Higgs

Implications of LHC results for supersymmetry

More than one Higgs at the LHC ?

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based on work with

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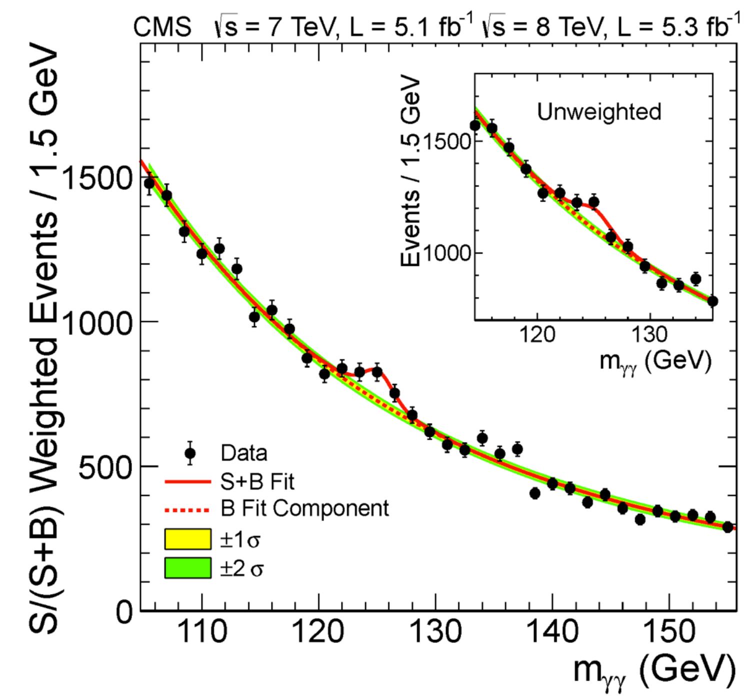
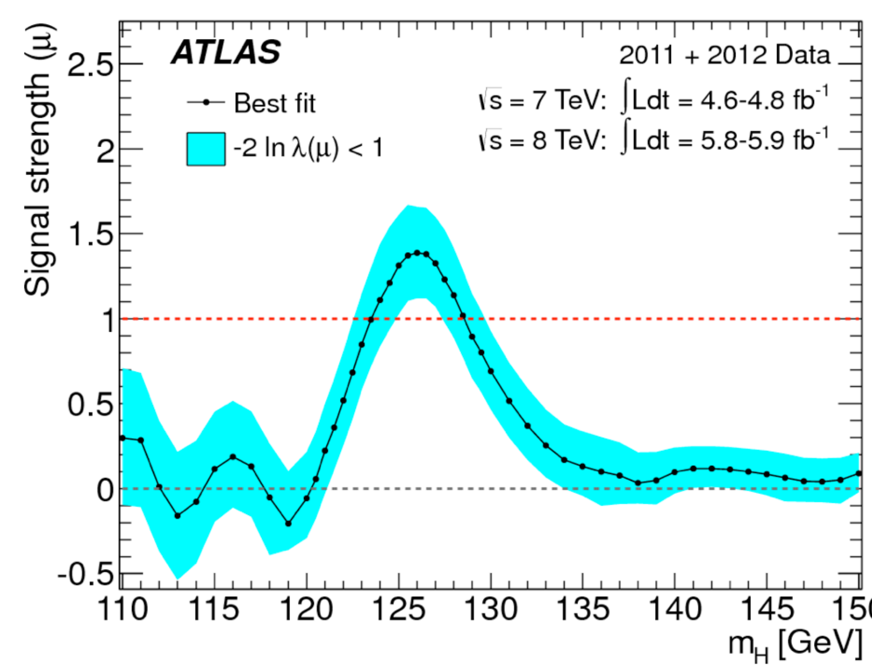
(thanks for a very rewarding collaboration)

Motivation

- On July 4, ATLAS and CMS announced the discovery of a Higgs-like boson with mass of ~125 GeV.
- This discovery completes the Standard Model; tremendous first success of the LHC program.
- However, this should not be regarded as the closing of a chapter but the opening of a new one.
- Most pressing issue: to explain the value of the electroweak (EW) scale itself. Why is the Higgs boson so light when it is predicted to be driven to the GUT or Planck scale by radiative corrections?





➩ new physics at the TeV scale
(or extreme fine-tuning)

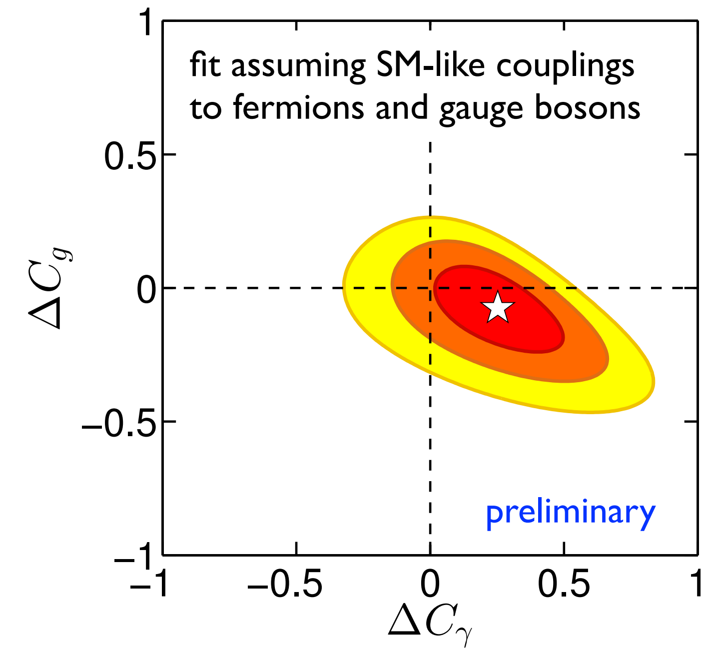
c.f. talks by G. Giudice and C. Hill

SUSY Higgs?

- While SM provides a good fit to to data, the situation not yet conclusive. Some new physics contribution to effective couplings to gluons and photons quite possible.

- From theory point of view, SUSY is a very attractive framework to stabilize the EW scale, i.e. explain the smallness of the Higgs mass.

- In the MSSM, need 100% radiative corrections to achieve Higgs mass around 125 GeV

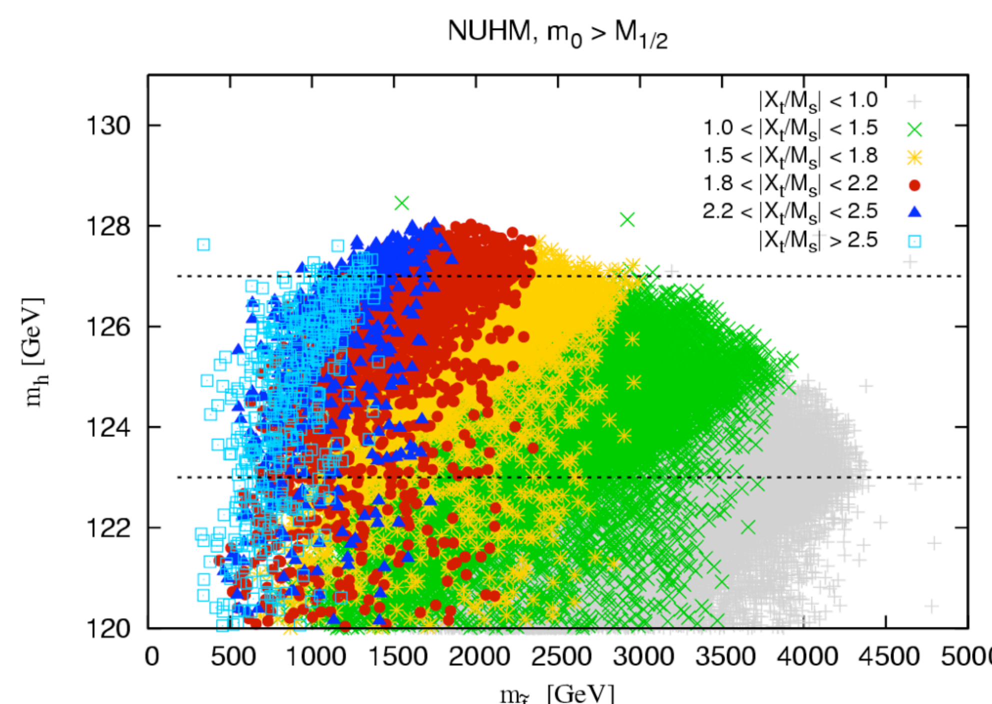


$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$$(126\,\mathrm{GeV})^2 = (91\,\mathrm{GeV})^2 + (87\,\mathrm{GeV})^2$$

$$\Delta m_h^2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\,M_S^2}\right)\right)$$

heavy stops   maximal mixing (large A-term)



Brummer, Kulkarni, SK, arXiv:1204.5977

Next-to-minimal SUSY

- MSSM with the addition of a singlet superfield

$$W_{\rm MSSM} = \mu H_u H_d + \ldots \;\rightarrow\; W_{\rm NMSSM} = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \ldots$$

- Neutral Higgs sector: 3 CP-even states (h_1, h_2, h_3); 2 CP-odd states (a_1, a_2)

MSSM →

$$\begin{aligned} h_1 &= S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S, \\ h_2 &= S_{2,d} H_d + S_{2,u} H_u + S_{2,s} S, \\ h_3 &= S_{3,d} H_d + S_{3,u} H_u + S_{3,s} S. \end{aligned}$$

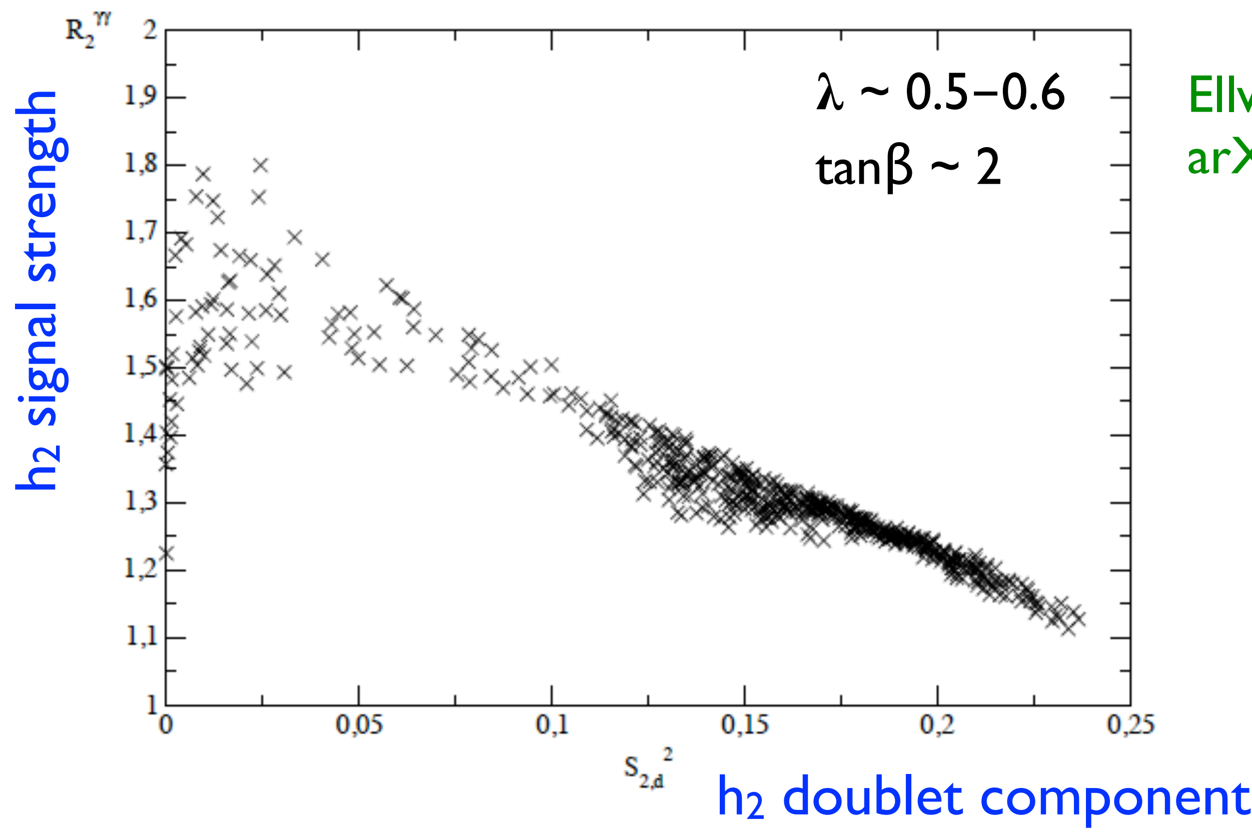
$$\frac{g_{h_i bb}}{g_{H_{SM} bb}} = \frac{S_{i,d}}{\cos\beta}, \qquad \frac{g_{h_i VV}}{g_{H_{SM} VV}} = \cos\beta S_{i,d} + \sin\beta S_{i,u}$$

- Extra tree-level contribution to Higgs mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$$

Enhancement of $\gamma\gamma$ rate

- In 2010, Ulrich Ellwanger pointed out that for large λ (and small $\tan\beta$), doublet-singlet mixing can reduce the hbb coupling, thus enhancing $h \to \gamma\gamma$.



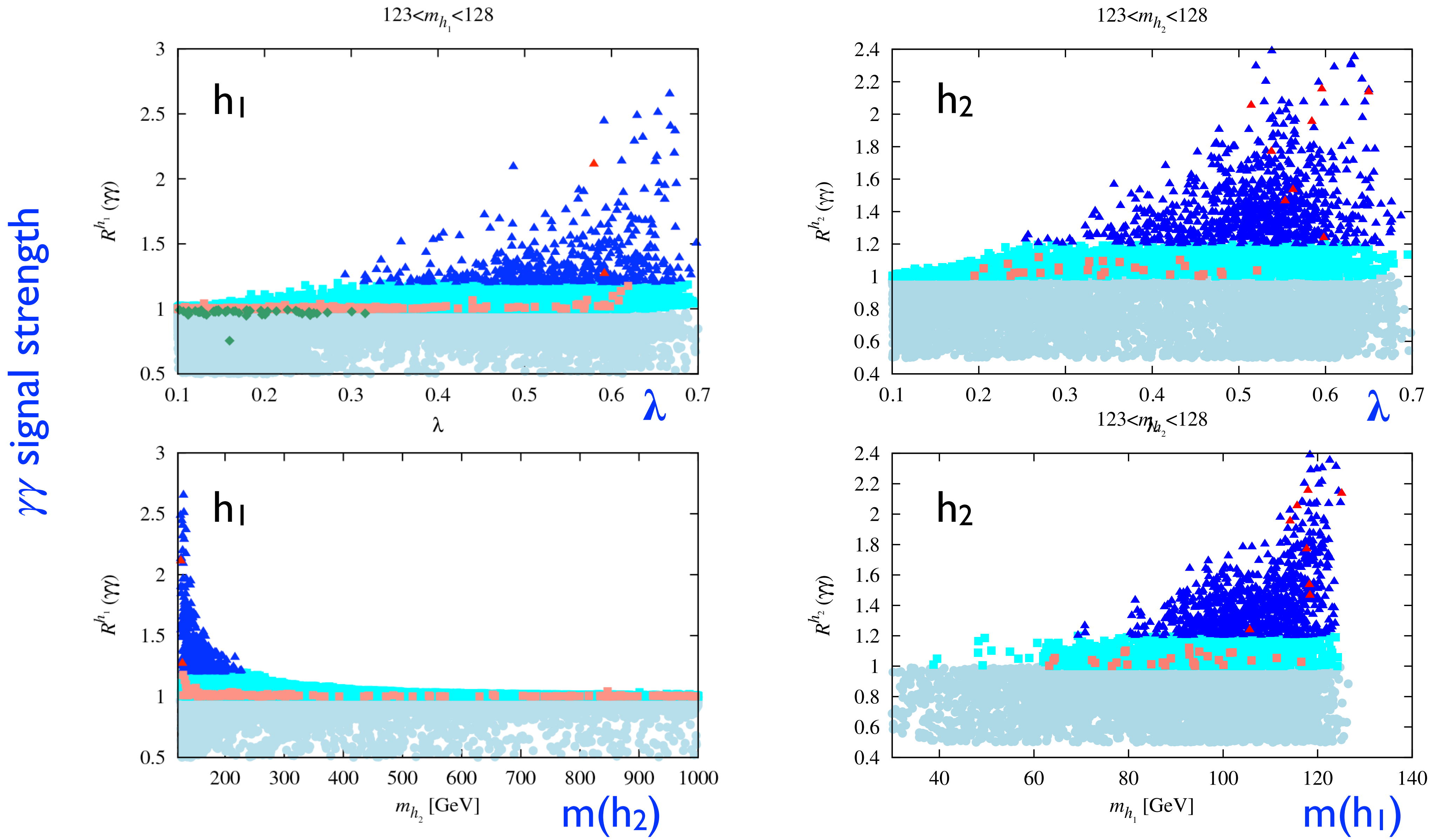
Ellwanger, arXiv:1112.3548

- This works for both CP-even scalars, h_1 and h_2 (but not for h_3)
- In the following, we will use the "semi-constrained" NMSSM with universal m_0, $m_{1/2}$, A_0 at the GUT scale, plus λ, κ, A_λ, A_κ, μ_{eff} and $\tan\beta$ at EW scale.

h_1 or h_2 at 125 GeV?

J. F. Gunion, Y. Jiang, SK

- Scan over "semi-constrained" NMSSM, limits imposed: mass limits, B-physics, $\Omega h^2 < 0.135$



h_1 at 98, h_2 at 125 GeV

arXiv:1210.1076

- If the state at 125 GeV is the h_2, then h_1 must have been missed at the LHC and at LEP → reduced couplings of h_1 to Z.
- Consider the small (2σ) excess in $e^+e^- \to Zb\bar{b}$ around $M_{b\bar{b}}$~98 GeV at LEP.

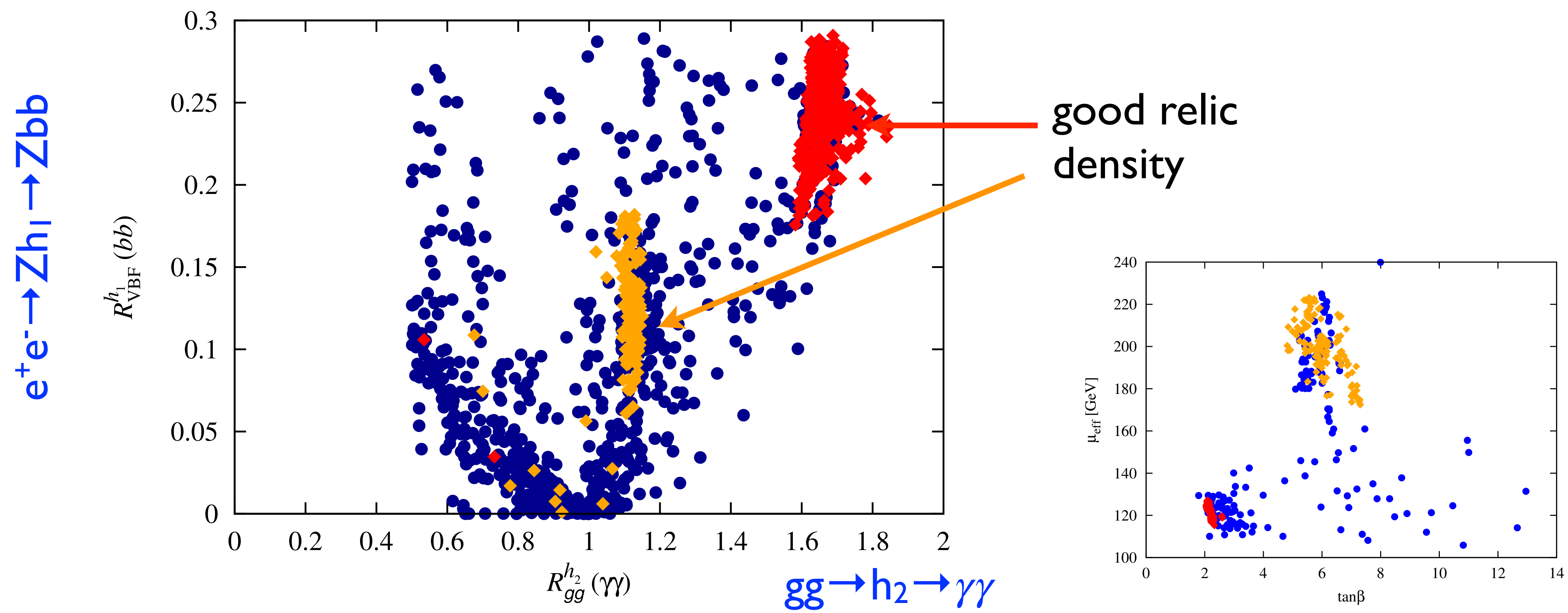


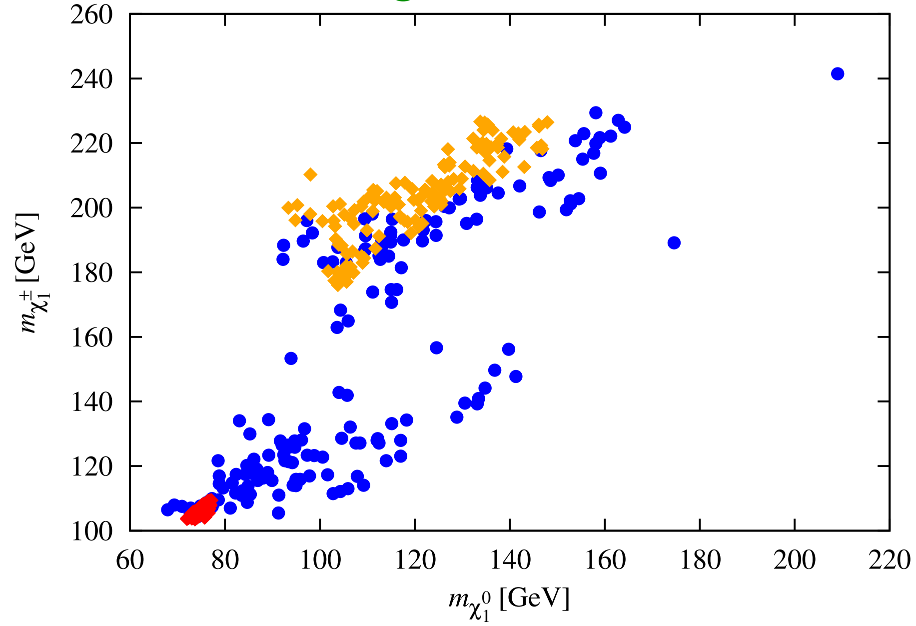
FIG. 1. Signal strengths (relative to SM) $R^{h_1}_{VBF}(bb)$ versus $R^{h_2}_{gg}(\gamma\gamma)$ for $m_{h_1} \in [96, 100]$ GeV and $m_{h_2} \in [123, 128]$ GeV. In this and all subsequent plots, points with $\Omega h^2 < 0.094$ are represented by blue circles and points with $\Omega h^2 \in [0.094, 0.136]$ (the "WMAP window") are represented by red/orange diamonds.

h1 at 98, h2 at 125 GeV

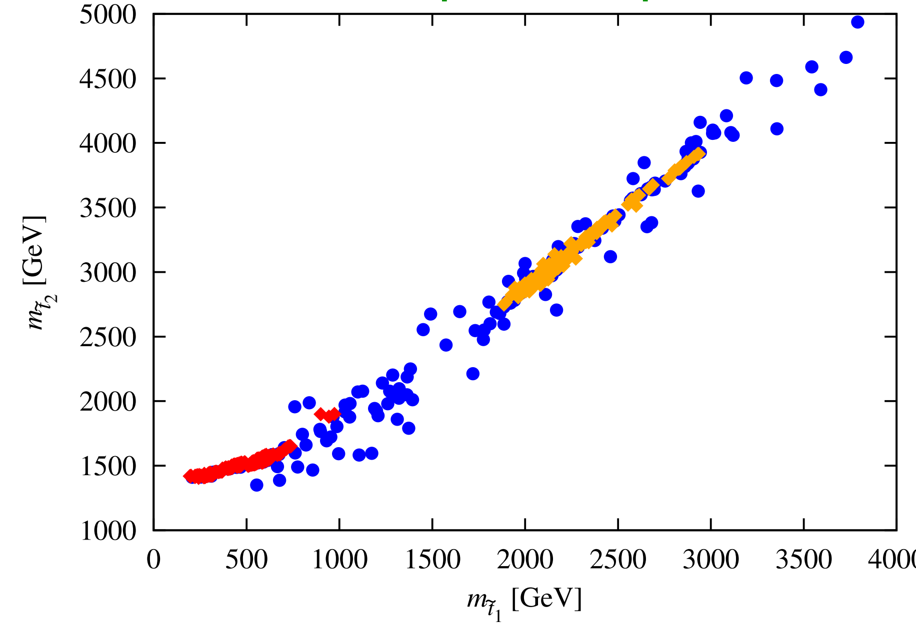
arXiv:1210.1076

other (s)patricles

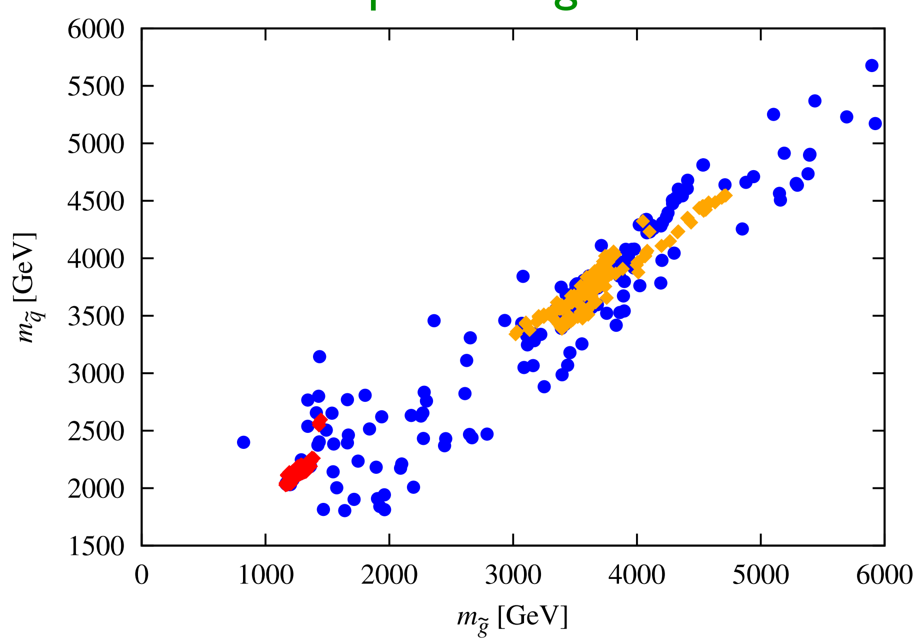
chargino vs. neutralino



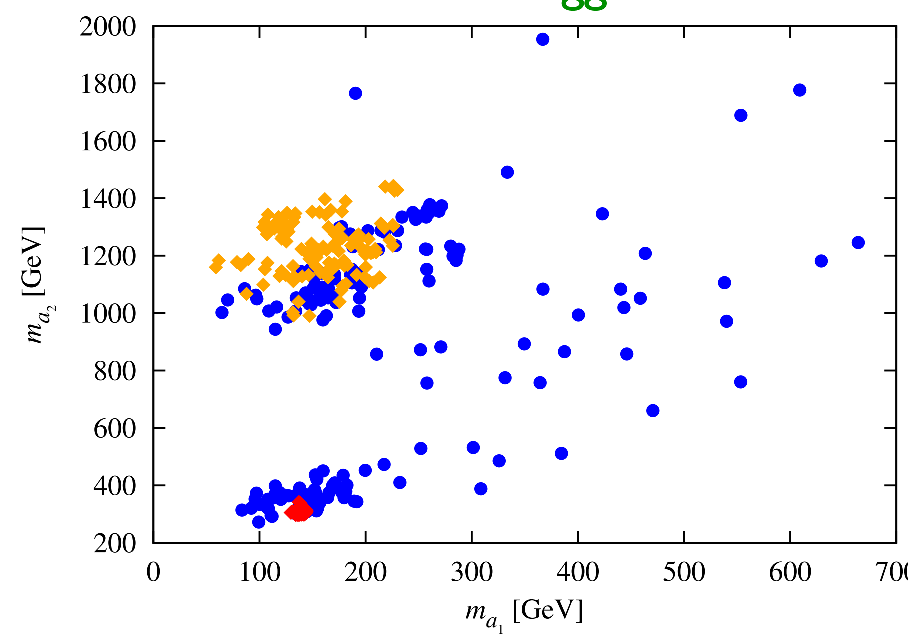
stop2 vs. stop1



squark vs. gluino



other higgses



h_1 at 98, h_2 at 125 GeV

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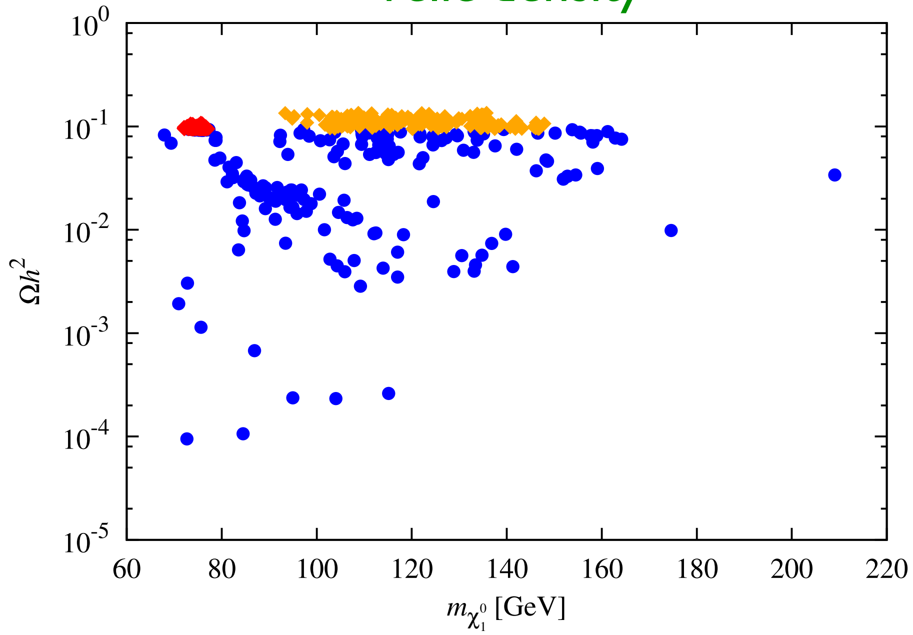
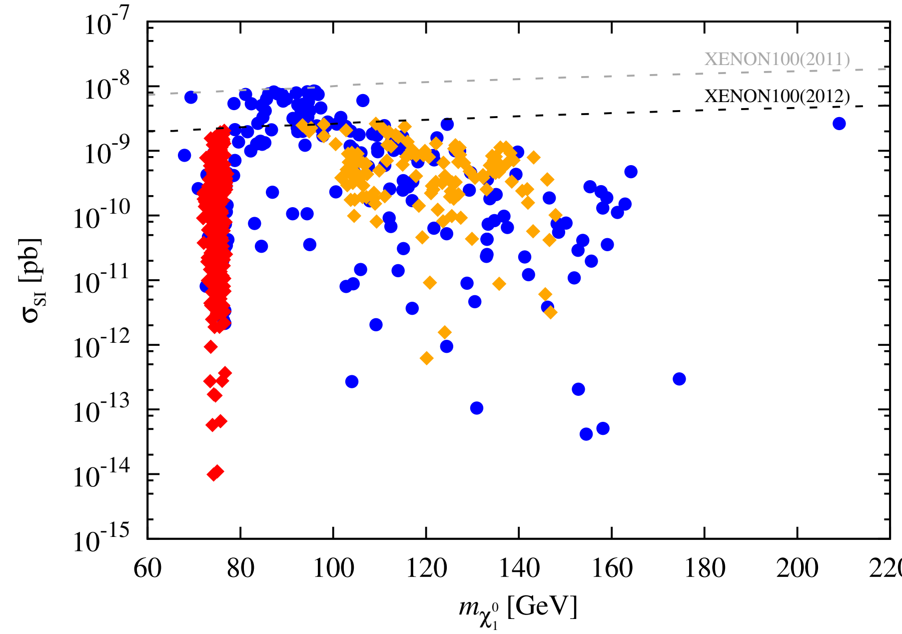
implications for dark matter

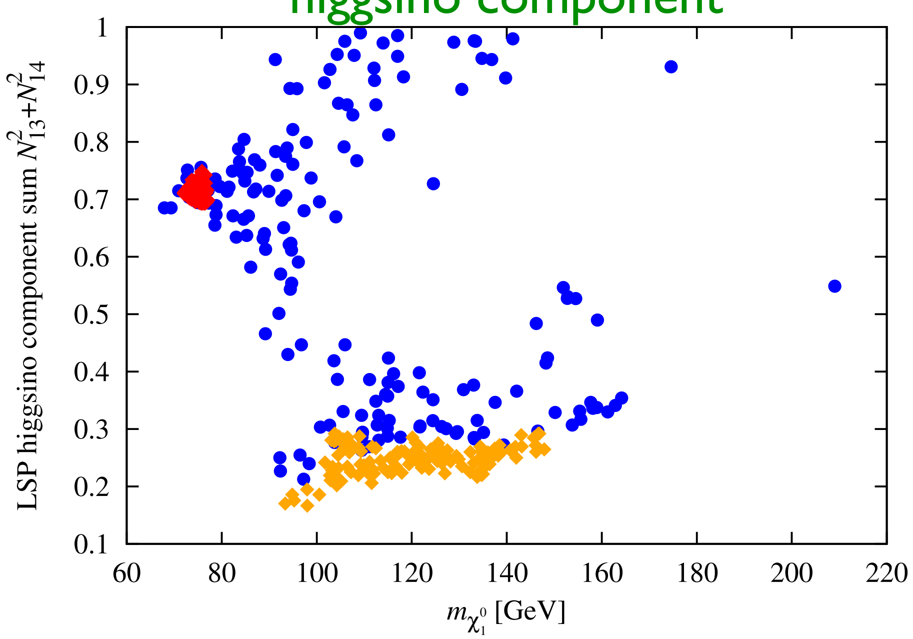
relic density



direct detection Xsection



higgsino component



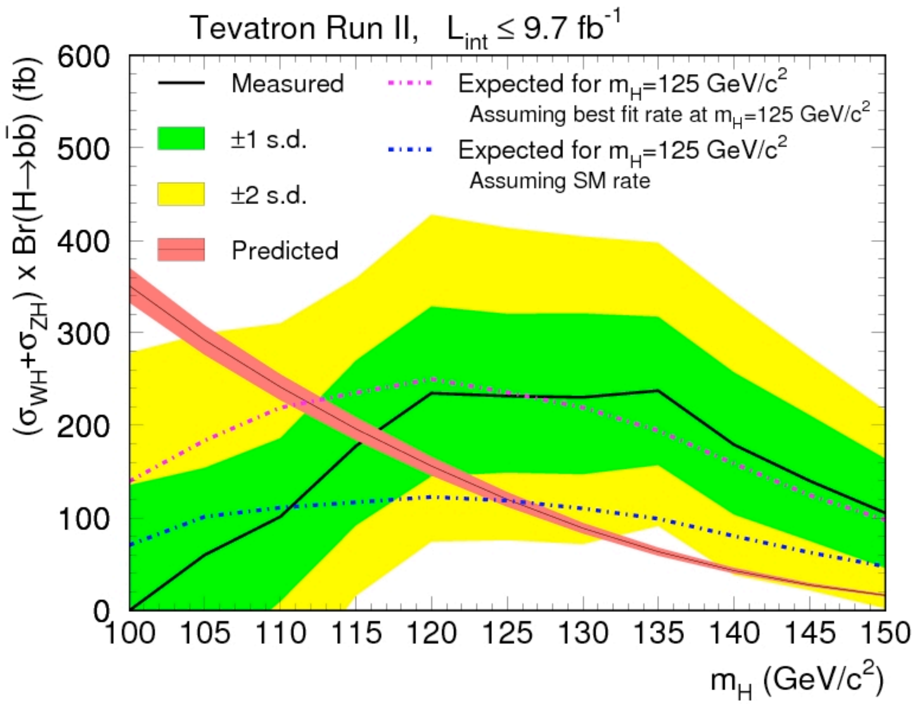
Two very distinct regions:

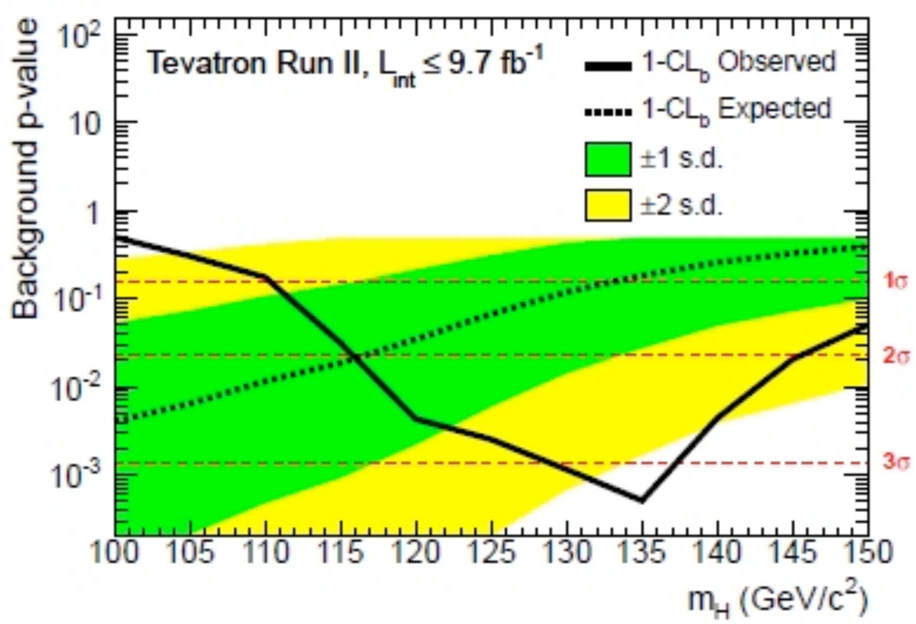
1. higgsino-like LSP, stops below 1 TeV

2. mixed LSP of 100-150 GeV, stops ~2-3 TeV, gluinos and squarks >3TeV

Two Higgs bosons at 125 and 135 GeV ?

A second Higgs at 130-140 GeV ?

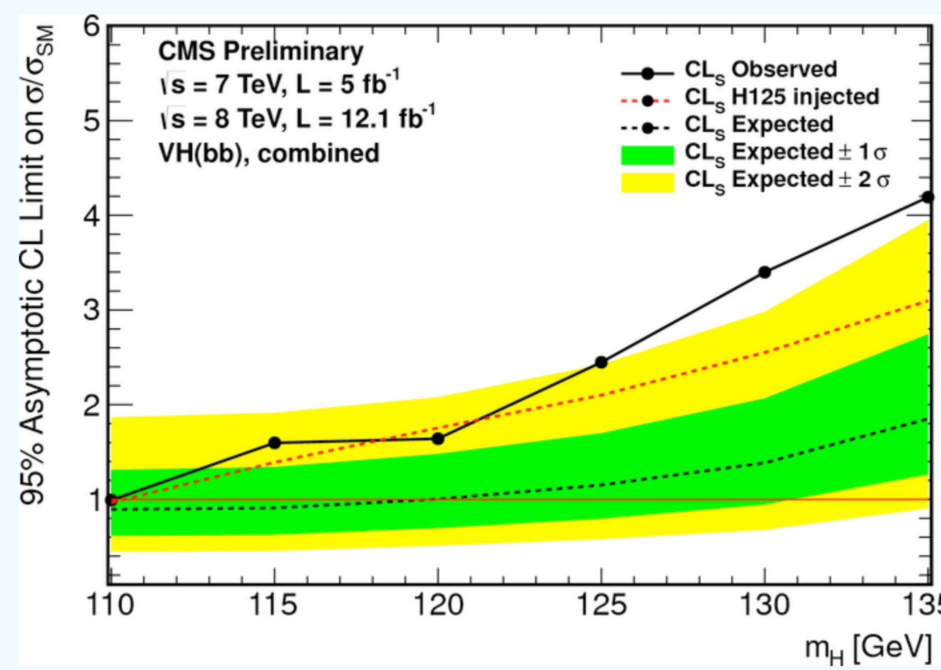




The LHC Higgs discovery is supported by an excess in the bb channel at the Tevatron. Consistent with 125 GeV Higgs, but best fit for m_H~135 GeV.

CMS also sees some excess at higher mass in WW and bb channels

→ talk by M. Velasco



Two Higges at Tevatron and LHC?

arXiv:1208.4952

$$R_i^X(Y) = \frac{\sigma_Y(H_i)}{\sigma_Y(H_{\rm SM})} \times \frac{BR(H_i \to X)}{BR(H_{\rm SM} \to X)}$$

- H_1 at 125-126 GeV

$$R_1^{\gamma\gamma}(ggF) \simeq 1.66 \pm 0.36 \quad ✔$$

$$R_1^{ZZ^{(*)}}(ggF) \simeq 1.02 \pm 0.38 \quad ✔$$

- H_2 at 135-136 GeV

$$R_2^{\gamma\gamma}(ggF) \simeq 0.45 \pm 0.3, \quad ✔$$

$$R_2^{ZZ^{(*)}}(ggF) \lesssim 0.2 \quad ✔$$

$$R_2^{\tau\tau}(VBF) < 1.81 \quad ✔$$

$$R_{\rm eff}^{bb}(VH) \simeq 3.53 + 1.26 - 1.16$$

$$\simeq R_2^{bb}(VH) + 1.3 \times R_1^{bb}(VH)$$

a point that fits

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	$S_{i,d}$	$S_{i,u}$	$S_{i,s}$
H_1	-0.24	-0.67	0.70
H_2	0.54	0.51	0.67
H_3	0.81	-0.54	-0.24

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

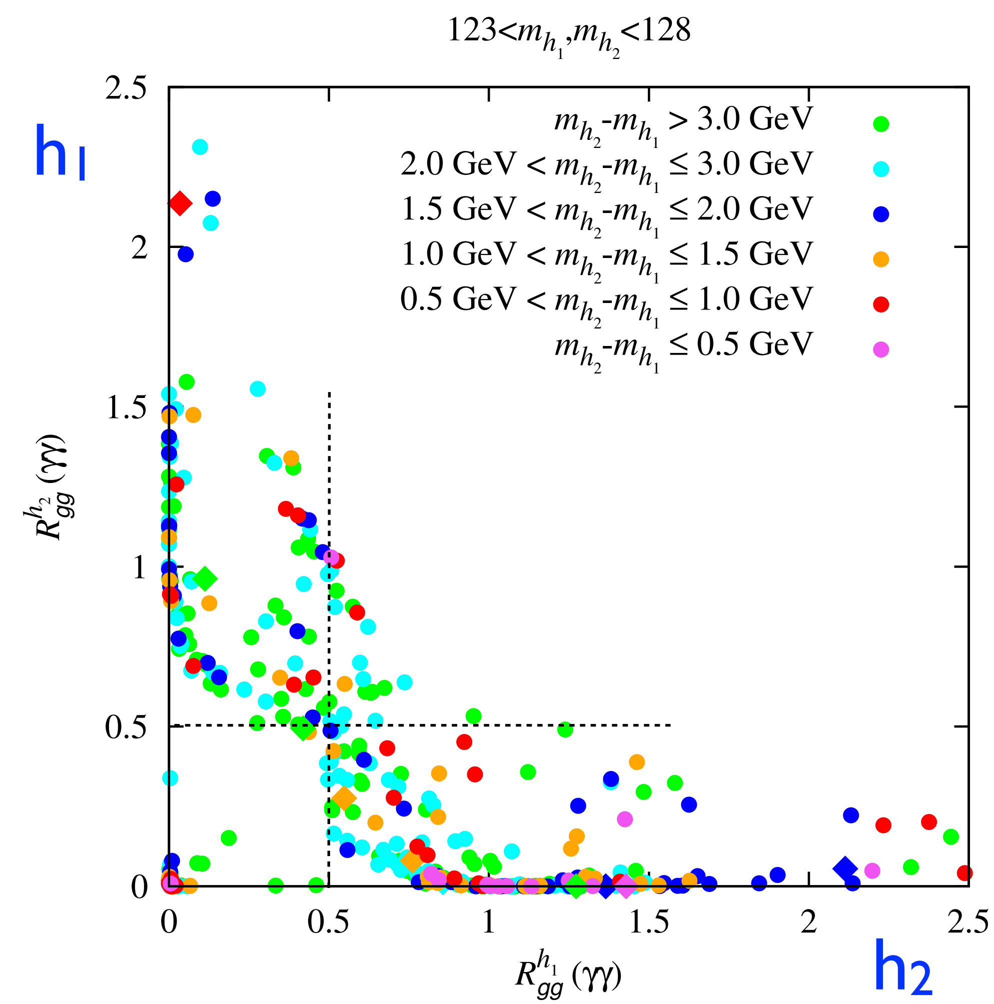
$$R_{\rm eff}^{bb}(VH) \sim 1.20 \quad (2\sigma)$$

Degenerate case:
Two Higgses hiding in the 125 GeV signal?

Two NMSSM Higgses near 125 GeV?

arXiv:1207.1545

- In the previous scenarios, we had either h_1 or h_2 at 125 GeV, but the "other" Higgs was never very far away.
- It is possible the h_1 and h_2 are so close in mass that they both fall into the 123-128 GeV mass window.
- In this case they may either both contribute to the signal at 125 GeV, or one Higgs contributes dominantly while the other one is hidden.
- Effective Higgs mass and signal rate:



$$m_h^Y(X) \equiv \frac{R_Y^{h_1}(X) m_{h_1} + R_Y^{h_2}(X) m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)}$$

$$R_Y^h(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X)$$

$$R_{gg}^{h_i}(X) = \frac{\Gamma(gg \to h_i)\ BR(h_i \to X)}{\Gamma(gg \to H_{\rm SM})\ BR(H_{\rm SM} \to X)}$$

Two NMSSM Higgses near 125 GeV?

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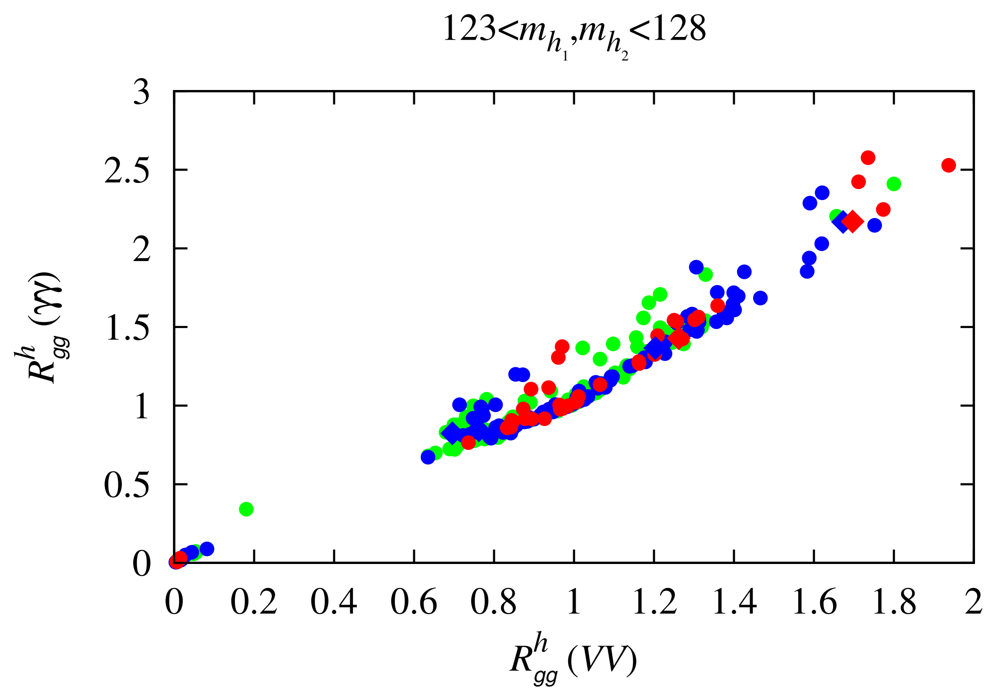
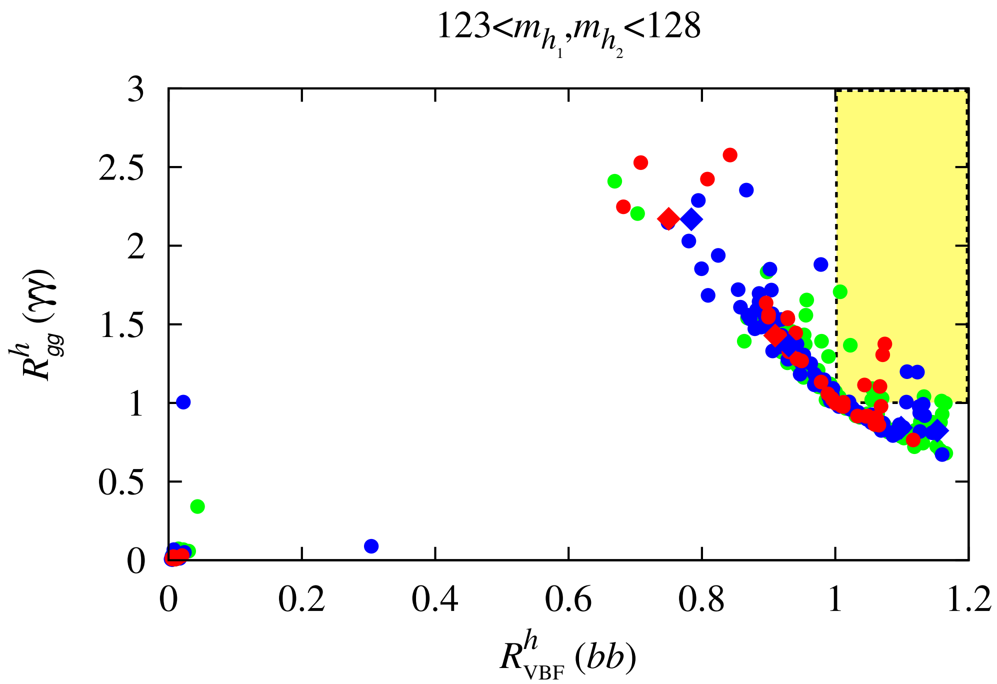
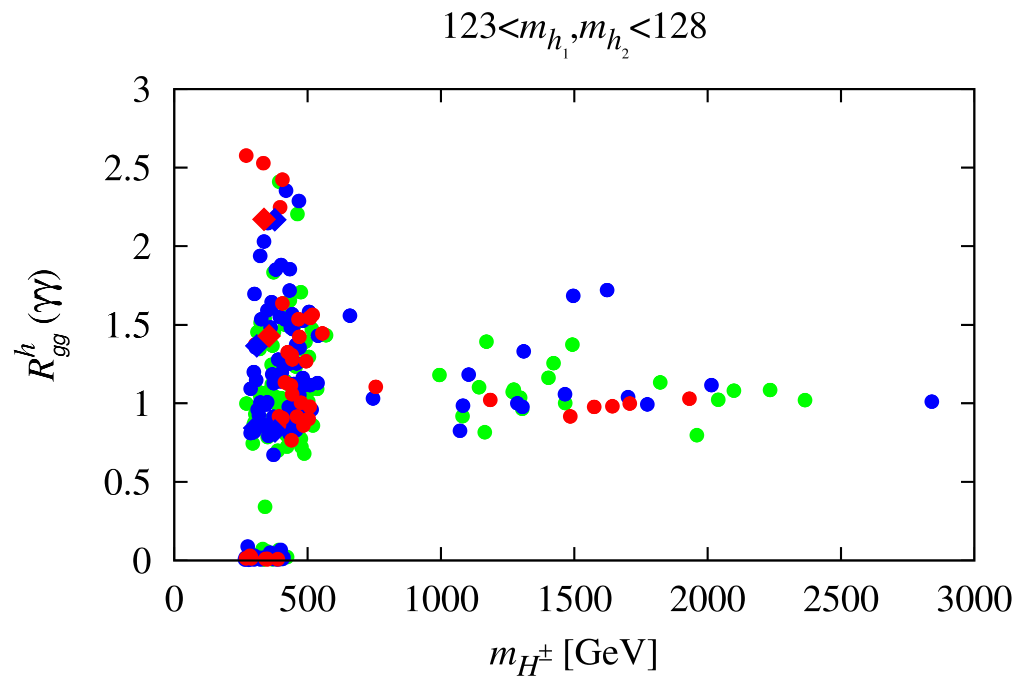


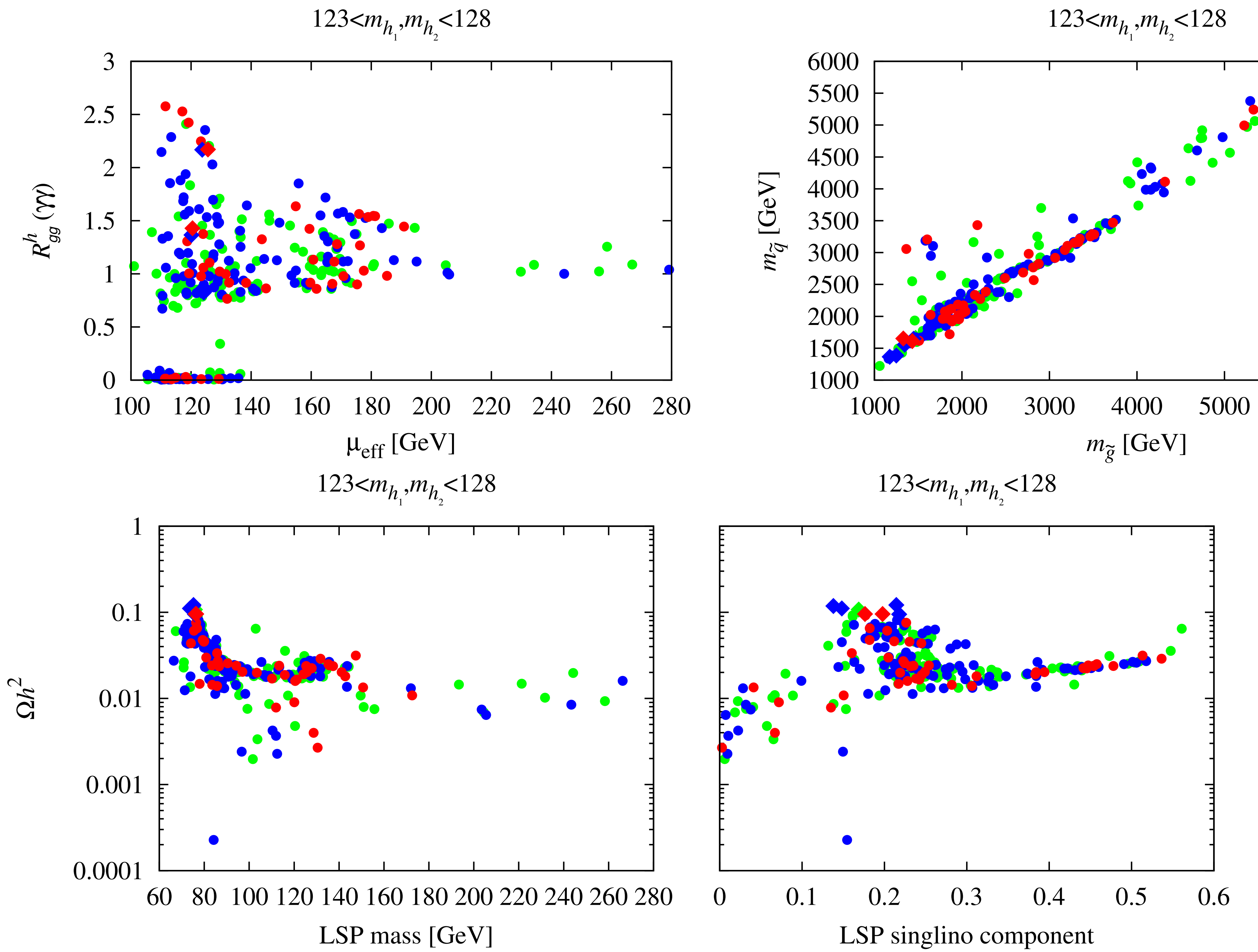




red: Δm < 1 GeV
blue: Δm = 1-2 GeV
green: Δm = 2-3 GeV

Two NMSSM Higgses near 125 GeV?

arXiv:1207.1545



red: Δm < 1 GeV
blue: Δm = 1-2 GeV
green: Δm = 2-3 GeV

Diagnosing degenerate Higgs bosons

arXiv:1208.1817

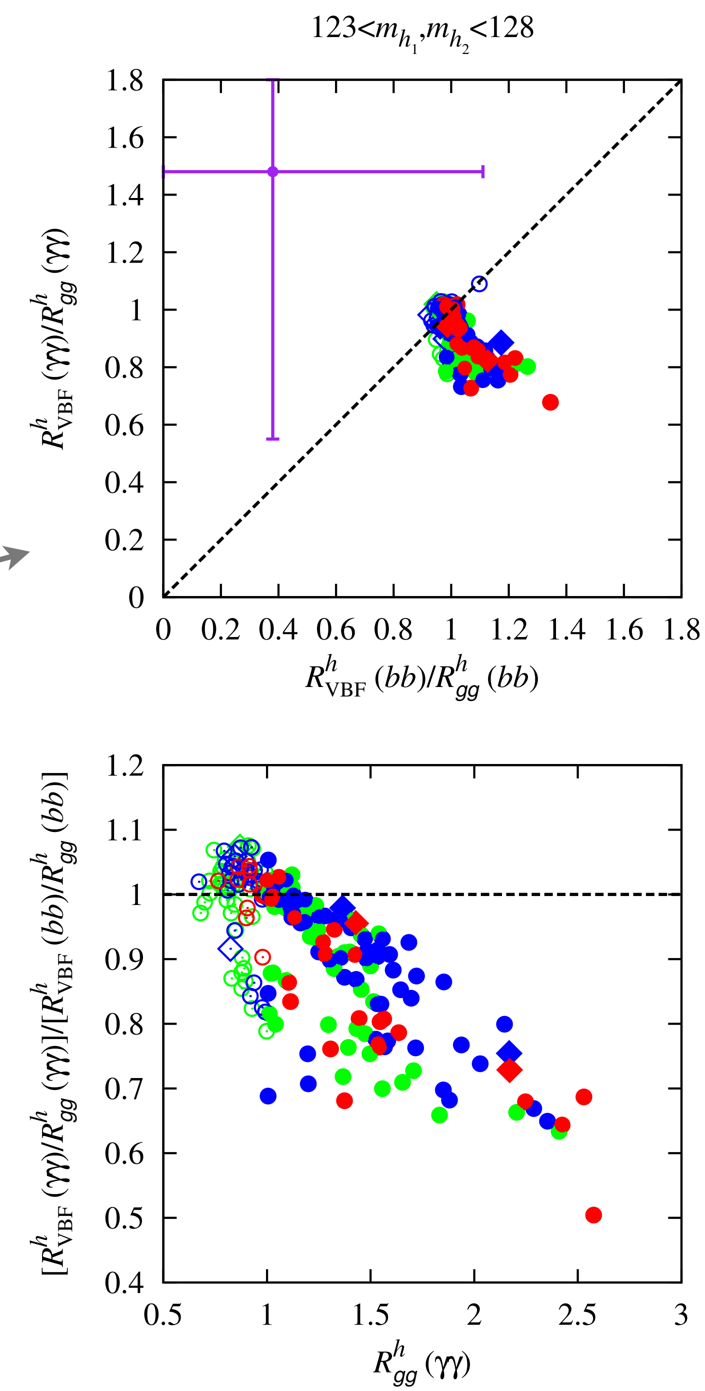
- A way to reveal the presence of degenerate Higgs bosons is through double ratios of signal strengths.

- Not all signal strengths are independent from each other. In models with doublets +singlets, we can form 3 independent double ratios:

$$\text{I)}: \quad \frac{R^h_{VBF}(\gamma\gamma)/R^h_{gg}(\gamma\gamma)}{R^h_{VBF}(bb)/R^h_{gg}(bb)},$$

$$\text{II)}: \quad \frac{R^h_{VBF}(\gamma\gamma)/R^h_{gg}(\gamma\gamma)}{R^h_{VBF}(WW)/R^h_{gg}(WW)},$$

$$\text{III)}: \quad \frac{R^h_{VBF}(WW)/R^h_{gg}(WW)}{R^h_{VBF}(bb)/R^h_{gg}(bb)},$$



- If there is only one Higgs, each of these double ratios = 1.

Conclusions

- A SM-like Higgs in the 125-126 GeV mass range poses a severe constraint on SUSY models.
- Typically points towards heavy SUSY → need 14 TeV LHC.
- "Natural" SUSY spectra with 125 GeV Higgs easier to obtain in the NMSSM; enhanced $\gamma\gamma$ signal for large λ and small $\tan\beta$ from doublet-singlet mixing.
- Intriguing possibilities in the NMSSM

  a) h_2 is the state at 125 GeV; h_1 has reduced couplings to Z, missed by LEP

  b) the state at 125 GeV is h_1; h_2 accounts for the slight excess at 130-140 GeV

  c) both h_1 and h_2 are degenerate and contribute to the signal at 125 GeV
- All these scenarios feature light higgsino-like LSP of 60-150 GeV (if DM), light stops < 1 TeV, light charged Higgs <500 GeV; other SUSY particles heavy
- It is worthwhile to search for more Higgses, even below LEP limit. Need precision measurements at 14 TeV LHC to reveal non-standard Higgs.

References

John F. Gunion, Yun Jiang, SK

- The constrained NMSSM and Higgs near 125 GeV. arXiv:1201.0982
- Could two NMSSM Higgs bosons be present near 125 GeV? arXiv:1207.1545
- Diagnosing degenerate Higgs bosons at 125 GeV. arXiv:1208.1817

G. Belanger, U. Ellwanger, J.F. Gunion, Y. Jiang, SK

- Two Higgs bosons at the Tevatron and the LHC? arXiv:1208.4952

G. Belanger, U. Ellwanger, J.F. Gunion, Y. Jiang, SK, John H. Schwarz

- Higgs bosons at 98 and 125 GeV at LEP and the LHC arXiv:1210.1076