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A 95 GeV Higgs boson within a 2-Higgs Doublet Model

BASED ON : JHEP 05 (2024) 209

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Outline

- Introduction
- Evidence for a light Higgs boson
- Possible model interpretation
- Future prospects
- Conclusion

Introduction

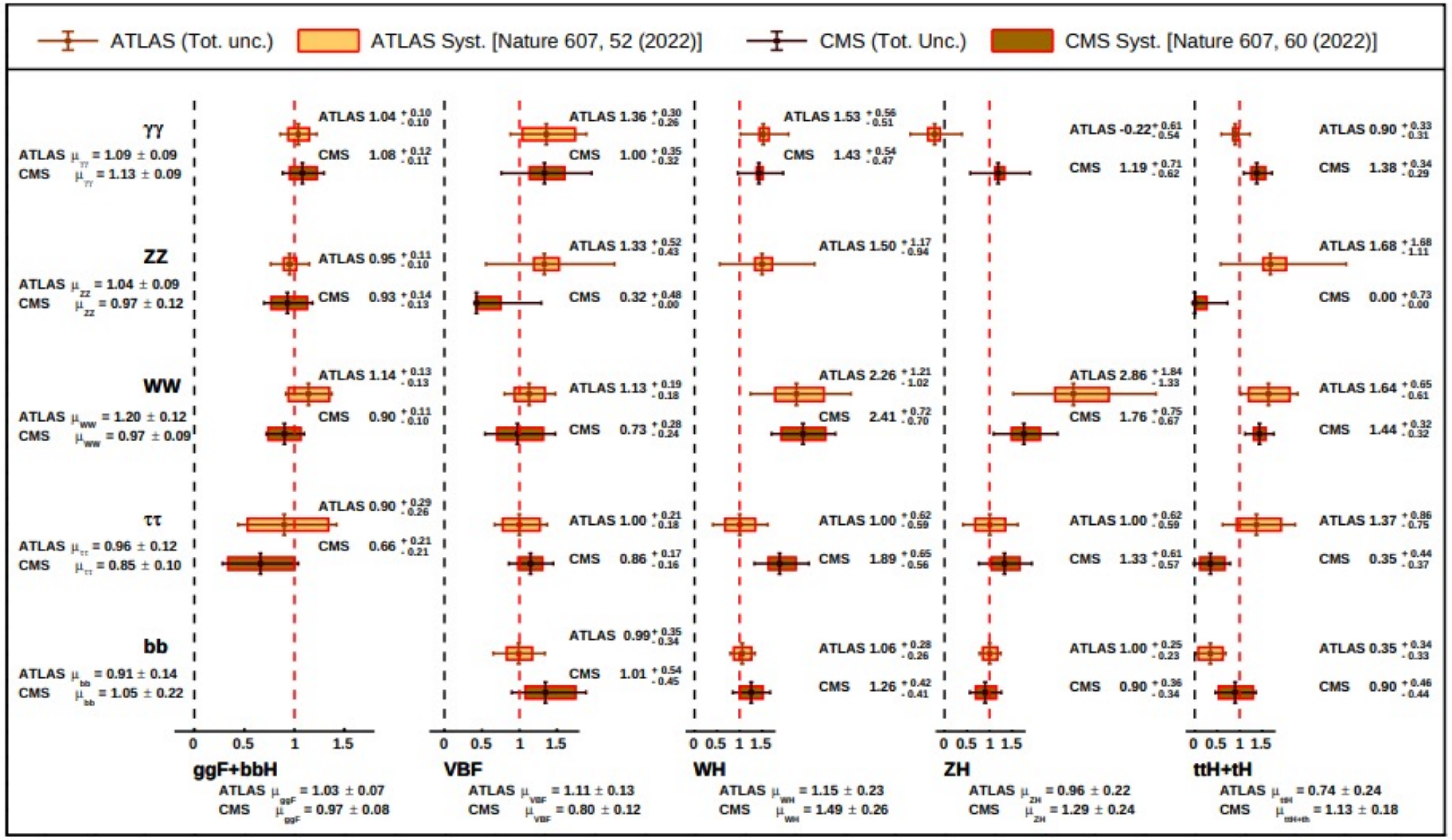
- 125 GeV Higgs properties are consistent with SM

- More scalars to come ?

- Where to look ?

  - Above and Below 125 GeV

$\sigma\,.\,BR$ (Normalised to SM)

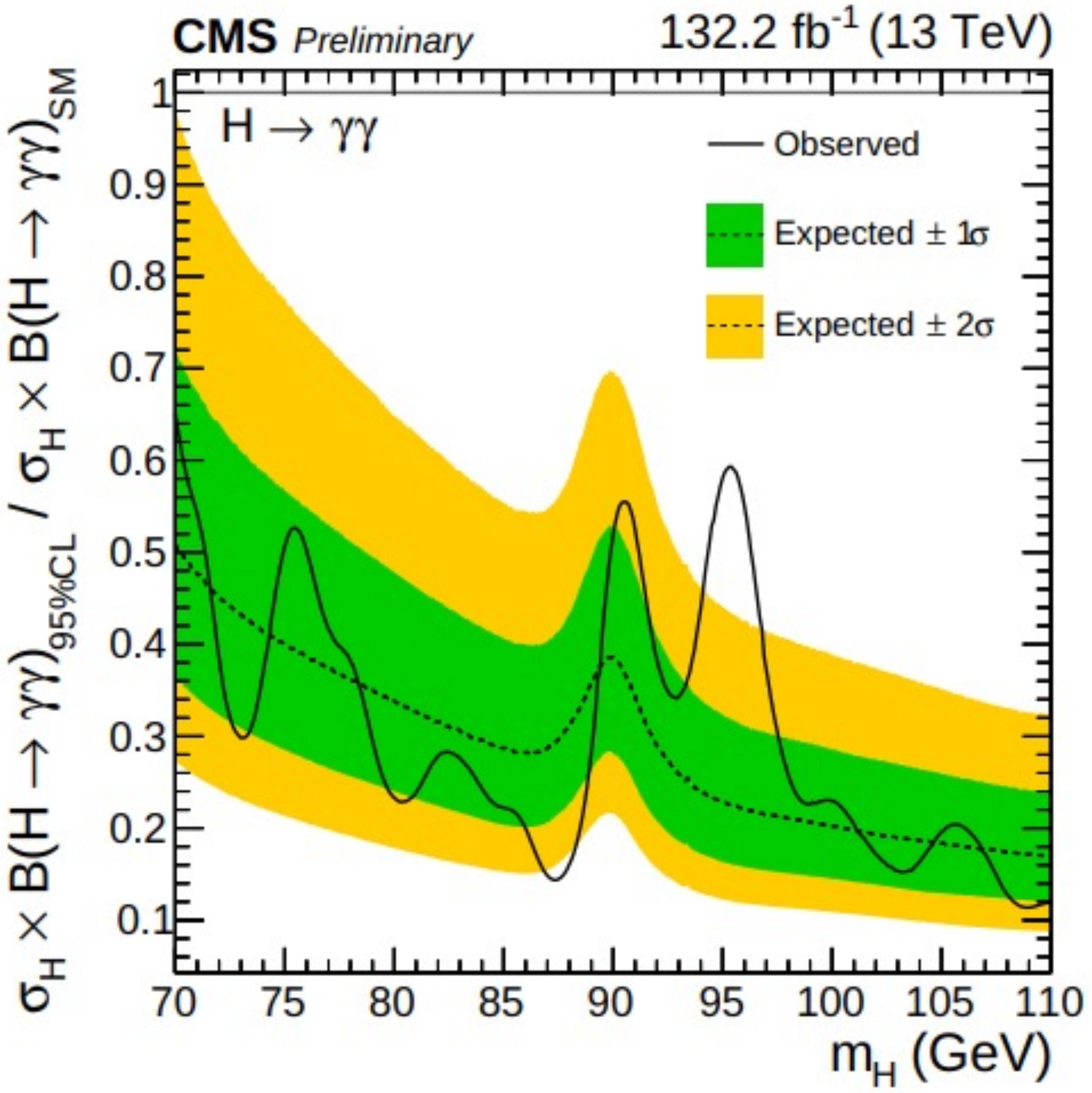


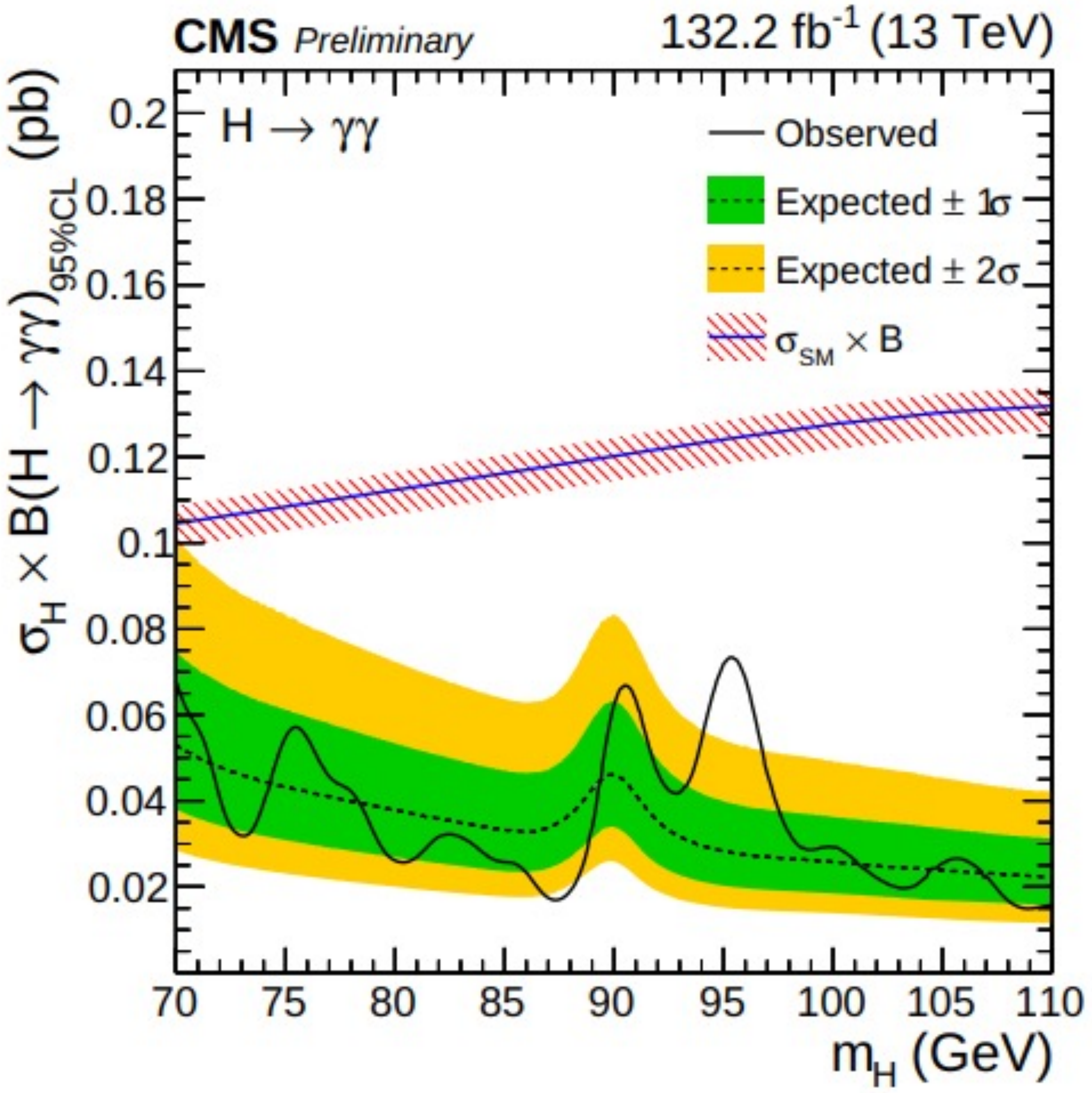
PDG 2023

Motivation - I

"Excess" at ~ 95.4 GeV with local (global) significance ~ 2.9 (1.3) σ

CMS-PAS-HIG-20-002

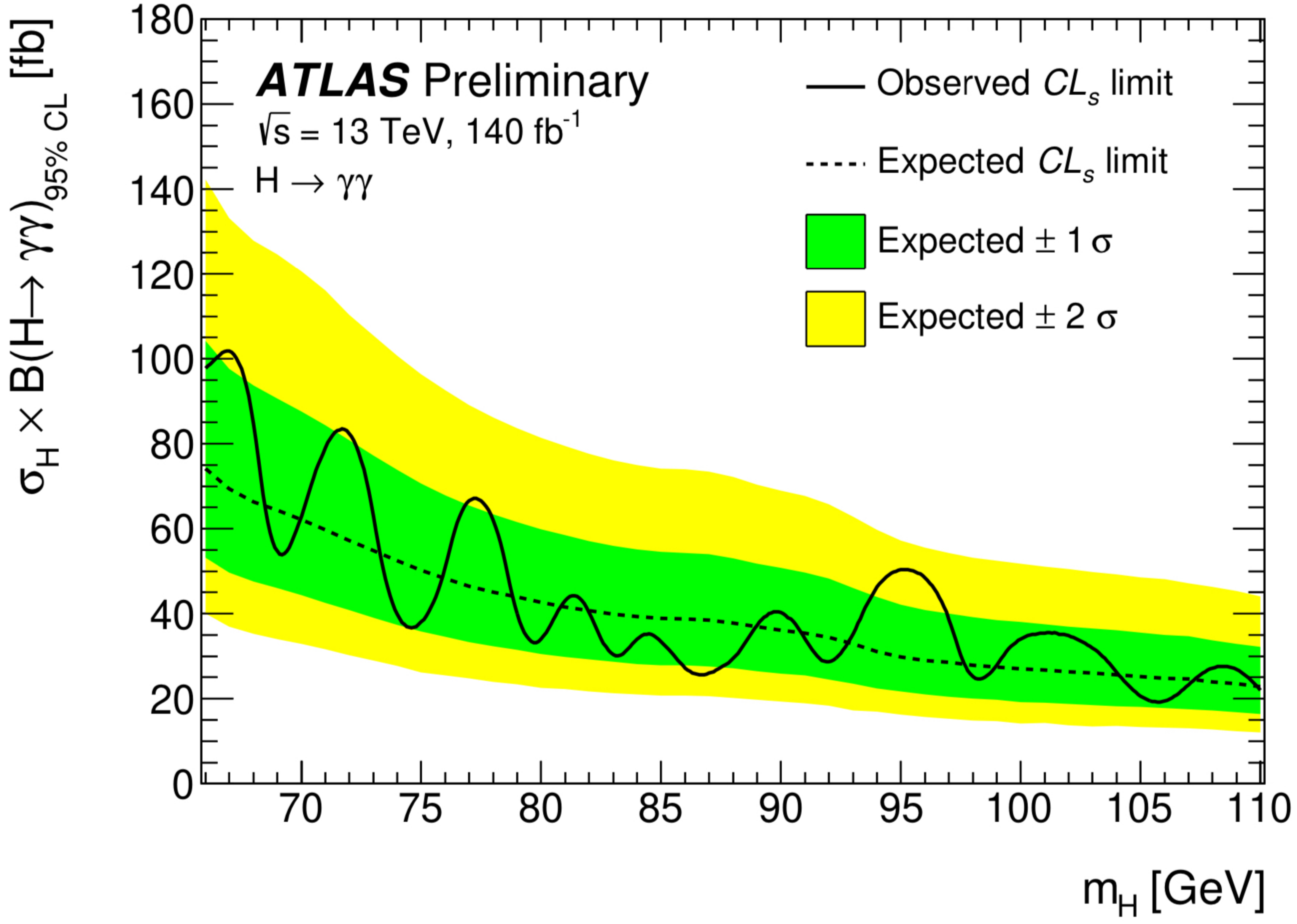




$$\mu_{\gamma\gamma}^{\rm CMS} = \frac{\sigma^{\rm exp}(pp \to \phi \to \gamma\gamma)}{\sigma^{\rm SM}(pp \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

Motivation - II : ATLAS results

A scan over different m_X hypotheses is performed in the range 66 to 110GeV.



Small "excess" at ~95 GeV with local ~ 1.7 σ

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

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

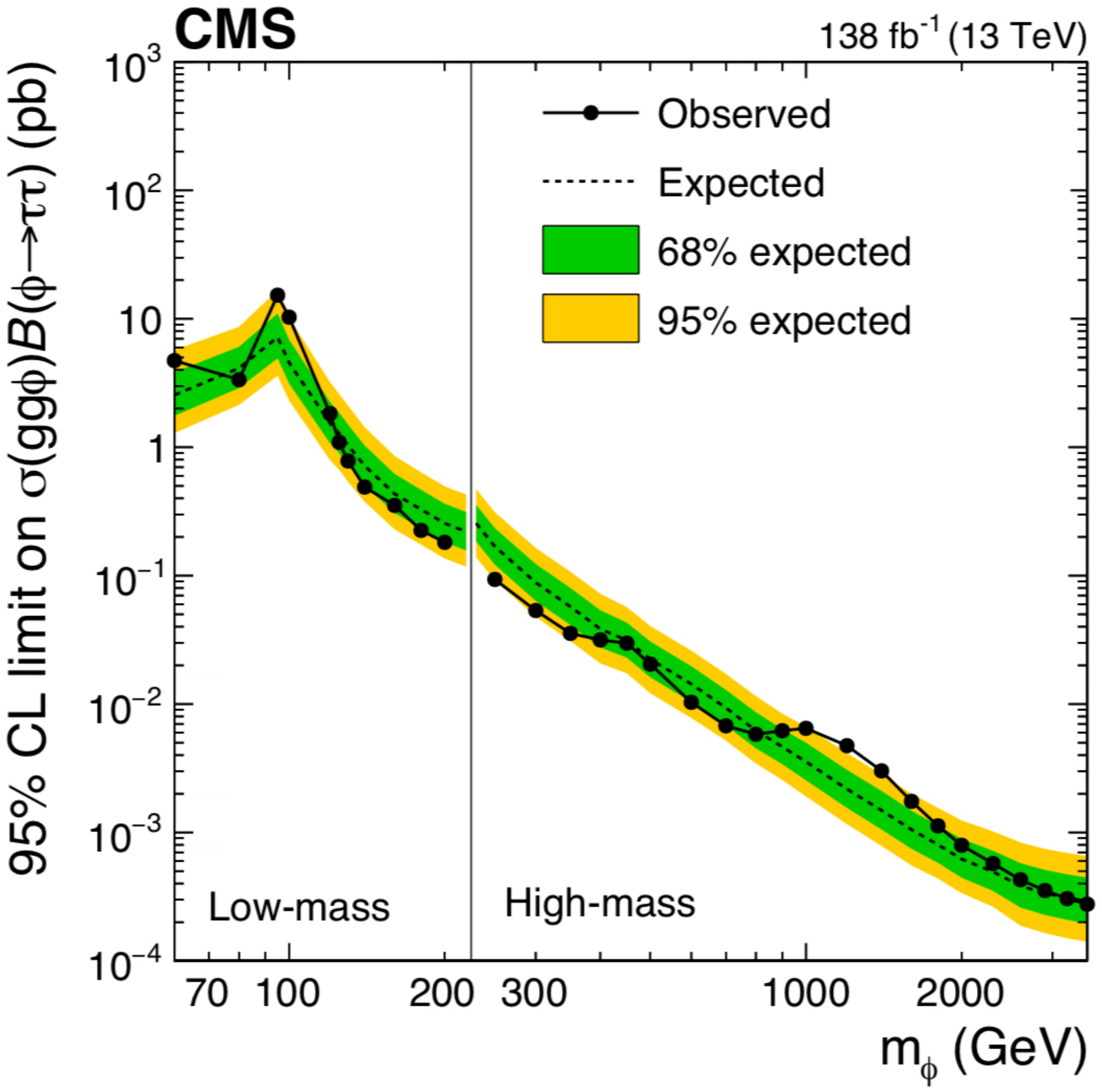
[T. Biekotter, S. Heinemeyer, G. Weiglein 2306.03889]

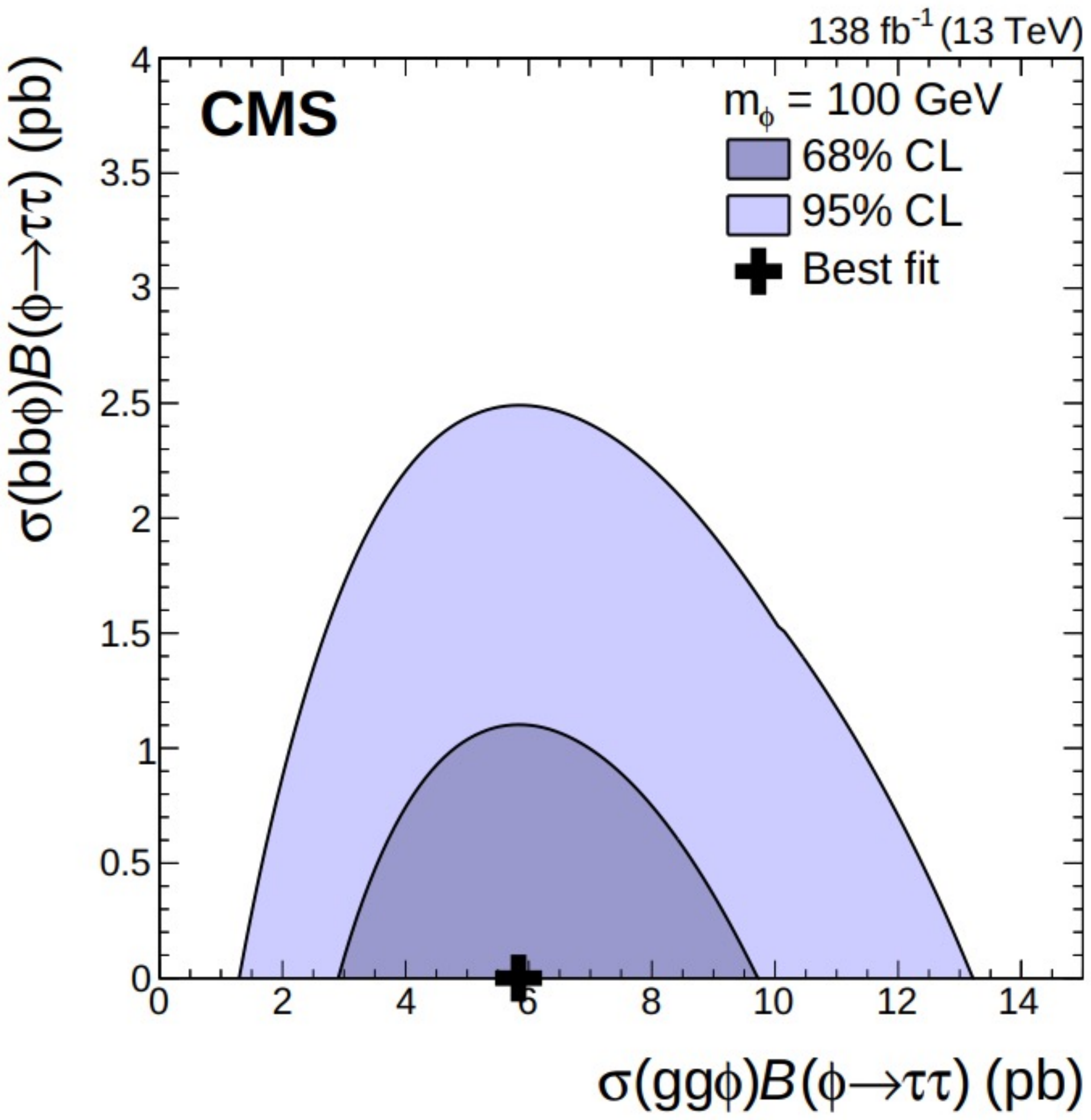
- https://indico.cern.ch/event/1281604/attachments/2660420/4608571/LHCSeminarArcangeletti_final.pdf

Motivation - III

- Excess at ~100 GeV with local ~ $3\,\sigma$

CMS 2208.02717



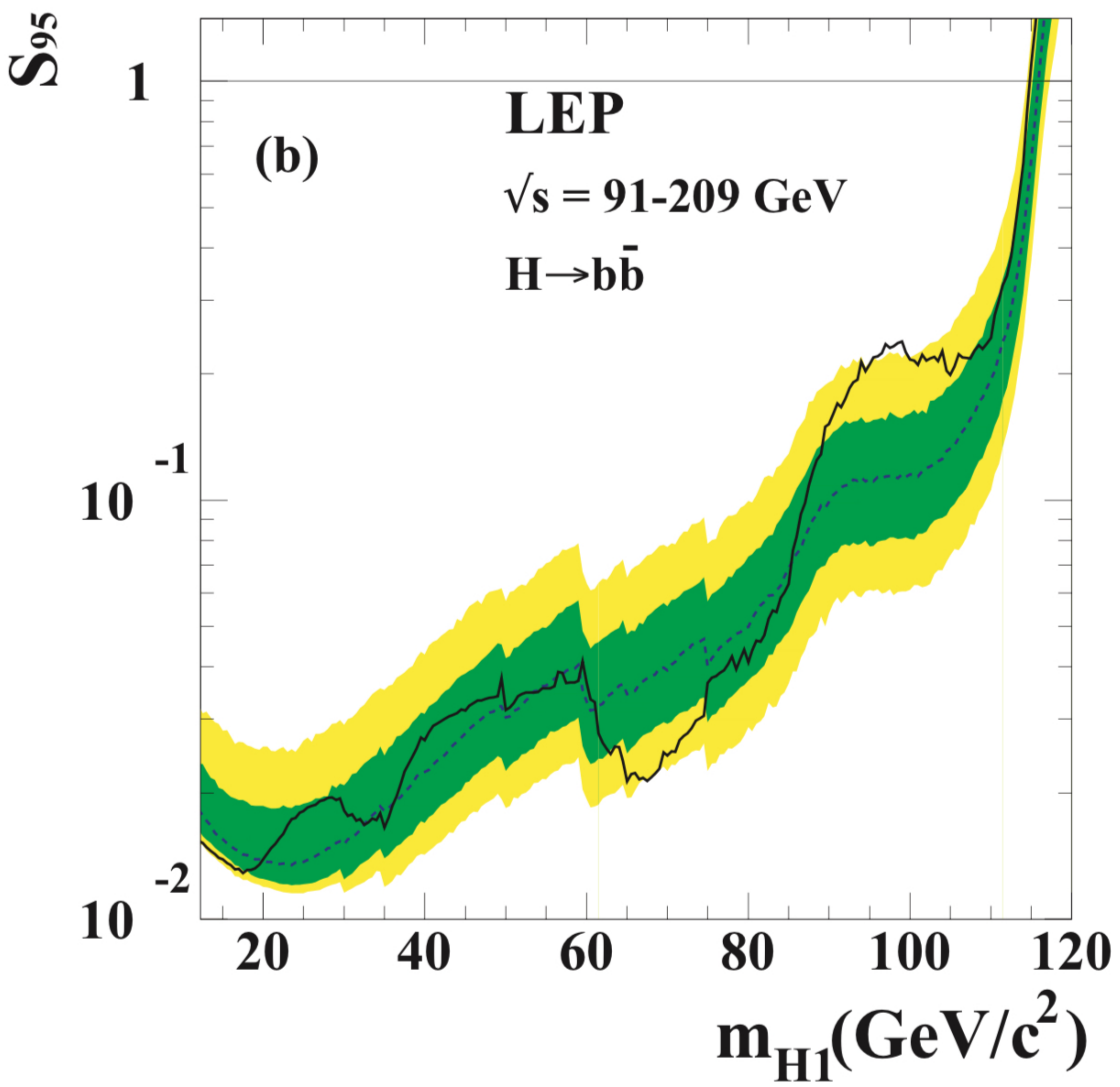


$$\mu_{\tau\tau}^{\rm exp} = \frac{\sigma^{\rm exp}(gg \to \phi \to \tau^+\tau^-)}{\sigma^{\rm SM}(gg \to H \to \tau^+\tau^-)} = 1.2 \pm 0.5$$

Evidence - IV

LEP hep-ex/ 0602042, 0306033

"Excess" at ~98 GeV with local ~ 2.3 σ



Particle with production cross section ~10% of the SM

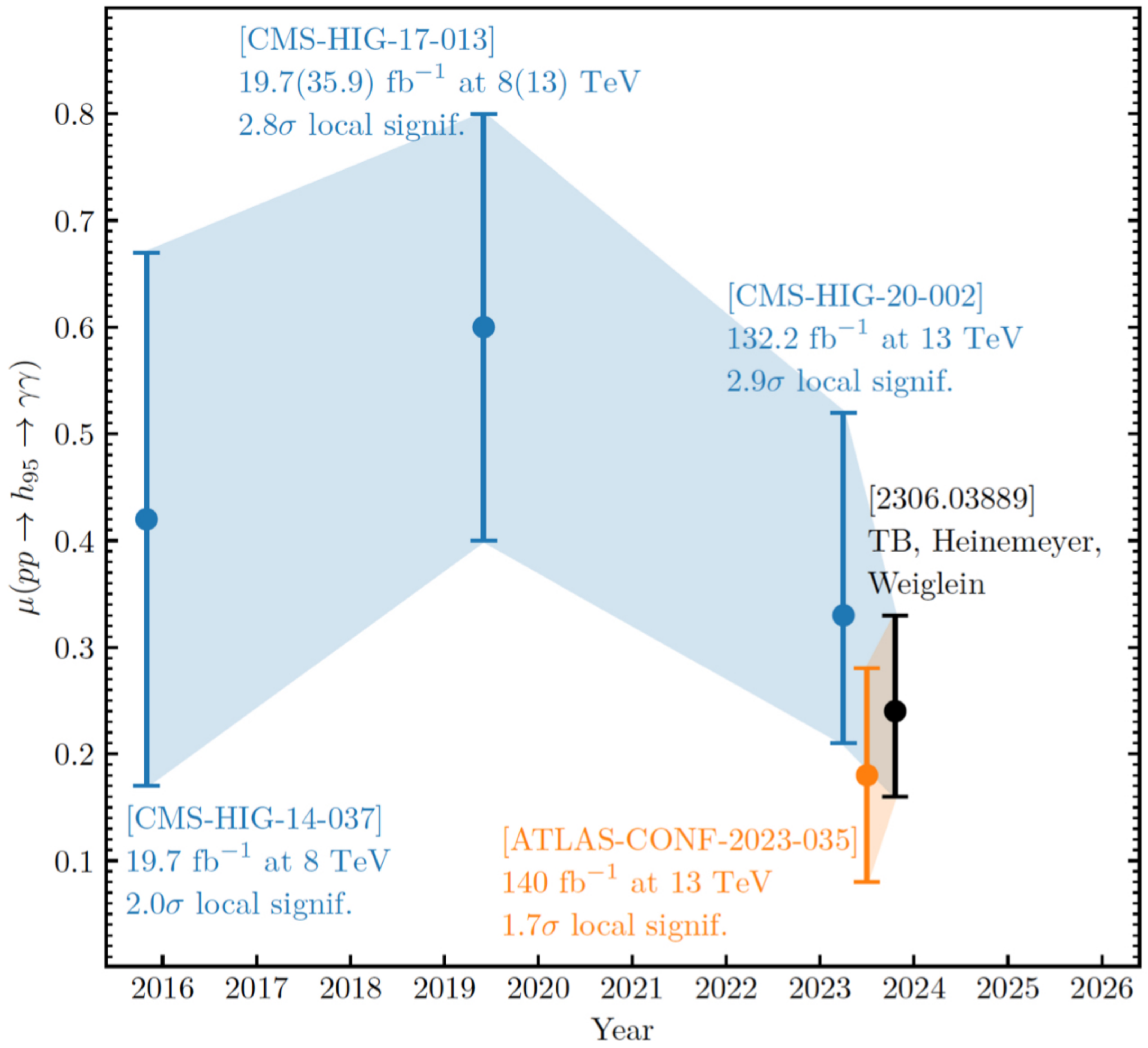
→ Suppressed VV coupling

Same origin ?

$$\mu_{bb}^{\text{exp}} = \frac{\sigma^{\text{exp}}\left(e^+e^- \to Z\phi \to Zb\bar{b}\right)}{\sigma^{\text{SM}}\left(e^+e^- \to ZH \to Zb\bar{b}\right)} = 0.117 \pm 0.057$$

arXiv : 1612.08522

Diphoton over time



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

Heinemeyer SUSY'24

2HDM

The most general scalar potential of the 2HDM :

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

- CP conserving scenario : 10 free parameters $m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_{1,\ldots,7}$

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

- Minimization conditions and $v_1^2 + v_2^2 = v^2$ $m_h,\quad m_H,\quad m_A,\quad m_{H^\pm},\quad \sin(\beta-\alpha),\quad \tan\beta,\quad m_{12}^2$

- Physical states : h, H (CP-even), A (CP-odd), $H^\pm$ (Charged)

2HDM

$$\mathcal{L}_{\rm Yukawa}^{\rm 2HDM} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - i\xi_A^f \overline{f}\gamma_5 f A\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u\xi_A^u \mathrm{P}_L + m_d\xi_A^d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2}m_\ell \xi_A^\ell}{v}\,\overline{\nu_L}\ell_R H^+ + \mathrm{H.c.}\right\}$$

Discreet Z_2 to forbid tree FCNC

$\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
(lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

Allowed fermion couplings

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

Requirements to fit excesses

$m_h = 95\ GeV \quad m_H = 125\ GeV$

c_{hVV} ▫ must be strongly suppressed

$\mu_{b\bar{b}}^{\rm exp} = 0.117 \pm 0.057$

$c_{hb\bar{b}}$ ▫ must be suppressed to enhance $BR(h \to \gamma\gamma)$

$\mu_{\gamma\gamma}^{\rm exp} = \mu_{\gamma\gamma}^{\rm ATLAS+CMS} = 0.24^{+0.09}_{-0.08}$

$c_{ht\bar{t}}$ ▫ must not be strongly suppressed

$c_{h\tau\bar{\tau}}$ ▫ must not be suppressed

$\mu_{\tau\tau}^{\rm exp} = 1.2 \pm 0.5$

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

▫ Type-II and flipped : tension between STU parameter measurements and $b \to s\gamma$

Azevedo, Biekotter, Ferreira '23

Type-III 2HDM

$$
\begin{aligned}
-\mathcal{L}_Y &= \bar{Q}_L Y_1^u U_R \tilde{\Phi}_1 + \bar{Q}_L Y_2^u U_R \tilde{\Phi}_2 + \bar{Q}_L Y_1^d D_R \Phi_1 + \bar{Q}_L Y_2^d D_R \Phi_2 \\
&+ \bar{L} Y_1^\ell \ell_R \Phi_1 + \bar{L} Y_2^\ell \ell_R \Phi_2 + \mathrm{H.c.},
\end{aligned}
$$

- Generic Yukawa couplings, no discreet symmetry

- Specific Yukawa texture : Must reproduce observed fermion masses and mixings

$$
M_l = \begin{pmatrix} 0 & C_l & 0 \\ C_l^* & 0 & B_l \\ 0 & B_l^* & A_l \end{pmatrix}
\qquad A_l \simeq m_3,\ B_l \simeq \sqrt{m_2 m_3} \text{ and } C_l \simeq \sqrt{m_1 m_2}
$$

- FCNC effects $\sim \sqrt{m_i m_j}/m_W$ **Cheng, Sher PRD'1987**

See Hernandez-Sanchez, Moretti, Noriega-Papaqui, Rosado 1212.6818

Type-III 2HDM

After EWSB

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

Type-III 2HDM Yukawa couplings

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	$\frac{1}{t_\beta}\delta_{ij} - \frac{1}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$

- Free parameters $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \sin(\beta-\alpha),\ \tan\beta,\ m_{12}^2,\ \chi_{ij}$

Explaining the excesses

$m_h = 95\ GeV \quad m_H = 125\ GeV$

$$\mu_{b\bar{b}} = \frac{\sigma_{2\text{HDM}}(e^+e^- \to Z\phi)}{\sigma_{\text{SM}}(e^+e^- \to Zh_{\text{SM}})} \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to b\bar{b})}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to b\bar{b})} = |c_{\phi ZZ}|^2 \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to b\bar{b})}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to b\bar{b})}$$

$$\mu_{\tau\tau} = \frac{\sigma_{2\text{HDM}}(gg \to \phi)}{\sigma_{\text{SM}}(gg \to h_{\text{SM}})} \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to \tau\tau)}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to \tau\tau)} = |c_{\phi tt}|^2 \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to \tau\tau)}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to \tau\tau)}$$

$$\mu_{\gamma\gamma} = \frac{\sigma_{2\text{HDM}}(gg \to \phi)}{\sigma_{\text{SM}}(gg \to h_{\text{SM}})} \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to \gamma\gamma)}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to \gamma\gamma)} = |c_{\phi tt}|^2 \times \frac{\mathcal{BR}_{2\text{HDM}}(\phi \to \gamma\gamma)}{\mathcal{BR}_{\text{SM}}(h_{\text{SM}} \to \gamma\gamma)}$$

$$\chi^2_{\gamma\gamma,\tau\tau,b\bar{b}} = \frac{\left(\mu_{\gamma\gamma,\tau\tau,b\bar{b}} - \mu^{\text{exp}}_{\gamma\gamma,\tau\tau,b\bar{b}}\right)^2}{\left(\Delta\mu^{\text{exp}}_{\gamma\gamma,\tau\tau,b\bar{b}}\right)^2}$$

$$\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}} = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau} + \chi^2_{b\bar{b}}$$

See Benbrik, Boukidi, Moretti 2405.02899 for CP-odd contributions

Numerical analysis

2HDMC-1.8.0

Theoretical constraints

- Unitarity : tree 2-to-2 scattering matrix eigenvalues $|e_i| < 8\pi$
- Perturbativity $|\lambda_i| < 8\pi$
- Vacuum stability

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

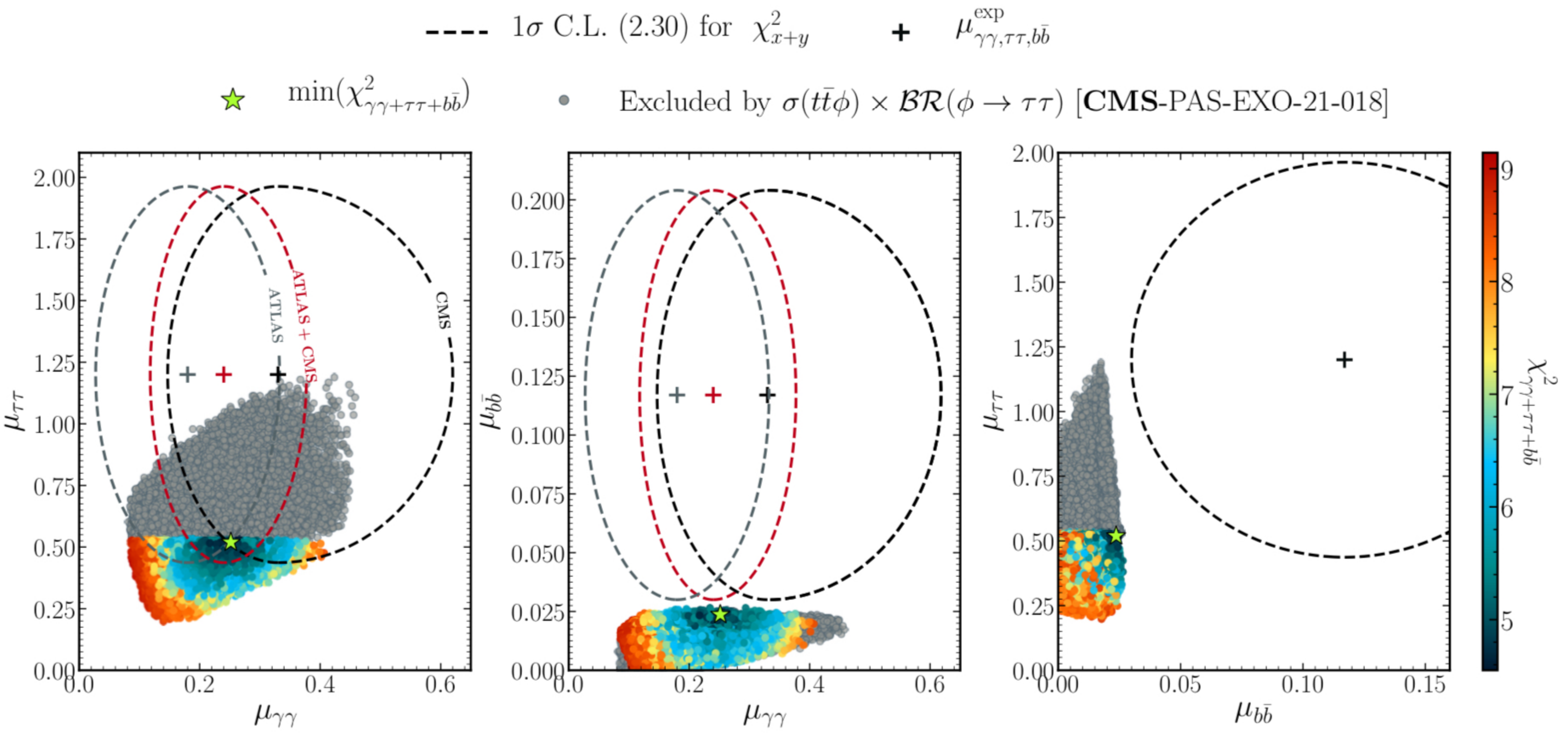
Experimental constraints

- EWPO. $S = 0.05 \pm 0.08$, $T = 0.09 \pm 0.07$, $\rho_{ST} = 0.92$ (for $U = 0$)
- SM-like Higgs boson constraints
  HiggsSignals-3 via HiggsTools
- Non-SM-like Higgs constraints
  HiggsBounds-6 via HiggsTools
- B-physics observables
  (mainly $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$)
  SuperIso_v4.1

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; 200]	[−0.5; 0]	[1; 30]	$m_h^2 \tan\beta/(1+\tan^2\beta)$	[−3; 3]

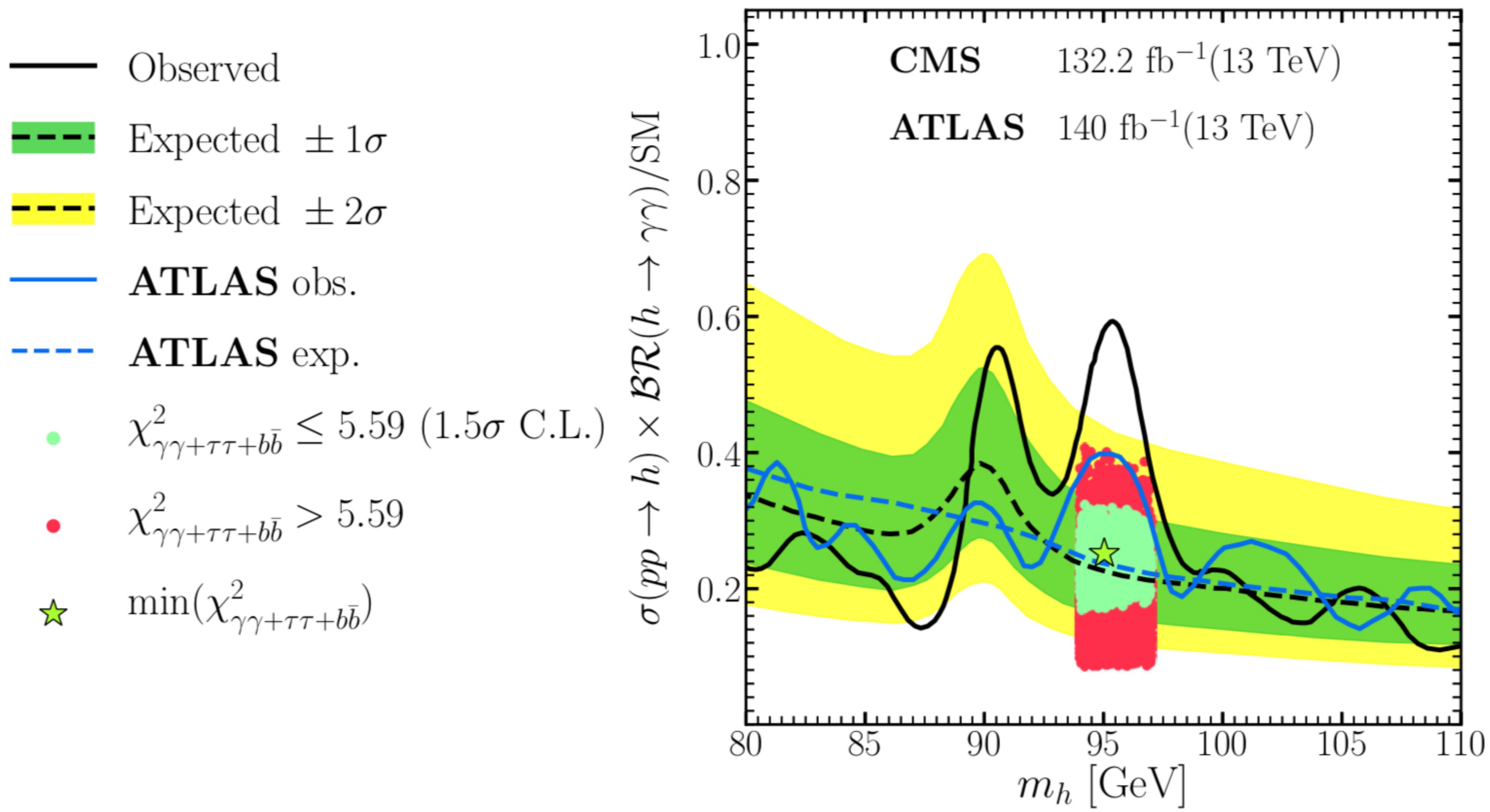
2HDM Type-III interpretation

$\chi^2_{125} \leq 189.4 \quad (159 \text{ dof})$

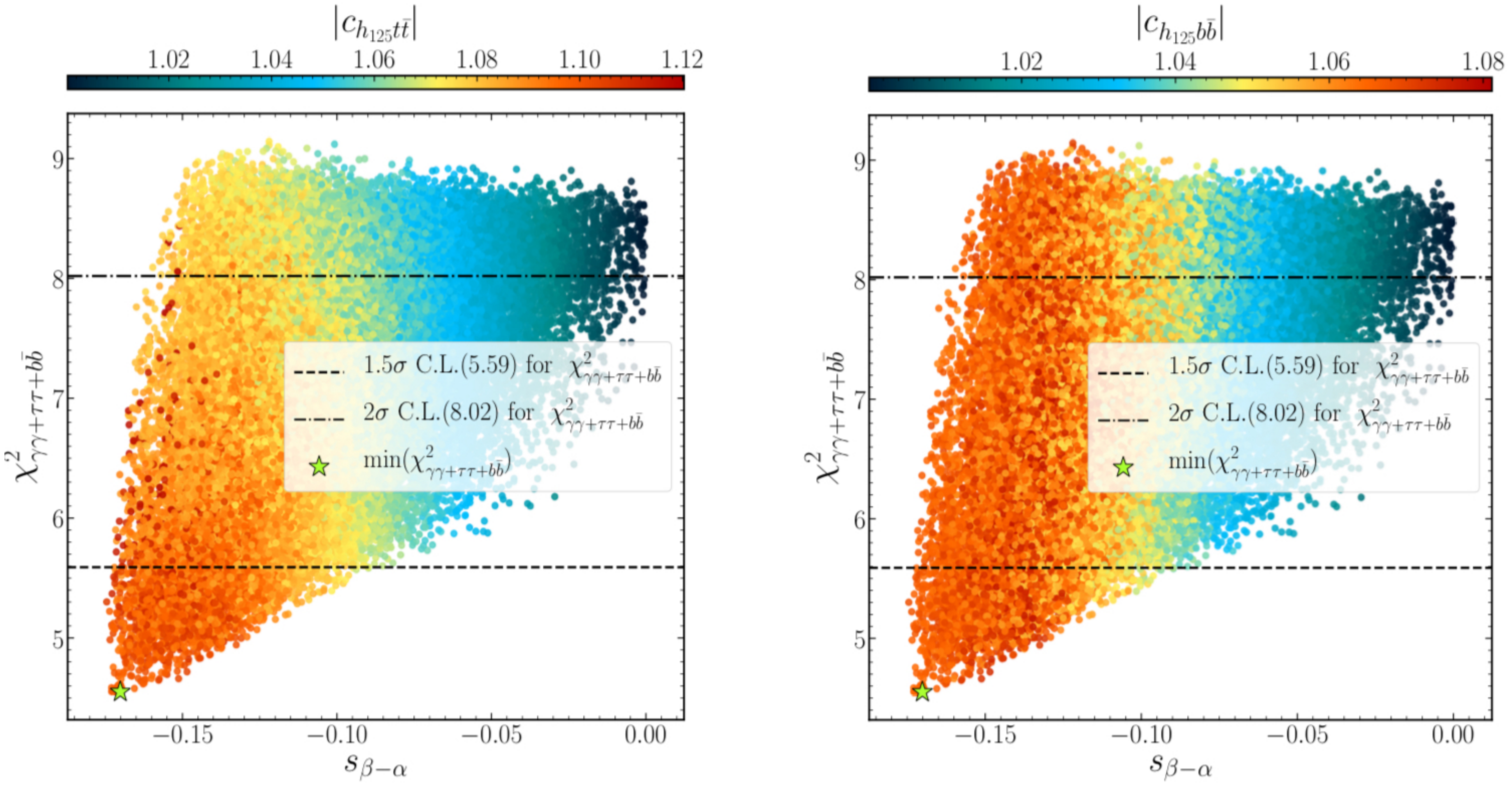


Best fit point : $\chi^2_{\gamma\gamma+\tau\tau+b\bar{b}} = 4.55 \sim 1.2\sigma$

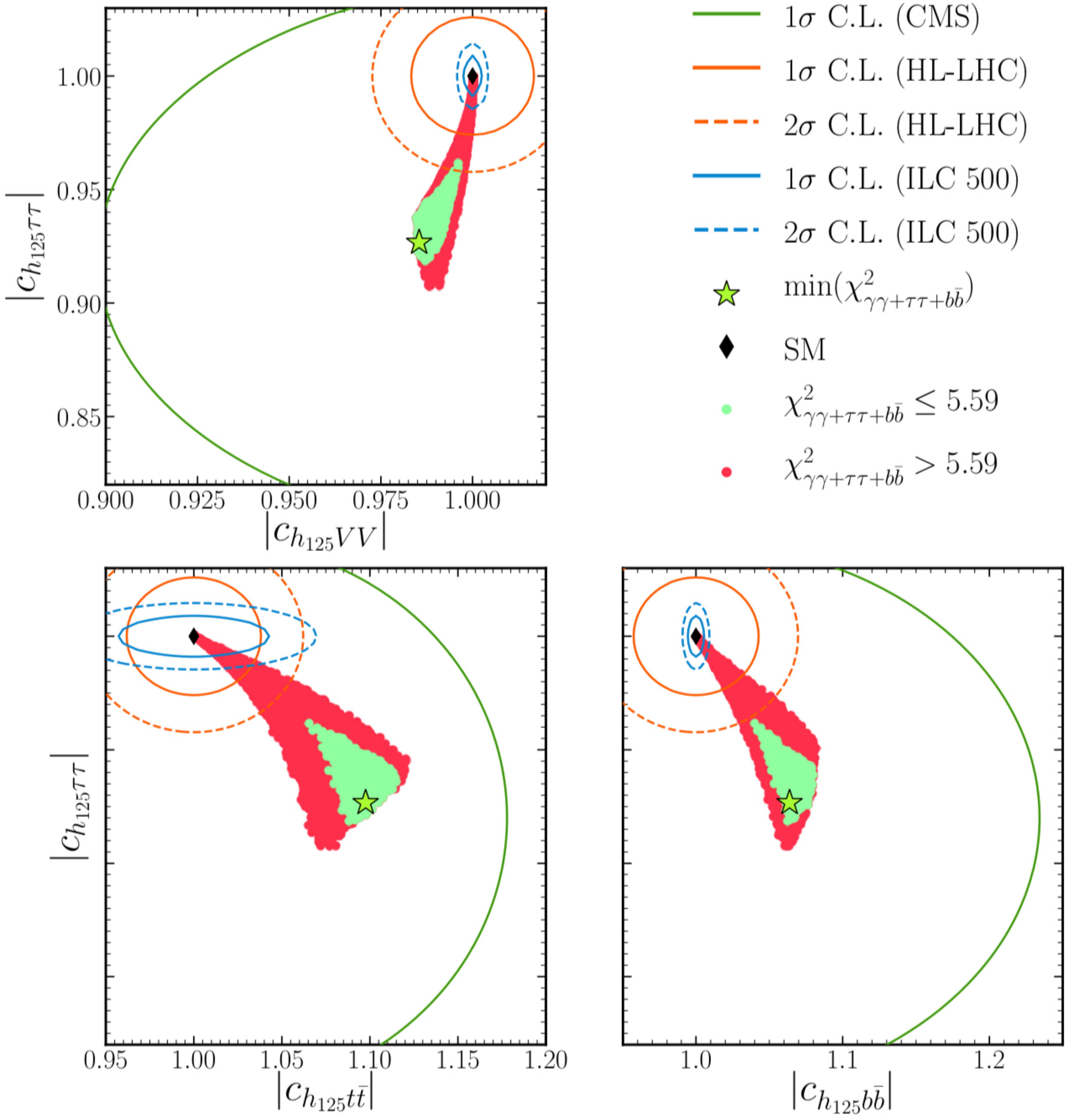
2HDM Type-III interpretation



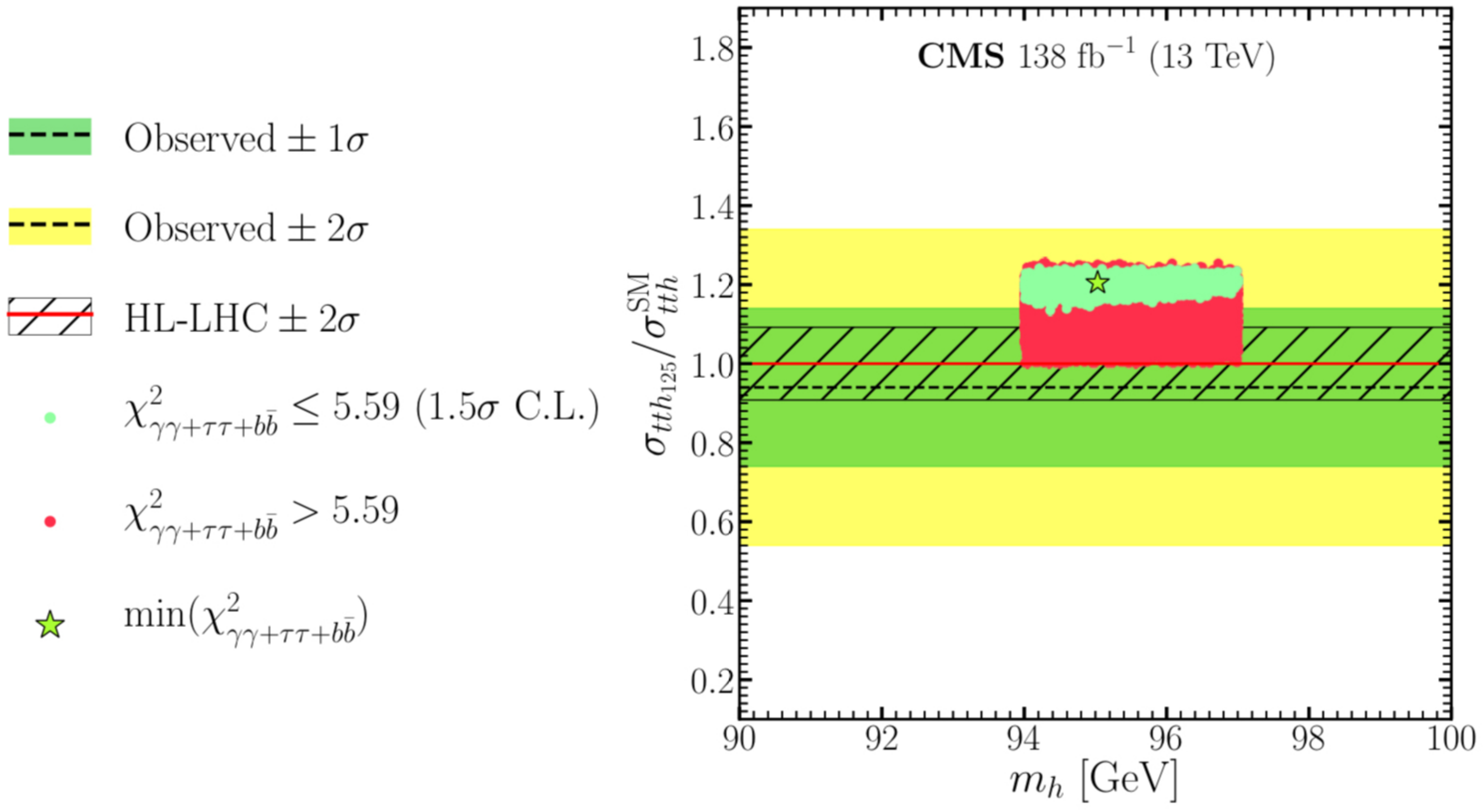
2HDM Type-III interpretation



Correlation between couplings



Testability in future colliders



Best-fit point

Parameters	★
(Masses are in GeV)	
m_h	95.03
m_H	125.09
m_A	94.77
$m_{H^\pm}$	162.95
$\tan\beta$	1.74
$\sin(\beta-\alpha)$	−0.17
χ^u_{11}	0.02
χ^u_{22}	0.54
χ^u_{33}	−0.08
χ^d_{11}	−0.41
χ^d_{22}	0.24
χ^d_{33}	1.55
χ^ℓ_{11}	−0.06
χ^ℓ_{22}	0.33
χ^ℓ_{33}	0.97
Effective coupling $c_{h_{125}i\bar{i}}$	
$c_{h_{125}t\bar{t}}$	1.10
$c_{h_{125}b\bar{b}}$	1.06
$c_{h_{125}\tau\tau}$	0.92
Collider signal strength	
$\mu_{\gamma\gamma}$	0.25
$\mu_{\tau\tau}$	0.51
$\mu_{b\bar{b}}$	0.02
Total decay width in MeV	
$\Gamma(h)$	0.27
$\Gamma(H)$	4.73
$\Gamma(A)$	0.66
$\Gamma(H^\pm)$	4.77

$\mathcal{BR}(h\to XY)$ in %	
$\mathcal{BR}(h\to\gamma\gamma)$	0.15
$\mathcal{BR}(h\to gg)$	13.82
$\mathcal{BR}(h\to b\bar{b})$	65.37
$\mathcal{BR}(h\to c\bar{c})$	—
$\mathcal{BR}(h\to s\bar{s})$	0.50
$\mathcal{BR}(h\to\mu^+\mu^-)$	0.67
$\mathcal{BR}(h\to\tau\tau)$	19.33
$\mathcal{BR}(h\to ZZ)$	—
$\mathcal{BR}(h\to W^+W^-)$	0.12
$\mathcal{BR}(H\to XY)$ in %	
$\mathcal{BR}(H\to\gamma\gamma)$	0.16
$\mathcal{BR}(H\to gg)$	8.16
$\mathcal{BR}(H\to b\bar{b})$	64.08
$\mathcal{BR}(H\to c\bar{c})$	3.07
$\mathcal{BR}(H\to\tau\tau)$	4.70
$\mathcal{BR}(H\to ZZ)$	2.19
$\mathcal{BR}(H\to W^+W^-)$	17.48
$\mathcal{BR}(A\to XY)$ in %	
$\mathcal{BR}(A\to\gamma\gamma)$	0.046
$\mathcal{BR}(A\to gg)$	28.70
$\mathcal{BR}(A\to b\bar{b})$	66.95
$\mathcal{BR}(A\to c\bar{c})$	0.40
$\mathcal{BR}(A\to\mu\mu)$	0.16
$\mathcal{BR}(A\to\tau\tau)$	3.53
$\mathcal{BR}(H^\pm\to XY)$ in %	
$\mathcal{BR}(H^\pm\to cs)$	0.11
$\mathcal{BR}(H^\pm\to W^+h)$	33.79
$\mathcal{BR}(H^\pm\to W^+A)$	35.62
$\mathcal{BR}(H^\pm\to\tau\nu)$	0.84
$\mathcal{BR}(H^\pm\to tb)$	29.47

Summary

- Interesting set of anomalies around ~ 95 GeV in CMS $\gamma\gamma$, $\tau\tau$, LEP $b\bar{b}$ channels
- ATLAS $\gamma\gamma$ searches also see hints
- Same origin ?
- Type-III 2HDM offers explanation with $m_h \approx 95$ GeV and $m_H \approx 125$ GeV
- Stringent constraints on $\mu_{\tau\tau}$ from CMS $t\bar{t}h$, Zh production searches
- Precision measurement of 125 GeV Higgs couplings @ HL-LHC, ILC can be conclusive

ALIGNMENT LIMIT

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

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

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

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

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

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

- $\cos(\beta-\alpha) \to 0$, $h \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 92 (2015) no.7, 075004) ; standard 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) ; inverted hierarchy