U(1)-extensions of the MSSM in light of the Higgs discovery.

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Outline

Why are we interested in $U(1)'$ extentions?

- Boosted tree level mass
- Larger 1-loop corrections with smaller soft masses $\Rightarrow$ more natural stop sector.
- Extended Higgs Sector $\sim$ lightest Higgs: SM-like
- Extended Neutralino Sector$\rightsquigarrow$ Singlino LSP $\rightsquigarrow$ possibly large $\Gamma(h \to \tilde{\chi}_i^0 \tilde{\chi}_j^0)$.
- Constrained parameter space: M_Z' searches, EW precision data, invisible Higgs decays etc. Still room to play.

Theoretical Motivation

- MSSM: μ problem $\mu \sim \mathcal{O}(TeV) \sim m_{soft}$ but μ is supersymmetry respecting parameter.

  USSM/NMSSM: generates μ-term effectively

$$W = W_{MSSM}(\mu = 0) + \lambda S H_u H_d \quad (1)$$

  after EWSB: $\mu_{eff} = \lambda < S > H_u H_d$
  Now μ_{eff} is supersymmetry breaking parameter

- NMSSM $\mu H_u H_d \xrightarrow{replaced} \lambda S H_u H_d$: W_{NSSM} PQ-symmetry

$$\phi_i \rightarrow \phi_i' = e^{iQ_{PQ}}\phi \quad (2)$$

  PQ=continuous symmetry $\rightarrow$ SSB produces massless Goldstone mode (not observed)

Theoretical Motivation

- USSM Solution: PQ global $\xrightarrow{promote}$ $U(1)'$ local
  massless axion eaten by new $U(1)'$ gauge boson B' $\rightarrow$ massive extra Z' at the TeV scale.
- no cubic term $\frac{1}{3}\kappa S^3$ (NMSSM)$\rightarrow$ no domain problems (spoil CMB radiation)
- Extra $U(1)'$ also emerge from GUT's and string theories.

  Larger groups:
  $SU(5), SO(10)$ and $E_6 \xrightarrow{break} G_{SM} \times U(1)'^{\,n},\ n \geq 1$.
    - Breaking mechanism imposes charge constraints.

Phenomenological motivations/MSSM Vs USSM

Higgs discovery $m_h \simeq 125$GeV

- MSSM:
  - lightest CP even Higgs h_1 saturates the upper bound
  - large 1-loop corrections $\rightarrow$ naturalness is spoiled
  - large stop mixing X_t is required $\rightarrow m_{\tilde{t}_1} \downarrow \quad m_{\tilde{t}_2} \uparrow$
    ATLAS lower limit on $m_{\tilde{t}_1} > 600$GeV
  - large soft masses $m_{\tilde{t}_L}$ $m_{\tilde{t}_R}$

USSM Advantages

- $m_{h^0}^2 \lesssim m_z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + v^2(Q_{H_d} \cos^2(\beta) + Q_{H_u} \sin^2(\beta))^2 + \Delta m_{h^0}^2$
- extra D-term contributions $\rightarrow M_{\tilde{t}}^2$ diagonal terms increase stop masses

$$M_{\tilde{t}}^2 = \begin{pmatrix} \tilde{m}_{\tilde{t}_L}^2 + m_t^2 + \Delta_{\tilde{t}_L}^{U_1} + Q_{\tilde{t}_L} d' & y_t(A_t^* v_u - \mu_{eff} v_d) \\ y_t(A_t v_u - \mu_{eff}^* v_d) & \tilde{m}_{t_R}^2 + m_t^2 + \Delta_{\tilde{t}_R}^{U_1} + Q_{\tilde{t}_R} d' \end{pmatrix}$$

$\Delta_{\tilde{t}_{L,R}}^{U_1}$ $\rightsquigarrow$ MSSM $U(1)$ D-term

$Q_{\tilde{t}_{L,R}} d'$ $\rightsquigarrow$ USSM extra $U(1)'$ D-term

- large radiative corrections without large soft masses $m_{\tilde{t}_L}$ $m_{\tilde{t}_R}$: more natural stop sector than MSSM.
- smaller stop mixing for $m_{h_1} \simeq 125$GeV
- Loop corrections: Coleman-Weinberg effective potential $\rightsquigarrow$ top and stop loops [MSSM: Carena, Quiros, Wagner (1996) USSM: H. Amini(2003)]

Bottom-up approach: pUSSM

- Here: we follow bottom-up, phenomenological approach to quantify these virtues in the light of existing data
- Charge constraints: W_{USSM} invariant under $U(1)'$ gauge symmetry

$$\lambda S H_u H_d \rightarrow \underbrace{Q_{H_u}} + Q_{H_d} + \underbrace{Q_s} = 0 \quad (3)$$

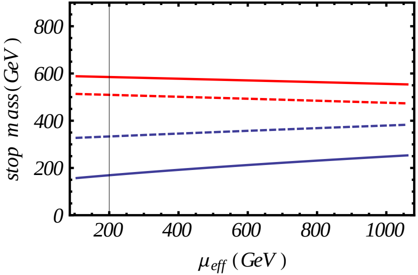
$$y_u \bar{u} Q H_u \rightarrow Q_{H_u} + \underbrace{Q_{\tilde{u}_L}} + Q_{\tilde{u}_R} = 0 \quad (4)$$

$$y_e \bar{e} L H_d \rightarrow Q_{H_d} + Q_{\tilde{e}_L} + Q_{\tilde{e}_R} = 0 \quad (5)$$

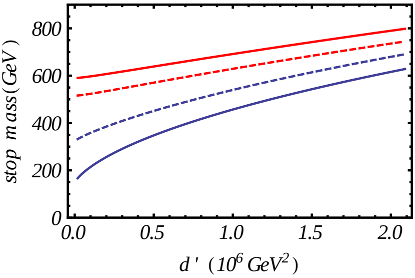
  eq.(3),(4): enter Higgs Sector and Stop masses. eq.(5): less relevant for current study. Charges are free parameters $\Rightarrow$ d.o.f = 3
- Allow generation non-universal charges: general framework $\Rightarrow$ results applicable to a variety of models. Do not impose anomaly cancellation as we allow for generic exotics, though possible to do with non-universal charges [Demier et al 2005]

USSM Advantages/Stop Sector

D-terms: $D_a = \sum_{a,i} g_a(\phi_i^\star T^a \phi) \xrightarrow{U(1)'} D' = \sum_i Q_i|\phi|^2$[1]



(a) MSSM



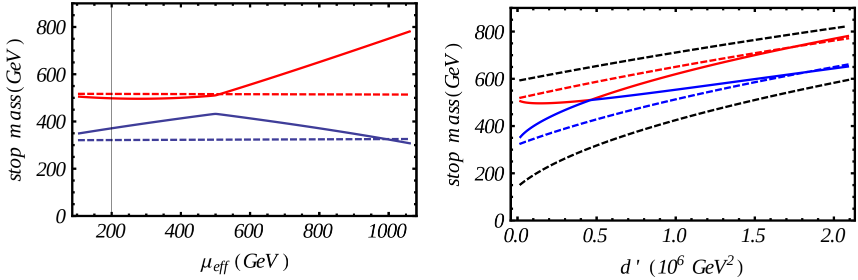
(b) USSM

Figure : Both graphs $\lambda = 0.3, \tan\beta = 4$, $\tilde{m}_{q_3} = \tilde{m}_{t_R} = 0.4$TeV. Solid lines $A_t = 1$TeV (large mixing). Dashed lines $A_t = 0.5$TeV (small mixing).

[1] Note that the charges have absorbed the new gauge coupling

MSSM Vs USSM/Stop Sector

$D' = Q_{\tilde{t}_L} |\tilde{t}_L|^2 + Q_{\tilde{t}_R} |\tilde{t}_R|^2 + d' + \ldots$ where $d' =< D' >= \sum_\phi Q_\phi v_\phi^2$.



(a) MSSM (b) USSM

Figure : $\lambda = 0.3,\ A_t = 0.5,\ m_{\tilde{t}_L} = m_{\tilde{t}_R} = 0.4$TeV. Solid: $\tan\beta = 1$ Dashed: $\tan\beta = 50$. Black lines correspond to large mixing $A_t = 1$TeV for $\tan\beta = 50$.

MSSM Vs USSM/Higgs Sector

- Extra D-term (& F-terms) contributions to V_{Higgs} at tree level $\Rightarrow$ boosted tree level m_{h_1} $\Rightarrow$ no need for large loops.

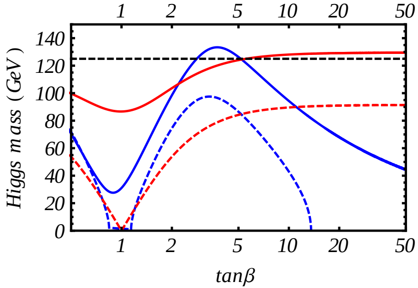
$$M_H^2 =$$

$$\begin{pmatrix} \left[\frac{G^2}{4} + Q_{H_d}^2 g_{1'}{}^2\right] v_d^2 + \frac{h_s A_s}{\sqrt{2}} \frac{v_u v_s}{v_d} & -\left[\frac{G^2}{4} - h_s^2 - Q_{H_d} Q_{H_u} g_{1'}{}^2\right] v_d v_u - \frac{h_s A_s}{\sqrt{2}} v_s & \left[h_s^2 + Q_{H_d} Q_S g_{1'}{}^2\right] v_d v_s - \frac{h_s A_s}{\sqrt{2}} v_u \\ -\left[\frac{G^2}{4} - h_s^2 - Q_{H_d} Q_{H_u} g_{1'}{}^2\right] v_d v_u - \frac{h_s A_s}{\sqrt{2}} v_s & \left[\frac{G^2}{4} + Q_{H_u}^2 g_{1'}{}^2\right] v_u^2 + \frac{h_s A_s}{\sqrt{2}} \frac{v_d v_s}{v_u}, & \left[h_s^2 + Q_{H_u} Q_S g_{1'}{}^2\right] v_u v_s - \frac{h_s A_s}{\sqrt{2}} v_d, \\ \left[h_s^2 + Q_{H_d} Q_S g_{1'}{}^2\right] v_d v_s - \frac{h_s A_s}{\sqrt{2}} v_u & \left[h_s^2 + Q_{H_u} Q_S g_{1'}{}^2\right] v_u v_s - \frac{h_s A_s}{\sqrt{2}} v_d, & Q_S^2 g_{1'}{}^2 v_s^2 + \frac{h_s A_s}{\sqrt{2}} \frac{v_d v_u}{v_s}. \end{pmatrix}$$

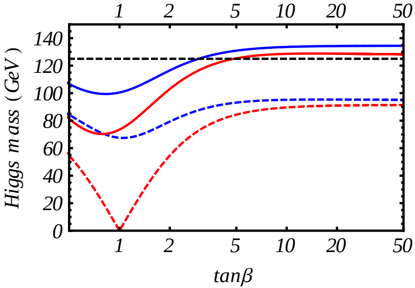
- USSM Sector: 2 complex Higgs doublets + singlet somplex scalar$=$10 d.o.f

  $< H_u >, < H_d >, < S > \rightsquigarrow$
  4 d.o.f = Goldstone bosons "eaten" by $W^{\pm}, Z, Z'$
  6 d.o.f will give 3 CP-even h_1^0, H_2^0, H_3^0
  1 CP-odd Higgs A^0 and 2 charged $H^{\pm}$

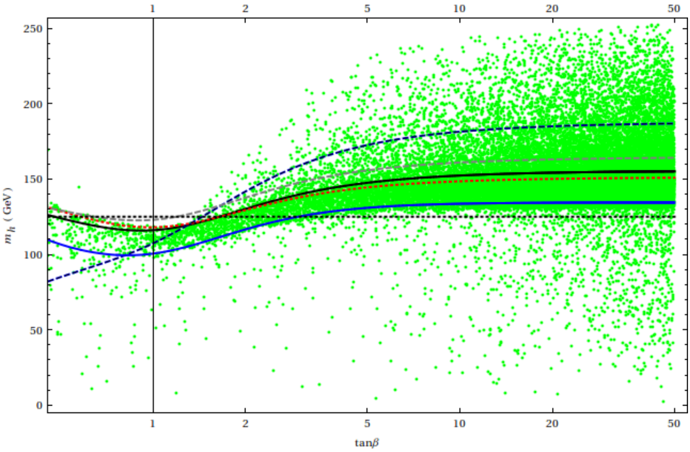
Higgs Sector: U Vs MSSM



(a) 1-loop MSSM (Red) and USSM (Blue). Dashed = Tree level. $m_{\tilde{t}_L} = m_{\tilde{t}_R} = 1TeV,\ v_s = 0.5TeV, \lambda = 0.5$



(b) $m_{\tilde{t}_L} = m_{\tilde{t}_R} = 0.4TeV,\ v_s = 2.5TeV,\ \lambda = 0.3$. 1-loop MSSM (Red) and USSM (Blue). Dashed = tree level



- (Preliminary) Scatter plot for various charges and light soft masses $m_{\tilde{t}_L} = m_{\tilde{t}_R} = 0.4TeV,\ v_s = 2.5$TeV . In this plot charges are varied. Black horizontal corresponds to $m_h = 125$GeV. Everything else fixed. Blue thick: E_6 charges. $Q_{H_u}, Q_s, Q_{\tilde{t}_L}$ Black:(-2,3,1) Blue Dashed:(-2,1,1) Red Dashed:(2,-4,-1) Black Dashed:(2,-1,-1) Gray Dashed:(-4,5,1)

More "Natural" stop spectrum

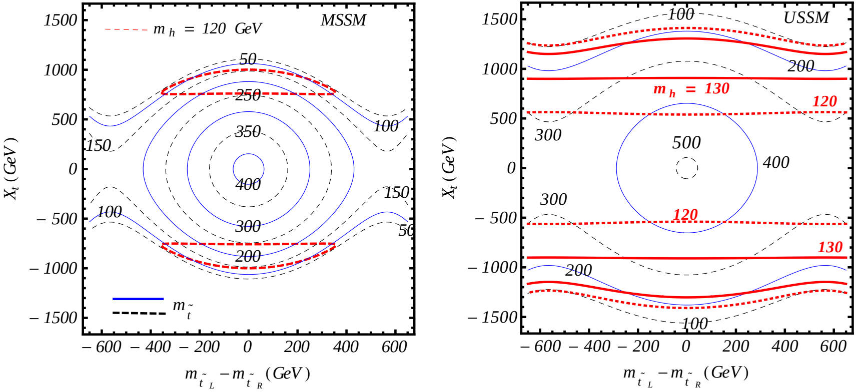
- $-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2 + \Sigma(Q_i, v_i, \tan\beta)$ [Athron, King (2013)]
- $\delta m_{H_u}^2$ should not be too large for a natural theory.
- Fine tuning: $\Delta = \frac{\delta m_{H_u}^2}{m_{H_u}^2} \xrightarrow{M_h^2 = -2m_{H_u}} = \frac{2\delta m_{H_u}^2}{M_h^2}$ [Kitano and Nomura (2007)]
- $m_{H_u}^2 \rightsquigarrow$ receives large loop corrections from stop and top loops
  [RGE's: P. Athron, S. F. King et al(2009)]

$$\delta m_{H_u}^2|_{stops} = -\underbrace{\frac{3}{8\pi^2} y_t^2 (m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t^2|) \log(\frac{\Lambda}{TeV})}_{MSSM} - \underbrace{\frac{\lambda^2}{8\pi} m_s^2 \log(\frac{\Lambda}{TeV})}_{USSM} + \dots$$

Fine tuning in U(1) extended models $\Rightarrow$[M. Cvetič et al(1998)/R. Barbieri et al (2006)]

Stop Sector Fine-Tuning

- Fix fine-tuning from stop sector [M. Papucci et al 2011]
  $\Rightarrow \; m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} = const$
- $X_t = A_t - \mu_{eff} \cot\beta$ needs to be not very large
- what about the Higgs mass?



Extended Neutralino Sector

- Extra gaugino $(\tilde{B}',\ \tilde{S})$ mixes with the MSSM gaugino's $\Rightarrow$ # 6 $\tilde{\chi}_i^0$
- Extra 2×2 matrix for $M_1' \gg v_s$ "see-saw" like mechanism $\rightsquigarrow$ 1 massive $\tilde{\chi}_6^0$ and 1 light $\tilde{\chi}^0$: LSP candidate.

B. de Carlos, Espinosa (1997), Choi et al(2006), Barger et al(2005)

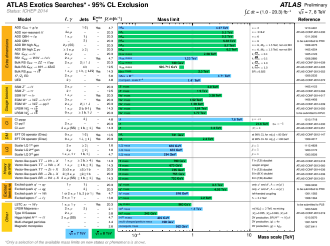
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & 0 & 0 \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & 0 & 0 \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu_{\text{eff}} & -\frac{\lambda v_u}{\sqrt{2}} & Q_{H_d}g_1'v_d \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu_{\text{eff}} & 0 & -\frac{\lambda v_d}{\sqrt{2}} & Q_{H_u}g_1'v_u \\ 0 & 0 & -\frac{\lambda v_u}{\sqrt{2}} & -\frac{\lambda v_d}{\sqrt{2}} & 0 & Q_S g_1' v_s \\ 0 & 0 & Q_{H_d}g_1'v_d & Q_{H_u}g_1'v_u & Q_S g_1' v_s & M_1' \end{pmatrix}$$

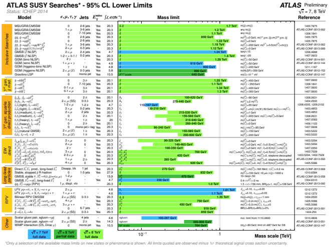
- In our study: $M_1,\ M_2,\ M_3\ \Rightarrow$ free param. (no constraints from gaugino unification.)

$\Rightarrow$ can have $h_1 \to \tilde{\chi}_1^0\tilde{\chi}_1^0,\ \tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_1^0\tilde{\chi}_3^0,\ \ldots$

Constraints

- Experimental Constraints:
  - Higgs discovery: $m_h \sim 125$GeV
  - Stop searches: $\tilde{t}_1 > 400 - 600$GeV
  - Exotic Z' searches: $M_{Z'} > 2.5$TeV
  - Charged Higgs searches $M_{H^\pm} > 140$GeV
  - EW constraints $\sin\theta_{z-z'} < \mathcal{O}(10^{-3})$
  - $\Gamma(Z \to \text{inv}) < 3$MeV
  - $\Gamma(h \to \text{inv}) < 1.5$MeV since $\Gamma_{h_{SM}} \simeq 4.15$MeV
  - Chargino $m_{\tilde{\chi}^\pm} > 104$GeV



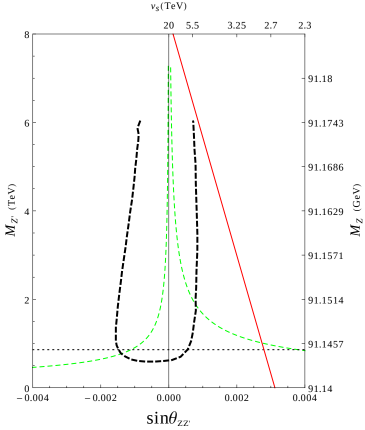


$Z - Z'$ mixing $\Leftarrow$ kinetic mixing & mass term. Kinetic: eliminated by field redefinition $\Rightarrow$ absorbed by $U(1)'$ charges (generic charges take into account kinetic mixing)

$$M^2_{ZZ'} = \begin{pmatrix} m^2_Z & \Delta^2_Z \\ \Delta^2_Z & m^2_{Z'} \end{pmatrix}$$

$$m^2_Z = \tfrac{1}{4} g^2_Z v^2$$
$$m^2_{Z'} = v^2 \left(Q^2_{H_d} c^2_\beta + Q^2_{H_u} s^2_\beta\right) + 2 Q^2_S v^2_S$$
$$\Delta^2_Z = \tfrac{1}{2} g_Z v^2 \left(Q_{H_u} s^2_\beta - Q_{H_d} c^2_\beta\right)$$
$$\tan 2\theta_{ZZ'} = -2\,\Delta^2_Z / (m^2_{Z'} - m^2_Z)$$

- $\Rightarrow$ need for large singlet vev.



Black curve: [Erler et al (2009)]. $\tan\beta = 4$

E_6 model. (Preliminary)

- Extra singlet extensions?$\Rightarrow$ relax this requirement

Conclusions

- U(1) SUSY gauge extensions well motivated theoretically and phenomenologically.
- Extended sector increases the mass of the Higgs making it a more viable scenario in light of the Higgs discovery.
- In particular D-term contributions to stops and tree level mass of the Higgs might improve naturalness.
- Interesting Higgs phenomenology. There is still room for invisible Higgs decays.
- A very light singlino is possible in this scenario.
- Interesting to look for viable points of the parameter space in case we are missing something with more "strict" UV complete models