



**I FOUND THE HUGS BISON.**

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# The 95 GeV Higgs Boson at CEPC

*Sven Heinemeyer, IFT (CSIC, Madrid)*

Nanjing, 10/2024


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

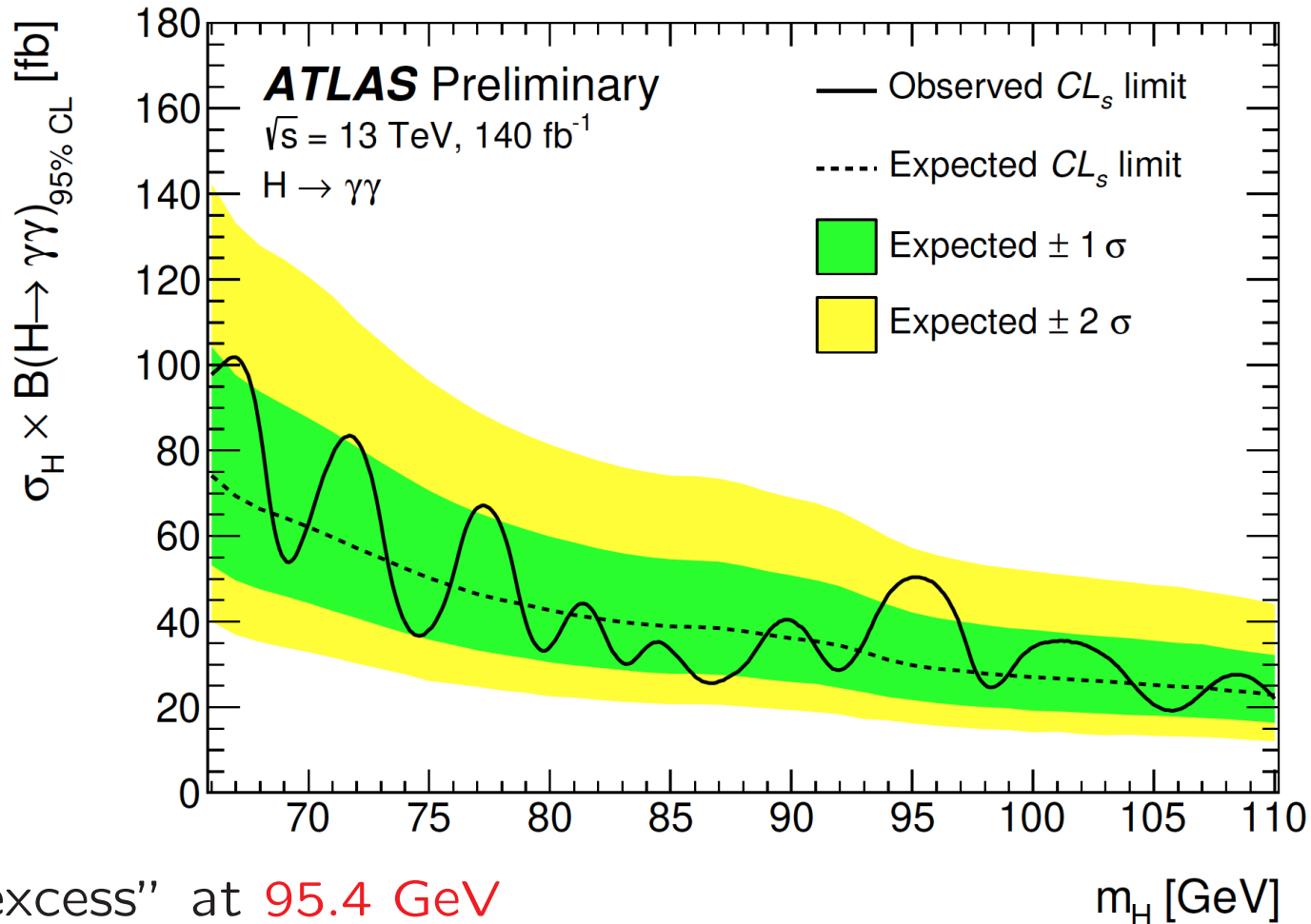
# Measurement of Higgs boson production and search for new resonances in final states with photons and Z bosons

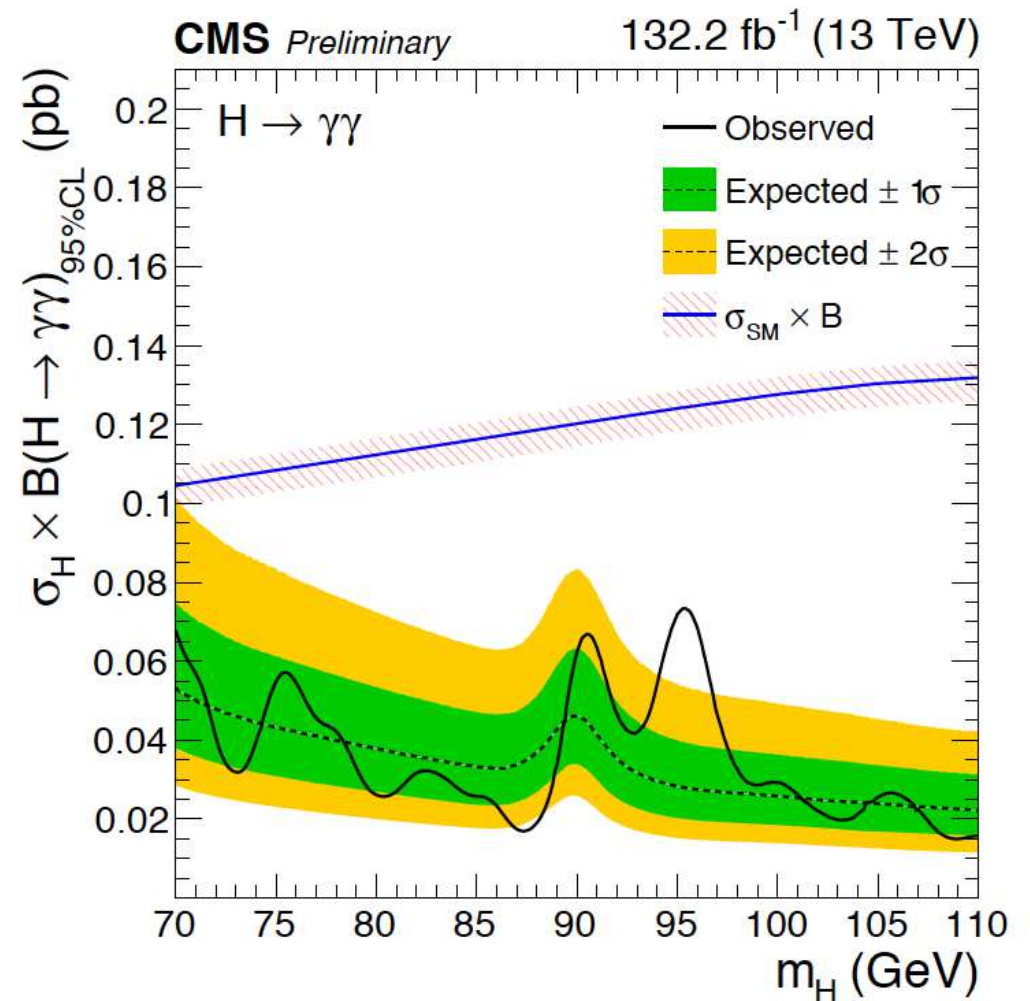
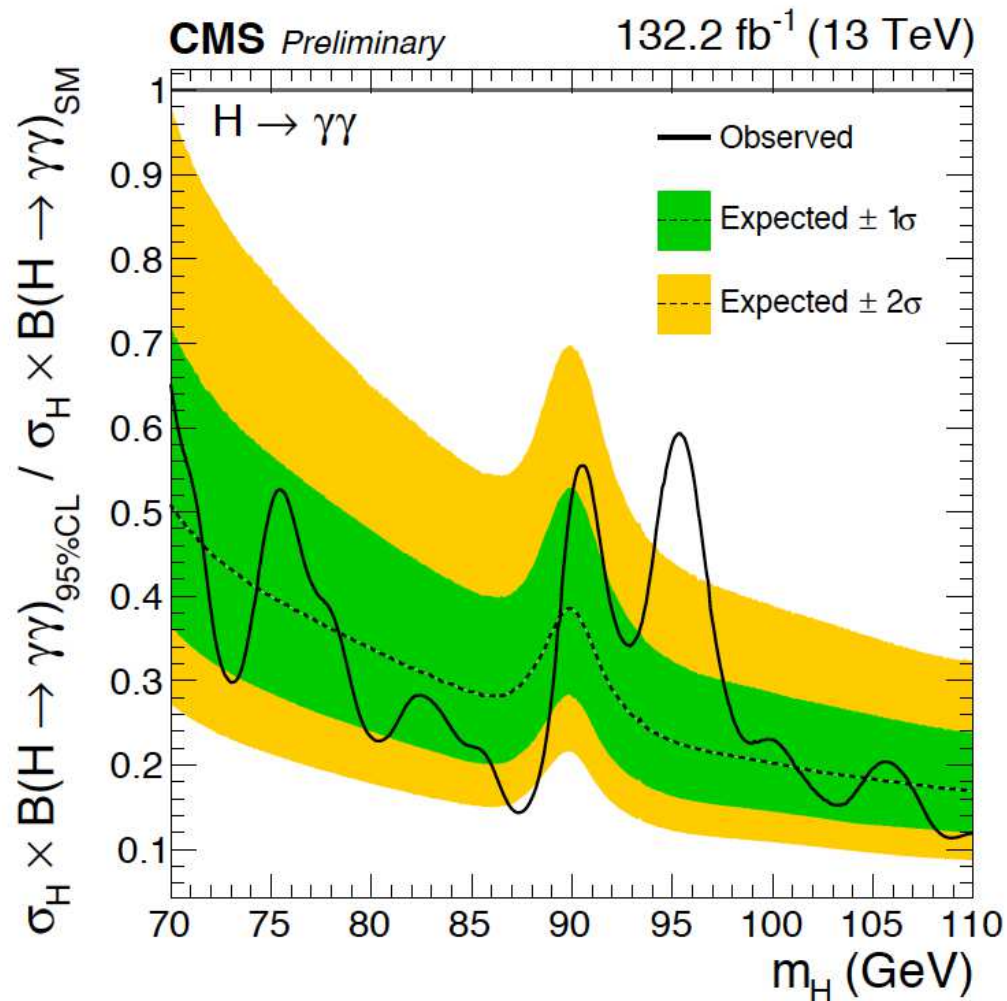
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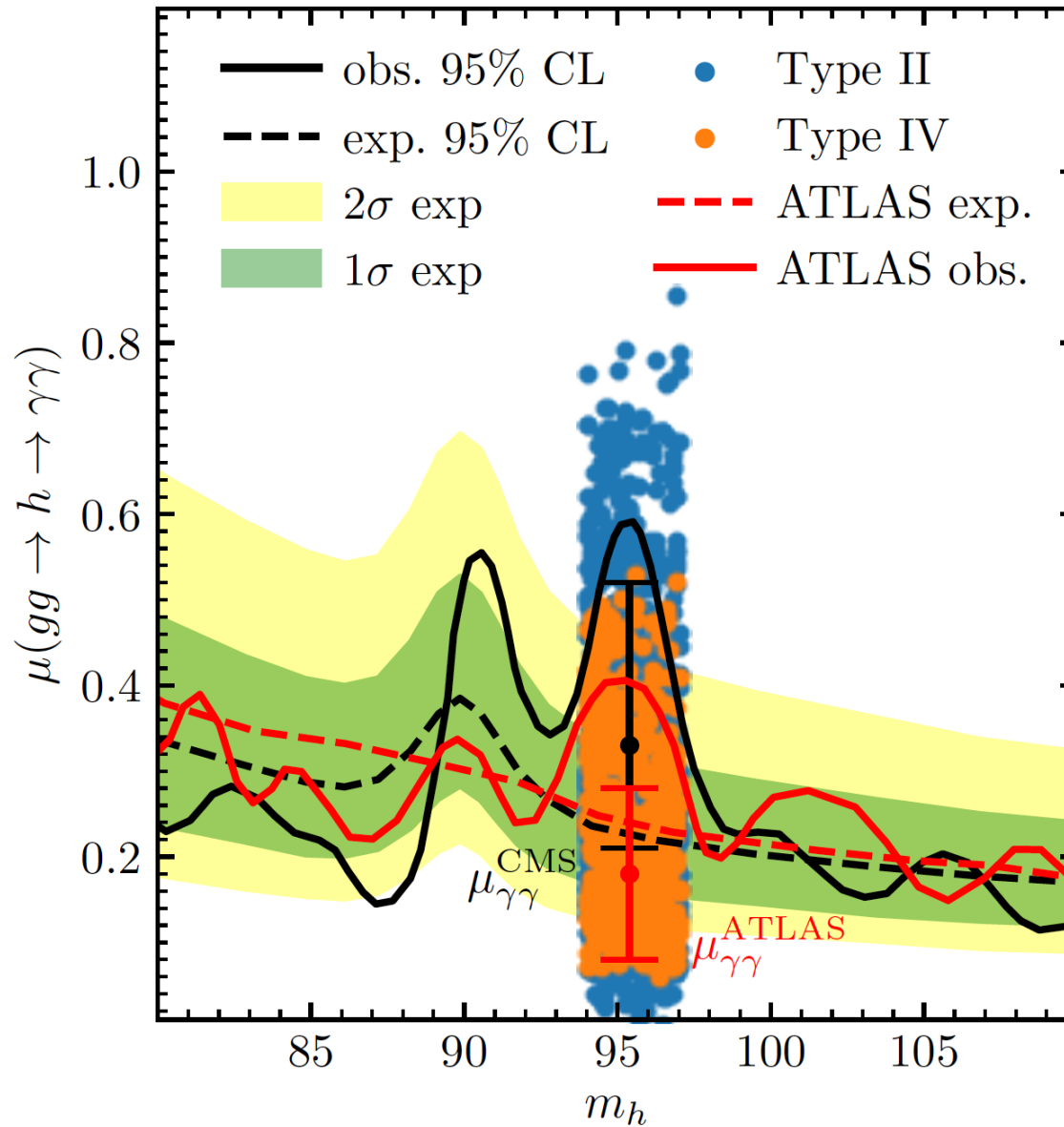
## New ATLAS result on the low-mass Higgs search in $pp \rightarrow \phi \rightarrow \gamma\gamma$



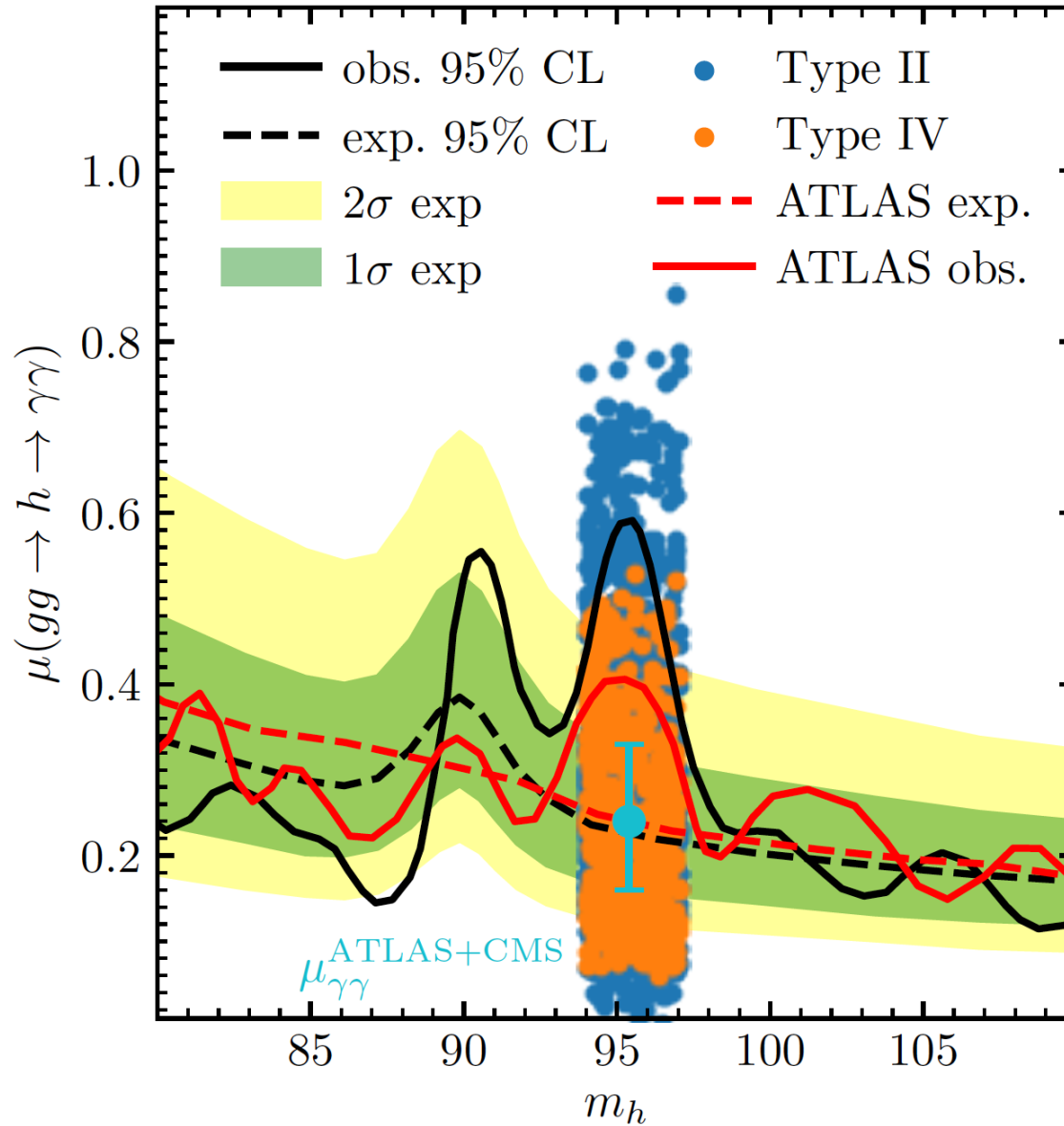


$$\mu_{\gamma\gamma}^{CMS} = [\sigma(gg \rightarrow h_{95}) \times BR(h_{95} \rightarrow \gamma\gamma)]_{exp/SM} = 0.33_{-0.12}^{+0.19} \quad (2.9 \sigma)$$

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



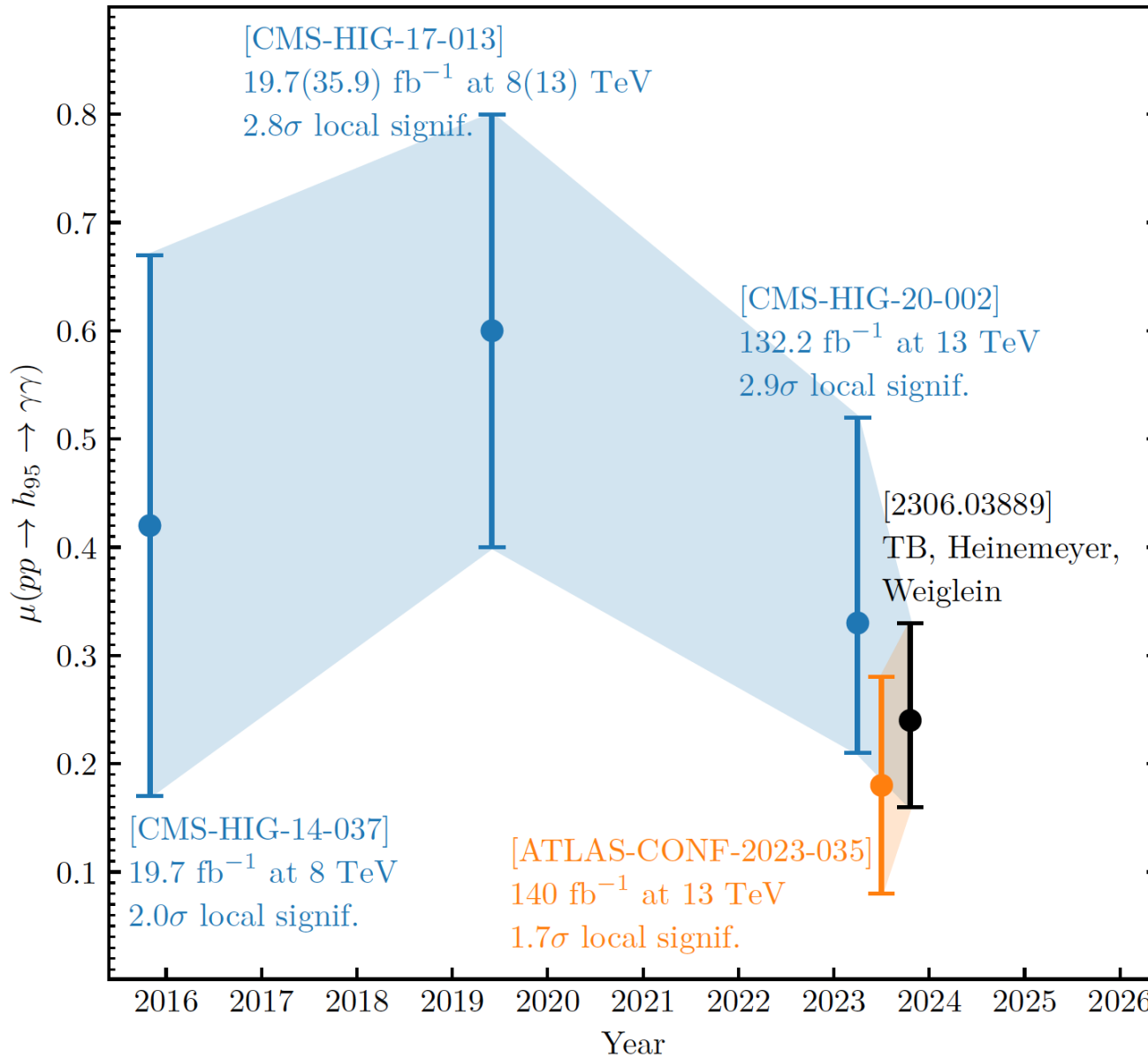
⇒ agreement between ATLAS and CMS!



$\Rightarrow$  agreement between ATLAS and CMS!

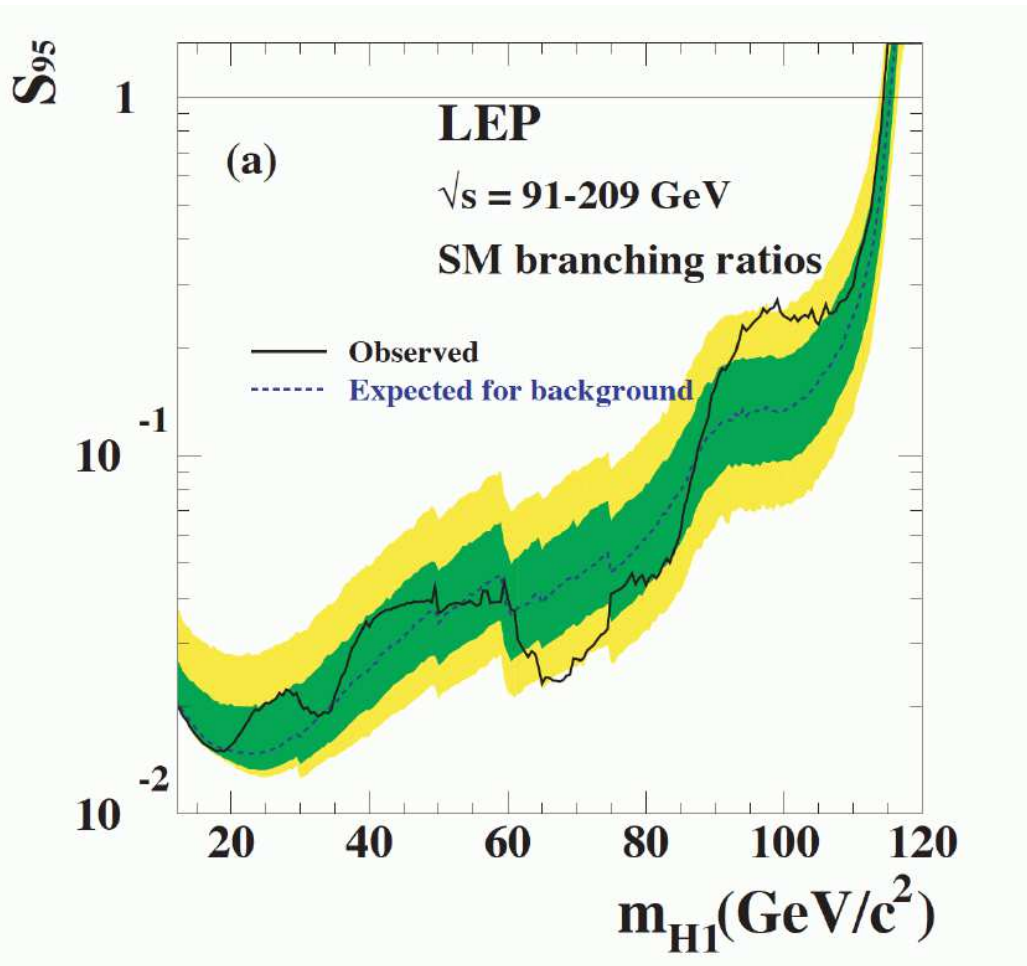
$$\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08} (3.1 \sigma)$$





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

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

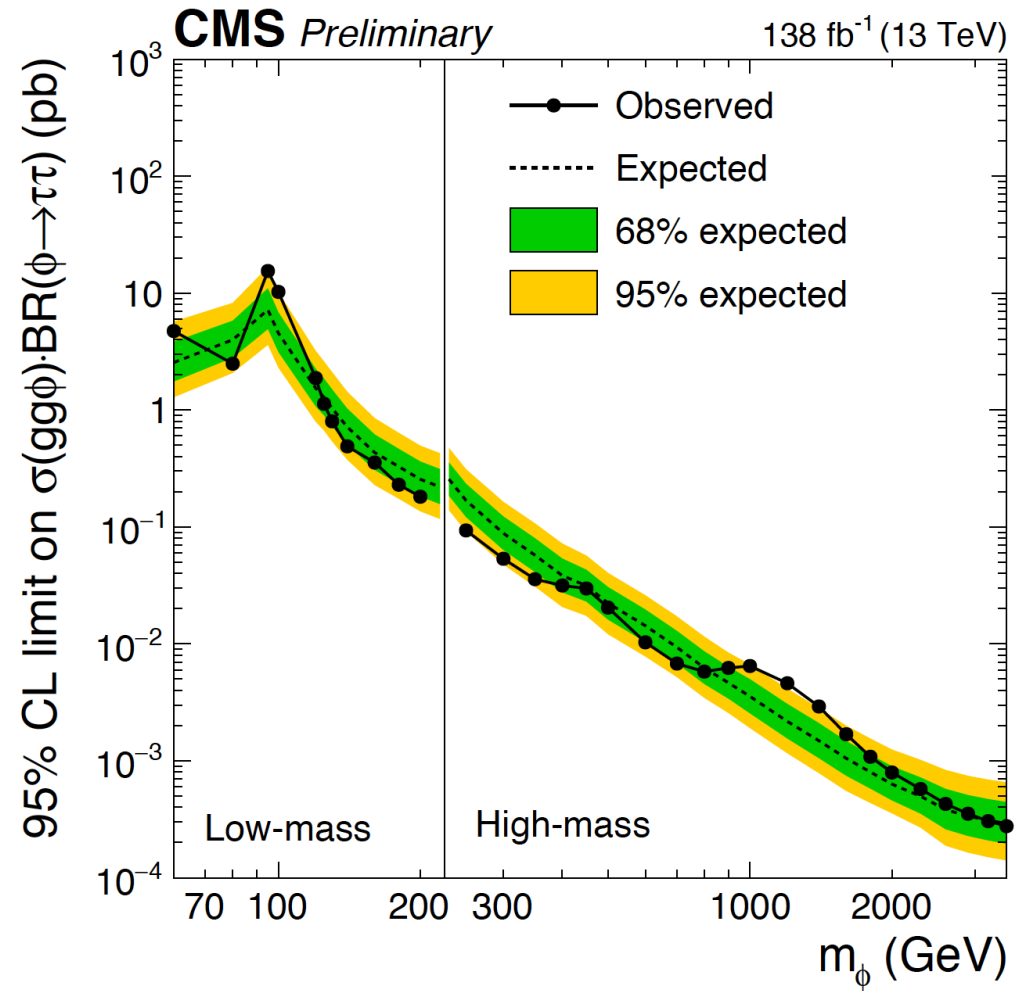


$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057,$$

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

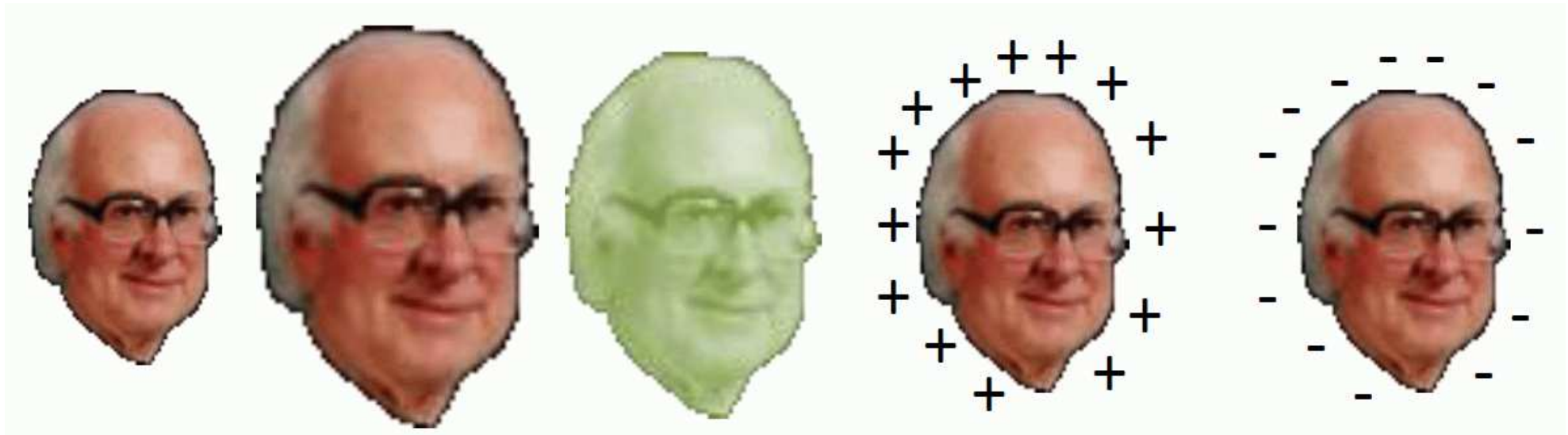
$$\Rightarrow \sim 4.6\sigma$$

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



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

## 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	$\Phi_2$	$\Phi_2$	$\Phi_2$
type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
type III (lepton-specific)	$\Phi_2$	$\Phi_2$	$\Phi_1$
type IV (flipped)	$\Phi_2$	$\Phi_1$	$\Phi_2$

$\Rightarrow$  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  $\mu_{\gamma\gamma}$

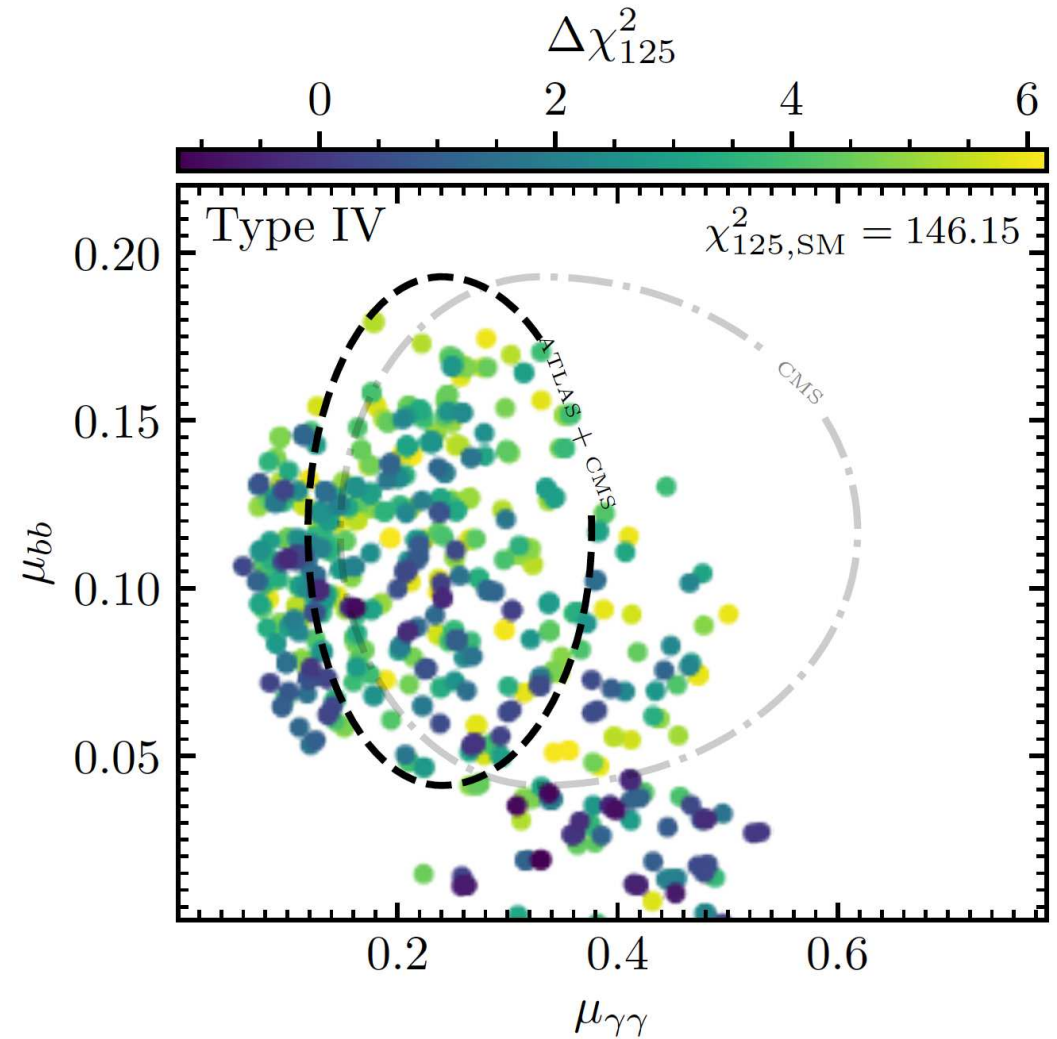
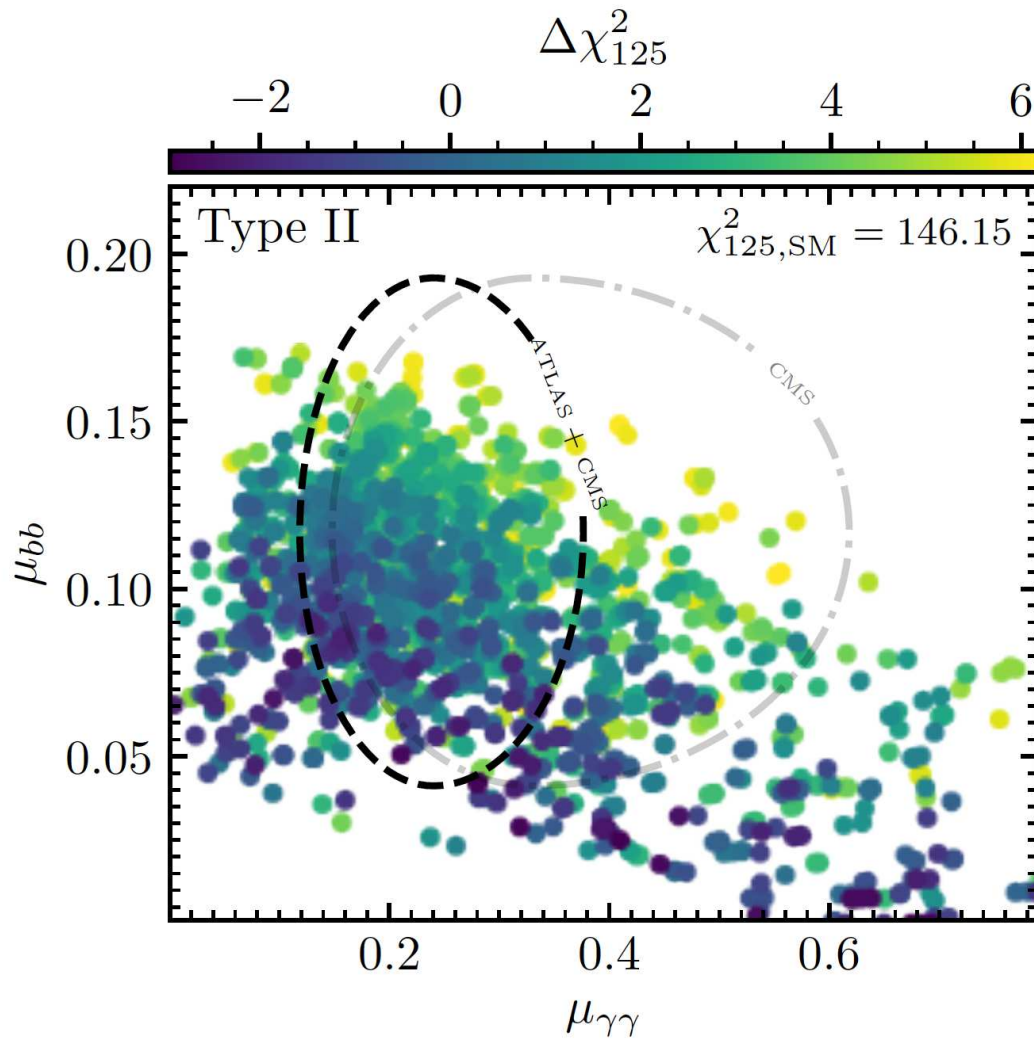
	Decrease $c_{h_1 b\bar{b}}$	No decrease $c_{h_1 t\bar{t}}$	No enhancement $c_{h_1 \tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta}) :-)$	$(\frac{R_{12}}{s_\beta}) :-)$	$(\frac{R_{12}}{s_\beta})$
type II	$(\frac{R_{11}}{c_\beta}) :-)$	$(\frac{R_{12}}{s_\beta}) :-)$	$(\frac{R_{11}}{c_\beta})$
type III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

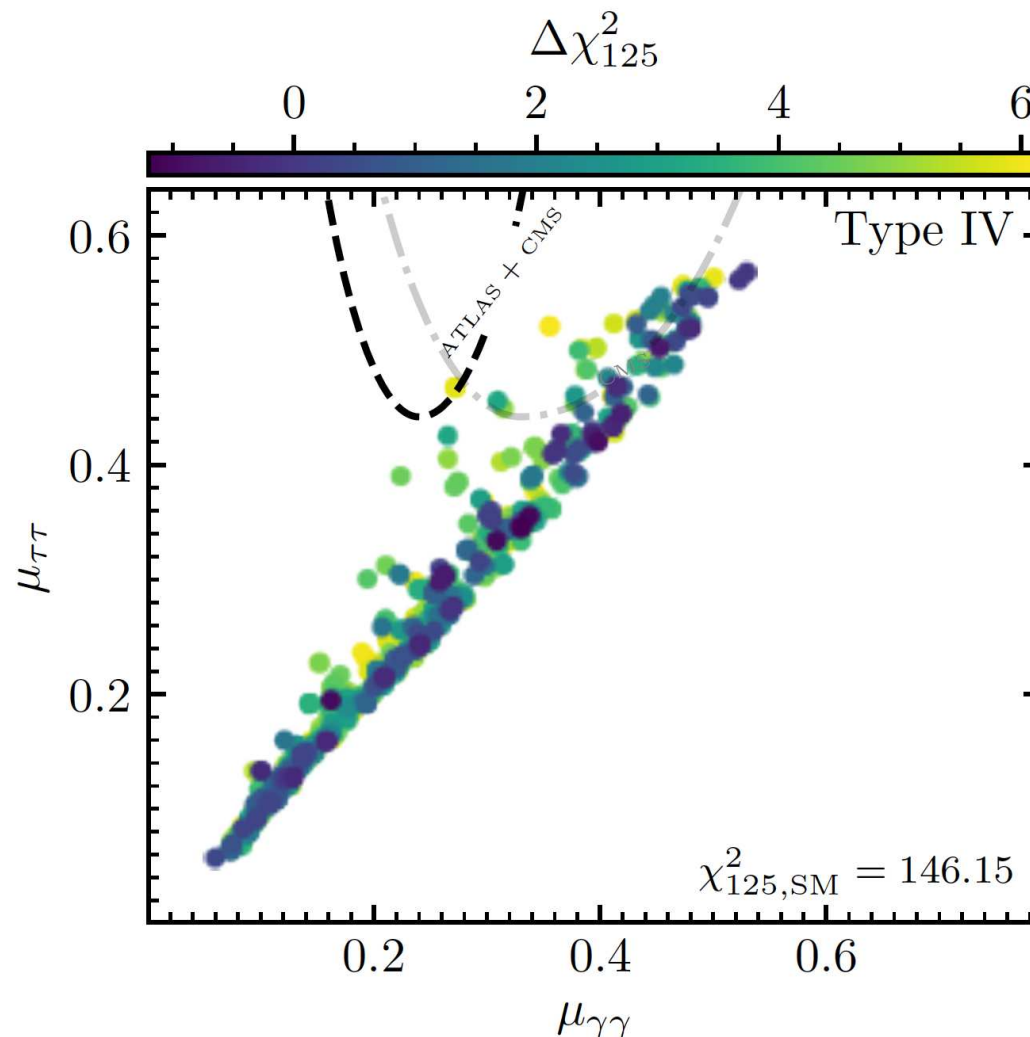
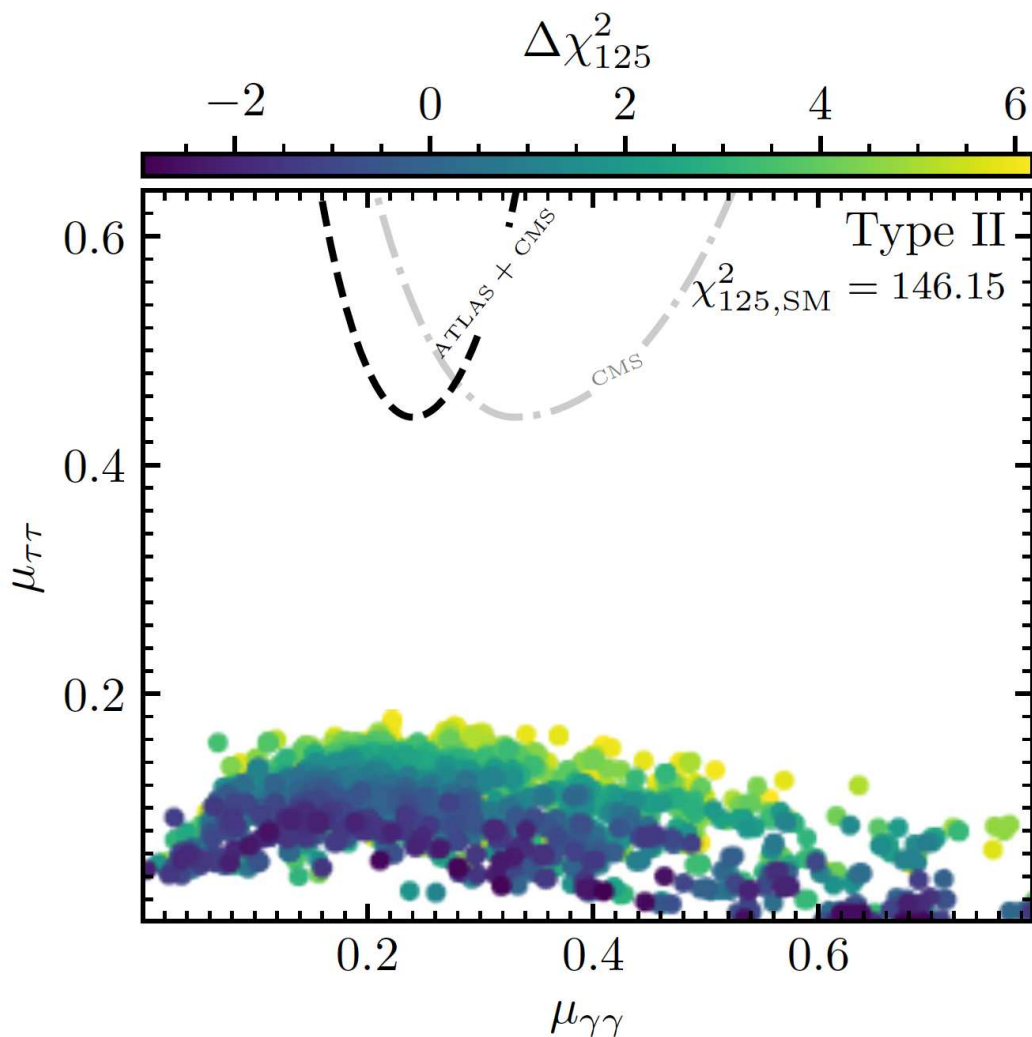
$\Rightarrow \tau\tau$  excess may decide between type II and IV



Color coding:  $\chi_{125}^2$  from HiggsSignals

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





Color coding:  $\chi_{125}^2$  from HiggsSignals

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

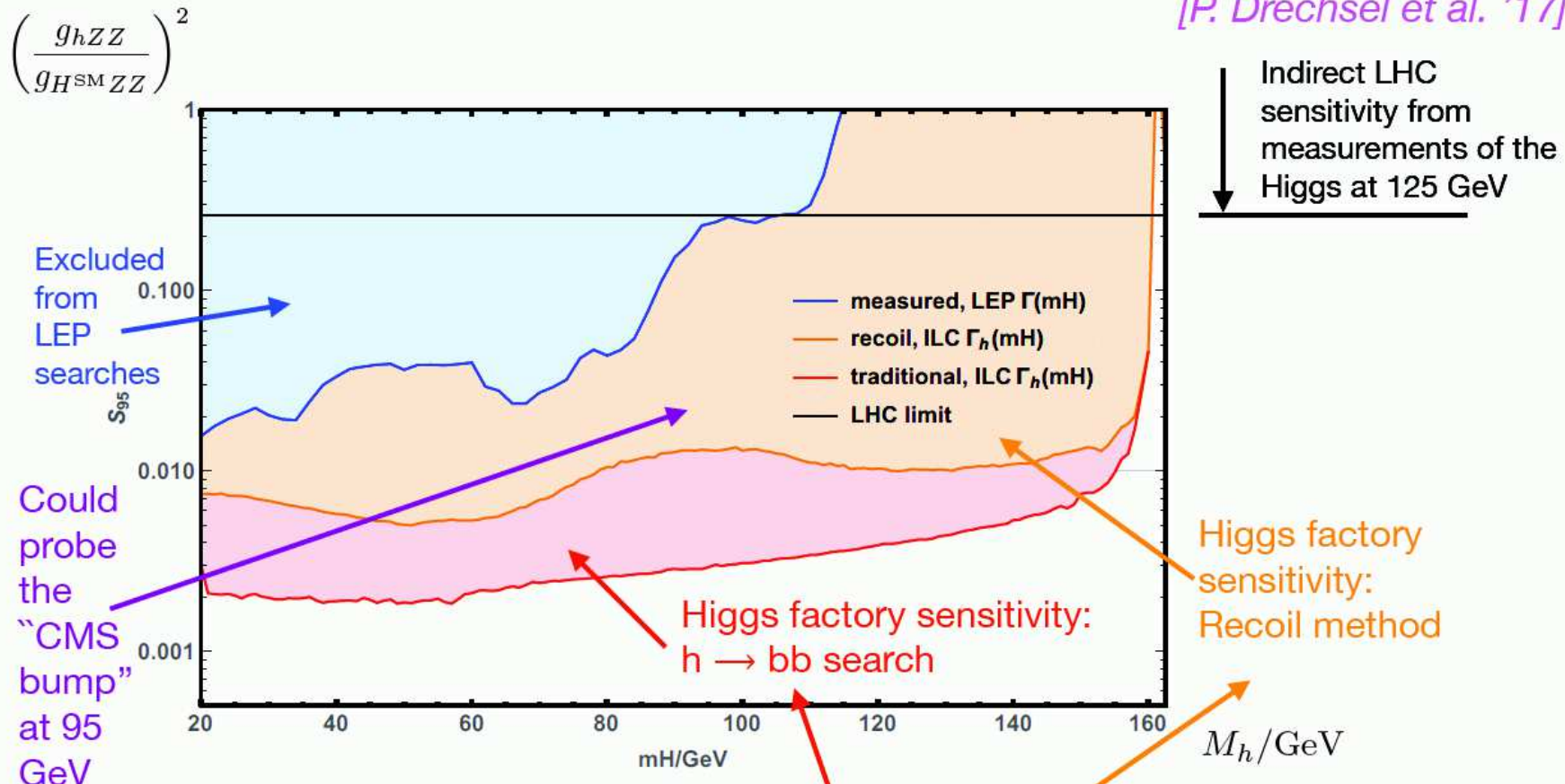
### 3. Physics opportunities at $e^+e^-$ colliders

#### What can we learn from future measurements?

- LHC  $h_{125}$  coupling measurements
  - HL-LHC  $h_{125}$  coupling measurements
  - **CEPC**  $h_{125}$  coupling measurements
  
  - direct production of  $\phi_{95}$  at the LHC
  - direct production of  $\phi_{95}$  at the HL-LHC
  - direct production of  $\phi_{95}$  at the **CEPC**
  - **CEPC**  $\phi_{95}$  coupling measurements
  
  - production of other BSM Higgs bosons at the LHC/HL-LHC/CEPC/...
- CEPC** = CEPC (or other  $e^+e^-$  collider at  $\sqrt{s} = 250$  GeV)

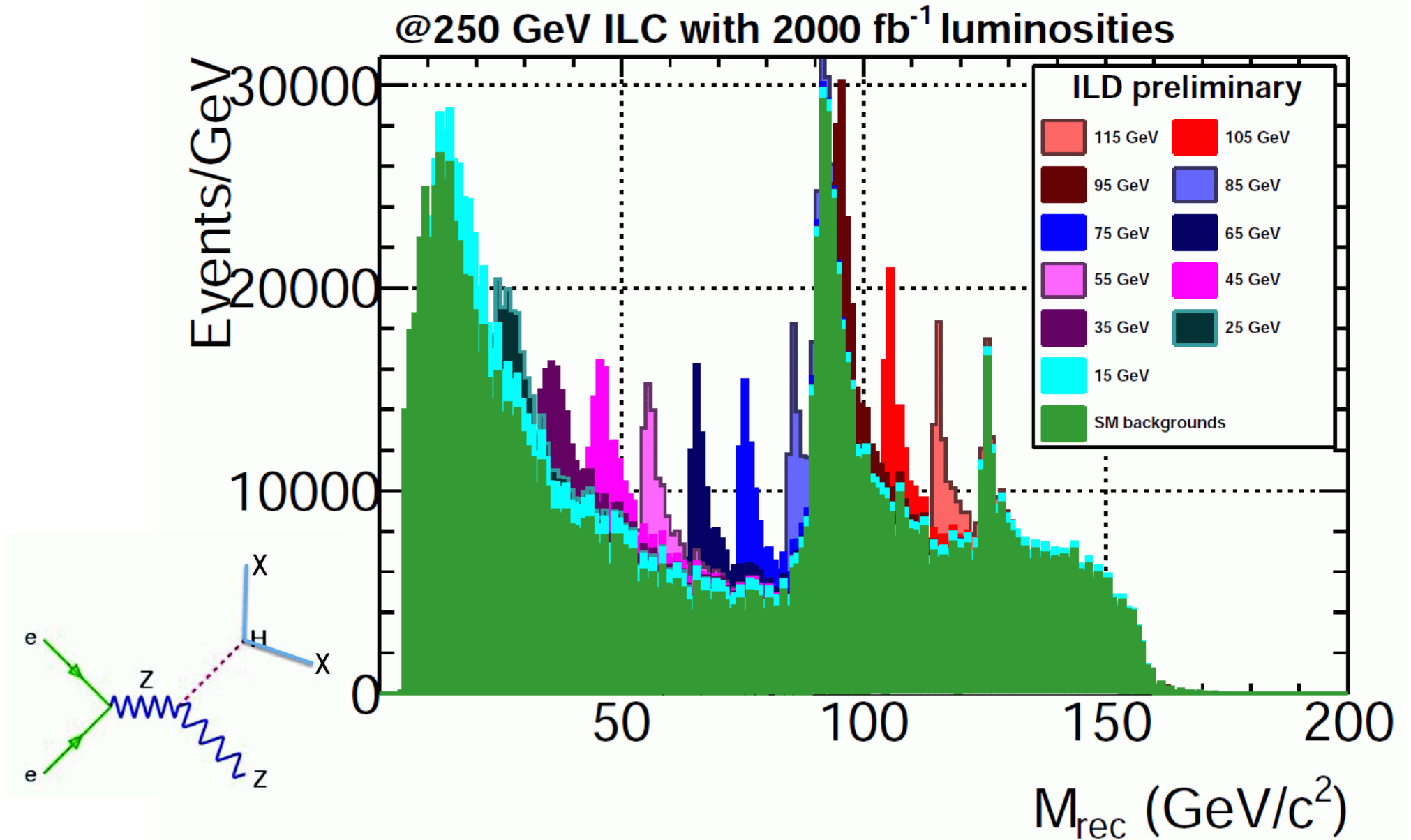
# Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb<sup>-1</sup> to a new light Higgs

[P. Drechsel et al. '17]



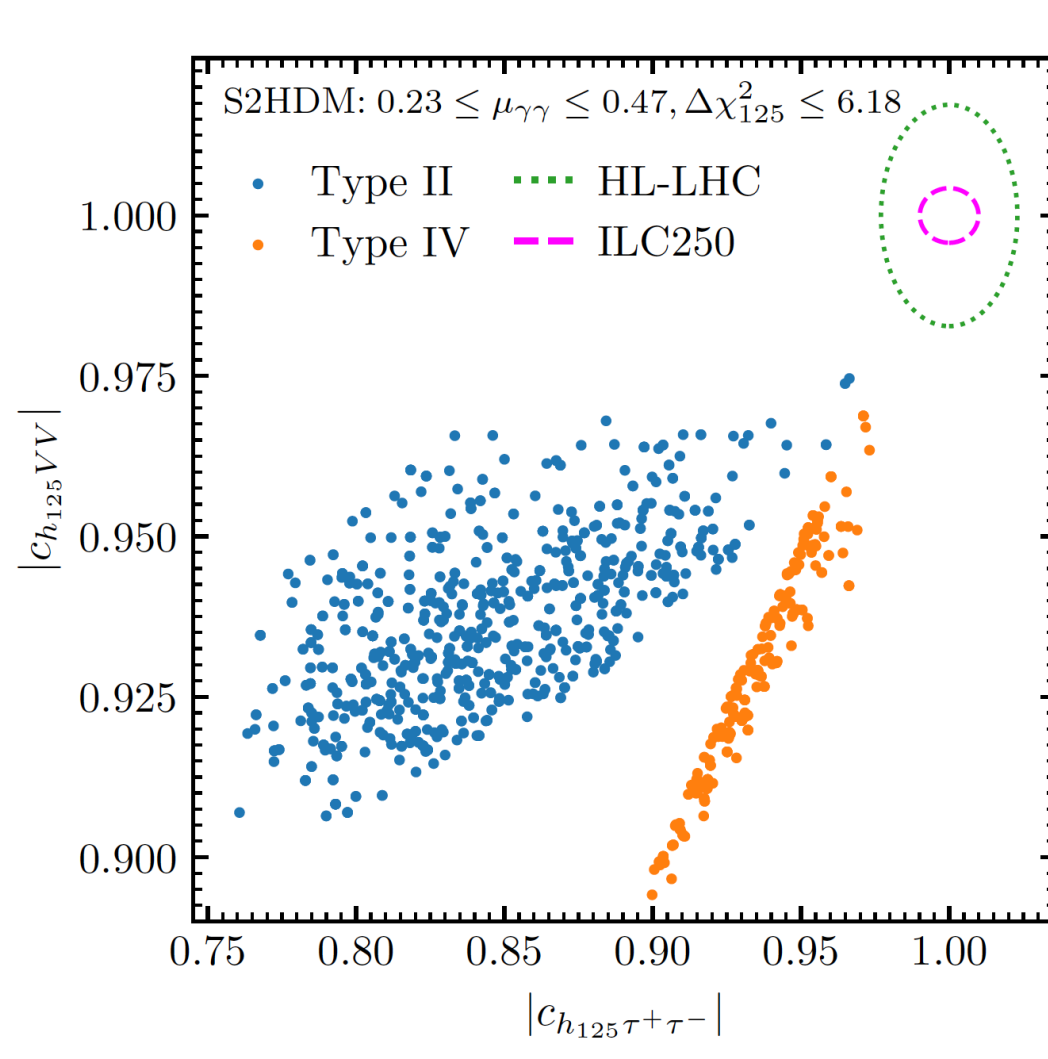
⇒ Higgs factory at 250 GeV will explore a large untested region!

[Taken from G. Weiglein '18]



# $h_{125}$ coupling measurements at the HL-LHC/CEPC

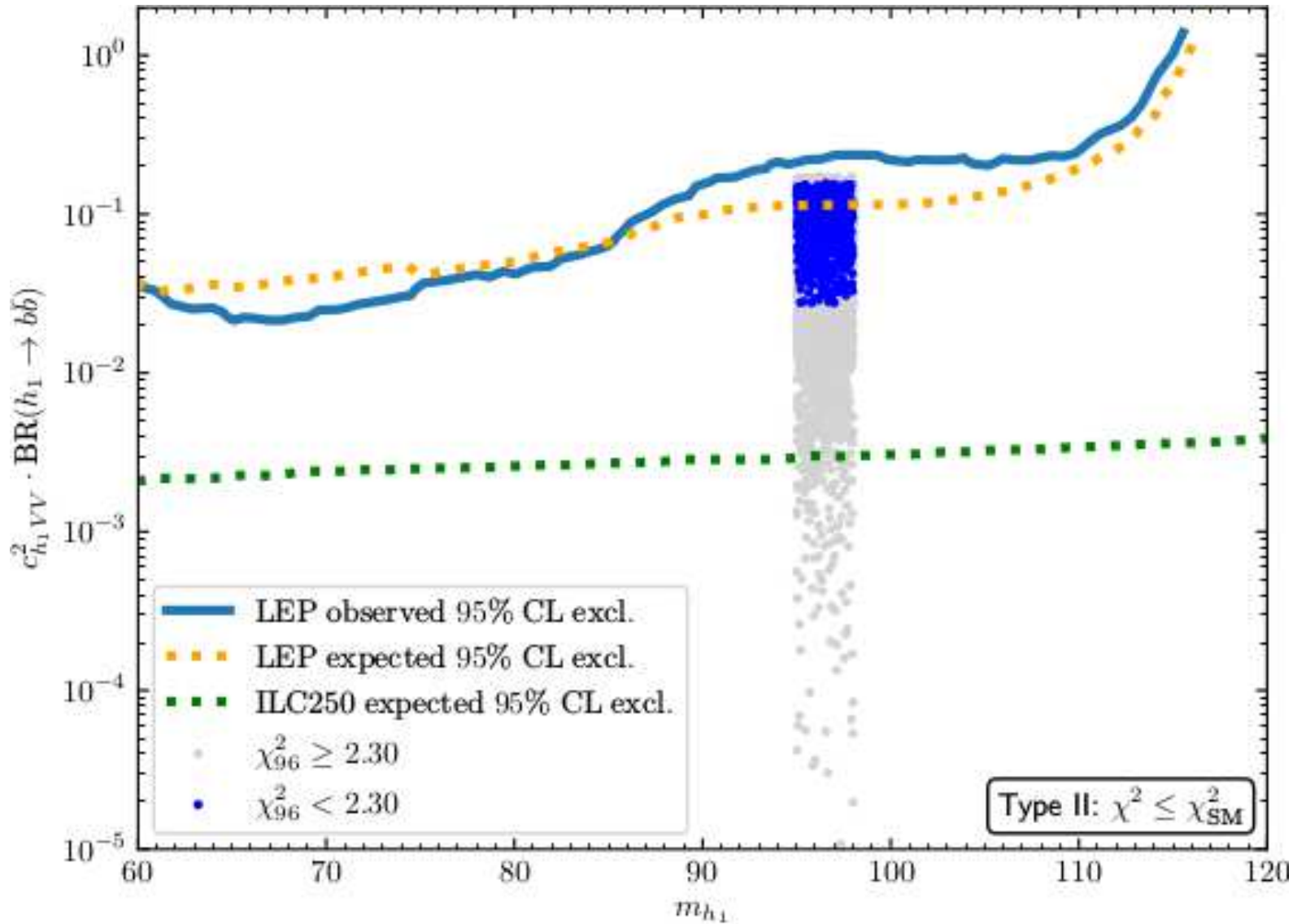
[T. Biekötter, S.H., G. Weiglein '23]



⇒ both types show some deviation from SM

# Production of the light Higgs at the CEPC:

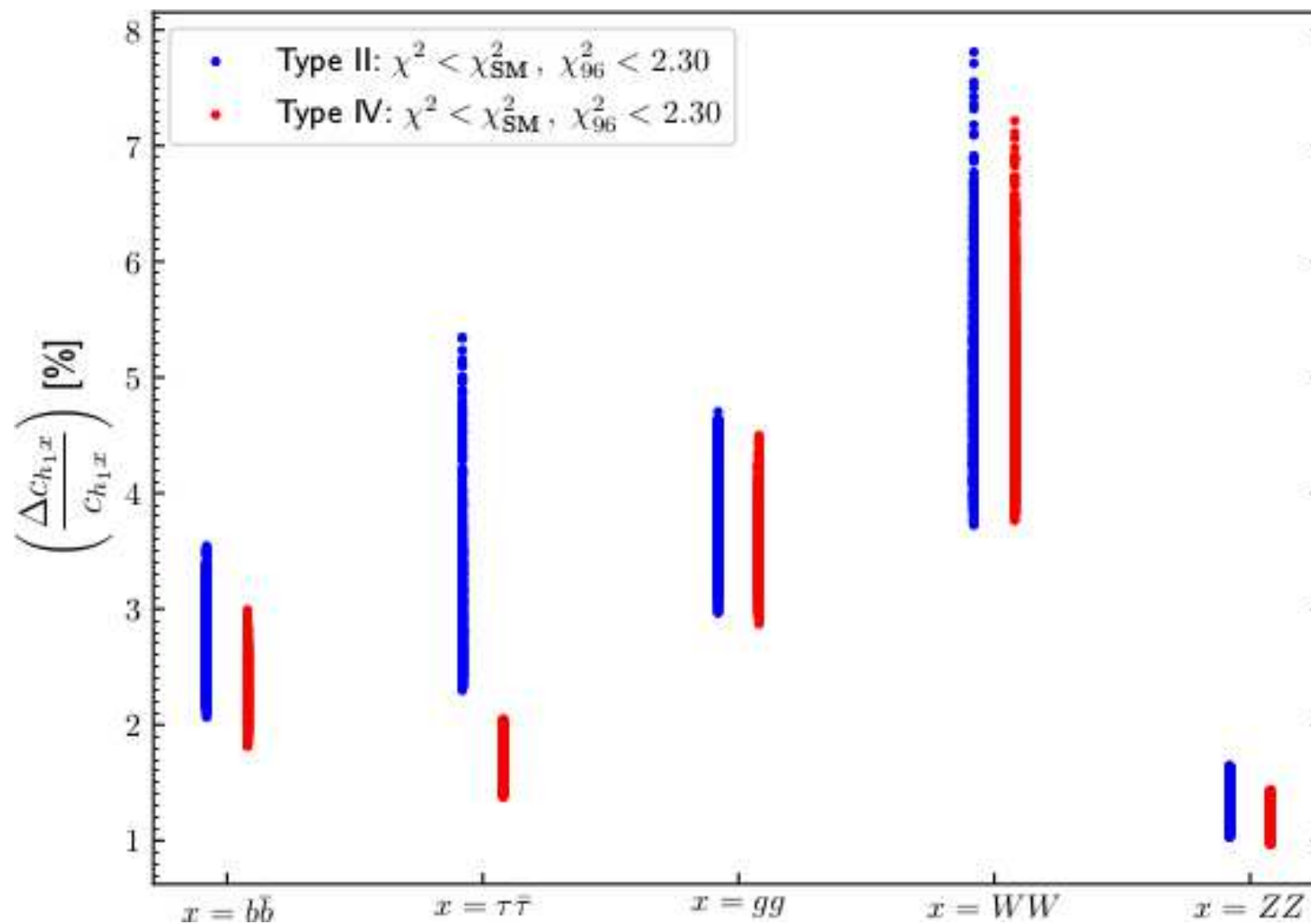
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



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

# $h_{95}$ coupling measurements at the HL-LHC/CEPC

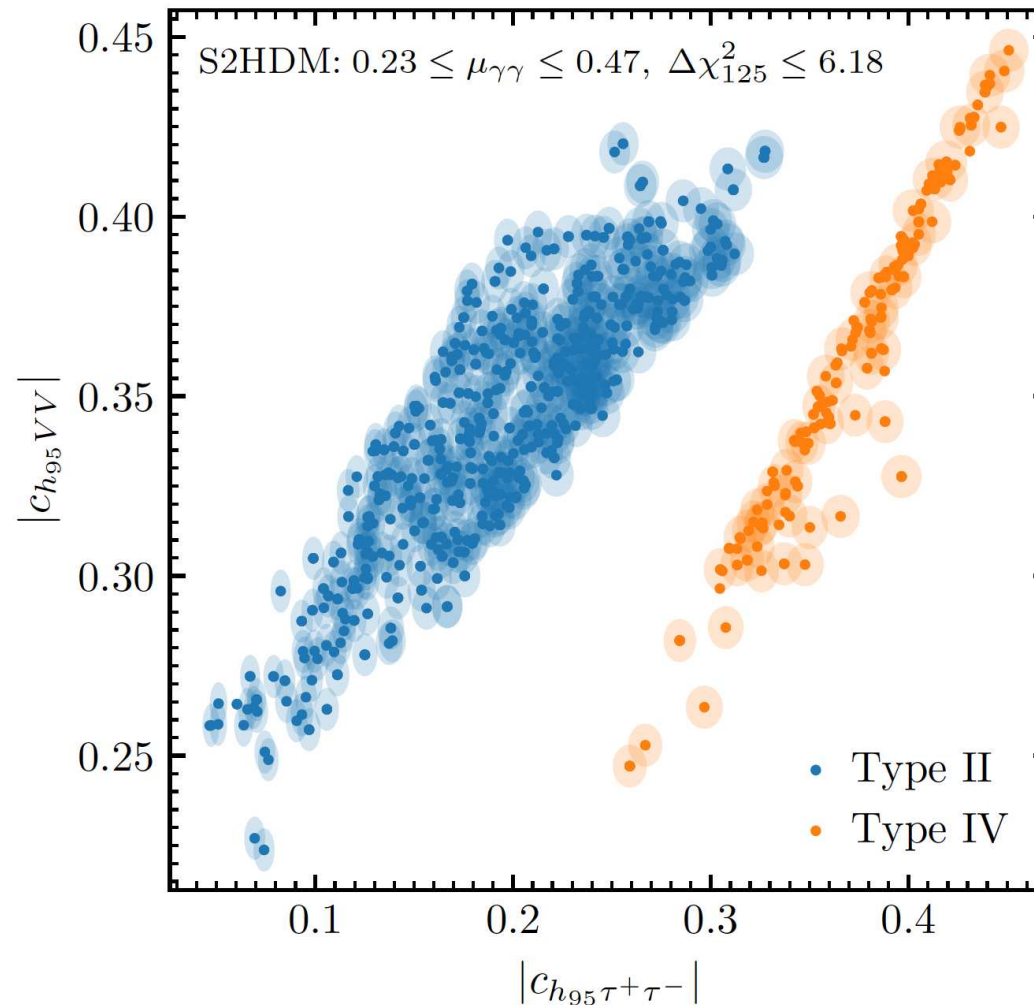
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



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

# $h_{95}$ coupling measurements at the HL-LHC/CEPC

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



⇒ models clearly distinguishable!



Now experimentalists take over! :-)

[A.F. Zarnecki et al. '23]

Now experimentalists take over! :-)

[A.F. Zarnecki et al. '23]

⇒ ECFA HTE: Focus Group EXScalar

Analysis strategy:

## Signal scenarios

Consider production of light scalar in scalar-strahlung process:

$$e^+ e^- \rightarrow Z S$$

with hadronic Z decays (for statistics) and scalar decays to tau lepton pairs:

$$Z \rightarrow q \bar{q} \quad S \rightarrow \tau^+ \tau^-$$

⇒ look for fully hadronic ( $jjjj$ ), semi-leptonic ( $ljjj$ ) or leptonic ( $lljj$ ) final state depending on the decays of two tau leptons

Considered mass range  $M_S = 15 - 140$  GeV

More analysis details:

## Event samples

Signal and background samples generated with WHIZARD 3.1.2 using built-in SM\_CKM model.

Signal samples generated by varying H mass in the model and forcing its decay to  $\tau^+\tau^-$ .

All relevant four-fermion final states considered as background.

SM-like Higgs boson contribution included in the background estimate.

Contribution from two-fermion and six-fermion processes found to be small.

ISR and luminosity spectra for ILC running at 250 GeV taken into account

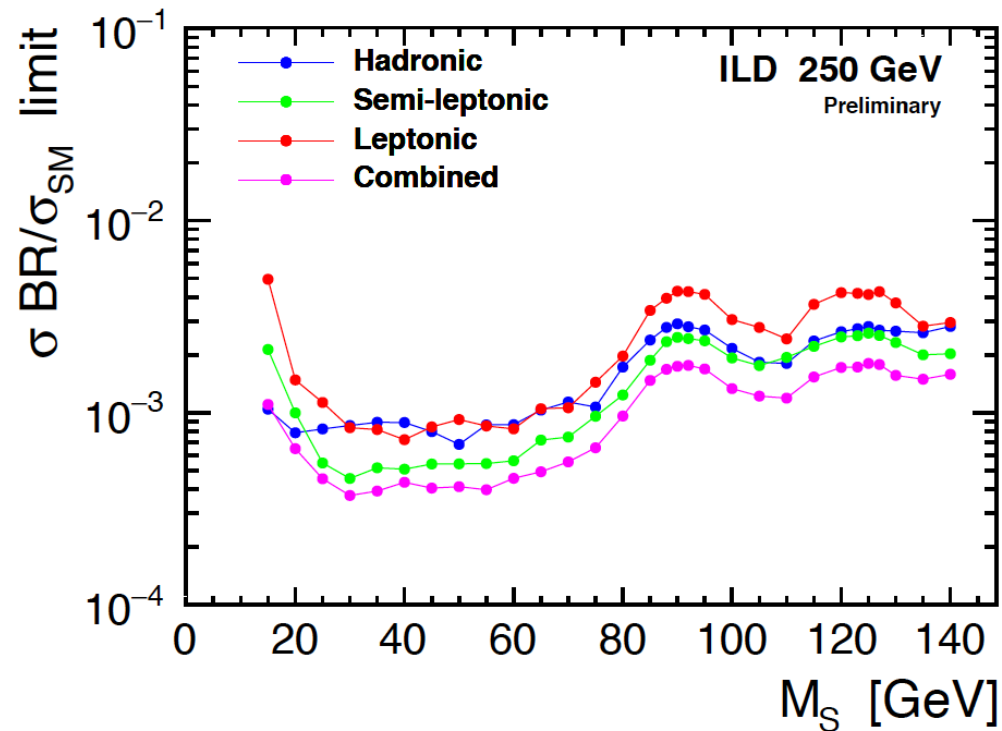
Total luminosity of  $2 \text{ ab}^{-1}$ , with  $\pm 80\% / \pm 30\%$  polarisation for  $e^-/e^+$  (H-20 scenario).

Fast detector simulation with Delphes ILCgen model.

## Cross section limits

Cross section limits for  $\sigma(e^+e^- \rightarrow Z S) \cdot BR(S \rightarrow \tau\tau)$

BDT cut optimized for 1% signal level; combined data, polarisation not taken into account!



$\Rightarrow$  do the same for CEPC! :-)

## 4. Evidence for SUSY Higgses?!

**What about SUSY??** (I am wearing my MSSM T-Shirt!)

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- NMSSM
- $\mu\nu$ SSM
- ...



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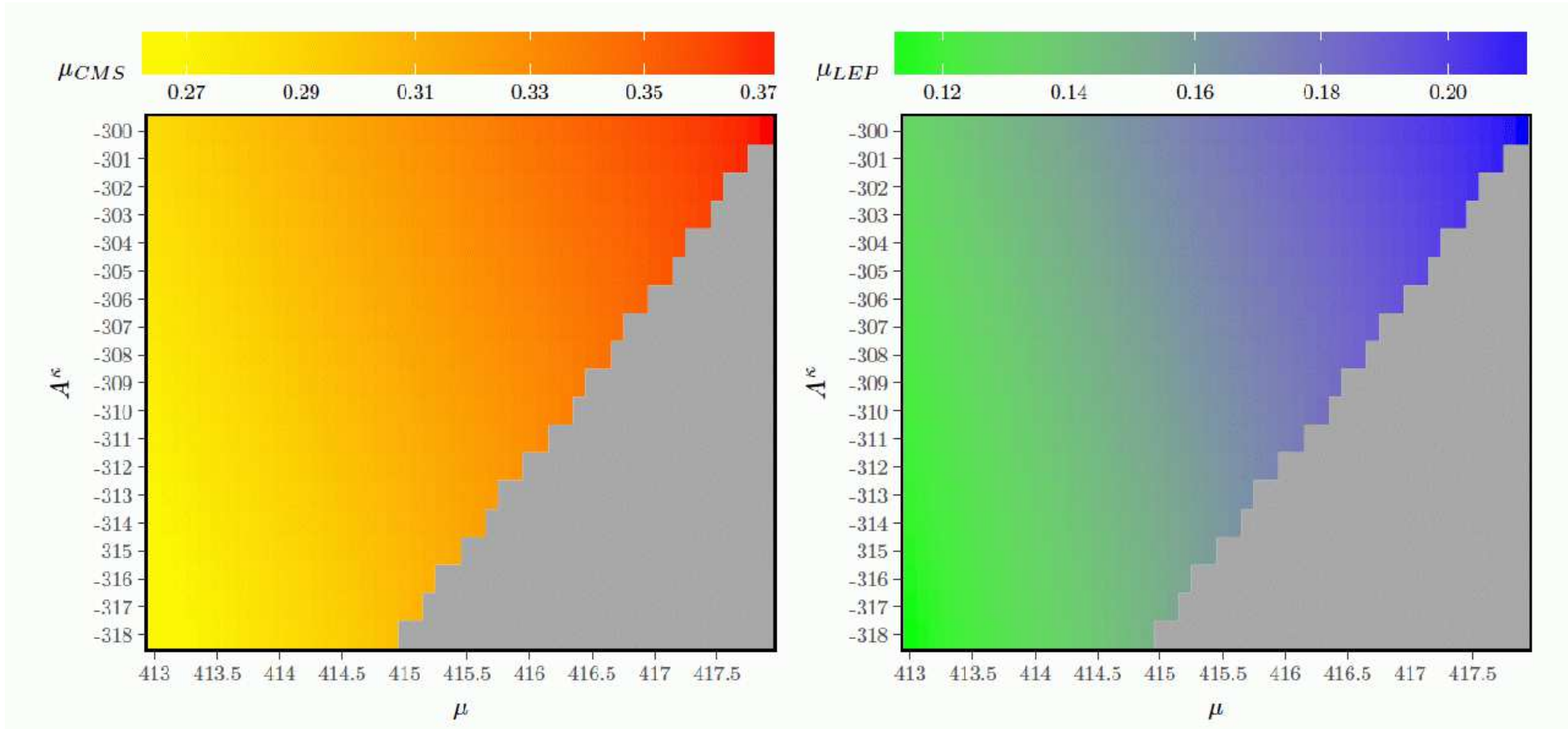
Can the  $\mu\nu$ SSM explain the two excesses?

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

$v_{iL}$	$Y_i^\nu$	$A_i^\nu$	$\tan\beta$	$\mu$	$\lambda$	$A^\lambda$	$\kappa$	$A^\kappa$	$M_1$
$\sqrt{2} \cdot 10^{-5}$	$10^{-7}$	-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]

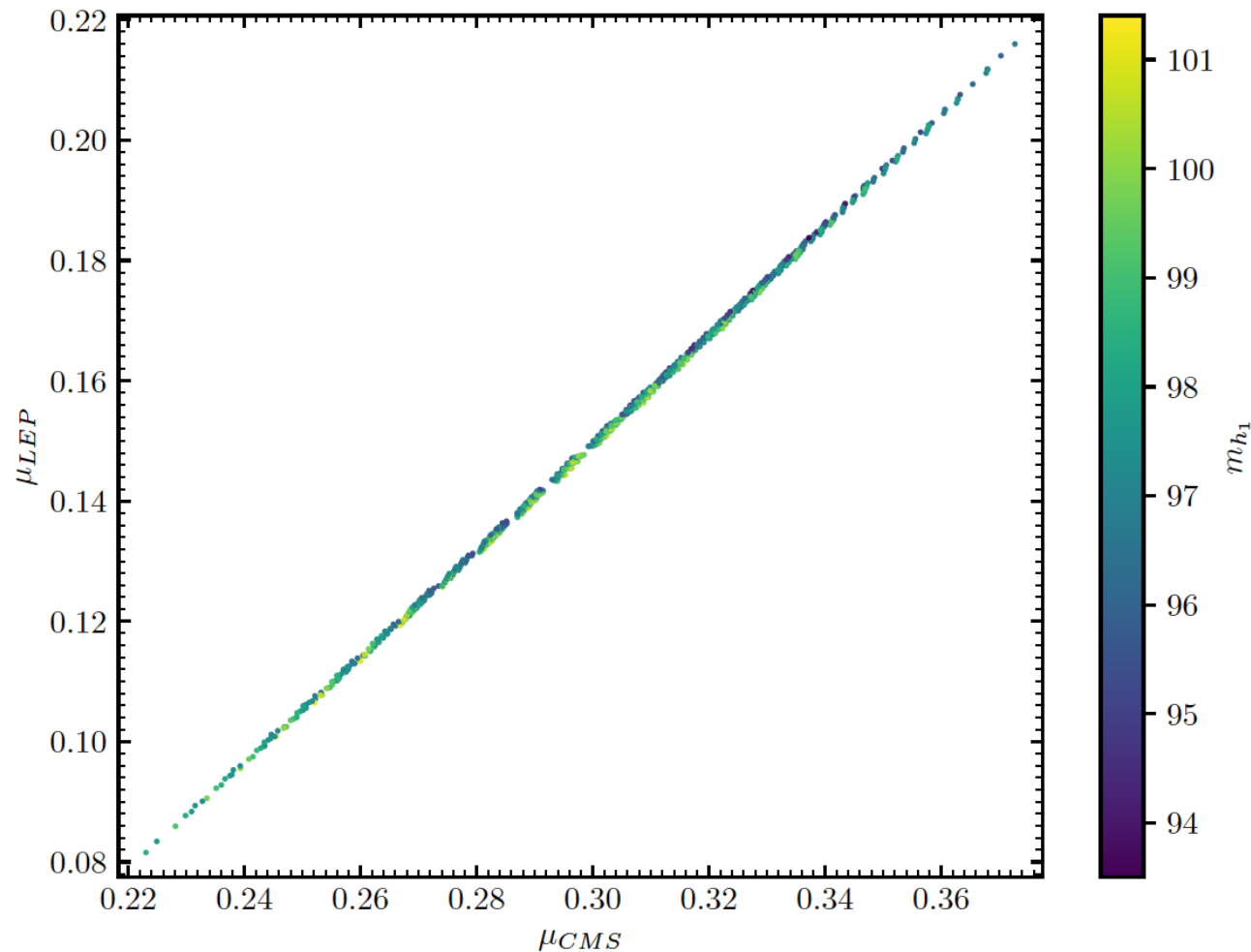


⇒ Yes! :-)

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  $\sim 95.4$  GeV
    - $pp \rightarrow h_{95} \rightarrow \gamma\gamma \Rightarrow$  CMS:  $2.9\sigma$ , ATLAS:  $1.7\sigma$
    - $e^+e^- \rightarrow Zh_{95} \rightarrow Zb\bar{b} \Rightarrow$  LEP:  $2\sigma$
    - $pp \rightarrow h_{95} \rightarrow \tau\tau \Rightarrow$  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  
 $\Rightarrow$  possible explanations:  $\gamma\gamma$ ,  $b\bar{b}$ : type II/IV,  $\tau\tau$ : type IV only
- CEPC: analysis of  $h_{125}$ :
  - precision measurements of couplings can distinguish N2HDM vs. SM
  - possible distinction between type II and IV
- CEPC: 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! :-)

A man with short brown hair, wearing a grey shirt, is looking up at a full-body figure of Darth Vader. The scene is set in a dark, industrial environment with blue lighting and rectangular light fixtures on the wall. The text "Further Questions?" is overlaid in white on the left side of the image.

Further Questions?

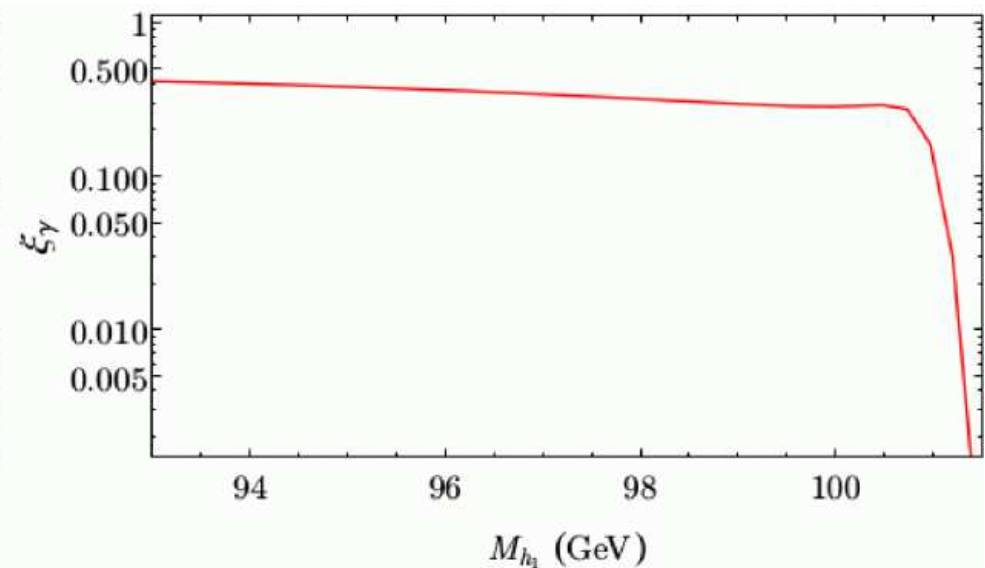
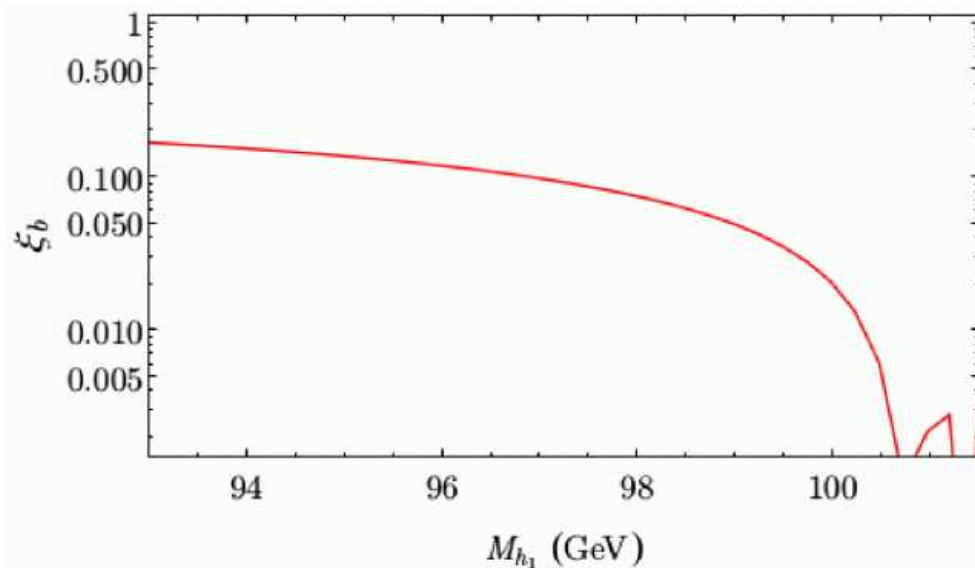
## What about the NMSSM?

[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 $\phi_{g5}$ coupling measurements?

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

SM Higgs **BRs**:

[YR4 LHCHXSWG]

final state	$b\bar{b}$	$gg$	$\tau^+\tau^-$	$WW^*$	$\sigma_{ZH}$
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	$H \rightarrow b\bar{b}$	$H \rightarrow gg$	$H \rightarrow \tau^+\tau^-$	$H \rightarrow WW$	$\sigma_{ZH}$
$S/B$	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 $\phi_{95}$ :

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

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

$\Rightarrow \mathcal{O}(10^5)$   $\phi_{95}$ '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  $\phi$  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

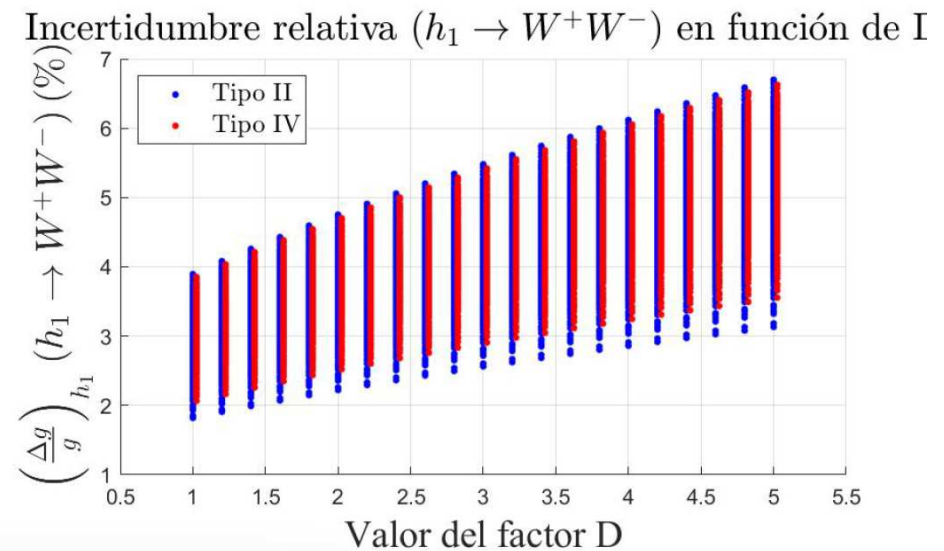
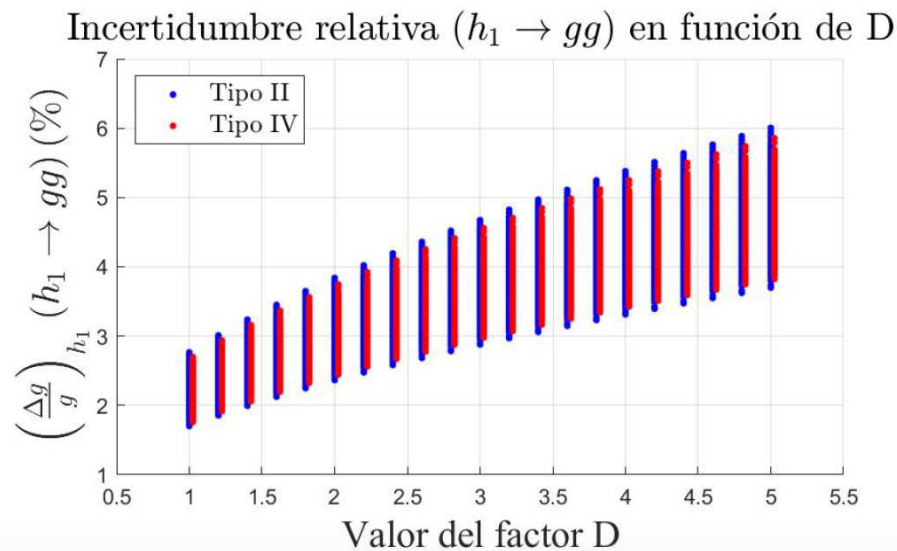
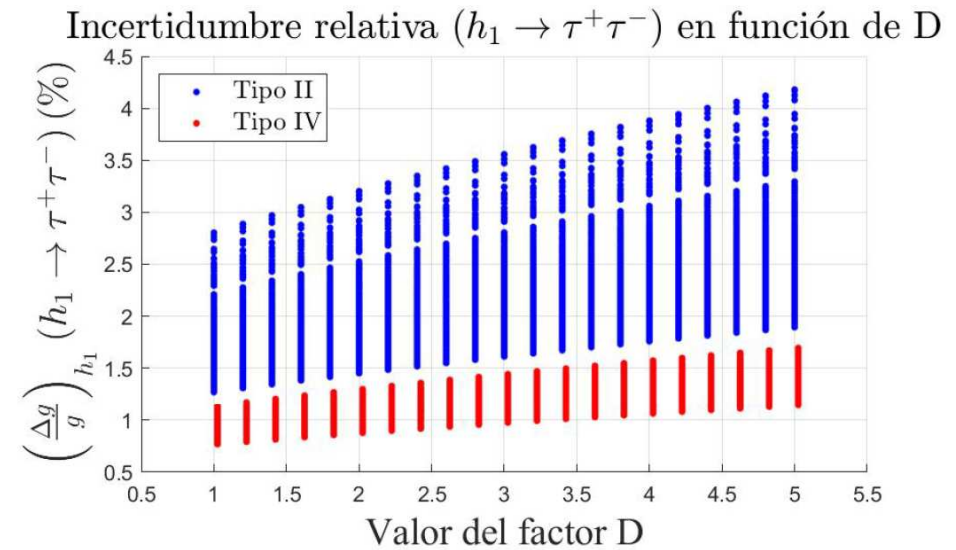
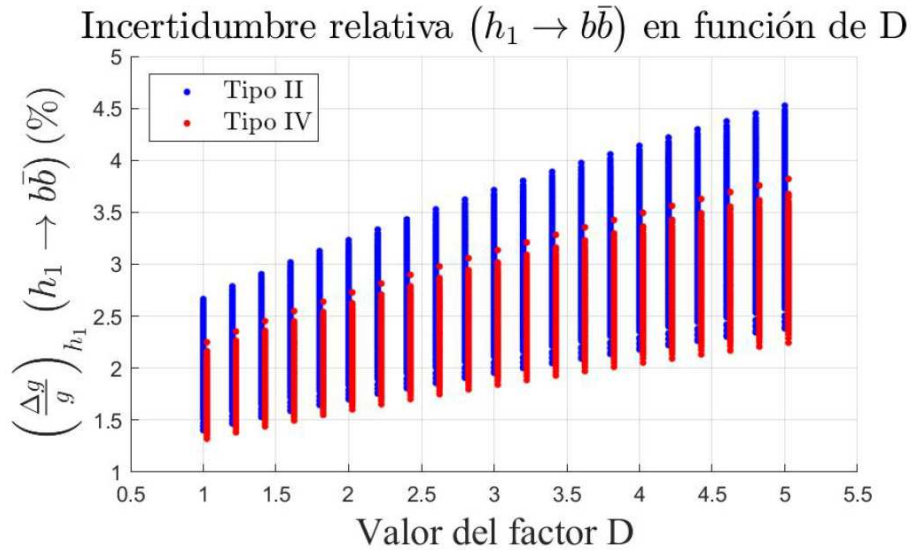
## Evaluating uncertainties of $\phi_{95}$ :

- 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