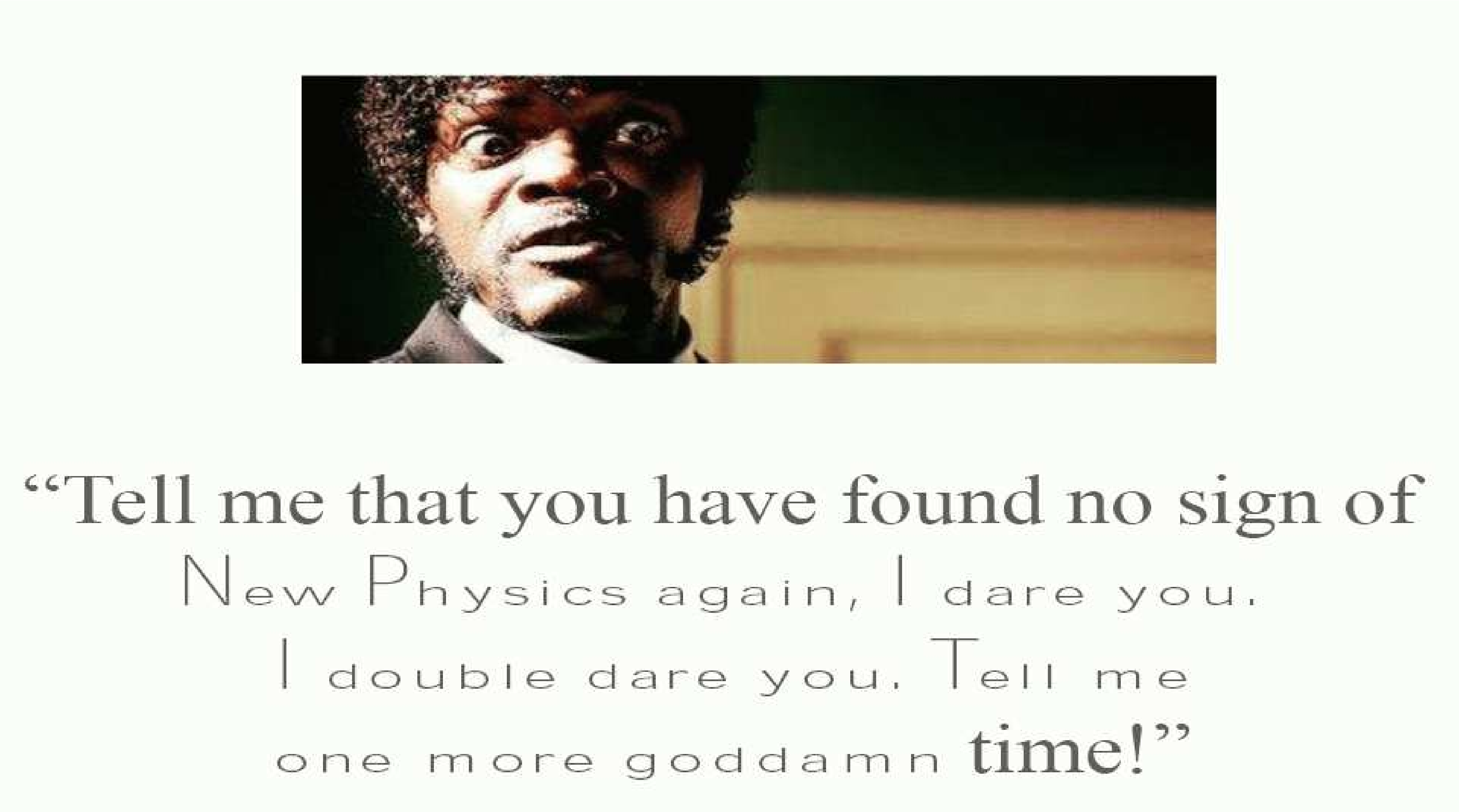
“Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!”

New BSM Higgs bosons:
e^+e^- Collider Physics Potential

Sven Heinemeyer, IFT (CSIC, Madrid)

Hamburg, 10/2022

1. Introduction

2. Heavy BSM Higgs bosons

3. Light BSM Higgs bosons

4. Light and heavy BSM Higgs bosons and $M_W^{\rm CDF}$

5. Conclusions

1. Introduction

We have discoved an SM-like Higgs!

The SM cannot be the ultimate theory!

Conclusion: The discovered Higgs cannot be "the SM Higgs"!

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$\Rightarrow$ any hints from LHC results (as guideline/toy example)?
Q': Which model?

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$\Rightarrow$ any hints from LHC results (as guideline/toy example)?
Q': Which model?

A1: check changed properties of the h_{125}

A2: check for additional Higgs bosons
check for additional Higgs bosons above and below 125 GeV

Toy example:

Two Higgs Doublet Model (2HDM):

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} , \; \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \end{aligned}$$

Physical states: h, H, ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

“Physical” input parameters:

$$c_{\beta-\alpha} \; , \quad \tan\beta \; , \quad v \; , \quad M_h , \quad M_H \; , \quad M_A \; , \quad M_{H^\pm} \; , \quad m_{12}^2$$

Alignment limit: $c_{\beta-\alpha} \to 0$ (for $M_h \sim 125$ GeV)

Assumption (for now): $h \sim h_{125}$

Z_2 symmetry to avoid FCNC:

$$\Phi_1 \to \Phi_1 \, , \; \Phi_2 \to -\Phi_2$$

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	$\to$ MSSM type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

Sum rule (with h SM-like): $\sin(\beta-\alpha) \approx 1$, $\cos(\beta-\alpha) \approx 0$

Unitarity/perturbativity and EWPO (so far): $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

Second toy example:

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:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

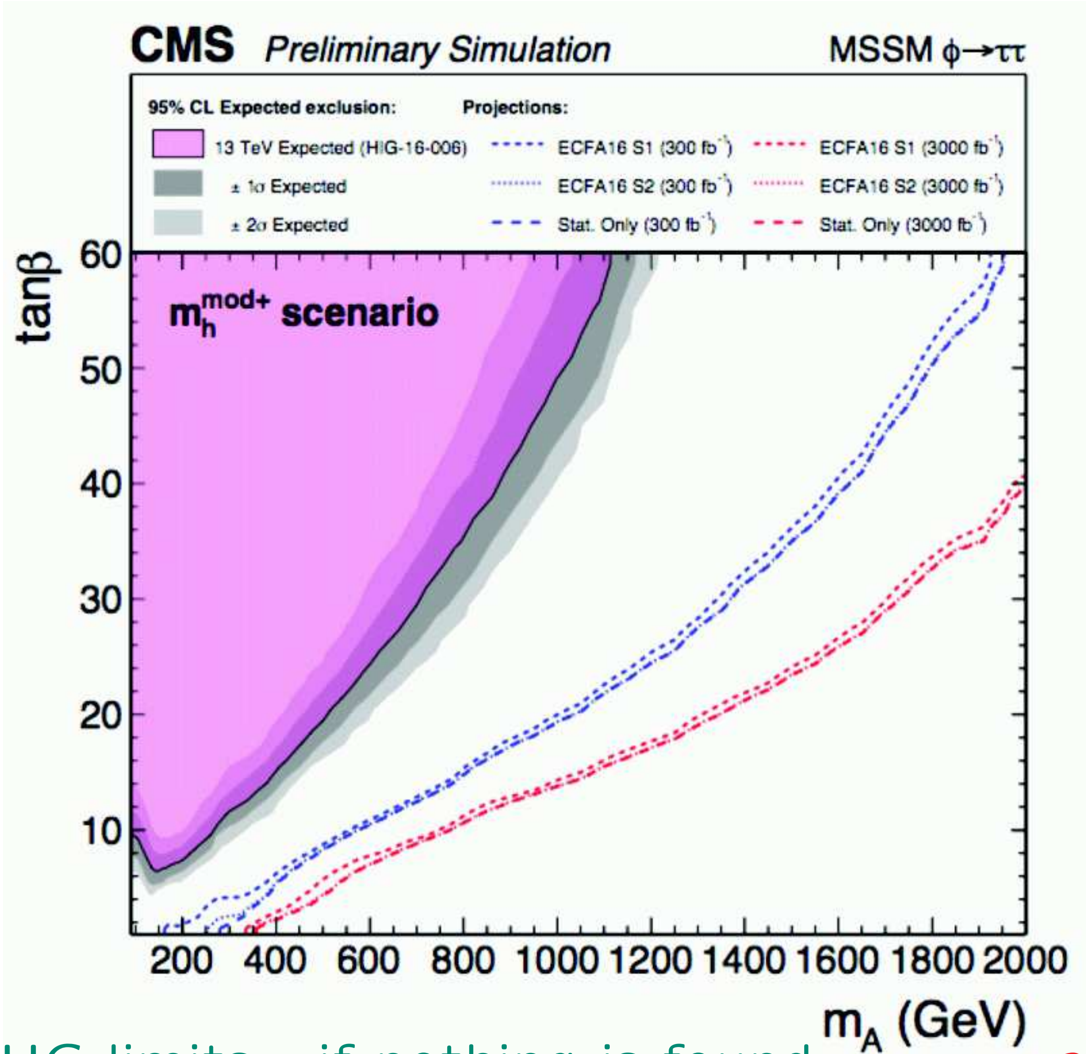
Z_2 symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_S \to \Phi_S$

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)

2. Heavy BSM Higgs bosons

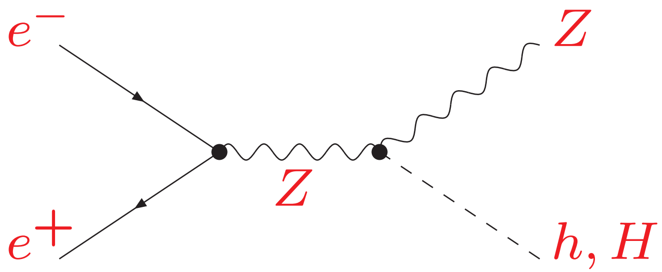
Reach in the MSSM (type II 2HDM Higgs sector):



$\Rightarrow$ strong (HL-)LHC limits - if nothing is found analyzed in detail
$\Rightarrow$ but if there is something in the kinematical e^+e^- reach, it can be

Search for neutral Higgs bosons in the 2HDM at e^+e^- colliders:

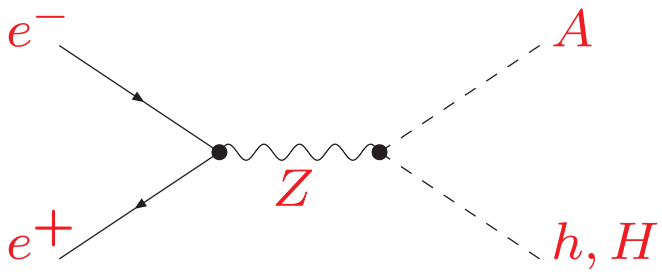
$e^+e^- \to Zh, ZH$



$\sigma_{hZ} \approx \sin^2(\beta-\alpha)\sigma_{hZ}^{\rm SM}$

$\sigma_{HZ} \approx \cos^2(\beta-\alpha)\sigma_{hZ}^{\rm SM}$

$e^+e^- \to Ah, AH$



$\sigma_{hA} \propto \cos^2(\beta-\alpha)\sigma_{hZ}^{\rm SM}$

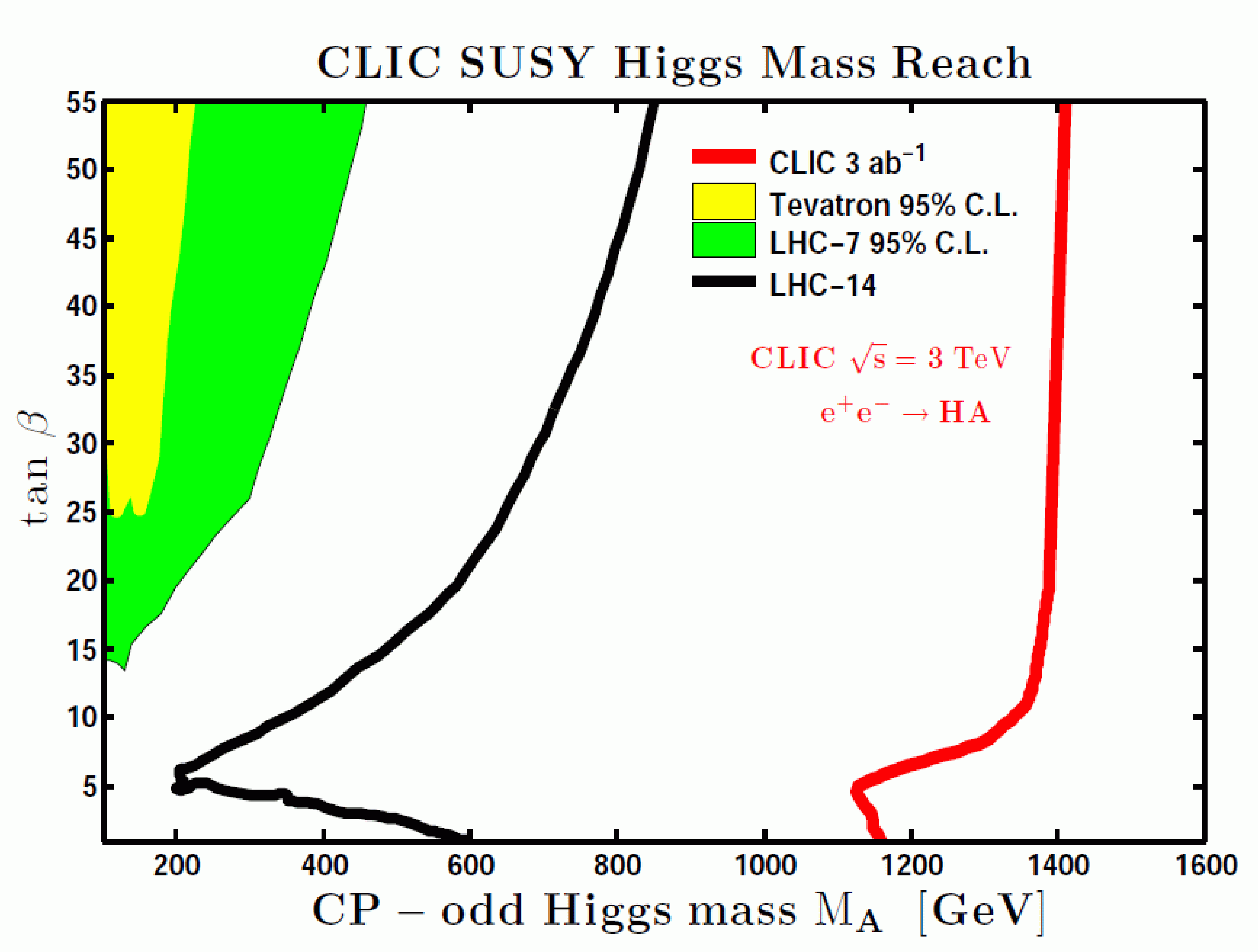
$\sigma_{HA} \propto \sin^2(\beta-\alpha)\sigma_{hZ}^{\rm SM}$

$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

$\Rightarrow$ maximum ILC reach: $\sim$ 500 GeV, CLIC $\sim$ 1500 GeV

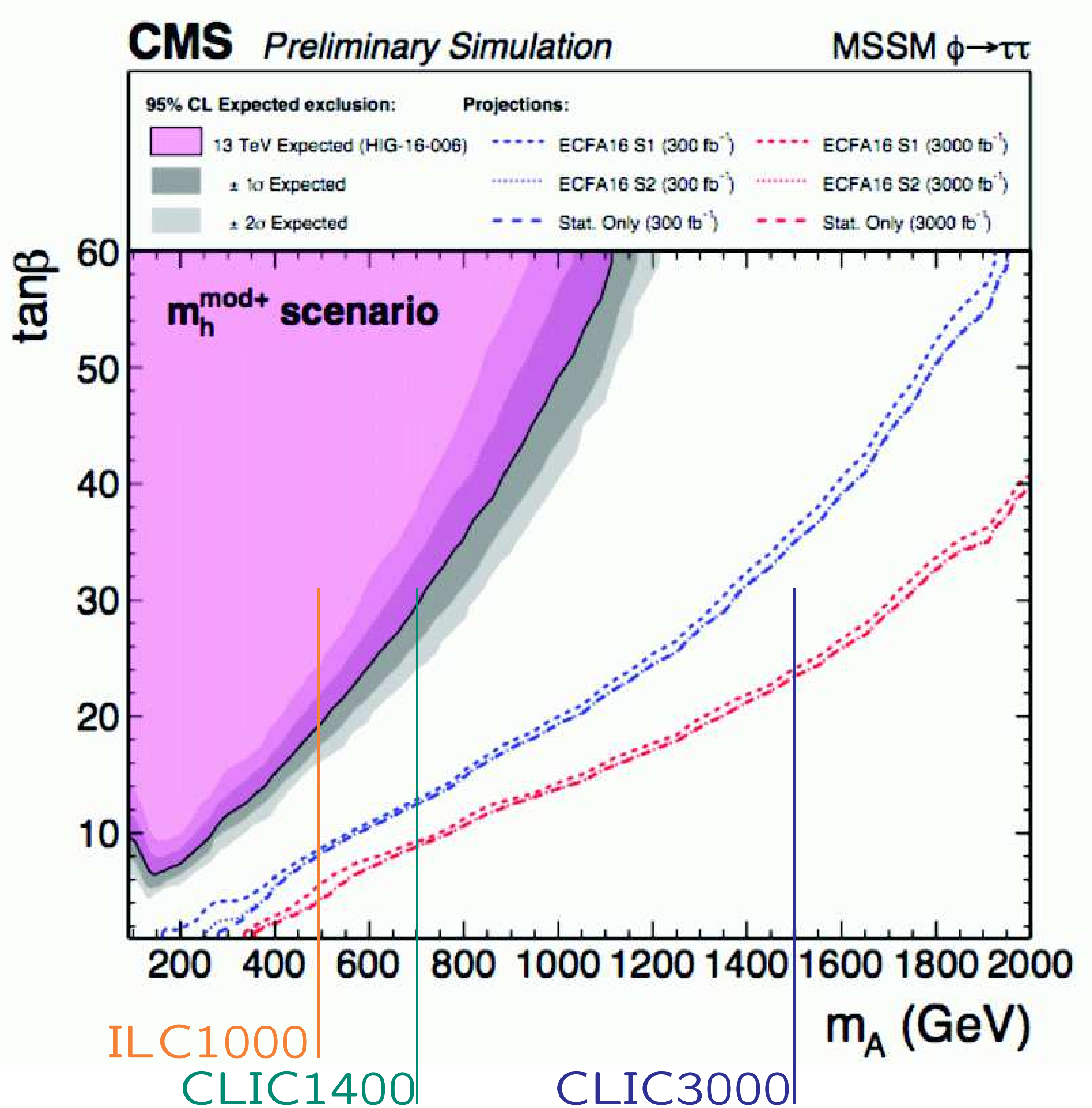
CLIC reach:

[*L. Linssen et al. '12*]



$\Rightarrow$ close to kinematic limit

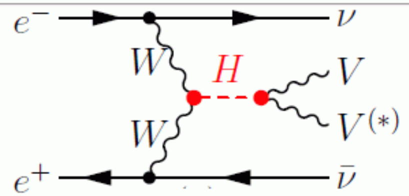
"Simple" LC reach in the 2HDM (neglecting $t\bar{t}$ final states)



⇒ the larger the mass splitting, the larger the reach

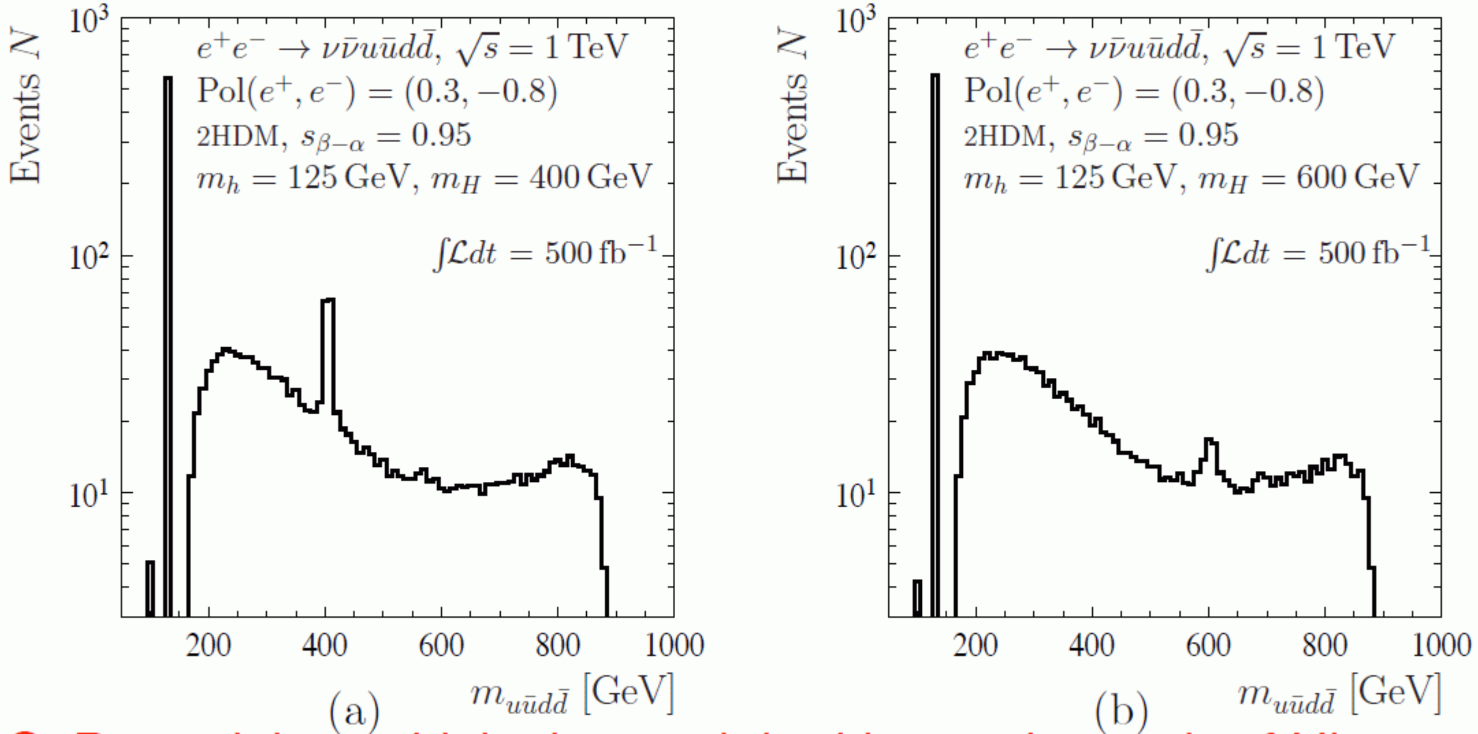
Single heavy Higgs production beyond kinematic reach:

Sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)



[S. Liebler et al. '15]

$$g_{\rm hVV} = \sin(\beta-\alpha)\, g^{\rm SM}_{\rm HVV}, \quad g_{\rm HVV} = \cos(\beta-\alpha)\, g^{\rm SM}_{\rm HVV}, \quad V = W^\pm, Z$$

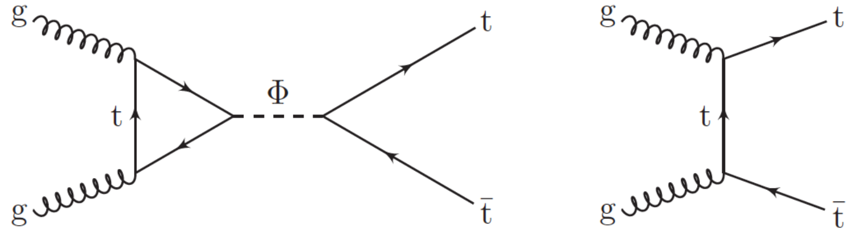


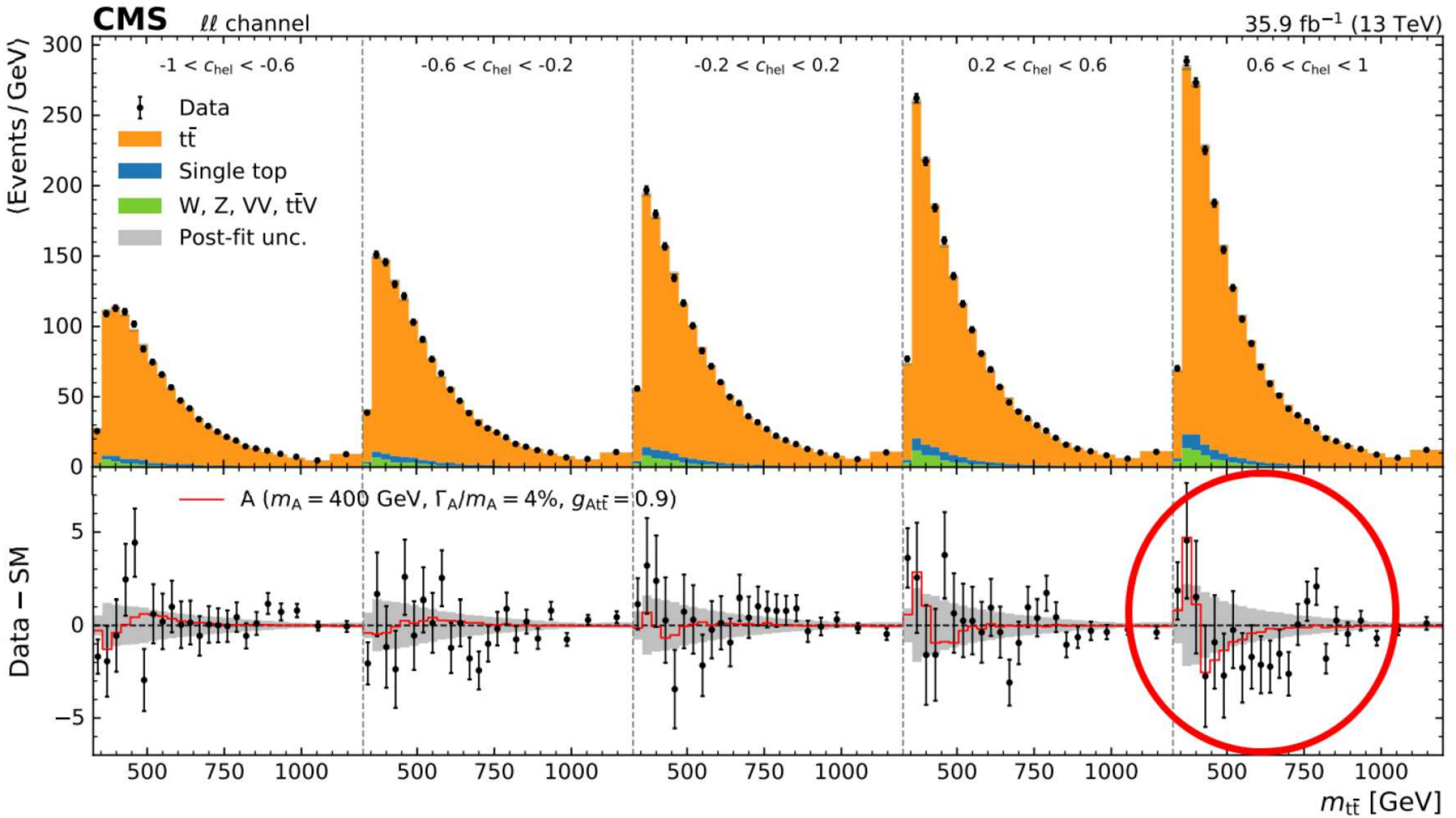
$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[Taken from G. Weiglein '18]

Possible hint for heavy Higgses at the LHC:

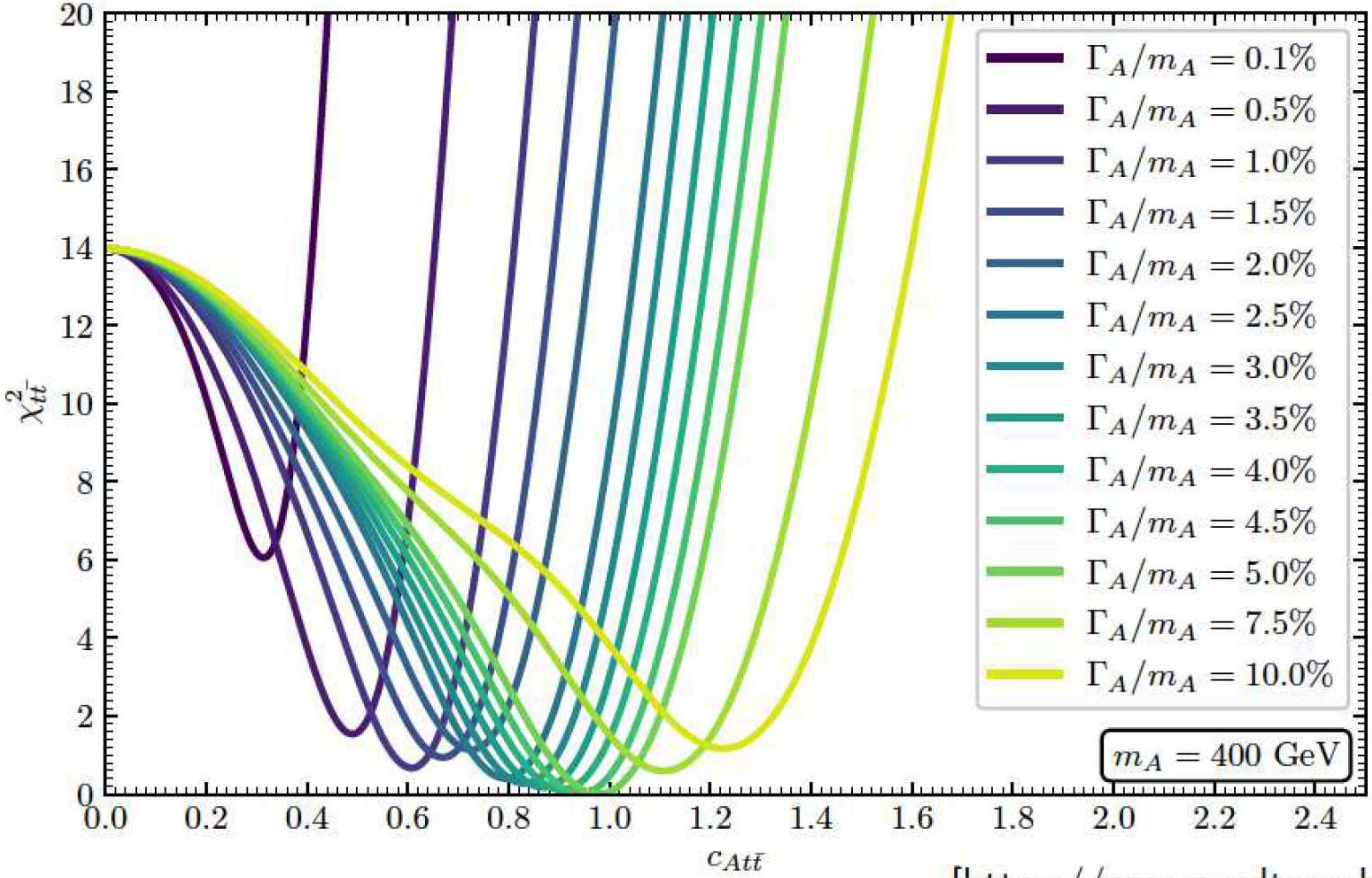
CMS Higgs-boson search in $pp \to \phi \to t\bar{t}$ at $m_\phi \sim 400$ GeV





[CMS: 1908.01115]

χ^2 distribution from the excess: local: $3.5\,\sigma$, global: $\lesssim 2\,\sigma$



[https://cms-results.web.cern.ch]

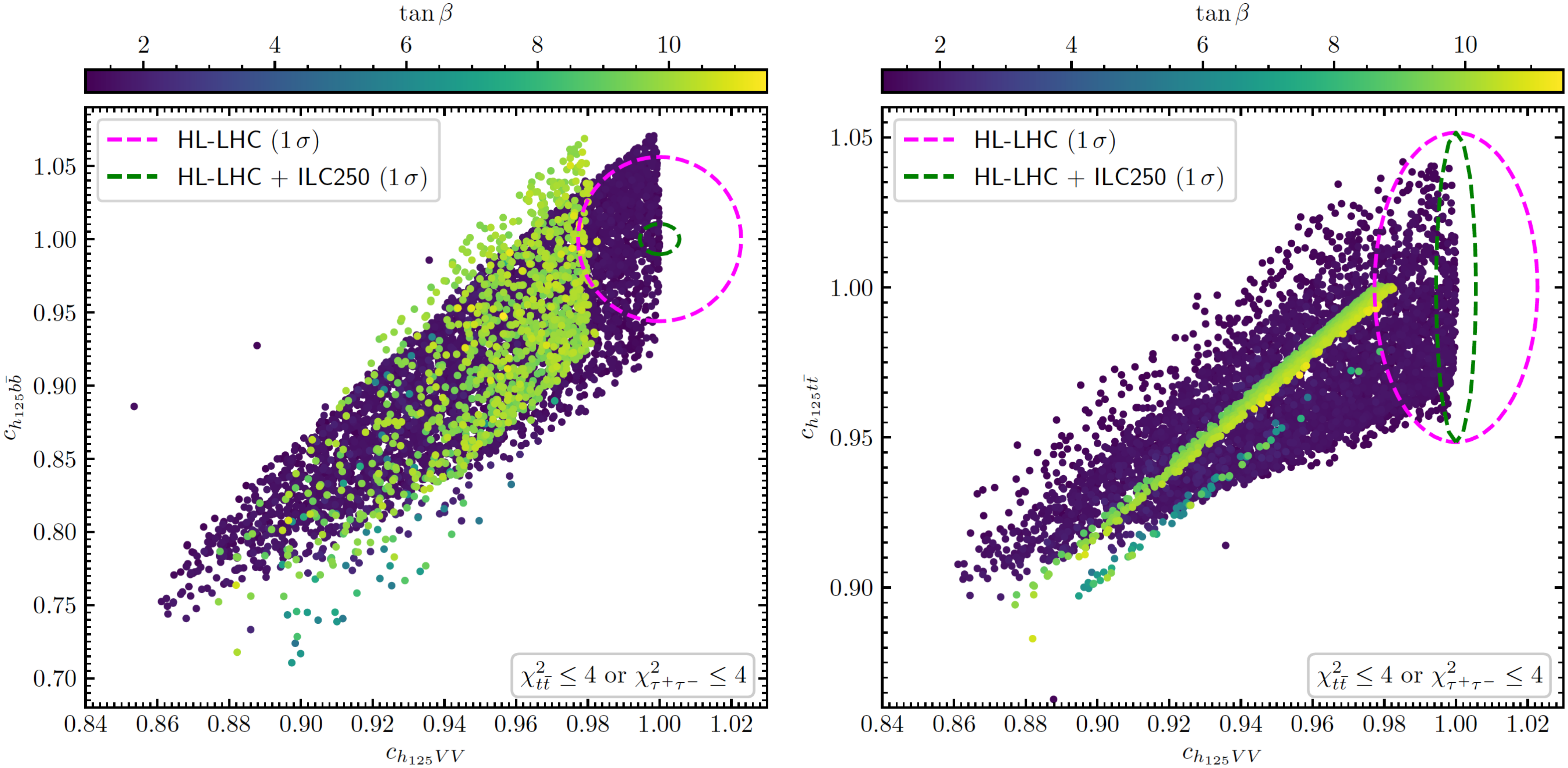
$\Rightarrow$ can be explained in the N2HDM/NMSSM for $\tan\beta \sim 1.5$ $\Rightarrow$ in ILC reach

[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]

h_{125} coupling measurement for the ~ 400 GeV excess? $\rightarrow$ N2HDM:

h_{125} coupling measurement for the $\sim$ 400 GeV excess? $\to$ N2HDM:

[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]

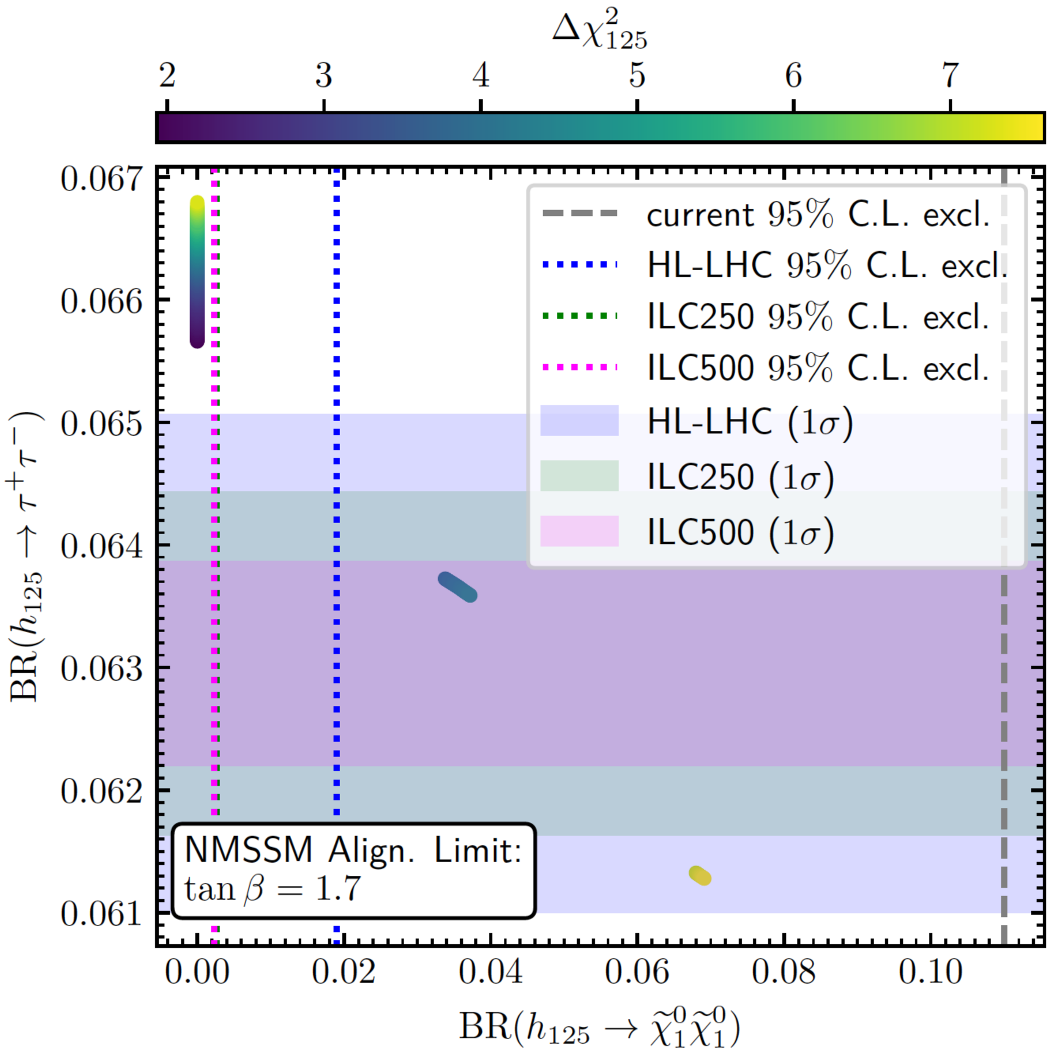


low $\tan\beta$ ($t\bar{t}$): SM limit reached, but many points show large deviation

h_{125} coupling measurement for the ~ 400 GeV excess? $\rightarrow$ NMSSM:

h_{125} coupling measurement for the ~ 400 GeV excess? $\rightarrow$ NMSSM:

[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]

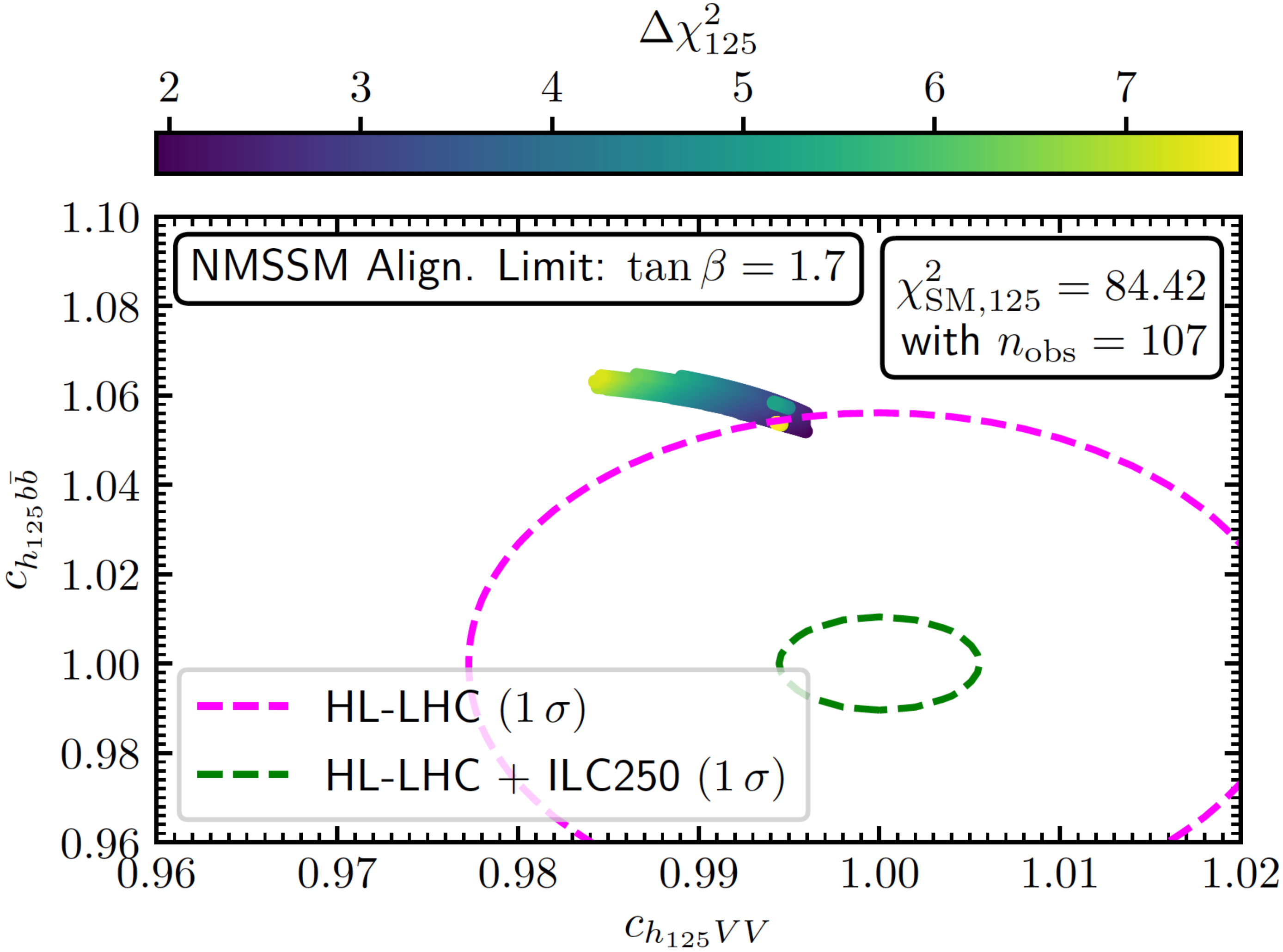


$\Rightarrow$ HL-LHC can test $h_{125} \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ (small part of allowed parameter space)

$\Rightarrow$ ILC can test all points via $h_{125} \to \tau^+\tau^-$ (and via $h_{125} \to \tilde{\chi}^0_1\tilde{\chi}^0_1$)

h_{125} coupling measurement for the ~ 400 GeV excess? $\rightarrow$ NMSSM:

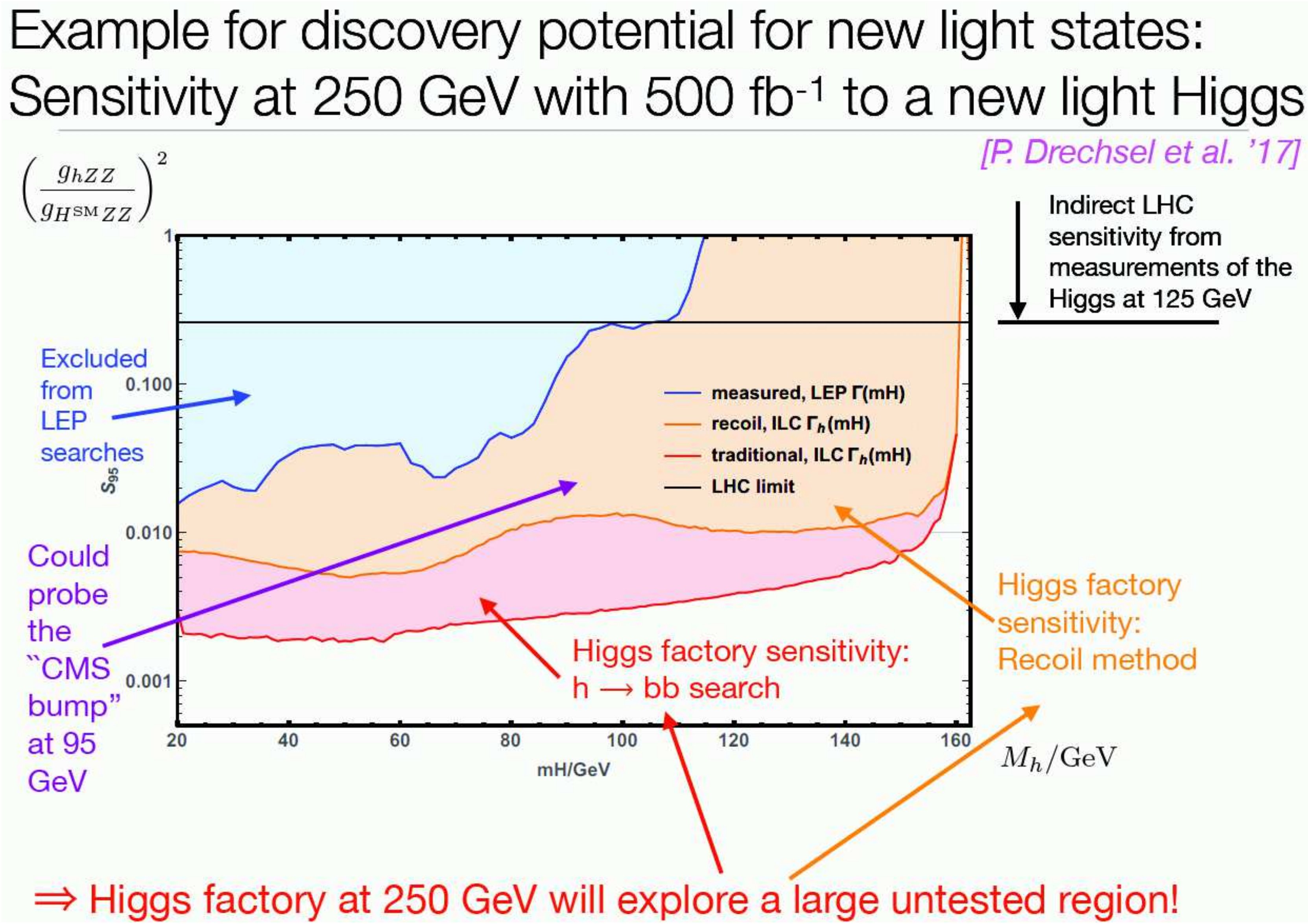
[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]



$\Rightarrow$ HL-LHC cannot resolve the h_{125} coupling deviations

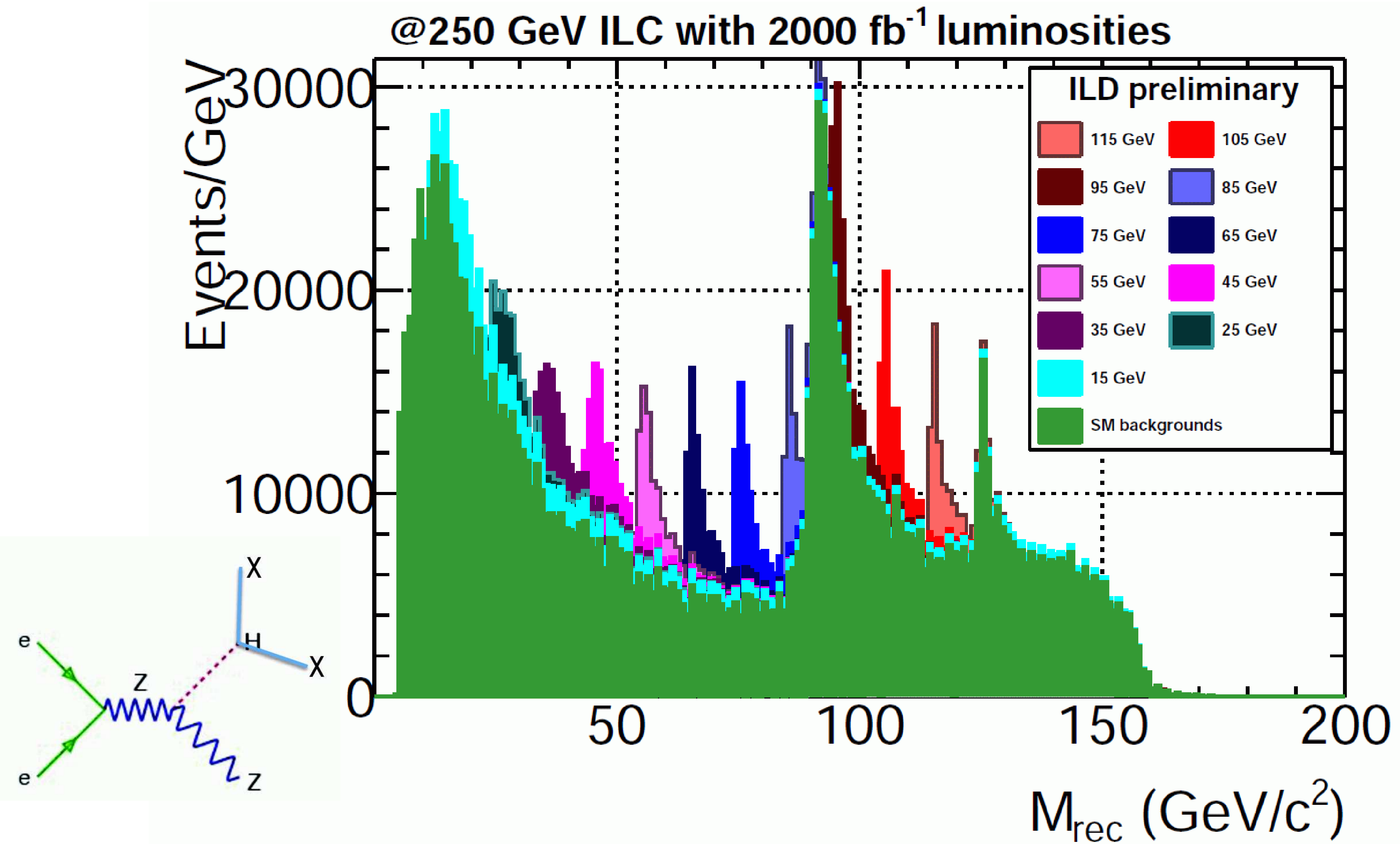
$\Rightarrow$ ILC can easily test this scenario via $c_{h_{125}VV}$ and $c_{h_{125}bb}$

3. Light BSM Higgs bosons



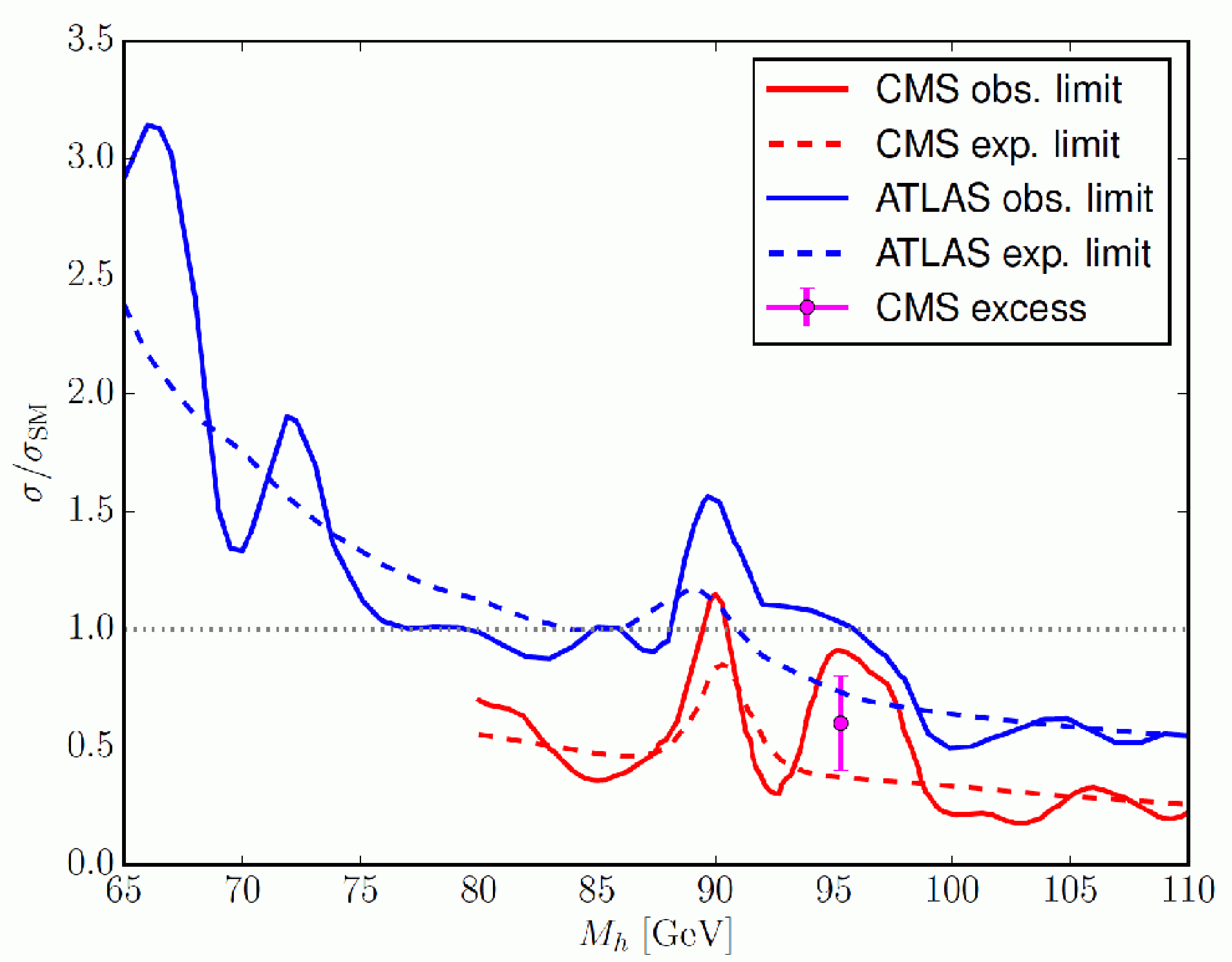
[*Taken from G. Weiglein '18*]

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



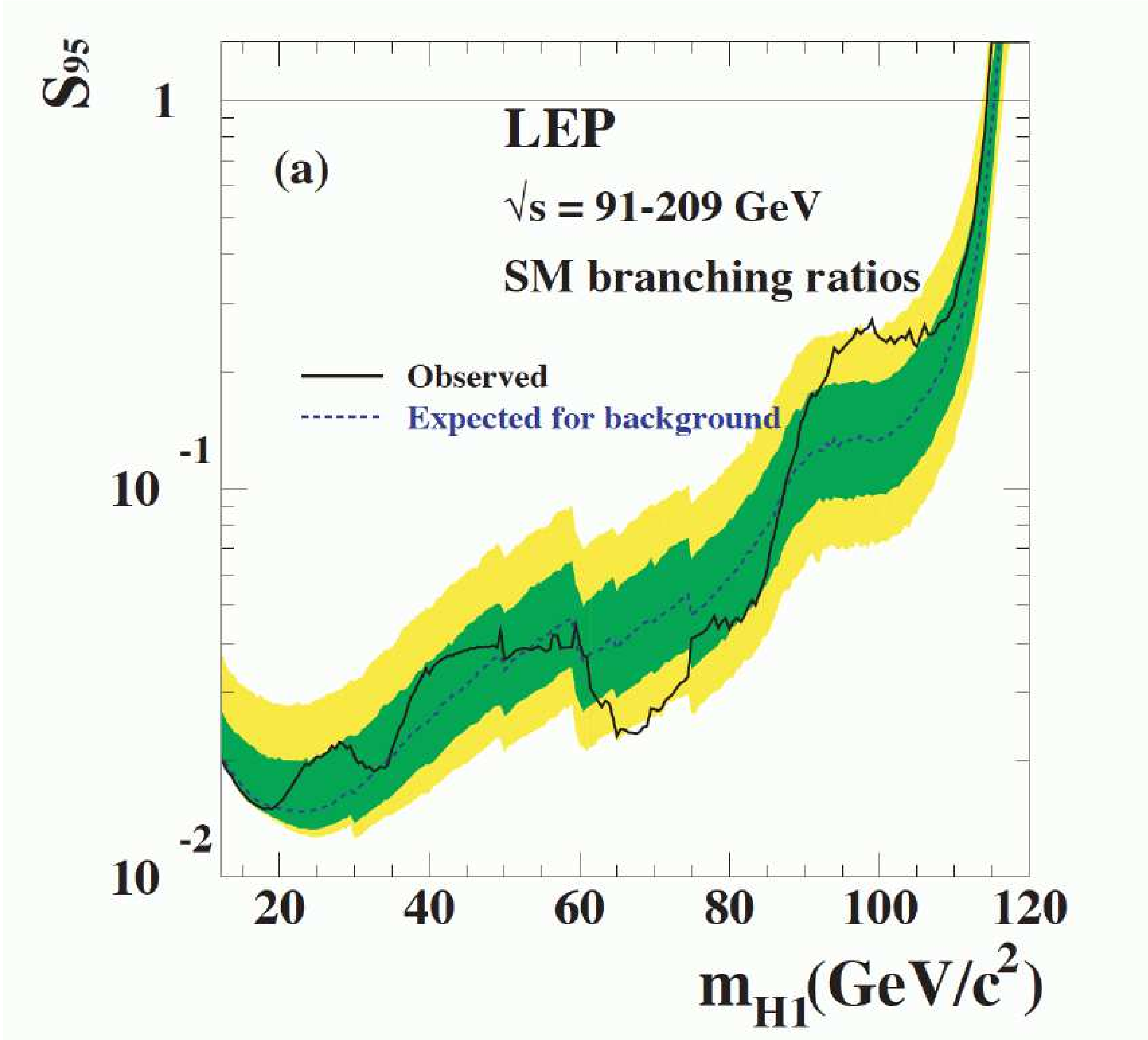
Case study: Search for $pp \to \phi \to \gamma\gamma$: excess at $m_\phi \sim 95$ GeV

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



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

Remember the LEP excess?



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

N2HDM:

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 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 two excesses: $m_{h_1} \sim 96$ GeV, $m_{h_2} \sim 125$ GeV

– $c^2_{h_1 VV}$ strongly reduced for μ_{LEP}
– $c_{h_1 bb}$ reduced to enhance BR$(h_1 \to \gamma\gamma)$
– $c_{h_1 tt}$ not reduced for μ_{CMS}
– $c_{h_1 \tau\tau}$ possibly reduced to enhance BR$(h_1 \to \gamma\gamma)$

	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 CMS and LEP excesses

Mini excursion: 2HDMS (in comparison to N2HDM) - type II only

[S.H., C. Li, F. Lika, G. Moortgat-Pick, S. Paasch '21]

N2HDM: 2 complex Higgs doublets, 1 real Higgs singlet
Z_2 and Z_2' symmetry

2HDMS: 2 complex Higgs doublets, 1 complex Higgs singlet
Z_2 and Z_3 symmetry
$\Rightarrow$ resembles the NMSSM Higgs sector (but without SUSY)

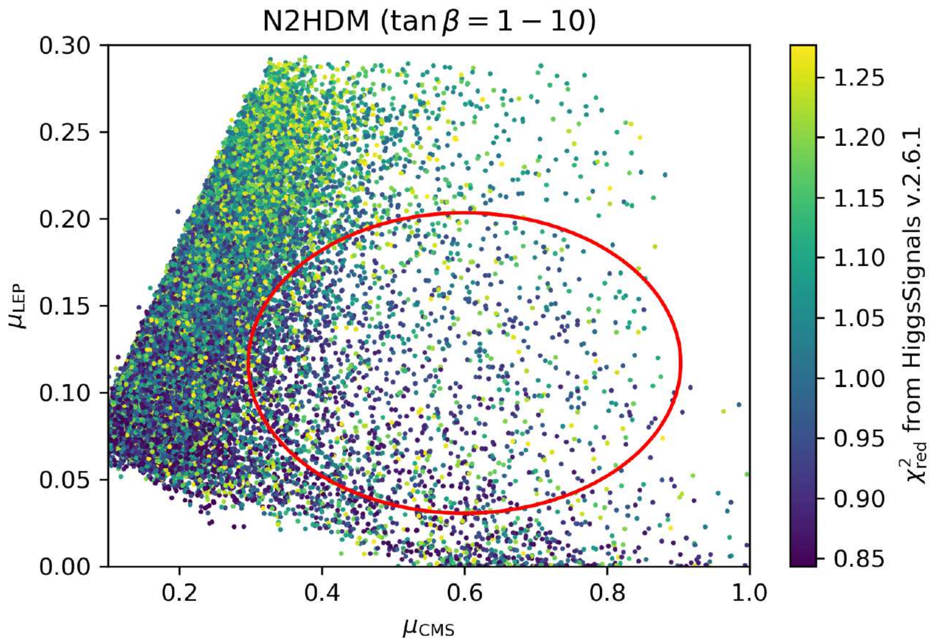
Constraints: for the S2HDM and N2HDM:
$\Rightarrow$ ScannerS, Evade, HiggsBounds, HiggsSignals, SuSHi, SuperIso

Q: Can 2HDMS and/or N2HDM fit both excesses?

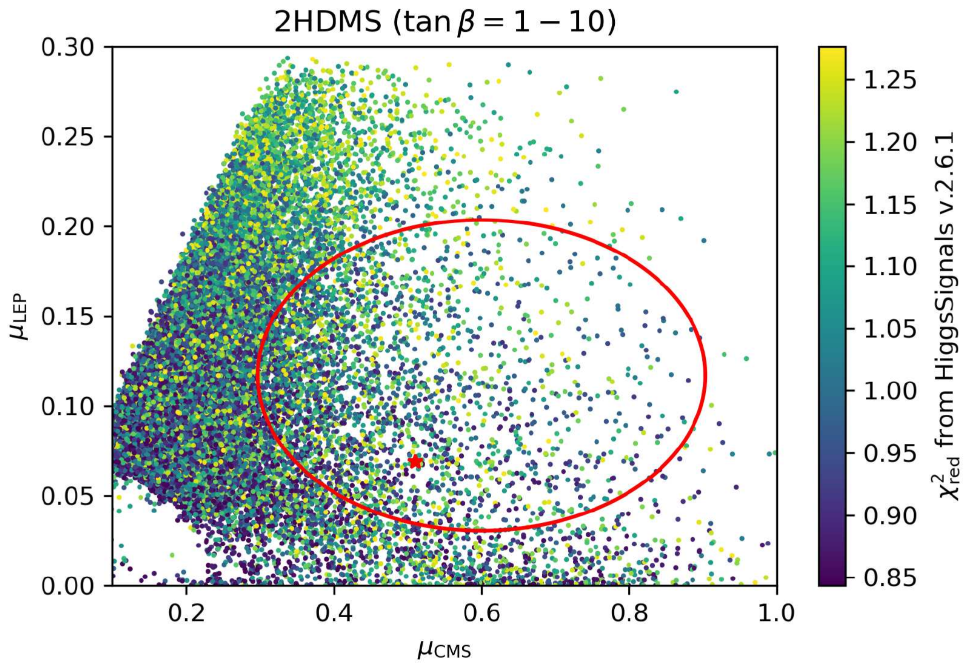
Q: Are there relevant differences?
(apart from the extra $\mathcal{CP}$-odd Higgs?)

Comparison of the two models: [S.H., C. Li, F. Lika, G. Moortgat-Pick, S. Paasch '21]

N2HDM



2HDMS

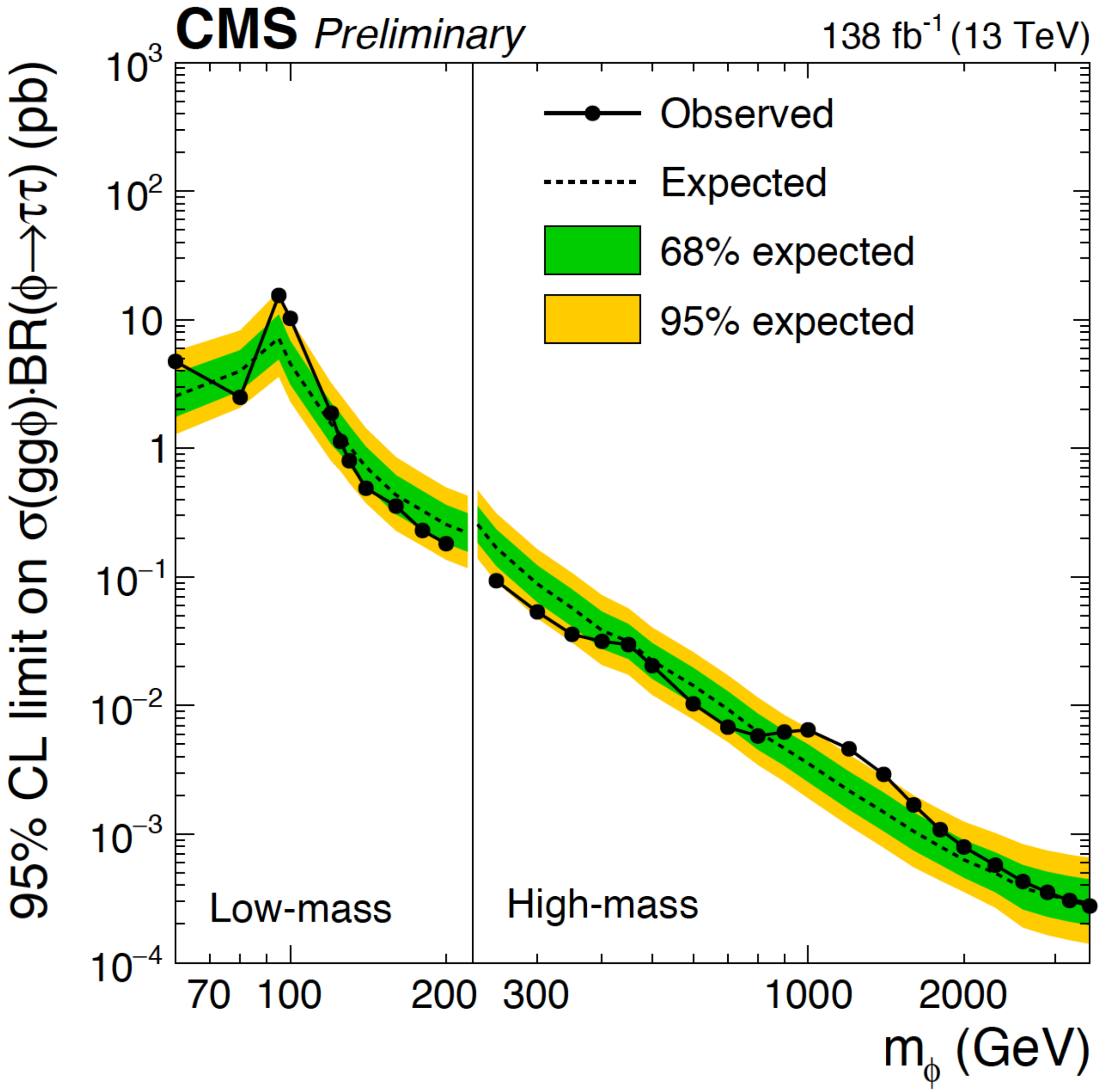


$\Rightarrow$ no visible differences

$\Rightarrow$ very difficult to distinguish the 2HDMS from the N2HDM!

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

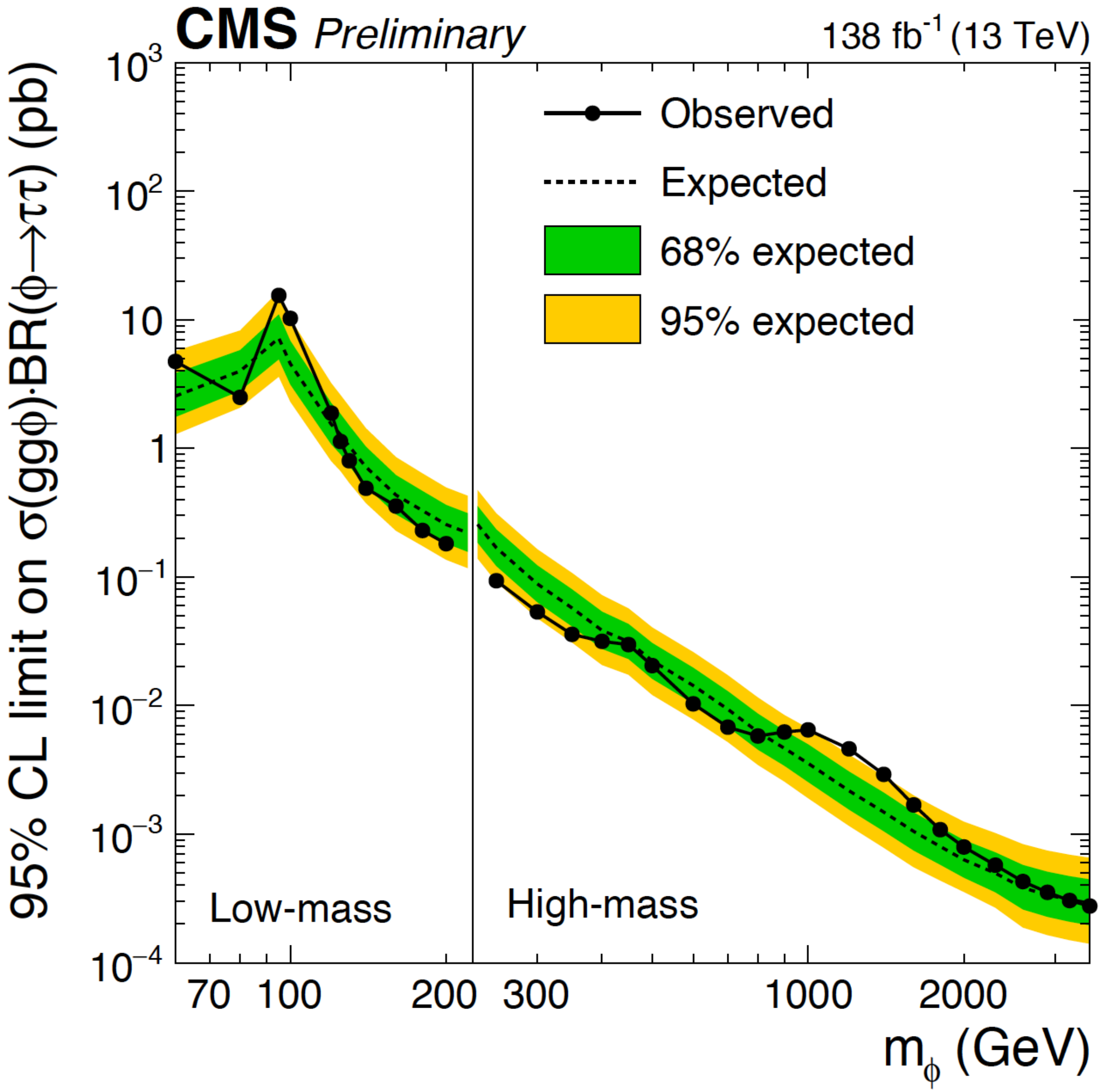
[*CMS '22*]



Can you spot the excess?

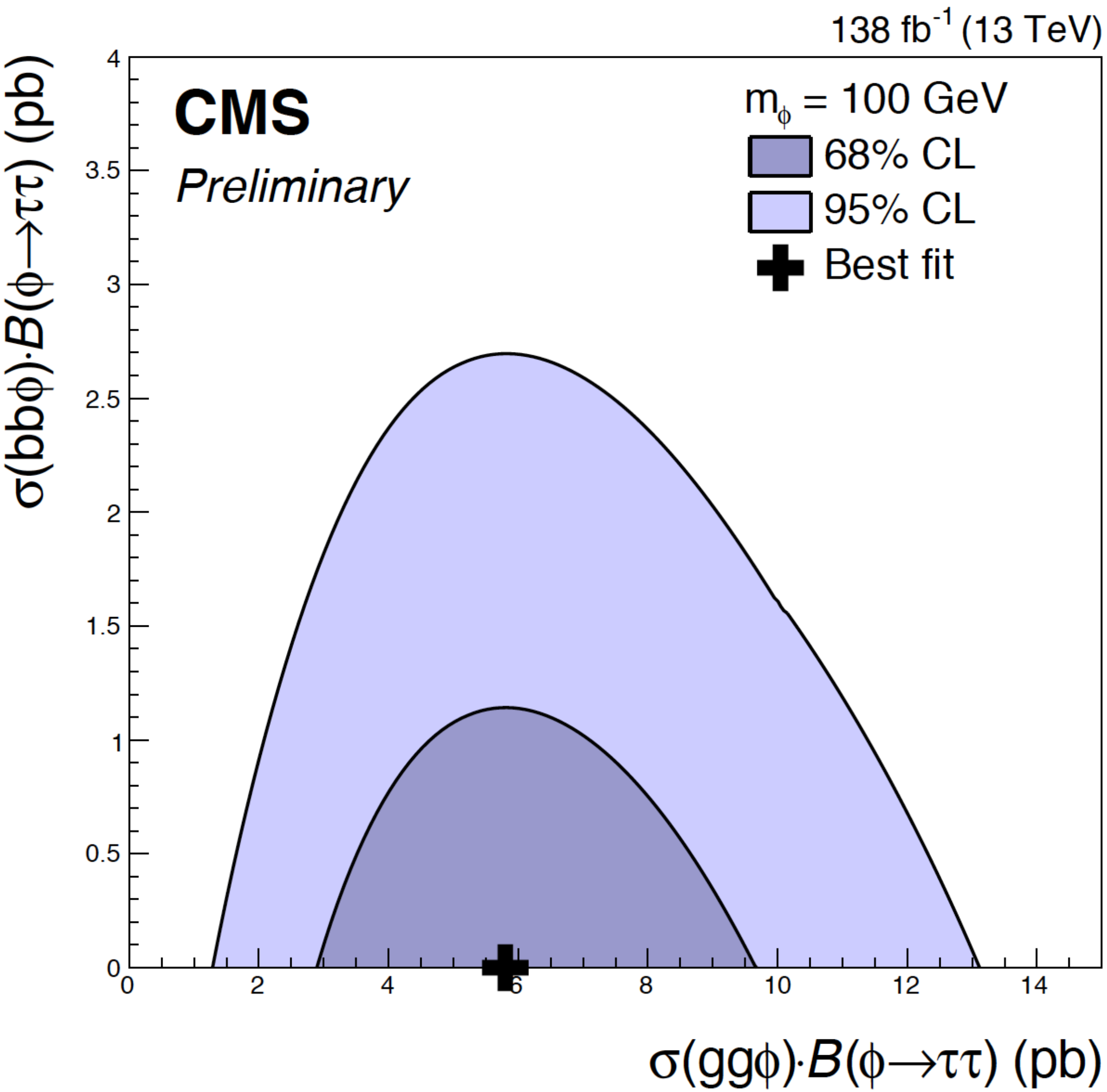
The new $\tau^+\tau^-$ excess

[*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 $\sim$ 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)

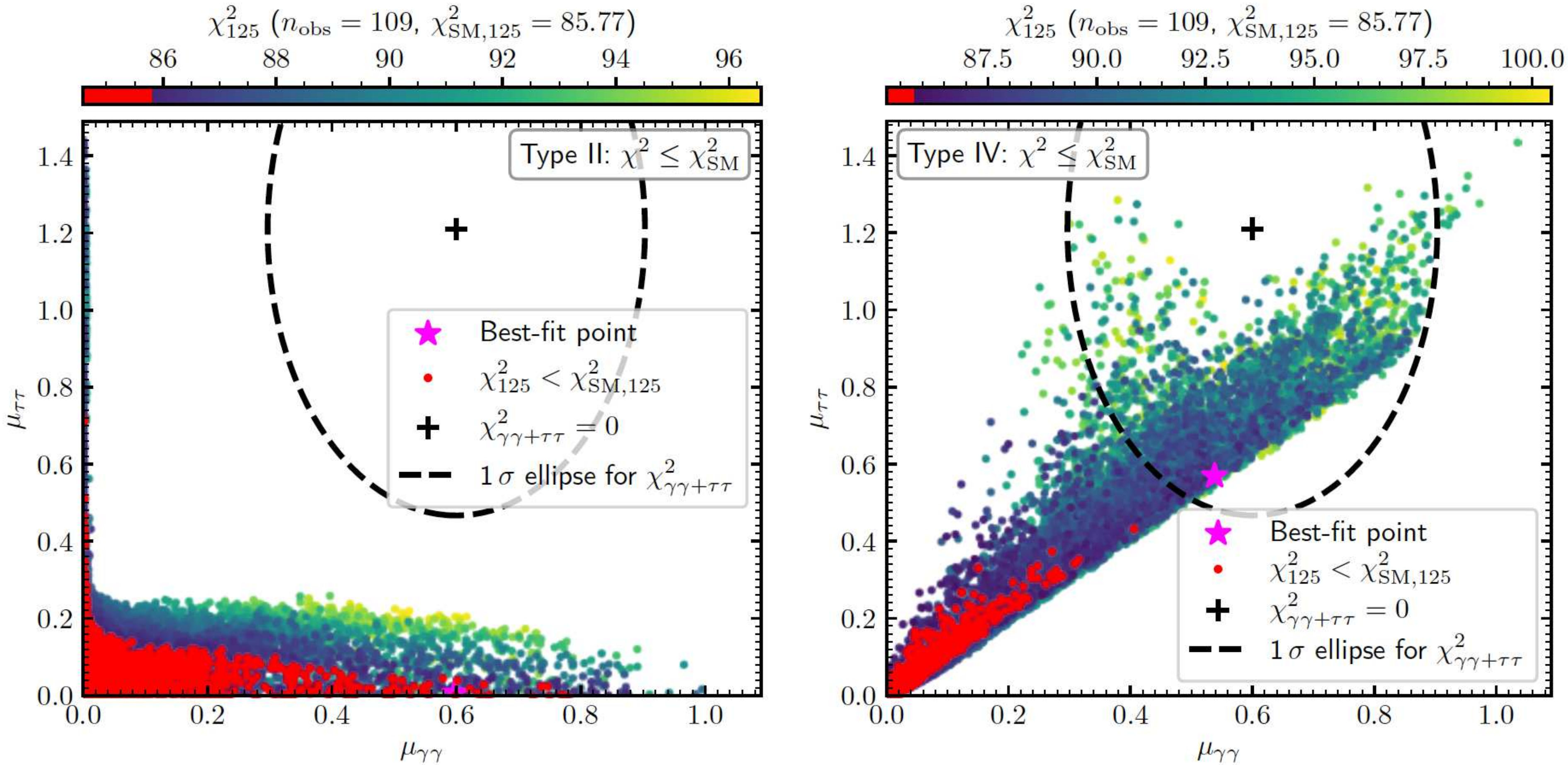
$$\Rightarrow \sim 4.3\,\sigma$$

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

Can we fit all excesses together?

N2HDM type II vs. type IV

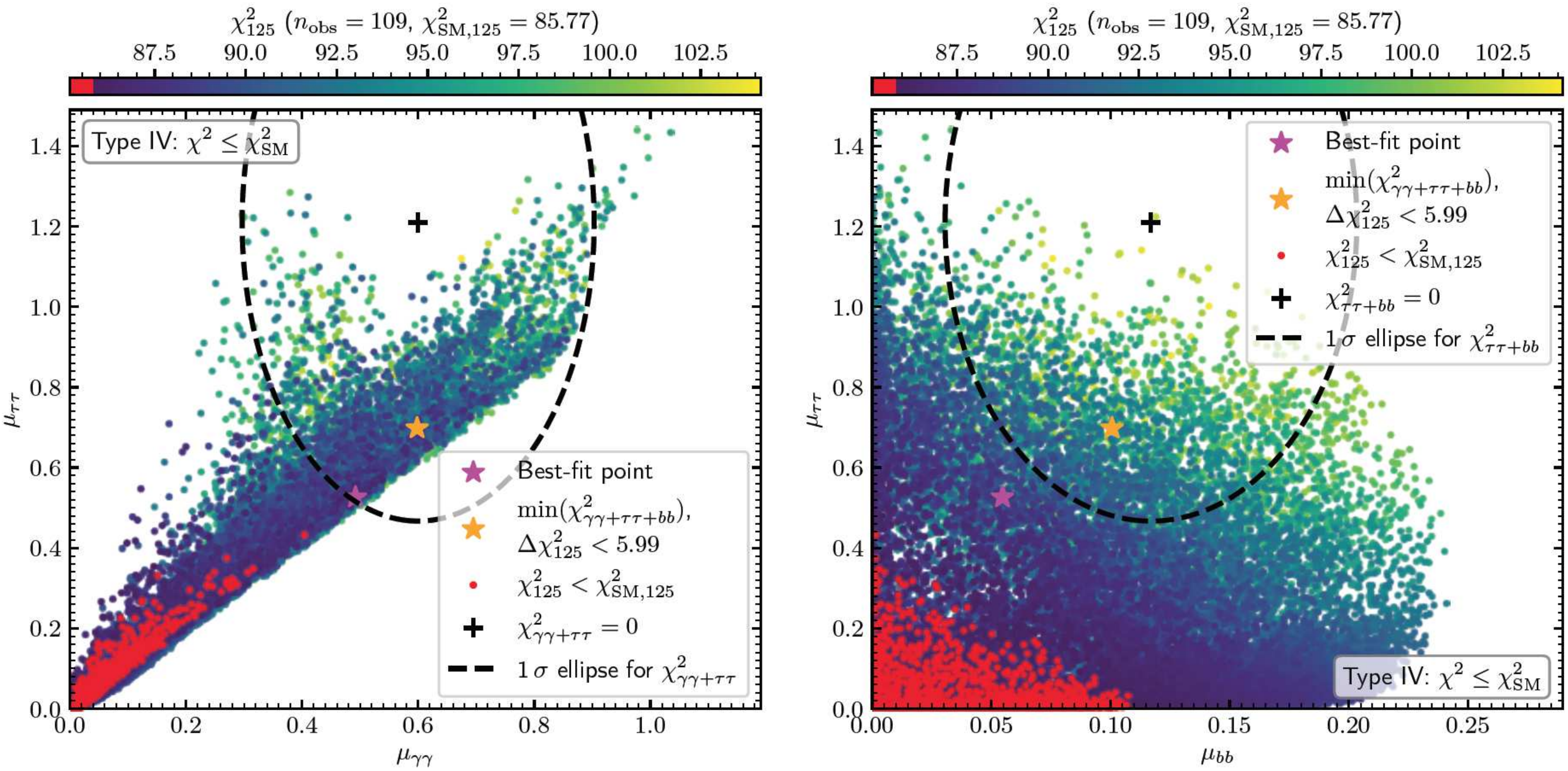
[*T. Biekötter, S.H., G. Weiglein '22*]



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*]

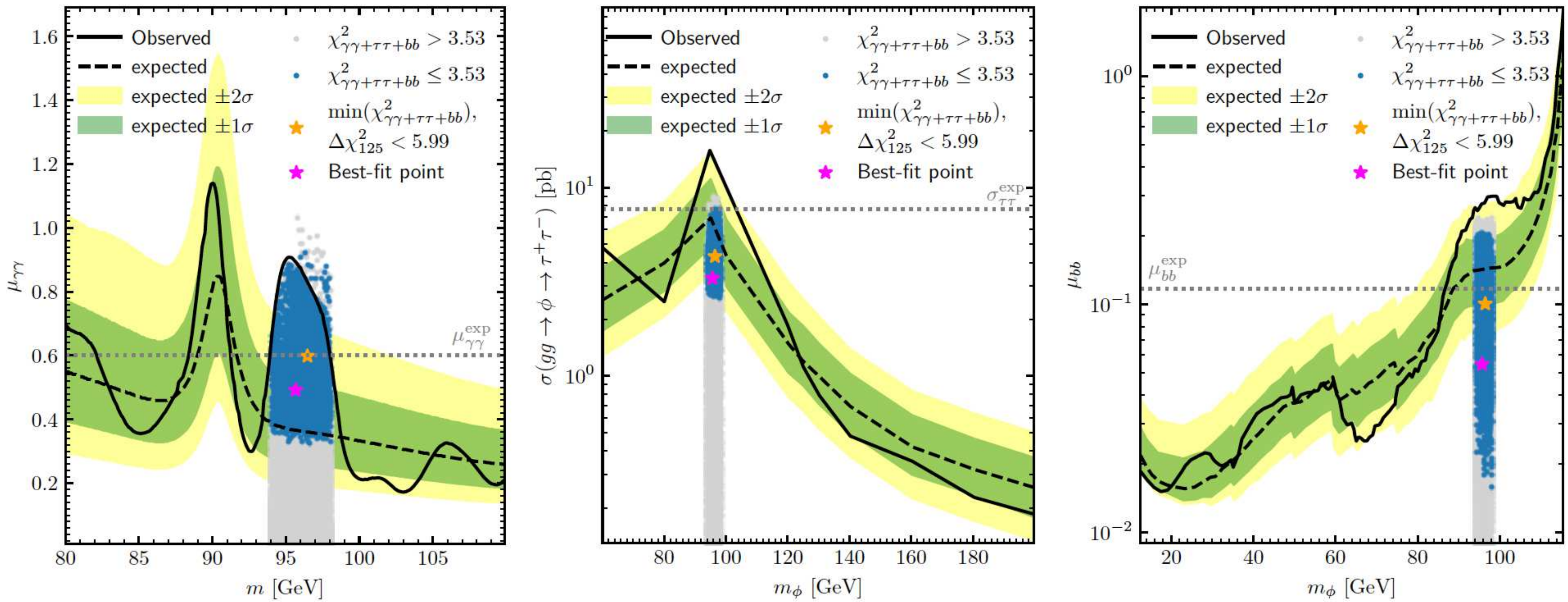


Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ 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*]

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

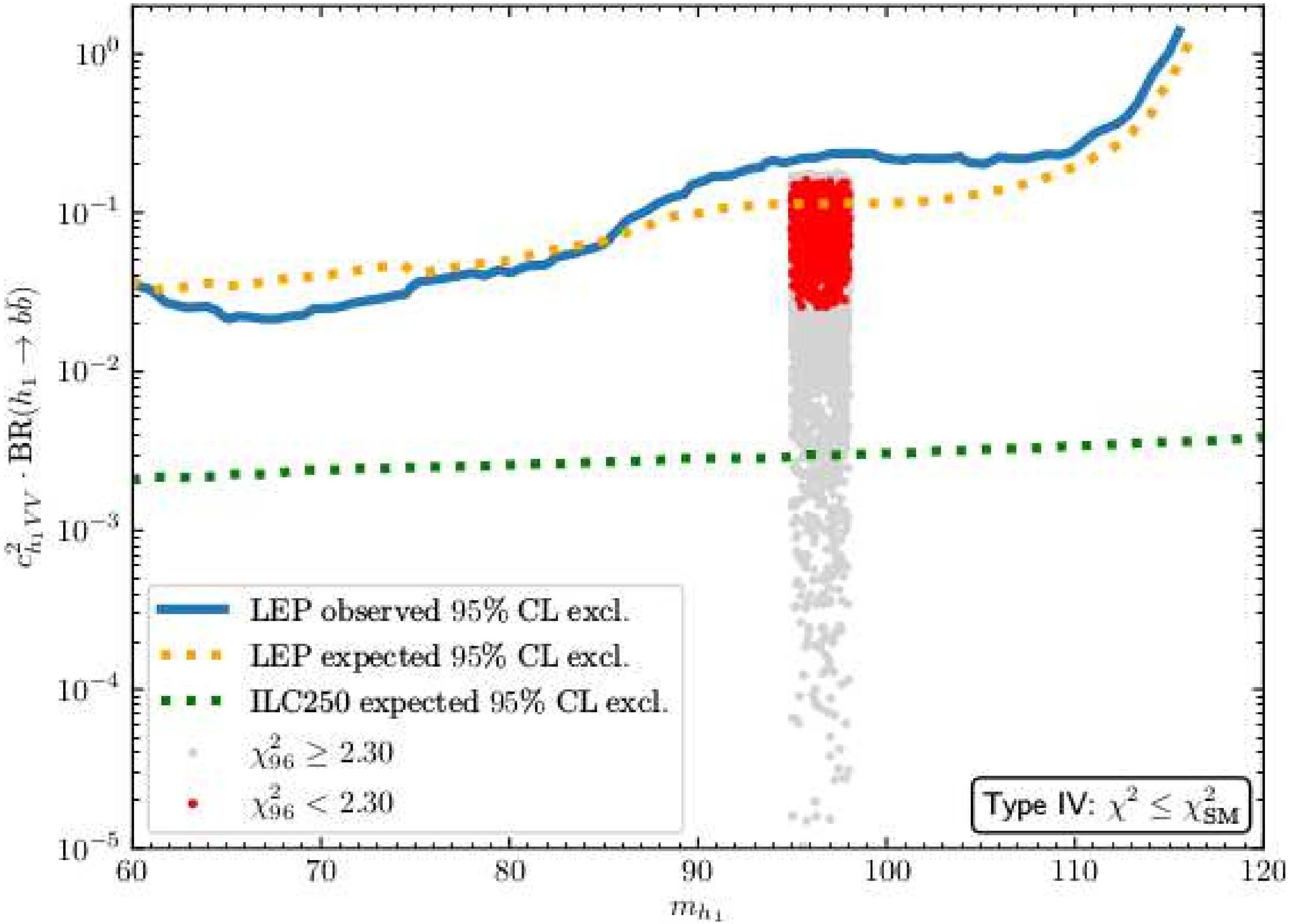


gray lines: central values of excesses

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

Production of the light Higgs at the ILC:

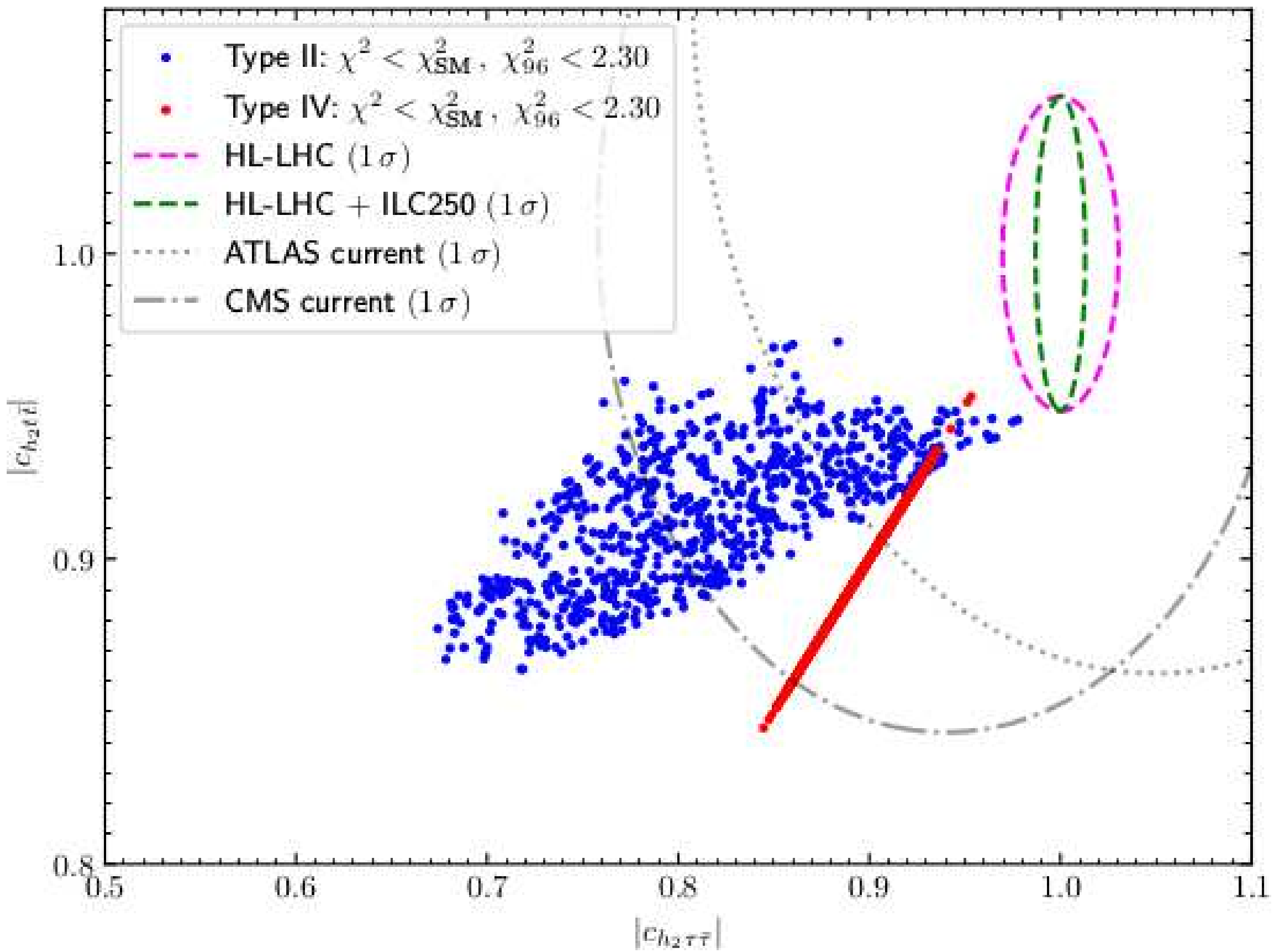
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



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

HL-LHC/ILC Higgs coupling measurements

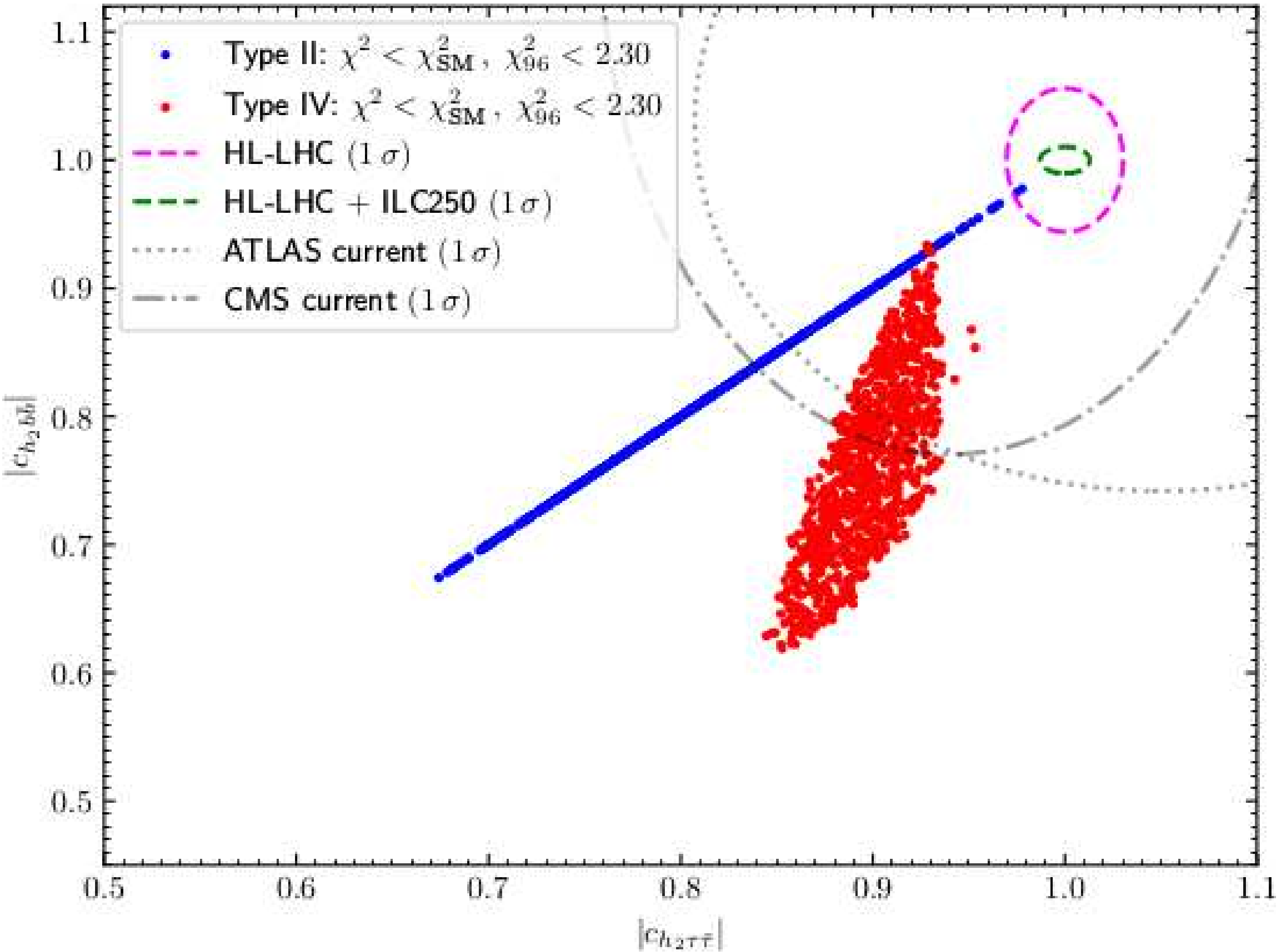
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



$\Rightarrow$ both types show some deviation from SM

HL-LHC/ILC Higgs coupling measurements

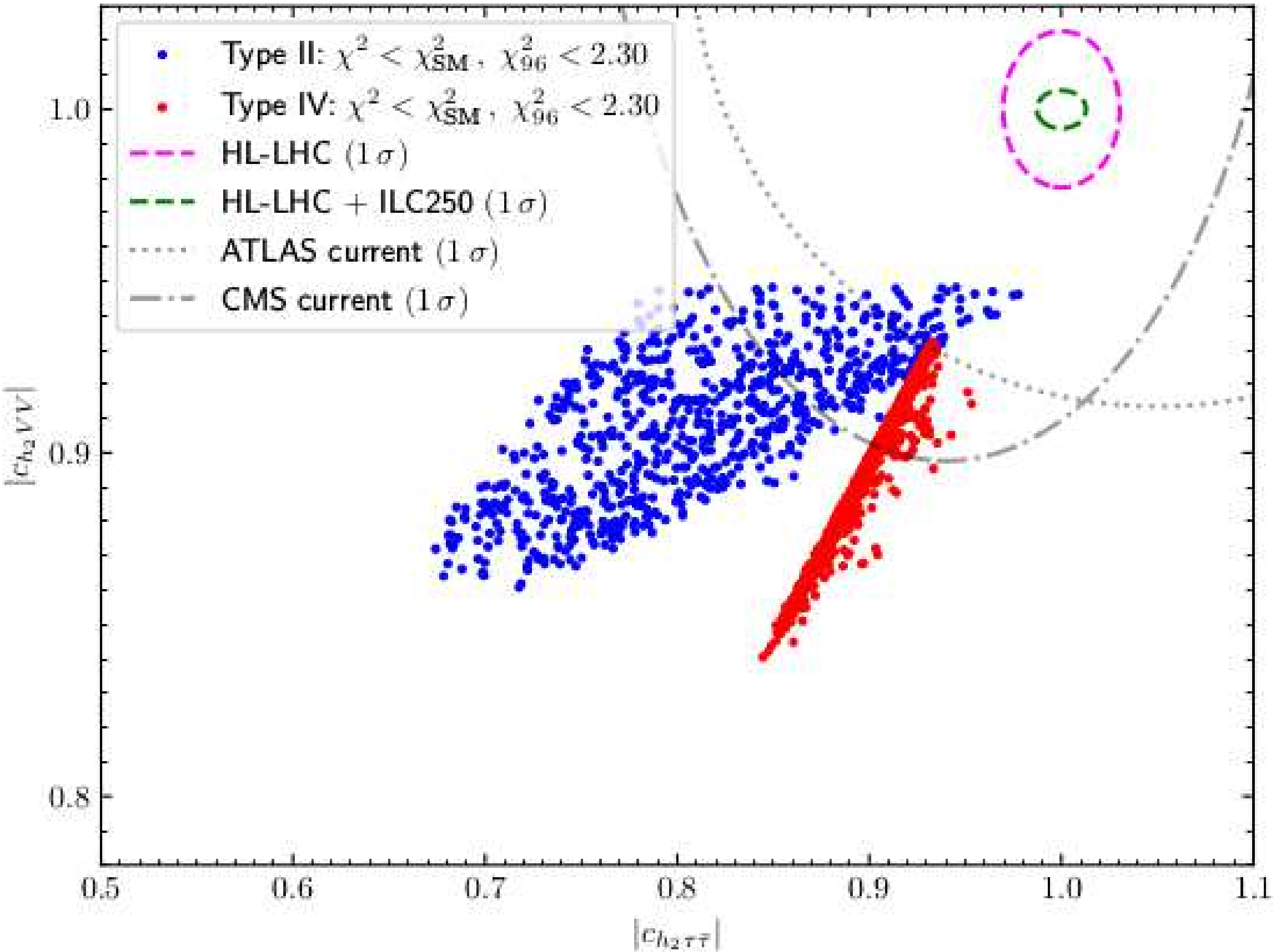
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ bothg types show deviations from SM

HL-LHC/ILC h_{125} coupling measurements

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

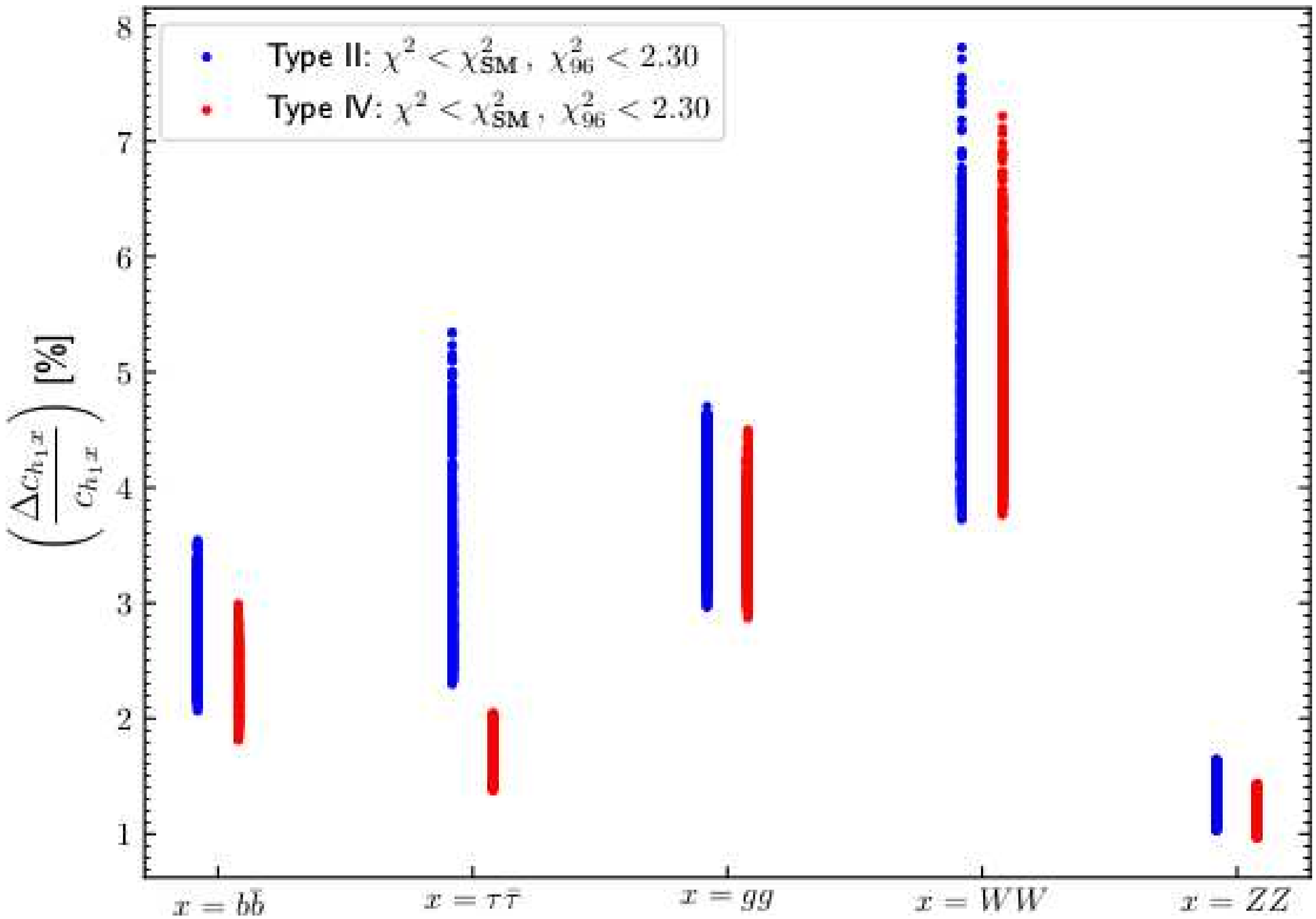


⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM at the ILC

Towards an ILC coupling measurements of ϕ_{95}:

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

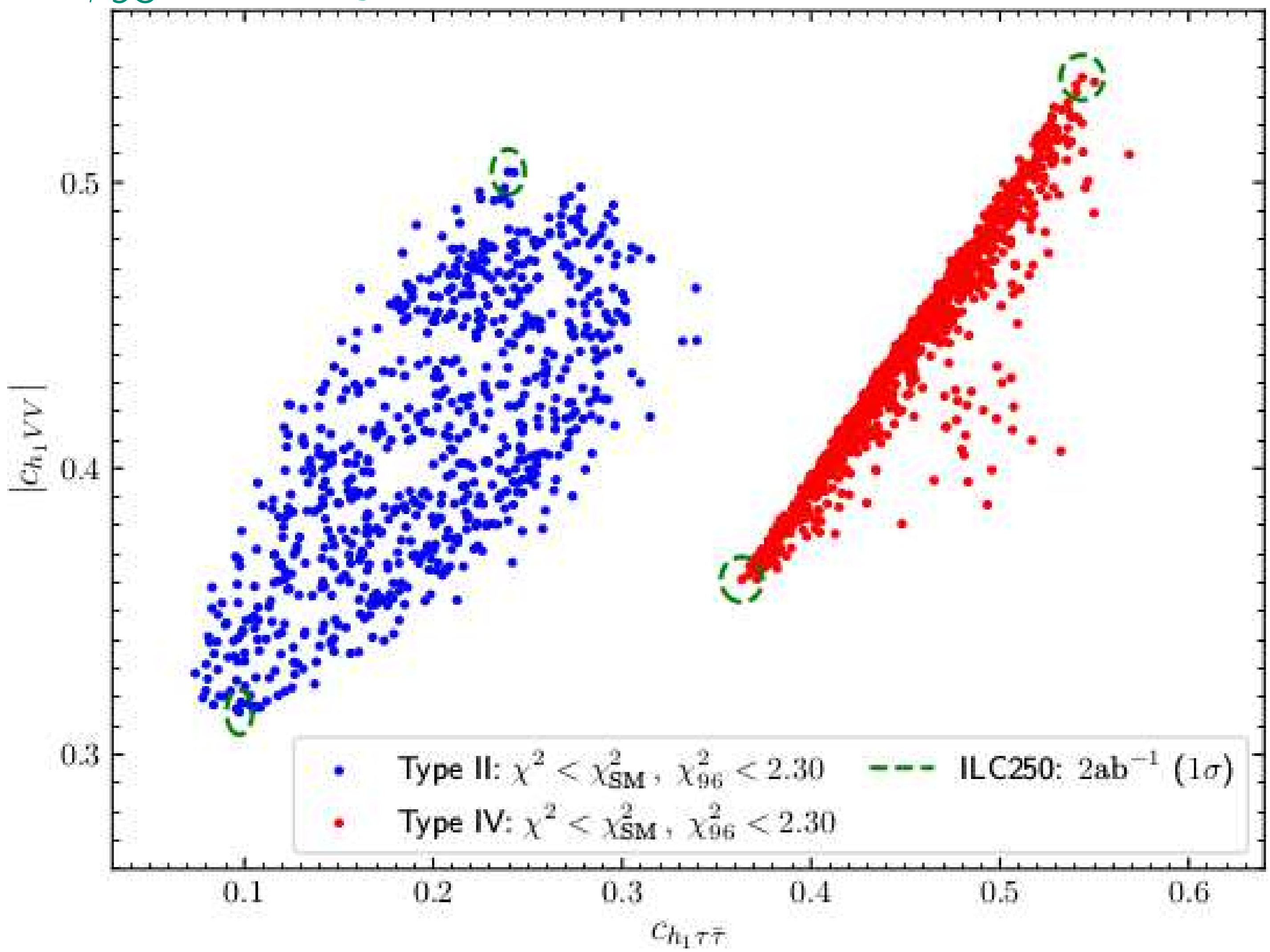


$\Rightarrow$ clear difference in $g_{h_1\tau\tau}$ as expected

ILC ϕ_{95} coupling measurements at the ILC

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

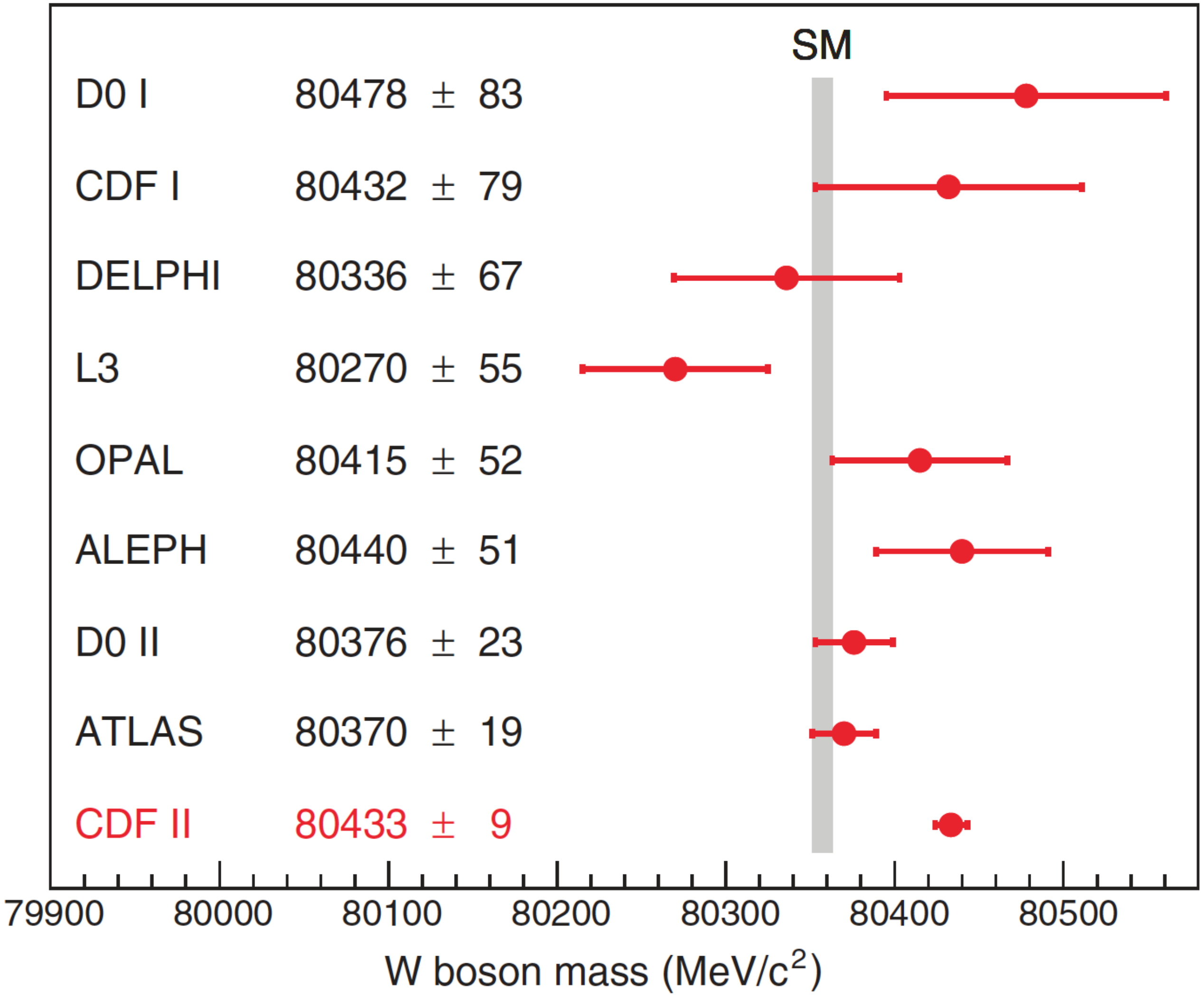
green circles: ϕ_{95} coupling precision at the ILC250



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

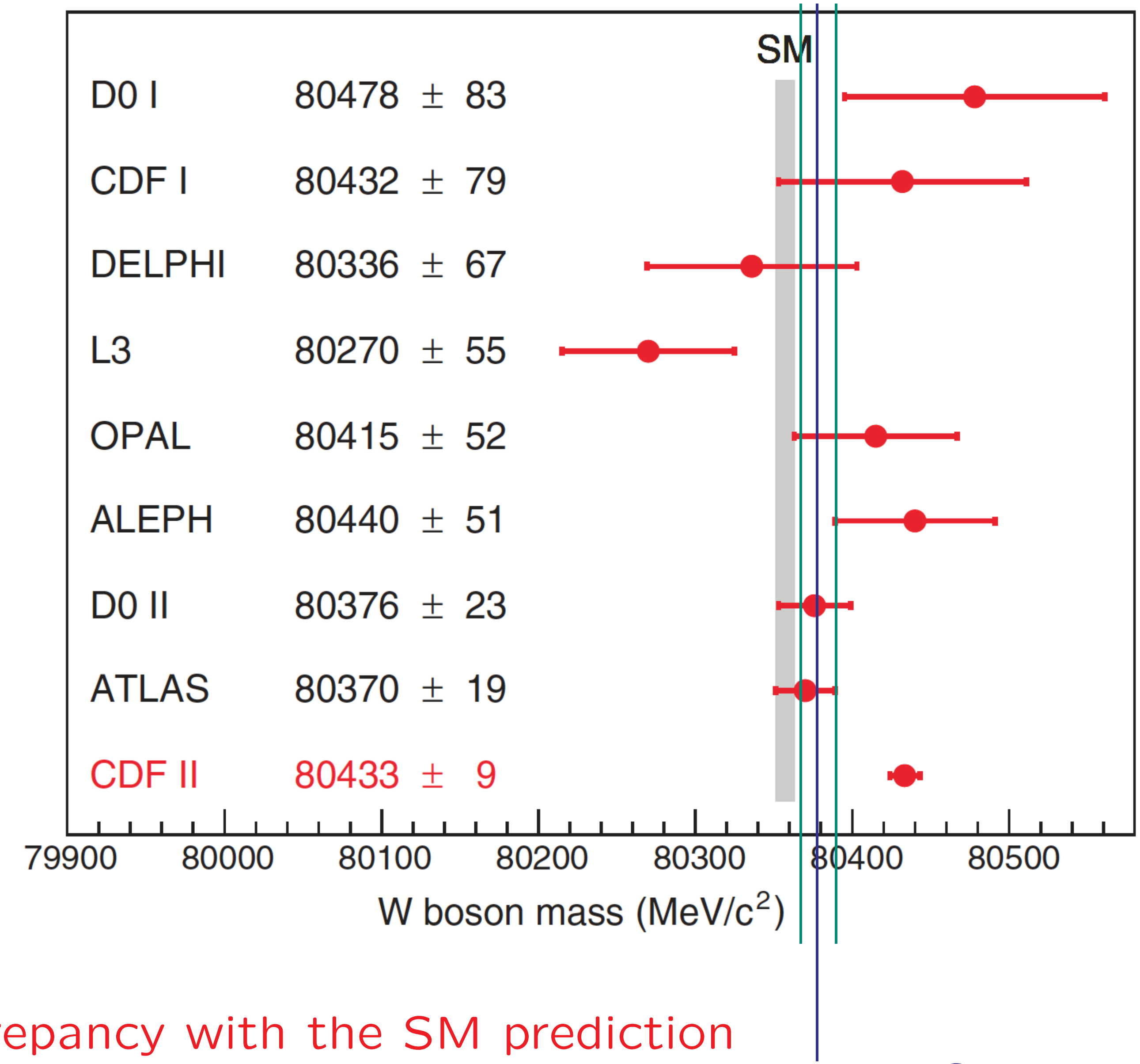
4. The mass of the W boson: theory vs. experiment

[*CDF '22*]



$\Rightarrow$ large discrepancy with the SM prediction

4. The mass of the W boson: theory vs. experiment [CDF '22]



⇒ large discrepancy with the SM prediction

⇒ large discrepancy with other measurements: $M_W^{\text{PDG}} = 80379 \pm 12$ MeV

Approximation of M_W with S, T, U: [M. Peskin, T. Takeuchi '90]

$\rightarrow$ capture the gauge boson self-energies

$\Rightarrow$ good approximation in multi-Higgs models

$$M_W^2 = M_W^2\big|_{\rm SM}\left(1 + \frac{s_w^2}{c_w^2 - s_w^2}\Delta r'\right) ,$$

$$\Delta r' = \frac{\alpha}{s_w^2}\left(-\frac{1}{2}S + c_w^2 T + \frac{c_w^2 - s_w^2}{4 s_w^2}U\right) .$$

Main contribution:

$$+\frac{\alpha c_{\rm W}^2}{s_{\rm W}^2}\frac{s_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}T$$

$$=: +\frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}(\alpha T)$$

$$=: +\frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho \qquad \alpha T \equiv \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

Implications for BSM models

Contribution from 2HDM Higgs sector to $\Delta\rho$:

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2}\left\{\frac{m_A^2 m_H^2}{m_A^2 - m_H^2}\ln\frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H\pm}^2}{m_A^2 - m_{H\pm}^2}\ln\frac{m_A^2}{m_{H\pm}^2} - \frac{m_H^2 m_{H\pm}^2}{m_H^2 - m_{H\pm}^2}\ln\frac{m_H^2}{m_{H\pm}^2} + m_{H\pm}^2\right\}$$

$\Rightarrow$ large $\Delta\rho$ needed to accomodate M_W^{CDF}

Before M_W^{CDF}:

$\Rightarrow$ small mass splittings between $m_{H\pm}$-m_H and $m_{H\pm}$-m_A

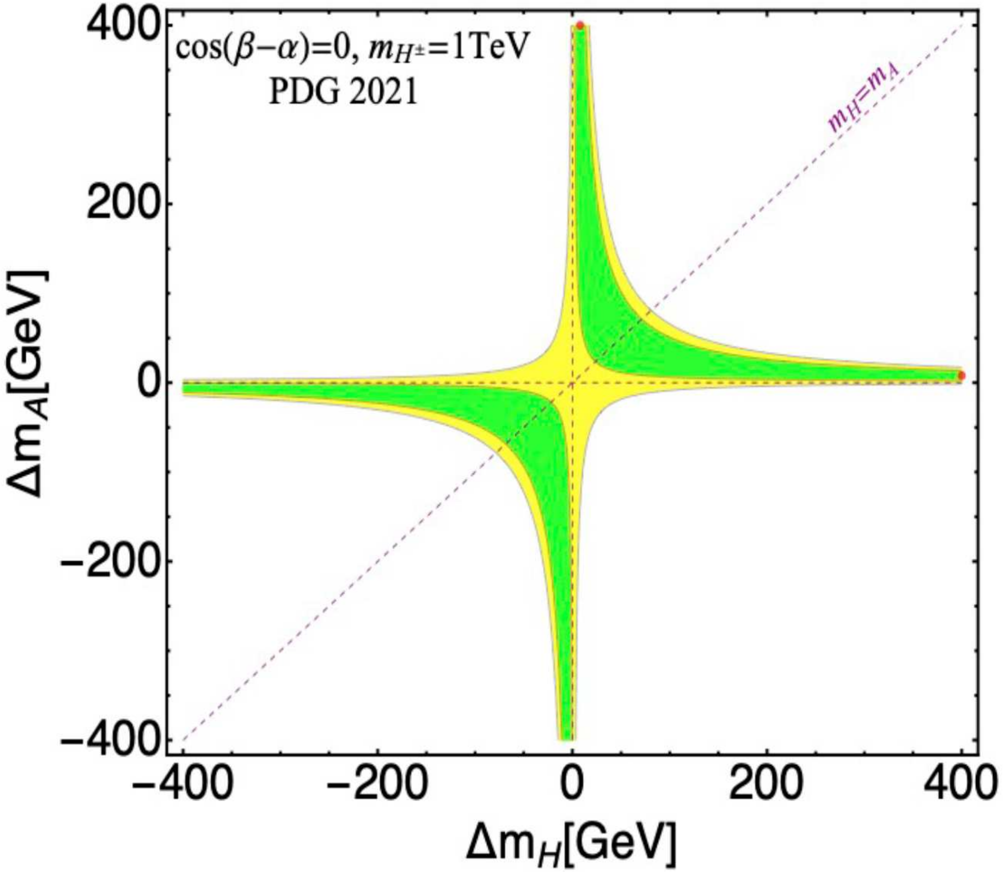
After M_W^{CDF}:

$\Rightarrow$ increased mass splittings to accomodate M_W^{CDF}

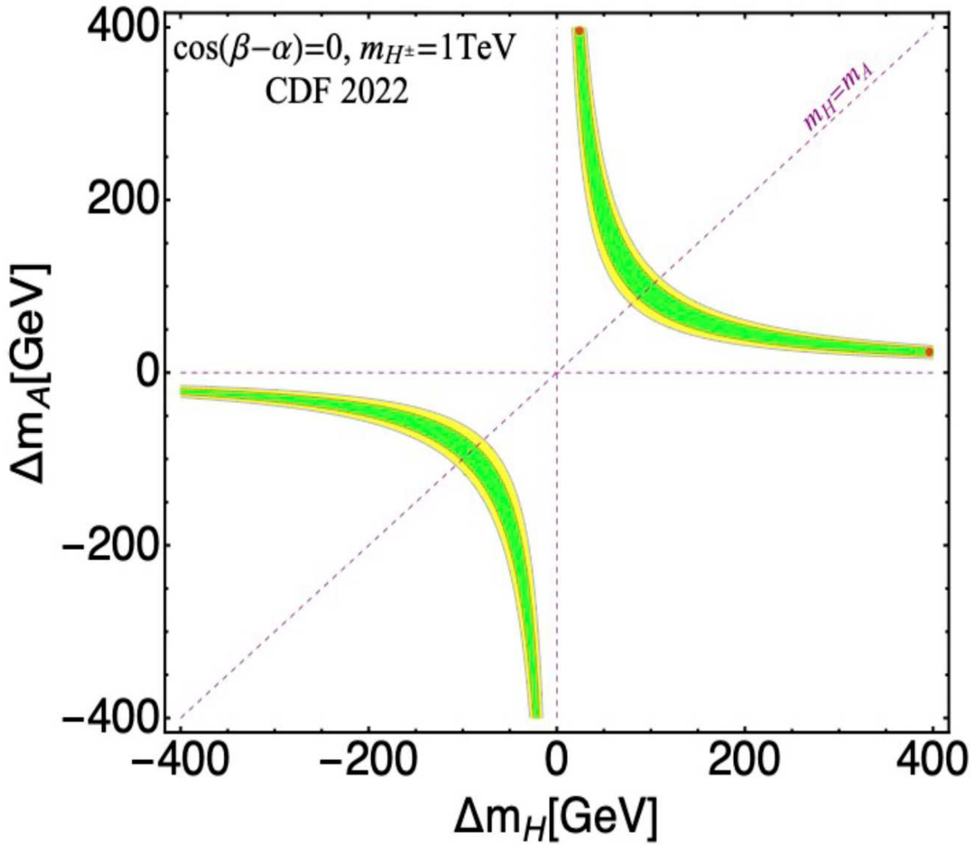
Example: $m_{H^\pm} = 1000$ GeV, $\cos(\beta - \alpha) = 0$

[C. Lu, L. Wu, Y. Wu, B. Zhu '22]

PDG 2021



M_W^{CDF}



⇒ nearly no overlap of the 2σ regions

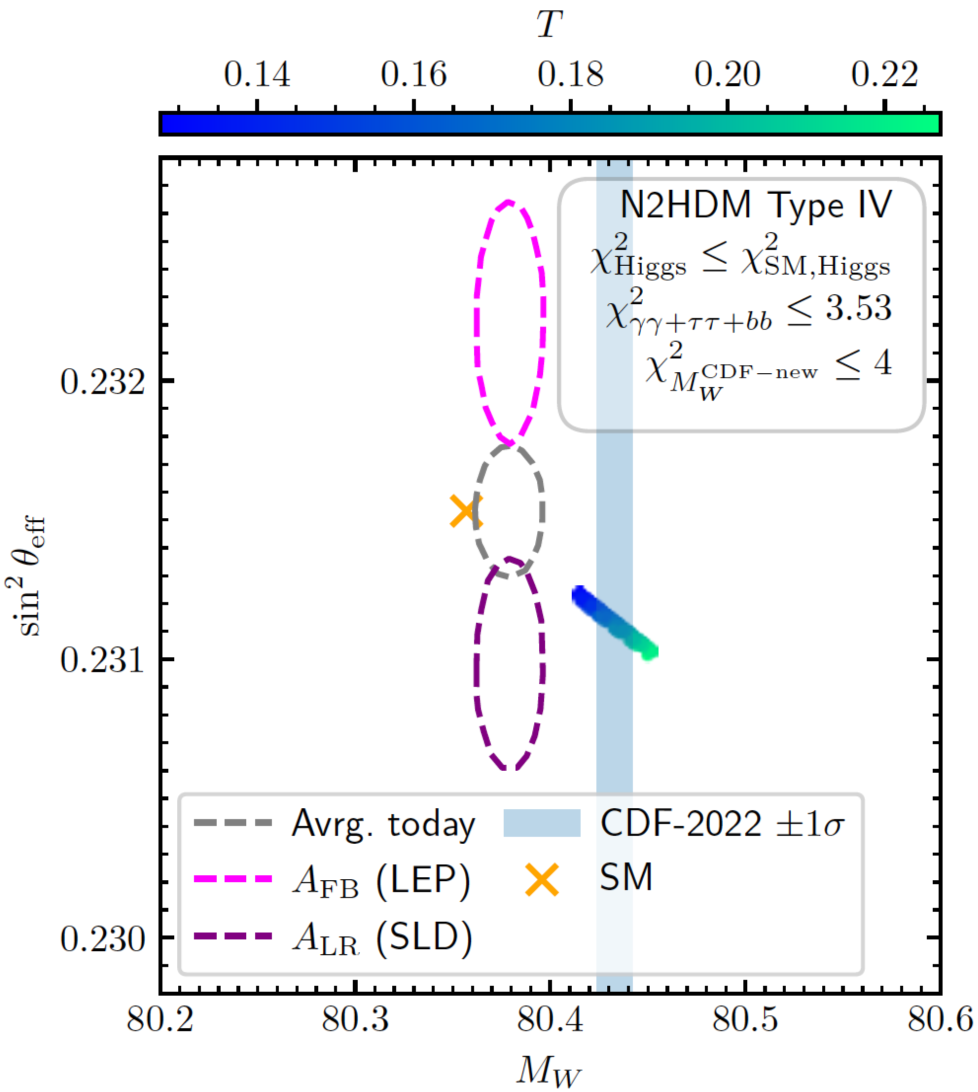
⇒ new CDF value requires relatively large BSM Higgs mass splitting

⇒ but no upper limit on heavy Higgs-boson mass scale

Can we fit three 95 GeV excesses and M_W^{CDF}?

Can we fit three 95 GeV excesses and M_W^{CDF}? $\Rightarrow$ N2HDM type IV

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



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

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

5. Conclusinos

- The discovered Higgs boson cannot be the SM Higgs boson
  - check changed properties of h_{125}
  - search for additional Higgs bosons above and below 125 GeV

- Experimental hints (as motivation/toy examples)
  - $t\bar{t}$ (CMS) (and $\tau^+\tau^-$ (ATLAS)) at $\sim$ 400 GeV
  - $\gamma\gamma$ (CMS) and $b\bar{b}$ (LEP) and $\tau^+\tau^-$ (CMS) at $\sim$ 95 GeV ($\Rightarrow$ 4.3 σ?)

- ILC physics opportunities:
  - ILC direct detection (at least) up to $\sqrt{s}/2$ (400 $<$ 500 :-)
  - CLIC direct detection: substantial gain w.r.t. HL-LHC
  - ILC250: light Higgs bosons up to $\sim$ 160 GeV detectable
  - ILC250/500: h_{125} coupling meas. are likely to see a deviation
  - ILC250: precision study of light Higgs bosons possible

    $\Rightarrow$ to disentangle the underlying model

- M_W^{CDF}: can be accomodated in the N2HDM (fitting ϕ_{95})

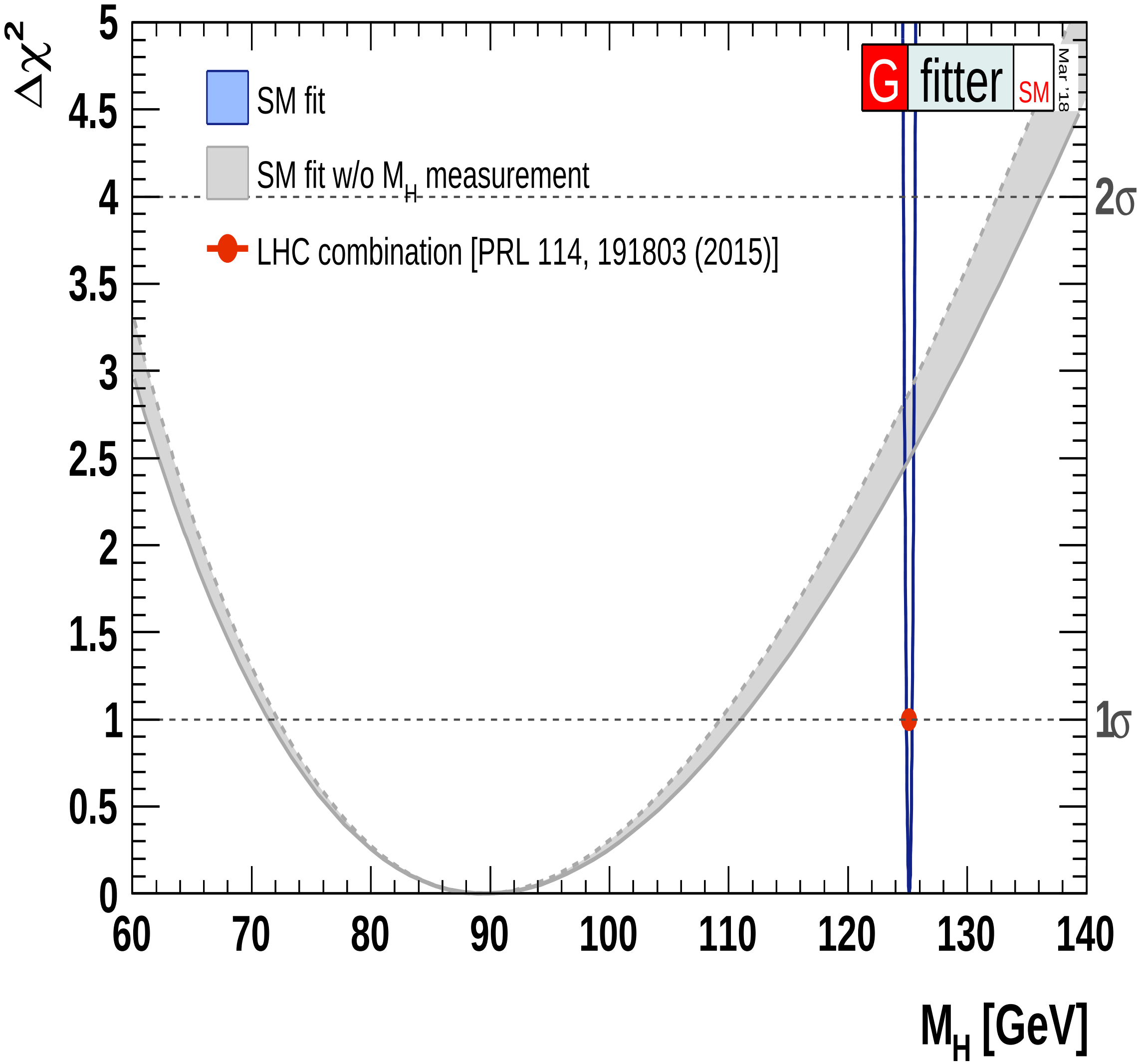

Further Questions?

Global fit to all SM data (w/o M_W^{CDF}):

[*GFitter '18*]

$\Rightarrow$ $M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:

SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ effect of M_W^{CDF}?

$\Rightarrow$ no new global fit available $\Rightarrow$ individual contributions?

Results for M_H from individual EWPO:

[GFitter '18]

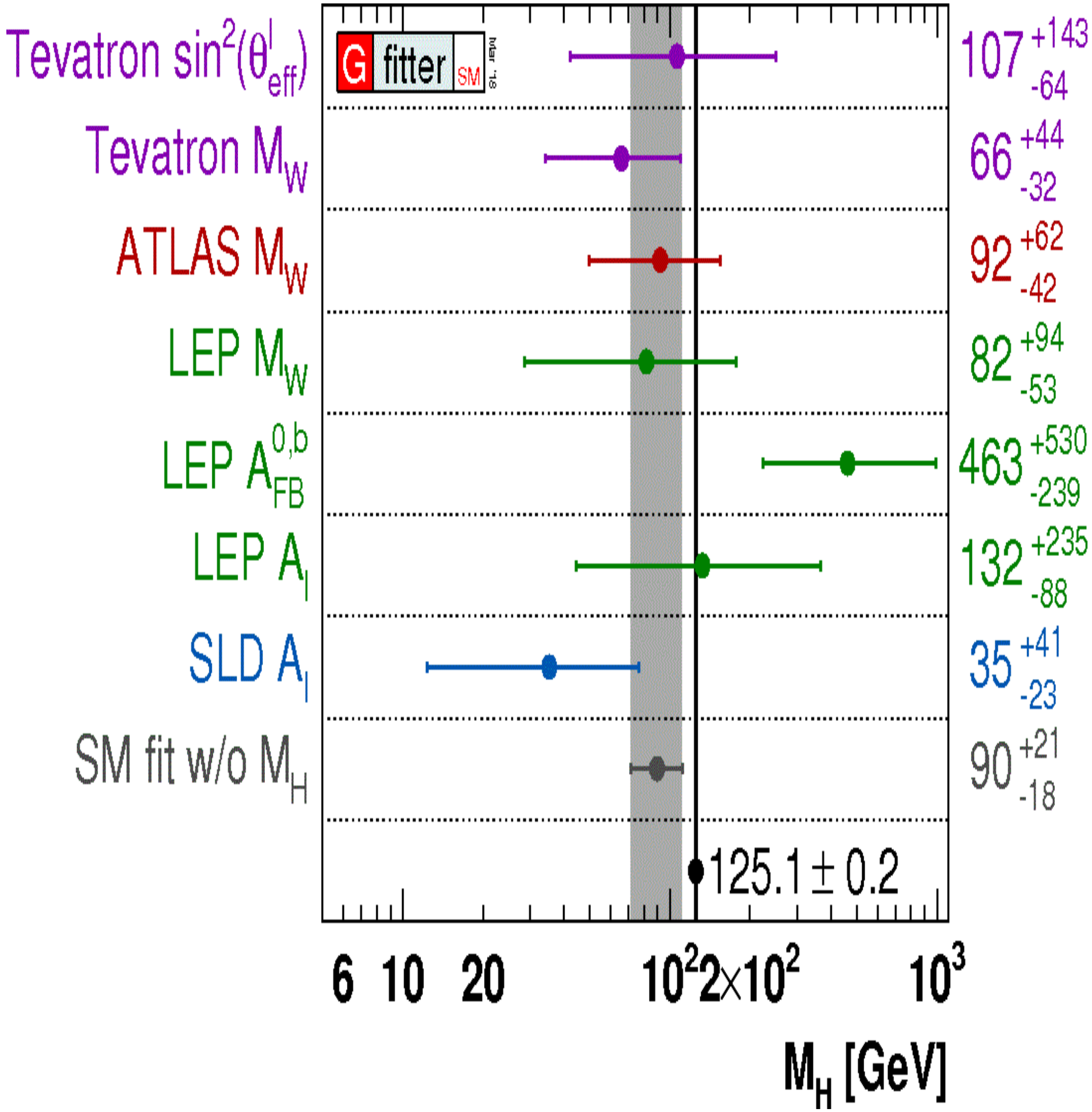
light Higgs preferred by:

M_W, $A^l_{\rm LR}$ (SLD)

heavier Higgs preferred by:

$A^b_{\rm FB}$ (LEP)

$\Rightarrow$ keeps SM alive



$\Rightarrow$ Which M_H value is preferred by $M_W^{\rm CDF}$?

Results for M_H from individual EWPO:

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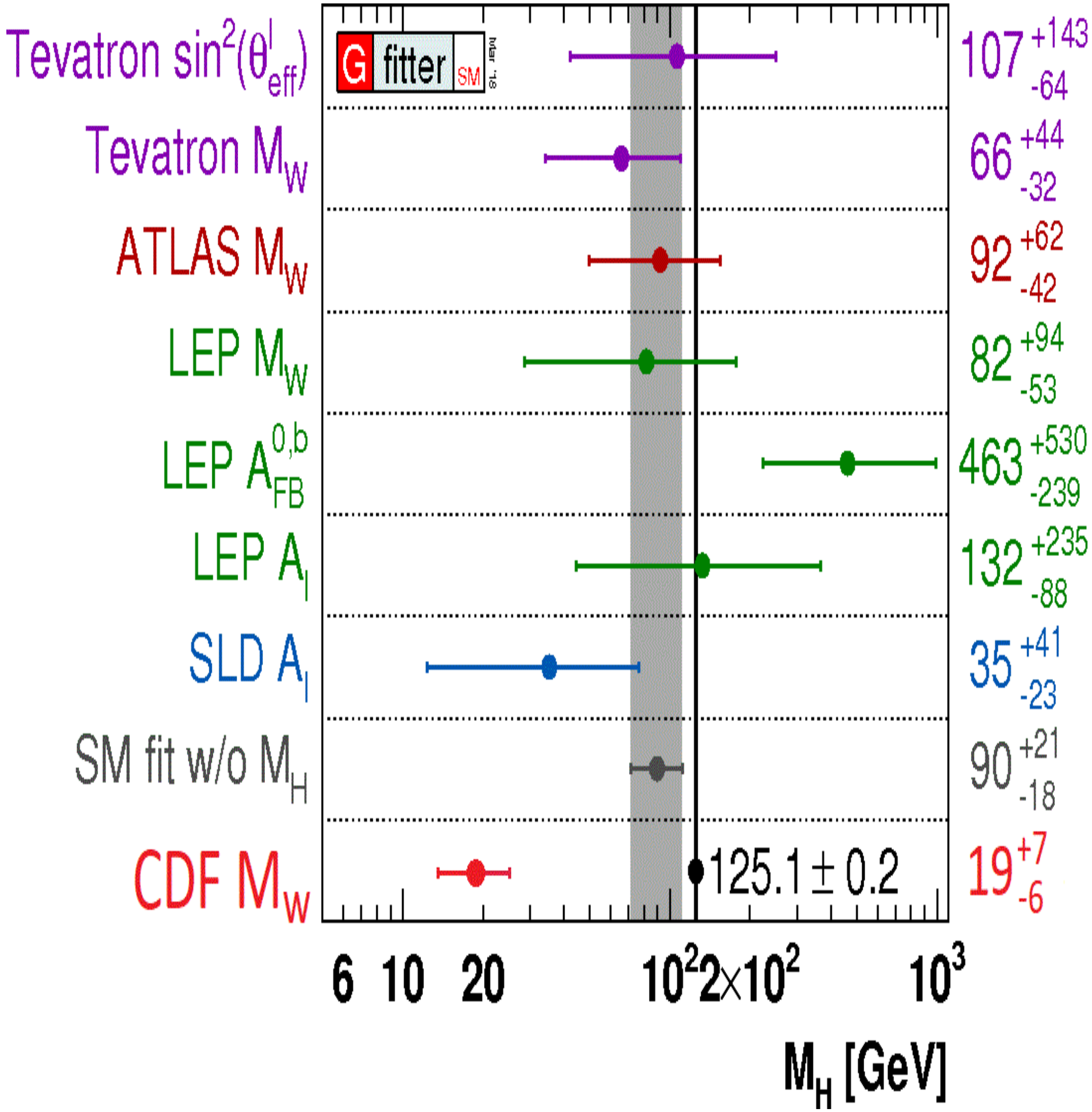


⇒ $M_W^{\rm CDF}$ prefers a too light Higgs mass!

Possible hint for heavy Higgses in the N2HDM:

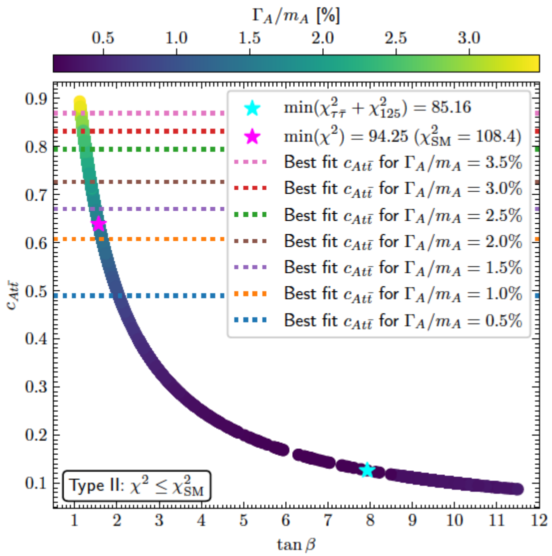
[*taken from T. Biekötter '21*]

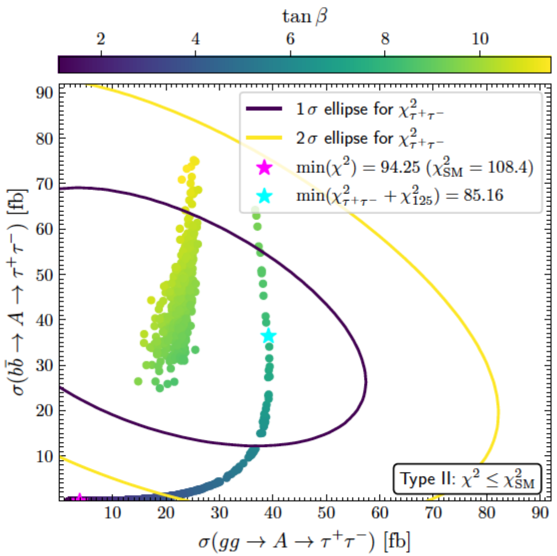
A 400 GeV pseudoscalar in the type II N2HDM

$$\chi^2 = \chi^2_{125} + \chi^2_{t\bar{t}} + \chi^2_{\tau^+\tau^-} \text{ , we demand: } \chi^2 \leq \chi^2_{\rm SM}$$

$$20\ {\rm GeV} \leq m_{h_{a,c}} \leq 1000\ {\rm GeV}\ , \quad m_{h_b} = 125.09\ {\rm GeV}\ , \quad m_A = 400\ {\rm GeV}\ ,$$

$$550\ {\rm GeV} \leq m_{H^\pm} \leq 1000\ {\rm GeV}\ , \quad 10\ {\rm GeV} \leq v_s \leq 1500\ {\rm GeV}\ , \quad 0.5 \leq \tan\beta \leq 12.5$$





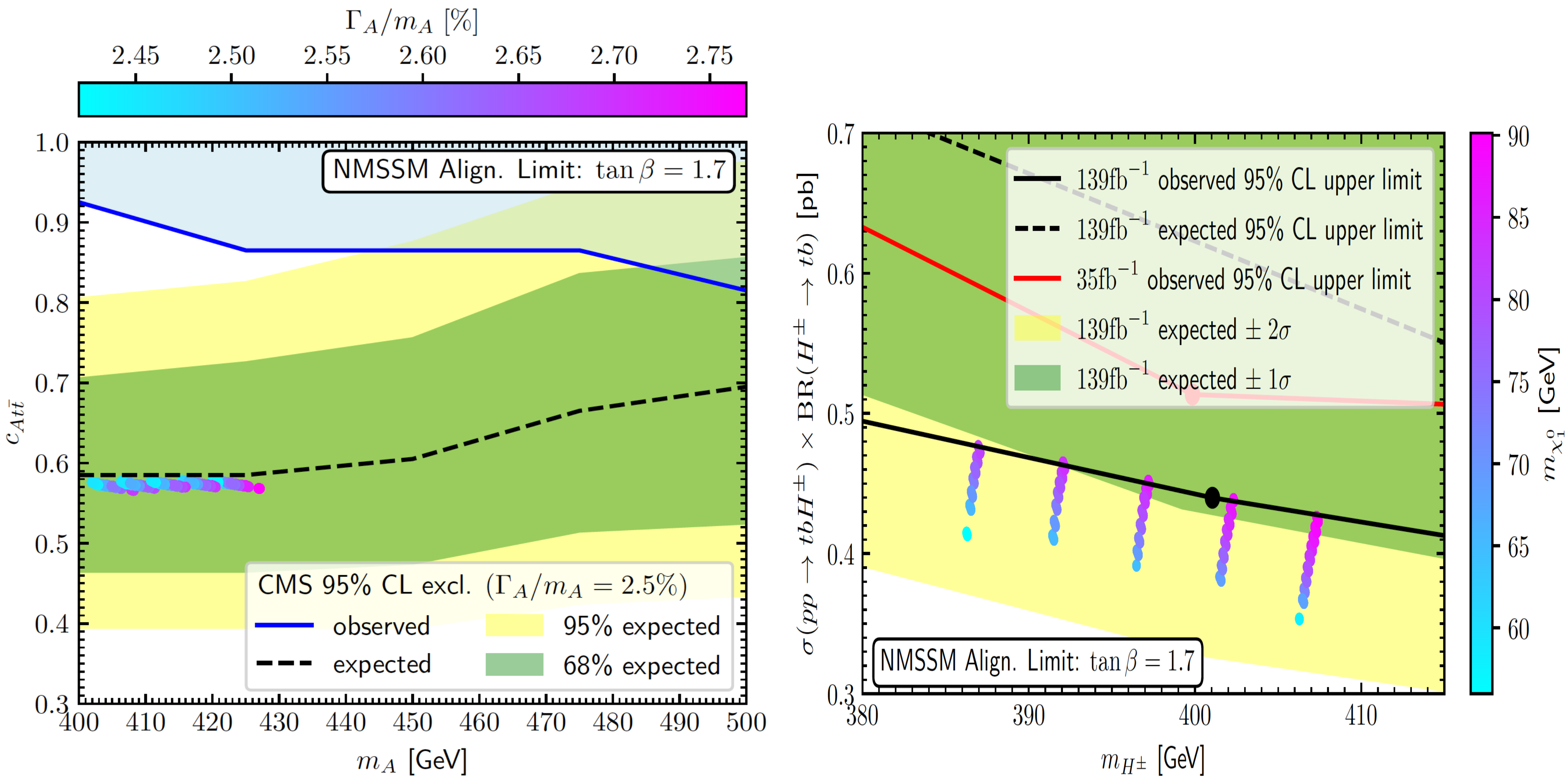
(Also the "$A \to Zh$" excess can be realized)
$\to$ Later

Both the $t\bar{t}$ and the $\tau^+\tau^-$ excesses can be realized, but not simultaneously

$\tan\beta \lesssim 2.5$ for $t\bar{t}$ excess
$\tan\beta \gtrsim 5.5$ for $\tau^+\tau^-$ excess

[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]

Possible hint for heavy Higgses in the NMSSM (with $\tan\beta = 1.7$):



$\Rightarrow$ $t\bar{t}$ excess can be explained in the NMSSM (with $\tan\beta \sim 1.7$)

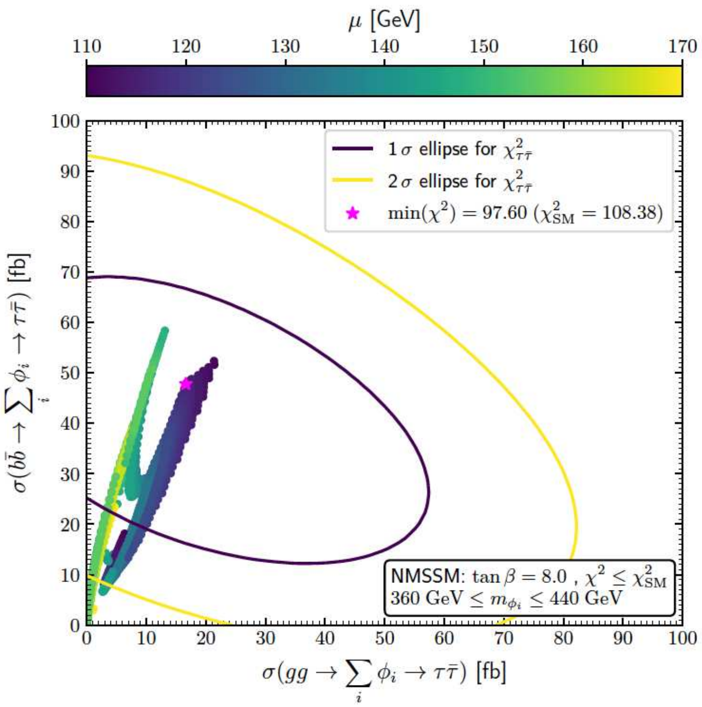
[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]

Possible hint for heavy Higgses in the NMSSM (with $\tan\beta = 8$):

[*taken from T. Biekötter '21*]

A pseudoscalar at ~ 400 GeV in the NMSSM

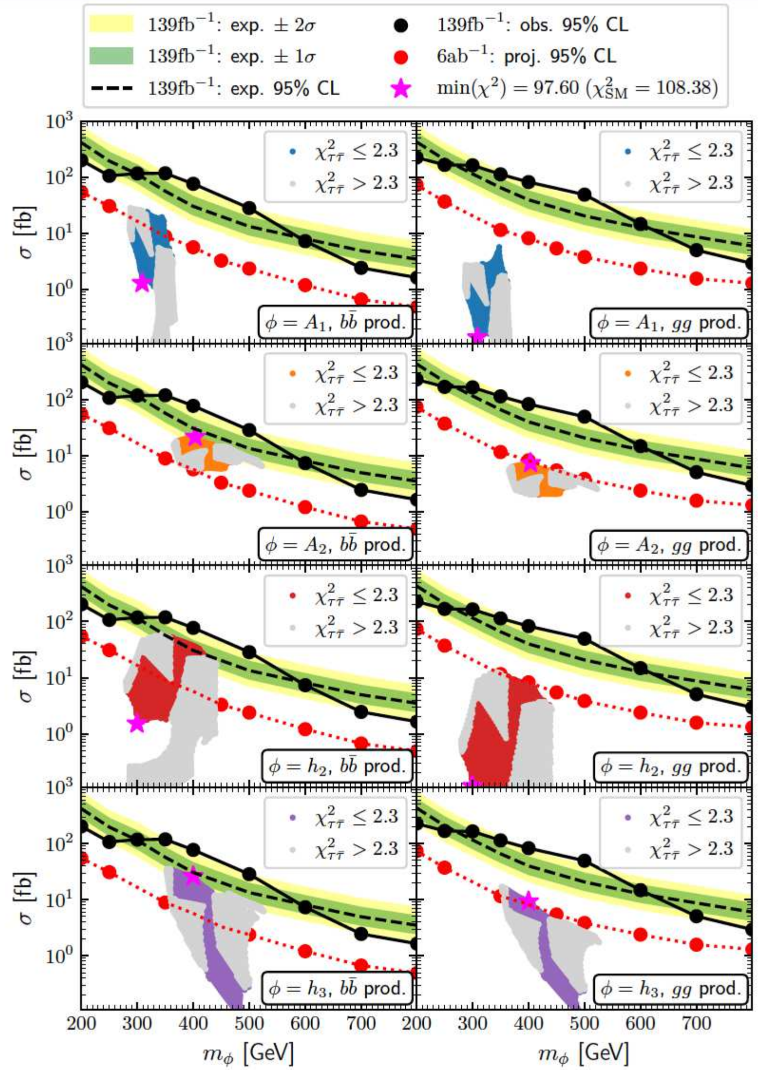
$\tau^+\tau^-$ **excess** $\rightarrow$ moderate $\tan\beta = 8$



Interference effects not important:

$m_{h_3} - m_{h_2} \gg \Gamma_{h_2} + \Gamma_{h_3}$

$m_{A_2} - m_{A_1} \gg \Gamma_{A_1} + \Gamma_{A_2}$



[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]

SUSY realizations

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– . . .

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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?

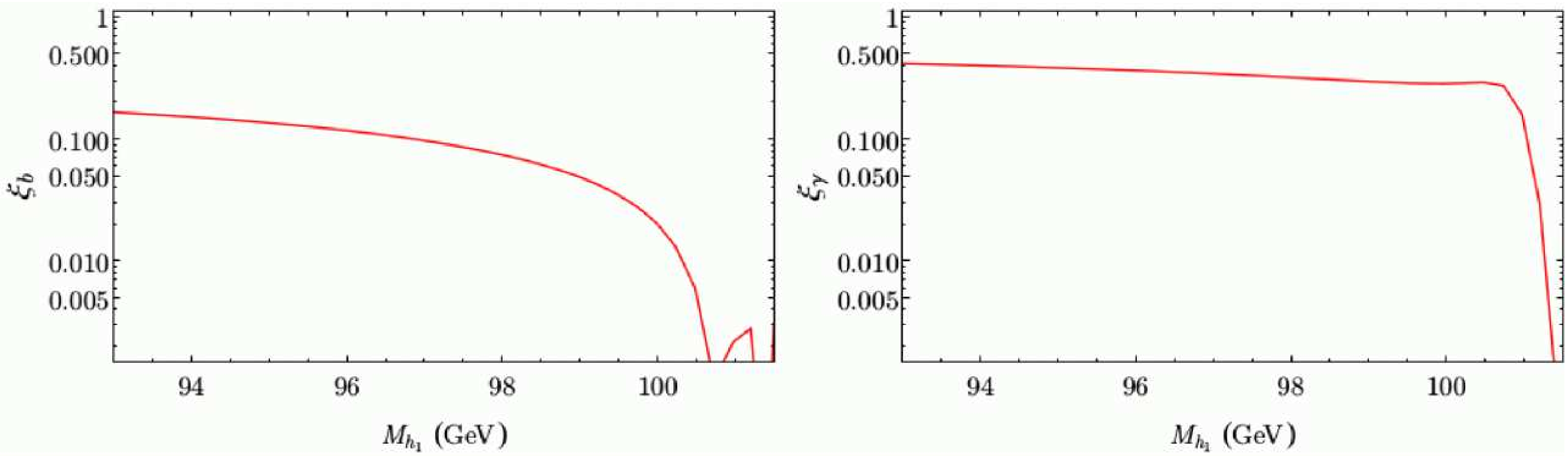
[*F. Domingo, S.H., S. Passehr, G. Weiglein '18*]

Parameters:

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

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

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



$\Rightarrow$ both excesses can be fitted simultaneously (at $1 - 1.5\,\sigma$)!

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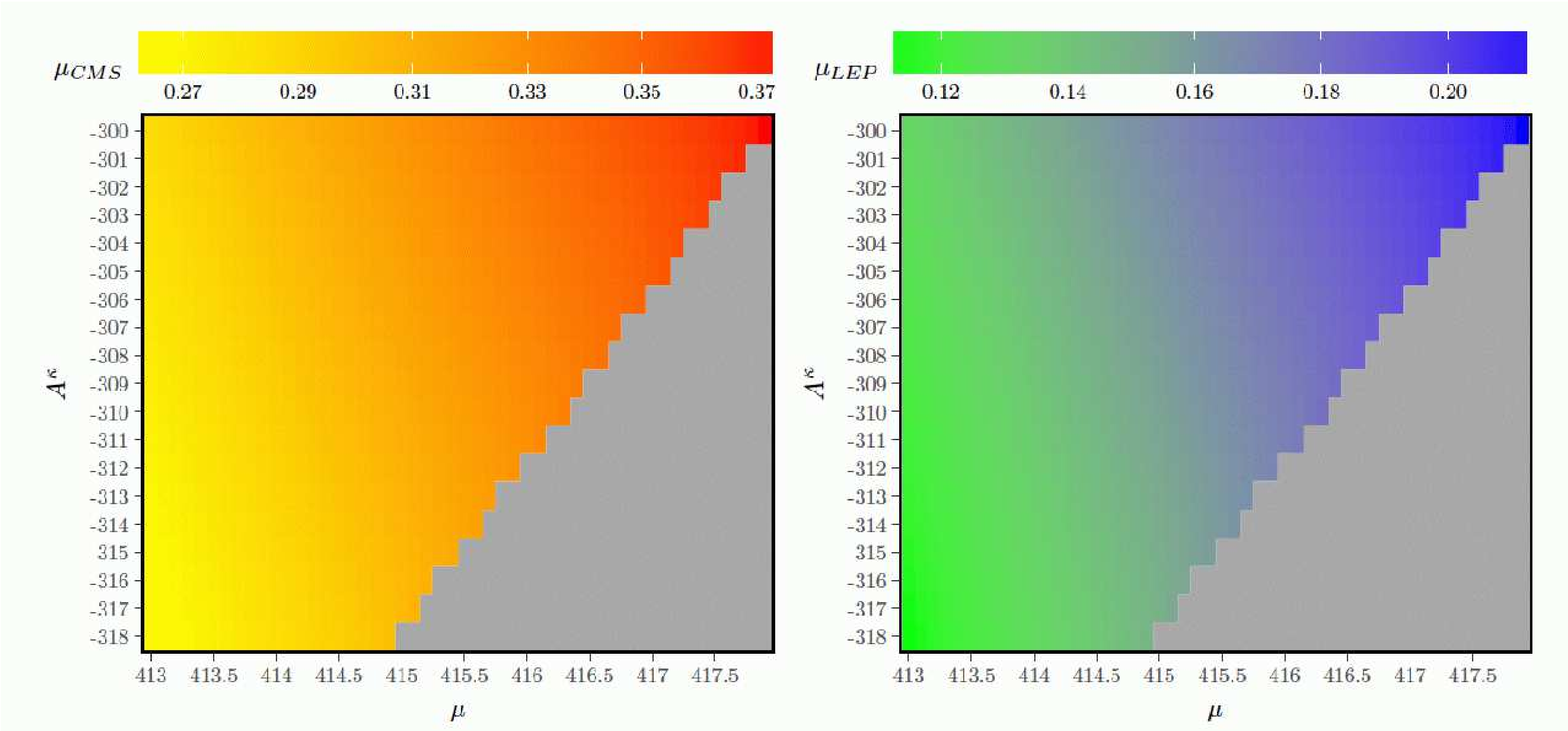
Can the $\mu\nu$SSM explain the two excesses?

[*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	$m^2_{\widetilde{Q}_{iL}}$	$m^2_{\widetilde{u}_{iR}}$	$m^2_{\widetilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\widetilde{e}})_{ii}$	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*]

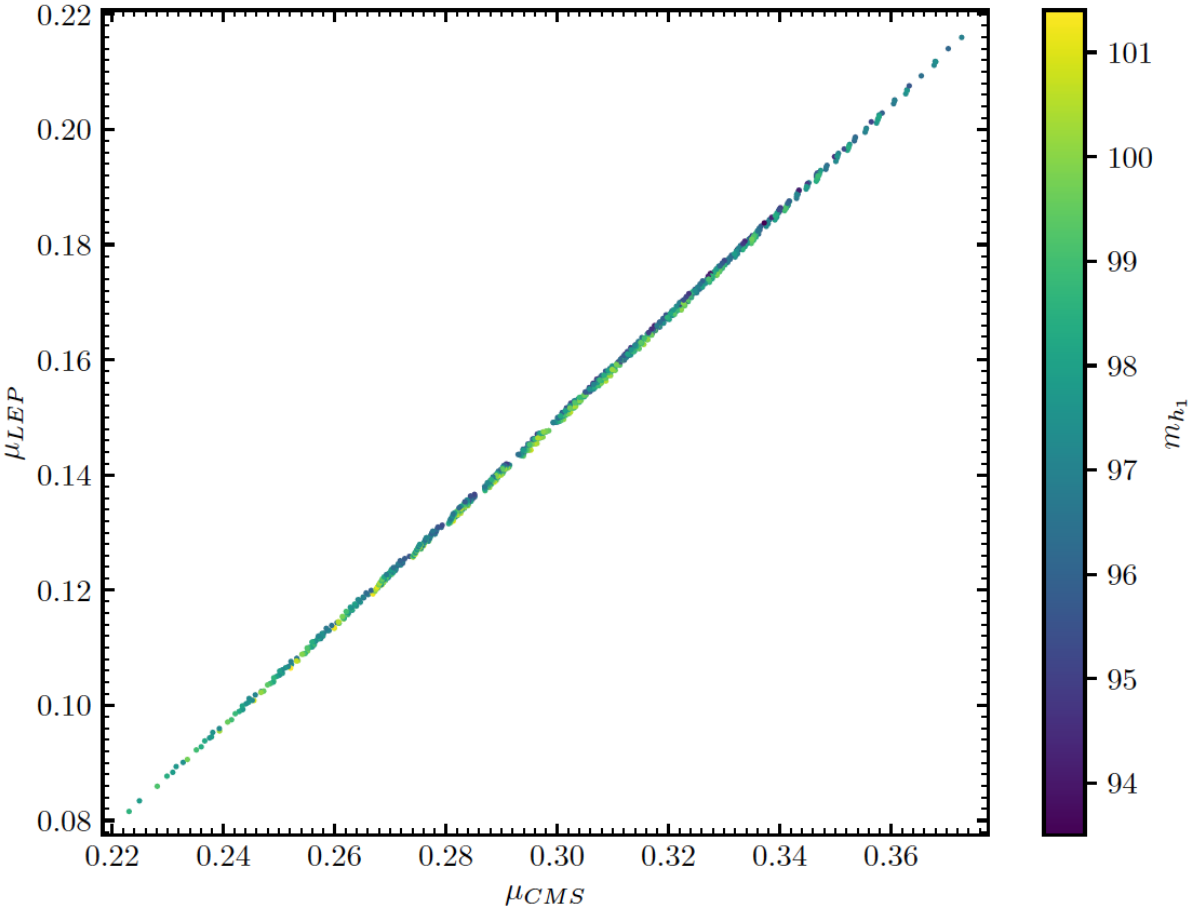


$\Rightarrow$ YES, WE CAN! :-)

at the $1 - 1.5\,\sigma$ level

Why can SUSY explain the excesses only at $1 - 1.5\,\sigma$?

[*T. Biekötter, S.H., C. Muñoz '19*]



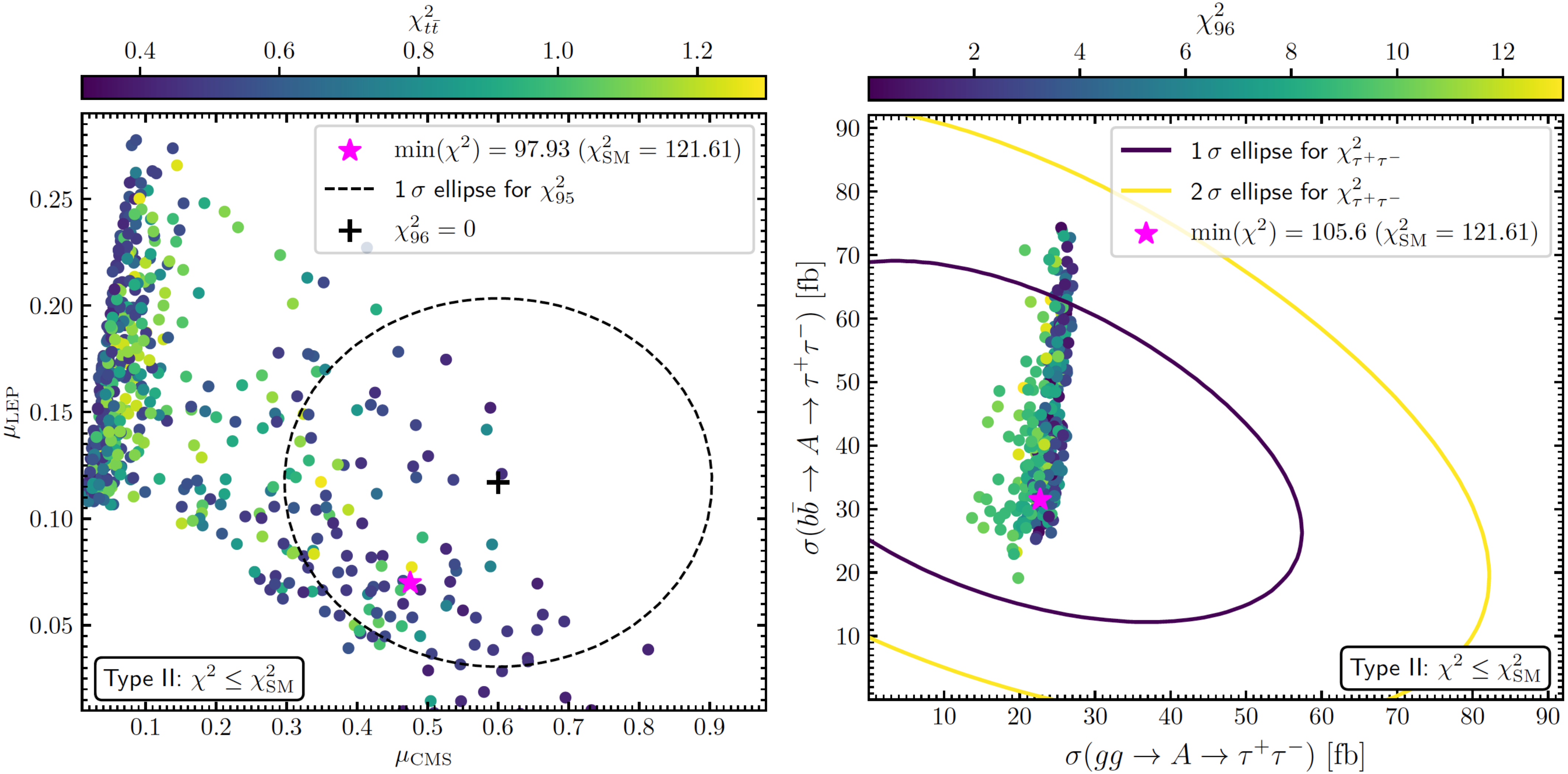
⇒ SUSY enforces strong correlation!

⇒ note: ATLAS limits and CMS "observation"
will likely result in a lower $\mu_{\rm LHC}$!

The final challenge:
can the excesses at $400\ \mathrm{GeV}$ and $96\ \mathrm{GeV}$ be explained simultaneously?

The final challenge:
can the excesses at 400 GeV and 96 GeV be explained simultaneously?

⇒ Yes, in the N2HDM



[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]