

# Implications of Higgs results in extensions of the MSSM

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- LHC data suggest an excess in  $H \rightarrow \gamma\gamma$  at 125 GeV
- Signal strength larger than expected in SM (but consistent)
- Compatible with Higgs in MSSM (but fine-tuning)
- In the NMSSM additional corrections to Higgs mass makes it easier to reach 125 GeV even without very large stop corrections
  - Ellwanger et al JHEP1109,105; Hall et al 1112.2703
- Furthermore possible to increase branching ratios in two photons.
  - Ellwanger, 1012.1201,1112.3548
- In general NMSSM with input parameters at EW scale, what are implication of Higgs results after taking into account B physics, DM and LHC SUSY searches?

- NMSSM with light neutralinos
- NMSSM with weak scale input parameters
- UMSSM with light dark matter

# Higgs sector of NMSSM

- 3 CP-even, 2 CP-odd + charged Higgs

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

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

- Increase in Higgs mass  $m_h^2 < M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$
- Doublet singlet mixing - light Higgs can be very light escape LEP bounds
- Mixing can lead to reduce hbb, reduced total width, increased branching ratios

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

- $R_{gg\gamma\gamma} > 1$  when  $\lambda$  large (determines singlet-doublet mixing),  $\tan\beta$  small or as in the MSSM

- $\mu = \lambda s$  related to vev of singlet
- 5 neutralinos

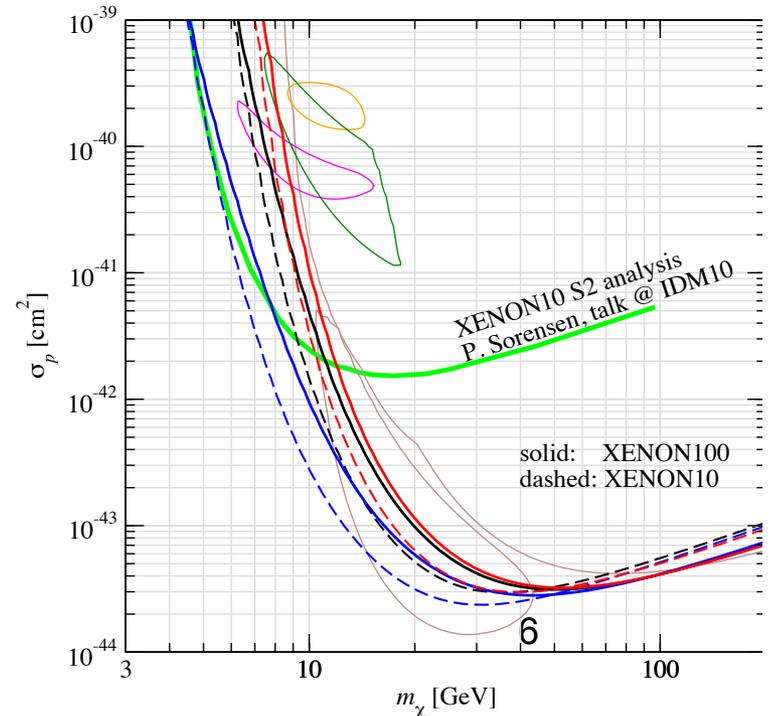
$$\begin{pmatrix} M_1 & 0 & M_Z \sin\theta_W \sin\beta & -M_Z \sin\theta_W \cos\beta & 0 \\ 0 & M_2 & -M_Z \cos\theta_W \sin\beta & M_Z \cos\theta_W \cos\beta & 0 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & 0 & -\mu & -\lambda v \cos\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W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

- LSP can be dominantly singlino
- Leads to new features in SUSY decays -e.g.
  - squark  $\rightarrow q + (\chi_2 \rightarrow \chi_1 + f f)$
- Singlino : handle to differentiate NMSSM from MSSM

# 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

- Case  $m < 15$  GeV
  - D. Albornoz Vasquez, et al.
  - 1107.1614, 1201.6150, 1203.3446



# NMSSM parameter space

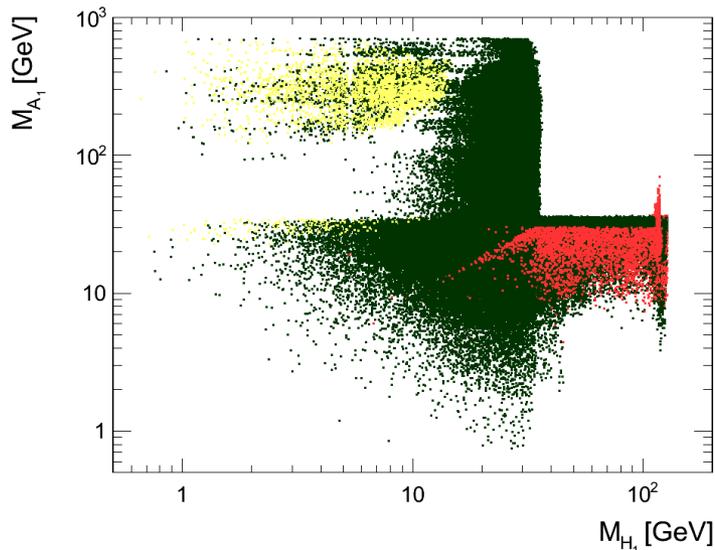
- MCMC with 11 free parameters :
  - $M_1, M_2 = M_3/3, \mu, \tan\beta, M_l, M_q, A_t, \lambda, \kappa, A_\lambda, A_\kappa$
- Constraints : B, g-2, relic density...
- NMSSMTools (Higgs)
- a posteriori:
  - HiggsBounds3.6.1
  - LHC jets+missing  $E_T(1\text{fb}^{-1})$ ,
  - direct detection (Xenon100),
  - FermiLAT (photons from dwarf Spheroidals)
  - LHCb ( $B_s \rightarrow \mu^+ \mu^-$ )

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

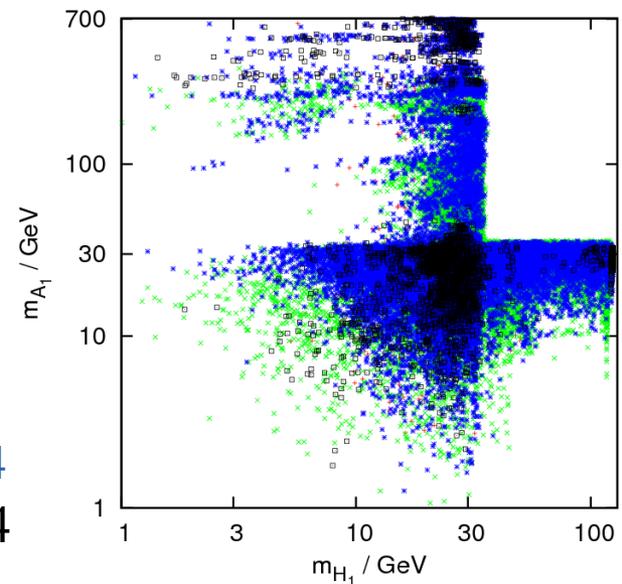
# NMSSM with light neutralino

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

Yellow: Direct detection  
Red : gamma-ray Fermi



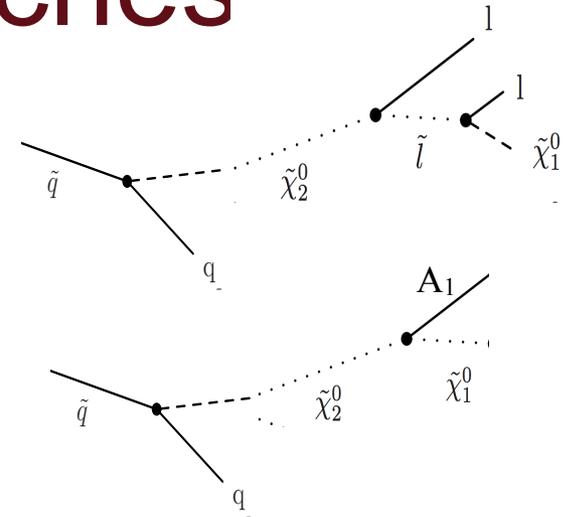
$R < 0.4$   
 $R > 0.4$



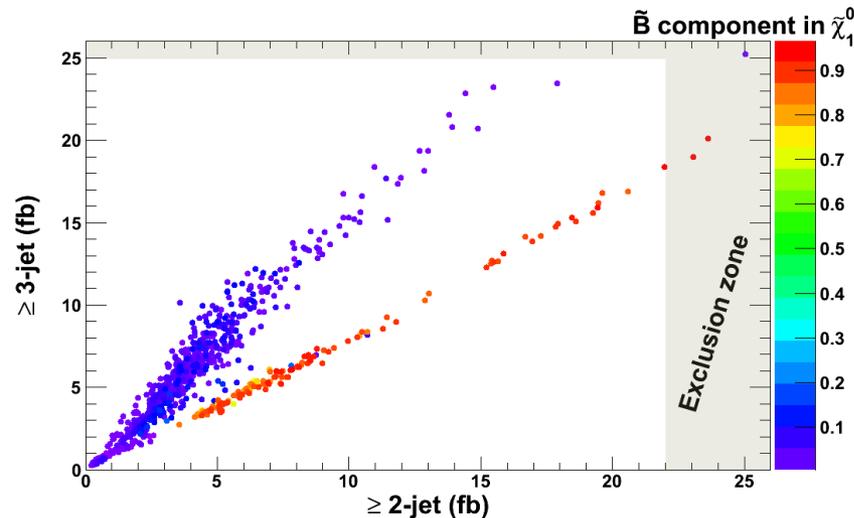


# LHC -SUSY searches

- Squarks decay through intermediate step ( $q+\chi_2^0$ )
- Reduced acceptance into jets +missing  $E_T$
- Higher number of jets and or leptons (complementary search with leptons)
- Reduce missing  $E_T$
- Decay through Higgs: alignment between missing  $p_T$  and one jet, fail angular separation trigger
- Note: squarks are generally heavy

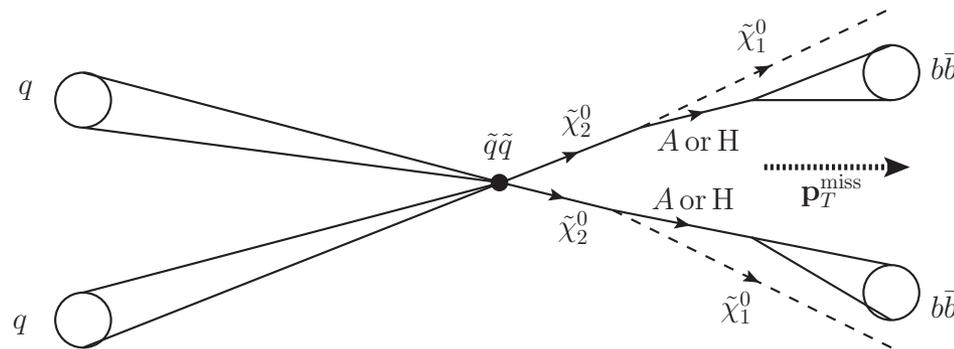


- The jets+missing  $E_T$  involve more jets when LSP singlino

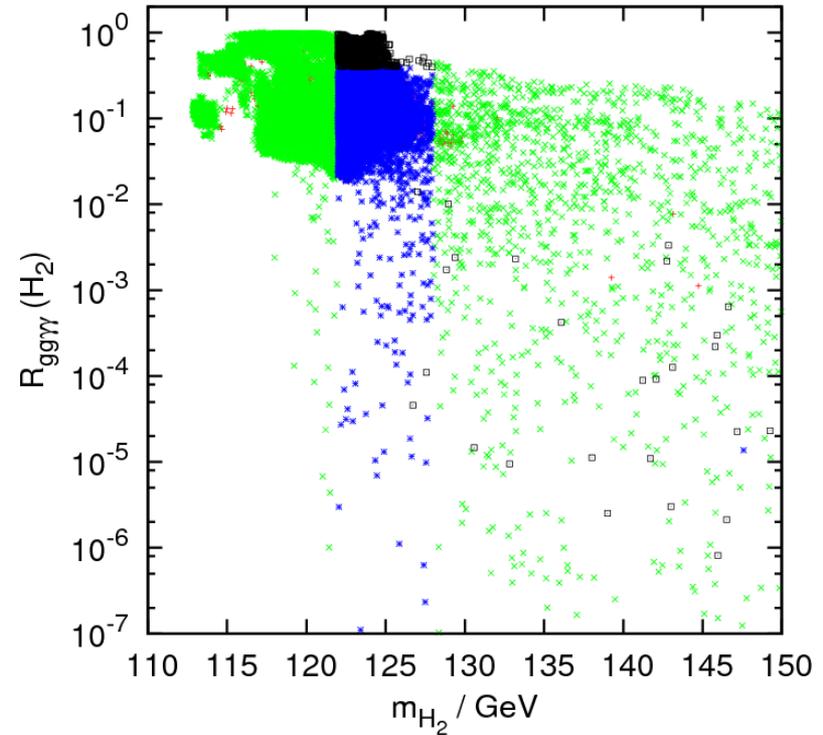
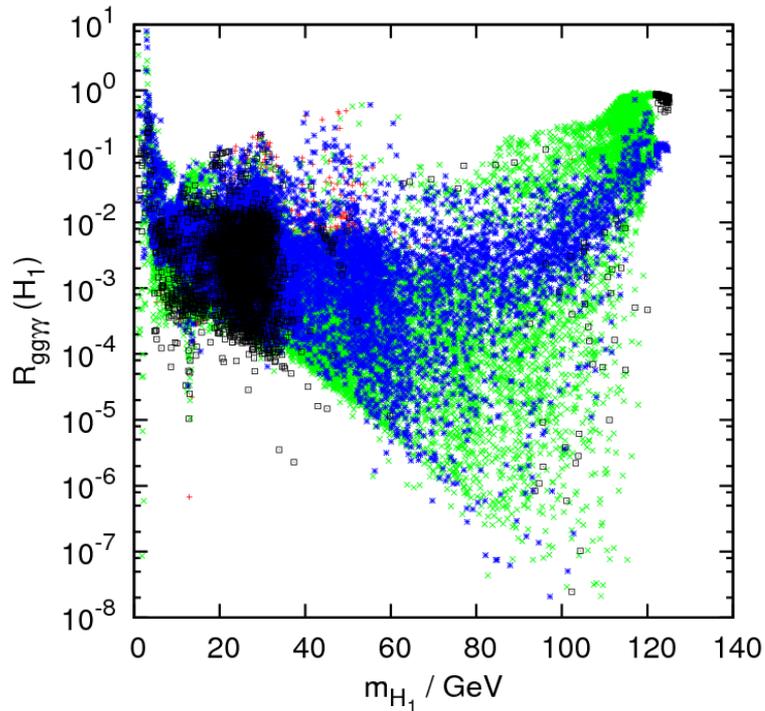


- Weaker limits on squarks also obtained in analysis in CNMSSM both with jets+missing  $E_T$  and jets+leptons +missing  $E_T$ 
  - Das et al 1202.5244

- SUSY sector: main difference with NMSSM: singlino LSP
  - bino  $\rightarrow$  singlino + soft leptons (Kraml, Raklev, Wilte, 0811.0011)
  - Neutralino very boosted, missing  $p_T$  points in between 2 b-jets

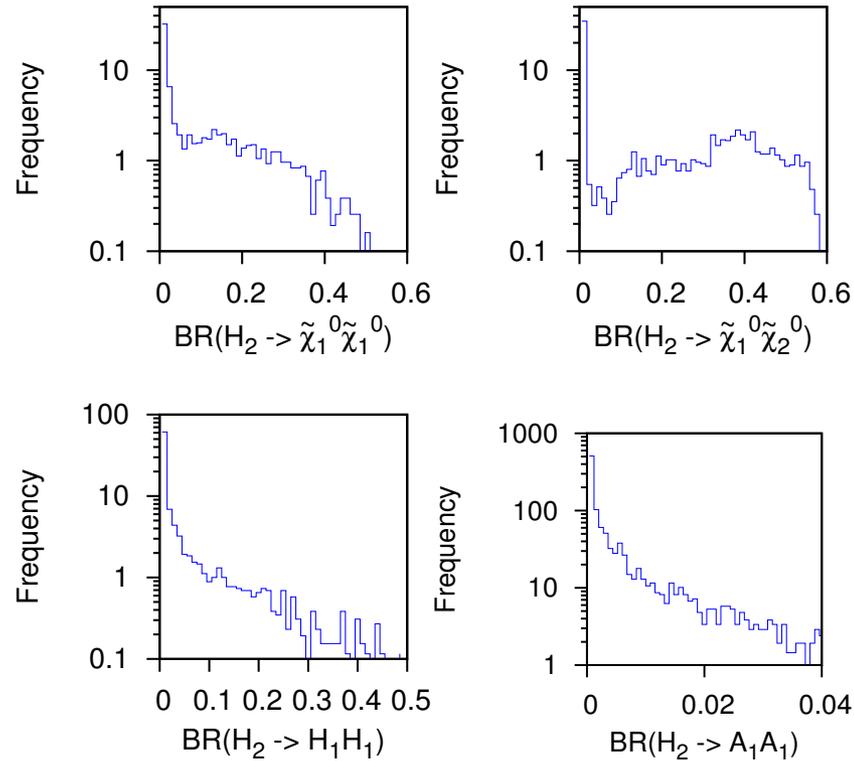


# Higgs signal strength



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

- If NLSP partly singlino  $\rightarrow$  can be lighter than 100GeV
- Non standard H decays:  $H_2 \rightarrow \tilde{\chi}_{1,2}^0 \tilde{\chi}_{1,2}^0$ ,  $H_1 H_1$  or  $A_1 A_1$



# NMSSM Higgs signatures

- Higgs ( in addition to standard channels):
  - $H_2 \rightarrow 2A_1(H_1) \rightarrow \tau\tau\tau, \mu\mu\tau$ 
    - Englert et al, PRD84 075026(2011) Lisanti, Wacker PRD79 115006(2009)
  - Higgs  $\rightarrow \chi_2\chi_1$ ,  $\chi_2 \rightarrow \chi_1 f f$  or  $\chi_2 \rightarrow \chi_1 H/A$
- Also search for light Higgs but couplings of  $H_1$  to SM suppressed because singlet component
- $H_1 b\bar{b}$  at most SM-like (even though coupling can be  $\tan\beta$  enhanced )
- Higgs production in SUSY decays

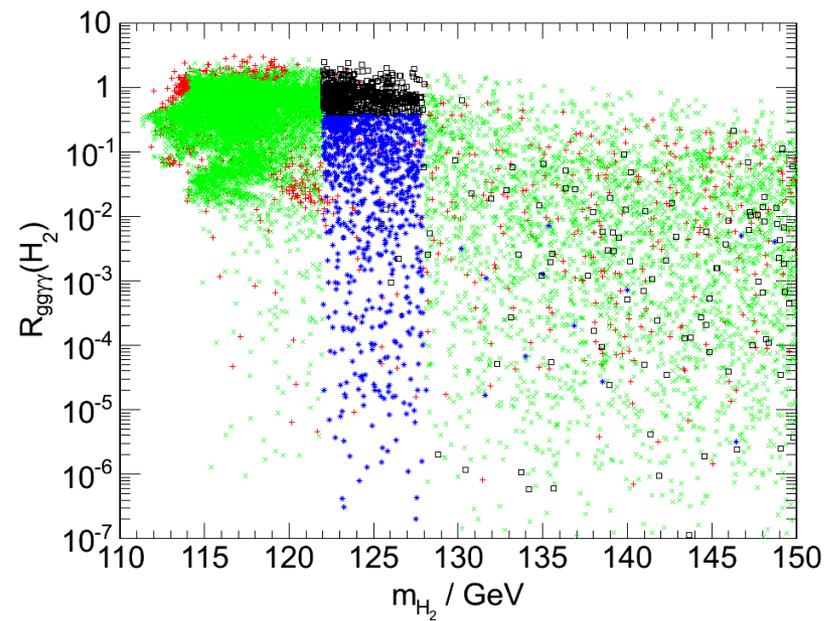
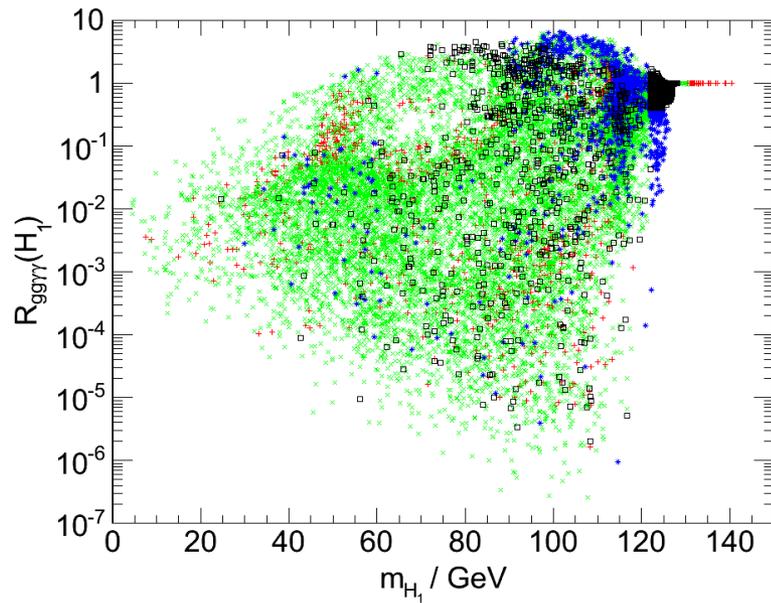
# “general” NMSSM

- No constraint on light neutralino
- MCMC with 14 free parameters :  $\lambda, \kappa, A_\lambda, A_\kappa$

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

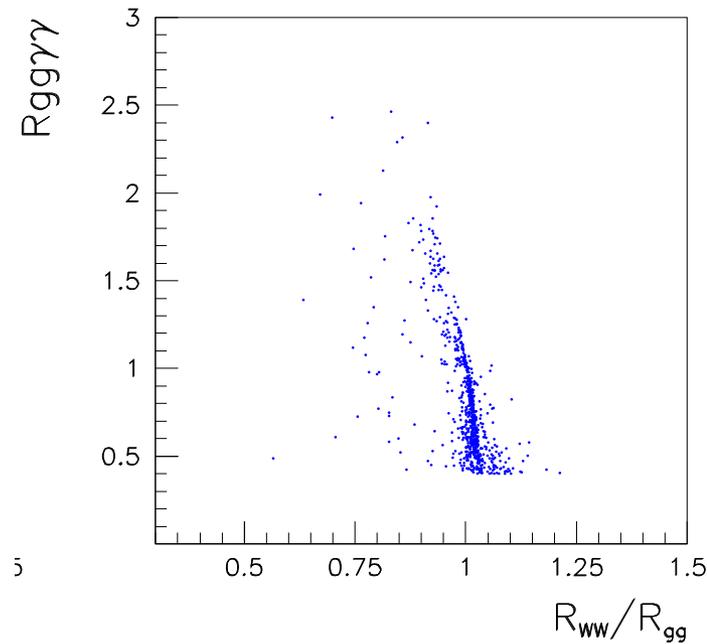
- Constraints : as before (B,g-2, relic, Higgs)
- a posteriori:
  - HiggsBounds3.6.1,
  - LHC jets+missing  $E_T(1\text{fb}^{-1})$ ,
  - direct +indirect detection

# Higgs signal strength



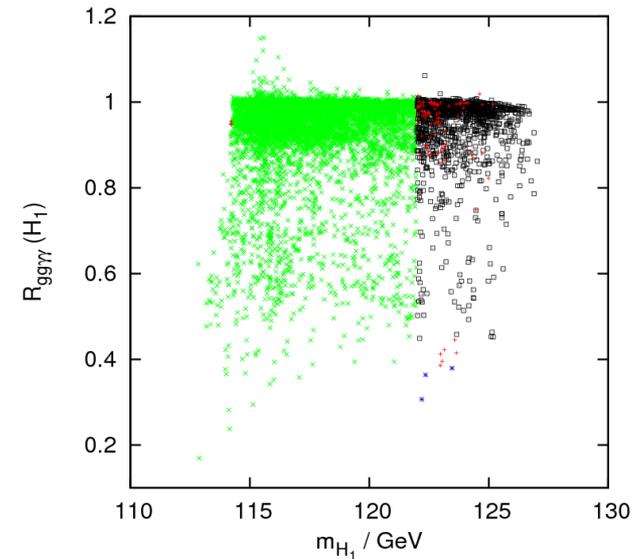
- Both  $H_1$  and  $H_2$  can be in 122-128GeV range
- MCMC+HiggsBounds3.6.1

- Correlation between signal strength  $R_{gg\gamma\gamma}$  and  $R_{WW\gamma\gamma}$
- For  $H_2$  (similar results for  $H_1$ )



- With WMAP lower/upper limit + LHC jet+missing  $E_T$
- Insisting on WMAP - most points with  $R_{gg\gamma\gamma} > 1$  disappear
- Few points with  $H_2 \sim 125 \text{ GeV}$
- $R_{gg\gamma\gamma} > 1$  - associated with small  $\mu$ , light charginos because singlet mass light

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

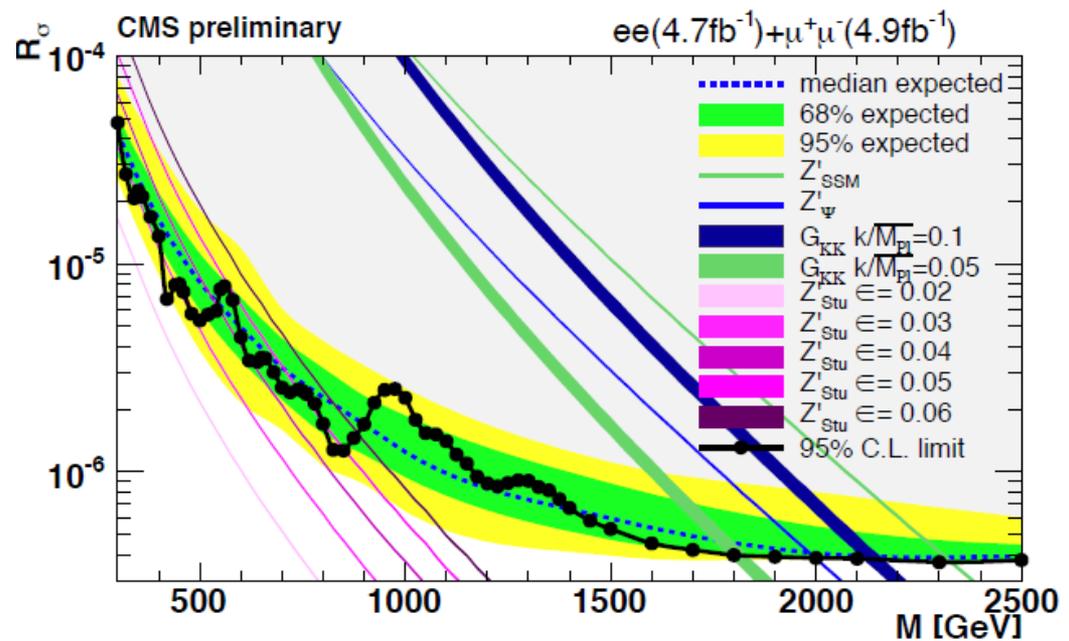


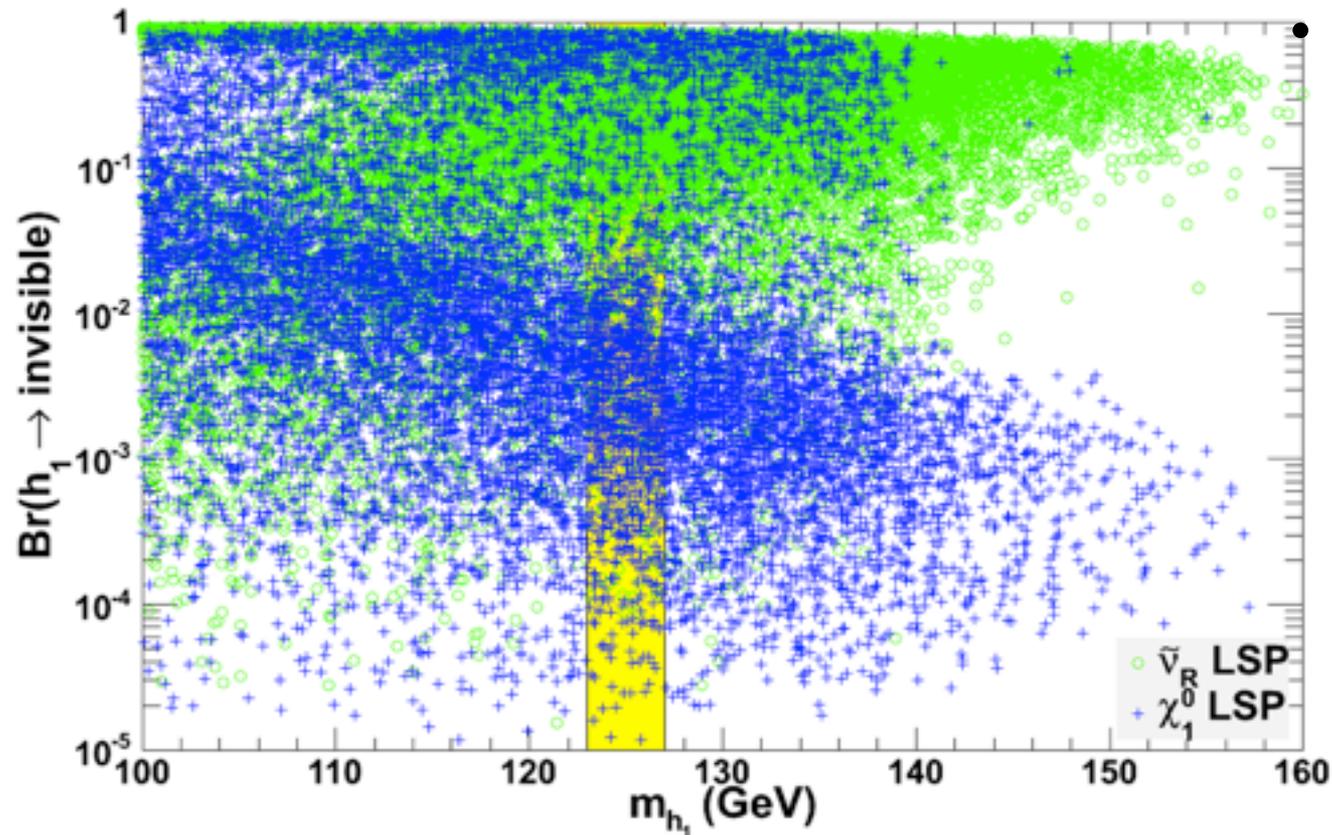
- Studies concentrating on  $R_{gg\gamma\gamma} > 1$  (in NUHMNMSSM- Ellwanger, Hugonie, 1203.5048) and/or on large  $\lambda$  (NMSSM- Chang et al, 1202.0054) also find  $\mu < 250 \text{ GeV}$

# UMSSM

- MSSM+U(1) symmetry
  - see also W. Porod's talk
- Vector superfield B' + Singlet superfield S
- as in NMSSM,  $\mu=\lambda v$  generated from vev S
- new particles: Z', RH neutrino+ new fermions
- Neutralino sector: 6 neutralinos
- Higgs sector: 3 CP-even, CP-odd+charged Higgs
- Higgs mass
  - new contributions from superpotential (as in NMSSM)
  - U(1)' D-term ( $Q_1, Q_2$  are  $E_6$  charges of doublets)
$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + g_1'^2 v^2 (Q_2 \cos^2 \beta + Q_1 \sin^2 \beta)$$
  - natural to have light Higgs mass  $\sim 125\text{GeV}$

- mass of singlet Higgs near that of  $Z'$
- Constraints on  $Z'$  from LHC ( $M_{Z'} \sim 1.8 - 2 \text{ TeV}$  for  $Z_\psi$ )
- light Higgs is typically SM-like
- Possible contributions to invisible Higgs decays (neutralino or RH sneutrino can be dark matter)
- DM constraints
  - WMAP, direct detection
  - GB, DaSilva, Pukhov, JCAP1112(2011)014





•  $U(1)_\psi$  of  $E_6$

- Even with light DM, can easily have small invisible width--> SM-like Higgs,  $R \sim I$

# CONCLUSION

- In NMSSM and UMSSM natural extensions of MSSM that provide a Higgs 125 GeV which satisfies all constraints including DM ones
- In NMSSM: constraints on squarks/gluinos weaker than in MSSM
- Specific signatures especially if singlino LSP and/or light Higgses

