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95 GeV Excess Theory Insight

Sven Heinemeyer, IFT (CSIC, Madrid)

Shanghai/zoom, 09/2023

1. Evidence for a light Higgs boson

2. Possible model interpretation

3. SUSY realizations

4. Physics opportunities at future e^+e^- colliders

5. Conclusions

1. Evidence for a light Higgs boson

LHC Seminar

Measurement of Higgs boson production and search for new resonances in final states with photons and Z bosons

by Chiara Arcangeletti (INFN e Laboratori Nazionali di Frascati (IT))

Tuesday 6 Jun 2023, 11:00 → 12:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

New ATLAS result on the low-mass Higgs search in $pp \to \phi \to \gamma\gamma$

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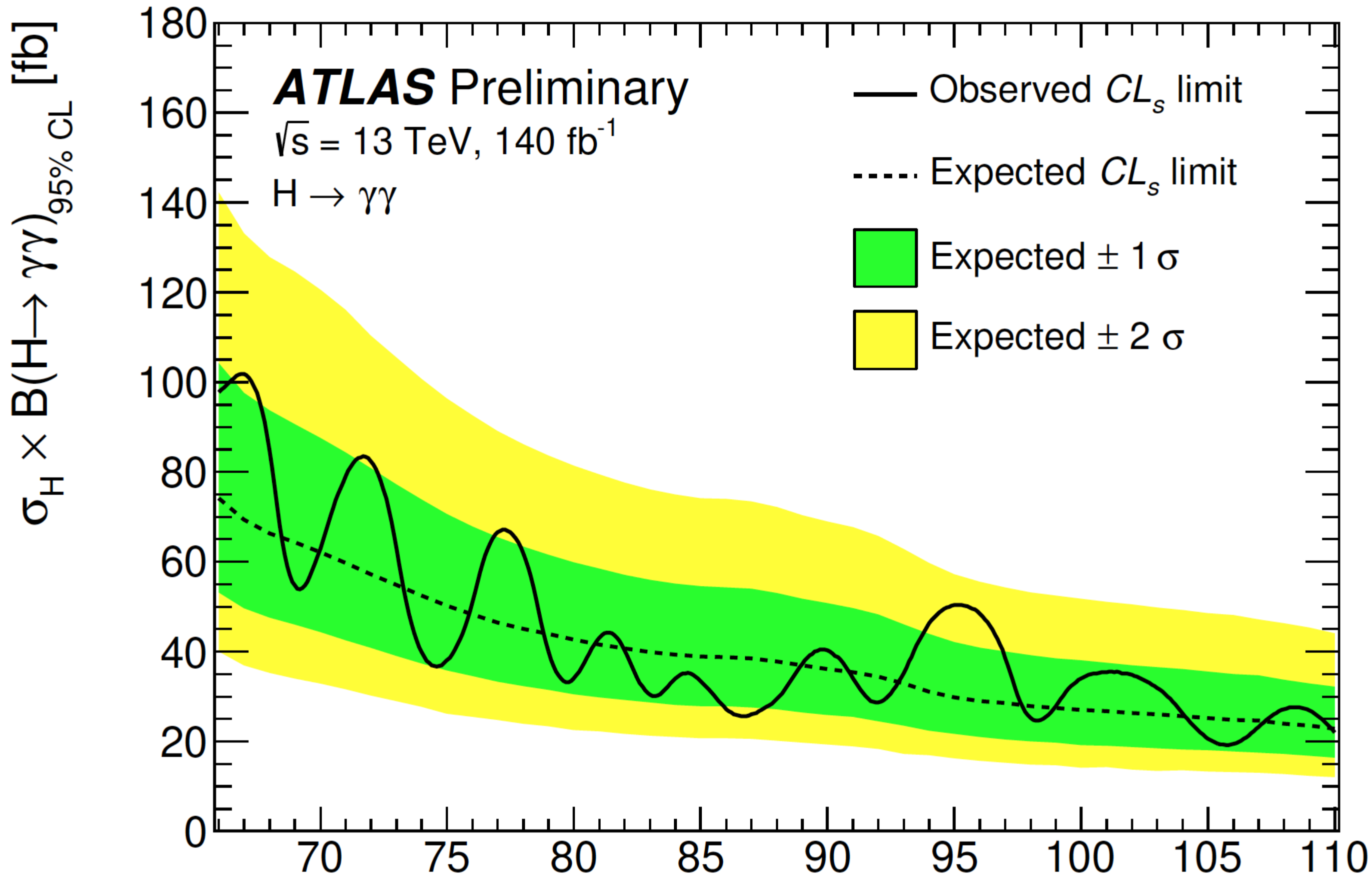
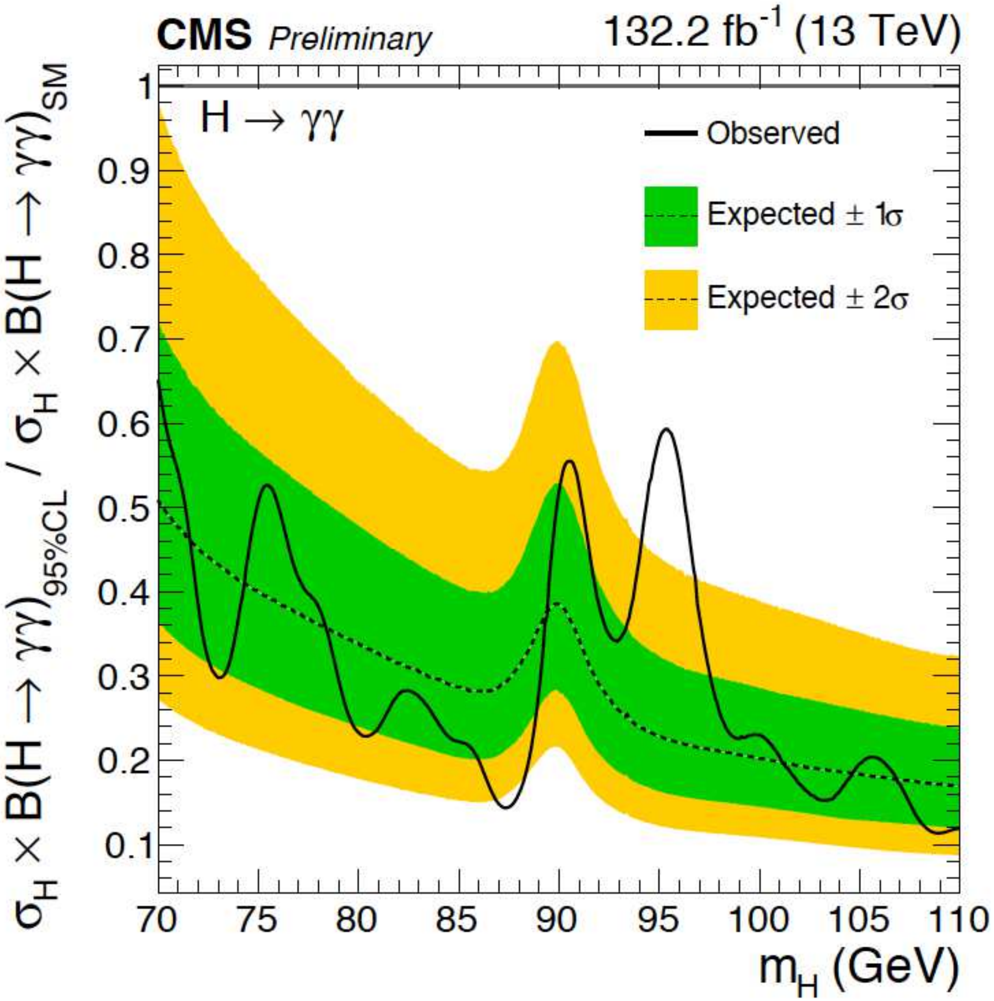
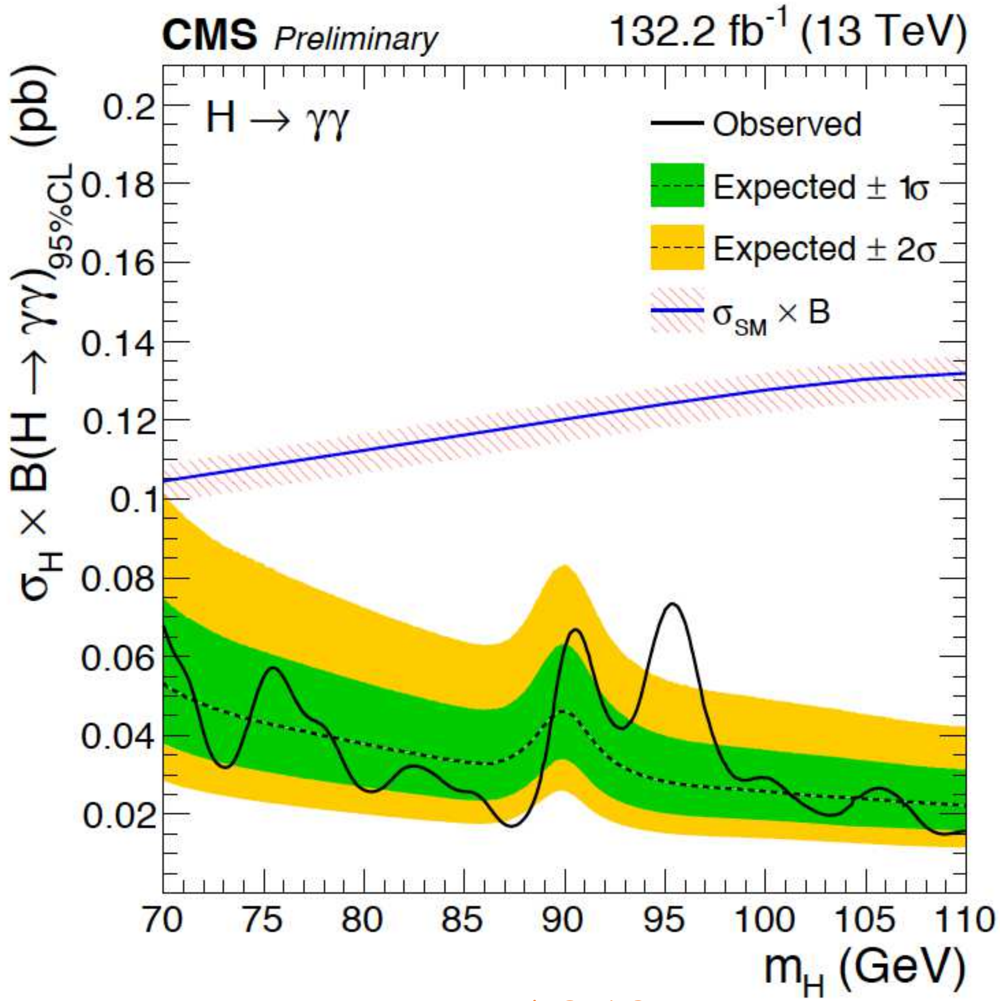


⇒ higest "excess" at 95.4 GeV

Full Run 2 results from CMS: excess at 95.4 GeV [CMS '23]



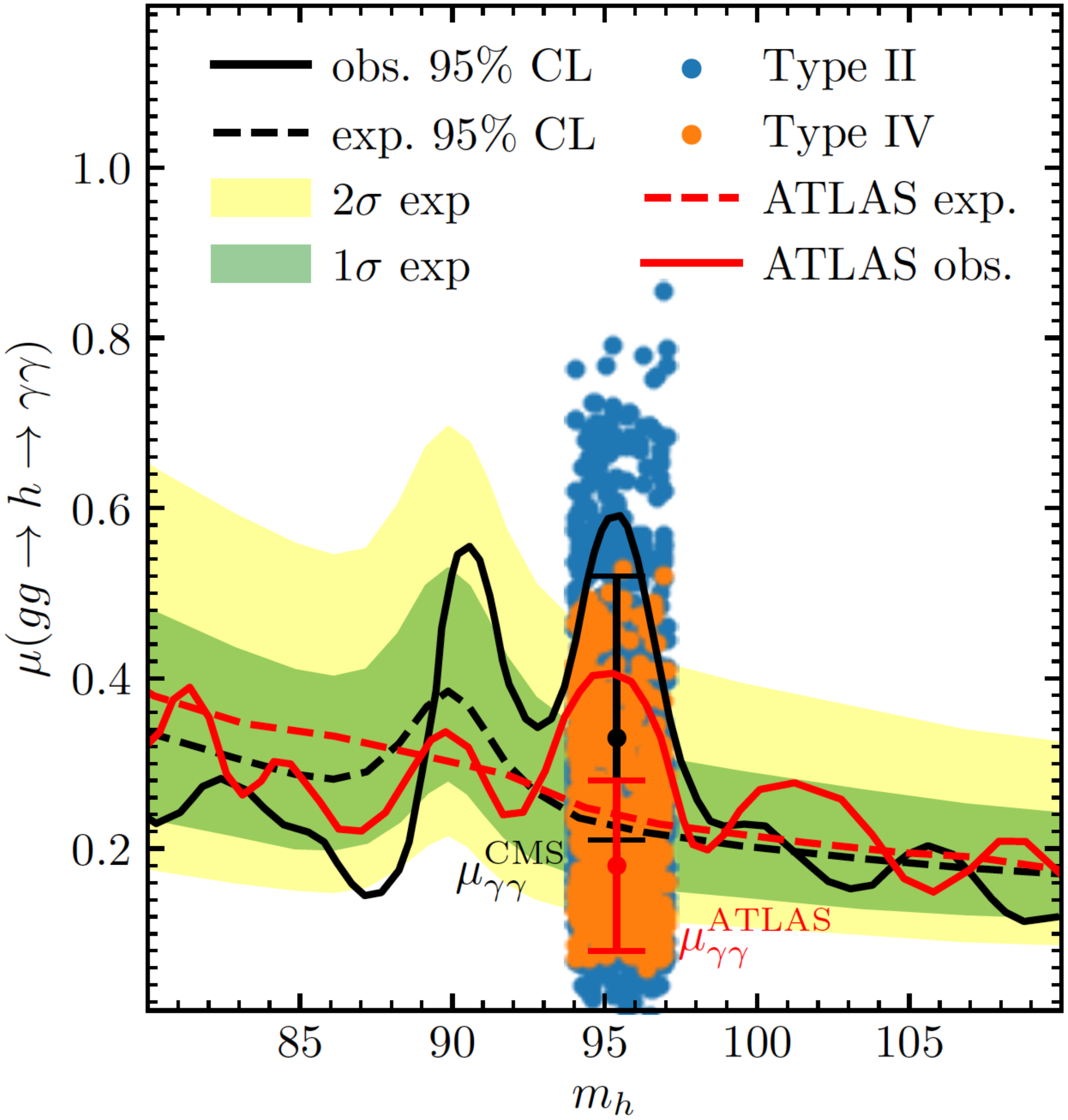


$$\mu_{\gamma\gamma}^{\text{CMS}} = [\sigma(gg \to h_{95}) \times \text{BR}(h_{95} \to \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}\ (2.9\,\sigma)$$

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

New CMS/ATLAS comparison:

[T. Biekötter, S.H., G. Weiglein '23]



$\Rightarrow$ agreement between ATLAS and CMS!

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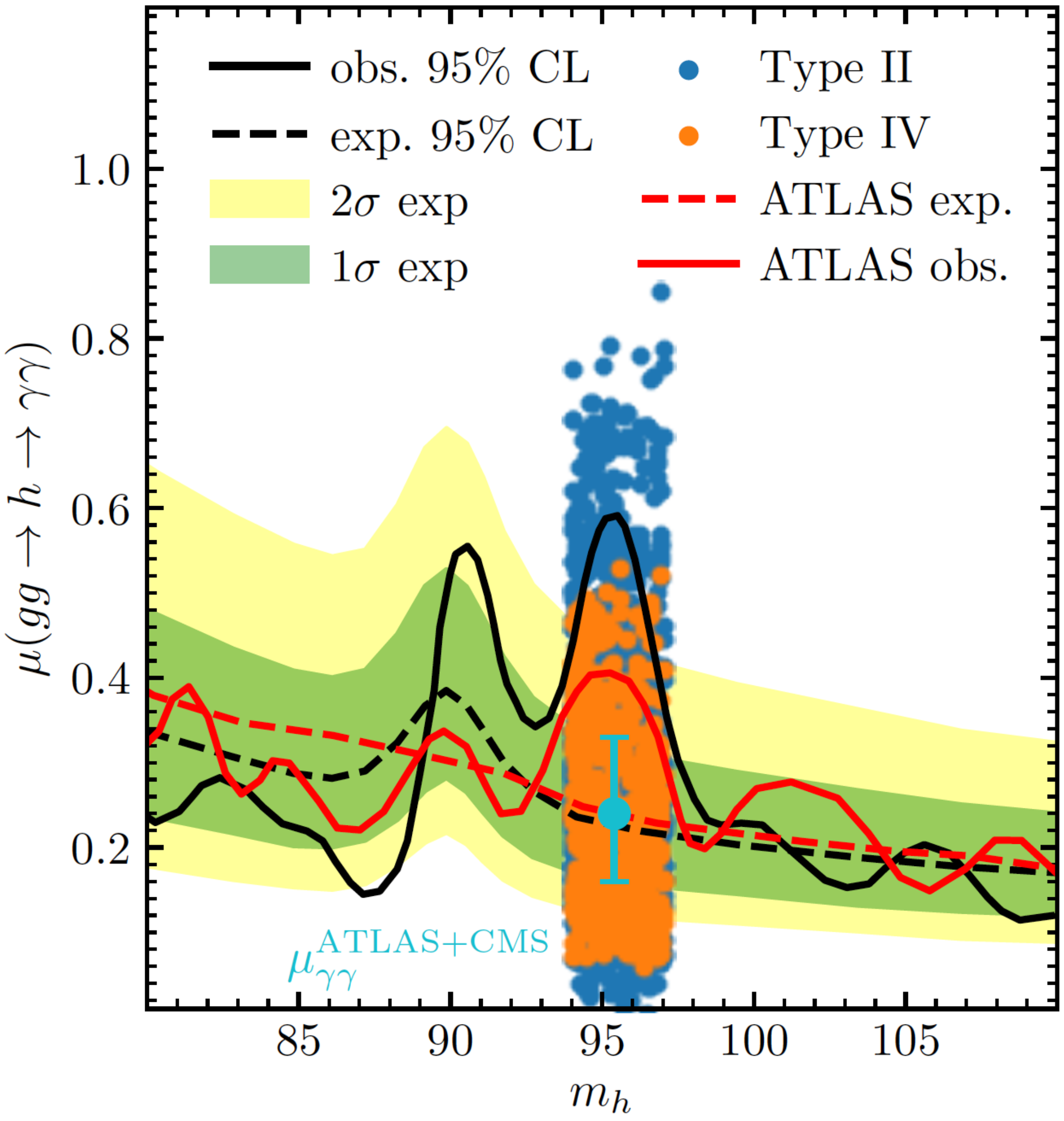
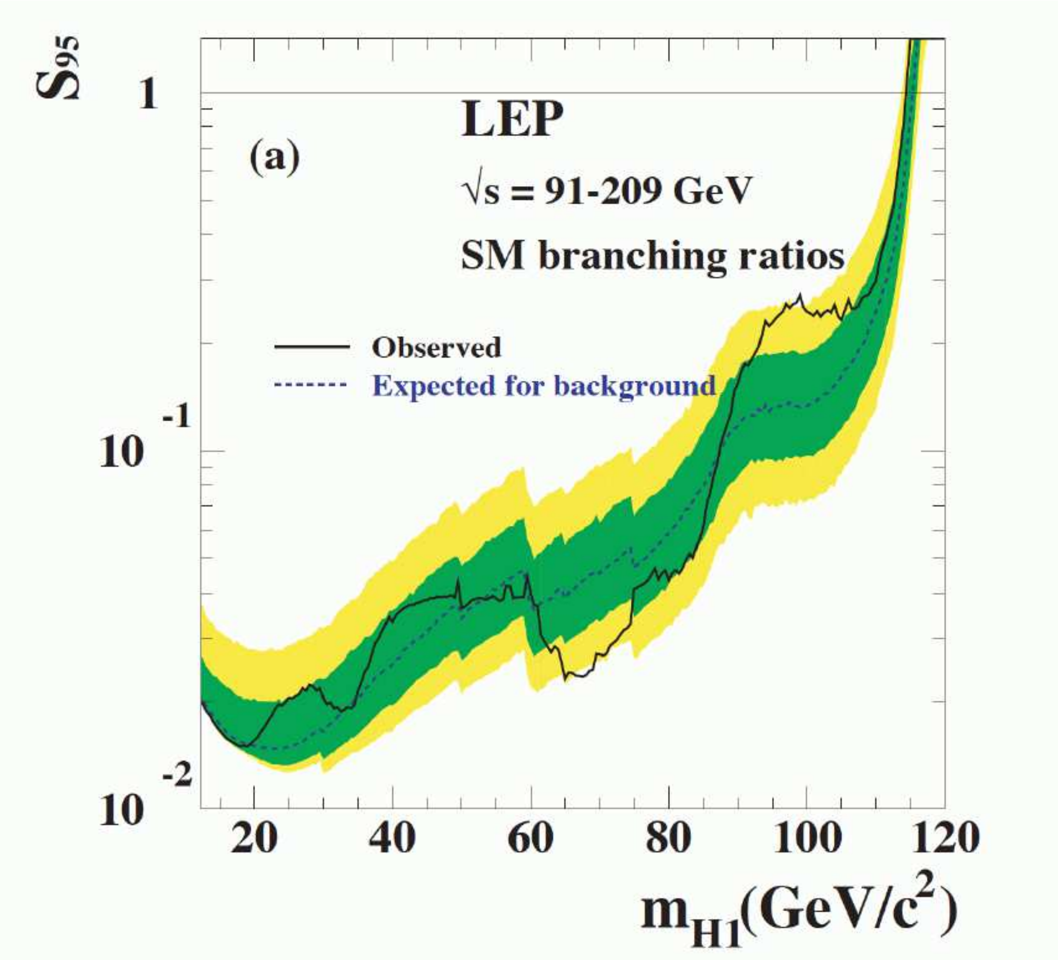
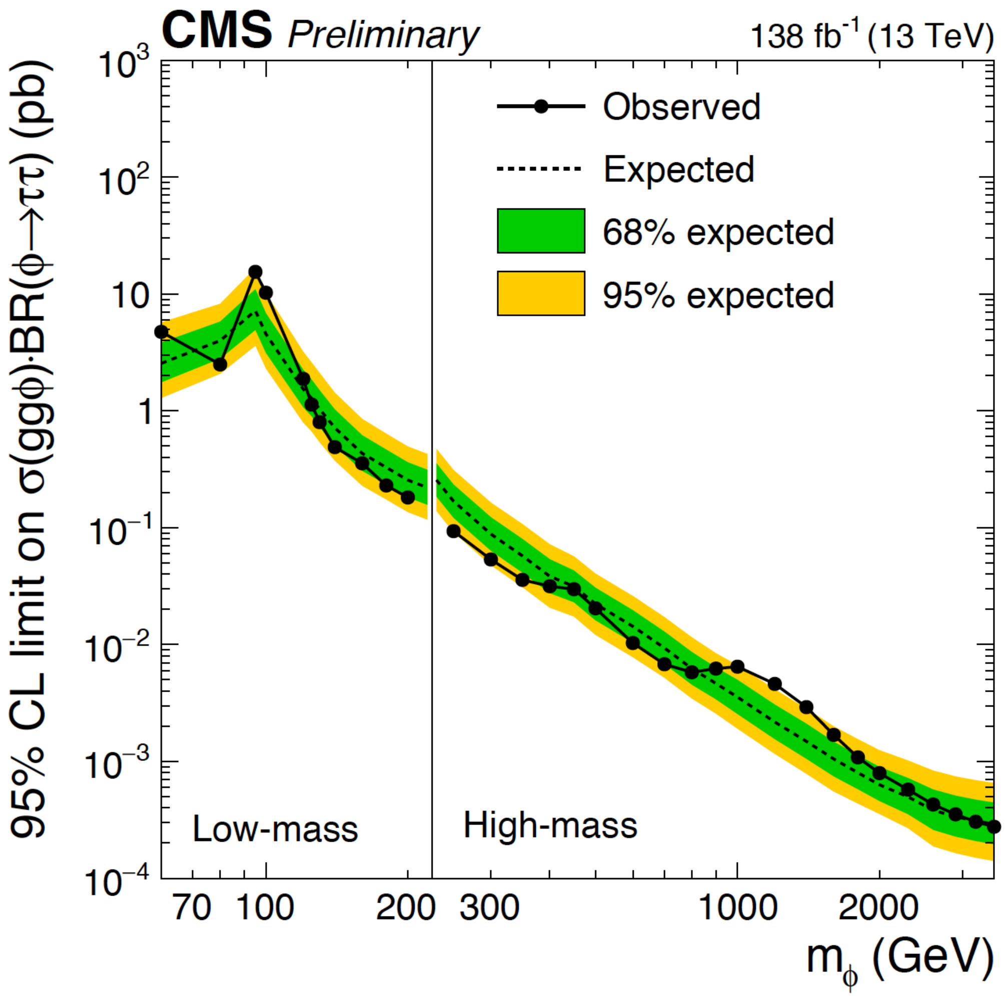


⇒ agreement between ATLAS and CMS! $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ $(3.1\,\sigma)$

LEP: $e^+e^- \to Z\phi \to Zb\bar{b}$ $(2\,\sigma)$ CMS: $pp \to \phi \to \tau^+\tau^-$ $(2.4\,\sigma)$

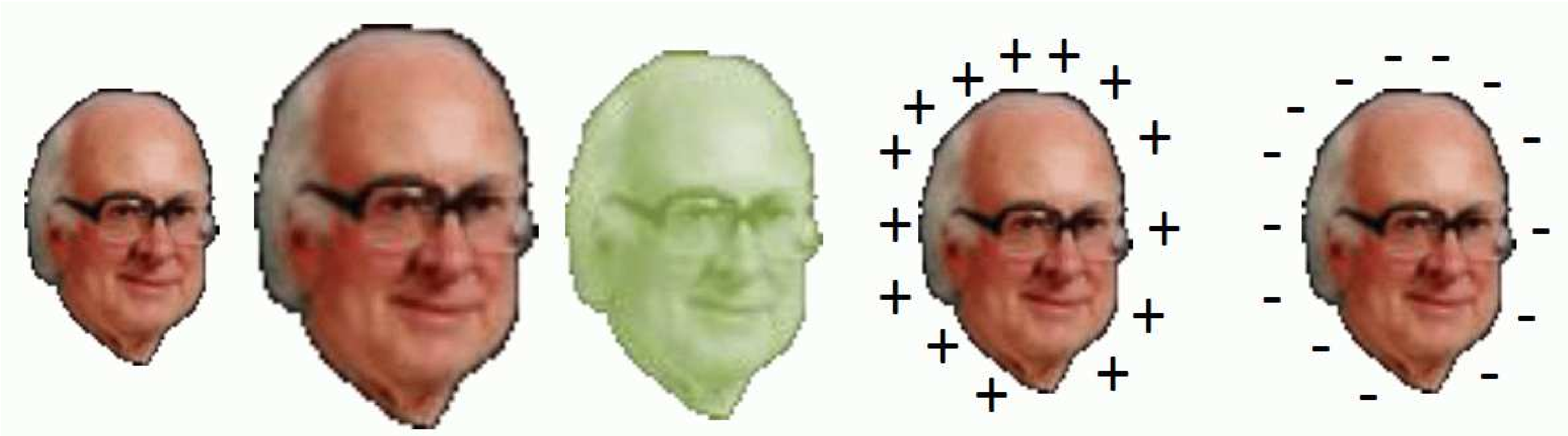




$\Rightarrow$ no LEE (as theorist I am allowed to add naively)

$\Rightarrow \sim 4.6\,\sigma$

2. Possible model interpretation



Models: Summary

Authors	Model	arXiv	Excesses	Comments
Cao, Guo, He et al.	nNMSSM	1612.08522	$bb + \gamma\gamma$	
Fox, Weiner	2HDM + VL	1710.07649	$bb + \gamma\gamma$	
Haisch, Malinauskas	2HDM	1712.06599	$bb + (\gamma\gamma)$	
TB, Heinemeyer, Muñoz	$\mu\nu$SSM	1712.07475	$bb + \gamma\gamma$	EW seesaw
Liu, Liu, Wagner, Wang	$U(1)_{L_\mu - L_\tau}$	1805.01476	$bb + \gamma\gamma$	B-anomalies
Domingo, Heinemeyer, Paßehr, Weiglein	NMSSM	1807.06322	$bb + \gamma\gamma$	
Hollik, Liebler, Moortgat-Pick et al.	μNMSSM	1809.07371	$bb + \gamma\gamma$	Inflation
TB, Chakraborti, Heinemeyer	N2HDM	1903.11661	$bb + \gamma\gamma$	
Cline, Toma	pNG + squarks	1906.02175	$bb + \gamma\gamma$	DM
Choi, Hui Im, Sik Jeong et al.	gNMSSM	1906.03389	$bb + \gamma\gamma$	
Cao, Jia, Yue et al.	nNMSSM	1908.07206	$bb + \gamma\gamma$	Type-I seesaw
Aguilar-Saavedra, Joaquim	SM + $U(1)_{Y'}$	2002.07697	$bb + \gamma\gamma$	
TB, Olea-Romacho	S2HDM	2108.10864	$bb + \gamma\gamma$	DM, GC excess
TB, Grohsjean, Heinemeyer et al.	NMSSM	2109.01128	$\gamma\gamma$	400 GeV excess
Heinemeyer, Lika, Moortgat-Pick et al.	2HDM+s	2112.11958	$bb + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2203.13180	$bb + (\tau\tau) + \gamma\gamma$	
TB, Heinemeyer, Weiglein	N2HDM	2204.05975	$bb + (\tau\tau) + \gamma\gamma$	CDF M_W
Benbrik, Boukidi, Moretti et al.	A2HDM-III	2204.07470	$bb + \gamma\gamma$	LFV

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

[taken from T. Biekötter '23]

Models: Summary

Karlsruher Institut für Technologie

Authors	Model	arXiv	Excesses	Comments
TB, Heinemeyer, Weiglein	S2HDM	2303.12018	$bb + (\tau\tau) + \gamma\gamma$	DM
Azevedo, TB, Ferreira	C2HDM	2305.19716	$bb + \tau\tau + \gamma\gamma$	
Bonilla, Carcamo, Kovalenko et al.	Left-Right model	2305.11967	$\gamma\gamma$	DM
TB, Heinemeyer, Weiglein	S2HDM	2306.03889	$bb + (\tau\tau) + \gamma\gamma$	ATLAS-$\gamma\gamma$
Escribano, Martín Lozano, Vicente	Scotogenic	2306.03735	$bb + \gamma\gamma$	DM, ν masses
Belyaev, Benbrik, Boukidi et al.	A2HDM	2306.09029	$bb + (\tau\tau) + \gamma\gamma$	
Ashanuman, Banik, Coloretti et al.	$Y = 0$ triplet	2306.15722	$\gamma\gamma$	CDF M_W
Aguilar-Saavedra, Camara, Joaquim et al.	UN2HDM	2307.03768	$(\tau\tau)$, $\gamma\gamma$	

Green: 2HDM(+X), blue: Susy, red: Extra charged fields

Our example: **N2HDM** [**S2HDM** similar with complex singlet]

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S$$

Potential:

$$\begin{aligned} V = \; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & +\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1\,,\ \Phi_2 \to -\Phi_2\,,\ \Phi_S \to \Phi_S$

Z_2' symmetry: $\Phi_1 \to \Phi_1\,,\ \Phi_2 \to \Phi_2\,,\ \Phi_S \to -\Phi_S$ (broken by $v_S \Rightarrow$ no DM)

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Extension of the Z_2 symmetry to fermions determines four types:

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

$\Rightarrow$ exactly as in 2HDM

Three neutral $\mathcal{CP}$-even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} , \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Coupling to massive gauge bosons: (identical for all four types)

	$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2}$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

Coupling to fermions: (same pattern as in 2HDM)

	u-type ($c_{h_i tt}$)	d-type ($c_{h_i bb}$)	leptons ($c_{h_i \tau\tau}$)
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

"Physical" input parameters:

$\alpha_{1,2,3}$, $\tan\beta$, v , v_S , $m_{h_{1,2,3}}$, m_A , $M_{H^\pm}$, m_{12}^2

Needed to fit the $\gamma\gamma$ and $b\bar{b}$ excesses: $m_{h_1} \sim 95$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1 VV}$ strongly reduced for $\mu_{b\bar{b}}$
- $c_{h_1 bb}$ reduced to enhance BR($h_1 \to \gamma\gamma$)
- $c_{h_1 tt}$ not reduced for $\mu_{\gamma\gamma}$

	Decrease $c_{h_1 b\bar{b}}$	No decrease $c_{h_1 t\bar{t}}$	No enhancement $c_{h_1 \tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$
type II	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$

Type II and IV: $c_{h_1 bb}$ and $c_{h_1 tt}$ independent

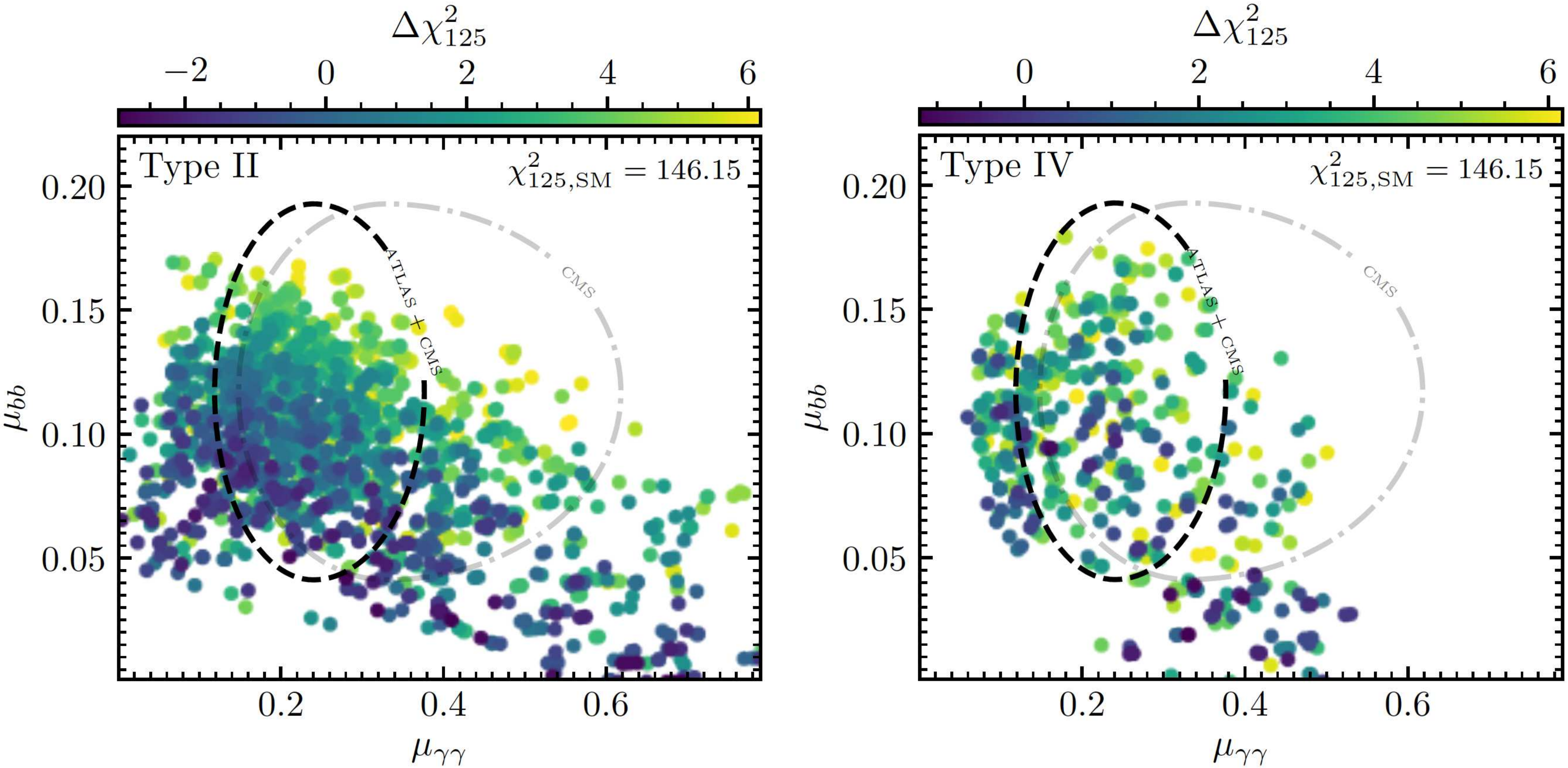
Type II vs. IV: $c_{h_1 \tau\tau}$ can be suppressed or enhanced

$\Rightarrow$ only type II and IV can fit the $\gamma\gamma$ and $b\bar{b}$ excesses

$\Rightarrow$ $\tau\tau$ excess may decide between type II and IV

S2HDM type II vs. type IV

[*T. Biekötter, S.H., G. Weiglein '23*]

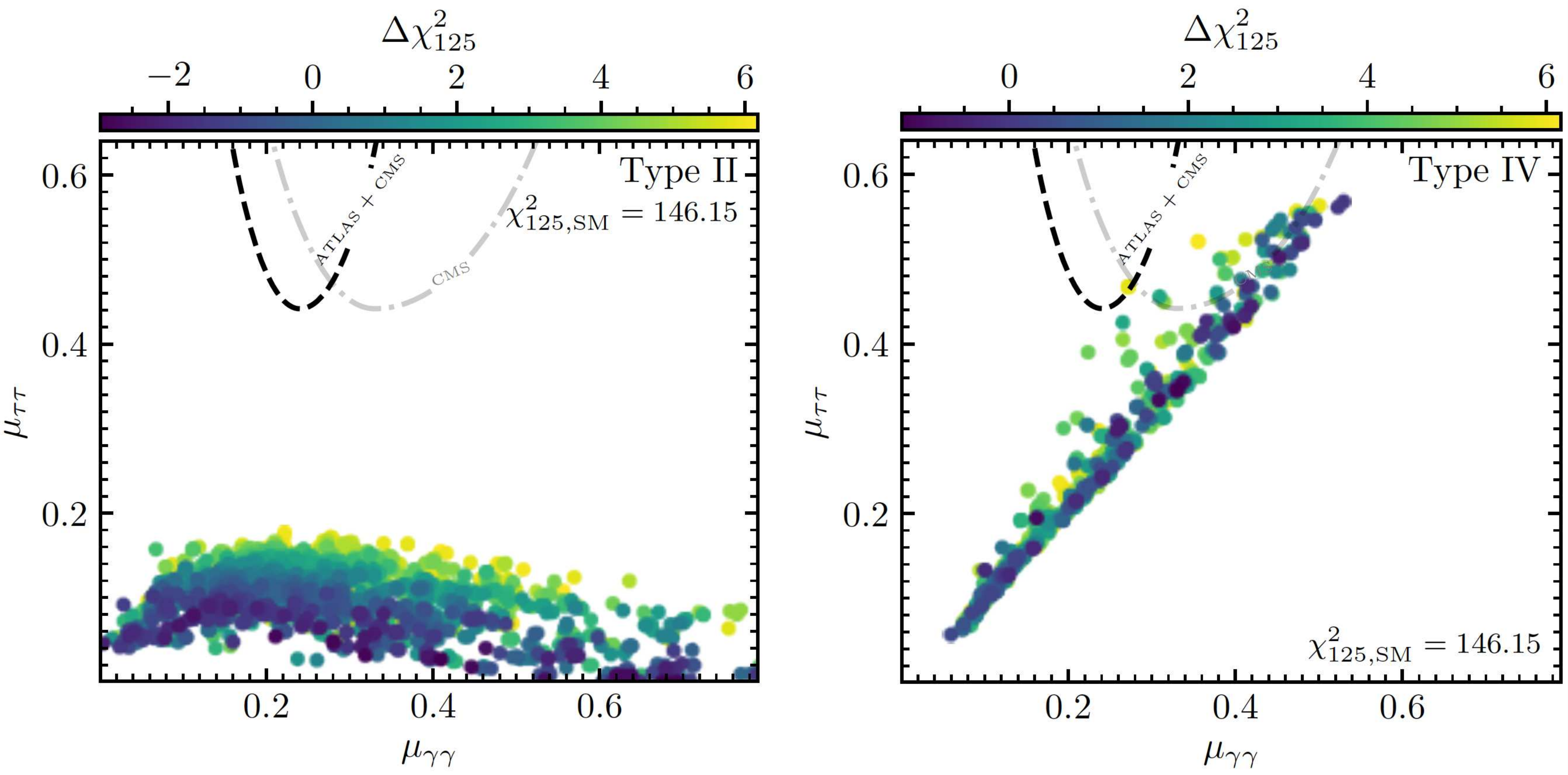


Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ both type II and IV can fit the $\gamma\gamma$ and bb excesses

S2HDM type II vs. type IV

[T. Biekötter, S.H., G. Weiglein '23]



Color coding: χ^2_{125} from HiggsSignals

⇒ only type IV can fit marginally the $\gamma\gamma$ and $\tau\tau$ excesses

3. SUSY realizations

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⇒ models with an additional singlet??

– NMSSM
– $\mu\nu$SSM
– . . .

Q: Can the models fit the excesses despite the additional SUSY constraints on the Higgs sector **???**

What about the NMSSM?

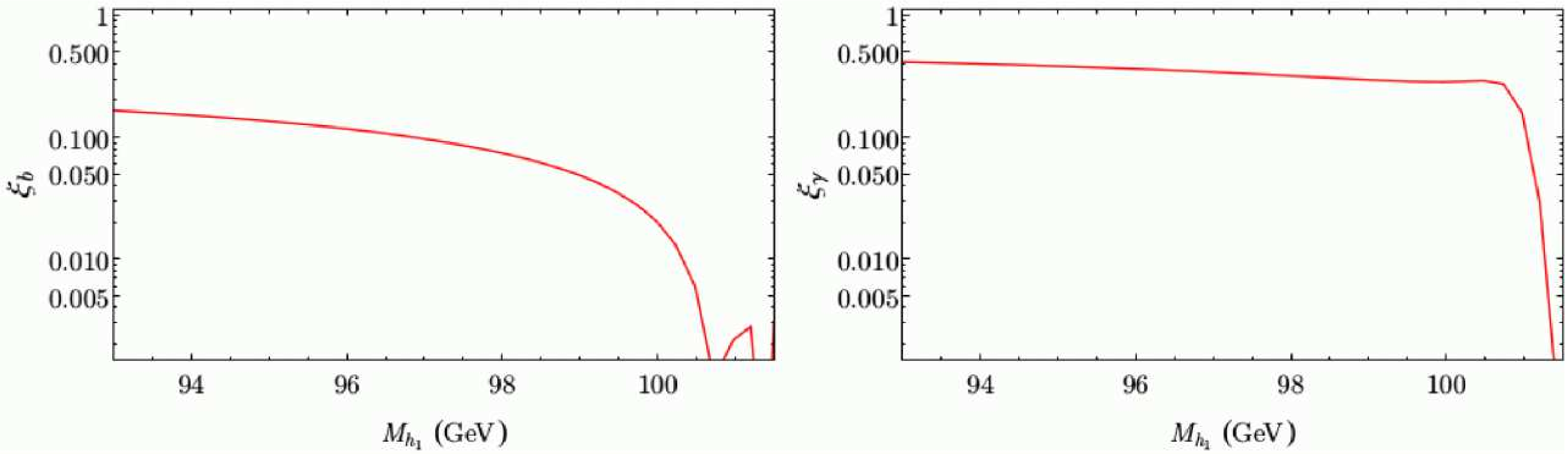
[*F. Domingo, S.H., S. Passehr, G. Weiglein '18*]

Parameters:

$\lambda = 0.6$, $\kappa = 0.035$, $\tan\beta = 2$, $\mu_{\text{eff}} = (397 + 15x)$ GeV, $M_{H^\pm} = 1$ TeV, $A_\kappa = -325$ GeV, $M_{\text{SUSY}} = 1$ TeV, $A_t = A_b = 0$

$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot \text{BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to ZZ] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\text{SM}}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot \text{BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} .$$



⇒ both excesses can be fitted simultaneously well with new $\mu_{\gamma\gamma}$!

What about the $\mu\nu$SSM?

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)
$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

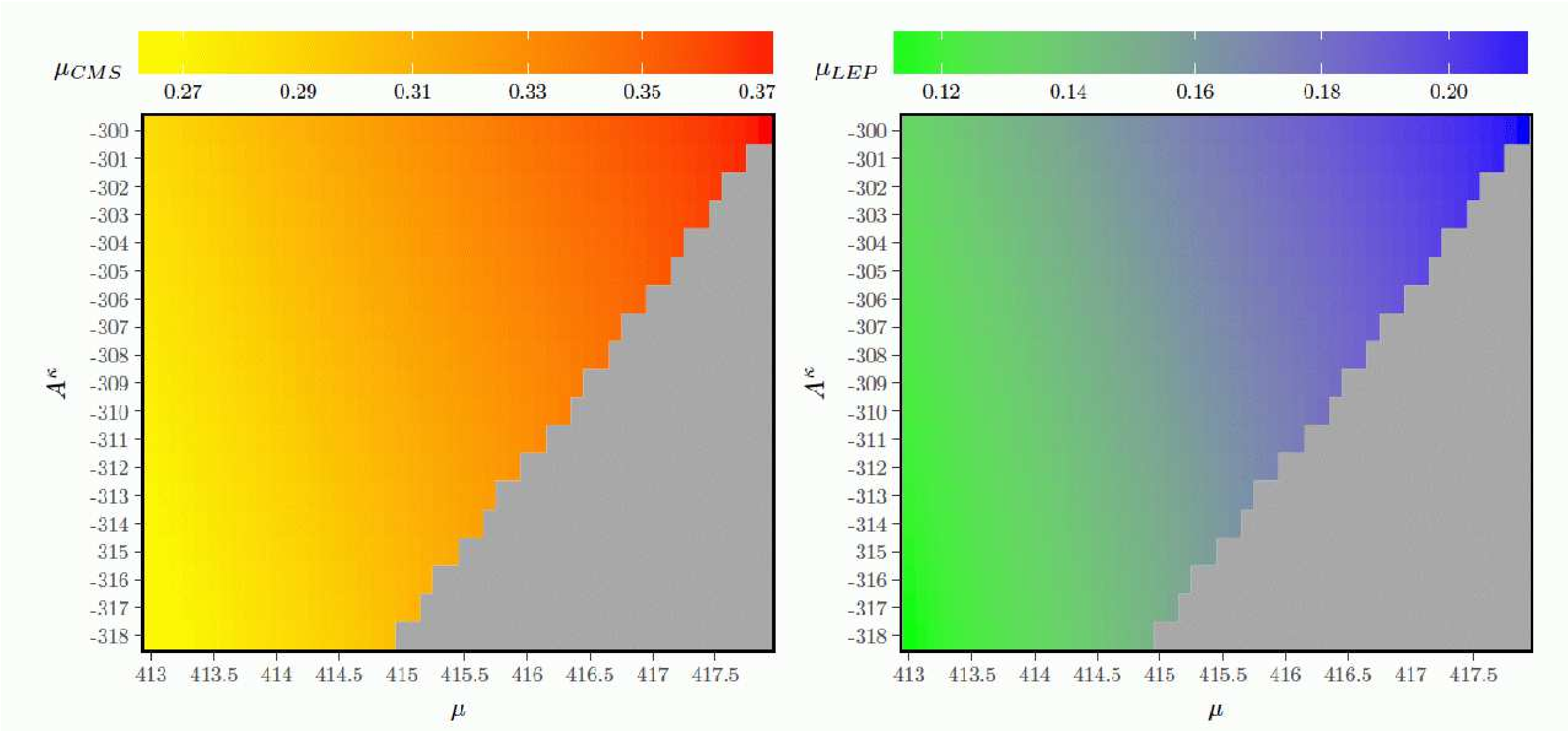
Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413;418]$	0.6	956.035	0.035	$[-300;-318]$	100
M_2	M_3	$m^2_{\widetilde{Q}_{iL}}$	$m^2_{\widetilde{u}_{iR}}$	$m^2_{\widetilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\widetilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

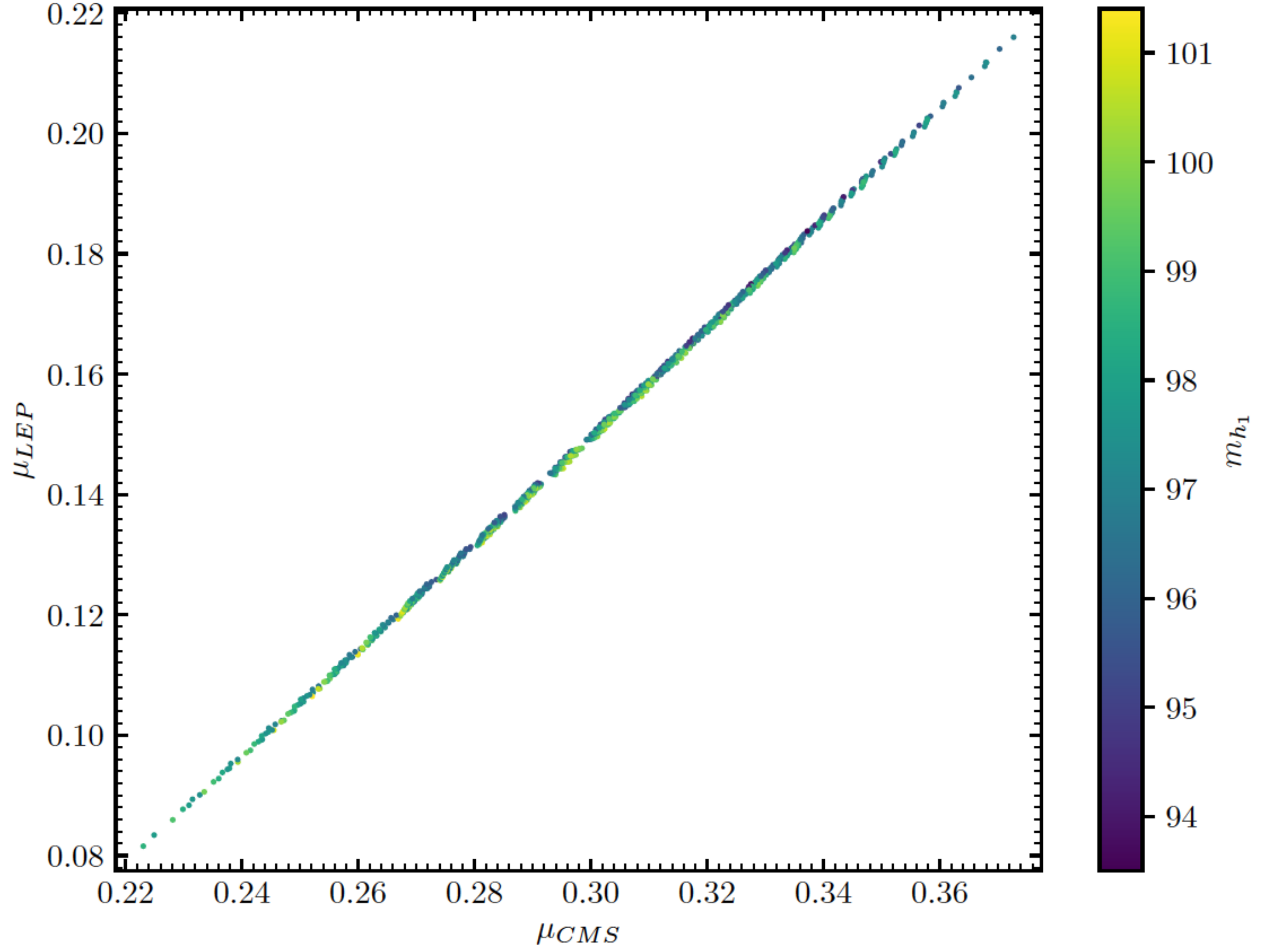


⇒ Yes! :-)

using the <u>new</u> $\mu_{\gamma\gamma}$!

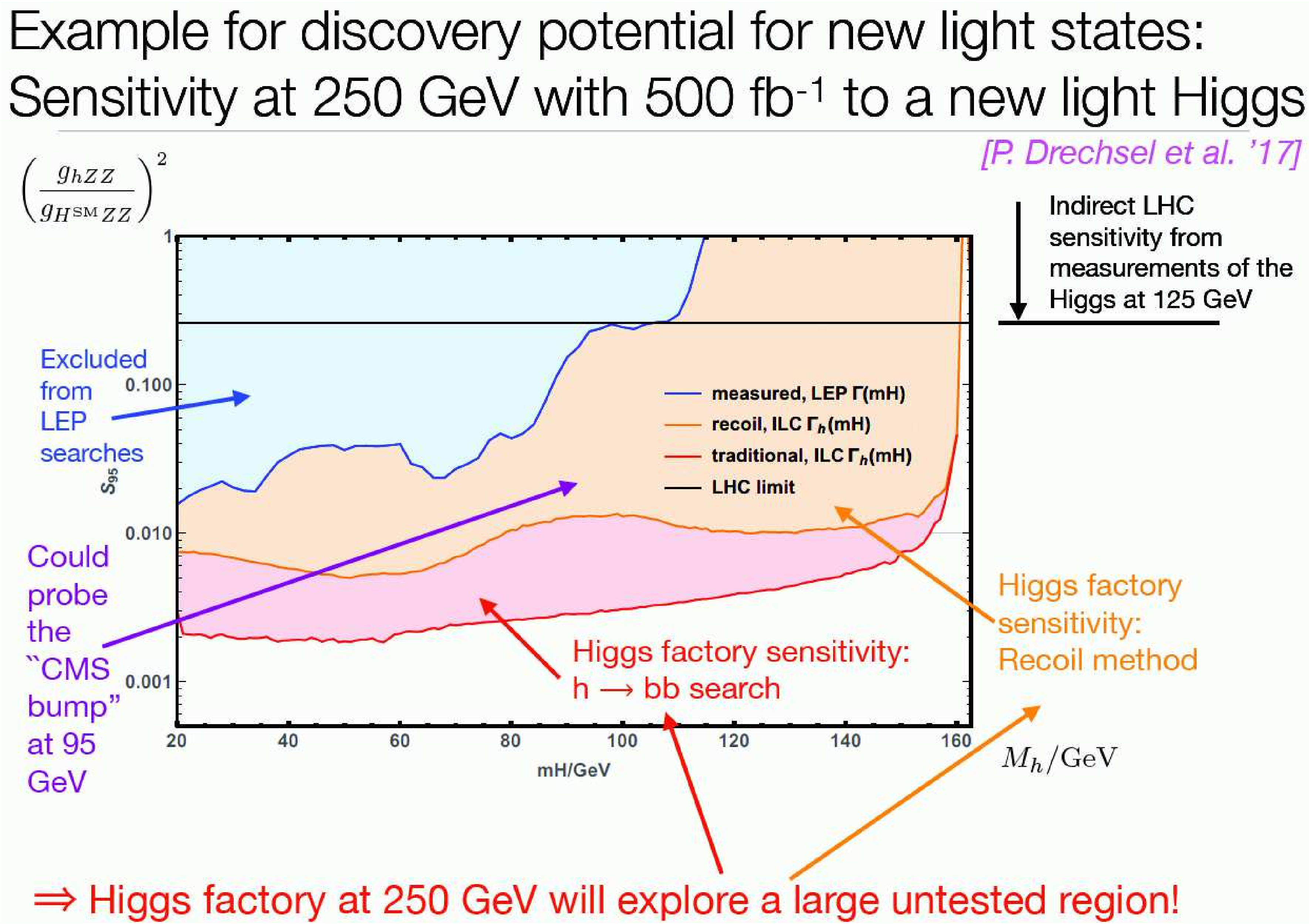
Why does SUSY prefer the new $\mu_{\gamma\gamma}$?

[*T. Biekötter, S.H., C. Muñoz '19*]



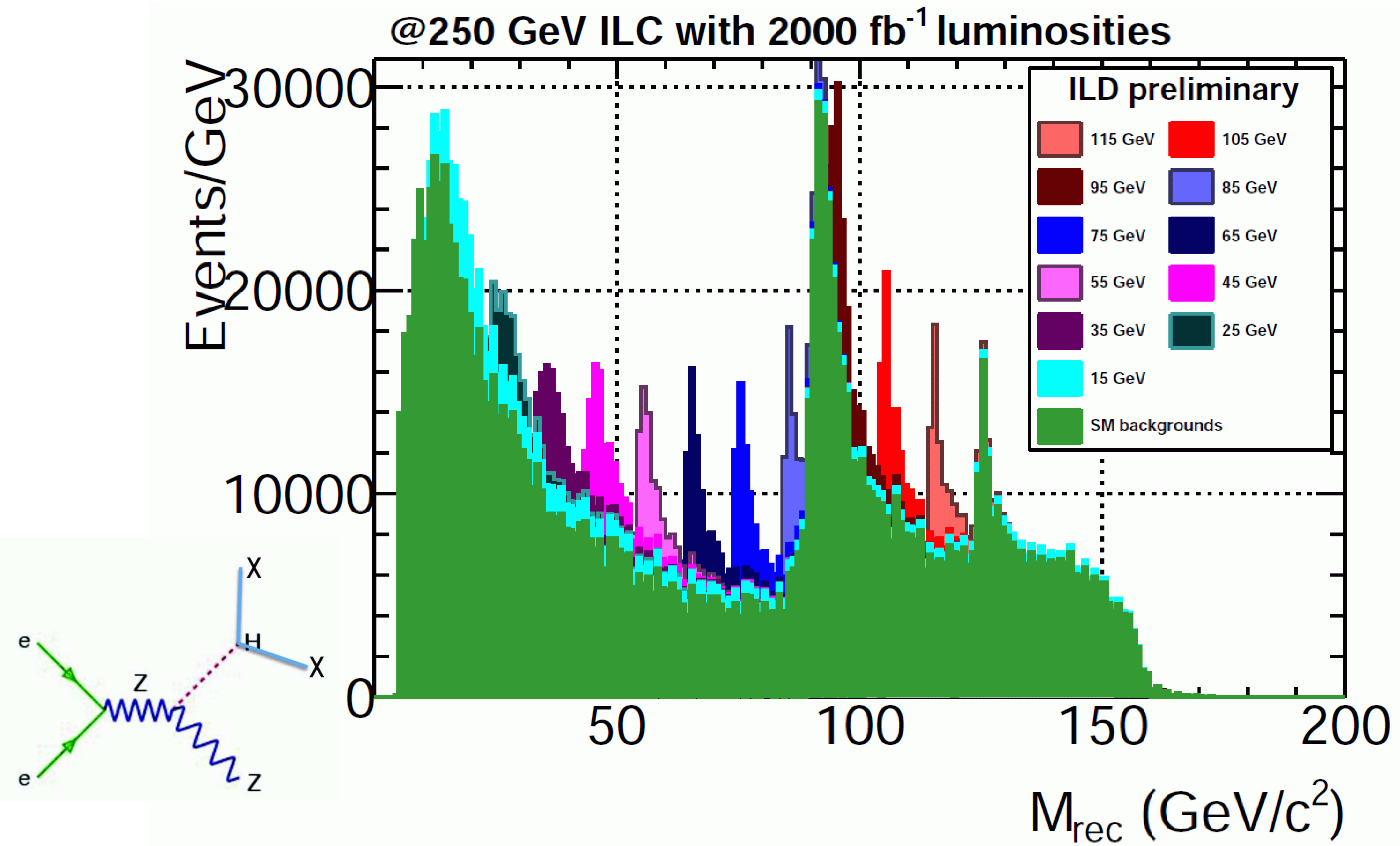
⇒ SUSY enforces strong correlation!

⇒ LEP excess enforces $\mu_{\gamma\gamma} \lesssim 0.35$



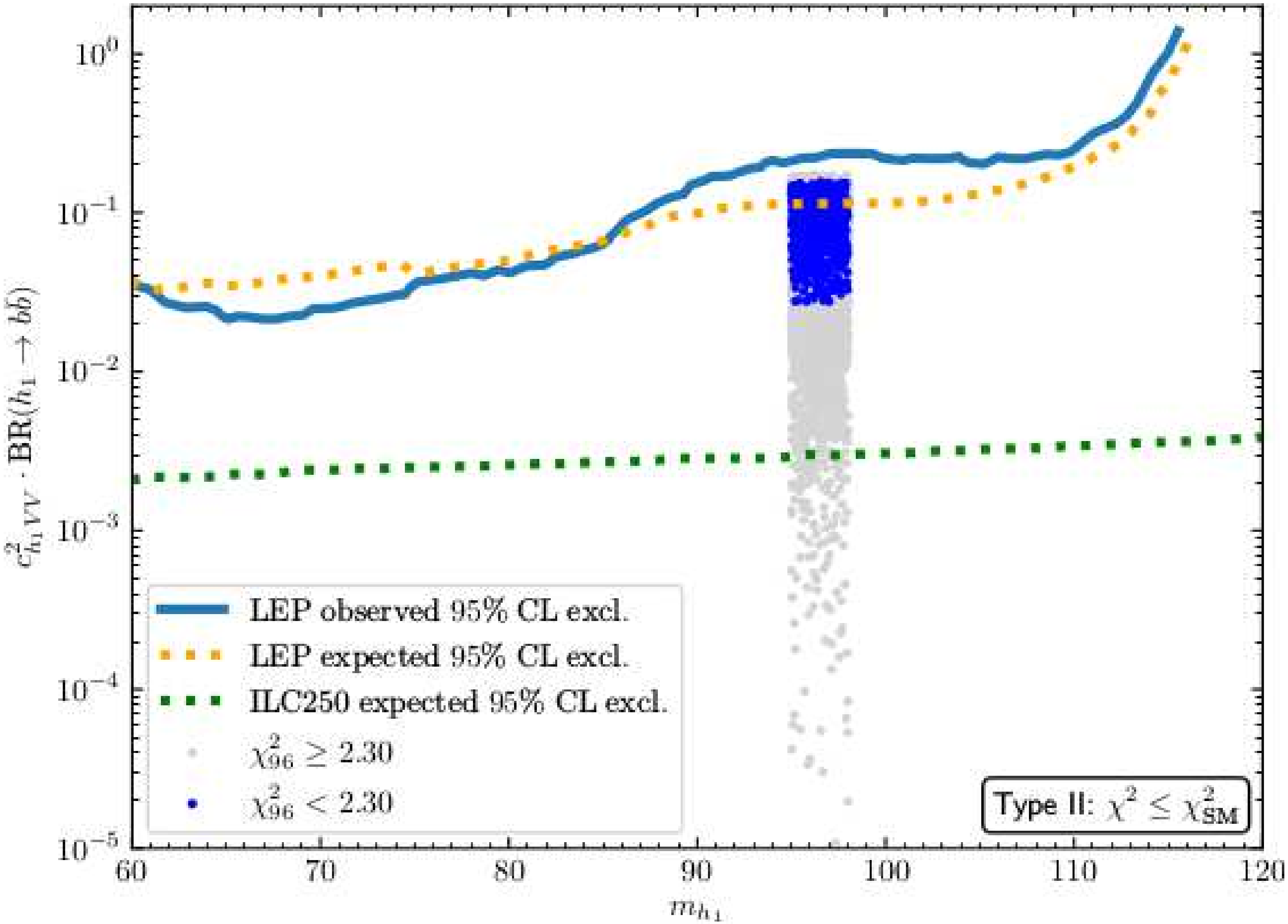
[Taken from G. Weiglein '18]

Search for invisibly decaying light Higgses via recoil method: [*Y. Wang et al. '18*]



Production of the light Higgs at the ILC

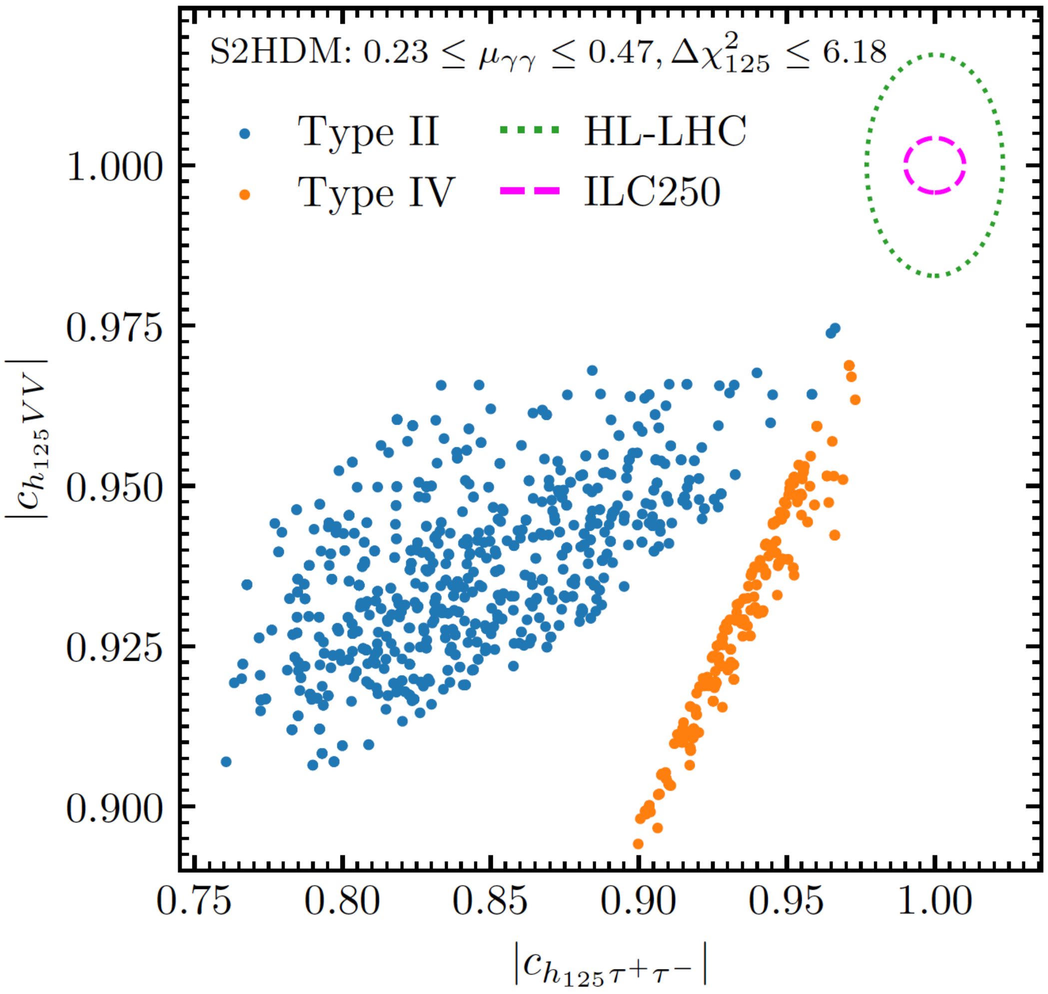
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ new state easily in the reach of the ILC250 ⇒ coupling measurements

h_{125} coupling measurements at the HL-LHC/ILC

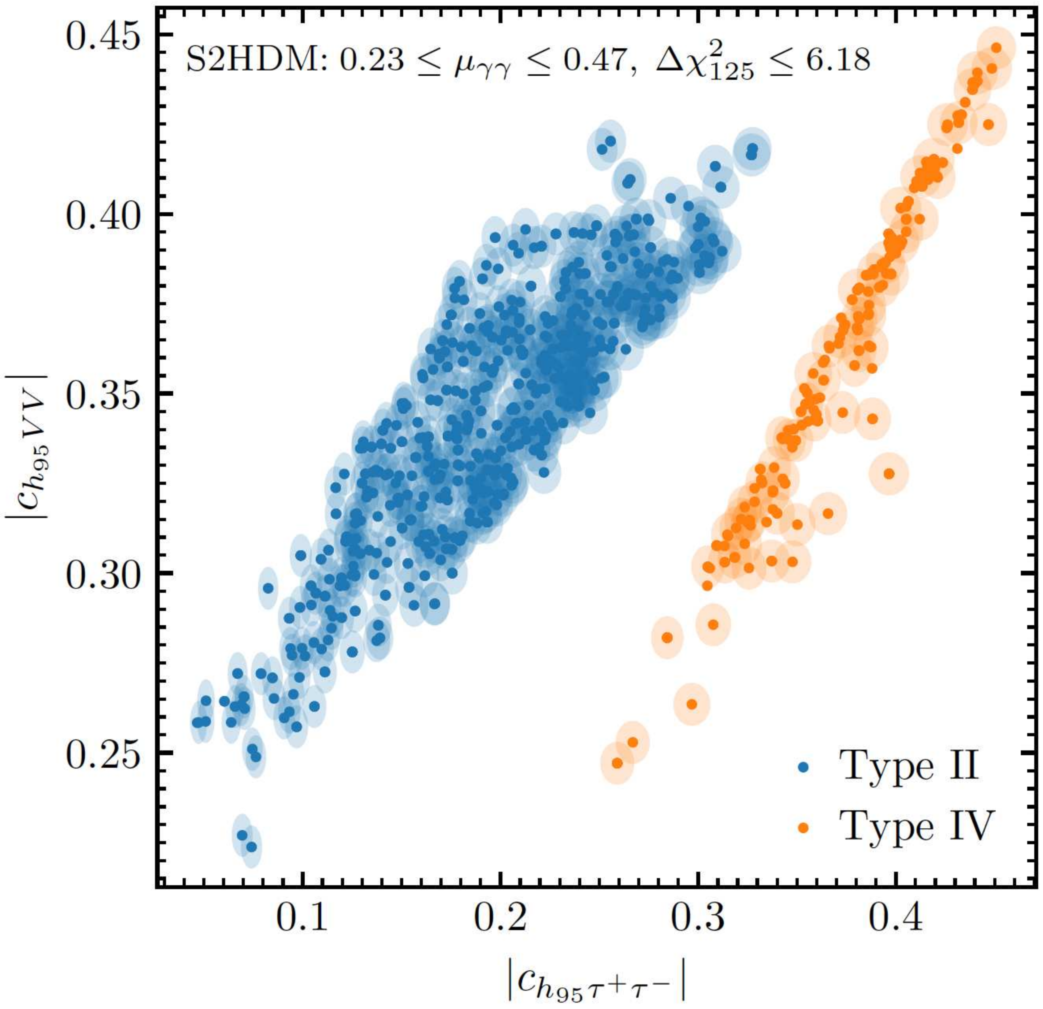
[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ both types show some deviation from SM

h_{95} coupling measurements at the HL-LHC/ILC

[*T. Biekötter, S.H., G. Weiglein '23*]



⇒ models clearly distinguishable!

5. Conclusinos

- Evidence for a Higgs boson at ~ 95.4 GeV
  - $pp \to h_{95} \to \gamma\gamma$ $\Rightarrow$ CMS: $2.9\,\sigma$, ATLAS: $1.7\,\sigma$
  - $e^+e^- \to Zh_{95} \to Zb\bar{b}$ $\Rightarrow$ LEP: $2\,\sigma$
  - $pp \to h_{95} \to \tau\tau$ $\Rightarrow$ CMS: $2.4\,\sigma$

  $\Rightarrow$ no LEE (as theorist I am allowed to add naively)

  $\Rightarrow \sim 4.6\,\sigma$

- Possible model interpretation:
  N2HDM or S2HDM: two Higgs doublets plus a real or complex singlet

  Type II and IV: $c_{h_1 bb}$ and $c_{h_1 tt}$ independent

  $\Rightarrow$ only type II and IV can fit the $\gamma\gamma$ and $b\bar{b}$ excesses

  $\Rightarrow$ $\tau\tau$ excess may decide between type II and IV

- SUSY realizations:
  NMSSM, $\mu\nu$SSM, ... can describe $\gamma\gamma$ and $b\bar{b}$ using the new $\mu_{\gamma\gamma}$

- Physics opportunities at ILC250:
  - h_{125} couplings: both types clearly distinguishable frm the SM
  - h_{95} can be produced in large numbers at CEPC
    - $\Rightarrow$ high precision coupling measurements
    - $\Rightarrow$ information about the underlying model


Further Questions?