NMSSM AND GAUGE MEDIATION

Charles-Christophe JEAN-LOUIS
JHEP 0805:044,2008

LPT Orsay

LPSC, 19/11/08

NMSSM and gauge mediation

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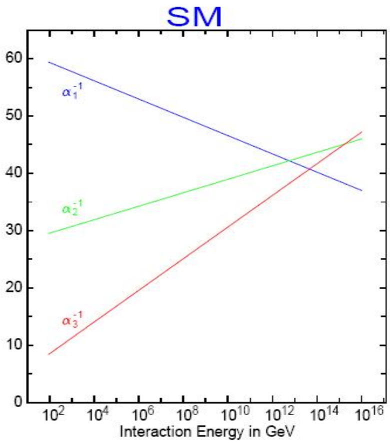
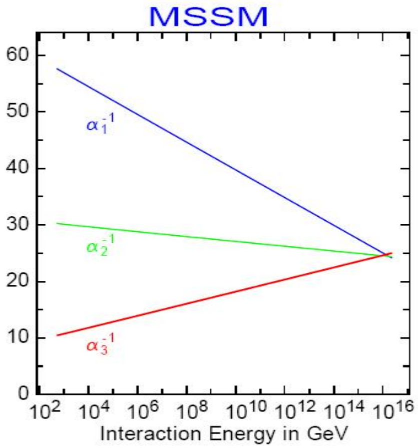
Motivation to use Supersymmetry

- Supersymmetry is a general symmetry between fermions and bosons
- Gauge couplings unification at GUT scale
- Supersymmetry solves the Hierarchy problem
- There is a supersymmetric particle which is a dark matter candidate
- Nevertheless, we need to break SUSY because we still do not observe any supersymmetric partners at low energy scale. We will make a description of some supersymmetric models and we will investigate a class of models of supersymmetry breaking called Gauge Mediated Supersymmetry Breaking (GMSB).

Motivation to use Supersymmetry





NMSSM and gauge mediation

Superfields

There are two kinds of superfields:

- Chiral superfield: $\hat{\Phi} = (z, \psi, F)$
  - *a)* leptons $\rightarrow$ sleptons
  - *b)* quarks $\rightarrow$ squarks
  - *c)* higgs $\rightarrow$ higgsinos
- Vector superfield: $\hat{V} = (v^{\mu}, \lambda, \mathrm{D})$
  - *a)* U(1) gauge boson $\rightarrow$ bino
  - *b)* SU(2) gauge bosons $\rightarrow$ winos
  - *c)* gluons $\rightarrow$ gluinos

F and D are auxiliary fields, they don't have kinetic terms.

Superpotential

The most general renormalizable superpotential is:

$$W(\Phi_i) \;=\; \tfrac{1}{3}g_{ijk}\hat{\Phi}_i\hat{\Phi}_j\hat{\Phi}_k + \tfrac{1}{2}m_{ij}\hat{\Phi}_i\hat{\Phi}_j + \lambda_i\hat{\Phi}_i \tag{1}$$

We can obtain the fermionic part of the lagrangian:

$$\mathcal{L} = (g_{ijk}\psi_i\psi_j z_k + \frac{1}{2}m_{ij}\psi_i\psi_j) + h.c \tag{2}$$

There is no fermionic component of the linear term in the lagrangian.

Supersymmetry breaking

Experimental limits on supersymmetric particles masses obviously shows that SUSY has to be broken. Thus, the supersymmetric particles masses will be different from Standard Model particles masses.
Thereby, for the Hierarchy problem there will be no exact cancellation between graphs with Standard Model particles and graphs with supersymmetric partners.
The induced fine-tuning can be solved in SUSY theories with a little energy gap between M_W and M_{SUSY}. If we want to solve the Hierarchy problem, we need $M_{SUSY} = O(TeV)$.

Supersymmetry breaking

Spontaneous SUSY breaking produces soft breaking terms proportional to the M_{SUSY} scale:

- mass terms for gauginos M_1, M_2 et M_3
- mass terms for sfermions (squarks et sleptons)
- mass terms for Higgs bosons
- trilinear couplings terms between sfermions and Higgs scalars
- trilinear couplings terms between Higgs scalars
- bilinear mixing term between Higgs scalars

Supersymmetry breaking

There are a lot of possibly complex parameters in the soft breaking potential of SUSY. Many models are able to reduce the number of parameters by making assumptions on the origin of these terms at high energy scale. The most widely-known models are Supergravity and Gauge Mediated Supersymmetry Breaking (GMSB). We will investigate various classes of GMSB models in the following. All these models assume the existence of a hidden sector that interact with particles of the observable sector by gravity mediation (SUGRA) or by gauge mediation (GMSB).

NMSSM and gauge mediation

MSSM Superpotential

This is the simplest supersymmetric model we can build. The MSSM Superpotential is:

$$W = \mu \hat{H}_u.\hat{H}_d + h_t \hat{Q}.\hat{H}_u \hat{T}^c_R - h_b \hat{Q}.\hat{H}_d \hat{B}^c_R - h_\tau \hat{L}.\hat{H}_d \hat{L}^c_R \quad (3)$$

where we didn't note the color indices.

$$\hat{Q} = \begin{pmatrix} \hat{T}_L \\ \hat{B}_L \end{pmatrix}, \hat{L} = \begin{pmatrix} \hat{\nu}_{\tau_L} \\ \hat{\tau}_L \end{pmatrix}, \hat{H}_u = \begin{pmatrix} \hat{H}^+_u \\ \hat{H}^0_u \end{pmatrix}, \hat{H}_d = \begin{pmatrix} \hat{H}^0_d \\ \hat{H}^-_d \end{pmatrix} \quad (4)$$

where:

$$\hat{H}_u.\hat{H}_d = \hat{H}^+_u \hat{H}^-_d - \hat{H}^0_u \hat{H}^0_d \quad (5)$$

MSSM Superpotential

We can write the fermionic lagrangian:

$$L = \mu\psi_{H_u}.\psi_{H_d} + h_t\psi_Q.H_u\psi_{T_R^c} - h_b\psi_Q.H_d\psi_{B_R^c} - h_\tau\psi_L.H_d\psi_{L_R^c} (+h.c) + ... \quad (6)$$

Here L just contain the matter particles.
In supersymmetry we need 2 Higgs bosons to give masses to the other particles.

MSSM Soft Susy breaking Potential

The soft breaking terms in MSSM are:

a) mass terms for scalar particles:

$$m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_Q|Q|^2$$

$$+m^2_T|T_R|^2 + m^2_B|B_R|^2 + m^2_L|L|^2 + m^2_\tau|L_R|^2$$

b) mass terms for gauginos:

$$\frac{1}{2}M_1\lambda_1\lambda_1 + \frac{1}{2}M_2\overrightarrow{\lambda_2}.\overrightarrow{\lambda_2} + \frac{1}{2}M_3\overrightarrow{\lambda_3}.\overrightarrow{\lambda_3}$$

c) soft terms associated to the superpotential:

$$(m^2_3 H_u.H_d + h_t A_t Q.H_u T^c_R - h_b A_b Q.H_d B^c_R - h_\tau A_\tau L.H_d L^c_R + h.c)$$

MSSM Particle Content

In this model, there are:

- Standard Model fermions and their scalar supersymmetric partners (sfermions)
- Standard Model gauge bosons
- 2 neutral scalar Higgs (h, H^0)
- 1 neutral pseudo-scalar Higgs (A^0)
- 1 charged Higgs ($H^\pm$)
- 2 charginos ($\chi^\pm_{1,2}$) originally from mixing between charged gauginos and charged fermionic superpartners of Higgs bosons (higgsinos)
- 4 neutralinos ($\chi^0_{1...4}$) of which the lighest called lighest supersymmetric particle (LSP) is gererally stable and is thence a natural candidate for Dark Matter. They come from the mixing between neutral gauginos et neutral higgsinos.

μ-problem

- We need $\mu \gtrsim 100 GeV$ to fulfil LEP constraints on charginos masses
- We must have $\mu \lesssim M_{SUSY}$ in order to have non-vanishing Higgs vev ($< H_{u,d} > \neq 0$)
- But spontaneous breaking of SUSY does not generate supersymmetric mass terms like μ of the order of M_{SUSY} in SUGRA framework
- $\longrightarrow$ μ-problem

NMSSM

In the NMSSM, we consider an additional gauge singlet Higgs superfield $\hat{S}$:

$$W = \not{\mu} \not{\hat{H}_u} . \not{\hat{H}_d} + \lambda \hat{S} \hat{H}_u . \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \quad (7)$$

$$L = \lambda S \psi_{H_u} . \psi_{H_d} + \kappa S \psi_S \psi_S + \dots \quad (8)$$

- Here we just keep the dimensionless supersymmetric couplings, these generate a $\mathbb{Z}_3$ symmetry.
- $< S > \sim M_{SUSY}$ solves the μ-problem

NMSSM Soft Susy breaking Potential

The soft breaking terms in NMSSM are:

a) mass terms for scalar particles:

$$m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + m_Q^2|Q|^2$$

$$+m_T^2|T_R|^2 + m_B^2|B_R|^2 + m_L^2|L|^2 + m_\tau^2|L_R|^2$$

b) mass terms for gauginos:

$$\frac{1}{2}M_1\lambda_1\lambda_1 + \frac{1}{2}M_2\overrightarrow{\lambda_2}.\overrightarrow{\lambda_2} + \frac{1}{2}M_3\overrightarrow{\lambda_3}.\overrightarrow{\lambda_3}$$

c) soft terms associated to the superpotential:

$$(m_3^2 H_u.H_d + \lambda A_\lambda S H_u.H_d + \frac{\kappa}{3}A_\kappa S^3$$

$$+h_t A_t Q.H_u T_R^c - h_b A_b Q.H_d B_R^c - h_\tau A_\tau L.H_d L_R^c + h.c)$$

NMSSM Particle Content

In this model, there are:

- Standard Model fermions and their scalar supersymmetric partners (sfermions)
- Standard Model gauge bosons
- 3 neutral scalar Higgs (h, H^0, S_R)
- 2 neutral pseudo-scalar Higgs (A^0, S_I)
- 1charged Higgs ($H^\pm$)
- 2 charginos ($\chi^\pm_{1,2}$)
- 5 neutralinos ($\chi^0_{1...4}, \chi^0_S$)

General NMSSM

We will see later that if we consider gauge mediated supersymmetry breaking, the radiative corrections generate the general NMSSM. In this generalization, the $\mathbb{Z}_3$ symmetry is broken, thus we avoid the problem of domain walls.

$$W = \lambda \hat{S}\hat{H}_u.\hat{H}_d + \frac{\kappa}{3}\hat{S}^3 + \mu' \hat{S}^2 + \xi_F \hat{S} \tag{9}$$

$$L = \lambda S \psi_{H_u}.\psi_{H_d} + \kappa S \psi_S \psi_S + \mu' \psi_S \psi_S + \dots \tag{10}$$

the linear term in S does not appear in the fermionic. The fields are the same as in the NMSSM but there are new couplings Thence the phenomenology of the general NMSSM can be different.

NMSSM and gauge mediation

Theoretical frame

In order to recreate the mass splitting between the Standard Model particles and supersymmetric particles, we need to break SUSY in a hidden sector. We use a field $\widehat{X}$ of which the scalar and the F components take vev:

$$\widehat{X} = M_{mess} + \theta^2 m^2 \tag{11}$$

Then we couple the observable sector to the hidden sector by using messenger fields $\hat{\varphi}_i$ charged under the gauge groups.

Theoretical frame

Due to a coupling $\hat{X}\hat{\bar{\varphi}}_i\hat{\varphi}_i$, the scalar vev of $\hat{X}$ induces a mass term M_{mess} for the scalar fields z_{φ_i} and the non-vanishing F_X-component

$$F_X = m^2 \tag{12}$$

induces a mass term

$$\frac{1}{2}m^2\left(z_{\varphi_i}^2 + {z_{\varphi_i}^*}^2\right) \tag{13}$$

which gives opposite contributions to the squared masses of the real and imaginary components of the scalar components of the messengers $\widehat{\varphi}_i$. This constitutes the original source of supersymmetry breaking.

Generation of the soft Susy breaking terms in GMSB

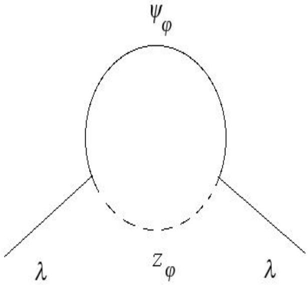
a) generation of gaugino masses at one loop level:

$$M_{1,2,3} \sim \frac{m^2}{16\pi^2 M_{mess}} \equiv M_{susy}$$

b) generation of scalar masses at the two loop level:

$$m_i^2 \sim \left(\frac{m^2}{16\pi^2 M_{mess}} \right)^2 \equiv M_{susy}^2$$

μ and m_3^2 are absent here. This is an important motivation to consider the NMSSM.



superspace power counting rules

We allow for couplings $\hat{S}\hat{\bar{\varphi}}_i\hat{\varphi}_i$ of the singlet to the messengers (always allowed because $\hat{S}$ and $\hat{X}$ have the same quantum numbers). Integrating out the messengers generates not only gaugino masses, but also m_S^2, $A_\lambda = \frac{1}{3}A_\kappa$, ... + possibly terms linear in $\hat{S}$ in the superpotential $W \sim \xi_F \hat{S}$ and in $V_{soft} \sim \xi_S S$, so-called tadpoles. We parametrize the effective superpotential ΔW and the soft terms ΔV_{soft} of the general NMSSM in agreement with SLHA2 conventions:

$$\Delta W = \mu' \widehat{S}^2 + \xi_F \widehat{S}\,, \tag{14}$$

$$\begin{aligned} \Delta V_{soft} &= m_S^2 |S|^2 + (\lambda A_\lambda S H_u H_d + \tfrac{1}{3}\kappa A_\kappa S^3 \\ &+ m_S'^2 S^2 + \xi_S S + h.c.)\,. \end{aligned} \tag{15}$$

superspace power counting rules

The parameters from ΔW and ΔV_{soft} are given by:

$$\mu' \sim \frac{m^2}{M} \sim M_{susy} \ , \tag{16}$$

$$\xi_F \sim m^2 \sim M_{susy} M_{mess} \ , \tag{17}$$

$$m_S^2 \sim \frac{m^4}{M^2} \sim M_{susy}^2 \ , \tag{18}$$

$$A_\lambda = \frac{1}{3} A_\kappa \sim \frac{m^2}{M} \sim M_{susy} \ , \tag{19}$$

$$m_S'^2 \sim \frac{m^4}{M^2} \sim M_{susy}^2 \ , \tag{20}$$

$$\xi_S \sim \frac{m^4}{M} \sim M_{susy}^2 M_{mess} \ . \tag{21}$$

Scenarios with tadpole terms

We will restrict ourselves here to the simplest case with only one messenger field φ: $W \sim \eta \hat{S} \hat{\bar{\varphi}} \hat{\varphi}$.
η is a Yukawa coupling.
The tadpole parameters ξ_F, ξ_S tend to be somewhat large: we require $\xi_F \lesssim M_{susy}^2$ and $\xi_S \lesssim M_{susy}^3$ but: $\xi_F \sim \eta M_{mess} M_{susy}$ and $\xi_S \sim 16\pi^2 \eta M_{mess} M_{susy}^2$.
Typically $M_{mess} \gtrsim 10^3 M_{susy} \rightarrow$ we need $\eta \lesssim 10^{-5}$.
As a consequence, μ' and $m_S'^2$ will be negligible.

Scenarios with tadpole terms

One phenomenologically viable region in parameters space is given for $\lambda \gtrsim 0.5$ and $tan\beta \lesssim 2$, the NMSSM specific contribution to the scalar Higgs mass matrix pushes the lightest Higgs mass above the LEP bound.

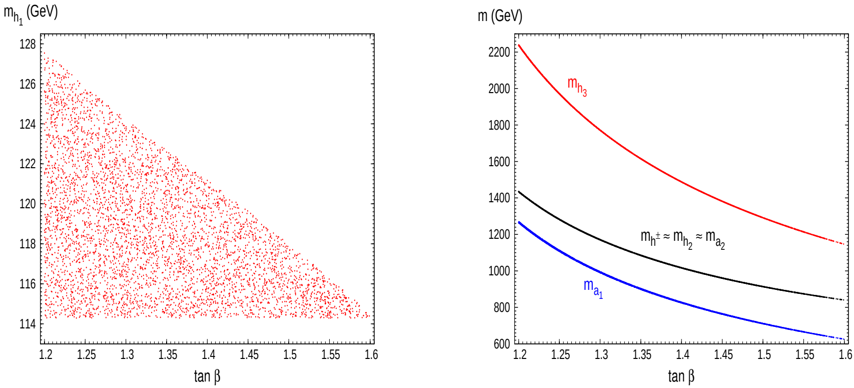
We investigate this region for:

- $M_{mess} = 10^6 GeV$
- $M_{susy} = 500 GeV$
- $\xi_F = 3.10^4 GeV^2$
- $0.45 < \lambda < 0.6$
- $1.2 < tan\beta < 2$

The sparticle spectrum is:

- $Bino \sim 105 GeV$
- $Winos \sim 200 GeV$
- $Higgsinos \sim 670 - 1000 GeV$
- $Singlino \sim 900 - 1800 GeV$
- $Sleptons \sim 140 - 290 GeV$
- $Squarks \sim 640 - 890 GeV$
- $Gluino \sim 660 GeV$

Scenarios with tadpole terms



Scenarios without tadpole terms (Delgado, Giudice, Slavich)

Tadpole terms can also be forbidden by discrete symmetries, hence the Yukawa coupling η can be much larger, if the messenger sector is enlarged to φ_1, $\bar{\varphi}_1$, φ_2, $\bar{\varphi}_2$. These can couple to $\widehat{S}$ and to $\widehat{X}$ in such a way that a discrete $\mathbb{Z}_3$ symmetry is left unbroken by the VEV of $\widehat{X}$

$$\widetilde{W} = \widehat{X}\left(\widehat{\bar{\varphi}}_1\widehat{\varphi}_1 + \widehat{\bar{\varphi}}_2\widehat{\varphi}_2\right) + \eta\widehat{S}\,\widehat{\bar{\varphi}}_1\widehat{\varphi}_2 \qquad (22)$$

There are phenomenologically viable regions (islands) in parameter space for $M_{mess} \sim 10^{13} GeV$, $M_{susy} \sim 1\, TeV$, $\lambda = 0.02...0.5$, $\eta = 0.05...2$, $tan\beta = 1.5...10$

Scenarios without tadpole terms (Delgado, Giudice, Slavich)

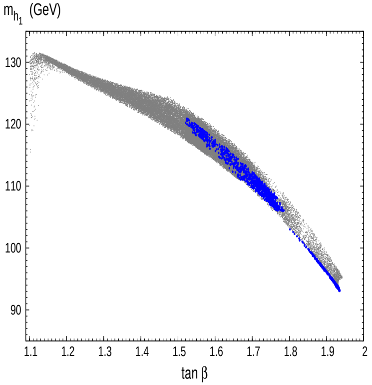
The stop masses are quite large (up to $\sim$ 2TeV) such that the stop/top induced radiative corrections to m_{h1} lift it (not far) above the LEP bound of $\simeq$ 114GeV.
The sparticle spectrum is:

- $Bino \sim 470GeV$
- $Winos \sim 900GeV$
- $Higgsinos \sim 1.4 - 2.4TeV$
- $Singlino \sim 800 - 5000GeV$
- $Sleptons \sim 690 - 1100GeV$
- $Squarks \sim 2TeV$
- $Gluino \sim 2.4TeV$

Scenarios without tadpole and A-terms

- All soft terms for the singlet vanish at M_{mess} except for m_S^2
- the scalar sector of the NMSSM has an R-symmetry (at M_{mess}), which is broken by radiative corrections to A_κ, A_λ induced by the gaugino mass terms
- at the weak scale: the explicit R-symmetry breaking by $A_\kappa, A_\lambda \sim$ a few GeV is small (if M_{mess} is not too large)
- the spontaneous R-symmetry breaking by $< H_u >, < H_d >, < S > \neq 0$ generates a pseudo-Goldstone Boson, a light CP-odd Higgs scalar a_1
- the lightest Higgs scalar h_1 decays via $h_1 \to a_1 a_1$, escaping LEP constraints if $m_{h1} > 90 GeV$ (depending on m_{a1})

Scenarios with tadpole terms and A-terms



- *Bino* $\sim 80 - 200 GeV$
- *Winos* $\sim 150 - 400 GeV$
- *Higgsinos* $\sim 400 - 700 GeV$
- *Singlino* $\sim 100 - 800 GeV$
- *Sleptons* $\sim 100 - 500 GeV$
- *Squarks* $\sim 300 - 900 GeV$
- *Gluino* $\sim 500 - 1200 GeV$

NMSSM and gauge mediation

The NMSSM allows to solve the μ-problem of GMSB models in a phenomenologically viable way, provided S couples to the messenger sector which induces soft Susy breaking terms for S. Depending on the messenger sector, different scenarios can be realized implying different phenomenologies in the Higgs and sparticle sectors. Possible are amongst others

- $\longrightarrow$ light CP-even scalars with large singlet component
- $\longrightarrow$ light CP-odd scalars (pseudo-Goldstone Bosons)

The analysis of generalized NMSSM models with general GMSB-like boundary conditions at M_{mess} is possible with the help of a Fortran code on the web page:
www.th.u-psud.fr/nmhdecay/nmssmtools.html