Little Z' Models

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Abstract

We propose a new class of models called \textit{Little Z'} models in order to reduce the fine-tuning due to the current experimental limits on the \(Z'\) mass in \(E_6\) inspired supersymmetric models, where the Higgs doublets are charged under the extra \(U(1)'\) gauge group. The proposed \textit{Little Z'} models allow a lower mass \(Z'\) due to the spontaneously broken extra \(U(1)'\) gauge group having a reduced gauge coupling. We show that reducing the value of the extra gauge coupling relaxes the experimental limits, leading to the possibility of low mass \(Z'\) resonances, for example down to 200 GeV, which may yet appear in LHC searches. Although the source of tree level fine-tuning due to the \(Z'\) mass is reduced in \textit{Little Z'} models, it typically does so at the expense of increasing the vacuum expectation value of the \(U(1)'\)-breaking standard model singlet field, reducing the fine-tuning to similar levels to that in the Minimal Supersymmetric Standard Model.

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1 Introduction

The Large Hadron Collider (LHC) has so far not seen any signal of new physics beyond the standard model (BSM). On the other hand ATLAS and CMS have recently observed a new state consistent with a Standard-Model-like Higgs boson at $m_h = 125 - 126$ GeV [1, 2], which is within the range for it to be consistent with the lightest Higgs in supersymmetric models. In the minimal supersymmetric standard model (MSSM) the light Higgs mass at tree-level is bounded from above by the $Z$ boson mass ($M_Z$). The large radiative contributions from stops needed to raise it to the observed value typically imply very large fine-tuning.

Conventional $E_6$ inspired SUSY models involve both a singlet generated $\mu$ term, denoted $\mu_{\text{eff}}$, and a massive $Z'$ gauge boson at the TeV scale. Such models can increase the tree level physical Higgs boson mass above the $M_Z$ limit of the MSSM, due to both F-term contributions of the singlet and the D-term contributions associated with the $Z'$, allowing lighter stop masses and hence reducing fine-tuning due to stop loops. The exceptional supersymmetric standard model ($E_6$SSM) [4, 5] is an example of such a model, inspired by the $E_6$ group. It involves an extra singlet responsible for $\mu_{\text{eff}}$ and an extra $U(1)$ gauge symmetry at low energy, giving both new F-term and D-term contributions at tree level to the light Higgs mass, which is larger than both the MSSM and the next-to-minimal supersymmetric standard model (NMSSM) [6]. In the $E_6$SSM the light Higgs mass is given by,

$$m_h^2 \approx M_{Z'}^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2 \sin^2 2\beta + g_1^2 v^2 (Q_1 \cos^2 \beta + Q_2 \sin^2 \beta)^2 + \Delta m_h^2. \quad (1)$$

where $\tan \beta$ is the ratio between the two Higgs doublets’ vacuum expectation values (VEVs), $\lambda$ is the Yukawa coupling of the singlet field to the Higgs doublets, the extra $U(1)'$ gauge group has a gauge coupling $g_1'$ and $\Delta m_h^2$ represents loop corrections.

Eq.(1) exhibits two extra terms proportional to $v^2$, relative to the MSSM, which contribute at tree level to the Higgs mass squared. This means that the $E_6$SSM permits lower stop masses than in the MSSM (or the NMSSM) corresponding to lower values required for the radiative correction term $\Delta m_h^2$. However, as we shall discuss, one of the minimisation conditions of the $E_6$SSM can be written in the form,

$$c \frac{M_{Z'}^2}{2} = -\mu_{\text{eff}}^2 + \frac{(m_d^2 - m_u^2 \tan^2 \beta)}{\tan^2 \beta - 1} + d M_{Z'}^2, \quad (2)$$

where $c, d$ are functions of $\tan \beta$ which are of order $\mathcal{O}(1)$, $m_d, m_u$ are soft Higgs mass squared parameters, $M_{Z'} \sim g_1's$ and $\mu_{\text{eff}} \sim \lambda s$ arise from the singlet VEV $s$. Written in this form it is clear that there is a new source of tree-level fine-tuning, due to the $Z'$ mass squared term in Eq.(2) which will increases quadratically as $M_{Z'}^2$, eventually coming to dominate the fine-tuning for large enough values of $M_{Z'}$. This tree-level fine-tuning
can be compared to that due to $\mu_{\text{eff}}$ which typically requires this quantity to be not much more than 200 GeV, and similar limits also apply to $M_{Z'}$. With the current CMS experimental mass limit for the $Z'$ in the $E_6$SSM of $M_{Z'} \gtrsim 2.08$ TeV [7] it is clear that there is already a significant, perhaps dominant, amount of fine-tuning due to the $Z'$ mass limit, and furthermore this source of fine-tuning increasing quadratically with $M_{Z'}$ will rapidly overtake the logarithmic fine-tuning due to the stop mass limits, as the experimental mass limits of both types of particles increases in the future. This was first pointed out in [8] and has been discussed quantitatively [9] in the framework of the constrained $E_6$SSM [10], where it has been verified that this new source of fine-tuning dominates over all other sources.

In this paper we propose a new class of models called Little $Z'$ models which differ from the usual class of $E_6$ models by having a reduced gauge coupling $g'_1$ leading to the possibility of lower mass $Z'$ bosons. Such a reduction in the gauge coupling $g'_1$ at the unification scale has some motivation from F-theory constructions [11]. We show that reducing $g'_1$ relaxes the experimental limit on the $Z'$ mass, allowing a lighter value and hence reducing the tree-level fine-tuning associated with $E_6$ models. We show that, although for sufficiently small values of $g'_1$ the new source of fine-tuning due to the $Z'$ mass can be essentially eliminated, it does so at the expense of increasing the singlet vacuum expectation value, leading to overall fine-tuning similar to that in the Minimal Supersymmetric Standard Model. We emphasise that the main prediction of Little $Z'$ models is the presence of weakly coupled low mass $Z'$ resonances, perhaps as low as 200 GeV.

The layout of the remainder of the paper is as follows. In section 2 we briefly review the $E_6$SSM, followed by a discussion of the Electroweak Symmetry Breaking (EWSB) conditions and the impact of the $Z'$ mass on fine-tuning in section 3. Little $Z'$ models are introduced in section 4, where the experimental limits on such a boson are studied as a function of its mass and (reduced) gauge coupling. Section 5 concludes the paper.

2 The $E_6$SSM

At low energies, the group structure of the Exceptional Supersymmetric Standard Model ($E_6$SSM) is that of the Standard Model (SM), along with the additional $U(1)_N$ symmetry,

$$E_6 \rightarrow SU(5) \times U(1)_N$$

$$SU(5) \rightarrow SU(3)_c \times SU(2)_w \times U(1)_Y$$

The matter content of the model is contained in the complete 27-dimensional representation which decomposes under $SU(5) \times U(1)_N$ to,
27 \rightarrow (10, 1)_i + (5^*, 2)_i + (5^*, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i \quad (5)

Ordinary Quarks and Leptons are contained in the representations: (10, 1) and (5^*, 2). The Higgs doublets and exotic quarks are contained in (5^*, -3) and (5, -2). The singlets are contained in (1, 5), and finally the right handed neutrinos are included in (1, 0).

Moreover, the model requires three 27 representations, hence \(i = 1, 2, 3\), in order to ensure anomaly cancellation. This means that there are three copies of each field present in the model. However, only the third generation (by choice) of the two Higgs doublets, and the SM singlet acquire VEVs. The other two generations are called: inert. Furthermore, in order to keep gauge coupling unification, non-Higgs fields that come from extra incomplete 27', 27'' representations are added to the model. As a result, a \(\mu'\) term, which is not necessary related to the weak scale, is present in the model.

The full superpotential consistent with the low energy gauge structure of the \(E_6\) SSM contains includes both \(E_6\) invariant invariant terms and \(E_6\) breaking terms, full details of which are given in [4].

To prevent proton decay and flavour changing neutral currents a discrete \(Z_2^H\) symmetry is imposed. All superfields except the third generation Higgs doublets and singlet are odd under this symmetry. The \(Z_2^H\) invariant superpotential then reads,

\[
W_{E_6\text{SSM}} \approx \lambda_i \hat{S}(\hat{H}_d^u \hat{H}_u^d) + \kappa_i \hat{S}(\hat{D}_i \hat{D}_i) + f_{\alpha\beta} \hat{S}_\alpha(\hat{H}_d \hat{H}_u^\beta) + \tilde{f}_{\alpha\beta} \hat{S}_\alpha(\hat{H}_d^d \hat{H}_u)
\]

\[+ \frac{1}{2} M_{ij} \hat{N}^c_i \hat{N}^c_j + \mu'(\hat{H}' \hat{H}') + h^E_{ij}(\hat{H}_d \hat{H}_d^c) \hat{\tilde{e}}^c_j + h^N_{ij}(\hat{H}_u \hat{H}_u^d) \hat{\tilde{N}}^c_j
\]

\[+ W_{\text{MSSM}}(\mu = 0), \quad (6)
\]

where the indices \(\alpha, \beta = 1, 2\) and \(i = 1, 2, 3\) denote the generations. \(S\) is the SM singlet field, \(H_u\), and \(H_d\) are the Higgs doublet fields corresponding to the up and down types. Exotic quarks and the additional non-Higgs fields are denoted by \(D\) and \(H'\) respectively.

Finally to ensure that only third generation Higgs like fields get VEVs a certain hierarchy between the Yukawa couplings must exist. Defining \(\lambda \equiv \lambda_3\), we impose \(\kappa_i \sim \lambda_3 \gg f_{\alpha\beta}, \tilde{f}_{\alpha\beta}, h^E_{ij}, h^N_{ij}.\)
3 The Higgs potential and the EWSB conditions

The scalar Higgs potential is,

\[ V(H_d, H_u, S) = \lambda^2 |S|^2 (|H_d|^2 + |H_u|^2) + \lambda^2 |H_d H_u|^2 \]

\[ + \frac{g_2^2}{8} (H_d^\dagger \sigma_a H_d + H_u^\dagger \sigma_a H_u)^2 (H_d^\dagger \sigma_a H_d + H_u^\dagger \sigma_a H_u) \]

\[ + \frac{g^2}{8} (|H_d|^2 - |H_u|^2)^2 + g_1^2 \left( Q_1 |H_d|^2 + Q_2 |H_u|^2 + Q_s |S|^2 \right)^2 \]

\[ + m_a^2 |S|^2 + m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + [\lambda A \lambda S H_d H_u + c.c.] + \Delta_{\text{Loops}} \]

(7)

where, \( g_2, g' = \sqrt{3/5} g_1 \), and \( g_1' \) are the gauge couplings of \( SU(2)_L, U(1)_Y \) (GUT normalized), and the additional \( U(1)_N \), respectively. \( Q_1 = -3/\sqrt{40}, Q_2 = -2/\sqrt{40}, \) and \( Q_s = 5/\sqrt{40} \) are effective \( U(1)_N \) charges of \( H_u, H_d \) and \( S \), respectively. \( m_s \) is the mass of the singlet field, and \( m_{u,d} \equiv m_{H_u,d} \).

The Higgs field and the SM singlet acquire VEVs at the physical minimum of this potential,

\[ <H_d> = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad <H_u> = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad <S> = s \sqrt{2}. \]

(8)

It is reasonable to exploit the fact that \( s \gg v \), which will help in simplifying our master formula for fine-tuning as will be seen in Section 4. Then, from the minimisation conditions,

\[ \frac{\partial V_{E_{a,SSM}}}{\partial v_1} = \frac{\partial V_{E_{a,SSM}}}{\partial v_2} = \frac{\partial V_{E_{a,SSM}}}{\partial s} = 0, \]

(9)

the Electroweak Symmetry Breaking (EWSB) conditions are,

\[ \frac{M_Z^2}{2} = -\frac{1}{2} \lambda^2 s^2 + \frac{g_1^2}{2} \left( Q_1 v_1^2 + Q_2 v_2^2 + Q_s s^2 \right) \left( Q_1 - Q_2 \tan^2 \beta \right) \frac{\tan^2 \beta - 1}{\tan^2 \beta - 1} \]

(10)

\[ \sin 2\beta \approx \frac{\sqrt{2} \lambda A \lambda s}{m_d^2 + m_u^2 + \lambda^2 s^2 + \frac{g_1^2}{2} Q_s s^2 (Q_1 + Q_2)}, \]

(11)

\[ m_s^2 \approx -\frac{1}{2} g_1^2 Q_s s^2 = -\frac{1}{2} M_{Z'}^2, \]

(12)

where \( M_Z^2 = \frac{1}{4} (g^2 + g_2^2) (v_2^2 + v_1^2) \) and \( M_{Z'}^2 \approx g_1^2 Q_s s^2 \).
Eq. 10 can be written,
\[
\frac{M_Z^2}{2} \left( 1 - \frac{g_1^2}{g^2 + g_Z^2} P(\tan \beta) R(\tan \beta) \right) = -\left( \frac{\lambda s}{\sqrt{2}} \right)^2 + \frac{m_3^2 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} + \frac{M_Z'^2}{2} R(\tan \beta)
\]

where
\[
R(\tan \beta) = \frac{Q_1 - \tan^2 \beta Q_2}{\tan^2 \beta - 1}
\]
and
\[
P(\tan \beta) = 4 \left( \frac{Q_1 (1 - \frac{Q_1}{Q_2}) + \tan^2 \beta Q_2 (1 - \frac{Q_2}{Q_2})}{\tan^2 \beta + 1} \right)
\]

If one takes \( g_1' = 0 \) we have \( M_{Z'} = 0 \) and the factor in front of \( M_Z^2 \) in (13) is equal to one and we recover the well known MSSM relation between \( M_Z, \mu(= s\lambda/\sqrt{2}) \) and the soft Higgs masses \( m_1, m_2 \). Written in this form, which may be compared to Eq. 2 but with the coefficients \( c, d \) explicitly given, it is clear that fine-tuning will increase quadratically as \( M_{Z'} \) increases.

To avoid any fine-tuning we would like to keep \( \mu \sim M_{Z'} \sim 200 \text{ GeV} \) or less. This motivates the main idea of this paper, namely to relax the CMS experimental mass limit of \( M_{Z'} \gtrsim 2.08 \text{ TeV} \) down to \( M_{Z'} \sim 200 \text{ GeV} \) by reducing its gauge coupling \( g_1' \). Indeed, as we shall see, such a low value of \( M_{Z'} \sim 200 \text{ GeV} \) may be made consistent with the experimental limit by choosing \( g_1' \sim 10^{-2} \times 0.46 \) and \( s \sim 20 \times 2.75 \sim 55 \text{ TeV} \). In order to keep \( \mu \) close to the electroweak scale this requires a very small value of \( \lambda \sim g_1' \). In Fig. 1 the contribution \( \Delta_{M_{Z'}} \) to fine-tuning from \( M_{Z'} \) is plotted, where \( \Delta_{M_{Z'}} \) is defined as follows.

\[
\Delta_{M_{Z'}} = \frac{M_{Z'}^2 \partial M_{Z'}^2}{M_Z^2 \partial M_{Z'}^2}
\]

We emphasise that the appearance of \( M_{Z'} \) in the tree-level minimisation condition is characteristic of all SUSY \( Z' \) models where the usual Higgs doublets carry \( U(1)' \) charges (e.g. it applies to all \( E_6 \) models but not, for example the \( U(1)_{B-L} \) model.) This provides a motivation for Little \( Z' \) models in which the extra gauge coupling \( g_1' \) is reduced and the experimental lower bound on \( M_{Z'} \) may be relaxed.

4 Little \( Z' \) Models

In general Little \( Z' \) Models can be defined by the gauge group
\[
SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'
\]

where the Standard Model is augmented by an additional \( U(1)' \) gauge group with a gauge coupling \( g_1' \) which is significantly smaller than the hypercharge gauge coupling \( g' \).
The $U(1)'$ gauge group is broken at low energies giving rise to a massive $Z'$ gauge boson with couplings to a SM fermion $f$ given by [3]:

$$\mathcal{L}_{NC} = \frac{g_{\nu}'}{2} Z_{\mu} f \gamma^\mu (g_V' - g_A' \gamma^5) f.$$ 

The values of $g_{U}^f, g_{A}^f$ depend on the particular choice of $U(1)'$ and on the particular fermion $f$. We assume universality amongst the three families. More explicitly, this assumption implies that $g_{U}^u = g_{U}^d = g_{U}^e$, $g_{A}^u = g_{A}^d = g_{A}^e$, and $g_{A}^u = g_{A}^d = g_{A}^e$ for up-quarks, down-quarks, charged leptons and neutrinos respectively. The axial couplings, $g_{A}^f$, behave accordingly.

In a given model there are eight model dependent couplings of the extra $Z'$ boson to SM fermions, that is $g_{U,A}^f$ with $f = u, d, e, \nu_e$. These are fixed by group theory, so cannot be changed for a given model. However the low energy $U(1)'$ gauge coupling $g_1'$ is fixed by a unification condition. E.g. in $E_6$SSM $g_1' \approx 0.46$ which is approximately equal to the (GUT normalised) hypercharge gauge coupling. If unification of $g_1'$ with the other gauge couplings is relaxed, then $g_1'$ becomes a free parameter. In this paper we are interested in taking it to be smaller than the GUT prediction, namely we shall consider $g_1' \ll g' \approx 0.46$, keeping $g_{U,A}^f$ fixed at their model predictions.

Specializing to the charged lepton pair production cross-section relevant for the first runs at the LHC, the cross-section may be written at the leading order (LO) as [3]:

$$\sigma_{e^+e^-}^{LO} = \frac{\pi}{48s} [c_u w_u(s, M_{Z'}^2) + c_d w_d(s, M_{Z'}^2)]$$  

Figure 1: Contribution to fine-tuning from the $Z'$ mass.
where the coefficients $c_u$ and $c_d$ are given by:

\[ c_u = \frac{g_1^2}{2}(g_V^u + g_A^u)Br(\ell^+\ell^-), \quad c_d = \frac{g_1^2}{2}(g_V^d + g_A^d)Br(\ell^+\ell^-), \]

and $w_u(s, M_{Z'}^2)$ and $w_d(s, M_{Z'}^2)$ are related to the parton luminosities $\left(\frac{dL_{e^+e^-}}{dM_{Z'}^2}\right)$ and $\left(\frac{dL_{e^+e^-}}{dM_{Z'}^2}\right)$ and therefore only depend on the collider energy and the $Z'$ mass. All the model dependence of the cross-section is therefore contained in the two coefficients, $c_u$ and $c_d$. These parameters can be calculated from $g_V^1, g_A^1$ and $g_1'$, assuming only SM decays of the $Z'$ boson. Note that the cross-section is proportional to $g_1'^2$ and will therefore be reduced in Little $Z'$ models in which $g_1^I \ll g' \approx 0.46$.

A given model such as the $E_6$SSM [4] appears as a point in the $c_d - c_u$ plane, assuming that the low energy $U(1)'$ gauge coupling $g_1'$ is fixed by a unification condition. If we relax the unification condition then the point will become a line in the $c_d - c_u$ plane, since each of $c_u$ and $c_d$ are proportional to $g_1'^2$ and the points on the line will approach the origin as $g_1' \rightarrow 0$. For example in the $E_6$SSM we have:

\[ c_u = 5.94 \times 10^{-4} \left( \frac{g_1'}{0.46} \right)^2, \quad c_d = 1.48 \times 10^{-3} \left( \frac{g_1'}{0.46} \right)^2. \]

Since the experimental $Z'$ mass contours in the $c_d - c_u$ plane are fixed for a given limit on the cross-section, the effect of reducing $g_1'$ will not change those contours. The only effect of reducing $g_1'$ is to move the model point in the $c_d - c_u$ plane closer to the origin, resulting in a reduced experimental limit on the $Z'$ mass. See for example [3] where this approach is followed for conventional $Z'$ models. Although this provides a simple way to understand qualitatively why the experimental limits are relaxed by reducing $g_1'$, it turns out that for the lower mass $Z'$ signal regions backgrounds and other constraints become more important for this reason we shall not present our results in the $c_d - c_u$ plane.

In the $E_6$SSM the $Z'$ mass is given to good approximation by:

\[ M_{Z'}^2 = g_1'^2v^2\left(\hat{Q}_1^2\cos^2\beta + \hat{Q}_2^2\sin^2\beta\right) + g_1'^2\hat{Q}_S^2s^2 \approx g_1'^2\hat{Q}_S^2s^2, \]

where the charges are $\hat{Q}_S = 5/\sqrt{40}, \hat{Q}_1 = -3/\sqrt{40}, \hat{Q}_2 = -2/\sqrt{40}$. The last approximation in Eq.21 assumes $s \gg v$ where we can neglect the terms involving the electroweak VEV $v = 246$ GeV. What is the effect of reducing $g_1'$ in this model? On the one hand, reducing $g_1'$ will reduce $M_{Z'}$ in direct proportion, since $M_{Z'} \propto g_1'$ for a fixed value of $s$. On the other hand, reducing $g_1'$ will reduce the cross-section since $c_{ud} \propto g_1'^2$ (see Eq.20).

In Fig.2 we show the cross section for lepton ($e, \mu$) pair-production via $Z'$ at LHC at $\sqrt{s} = 8$ TeV in the $g_1' - M_{Z'}$ plane for the Little $Z'$ models with charges corresponding to the $E_6$SSM. The horizontal, dashed line indicates the standard GUT predicted $g_1'$.
value. The dash-dotted lines are cross section limits on the E6SSM Z' from DΦ[12], CMS[13] and ATLAS[14] that have been converted to limits on the coupling g'1.

The estimated indirect exclusion limits from electro-weak precision tests (EWPT)[15, 16, 17], mostly by LEP, on the ratio $\frac{M_{Z'}}{g'_1}$ are plotted with red crosses. These are not available for the E6SSM but the limit for the $U(1)_χ$ Z' is

$$\frac{M_{Z'}}{g'_1} > 3.8 \text{ TeV},$$

and the limit for the $U(1)_ψ$ Z' is

$$\frac{M_{Z'}}{g'_1} > 2.5 \text{ TeV}.$$

As an estimate of these limits for the E6SSM, we plot with red crosses an intermediate limit

$$\frac{M_{Z'}}{g'_1} ≥ 3.0 \text{ TeV}.$$

Figure 2 also shows contours of constant values of the singlet VEV s, so it is possible to read off exclusions limits on s. At large masses the limits from ATLAS and CMS follow the cross section contours well but in the low mass regime the standard model background is large which weakens the limits on the cross section. In this region, just above 200 GeV, the direct searches by the LHC and Tevatron experiments place the strongest bounds on the coupling and all place limits of about $g'_1 < 0.03$.

It is obvious from Fig. 2 that it is possible to lower the limit on $M_{Z'}$ by decreasing the coupling $g'_1$ but by doing this the value of the singlet VEV, s, generally has to increase. The limit on s is however strongest for $M_{Z'}$ of about 500-800 GeV and gets slightly relaxed in the lowest mass region, 200-500 GeV. Examples of how the limits on $M_{Z'}$, s and the fine-tuning with respect to $M_{Z'}$ changes as the coupling $g'_1$ decreases are tabulated in Tab. 1.

5 Conclusion

The current experimental limits from the LHC on the Z' boson mass of 2-3 TeV raises the fine-tuning in E6 supersymmetric models to undesirably high levels. This is a generic property of SUSY models where the Higgs doublets carry the $U(1)'$ charge. In order to solve this problem we have proposed a new class of models called Little Z' models involving a weakly coupled lower mass Z'. These models can originate from supersymmetric E6 inspired supersymmetric models where the spontaneously broken extra $U(1)'$ gauge group has a reduced gauge coupling.
Figure 2: Cross section for lepton \((e, \mu)\) pair-production via \(Z'\) at LHC at \(\sqrt{s} = 8\) TeV in the \(g'_1 - M_{Z'}\) plane for Little \(Z'\) models with charges corresponding to the \(E_6\)SSM. The horizontal, dashed line indicates the standard GUT predicted \(g'_1\) value. Exclusion limits from direct searches are plotted with dash-dotted lines in magenta, black and blue for DØ, CMS and ATLAS respectively. Indirect constraint on the mass-coupling ratio from electro-weak precision tests are plotted with red crosses and coincides with the contour for the singlet VEV \(s \approx 4\) TeV.

We have shown that reducing the value of the extra gauge coupling relaxes these limits, leading to the possibility of low mass \(Z'\) resonances, for example down to about 200 GeV, thereby reducing fine-tuning due to the \(Z'\) mass down to acceptable levels. Such a reduced extra gauge coupling does not affect conventional gauge coupling unification of the strong, weak and electromagnetic gauge couplings and in fact is well motivated in certain classes of F-theory models. We emphasise the main experimental prediction of such Little \(Z'\) models which is the appearance of a low mass weakly coupled \(Z'\) which may yet appear in future LHC searches. Although the source of tree level fine-tuning due to the \(Z'\) mass is reduced in Little \(Z'\) models, it does so at the expense of increasing
Table 1: Scenarios with different values of $g'_1$ for the Little $Z'$ models with charges corresponding to the $E_6$ SSM. The $Z'$ mass and thus its source of fine-tuning, $\Delta M_{Z'} = \frac{M^2_{Z'} \partial M^2_{Z'}}{M^2_Z \partial M^2_{Z'}}$, can be reduced by reducing $g'_1$ at the cost of increasing the singlet VEV, $s$. Because experimental limits on the cross section get weaker in the low mass region the limit on $s$ gets slightly weaker, hence the weaker limit on $s$ in the case of $g'_1 = 0.46/15$.

the singlet vacuum expectation value, leading to overall fine-tuning similar to that in the Minimal Supersymmetric Standard Model.

Acknowledgements

SFK acknowledges partial support from the STFC Consolidated ST/J000396/1 and EU ITN grants UNILHC 237920 and INVISIBLES 289442. PS is thankful for support from the NExT institute, a part of SEPnet.

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