Emilian Dudas

CPhT-Ecole Polytechnique

LOW-SCALE SUPERSYMMETRY BREAKING AND ITS IMPLICATIONS

review and collaborations with

I.Antoniadis, D.Ghilencea, C.Petersson, P.Tziveloglou

e-Prints: arXiv:1006.1662 [hep-ph], arXiv:1211.5609 [hep-ph].

Outline

- Coupling the SUSY breaking sector to the MSSM.
- Non-linear SUSY and its standard realization.
- The formalism of constrained superfields.
- Non-linear MSSM
- Phenomenological implications

- Implications for Higgs masses.
- Contributions to $h \to \gamma\gamma$ and $gg \to h$.
- Invisible decays of Higgs and Z bosons.

- Conclusions and perspectives.

Large literature on SUSY non-linear realizations and low-energy goldstino interactions

- Volkov-Akulov, Ivanov-Kapustinov, Siegel, Samuel-Wess, Clark and Love...

- Casalbuoni, Dominicis, de Curtis, Feruglio, Gatto; Luty, Ponton; Brignole, Feruglio, Zwirner; Brignole,Casas, Espinosa, Navarro; Komargodski and Seiberg

1. Coupling the SUSY breaking sector to the MSSM

Two frameworks one can use in order to parametrize the couplings of the goldstino to MSSM.
Consistency condition : the effective action reproduces the standard MSSM with soft breaking terms in the decoupling limit $f \to \infty$, with fixed values of the soft terms.

i) Couplings of the SUSY breaking sector X to MSSM has manifest SUSY spontaneously at a scale f.

- There is a SUSY messenger sector that mediates interactions between X and the MSSM by integrating out heavy states with a mass scale M. The theory can be weakly coupled if $\sqrt{f}, M \geq$ 50 TeV and strongly coupled for lower values of M. All induced operators are manifestly supersymmetric.

- SUSY is linearly realized; goldstino superfield contains an elementary sgoldstino scalar degree of freedom.

The effective Lagrangian is

$$\mathcal{L} \;=\; \mathcal{L}_X + \mathcal{L}_{MSSM} + \mathcal{L}_{soft} + \mathcal{L}_{hdo} + \mathcal{L}_{corr} \;, \qquad (1)$$

where $\mathcal{L}_X$ and $\mathcal{L}_{MSSM}$ are the SUSY breaking sector

Lagrangian and the supersymmetric part of the MSSM action, respectively, whereas,

$$\mathcal{K}_{soft} = -\frac{c_{XQ}}{M^2}\ (X^\dagger X)(Q^\dagger Q)\ ,$$
$$\mathcal{K}_{hdo} = -\frac{c_{XX}}{M^2}(X^\dagger X)^2 - \frac{c_{QQ}}{M^2}\ (Q^\dagger Q)^2\ , \tag{2}$$
$$\mathcal{K}_{corr} = -\frac{c_u}{M^2} X^\dagger Q U H_1^\dagger - \frac{d_n}{M^{2+2n}}(X^\dagger X)(\bar{D}^2\bar{X})^n(Q^\dagger Q)$$

Soft mass terms are

$$m_Q^2\ =\ c_{XQ}\ \frac{f^2}{M^2}\ . \tag{3}$$

- All the soft terms have the structure $m_{soft} \sim f/M$.

H.d.o $\mathcal{L}_{hdo}$ in (2) are suppressed by appropriate powers of m^2_{soft}/f^2; corrections to MSSM couplings are

$$\delta y_u \sim \frac{m^2_{soft}}{f} \quad , \quad \delta m^2_Q \sim \left(\frac{m^2_{soft}}{f}\right)^n \; m^2_{soft} \; . \qquad (4)$$

Low values of $\sqrt{f}$ $\rightarrow$ strong dynamics $\Rightarrow$ dimensionless coefficients are of order one (or 4π).

ii) No assumptions about how the SUSY breaking sector couples to the MSSM. The Lagrangian contains the SUSY breaking scale f and the cutoff scale Λ. SUSY is non-linearly realized in the goldstino multiplet X by imposing a superfield constraint $X^2 = 0$. Sgoldstino is absent as an elementary degree of freedom.

It was argued by Komargodski and Seiberg that in this case any goldstino coupling should appear in the combination $(m_{soft}/f)X$.

- Other higher-dimensional operators are further suppressed by appropriate powers of Λ.

- Couplings of the goldstino multiplet by (m_{soft}/f) ensures the validity of the effective operator expansion.

Relevant operators are now

$$\mathcal{K}_{soft} = -\frac{m_Q^2}{f^2}\ (X^\dagger X)(Q^\dagger Q),$$
$$\mathcal{K}_{hdo} = -\frac{c_{QQ}}{\Lambda^2}\ (Q^\dagger Q)^2, \tag{5}$$
$$\mathcal{K}_{corr} = -\frac{c_u}{\Lambda}\frac{m_{soft}}{f} X^\dagger Q U H_1^\dagger - \left(\frac{m_{soft}}{f}\right)^{n+2} \frac{d_n}{\Lambda^n}(X^\dagger X)(\bar{D}^2 \bar{X})^n (Q^\dagger Q)$$

We expect $\Lambda \lesssim \sqrt{f}$. Corrections to the MSSM couplings are

$$\delta y_u \sim \frac{m_{soft}}{\sqrt{f}}\,, \quad \delta m_Q^2 \sim \left(\frac{m_{soft}}{\sqrt{f}}\right)^n m_{soft}^2\ . \tag{6}$$

$\Rightarrow$ corrections to MSSM couplings are larger in case ii), compared to i).

- In both cases, sizable corrections to couplings are possible only for low scale SUSY breaking, $\sqrt{f} \sim$ TeV. In case i), consistency of effective field theory asks

$$m_{soft} \lesssim \sqrt{f} \lesssim M \ . \tag{7}$$

- For $\sqrt{f} < 10$ TeV, suppression in the hdo's is compensated by particular values of MSSM parameters: angles α and β in the Higgs sector, mixing angle determining the LSP composition.

- Some parameters are small: Higgs self-coupling, Yukawas, Higgs coupling to photons. These couplings are sensitive to corrections from hdo's.

2. Non-linear SUSY and its standard realization.

Goldstino is part of a multiplet $X = (x, G, F_X)$. Thhe sgoldstino mass m_x depends on the microscopic theory. In a SUSY theory well below the scale of SUSY breaking $E << \sqrt{f}$, SUSY is non-linearly realized.

There is always one light fermion in the effective theory, the goldstino G, of mass

$$m_G \sim \frac{f}{M_P}$$

In the decoupling limit $M_P, m_x \to \infty$, the transverse polarizations of the gravitino decouple.

Standard Realization: starts from a SUSY transf.

$$x'_m = x_m + i(\theta\sigma_m\bar{\xi} - \xi\sigma_m\bar{\theta}) \ , \ \theta' = \theta + \xi \ , \ \bar{\theta}' = \bar{\theta} + \bar{\xi}$$

In analogy with goldstone bosons, Goldstino transforms as

$$G'(x') = G(x) + \frac{1}{k}\xi \ .$$

Taylor expansion $\Rightarrow$ SUSY transformation

$$\delta G = \frac{1}{k}\xi + k\Lambda_\xi^m \partial_m G \ , \ \text{where } \Lambda_\xi^m = i(G\sigma^m\bar{\xi} - \xi\sigma^m\bar{G})$$

k is the Goldstino decay constant, related to the SUSY breaking scale as

$$k = \frac{1}{\sqrt{2}f} = \frac{1}{\sqrt{2}M_{\text{SUSY}}^2}$$

In the standard VA prescription, couplings to matter proceed as in gravity. There is a vierbein

$$E_m^n = \delta_m^n + ik^2(\partial_m G\sigma^n \bar{G} - G\sigma^n \partial_m \bar{G})$$

Then

$$\delta(detE) = k\partial_m(\Lambda_\xi^m detE)$$

The Volkov-Akulov lagrangian is then

$$\mathcal{L}_{AV} = -\frac{1}{2k^2}detE = -\frac{1}{2k^2} + \frac{i}{2}(\partial_m G\sigma^m \bar{G} - G\sigma^m \partial_m \bar{G}) + \cdots$$

SUSY standard realization is defined for any field ϕ_i as

$$\delta\phi_i = k\Lambda_\xi^m \partial_m \phi_i \qquad (8)$$

Derivatives have to be covariantized according to

$$\mathcal{D}_m\phi_i \equiv (E^{-1})^{\mu}_{m} D_\mu \phi_i \ , \ \mathcal{F}^a_{mn} \equiv (E^{-1})^{\mu}_{m}(E^{-1})^{\nu}_{n} F_{\mu\nu}$$

We can then supersymmetrize any lagrangian by

$$\mathcal{S}_{\text{eff}} = \int d^4x \ detE \ \mathcal{L}(\phi_i, \mathcal{D}_m\phi_i, \mathcal{F}^a_{mn})$$

Low-energy limit $\Rightarrow$ expansion in powers of k

$$\mathcal{L}_{\text{eff}} = \mathcal{L}(\phi_i, D_m\phi_i, F^a_{mn}) + ik^2 \ G\sigma^m \partial^n \bar{G} \ T_{mn} + \cdots$$

where T_{mn} is the energy-momentum tensor. The above procedures is model-independent. However, it does not give the most general couplings of goldstino to matter.

There are two cases of goldstino couplings to matter :

i) Non-SUSY matter spectrum (ex: SM...)

$$E \ << \ m_{sparticles} \ , \ m_x \ , \ \sqrt{f}$$

$\longrightarrow$ non-linear SUSY in the matter sector.

ii) SUSY matter multiplets : $(\tilde{q}, q)$, etc.

$$m_{sparticles} \leq E << \sqrt{f} \ , m_x$$

$\longrightarrow$ linear SUSY matter sector coupled to the goldstino :

new MSSM couplings, correction to the higgs potential.

3. The formalism of constrained superfields.

There are various formalisms developed over the years. Here we are using the superfield approach of Siegel, Casalbuoni et al., Komargodski and Seiberg. The Goldstino G can be described by a chiral superfield X, with the constraint

$$X^2 \ = \ 0 \ .$$

The constraint is solved by

$$X \ = \ \frac{GG}{2\,F_X} + \sqrt{2}\,\theta G + \theta\theta \ F_X \ .$$

F_X is an auxiliary field to be eliminated via its field eqs.

After eliminating F_X, the Volkov-Akulov lagrangian is then given by

$$\mathcal{L}_X = \int d^4\theta \ X^\dagger X + \left\{ \int d^2\theta \, f \ X + h.c. \right\}$$

$$= det \ (E_\mu^a) \ , \quad \text{where} \quad E_\mu^a = e_\mu^a + (\frac{i}{2f^2} G\sigma^a \partial_\mu \bar{G} + h.c.)$$

is the VA "vierbein". Volkov-Akulov and the SUSY constrained formalism are not obviously equivalent if coupling to other (super) fields, due to F_X.

4. MSSM+goldstino: Non-linear MSSM.

We now consider the case :

$$m_{sparticles} \leq E << \sqrt{f}\ , m_x$$

$\rightarrow$ full MSSM spectrum coupled to the constrained goldstino superfield X, which satisfies $X^2 = 0$.

For our purposes: gauge, Higgs and lepton sector superpartner masses are $<< \sqrt{f}$.

However: nothing will depend on the squarks mass $\rightarrow$ they can be decoupled.

Usually we parameterize SUSY breaking in MSSM by a coupling to a spurion

$$S \;=\; \theta^2 m_{soft}$$

The main difference in non-linear MSSM is the replacement $S \rightarrow \frac{m_{soft}}{f}\ X$.

This reproduces the MSSM soft terms, but it adds new dynamics :

- F_X is a dynamical auxiliary field $\rightarrow$ new couplings from

$$-\bar{F}_X = f + \frac{B}{f} h_1 h_2 + \frac{A_u}{f} q u h_2 + \cdots$$

- it contains in a compact form the goldstino couplings to matter.

All couplings to the Goldstino are proportional to soft-terms. The lagrangian is

$$\mathcal{L} \;=\; \mathcal{L}_{MSSM} + \mathcal{L}_X + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g \quad \text{where}$$

$$\mathcal{L}_H = \sum_{i=1,2} \frac{m_i^2}{f^2} \int d^4\theta \;\, X^\dagger X \;\, H_i^\dagger e^{V_i} H_i \;,$$

$$\mathcal{L}_m = \sum_{\Phi} \frac{m_\Phi^2}{f^2} \int d^4\theta \;\, X^\dagger X \Phi^\dagger e^V \Phi \;, \;\; \Phi = Q, U_c, D_c, L, E_c$$

$$\mathcal{L}_{AB} = \frac{B}{f} \int d^2\theta \;\, X H_1 H_2 + (\frac{A_u}{f} \int d^2\theta \;\, X Q U_c H_2 + \cdots)$$

$$\mathcal{L}_g = \sum_{i=1}^{3} \frac{1}{16\, g_i^2\, \kappa} \frac{2\, m_{\lambda_i}}{f} \int d^2\theta \, X \, \mathrm{Tr} \, [\, W^\alpha \, W_\alpha]_i + h.c.$$

Matter terms coming from solving for F_X do not come from the Volkov-Akulov lagrangian. Ex : the scalar potential is modified compared to MSSM :

$$V = \left(|\mu|^2 + m_1^2\right) |h_1|^2 + \left(|\mu|^2 + m_2^2\right)|h_2|^2 + (B\, h_1.h_2 + \text{h.c.})$$
$$+\frac{g_1^2 + g_2^2}{8}\left[|h_1|^2 - |h_2|^2\right]^2 + \frac{g_2^2}{2}|h_1^\dagger\, h_2|^2$$
$$+\frac{1}{f^2}\left|m_1^2\,|h_1|^2 + m_2^2\,|h_2|^2 + B\, h_1.h_2\right|^2$$

The last term is new , generated by integrating out the sgoldstino.

Physical interpretation : new couplings of the Higgs to the (low-scale) SUSY breaking sector.

Equivalence theorem: leading Goldstino couplings are

$$\frac{1}{f}\,\partial^\mu G\; J_\mu = \;-\frac{1}{f}\;G\;\partial^\mu J_\mu,$$

where J_μ is the supercurrent. We use the on-shell action $\rightarrow$ all goldstino couplings are proportional to soft terms. The superfield formalism gives all couplings directly in this form. Indeed, the supercurrent for chiral (z_i, ψ_i, F_i) and vector (A_m^a, λ^a, D^a) multiplets is

$$J_m = \sigma^n \bar{\sigma}_m \Psi^i D_n \bar{z}^i + \sigma_m \sigma^{np} \bar{\lambda}^a F^a_{np} + F^i \bar{\Psi}^i \bar{\sigma}_m + D^a \bar{\lambda}^a \bar{\sigma}_m \;.$$

Then we find (using field eqs)

$$\partial^m J_m \;=\; m_0^2 \Psi^i \bar{z}^i + m_\lambda \sigma^{mn} \lambda^a F^a_{mn} \;.$$

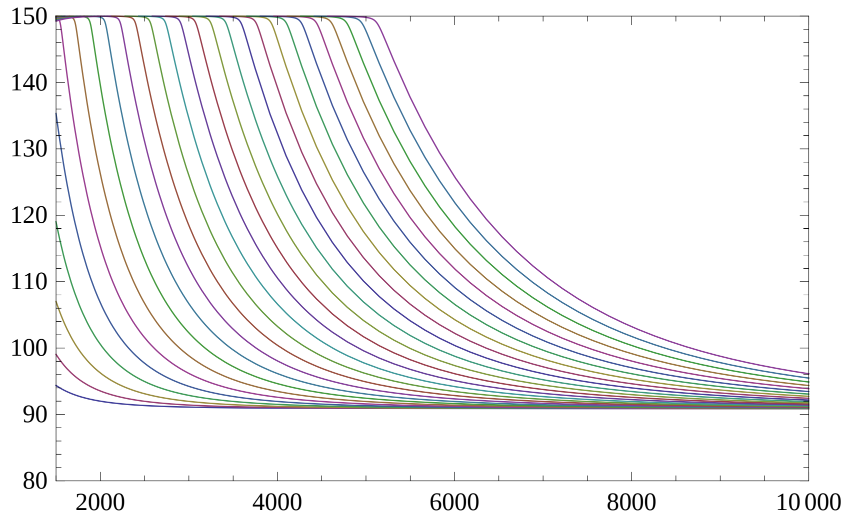
5. Implications

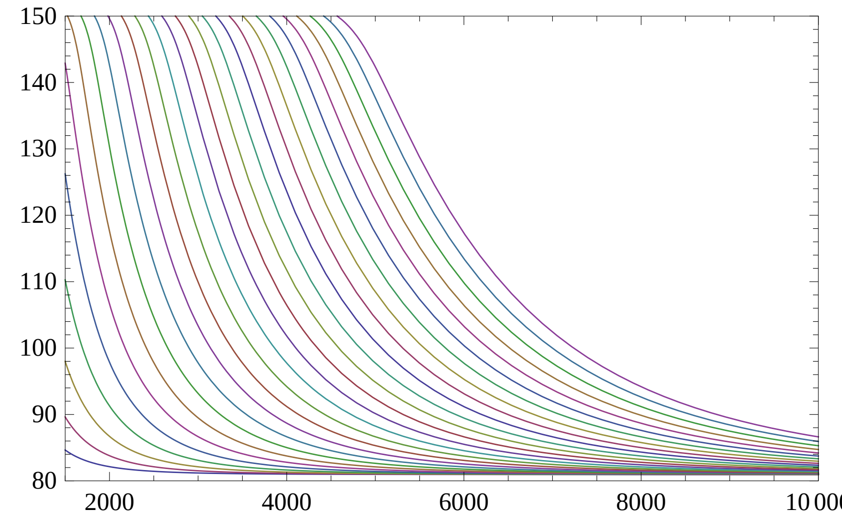
- 5.1 Higgs masses

Due to the new quartic couplings, the Higgs masses change

$$\Delta m_h^2 = \frac{v^2}{16 f^2}\frac{1}{\sqrt{w}}\Big[16 m_A^2 \mu^4 + 4\, m_A^2\, \mu^2\, m_Z^2 + (m_A^2 - 8\,\mu^2)\, m_Z^4$$
$$-2\, m_Z^6 + 2\,(-2\, m_A^2\, \mu^2 + 8\mu^4 + 4\mu^2\, m_Z^2 + m_Z^4)\,\sqrt{w} + \cdots\Big]$$

with $w = (m_A^2 + m_Z^2)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta$. The increase in the Higgs mass is significant for $1.5\ TeV \leq f \leq 10\ TeV$. Fine-tuning of the electroweak scale is also reduced.





(a) m_h as function of $\sqrt{f}$ and μ as a parameter, for $\tan\beta = 50$.

(b) m_h as function of $\sqrt{f}$ and μ as a parameter, for $\tan\beta = 5$.

Tree-level Higgs masses (GeV) as functions of $\sqrt{f}$.

In both figures, $M_A = 150$ GeV and μ increases upwards from 400 to 3000 GeV in steps of 100 GeV.

We can also add model-dependent hdo's, with the structure,

$$\delta\mathcal{L} \;=\; -\frac{c_\lambda}{M^4}\int d^4\theta\ (X^\dagger X)(H_i^\dagger H_i)^2 + \cdots \tag{9}$$

in case i), and

$$\delta\mathcal{L} \;=\; -\frac{c_\lambda}{\Lambda^2}\frac{m_{soft}^2}{f^2}\int d^4\theta\ (X^\dagger X)(H_i^\dagger H_i)^2 + \cdots \tag{10}$$

in case ii). In case i), corrections to Higgs self-coupling are of the order $\delta\lambda \sim m_{soft}^4/f^2$, i.e. the same order as the ones discussed previously. However, in case ii), for $\Lambda \sim \sqrt{f}$, the corrections are $\delta\lambda \sim m_{soft}^2/f \Rightarrow$ corrections to the quartic Higgs self-coupling are dominated by the model-dependent terms in case ii).

5.2 $h \to \gamma\gamma$, $h \to \gamma Z$ and $gg \to h$

The renormalizable tree level Higgs couplings can be parametrized as

$$\begin{aligned}\mathcal{L}_{\mathrm{ren}} &= -c_t \frac{m_t}{v} h\, t\, \bar{t} - c_c \frac{m_c}{v} h\, c\, \bar{c} - c_b \frac{m_b}{v} h\, b\, \bar{b} - c_\tau \frac{m_\tau}{v} h\, \tau\, \bar{\tau} \\ &\quad + c_Z \frac{m_Z^2}{v} h\, Z^\mu\, Z_\mu + c_W \frac{2m_W^2}{v} h\, W^{+\mu}\, W_\mu^- \ . \qquad (11)\end{aligned}$$

MSSM decoupling limit: $c = 1$; the c^{loop}-coefficients equals the SM ones.

New ingredient : goldstino-Higgs mixing, coming from

$$\mathcal{L} \supset x \left(-\frac{m_i^2}{f^2} F_X^\dagger \, h_i^\dagger F_i + \frac{B}{f}(F_1 h_2 + h_1 F_2) - \frac{M_a}{4f}(F^{k\,\mu\nu} F^k_{\mu\nu})_a \right) + h.c.$$
$$-|x|^2 \left(\frac{m_i^2}{f^2} |F_i|^2 + m_X^2 \right) \quad . \qquad (12)$$

If sgoldstino x is heavy we can use its e.o.m. (zero-momentum limit), to integrate it out. We obtain

$$-\frac{M_a}{4 m_X^2 f^2}(F^{k\,\mu\nu} F^k_{\mu\nu})_a \left(m_i^2 h_i^\dagger \, F_i + B(F_1 h_2 + h_1 F_2) \right) + h.c. \; . \qquad (13)$$

$\Rightarrow$ effective interactions between h and the gauge field strengths

$$c_x \Big[(M_1 \cos^2\theta_w + M_2 \sin^2\theta_w) h F^{\mu\nu} F_{\mu\nu}$$

$$+(M_1 \sin^2\theta_w + M_2 \cos^2\theta_w) h Z^{\mu\nu} Z_{\mu\nu}$$

$$+2\cos\theta_w \sin\theta_w (M_1 - M_2) h Z^{\mu\nu} F_{\mu\nu} + M_3\, h\, Tr\ G^{\mu\nu} G_{\mu\nu} \Big] ,$$

where,

$$c_x = -\frac{\mu\, v}{2f^2 m_X^2} \left(\mu^2 \cos(\alpha+\beta) + B \left(\frac{\cos(\alpha+\beta)}{\sin 2\beta} + \sin(\alpha-\beta) \right) \right) \tag{14}$$

Then

$$c_\gamma = c_\gamma^{\text{loop}} + c_\gamma^{\text{sgold}} \ , \ c_g = c_g^{\text{loop}} + c_g^{\text{sgold}} \ , \ c_{Z\gamma} = c_{Z\gamma}^{\text{loop}} + c_{Z\gamma}^{\text{sgold}} \ , \tag{15}$$

where,

$$
\begin{aligned}
c_\gamma^{\text{sgold}} &= -\frac{4\pi\, v^2 \mu}{f^2 m_X^2 \alpha_{\text{EM}}} (M_1 \cos^2\theta_w + M_2 \sin^2\theta_w)\, \Delta \\
c_{Z\gamma}^{\text{sgold}} &= -\frac{4\pi\, v^2 \mu \cos\theta_w \sin^2\theta_w}{f^2 m_X^2 \alpha_{\text{EM}}} (M_1 - M_2)\, \Delta \\
c_g^{\text{sgold}} &= -\frac{6\pi\, v^2 \mu}{f^2 m_X^2 \alpha_{\text{S}}}\, M_3\, \Delta\ .
\end{aligned}
\tag{16}
$$

The factor Δ is given by,

$$
\Delta = \mu^2 \cos(\alpha+\beta) + B \left(\frac{\cos(\alpha+\beta)}{\sin 2\beta} + \sin(\alpha-\beta) \right) \to \mu^2 \sin 2\beta
\tag{17}
$$

where we took the MSSM decoupling limit.

- We can use the experimental bound on the gluino mass, which enters the c_g^{sgold} to estimate how much the Higgs couplings to $\gamma\gamma$ and $Z\gamma$ can be enhanced.

- Do not want gluon fusion to deviate from SM value by more than around 30%, i.e. $|c_g^{\text{sgold}}| \leqslant 0.14 \cdot |c_g^{\text{SM}}|$. Then

$$\left| -\frac{\mu^3 \sin 2\beta}{f^2 m_X^2} \right| \leqslant 0.14 \cdot 0.98 \, \frac{\alpha_{\text{S}}}{6\pi \, v^2 \, |M_3|} \tag{18}$$

which combined with c_γ^{sgold} gives the bound

$$\left| c_\gamma^{\text{sgold}} \right| \leqslant 0.14 \cdot 0.98 \, \frac{\alpha_{\text{S}}}{6\pi \, v^2 \, |M_3|} \frac{4\pi \, v^2}{\alpha_{\text{EM}}} \left| M_1 \cos^2\theta_w + M_2 \sin^2\theta_w \right| \approx 1.37$$

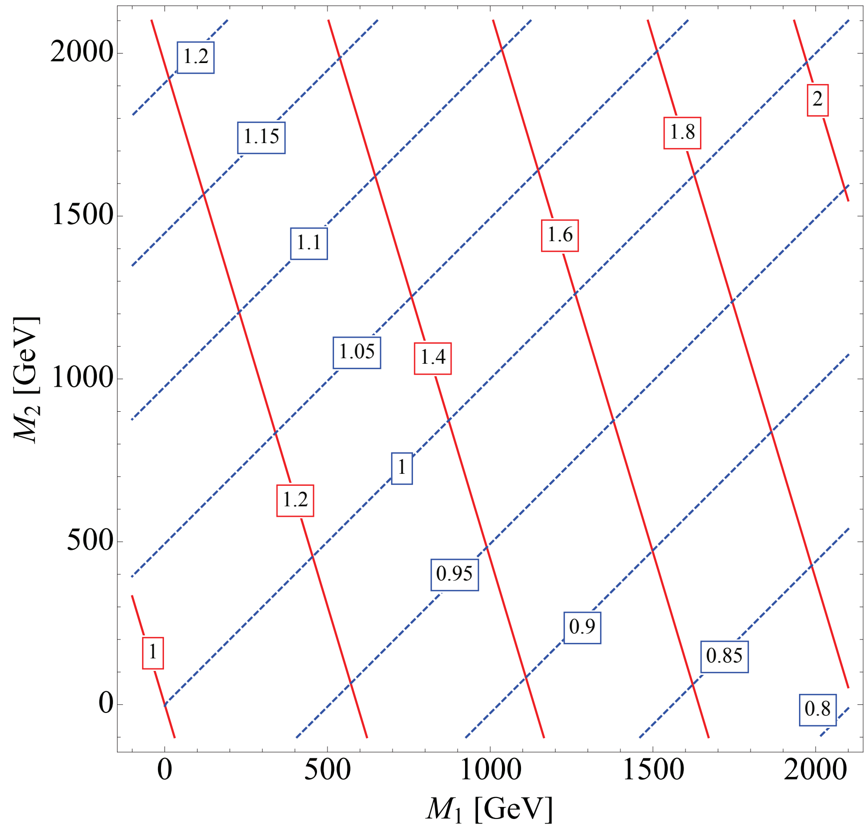
where $M_{12} = M_1 \cos^2\theta_w + M_2 \sin^2\theta_w$. Assuming the signs of μ and M_{12} are such that the sgoldstino mixing contribution is constructive, this implies

$$\frac{\Gamma_{h\gamma\gamma}}{\Gamma_{h\gamma\gamma}^{\mathsf{SM}}} = \left|\frac{c_\gamma}{c_\gamma^{\mathsf{SM}}}\right|^2 \leqslant \left|\frac{-6.51 - 1.37\frac{M_{12}}{M_3}}{-6.51}\right|^2 \approx \left|1 + 0.21\frac{M_{12}}{M_3}\right|^2 . \tag{20}$$

We can also constrain the $Z\gamma$ channel. The result is

$$\frac{\Gamma_{hZ\gamma}}{\Gamma_{hZ\gamma}^{\mathsf{SM}}} = \left|\frac{c_{Z\gamma}}{c_{Z\gamma}^{\mathsf{SM}}}\right|^2 \leqslant \left|\frac{5.47 + 0.28\frac{M_2-M_1}{M_3}}{5.47}\right|^2 \approx \left|1 + 0.05\frac{M_2 - M_1}{M_3}\right|^2 . \tag{21}$$

$\Rightarrow$ we expect a smaller deviation from the SM value in the $h \to Z\gamma$ channel.



The $h \to \gamma\gamma$ and $h \to Z\gamma$ partial decay widths $\Gamma_{h\gamma\gamma}/\Gamma^{\mathrm{SM}}_{h\gamma\gamma}$ (red solid lines) and $\Gamma_{hZ\gamma}/\Gamma^{\mathrm{SM}}_{hZ\gamma}$ (blue dashed lines), as functions of the bino and wino masses.

- **5.3 Invisible decays of Higgs and Z boson.**

Other relevant (order $1/f$ terms) in the non-linear MSSM action are

$$-\frac{1}{f}\left[m_1^2\, G\psi_{h_1^0}\, h_1^{0\,*} + m_2^2\, G\psi_{h_2^0}\, h_2^{0\,*}\right] - \frac{B}{f}\left[G\psi_{h_2^0}\, h_1^0 + G\psi_{h_1^0}\, h_2^0\right]$$
$$-\frac{1}{f}\sum_{i=1,2,3}\frac{m_{\lambda_i}}{\sqrt{2}}\,\tilde{D}_i^a\, G\lambda_i^a + \sum_{i=1}^{3}\frac{m_{\lambda_i}}{\sqrt{2}\, f}\, G\,\sigma^{\mu\nu}\,\lambda_i^a\, F_{\mu\nu,\,i}^a + \text{h.c.}$$

We consider for illustration the case of the lightest neutralino χ to be lighter than the Higgs or the Z boson.

Comments :

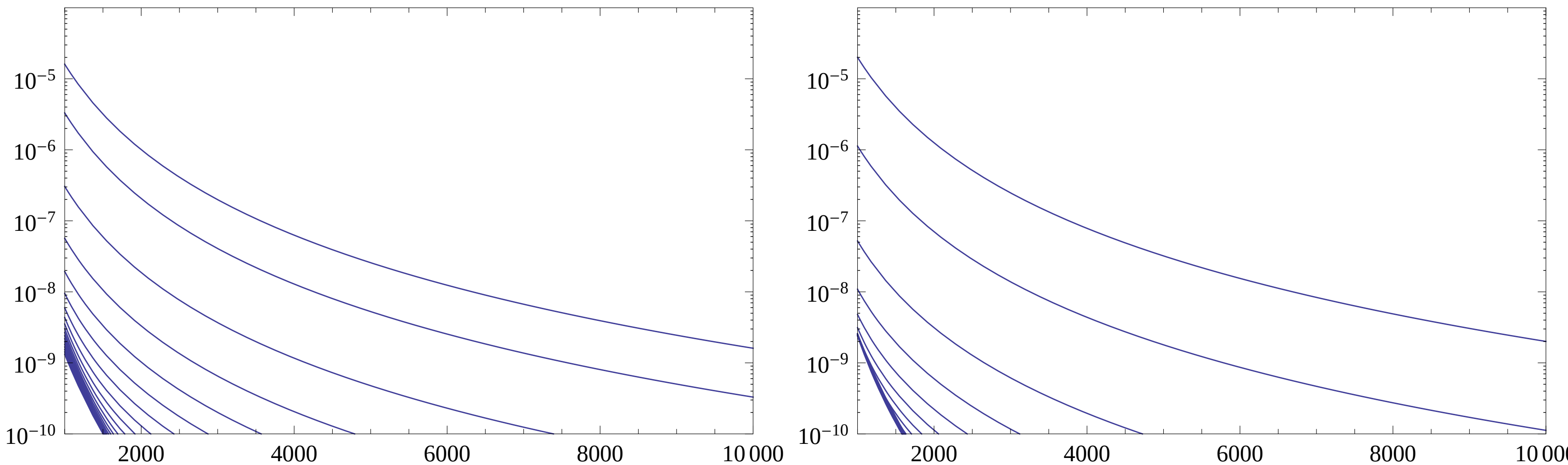
Similar decay rates as the inverse ones

$$\chi \;\rightarrow\; h\ G \quad , \quad \chi \;\rightarrow\; Z^\mu\ G$$

computed some time ago in models of gauge mediation (Djouadi-Dress).

$$Z \rightarrow \chi\ G$$

Imposing $\Delta\Gamma_Z < 2.3$ MeV (LEP) puts a lower bound on $\sqrt{f} \geq 400-600$ GeV, stronger than previous bounds.



The partial decay rate of $h^0 \to G\chi_1^0$ as function of $\sqrt{f}$ for

(a): $\tan\beta = 50$, $m_{\lambda_1} = 70$ GeV, $m_{\lambda_2} = 150$ GeV, μ from 100 GeV (top) to 1000 GeV (bottom) by a step 100 GeV, $m_A = 150$ GeV.

(b) : As for (a) but with $\tan\beta = 5$.

The branching ratio in the above cases is comparable to that of SM Higgs going into $\gamma\gamma$.

Conclusions and perspectives

• Two different frameworks to couple goldstino to matter: with messengers (scale M and "directly" (no messengers). It would be interesting to construct explicit models of the second kind.

• The couplings of goldstino to matter are not unique. More general couplings captured by hdo's and the constrained superfield formalisms.

• Goldstino couplings coming from hdo's can be important and even dominant for $\sqrt{f} \lesssim 10$ TeV.

• Change of MSSM couplings $\Rightarrow$ various low-energy implications:

- contributions to higgs mass

- possible enhancement of $h \to \gamma\gamma$ if sgoldstino in the TeV range (mixing higgs-sgoldstino)

- changes of Higgs couplings to fermions

- specific processes with one photon $+$ goldstinos (missing energy).

• Interesting to apply this formalism to non-standard SUSY spectra: inverted hierarchy models or various variants of split susy models, or to gravitino dark matter scenarios.

Thank you !

BACKUP SLIDES

3. Heavy superpartners: matter constraints

Non-linear matter $\rightarrow$ additional constraints (KS) :

- Heavy scalars : $XQ_i = 0$: eliminates the complex scalars. We get

$$Q_i = \frac{1}{F_X}(\Psi_i - \frac{F_i}{2F_X}G)G + \sqrt{2}\theta\Psi_i + \theta^2 F_i$$

Obs: $X^2 = XQ_i = 0$ uniquely determines the solutions. However, other constraints are verified

$$Q_i \; Q_j \; Q_k \;=\; 0 \; ,$$

where are "redundant".

The constraints should be understood as IR consequences of UV dynamics generating SUSY breaking and large superpartner masses. It was argued (Komargodski-Seiberg) that the superfield constraints are unique and independent of high-energy physics. Ex :

$$W = f\ X\ ,$$
$$K = X^\dagger X + Q^\dagger Q - \frac{c_x}{\Lambda^2}(X^\dagger X)^2 - \frac{c_q}{\Lambda^2}(X^\dagger X)(Q^\dagger Q)$$

For $c_i = 0$ we get an O'R model, $F_X = -f$ and X is a flat direction. $c_i > 0$ stabilize $\langle X \rangle = \langle Q \rangle = 0$.

The fermions stays massless $\rightarrow$ non-linear SUSY at low-energy. The low-energy lagrangian is obtained by "integrating-out" the scalars:

$$\mathcal{L} = -f^2 + |F_X + f|^2 - \frac{c_x}{\Lambda^2}\,|2xF_X - GG|^2 - \frac{c_q}{\Lambda^2}\,|qF_X + xF_q - G\Psi_q|^2 + \text{derivative terms}$$

Field eqs. for X, q give

$$x = \frac{GG}{2F_X} \quad , \quad q = \frac{1}{F_X}(\Psi_q - \frac{F_q G}{2F_X})G$$

i.e. the previous superfield constraints, independently of c_i. Are these constraints unique, independent of the high-energy theory ?

- General Kahler potential and generalized chiral constraints

Let's add another UV correction to the Kahler potential

$$\Delta K \;=\; -\frac{c_3}{\Lambda^2}(Q^\dagger Q)^2 \;-\; \frac{c_4}{\Lambda^2}(X^\dagger)^2 Q^2$$

- c_3 is not protected by any symmetry.

In this case, we find $(\Psi_i = G, \Psi_q)$

$$X = a_{ij}\Psi_i\Psi_j + \sqrt{2}\theta G + \theta^2 F_X$$
$$Q = b_{ij}\Psi_i\Psi_j + \sqrt{2}\theta\Psi_q + \theta^2 F_q$$

where a_{ij}, b_{ij} are easily calculated as functions of ϵ_a, F_i.

Here $\quad X^2 \neq 0, XQ \neq 0.$

Nonetheless we find the cubic constraints

$$X^3 = X^2 Q = X Q^2 = Q^3 = 0 \tag{22}$$

Interestingly, the solution of (22) is not unique, it depends on two free parameters. It can be parameterized as

$$\begin{aligned} X &= \frac{GG}{2F_X} - \frac{c_1}{2F_X}(F_q G - F_X \Psi_q)^2 \ , \\ Q &= \frac{\Psi_q \Psi_q}{2F_q} - \frac{c_2}{2F_q}(F_q G - F_X \Psi_q)^2 \ . \end{aligned}$$

- Non-uniqueness of the solutions of the constraints reflect the UV sensitivity of the low-energy lagrangian.

• Previous constraints recovered if $c_x, c_q >> c_3, c_4$. Notice that c_x, c_q determine the scalar masses

$$m_x^2 = \frac{4c_x f^2}{\Lambda^2} \quad , \quad m_q^2 = \frac{c_q f^2}{\Lambda^2} \ .$$

• The higher-order constraints $\leftrightarrow$ UV sensitivity come because we don't take the limit $m_{sparticles} >> f$ that KS used. This limit would ask for $c_x, c_q >> 1$, not easy to justify.

Our new results change low-energy actions for $m_{sparticles} \lesssim f$.

- **Yukawas and generalized chiral constraints**

Yukawas (R-parity violating couplings in MSSM) increase the order of the monomial chiral constraints. Simplest example

$$
\begin{aligned}
K &= X^\dagger X + Q^\dagger Q - \frac{c_x}{\Lambda^2}(X^\dagger X)^2 - \frac{c_q}{\Lambda^2}(Q^\dagger Q)(X^\dagger X) \ , \\
W &= \ f \ X \ + \frac{\lambda}{3} Q^3 \ .
\end{aligned}
$$

In this case the integration of the heavy scalars leads to low-energy fields of the form

$$
\begin{aligned}
X &= a_{ij}\, \psi_i \psi_j + a_2 \ (\bar{F}_q \, \bar{\psi}_X - \bar{F}_X \, \bar{\psi}_q)^2 \ + \sqrt{2} \ \theta \ \psi_X \ + \ \theta^2 \ F_X \ , \\
Q &= b_{ij}\, \psi_i \psi_j + b_2 \ (\bar{F}_q \, \bar{\psi}_X - \bar{F}_X \, \bar{\psi}_q)^2 \ + \sqrt{2} \ \theta \ \psi_q \ + \ \theta^2 \ F_q
\end{aligned}
$$

By Grassmann variable arguments one can check that in this case we obtain quartic constraints

$$X^4 = X^3 Q = X^2 Q^2 = X Q^3 = Q^4 = 0 \; .$$

6 Heavy higgsinos and gauginos (KS proposal) :

- heavy fermions : $X\bar{H} =$ chiral : eliminates the fermions.

In this case

$$H = h + i\sqrt{2}\theta\sigma^m\partial_m h\frac{\bar{G}}{\bar{F}_X} + \theta^2[-\partial_n(\frac{\bar{G}}{\bar{F}_X})\bar{\sigma}^m\sigma^n\partial_m h\frac{\bar{G}}{\bar{F}_X} + \frac{1}{2\bar{F}_X^2}\bar{G}^2\partial^2 h]$$

In this case there is not anymore an auxiliary field F_h.

The leading higgs-goldstino interactions come from:

$$-i\Psi_{h,i}\sigma^m\partial_m\bar{\Psi}_{h,i} \;\rightarrow\; -\frac{i}{f^2}\; G\partial_m\bar{h}_i\;\sigma^m\Box(\bar{G}h_i)$$

$$-\mu\Psi_{h,1}\Psi_{h,2} \;\rightarrow\; -\frac{\mu}{f^2}\;\bar{G}\bar{G}\;\partial^m h_1\partial_m h_2$$

- heavy gauginos : $XW_\alpha = 0$ eliminates the gauginos. The solution is

$$W_\alpha = \frac{1}{\sqrt{2}F_X}(D - i\sigma^{mn}F_{mn})G - \frac{G^2}{2F_X^2}\sigma^m\partial_m\bar{\lambda}$$
$$+(D - i\sigma^{mn}F_{mn})\theta + \theta^2\sigma^m\partial_m\bar{\lambda} \ .$$

Leading gauge field-gaugino coupling comes from the kinetic term

$$-i\lambda\partial\bar{\lambda} \ \rightarrow \ \frac{i}{2f^2}\ (G\sigma^{mn}F_{mn})\ \partial(\bar{G}\bar{\sigma}^{pn}F_{pn})$$

- Heavy gauginos from UV: constrained vector superfields

Simplest UV lagrangian providing large masses to the sgoldstino scalar and the gaugino :

$$\begin{aligned}\mathcal{L} \;=\; & \int d^4\theta \, \left[X^\dagger X \;-\; \epsilon \, (X^\dagger X)^2 \right] \\ + \; & \left\{ \int d^2\theta \, \left(f X \;+\; \frac{1}{4} W^\alpha W_\alpha \;+\; \frac{M}{f} \, X \, W^\alpha W_\alpha \right) + \text{h.c.} \right\} ,\end{aligned}$$

where M is the gaugino mass. The zero-momentum gaugino equation has the solution

$$\lambda \;=\; \frac{i}{\sqrt{2} F_X} (D - i \sigma^{mn} F_{mn}) \; G \; .$$

The corresponding field strength is

$$W_\alpha = \frac{1}{\sqrt{2}F_X}(D - i\sigma^{mn}F_{mn})G + (D - i\sigma^{mn}F_{mn})\theta + \theta^2\sigma^m\partial_m\bar{\lambda} \tag{23}$$

and satisfies

$$X\ W_\alpha = \frac{GG}{2F_X}\,(\sigma^m\partial_m\bar{\lambda})_\alpha\,\theta^2, \qquad X\ W^\alpha\ W_\alpha = 0\ ,$$

where the second equation is the generalized constraint whose unique solution is (23). The KS gauginos are the solution of the implicit eq.

$$\lambda = \frac{i}{\sqrt{2}F_X}(D - i\sigma^{mn}F_{mn})\,G - i\frac{GG}{2F_X^2}\sigma^m\partial_m\bar{\lambda}$$

- The difference between KS solution and (23) is of higher-order in an $1/f$ expansion in the low-energy action.
- In both cases the leading goldstino-gauge field interaction comes from the gaugino kinetic term by using the common terms prop. to $\sigma^{mn}F_{mn}\, G$ in (23).

4. Leading-order low-energy lagrangians

Consider N superfields (quarks and/or leptons for MSSM) plus the goldstino superfield X. We add the minimal high-energy Kahler potential needed to decouple all scalars and add also an R-parity violating coupling, denoted generically λ_{ijk} below.

$$
\begin{aligned}
K &= X^\dagger X + Q_i^\dagger Q^i - \frac{m_x^2}{4f^2}(X^\dagger X)^2 - \frac{m_i^2}{f^2}(Q_i^\dagger Q^i)(X^\dagger X) \ , \\
W &= \ f \ X \ + \frac{1}{3}\lambda_{ijk} Q^i Q^j Q^k \ .
\end{aligned}
$$

By integrating-out the $N+1$ heavy scalars of mass $4m_X^2, m_i^2$ we get higher-order chiral constraints.

We use here a more pragmatic approach, by expanding the solution in F_i/F_X. First order in the expansion :

$$x \ = \ \frac{GG}{2F_X} \ , \ q_i \ = \ \frac{G\psi_i}{F_X} \ - \ \frac{1}{m_i^2}\lambda_{ijk}\bar{\psi}_j\bar{\psi}_k \ .$$

The low-energy lagrangian, up to four-fermion fields :

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{kin}} - \frac{1}{4f^2}\bar{G}^2\Box G^2 - \frac{1}{f^2}(\bar{G}\bar{\psi}_i)\Box(G\psi_i) + \frac{1}{m_i^2}(\lambda_{ijk}\bar{\psi}_j\bar{\psi}_k)(\bar{\lambda}_{imn}\psi_m\psi_n) - \frac{2}{m_i^2 f}\ (\bar{\lambda}_{ijk}\psi_j\psi_k)\Box(G\psi_i) - \frac{3}{m_i^4}\ (\lambda_{ijk}\bar{\psi}_j\bar{\psi}_k)\Box(\bar{\lambda}_{imn}\psi_m\psi_n) - f^2 \ .$$

The terms $(\bar{\lambda}_{ijk}\psi_j\psi_k)\Box(G\psi_i)$ are R-parity violating, lead to $qq \to qG$ processes, LHC relevance ? (detailed study of $qq \to GGg, GG\gamma$ by Brignole,Feruglio,Zwirner)

As expected, non-derivative terms involving the goldstino canceled. The first line contains universal goldstino couplings, whereas the second and third lines describe model-dependent couplings.

- For $m_i^2 \lesssim f$, the model-dependent couplings are as important at low-energy as the universal couplings of the goldstino to matter.
- Pragmatic question : is it possible to write the same low-energy action by using the KS constraints ?
- If yes, what is the most convenient formalism to write general low-energy SM actions with non-linear SUSY ?

Using the KS constraints.

Previous action can also be written using KS constraints

$$\mathcal{L} \; = \; \int d^4\theta \Big(X^\dagger X + Q_i^\dagger Q_i \; + \frac{\lambda_{ijk}\lambda_{imn}}{m_i^2} Q_i^\dagger Q_j^\dagger Q_m Q_n$$
$$+ \frac{\lambda_{ijk}}{m_i^2} Q_i Q_j D^2 Q_k + \frac{\lambda_{ijk}\lambda_{imn}}{m_i^4} Q_i^\dagger Q_j^\dagger \Box (Q_m Q_n) \Big)$$
$$+ (\int d^2\theta f X + \text{h.c.}) \; . \tag{24}$$

• Arbitrary coefficients in (24) (ex. $\epsilon_{ijmn} Q_i^\dagger Q_j^\dagger Q_m Q_n$) do not correspond to a simple UV theory $\rightarrow$ "swampland"?

• The operators in red seem irrelevant. However, they give contributions similar to the universal couplings in blue for $m_i^2 \sim f$.

Actually, we can probably write any low-energy action by using the KS formalism with the constraints :

$$X^2 = XQ_i = Q_iQ_jQ_k = 0$$

and the field equations for the constrained superfields

$$\frac{1}{4}X\bar{D}^2X^\dagger = fX \quad , \quad \frac{1}{4}Q_iQ_j\bar{D}^2X^\dagger = fQ_iQ_j \ ,$$
$$X\bar{D}^2Q_i^\dagger = 0 \quad , \quad Q_j\bar{D}^2Q_i^\dagger = 0.$$

However, operator dimensions can give wrong intuition about their low-energy relevance.

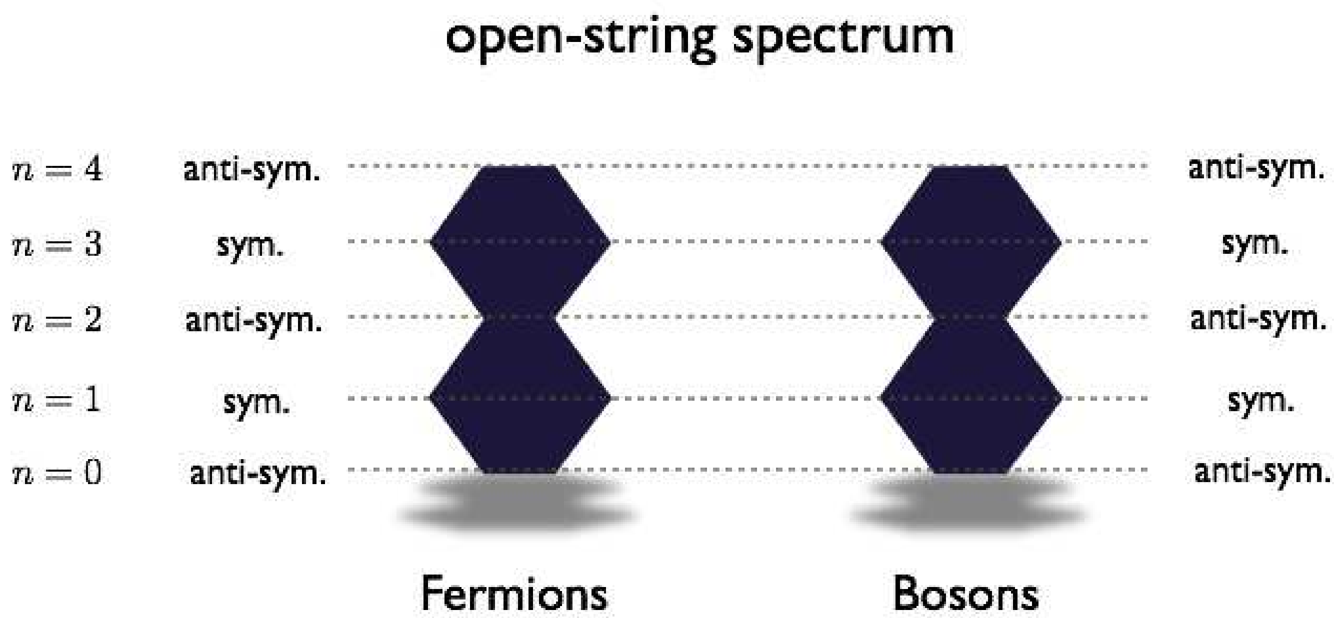
7. Non-linear SUSY in string theory

(Brane Supersymmetry Breaking: Sugimoto; Antoniadis, E.D.,Sagnotti; Aldazabal,Uranga)

In these constructions, the closed (bulk) sector is SUSY to lowest order, whereas SUSY is broken at the string scale on some stack of (anti)branes.

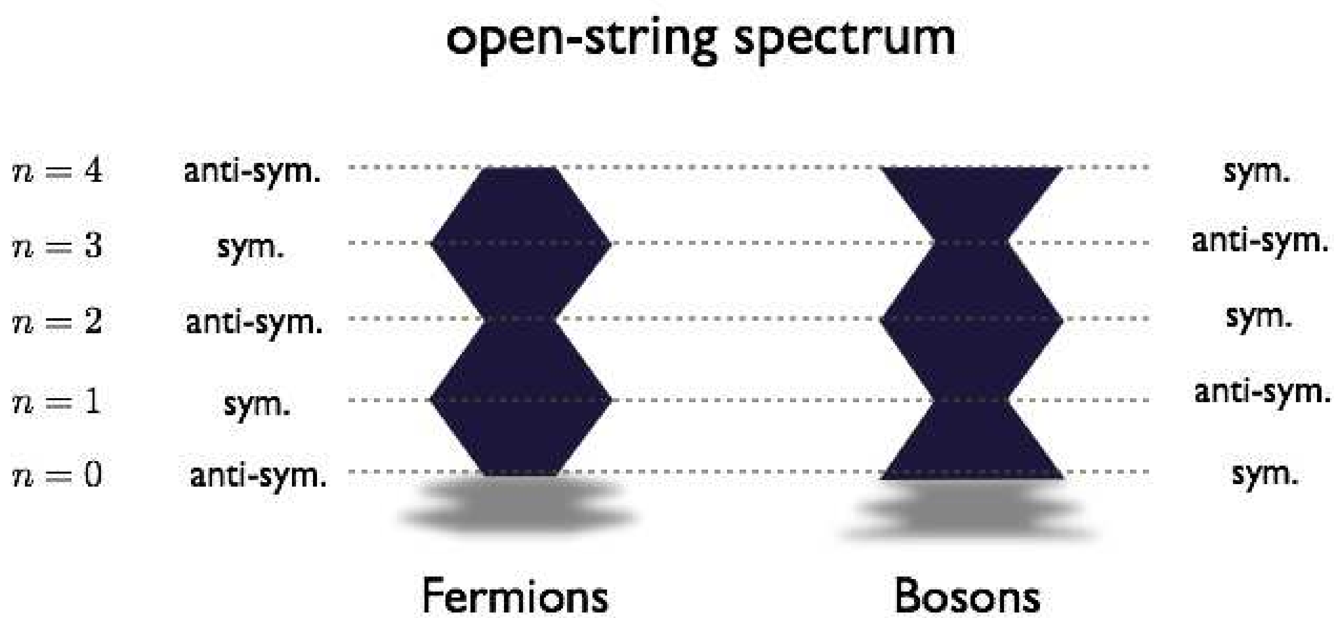
- String consistency asks for the existence of exotic $O9_+$ planes of positive RR charge. Then charge conservation /RR tadpoles ask for antibranes in the open sector.

SUSY case (SO gauge group) : Bose-Fermi degeneracy



Brane SUSY breaking case (USp gauge group):

spectrum is "misaligned"



- $\overline{Dp} - Op_+$ system is non-BPS but tachyon-free. Breaks SUSY at string scale.

- There is a NS-NS dilaton tadpole ($V \sim e^{-\Phi}$)

$$\sum_{Dp} T_{Dp}^{(n)} \; + \; \sum_{Op} T_{Op}^{(n)} \; \neq \; 0 \; ,$$

which leads to a Volkov-Akulov lagrangian.

Simplest 10d example, gauge group : $USp(32)$

- fermions in $\mathbf{32(32-1)/2 = 495 + 1}$.

- Singlet in the open string spectrum, can be identified with the goldstino realizing a nonlinear SUSY on antibranes (E.D.,Mourad; Schwarz-Witten).

The lagrangian is of the form

$$\mathcal{L} = \mathcal{L}_{\text{bulk}}(g_{\mu\nu}, \Phi \cdots) + \mathcal{L}_{\text{brane}}(A_\mu, \lambda, G, G_{\mu\nu}, \hat{\Phi} \cdots)$$

where

$$E^a_\mu = e^a_\mu + \frac{1}{4}\bar{G}\Gamma^a D_\mu G - \frac{1}{2}\bar{G}\Gamma^a \Psi_\mu + \cdots$$
$$\hat{\Phi} = \Phi - \frac{1}{\sqrt{2}}\bar{G}\lambda_\Phi + \cdots$$

where λ_Φ is the dilatino.

Stability and ground state of such models a very subtle and still open issue.

An interesting pheno string-inspired setup: KKLT. Non-linear SUSY aspects discussed by H.P. Nilles et coll.