Higgs in the NMSSM and the LHC

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- Overview Higgs results, mass and couplings
- Higgs in NMSSM
- Specific NMSSM scenarios
  - Higgs in two-photons
  - Light DM

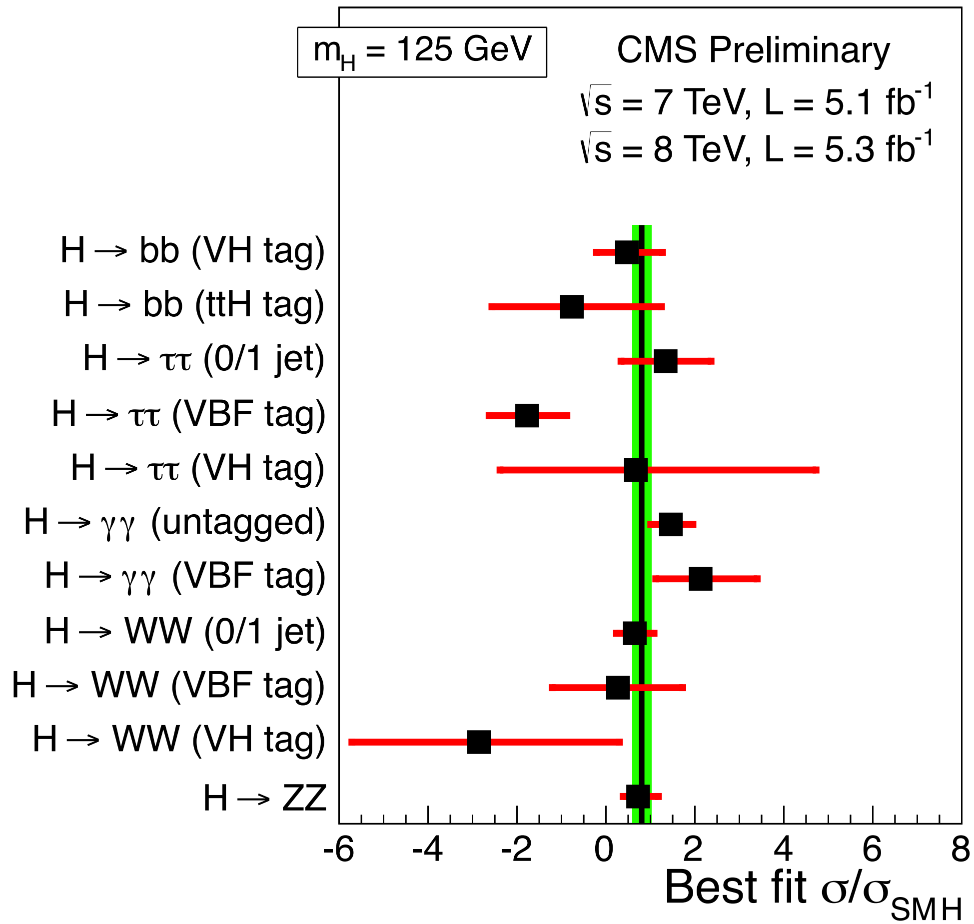
Introduction

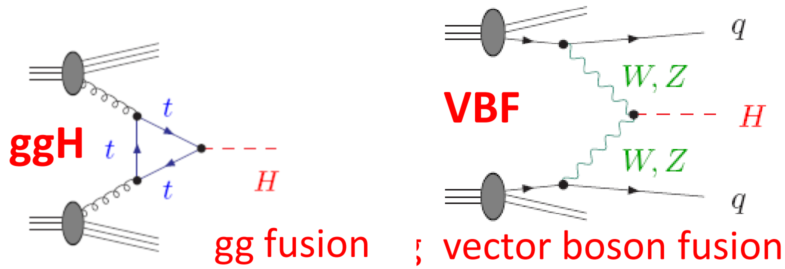
- Higgs mass is compatible with SM up to high scale (see e.g. Degrassi's lecture)
- No sign (yet) of supersymmetry at LHC
- Supersymmetry offers a good DM candidate, remains strong motivation for beyond standard model
- Evidence for DM from many different scales + precise determination of relic density from cosmology (WMAP)
- WIMPs are still best explanation for DM and have naturally cross section that gives $\Omega h^2 \sim 0.1$

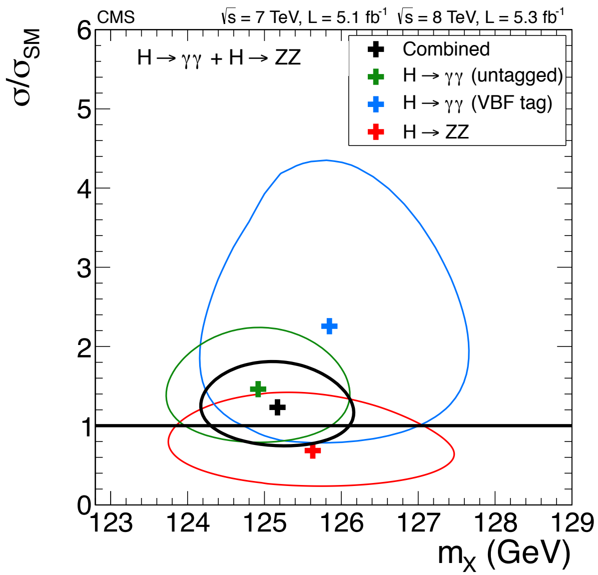
Higgs at LHC

- July 4th 2012: ATLAS and CMS reported a signal consistent with a Higgs boson with mass
- m_h =125.3+/-0.4+/-0.5GeV (CMS)
- =126.0+/-0.4+/-0.4GeV (ATLAS)
- Such a mass can be reached in MSSM require large mixing in stop sector, fine-tuning
- Also measure the signal strength in various production/ decay channels : give indication whether the new particle is a SM Higgs
- Results not precise enough yet : indications that signal strength is larger than expected in two-photon mode
- If this result is confirmed : precious information/constraints on physics beyond the standard model, e.g. challenge for MSSM

CMS - Higgs results

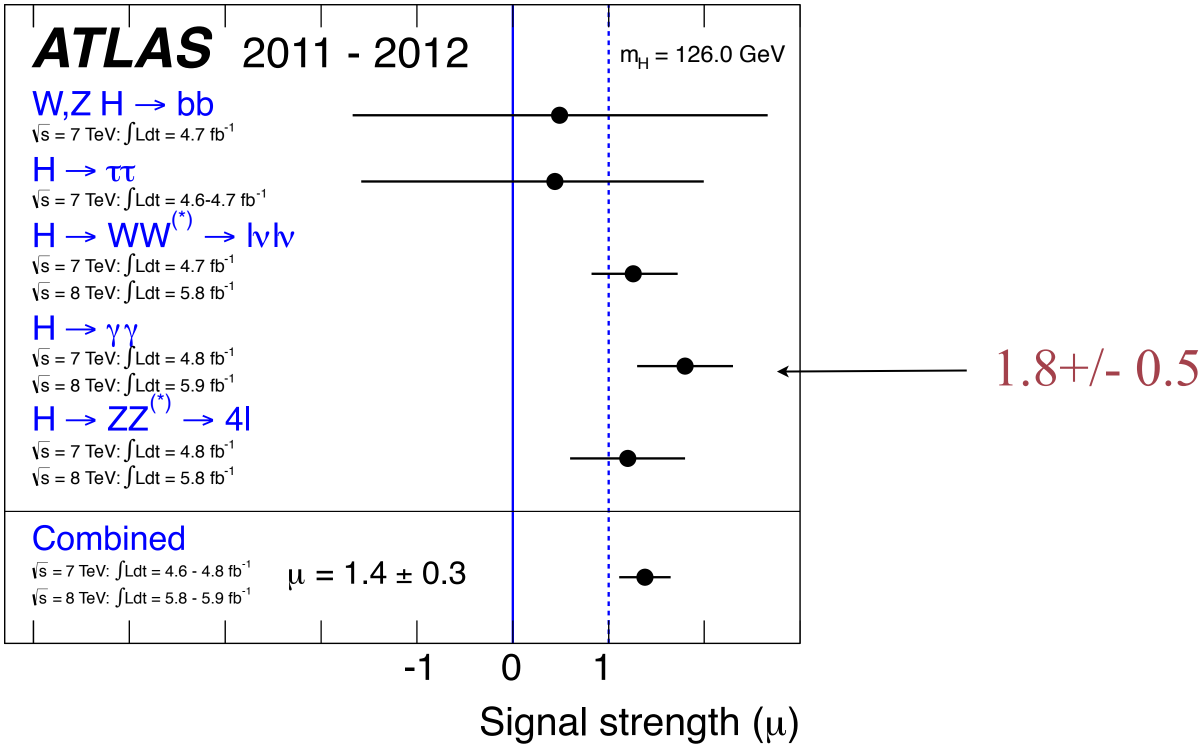






ATLAS - Higgs results

- Also has an excess in two-photon mode
- Results for signal strength relative SM combining all production modes



Implications for MSSM

- Mass at 125 GeV
  - need large radiative corrections

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

  - δ_t~85 GeV (comparable to tree-level)
  - Large stop mixing

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right].$$

  - Fine-tuning issue

$$M_Z^2 \simeq -2\mu^2 + \frac{2(m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2)}{\tan^2\beta - 1}.$$

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

  –

Higgs couplings in MSSM

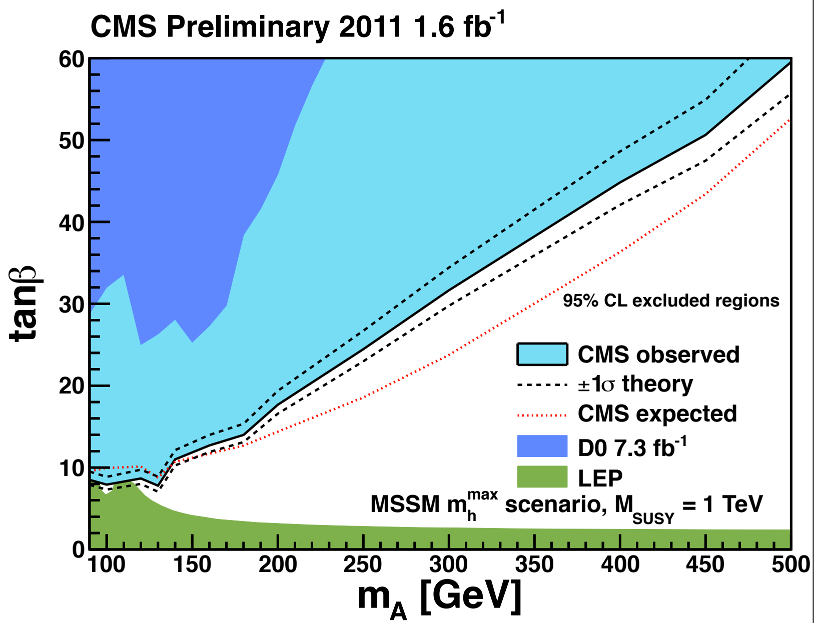
- In decoupling limit (large mA)
- Ignoring radiative corrections

$$\cos^2(\beta-\alpha) = \frac{M_h^2(M_Z^2 - M_h^2)}{M_A^2(M_H^2 - M_h^2)}$$

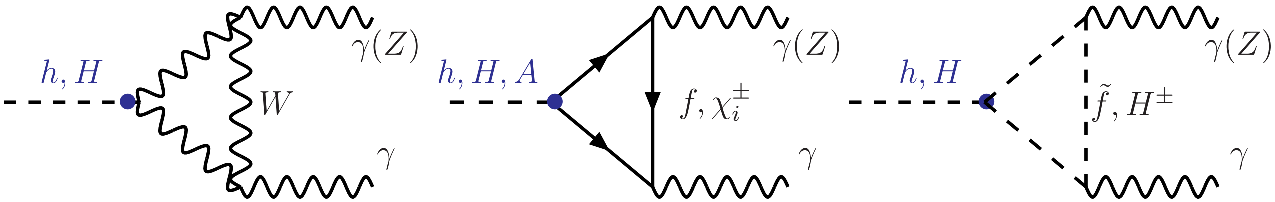
- Tree-level Higgs coupling to SM particles close to SM value

$$\frac{g_{W^+W^-h}}{g_{SM}} = \sin(\beta-\alpha)\,, \qquad \frac{g_{\bar{t}th}}{g_{SM}} = \frac{\cos\alpha}{\sin\beta}\,, \qquad \frac{g_{\bar{b}bh}}{g_{SM}} = -\frac{\sin\alpha}{\cos\beta}\,.$$

- Search for pp-H-> ττ in CMS and ATLAS
- Production gg->H and bbH
- Strong enhancement for MSSM heavy doublet at large values of tanβ



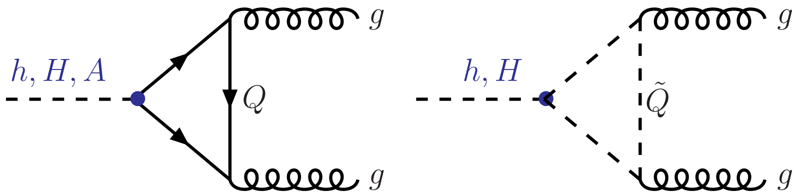
Loop-induced couplings



- hγγ: dominant contribution: W loop , top loop opposite sign
- If hWW coupling not modified, hγγ not much affected
- possible large contributions from susy in the loop (stop,chargino,stau) - colored particles also affect gg
- Branching hγγ can be modified because total width
- to increase branching hγγ -> suppress total width (see example in NMSSM)

$$R_{\gamma\gamma} = \frac{BR^{SUSY}(h \to \gamma\gamma)}{BR^{SM}(h \to \gamma\gamma)}$$

ggH



- hgg dominant contribution top loop
- Stop contribution can be large
  - Djouadi, PLB345(98) 101

$$V_{\tilde{t}_1\tilde{t}_1h} \simeq \frac{g}{M_W}\left(\sin^2(2\theta_{\tilde{t}})\frac{(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2})}{4} + m_t^2 + M_Z^2\cos(2\beta)\left((\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos^2\theta_{\tilde{t}} + \frac{2}{3}\sin^2\theta_W\sin^2\theta_{\tilde{t}}\right)\right)$$

  –
  - large mixing : stop interferes destructively with top
  - When m_h=125GeV : suppression of ggh larger than increase in hγγ - no large increase in $R_{gg\gamma\gamma}$

$$R_{gg\gamma\gamma} = \frac{\sigma(gg \to h)_{MSSM}BR(h \to \gamma\gamma)_{MSSM}}{\sigma(gg \to h)_{SM}BR(h \to \gamma\gamma)_{SM}}$$

- Only way to increase $R_{gg\gamma\gamma}$ is use weak sector - chargino/stau, (for example R ~1.5-2 for light stau with large mixing - Carena et al 1205.5842)

NMSSM

- MSSM with additional singlet superfield

$$W_{\rm NMSSM} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3}\kappa \hat{S}^3,$$

$$V_{\rm soft}^{\rm NMSSM} = \tilde{m}_u^2 |H_u|^2 + \tilde{m}_d^2 |H_d|^2 + \tilde{m}_S^2 |S|^2 + (A_\lambda \lambda S H_u \cdot H_d + \frac{A_\kappa}{3}\kappa S^3 + h.c.).$$

- μ parameter is related to vev of singlet $\mu = \lambda s$
  - naturally of order of weak scale
- Higgs sector : 3 CP-even, 2 CP-odd + charged Higgs
  - much richer phenomenology than in MSSM
- Also extra neutralino -> singlino
  - can impact dark matter properties

Higgs mass

- Light Higgs mass : new contribution at tree level
- Increase in Higgs mass $m_h^2 < M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$
- largest increase is for low values of tanβ
- Easier to reach 125GeV even without very large stop corrections (Ellwanger et al JHEP1109,105; Hall et al 1112.2703)
- Fine tuning reduced :
  - With large lambda stop mass/mixing not so large, m_{Hu} not so large
  - in constrained NMSSM (Ellwanger, Espitalier-Noel,Hugonie,1107.2472)
- Doublet singlet mixing - the lightest Higgs scalar can be very light escape LEP bounds

- Mixing can lead to reduce hbb, reduced total width--> increased branching ratios

$$H_1 = S_{1,d}\ H_d + S_{1,u}\ H_u + S_{1,s}\ S$$

$$c_{D_i} = \frac{S_{i,d}}{\cos\beta}\ , \qquad c_{U_i} = \frac{S_{i,u}}{\sin\beta}\ , \qquad c_{V_i} = \cos\beta\, S_{i,d} + \sin\beta\, S_{i,u}$$

- Possible to increase branching ratios in two photons.
  - Ellwanger, 1012.1201,1112.3548
- $R_{gg\gamma\gamma}$>1 for m_H=125GeV, when λ large (determines singlet-doublet mixing), tanβ small
- In NMSSM with input parameters at EW scale, what are implication of Higgs results after taking into account B physics, DM and LHC SUSY searches?

weak scale NMSSM

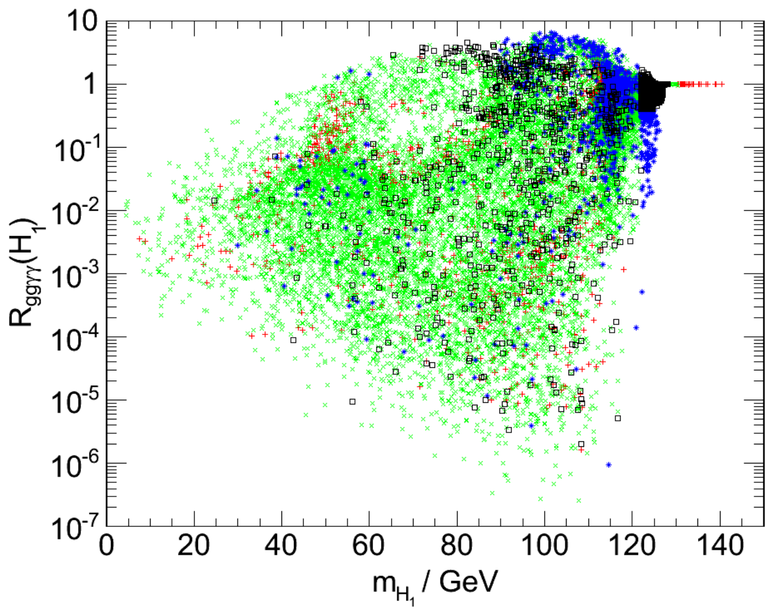
- MCMC with 14 free parameters :
- $\lambda, \kappa, A_\lambda, A_\kappa$

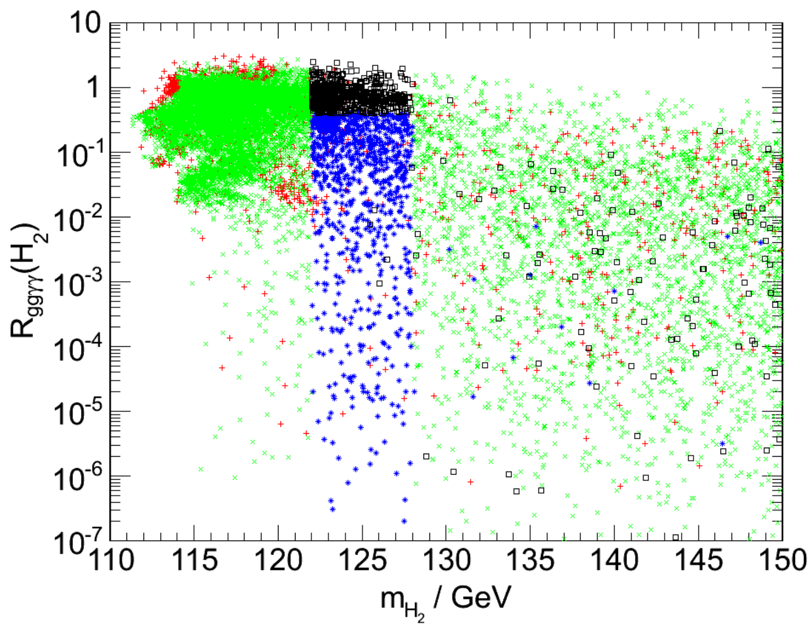
$$M_1,\ M_2,\ M_3,\ \mu,\ \tan\beta,$$
$$M_{\tilde{l}_L},\ M_{\tilde{l}_R},\ M_{\tilde{q}_{1,\,2}},\ M_{\tilde{q}_3},\ A_t.$$

- Constraints : B, g-2, relic density...
- NMSSMTools (Higgs)
- a posteriori:
  - HiggsBounds3.6.1
  - LHC jets+missing E_T($1fb^{-1}$),
  - direct detection (Xenon100),
  - FermiLAT (photons from dwarf Spheroidals)
  - LHCb ($B_s \to \mu^+\mu^-$)

constraint	value/range	tolerance
Smasses	-	none
$\Omega_{WMAP}h^2$	0.01131 - 0.1131	0.0034
$(g-2)_\mu$	$25.5\ 10^{-10}$	stat: $6.3\ 10^{-10}$ sys: $4.9\ 10^{-10}$
$\Delta\rho$	≤ 0.002	0.0001
$b \to s\gamma$	$3.52\ 10^{-4}$ [? ?]	th: $0.24\ 10^{-4}$ exp: $0.23\ 10^{-4}$
$B_s \to \mu^+\mu^-$	$\leq 4.7\ 10^{-8}$	$4.7\ 10^{-10}$
$R(B \to \tau\nu)$	1.28 [?]	0.38
$Z \to \chi_1\chi_1$	≤ 1.7 MeV	0.3 MeV none
$e^+e^- \to \chi_1\chi_{2,3}$	≤ 0.1 pb [?]	0.001 pb none
ΔM_s	$117.0\ 10^{-13}$ GeV	th: $21.1\ 10^{-13}$ GeV exp: $0.8\ 10^{-13}$ GeV
ΔM_d	$3.337\ 10^{-13}$ GeV	th: $1.251\ 10^{-13}$ GeV exp: $0.033\ 10^{-13}$ GeV

Higgs signal strength



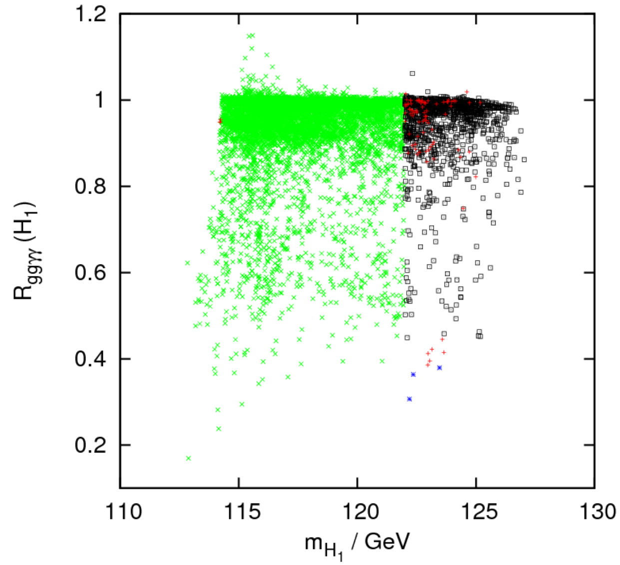


- Both H_1 and H_2 can be in 122-128GeV range - H_1 has $R_{gg\gamma\gamma}$~1
- MCMC+HiggsBounds3.6.1

- Insisting on WMAP lower/upper limit - most points with $R_{gg\gamma\gamma}>1$ disappear
- Few points with H_2 ~125GeV
- $R_{gg\gamma\gamma}>1$- associated with small μ, light charginos because singlet mass light

$$m_S^2 = \kappa\mu/\lambda(A_\kappa + 4\kappa\mu/\lambda)$$

- small μ means LSP has significant higgsino component
  - efficient annihilation into WW
  - 'typically' Ω< 0.1

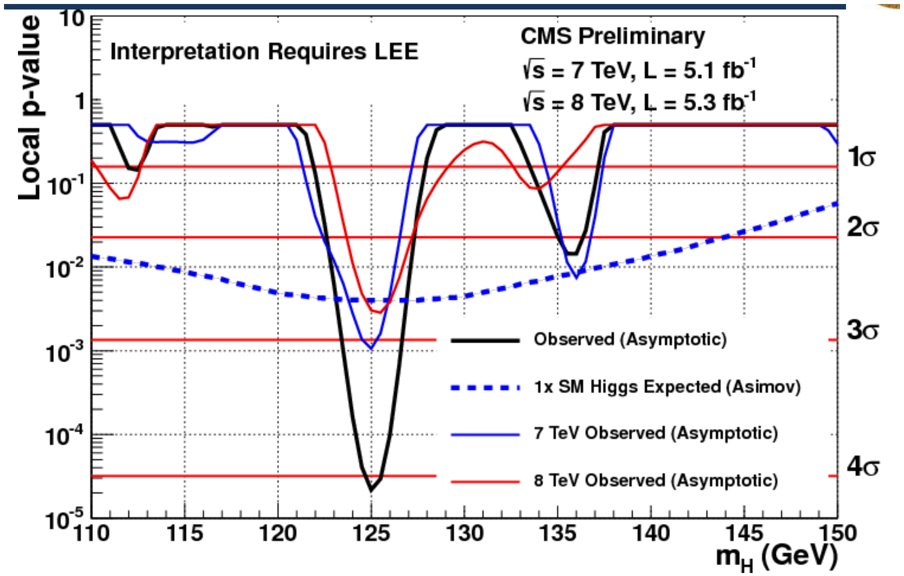


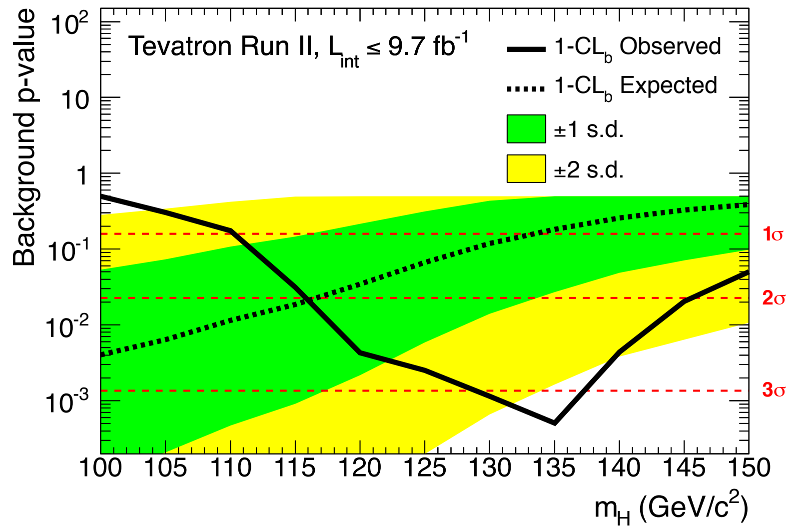
- Small μ also found in other studies
  - $R_{gg\gamma\gamma}>1$ in NUHNMSSM- Ellwanger et al (1203.5048)
  - large λ in NMSSM- (Chang etal,1202.0054)

- While it is possible to satisfy all constraints and R>1 confined to very special corner of parameter space
- Hard to explain also all of DM (could have other DM component)
- Light ‘Higgsinos’ present
- Challenge for LHC ... nearly mass degenerate -> di,tri-lepton signatures have soft p_T spectrum (Baer et al 1107.5581)
- Signal for NMSSM Higgs sector ?

NMSSM signal already there?

- Could it be that Tevatron and LHC have seen two Higgs bosons?





- At Tevatron enhanced signal in VH,H->bb between 110-140GeV best value, M_H~135GeV,
- Can this be compatible with two lightest Higgses in NMSSM?

Sample point

- ‘Fit’ CMS+Tevatron Higgs signal
- Here ignore DM requirement

λ	0.617	μ_{eff}	143
κ	0.253	A_λ	164
$\tan\beta$	1.77	A_κ	337
M_{H_1}	125	M_{A_1}	95
M_{H_2}	136	M_{A_2}	282
M_{H_3}	289	$M_{H^\pm}$	272

Higgs	$R^{\gamma\gamma}(ggF)$	$R^{\gamma\gamma}(VBF)$	$R^{VV^{(*)}}(ggF)$	$R^{VV^{(*)}}(VH)$	$R^{bb}(VH)$	$R^{\tau\tau}(ggF)$
H_1	1.30	1.09	0.90	0.75	0.36	0.42
H_2	0.16	0.27	0.18	0.31	0.74	0.43
H_3	0.58	0.01	0.04	0.004	0.23	19.6

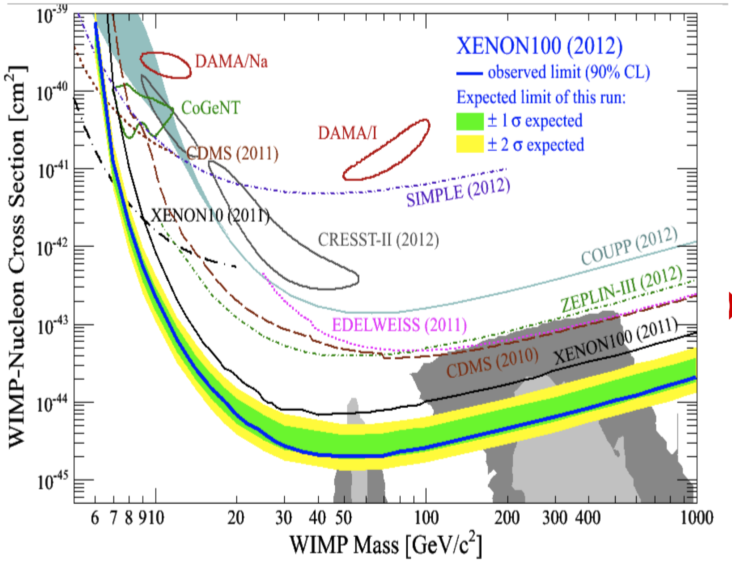
- At Tevatron - poor mass resolution in bb + production H_1>H_2
- $R^{bb}_{\text{eff}}(VH) \simeq R^{bb}_2(VH) + 1.3 \times R^{bb}_1(VH) \sim 1.3$
- More data at LHC (γγ) will confirm/rule out this possibility
- Search for H_3 - look at decays in light Higgs/ neutralino pairs

- Higgs searches at LHC could still provide exciting news - certainly powerful constraints on extended Higgs sector

Light neutralino DM in the NMSSM

NMSSM with light neutralino

- A closer look at the light neutralino (<$m_Z/2$)
- Possibility of invisible Higgs - is it ruled out? specific signatures?
- Light neutralino motivated by hints in direct detection (although latest Xenon2012 make it hard to reconcile all DD results)



- Case m<15 GeV

- μ=λs related to vev of singlet
- 5 neutralinos

$$
\begin{pmatrix}
M_1 & 0 & M_Z \sin\theta_W \sin\beta & -M_Z \sin\theta_W \cos\beta & 0 \\
0 & M_2 & -M_Z \cos\theta_W \sin\beta & M_Z \cos\theta_W \cos\beta & 0 \\
M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & 0 & -\mu & -\lambda v \cos\beta \\
-M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & -\mu & 0 & -\lambda v \sin\beta \\
0 & 0 & -\lambda v \cos\beta & -\lambda v \sin\beta & 2\nu
\end{pmatrix}
$$

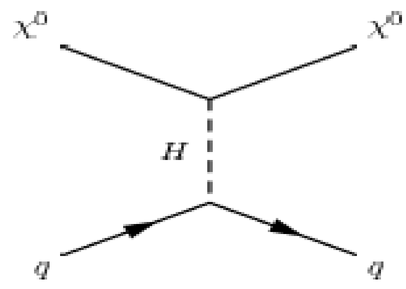
- LSP can be either bino or singlino (higgsino only if m>100GeV)
- Singlino : handle to differentiate NMSSM from MSSM

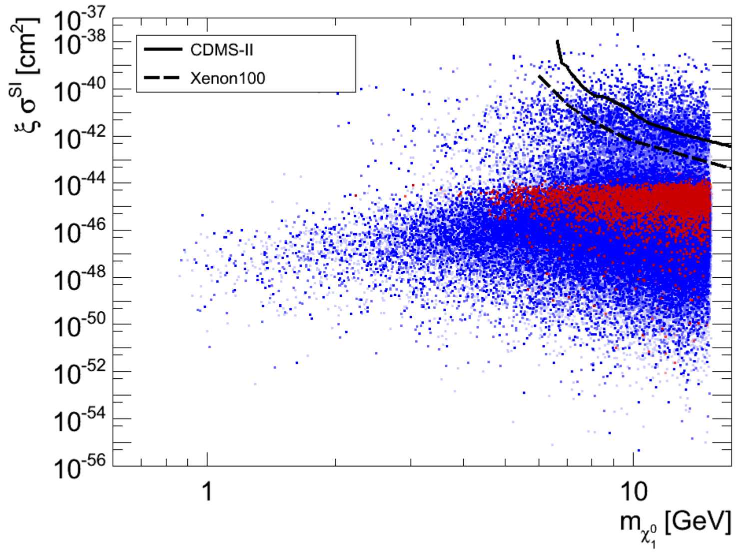
NMSSM parameter space

- MCMC with 11 free parameters :
  - $M_1, M_2 = M_3/3, \mu, \tan\beta$, M_l, M_q, A_t, λ, κ, A_λ, A_κ
- Constraints : B, g-2, relic density...
- NMSSMTools (Higgs)
- a posteriori:
  - HiggsBounds3.6.1
  - LHC jets+missing E_T($1 fb^{-1}$),
  - direct detection (Xenon100)
  - FermiLAT (photons from dwarf Spheroidals)
  - LHCb ($B_s \to \mu^+\mu^-$)
  - Require invisible branching Higgs <60% (3sigma)

Direct DM detection

- Direct detection : DM elastic scattering on nuclei
- Dominate by Higgs exchange
- Enhanced for very light Higgs



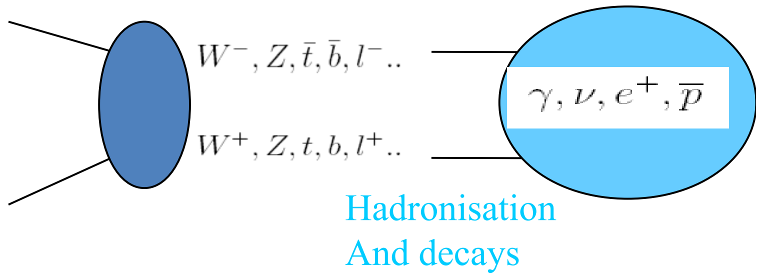


Indirect detection

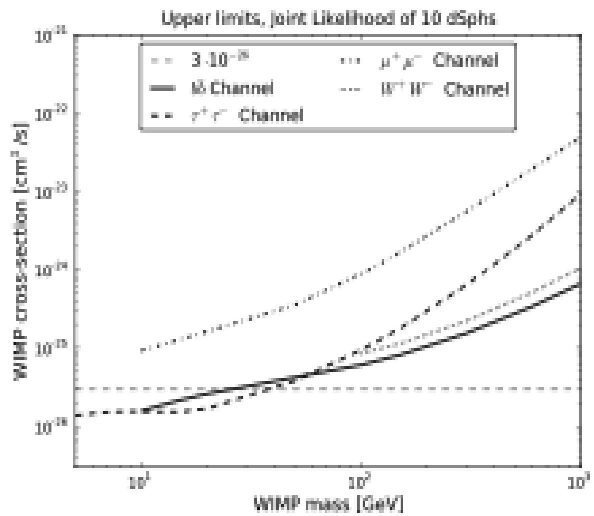
- Annihilation of pairs of DM into SM particles : decay products observed
- FermiLAT : Photons from Dwarf Spheroidal Galaxies probe typical DM annihilation cross section at freeze-out for light DM

$$< \sigma v > = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

- Also if $2m_{LSP} \sim m_A$ possible resonance enhancement at $v \sim 0.001c$

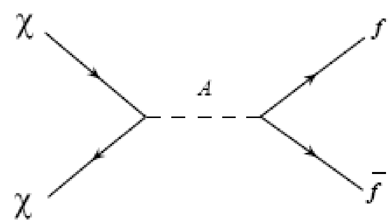


$$\Phi_{\gamma,\nu} = \frac{1}{8\pi} \frac{< \sigma_{ann} v >}{m_\chi^2} \sum_{f.s.} \left(\frac{dN_{\gamma,\nu}}{dE} \right)_{f.s.} \int_{l.o.s.} \rho_s^2$$

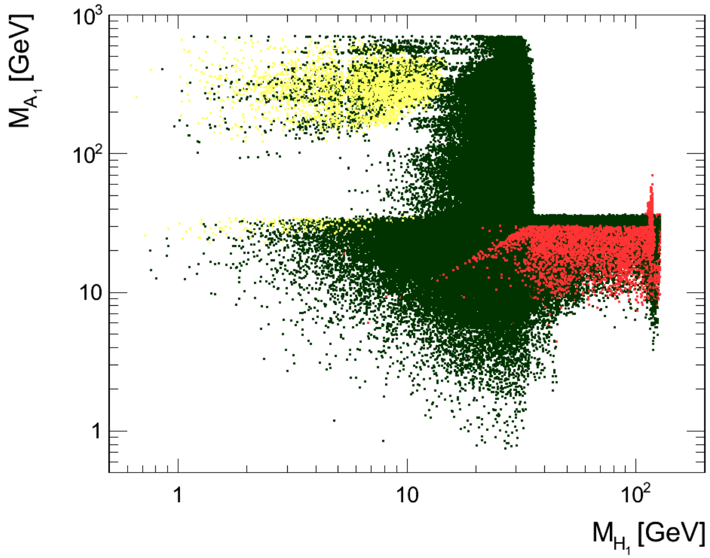


NMSSM with light neutralino

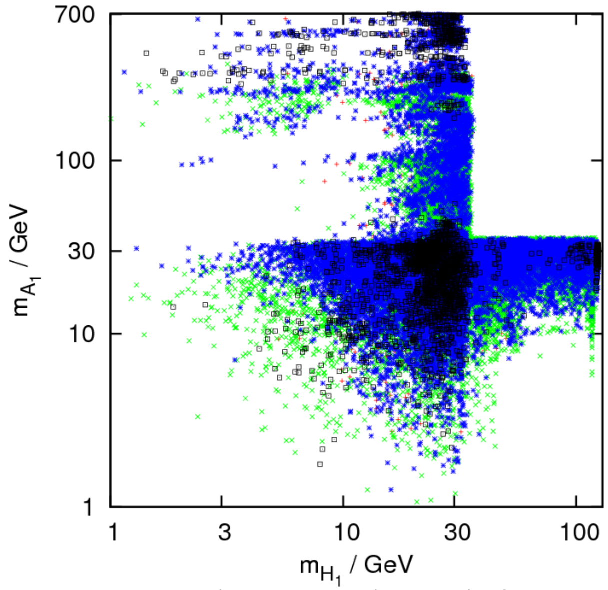
- To satisfy DM constraints (Relic density) need an efficient annihilation mechanism for light neutralino
  - H_1 or A_1 ~$2M_{LSP}$
  - H_1 or H_2 in 122-128GeV range



Yellow: Direct detection
Red : gamma-ray Fermi

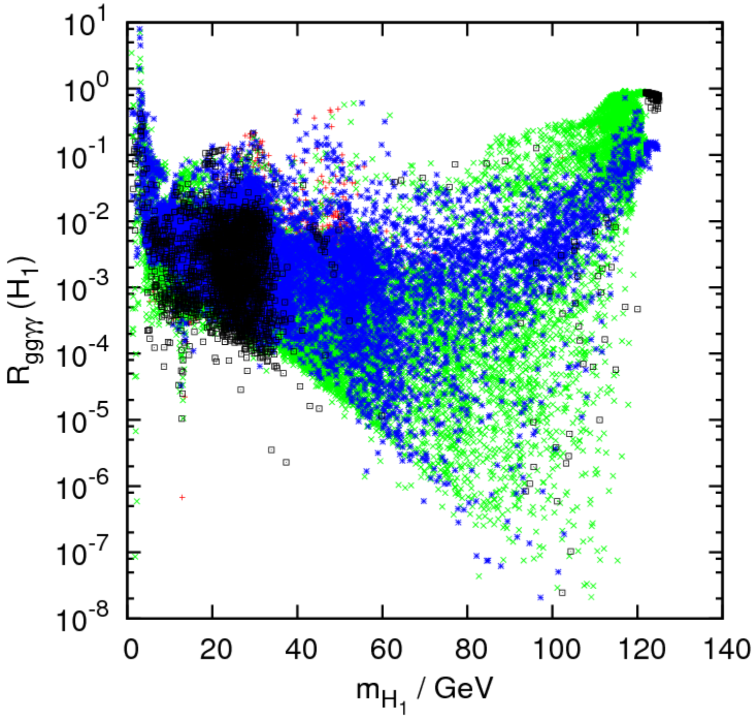


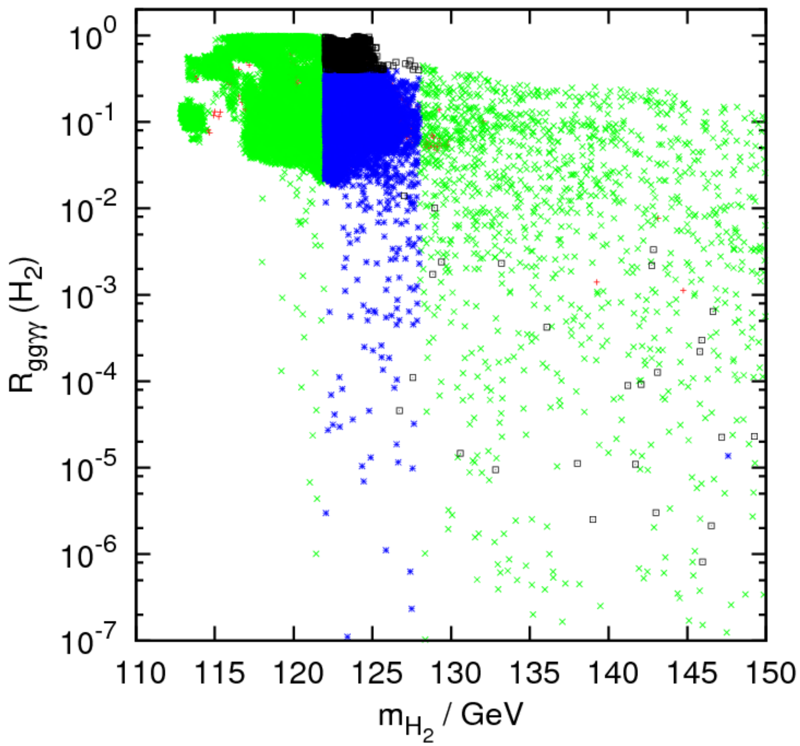
R<0.4
R>0.4



Two-photon signal for H125

Higgs signal strength

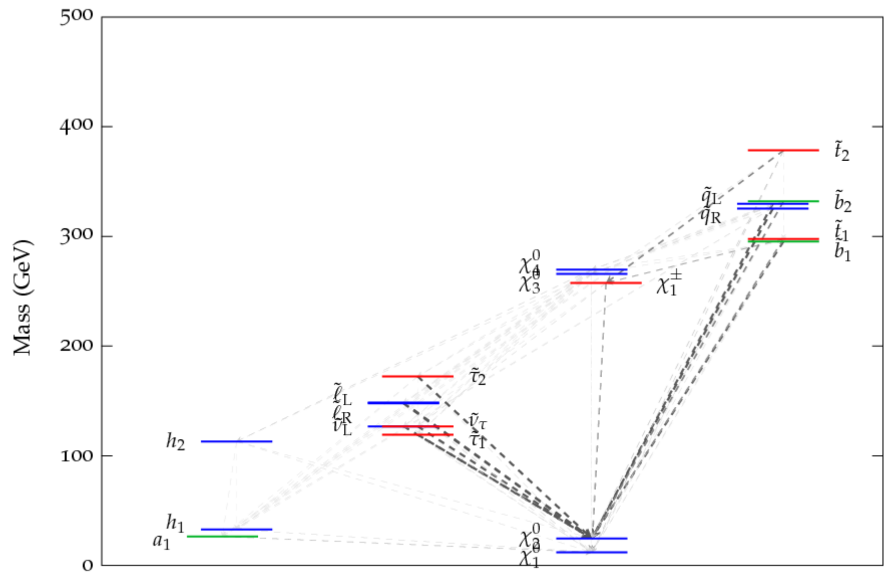




- H_1 or usually H_2 MSSM-like $R_{gg\gamma\gamma}<1$
- invisible modes - possible strong suppression

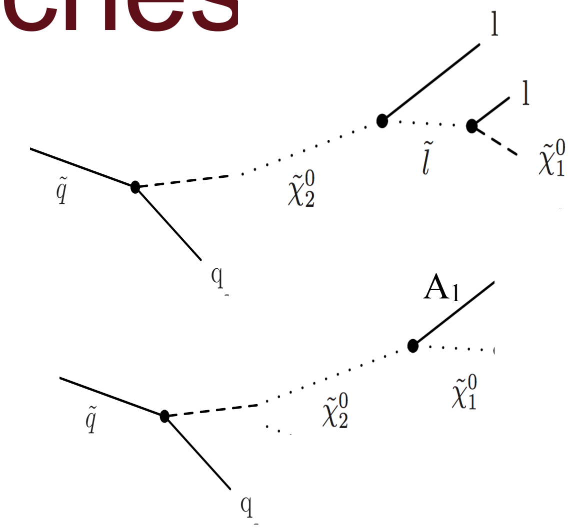
LHC -SUSY searches

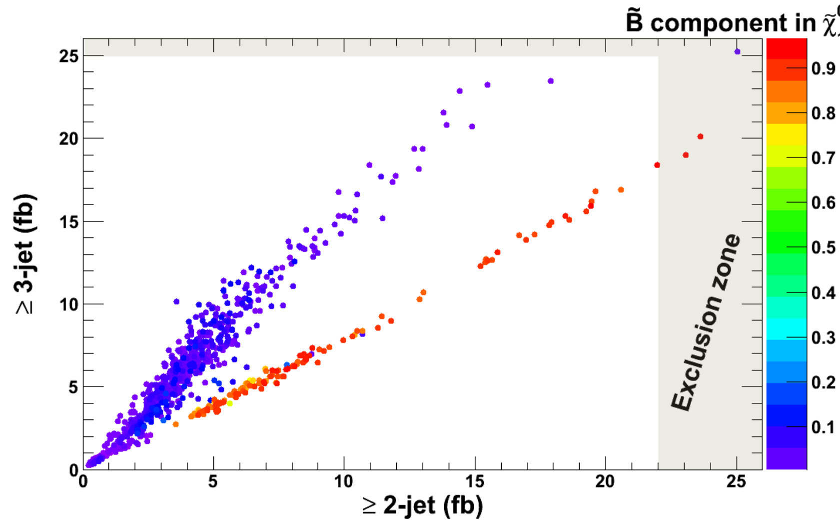
- Jets + missing E_T ATLAS 1fb^{-1}
- MCMC+micrOMEGAs+NMSSMTools-> SLHA file
- Event generator Herwig++2.5.1
- Rivet 1.5.2 (Grellscheid et al 1111.3365)
- Limits on squarks can be weaker than in MSSM when LSP is singlino



LHC -SUSY searches

- Squarks decay through intermediate step (q+χ_2)
- Reduced acceptance into jets +missing E_T
- Higher number of jets when LSP singlino
- Higher number of leptons (complementary search with leptons)
- Decay through Higgs: alignment between missing p_T and one jet, fail angular separation trigger
- Note: squarks are generally heavy so new LHC limits do not rule out the scenario

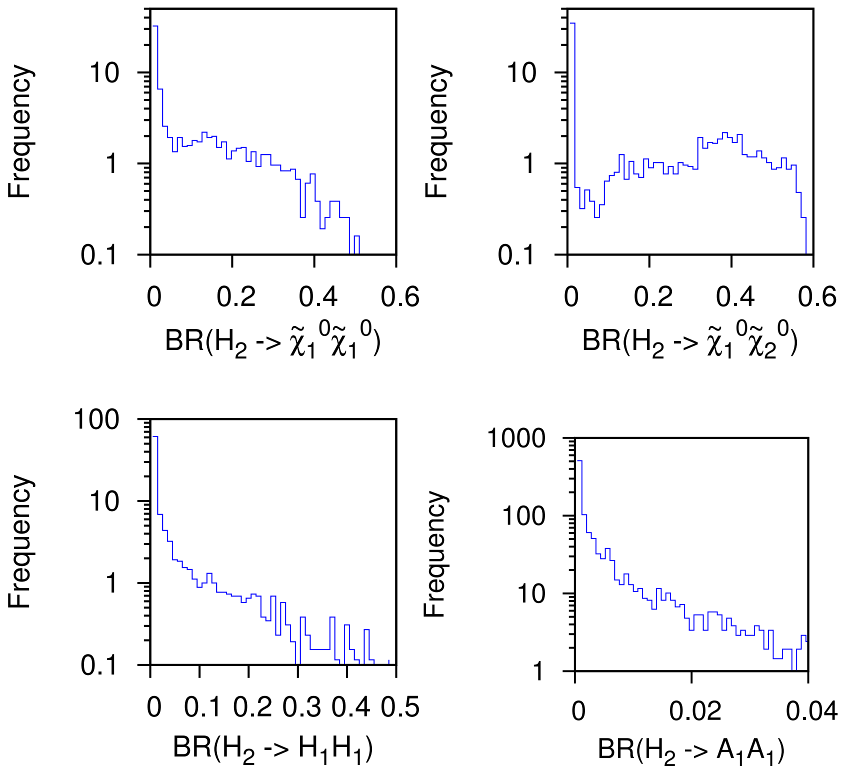




NMSSM signatures

- SUSY sector: main difference with MSSM: singlino LSP
  - bino -> singlino + soft leptons (Kraml, Raklev, White, 0811.0011)
- Higgs sector (in addition to standard channels):
  - H_2->$2A_1(H_1)$->ττττ,μμττ
    - Englert et al, PRD84 075026(2011) Lisanti, Wacker PRD79 115006(2009)
  - Higgs->$\chi_2\chi_1$, χ_2->χ_1 f f or χ_2->χ_1 H/A
- Also search for light Higgs but couplings of H_1 to SM suppressed because singlet component
  - H_1bb at most SM-like (even though coupling can be tanβ enhanced)
- Higgs production in SUSY decays

- If NLSP partly singlino -> can be lighter than 100GeV
- Non standard H decays: $H_2 \to \tilde{\chi}^0_{1,2}\tilde{\chi}^0_{1,2}$, H_1H_1 or A_1A_1



CONCLUSION

- NMSSM is extension of MSSM that provide a Higgs 125 GeV which satisfies all constraints
- Possibility of increasing two-photon signal
- Specific signatures both in Higgs sector (including extra states) and in SUSY sector (especially if singlino LSP)
- Detailed investigation of Higgs sector at LHC