Yukawa Unification Predictions with effective “Mirage” Mediation

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Abstract

In this letter we analyze the consequences, for the LHC, of gauge and third family Yukawa coupling unification with a particular set of boundary conditions defined at the GUT scale, which we characterize as effective “mirage” mediation. We perform a global $\chi^2$ analysis including the observables $M_W, M_Z, G_F, \alpha_{em}^{-1}, \alpha_s(M_Z), M_t, m_b(m_b), M_\tau, BR(B \to X_s\gamma), BR(B_s \to \mu^+\mu^-)$ and $M_h$. The fit is performed in the MSSM in terms of 10 GUT scale parameters, while $\tan \beta$ and $\mu$ are fixed at the weak scale. We find good fits to the low energy data and a SUSY spectrum which is dramatically different than previously studied in the context of Yukawa unification.

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Gauge coupling unification in supersymmetric grand unified theories (SUSY GUTs) [1–6] provides an experimental hint for low energy SUSY. However, it does not significantly constrain the spectrum of supersymmetric particles. On the other hand, it has been observed that Yukawa coupling unification for the third generation of quarks and leptons in models, such as SO(10) or SU(4)_c × SU(2)_L × SU(2)_R, can place significant constraints on the SUSY spectrum in order to fit the top, bottom and tau masses [7–11]. These constraints depend on the particular boundary conditions for sparticle masses chosen at the GUT scale (see for example, [9, 12–14], which consider different GUT scale boundary conditions). In this letter we consider effective “mirage” mediation boundary conditions and show that they are consistent with gauge and Yukawa coupling unification with a dramatically different low energy SUSY spectrum. The GUT scale boundary conditions are given by an effective “mirage” pattern with gaugino masses defined in terms of two parameters, $M_{1/2}$ an overall mass scale and $\alpha$ the ratio of the anomaly mediation to gravity mediation contribution [15–18]. Scalar masses are given in terms of $m_{16}$ (for squarks and sleptons) and $m_{10}$ (for Higgs doublets). In addition, the $H_u$ and $H_d$ masses are split, either with “Just-So” splitting or with a U(1) D-term which affects all scalar masses. Note, as in Ref. [18], we allow for several origins of SUSY breaking. For example, the dilaton and conformal compensator fields break SUSY at a scale of order $M_{1/2}$, while the dominant contribution to SUSY breaking is at a scale of order $m_{3/2} \geq m_{16} \approx m_{10}$. We fit the low energy observables, $M_W, M_Z, G_F, \alpha_{em}^{-1}, \alpha_s(M_Z), M_t, m_b(m_b), M_\tau, BR(B \rightarrow X_s \gamma), BR(B_s \rightarrow \mu^+ \mu^-)$ and $M_h$ in terms of 12 arbitrary parameters. The low energy sparticle spectrum is imminently amenable to testing at the LHC. Two benchmark points are contained in Table III.

Fermion masses and quark mixing angles are manifestly hierarchical. The simplest way to describe this hierarchy is with Yukawa matrices which are also hierarchical. Moreover the most natural way to obtain the hierarchy is in terms of effective higher dimension operators of the form

$$W \supset \lambda \, 16_3 \, 10 \, 16_3 + 16_3 \, 10 \, \frac{45}{M} \, 16_2 + \cdots.$$ \hfill (1)

This version of SO(10) models has the nice features that it only requires small representations of SO(10), has many predictions and can, in principle, find an UV completion in string theory. The only renormalizable term in $W$ is $\lambda \, 16_3 \, 10 \, 16_3$ which gives Yukawa coupling unification

$$\lambda = \lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau}$$ \hfill (2)
at $M_{\text{GUT}}$. Note, one cannot predict the top mass due to large SUSY threshold corrections to the bottom and tau masses, as shown in [19–21]. These corrections are of the form

$$
\delta m_b/m_b \propto \frac{\alpha_3 \mu M_\tilde{g} \tan \beta}{m_b^2} + \frac{\lambda_2^2 \mu A_t \tan \beta}{m_t^2} + \text{log corrections.}
$$

(3)

So instead we use Yukawa unification to predict the soft SUSY breaking masses. In order to fit the data, we need

$$
\delta m_b/m_b \sim -2\%.
$$

(4)

We take $\mu < 0$, $M_\tilde{g} > 0$. For a short list of references on this subject, see [7–11, 22–27].

We assume the following GUT scale boundary conditions, namely a universal squark and slepton mass parameter, $m_{16}$, universal cubic scalar parameter, $A_0$, “mirage” mediation gaugino masses,

$$
M_i = \left(1 + \frac{g_i^2 b_i \alpha}{16\pi^2} \log \left(\frac{M_{\text{Pl}}}{m_{16}}\right)\right) M_{1/2}
$$

(5)

(where $M_{1/2}$ and $\alpha$ are free parameters and $b_i = (33/5, 1, -3)$ for $i = 1, 2, 3$). Note, this expression is equivalent to the gaugino masses defined in [28]. $\alpha$ in the above expression is related to the $\rho$ in Ref.[18] as: $\frac{1}{\rho} = \frac{\alpha}{10\pi^2} \ln \frac{M_{\text{Pl}}}{m_{16}}$. We consider two different cases for non-universal Higgs masses [NUHM] with “just so” Higgs splitting

$$
m_{H_u(d)}^2 = m_{10}^2 - (+)2D
$$

(6)

or, D-term Higgs splitting, where, in addition, squark and slepton masses are given by

$$
m_a^2 = m_{16}^2 + Q_a D, \ \{Q_a = +1, \{Q, \bar{u}, \bar{e}\}; -3, \{L, \bar{d}\}\}
$$

(7)

with the U(1) D-term, $D$, and SU(5) invariant charges, $Q_a$. Note, we take $\mu$, $M_{1/2} < 0$. Thus for $\alpha \geq 4$ we have $M_3 > 0, M_1, M_2 < 0$. (Note, the case of D-term splitting is similar to the analysis of Ref. [13]. However our low energy SUSY spectrum is much different.) In the set of boundary conditions above, the scalar masses and tri-linear couplings are large (of order $m_{3/2}$), while the magnitude of the gaugino masses is given by $M_{1/2} \ll m_{3/2}$. Note, this does not agree with the examples of mirage mediation in the literature. For example, in the context of Type IIB strings, Ref. [15–17], the scalar, gaugino and tri-linear couplings are all of order $m_{3/2}$, while in the heterotic version of mirage mediation, Ref. [18], the soft terms for scalar masses are of order $m_{3/2}$, while the gaugino masses and tri-linear couplings are given by $M_{1/2} \ll m_{3/2}$. Finding a SUSY breaking mechanism with the set of boundary
conditions presented here is still an open challenge. Nevertheless, we are using the SO(10) symmetry to justify Yukawa unification for the third family and then finding the minimal set of SUSY breaking parameters at the GUT scale consistent with the low energy data. This forces $A_0$ to be large.

We perform a global $\chi^2$ analysis varying the parameters in Table I used to calculate the total $\chi^2$ function in terms of all the observables given in Table II defined at the electroweak scale as discussed in Ref. [14]. We minimize the $\chi^2$ function using the Minuit package maintained by CERN [29]. Note that Minuit is not guaranteed to find the global minimum, but will in most cases converge on a local one. For that reason, we iterate $O(100)$ times the minimization procedure for each set of input parameters, and in each step we take a different initial guess for the minimum (required by Minuit) so that we have a fair chance of finding the true minimum. We realize that the system is under-constrained and thus we obtain values of $\chi^2 \ll 1$. For this reason, it is not possible to define a goodness of fit or $\chi^2$/d.o.f. However, in Fig. 1, we fix certain parameters such that we have 2 degrees of freedom, and plot contours of $\chi^2$/dof = 1, 2, 3, 3 corresponding to 95%, 90%, and 68% CLs, respectively. One could also add more observables to the fit and this is possible when one considers a three family model, which is the subject of an ongoing study. The additional parameters determining fermion masses, mixing angles and flavor observables for the first two families introduce more degrees of freedom (as discussed previously in Ref. [14] with different GUT scale boundary conditions), but they do not significantly affect the SUSY spectrum.

Consider first the SUSY spectrum in our analysis. Two benchmark points are given in Table III with fixed $m_{16} = 5$ TeV. The first and second family squarks and sleptons have mass of order $m_{16}$, while stops, sbottoms and staus are all a factor of about 2 lighter. In addition, gluinos are always lighter than the third family squarks and sleptons, and the lightest charginos and neutralinos are even lighter. Fig.1 shows that the gluino mass increases as $\alpha$ increases and we are able to find good fits for gluino masses up to at least 3 TeV. In models with universal gaugino masses, however, it was found that for fixed values of $m_{16}$, there is an upper bound on the gluino mass [14], which is not the case here. Note, CMS and ATLAS have used simplified models to place lower bounds on the gluino mass. However the allowed decay modes for our model, as presented below, do not in any way resemble any simplified model. Preliminary analysis, Ref. [34], shows that with such decay branching fractions the bounds coming from published LHC data are at least 20% lower than
TABLE I: The model is defined by three gauge parameters, \( \alpha_G, M_G \) (where \( \alpha_1(M_G) = \alpha_2(M_G) \equiv \alpha_G \)), and \( \epsilon_3 = \frac{\alpha_3 - \alpha_G}{\alpha_G} \); one large Yukawa coupling, \( \lambda \); 6 SUSY parameters defined at the GUT scale, \( m_{16} \) (universal scalar mass for squarks and sleptons), \( M_{1/2} \) (universal gaugino mass), \( \alpha \) (the ratio of anomaly mediation to gravity mediation contribution to gaugino masses), \( m_{10} \), (universal Higgs mass), \( A_0 \) (universal trilinear scalar coupling) and \( D \) which fixes the magnitude of Higgs splitting in the case of “Just-so” Higgs splitting or the magnitude of all scalar splitting in the case of D-term splitting. The parameters \( \mu, \tan \beta \) are obtained at the weak scale by consistent electroweak symmetry breaking.

FIG. 1: The figure shows total \( \chi^2 \) in the \( \alpha - M_{1/2} \) plane. The different shades of blue regions have \( \chi^2/d.o.f = 1, 2.3, 3 \) and greater (from light to dark), and the olive curves show contours of constant gluino mass.

obtained using any simplified model. The states \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_1^0 \) are approximately degenerate. In Table III we include the running masses for the chargino and neutralino and the dominant one-loop contribution to the mass splitting, \( \Delta M \) [35]. Thus the chargino signature at the LHC is dominated by the decay \( \tilde{\chi}^+ \rightarrow \tilde{\chi}^0 + \pi^+ \) [36]. This typically results in a disappearing
Table II: The 11 observables that we fit and their experimental values. Capital letters denote pole masses. We take LHCb results into account, but use the average by Ref. [32]. All experimental errors are 1σ unless otherwise indicated. Finally, the Z mass is fit precisely via a separate χ² function solely imposing electroweak symmetry breaking.

| Observable | Exp. Value | Ref. |
|------------|------------|------|
| α₃(MZ)     | 0.1184 ± 0.0007 | [30] |
| α_em       | 1/137.035999074(44) | [30] |
| Gµ         | 1.16637876(7) × 10⁻⁵ GeV⁻² | [30] |
| MW         | 80.385 ± 0.015 GeV | [30] |
| MZ         | 91.1876 ± 0.0021 | [30] |
| Mt         | 173.5 ± 1.0 GeV | [30] |
| m_b(m_b)   | 4.18 ± 0.03 GeV | [30] |
| Mt         | 1776.82 ± 0.16 MeV | [30] |
| Mh         | 125.3 ± 0.4 ± 0.5 GeV | [31] |
| BR(b → sγ) | (343 ± 21 ± 7) × 10⁻⁶ | [32] |
| BR(Bs → µ⁺µ⁻) | (3.2 ± 1.5) × 10⁻⁹ | [33] |

Note, in the case of “Just-so” Higgs splitting, stops are the lightest sfermion, while in the case of D-term splitting, sbottoms are lighter. In addition, at low energies, A_t, A_b are small.
and thus we have small left-right mixing. These affect the gluino decay branching ratios. Finally, since both $\mu, M_2$ and $M_1$ are negative we obtain the correct sign for the SUSY correction to $(g - 2)_\mu$, however, in practice, our sleptons are too heavy to give a good fit, and therefore $(g - 2)_\mu$ is not included in the $\chi^2$ function. This does not agree with the results of Badziak et al., Ref. [13] who are able to fit $(g - 2)_\mu$, with non-universal gaugino masses and Yukawa unification. Unfortunately the sparticle spectrum obtained in their paper is now ruled out by LHC Higgs data [44]. In Tables IV and V we give different benchmark points, all with $\chi^2 \ll 1$, in order to present the variation of sparticle masses with different values of $m_{16}$ and $M_{1/2}$.

With regards to GUT scale parameters, we find $\alpha \approx 12$ which corresponds to approximately equal dilaton and anomaly mediated contributions to gaugino masses. We also find $|\epsilon_3| \leq 1\%$ in the case of D-term splitting or precise gauge coupling unification [45].

In conclusion, we have performed a global $\chi^2$ analysis of an SO(10) SUSY GUT with gauge coupling unification and top, bottom, $\tau, \nu_\tau$ Yukawa unification at $M_{\text{GUT}}$. We have analyzed the model for the third family alone. We have shown that the SUSY spectrum is predominantly determined by fitting the third family and light Higgs masses and the branching ratio $BR(B_s \rightarrow \mu^+ \mu^-)$.

A generic prediction of third family Yukawa unification is that we have $\tan \beta \approx 50$. In addition, in order to fit the branching ratio $BR(B_s \rightarrow \mu^+ \mu^-)$ we find the CP odd Higgs mass, $m_A \gg M_Z$. Hence we are in the decoupling limit and the light Higgs is predicted to be Standard Model-like. Our model, makes several additional predictions which are unique to the effective “mirage” mediation boundary conditions.

- The first and second family of squarks and sleptons obtain mass of order $m_{16}$, while the third family scalars are naturally about a factor of 2 lighter. Gluinos and the lightest chargino and neutralino are always lighter than the third family squarks and sleptons. We also find that there is no upper bound on the gluino mass.

- Our LSP is predominantly wino and thus assuming a thermal calculation of the relic abundance, we find $\Omega_{\tilde{\chi}_1^0} \sim 10^{-5}$.

- $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are approximately degenerate. Thus the chargino signature at the LHC is predominantly due to the decay $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$. This typically results in a disappearing charged track since the pion would carry too little energy.
• For the two benchmark points, Table III, the dominant decay modes for the gluino are for “just so” Higgs splitting - (63% → $\tilde{\chi}^0 g$; 28% → $\tilde{\chi}^+ b\bar{t}$, $\tilde{\chi}^- t\bar{b}$ and 8% → $\tilde{\chi}^0 t\bar{t}$) and D-term splitting - (76% → $\tilde{\chi}^+ b\bar{t}$, $\tilde{\chi}^- t\bar{b}$; 14% → $\tilde{\chi}^0 t\bar{t}$; 3.5% → $\tilde{\chi}^0 b\bar{b}$, and the rest to light quarks or gluons).

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| NUHM   | “Just-so” | D-term |
|--------|-----------|--------|
| $m_{16}$ | 5000      | 5000   |
| $\sqrt{D}$ | 1877     | 1242   |
| $m_{10}$  | 6097      | 5261   |
| $A_0$     | 8074      | 5593   |
| $\mu$    | -615      | -1294  |
| $M_{1/2}$ | -105      | -100   |
| $\alpha$ | 11.59     | 12.00  |
| $M_{\text{GUT}} \times 10^{-16}$ | 4.50 | 2.38 |
| $1/\alpha_{\text{GUT}}$ | 25.11 | 25.64 |
| $\epsilon_3$ | -0.039  | -0.007 |
| $\lambda$ | 0.59      | 0.56   |
| $\tan \beta$ | 49.43 | 48.73 |
| $M_A$     | 1558      | 1237   |
| $m_{\tilde{t}_1}$ | 1975      | 2921   |
| $m_{\tilde{b}_1}$ | 2049      | 2159   |
| $m_{\tilde{\tau}_1}$ | 2473      | 3601   |
| $m_{\tilde{\mu}}$ | 4905      | 5081   |
| $m_{\tilde{d}}$ | 4944      | 4467   |
| $m_{\tilde{e}}$ | 4947      | 4477   |
| $m_{\tilde{\chi}_1^0}$ | 231.98   | 219.11 |
| $m_{\tilde{\chi}_1^+}$ | 232.05   | 219.11 |
| $\Delta M \equiv M_{\tilde{\chi}_1^+} - M_{\tilde{\chi}_1^0}$ | 0.519    | 0.438  |
| $M_{\tilde{g}}$ | 882       | 874    |

**TABLE III:** Benchmark points and SUSY Spectrum. For each case we have $\chi^2 \ll 1$. The chargino and neutralino masses are tree level and the one loop correction to the mass difference is given by $\Delta M$. All masses are in GeV.
| Parameter | Case 1 | Case 2 | Case 3 | Case 4 |
|-----------|--------|--------|--------|--------|
| $m_{16}$  | 4000   | 4000   | 10000  | 8000   |
| $\sqrt{D}$ | 1725   | 1511   | 5516   | 3207   |
| $m_{10}$  | 5144   | 5079   | 13036  | 10168  |
| $A_0$     | 7050   | 7542   | 15789  | 14687  |
| $\mu$     | -259   | -391   | -1364  | -612   |
| $M_{1/2}$ | -100   | -240   | -120   | -260   |
| $\alpha$  | 12.00  | 11.99  | 10.88  | 11.58  |
| $M_{GUT} \times 10^{-16}$ | 2.69   | 2.27   | 2.52   | 2.55   |
| $1/\alpha_{GUT}$ | 25.29  | 25.53  | 25.88  | 25.76  |
| $\epsilon_3$ | -0.019 | -0.017 | -0.005 | -0.018 |
| $\lambda$ | 0.616  | 0.616  | 0.560  | 0.606  |
| $\tan\beta$ | 50.25  | 49.96  | 48.68  | 49.93  |
| $M_A$     | 1658   | 1041   | 6975   | 2825   |
| $m_{\tilde{t}_1}$ | 1308   | 1679   | 4028   | 2751   |
| $m_{\tilde{b}_1}$ | 1279   | 1760   | 3068   | 2861   |
| $m_{\tilde{\tau}_1}$ | 1613   | 1580   | 5021   | 3282   |
| $m_{\tilde{u}}$ | 3929   | 4144   | 9659   | 7910   |
| $m_{\tilde{d}}$ | 3974   | 4155   | 9876   | 7978   |
| $m_{\tilde{\epsilon}}$ | 3952   | 3995   | 9808   | 7924   |
| $m_{\tilde{\chi}_1^0}$ | 187    | 367    | 278    | 525    |
| $m_{\tilde{\chi}_1^+}$ | 190    | 371    | 278    | 526    |
| $\Delta M$ | 3.61   | 4.54   | 0.452  | 1.67   |
| $M_{\tilde{g}}$ | 858    | 1834   | 853    | 1902   |

TABLE IV: Generic Features of the “Just-so” Higgs splitting with the mirage pattern for gaugino masses and with different values of $m_{16}$ and $M_{1/2}$. For each case we have $\chi^2 \ll 1$. The chargino and neutralino masses are tree level and the one loop correction to the mass difference is given by $\Delta M$. All masses are in GeV.
| Parameter         | Case 1  | Case 2  | Case 3  | Case 4  |
|-------------------|---------|---------|---------|---------|
| $m_{16}$          | 4000    | 4000    | 8000    | 8000    |
| $\sqrt{D}$       | 1037    | 1018    | 2531    | 1641    |
| $m_{10}$          | 4598    | 4594    | 8094    | 7351    |
| $A_0$             | 5588    | 5654    | 8325    | 4810    |
| $\mu$             | -541    | -591    | -2945   | -2636   |
| $M_{1/2}$         | -100    | -280    | -100    | -280    |
| $\alpha$         | 12.00   | 11.91   | 12.00   | 10.39   |
| $M_{GUT} \times 10^{-16}$ | 2.41 | 1.87    | 1.93    | 2.35    |
| $1/\alpha_{GUT}$ | 25.46   | 25.73   | 26.05   | 26.00   |
| $\epsilon_3$     | -0.011  | -0.009  | 0.007   | -0.009  |
| $\lambda$        | 0.582   | 0.599   | 0.540   | 0.569   |
| $\tan \beta$     | 49.20   | 49.31   | 48.13   | 48.70   |
| $M_A$             | 969     | 728     | 3719    | 726     |
| $m_{\tilde{t}_1}$| 2026    | 2421    | 5178    | 5344    |
| $m_{\tilde{b}_1}$| 1255    | 1825    | 2634    | 4702    |
| $m_{\tilde{\tau}_1}$ | 2622   | 2644    | 5266    | 6218    |
| $m_{\tilde{\mu}}$| 4091    | 4324    | 8233    | 8105    |
| $m_{\tilde{d}}$  | 3553    | 3825    | 6594    | 7445    |
| $m_{\tilde{e}}$  | 3546    | 3615    | 6607    | 7445    |
| $m_{\tilde{\chi}_0^0}$ | 215   | 529     | 226     | 529     |
| $m_{\tilde{\chi}_1^+}$ | 216   | 531     | 226     | 529     |
| $\Delta M$       | 0.554   | 2.25    | 0.436   | 0.475   |
| $M_{\tilde{\chi}}$ | 867   | 2085    | 855     | 1842    |

TABLE V: Generic Features of D-term Higgs splitting with the mirage pattern for gaugino masses and with different values of $m_{16}$ and $M_{1/2}$. For each case we have $\chi^2 \ll 1$. The chargino and neutralino masses are tree level and the one loop correction to the mass difference is given by $\Delta M$. All masses are in GeV.