Phenomenological Consequences of the Constrained Exceptional Supersymmetric Standard Model

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Abstract. The Exceptional Supersymmetric Standard Model (E6SSM) provides a low energy alternative to the MSSM, with an extra gauged U(1)N symmetry, solving the µ-problem of the MSSM. Inspired by the possible embedding into an E6 GUT, the matter content fills three generations of E6 multiplets, thus predicting exciting exotic matter such as diquarks or leptoquarks. We present predictions from a constrained version of the model (cE6SSM), with a universal scalar mass m0, trilinear mass A and gaugino mass M1/2. We reveal a large volume of the cE6SSM parameter space where the correct breakdown of the gauge symmetry is achieved and all experimental constraints satisfied. We predict a hierarchical particle spectrum with heavy scalars and light gauginos, while the new exotic matter can be light or heavy depending on parameters. We present representative cE6SSM scenarios, demonstrating that there could be light exotic particles, like leptoquarks and a U(1)N Z' boson, with spectacular signals at the LHC.

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INTRODUCTION

The E6SSM[2, 1] is an E6 inspired model with an extra gauged U(1)N symmetry at low energies, defined by U(1)N = 1/4U(1)χ + √15/4U(1)ψ, with U(1)χ and U(1)ψ in turn, defined by the breaking, E6 → SO(10)×U(1)ψ and SO(10)→SU(5)×U(1)χ. The low energy gauge group of the E6SSM is then SU(3)×SU(2)×U(1)Y×U(1)N. The matter content fills three generations of 27plet representations of E6, leading to an automatic cancellation of anomalies. Each 27plet contains one generation of ordinary matter; singlet fields, S; up and down type Higgs like field, H2,i and H1,i and exotic squarks, D1,i, 1, Di. The model also contains two extra SU(2) doublets, H' and H''', which are required for gauge coupling unification.

To evade rapid proton decay we introduce either a Z2B or Z2L symmetry which work like R-parity except that the exotic quark is odd while it’s scalar partners are even. Under Z2B the exotic quarks are leptoquarks while under Z2L they are diquarks. To evade large Flavour Changing Neutral Currents, we also introduce an approximate Z2H symmetry, where the Higgs superfields are even, and all others are odd. All couplings through which the exotic quarks and inert Higgs decay violate Z2H, so the symmetry must only be approximate, but for our Renormalisation Group (RG) analysis they can be neglected.

Finally so that only the third generation gets VEVs we assume a hierarchical Yukawa sector. Keeping only the dominant couplings the superpotential W_{E6SSM} ∼ λiSH1,iH2,i +
\[ \kappa_i SD \tilde{D}_1 + h_u H_u Q b^c + h_b H_d Q c^c + h_t H_d L \tau^c \] \[ H_u = H_{2,3} \text{ and } H_d = H_{1,3} \text{ and } S = S_3 \text{ develop VEVs, } \langle H_u^0 \rangle = v_u, \langle H_d^0 \rangle = v_d, \text{ giving mass to ordinary matter while } \langle S \rangle = s \text{ gives exotic quark masses, } \kappa_i S \rightarrow \kappa_i s = \mu_D, \text{ and an effective } \mu \text{-term, } \mu_{\text{eff}} = \lambda_3 s. \]

**THE CONSTRAINED E\textsubscript{6}SSM**

The constrained E\textsubscript{6}SSM (cE\textsubscript{6}SSM) is defined by applying universality constraints to the E\textsubscript{6}SSM at the scale where the gauge couplings unify, \( M_X \). For all scalar (\( m_i \)), gaugino (\( M_i \)) and trilinear (\( A_i \)) masses we have, \( M_i(M_X) = M_{1/2}, A_i(M_X) = A \) and \( m_i(M_X) = m_0 \).

To connect these high scale constraints with low energy phenomenology we employ the RG Equations (RGEs) of the E\textsubscript{6}SSM given in Ref. [3]. Due to the presence of new exotic colored matter the RGE for the strong gauge coupling vanishes at 1-loop, so we use 2-loop RGEs for gauge and Yukawa couplings. We also employ 2-loop RGEs for the gaugino masses and trilinear couplings but only 1-loop RGEs for the soft scalar masses.

The RGEs for the gauge and Yukawa couplings are independent of the soft breaking masses, but nonlinear even at 1-loop while the soft SUSY breaking sector depends on the gauge and Yukawa couplings as well as the soft SUSY breaking masses but have a simple enough structure that they can be solved semi-analytically to give,

\[ m_i^2(Q) = a_i(Q)M_{1/2}^2 + b_i(Q)A_0^2 + c_i(Q)A_0M_{1/2} + d_i(Q)m_0^2 \]

(1)

\[ A_i(Q) = e_i(Q)A_0 + f_i(Q)M_{1/2} \]

(2)

where the coefficients depend not only on renormalisation scale, \( Q \), but also on the gauge and Yukawa couplings and can be determined numerically for a given \( Q \) by selectively setting \( M_{1/2}, m_0 \) and \( A \) to zero and evolving between \( M_X \) and \( Q \) with the full set E\textsubscript{6}SSM RGEs. Unlike the constrained MSSM, in the cE\textsubscript{6}SSM we find that in contrast with the cMSSM RG coefficients obey \( p_j, q_j \lesssim a_i, d_i \), for all \( j \) and all \( i \) from ordinary matter. This implies a gaugino sector which is light in comparison to the sfermions.

To make physical predictions we then combine these with the electroweak symmetry breaking (EWSB) conditions \( \partial V/\partial s = \partial V/\partial v_1 = \partial V/\partial v_2 = 0 \), where \( V \) is the Higgs potential including leading 1-loop stop contributions. This gives \( M_{1/2}, A \) and \( m_0 \) values consistent with both the high scale universality conditions and the EWSB. Finally we calculate the physical masses and test against experimental constraints. We require a mass bound of 300 GeV for the squarks, gluinos, exotic quarks and squarks; 100 GeV for the inert Higgs and Higgsinos and 860 GeV for the \( Z' \) boson. We also keep Yukawa couplings less than 3 to maintain perturbativity and insist on a neutralino LSP.

**RESULTS**

As shown in Fig. (1) left) for fixed values of \( s \) we find many phenomenologically acceptable solutions at the TeV scale by varying the Yukawa couplings \( \lambda \) and \( \kappa \). Notice also that although \( m_0 \) and \( M_{1/2} \) vary with the Yukawas, in general the mass scale increases with singlet VEV \( s \). Scanning over \( s \) too, Fig. (1) right) we see that \( m_0 \gtrsim M_{1/2} \), which further pushes up the masses of the sfermions and in combination with the comparative
magnitudes of the RG coefficients implies that all the sfermions of ordinary matter are heavier than the gluino, the lightest two neutralinos and the lightest chargino.

We also present representative scenarios in Fig. 2 showing the range of possible signatures that could be seen at the LHC. Scenario 1, top left, is drawn from the bottom left corner of Fig. 1 (right) so that $m_0$ and $M_{1/2}$ are as light as possible. Nonetheless all the sfermions of ordinary matter are rather heavy, with only the lightest stop below 500 GeV. As well as the characteristic light gaugino sector and the light Higgs, we also have light Inert Higgs bosons and the Inert Higgsinos. The Inert Higgs bosons decay via $Z H^2$ violating terms that are analogous to the Yukawa interactions of the Higgs superfields, $H_u$ and $H_d$. So the inert Higgs bosons decay predominantly into 3rd generation fermion– anti-fermion pairs like $H_{1,i}^0 \rightarrow b \bar{b}$ for neutral states or $H_{1,i}^- \rightarrow \tau \bar{\nu}_{\tau}$ for charged states. Similarly the inert Higgsinos decay into fermion-anti-sfermion pairs, e. g. $\tilde{H}_{i}^0 \rightarrow t \tilde{t}^*.$

In scenario 1 all exotics squarks are heavy due to the large singlet VEV contribution to their mass, but mixing effects can render one of these masses light as in scenario 2, top right. With a universal $\kappa$ coupling though all exotic quarks must be heavy as a large $\kappa$ is required to drive EWSB. However if we split the $\kappa_i$ couplings then only one generation need be heavy, as in scenario 3, bottom left, giving rise to a remarkable signature.

Exotic quarks also decay through $Z H^2$ violating couplings and assuming the third generation couplings dominate, the lightest exotic quarks decay into states like $t \tilde{b}$, (if diquarks) or $t \tilde{\tau}$, (if leptoquarks), substantially enhancing the cross section of either $pp \rightarrow t \tilde{b} \bar{b} + E_T^{\text{miss}} + X$ (if diquarks) or $pp \rightarrow t \tilde{t} \tau \bar{\tau} + E_T^{\text{miss}} + X$ or $pp \rightarrow b \bar{b} + E_T^{\text{miss}} + X$ (if leptoquarks). SM production of $t \tilde{t} \tau^+ \tau^-$ is $(\alpha_W/\pi)^2$ suppressed in comparison to the leptoquark decays, so light leptoquarks should produce a strong signal at the LHC. Similarly scalar leptoquarks decay into quark–lepton final states like $D \rightarrow t \tau$, and pair production leads to an enhancement of $pp \rightarrow t \tilde{t} \tau \bar{\tau}$ (without missing energy) at the LHC. Although such scenarios are phenomenologically exciting it is not guaranteed that any new matter from the 27plets is very light. All such particles could be rather heavy and challenging to detect, like scenario 4, bottom right, but even in such a pessimistic case there is still the striking prediction of the light gluino. Due to the hierarchical spectrum, the gluinos can be relatively narrow states with width $\Gamma_{\tilde{g}} \propto M_{\tilde{g}}^5/m_{\tilde{q}}^4$, comparable to that of

![Graph](image-url)
$W^\pm$ and $Z$ bosons. They will decay via $\tilde{g} \rightarrow q\tilde{q}^* \rightarrow q\tilde{q} + E_T^{\text{miss}}$, so gluino pair production implies an appreciable enhancement of the cross section for $pp \rightarrow q\tilde{q}q\tilde{q} + E_T^{\text{miss}} + X$, where $X$ refers to any number of light quark/gluon jets.

FIGURE 2. Mass spectra for scenarios 1 (top left), 2 (top right), 3 (bottom left), 4 (bottom right).

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