Splitting supersymmetry in no-scale models

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Outline

- Motivations
- General Introduction
  - Basics of $N = 1$, $D = 4$ Supergravity
  - The Simplest No-Scale Model with Pure F-breaking
  - No-Scale Model with F- $\&$ D- breaking
- Towards realistic models with F- $\&$ D- breaking
  - A model with MSSM-like Higgs and gauge sector
  - Classical mass spectrum
- Temporary 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

    $\Rightarrow$ simplest SUSY models under stress
  - Final verdict on EW naturalness after LHC-14

Motivations

- Naturalness principle:
  - Based on assumptions of lack of conspiracies between different scales & rooted in effective theories
  - Gave right hints in the past for new physics discovery
  - Seems to fail for the vacuum energy density
- SUSY too good to be wasted by nature
  - Give up naturalness?
  - Look for some additional ingredients to restore naturalness (with gravity?) e.g. try harder with no-scale supergravity?

Traditional No-scale Models

- Positive-semi-definite classical potential
  Pure F-term SUSY breaking with vanishing vacuum energy
  Gravitino mass slides along a complex flat direction
- $m_{W,Z} \sim m_{3/2} \ll M_P$ by log quantum correction
  Unsolved vacuum energy problem at quantum level
  Difficult to split $m_{W,Z} < m_{3/2} \ll M_P$
  (see however an attempt by Barbieri-Strumia, 2000)

A New Class of (classical) No-scale Models

- Very 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
  [G. Dall'Agata $\&$ F. Zwirner, arXiv:1308.5685, PRL]
- No-scale model with MSSM gauge $\&$ Higgs sector
  SUSY and gauge symmetry breaking with $\langle V \rangle = 0$
  Two independent real flat directions for $m_{W,Z}$ $\&$ $m_{3/2}$
  Massless real SM-singlet and SM-like Higgs boson
  Extra Higgses/Higgsinos/Gauginos with masses $\sim m_{3/2}$
  [H.L. $\&$ F. Zwirner, in slow progress, to appear]

Waiting to include MSSM matter fields
and to compute quantum corrections . . .

$N = 1$, $D = 4$ Supergravity

- Chiral Mutltiplets: $\Phi^i \sim (\phi^i, \psi^i)$
  Vector Mutltiplets: $U^a \sim (\lambda^a, A^a_\mu)$
  Gravitational Multiplet: $(g_{\mu\nu}, \psi_\mu)$

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- Specified by 3 ingredients:
  - Gauge invariant function: $G = K + \log |W|^2$
    K: Kahler potential W: Holomorphic superpotential
  - Holomorphic gauge kinetic function: f_{ab}
  - Holomorphic Killing vectors: X_a^i
    gauge transformation $\&$ covariant derivative
    $$\delta\phi^i = X_a^i \epsilon^a, \quad D_\mu \phi^i = \partial_\mu \phi^i - A_\mu^a X_a^i$$
    with realizations

$$X_a^i = i q_a^i \qquad \textit{Axionic } U(1)$$
$$X_a^i = i (T_a)_k^i \phi^k \qquad \textit{Linear Gauge Symmetries}$$

$N = 1$, $D = 4$ Supergravity

- Scalar potential: controlled by auxiliary fields of the gravitational, chiral and vector multiplets:

$$V = V_G + V_F + V_D$$

  - Gravitational

$$V_G = -3e^G \leq 0$$

  - Chiral

$$V_F = e^G G^{k\bar{l}} G_k G_{\bar{l}} \geq 0$$

  - Vector

$$V_D = \frac{[(Ref)^{-1}]^{ab}}{2} D_a D_b \geq 0$$

With $G_i = \partial G / \partial \phi^i$, $D_a = i G_i X_a^i$ and $G^{k\bar{l}} G_{\bar{l}m} = \delta_m^k$

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- $M_{3/2}^2 = e^G$ (field-dependent gravitino mass)
- Goldstino for SUSY breaking

$$\eta = e^{G/2} G_i \psi^i - \frac{i}{\sqrt{2}} D_a \lambda^a$$

The Simplest No-Scale Model with Pure F-breaking

[Cremmer-Ferrara-Kounnas-Nanopoulos, 1983]

- One chiral multiplet $\mathcal{T} \sim (T, \widetilde{T})$ with

$$K = -3\log(T + \overline{T}), \quad W = W_0$$

$$V = (G^T G_T - 3)e^G = 0$$

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- In the simplest no-scale model
  - SUSY breaking with vanishing vacuum energy
  - F-term: $F_T = e^{G/2} G_T \neq 0$
  - Goldstino $\widetilde{T}$ absorbed by gravitino, with $M_{3/2}^2 = |W_0|^2/(8t^3)$
  - $T = t + i\tau (t > 0)$: a classical complex flat direction

No-Scale Model with F- $\&$ D- breaking

[G. Dall'Agata-F. Zwirner, 2013]

- Supermultiplets and gauge symmetry

$$\text{Axionic } \widetilde{U(1)} \Rightarrow \begin{cases} \mathcal{T} \sim (T, \widetilde{T}) & \text{Chiral Multiplet} \\ U \sim (\lambda, A_\mu) & \text{Vector Multiplet} \end{cases}$$

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- Kahler potential, superpotential and gauge kinetic function

$$K = -2\log(T + \overline{T}) \quad W = W_0 \quad f = 1/\widetilde{g}^2$$

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$$K = -2\log(T + \overline{T}) \quad W = W_0 \quad f = 1/\widetilde{g}^2$$

- Contributions to scalar potential (Killing vector $X^T = iq$)

$$V_G = -\frac{3|W_0|^2}{4t^2} \quad V_F = \frac{|W_0|^2}{2t^2} \quad V_D = \frac{\widetilde{g}^2 q^2}{2t^2}$$

No-Scale Model with F- $\&$ D- breaking

[G. Dall'Agata-F. Zwirner, 2013]

- $|W_0| = \sqrt{2}\,\widetilde{g}\,|q| \quad \Rightarrow \quad V = V_G + V_F + V_D = 0$

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- $|W_0| = \sqrt{2}\,\widetilde{g}\,|q|$ not a fine-tuning: truncation of $N=2$ SUGRA with single gauge coupling constant

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- $|W_0| = \sqrt{2}\,\widetilde{g}\,|q|$ not a fine-tuning: truncation of $N = 2$ SUGRA with single gauge coupling constant
- Goldstino of SUSY breaking: $\widetilde{G} \propto \underbrace{\widetilde{g}\,\widetilde{T} + it\lambda}$
  Single Goldstone boson of axionic $\widetilde{U(1)}$: τ
  A real flat direction: t

No-Scale Model with F- & D- breaking

[G. Dall'Agata-F. Zwirner, 2013]

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- $|W_0| = \sqrt{2}\,\widetilde{g}\,|q|$ not a fine-tuning: truncation of $N = 2$ SUGRA with single gauge coupling constant
- Goldstino of SUSY breaking: $\widetilde{G} \propto \widetilde{g}\,\widetilde{T} + it\lambda$
  Single Goldstone boson of gauged axionic $\widetilde{U(1)}$: τ
  A single real flat direction: t
- Mass spectrum

$$M^2_{3/2} = \frac{\widetilde{g}^2 q^2}{2t^2}, \quad M^2_1 = 2M^2_{3/2}, \quad M^2_{1/2} = M^2_{3/2}$$

with $Str\mathcal{M}^2 = (-4 + 2 \times 3 - 2) = 0$

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

Towards a realistic model: gauge and Higgs sector

- Gauge symmetry: $\widetilde{U(1)} \times SU(2)_L \times U(1)_Y$

  $\widetilde{U(1)}$: for hidden sector

  $SU(2)_L \times U(1)_Y$: for the SM

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  $\widetilde{U(1)}$: for hidden sector
  $SU(2)_L \times U(1)_Y$: for the SM
- Chiral and vector multiplets

$$\text{Chiral} \Rightarrow \begin{cases} \mathcal{T}(T,\ \widetilde{T}) & \widetilde{U(1)} \\ \mathcal{H}_u(H_u, \widetilde{H}_u) & (\mathbf{2},\ +\frac{1}{2}) \\ \mathcal{H}_d(H_d, \widetilde{H}_d) & (\mathbf{2},\ -\frac{1}{2}) \end{cases}$$

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

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

Kahler potential, superpotential & gauge kinetic functions

- Kahler potential (real and gauge invariant):
  $K = -\log Y \quad Y = \left[(T+\overline{T})^2 - |H_u^0 + \overline{H}_d^0|^2 - |H_u^+ - \overline{H}_d^-|^2\right]$
  SO(2,5)/[SO(2)xSO(5)] manifold (truncation of N>1)
- Superpotential (holomorphic): $W = W_0 = \sqrt{2}\,\widetilde{g}\,|q|$
- Gauge kinetic functions (holomorphic):

$$\begin{cases} f_{\widetilde{U(1)}} = 1/\widetilde{g}^2 & \widetilde{U(1)} \\ f_{U(1)} = 5\,T/3 & U(1)_Y \text{ [GUT normalization]} \\ f_{SU(2)} = \delta_{ab}\,T & SU(2)_L \end{cases}$$

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

- Scalar potential

$$
\begin{aligned}
V &= V_G + V_F + V_D \\
&= \frac{|W_0|^2}{Y^2}(A+B) \\
&\quad + \frac{1}{10tY^2}\left[\frac{1}{2}(C-D)^2 + \frac{3}{2}(C^2+D^2) + 5|E|^2\right] \geq 0
\end{aligned}
$$

$$A = |H_d^0 + \overline{H}_u^0|^2 \qquad B = |H_d^- - \overline{H}_u^+|^2$$

$$C = |H_u^+|^2 - |H_d^-|^2 \qquad D = |H_u^0|^2 - |H_d^0|^2$$

$$E = H_d^0 \overline{H}_u^- + \overline{H}_u^0 H_u^+$$

- Minimized at $\langle V \rangle = 0$ for

$$\langle H_u^0 \rangle = -\langle H_d^0 \rangle = v \quad \langle H_u^+ \rangle = \langle H_d^- \rangle = 0$$

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

SUSY and internal symmetry breaking at the same time

- Goldstino of SUSY breaking: $\widetilde{G} \propto \widetilde{g}\,\widetilde{T} + it\lambda$
- 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 in T
  - 1 neutral GB for G_{SM}: $ImH_u^0 + ImH_d^0$
  - 2 charged GBs for G_{SM}: $\overline{H_u^+} + H_d^-$ & $H_u^+ + \overline{H_d^-}$
- Two real flat directions: t and v
  Gravitino mass: $M_{3/2}^2 = \widetilde{g}^2 q^2/(2t^2)$
  Weak boson masses: $M_W^2 = v^2/(4t^3) = 5M_Z^2/8$
- Hidden sector: the same spectrum as before

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

Classical mass spectrum in Higgs sector

- Neutral Higgs
  - CP-even states: real parts of (H_u^0, H_d^0)

$$m_h^2 = 0 \qquad m_H^2 = 2M_{3/2}^2 + M_Z^2 \text{ with}$$
$$h = \frac{1}{\sqrt{2}}(ReH_1^0 - ReH_2^0)$$
$$H = \frac{1}{\sqrt{2}}(ReH_1^0 + ReH_2^0)$$

The field related to $m_h = 0$: SM-like Higgs

  - CP-odd state: imaginary parts of (H_u^0, H_d^0)

$$m_A^2 = 2M_{3/2}^2 \text{ with } A = \frac{1}{\sqrt{2}}(ImH_1^0 - ImH_2^0)$$

- Charged Higgs

$$m_\pm^2 = 2M_{3/2}^2 + M_W^2 \text{ with } H_+ = \frac{1}{\sqrt{2}}(H_1^- - \overline{H}_2^+) \; H_- = H_+^*$$

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

Classical mass spectrum for Higgsinos and gauginos

- Neutralinos: $(\widetilde{H}_u^0, \widetilde{H}_d^0, \widetilde{W}^0, \widetilde{B}^0)$

$$m_1^2 = m_2^2 = M_{3/2}^2$$
$$m_3^2 = (M_{3/2} + M_Z)^2$$
$$m_4^2 = (M_{3/2} - M_Z)^2$$

- Charginos: $(\widetilde{H}_u^+ / \widetilde{H}_d^-, \widetilde{W}^\pm)$

$$m_1^2 = (M_{3/2} + M_W)^2$$
$$m_2^2 = (M_{3/2} - M_W)^2$$

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 (t, v) at the classical level
  - Gravitino mass $\sim 1/t$
    Weak boson masses $\sim v/t^{3/2}$
  - Massless SM-like Higgs h
  - Higgsino, gaugino $\&$ (H, A, $H^{\pm}$) masses $\sim M_{3/2}$
- Should include matter fields, expecting squark and slepton masses $\sim M_{3/2}$ for suitable Kahler potential
- Should compute quantum corrections to discuss (parameterizing incalculable ones) the hierarchies

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

Thank you!

Towards Realistic Models with F- & D- breaking

[H.L.-F. Zwirner, in slow progress]

An attempt on matter fields including model: top/stop only

- Extend Kahler potential with $\Delta K = |\widetilde{t}_L|^2 Y^{\lambda_L} + |\widetilde{t}^*_R|^2 Y^{\lambda_R}$ with $Y = \left[(T+\overline{T})^2 - |H_u^0 + \overline{H}_d^0|^2 - |H_u^+ - \overline{H}_d^-|^2\right]$
- Extend superpotential as MSSM $\Delta W = y_t \widetilde{t}_L \widetilde{t}^*_R H_u^0$
- Expecting stops with masses $\sim M_{3/2}$, however, in this case

$$(M_0^2)_{\widetilde{t}_L} = \frac{2(|W_0|^2 - 2\widetilde{g}^2 q^2)\lambda_L}{4t^2} M_{3/2}^2 + O(M_W^2) \sim M_W^2$$

$$(M_0^2)_{\widetilde{t}^*_R} = \frac{2(|W_0|^2 - 2\widetilde{g}^2 q^2)\lambda_R}{4t^2} M_{3/2}^2 + O(M_W^2) \sim M_W^2$$

With $|W_0| = \sqrt{2}\widetilde{g}|q|$, $M_{3/2}^2$ terms vanish (not expected)

$$(M_0^2)_{t_L t^*_R} \sim M_{3/2} M_W$$

- Other Kahler potential & gauge kinetic function forms work in progress