Scalars and New Physics

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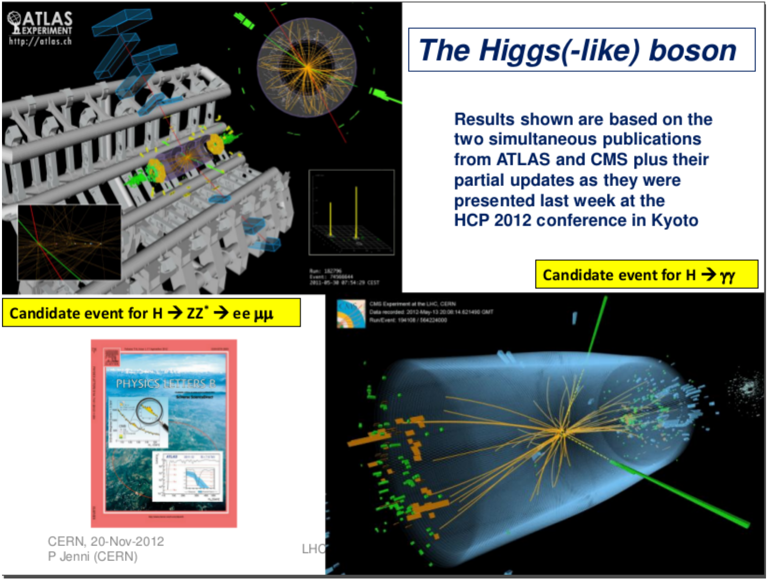
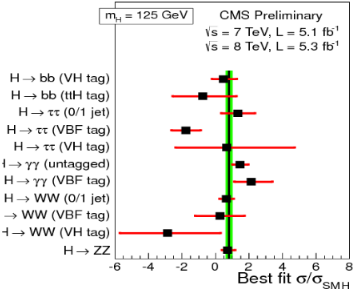
LHC new boson

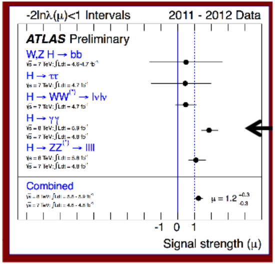


Higgs at LHC

After the 4th of July 2012

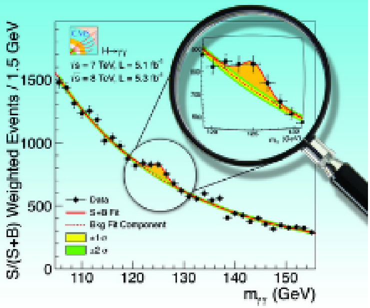
We have a Higgs-like state:

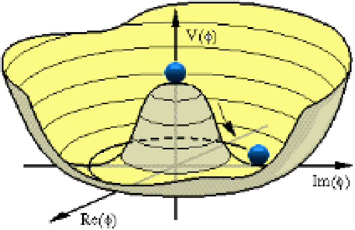




$$m_H = 126.5 \text{ GeV}$$

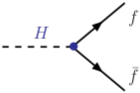
Habemus Higgs?





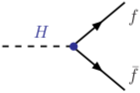
SM Higgs Couplings

1)



f=top

2)



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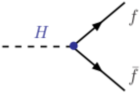
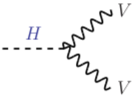
3)

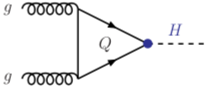


f=tau

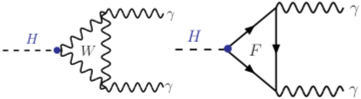
4)



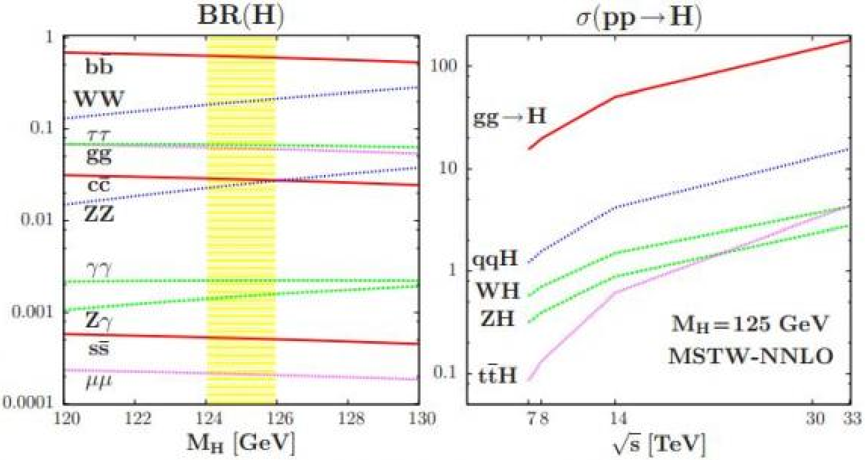
5)



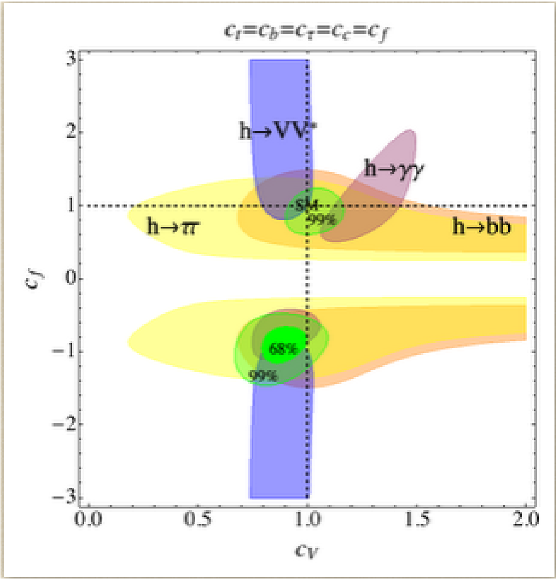
6)



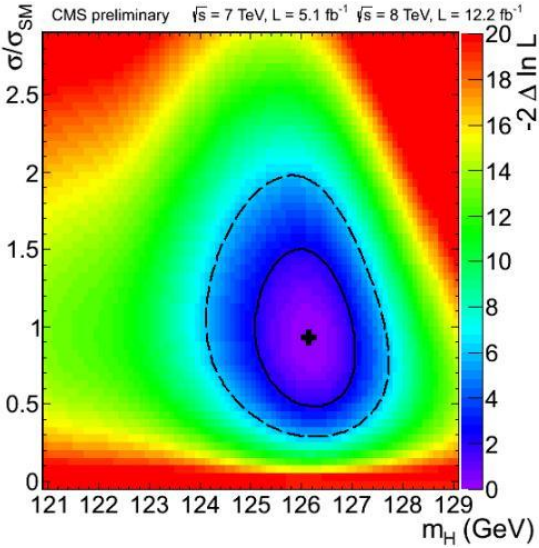
SM Higgs Br's and CSx



Higgs Couplings



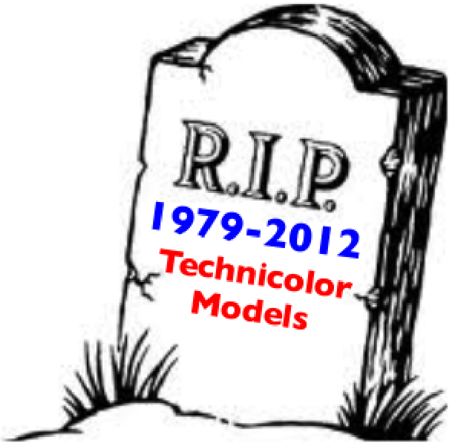
Higgs Couplings



What have we learned?

- A New boson has been detected at LHC,
- It looks like the SM Higgs: $S = 0$, $T = \frac{1}{2}$, $Y = -1$ $(Q = T_3 + \frac{Y}{2}\ )$,
- But only some couplings have been be measured $(hVV, hbb, h\tau\tau, htt/hgg, h\gamma\gamma)$
- Still, need to measure hhh vertex to probe Higgs potential with SSB, ($\rightarrow$ ILC),
- Couplings with light fermions are very difficult to probe,
- Probe FCNC Higgs couplings (vanishing small in SM)

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


R.I.P.
1979-2012
Technicolor
Models

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	?	?

$$Q_{em} = T_3 + Y \qquad (1)$$

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 gest corrected, i.e.

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

Some solutions:

- Accidental cancelacion (NO LONGER WORKS!) ,

$$\lambda = y_t^2 - \frac{1}{8}[3g^2 + g'^2] \tag{3}$$

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

Open problems in the SM

- Large/Little hierarchy problem,
- Neutrino masses and flavor problem,
- Strong CP problem,
- Dark Matter,
- Cosmological constant (Dark energy),
- Some deviations from the SM (a few std. dev.), e.g. Δa_μ, etc.
- Aesthetical questions,

They all suggest the need for New Physics.

Beyond the SM

- Models with new fermions (4ta family, etc)
- Models with new gauge forces ($U(1)'$, Left-Right, ..)
- Models with extra Higgs multiplets (2HDM, triplets,..)
- Models with Grand Unification (ex. $SU(5), SO(10), E_6$,..)
- Models with new symmetries (SUSY),
- Models with extra dimensions extra.
- etc.

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

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.

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 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 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,

The MSSM Higgs sector

At tree-level MSSM Higgs sector is a 2HDM of type-II, i.e. it contains two Higgs doublets, with:

- 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 search uses SM techniques.
- But $H^0, A^0, H^{\pm}$ may decay into SUSY modes; LHC search gets more complicated!,

The MSSM Higgs mass

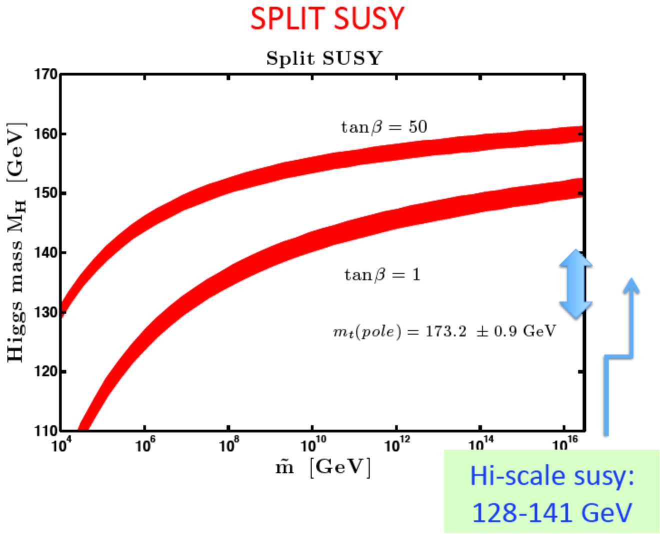
Radiative effects of Stop-top loops can make: $m_h > m_Z$

$$m_h^2 = m_Z^2[1 + \frac{3m_t^2}{2\pi^2 m_Z^2} log(\frac{m_{stop}}{m_t})] \qquad (4)$$

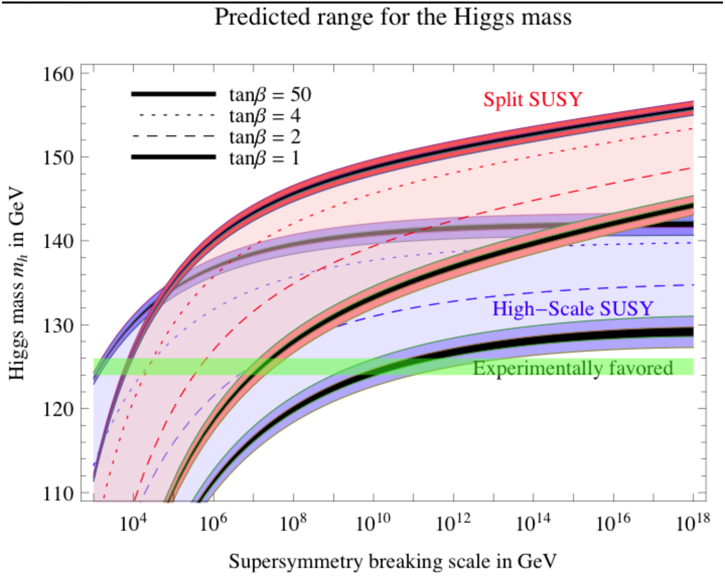
But to get $m_h = 125$ GeV, and with SM-like couplings, need:

- Large masses of O(TeV) for 3rd family squarks, or
- Values of $tan\beta$ of O(10), or
- Large A-terms,
- Given that large stop masses are prefered, can choose decoupling solution for SUSY CP and flavor problems,

MSSM Higgs mass (Giudice and Strumia)



MSSM Higgs mass



The MSSM with $m_h = 125$ GeV

Three options:

- Look for small corners of the more traditional MSSM
  $\rightarrow$ phenomenological (pMSSM),
- Heavy scalars, except a fine tunnned SM like Higgs
  $\rightarrow$ Split SUSY, Spread SUSY, High Scale SUSY,...
- MSSM with heavy sfermions can also arise within other Natural models
  $\rightarrow$ More minimal MSSM, Natural SUSY, String based models,

SUSY spectrum (Nilles et al.)

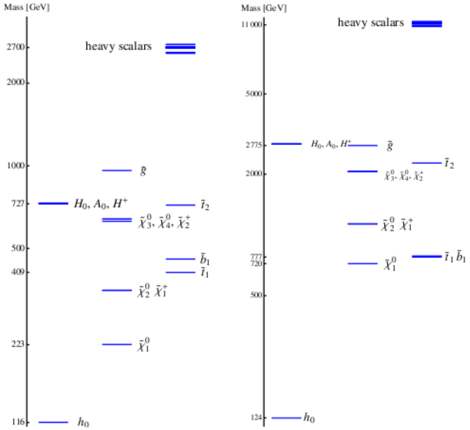
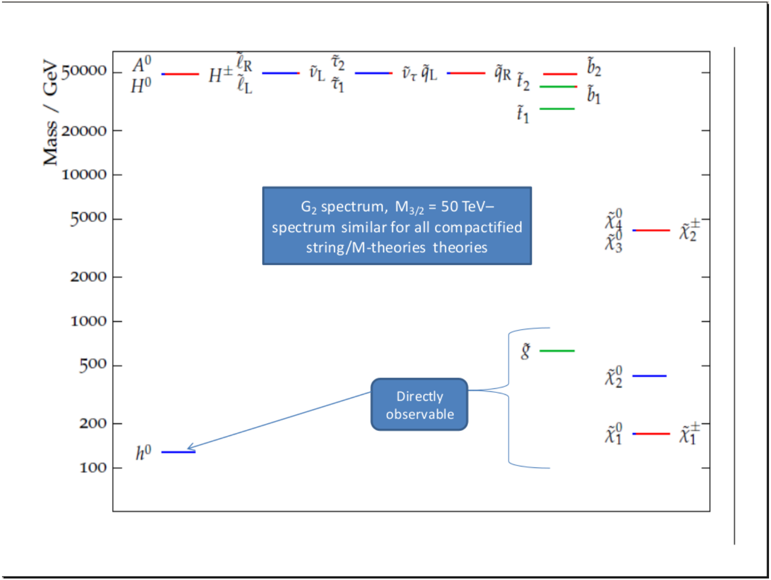


Figure 3: Particle spectra for the benchmark points BP1 (left) and BP2 (right).

SUSY spectrum (From G. Kane et al.)



Old SUSY spectrum

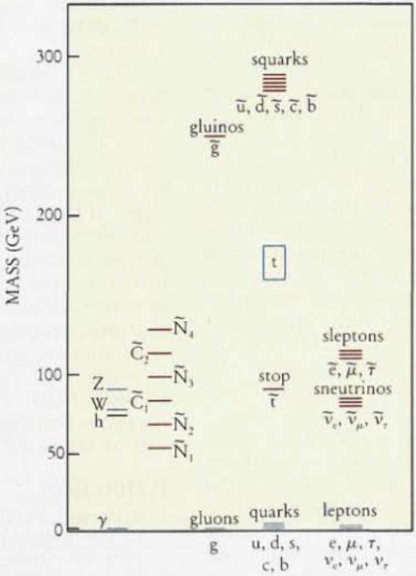
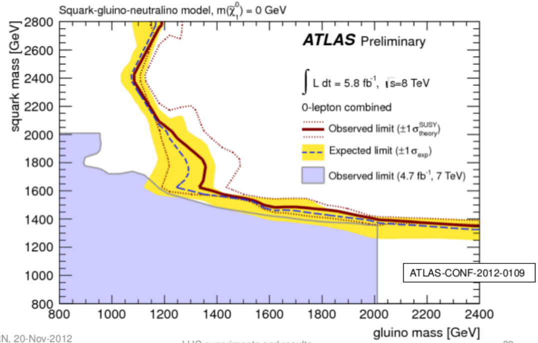


FIGURE 2. A POSSIBLE SPECTRUM of particles (blue) and their superpartners (red). The existence of superpartners is a prediction of supersymmetry, which, in turn, is a prediction of string models. The spectrum shown is consistent with all data at present. The neutralinos ($\tilde{N}_i$) and charginos ($\tilde{C}_i$) are mass eigenstates of the electroweak superpartners $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{W}$ and so on. The Higgs boson (h, green) will be accompanied by three other Higgs boson states with higher mass. The primary theory would predict a specific spectrum of particles and superpartners that can be compared with experimental data.

Recent results from LHC

Interpretation of the results

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



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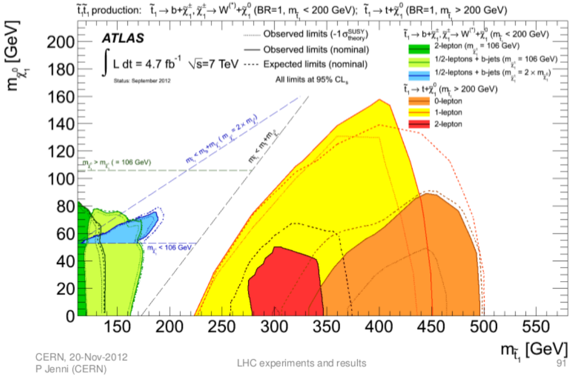
LHC experiments and results

89

Recent results from LHC

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



Our proposal: SLIM SUSY [1]

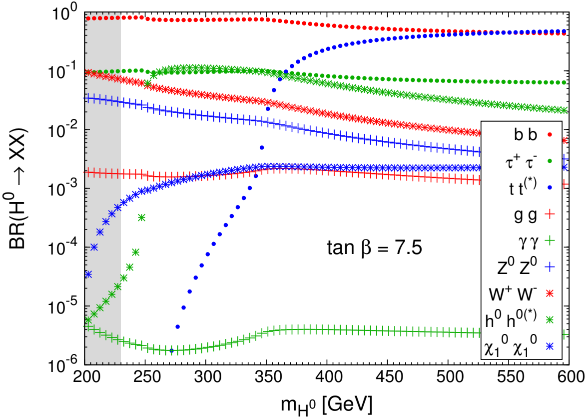
- O(5) TeV sfermions of 3rd family (to account for $m_h = 125$ GeV)
- O(50) TeV sfermions of 1st,2nd family to solve SUSY CP and Flavor problems,
- Full Higgs spectrum near EW scale (at the reach of LHC),
- Minimal Chargino/Neutralino sector at EW scale (Wino or Higgsino DM, but not pure bino)
- No colored sparticles at LHC reach,

[1] E. Arganda, J.L. Diaz-Cruz, A. Szynkman

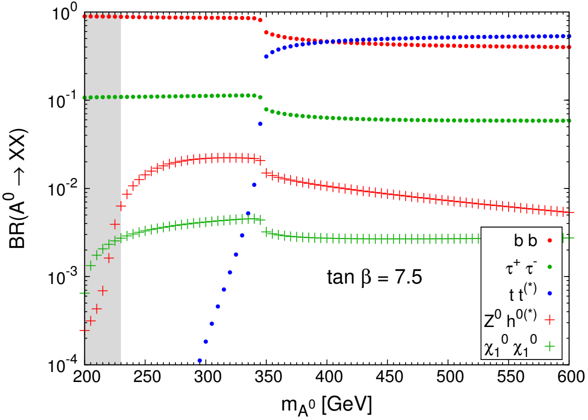
Implications for heavy Higgs bosons

- Decays $H \to hh$, $A \to Zh$ have interesting signature but 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 $tan\beta$ $\to$ enhanced production of $H + bb$ at LHC,
- Only a few superpartners could be at the reach of LHC,

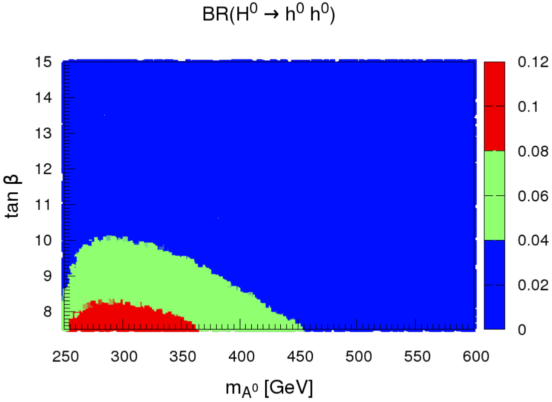
Heavy Higgs decays



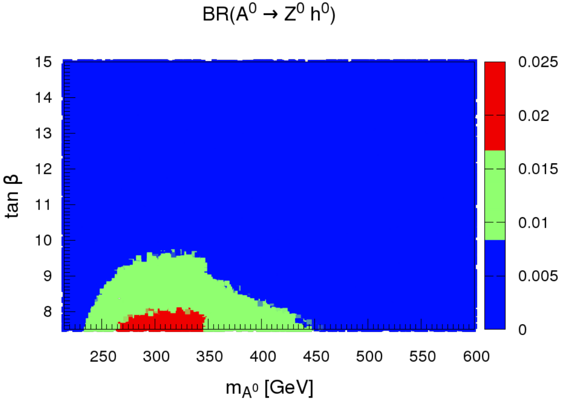
Heavy Higgs decays



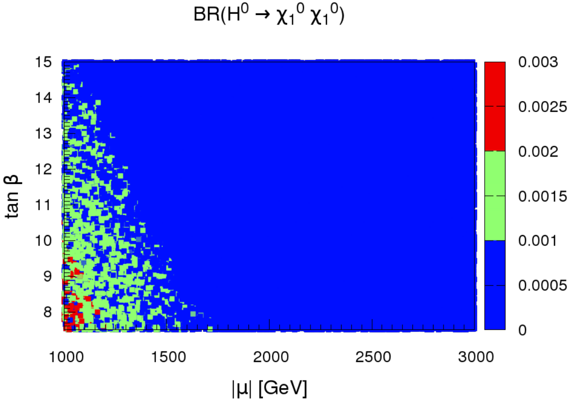
Heavy Higgs decays



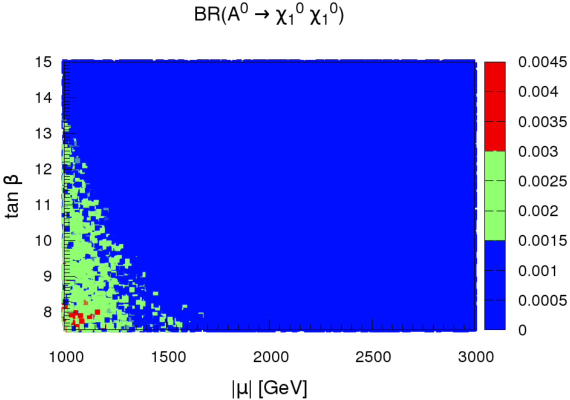
Heavy Higgs decays

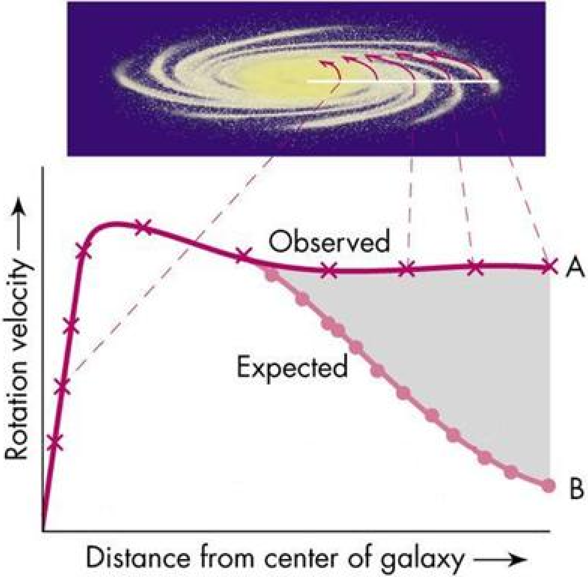


Heavy Higgs decays



Heavy Higgs decays




Observed
Expected
A
B
Rotation velocity
Distance from center of galaxy

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:

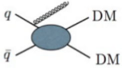
$$\Omega_X h^2 = C_X (\frac{m_X}{TeV})^2 \tag{5}$$

- 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,

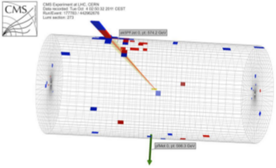
In such case detection at LHC may be harder,

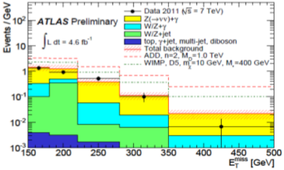
DM limits from LHC

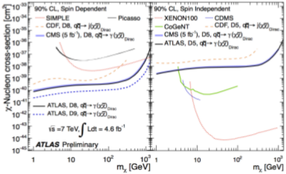
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss







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

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

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

LHC experiments and results

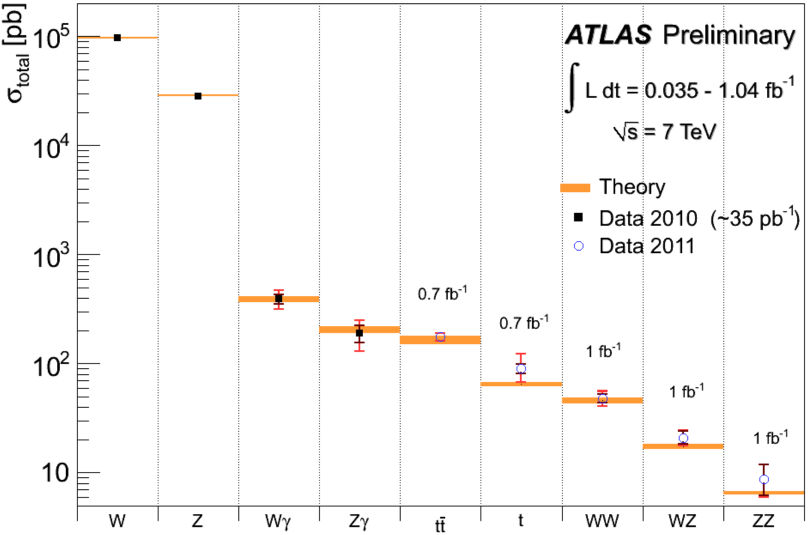
Is SUSY near a catastrophe?

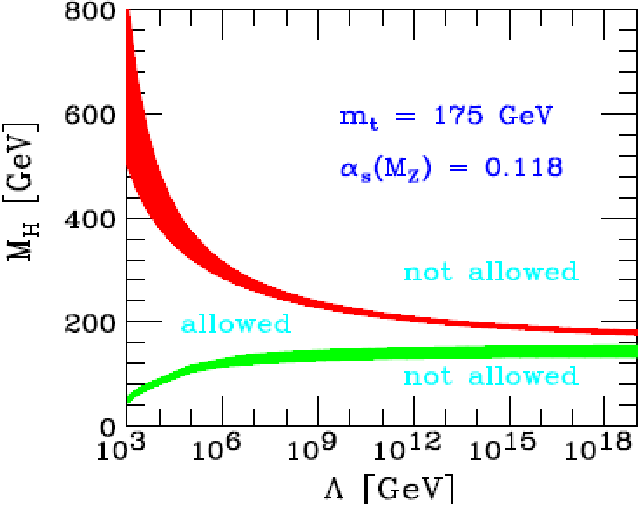
Where have you gone Mrs SUSY?

Conclusions.

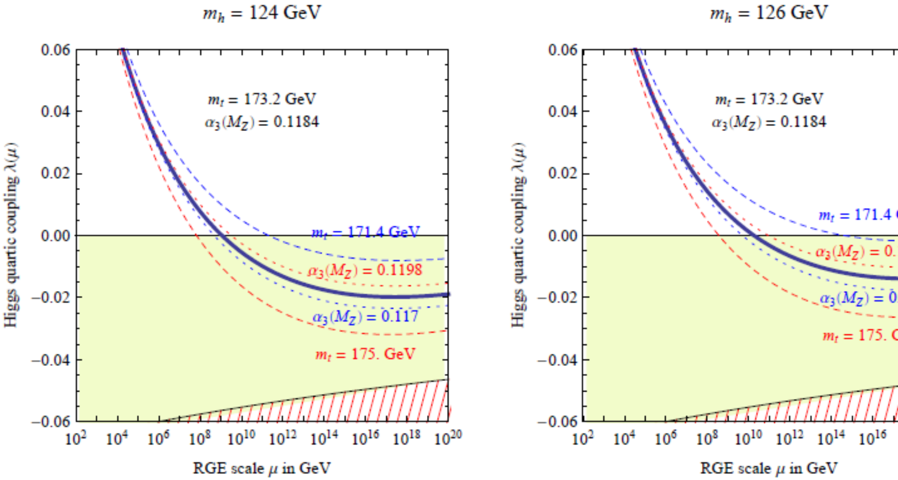
- LHC is already giving great results,
- Some evidence for a SM-like Higgs with $m_h = 125$ GeV,
- This is already pushing the SUSY scale to $O(10)$ TeV,
- Only a few superpartners may be detectable at LHC (LSP chargino, stop, gluino,...),
- Still possible to find evidence of SUSY Dark matter,
- Slim SUSY, still attractive,
- If no signal of BSM physics shows up at LHC, then what? Super-split SUSY (=SM).

LHC is confirming the SM:





800
600
400
200
0
M_H [GeV]
m_t = 175 GeV
$\alpha_s(M_Z)$ = 0.118
not allowed
allowed
not allowed
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
Λ [GeV]



m_h = 124 GeV
m_t = 173.2 GeV
$\alpha_3(M_Z)$ = 0.1184
m_t = 171.4 GeV
$\alpha_3(M_Z)$ = 0.1198
$\alpha_3(M_Z)$ = 0.117
m_t = 175. GeV
Higgs quartic coupling $\lambda(\mu)$
RGE scale μ in GeV
m_h = 126 GeV
m_t = 173.2 GeV
$\alpha_3(M_Z)$ = 0.1184
Higgs quartic coupling $\lambda(\mu)$
RGE scale μ in GeV

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 $sgn(mu)$.

EWSB in the MSSM

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

$$M_Z^2 = 2c_1 M_{H_u}^2 - 2t_\beta^2 M_{H_d}^2 - 2\mu^2 \tag{6}$$

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 ($\tilde{m} \leq 200$ GeV) ruled out such case,
- Including RGE and recent LHC limits make it worse (A. Strumia, ArXive:1101.2195 [hep-ph]):

$$M_Z^2 = 0.2m_0^2 + 0.7M_3^2 - 2\mu^2 \simeq (91GeV)^2 \times 50(\frac{M_3}{780})^2 + ... \tag{7}$$

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

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 $H^{\pm}$.

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,