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Non-linear Supersymmetric Standard Model

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Outline

- Non-linear SUSY realizations.
- Couplings in non-linear MSSM.
- Implications for Higgs masses.
- Invisible decays of Higgs and Z boson.
- Conclusions

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GDR Terascale, Bruxelles,

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...

All phenomenological studies were based on a component formalism, tedious computations. We will use a constrained superfield formalism, much faster computations. Some conceptual differences also.

1. Non-linear SUSY realizations.

In supergravity, the gravitino Ψ_μ becomes massive by absorbing a spin 1/2 fermion, the goldstino G

$$\Psi_\mu \begin{pmatrix} 3/2 \\ - \\ - \\ -3/2 \end{pmatrix} + G \begin{pmatrix} - \\ 1/2 \\ -1/2 \\ - \end{pmatrix} = \Psi_\mu \begin{pmatrix} 3/2 \\ 1/2 \\ -1/2 \\ -3/2 \end{pmatrix}$$

Goldstino is part of a multiplet $X = (x, G, F_X)$. The gravitino mass is

$$m_{3/2} \sim \frac{F_X}{M_P}$$

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 $M_P \to \infty$, SUSY breaking sector (sgoldstino x) decouples; goldstino couplings to matter scale as $1/f$.

There are two different cases of goldstino couplings to matter :

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

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

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

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

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

$\rightarrow$ linear SUSY matter sector.

We will consider $\sqrt{f} \sim \ 1 - 10$ TeV , $m_G \sim 10^{-3} - 10^{-2}$ eV .

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

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

Here F_X is an auxiliary field to be eliminated via its field equations.

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". In the standard VA prescription, couplings to matter proceed as in gravity :

$$G^{\mu\nu} \ T_{\mu\nu,M} \ = \ g^{\mu\nu} \ T_{\mu\nu,M} \ + \ (\frac{i}{2f^2} G\sigma^\mu \partial^\nu \bar{G} + h.c.) \ T_{\mu\nu,M}$$

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

Case i) (non-linear matter) $\rightarrow$ additional constraints :

- light fermions : $XQ = 0$: eliminates the complex scalars.

- light scalars : $X\bar{Q} =$ chiral : eliminates the fermions.

We make the BIG assumption that we are in case ii): whole MSSM spectrum/lagrangian coupled to the constraint goldstino superfield X.

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

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

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

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

Then we find (using field eqs)

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

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 $S \to \frac{m_{soft}}{f} \; X$.

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

- F_X is a dynamical auxiliary field $\to$ 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.

2. Couplings in non-linear MSSM.

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

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

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

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

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

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

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.

It will play a crucial role in the increase of the Higgs mass at tree-level and in reducing the little fine-tuning problem of MSSM.

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

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

3. Implications for Higgs masses.

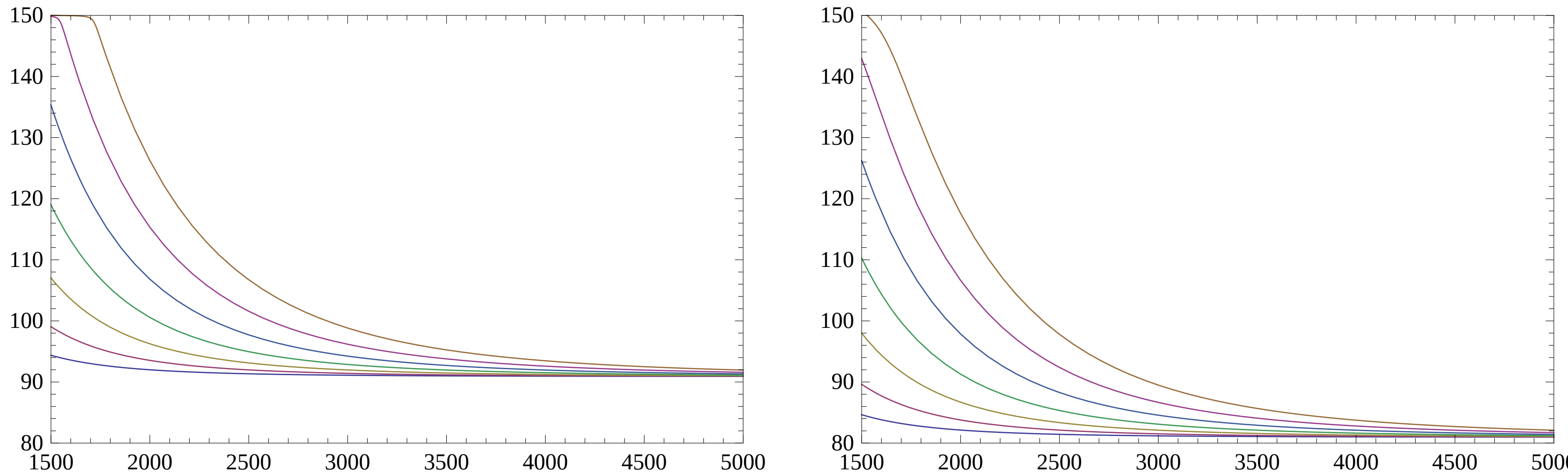
Due to the new quartic couplings, the Higgs masses change

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

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

$$1.5\ TeV \leq f \leq 10\ TeV$$

The 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 1000 GeV in steps of 100 GeV.

4. **Invisible decays of Higgs and Z boson.**

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

Comments :

Similar decay rates or the inverse ones

$$\chi \; \longrightarrow \; h \; G \quad , \quad \chi \; \longrightarrow \; Z^{\mu} \; G$$

computed some time ago in models of gauge mediation.

We find some differences.

We take into account the goldstino components of higgsinos and gauginos :

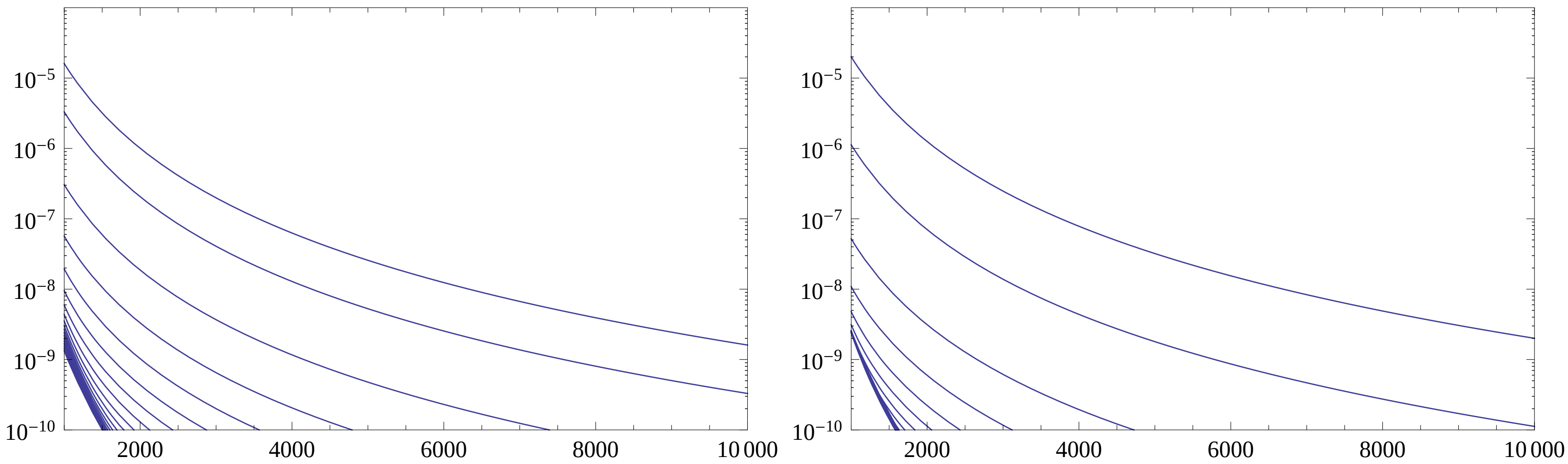
$$\mu\,\psi_{h_1^0} \;=\; \frac{1}{f\,\sqrt{2}}\Big(-m_2^2\,v_2 - B\,v_1 - \frac{1}{2}\,v_2\,\langle g_2 D_2^3 - g_1 D_1\rangle\Big)\,G + \cdots$$

$$\mu\,\psi_{h_2^0} \;=\; \frac{1}{f\,\sqrt{2}}\Big(-m_1^2\,v_1 - B\,v_2 + \frac{1}{2}\,v_1\,\langle g_2 D_2^3 - g_1 D_1\rangle\Big)\,G + \cdots$$

$$\lambda_1 \;=\; \frac{-1}{f\,\sqrt{2}}\,\langle D_1\rangle\;G + \cdots\,, \qquad \lambda_2^3 = \frac{-1}{f\,\sqrt{2}}\,\langle D_2^3\rangle\;G + \cdots$$

The leading order (in $1/f$) decay rates are into one goldstino and one neutralino.

The usual MSSM lagrangian also contributes to $1/f$ due to the goldstino components above.



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 $\gamma\gamma$.

$Z \longrightarrow \chi \; G$

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

Until now we only discussed the leading (in $1/f$ and number of derivatives) couplings to the goldstino. The universal "gravit." VA interaction appears through the Ferrara-Zumino current

$$
\begin{aligned}
&\frac{1}{f^2}\int d^4\theta\ D^\alpha X \bar{D}^{\dot\alpha} X^\dagger\ J_{\alpha\dot\alpha} \\
&= \frac{2}{3f^2}\int d^4\theta\ (D^\alpha X \bar{D}^{\dot\alpha} X^\dagger)(D_\alpha Q \bar{D}_{\dot\alpha} Q^\dagger)\ +\ \cdots \\
&= \frac{1}{f^2}\, T_G^{\mu\nu}\ T_{\mu\nu,Q}\ +\ \cdots
\end{aligned}
$$

Conclusions

• The Volkov-Akulov nonlinear lagrangian/couplings are not unique. More general couplings easily captured by the constrained superfield formalism.

• Narrow window of validity of non-linear MSSM $m_{sparticles} \leq E << \sqrt{f}$, still worth to explore.

• There is an new quartic Higgs coupling: contribution to the Higgs mass, important for $\sqrt{f} < 10$ TeV.

• Alleviated fine-tuning of the electroweak scale.

• Other new MSSM couplings coming from F_X, not present in the previous component formalism.

• If neutralino light, Γ_Z gives a lower bound $\sqrt{f} \geq 600$ GeV, $h \to \chi\ G$ comparable with $h \to \gamma\gamma$ in SM.

• Other phenomenological consequences of the F_X-induced MSSM couplings (in progress).

• Dark Matter ?