Two Higgs at LEP, Tevatron and the LHC?

Genevieve Bélanger
LAPTH, Annecy-le-Vieux

GB, U. Ellwanger, J.Gunion, Y.Jiang, S. Kraml, J. Schwarz (1210.1976)
GB, U. Ellwanger, J.Gunion, Y.Jiang, S. Kraml (1208.4952)

Firenze, November 2012

Introduction

- Higgs discovery at LHC raises many questions
  - Is the new boson the SM Higgs
  - Deviations from SM couplings?
  - A probe of BSM
  - Is it lightest Higgs in MSSM? fine tuning-problem
  - Are there more light Higgses?
- Here consider two possibilities
  - 125GeV Higgs is the heavy Higgs - another one at 100GeV
  - LHC/Tevatron might not have seen the same Higgs: 125-135GeV
- No sign (yet) of supersymmetry at LHC
- Supersymmetry offers a good DM candidate, strong evidence for DM - motivation for beyond standard model

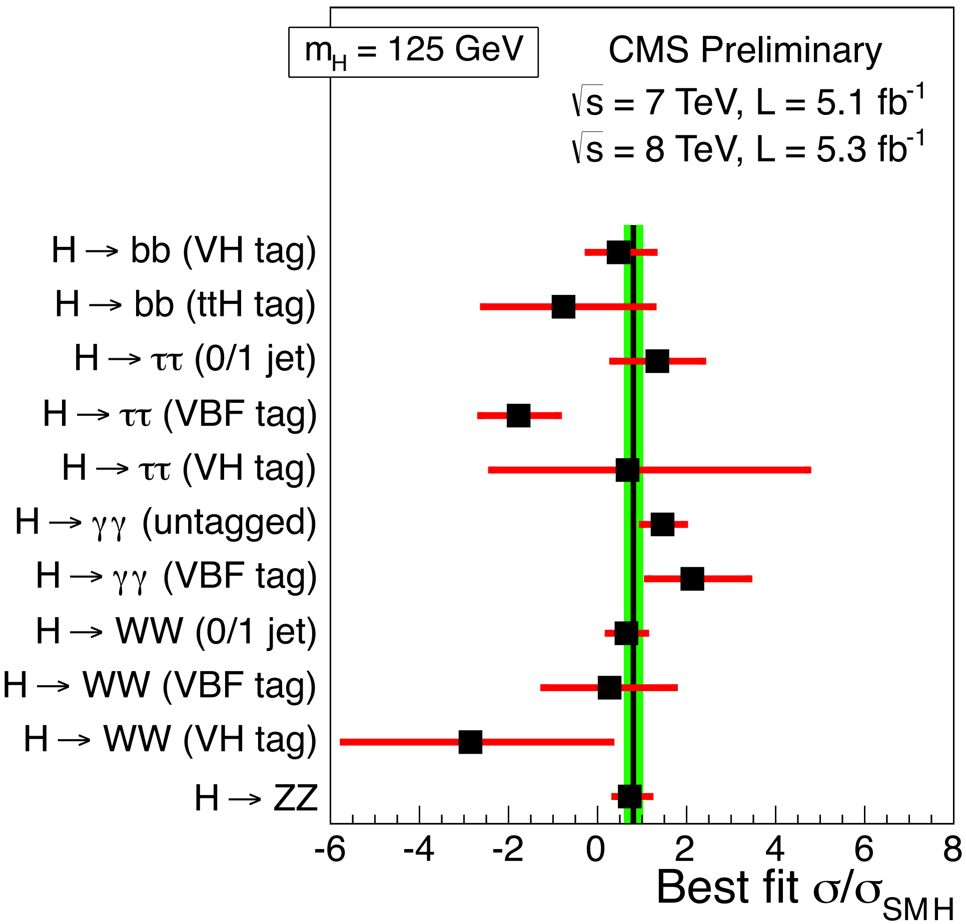
Outline

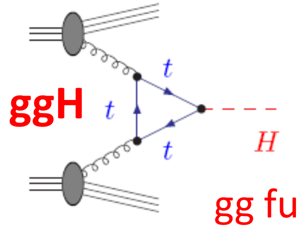
- Higgs at LHC and LEP
- Higgs in the NMSSM
- Two light Higgses
  - implications for LHC, DM ...
- Two Higgses at Tevatron and LHC

Higgs at LHC

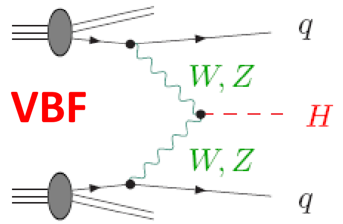
- July 4th 2012: ATLAS and CMS reported a signal consistent with a Higgs boson with mass
- m_h =125.3+/-0.4+/-0.5GeV (CMS)
- =126.0+/-0.4+/-0.4GeV (ATLAS)
- Such a mass can be reached in MSSM require large mixing in stop sector, fine-tuning
- Also measure the signal strength in various production/ decay 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

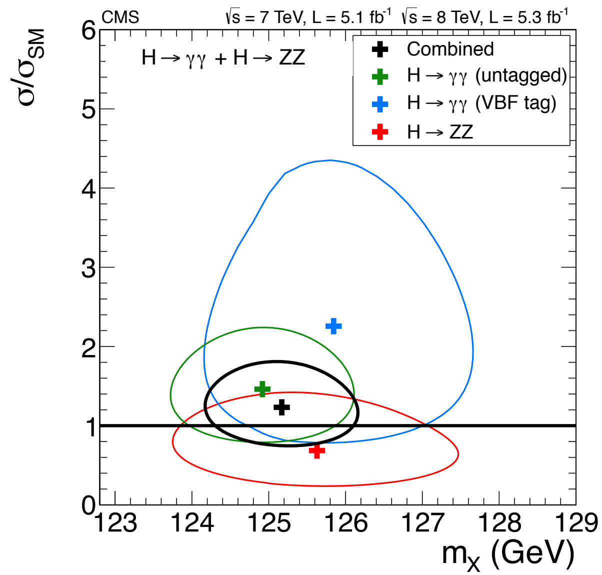




gg fusion

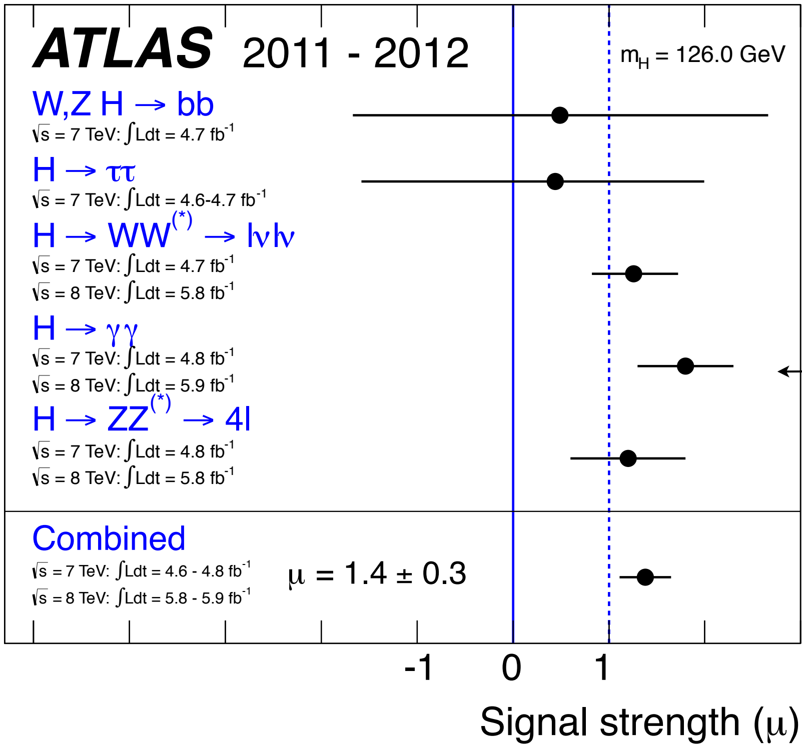


vector boson fusion



ATLAS - Higgs results

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



1.8+/- 0.5

LEP results

- Small excess in e^+e^--> Zbb (~2sigma) at LEP with M_h~98GeV.
- How can it be consistent with bound M_h>114 GeV? coupling to ZZ must be much weaker than in SM, only 0.1-0.25 SM
- Could that be a second Higgs h'?
- h' can mix with h and shift its properties, e.g. mixing with h' can suppress hbb, Br(h-$\gamma\gamma$) can be modified because total width is suppressed
  - Br(h-> $\gamma\gamma$) ~ Γ(h-> $\gamma\gamma$)/Γ(h->bb)

SUSY Higgs at LEP

- Characteristics of the LEP 'signal' at 100GeV
  - e.g. Drees (hep-ph/0502075) the light Higgs of MSSM with suppressed couplings to ZZ (MSSM in non-decoupling limit)
- Is the LHC Higgs the lightest Higgs?
  - This question was addressed in framework of MSSM
    - Heinemeyer et al, 1112.3026
    - Hagiwara et al, 1207.0802
    - Drees, 1210.6507
- As an example of a model that can be consistent with both LEP and LHC observations (including enhanced two-photon) here will consider NMSSM

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
  - one singlet CP-even scalar + one singlet CP-odd scalar
- Also extra neutralino -> singlino
  - can impact dark matter properties

Higgs mass in NMSSM

- 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:

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

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

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

  - in NMSSM with lambda~1 stop mass/mixing not so large
  - fine-tuning reduced in CNMSSM (Ellwanger et al 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
  - Does not require light sparticles

$$R^{h_i}_{gg}(X) \equiv \frac{\Gamma(h_i \to gg)\ \mathrm{BR}(h_i \to X)}{\Gamma(h_{\rm SM} \to gg)\ \mathrm{BR}(h_{\rm SM} \to X)}, \quad R^{h_i}_{\rm VBF}(X) \equiv \frac{\Gamma(h_i \to WW)\ \mathrm{BR}(h_i \to X)}{\Gamma(h_{\rm SM} \to WW)\ \mathrm{BR}(h_{\rm SM} \to X)}$$

- $R_{gg}(\gamma\gamma)_{>1}$ for m_H=125GeV, when λ large (determines singlet-doublet mixing), tanβ small

- $R_{gg\gamma\gamma}>1$- associated with small μ, light charginos because singlet mass light

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

- Signal strength for Higgs in different channels

- Complete independent set of R^h

$$R^h_{gg}(WW),\quad R^h_{gg}(bb),\quad R^h_{gg}(\gamma\gamma),\quad R^h_{VBF}(WW),\quad R^h_{VBF}(bb),\quad R^h_{VBF}(\gamma\gamma)\,.$$

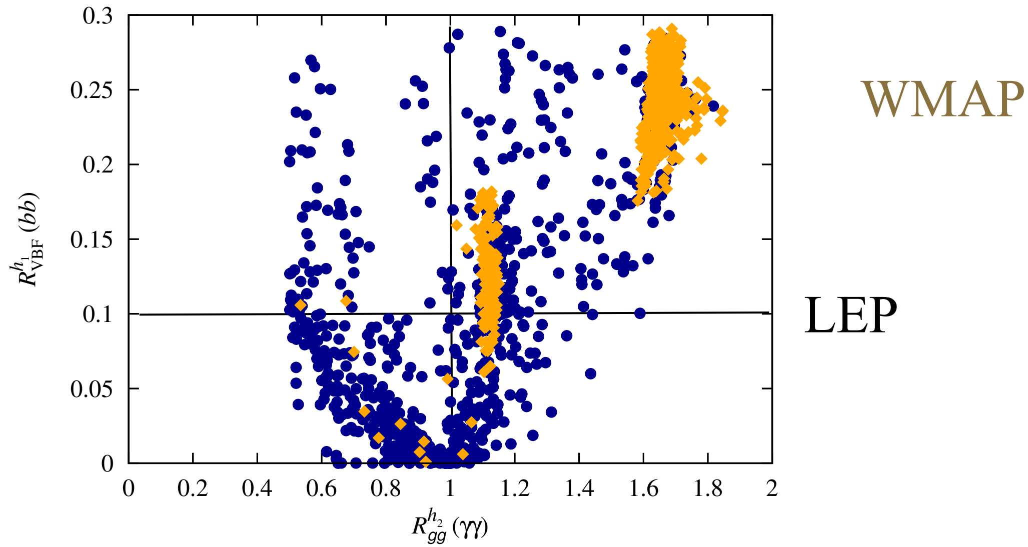
- Note for LEP : $R_{VBF}(bb)$

- Can one explain M_{h1}~100 + M_{h2}~125 with $R_{gg\gamma\gamma}$>1 in NMSSM?
- Framework: NMSSM with semi-unified GUT scale soft SUSY breaking
  - $m_{1/2}, m_0, A_0, m^2_{Hu}, m^2_{Hd}, m_S, A_\lambda, A_\kappa, \tan\beta$

- Take into account Higgs constraints in NMSSMTools + B physics, DM (WMAP upper bound and Xenon100), g-2
  - Gunion, Jiang, Kraml, arXiv:1207.1545
- Note that g-2 does not explain discrepancy with SM

Higgs signal strength

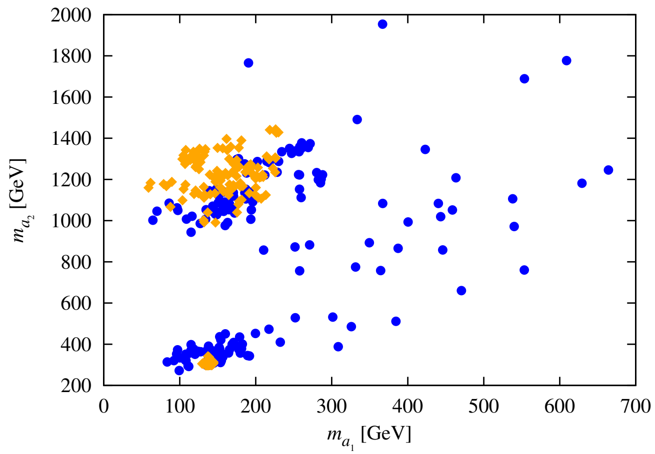
- Two Higgses at 98GeV+125GeV

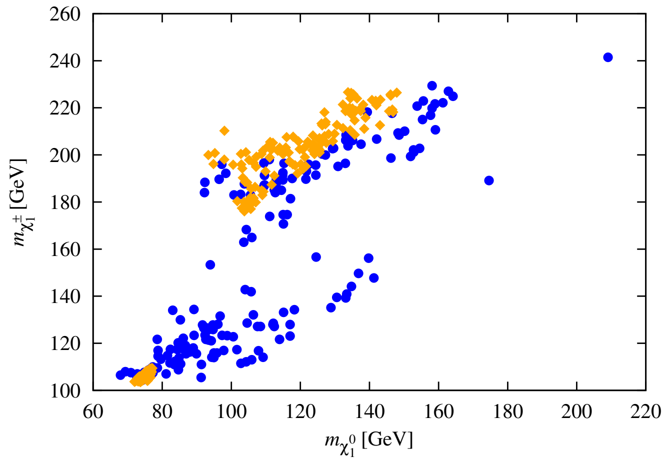


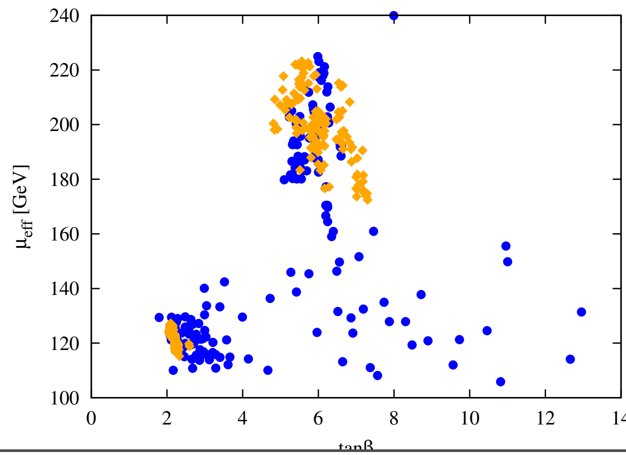
- For discovery of light Higgs in bb channel need to increase current LHC sensitivity (R~1) by a factor 4-10 -> higher luminosity LHC run
- h_1 in two-photon very small R~0.02

Other NMSSM particles

- Other particles below TeV scale : pseudoscalars, neutralino,chargino,stop



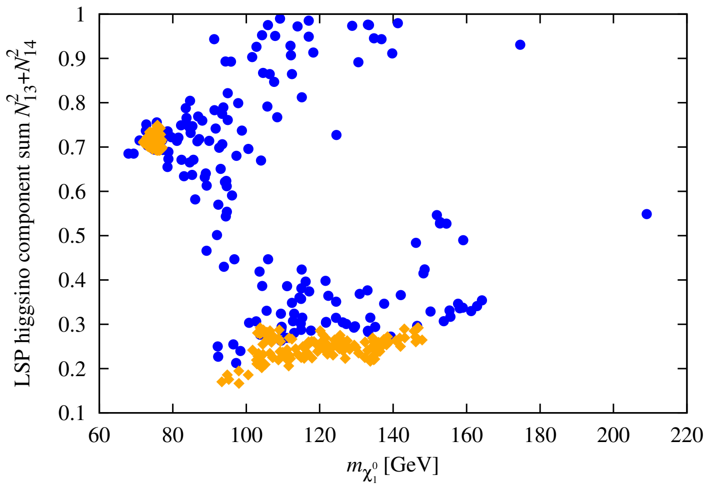




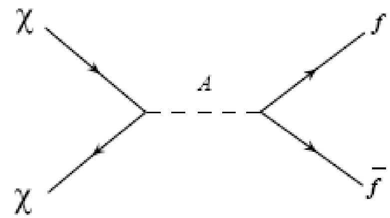
Dark matter issues

- 5 neutralinos

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



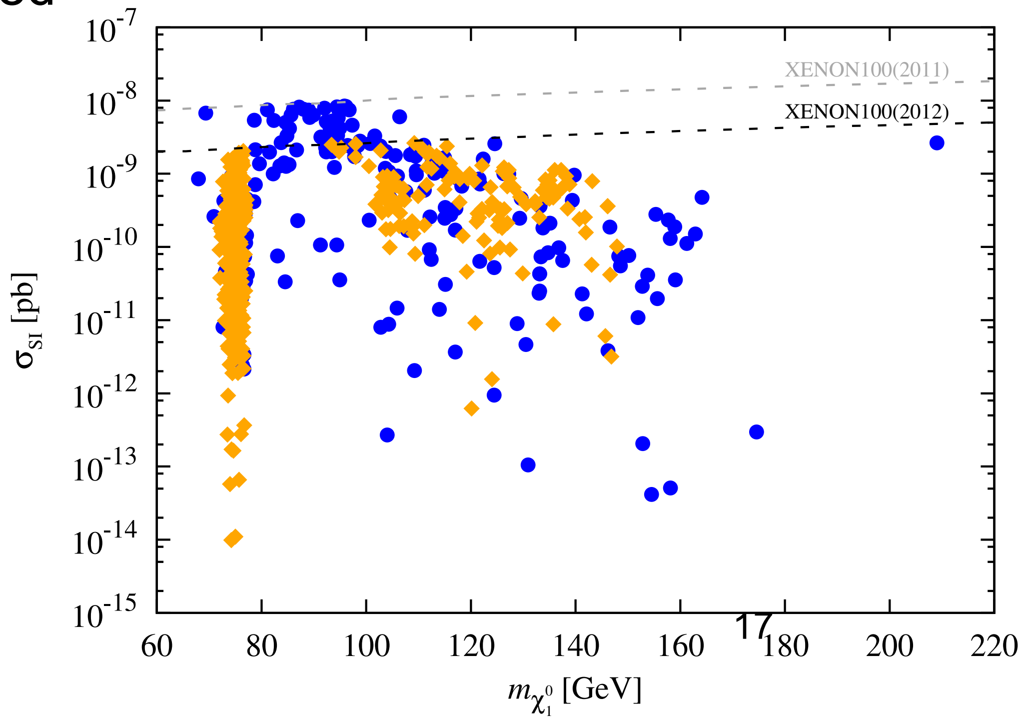
- LSP either higgsino or singlino
  - higgsino annihilate into W pairs - Ωh^2 ~0.1 because just below threshold
  - Singlino component annihilate via singlet Higgs exchange



Direct detection

- Searches for DM scattering with nuclei in large detectors - best limits from Xenon100 (2012)

- DM direct detection: from just below Xenon to quite a bit suppressed



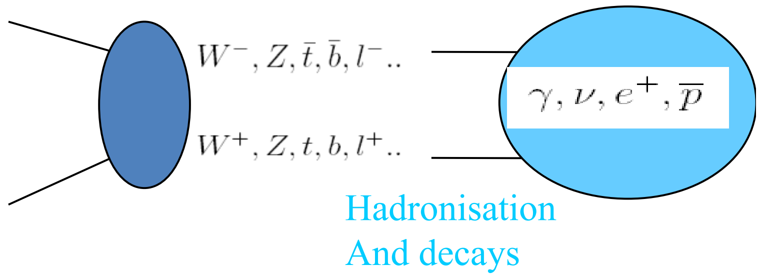
Indirect detection

- 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

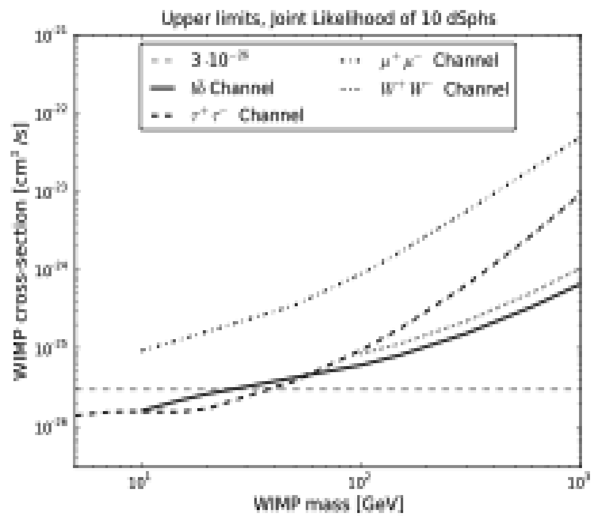
$$< \sigma v >= 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

- Gamma-ray line at 130GeV
  - Weniger, arXiv:1204.2797

$$\langle \sigma v \rangle (\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma) \sim 10^{-27} \mathrm{cm}^3/\mathrm{sec}$$



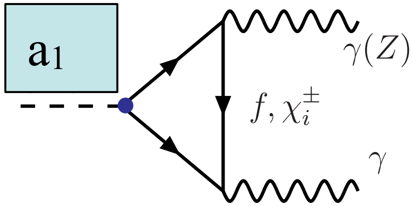
$$\Phi_{\gamma,\nu} = \frac{1}{8\pi} \frac{< \sigma_{ann} v >}{m_\chi^2} \sum_{f.s.} \left(\frac{dN_{\gamma,\nu}}{dE} \right)_{f.s.} \int_{l.o.s.} \rho_s^2$$



Photons

- In general NMSSM (no GUT scale unification) gamma-ray line possible (Das, Ellwanger, Mitropoulos,1206.2639)

$$\langle \sigma v \rangle (\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to a_1 \to \gamma\gamma)$$



- If $2m_{LSP} \sim m_A$ (extremely fine tuned) can have resonance enhancement at v~0.001c

$$v\sigma(v) \propto \frac{1}{(s-m_A^2)^2+\Gamma_A^2 m_A^2} = \frac{1}{16 m_\chi^4} \frac{1}{(v^2/4+\Delta)^2+\Gamma_A^2(1-\Delta)/4m_\chi^2}$$

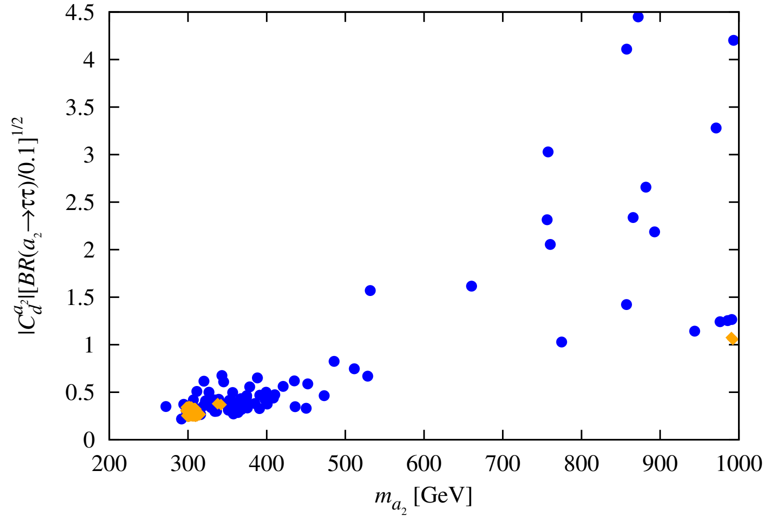
- In semi-unified NMSSM with 98+125GeV Higgs and enhanced two-photon width : gamma-ray line much suppressed and limits from Fermi dSPh's easily satisfied

- Apart from possible signals in future ton-scale direct detection experiments, for the moment no constraints on this scenario from DM observables other than relic density

- How to probe further this scenario?

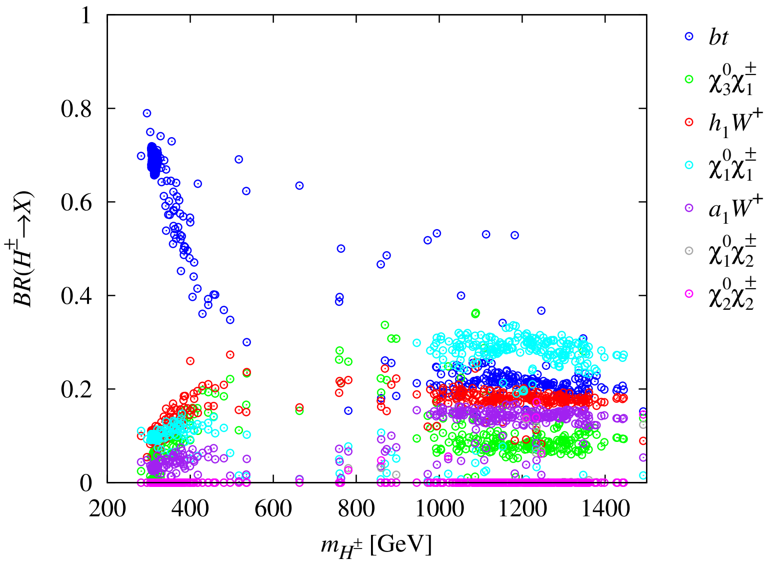
How to probe further this scenario?

- LHC:
  - h_1 (bb) with high luminosity
  - a_1 : light but mostly singlet - low rates
  - a_2 : mainly doublet better prospect (no dedicate study yet)
    - gg->a_2-> tt (~0.01pb for mass 500 GeV)
    - or a_2-> $a_1 h_1$ -> 4b
    - gg-> a_2, h_3 -> ττ
    - Current limit at 200GeV ~8
      - need high luminosity
  -

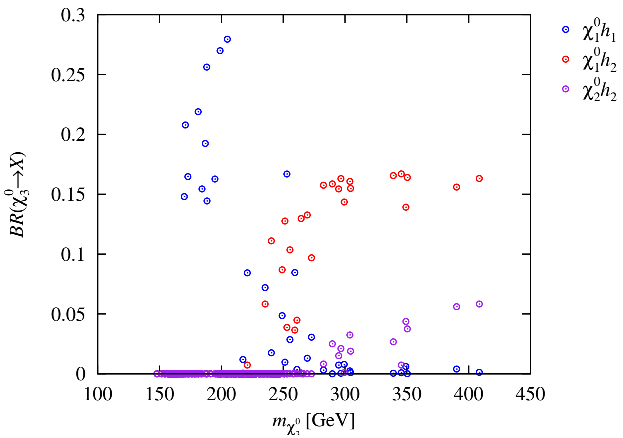


... at the LHC

- Charged Higgs
  - 20% branching ratio into h_1W
  - possible detection of h_1 with high luminosity

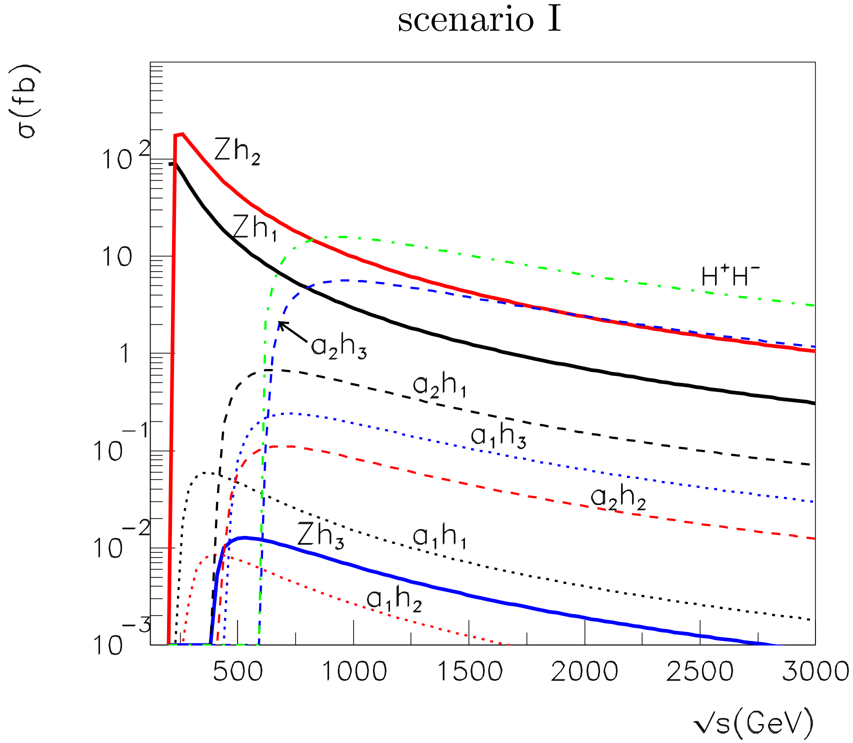


- Higgses from neutralino decays
  - several channels have BR ~10% for decay into h_1



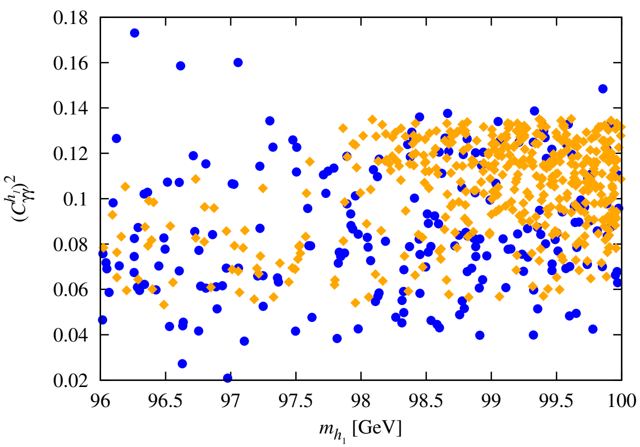
... at future colliders

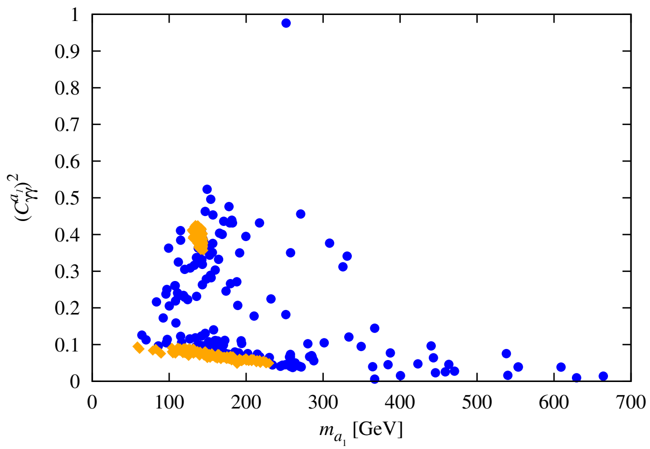
- ILC
  - Large rate for Zh_1
  - In some cases can detect all 5 neutral Higgses



... at future colliders(2)

- Photon collider
  - h_2 - SM-like coupling to two-photons : large cross section can measure also bb/WW partial widths
  - h_1, a_1 - suppressed because singlet but important contribution from light chargino loop





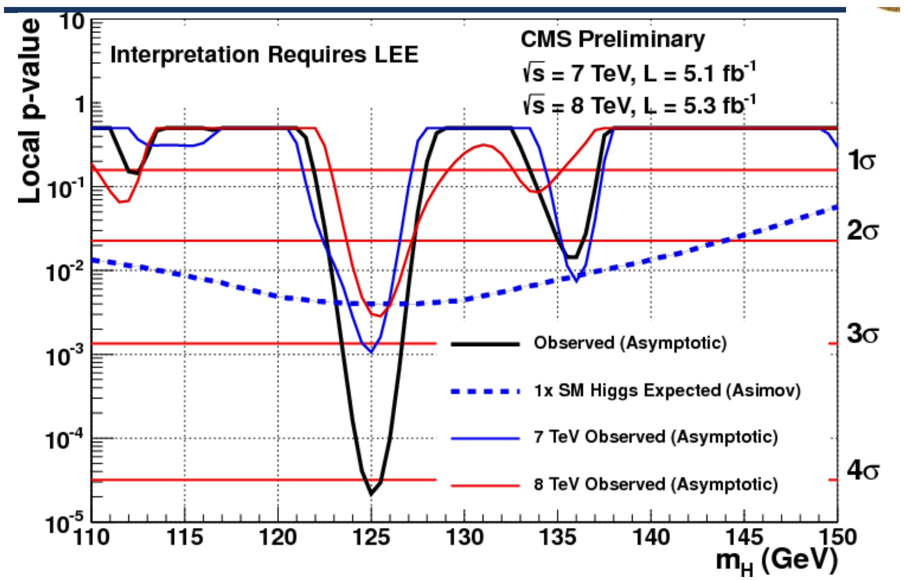
- Possibility of having a Higgs at 98 GeV hidden in LEP data - fits in the NMSSM with distinctive signatures

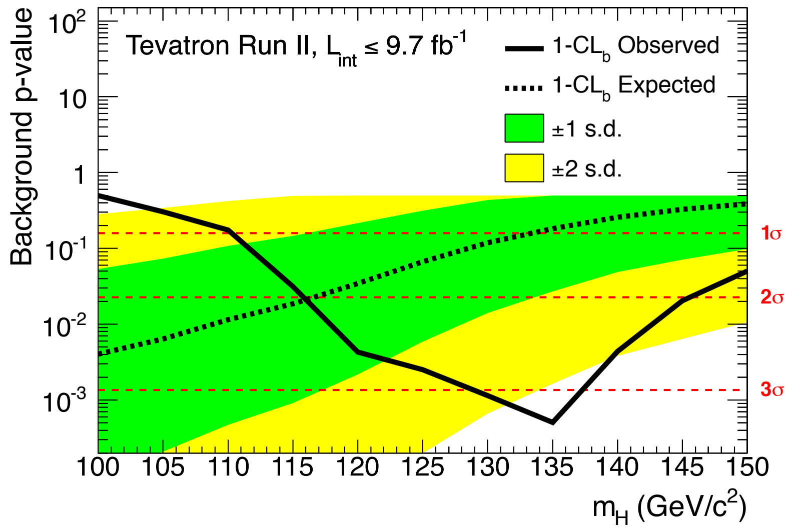
- LHC can look for it in some standard search channels, and remains to be seen how well new channel can be exploited to search for h_1,a_1

- Note that in NMSSM light singlet can have any mass

Two Higgses at LHC and Tevatron

- 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,
- ττ mode: CMS has deficit at 125GeV for VBF-tag mode, excess at 132 GeV
- Can al these small deviations be compatible with two lightest Higgses in NMSSM?

- Signal strength for 125 GeV

$R_1^{\gamma\gamma}(ggF) \simeq 1.66 \pm 0.36\,.$ $R_1^{ZZ^{(*)}}(ggF) \simeq 1.02 \pm 0.38\,.$

- Signal strength for 135 GeV

$R_2^{\gamma\gamma}(ggF) \simeq 0.45 \pm 0.3$ $R_2^{ZZ^{(*)}}(ggF) \lesssim 0.2$

$R_2^{\tau\tau}(VBF) < 1.81$ $R_{135}^{bb}(VH) \simeq 3.53 + 1.26 - 1.16$

Sample point

- 'Fit' CMS+Tevatron Higgs signal
- Here ignore DM requirement

λ	0.617	$\mu_{\rm eff}$	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	$S_{i,d}$	$S_{i,u}$	$S_{i,s}$	c_{D_i}	c_{U_i}	c_{V_i}	c_{g_i}	c_{γ_i}
H_1	-0.24	-0.67	0.70	-0.48	-0.77	-0.70	0.77	0.85
H_2	0.54	0.51	0.67	1.09	0.58	0.71	0.54	0.66
H_3	0.81	-0.54	-0.24	1.64	-0.62	-0.07	0.65	0.28

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 $H_1 > H_2$
- $R^{bb}_{\rm eff}(VH) \simeq R^{bb}_2(VH) + 1.3 \times R^{bb}_1(VH) \sim 1.3$
- Below central value of Tevatron
- More data at LHC (γγ) will confirm/rule out this possibility
- Search for H_3 - look at decays into light Higgs/ neutralino pairs

CONCLUSION

- Higgs searches at LHC could still provide exciting news
- Important to look for light Higgses - in particular mainly singlet Higgs at 100GeV
- NMSSM is extension of MSSM that provide a Higgs 125 GeV with possibly enhanced di-photon rate and some extra light Higgs state