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The 95.4 GeV Higgs boson at future e^+e^- colliders

Sven Heinemeyer, IFT (CSIC, Madrid)

Paestum, 10/2023

1. Evidence for a light Higgs boson

2. Possible model interpretation

3. Physics opportunities at e^+e^- colliders

4. 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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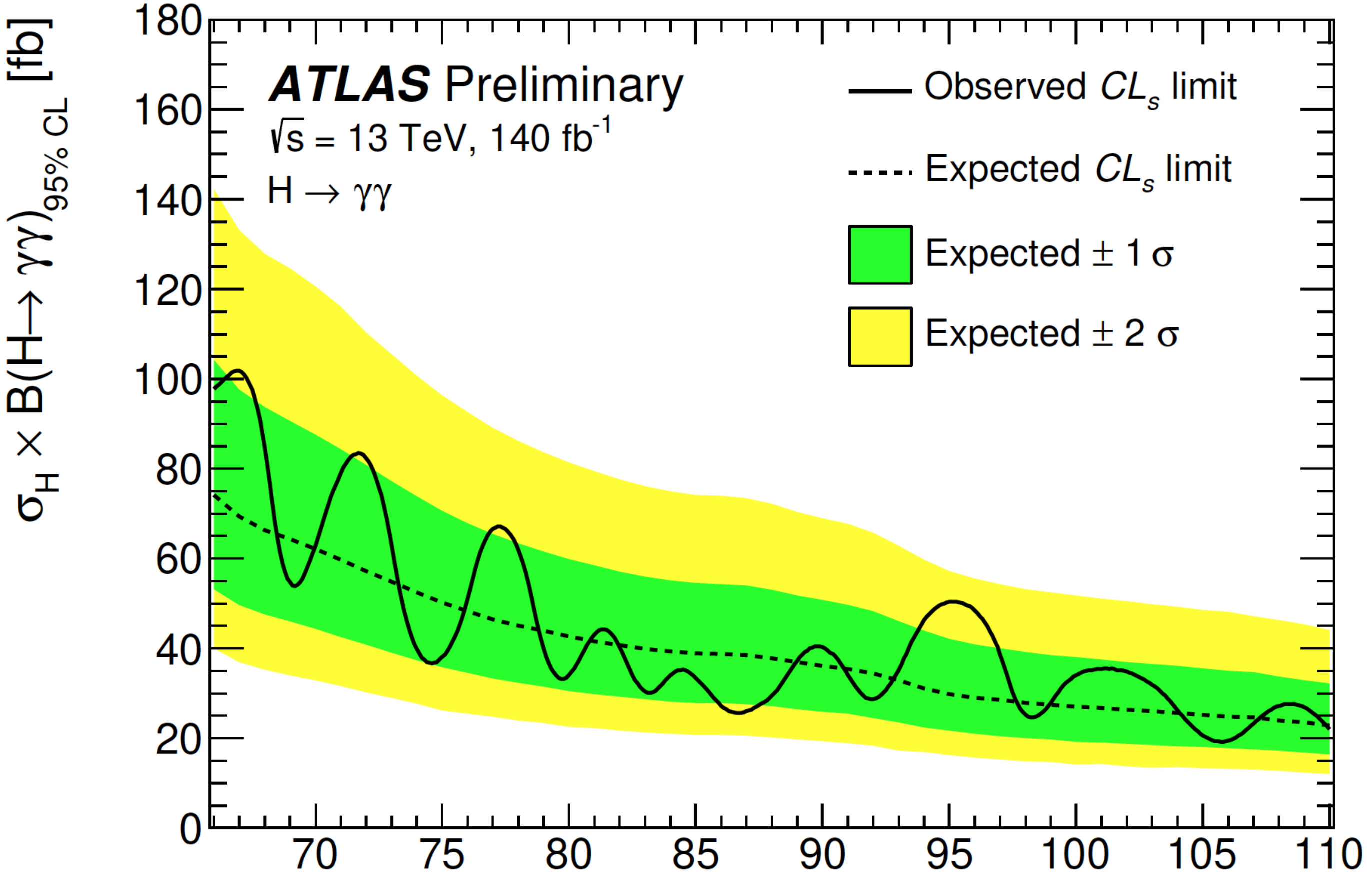
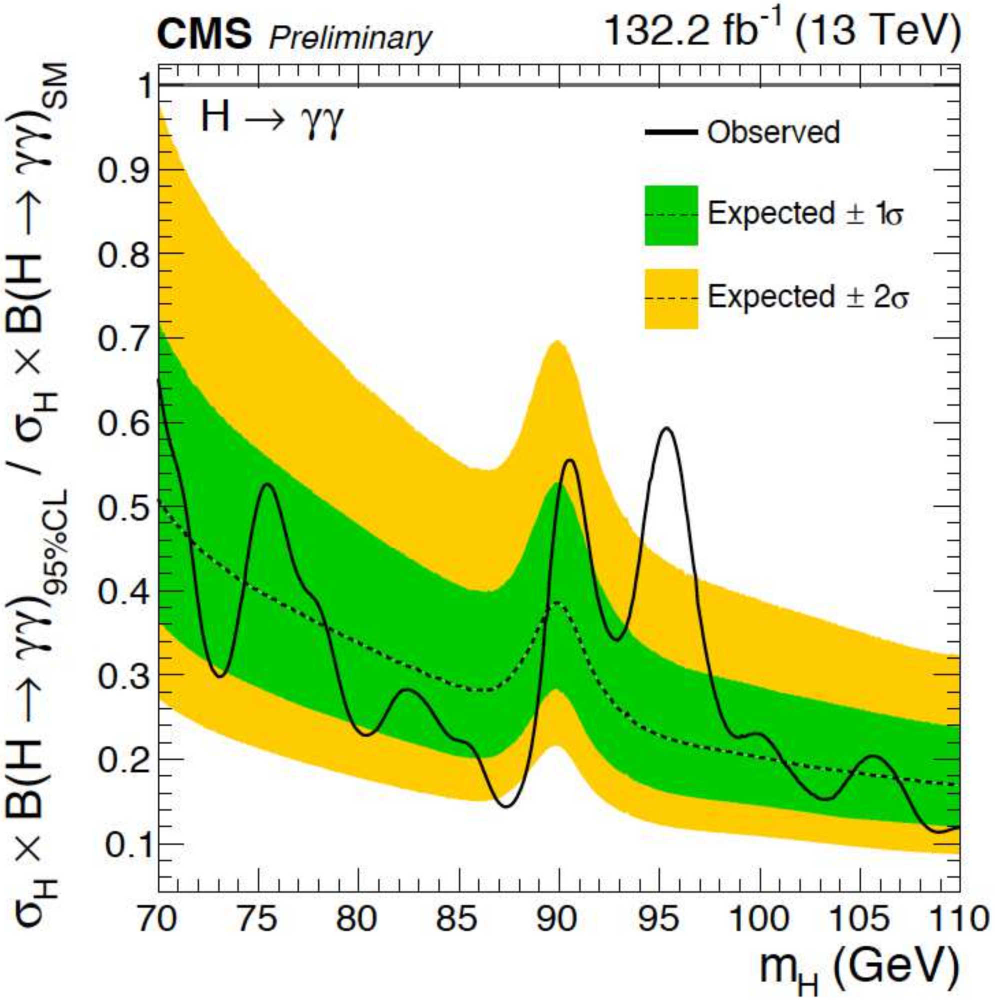
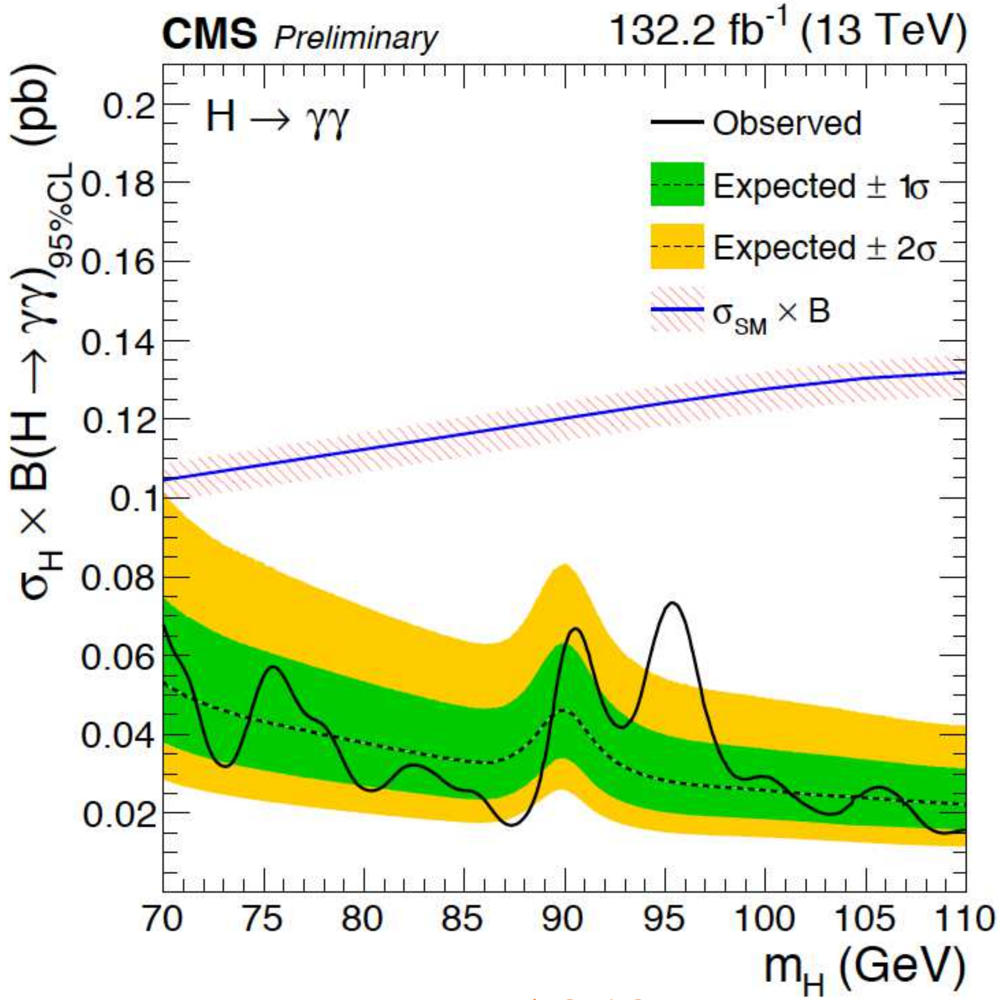


⇒ higest “excess” at 95.4 GeV

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



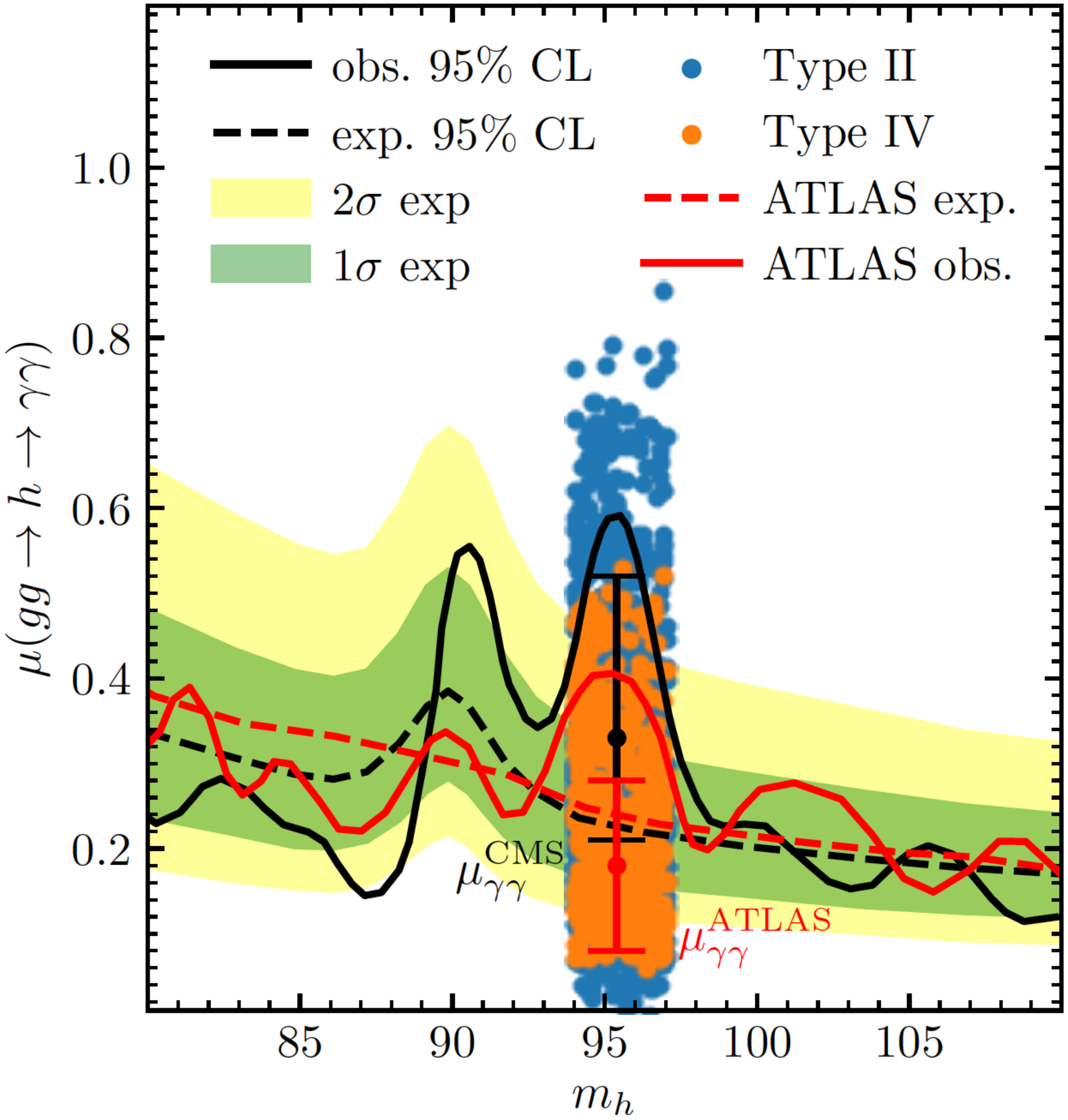


$$\mu_{\gamma\gamma}^{\text{CMS}} = [\sigma(gg \to h_{95}) \times \text{BR}(h_{95} \to \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}\ (2.9\,\sigma)$$

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

New CMS/ATLAS comparison:

[T. Biekötter, S.H., G. Weiglein '23]



⇒ agreement between ATLAS and CMS!

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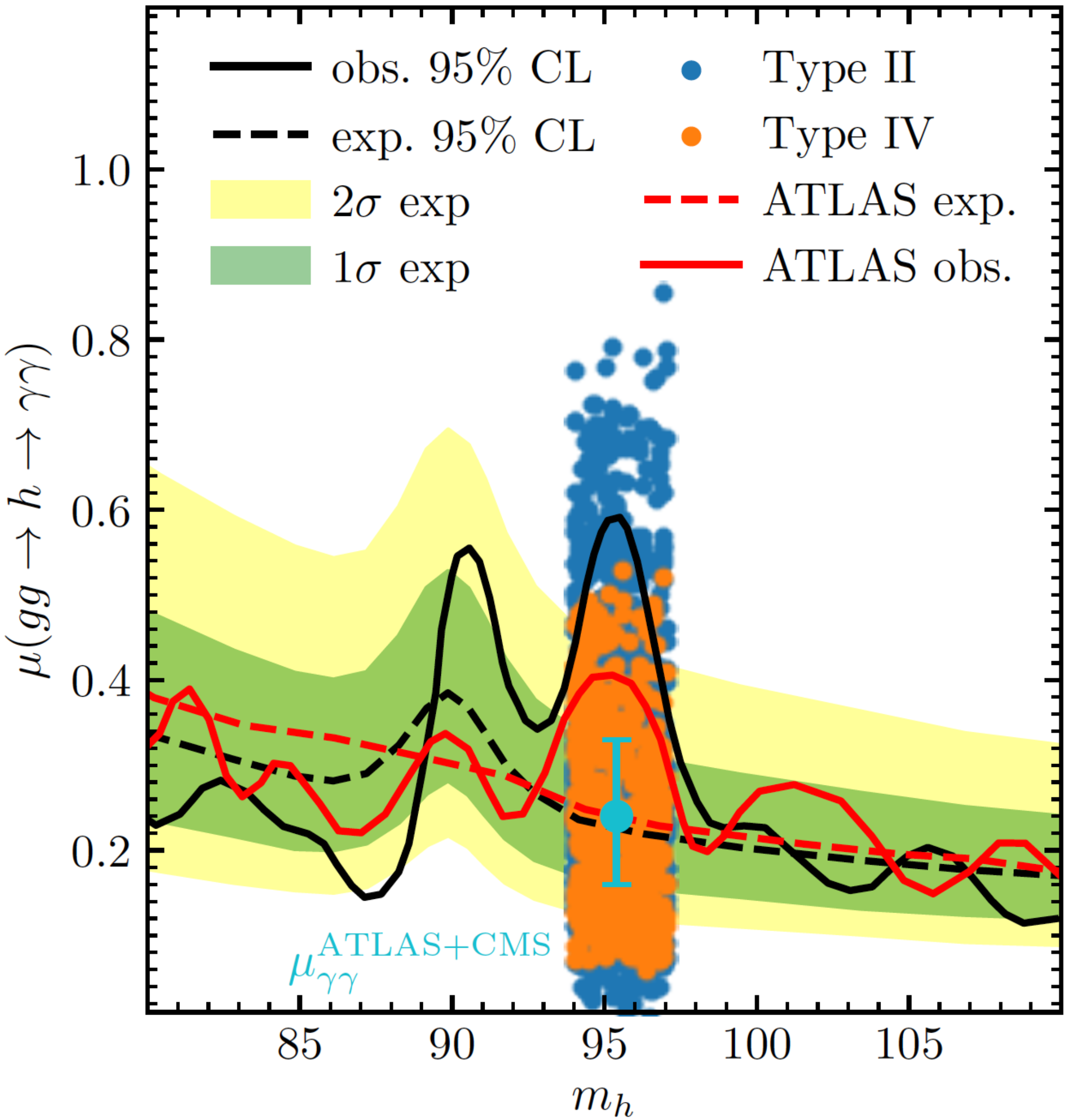
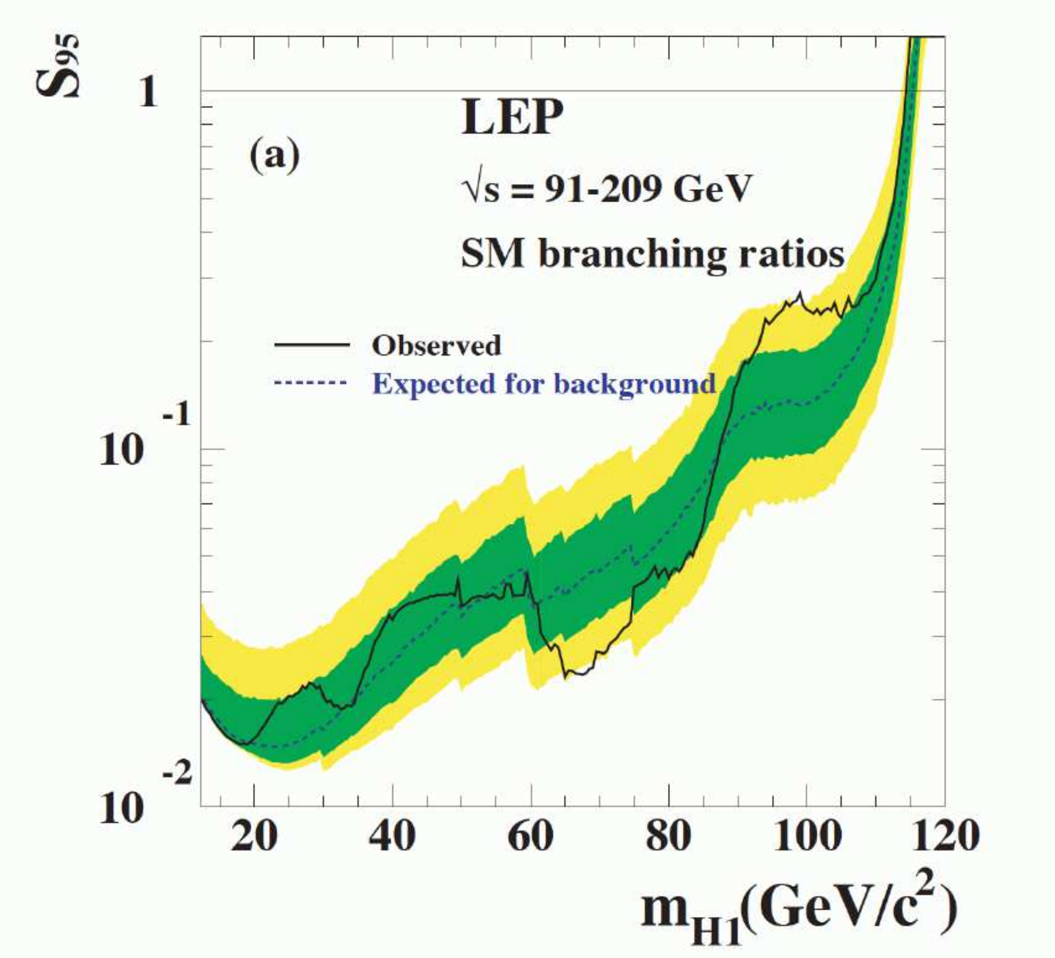
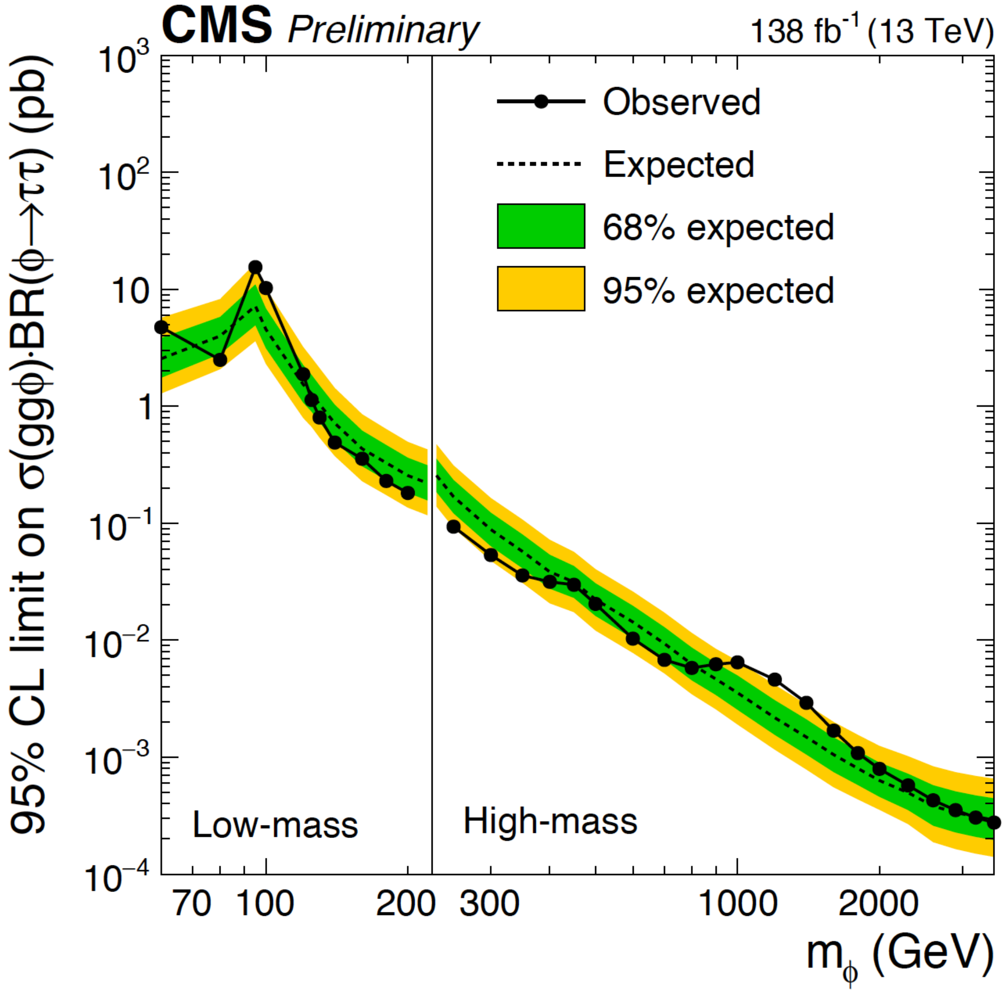


⇒ agreement between ATLAS and CMS! $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ $(3.1\,\sigma)$

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

CMS: $pp \to \phi \to \tau^+\tau^-$ $(2.4\,\sigma)$



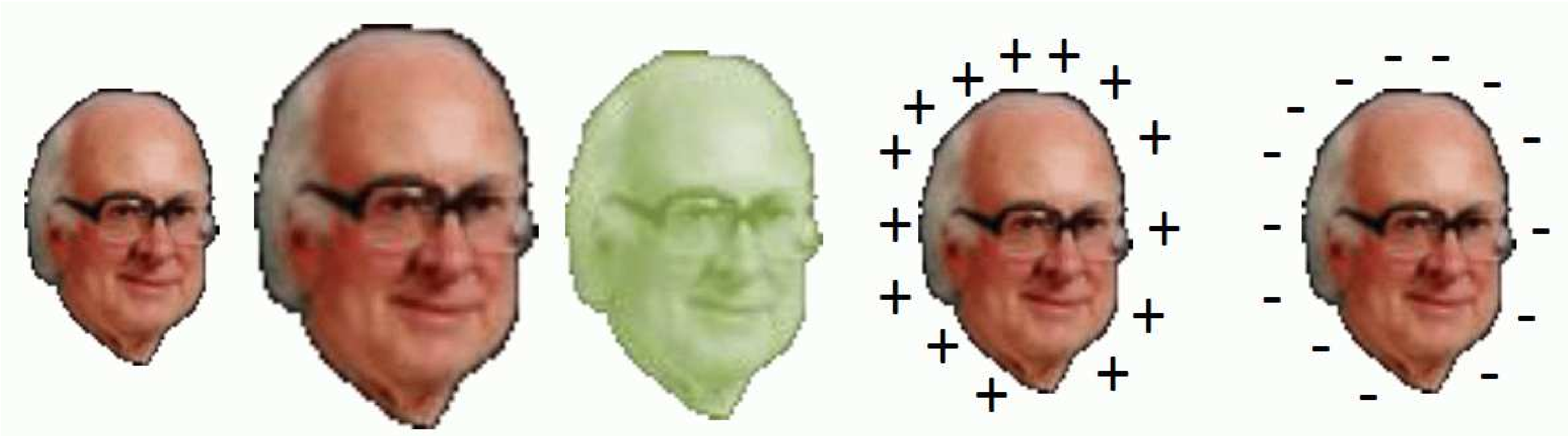


$\mu_{bb}^{\rm exp} = 0.117 \pm 0.057,$ $\mu_{\tau\tau}^{\rm exp} = 1.2 \pm 0.5$

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

$\Rightarrow \sim 4.6\,\sigma$

2. Possible model interpretation



Toy 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)

	$c_{h_iVV} = c_\beta R_{i1} + s_\beta R_{i2}$
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_itt})	d-type (c_{h_ibb})	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:

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

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

– $c^2_{h_1VV}$ strongly reduced for $\mu_{b\bar{b}}$
– c_{h_1bb} reduced to enhance BR($h_1 \to \gamma\gamma$)
– c_{h_1tt} not reduced for $\mu_{\gamma\gamma}$

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	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_1bb} and c_{h_1tt} independent

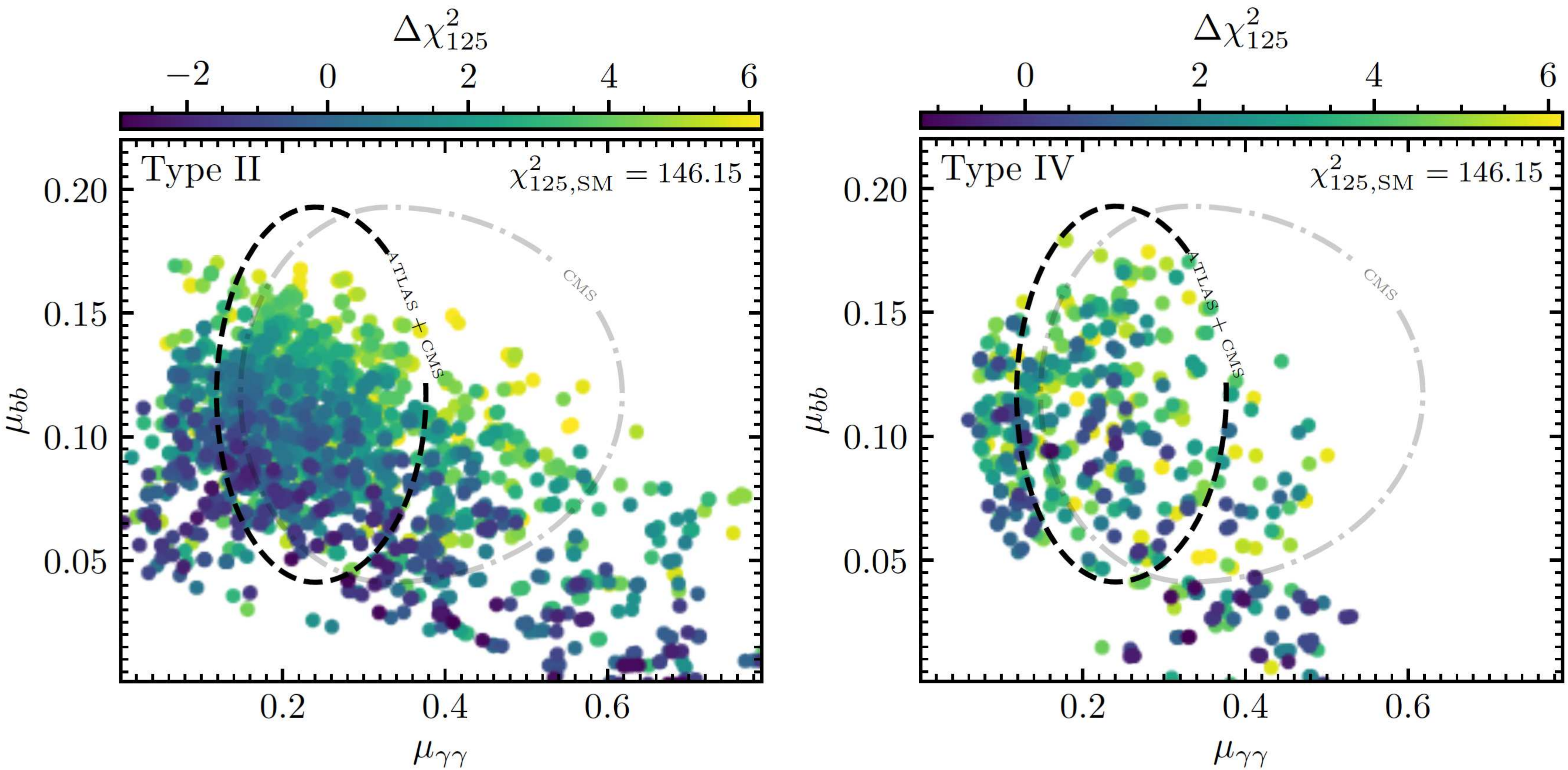
Type II vs. IV: $c_{h_1\tau\tau}$ can be suppressed or enhanced

$\Rightarrow$ 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*]

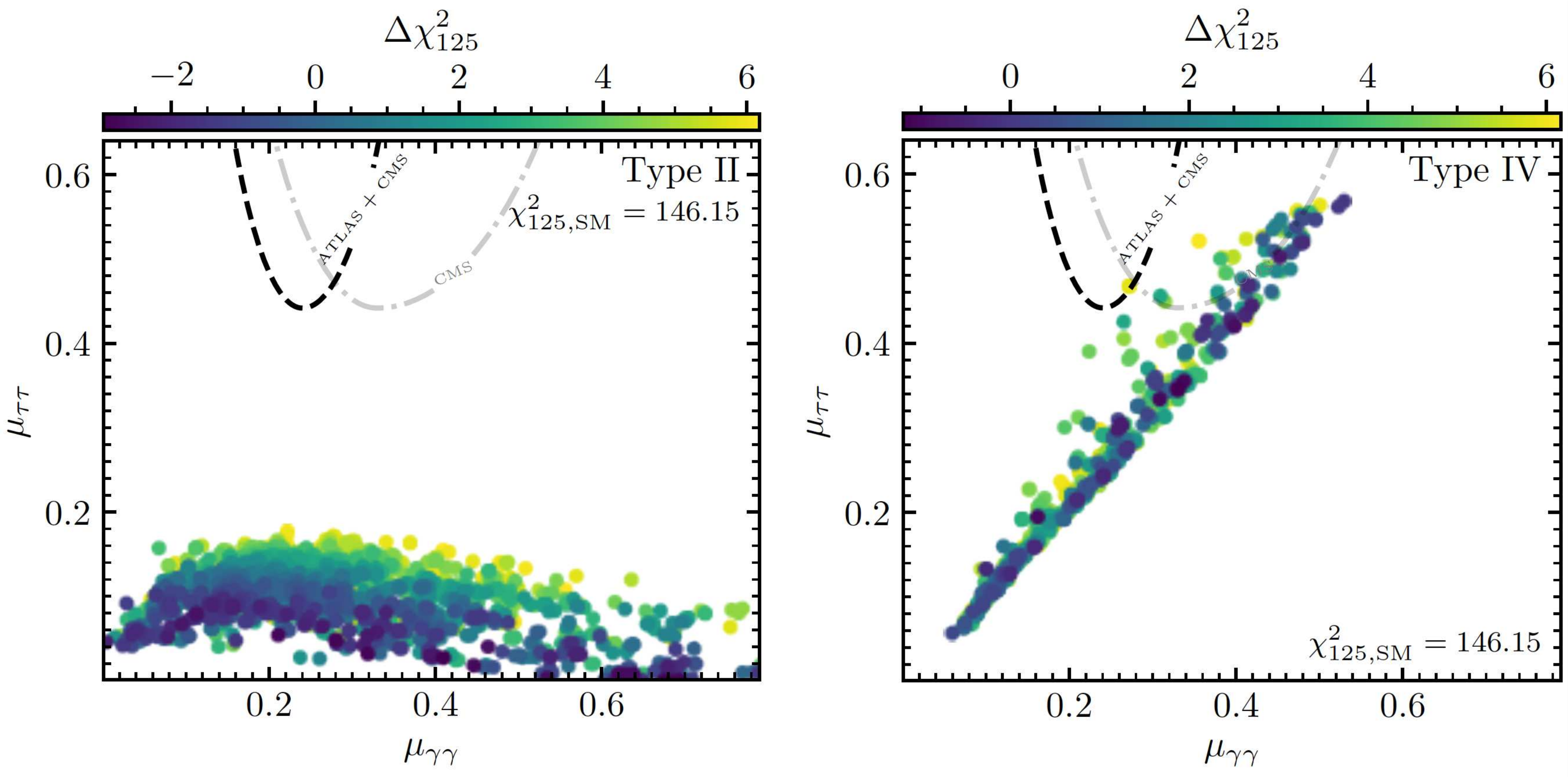


Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ 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

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

3. Physics opportunities at e^+e^- colliders

What can we learn from future measurements?

– LHC h_{125} coupling measurements

– HL-LHC h_{125} coupling measurements

– ILC h_{125} coupling measurements

– direct production of ϕ_{95} at the LHC

– direct production of ϕ_{95} at the HL-LHC

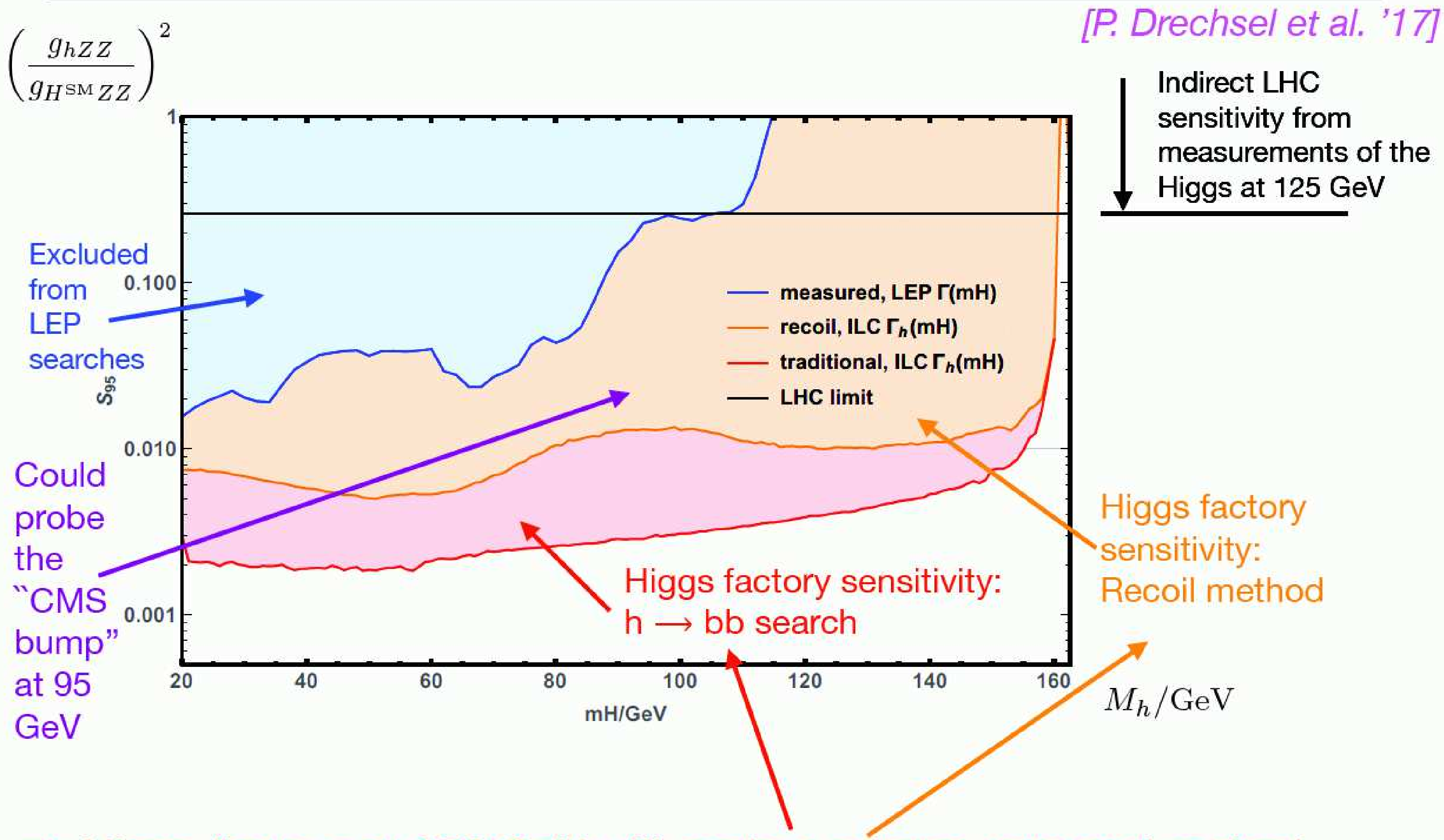
– direct production of ϕ_{95} at the ILC

– ILC ϕ_{95} coupling measurements

– production of other BSM Higgs bosons at the LHC/HL-LHC/ILC/. . .

ILC = ILC (or other e^+e^- collider)

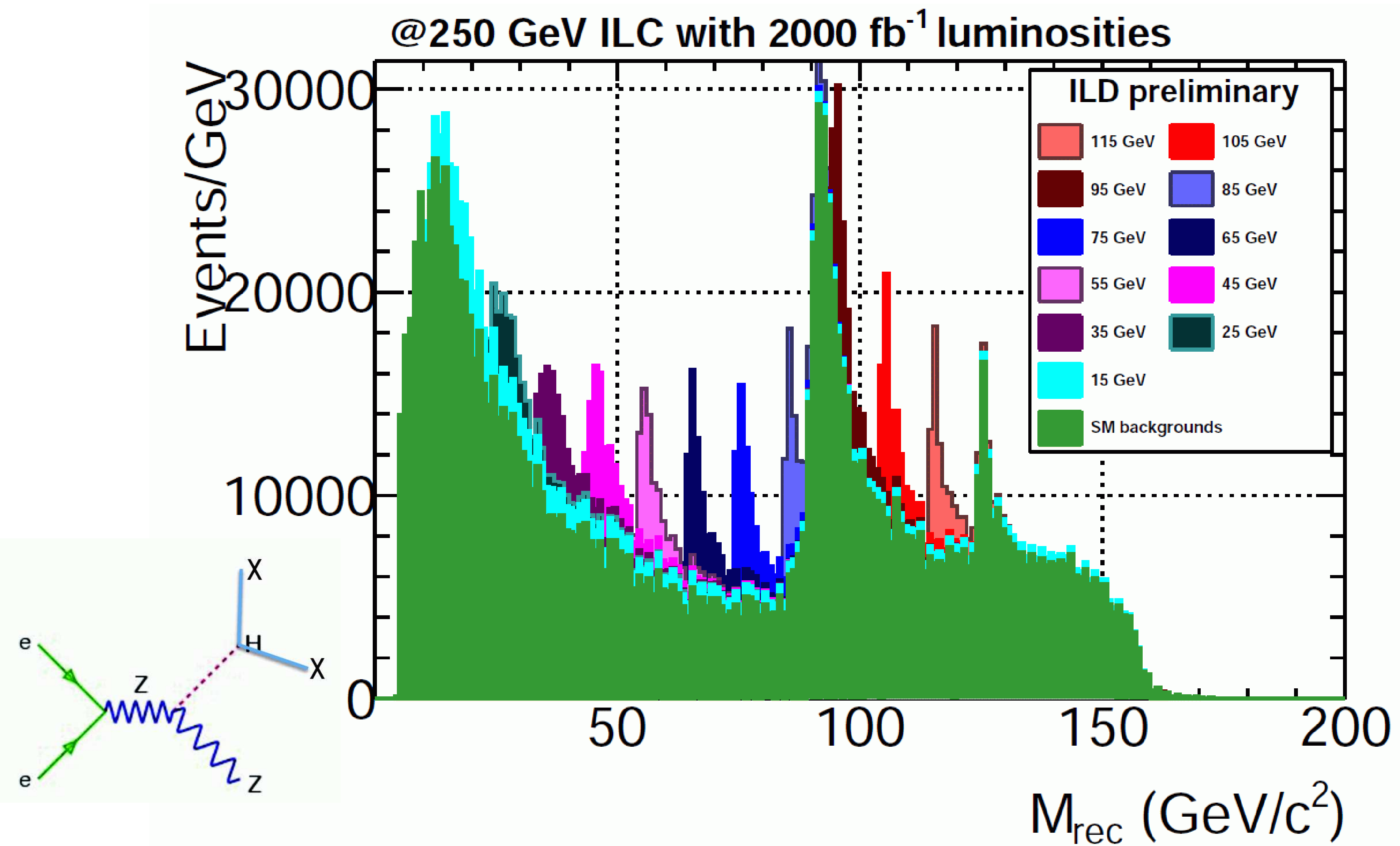
Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs



$\Rightarrow$ Higgs factory at 250 GeV will explore a large untested region!

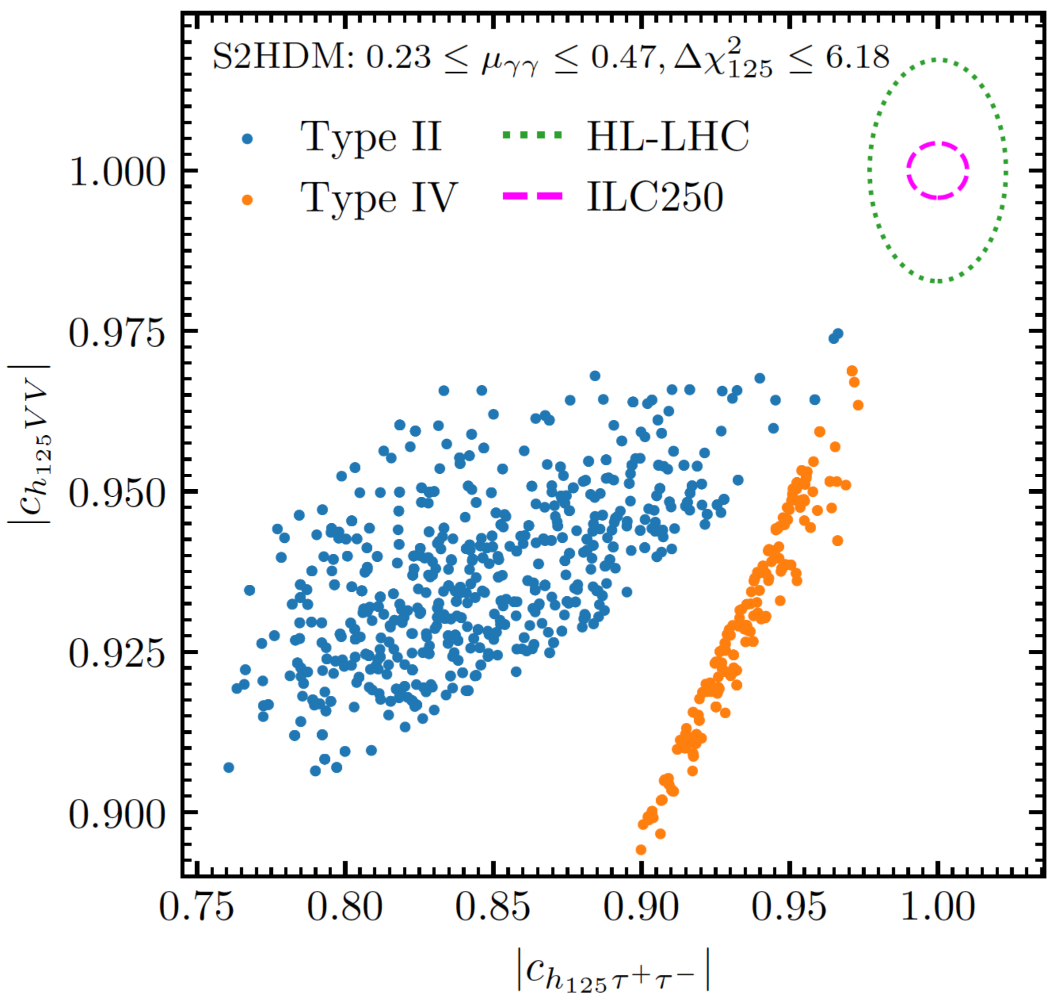
[*Taken from G. Weiglein '18*]

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



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

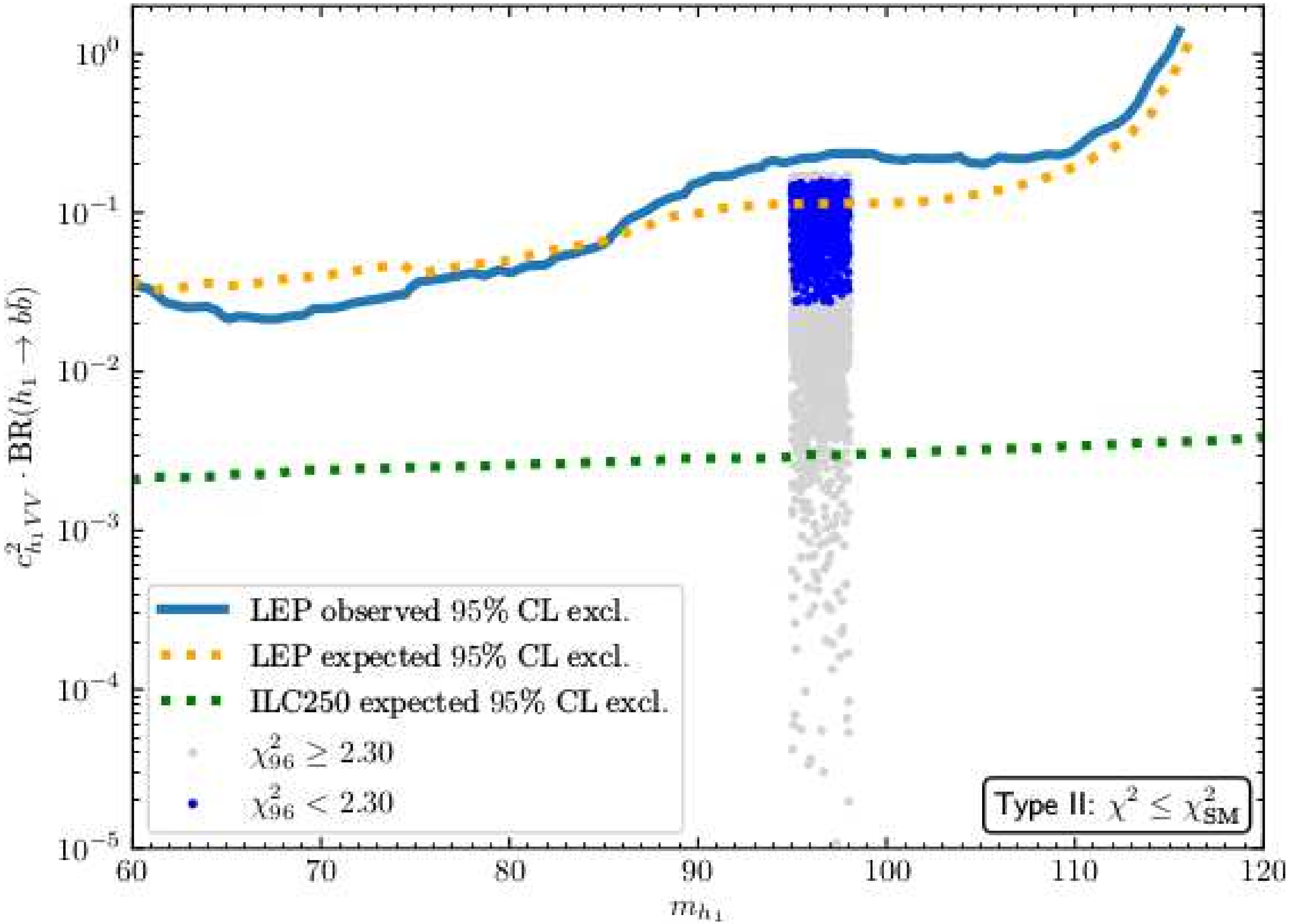
[*T. Biekötter, S.H., G. Weiglein '23*]



$\Rightarrow$ both types show some deviation from SM

Production of the light Higgs at the ILC:

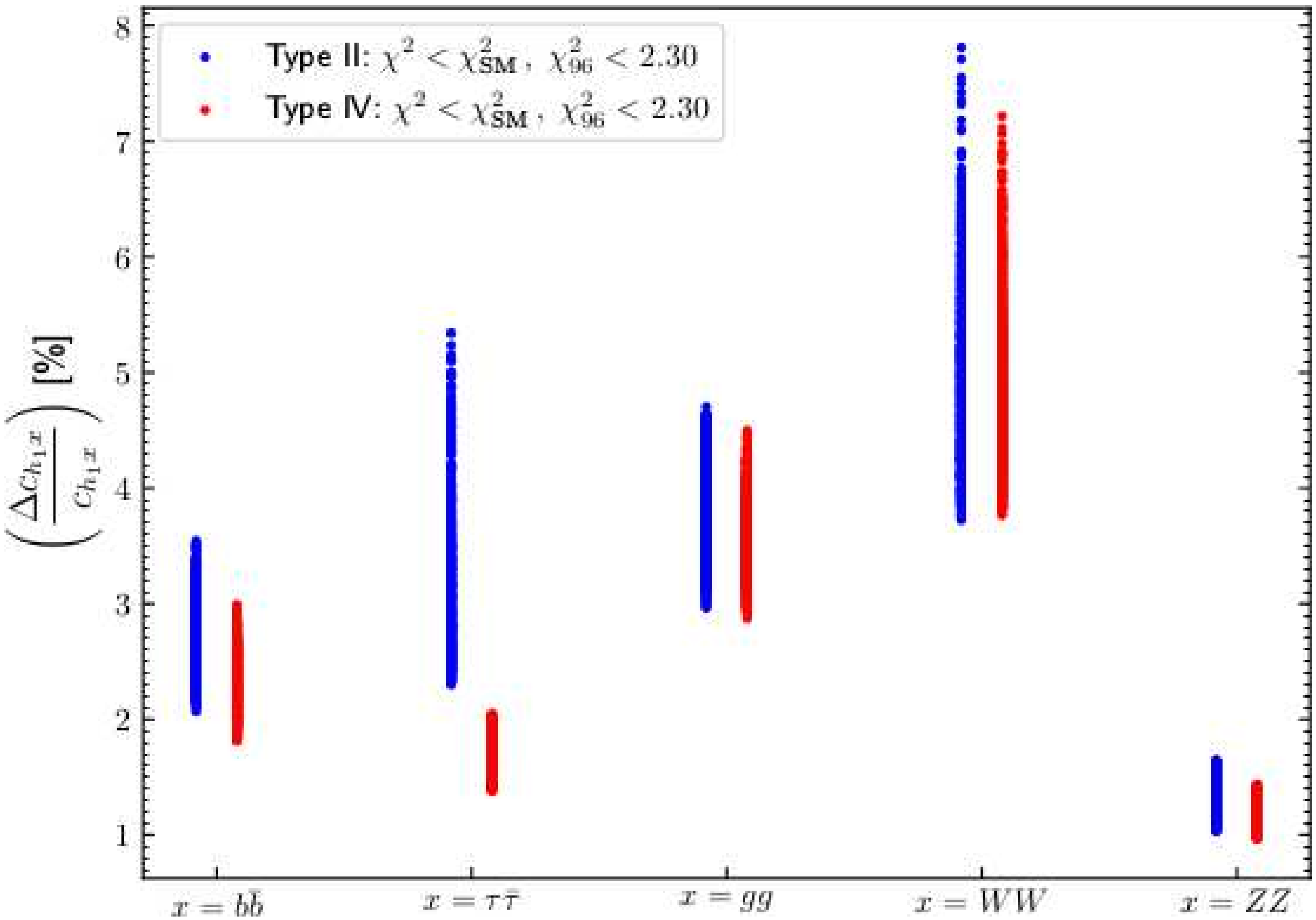
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

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

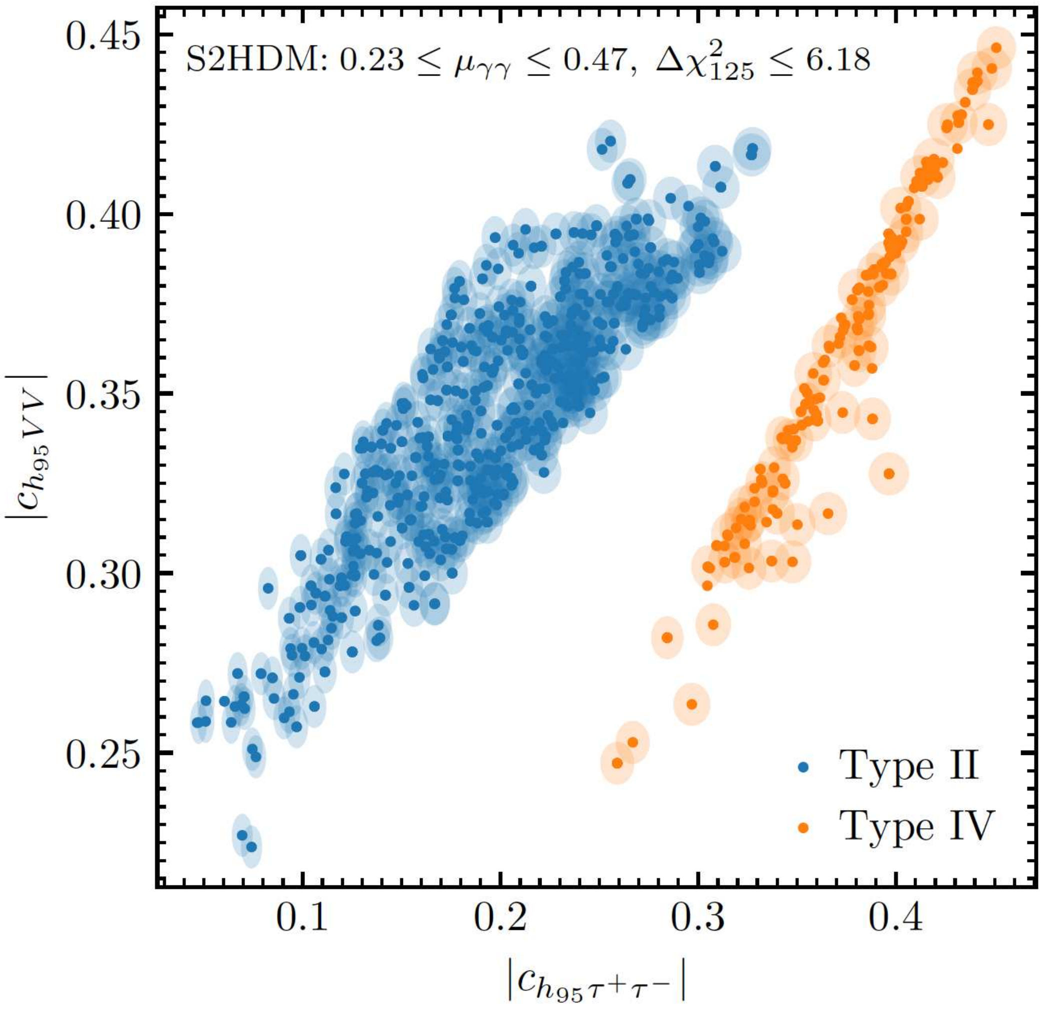
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ clear difference in $g_{h_{95}\tau\tau}$ as expected

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

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



$\Rightarrow$ models clearly distinguishable!

4. Conclusinos

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

  $\Rightarrow$ possible explanations: $\gamma\gamma$, $b\bar{b}$: type II/IV, $\tau\tau$: type IV only

- ILC250: analysis of h_{125}:
  - precision measurements of couplings can distinguish N2HDM vs. SM
  - possible distinction between type II and IV

- ILC250: analysis of h_{95}:
  - h_{95} can be produced abundantly
  - precision in couplings: 1-8%: g_Z best from production
  - coupling measurements ($\tau\tau$, ZZ) clearly distinguishes type II and IV


Further Questions?

SUSY realizations

What about SUSY??

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$\Rightarrow$ type II is needed for SUSY

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– NMSSM
– $\mu\nu$SSM
– . . .

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– $\mu\nu$SSM
– . . .

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

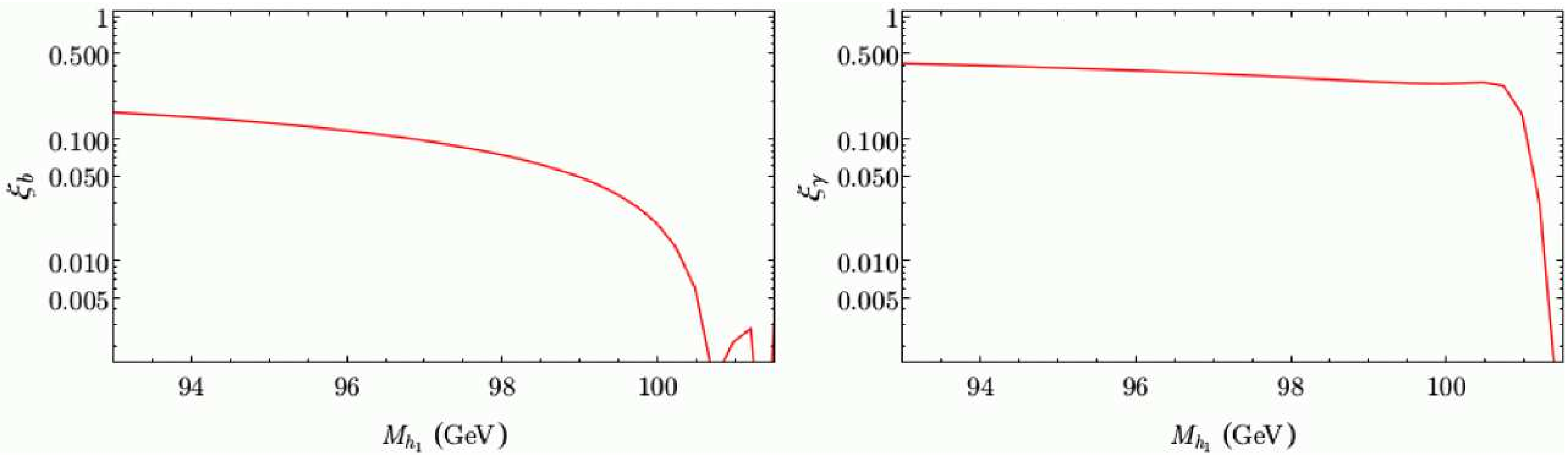
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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



⇒ 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	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\tilde{e}})_{ii}$	A_{33}^e	$A_{11,22}^e$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

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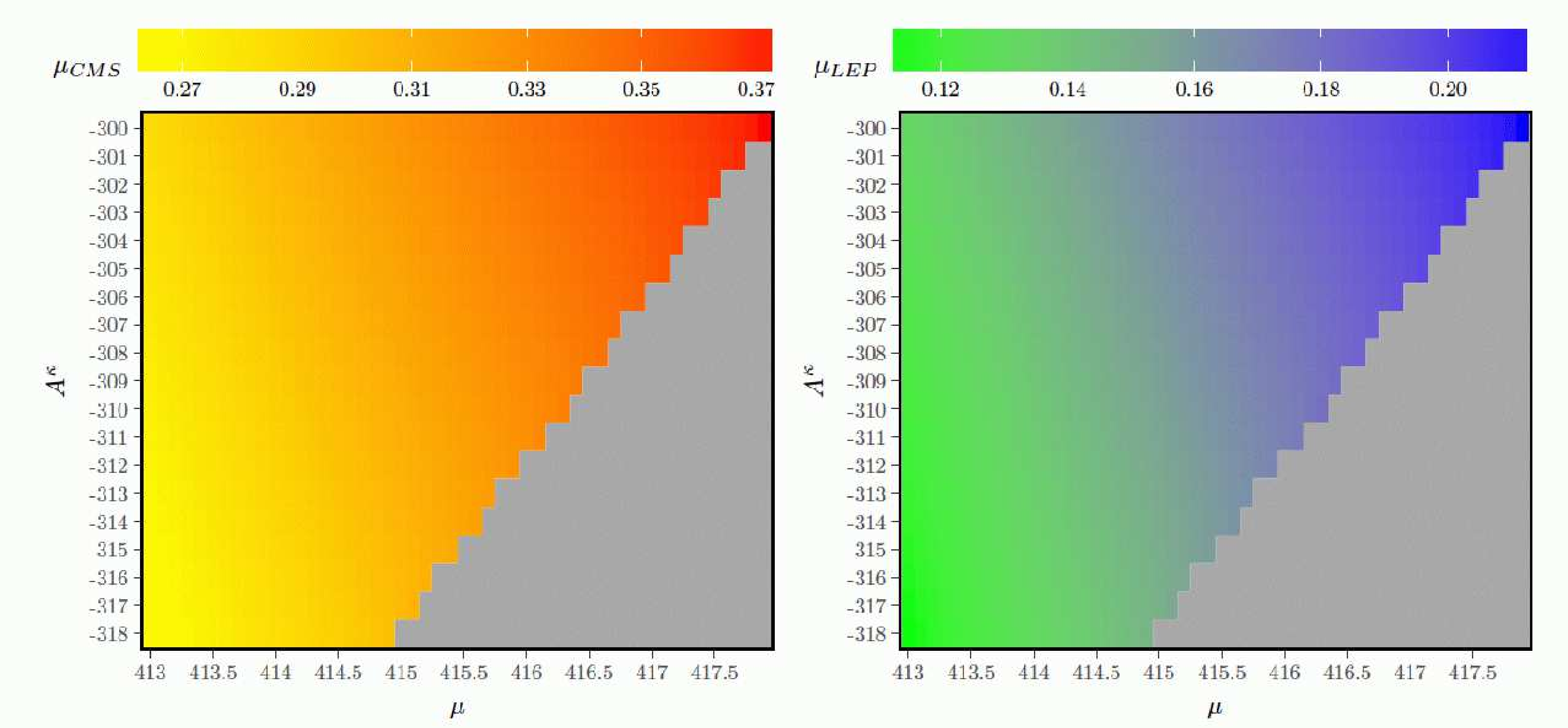
[*T. Biekötter, S.H., C. Muñoz '17*]

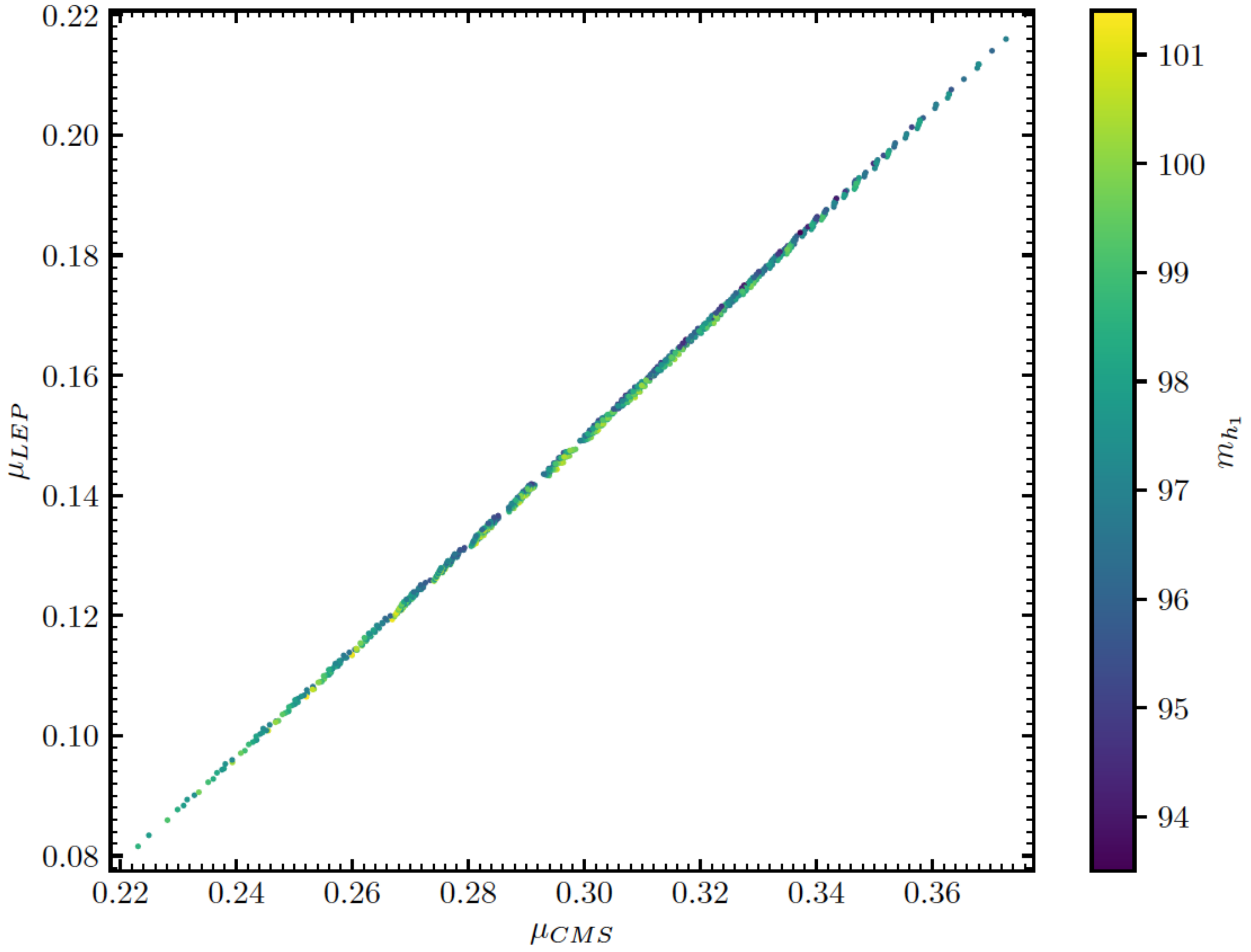


$\Rightarrow$ Yes! :-)

using the new $\mu_{\gamma\gamma}$!

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

[*T. Biekötter, S.H., C. Muñoz '19*]



⇒ SUSY enforces strong correlation!

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

How to evaluate the precision of ϕ_{95} coupling measurements?

Start with data of the SM Higgs:

SM Higgs BRs: [*YR4 LHCHXSWG*]

final state	$b\bar{b}$	gg	$\tau^+\tau^-$	WW^*	σ_{ZH}
BR	0.582	0.082	0.063	0.214	206 fb

SM Higgs coupling uncertainties:

ILC, $\mathcal{L}_{\text{int}} = 2\,\text{ab}^{-1}$ at $\sqrt{s} = 250$ GeV [*T. Barklow et al. '17*]

coupling	$b\bar{b}$	gg	$\tau^+\tau^-$	WW	ZZ
rel. unc. [%]	1.04	1.60	1.16	0.65	0.66

SM Higgs S/B: [*S. Dawson et al. '13*] [*J. Tian, priv. commun.*]

coupling	$H \to b\bar{b}$	$H \to gg$	$H \to \tau^+\tau^-$	$H \to WW$	σ_{ZH}
S/B	1/0.89	1/13	1/0.44	1/0.96	1/1.65

Some more basics:

$$f := S/B \equiv N_S/N_B$$

$$\frac{\Delta N_S}{N_S} = \frac{1}{\sqrt{N_S}} \sqrt{1 + 1/f}$$

Holds is background is known perfectly and the overall uncertainty is dominated by statistical precision

Uncertainty improves with $1/\sqrt{N_S}$ for $f = S/B \gg 1$

Cross section for ϕ_{95}:

$$\sigma(e^+e^- \to \phi Z) = \sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 95}) \times |c_{\phi VV}|^2$$

$$\sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 95}) = 0.332\,\text{pb}$$

$\Rightarrow \mathcal{O}\left(10^5\right)$ ϕ_{95}'s can be produced at $\sqrt{s} = 250$ GeV and $\mathcal{L}_{\text{int}} = 2\,\text{ab}^{-1}$

Evaluating uncertainties:

- Coupling is measured via decay
  A new Higgs boson ϕ couples with g_x to xx

$$\Gamma(\phi \to xx) \propto g_x^2$$

$$\mathrm{BR}(\phi \to xx) =: 1/p$$

$$\frac{\Delta N_S}{N_S} = 2\,\frac{\Delta g_x}{g_x}\left(1 - \frac{1}{p}\right)$$

- Coupling is measured via production: g_Z

$$\sigma(e^+e^- \to Z\phi) \propto g_Z^2$$

$$\frac{\Delta N_S}{N_S} = 2\,\frac{\Delta g_x}{g_x}$$

- Final assumption: $\left(\frac{N_S}{N_B}\right)_H / \left(\frac{N_S}{N_B}\right)_\phi = f_H/f_\phi =: D$

  with $D = 3$ as starting point

Evaluating uncertainties of ϕ_{95}:

- Coupling is measured via decay

$$\left(\frac{\Delta g_x}{g_x}\right)_\phi = \left(\frac{\Delta g_x}{g_x}\right)_H \times \frac{\left(\frac{\Delta N_S}{N_S}\right)_\phi}{\left(\frac{\Delta N_S}{N_S}\right)_H} \times \frac{\left(1-\frac{1}{p_H}\right)}{\left(1-\frac{1}{p_\phi}\right)}$$

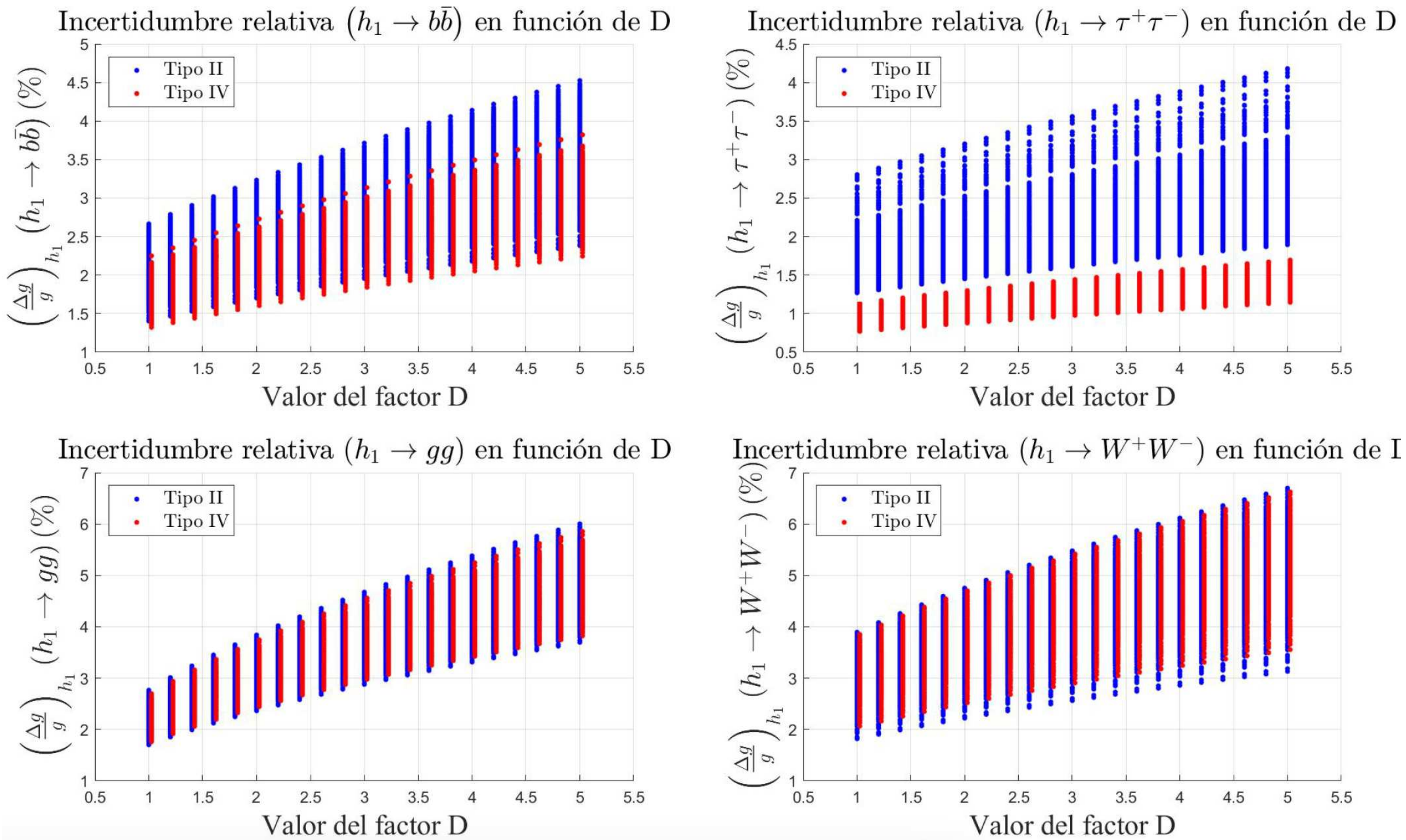
$$\to \sqrt{\frac{D+f_H}{1+f_H}} \times \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}} \times \sqrt{\frac{\mathrm{BR}(H \to xx)}{\mathrm{BR}(\phi \to xx)}} \times \frac{(1-\mathrm{BR}(H \to xx))}{(1-\mathrm{BR}(\phi \to xx))}$$

- Coupling is measured via production: g_Z (S/B does not change)

$$\left(\frac{\Delta g_Z}{g_Z}\right)_\phi = \left(\frac{\Delta g_Z}{g_Z}\right)_H \times \frac{\left(\frac{\Delta N_S}{N_S}\right)_\phi}{\left(\frac{\Delta N_S}{N_S}\right)_H}$$

$$\to \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}}$$

N2HDM: dependence on $D = f_H/f_\phi$: [S.H., P. Toledo '20]



$\Rightarrow$ non-negligible, but small $\Rightarrow$ "robust" result