
I FOUND THE HUGS BISON.
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Light Higgs Bosons at Future $e+e-$ Colliders

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zoom, 05/2022

- Introduction
- The evidence
- Physics opportunities at e^+e^- colliders
- Conclusions

1. Introduction

The SM cannot be the ultimate theory!

Some facts:

1. gravity is not included

2. the hierarchy problem

3. no unification of the three forces

4. Dark Matter is not included

5. Baryon Asymmetry of the Universe cannot be explained

6. neutrino masses are not included

7. . . .

How to search for BSM physics?

There are two complementary ways:

1. Direct searches

– direct production of BSM particles at (high-energy) colliders

– obvious at high $\sqrt{s}$, but also lower $\sqrt{s}$ is possible

– mostly at pp colliders

– also (future) e^+e^- colliders have a chance
(clean environment, uncolored particles)

2. Indirect searches

– high precision measurement of "SM processes" ($(g-2)_\mu$, M_W, ...)

– search for processes forbidden/suppressed in the SM

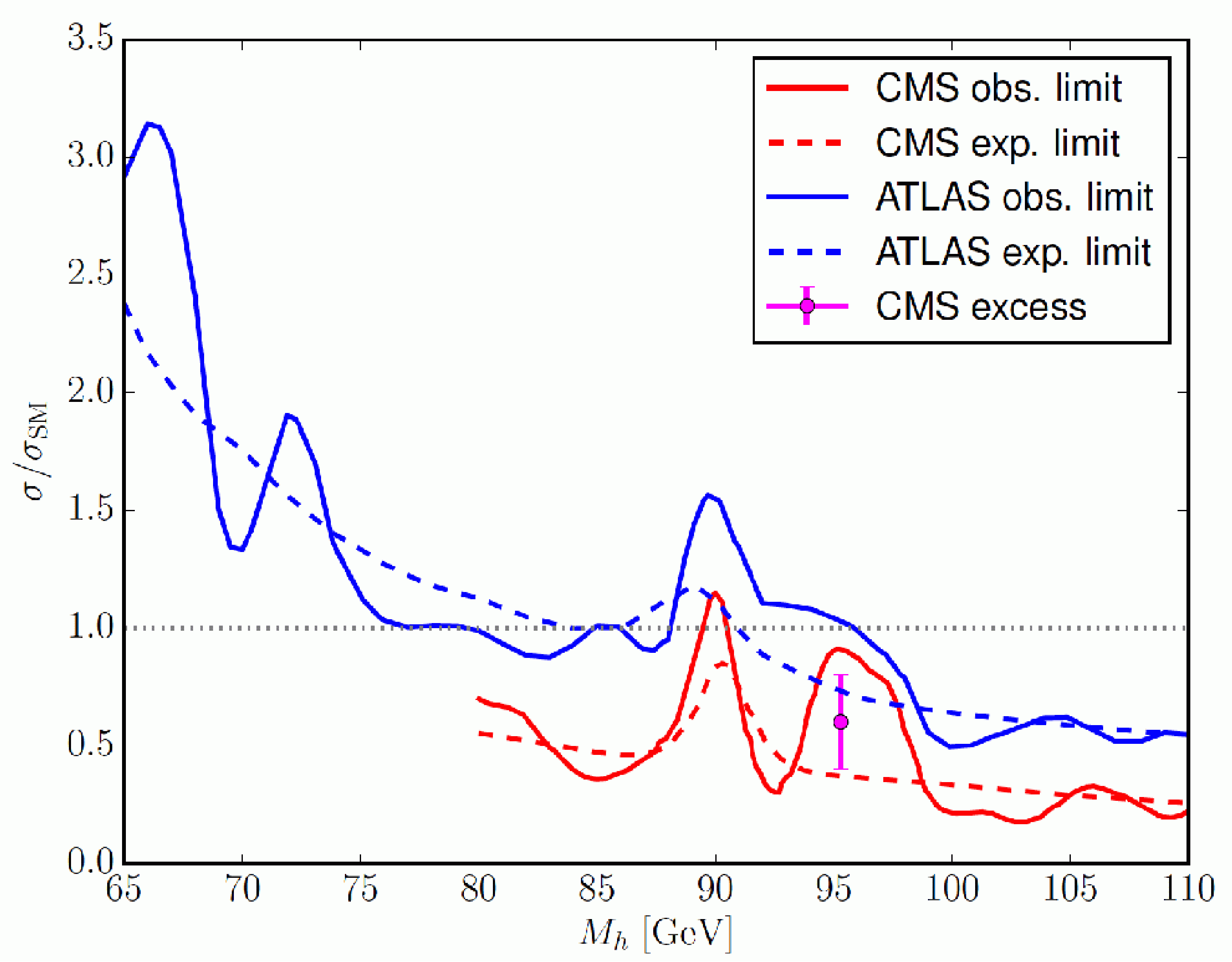
– possible at high and low $\sqrt{s}$

– high precision required on the experimental and theoretical side

2. The evidence

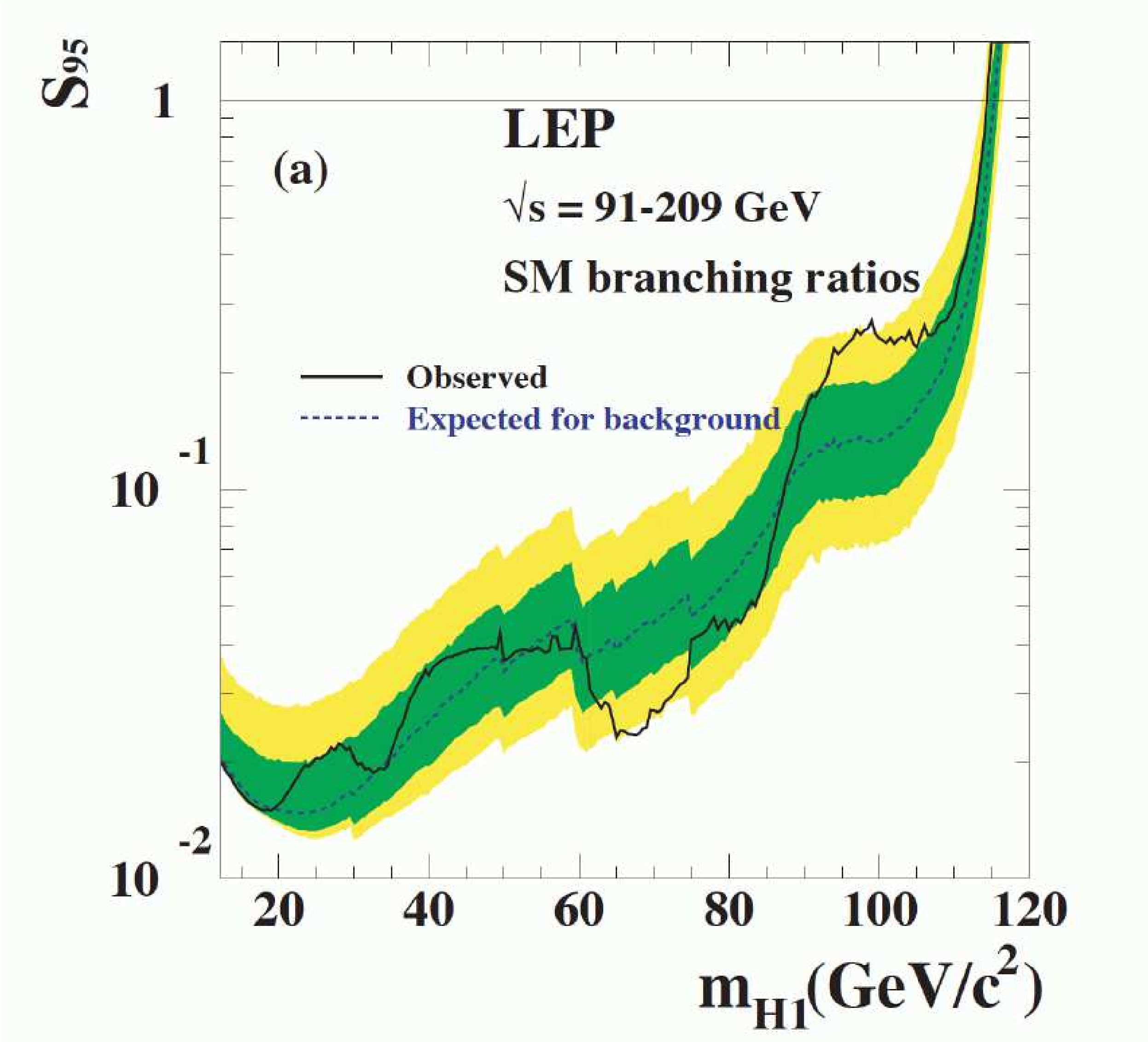
Experimental hint: Search for $pp \to \phi \to \gamma\gamma$: excess at $m_\phi \sim 95$ GeV

[*CMS '17, ATLAS '18, S.H., T. Stefaniak '18*] $\mu_{\gamma\gamma} = 0.6 \pm 0.2$



$\Rightarrow$ if there is something, it would look exactly like this!

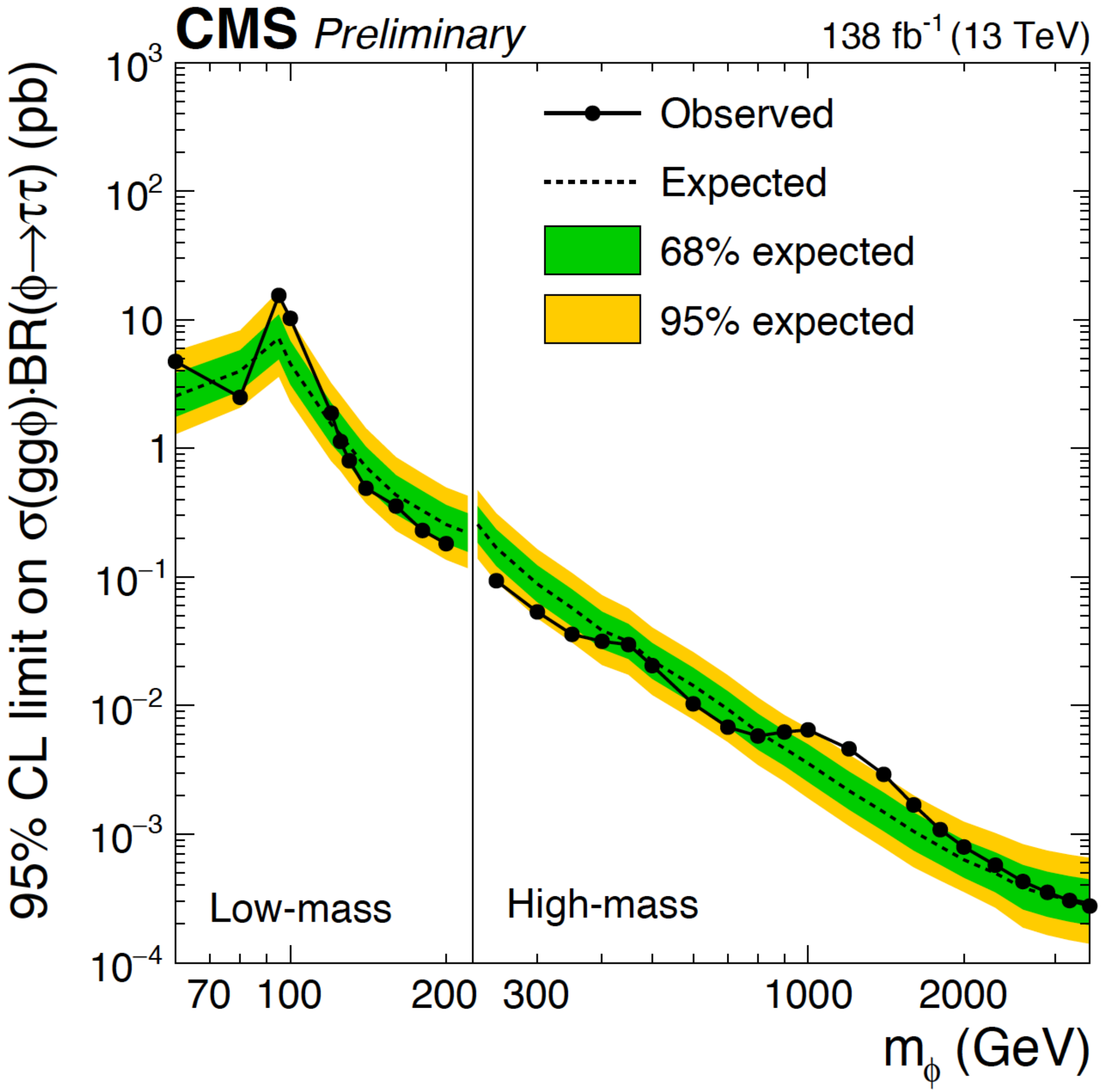
Remember the LEP excess?



$$\mu_{bb}(98\text{ GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \text{BR}(h_1 \to b\bar{b})\right]_{\text{exp/SM}} = 0.117 \pm 0.057$$

The new $\tau^+\tau^-$ excess

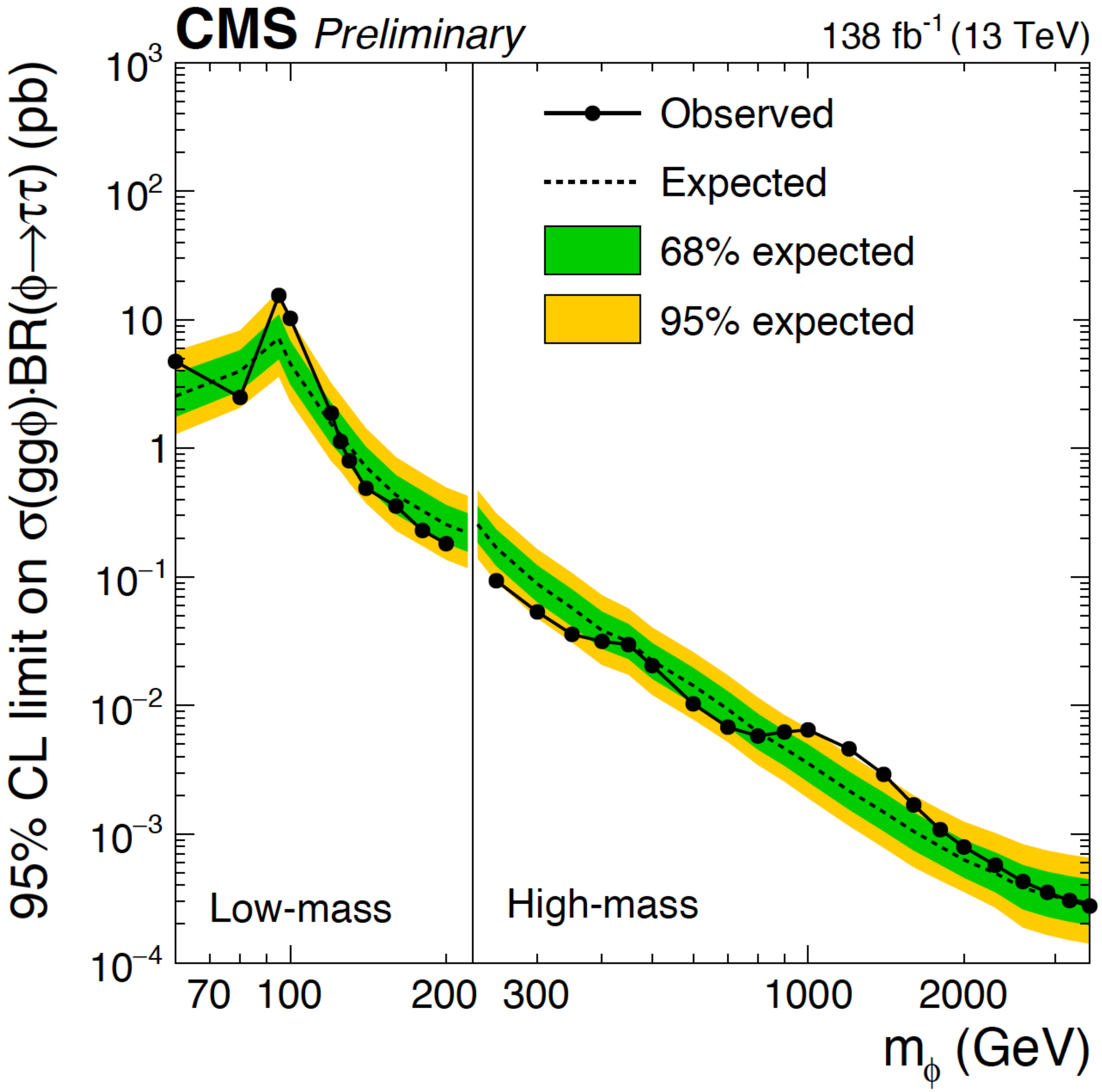
[*CMS '22*]



Can you spot the excess?

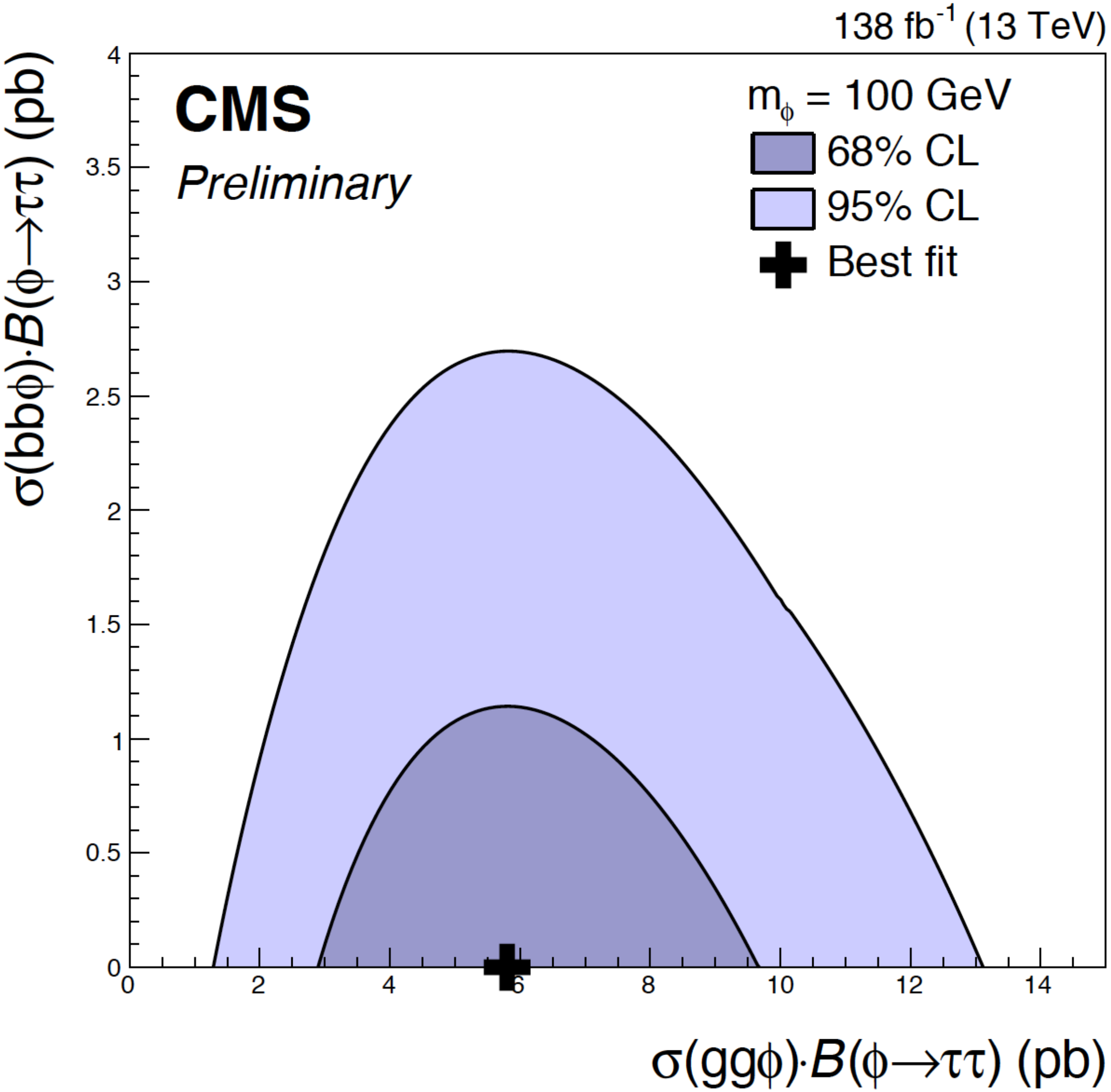
The new $\tau^+\tau^-$ excess

[CMS '22]



Can you spot the excess? At 95 – 100 GeV?

Better visible here, focusing on 100 GeV: [*CMS '22*]



$\Rightarrow$ clear excess of $\sim 3\,\sigma$ at ~ 100 GeV

Now we have three excesses at ~ 95 GeV

$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057, \quad \mu_{\gamma\gamma}^{\text{exp}} = 0.6 \pm 0.2, \quad \mu_{\tau\tau}^{\text{exp}} = 1.2 \pm 0.5$$

corresponding to

$$\mu_{bb}^{\text{exp}} \sim 2\,\sigma, \quad \mu_{\gamma\gamma}^{\text{exp}} \sim 3\,\sigma, \quad \mu_{\tau\tau}^{\text{exp}} \sim 2.4\,\sigma$$

Three (effectively) independent channels

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

$$\Rightarrow \sim 4.3\,\sigma$$

$$\chi^2_{95} = \frac{(\mu_{bb}^{\text{theo}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\gamma\gamma}^{\text{theo}} - 0.6)^2}{(0.2)^2} + \frac{(\mu_{\tau\tau}^{\text{theo}} - 1.2)^2}{(0.5)^2}$$

Can we fit all excesses together?

Simple example of an extended Higgs sector:

Next-Two Higgs Doublet Model (N2HDM): $\to$ (nearly) NMSSM type

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:

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

“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 three excesses: $m_{h_1} \sim 95$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1VV}$ strongly reduced for μ_{bb}
- c_{h_1bb} reduced to enhance BR$(h_1 \to \gamma\gamma)$
- c_{h_1tt} not reduced for $\mu_{\gamma\gamma}$
- $c_{h_1\tau\tau}$ not reduced for $\mu_{\tau\tau}$

	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 IV $c_{h_1\tau\tau}$ can be enhanced (together with c_{h_1tt})

$\Rightarrow$ only type IV can fit all three excesses

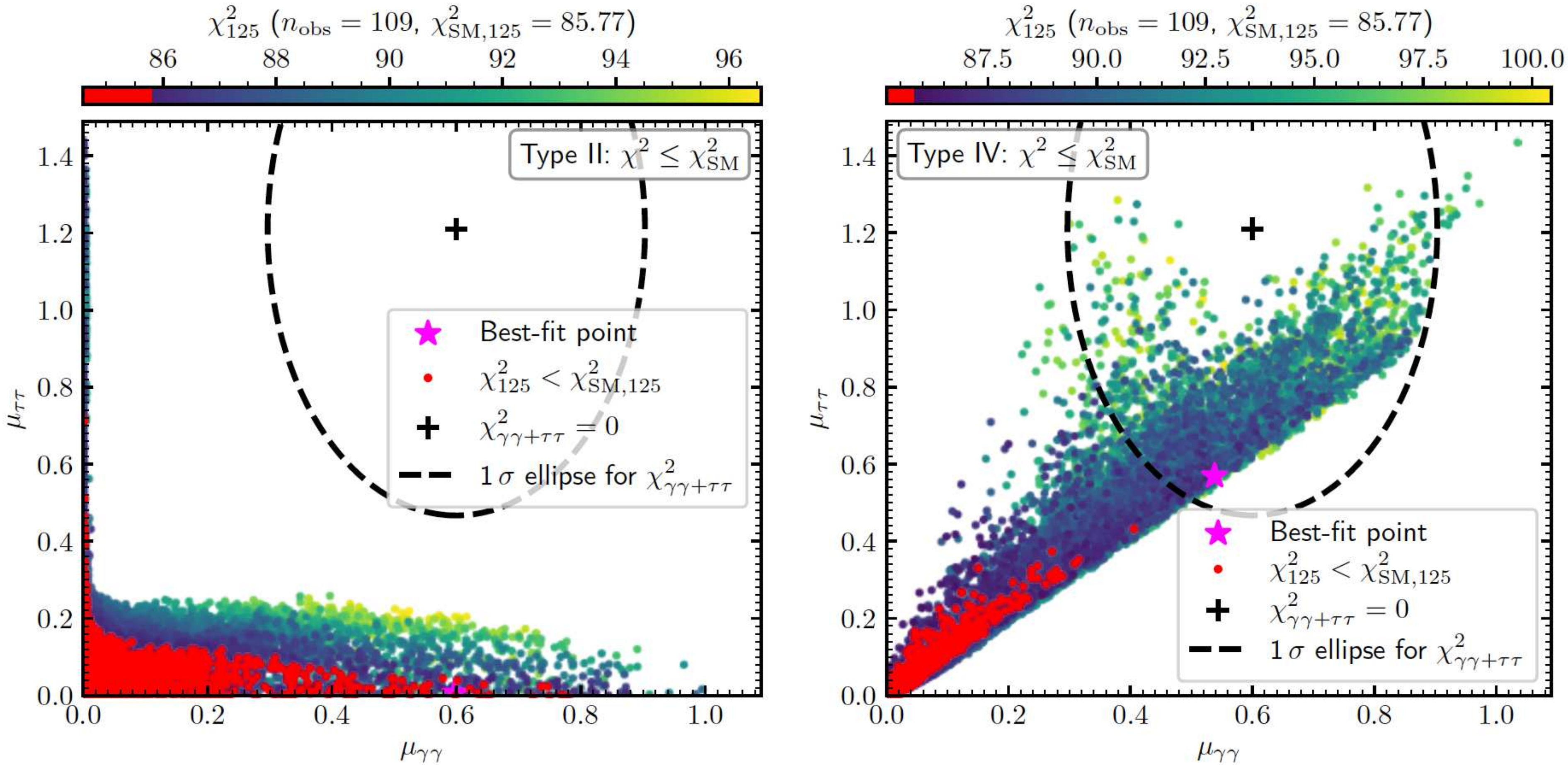
$\Rightarrow$ Parameter scan $\Rightarrow$ ScannerS

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
  . . . or sufficiently long-lived $\Rightarrow$ Evade
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (N2HDECAY, SusHi)
  $\Rightarrow \chi^2_{125}$ (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

N2HDM type II vs. type IV

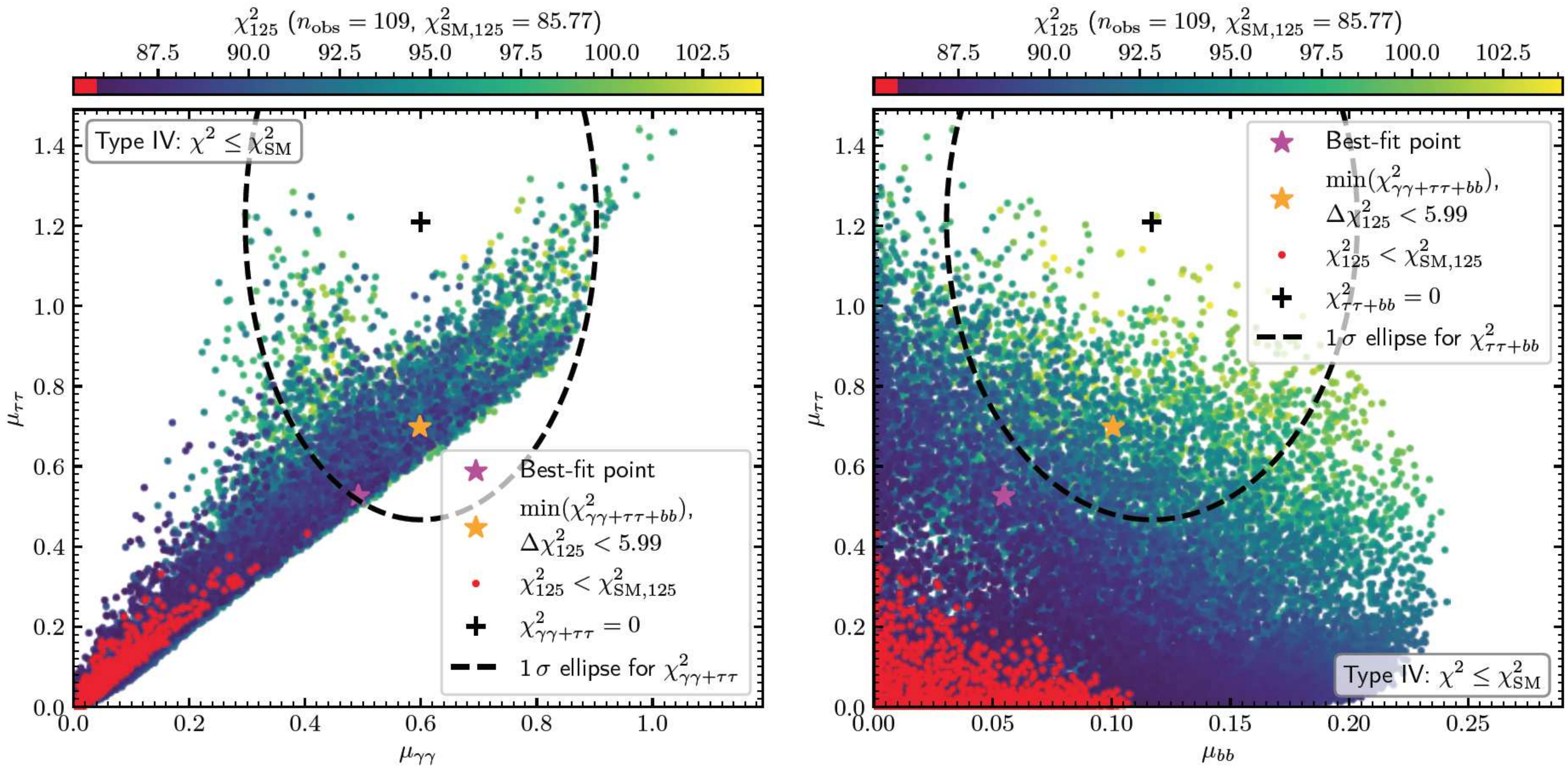
[*T. Biekötter, S.H., G. Weiglein '22*]



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

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

N2HDM type IV: fitting all three excesses: [T. Biekötter, S.H., G. Weiglein '22]

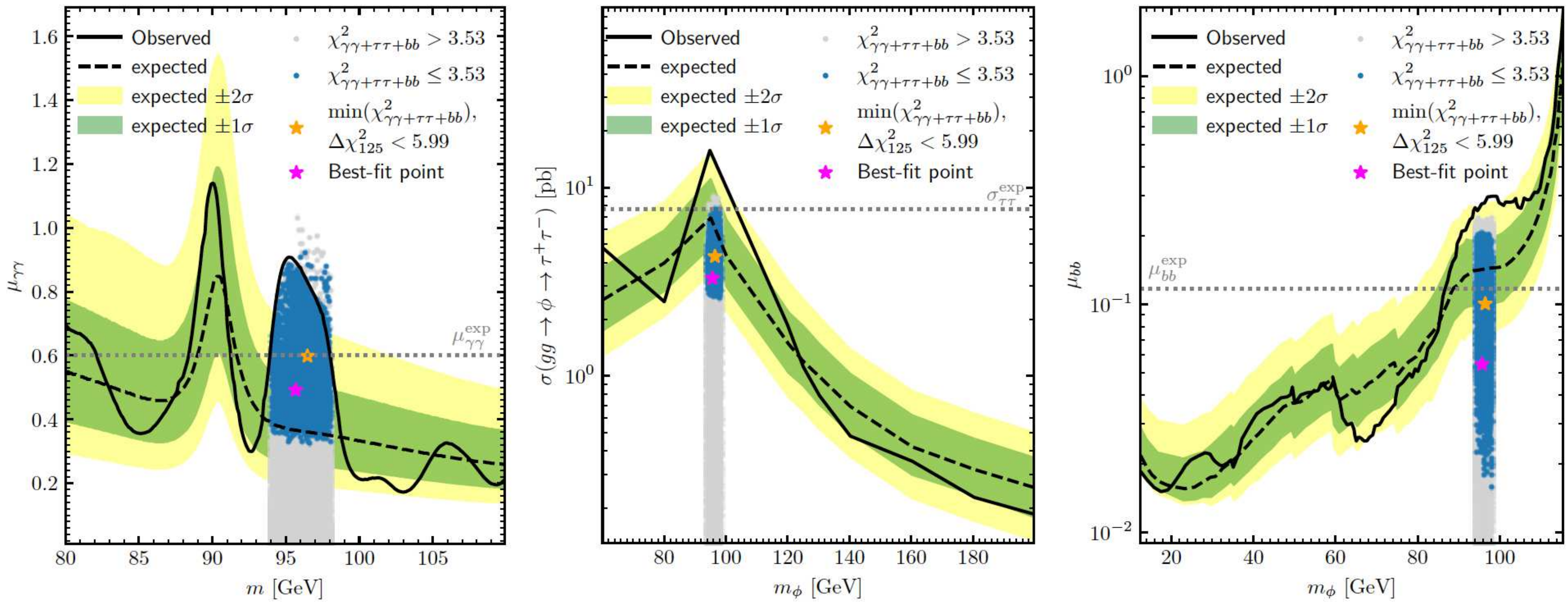


Color coding: χ^2_{125} from HiggsSignals

⇒ type IV can fit the $\gamma\gamma$, $\tau\tau$ and bb excesses

N2HDM type IV: fitting all three excesses: [T. Biekötter, S.H., G. Weiglein '22]

$pp \to h_{95} \to \gamma\gamma$ $\quad gg \to h_{95} \to \tau^+\tau^-$ $\quad e^+e^- \to Zh_{95} \to Zb\bar{b}$

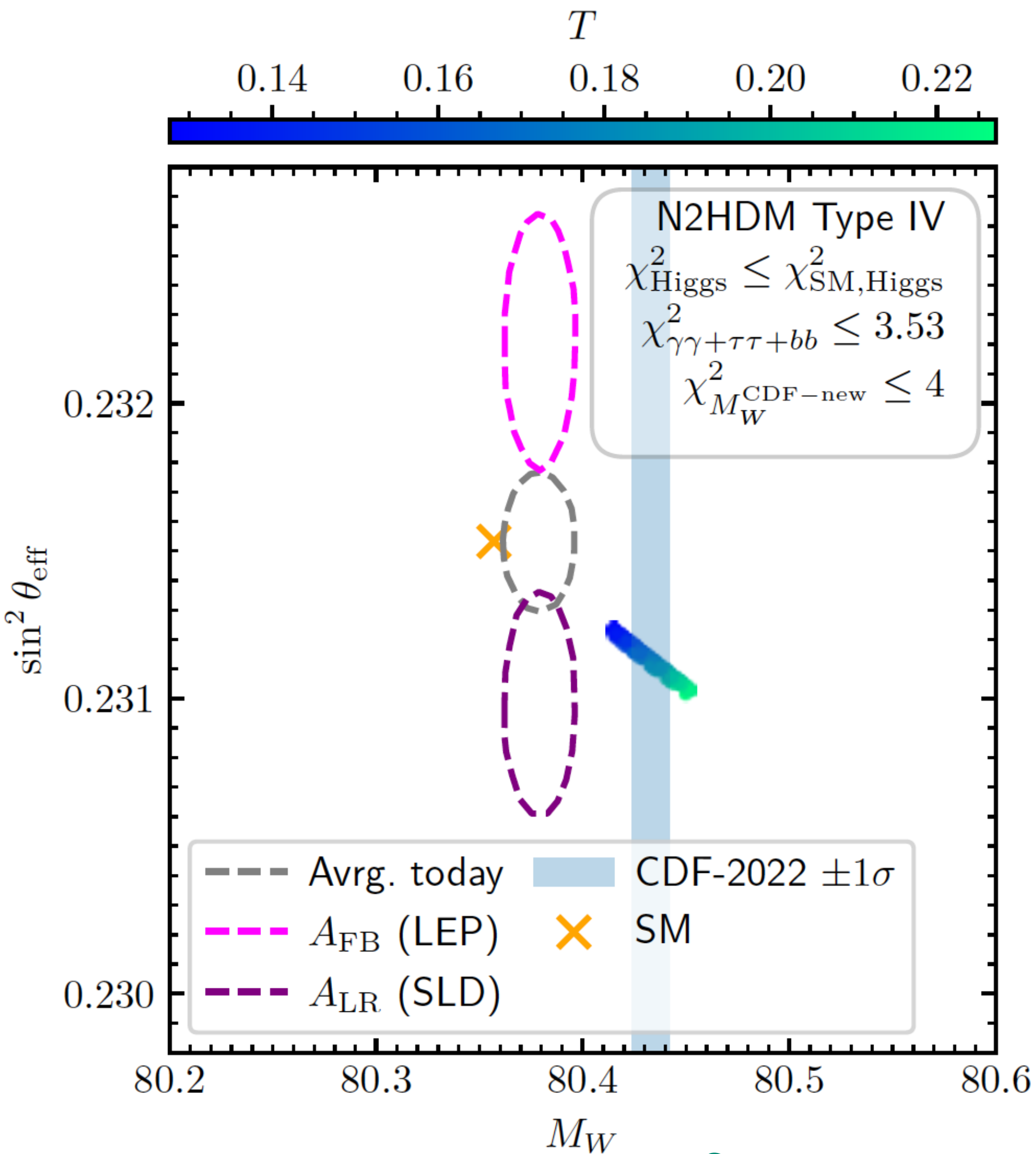


gray lines: central values of excesses

$\Rightarrow$ type IV can fit the $\gamma\gamma$, $\tau\tau$ and bb excesses very well

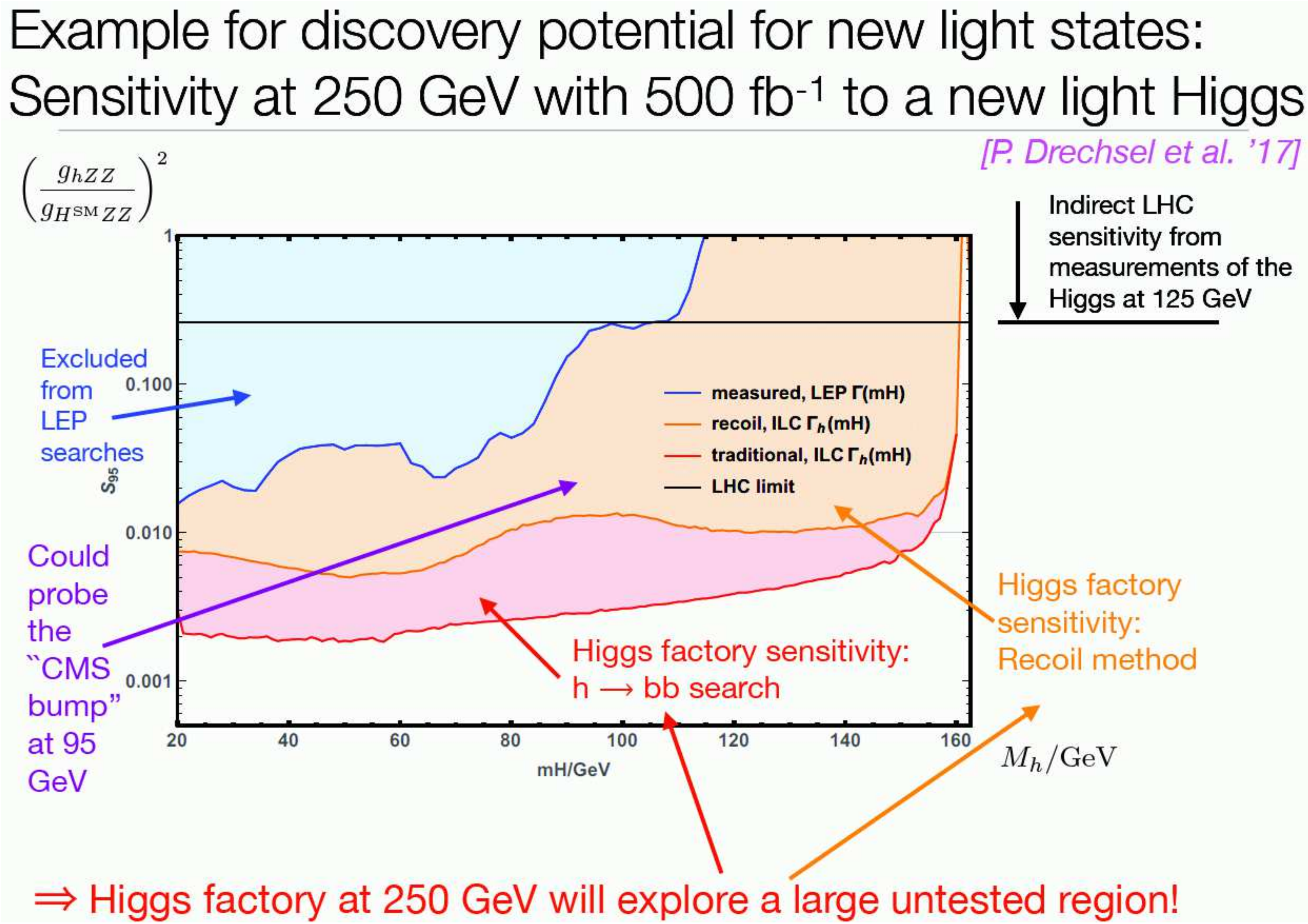
$M_W^{\rm CDF}$ vs. $\sin^2\theta_{\rm eff}$ in the N2HDM

[*T. Biekötter, S.H., G. Weiglein '22*]



Remember: $\Delta\rho$ goes up $\Rightarrow M_W$ goes up, $\sin^2\theta_{\rm eff}$ goes down

$\Rightarrow$ agreement only with SLD value of $\sin^2\theta_{\rm eff}$



[*Taken from G. Weiglein '18*]

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, operating at $\sqrt{s} = 250$ GeV)

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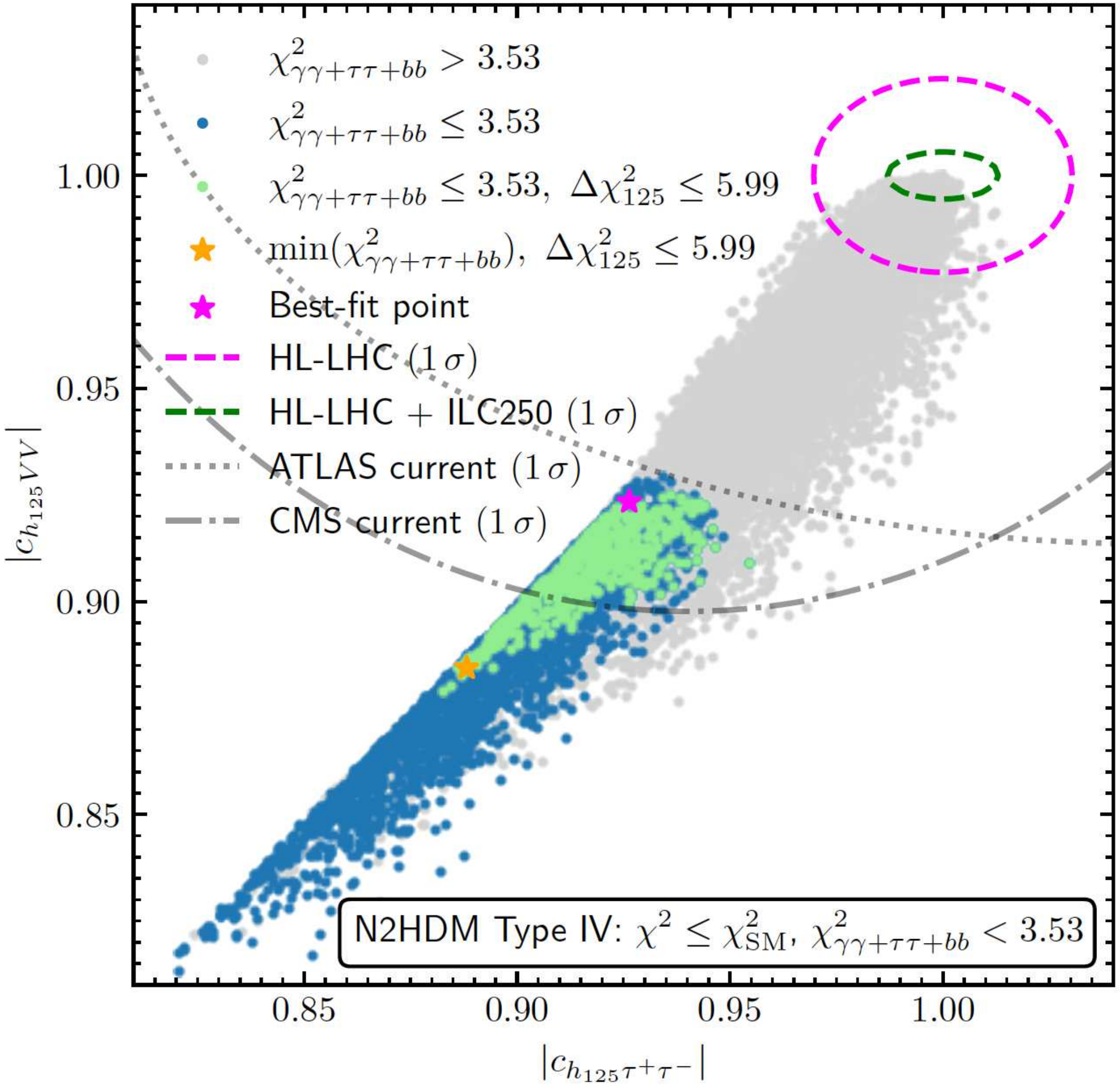
- HL-LHC h_{125} coupling measurements $\Leftarrow$ focus
- ILC h_{125} coupling measurements $\Leftarrow$ focus

- 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 $\Leftarrow$ focus
- ILC ϕ_{95} coupling measurements $\Leftarrow$ focus

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

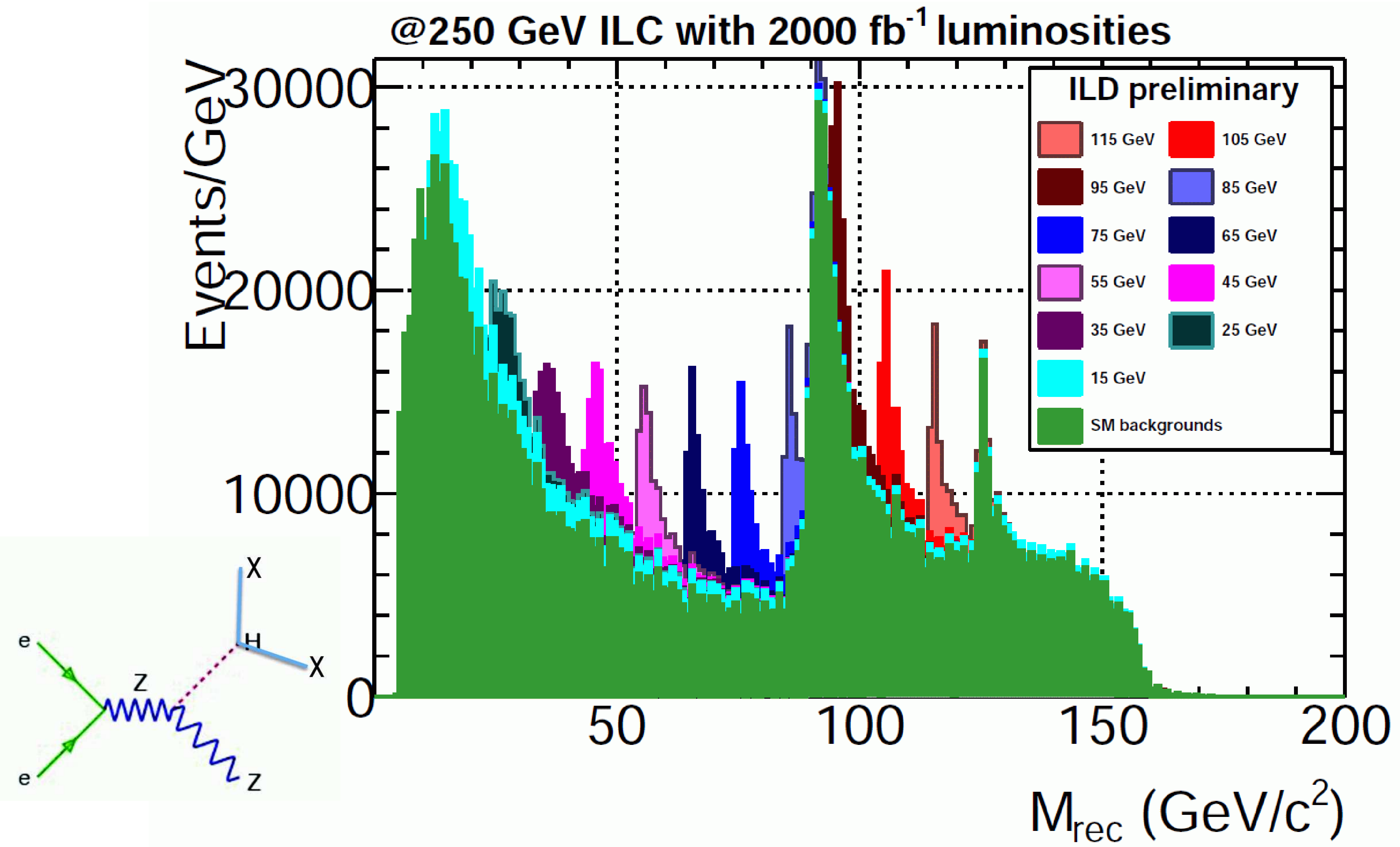
ILC = ILC (or other e^+e^- collider, operating at $\sqrt{s} = 250$ GeV)

HL-LHC/ILC h_{125} coupling measurements: [T. Biekötter, S.H., G. Weiglein '22]



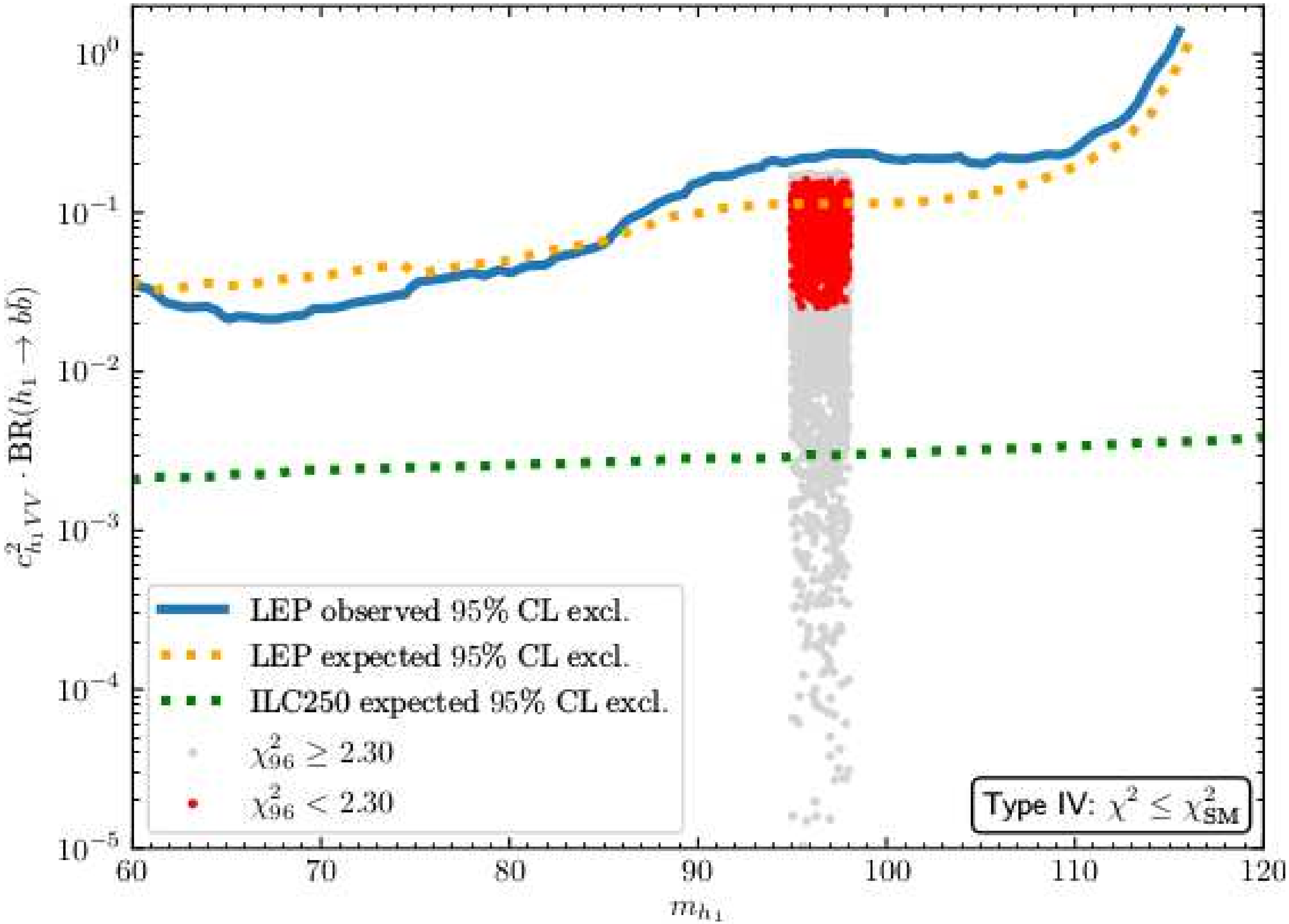
$\Rightarrow$ measurable deviation from the SM

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



ILC production of the light scalar in the N2HDM type IV:

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

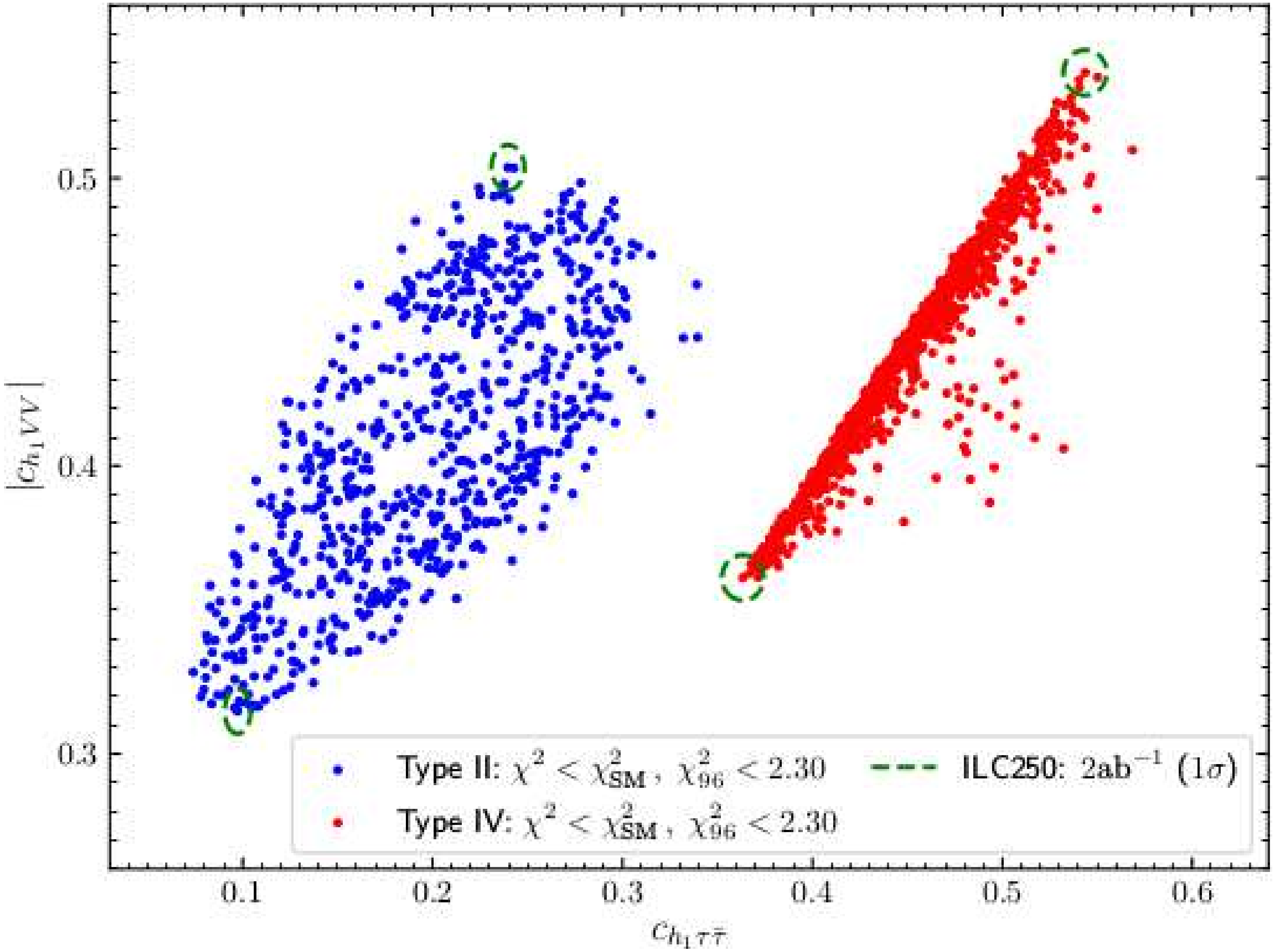


⇒ new state easily in the reach of the ILC ⇒ coupling measurements

ILC ϕ_{95} coupling measurements at the ILC

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

green circles: ϕ_{95} coupling precision at the ILC250



$\Rightarrow$ model distinction possible via coupling measurements at the ILC

4. Conclusinos

- Three (mostly) independent excesses in the search for light Higgs bosons at $\sim$ 95 GeV:

$$\mu_{bb}^{\rm exp} = 0.117 \pm 0.057, \quad \mu_{\gamma\gamma}^{\rm exp} = 0.6 \pm 0.2, \quad \mu_{\tau\tau}^{\rm exp} = 1.2 \pm 0.5$$

corresponding to

$$\mu_{bb}^{\rm exp} \sim 2\,\sigma, \quad \mu_{\gamma\gamma}^{\rm exp} \sim 3\,\sigma, \quad \mu_{\tau\tau}^{\rm exp} \sim 2.4\,\sigma$$

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

$$\Rightarrow \sim 4.3\,\sigma$$

- Physics opportunites at e^+e^- colliders:
  - coupling measurements of the h_{125}
    $\Rightarrow$ deviations from the SM will be visible
  - production of the h_{95}
    $\Rightarrow$ easily possible at the ILC
    (or other e^+e^- collider, operating at $\sqrt{s} = 250$ GeV)
  - coupling measurement of the h_{95}
    $\Rightarrow$ determination of underlying parameters


Higgs Days at Santander 2022
Theory meets Experiment
5 – 9 September
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Local: Alicia.Calderon@cern.ch
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Further Questions?