



I FOUND THE HUGS BISON.

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The h_{95} at the LHC and e^+e^- colliders

Sven Heinemeyer, IFT (CSIC, Madrid)

Madrid, 06/2024

1. Evidence for a light Higgs boson at the LHC
2. Possible model interpretation
3. Physics opportunities at e^+e^- colliders
4. Evidence for SUSY Higgses?!
5. Conclusions

1. Evidence for a light Higgs boson



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 $pp \rightarrow \phi \rightarrow \gamma\gamma$

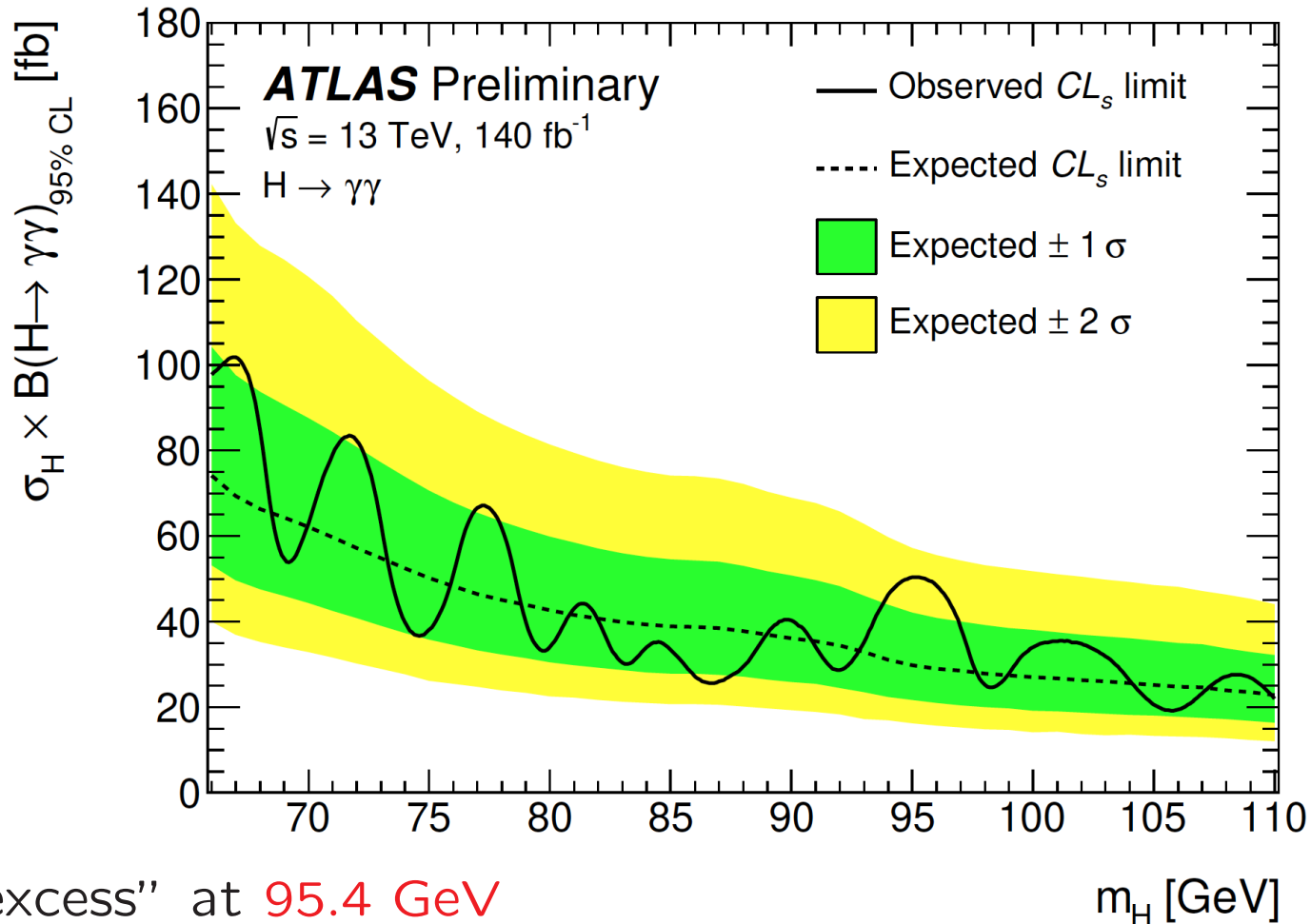
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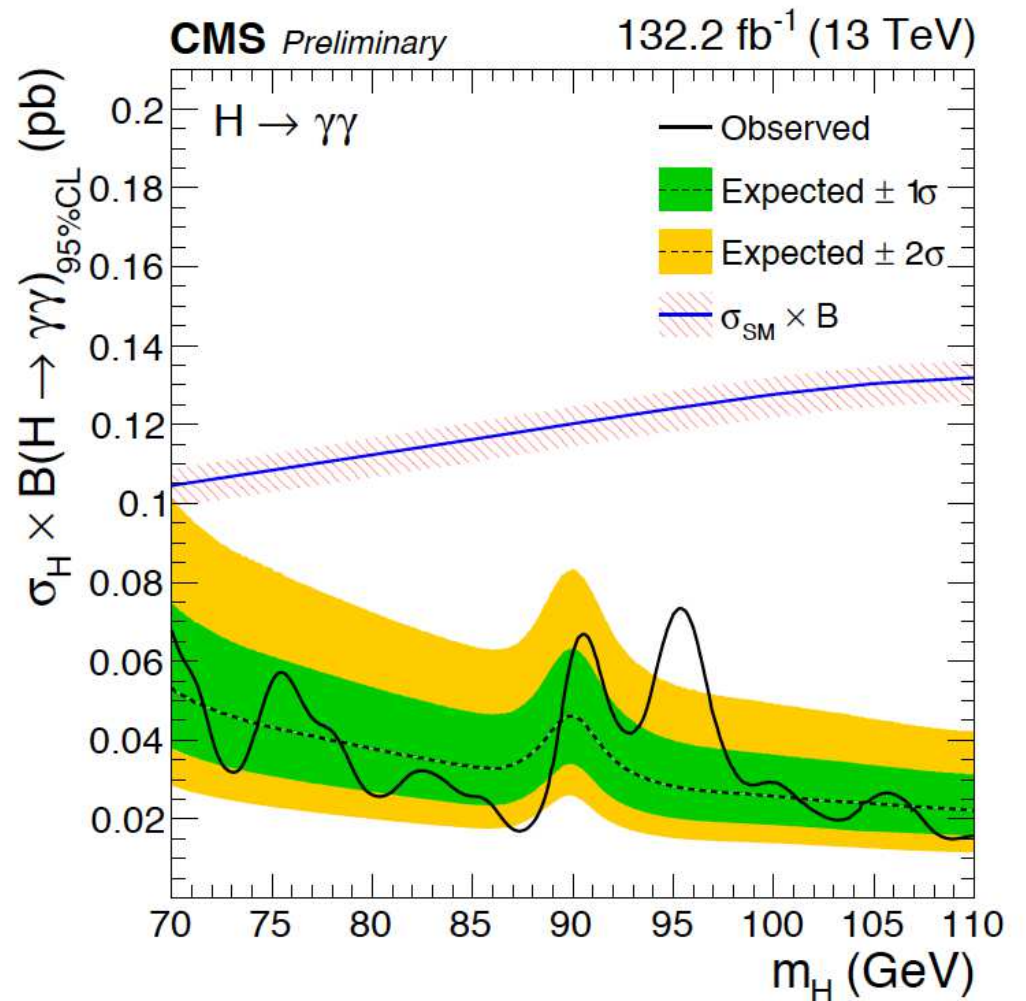
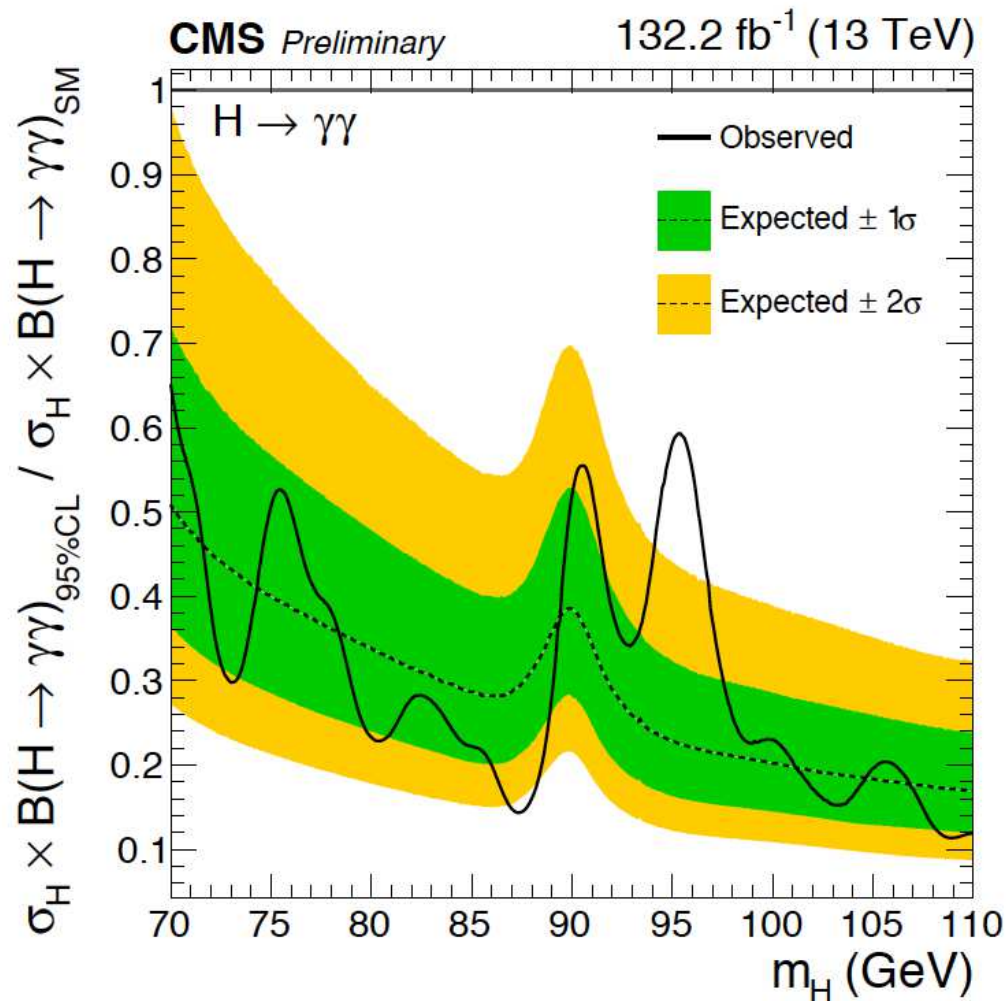
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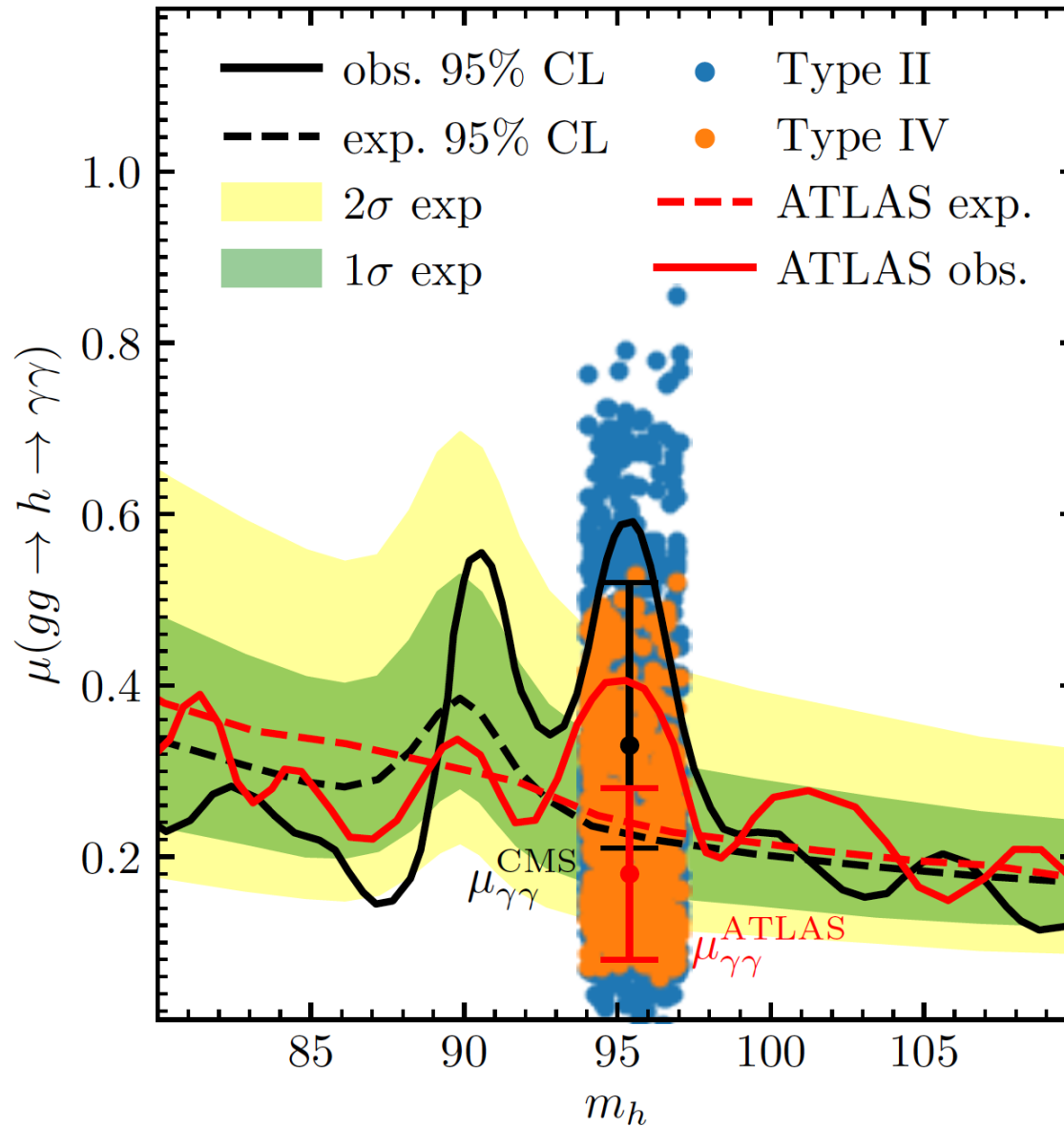
New ATLAS result on the low-mass Higgs search in $pp \rightarrow \phi \rightarrow \gamma\gamma$



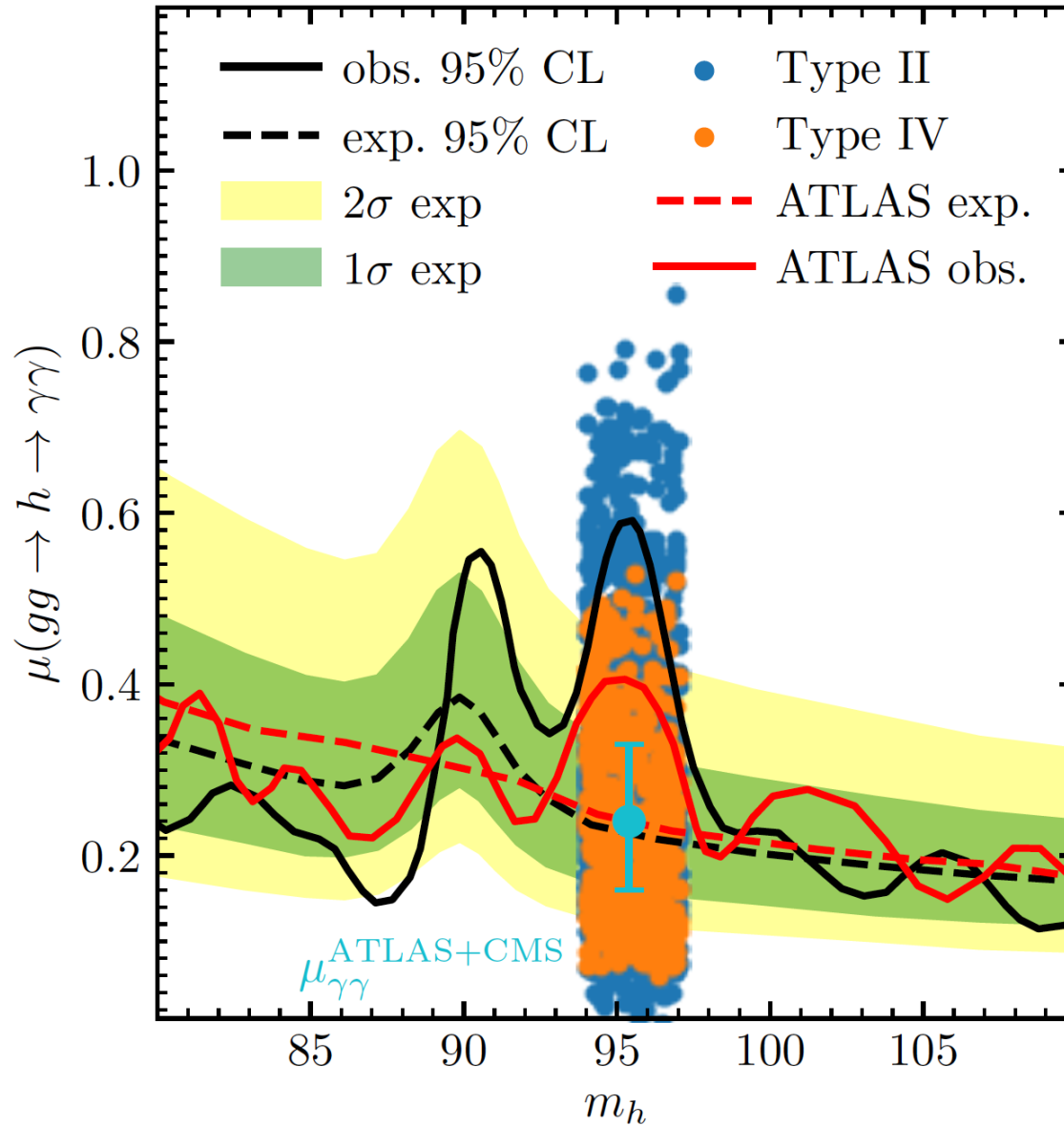


$$\mu_{\gamma\gamma}^{CMS} = [\sigma(gg \rightarrow h_{95}) \times BR(h_{95} \rightarrow \gamma\gamma)]_{exp/SM} = 0.33^{+0.19}_{-0.12} \quad (2.9 \sigma)$$

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

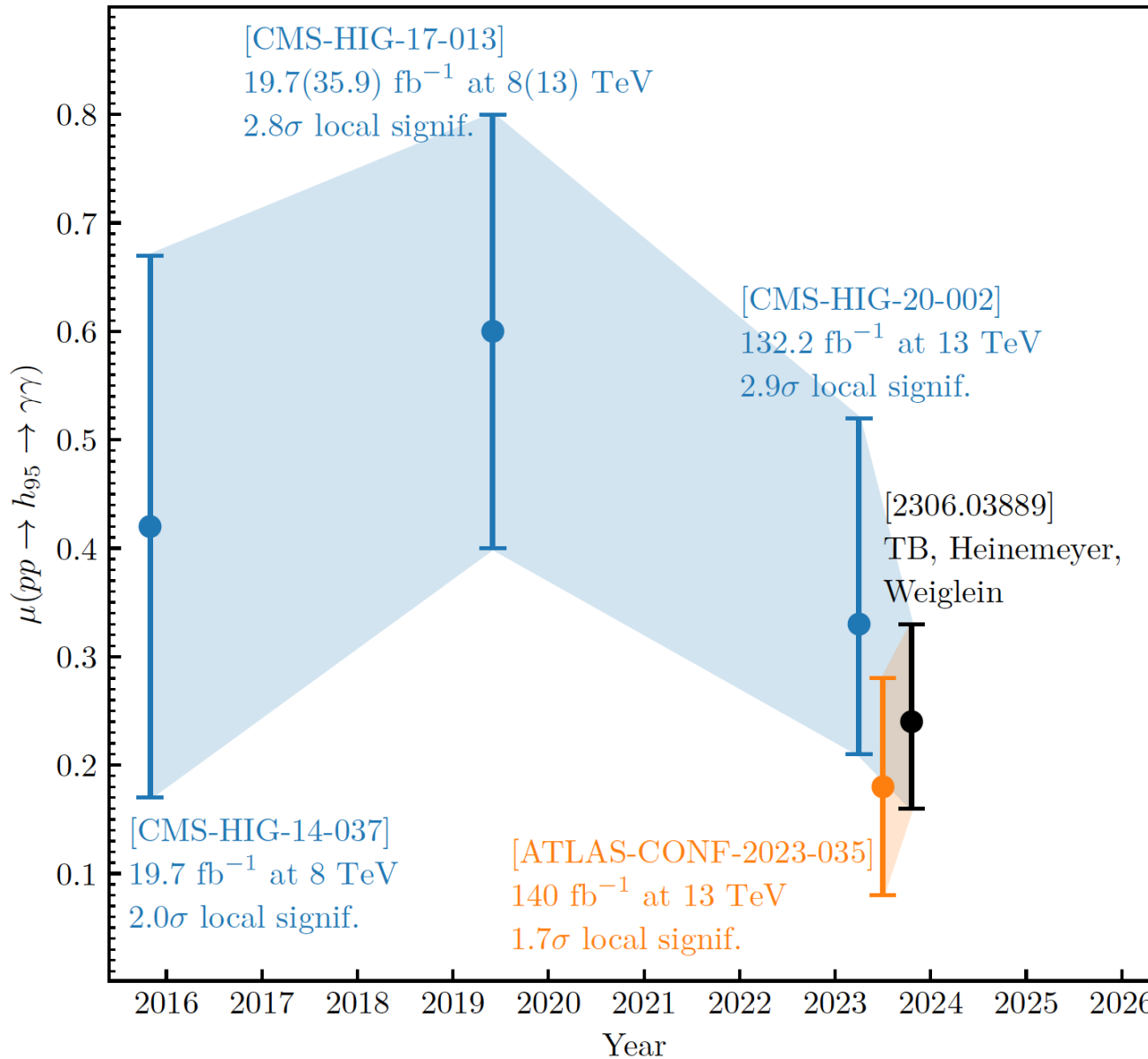


\Rightarrow agreement between ATLAS and CMS!



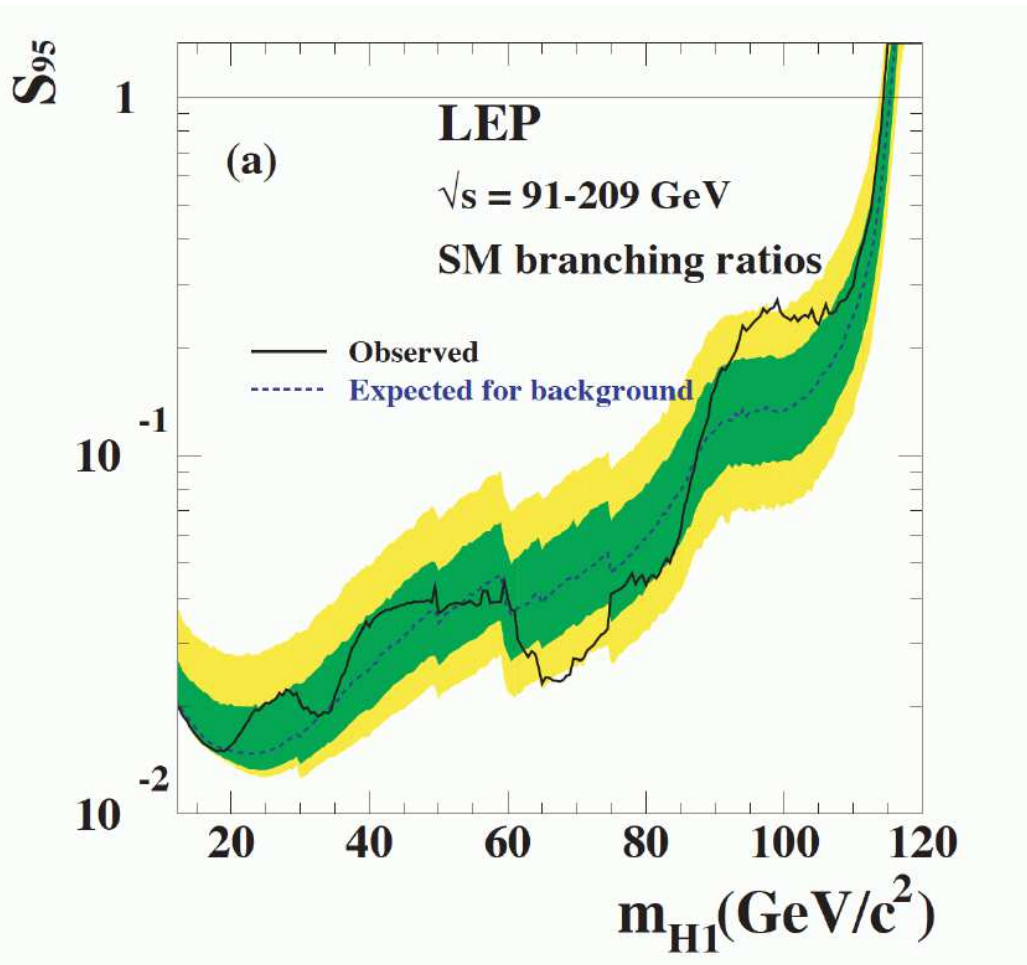
\Rightarrow agreement between ATLAS and CMS!

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



⇒ note the reduction of $\mu_{\gamma\gamma}$ over time!

LEP: $e^+e^- \rightarrow Z\phi \rightarrow Zb\bar{b}$ (2σ)

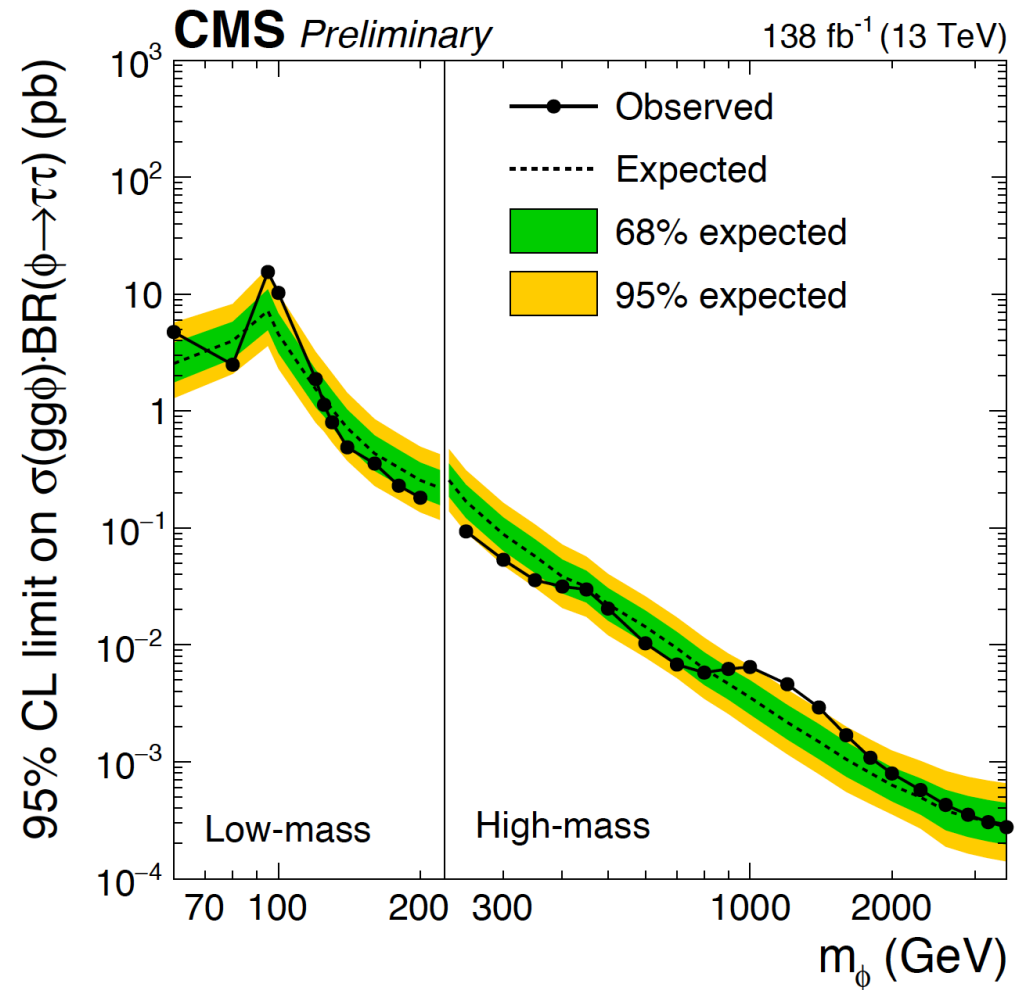


$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057,$$

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

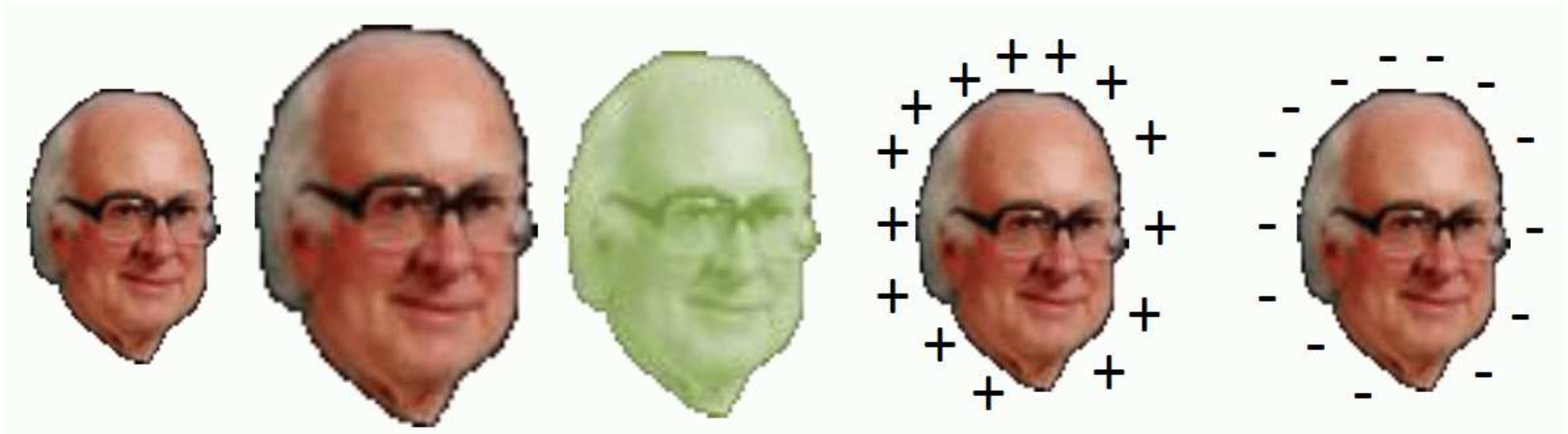
$$\Rightarrow \sim 4.6\sigma$$

CMS: $pp \rightarrow \phi \rightarrow \tau^+\tau^-$ (2.4σ)



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

2. Possible model interpretation



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: $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$, $\Phi_S \rightarrow \Phi_S$ Z'_2 symmetry: $\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow \Phi_2$, $\Phi_S \rightarrow -\Phi_S$ (broken by $v_S \Rightarrow$ no DM)Physical states: h_1, h_2, h_3 (CP -even), A (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)

$$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2}$$

$$h_1 \quad c_{\alpha_2} c_{\beta - \alpha_1}$$

$$h_2 \quad -c_{\beta - \alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta - \alpha_1}$$

$$h_3 \quad -c_{\alpha_3} c_{\beta - \alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta - \alpha_1}$$

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:

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

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

- $c_{h_1 VV}^2$ strongly reduced for $\mu_{b\bar{b}}$
- $c_{h_1 bb}$ reduced to enhance $\text{BR}(h_1 \rightarrow \gamma\gamma)$
- $c_{h_1 tt}$ 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

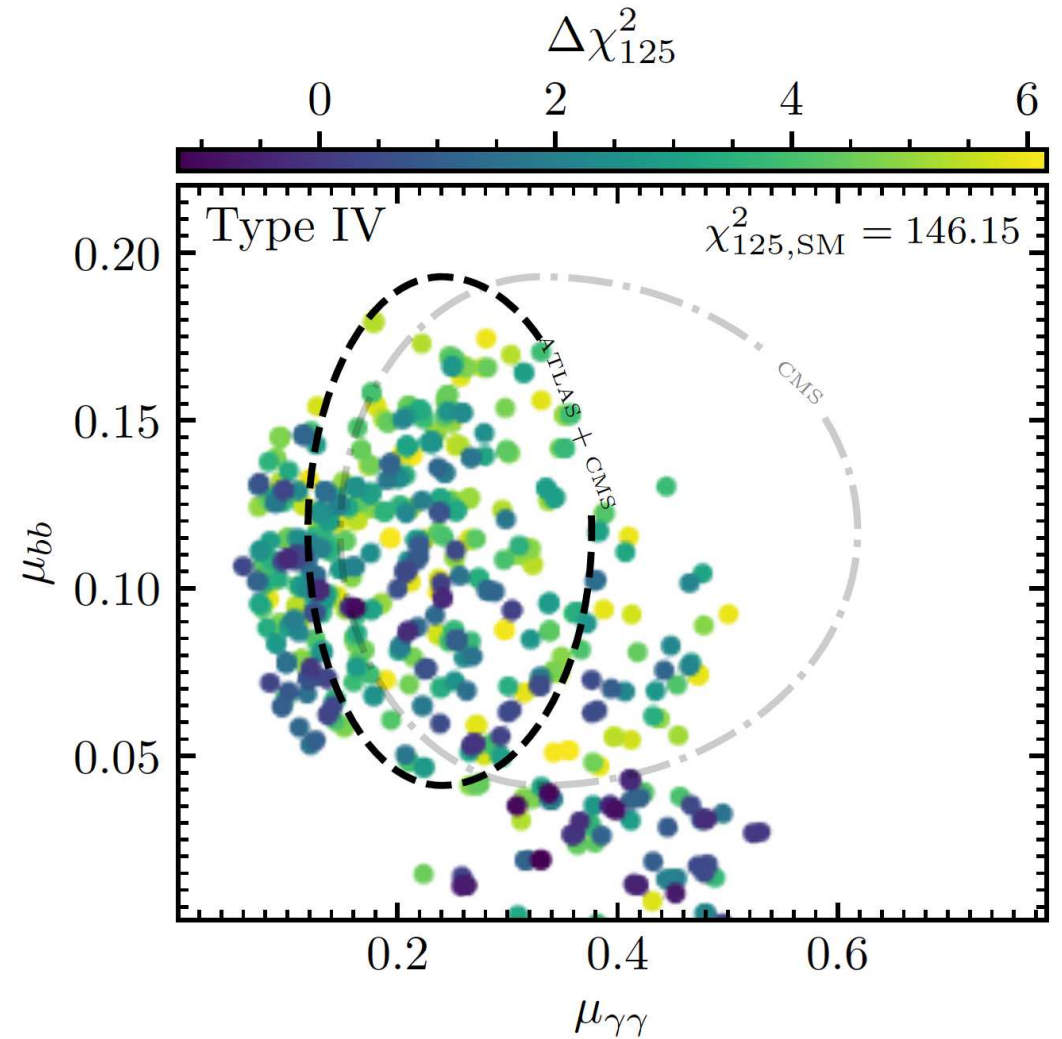
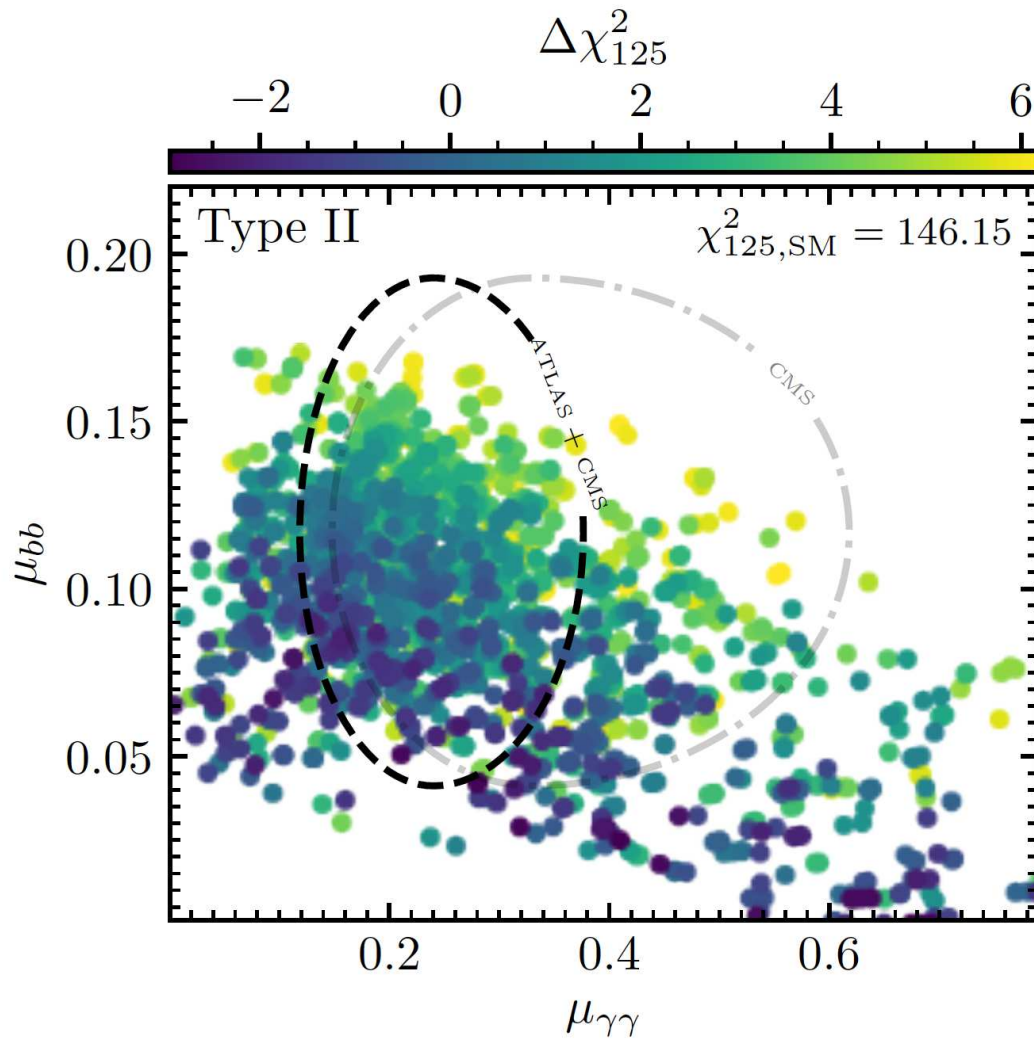
Type II vs. IV: $c_{h_1 \tau\tau}$ can be suppressed or enhanced

\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]

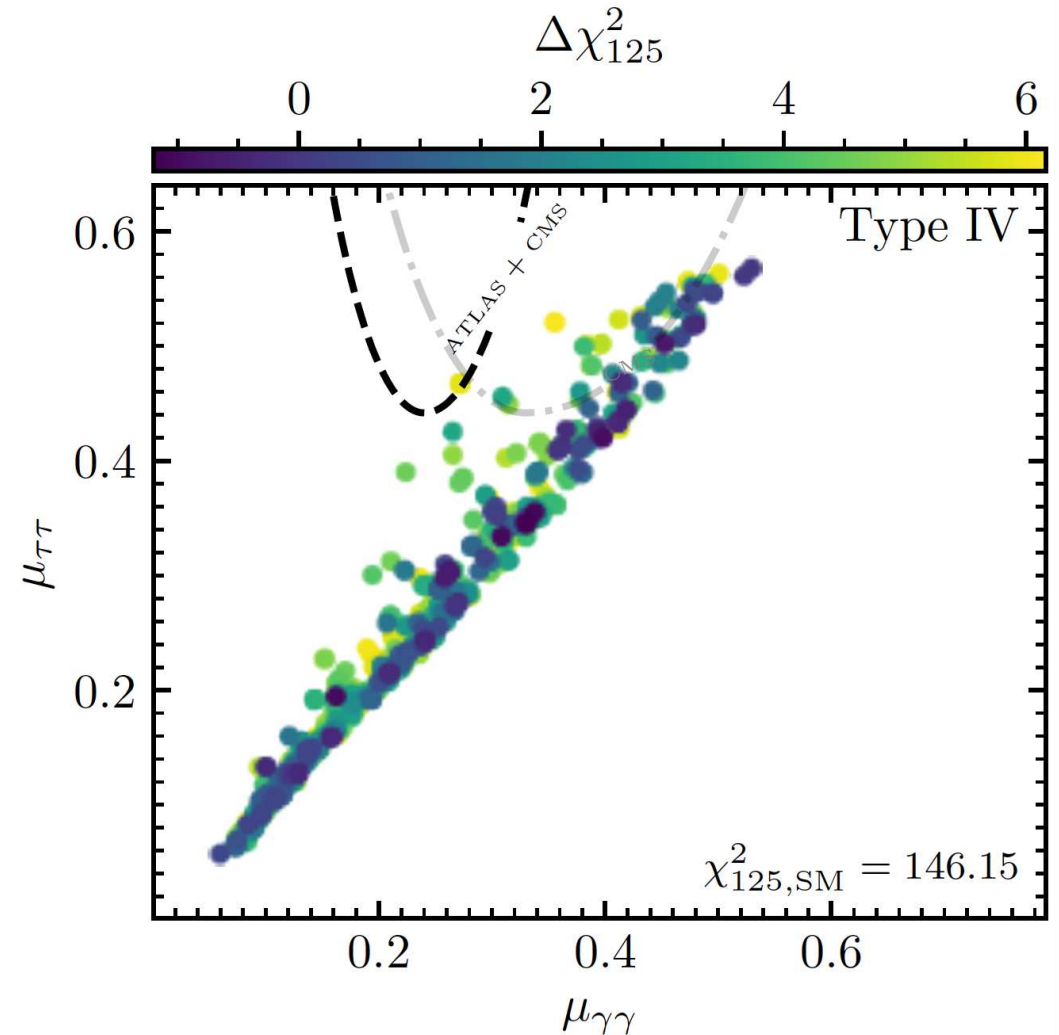
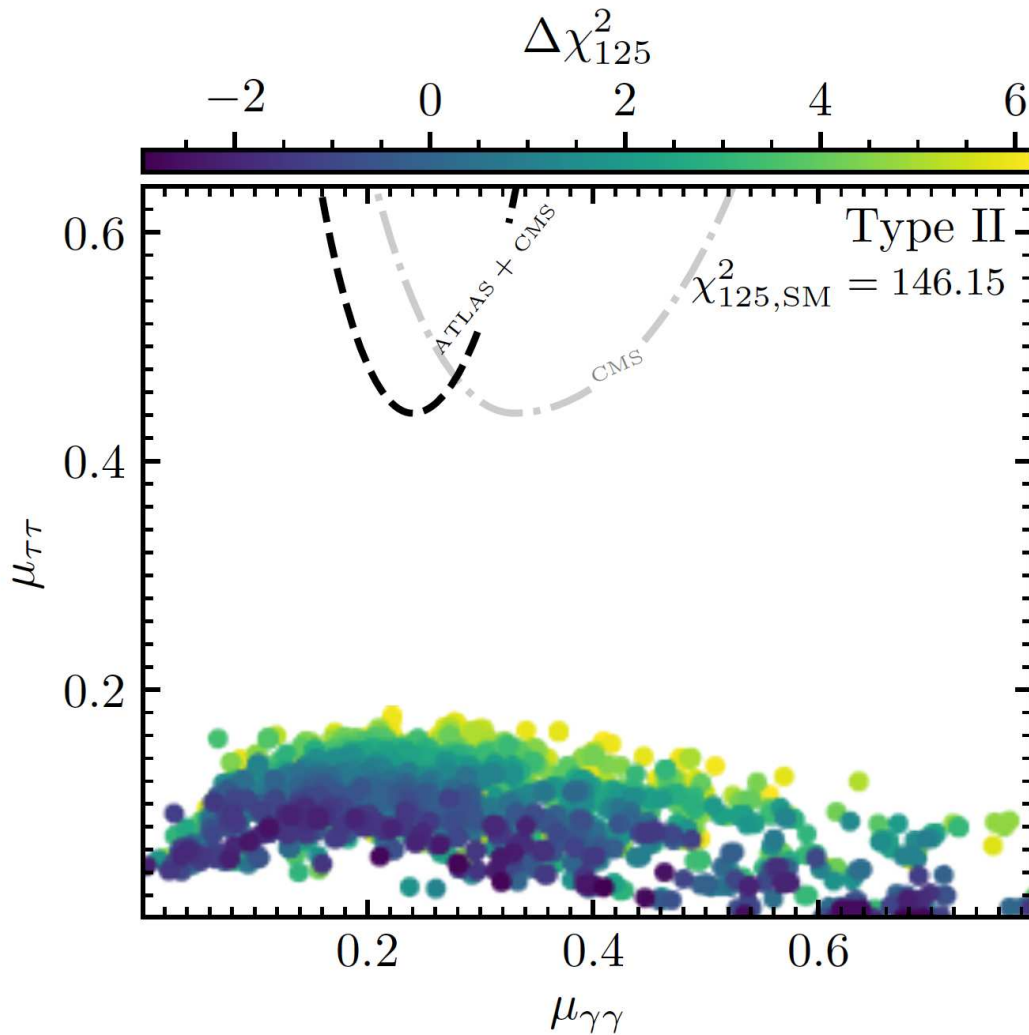


Color coding: χ^2_{125} from HiggsSignals

\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_{125}^2 from HiggsSignals

⇒ 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

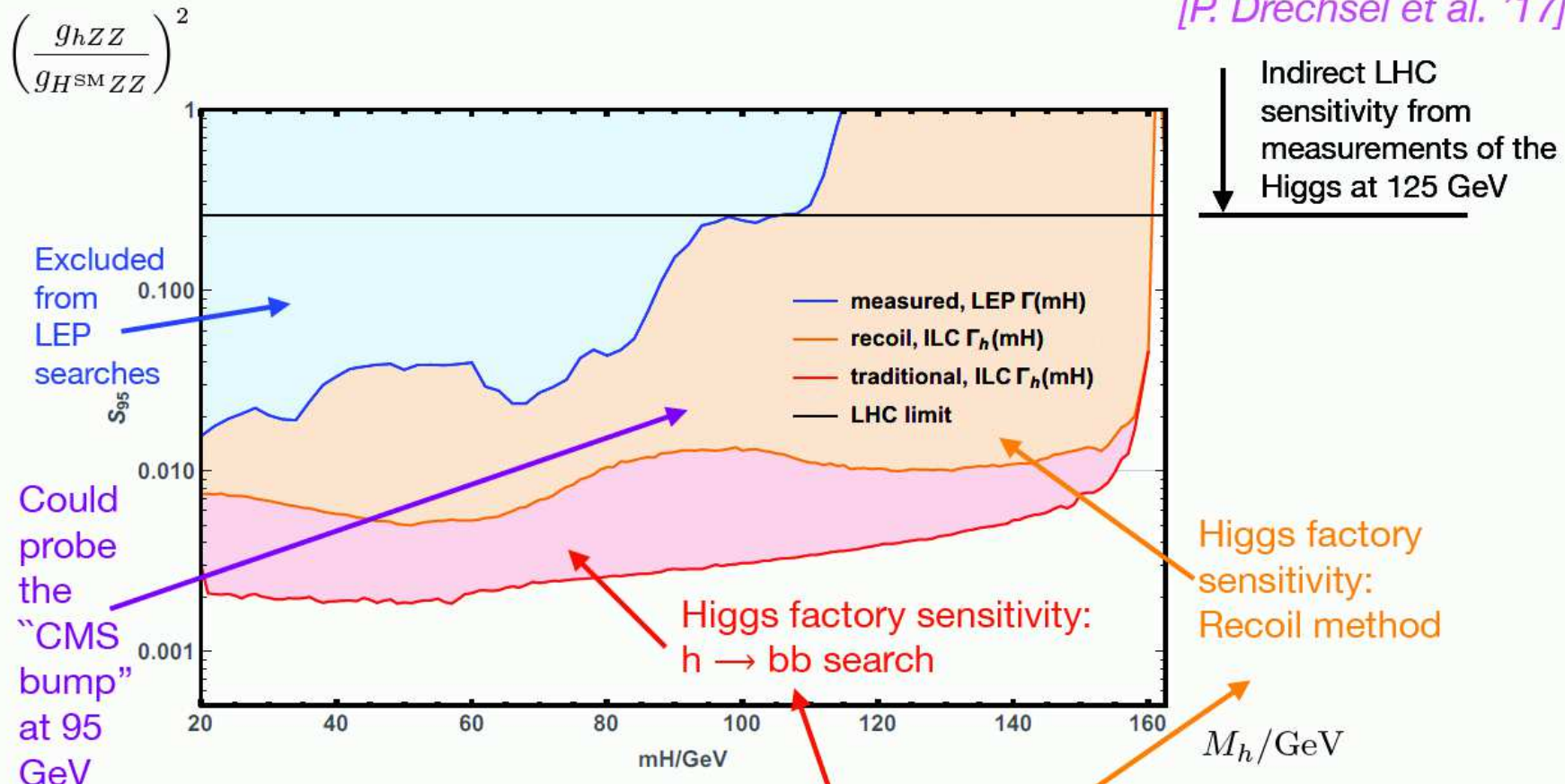
- direct production of ϕ_{95} at the LHC
- direct production of ϕ_{95} at the HL-LHC
- direct production of ϕ_{95} at the **ILC**
- **ILC** ϕ_{95} coupling measurements

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

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

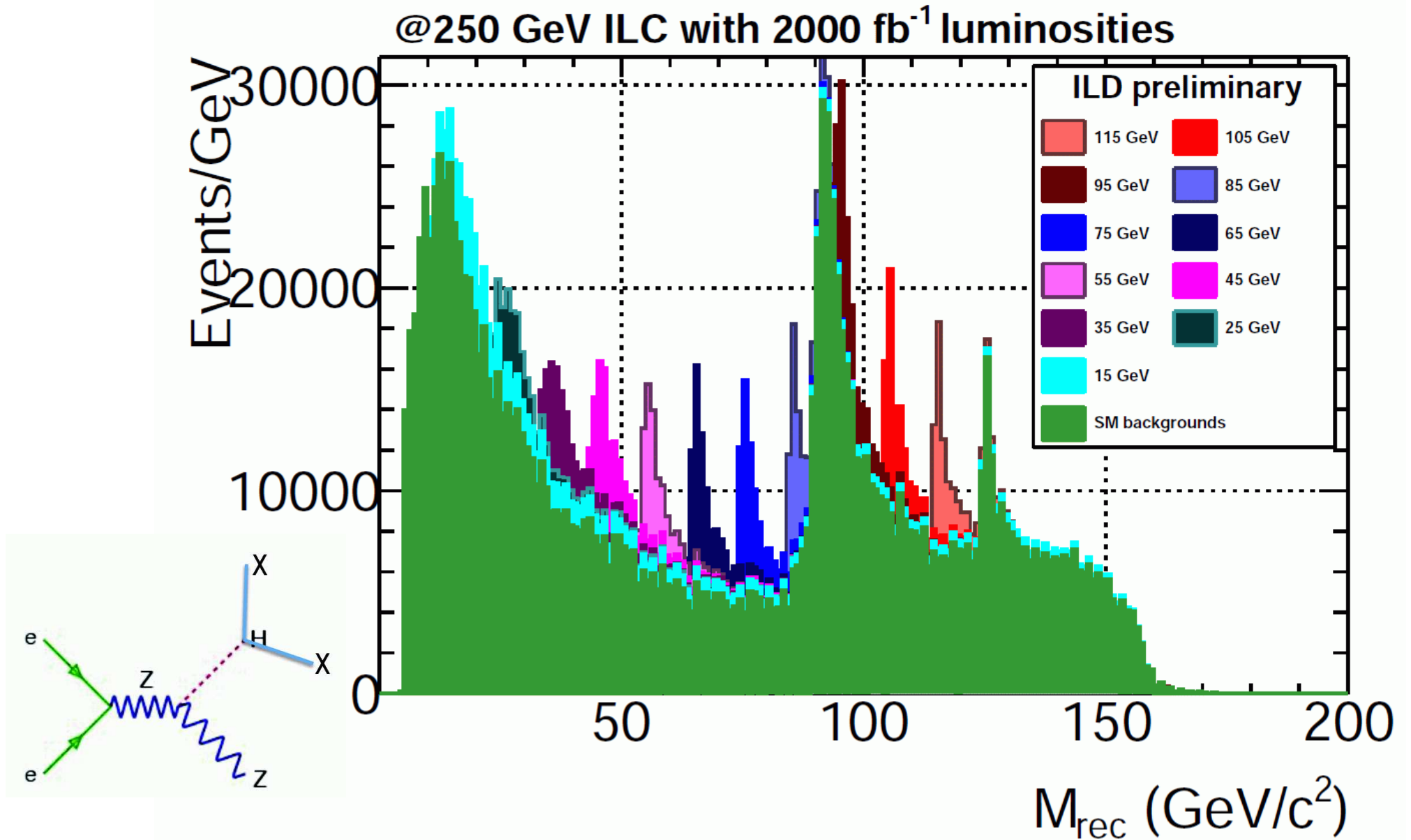
Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb⁻¹ to a new light Higgs

[P. Drechsel et al. '17]



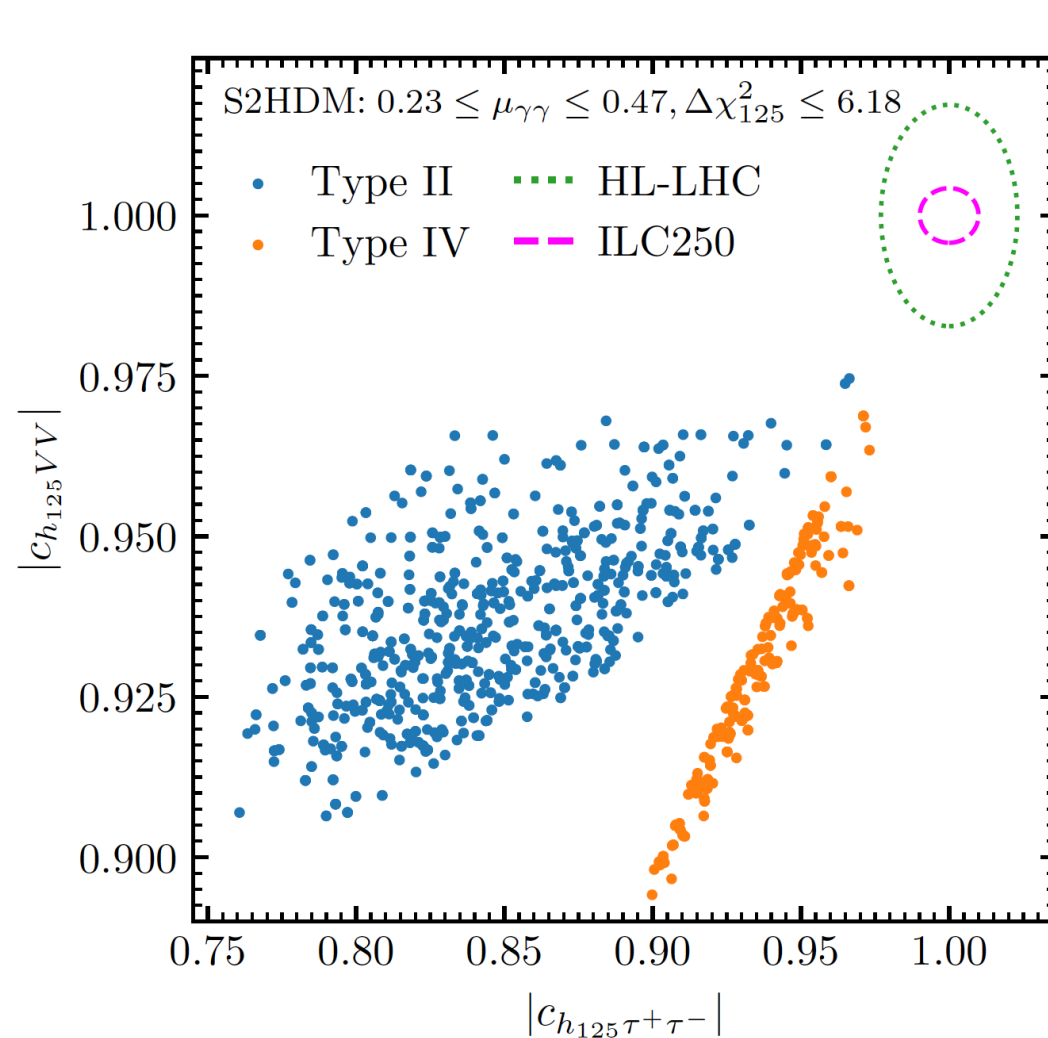
⇒ Higgs factory at 250 GeV will explore a large untested region!

[Taken from G. Weiglein '18]



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

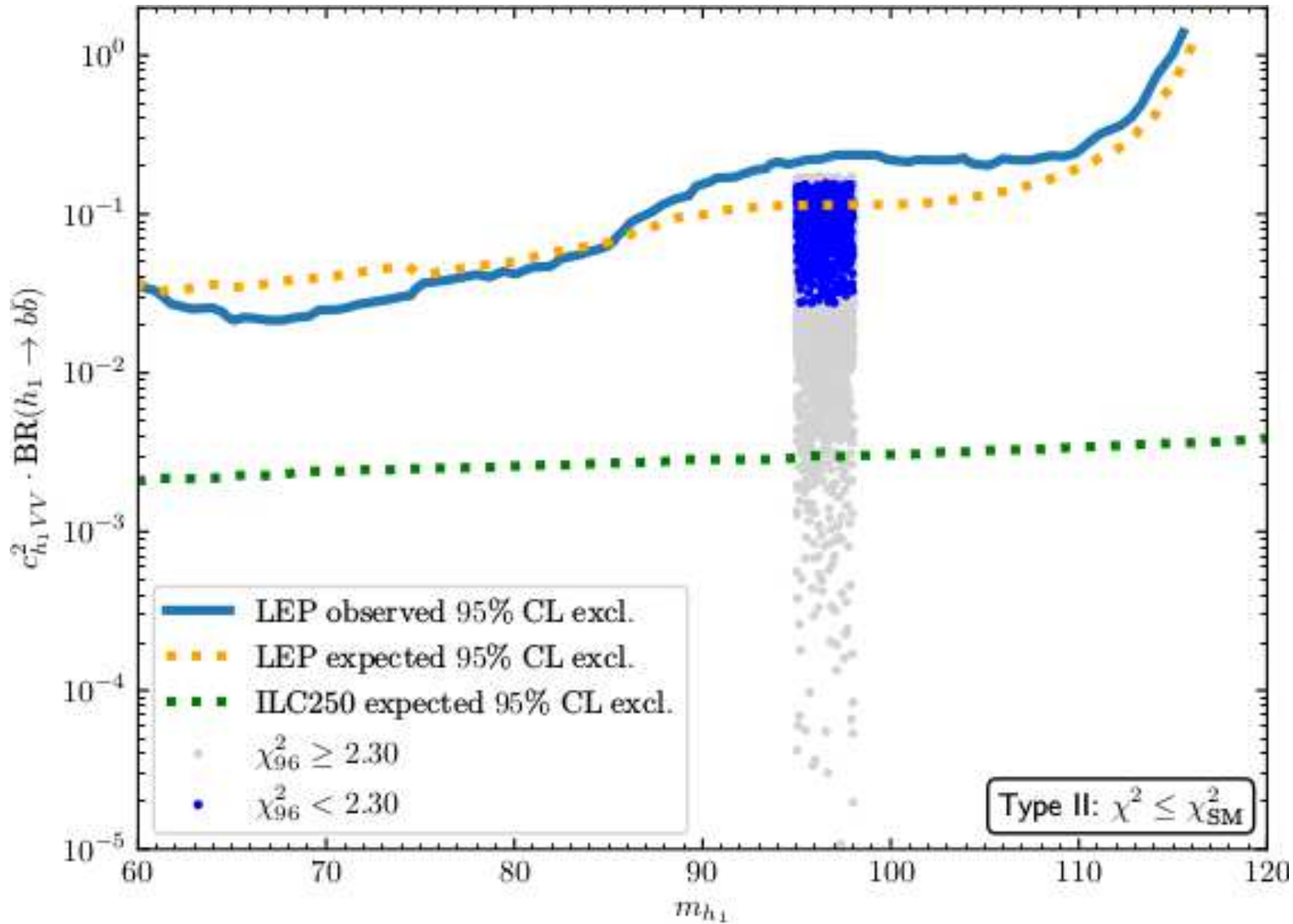
[T. Biekötter, S.H., G. Weiglein '23]



⇒ both types show some deviation from SM

Production of the light Higgs at the ILC:

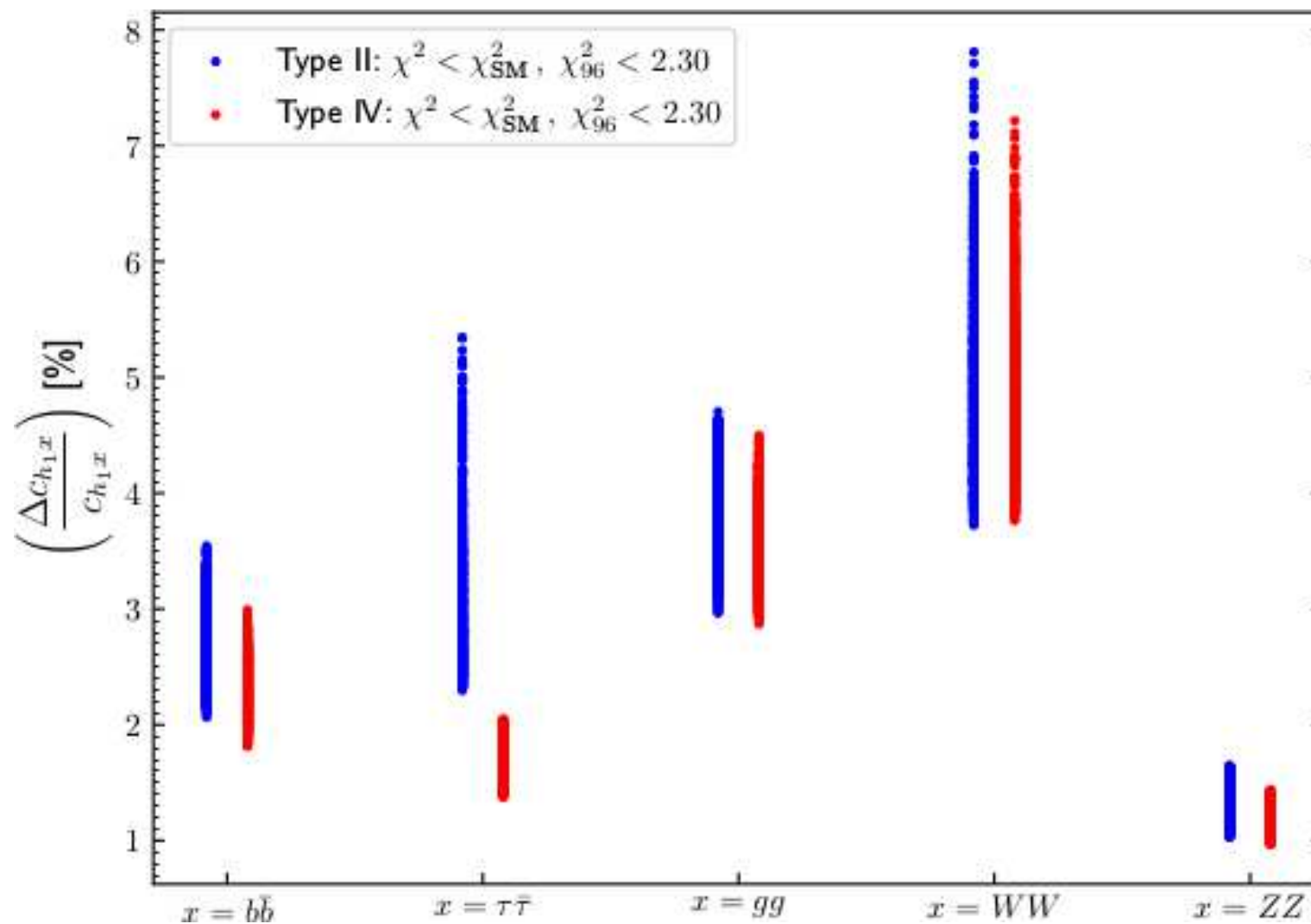
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



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

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

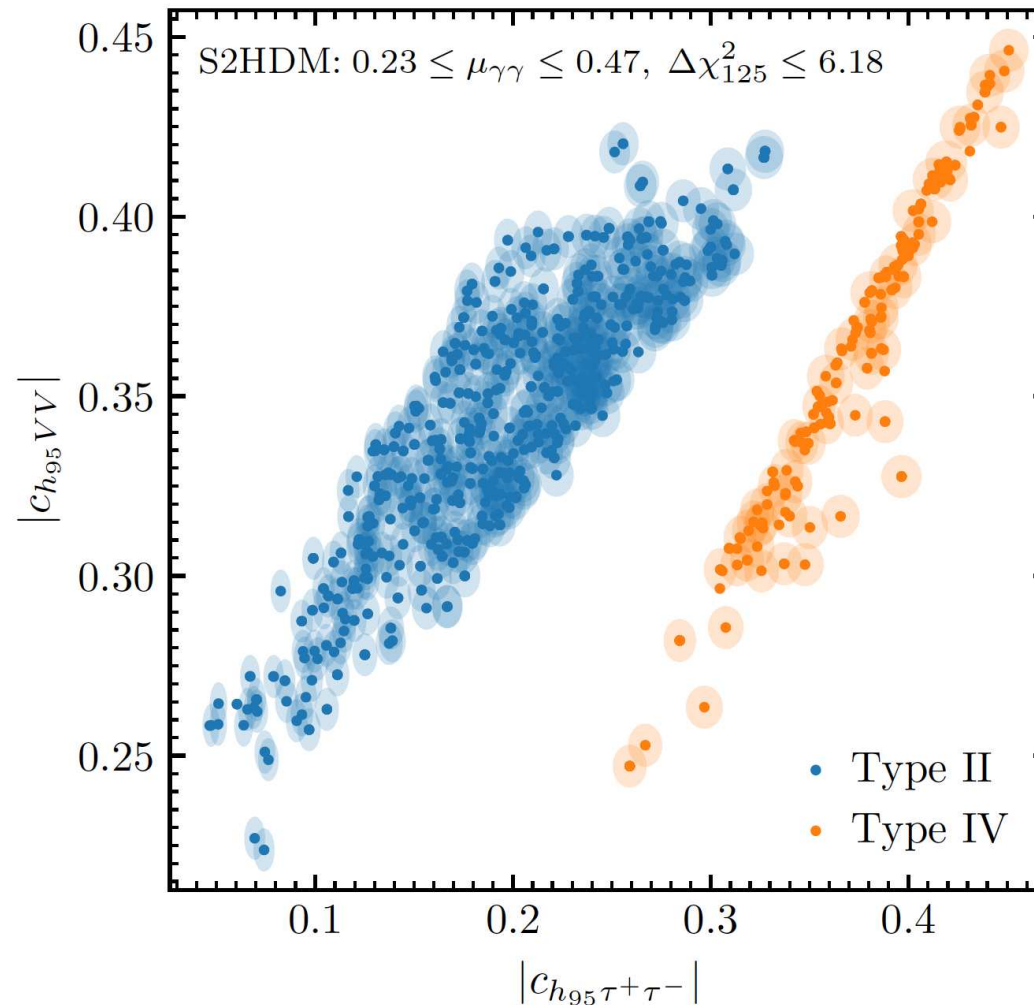
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ 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*]



⇒ models clearly distinguishable!

4. Evidence for SUSY Higgses?!

What about SUSY?? We are at SUSY 2024!!

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⇒ type II is needed for SUSY

⇒ $\tau\tau$ excess most strongly in contradiction with other measurements

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– NMSSM

– $\mu\nu$ SSM

– ...

4. Evidence for SUSY Higgses?!

What about SUSY?? We are at SUSY 2024!!

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

One example: 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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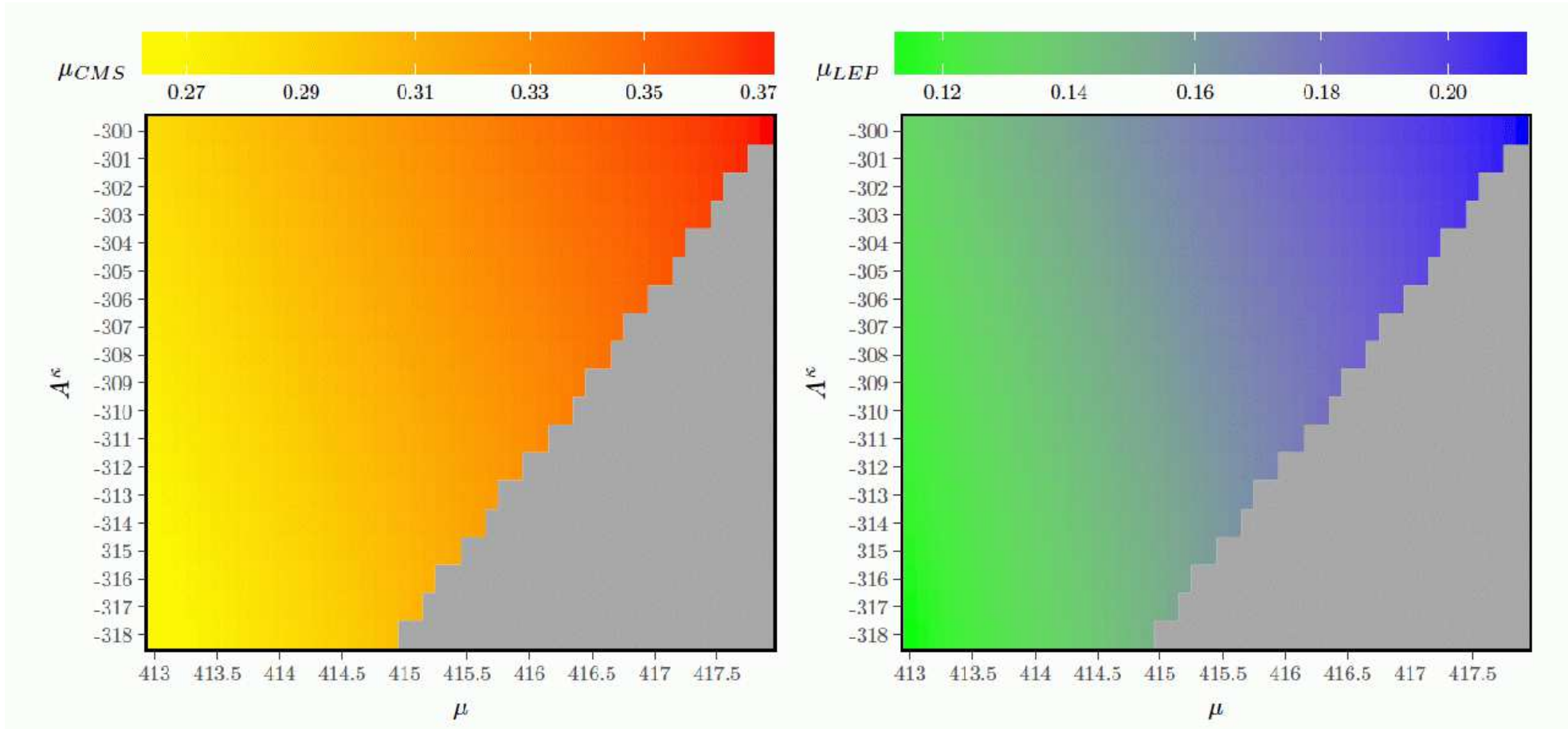
Can the $\mu\nu$ S SM explain the two excesses?

[T. Biekötter, S.H., C. Muñoz '17, '19]

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	$m_{\tilde{Q}_{iL}}^2$	$m_{\tilde{u}_{iR}}^2$	$m_{\tilde{d}_{iR}}^2$	A_1^u	$A_{2,3}^{u,d}$	$(m_e^2)_{ii}$	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]

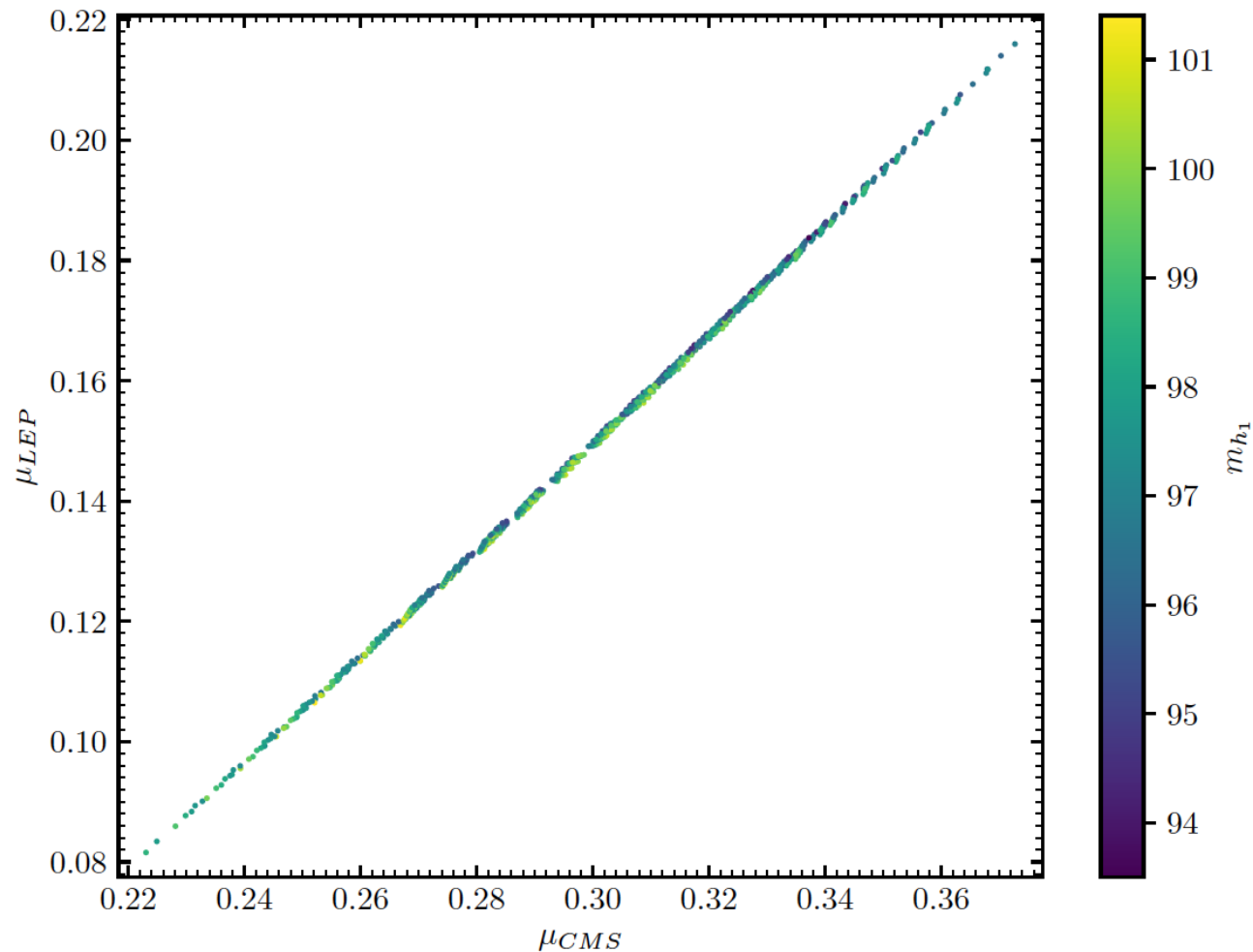


⇒ Yes! :-)

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

SUSY enforces strong correlation:

[*T. Biekötter, S.H., C. Muñoz '19*]



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

⇒ SUSY predicted that $\mu_{\gamma\gamma}$ has to go down - as observed! :-)

5. Conclusinos

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

- SUSY predicted that $\mu_{\gamma\gamma}$ has to go down - as observed! :-)

Further Questions?



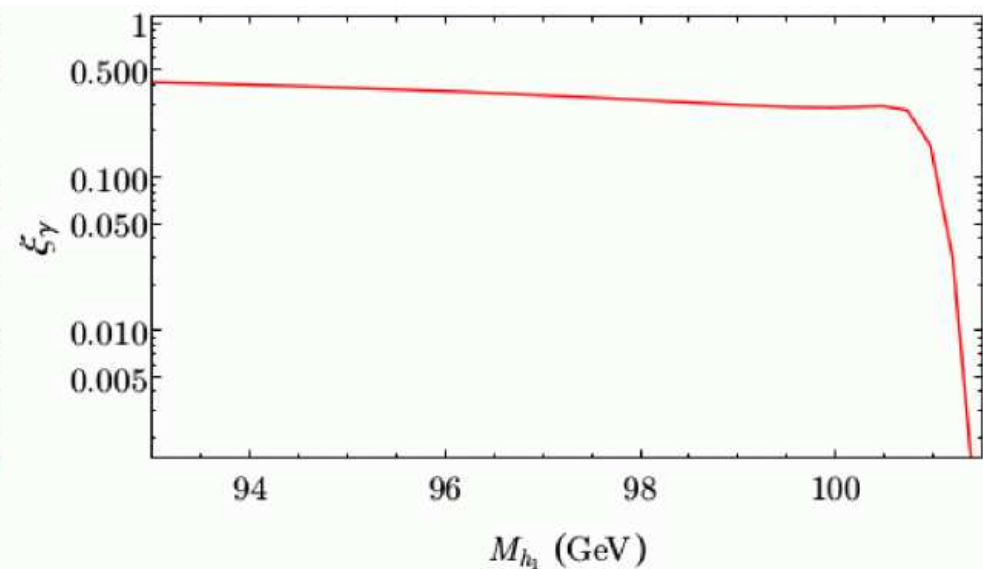
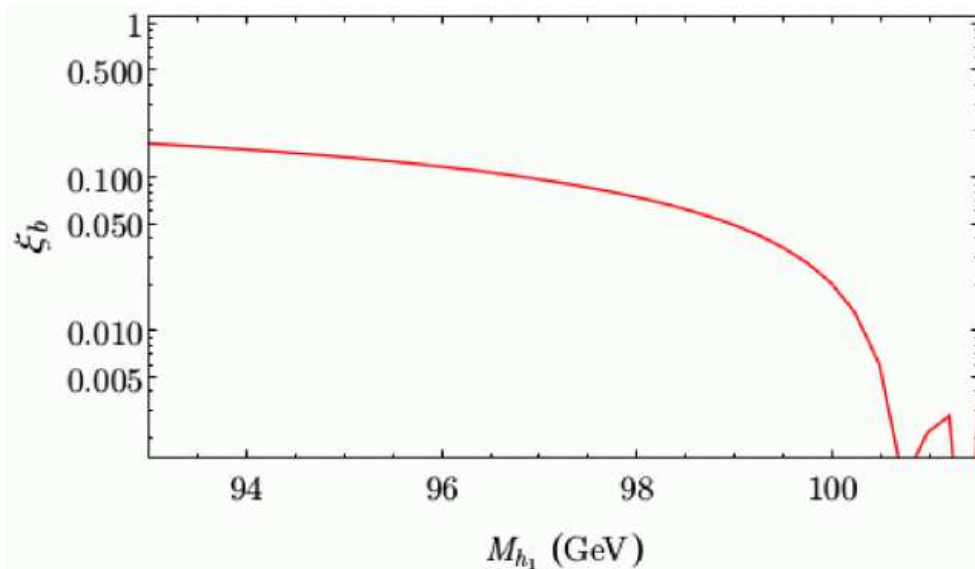
What about the NMSSM?

[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, $A_t = A_b = 0$

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



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

How to evaluate the precision of ϕ_{g5} coupling measurements?

Start with **data of the SM Higgs**:

SM Higgs **BRs**:

[YR4 LHCHSWG]

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 $\sqrt{s} = 250 \text{ GeV}$

[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	$H \rightarrow b\bar{b}$	$H \rightarrow gg$	$H \rightarrow \tau^+\tau^-$	$H \rightarrow WW$	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 if 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} :

$$\sigma(e^+e^- \rightarrow \phi Z) = \sigma_{\text{SM}}(e^+e^- \rightarrow Z H_{\text{SM}}^{\phi_{95}}) \times |c_{\phi V V}|^2$$

$$\sigma_{\text{SM}}(e^+e^- \rightarrow Z H_{\text{SM}}^{\phi_{95}}) = 0.332 \text{ pb}$$

$\Rightarrow \mathcal{O}(10^5)$ ϕ_{95} 's can be produced at $\sqrt{s} = 250 \text{ GeV}$ 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

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

$$\text{BR}(\phi \rightarrow xx) =: 1/p$$

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

- Coupling is measured via production: g_Z

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

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

- 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

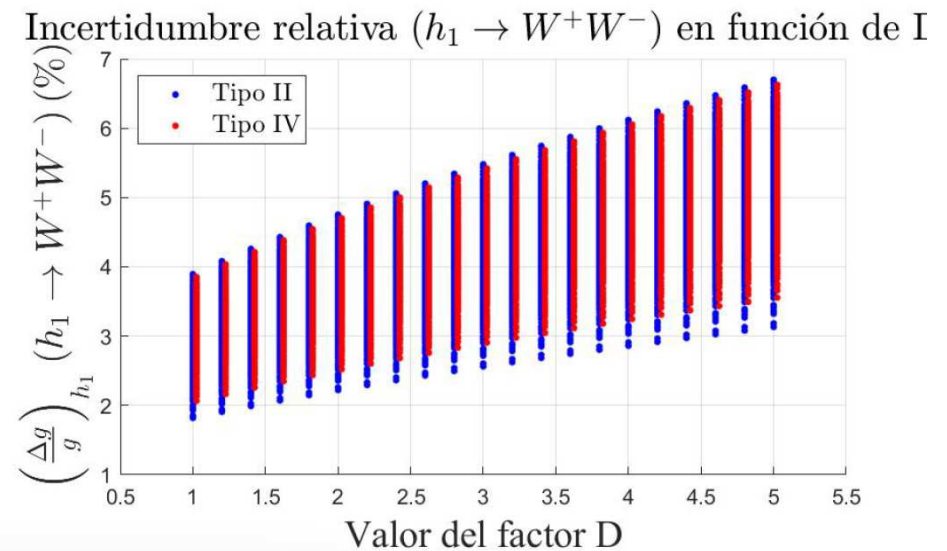
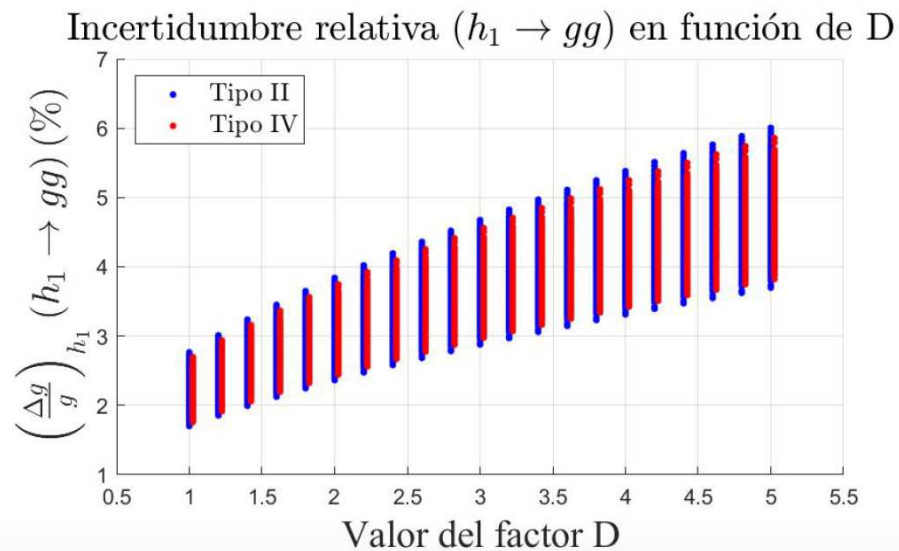
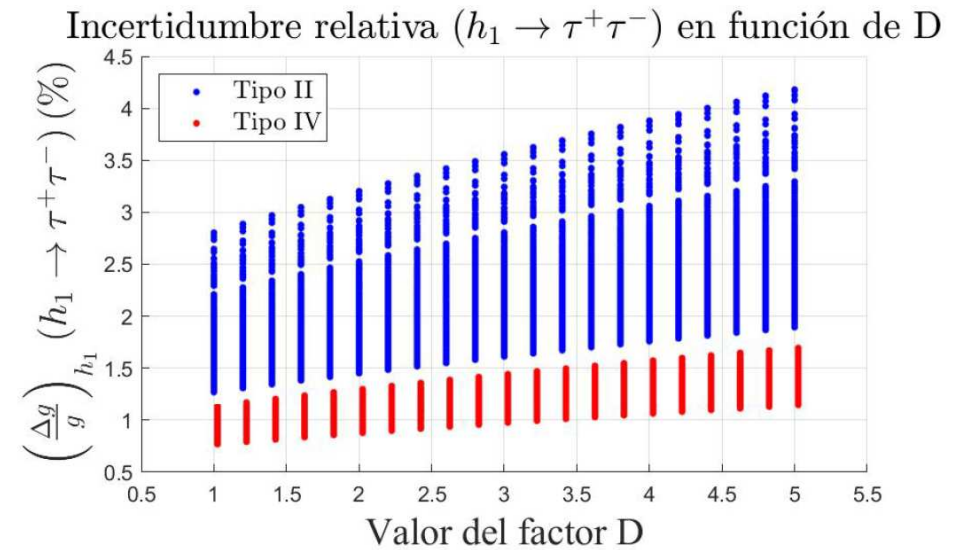
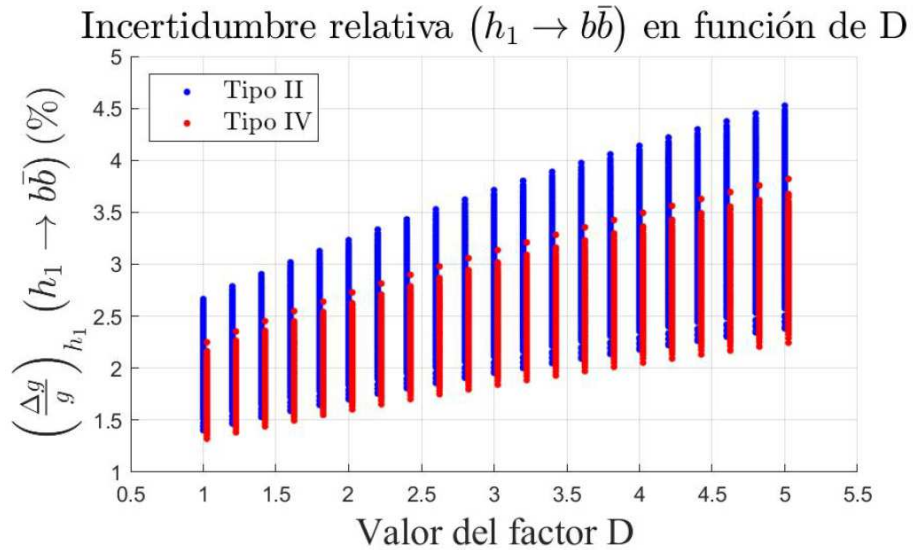
Evaluating uncertainties of ϕ_{95} :

- Coupling is measured via decay

$$\begin{aligned} \left(\frac{\Delta g_x}{g_x} \right)_\phi &= \left(\frac{\Delta g_x}{g_x} \right)_H \times \frac{\left(\frac{\Delta N_S}{N_S} \right)_\phi}{\left(\frac{\Delta N_S}{N_S} \right)_H} \times \frac{\left(1 - \frac{1}{p_H} \right)}{\left(1 - \frac{1}{p_\phi} \right)} \\ &\rightarrow \sqrt{\frac{D + f_H}{1 + f_H}} \times \sqrt{\frac{\sigma(e^+e^- \rightarrow ZH)}{\sigma(e^+e^- \rightarrow Z\phi)}} \times \sqrt{\frac{\text{BR}(H \rightarrow xx)}{\text{BR}(\phi \rightarrow xx)}} \times \frac{(1 - \text{BR}(H \rightarrow xx))}{(1 - \text{BR}(\phi \rightarrow xx))} \end{aligned}$$

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

$$\begin{aligned} \left(\frac{\Delta g_Z}{g_Z} \right)_\phi &= \left(\frac{\Delta g_Z}{g_Z} \right)_H \times \frac{\left(\frac{\Delta N_S}{N_S} \right)_\phi}{\left(\frac{\Delta N_S}{N_S} \right)_H} \\ &\rightarrow \sqrt{\frac{\sigma(e^+e^- \rightarrow ZH)}{\sigma(e^+e^- \rightarrow Z\phi)}} \end{aligned}$$



⇒ non-negligible, but small ⇒ “robust” result