Geometrical Hierarchies in Classical Supergravity

[H. L. and F. Zwirner, arXiv:1403.4942]

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Outline

- Motivations
- A no-scale model with MSSM-like
  Higgs and gauge sector
- Discussions on the results
- Including MSSM matter fields (top/stop)
- Variations of the model
- Conclusions and Outlook

Motivations

- SM-like Higgs boson discovered in LHC-8 at 125.6 GeV
  - ▶ Expectations for new physics not substantiated so far
- Origin of the Higgs and naturalness?
  - Challenge to naturalness of EW breaking (e.g. MSSM)
  - Keep SUSY and broaden the spectrum of SUSY models
    - ▶ Give up naturalness: split/mini-split/high-scale SUSY
    - ▶ Insist on naturalness: RPV, Dirac gauginos,...
    - ▶ Are there any other possibilities in SUGRA?
  - Final verdict on EW naturalness after LHC-14

No-scale SUGRA Models

- Original no-scale model *[Cremmer et al., 1983]*
  - Positive-semi-definite classical potential
  - *Pure F-SUSY breaking* with vanishing vacuum energy
  - Gravitino mass slides along a *complex* flat direction
- A New class of no-scale models *[See Prof. F. Zwirner's talk]*
  - Simple hidden sector with *F- and D- breaking* (just a chiral and a $\widetilde{U(1)}$ vector supermultiplet)
  - *A single real* flat direction after SUSY and $\widetilde{U(1)}$ breaking

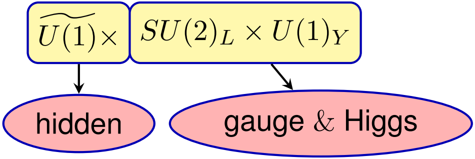
Towards Realistic Models with F- and D-breaking

[H.L.-F. Zwirner, 2014]

- No-scale model with MSSM-like gauge $\&$ Higgs sector
- SUSY and $SU(2)_L \times U(1)_Y$ breaking with $\langle V \rangle = 0$
- Two independent real flat directions for $m_{W,Z}$ $\&$ $m_{3/2}$
- Two massless scalars: SM-singlet t $+$ SM Higgs h
- Extra Higgses/Higgsinos/Gauginos with masses $\sim m_{3/2}$

Towards Realistic Models with F- & D- breaking

- Gauge symmetry:



- Chiral and vector multiplets

$$\text{Chiral} \Rightarrow \begin{cases} \mathcal{T} \sim (T,\ \widetilde{T}) & \widetilde{U(1)} \\ \mathcal{H}_1 \sim (H_1, \widetilde{H}_1) & (\mathbf{2}, +\frac{1}{2}) \\ \mathcal{H}_2 \sim (H_2, \widetilde{H}_2) & (\mathbf{2}, -\frac{1}{2}) \end{cases}$$

$$\text{Vector} \Rightarrow \begin{cases} (\widetilde{V}, V) & \widetilde{U(1)} \\ (\widetilde{W}^I, W^I) & SU(2)_L \\ (\widetilde{B}, B) & U(1)_Y \end{cases}$$

Towards Realistic Models with F- & D- breaking

Kahler potential, superpotential & gauge kinetic functions

- Kahler potential (real & gauge invariant):
  $SO(2,5)/[SO(2) \times SO(5)]$

$$K = -\log Y, \;\; Y = \left[(T+\overline{T})^2 - |H_1^0 - \overline{H_2^0}|^2 - |H_1^- + \overline{H_2^+}|^2\right]$$

- Superpotential (holomorphic): $W = W_0 = \sqrt{2}\,\widetilde{g}$

- Gauge kinetic functions (holomorphic):

$$\begin{cases} \widetilde{f} = 1/\widetilde{g}^2 & \widetilde{U(1)} \\ f_Y = a_Y + b_Y\, T & U(1)_Y \\ f_L = a_L + b_L\, T & SU(2)_L \end{cases}$$

Towards Realistic Models with F- & D- breaking

Scalar potential: $V = V_G + V_F + V_D = e^{2K}\,(A + B + C + D)$

$$
\begin{aligned}
A &= 2\,\widetilde{g}^2\,(|H_1^0 - \overline{H_2^0}|^2 + |H_1^- + \overline{H_2^+}|^2)\,,\\
B &= \frac{g'^2}{8}\,(|H_1^0|^2 - |H_2^0|^2 + |H_1^-|^2 - |H_2^+|^2)^2\,,\\
C &= \frac{g^2}{2}\,|H_1^0\,\overline{H_1^-} + \overline{H_2^0}\,H_2^+|^2\,,\\
D &= \frac{g^2}{8}\,(|H_1^0|^2 - |H_2^0|^2 - |H_1^-|^2 + |H_2^+|^2)^2
\end{aligned}
$$

Minimized $\langle V\rangle = 0$ with

$$\langle T\rangle = x, \quad \langle H_1^0\rangle = \langle H_2^0\rangle = 2\,x\,v, \quad \langle H_1^-\rangle = \langle H_2^+\rangle = 0$$

Towards Realistic Models with F- & D- breaking

Field decompositions to mass eigenstates with canonical kinetic terms

- Hidden sector: $$T = x\,(1 + t + i\,\tau)$$

  Mass spectrum in hidden sector [Dall'Agata-Zwirner, 2013]

$$m^2_{3/2} = m^2_{1/2} = \widetilde{g}^2/(2x^2), \quad m^2_V = 2m^2_{3/2}, \quad m^2_0 = 0$$

- Observable sector:

$$\begin{aligned} H_1^- &= \sqrt{2}\,x\,(H^- - G^-), \\ H_2^+ &= \sqrt{2}\,x\,(H^+ + G^+), \\ H_1^0 &= 2\,x\left(v + \tfrac{h^0+H^0}{2} + i\,\tfrac{A^0-G^0}{2}\right) \\ H_2^0 &= 2\,x\left(v + \tfrac{h^0-H^0}{2} + i\,\tfrac{A^0+G^0}{2}\right) \end{aligned}$$

Towards Realistic Models with F- & D- breaking

Classical mass spectrum in observable sector

- Gauge bosons with $\overline{g}^2 \equiv \langle 1/Re\, f_Y \rangle$ & $\overline{g}'^2 \equiv \langle 1/Re\, f_L \rangle$

$$m_\gamma^2 = 0\,, \quad m_W^2 = \overline{g}^2\, v^2\,, \quad m_Z^2 = (\overline{g}^2 + \overline{g}'^2)\, v^2$$

- Neutral Higgs
  - CP-odd state: $m_A^2 = 2m_{3/2}^2$
  - CP-even states: $m_h^2 = 0 \qquad m_H^2 = m_A^2 + m_Z^2$

  h= SM Higgs

- Charged Higgs $$m_\pm^2 = m_A^2 + m_W^2$$

- In MSSM notation

$$m_1^2 = m_2^2 = -m_3^2 = m_{3/2}^2\,, \quad (\beta = -\alpha = \pi/4)\,.$$

Towards Realistic Models with F- & D- breaking

Classical mass spectrum for Higgsinos and gauginos

- Neutralinos $(\widetilde{B}^0, \widetilde{W}^0, \widetilde{H}_1^0, \widetilde{H}_2^0)$ Charginos $(\widetilde{W}^{\pm}, \widetilde{H}_1^- / \widetilde{H}_2^+)$

$$\begin{pmatrix} M_1 & 0 & -\frac{m_Z s_W}{\sqrt{2}} & \frac{m_Z s_W}{\sqrt{2}} \\ 0 & M_2 & \frac{m_Z c_W}{\sqrt{2}} & -\frac{m_Z c_W}{\sqrt{2}} \\ -\frac{m_Z s_W}{\sqrt{2}} & \frac{m_Z c_W}{\sqrt{2}} & 0 & -\mu \\ \frac{m_Z s_W}{\sqrt{2}} & -\frac{m_Z c_W}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \qquad \begin{pmatrix} M_2 & m_W \\ m_W & \mu \end{pmatrix}$$

$$\mu = m_{3/2}, \quad M_1 = m_{3/2}\,(1 - g'^{\,2}\, a_Y)\,, \quad M_2 = m_{3/2}\,(1 - g^2\, a_L)\,.$$

- Two extreme choices for the gauge kinetic function

$b_Y = b_L = 0$	$a_Y = a_L = 0$
$M_1 = M_2 = 0$	$M_1 = M_2 = m_{3/2}$
$Str\,\mathcal{M}^2 = 0$	$Str\,\mathcal{M}^2 = -8m_{3/2}^2$

Discussions on the results

SUSY and gauge symmetry breaking at the same time

- Reproduce all the MSSM renormalizable interactions (x-dependent masses)
- Operators with $d > 4$ suppressed by M_P^{4-d}
- Goldstino of SUSY breaking: $\widetilde{G} \propto \widetilde{g}\,\widetilde{T} + ix\widetilde{V}$
- Goldstone bosons of $\widetilde{U(1)} \times SU(2)_L \times U(1)_Y \Rightarrow U(1)_{em}$:
  - 1 Goldstone boson for $\widetilde{U(1)}$: τ
  - 1 neutral $+$ 2 charged GBs for G_{SM}: $G^0 \, + \, G^{\pm}$
- Two real flat directions: x and v

Discussions on the results

Two massless scalars as pseudo-Goldstone bosons of some accidental symmetry

- Fixing $\widetilde{U}(1)$ with $\tau = 0$ (unitarity gauge)
- $A^0 = H^0 = H^\pm = 0$ satisfy the classical e. o. m.
- Massless scalar t from scale transformation

$$(T, H_1^0 + \overline{H_2^0}, H_1^- - \overline{H_2^+}) \to \rho\,(T, H_1^0 + \overline{H_2^0}, H_1^- - \overline{H_2^+})$$

Massless scalar h from shift symmetry
[Hebecker-Knochel-Weigand, 2012]

$$H_1^0 + \overline{H_2^0} \to H_1^0 + \overline{H_2^0} + \sigma$$

Including MSSM matter fields: top/stop

- MSSM-like matter superfields included in the model

superfields	gauge symmetry	components
$(U, D)^T$	$(3, 2, +1/6)$	$U = (t, \widetilde{t}\,); \ldots$
U^c	$(\overline{3}, 1, -2/3)$	$U^c = (t^c, \widetilde{t^c})$

- The top-Dirac spinor $\psi \equiv (t, \overline{t^c}\,)^T$
- Extend Kahler potential: $\Delta K = |U|^2\, Y^{\lambda_L} + |U^c|^2\, Y^{\lambda_R} + \ldots$
- Extend superpotential: $\Delta W = y_t\, U\, U^c\, H_2^0 + \ldots$
- Top effective Lagrangian

$$
\begin{aligned}
\mathscr{L}_{top} \quad = \quad & -(2x)^{2\lambda_L} \left(\partial_\mu \widetilde{t}\, \partial^\mu \widetilde{t}^* \;+\; i t\, \sigma^\mu \partial_\mu \bar{t}\right) \\
& -(2x)^{2\lambda_R} \left(\, \partial_\mu \widetilde{t^c}\, \partial^\mu\, (\widetilde{t^c})^* \;+\; i t^c\, \sigma^\mu \partial_\mu\, \overline{t^c}\right) \\
& -(2x)^{-2} \left(\partial_\mu\, H_2^0\, \partial^\mu\, H_2^{0*} \;-\; i\widetilde{H_2^0}\, \sigma^\mu \partial_\mu\, \overline{\widetilde{H_2^0}}\right) \\
& -(2x)^{-1} \left(\, y_t\, H_2^0\, t\, t^c + h.\,c.\right) + \ldots
\end{aligned}
$$

Including MSSM matter fields: top/stop

- Top quark mass from the above effective Lagrangian

$$M_t = y_t\, v\, (2\,x)^{-\lambda_L - \lambda_R}$$

In MSSM notation (canonical kinetic terms)

$$\widehat{y}_t = (2\,x)^{-(\lambda_R+\lambda_L)}\, y_t$$

- Stop squared mass
  - If $\lambda_L + \lambda_R = -1/2$, no tree-level SUSY-breaking masses

$$(M_0^2)_{LR} = \boxed{[1 + 2(\lambda_L + \lambda_R)]\, M_t\, m_{3/2}} = (M_0^2)_{RL}$$

  -

$$(M_0^2)_{LL} = M_t^2 \qquad (M_0^2)_{RR} = M_t^2$$

$$\langle \frac{\partial^2 V_D}{\partial \widetilde{t}^{(c)*} \partial \widetilde{t}^{(c)}} \rangle \langle K^{-1}_{\overline{U}U} \rangle = -2\,\lambda_{L/R}\, m^2_{3/2} = -\langle \frac{\partial^2 V_F}{\partial \widetilde{t}^{(c)*} \partial \widetilde{t}^{(c)}} \rangle \langle K^{-1}_{\overline{U}U} \rangle + M_t^2$$

Variations

Variations of the model

- e.g. Kahler potential with the foliowing structure

$$\widehat{K} = -3\,\log(T+\overline{T}) + (T+\overline{T})^{-n}\,(|H_1^0 - \overline{H_2^0}|^2 + |H_1^- + \overline{H_2^+}|^2)$$

- Weaker connection with string compactifications and N>1
- Spectrum as before except

$$m_A^2 = 2\,(n-2)\,(n-1)\,m_{3/2}^2\,, \qquad \mu = (1-n)\,m_{3/2}$$

- May compute the entries of the stop mass matrix as well
  Extend variation Kahler potential with
  $\Delta\widehat{K} = |U|^2\,(T+\overline{T})^{\lambda_L} + |U^c|^2\,(T+\overline{T})^{\lambda_R}$

$$\begin{aligned}(M_0^2)_{LR} &= [2+\lambda_L+\lambda_R]\,M_t\,m_{3/2} = (M_0^2)_{RL}\\ (M_0^2)_{LL} &= (1+\lambda_L)\,m_{3/2}^2 + M_t^2\\ (M_0^2)_{RR} &= (1+\lambda_R)\,m_{3/2}^2 + M_t^2\end{aligned}$$

Conclusions and Outlook

- A realistic no-scale model with hidden/Higgs/gauge sectors with $\widetilde{U(1)} \times SU(2)_L \times U(1)_Y$ gauge group
  - Breaking SUSY and gauge group on flat background
  - 2 real flat directions (x, v) at the classical level
  - Massless SM Higgs h and SM-singlet t
  - Higgsino, gaugino $\&$ (H, A, $H^{\pm}$) masses $\sim m_{3/2}$
- Variations of the original model studied
- Should now make some model-building choices and compute quantum corrections to discuss the hierarchies

$$M_P \gg m_{3/2} > (\gg ?) M_V \sim m_h \gg \Lambda_{cosm}$$

Thank you!