Additional Higgs Bosons near 95 and 650 GeV in the NMSSM

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based on arXiv:2309.07838

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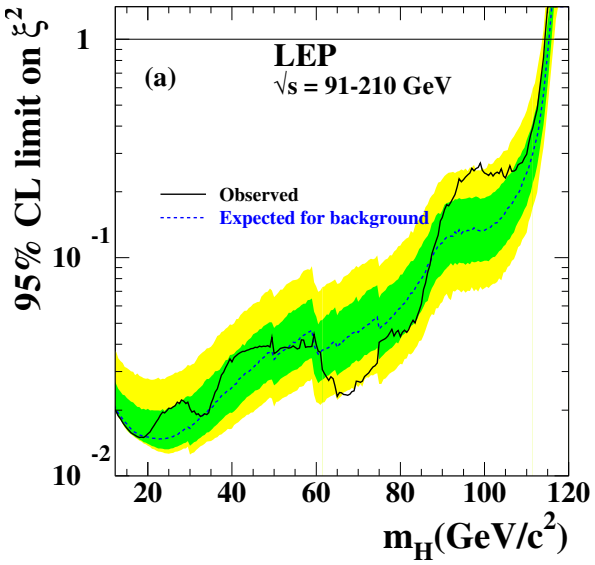
General Remarks

- A large number of searches for phenomena (excesses) beyond the Standard Model have been performed at the LHC and elsewhere.
- One has to expect $\geq 2\ \sigma$ deviations for $\sim 5\ \%$ of all search cannels.
- Such deviations can indicate statistical fluctuations, or hints for physics beyond the Standard Model (if the significance increases with more data in the future) – impossible to tell a priori.
- It is interesting to verify which combinations of $\geq 2\ \sigma$ deviations can originate from which model beyond the SM.

Possible signals for an extended Higgs sector

1) At $\sim$ 95 GeV

An old story from LEP (combining ALEPH, DELPHI, L3 and OPAL), $e^+ + e^- \to Z^* \to Z + (H \to b\bar{b})$:



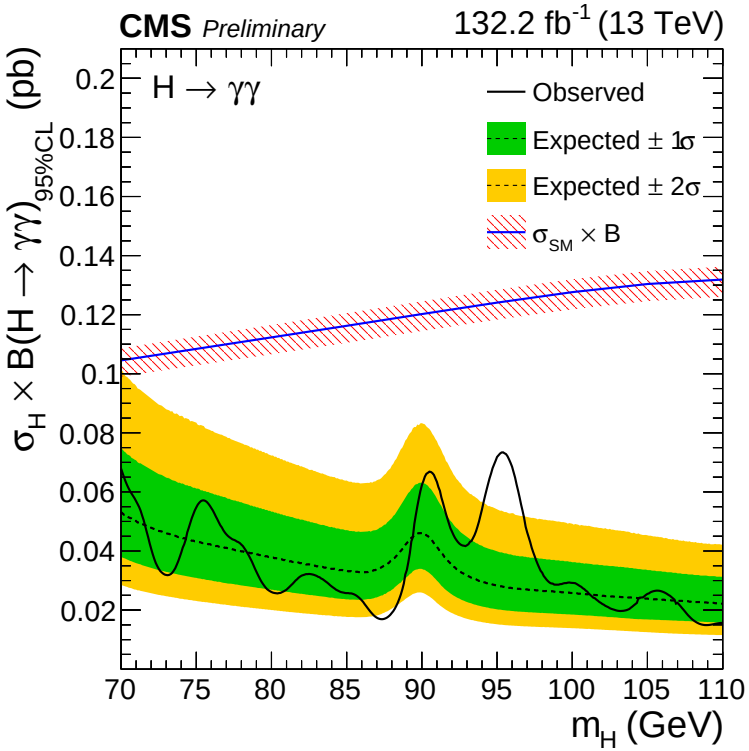
$\to$ A $2\,\sigma$ excess around 95 GeV, corresponding to (from Cao et al, 1612.08522)

$$\mu_{bb}^{LEP} \equiv C_V(H_1)^2 \times \frac{BR(H_1 \to b\bar{b})}{BR(H_{SM}^{95} \to b\bar{b})} = 0.117 \pm 0.057$$

H_1: an extra scalar near 95 GeV; $C_V(H_1)$: its reduced coupling to Z/W;
H_{SM}^{95}: a scalar at 95 GeV with SM-like couplings

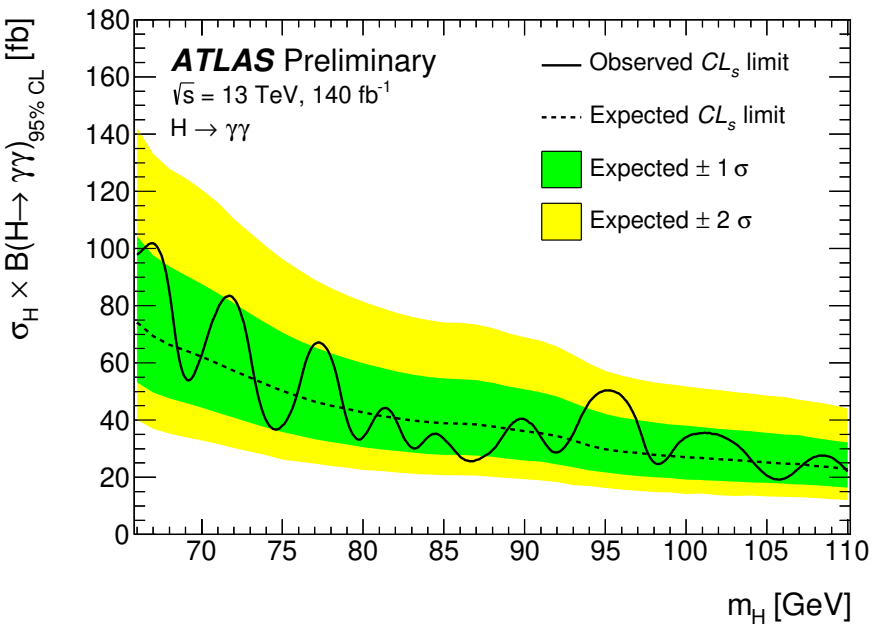
1) 95 GeV ff, $pp \to H \to \gamma\gamma$

CMS-PAS-HIG-20-002:



→ A 2.9 σ excess (local) at 95 GeV

ATLAS-CONF-2023-035:



→ A 1.7 σ excess (local) at 95 GeV

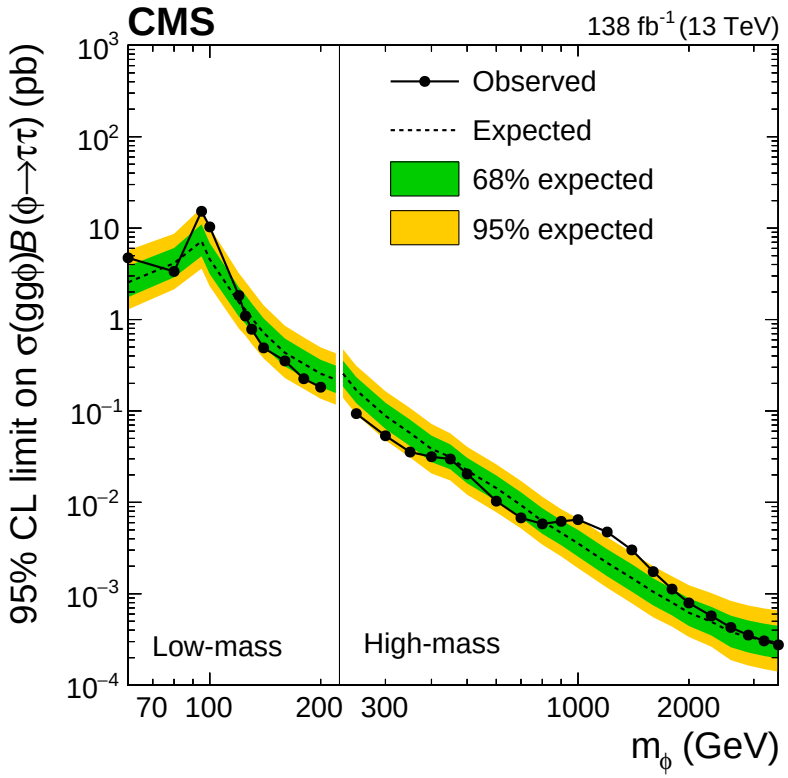
Combination, from Biekötter et al, arXiv:2306.03889:

$$\mu_{\gamma\gamma}^{LHC} = \frac{\sigma(gg \to H_1 \to \gamma\gamma)}{\sigma(gg \to H_{SM}^{95} \to \gamma\gamma)} = 0.24^{+0.09}_{-0.08}$$

→ A 3.2 σ excess (local) at 95 GeV

1) 95 GeV ff, $pp \to H \to \tau\tau$

CMS-HIG-21-001:

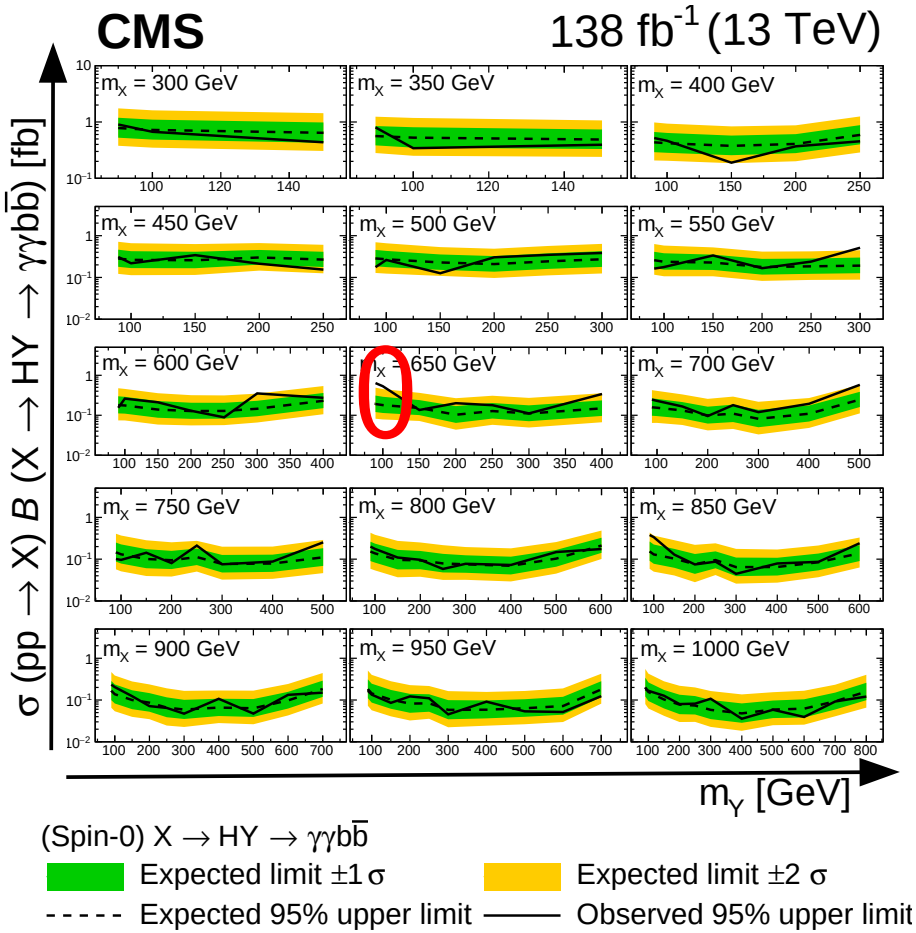


$\to$ A $3.1\,\sigma$ excess (local) around 100 GeV

$$\mu_{\tau\tau}^{LHC} = \frac{\sigma(gg \to H_1 \to \tau\tau)}{\sigma(gg \to H_{SM}^{95} \to \tau\tau)} = 1.38^{+0.69}_{-0.55}$$

2) 650 GeV, $pp \to X \to (H_{125} \to \gamma\gamma) + (Y \to b\bar{b})$

CMS arXiv:2310.01643:

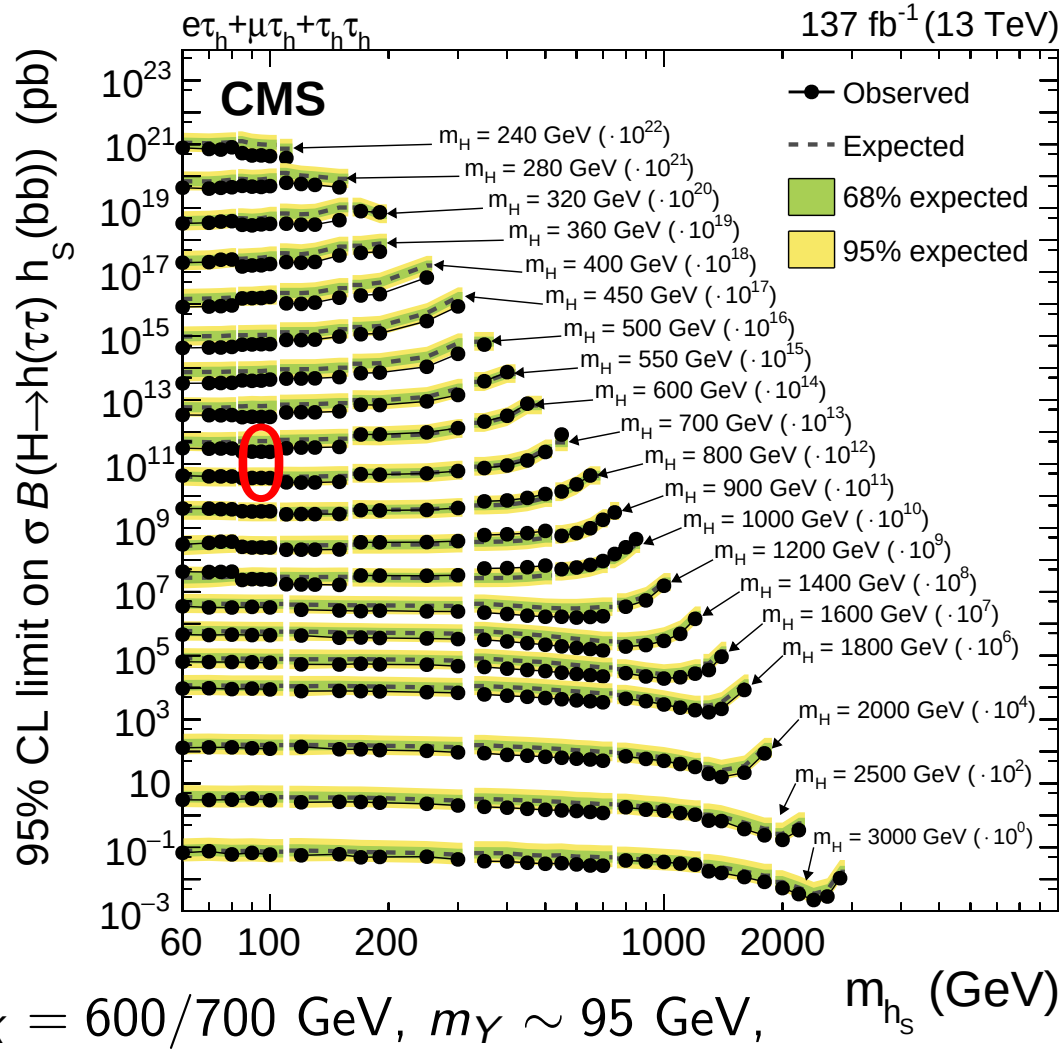


→ A 3.8 σ excess (local) is observed for $m_X = 650$ GeV and $m_Y \sim 95$ GeV

$$\sigma_{bb\gamma\gamma} = \sigma(gg \to X_{650} \to (Y \to b\bar{b}) + (H_{SM} \to \gamma\gamma)) = 0.35^{+0.17}_{-0.13}\ \text{fb}$$

2) 650 GeV ff

However: CMS arXiv:2106.10361, $pp \to X \to (Y \to bb) + (H_{125} \to \tau\tau)$:



No excess for $m_X = 600/700$ GeV, $m_Y \sim 95$ GeV,
95% CL upper limit on $\sigma_{bb\tau\tau}$ of ~ 3 fb;
$\to$ upper limit of 0.1 fb on $\sigma_{bb\gamma\gamma}$, at the boundary of (but within) the $2\,\sigma$ range

The Higgs Sector of the CP-conserving NMSSM:

- 3 CP-even scalars: H_S, H_{SM}, H where
  $H_S \simeq$ singlet-like, $H_{SM} \simeq$ SM-like, H $\simeq$ MSSM-like
- 2 CP-odd scalars: A_S, A where $A_S \simeq$ singlet-like, A $\simeq$ MSSM-like
- 1 complex charged $H^{\pm}$

H, A and $H^{\pm}$ form a nearly degenerate SU(2) doublet with masses $\gtrsim 400$ GeV due to constraints on $M_{H^{\pm}}$ from $b \to s + \gamma$ and direct searches.

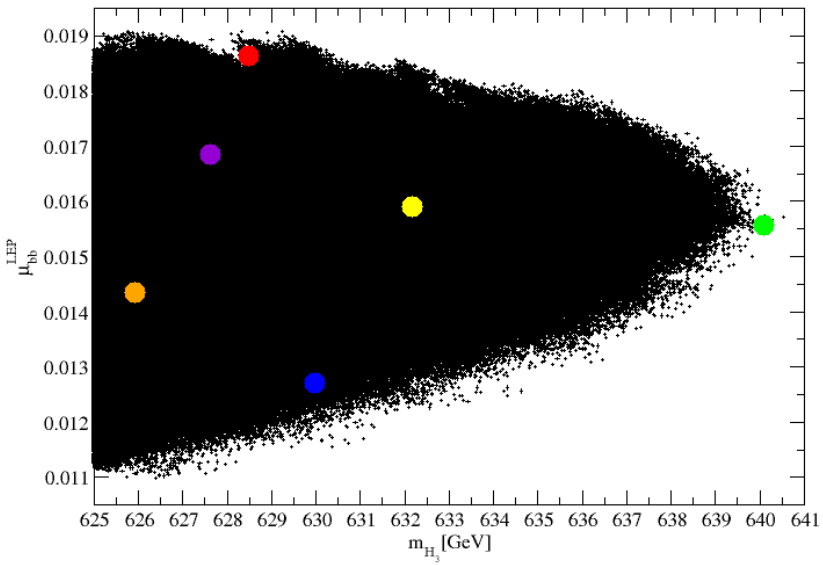
H_S is a candidate for H_1 at 95 GeV

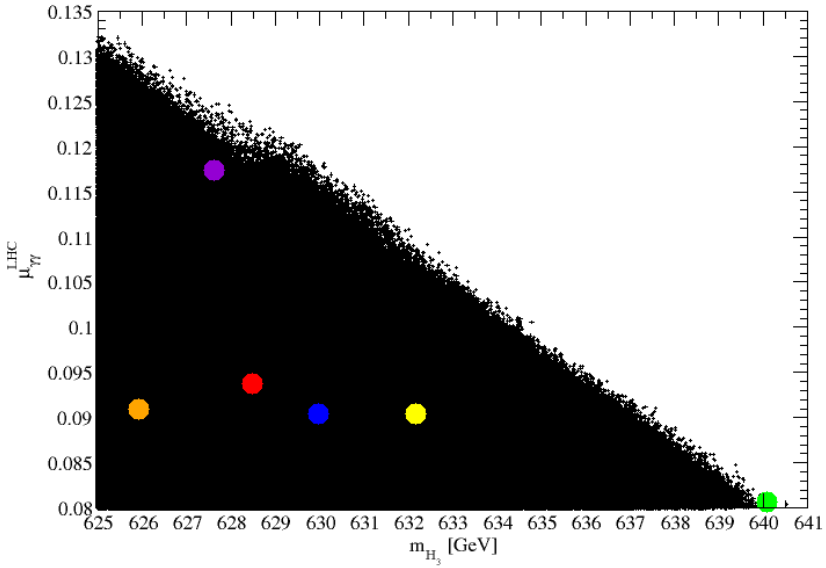
H is a candidate for X near 650 GeV

Scan of the NMSSM parameter space

- `NMSSMTools-6.0.0`: Impose constraints from SM Higgs mass and couplings, b-physics, dark matter detection cross sections, $\sim$ 20 BSM Higgs searches
- Require $M_{H_s} = 95.4 \pm 3$ GeV (allowing for a theoretical uncertainty of 3 GeV)
- M_H in the range 650 ± 25 GeV
  (in CMS 2310.01643, M_X is given in steps of $650 \pm n \times 50$ GeV)
- Excesses described by μ_{bb}^{LEP}, $\mu_{\gamma\gamma}^{LHC}$, $\sigma_{bb\gamma\gamma}$ within the $2\,\sigma$ ranges
- But: fits to $\mu_{\tau\tau}^{LHC}$ are left aside; the necessary couplings of H_{95} to $\tau\tau$ would require a large mixing angle $H_{SM} - H_{95}$ which is in conflict with the SM-like couplings of H_{SM}
- Constraints on $\sigma_{bb\tau\tau} \equiv pp \to X \to (H_{95} \to bb) + (H_{125} \to \tau\tau)$ imply upper bounds on $\sigma_{bb\gamma\gamma}$ since $H_{125} \to \tau\tau$ and $H_{125} \to \gamma\gamma$ are related by a factor ~ 30

Allowed Points in the NMSSM parameter space



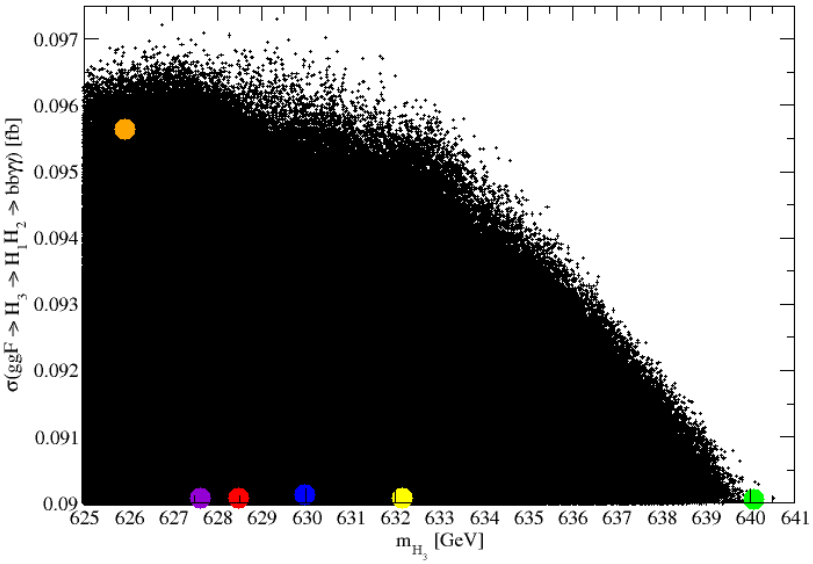


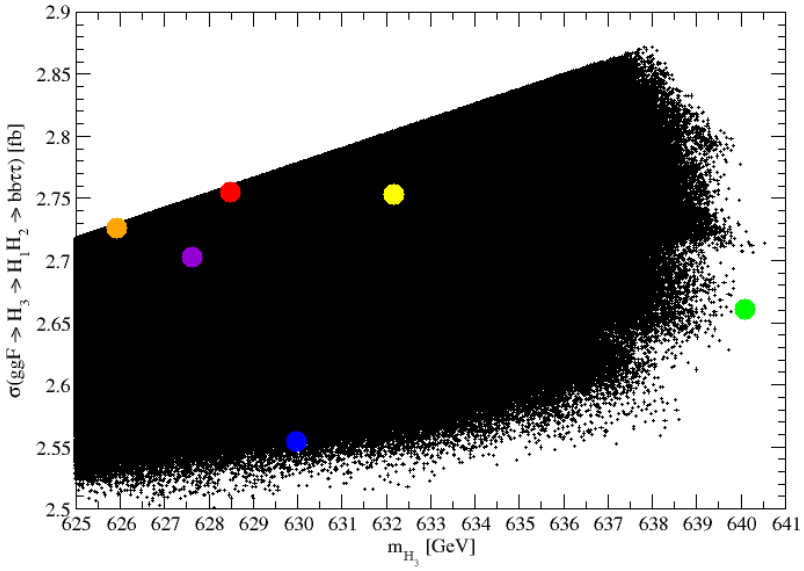
$\mu_{bb}^{LEP} \sim 0.01 - 0.02$ (left), $\mu_{\gamma\gamma}^{LHC} \sim 0.09 - 0.13$ (right) as function of M_{H_3}.
μ_{bb}^{LEP} and $\mu_{\gamma\gamma}^{LHC}$ are near their lower $2\,\sigma$ boundaries.

The larger is M_{H_3}, the larger has to be the $BR(H_{95} \to b\bar{b})$ in order to keep $\sigma_{bb\gamma\gamma}$ large enough. This reduces the $BR(H_{95} \to \gamma\gamma)$ and thus $\mu_{\gamma\gamma}^{LHC}$ on the r.h.s.

The coloured dots here and the subsequent figures denote six benchmark points.

Allowed Points in the NMSSM parameter space



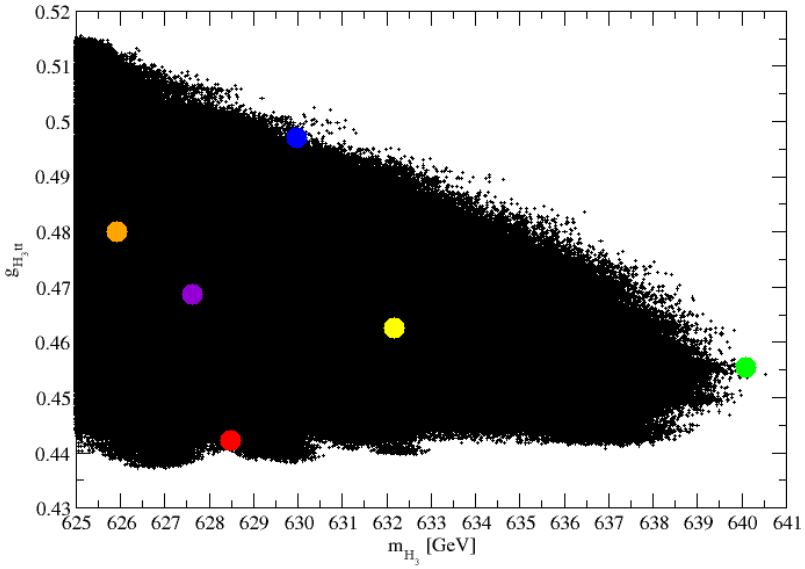


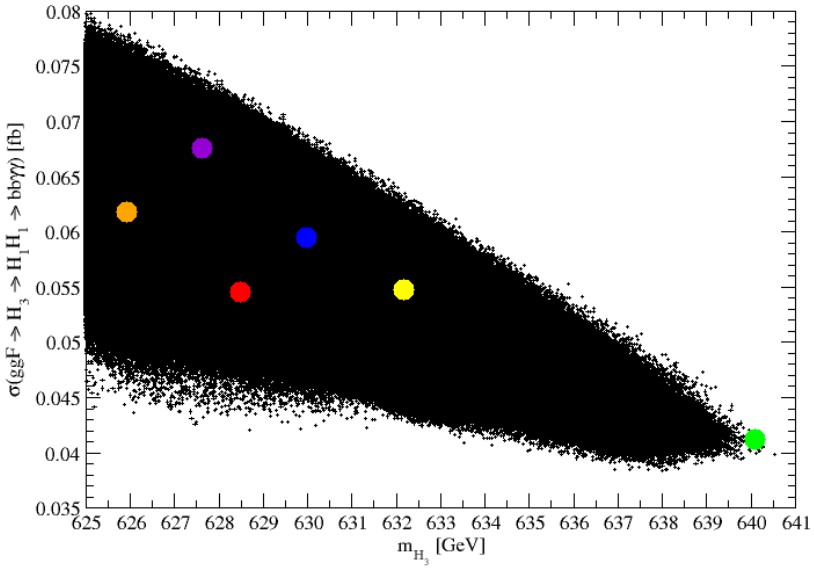
Left: $\sigma_{bb\gamma\gamma} \sim 0.09 - 0.1$ fb as function of M_{H_3}, near its lower $2\,\sigma$ boundary.

Right: $\sigma_{bb\tau\tau}$ as function of M_{H_3}, limited from above by constraints from the search by CMS for $pp \to X \to (Y \to bb) + (H_{125} \to \tau\tau)$

Predictions for $ggF \to H_{650} \to t\bar{t}$ (left)

and $\sigma(ggF \to H_{650} \to H_{95}H_{95} \to b\bar{b}\gamma\gamma)$ (right)

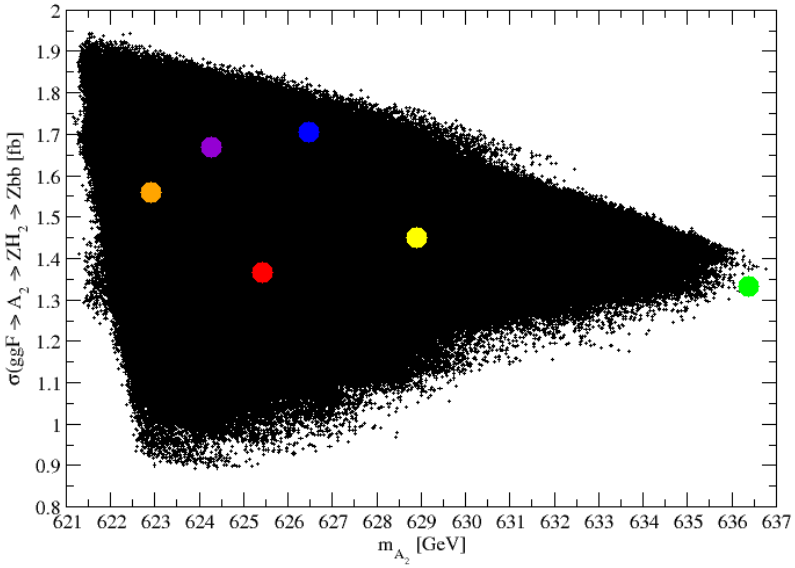


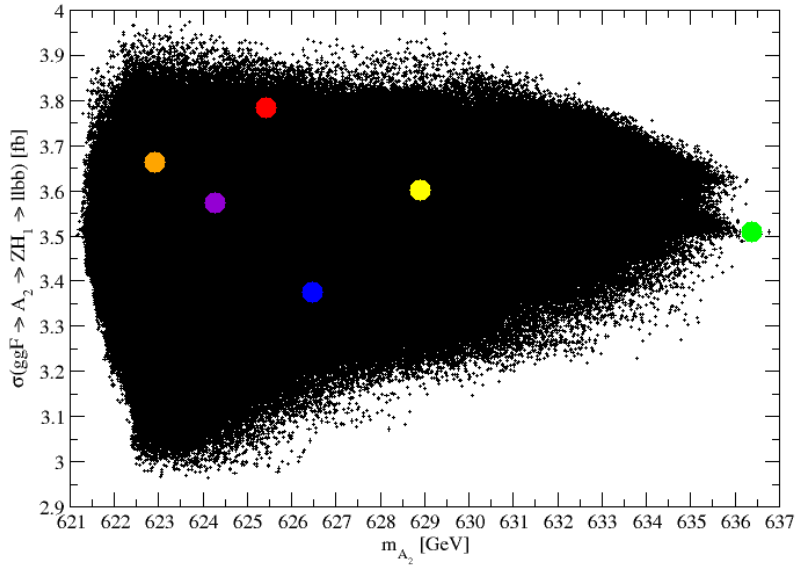


Left: Coupling strength modifier $g_{H_3tt} \sim 0.44 - 0.52$ as a function of the heavy scalar boson mass M_{H_3}. (Upper limits from CMS arXiv:1908.01115: $\sim .735$. Similar results hold for the CP-odd pseudoscalar A_2.)

Right: $\sigma(ggF \to H_{650} \to H_{95}H_{95} \to b\bar{b}\gamma\gamma) \sim 0.04 - 0.08$ fb, no search yet

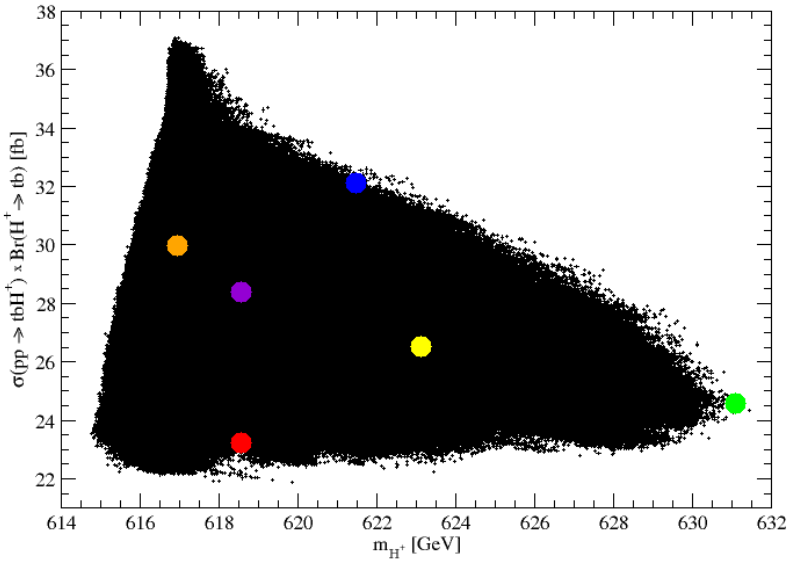
Predictions for $\sigma(ggF \to A_2 \to Z + (H_{SM} \to b\bar{b}))$ (left) and $\sigma(ggF \to A_2 \to (Z \to \ell\ell) + (H_{95} \to b\bar{b}))$ (right)





- The cross section into $Z + H_{95}$ is 30-40 times larger than the cross section into $Z + H_{SM}$
- Both cross sections are factors of 20 (for $Z + H_{SM}$) or 5 (for $Z + H_1$) below present limits from ATLAS(arXiv:2207.00230) and CMS(arXiv:1903.00941, arXiv:1911.03781).

Predictions for $\sigma(pp \to tbH^{\pm}) \times Br(H^{\pm} \to tb)$



- Recent searches: CMS in arXiv:2001.07763 (35.9 fb^{-1}),
  ATLAS in arXiv:2102.10076 (139 fb^{-1}),
  for $M_{H^{\pm}} \sim 600 - 650$ GeV: $\sigma(pp \to tbH^{\pm}) \times Br(H^{\pm} \to tb) < 150$ fb

- NMSSM: 30 ± 8 fb.

Conclusions

- In the NMSSM it is possible to explain simultaneously four hints for H_{95}, including a hint for H_{650} with a mass in the $625 - 640$ GeV range:
  - From $H_{95} \to b\bar{b}$ at LEP ($\sim 2\,\sigma$)
  - From $H_{95} \to \gamma\gamma$ at CMS ($\sim 2.9\,\sigma$)
  - From $H_{95} \to \gamma\gamma$ at ATLAS ($\sim 1.7\,\sigma$; combined: $\sim 3.2\,\sigma$)
  - From $ggF \to H_{650} \to (H_{95} \to b\bar{b}) + (H_{SM} \to \gamma\gamma)$ at CMS ($\sim 3.8\,\sigma$)
- However: An excess in $H_{95} \to \tau\tau$ cannot be described simultaneously
- Improved sensitivities in complementary search channels can help to test the corresponding parameter space of the NMSSM