Hierarchy problems in supersymmetry after LHC-8

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Based on

Gianguido Dall'Agata and F.Z.,
A new class of N=1 no-scale supergravity models
PRL 111 (2013) 251601 [arXiv:1308.5685]

Hui Luo and F.Z.,
Geometrical hierarchies in classical supergravity
arXiv:1403.4942

and work in progress

Motivations

Message from experiment (LHC-8 and more)

SM-like Higgs boson h found at 125-6 GeV: constraints not only from LHC Higgs data

but also from EWPT: e.g. under reasonable assumptions (for susy) hVV SM-like at ~2%

Direct and indirect bounds on extra Higgs bosons and susy particles pushed forward (with flavour physics also a major player)

Generic SUSY hardly restores naturalness:
simplest SUSY models now under stress to reproduce W,Z,h properties w/o fine-tuning
Further experimental scrutiny at LHC-14

A not so uncommon point of view:

SUSY too good idea to be wasted by Nature (gen. symmetry of RQFT, superstrings, etc)

Still some phenomenological appeal:
dark matter? gauge coupling unification?

➔ Broaden the spectrum of susy models

Within susy, two main approaches at present:

1. Insist on (quasi-) naturalness

Some new twists w.r.t. MSSM (RPV, singlet Higgs, Dirac gauginos, etc): tipically still light sparticles at the verge of being ruled out by the LHC-14 searches

2. Give up naturalness

Forget about naturalness, try to preserve at least dark matter and gauge coupling unification

(Mini-) split supersymmetry

Question:

Is this bifurcation really unavoidable? Can we make naturalness compatible with some little hierarchies?

No convincing example found so far

My own theoretical bias:

Might need some additional ingredient to solve the SM naturalness problem

Naturalness different in the presence of gravity (there is also the vacuum energy problem)

↓

Look for special incarnations of supergravity that might still solve the naturalness problem complying with present experimental bounds

One more reason to look at supergravity again:

(large-field, single-field) inflation

interplay of sgoldstinos, susy Higgses & inflaton

Basics of N=1, D=4 supergravity

Multiplets:

Gravitational	Vector	Chiral
$(g_{\mu\nu}, \psi_\mu)$	(λ^a, A^a_μ)	(z^i, ψ^i)

Ingredients:

$$G(z,\bar{z}) = K(z,\bar{z}) + \log|W(z)|^2$$

Kahler potential Superpotential

$f_{ab}(z)$ Gauge kinetic funtion

$X^i_a(z)$ Holomorphic Killing vectors defining the gauged symmetries

$$\delta z^i = X^i_a \epsilon^a \quad D_\mu z^i = \partial_\mu z^i - A^a_\mu X^i_a$$

$$X^i_a = i(T_a)^i{}_k z^k \qquad X^i_a = i\, q^i_a$$

Linear symmetry — Axionic shift

The supergravity potential (M_P=1 units):

$$V = V_G + V_F + V_D \quad V_G = -3\, e^G \leq 0$$

$$V_F = e^G G^i G_i \geq 0 \quad V_D = \frac{1}{2} D_a D^a \geq 0$$

$$e^G = m^2_{3/2}$$ Field-dependent gravitino squared mass

$$G_i = \frac{\partial G}{\partial z^i} \quad G^i = G^{i\bar{k}} G_{\bar{k}} \quad D^a = [(Ref)^{-1}]^{ab} D_b$$

$$D_a = i\, G_i\, X^i_a = i\, K_i\, X^i_a$$ (ungauged R-symmetry)

The simplest no-scale model

[Cremmer-Ferrara-Kounnas-Nanopoulos 1983]

1 chiral multiplet $(T, \widetilde{T})$

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

$$G^T G_T = 3 \quad \Rightarrow \quad V = V_G + V_F = 0$$

Classically vanishing vacuum energy

Broken SUSY $\quad Goldstino = \widetilde{T}$

Massless complex scalar (flat direction) $\quad T = t + i\,\tau$

Classically undetermined gravitino mass $\quad m_{3/2}^2 = \dfrac{|W_0|^2}{8\,t^3}$

A new model with F- and D-breaking

[G.Dall'Agata & F.Z. 2013 (30 years later...)]

1 chiral multiplet $(T, \widetilde{T})$

1 vector multiplet (λ, A_μ)

$$K = -2\,\log\left(T + \overline{T}\right) \qquad W = W_0$$

Gauged axionic symmetry $\quad X^T = i$

Constant gauge kinetic function $\quad f = 1/\widetilde{g}^{\,2}$

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

Same t-dependence! Then...

If we choose:

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

SUSY & gauged U(1) broken in flat space

Goldstone boson & fermion: $\tau \quad (\lambda, \widetilde{T})$

1 real flat direction: t

Spectrum (massive states):

$$m_{3/2}^2 = \frac{\widetilde{g}^2}{2\,t^2} \quad m_1^2 = 2\,m_{3/2}^2 \quad m_{1/2}^2 = m_{3/2}^2$$

Curiosity:

$$\mathrm{Str}\mathcal{M}^2 = (-4 + 2 \times 3 - 2)\,m_{3/2}^2 = 0$$

Is $W_0 = \sqrt{2}\,\widetilde{g}$ a fine-tuning?

NO, see e.g. SUGRA/string compactifications…

In the paper we prove that our N=1 model is the only consistent truncation of a gauged N=2 no-scale SUGRA with only 1 coupling g

Multiplets of the N=2 no-scale model:

	Gravitational	1 Vector	1 Hyper
	$(g_{\mu\nu}, \psi_{\mu\,A}, A^0_\mu)$	(A^1_μ, λ^A)	(q^u, ζ^α)
➔N=1	$(g_{\mu\nu}, \psi_\mu)$	(λ, A_μ)	$(T, \widetilde{T})$

Towards new realistic models

[Hui Luo & F.Z. 2014, and work in progress]

Step n.1 (achieved):

Break SUSY & SU(2)xU(1) on Minkowski with only 2 real flat directions (x,v) and (before including quantum corrections)

- Massless SM-like Higgs h
- Vector boson masses $m_{W,Z}$ scaling as v
- Gravitino mass $m_{3/2}$ scaling as 1/x
- Higgsino & $(H,A,H^{\pm})$ masses ~ $m_{3/2}$

Step n.2 (in progress):

Include matter fields and $SU(3)_C$

Study (model-dependent) tree-level sfermion and gaugino masses not necessarily ~ $m_{3/2}$

They could preserve supersymmetry at tree level if eventually $m_{3/2} >> m_{W,Z}$

Compute (log) quantum corrections and study dynamical generation & stability of

$$M_P >> m_{3/2} \sim m_H \geq m_{sq,sl,gau} > m_{W,Z} \sim m_h$$

Some first (classical) results

[Hui Luo & F.Z., 2014]

Consider the following simple model:

$$G = \widetilde{U(1)} \times SU(2)_L \times U(1)_Y$$

T SM-singlet, shifts as before under $\widetilde{U(1)}$

H_1 & H_2 as in MSSM, neutral under $\widetilde{U(1)}$

$$\widetilde{f} = 1/\widetilde{g}^2 \quad f^{(\prime)} = 1/g^{(\prime)\,2} \quad W = \sqrt{2}\,\widetilde{g}$$

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

SO(2,5)/[SO(2)xSO(5)]

[Lopes-Cardoso,Lust,Mohaupt & Antoniadis,Gava,Narain,Taylor 1994]

Positive semidefinite classical potential

↙ t- & Higgs-dependent "volume" factor

$$V_0 = e^{2K}(A + B + C + D) \geq 0$$

$$A = 2\,\widetilde{g}^2\,[H_1^\dagger H_1 + H_2^\dagger H_2 - (H_1 H_2 + \text{h.c.})]$$

↑ MSSM Higgs mass terms ↑

↓ MSSM Higgs quartic couplings ↓

$$B = \frac{g'^2}{8}\,(|H_1^0|^2 - |H_2^0|^2 + |H_1^-|^2 - |H_2^+|^2)^2$$

$$C = \frac{g^2}{2}\,|H_1^0\,\overline{H_1^-} + \overline{H_2^0}\,H_2^+|^2$$

$$D = \frac{g^2}{8}\,(|H_1^0|^2 - |H_2^0|^2 - |H_1^-|^2 + |H_2^+|^2)^2$$

V_0 minimized for $\langle H_1^- \rangle = \langle H_2^+ \rangle = 0$
$\langle T \rangle = x \neq 0$ and $\langle H_1^0 \rangle = \langle H_2^0 \rangle = 2\,x\,v$
2 and only 2 real flat directions

Gauge symmetry and supersymmetry spontaneously broken at generic vacuum (x,v), on flat Minkowski space: $\langle V_0 \rangle = 0$

Spectrum in the hidden sector as before
now also MSSM EW gauge/Higgs sector:

$$m_W^2 = \overline{g}^2\, v^2 \qquad m_Z^2 = (\overline{g}^2 + \overline{g}'^2)\, v^2$$

Classical spectrum in Higgs/Higgsino sector

$m_h^2 = 0$ (the v flat direction!)

$m_A^2 = 2\, m_{3/2}^2$ $\quad$ $m_H^2 = m_A^2 + m_Z^2$

$m_\pm^2 = m_A^2 + m_W^2$ $\quad$ $\mu^2 = m_{3/2}^2$

In MSSM notation, it is a model with

$$m_1^2 = m_2^2 = -m_3^2 = m_{3/2}^2 \qquad \left(\beta = -\alpha = \frac{\pi}{4}\right)$$

Possibly OK, since it is before quantum corrections!

Only source of (global) SUSY-breaking in MSSM is $B=m_{3/2}$ (plus SUSY $\mu=m_{3/2}$ a la Giudice-Masiero)

Curiosity: still $\mathrm{Str}\, M^2\,(x,v) = 0$ (non-trivial in sugra)

Symmetry considerations

Can we interpret t and h as pseudo-Goldstones?

(i) Masslessness of t related to rigid scale transf.

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

(ii) Massleness of h related to rigid shift symmetry

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

[Hebecker-Knochel-Weigand, arXiv:1204.2551]

However, none of the two is a symmetry of V_0
only symmetries of the consistent truncation to
$\tau=0$ and $H=A=H^{\pm}=0$, solving the classical e.o.m.

Open problems to carry out step n.2

(i) Gaugino masses

- Generated at tree level by gauge kinetic function

$$f_Y = a_Y + b_Y T \qquad f_L = a_L + b_L T$$

$$a_Y = a_L = 0 \quad \Rightarrow \quad M_1 = M_2 = m_{3/2}$$

(before for simplicity $b_Y=b_L=0$, leading to $M_1=M_2=0$)

- Generated by quantum corrections (as in anomaly mediation, but here $\mu=B=m_{3/2}$)

- Dirac gauginos? A possibility to explore, given the other features of the model coming from N>1 sugra

(ii) MSSM matter couplings to (H_1, H_2, T)

(➔fermion and sfermion masses, in particular in the top sector, crucial for naturalness)

First attempt (ΔW as in MSSM, a plausible ΔK):

$$\Delta W = y_t\, U\, U^c\, H_2^0 + \ldots \quad \Delta K = (|U|^2 + |U^c|^2 + \ldots)\, Y^\lambda$$

$$Y = (T + \overline{T})^2 - |H_1^0 - \overline{H_2^0}|^2 - |H_1^- + \overline{H_2^+}|^2$$ leads to

$$(M_0^2)_{LL} = (M_0^2)_{RR} = M_t^2 \quad (M_0^2)_{LR} = (1 + 4\lambda)\, M_t\, m_{3/2}$$

➔ no tree-level susy-breaking masses for λ=-1/4

Other possibilities:

(i) ΔW as in MSSM, other possible forms of ΔK

(ii) M_t from mixing with vector-like fermions

We are working on both (i) and (ii)…

Thank you for your attention

Back-up slides

Canonically normalized mass eigenstates

$$H_1^- = \sqrt{2}\, x\, (H^- - G^-)$$

$$H_2^+ = \sqrt{2}\, x\, (H^+ + G^+)$$

$$H_1^0 = 2\, x \left(v + \frac{h^0 + H^0}{2} + i\, \frac{A^0 - G^0}{2} \right)$$

$$H_2^0 = 2\, x \left(v + \frac{h^0 - H^0}{2} + i\, \frac{A^0 + G^0}{2} \right)$$

$$T = x\, (1 + t + i\, \tau)$$

A curious cancellation in the stop masses

Diagonal SUSY-breaking stop masses vanish
cancellation of F-term with U(1)tilde D-term

$(M_0^2)_{LL}$:

$$\langle \frac{\partial^2 V_D}{\partial \widetilde{t}_L^* \partial \widetilde{t}_L} \rangle \langle K^{-1}_{\overline{U}U} \rangle = -2\,\lambda\, m_{3/2}^2 = -\langle \frac{\partial^2 V_F}{\partial \widetilde{t}_L^* \partial \widetilde{t}_L} \rangle \langle K^{-1}_{\overline{U}U} \rangle + M_t^2$$

and similarly for $(M_0^2)_{RR}$