

Slim SUSY: light Higgs sector phenomenology in scenarios with heavy sfermions

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References

Work in collaboration with **L. Díaz Cruz** and **A. Szynkman**,
based on:

- E.A., J. L. Diaz-Cruz and A. Szynkman, “Decays of H^0/A^0 in supersymmetric scenarios with heavy sfermions”, Eur. Phys. J. C **73**, 2384 (2013) [arXiv:1211.0163 [hep-ph]].
- E.A., J. L. Diaz-Cruz and A. Szynkman, “Slim SUSY”, Phys. Lett. B **722**, 100 (2013) [arXiv:1301.0708 [hep-ph]].

Computations performed with:

- SuSpect 2.41 for SUSY spectrum.
- SDECAY 1.3b for sparticles decays.
- HDECAY 3.4 for Higgs boson decays.
- FeynHiggs 2.9.4 for Higgs production cross sections.

Outline

- ➊ Motivations
- ➋ Definition of Slim SUSY parameter space
- ➌ Higgs mass and LHC constraints
- ➍ Decays of H^0 and A^0 Higgs bosons in Wino-LSP scenario
- ➎ Favorable case: large bino-higgsino mixing
- ➏ Conclusions and future work

Motivation

LHC data

- Discovery of SM-like Higgs boson with $m_{h_{\text{SM}}} \simeq 125$ GeV.
- Direct searches for squarks and gluinos push their masses into the multi-TeV range.

Several avenues of reasoning in SUSY community:

- Phenomenological MSSM: “no compromise” model.
- Natural SUSY: solution of hierarchy problem, in tension with present SUSY bounds.
- Split SUSY: fine-tuning aside, scalars in multi-TeV range, gauginos and higgsinos with lower masses.

Full heavy Higgs spectrum with masses near the EW scale without any phenomenological conflict.

Introduction

Surviving MSSM from LHC data

- SM-like Higgs boson with $m_{h^0} \simeq 125$ GeV.
- Heavy sfermions of 3rd generation (with $m = \mathcal{O}(\text{TeV})$), to account for the Higgs mass value.
- Heavy masses of $\mathcal{O}(10\text{--}100 \text{ TeV})$ for 1st and 2nd generations of sfermions to solve the SUSY and CP flavor problems.
- A neutralino sector with an LSP mass of $\mathcal{O}(100 \text{ GeV})$, chosen as the DM candidate.
- The full MSSM Higgs sector (h^0, H^0, A^0, H^\pm) with masses near the EW scale.

Definition of Slim SUSY

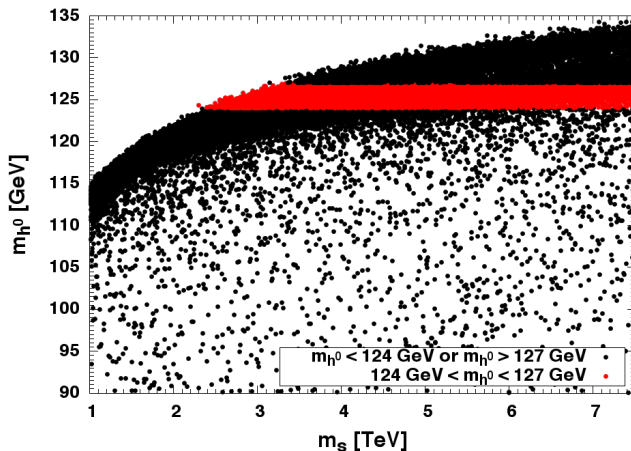
Parameter space

- $1 < \tan \beta < 60$
- $200 \text{ GeV} < m_{A^0} < 600 \text{ GeV}$
- $0.1 \text{ TeV} < |M_1|, |M_2|, |\mu| < 3 \text{ TeV}$
- $1 \text{ TeV} < M_3 < 3 \text{ TeV}$
- $-10 \text{ TeV} < A_t < 10 \text{ TeV}$
- $10 \text{ TeV} < M_S < 100 \text{ TeV}$
- $1 \text{ TeV} < m_s < 7.5 \text{ TeV}$

Not trivial choice. Important RGE effects: unstable electroweak Higgs minimum or tachyonic states of 3rd gen. sfermions. Scenarios with $m_s < 8 \text{ TeV}$ free of this difficulty.

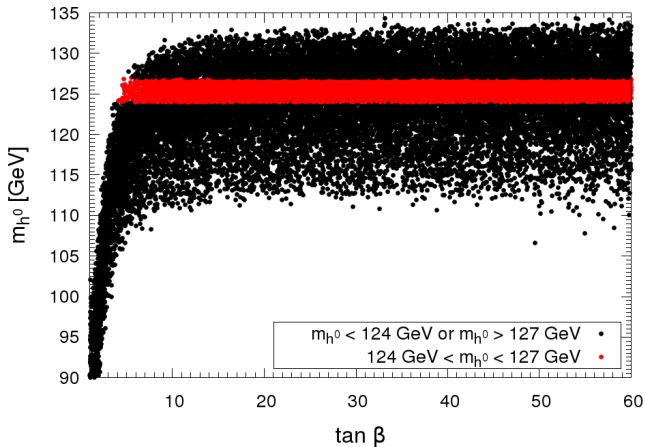
Higgs mass and LHC constraints

m_{h^0} dependence on m_s



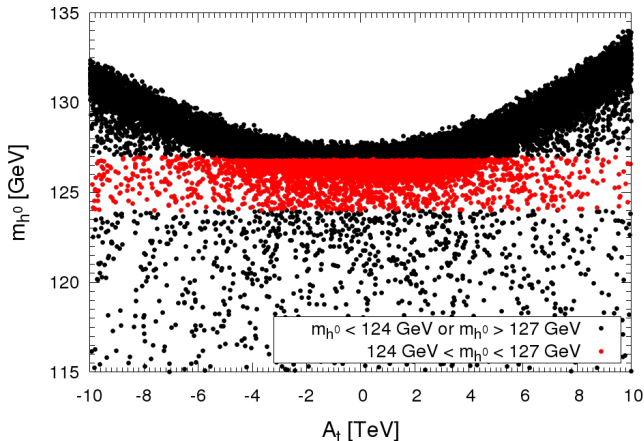
$m_s \gtrsim 2.5$ TeV in order to obtain $m_{h^0} \simeq 125$ GeV (with $A_t = 0$)

m_{h^0} dependence on $\tan \beta$



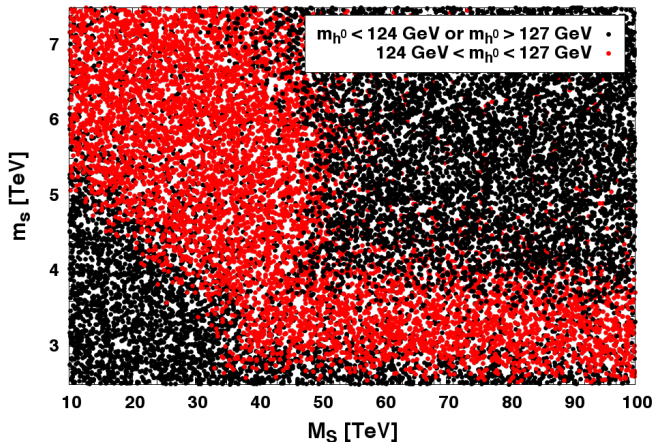
$\tan \beta \gtrsim 5$ in order to obtain $m_{h^0} \simeq 125$ GeV (with $A_t = 0$)

m_{h^0} dependence on A_t



$A_t = 0$ without any loss of generality for the pheno analysis.

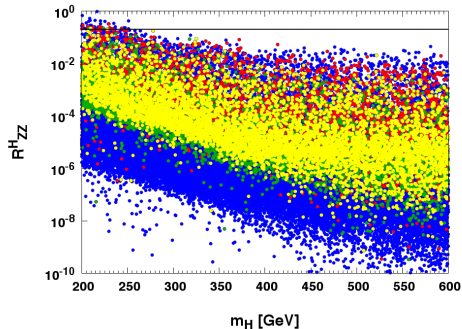
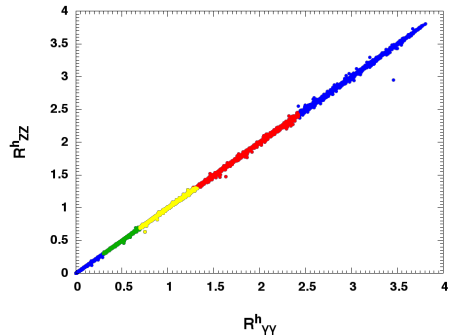
m_{h^0} dependence on m_s and M_S



Non-negligible radiative corrections to m_{h^0} from squarks of 1st and 2nd generations.

Signal rates of Higgs bosons

$$R_{XX}^{h,H} = \frac{\sigma(gg \rightarrow h^0, H^0)}{\sigma(gg \rightarrow h_{\text{SM}})} \frac{\text{BR}(h^0, H^0 \rightarrow XX)}{\text{BR}(h_{\text{SM}} \rightarrow XX)}$$



Red: $0.7 < R_{\gamma\gamma}^h < 2.42$. Green: $0.3 < R_{ZZ}^h < 1.3$. Yellow: both. Blue: none.

Slim SUSY scenarios

Defined according to the nature of the LSP and the number of neutralinos/charginos with masses similar to the Higgs bosons and reachable at the LHC:

- **Bino-LSP scenario:** Only one bino-like neutralino at the EW scale, thus we will have in this case $|M_1| \ll |M_2|, |\mu|$.
- **Wino-LSP scenario:** One wino-like neutralino and one wino-like chargino, degenerate in mass, which occurs for $|M_2| \ll |M_1|, |\mu|$.
- **Higgsino-LSP scenario:** Two higgsino-like neutralinos and one higgsino-like chargino, in this case: $|\mu| \ll |M_1|, |M_2|$.

Neutralino sector

The four-dimensional neutralino mass matrix in the $(-i\tilde{B}^0, -i\tilde{W}_3^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis read as

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix},$$

where $s_W = \sin \theta_W$, $c_W = \cos \theta_W$, $s_\beta = \sin \beta$, $c_\beta = \cos \beta$ and

- M_1 is the bino mass,
- M_2 is the wino mass,
- μ is the higgsino mass.

Chargino sector

The two-dimensional chargino mass matrix in the wino-higgsino basis read as

$$M_{\tilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2}M_W s_{\beta} \\ \sqrt{2}M_W c_{\beta} & \mu \end{pmatrix},$$

where $s_{\beta} = \sin \beta$, $c_{\beta} = \cos \beta$ and

- M_2 is the wino mass,
- μ is the higgsino mass.

Decays of H^0/A^0 Higgs bosons

Wino-LSP scenario as example

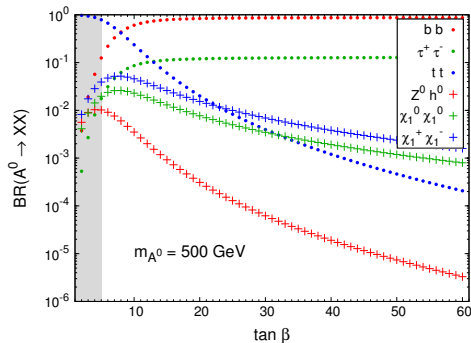
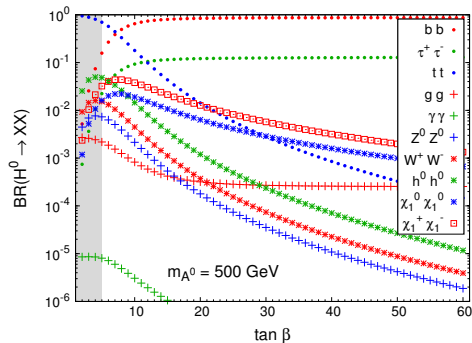
Content of particles below 1-TeV scale:

- one wino-like neutralino $\tilde{\chi}_1^0$ ($100 \text{ GeV} \lesssim m_{\tilde{\chi}_1^0} \lesssim 150 \text{ GeV}$)
- one wino-like chargino $\tilde{\chi}_1^\pm$ ($m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$)
- one light Higgs boson h^0 ($123 \text{ GeV} < m_{h^0} < 128 \text{ GeV}$)
- three heavy Higgs bosons H^0, A^0, H^\pm
($200 \text{ GeV} \lesssim m_{H^0}, m_{A^0}, m_{H^\pm} \lesssim 600 \text{ GeV}$)

Higgs couplings to bosons and SM fermions

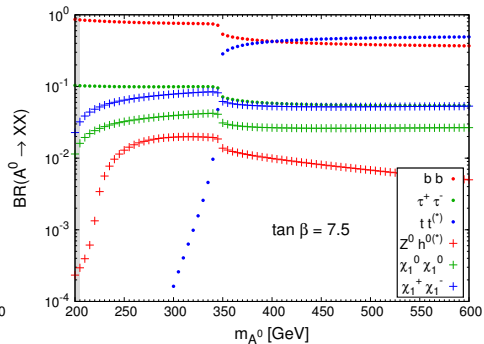
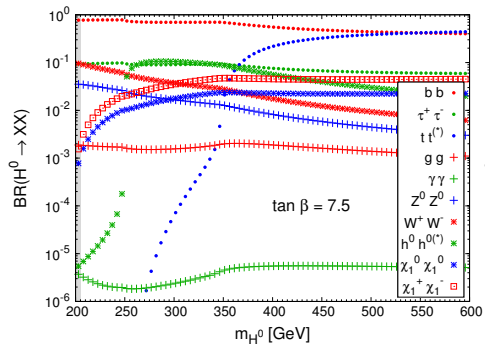
Vertex	Coupling
$\{h, H\}W_\mu W_\nu$	$ig_2 M_W g_{\mu\nu} \{\sin(\beta - \alpha), \cos(\alpha + \beta)\}$
$\{h, H\}Z_\mu Z_\nu$	$ig_2 \frac{M_W}{\cos^2 \theta_W} g_{\mu\nu} \{\sin(\beta - \alpha), \cos(\alpha + \beta)\}$
$\{h, H, A\}u\bar{u}$	$-\frac{i}{2} \left(\frac{m_u}{M_W} \right) \frac{g_2}{\sin \beta} \{\cos \alpha, \sin \alpha, -i\gamma_5 \cos \beta\}$
$\{h, H, A\}d\bar{d}$	$-\frac{i}{2} \left(\frac{m_d}{M_W} \right) \frac{g_2}{\cos \beta} \{-\sin \alpha, \cos \alpha, -i\gamma_5 \sin \beta\}$
$\{h, H\}AZ_\mu$	$-\frac{e(p+k)_\mu}{2 \cos \theta_W \sin \theta_W} \{\cos(\beta - \alpha), -\sin(\beta - \alpha)\}$
$\{h, H\}hh$	$\frac{g_2 M_Z}{2 \cos \theta_W} \{3 \cos 2\alpha \sin(\beta + \alpha), 2 \sin 2\alpha \sin(\beta + \alpha) - \cos 2\alpha \cos(\beta + \alpha)\}$

Dependence on $\tan \beta$



- For $\tan \beta \gtrsim 10$, $H^0, A^0 \rightarrow b\bar{b}$ are the dominant decays with $BR \simeq 0.9$.
- If $t\bar{t}$ channel is open, for $\tan \beta \lesssim 10$ it becomes the dominant one.
- $BR(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 2 \times 10^{-2}$ and $BR(A^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 4 \times 10^{-2}$.
- Decays of H^0 and A^0 into charginos larger than invisible ones, reaching values of almost 0.05 and 0.1, respectively.

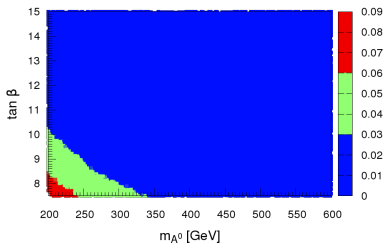
Dependence on m_{A^0}



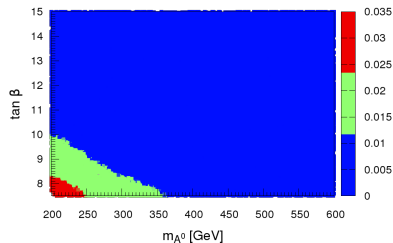
- $H^0 \rightarrow W^+ W^-$ channel reaches BR $\simeq 0.1$ when the $t\bar{t}$ channel closed.
- Maximum value of BR($H^0 \rightarrow Z^0 Z^0$) is 0.03, with $t\bar{t}$ not allowed.
- $H^0 \rightarrow h^0 h^0$ mode larger than $W^+ W^-$ and BR $\simeq 0.2$ with $t\bar{t}$ closed.
- BR($A^0 \rightarrow Z^0 h^0$) $\simeq 0.03$ for the same conditions as $H^0 \rightarrow W^+ W^-$, $Z^0 Z^0$, $h^0 h^0$.

Dependence on $[m_{A^0}, \tan \beta]$ plane

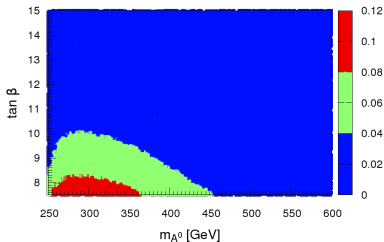
$\text{BR}(H^0 \rightarrow W^+ W^-)$



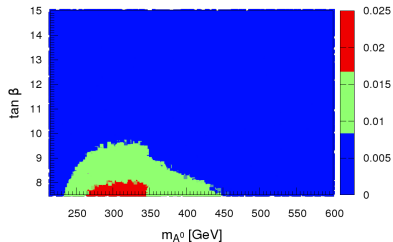
$\text{BR}(H^0 \rightarrow Z^0 Z^0)$



$\text{BR}(H^0 \rightarrow h^0 h^0)$



$\text{BR}(A^0 \rightarrow Z^0 h^0)$



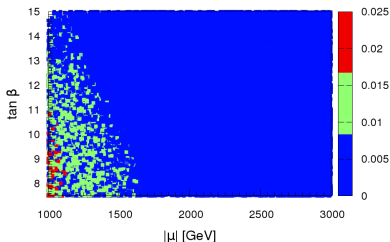
Higgs couplings to neutralinos and charginos

$$\begin{aligned}G_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 H^0}^{L,R} &= \frac{1}{2 \sin \theta_W} (Z_{12} - \tan \theta_W Z_{11}) (\cos \alpha Z_{13} - \sin \alpha Z_{14}) , \\G_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 A^0}^L &= \frac{1}{2 \sin \theta_W} (Z_{12} - \tan \theta_W Z_{11}) (-\sin \beta Z_{13} + \cos \beta Z_{14}) , \\G_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 A^0}^R &= -G_{\tilde{\chi}_1^0 \tilde{\chi}_1^0 A^0}^L , \\G_{\tilde{\chi}_1^- \tilde{\chi}_1^+ H^0}^{L,R} &= \frac{1}{\sqrt{2} \sin \theta_W} [\cos \alpha V_{11} U_{12} + \sin \alpha V_{12} U_{11}] , \\G_{\tilde{\chi}_1^- \tilde{\chi}_1^+ A^0}^L &= -\frac{1}{\sqrt{2} \sin \theta_W} [\sin \beta V_{11} U_{12} + \cos \beta V_{12} U_{11}] , \\G_{\tilde{\chi}_1^- \tilde{\chi}_1^+ A^0}^R &= -G_{\tilde{\chi}_1^- \tilde{\chi}_1^+ A^0}^L ,\end{aligned}$$

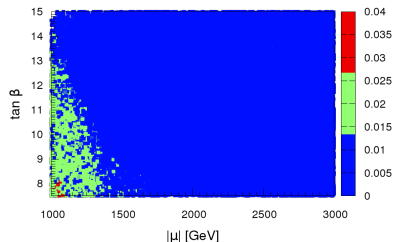
where Z_{ij} are the entries of the single real matrix Z which diagonalizes $M_{\tilde{\chi}^0}$ and U_{ij} and V_{ij} are the entries of the real matrices U and V that diagonalize $M_{\tilde{\chi}^\pm}$.

Dependence on $[\mu, \tan \beta]$ plane

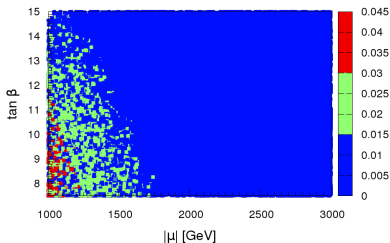
$BR(H^0 \rightarrow \chi_1^0 \chi_1^0)$



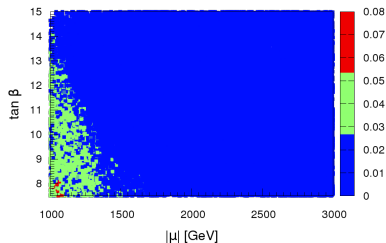
$BR(A^0 \rightarrow \chi_1^0 \chi_1^0)$



$BR(H^0 \rightarrow \chi_1^+ \chi_1^-)$

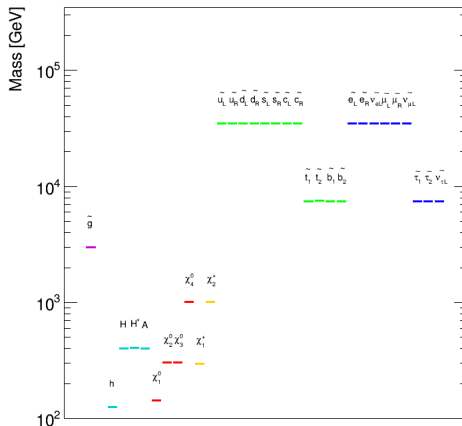


$BR(A^0 \rightarrow \chi_1^+ \chi_1^-)$

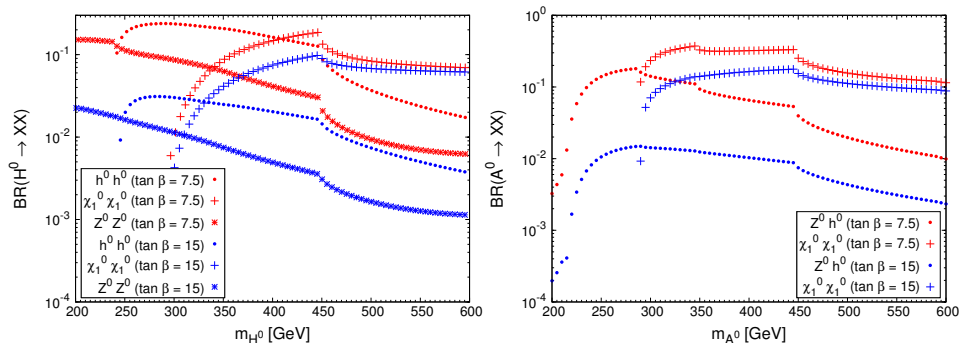


Favorable scenario: large bino-higgsino mixing

- $M_S = 35$ TeV, $m_s = 7.5$ TeV, $A_t = 0$, $M_3 = 3$ TeV.
- $m_{A^0} = 400$ GeV, $\tan \beta = 7.5$.
- $M_1 = 150$ GeV, $M_2 = 1$ TeV, $\mu = 300$ GeV.

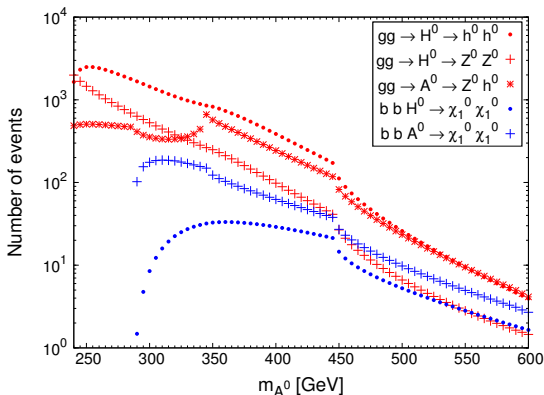


Favorable scenario: decays of H^0 and A^0



- $\tan \beta = 7.5$ (red points): $BR(H^0 \rightarrow h^0 h^0) \simeq 0.2$, $BR(A^0 \rightarrow Z^0 h^0) \simeq 0.2$, $BR(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 0.2$, $BR(A^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 0.4$.
- $\tan \beta = 15$ (blue points): $H^0 \rightarrow h^0 h^0$ and $A^0 \rightarrow Z^0 h^0$ decrease drastically. $BR(H^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \lesssim 6 \times 10^{-2}$, $BR(A^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 0.1$.

Favorable scenario: estimate of N_{events} at the LHC



- $N_{\text{events}}(H^0 \rightarrow h^0 h^0) \simeq 2 \times 10^3$ for $\mathcal{L} = 23 \text{ fb}^{-1}$ and $m_{A^0} < 300 \text{ GeV}$.
- $N_{\text{events}}(A^0 \rightarrow Z^0 h^0) \simeq 1 \times 10^3$ for $m_{A^0} \simeq 350 \text{ GeV}$.
- Invisible decays of H^0 and A^0 give 70 and 200 events at the most, respectively (production x-sections associated with $b\bar{b}$).

Conclusions

- LHC data suggest that a heavy SUSY scale should be part of the surviving MSSM.
- We propose alternative MSSM scenario with gluinos and sfermions within the multi-TeV range and gauginos/higgsinos at the EW scale, as in Natural SUSY, pure gravity mediation, Split and Spread SUSY...
- New feature: heavy MSSM Higgs bosons (H^0 , A^0 , H^\pm) near the EW scale too.
- Higgs scalars could be searched at the LHC and provide first signature of SUSY at the EW scale, together with a DM candidate.
- Combination of $gg \rightarrow H^0 \rightarrow h^0 h^0$ and $b\bar{b}A^0 \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$ could provide a clear hint of the presented Slim SUSY scenarios.

The mood of the 90's was to expect that LEP would start the detection of the full spectrum of superpartners of the MSSM, and the task would be completed at the LHC. We have learned by now that the possible realization of SUSY in nature, and its detection at the LHC, will not be as exuberant as it was thought then, but rather slim.

Future work

- Search strategies for $H^0 \rightarrow h^0 h^0$ and $A^0 \rightarrow Z^0 h^0$ channels and the invisible modes $H^0, A^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$.
- Study of one-loop flavor changing processes induced by SUSY in quark and charged lepton sectors, such as $\phi \rightarrow tc$, $\phi \rightarrow \tau\mu$ ($\phi = h^0, H^0, A^0$) or $t \rightarrow ch^0$. Take advantage of non-decoupling SUSY behavior in Higgs decays.
- Proposals of theoretical realizations of Slim SUSY from high-scale theories: flavor symmetries, string constructions, Higgs as pseudo-Goldstone bosons or composite states.
- ...

Backup slides

MSSM spectrum

Extended Standard Model spectrum	SUSY particles			
	$SU(3)_C \times SU(2)_L \times U(1)_Y$ interaction eigenstates		Mass eigenstates	
	Notation	Name	Notation	Name
$q = u, d, s, c, b, t$ $l = e, \mu, \tau$ $\nu = \nu_e, \nu_\mu, \nu_\tau$	\tilde{q}_L, \tilde{q}_R \tilde{l}_L, \tilde{l}_R $\tilde{\nu}$	squarks sleptons sneutrino	\tilde{q}_1, \tilde{q}_2 \tilde{l}_1, \tilde{l}_2 $\tilde{\nu}$	squarks sleptons sneutrino
g	\tilde{g}	gluino	\tilde{g}	gluino
W^\pm $H_1^+ \supset H^+$ $H_2^- \supset H^-$	\tilde{W}^\pm \tilde{H}_1^+ \tilde{H}_2^-	wino higgsino higgsino	$\tilde{\chi}_i^\pm$ ($i=1,2$)	charginos
γ Z $H_1^0 \supset h^0, H^0, A^0$ $H_2^0 \supset h^0, H^0, A^0$ W^3 B	$\tilde{\gamma}$ \tilde{Z} \tilde{H}_1^0 \tilde{H}_2^0 \tilde{W}^3 \tilde{B}	photino zino higgsino higgsino wino bino	$\tilde{\chi}_j^0$ ($j=1,\dots,4$)	neutralinos

Dynamical breaking of supersymmetry

The SUSY-breaking chiral supermultiplet S is charged under some symmetry and parametrized by

$$S = S + \sqrt{2}\psi\theta + F_S\theta^2,$$

where the nonzero F_S component is the source of SUSY breaking.

- Scalar masses generated at tree-level by

$$\int d^2\theta d^2\bar{\theta} c_i \frac{S^\dagger S}{M_{\text{Pl}}^2} \Phi_i^\dagger \Phi_i \rightarrow c_i \frac{F_S^\dagger F_S}{M_{\text{Pl}}^2} \phi_i^* \phi_i,$$

where c_i ($i = H, Q, U, D, L, E$) of $\mathcal{O}(1)$ and $m_0 \sim c_i m_{3/2}$ with $m_{3/2}^2 = \langle F_S^\dagger F_S \rangle / M_{\text{Pl}}^2$.

- Gaugino masses arise from anomaly mediation and read as

$$M_{\lambda_a} = \frac{\beta(g_a)}{g_a} m_{3/2}, \quad \beta(g_a) = \frac{b_a g_a^3}{16\pi^2}.$$

- For $m_{3/2} \sim 10$ TeV, we can simply assume $c_{H_u} \simeq c_{H_d} = \mathcal{O}(10^{-1})$, $c_{Q_{1,2}} \simeq c_{U_{1,2}} \simeq c_{D_{1,2}} = \mathcal{O}(10)$, $c_{Q_3} \simeq c_{U_3} \simeq c_{D_3} = \mathcal{O}(1)$.

Plausible routes from high-scale theories to Slim SUSY

- *SUSY theory of flavor based on the Froggatt-Nielsen mechanism*: matter supermultiplets charged under a flavor symmetry, while the Higgs assigned as singlets. Different behavior when the flavor symmetry is broken.
- *Heterotic string constructions*, where Higgs and third family arise in the untwisted sector, while first and second families belong to the twisted sector.
- Higgs multiplets would correspond to *pseudo-Goldstone bosons* of a global symmetry.
- Or Higgs bosons could be *composite states* and would not have consequently same mass as sfermions.