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# ECFA focus topic: New exotic scalars

*Sven Heinemeyer, IFT (CSIC, Madrid)*

zoom, 02/2024

Thanks go to *Aleksander Filip Zarnecki* (focus topic leader)

⇒ all slides "not my style" are from Filip :-)

1. Motivation

2. Focus topic: EXscalar

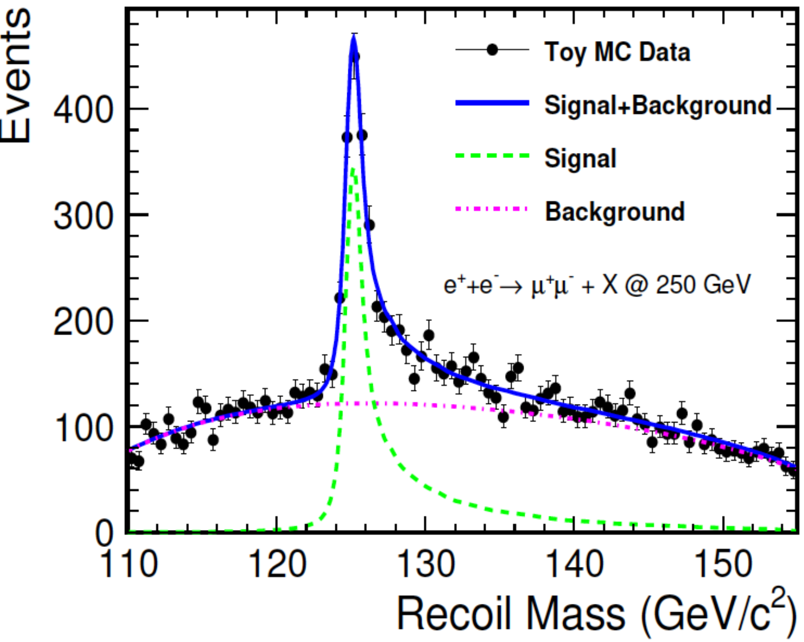
3. First Results

4. Conclusions

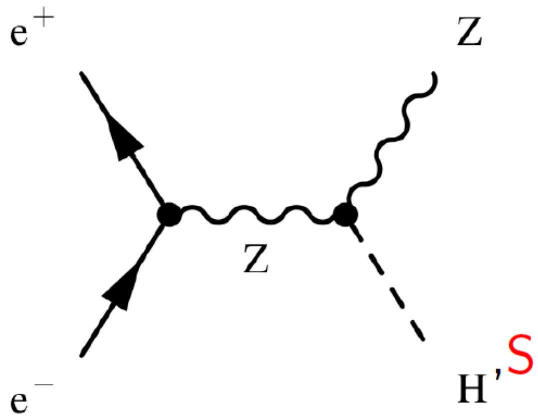
# 1. Motivation

## Higgs production at lower energies at $e^+e^-$ colliders:

$\Rightarrow$ recoil method for Higgs measurements/detection:




At 250 GeV we will focus on $H_{125}$ production



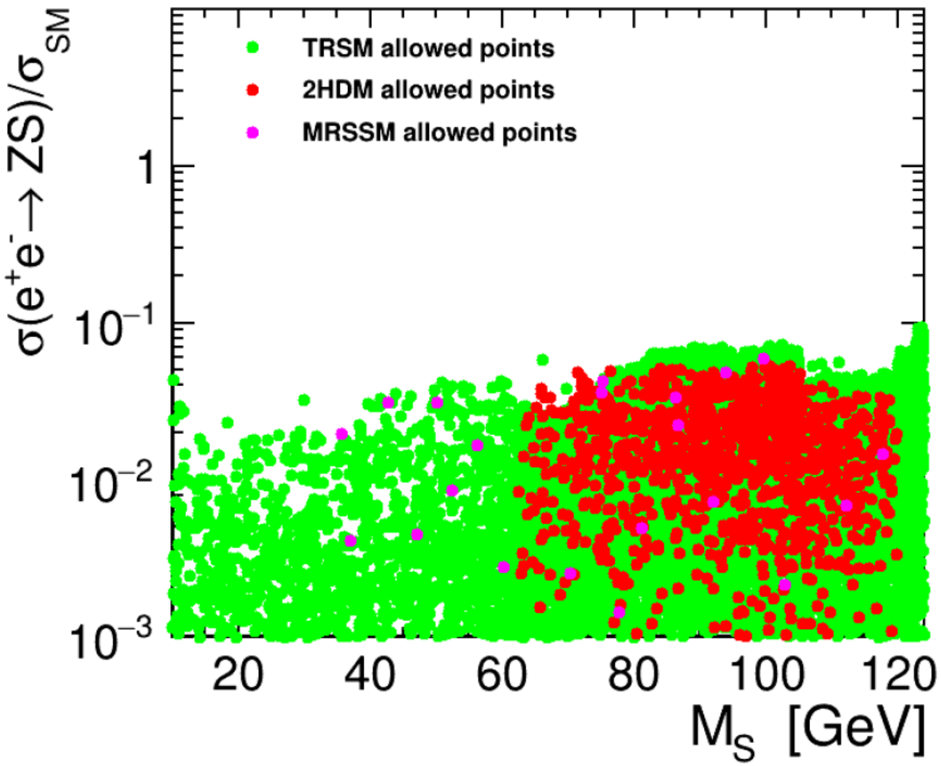

But production of additional, light exotic scalar states is still not excluded by the existing data!

# What is still allowed for the low mass range

⇒ parameter scan in different models

## Possible scenarios

Benchmark points consistent with current experimental and theoretical bounds

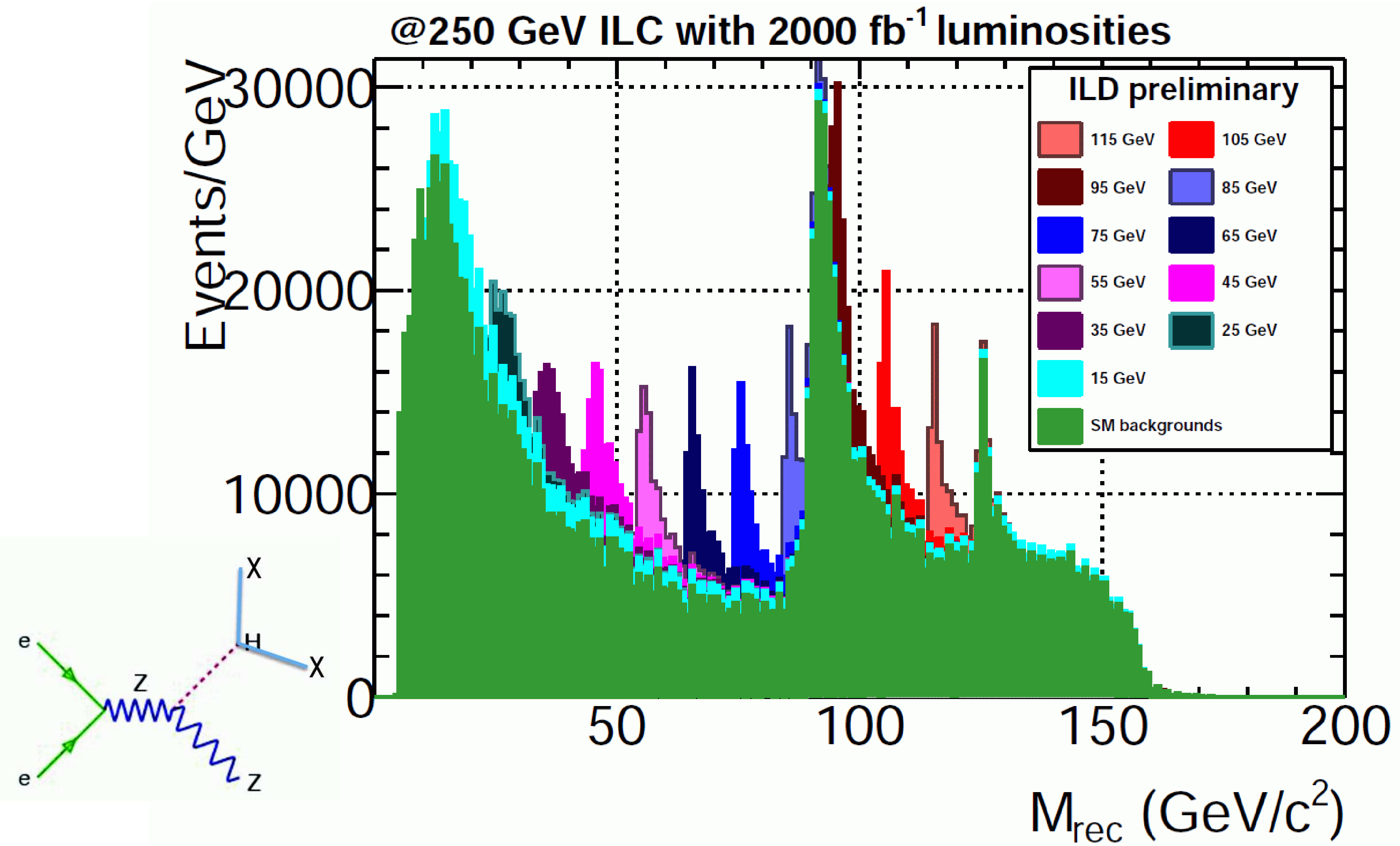



Two-Real-Singlet Model
thanks to Tania Robens
see arXiv:2209.10996 arXiv:2305.08595

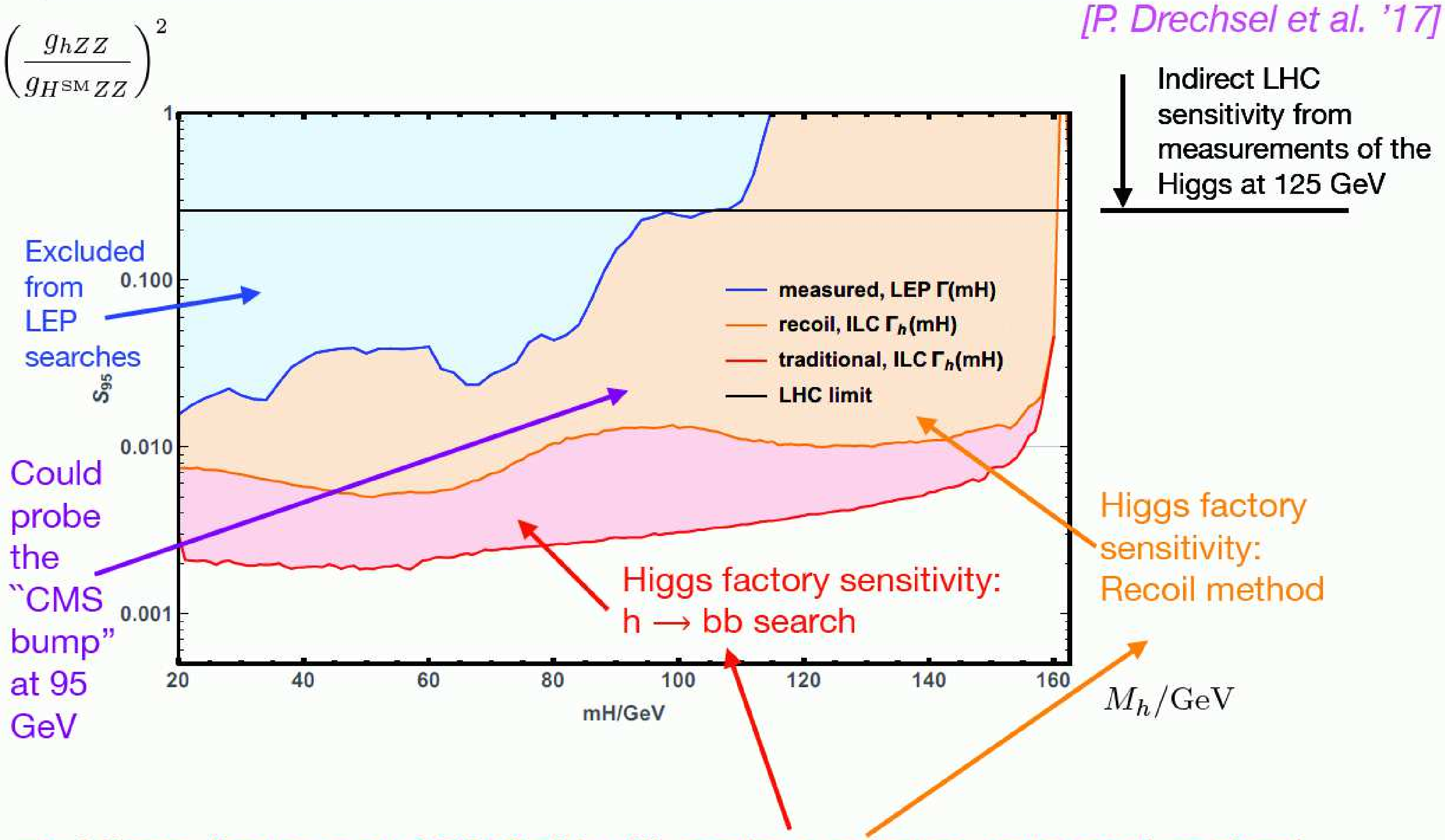
Two Higgs-Doublet Model
thanks to Kateryna Radchenko
thdmTool package, see arXiv:2309.17431

Minimal R-symmetric Supersymmetric SM
thanks to Wojciech Kotlarski arXiv:1511.09334

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



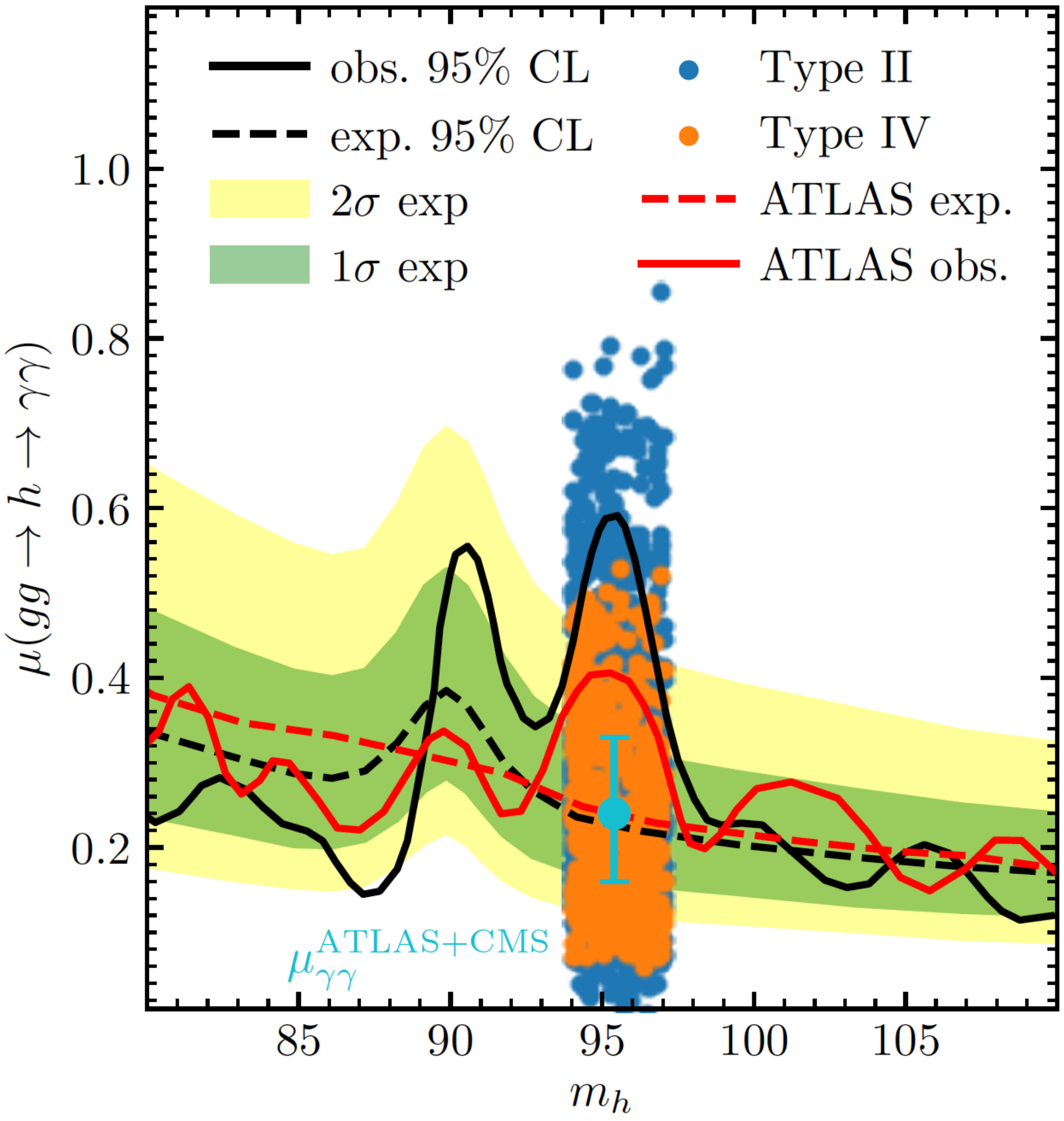
# Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb$^{-1}$ to a new light Higgs




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

[*Taken from G. Weiglein '18*]

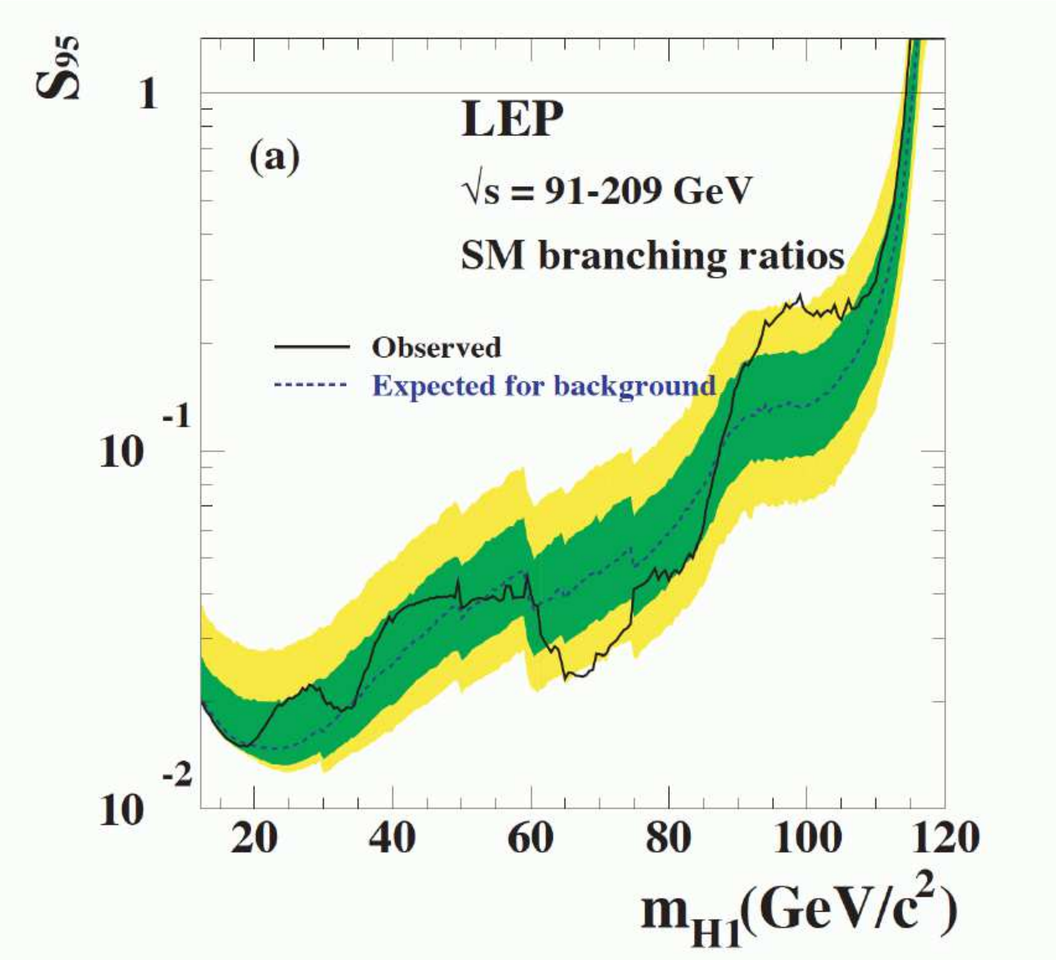
## Experimental hints: CMS/ATLAS $pp \to \phi \to \gamma\gamma$ [T. Biekötter, S.H., G. Weiglein '23]

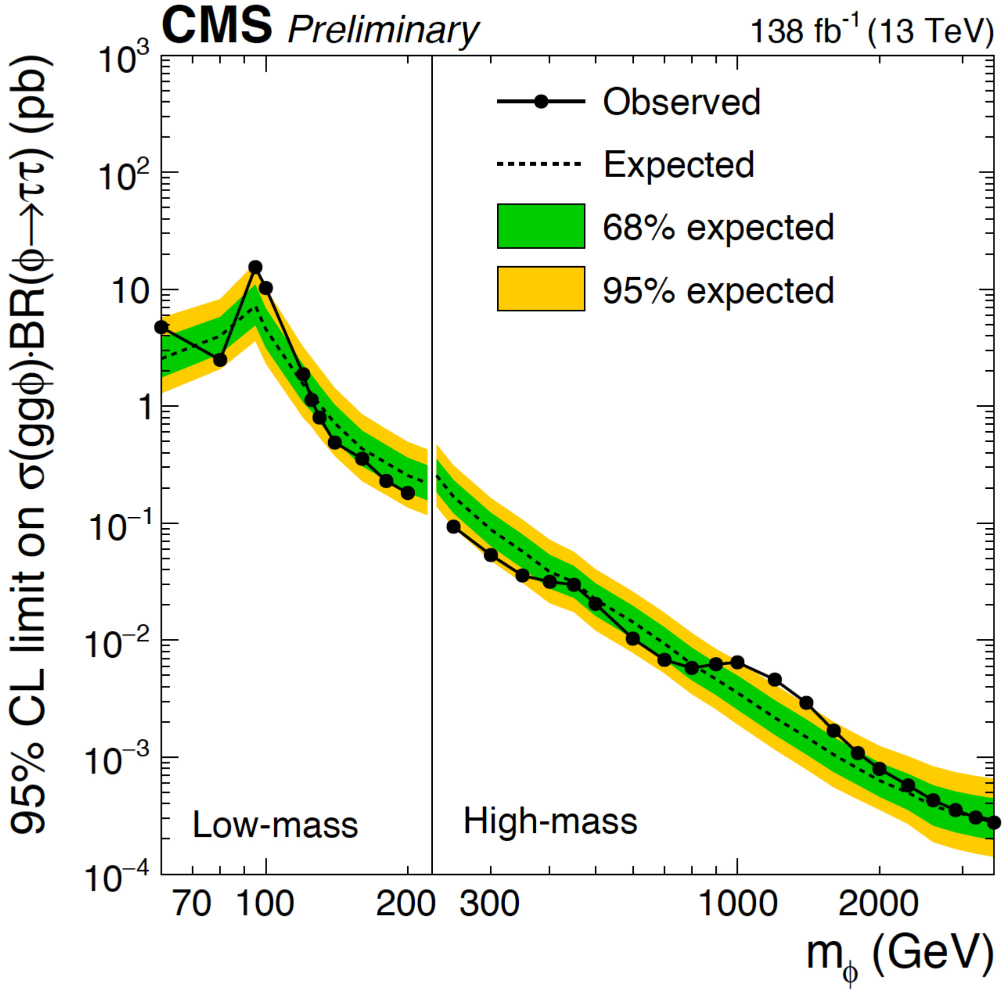



⇒ agreement between ATLAS and CMS! $\mu_{\gamma\gamma} = 0.24^{+0.09}_{-0.08}$ (3.1 σ)

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)

$\Rightarrow \sim 4.6\,\sigma$

## Physics opportunities at $e^+e^-$ colliders in the "$\phi_{95}$ scenario"

### 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 $\phi_{95}$ at the LHC
- direct production of $\phi_{95}$ at the HL-LHC
- direct production of $\phi_{95}$ at the ILC
- ILC $\phi_{95}$ coupling measurements

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

ILC = ILC or other $e^+e^-$ collider

# 2. Focus topic: EXscalar

## Expert team

Responsible WG1-SRCH convener: A. Filip Żarnecki
WG1 coordination contact: Jenny List

- FCCee contact: Sven Heinemeyer
- ILD contact: Mikael Berggren
- CLIC contact: A. FIlip Żarnecki
- Theory contact: Tania Robens

  LHC contacts:
  - Nikolaos Rompotis (ATLAS)
  - Abdollah Mohammadi (CMS, $C^3$)

⇒ more contributors welcome!

# Two different "light scalar topics" to be studied:

## Theoretical and phenomenological targets

Higgs factories are best suited to search for light exotic scalars in the process:

$$e^+e^- \to Z\,\phi$$

Production of new scalars can be tagged, independent of their decay, based on the recoil mass.

We should look for different scalar decay channels e.g. $b\bar{b}$, $W^{+(*)}W^{-(*)}$, $\tau^+\tau^-$ or invisible
Non-standard decays channels of the new scalar should also be looked for.

For maximum sensitivity, feasibility of including hadronic $Z$ decays should be explored.

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## Theoretical and phenomenological targets (2)

As as second benchmark scenario for the EXscalar focus topic,
light scalar pair-production in 125 GeV Higgs boson decays is proposed:

$$e^+e^- \to Z\,H \to Z\,\phi\,\phi$$

Here again, different decay channels should be considered, both SM-like and exotic.

While new scalar states could in general be long-lived, only scenarios with prompt decays are included in this focus topic (while a dedicated topic focuses on LLPs, see next presentation).

## Status and plans:

### Ready to go!

- Possible analysis targets defined
- Example model scenarios available
- Different channels to be considered - many volunteers needed!

### Planned activities

- First estimates of sensitivity in $\phi \to \tau\tau$ channel (student available to continue)

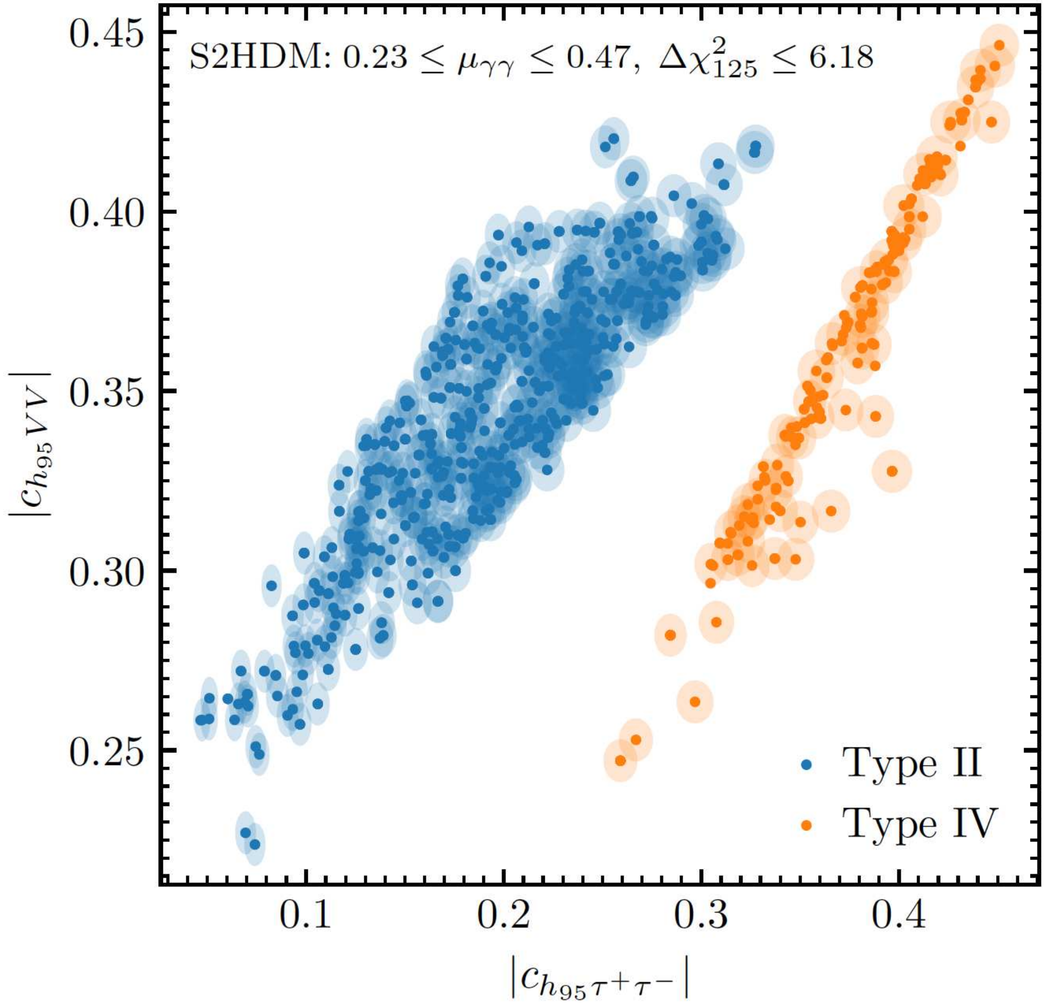
\+ Potential candidates identified to look at $e^+e^- \to Z\phi$ with
  - $\phi \to W^{(*)}W^{(*)}$ (S.S.Abdussalam)
  - $\phi \to b\bar{b}$ (A.F.Zarnecki)

# 3. First Results

- motivated by $h_{95}$
- poor-man theorists study
- now first experimental study
- comparison with different model predictions?
- comparison with $h_{95}$ prediction?

## $h_{95}$ coupling measurements at the ILC: S2HDM theory study!

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




⇒ high precision coupling measurements possible!

# Motivation

N2HDM scenario

Parameters of the best-fit point (minimal value of $\chi^2$)

| | | | | | | |
|---|---|---|---|---|---|---|
| $m_{h_1}$ | $m_{h_2}$ | $m_{h_3}$ | $m_A$ | $m_{H^\pm}$ | | |
| 95.68 | 125.09 | 713.24 | 811.20 | 677.38 | | |
| $\tan\beta$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $m_{12}$ | $v_S$ | |
| 10.26 | 1.57 | 1.22 | 1.49 | 221.12 | 1333.47 | |
| $\mathrm{BR}^{bb}_{h_1}$ | $\mathrm{BR}^{gg}_{h_1}$ | $\mathrm{BR}^{cc}_{h_1}$ | $\mathrm{BR}^{\tau\tau}_{h_1}$ | $\mathrm{BR}^{\gamma\gamma}_{h_1}$ | $\mathrm{BR}^{WW}_{h_1}$ | $\mathrm{BR}^{ZZ}_{h_1}$ |
| $\Rightarrow$ 0.005 | 0.348 | 0.198 | $\Rightarrow$ 0.412 | $6.630 \cdot 10^{-3}$ | 0.025 | $3.382 \cdot 10^{-3}$ |
| $\mathrm{BR}^{bb}_{h_2}$ | $\mathrm{BR}^{gg}_{h_2}$ | $\mathrm{BR}^{cc}_{h_2}$ | $\mathrm{BR}^{\tau\tau}_{h_2}$ | $\mathrm{BR}^{\gamma\gamma}_{h_2}$ | $\mathrm{BR}^{WW}_{h_2}$ | $\mathrm{BR}^{ZZ}_{h_2}$ |
| 0.553 | 0.085 | 0.032 | 0.069 | $2.537 \cdot 10^{-3}$ | 0.228 | 0.028 |
| $\mathrm{BR}^{tt}_{h_3}$ | $\mathrm{BR}^{bb}_{h_3}$ | $\mathrm{BR}^{\tau\tau}_{h_3}$ | $\mathrm{BR}^{h_1h_1}_{h_3}$ | $\mathrm{BR}^{h_1h_2}_{h_3}$ | $\mathrm{BR}^{h_2h_2}_{h_3}$ | $\mathrm{BR}^{WW}_{h_3}$ |
| 0.123 | 0.739 | 0.000 | 0.002 | 0.072 | 0.030 | 0.022 |
| $\mathrm{BR}^{tt}_{A}$ | $\mathrm{BR}^{bb}_{A}$ | $\mathrm{BR}^{\tau\tau}_{A}$ | $\mathrm{BR}^{Zh_1}_{A}$ | $\mathrm{BR}^{Zh_2}_{A}$ | $\mathrm{BR}^{Zh_3}_{A}$ | $\mathrm{BR}^{WH^\pm}_{A}$ |
| 0.053 | 0.173 | 0.000 | 0.024 | 0.001 | 0.015 | 0.734 |
| $\mathrm{BR}^{tb}_{H^\pm}$ | $\mathrm{BR}^{\tau\nu}_{H^\pm}$ | $\mathrm{BR}^{Wh_1}_{H^\pm}$ | $\mathrm{BR}^{Wh_2}_{H^\pm}$ | | | |
| 0.922 | 0.000 | 0.073 | 0.003 | | | |

Table 1: Parameters of the best-fit point for which the minimal value of $\chi^2$ is found ($\chi^2 = 88.07$, $\chi^2_{125} = 86.24$) and branching ratios of the scalar particles in the type IV scenario. Dimensionful parameters are given in GeV, and the angles are given in radian.

Interesting pattern for light Higgs ($h_1$): no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...

## Now experimentalists take over! :-)

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

Now experimentalists take over! :-) [A.F. Zarnecki et al. '23]

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:

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

$\Rightarrow$ look for fully hadronic ($jjjj$), semi-leptonic ($\ell jjj$) or leptonic ($\ell\ell jj$) 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

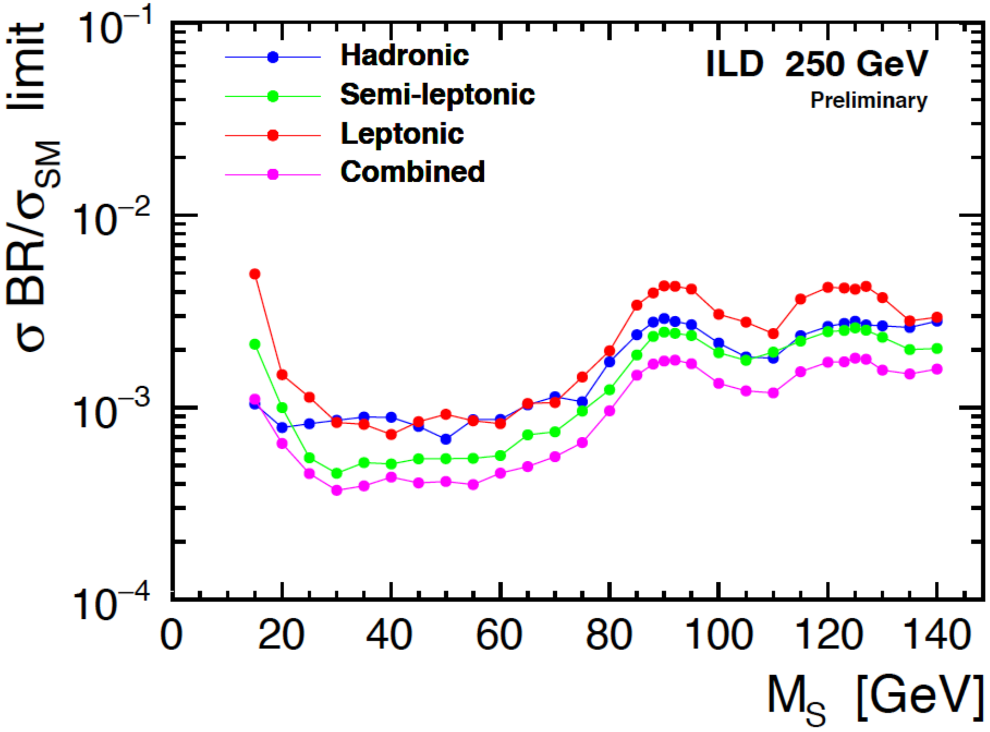
Total lumionsity of $2\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for $e^-/e^+$ (H-20 scenario).

Fast detector simulation with Delphes ILCgen model.

## Cross section limits

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

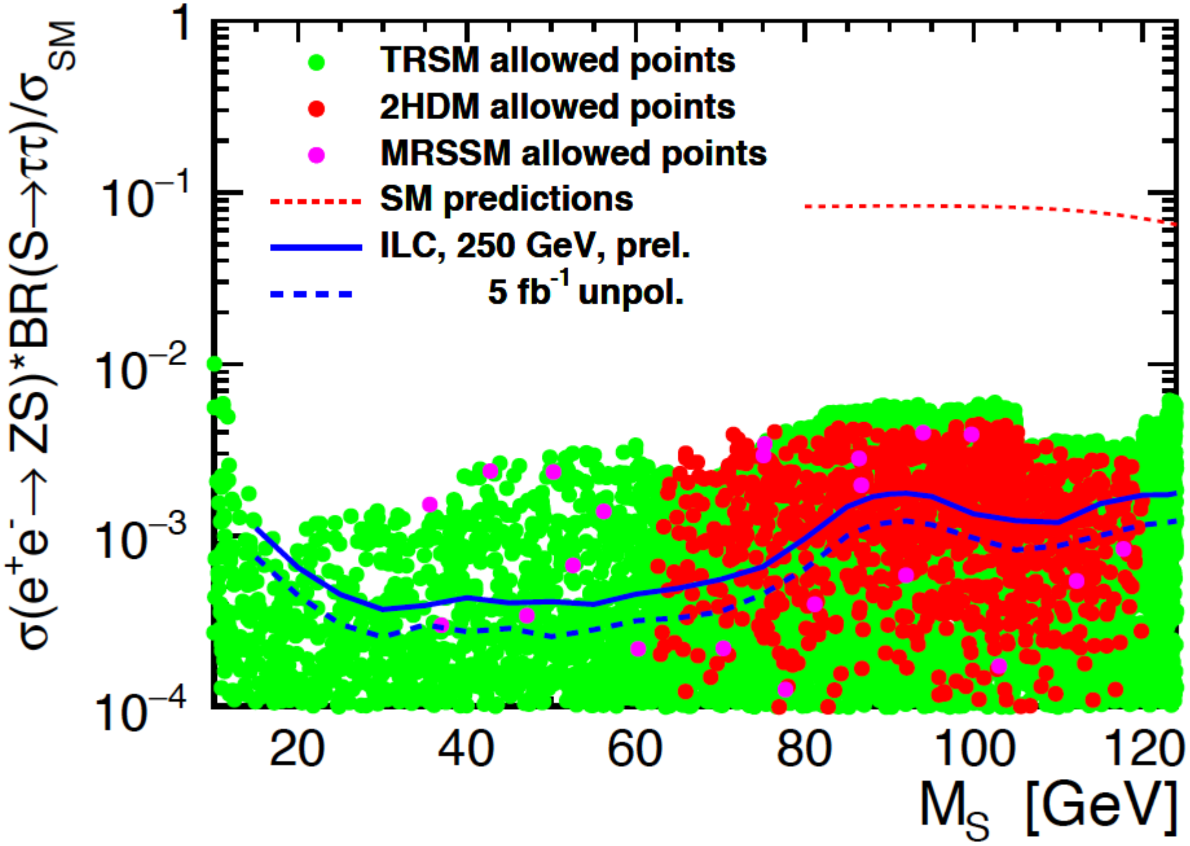
BDT cut optimized for 1% signal level; combined data, polarisation not taken into account!



## Comparison to model predictions:

# Cross section limits

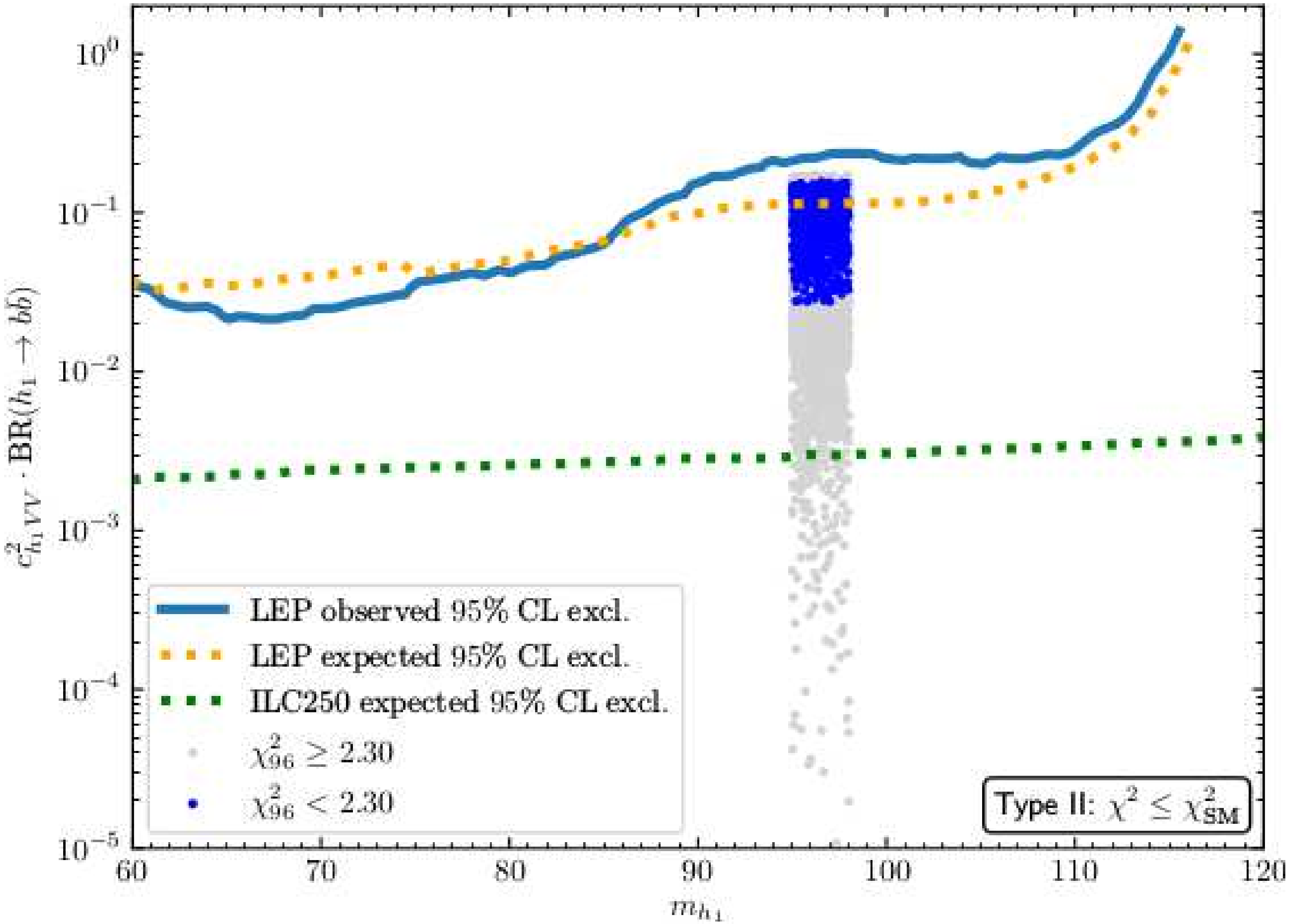
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with allowed scenarios in different models




⇒ some model realizations can be missed?!

# But focus on $h_{95}$ solutions:

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




$\Rightarrow$ new state cannot be missed! (theory analysis !!)

# 4. Conclusinos

- Good motivation for Higgs bosons below 125 GeV
  $\Rightarrow$ can be realized easily in multi-Higgs models

- **Focus topic: EXscalar**

  Physics case 1: $e^+e^- \to Z\phi$

  Physics case 2: $e^+e^- \to Zh_{125} \to Z\phi\phi$

- One analysis performed [*A.F. Zarnecki et al. '23*]
  – based on $h_{95}$ analysis: large BR($\phi \to \tau^+\tau^-$)
  – final states considered: $Z \to q\bar{q}$ and $\tau\tau \to jj, jl, ll$
  – $m_\phi = 15 \ldots 140$ GeV
  – $\Rightarrow$ cross section limits obtained: $\sigma/\sigma_{SM} \sim 10^{-3}$ (full mass range)
  – $h_{95}$ scenarios covered

- Planned acdtivities:
  – $\phi \to W^{(*)}W^{(*)}$
  – $\phi \to b\bar{b}$

- **More workforce highly appreciated!**


Further Questions?

## 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 | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ |
| 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)

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

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:

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

## SUSY realizations

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$\Rightarrow$ type II is needed for SUSY

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– NMSSM
– $\mu\nu$SSM
– . . .

## SUSY realizations

**What about SUSY??**

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$\Rightarrow$ 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 **???**

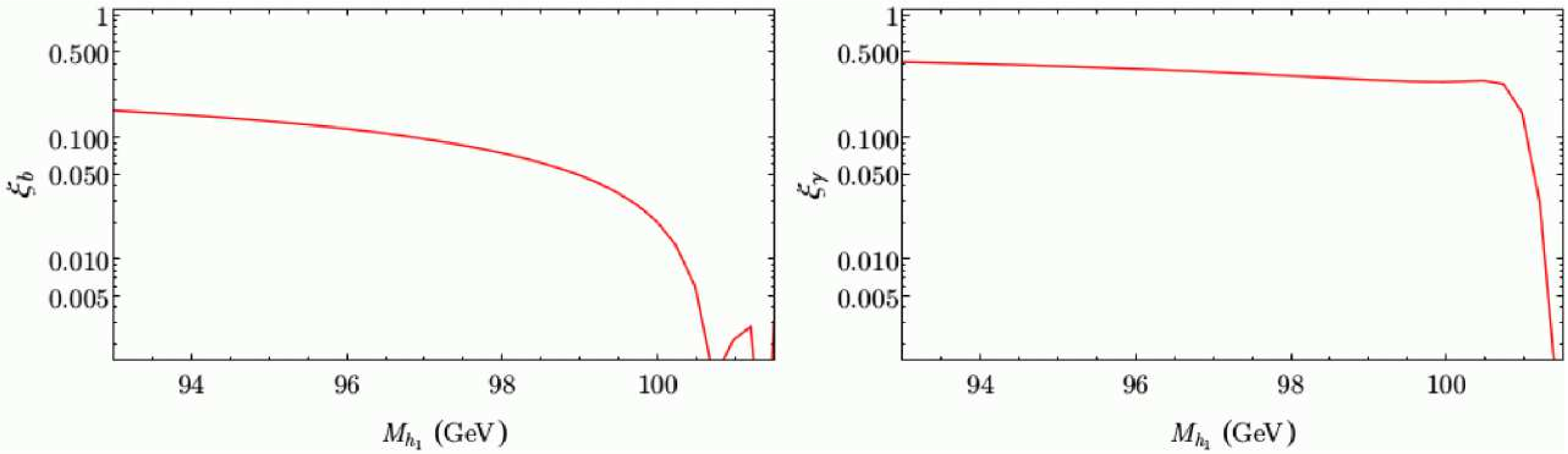
# What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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




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

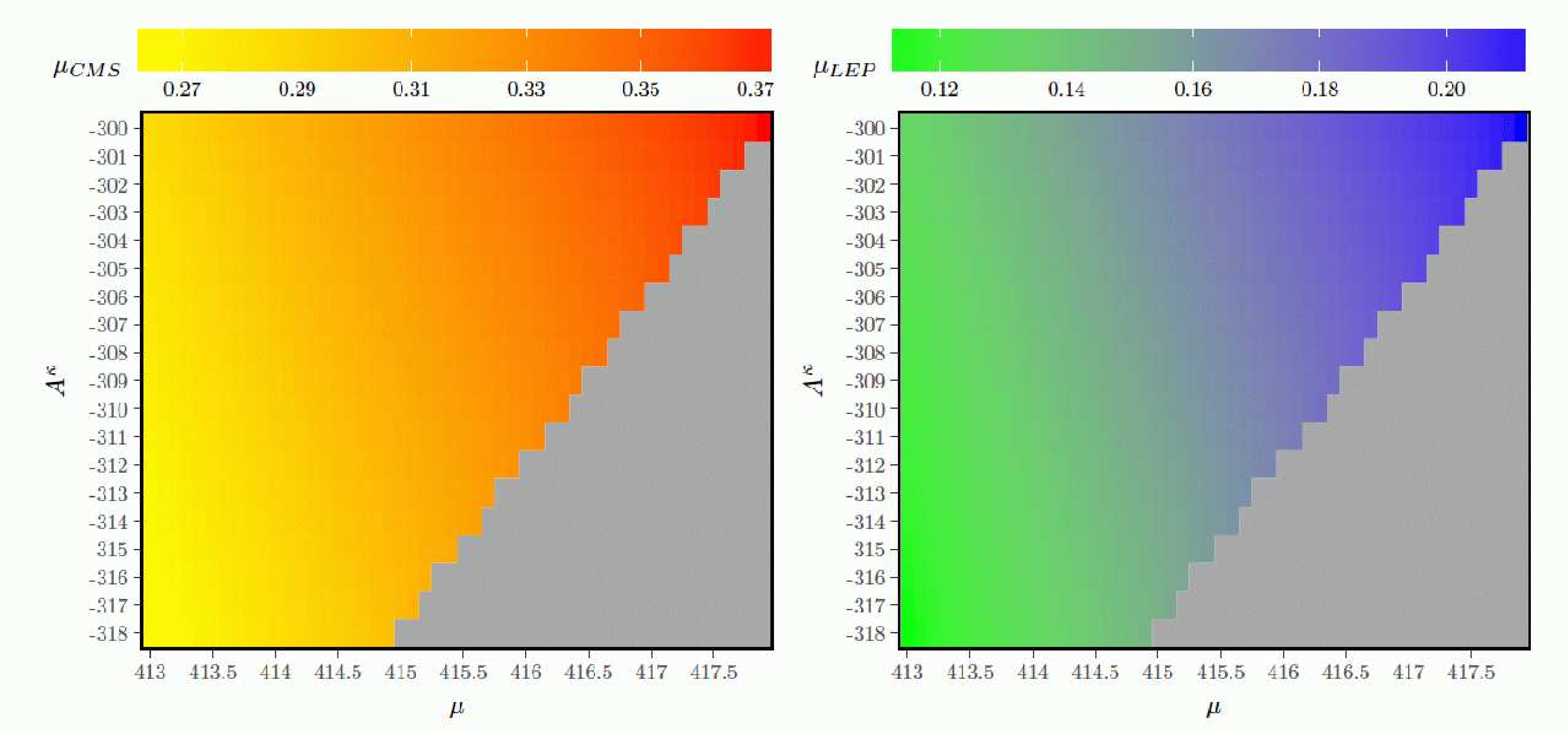
## Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]

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

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

[*T. Biekötter, S.H., C. Muñoz '17*]

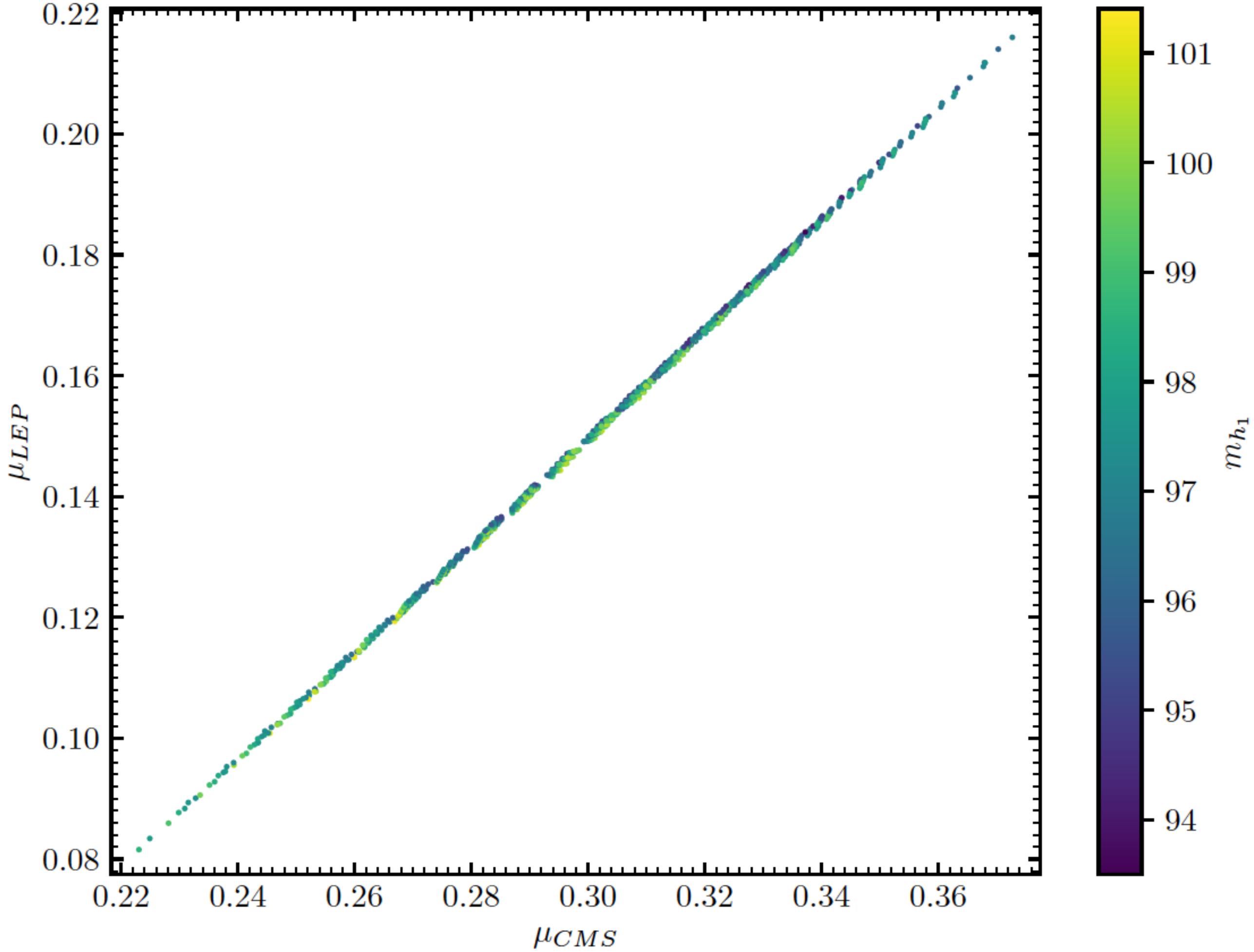



$\Rightarrow$ Yes! :-)

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 $\phi_{95}$ 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 $\sqrt{s} = 250$ 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 | $H \to b\bar{b}$ | $H \to gg$ | $H \to \tau^+\tau^-$ | $H \to WW$ | $\sigma_{ZH}$ |
|---|---|---|---|---|---|
| $S/B$ | 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 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 $\phi_{95}$:

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

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

$\Rightarrow \mathcal{O}\left(10^5\right)$ $\phi_{95}$'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 $\phi$ 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: $\left(\frac{N_S}{N_B}\right)_H \Big/ \left(\frac{N_S}{N_B}\right)_\phi = f_H/f_\phi =: D$

  with $D = 3$ as starting point

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

- Coupling is measured via decay

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

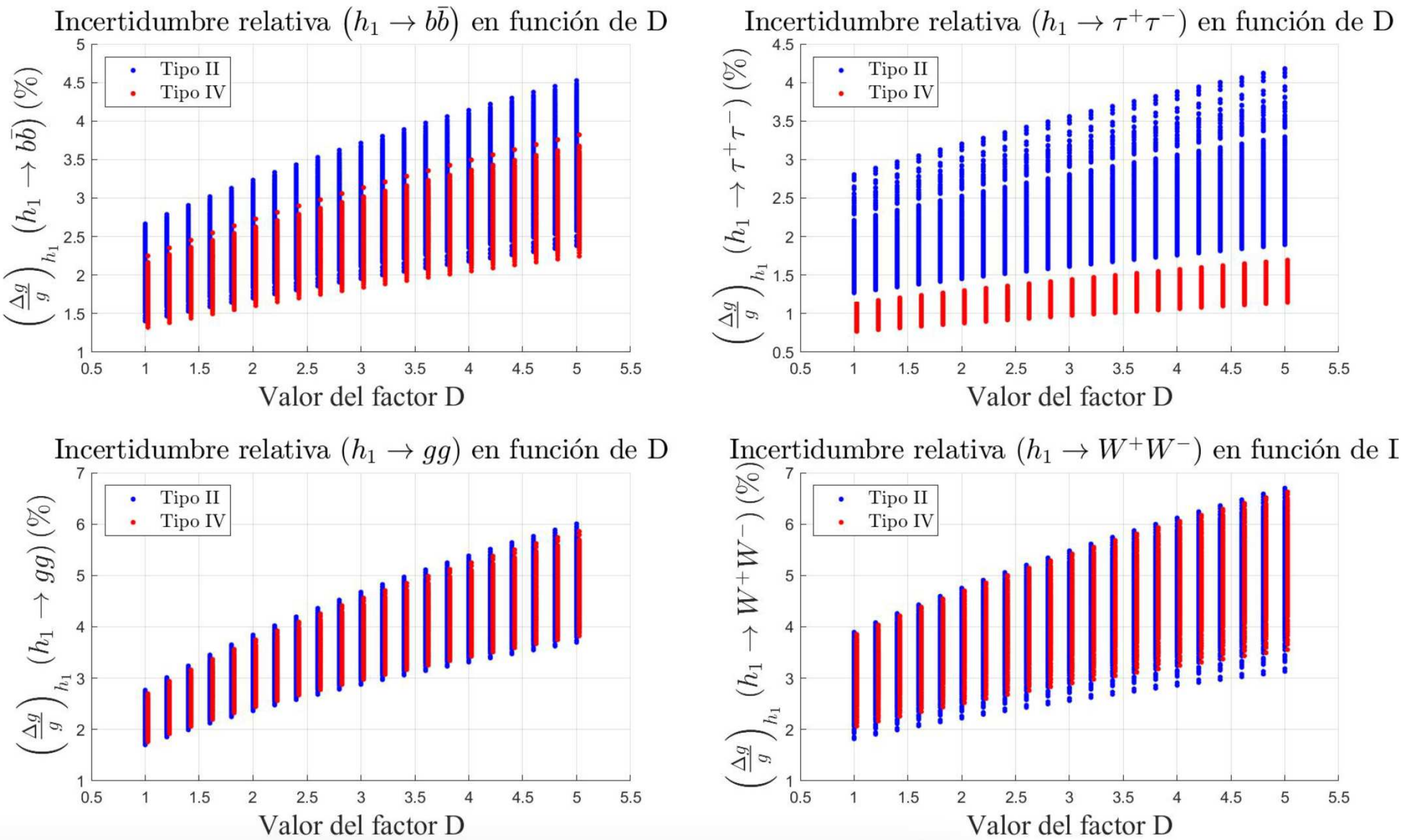
$$\to \sqrt{\frac{D + f_H}{1 + f_H}} \times \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}} \times \sqrt{\frac{\mathrm{BR}(H \to xx)}{\mathrm{BR}(\phi \to xx)}} \times \frac{(1 - \mathrm{BR}(H \to xx))}{(1 - \mathrm{BR}(\phi \to xx))}$$

- 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