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INTERPRETING THE 95 GEV HIGGS BOSON WITHIN A 2-HIGGS DOUBLET MODEL

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arXiv:2306.09029 [hep-ph]

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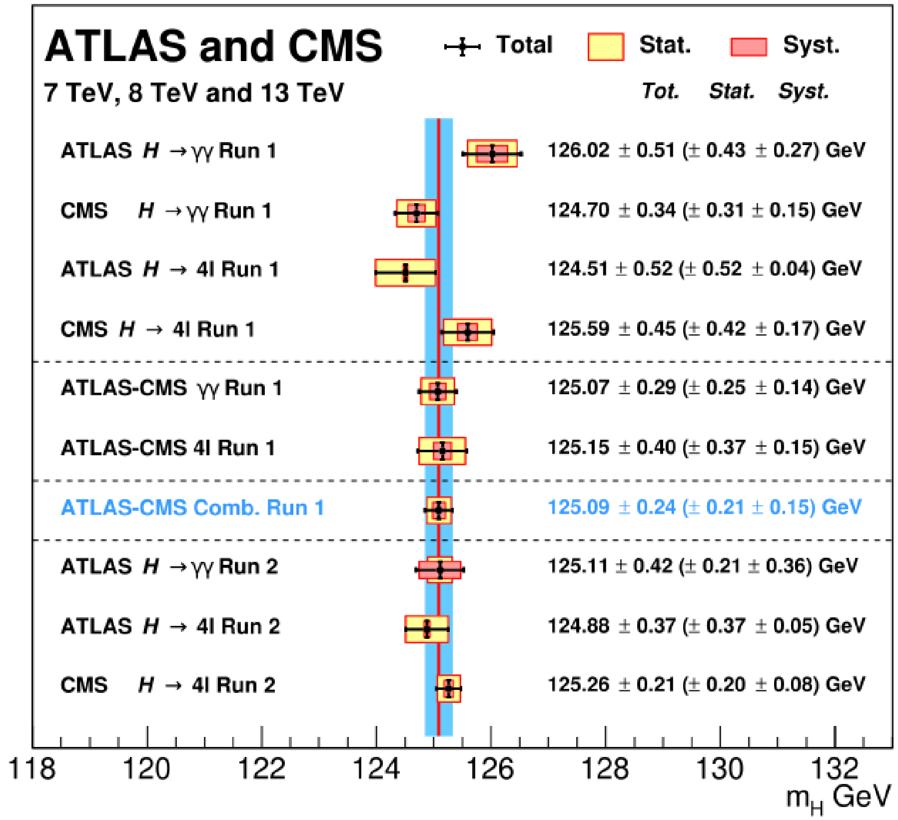
OUTLINE

INTRODUCTION

- Higgs properties measurements at run 1 and run 2 are in a good agreement with the SM
- Perhaps other scalars are not yet discovered
- Two Higgs Doublet Model (2HDM)
  - Minimal extension to the SM
  - Rich collider phenomenology
  - LHC benchmark mode
    - Benchmarks for light/heavy charged Higgs
    - Benchmarks for light /heavy neutral Higgses

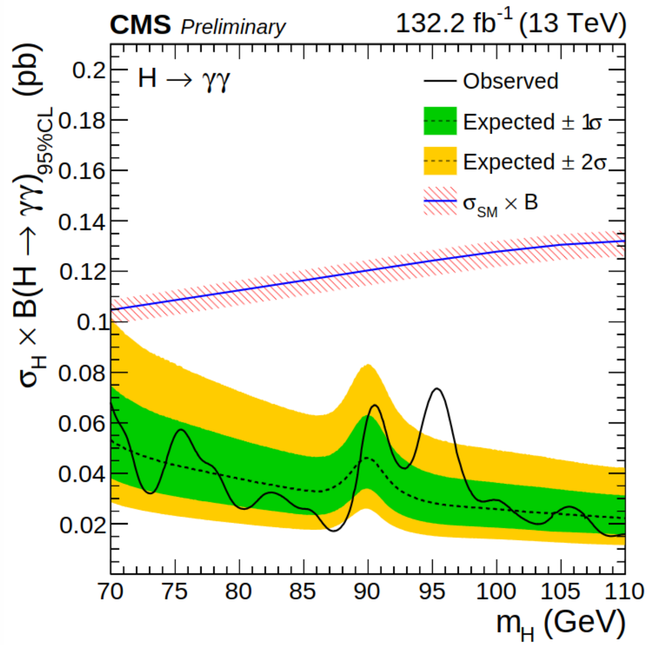


[C. Patrignani et al., Particle Physics Group, Chin. Phys. C, 40 100001]

$\gamma\gamma$ AND $\tau\tau$ EXCESSES (CMS)

☆ **a 2.9σ local excess at $\sim$ 95 GeV in $\gamma\gamma$ channel**

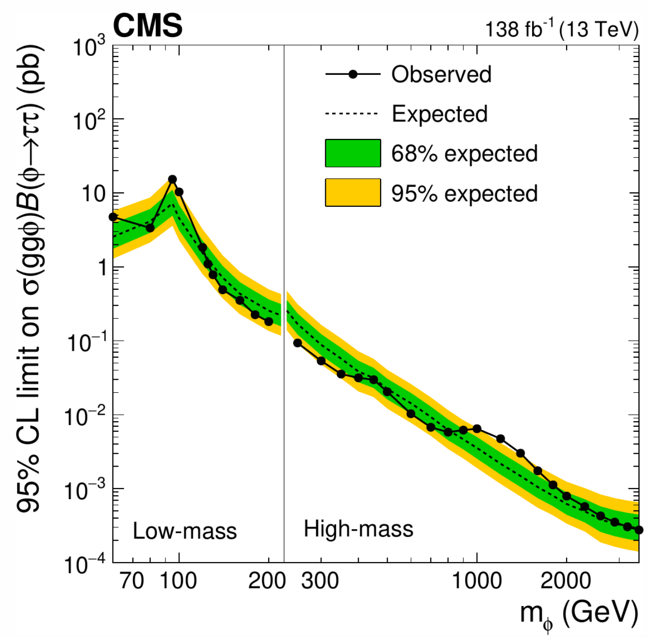
$$\mu_{\gamma\gamma} = \frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \times \frac{\mathcal{BR}(h \to \gamma\gamma)}{\mathcal{BR}_{SM}(h \to \gamma\gamma)} = |c_{htt}|^2 \times \frac{\mathcal{BR}(h \to \gamma\gamma)}{\mathcal{BR}_{SM}(h \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}.$$



[CMS-PAS-HIG-20-002]

☆ **a 2.6σ local excess at $\sim$ 95 GeV in $\tau\tau$ channel**

$$\mu_{\tau\tau} = \frac{\sigma(gg \to h)}{\sigma_{SM}(gg \to h)} \times \frac{\mathcal{BR}(h \to \tau\tau)}{\mathcal{BR}_{SM}(h \to \tau\tau)} = |c_{htt}|^2 \times \frac{\mathcal{BR}(h \to \tau\tau)}{\mathcal{BR}_{SM}(h \to \tau\tau)} = 1.2 \pm 0.5.$$



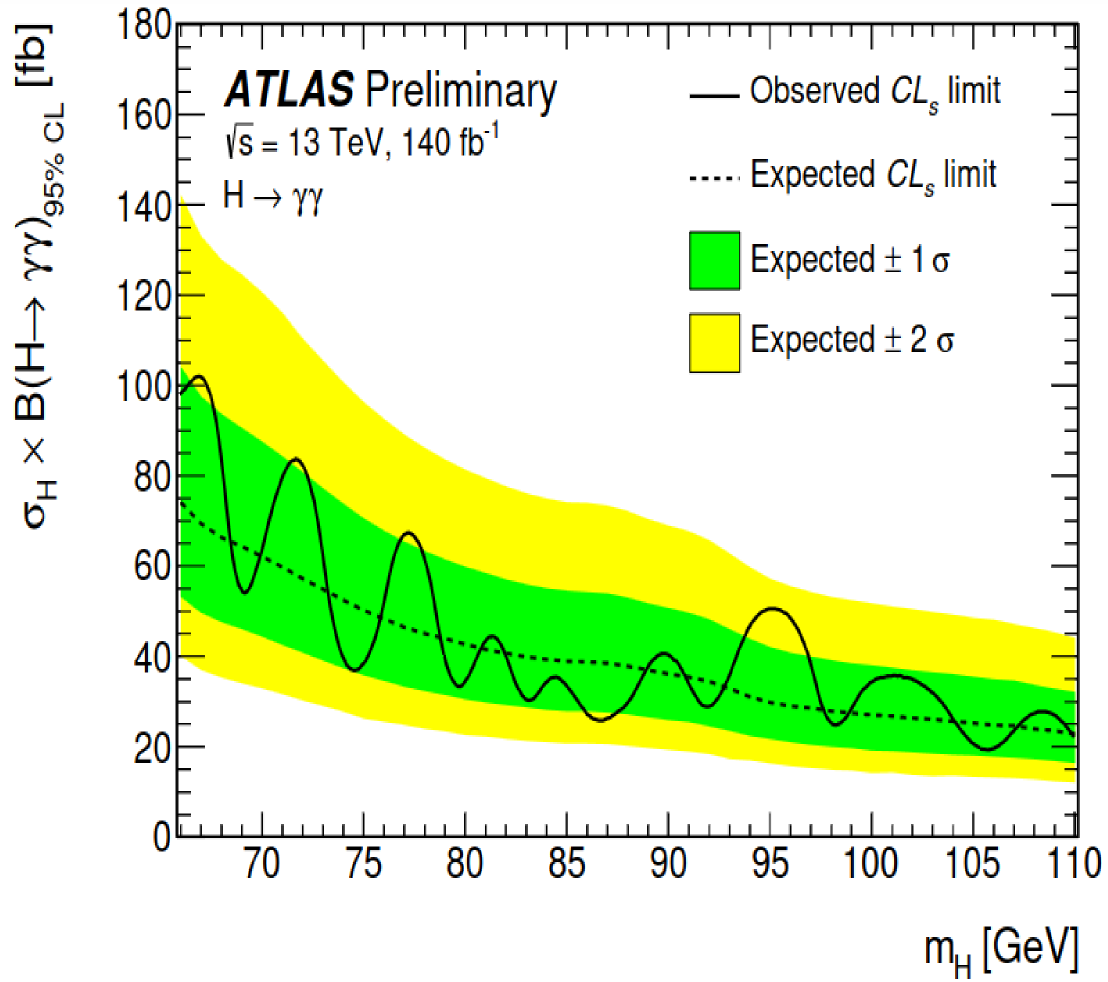
[CMS-HIG-21-001]

$\gamma\gamma$ EXCESS (ATLAS)

$$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.18 \pm 0.10 \quad (\mathbf{1.7\sigma})$$

$$\mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08} \quad (\mathbf{3.1\sigma})$$

[T. Biekotter, S. Heinemeyer, G. Weiglein 2306.03889]

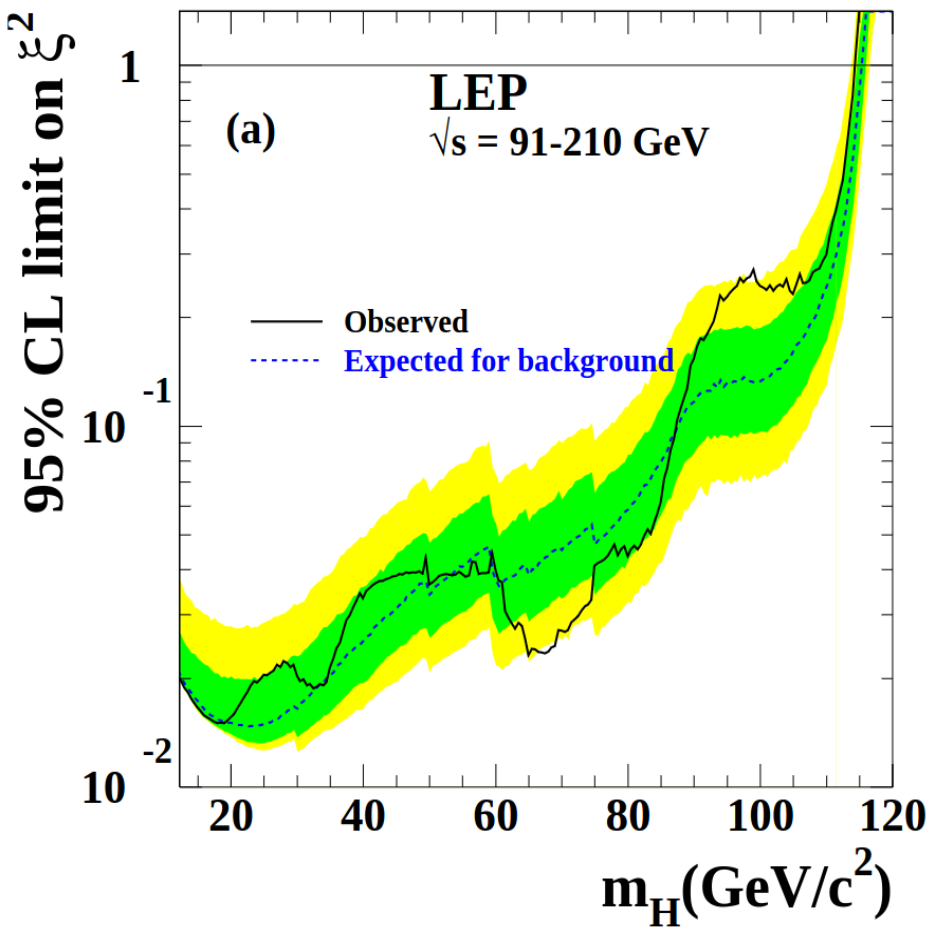


[ATLAS-CONF-2023-035]

$b\bar{b}$ EXCESS (LEP)

✯ a $\sim 2\sigma$ local excess at 95-98 GeV in $b\bar{b}$ channel

$$\mu^{bb}_{LEP} = \frac{\sigma(e^+e^- \to Zh)}{\sigma_{SM}(e^+e^- \to Zh)} \times \frac{\mathcal{BR}(h \to b\bar{b})}{\mathcal{BR}_{SM}(h \to b\bar{b})}$$
$$= |c_{hZZ}|^2 \times \frac{\mathcal{BR}(h \to b\bar{b})}{\mathcal{BR}_{SM}(h \to b\bar{b})}$$
$$= 0.117 \pm 0.057.$$



[LEP: hep-ex/030603]

2HDM PARAMETRIZATION

The most general scalar potential of the 2HDM :

$$V(\Phi_1\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]$$
$$+ \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+ \left\{\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \quad (1)$$

with :

$$\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ + i\varphi_{1,2}^+ \\ \frac{1}{\sqrt{2}}\left(v_{1,2} + \rho_{1,2} + i\eta_{1,2}\right) \end{pmatrix} \quad (2)$$

- ✦ The 10 independent parameters ($m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_{1,\ldots,7}$) are asumed to be real.
- ✦ 2 minimization conditions and the combination $v_1^2 + v_2^2 \implies$ 7 free parameters:

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \alpha,\ \tan\beta = \frac{v_2}{v_1} \text{ and } m_{1,2}^2.$$

- Tree-level FCNCs allowed $\Longrightarrow$ both doublets can couple to leptons and quarks.
- The associated model is called **2HDM type-III.**
- The Yukawa Lagrangian in terms of physical scalar masses:

$$
\begin{aligned}
-\mathcal{L}_Y^{III} &= \sum_{f=u,d,\ell} \frac{m_j^f}{v} \left[(\xi_h^f)_{ij} \bar{f}_{Li} f_{Rj} h + (\xi_H^f)_{ij} \bar{f}_{Li} f_{Rj} H - i (\xi_A^f)_{ij} \bar{f}_{Li} f_{Rj} A \right] \\
&+ \frac{\sqrt{2}}{v} \sum_{k=1}^{3} \bar{u}_i \left[\left(m_i^u (\xi_A^{u*})_{ki} V_{kj} P_L + V_{ik} (\xi_A^d)_{kj} m_j^d P_R \right) \right] d_j H^+ \\
&+ \frac{\sqrt{2}}{v} \bar{\nu}_i (\xi_A^\ell)_{ij} m_j^\ell P_R \ell_j H^+ + h.c.\,, \qquad (3)
\end{aligned}
$$

- To get naturally small **FCNCs**, one can use the ansatz formulated by: $\tilde{Y}_{ij} \propto \sqrt{m_i m_j}/v\, \chi_{ij}$

ϕ	$(\xi_\phi^u)_{ij}$	$(\xi_\phi^d)_{ij}$	$(\xi_\phi^\ell)_{ij}$
h	$\frac{c_\alpha}{s_\beta}\delta_{ij} - \frac{c_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
H	$\frac{s_\alpha}{s_\beta}\delta_{ij} + \frac{s_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
A	$\frac{1}{t_\beta}\delta_{ij} - \frac{1}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$

In the Higgs-basis the alignment limit is most clearly exhibited :

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \Phi_1 \cos\beta + \Phi_2 \sin\beta, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv -\Phi_1 \sin\beta + \Phi_2 \cos\beta$$

$$H_1 = \begin{pmatrix} G^+ \\ \left(v + S_1 + iG^0\right)/\sqrt{2} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \left(S_2 + iS_3\right)/\sqrt{2} \end{pmatrix}$$

The 2 physical Higgs states h et H are as follows:

$$H = \left(\sqrt{2}\mathrm{Re}H_1^0 - v\right)\cos(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \sin(\beta-\alpha) \tag{4}$$

$$h = \left(\sqrt{2}\mathrm{Re}H_1^0 - v\right)\sin(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \cos(\beta-\alpha) \tag{5}$$

- $\cos(\beta-\alpha) \to 0$, $h \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 92 (2015) no.7, 075004): Inverted hierarchy
- $\sin(\beta-\alpha) \to 0$, $H \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 93 (2016) no.3, 035027): Standard hierarchy

CONSTRAINTS & PARAMETER SCAN

Theoretical

- **Unitarity** constraints require a variety of scattering process to be unitary: specifically, the tree-level 2-to-2 body scattering matrix involving scalar-scalar, gauge–gauge and/or scalar-gauge initial and/or final states must have eigenvalues e_i's such that $|e_i| < 8\pi$.
- **Perturbativity** constraints impose the following condition on the quartic couplings of the scalar potential:$|\lambda_i| < 8\pi$
- **Vacuum stability** constraints require the potential be bounded from below and positive in any direction of the fields Φ_i, consequently, the parameter space must satisfy the following conditions:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

2HDMC-1.8.0 (D. Eriksson, J. Rathsman and O. Stal [0902.0851])

Experimental

- **EWPOs**, implemented through the EW oblique parameters S, T, we require $\Delta\chi^2(S,\ T) \leq 6.18$.
- **SM-like Higgs boson discovery**: an agreement between selected points in parameter space and the current measurements of the properties of the discovered Higgs boson at 125 GeV is enforced by means of the publicly available code HiggsSignals-3 via HiggsTools[2210.09332] (P. Bechtle et al).
- **Non-SM-like Higgs boson exclusions**: to check the parameter space points against the exclusion limits from null Higgs boson searches at LEP, Tevatron and, in particular, the LHC, we apply the public code HiggsBounds-6 via HiggsTools (P. Bechtle et al).
- **B-physics observables** are tested against data by resorting to the public code SuperIso_v4.1 (F. Mahmoudi [0808.3144]), (mainly $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).

- A systematic random scan covered the following parameters:

m_h	m_H	m_A	$m_{H^\pm}$	$s_{\beta-\alpha}$	$\tan\beta$	m_{12}^2	$\chi_{ij}^{f,\ell}$
[94; 97]	125.09	[80; 300]	[160; 300]	[−0.5; 0.5]	[1; 30]	$m_h^2 \tan\beta/(1+\tan^2\beta)$	[−3; 3]

Numerical results

2HDM TYPE-III INTERPRETATION

$\gamma\gamma - \tau\tau$

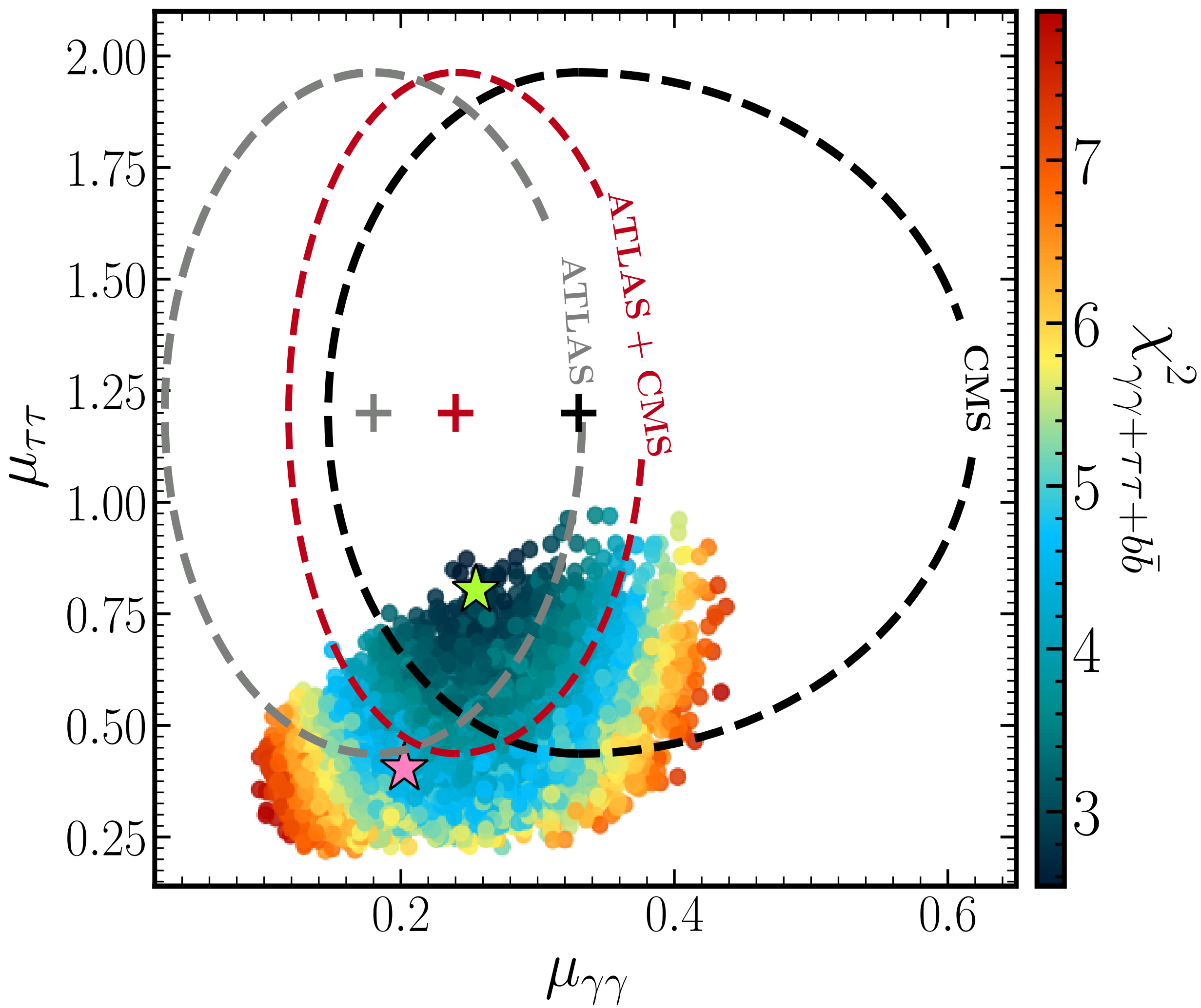
$$\Delta\chi^2_{125} \leq 5.99$$

- - - - 1σ C.L. for χ^2_{x+y}

+ $\mu^{exp}_{\gamma\gamma,\tau\tau}$

★ $\min(\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}})$

★ $\min(\chi^2_{125})$



$\gamma\gamma - b\bar{b}$

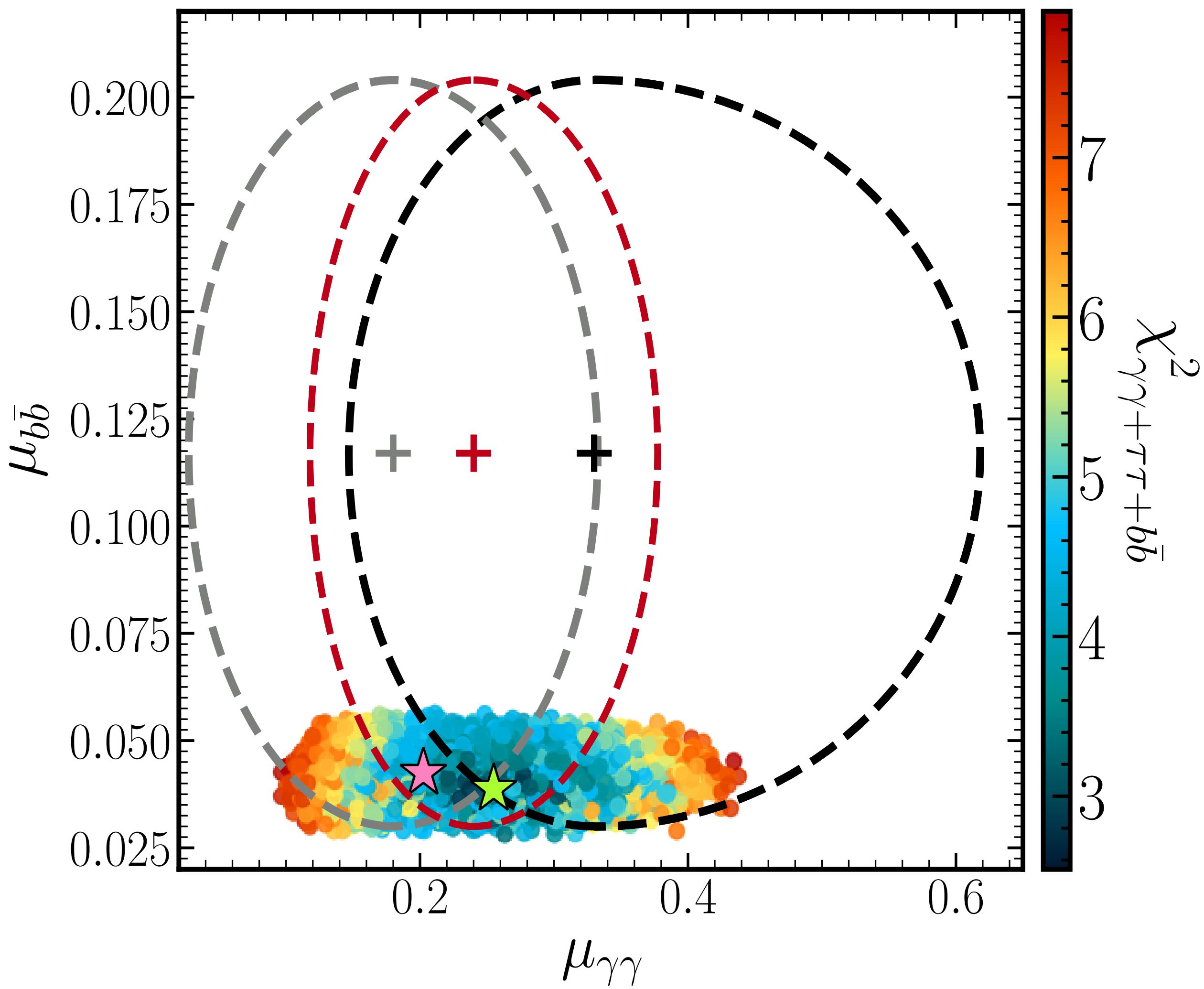
$\Delta\chi^2_{125} \leq 5.99$

- - - - 1σ C.L. for χ^2_{x+y}

+ $\mu^{exp}_{\gamma\gamma,\tau\tau}$

☆ $\min(\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}})$

☆ $\min(\chi^2_{125})$



$b\bar{b} - \tau\tau$

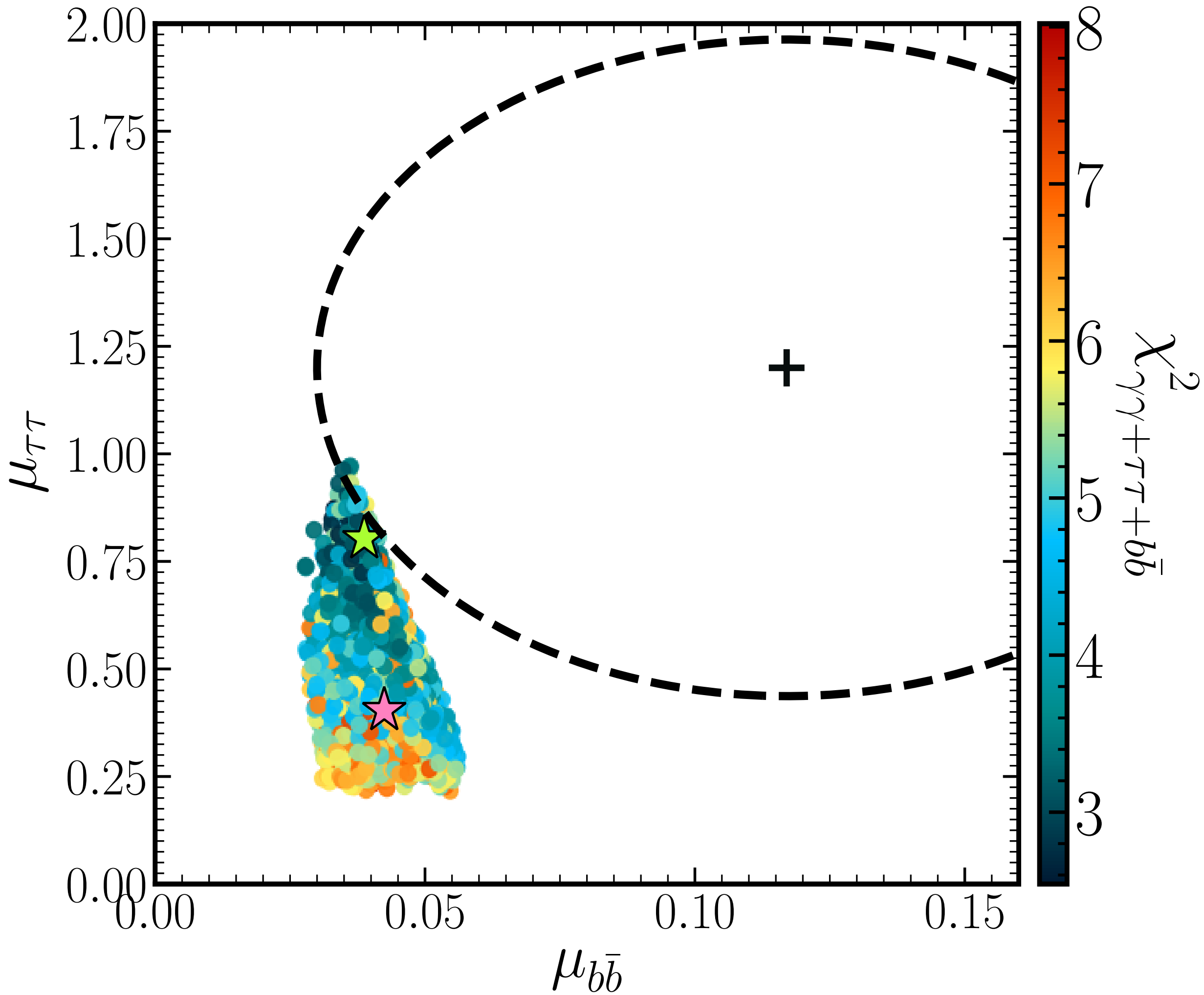
$\Delta\chi^2_{125} \leq 5.99$

- - - - 1σ C.L. for χ^2_{x+y}

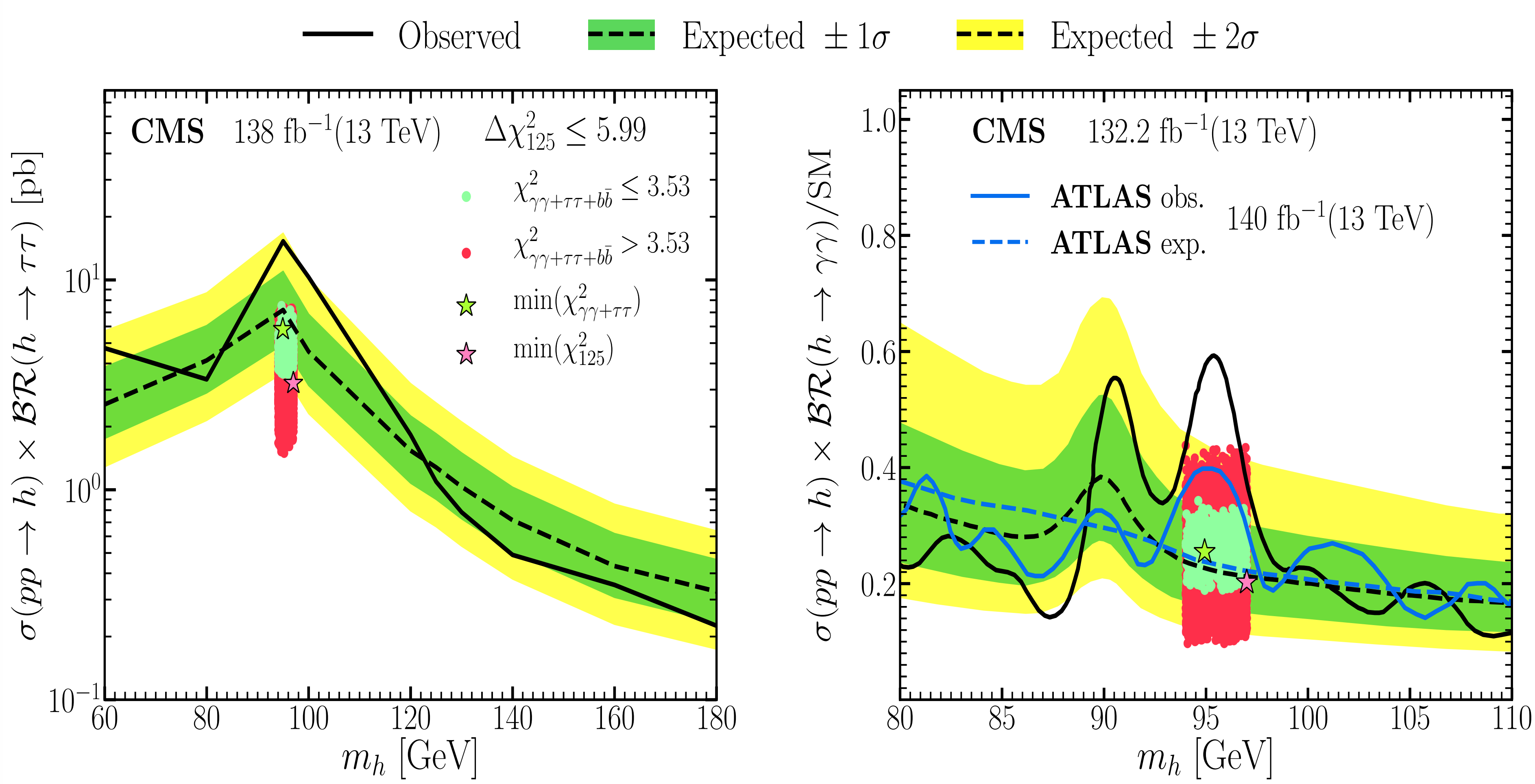
+ $\mu^{\mathrm{exp}}_{\gamma\gamma,\tau\tau}$

☆ $\min(\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}})$

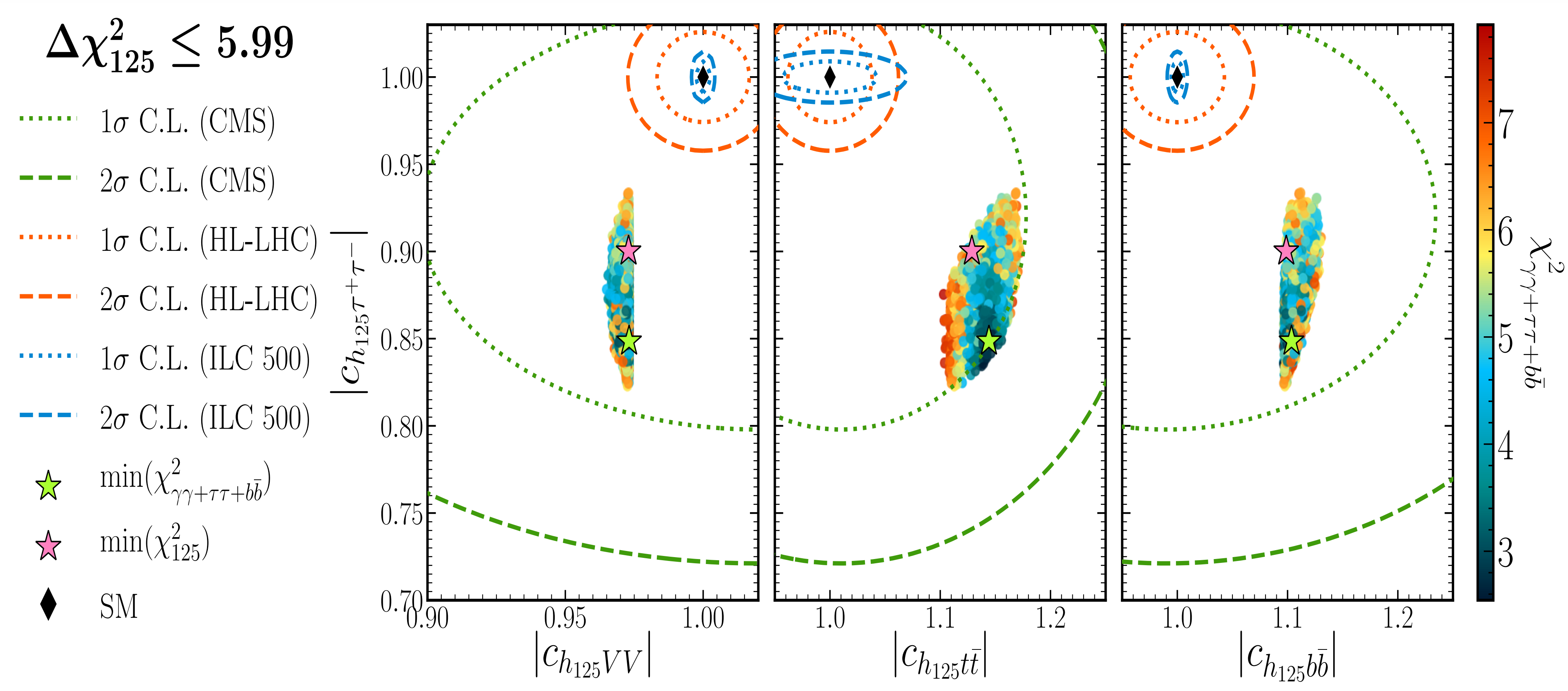
☆ $\min(\chi^2_{125})$



2HDM TYPE-III INTERPRETATION



2HDM TYPE-III INTERPRETATION

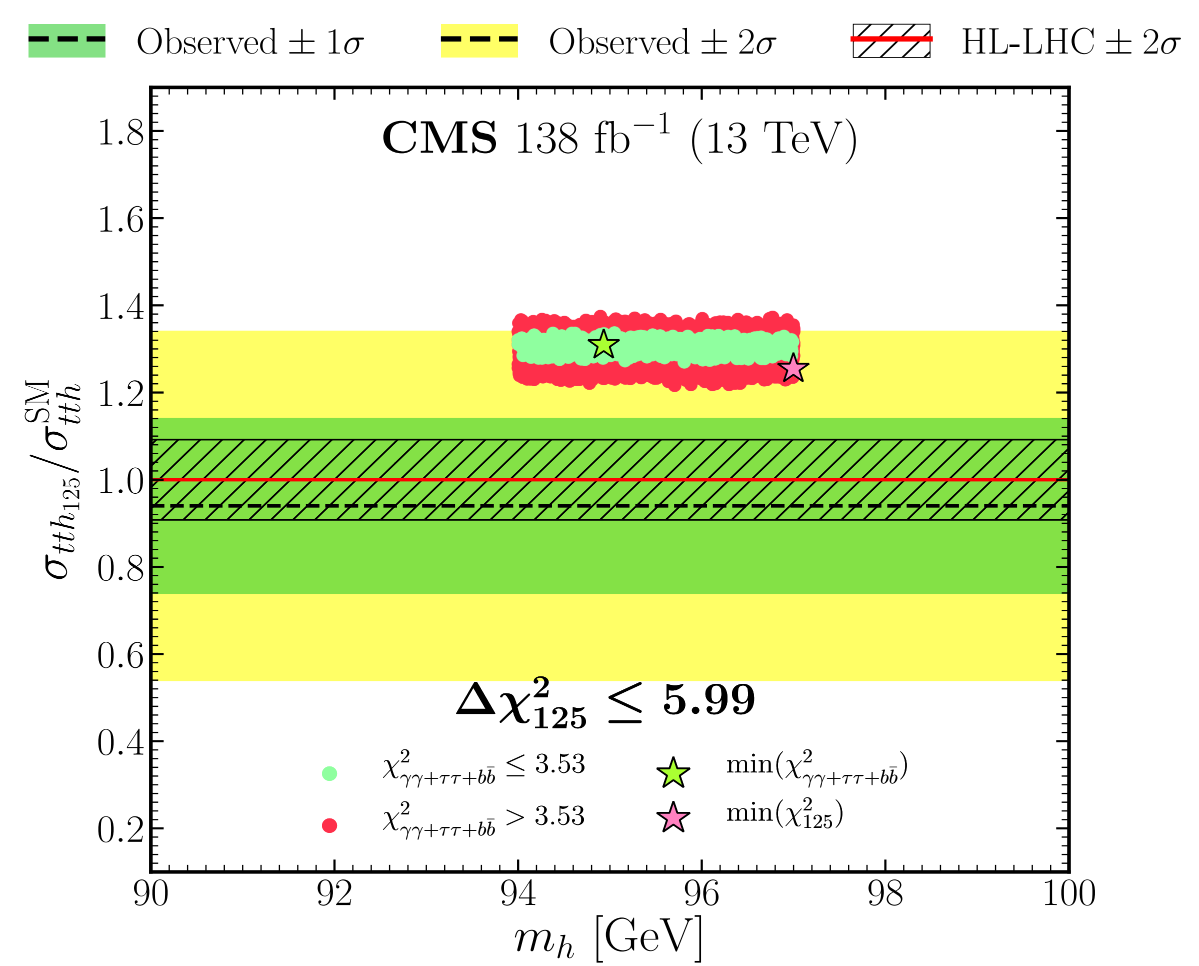


CONCLUSION

- Three distinct local excesses ($\gamma\gamma$: 2.9σ, $\tau\tau$: 2.6σ, $b\bar{b}$: 2σ) coincide at a mass of around 95 GeV.
- The generic 2HDM type III can accommodate the three excesses simultaneously.
- The explanation of the excesses requires an enhancement of the $c_{h_{125}t\bar{t}}$ and $c_{h_{125}b\bar{b}}$ couplings.

Thanks!

Back-up



Observed ± 1σ
Observed ± 2σ
HL-LHC ± 2σ
CMS 138 fb^{-1} (13 TeV)
$\Delta\chi^2_{125} \leq 5.99$
$\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}} \leq 3.53$
$\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}} > 3.53$
min($\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}}$)
min(χ^2_{125})
$\sigma_{tth_{125}}/\sigma^{SM}_{tth}$
m_h [GeV]