The MSSM with heavy scalars

Nicolás Bernal
LPT Orsay

Euro-GDR SUSY - Bruxelles

in collaboration with A. DJOUADI and P. SLAVICH
JHEP 0707:016,2007

14 November 2007

Supersymmetry & MSSM

➜ Hierarchy problem

Light fermionic partners

- ✔ Gauge coupling unification
- ✔ A candidate for cold dark matter

But light scalars brings along...

- ✘ Potentially > 100 parameters
- ✘ Quite light Higgs boson mass (tension with LEP searches)
- ✘ New sources of FCNC and CP violation
- ✘ New contributions to SM precision observables
- ✘ Fast proton decay from dimension-five operators

Supersymmetry & MSSM

➜ Hierarchy problem

Light fermionic partners

- ✔ Gauge coupling unification
- ✔ A candidate for cold dark matter

But light scalars brings along…

- ✘ Potentially > 100 parameters
- ✘ Quite light Higgs boson mass (tension with LEP searches)
- ✘ New sources of FCNC and CP violation
- ✘ New contributions to SM precision observables
- ✘ Fast proton decay from dimension-five operators

Scalar superpartners are needed to be light only to avoid fine tuning.
If we accept them to be heavy, we can retain the advantages of weak-scale SUSY and get rid of all its disadvantages. hep-th/0405159 Arkani-Hamed & Dimopoulos hep-ph/0406088 Giudice & Romanino hep-ph/0409232

Supersymmetry & MSSM

→ Hierarchy problem

Light fermionic partners

- ✔ Gauge coupling unification
- ✔ A candidate for cold dark matter

But light scalars brings along...

- ✘ Potentially > 100 parameters
- ✘ Quite light Higgs boson mass (tension with LEP searches)
- ✘ New sources of FCNC and CP violation
- ✘ New contributions to SM precision observables
- ✘ Fast proton decay from dimension-five operators

If we allow scalars to be heavy

- ✔ Gauge coupling unification
- ✔ A candidate for cold dark matter
- ✔ 5 parameters
- ✔ Higgs boson mass larger

✘ Fine-tuning more important

The MSSM with heavy scalars

There is no compelling criterion to define the maximal acceptable amount of fine tuning and the choice of the upper bound on the scalar mass scale is somewhat subjective.

Spectrum

- Scalars
  - Squarks
  - Sleptons
  - Higgs bosons but lighter one

  } at $M_S \gtrsim 10^4$ GeV
- SM-like Higgs boson H at EW scale ← fine-tuning
- Fermionic superpartners
  - Charginos $\tilde{\chi}^{\pm}$
  - Neutralinos $\tilde{\chi}^{0}$
  - Gluino $\tilde{g}$

  } at EW scale (protected by symmetries)

Effective Lagrangian

$$\mathcal{L} \supset m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \Big[h^u_{ij}\bar{q}_j u_i \epsilon H^* + h^d_{ij}\bar{q}_j d_i H + h^e_{ij}\bar{\ell}_j e_i H$$
$$+ \frac{M_3}{2}\tilde{g}^A\tilde{g}^A + \frac{M_2}{2}\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + \mu\,\tilde{H}_u^T\epsilon\tilde{H}_d$$
$$+ \frac{H^\dagger}{\sqrt{2}}\left(\tilde{g}_u\sigma^a\tilde{W}^a + \tilde{g}'_u\tilde{B}\right)\tilde{H}_u + \frac{H^T\epsilon}{\sqrt{2}}\left(-\tilde{g}_d\sigma^a\tilde{W}^a + \tilde{g}'_d\tilde{B}\right)\tilde{H}_d + \text{h.c.}\Big]$$

Standard Model like-Higgs boson

$$H = -\cos\beta\,\epsilon\,H_d^* + \sin\beta\,H_u$$

$$\tan\beta = \begin{cases} \frac{v_2}{v_1} & v_{1,2} \text{ vev for the Higgs fields} \quad \text{above } M_S \\ \text{Higgs mixing angle} & \text{below } M_S \end{cases}$$

$\tilde{g}_{u,d}$, $\tilde{g}'_{u,d}$ Higgs-higgsino-gaugino effective couplings

Effective Lagrangian

$$\mathcal{L} \supset m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \Big[h^u_{ij} \bar{q}_j u_i \epsilon H^* + h^d_{ij} \bar{q}_j d_i H + h^e_{ij} \bar{\ell}_j e_i H$$

$$+ \frac{M_3}{2} \tilde{g}^A \tilde{g}^A + \frac{M_2}{2} \tilde{W}^a \tilde{W}^a + \frac{M_1}{2} \tilde{B}\tilde{B} + \mu \tilde{H}_u^T \epsilon \tilde{H}_d$$

$$+ \frac{H^\dagger}{\sqrt{2}} \left(\tilde{g}_u \sigma^a \tilde{W}^a + \tilde{g}'_u \tilde{B}\right) \tilde{H}_u + \frac{H^T \epsilon}{\sqrt{2}} \left(-\tilde{g}_d \sigma^a \tilde{W}^a + \tilde{g}'_d \tilde{B}\right) \tilde{H}_d + \text{h.c.} \Big]$$

Matching conditions at the scale M_S

$$\lambda(M_S) = \tfrac{1}{4}\left[g^2(M_S) + g'^2(M_S)\right] \cos^2 2\beta$$

$$h^u_{ij}(M_S) = \lambda^{u*}_{ij}(M_S) \sin\beta, \qquad h^{d,e}_{ij}(M_S) = \lambda^{d,e*}_{ij}(M_S) \cos\beta$$

$$\tilde{g}_u(M_S) = g(M_S) \sin\beta, \qquad \tilde{g}_d(M_S) = g(M_S) \cos\beta$$

$$\tilde{g}'_u(M_S) = g'(M_S) \sin\beta, \qquad \tilde{g}'_d(M_S) = g'(M_S) \cos\beta$$

Spectrum determination

SuSpect subroutine (J.L. Kneur et al.) hep-ph/0211331

- Inputs
  - M_S — Soft SUSY-breaking sfermion mass parameter
  - $M_1, M_2, M_3\,(M_{GUT})$ — Gaugino mass parameters
  - $\mu\,(M_Z)$ — Higgs-higgsino mass parameter
  - $A_t\,(M_S)$ — Trilinear coupling $H - \tilde{t} - \tilde{t}$
  - $\tan\beta\,(M_S)$ — & SM inputs
- Evolution:

M_{EW}		M_S		M_{GUT}
g_1, g_2, g_3 h^t, h^b, h^τ μ	$\leftsquigarrow$ Split-SUSY 1-loop RGE $\rightsquigarrow$	$\tilde{g}_u, \tilde{g}_d$ $\tilde{g}'_u, \tilde{g}'_d$ λ, A_t	$\leftsquigarrow$ MSSM 1-loop RGE $\rightsquigarrow$	M_1, M_2, M_3

- Compute physical masses and couplings at the EW scale.

If the scalars are heavy, they will lead to significant quantum corrections, enhanced by large $\log(M_{EWSB}/M_S)$. So, one has to properly decouple the heavy states from the low-energy theory and resum the large logarithmic corrections by means of RGEs.

Spectrum determination

SuSpect subroutine (J.L. Kneur et al.) hep-ph/0211331

- Inputs
  - M_S — Soft SUSY-breaking sfermion mass parameter
  - $M_1, M_2, M_3\,(M_{GUT})$ — Gaugino mass parameters
  - $\mu\,(M_Z)$ — Higgs-higgsino mass parameter
  - $A_t\,(M_S)$ — Trilinear coupling $H-\tilde{t}-\tilde{t}$
  - $\tan\beta\,(M_S)$ — & SM inputs
- Evolution:

M_{EW}		M_S		M_{GUT}
g_1, g_2, g_3 h^t, h^b, h^τ μ	$\leftsquigarrow$ Split-SUSY 1-loop RGE $\rightsquigarrow$	$\tilde{g}_u, \tilde{g}_d$ $\tilde{g}'_u, \tilde{g}'_d$ λ, A_t	$\leftsquigarrow$ MSSM 1-loop RGE $\rightsquigarrow$	M_1, M_2, M_3

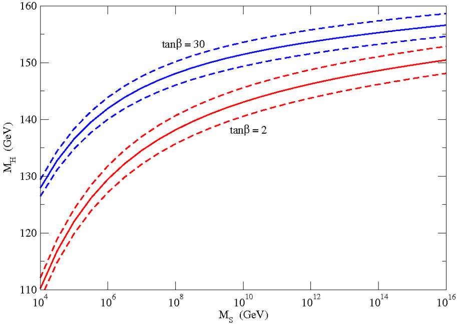
- Compute physical masses and couplings at the EW scale.

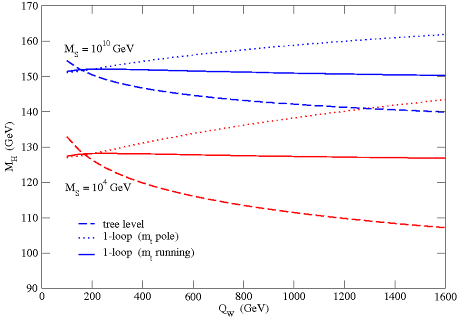
✚ adapt this scenario :
- Hdecay: Higgs boson decay — $H-\tilde{\chi}-\tilde{\chi}$ coupling — $H\to\tilde{\chi}\tilde{\chi}$
- Sdecay: χ^0 and χ^+ decays
- $\tilde{g}$ decays: P. Gambino, G.F. Giudice, P. Slavich, Nucl.Phys.B726:35-52,2005
- subroutine 'omega' (M. Drees & al.) with $H\to WW^*\to Wff$

Higgs mass

$$M_H = \sqrt{\frac{\lambda(Q)}{\sqrt{2}\,G_F}}\left[1 + \delta^{\rm SM}(Q) + \delta^{\chi}(Q)\right]$$

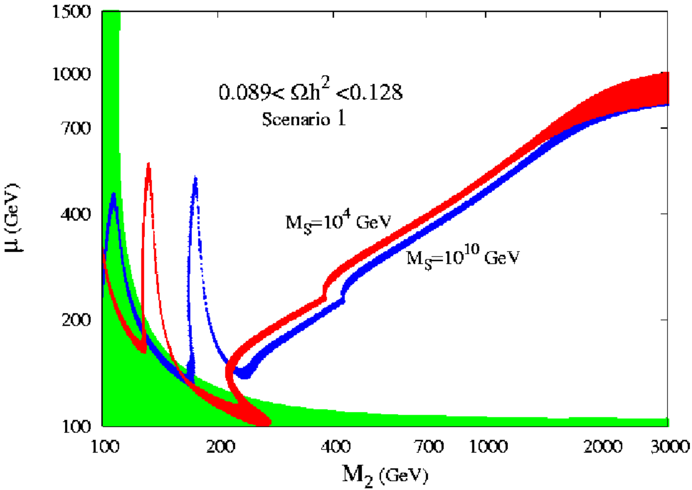
The radiative corrections to the Higgs mass are enhanced by a large logarithm





$\mu = m_{1/2} = 500$ GeV $\quad A_t = 0 \qquad M_t = 170.9$ GeV

Collider & Dark Matter constraints



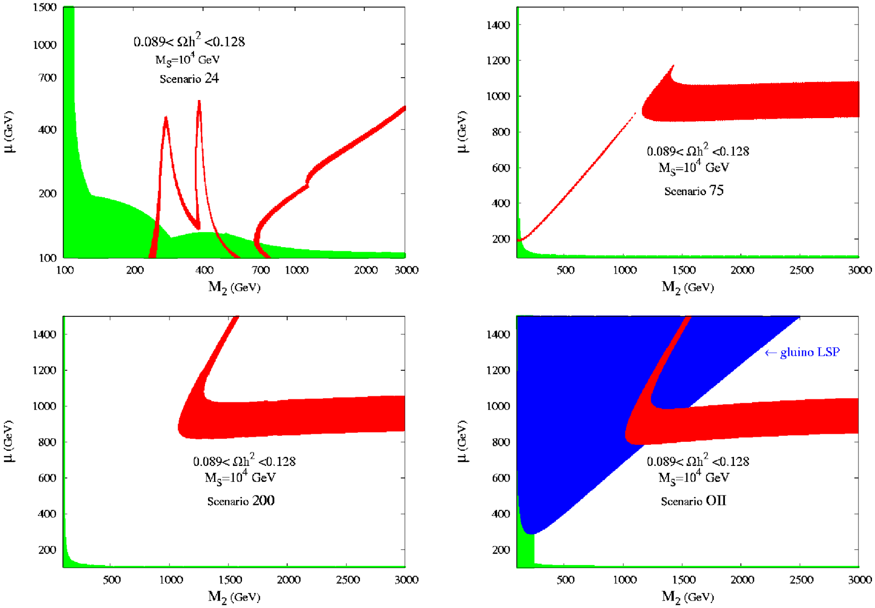
Universal gaugino masses $A_t = 0, \tan\beta = 30$

Dark Matter: non-universal gaugino masses

F_Φ	M_1	M_2	M_3
1	1 (∼ 1.0)	1(∼ 2.0)	1 (∼ 7.8)
24	1 (∼ 1.0)	3 (∼ 6.3)	−2 (∼ 15.2)
75	5 (∼ 1.0)	−3 (∼ −1.2)	−1 (∼ −1.5)
200	10 (∼ 2.4)	2 (∼ 1.0)	1 (∼ 1.9)
OII	53/5 (∼ 1.4)	5 (∼ 1.3)	1 (∼ 1.0)

Relative gaugino masses at M_{GUT} (M_Z) for differents non-universal gaugino masses cases, with $M_S = 10^4$ GeV.

Dark Matter: non-universal gaugino masses

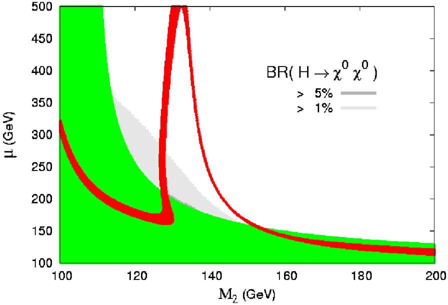


Higgs decays

This Higgs boson will decay mostly like the SM Higgs

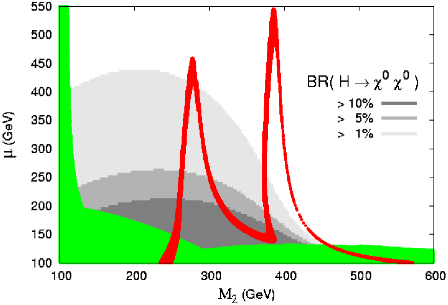
For $m_H \begin{cases} \lesssim 130 \text{ GeV} \rightsquigarrow & \sim 90\%\ b\bar{b}\ \&\ \tau\bar{\tau},\ gg,\ c\bar{c} \\ \gtrsim 140 \text{ GeV} \rightsquigarrow & \gtrsim 80\%\ WW \text{ and } ZZ \end{cases}$

Scenario **1**



$M2 \sim 2 \cdot M1$

Scenario **24**



$M2 \sim 6 \cdot M1$

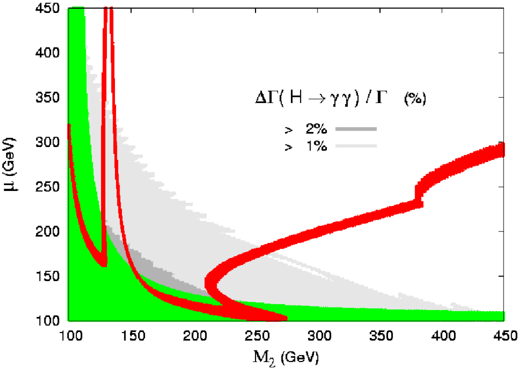
$M_S = 10^4$ GeV & $\tan\beta = 30$

$m_H \sim 130$ GeV

Mesurable at the **ILC**!

Higgs decays

$H \to \gamma\gamma, Z\gamma$ very rare but theoretically interesting!



$$\frac{\Delta\Gamma}{\Gamma} = \frac{\Gamma_{HS}-\Gamma_{SM}}{\Gamma_{SM}}$$

$M_S = 10^4$ GeV
$\tan\beta = 30$

$m_H \sim 130$ GeV

$\chi^+\chi^- h$ coupling not proportionally to $m_\chi \Rightarrow$ amplitudes are damped by inverse power of m_χ.

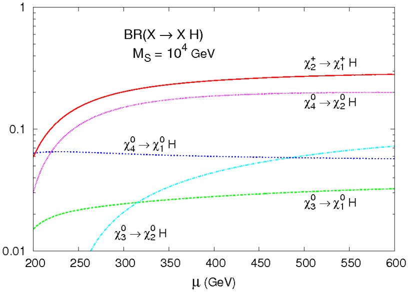
Potentially observable at the $\gamma\gamma$ option of the **ILC**!

$\rightsquigarrow$ Contributions to $H \to Z\gamma$ in general smaller.

Chargino & Neutralino decays: Higgs production

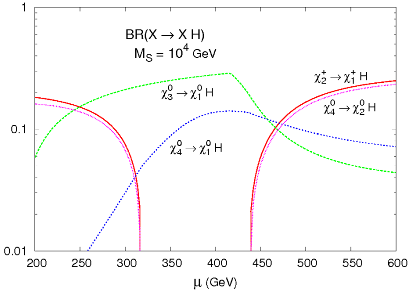
$$\begin{cases} \chi_i \rightarrow \chi_j V^* \rightarrow \chi_j f\bar{f} \\ \chi_i \rightarrow f\tilde{f}^* \rightarrow f\bar{f}\chi_j & \text{strongly suppressed by heavy scalars} \\ \chi_i \rightarrow \chi_j H \\ \chi_i^0 \rightarrow \chi_j^0 \gamma & < 1\% \end{cases}$$

Scenario **1**



$M_1 \sim 60$ GeV, $M_2 \sim 130$ GeV

Scenario **24**



$M_1 \sim 30$ GeV, $M_2 \sim 390$ GeV

Conclusions & Prospects

- The MSSM, in the case where the scalars are heavy, is a more predictive scenario.
- We still have
  - ✔ gauge coupling unification,
  - ✔ a good candidate for dark matter.

But we require a large fine-tuning for the Higgs boson.

- We have studied this model with heavy scalars
  - ✔ RGE for all couplings,
  - ✔ RC for Higgs, neutralino, chargino and gluino masses,
  - ✔ universal and non-universal gaugino masses at M_{GUT}
- scenario implemented in SuSpect,

- Constraints
  - collider searches and high-precision measurements
  - WMAP – DM relique density
  - gluino lifetime

- Phenomenology: Higgs & sparticles (charginos, neutralinos, gluinos)

  Differences between
  - SM and Heavy scalars
  - Universal and non-universal scenarios