge couplings, together with that of the new $U(1)'$, are assumed to perturbatively unify at a high scale as in the MSSM. This has two immediate consequences: (i)

we can add only sets of particles that would form complete multiplets under $SU(5)$, at least as far as their SM quantum numbers are concerned. (ii) The number and types of new fields is restricted since perturbative unification is lost if too many multiplets[18] are added.

- All anomalies including those associated with the new $U(1)'$ must cancel amongst the low energy matter fields in the model.
- Additional matter multiplets beyond those contained in the MSSM must be vector-like with respect to (at least) the SM. This not only helps with the anomaly problem but allows these new light fields not to make too large of a contribution to the oblique parameters[19] forcing a conflict with precision electroweak data. When combined with the above requirements this tells us that at low energies we may add at most four $\mathbf{5} + \overline{\mathbf{5}}$'s or one $\mathbf{5} + \overline{\mathbf{5}}$ plus one $\mathbf{10} + \overline{\mathbf{10}}$, in addition to $SU(5)$ singlets, to the MSSM spectrum. All higher dimensional representations are excluded. Note that the addition of SM or $SU(5)$ singlets will leave δ invariant since neither B_{YY} or $B_{YQ'}$ will be changed. However, $B_{Q'Q'}$ is altered in this case leading to a shift in the value of λ .
- The new matter fields are assumed to be low energy survivors from either $\mathbf{27} + \overline{\mathbf{27}}$'s or from $\mathbf{78}$'s of E_6 since these are automatically anomaly free even under the full E_6 gauge group and may arise from strings.

Given this set of conditions we can consider a number of specific cases beginning with E_6 itself.

3.1 E_6

Here we know that the low energy theory contains three $\mathbf{27}$'s as well as a pair of 'Higgs' doublets, which we label as H_1, H_1^c to avoid confusion with the members of the $\mathbf{27}$, as in the MSSM. Complete $\mathbf{27}$'s are necessary so that the $U(1)_\theta$ anomalies cancel for arbitrary values of θ . (The case $\theta = -90^\circ$ corresponding to the Z' from $SO(10)$ will be discussed separately in the next subsection.) These 'Higgs' are then the minimal split multiplet content at low energies. ('Higgs' is here in quotes as we really mean a pair of superfields with Higgs-like quantum numbers which may or may not obtain vacuum expectation values. In principle some combination of the fields H_1/H_1^c and those in the $\mathbf{27}$ will play the role of the Higgs doublets in the MSSM.) As was pointed out early on, the theory without these extra 'Higgs' and only the H/H^c components of the $\mathbf{27}$'s responsible for spontaneous symmetry breaking, will not unify[20]. These 'Higgs' must arise from either a $\mathbf{27} + \overline{\mathbf{27}}$ or $\mathbf{78}$ to avoid anomalies. Since the three $\mathbf{27}$'s already contain three pairs of $\mathbf{5} + \overline{\mathbf{5}}$ in addition to singlets in comparison to the MSSM, we are free *at most* to only add a single (ersatz) $\mathbf{5} + \overline{\mathbf{5}}$ to the low energy spectrum. Since the H_1, H_1^c fields also originate from a $\mathbf{5} + \overline{\mathbf{5}}$ it is necessary to examine the $U(1)_{\psi, \chi}$ quantum numbers of these additional fields since this is all that distinguishes amongst them. The $\mathbf{27} + \overline{\mathbf{27}}$ contains three different choices: (1) $\mathbf{5}(-2, 2) + \overline{\mathbf{5}}(2, -2)$, (2) $\mathbf{5}(2, 2) + \overline{\mathbf{5}}(-2, 2)$ and (3) $\mathbf{5}(-1, -3) + \overline{\mathbf{5}}(1, 3)$, where the numbers in the parentheses are the $Q_{\psi, \chi}$ quantum numbers as normalized in Table 1. The $\mathbf{78}$ on the otherhand contains only one candidate (4) $\mathbf{5}(3, -3) + \overline{\mathbf{5}}(-3, 3)$; this last case corresponds to the field content of the 'minimal' model presented by Babu *et al.* when η -type couplings are assumed[10]. For each of these cases the corresponding contributions to $B_{YQ'}$ and $B_{Q'Q'}$ can immediately written down. (The contribution of the three $\mathbf{27}$'s to $B_{Q'Q'}$ is 9, independently of θ .) For example, defining $a = \cos \theta / (2\sqrt{6})$ and $b = \sin \theta / (2\sqrt{10})$ one easily obtains the results for the H_1/H_1^c fields for

each of the cases (1)-(4) is given by

$$\begin{aligned}
B_{YQ'}(1) &= -4\sqrt{\frac{3}{5}}(a+b), \\
B_{YQ'}(2) &= 4\sqrt{\frac{3}{5}}(a-b), \\
B_{YQ'}(3) &= 2\sqrt{\frac{3}{5}}(-a+3b), \\
B_{YQ'}(4) &= 6\sqrt{\frac{3}{5}}(a+b),
\end{aligned} \tag{15}$$

and, correspondingly,

$$\begin{aligned}
\Delta B_{Q'Q'}(1) &= 16(a^2 + b^2 + 2ab), \\
\Delta B_{Q'Q'}(2) &= 16(a^2 + b^2 - 2ab), \\
\Delta B_{Q'Q'}(3) &= 4(a^2 + 9b^2 - 6ab), \\
\Delta B_{Q'Q'}(4) &= 36(a^2 + b^2 + 2ab).
\end{aligned} \tag{16}$$

The contribution of the color triplet pieces of the same $\mathbf{5} + \bar{\mathbf{5}}$'s is identical for $B_{Q'Q'}$ and of opposite sign for $B_{YQ'}$.

As discussed above there are thus only two possible subcases to consider. Either (i) H_1/H_1^c is the only pair of light superfields beyond the three $\mathbf{27}$'s or (ii) the field content of an additional $\mathbf{5} + \bar{\mathbf{5}}$ is also present. In case (i) we know immediately that $\beta_s = 0$, $\beta_L = 4$ and $B_{YY} = \frac{48}{5}$. The values of both $B_{Q'Q'}$ and $B_{YQ'}$ can also be directly calculated as above but depend visibly upon the choice, (1)-(4), into which we embed the H_1/H_1^c fields as well as the value of θ . With only 4 choices for the H_1/H_1^c quantum numbers, the calculation is straightforward and we arrive at the results shown in Figure 3. (For numerical purposes we

have taken $\alpha_s(M_Z) = 0.119$ [21], $\alpha_{em}^{-1}(M_Z) = 127.935$ [22] and $\sin^2 \theta_w = 0.23149$ [1]; our results depend only weakly on these particular choices.) From the Figure several observations are immediate. First, both δ and λ are constrained to rather narrow ranges and leptophobia is not obtainable. Second, the specific predicted values of δ and λ depend quite sensitively on the embedding choices (1)-(4). Lastly, both δ and λ are also strongly θ dependent but the choice of η couplings, *i.e.*, $\theta \simeq 37.76^\circ$, extremizes their values. Since $\delta \rightarrow 0$ and $\lambda \rightarrow 1$ as we raise the survivor mass scale above M_Z , the curves actually represent the extreme boundaries of the parameter range obtainable for these quantities for case (i). Note that for η couplings and H_1/H_1^c embedding (4) we recover the value $\delta \simeq -0.11$ obtained[10] by Babu *et al.* in their so-called ‘minimal’ model.

In case (ii) the situation is somewhat more complex since the low energy spectrum now contains two ‘Higgs’ doublets, $H_{1,2}/H_{1,2}^c$ as well as a pair of isosinglet, color triplet superfields, D_1, D_1^c . This uniquely fixes the values $\beta_s = 1$, $\beta_L = 5$ and $B_{YY} = \frac{53}{5}$ but allows for $4^3 = 64$ possible (but not necessarily independent), θ -dependent values for $B_{YQ'}$ and $B_{Q'Q'}$. We can label our cases by the triplet (i,j,k) where the first(second,third) index labels the embedding choice, *i.e.*, (1)-(4), for the field $H_1/H_1^c(H_2/H_2^c, D_1/D_1^c)$. For example, we may choose H_1/H_1^c to be from (1), H_2/H_2^c from (3) and D_1/D_1^c from (4) and we would label this subcase as (1,3,4). All of the contributions can be directly obtained from the last two equations by choosing appropriate combinations.

We have calculated both δ and λ for each of the 64 cases; Figure 4 shows the ‘envelope’ of the range of values of δ and λ as functions of θ . In all cases the actual values must lie within the ‘envelope’. Several observations are possible from these results. First, independently of the value of θ , we obtain the bounds $-0.286 \leq \delta \leq 0.250$ and $0.791 \leq \lambda \leq 1.080$ so that *exact* leptophobia is not achieved anywhere in the parameter space. (Just how close we are to

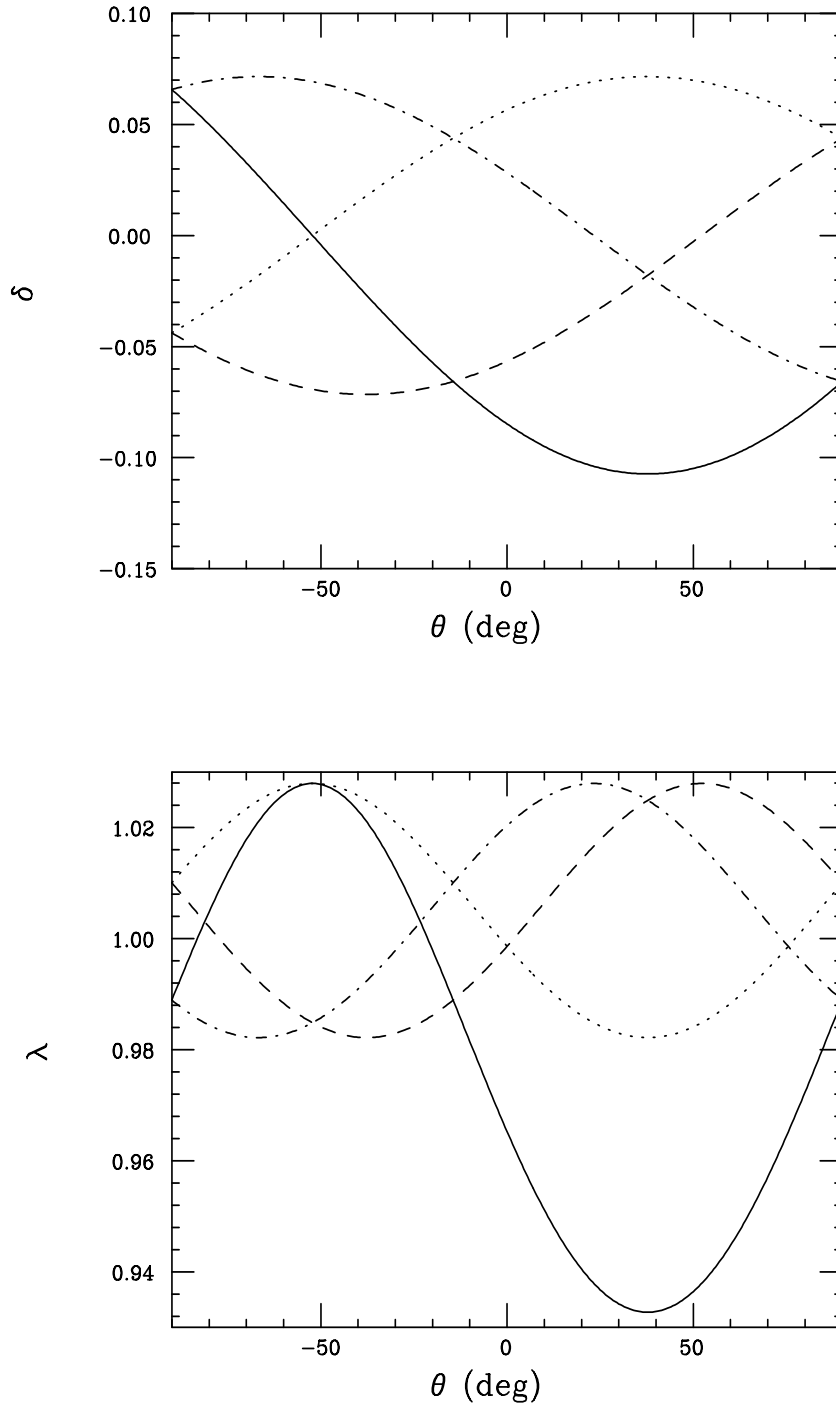


Figure 3: Predicted values of the parameters δ (top) and λ (bottom) for four E_6 case (i) possibilities discussed in the text. The dotted, dashed, dash-dotted and solid curves correspond to the embedding choices (1)-(4), respectively.

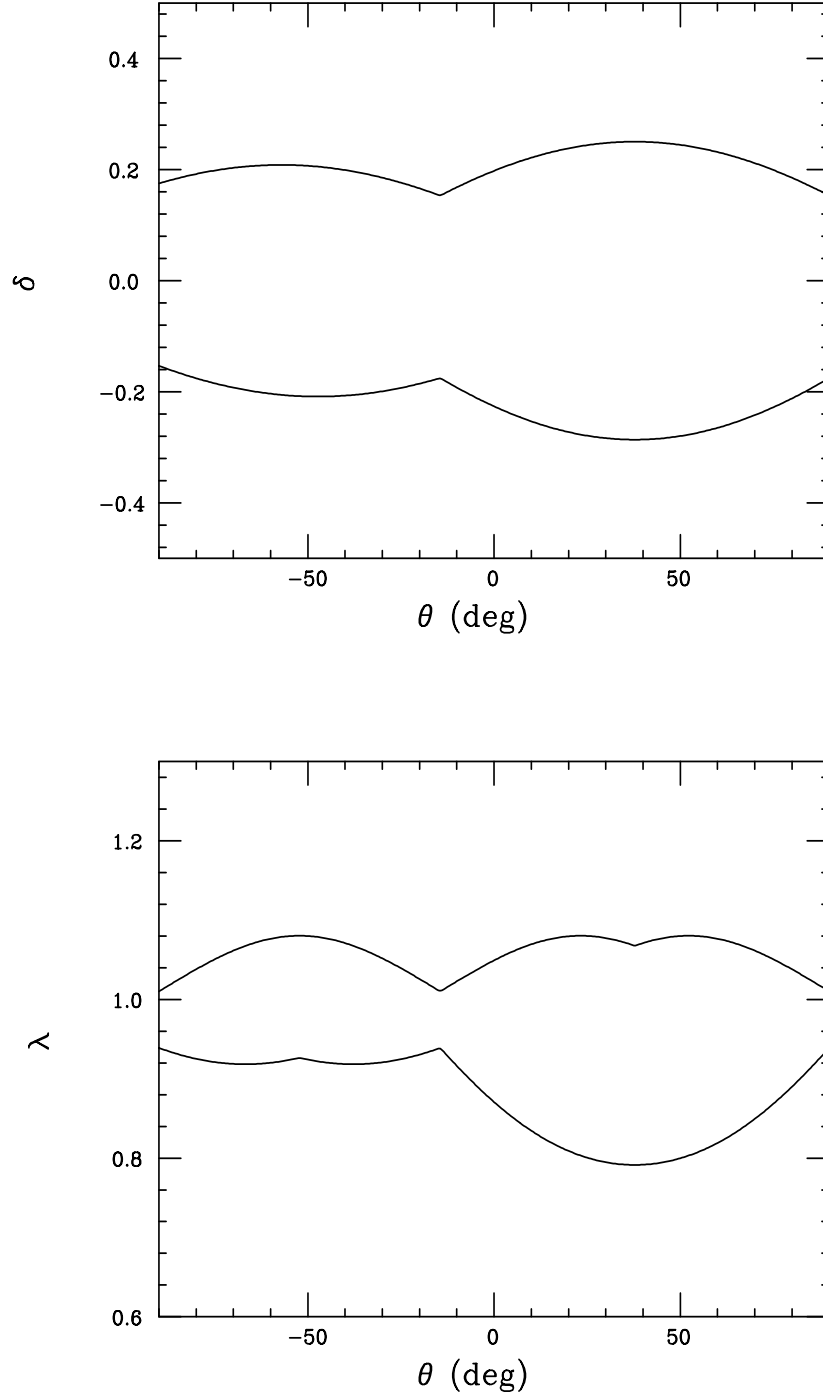


Figure 4: Boundaries of the allowed ranges for δ (top) and λ (bottom) for the 64 case, type (ii) E_6 models discussed in the text as functions of the mixing angle θ .

leptophobia will be discussed below.) The minimum[maximum] value of $\delta \simeq -0.286[+0.250]$ is achieved for η -type couplings with the embedding $(4,4,1)[(1,1,4)]$ which corresponds to the so-called ‘maximal’ model of Babu *et al.*[10]. The extrema for λ , *i.e.*, $\lambda = 0.791[1.080]$ are obtained for embeddings $(4,4,4)[(1,1,1)]$ for η -type couplings and $\theta = -52.24^\circ$ (model I), respectively. Interestingly, the range of δ is sufficiently narrow so that none of the models listed in Table 2 can achieve leptophobic conditions. Next, we note that a further contribution to apparent leptophobia can occur in the η coupling region since it is there that one obtains the smallest values of λ , rescaling the couplings to smaller values. (Recall, the Drell-Yan rate for the Z' scales as λ^2 .) It would be nice to perform a two-loop RGE calculation to verify these leading order results once these equations become available.

As models with η -type couplings are the only potential candidates for leptophobia, it is interesting to know the explicit $\delta - \lambda$ correlation in this case. We display in Figure 5 all of the 20 distinct solutions for δ and λ assuming this value of θ for models of either case (i) or (ii). To access just how leptophobic these models can be we calculated the Z' search reach in each case for both the Tevatron Run II and LHC following the procedure used to obtain Fig. 1. At the Tevatron, except for the most leptophobic case, the search reaches lie in the range $724 - 932(970 - 1150)$ GeV for an integrated luminosity of $2(30) fb^{-1}$ and generally conforms to the usual expectations. In the most leptophobic case, $(4,4,1)$, these values drop to only $524(778)$ GeV, which is not great but far from nonexistent. At the LHC with a luminosity of $100 fb^{-1}$, the mass reaches for all but the most leptophobic case lie in the range $3305 - 4415$ GeV; this then drops to only 2730 GeV in the $(4,4,1)$ case. Again this limit is poor relative to the others but it is quite substantial. Thus although the $(4,4,1)$ model is as close to leptophobia as possible, the Z' 's leptonic couplings remain large enough for this particle to be observed in Drell-Yan collisions but with a somewhat reduced reach.

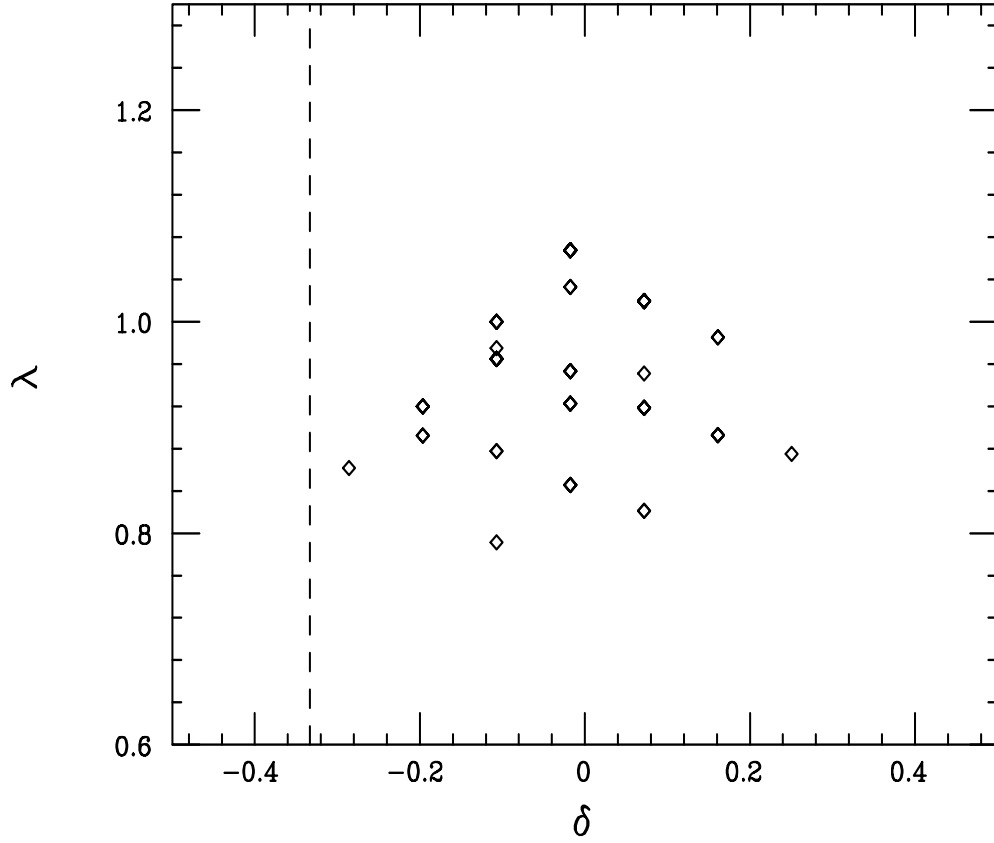


Figure 5: Calculated values of the parameters δ and λ for the $68=4+64 E_6$ models from cases (i) and (ii) discussed in the text when η -type couplings are assumed. The vertical dashed line corresponds to exact leptophobia. Almost all points are multiply occupied.

Since the allowed ranges for both δ and λ are reasonably restricted for these 68 models we would expect that the possibility of confusing a E_6 Z' with that of a different model would be at least somewhat reduced. Figure 6 shows the regions of coupling parameter space allowed by the θ -dependent δ and λ constraints obtained above. The regions are seen to be somewhat smaller than those shown in the more pessimistic Fig.2 where λ was set to unity and δ was free to vary over the range $-1/2 \leq \delta \leq 1/2$. There is certainly a significantly smaller overlap between the E_6 model predictions and those of other Z' models making it likely that these classes of models would be distinguishable given sufficiently precise data and combining the results obtained for different flavor fermions.

3.2 $SO(10)$

In some sense the $SO(10)$ case is easier to deal with than is E_6 since here the parameter $\theta = -90^\circ$ is completely fixed. On the otherhand, the number of split multiplets that we can add at low energies is much larger thereby increasing the number of subcases to be examined. The reason for this is that, unlike E_6 , the low energy content need only consist of the three $\mathbf{16}$'s of $SO(10)$, plus the 'Higgs' fields H_1/H_1^c for the anomaly cancelation constraint to be satisfied. This means that, as in the MSSM, we may add (i) up to four $\mathbf{5} + \overline{\mathbf{5}}$ ersatz pairs or (ii) one $\mathbf{10} + \overline{\mathbf{10}}$ either with or without an extra $\mathbf{5} + \overline{\mathbf{5}}$ to this low energy content without a loss of perturbative unification. Of course in none of these cases will leptophobia be achieved but we will be able to constrain the range of allowed values for both δ and λ . Given this potentially large split multiplet field content at low energies it will be no surprise to find that these ranges are *significantly* larger than what was obtained above in the more constrained case associated with E_6 . For n_5 $\mathbf{5} + \overline{\mathbf{5}}$'s and n_{10} $\mathbf{10} + \overline{\mathbf{10}}$'s, we already know from the MSSM that $\beta_L = 1 + n_5 + 3n_{10}$, $\beta_s = -3 + n_5 + 3n_{10}$ and $B_{YY} = \beta_Y = 33/5 + n_5 + 3n_{10}$ with $n_5 \geq 1$

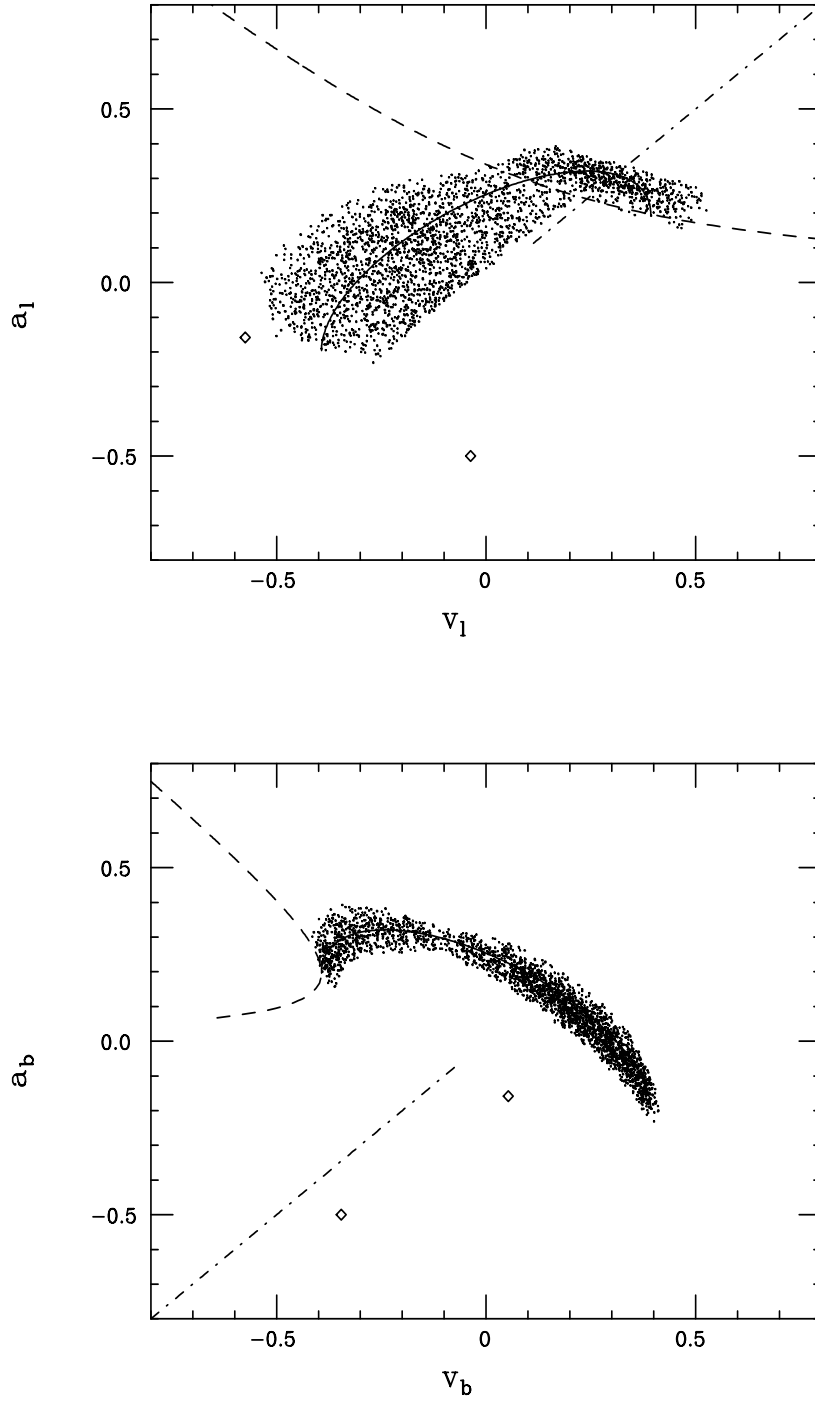


Figure 6: Calculated values for the vector and axial vector couplings for leptons(top) and b -quarks(bottom) arising from the 68 models E_6 models with kinetic mixing discussed in text in comparison to other Z' models as in Fig.2. Complete $\theta - \delta - \lambda$ constraints and correlations are included.

and $n_{10} \geq 0$. Similarly, we also know the contribution of the three $\mathbf{16}$'s to $B_{Q'Q'} = 6$. To be more specific we need to examine the two individual cases independently.

In case (i) we are again dealing only with particles that lie in the $\mathbf{5} + \overline{\mathbf{5}}$ as we did for E_6 . The particle content can be thought of as $3 \cdot \mathbf{16}'s \oplus H_1/H_1^c \oplus n[H_i/H_i^c + D_i/D_i^c]$ with $0 \leq n \leq 4$. Looking back at the E_6 case we see that there are only two possible χ quantum number assignments for these fields: (1) $\mathbf{5}(\mathbf{2}) + \overline{\mathbf{5}(-\mathbf{2})}$ and (2) $\mathbf{5}(-\mathbf{3}) + \overline{\mathbf{5}(\mathbf{3})}$. For fixed n , we may have (n_H, n_D) fields of type (1) and $(n+1-n_H, n-n_D)$ of type (2) with $0 \leq n_H \leq n+1$ and $0 \leq n_D \leq n$. Freely varying $n_{H,D}$ within their allowed ranges there are $2(6,12,20,30)$ subcases for $n = 0(1,2,3,4)$, for a total of 70. Here we find

$$B_{YQ'}(i) = \frac{6}{5} \sqrt{\frac{3}{5}} \left[1 + \frac{5}{3} (n_D - n_H) \right], \quad (17)$$

and

$$\Delta B_{Q'Q'}(i) = 0.4n_H + 0.6n_D + 0.9(n_5 + 1 - n_H) + 1.35(n_5 - n_D). \quad (18)$$

From these considerations we can immediately calculate the values of δ and λ which depend upon n, n_H and n_D ; these are shown in the top part of Fig. 7. Here we see that the results fill in a large crescent shaped region which extends to rather large values of both δ and $\lambda - 1$ in comparison to the E_6 case as we anticipated from the large split multiplet content.

In case (ii) we have a single $\mathbf{10} + \overline{\mathbf{10}}$ which may or may not be accompanied by an additional $\mathbf{5} + \overline{\mathbf{5}}$ so that $n_{10} = 1$ and $0 \leq n_5 \leq 1$. The possible χ quantum numbers of the $\mathbf{5} + \overline{\mathbf{5}}$ are given above and there are also two possibilities for the $\mathbf{10} + \overline{\mathbf{10}}$, *i.e.*, $\mathbf{10}(-\mathbf{1}) + \overline{\mathbf{10}(\mathbf{1})}$ or $\mathbf{10}(\mathbf{4}) + \overline{\mathbf{10}(-\mathbf{4})}$. The particle content can be thought of symbolically as $3 \cdot \mathbf{16}'s \oplus H_1/H_1^c \oplus n_5[H_i/H_i^c + D_i/D_i^c] \oplus [Q/Q^c, E/E^c, U/U^c]$, with $0 \leq n_5 \leq 1$ and, as in case (i), $0 \leq n_H \leq n_5 + 1$ and $0 \leq n_D \leq n_5$. If $n_Q(n_U, n_E)$ fields come from $\mathbf{10}(-\mathbf{1}) + \overline{\mathbf{10}(\mathbf{1})}$ then $1 - n_Q(1 - n_U, 1 - n_E)$ come from $\mathbf{10}(\mathbf{4}) + \overline{\mathbf{10}(-\mathbf{4})}$ since there is only one possible $\mathbf{10} + \overline{\mathbf{10}}$

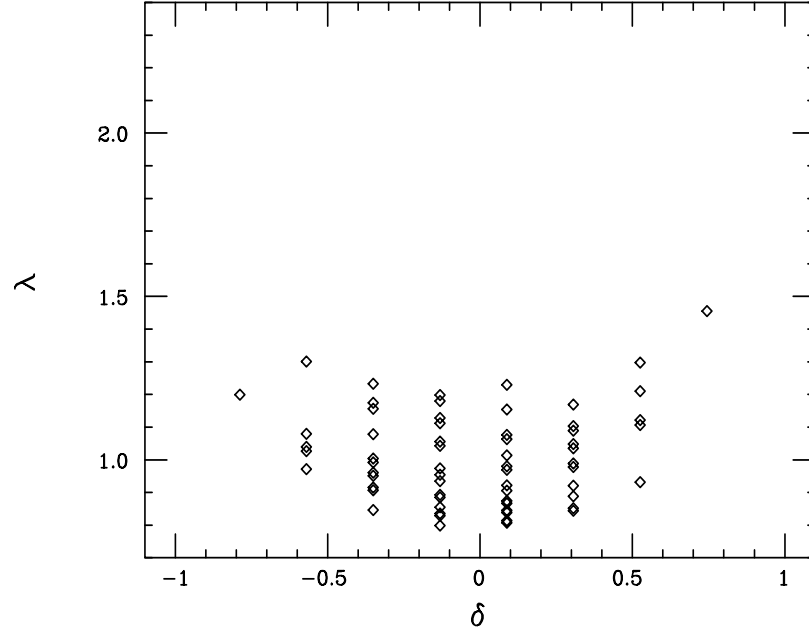
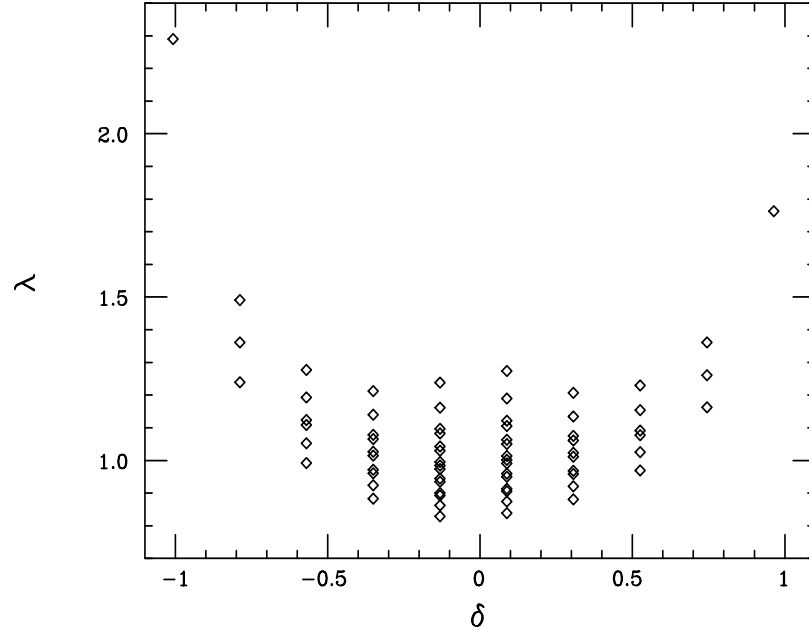


Figure 7: Distinct values of δ and λ for the models associated with the two $SO(10)$ subcases (i)(top) and (ii)(bottom) discussed in the text.

allowed. Clearly $0 \leq n_{Q,E,U} \leq 1$ independently of one another thus leading to a total of 64 subcases. We find for case (ii) the values

$$B_{YQ'}(ii) = \frac{6}{5} \sqrt{\frac{3}{5}} \left[1 + \frac{5}{3} (n_D + 2n_U - n_Q - n_E - n_H) \right], \quad (19)$$

and

$$\Delta B_{Q'Q'}(ii) = \Delta B_{Q'Q'}(i) + 8 - \frac{3}{4} [n_E + 3n_U + 6n_Q]. \quad (20)$$

From which we can immediately calculate the values of δ and λ ; these are shown in the bottom part of Fig. 7. As in case (i), the spread of δ and λ values obtained for case (ii) remains significantly larger than in E_6 but less so than case (i).

Due to the wide spread in the values of the $SO(10)$ Z' couplings in the presence of KM, we may wonder if the hadron collider search reaches are drastically altered. At the Tevatron, we find that the search reaches lie in the range 824 – 938(1040 – 1208) GeV for an integrated luminosity of 2(30) fb^{-1} and qualitatively conform to the usual model χ expectations, *e.g.*, 864 GeV for 2 fb^{-1} , in the absence of KM. At the LHC with a luminosity of 100 fb^{-1} , the mass reaches lie in the range 4100 – 5315 GeV again bracketing the non-KM expectation.

What about the Z' couplings themselves? These are completely specified by the values of δ and λ and are shown in Figure 8 for all of the 134 subcases. Notice that they span a large range but tend to cluster near, but not necessarily on top of, those of the LRM. We recall from our earlier discussion that in the absence of KM the model χ couplings are exactly the same as those of the LRM with $\kappa^2 = (g_R/g_L)^2 = \frac{5}{3} \frac{x_w}{(1-x_w)}$. It is apparent from the figure that once KM is turned on there is no obvious relationship between the two sets of couplings, though they do seem to track one another. A short analysis, however, shows that

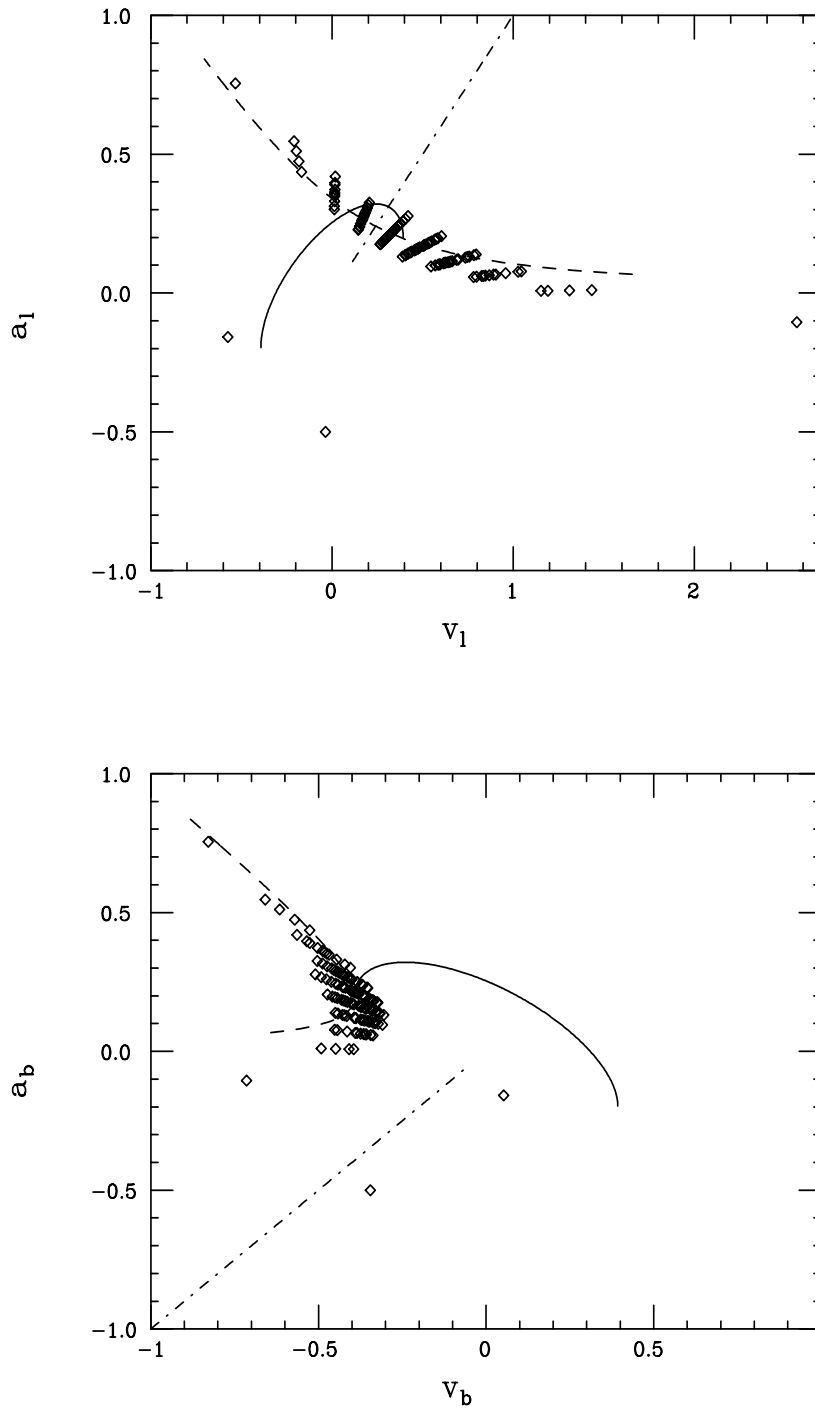


Figure 8: Predicted values of the vector and axial vector couplings in the $134=64+70$ $SO(10)$ cases discussed in the text compared with the predictions of other models as in Fig.2. Note the expanded scale in the present plots.

there does exist a value of κ in the LRM for which the *ratios* of couplings are the same as in the χ model with KM for any value of δ . This means that for this value of κ the couplings of the LRM and χ model with KM are identical apart from an overall normalization. This is easily proved by considering both the general form of the LRM couplings and remembering that the value of Q_χ can be written as a linear combination of T_{3R} and Y , where T_{3R} is the third component or the right-handed weak isospin. Specifically we find that correspondence in the couplings between the two models occurs when

$$\kappa^2 = \frac{5x_w}{3(1-x_w)}[1 - \sqrt{6}\delta/3]^{-1}, \quad (21)$$

and we see the conventional well-known result is recovered when $\delta \rightarrow 0$. Except for when δ is large and negative, $\simeq -1$, this equation has a solution in the physical region of the LRM, *i.e.*, $\kappa^2 > \frac{x_w}{(1-x_w)}$. This result has very important implications to issues involving around Z' coupling determinations at colliders.

As is well known, most techniques aimed at identifying a new Z' at hadron colliders[13, 16] actually employ observables which only determine various ratios of fermionic couplings. The extraction of coupling information from other observables, such as the Z' total width, are not only subject to larger systematic errors but depend on assumptions about how the Z' can decay. As we have just seen the ratios of $SO(10)$ -inspired χ model couplings in the presence of KM can be easily mimicked by those of the LRM with a suitably chosen value of the κ parameter. Thus the Z' 's of these two models could be easily confused.

As an example of this, let us consider the production of a $\simeq 700$ GeV Z' at the Tevatron during Run II. After a few fb^{-1} of luminosity are available several 100's of events in the dilepton channel will have been collected. Given the limited statistics, only a few of the variously proposed observables can be used to examine the Z' coupling. In addition to the charged lepton forward-backward asymmetry, A_{fb} , one might measure the relative cross

section in $b\bar{b}$ final states, R_{bl} , as suggested by[23], or the polarization of one of the τ 's, P_τ , in $Z' \rightarrow \tau^+\tau^-$, as suggested by[24]. Fig. 9 shows the correlations amongst these observables and, in particular, compares the LRM predictions with those of the χ model with kinetic mixing. We see immediately that the two models would be quite easily confused. Of course, in the LRM case a W' also exists with a mass somewhat less than the Z' ; finding the W' may be the only way to distinguish these two cases. (In some cases, finding the W' may also be difficult[16].)

At lepton colliders operating below the Z' production threshold, measurements made at a single \sqrt{s} are insensitive to the overall normalization of the Z' couplings. Their apparent values can be easily adjusted by a simple rescaling of the Z' mass. This weakness can be overcome at lepton colliders, however, by combining measurements taken at several distinct values of \sqrt{s} [16, 25]. Thus, in principle, lepton colliders can be used to distinguish the LRM and χ model with KM cases. Of course, if such a machine can operate on the Z' pole and the coupling normalization determined, there will be no ambiguities in Z' model identification.

4 Discussion and Summary

In this paper we have performed a detailed examination of the magnitude and influence of gauge kinetic mixing on couplings of the Z' 's which originate from either E_6 or $SO(10)$. These mixing effects were shown to be completely described by the values of the two parameters δ and λ which can be obtained via a renormalization group analysis. After introducing several model building assumptions we numerically analyzed the 68 E_6 and 134 $SO(10)$ models to which these assumptions naturally led. The values of both δ and λ were calculated for both sets of models, in particular, as functions of the mixing angle θ in the E_6 cases.

For the E_6 models, since the number of additional low energy matter representa-

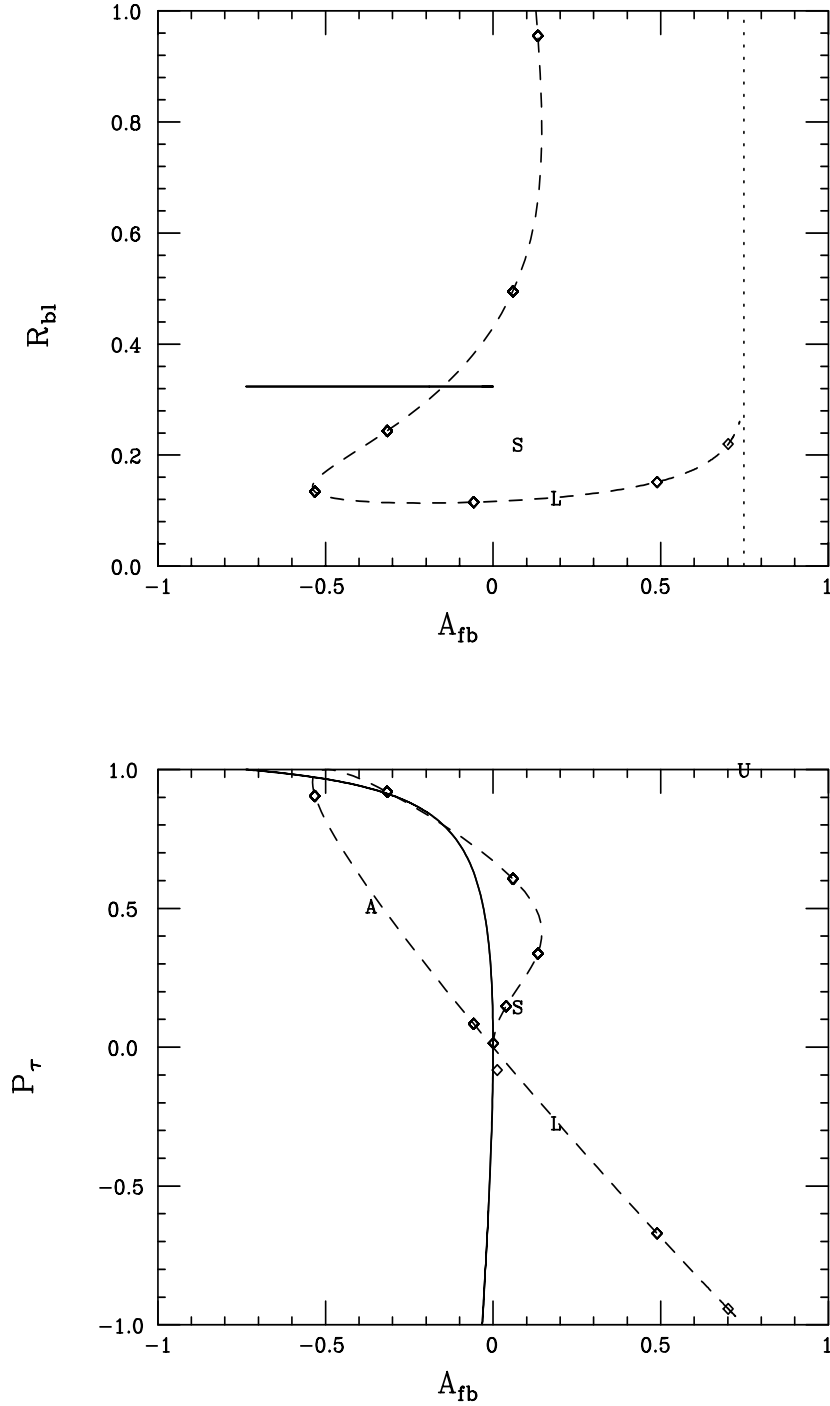


Figure 9: Correlations in the values of observables used to extract Z' coupling information at hadron colliders as discussed in the text. The diamonds are the predictions of the $SO(10)$ -inspired χ model with KM. The solid(dashed,dotted) curves correspond to the E_6 model without KM, the LRM and the Un-unified Model, respectively. The letters 'A,L,U,S' label the predictions for Ma's model, the LRM with $\kappa = 1$, the Un-unified Model and a heavy SM Z' , respectively.

tions inducing kinetic mixing was constrained to be rather limited due to our model building assumptions, the allowed ranges of both parameters was shown to be quite restricted. Furthermore, we demonstrated that exact leptophobia, which occurs when $\delta = -1/3$ for the conventional E_6 particle embedding in model η , is impossible to achieve in any of these models. This result was shown to be independent of how the fermions and additional vector-like matter fields necessary to induce kinetic mixing are embedded in GUT representations. In the case which was closest to being leptophobic, we determined that the leptonic couplings of the Z' were sufficiently large to render it visible in Drell-Yan collisions at both the Tevatron and the LHC. Of course in comparison to models where kinetic mixing is absent the reach for such a Z' was found to be significantly reduced by $\simeq 40\%$. Furthermore, in the general E_6 case, we showed that the couplings of the Z' remain sufficiently distinct from those of other models, such as the Left-Right Model, that they could be easily identified once sufficient statistics becomes available at future colliders. We demonstrated that this result would not hold if the magnitude of the kinetic mixing contributions to the Z' couplings were left unrestricted.

For the $SO(10)$ -inspired χ models, the potential effects of kinetic mixing were shown to be more pronounced (though leptophobia can never arise in these scenarios). This is due to the much larger range of split multiplets that may be introduced in this case while still satisfying our model building assumptions. In many cases kinetic mixing was shown to lead to values of λ significantly greater than unity which resulted in increased discovery reaches for these Z' at both the Tevatron and LHC. Qualitatively, the significantly expanded range of allowed χ couplings were found to track those of the LRM. In particular, we demonstrated that for all allowed values of δ there exists a corresponding value of the LRM parameter κ for which the couplings in the two theories are identical apart from an overall normalization. This was shown to have a serious impact on Z' model discrimination at hadron colliders as well as at lepton colliders unless data taken at multiple \sqrt{s} values is available for analysis.

The influence of gauge kinetic mixing leads to an enrichment in the phenomenology of new gauge bosons. Hopefully such particles will be found at future colliders.

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