Heavy Higgs bosons in Slim SUSY (and Beyond)

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1. SM, Higgs and the LHC
2. The 125 GeV Higgs signal in the MSSM
3. Slim SUSY - Heavy Higgs spectrum
4. Beyond (LFV Higgs decays, ...)
5. Conclusions

[1]

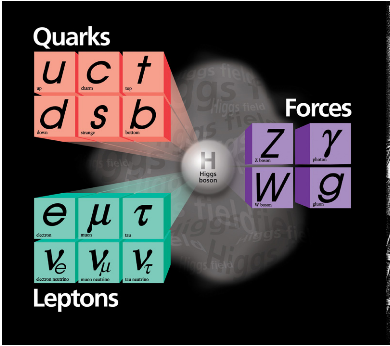
[1] Work with E. Arganda and A. Synkman (EJP-2013, PLB-2013)

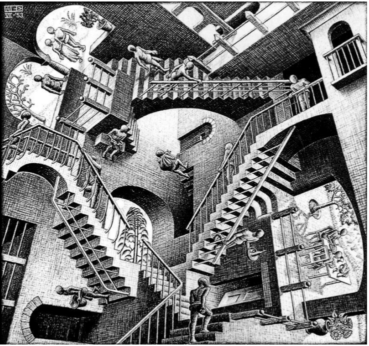
[2]

[2] Work with E. Arganda and A. Synkman (EJP-2013, PLB-2013)

Symmetry and Unification

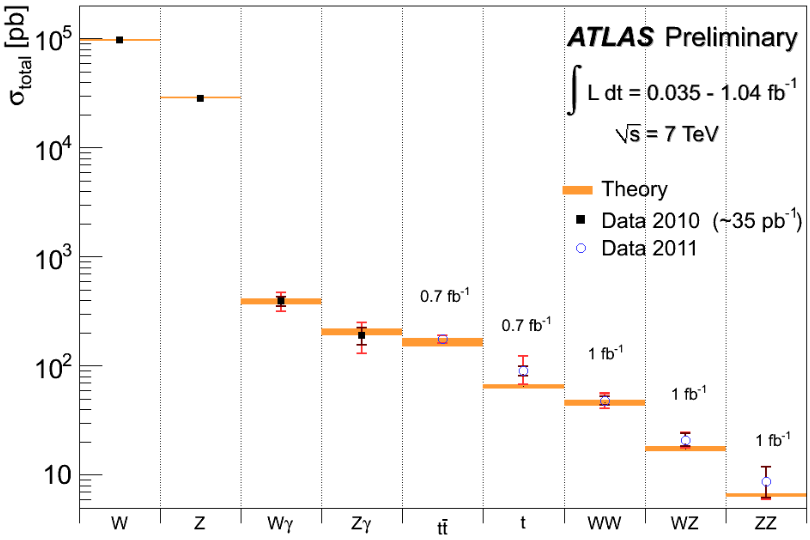
A powerfull method to search for beauty and truth in nature



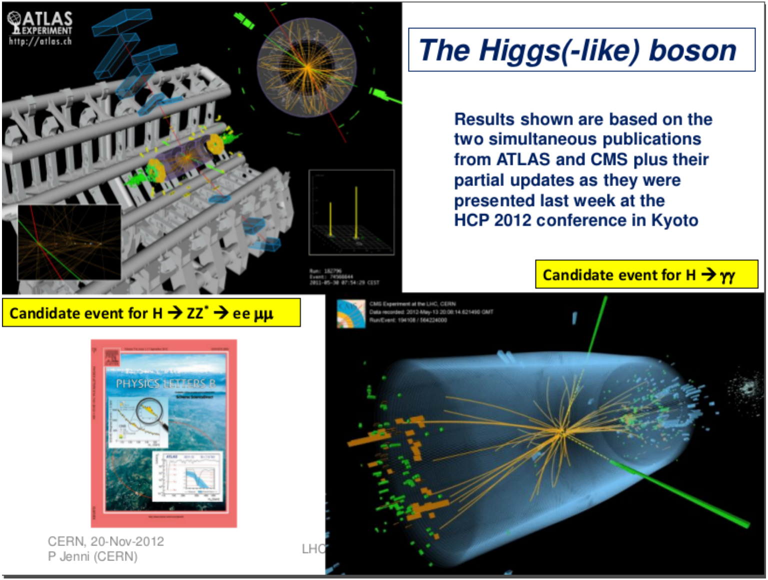


Supersymmetry could be the next stage, but how is it realized?

LHC is confirming the SM:



The LHC and the Higgs signal



Higgs Couplings

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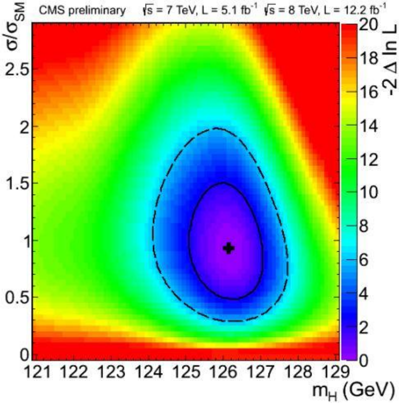
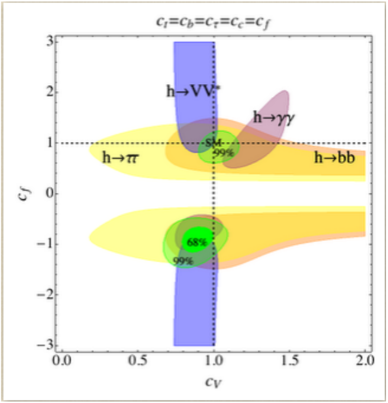




[3] a) Ellis et al, b) Falkowski et al.

Lessons from the Higgs-like signal?

- A New boson has been detected at LHC,
- Looks like SM Higgs: $S = 0$, $T = \frac{1}{2}$, $Y = 1$ $\quad (Q = T_3 + \frac{Y}{2})$,
- But only some couplings have been measured: $hVV, hbb, h\tau\tau, htt/hgg, h\gamma\gamma$,
- CP-parity tests points towards $CP - even$ state,
- Need to measure hhh vertex to probe Higgs potential with SSB ($\rightarrow$ ILC),
- Couplings with light fermions are very difficult to test; need new physics (e-mu conversion/DM-nucleus scattering) to probe them,

So, Nature likes scalars, and if one has been detected
... May be more will come !

Open problems in the SM

- Hierarchy problem,
- Neutrino masses and flavor problem,
- Strong CP problem,
- Dark Matter,
- BAU
- Cosmological constant (Dark energy),
- SM Parameters and its Structure,

However, so far, most of our attempts have searched for one-by-one solutions.

Open problems in the SM and SUSY

- Hierarchy problem ($\rightarrow$ SUSY),
- Unification ($\rightarrow$ SUSY)
- Neutrino masses and flavor problem,
- Strong CP problem,
- Dark Matter ($\rightarrow$ SUSY),
- BAU
- Cosmological constant (Dark energy),
- SM Parameters, Structure and other Aesthetical questions,,

The MSSM

The minimal extension of the SM consistent with SUSY, is based on:

- SM Gauge Group ($\rightarrow$ gauge bosons and gauginos),
- 3 families of fermions and sfermions,
- Two Higgs doublets (H_u and H_d),
- Soft-breaking of SUSY (Hidden sector),
- R-parity distinguish SM and their superpartners
  $\rightarrow$ LSP is stable and DM candidate.

The MSSM particle content

	SM	Superpartners
SM Bosons	$W^{\pm}, Z, \gamma$ gluon Higgs bosons	Wino,Zino, Photino gluino Higgsinos
SM Fermions	quarks leptons neutrinos	squarks sleptons sneutrinos

Mixing of gauginos and Higgsinos $\rightarrow$
Charginos ($\chi_i^{\pm}$, $i = 1, 2$) and Neutralinos (χ_j^0, $j = 1, 4$),

Gravitino is also part of the spectrum.

The MSSM Higgs sector

It is a 2HDM of type-II $\rightarrow h^0, H^0, A^0, H^\pm$,

- CP-even neutral Higgs bosons h^0, H^0, at tree-level $m_h < m_Z$,
- CP-odd neutral Higgs A^0 with $m_H^2 = m_A^2 + m_Z^2 \sin^2 2\beta$,
- Charged Higgs $H^\pm$, with $m_{H^+}^2 = m_A^2 + m_W^2$,
- Masses and mixing angles fixed with: m_A and $tan\beta = v_2/v_1$,
- When $m_A \leq \tilde{m}$, Higgs searches uses SM techniques.
- $H^0, A^0, H^\pm$ decays into SUSY modes may be allowed, but more constrained,

The MSSM Higgs mass

Radiative effects of Stop-top loops can make: $m_h > m_Z$; simple one-loop approx.:

$$m_h^2 = [m_Z^2 \cos^2 2\beta + \epsilon \sin^2 \beta] \tag{1}$$

where

$$\epsilon = \frac{3m_t^2}{2\pi^2 \sin^2 \beta}[log(\frac{m_S^2}{m_t^2}) + \frac{X_t^2}{m_S^2}(1 - \frac{X_t^2}{12m_S^2}] \tag{2}$$

$X_t = A_t - \mu \cot \beta$,
Thus, to get $m_h = 125$ GeV, and with SM-like couplings, need:

- Large masses for 3rd family squarks, of $m_S = O(\text{TeV})$, or
- Large X_t-terms,
- A milder combination of the above.

The MSSM with $m_h = 125$ GeV

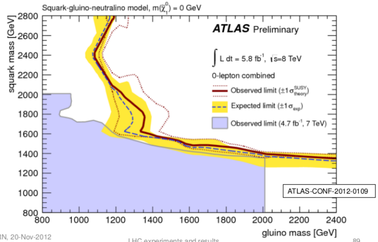
Three options for parameter space:

- Look for small corners of the more traditional MSSM
  $\rightarrow$ Constrained (cMSSM) or phenomenological (pMSSM),
- MSSM with heavy sfermions arising within quasi-natural models
  $\rightarrow$ More minimal MSSM, Natural SUSY, String based models,...
- Assume Heavy scalars, except for a fine tunnned SM-like Higgs
  $\rightarrow$ Split SUSY, Spread SUSY, High Scale SUSY,...

Recent limits on SUSY from LHC

Interpretation of the results

Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos

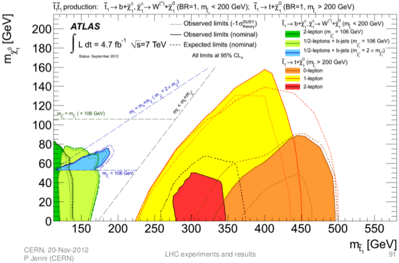


CERN, 20-Nov-2012
P Jenni (CERN)

LHC experiments and results

89

Summary of five dedicated searches for top squark pair production for theoretically preferred models with relatively light 3rd generation squarks



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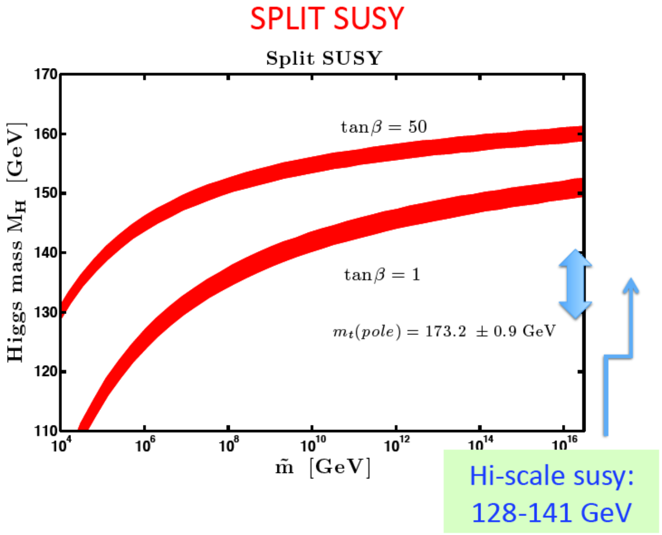
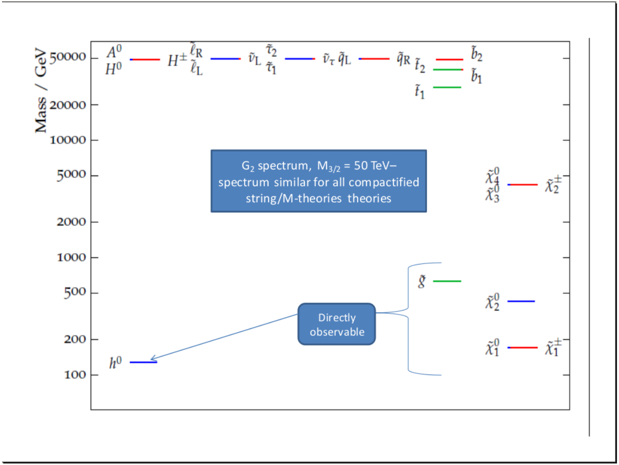
LHC experiments and results

91

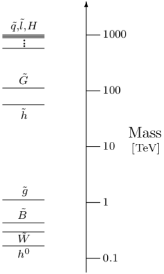
MSSM Higgs mass (Giudice and Strumia)



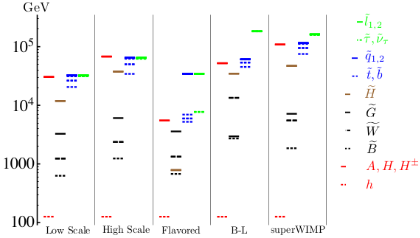
SUSY spectrum (Kane et al.)



Split-Spread (Hall, Nomura, Shirai) /Mini-split spectrum (Kahn,McCullough,Thaler)



Typical spectrum of Spread Supersymmetry with wino LSP.



Split SUSY and the Higgs spectrum

- In Split SUSY and its variants, all scalars are assumed to be quite heavy, except for a finely-tunned higgs boson (with $m_h = 125$ GeV),
- Anthropic arguments are involved to justify such tunning,
- Further, Heavy scalars give the decoupling solution for the SUSY CP and flavor problems,
- But, regarding the flavor problem, Higgs bosons are harmless, and could be much lighter than squarks and sleptons,
- So, to contain the hell, we need to find more Higgs particles,

$\rightarrow$ Our proposal: SLIM SUSY

Slim SUSY- definitions

- O(10) TeV sfermions of 3rd family (to account for $m_h = 125$ GeV)
- O(100) TeV sfermions of 1st,2nd family (to solve SUSY CP and Flavor problems,)
- Full Higgs spectrum near EW scale (at the reach of LHC),
- Minimal Chargino/Neutralino sector at EW scale (Wino or Higgsino DM, but not pure bino)
- No colored sparticles at LHC reach (Our prediction),

SUSY breaking and SLIM Spectrum

An effective description of SUSY breaking involves the chiral supermultiplet S, charged under some symmetry (Wells, PeV SUSY).

$$S = s + \sqrt{2}\psi\theta + F_S\theta^2 \,, \tag{3}$$

whose nonzero F_S component is the source of supersymmetry breaking. The scalar masses are generated at tree-level by

$$\int d^2\theta d^2\bar{\theta}\, c_i\, \frac{S^\dagger S}{M_{\rm Pl}^2} \Phi_i^\dagger \Phi_i \to c_i \frac{F_S^\dagger F_S}{M_{\rm Pl}^2} \phi_i^* \phi_i \,, \tag{4}$$

Therefore, one obtains $m_0 \simeq c_i\, m_{3/2}$ with $m_{3/2}^2 = \langle F_S^\dagger F_S \rangle / M_{\rm Pl}^2$.

Gaugino masses would arise from the anomaly mediation:

$$M_{\lambda_a} = \frac{\beta(g_a)}{g_a} m_{3/2} \,, \tag{5}$$

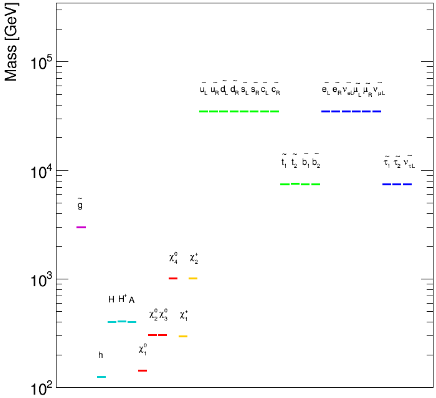
125 Higgs mass in SLIM SUSY

The parameters are varied within the following range, and we only select points that satisfy current direct bounds on SUSY masses.

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

Spectrum of SLIM SUSY

In order to obtain SLIM spectrum, for $M_{3/2} \simeq 10$ TeV, assume: $c_{H_u} \simeq c_{H_d} = \mathcal{O}(10^{-1})$, $c_{Q_3} \simeq c_{U_3} \simeq c_{D_3} = \mathcal{O}(1)$ and $c_{Q_{1,2}} \simeq c_{U_{1,2}} \simeq c_{D_{1,2}} = \mathcal{O}(10)$.



String-pheno (Nilles et al)

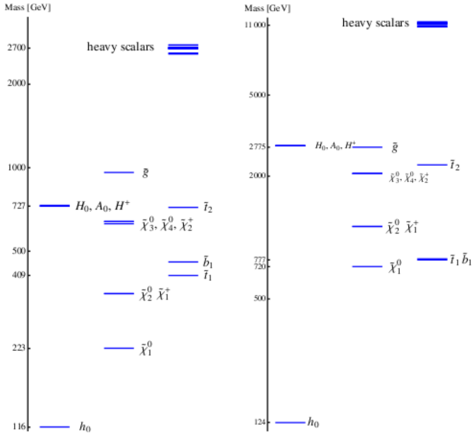
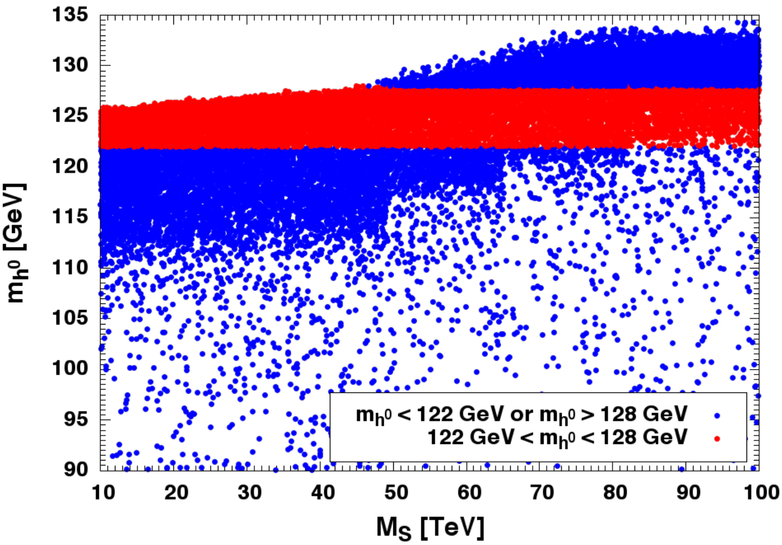


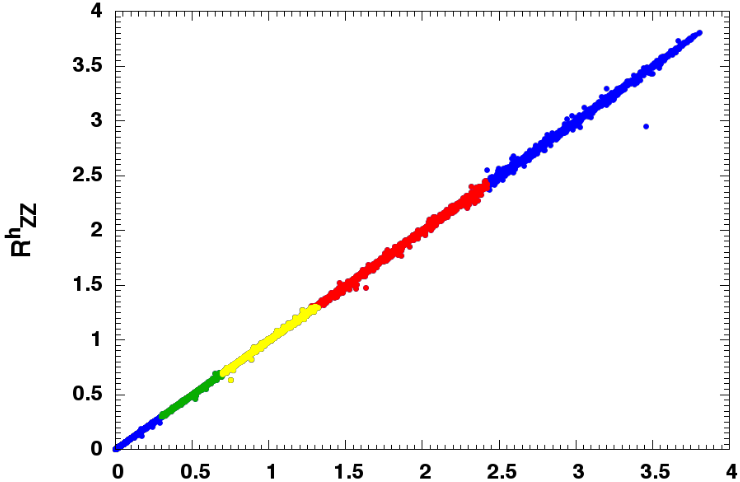
Figure 3: Particle spectra for the benchmark points BP1 (left) and BP2 (right).

125 Higgs mass in SLIM SUSY



Higgs couplings in SLIM SUSY

$$R_{XX} = \frac{\sigma(pp \to h + Y)}{\sigma(pp \to h_{sm} + Y)} \frac{B.R.(h \to XX)}{B.R.(h_{sm} \to XX)} \tag{6}$$

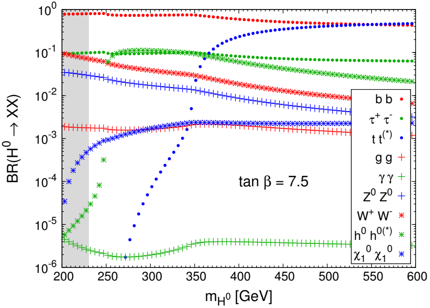


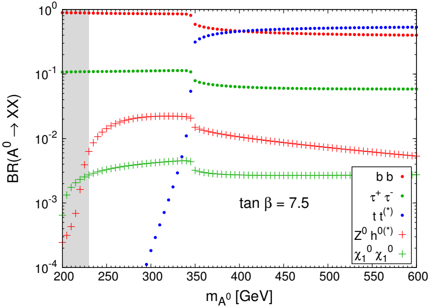
Implications for heavy Higgs decays -Scenarios

Defined according to the nature of LSP neutralinos and charginos, with masses similar to the Higgs ones, which could be reachable at LHC:

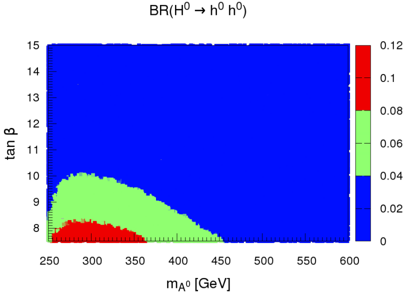
- **Bino-like LSP Scenario** $\rightarrow$ Only one bino-like neutralino at the EW scale; in this case: $|M_1| \ll |M_2|, |\mu|$.
- **Wino-like LSP Scenario** $\rightarrow$ One wino-like neutralino and one wino-like chargino, which occurs for $|M_2| \ll |M_1|, |\mu|$.
- **Higgsino-like LSP Scenario** $\rightarrow$ Two higgsino-like neutralinos and one higgsino-like chargino, in this case: $|\mu| \ll |M_1|, |M_2|$.

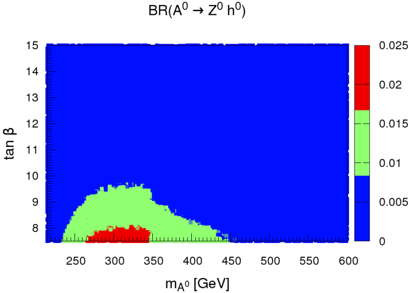
Heavy Higgs decays (Bino-like LSP)



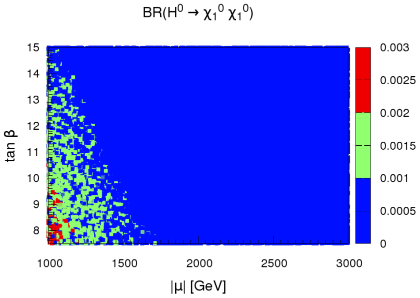


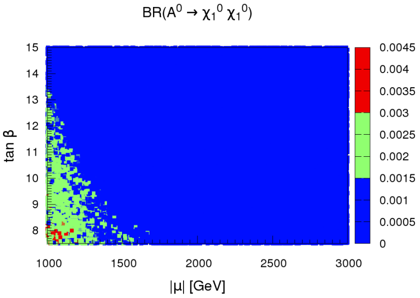
Heavy Higgs decays



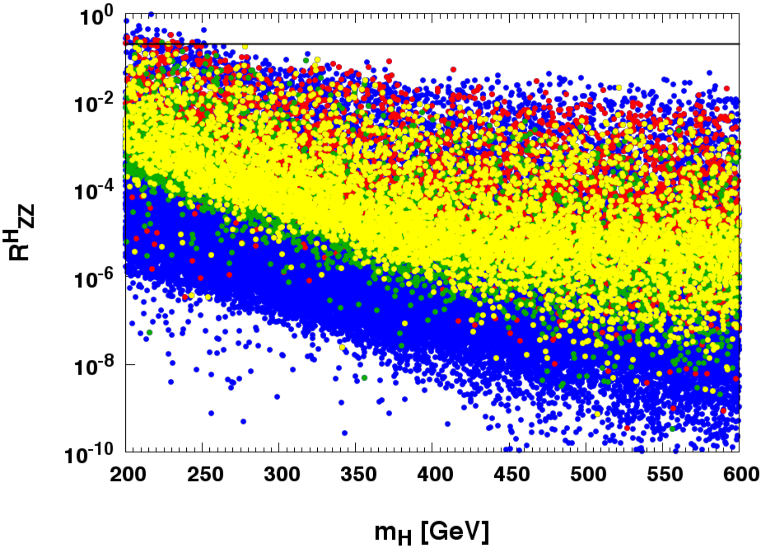


Heavy Higgs decays





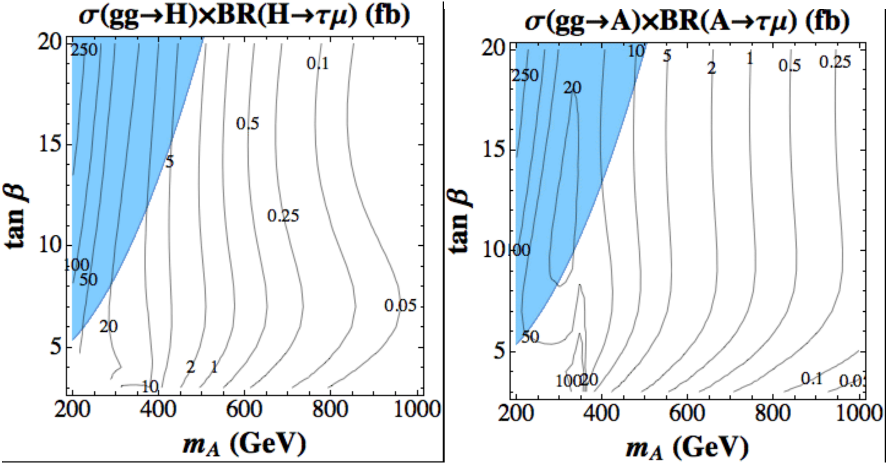
Heavy Higgs signal in ZZ channel



Searching for heavy Higgs bosons at LHC

A. Djouadi and J. Quevillon (arXiv:1304.1787 [hep-ph]), A. Arbey, M. Battaglia and F. Mahmoudi (arXiv:1303.7450 [hep-ph]), H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata (arXiv:1212.2655 [hep-ph]), Y. Kahn, M. McCullough and J. Thaler (arXiv:1308.3490 [hep-ph]), G. Barenboim, C. Bosch, M. L. Lpez-Ibaez and O. Vives (arXiv:1307.5973 [hep-ph]), A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon and V. Riquer (arXiv:1307.5205 [hep-ph]), T. Han, T. Li, S. Su and L. -T. Wang (arXiv:1306.3229 [hep-ph]), N. Craig, J. Galloway and S. Thomas (arXiv:1305.2424 [hep-ph]).

LFV Higgs decays: $h_i \to \tau\mu$ (Diaz-Cruz et al (2000), Arana, Arganda, Herrero (2013))



Conclusions.

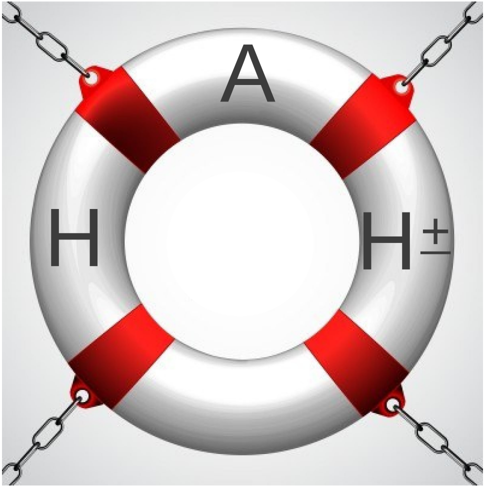
- Decays $H \to hh$, $A \to Zh$ have interesting signature; rate may be large enough for $\tan\beta \leq 10$,
- Decays $H(A) \to \chi_1^0 \chi_1^0$, $H(A) \to \chi_1^+ \chi_1^-$ are also interesting to look at,
- Large/Moderate $tan\beta \to$ enhanced production of $H + bb$ at LHC,
- Only a few superpartners could be at the reach of LHC,
- Slim SUSY, still attractive, so... "wake up little SUSY"

Conclusions

"The goal is to find one, two, three ...more Higgs bosons at LHC"

Is SUSY near a catastrophe?

SUSY Savers



Is the Higgs something artificial?

Spin (S) and Isospin (T)

T / S	0	1/2	1	3/2	2
0	?	Neutrinos-R	gluon	?	?
1/2	Higgs	electron quarks	?	?	?
1	?	?	W, Z	?	?

$$Q_{em} = T_3 + Y \tag{7}$$

The Hierachy problem

When an scalar interacts with a heavy fermion M, with $L_Y = y\bar{\Psi}\Psi\phi$, and UV cutoff Λ, the scalar mass gets corrected, i.e.

$$m_h^2 = m_0^2 + \frac{y^2}{16\pi^2}[c_1\Lambda^2 + c_2 m_0^2 ln\frac{\Lambda}{m} + M^2] \quad (8)$$

Some solutions:

- Accidental cancelacion (NO LONGER WORKS!) ,

$$\lambda = y_t^2 - \frac{1}{8}[3g^2 + g'^2] \quad (9)$$

  ($\rightarrow m_h \simeq 200$ GeV,)
- Composite Higgs (as in QCD!),
- Cancelation between boson-fermion loops ($\rightarrow$ SUSY),
- Higgs is part of $D - dim$ vector field: $A_M = (A_\mu, A_i)$,

Beyond the SM: models that solve something

- Models with Grand Unification (ex. $SU(5), SO(10), E_6$,..)
- Models with new symmetries (SUSY),
- Models with extra dimensions extra.
- etc.

But the prize for the solution, is that these models bring their own problems

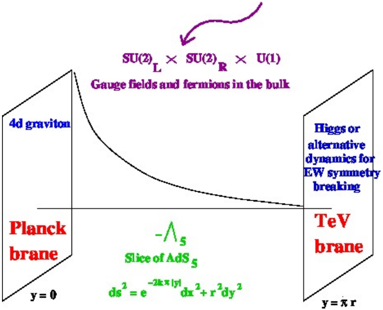
Beyond the SM: models "what if"

- Models with new fermions (4ta family, etc)
- Models with new gauge forces ($U(1)'$, Left-Right, ..)
- Models with extra Higgs multiplets (2HDM, triplets,..)
- etc.

Arkani-Hamed/Dimopoulos:
Theories should be consistentes, Theoreticians... not necesarily

Modern view of Physics BSM - Extra Dimensions

- Bosonic XD: $x^\mu \to X^M = (x^\mu, x^i)$,
- Curved Extra dimensions (RS):



- Fermionic/Quantum XD:
  $x^\mu \to z^M = (x^\mu, \theta, \bar{\theta})$ (Superspace) $\to$ Supersymetry!

Supersymmetry (SUSY)

Why is SUSY attractive? (Standard lore)

- It is a new simmetry that relates fermions and bosons,
- Offers the possibility to stabilize the Higgs mass and EWSB,
- Improves Unification and o.k. with proton decay,
- Favors a light Higgs boson, in agreement with EWPT (and LHC?), i.e. $m_h \leq 160$ GeV,
- New sources of flavor and CP violation may help to get the right BAU,
- LSP is stable and a possible Dark matter candidate.

The parameters of the MSSM

In addition to SM parameters, the MSSM includes O(100) new ones:

- Scalar masses (Sleptons, squarks, Higgs),
- Gaugino masses ($\tilde{M}_G, \tilde{M}_W, \tilde{M}_B$),
- Trilinear terms ($A_{\tilde{f}}$ for squarks and sleptons),
- From Higgs sector: $\tan\beta = v_2/v_1$ and μ,
- The masses of superpartners have important implications for EWSB,
- Spectrum of superpartners depends on mechanism of SUSY breaking,

Constraints on MSSM parameters

SUSY parameters must satisfy:

- Correct EWSB (radiative), (i.e. get right value of m_Z!)
- LHC limits on Higgs mass ($m_h = 125$ GeV?),
- LHC (Tevatron) limits on superpartners,
- Bounds on Flavor signals
  ($K - K$ mixing, $b \to s + \gamma$, $B \to \tau\nu$, $B_s \to \mu\mu$...etc.)
- Implications for cosmology (e.g. Relic density of DM),

Simplified models arise for specific SUSY breaking (and mediation) mechanisms,

CMSSM

To get MSSM parameters at TeV scale, one derive them from their values at high scale (SUGRA/GUT) through RGE,

$\rightarrow$ CMSSM = Constrained Minimal Supersymmetric Standard Model.
In the CMSSM one takes (at M_{pl}):

- Universal scalar masses ($=\tilde{m}_0$)
- Universal gaugino masses ($=\tilde{m}_{1/2}$)
- Universal trilinear terms ($=A_0$)
- Also $\tan\beta = v_2/v_1$ and $sgn(mu)$.

MSSM Higgs couplings:

- $(hVV):\quad \frac{2m_V^2}{v}\cos(\beta-\alpha),\quad v^2=v_1^2+v_2^2,$
- $(huu):\quad \frac{m_u}{v}(\frac{\cos\alpha}{\sin\beta}),$
- $(hdd):\quad \frac{m_d}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hll):\quad \frac{m_l}{v}(\frac{\sin\alpha}{\cos\beta}),$
- $(hhh):\quad \simeq\lambda v,\quad \lambda=\frac{g^2+g'^2}{8},$
- $(hhhh):\quad \simeq\lambda.$

Similar expressions hold for H^0, A^0 and $H^{\pm}$.

EWSB in the MSSM- problems

- EWSB gives a relation between the Z-mass, the soft-Higgs masses and the mu-term (at tree-level):

$$M_Z^2 = 2c_1 M_{H_u}^2 - 2t_\beta^2 M_{H_d}^2 - 2\mu^2 \tag{10}$$

with $c_1 = 1/(t_\beta^2 - 1)$,

- Thus, for a natural solution, SOFT terms should be of O(m_Z),
- But already LEP limits on superpartners ($\tilde{m} \geq 200$ GeV) ruled out such case,
- Including RGE and recent LHC limits make it worse (A. Strumia, ArXive:1101.2195 [hep-ph]):

$$M_Z^2 = 0.2m_0^2 + 0.7M_3^2 - 2\mu^2 \simeq (91GeV)^2 \times 50(\frac{M_3}{780})^2 + ... \tag{11}$$

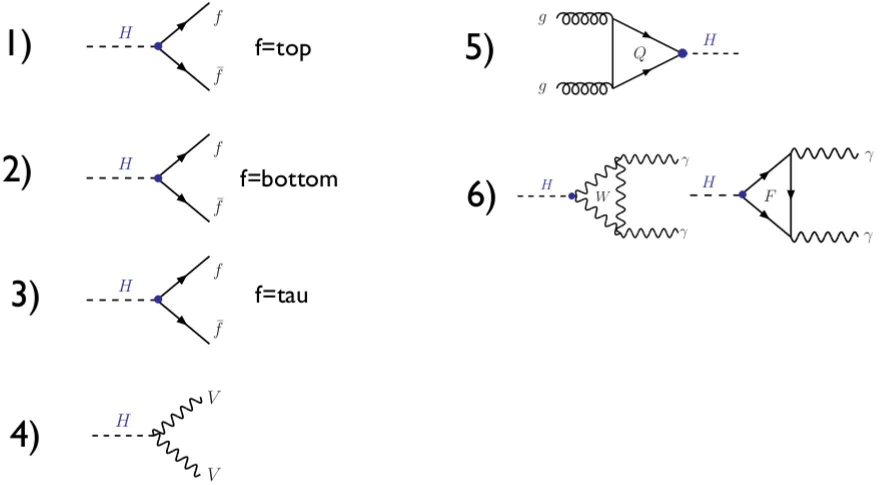
- Thus, MSSM suffers already of some fine-tunning problem,

SUSY Phenomenology- LSP scenarios

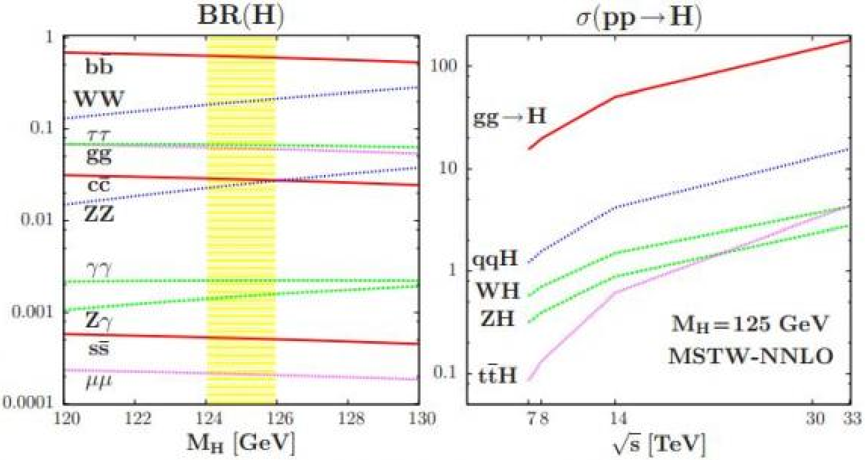
With R-parity, LSP and NLSP nature determine the exp. search for SUSY,

- Production: SM+SM $\rightarrow$ SP+SP
- Some SP decays into NSP+ SM
- NSP decays into LSP+SM
- Neutralino LSP most widely studied,
- Gravitino LSP gives very different phenomenology,

SM Higgs Couplings

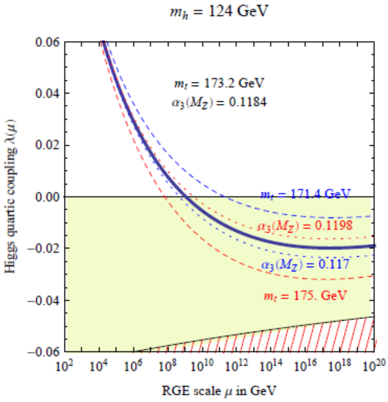


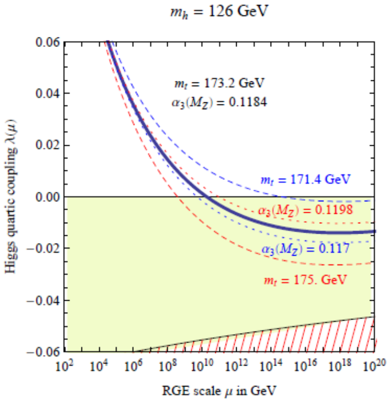
SM Higgs Br's and CSx



Vacuum stability

RGE evolution of Higgs self-coupling: $m_h \simeq \lambda v$





Scalars and new physics

Extra scalar singlets, doublets, triplets, have been studied in connection with Physics BSM:

- 2HDM per se (I,II,III,X,Y, Inert) ,
- 2HDM within MSSM context (SUSY) ,
- New Scalars with lepton number (ex. sleptons),
- Colored scalars (ex. squarks),
- Singlets and Triplets for neutrino masses,
- Triplets and bi-doublets within LRSM,
- etc., etc.

What is the LSP?

- Most popular choice Neutralino LSP,
  - Higgsino-like, Bino-like, wino-like
- With $\chi_1^0 = LSP$, signal of SUSY is cascade decays and missing energy , e.g. $\chi_2^0 \to l^+ l^- + \chi_1^0$.
- Another possibility: sneutrino LSP,
  $\tilde{\nu}_L$ is not favored by direct DM search,
  But $\tilde{\nu}_R$ is still allowed by direct DM search.
- Still another option is: Gravitino (Ψ_μ) LSP,
- Within GMM $\Psi_\mu = LSP$ gives signals with photons from $\chi_1^0 \to \Psi_\mu + \gamma$.

MSSM Higgs and Dark matter

For heavy sfermions the DM relic density is:

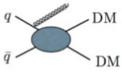
$$\Omega_X h^2 = C_X (\frac{m_X}{TeV})^2 \tag{12}$$

- For DM $X =$ pure Bino, no aceptable solution,
- For DM $X = \tilde{H}$ pure Higgsino, $C_{\tilde{H}} = 0.09$ and an aceptable solution is otained for $1 < M_{\tilde{H}} < 1.2$ TeV,
- For DM $X = \tilde{W}$ pure Wino, $C_{\tilde{H}} = 0.02$ and an aceptable solution is otained for $2 < M_{\tilde{W}} < 2.5$ TeV,

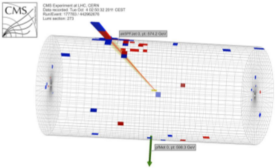
In such case detection at LHC may be harder,

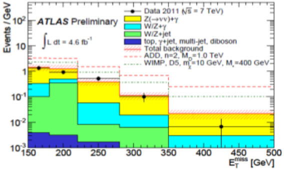
DM limits from LHC

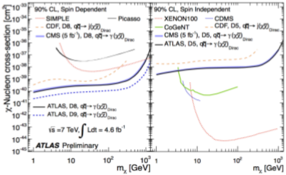
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss







ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

CERN, 20-Nov-2012
P Jenni (CERN)

CMS: Sub. to Phys. Rev. Lett.
arXiv:1204.0821v1[hep-ex]
arXiv:1206.5663[hep-ex]

LHC experiments and results