
I FOUND THE HUGS BISON.
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BSM Higgs Bosons at the ILC
in the Light of HL-LHC Results

Sven Heinemeyer, IFT (CSIC, Madrid)

Matsue, 05/2022

1. Introduction
2. Direct detection of “heavy” BSM Higgs bosons
3. Inirect detection of “heavy” BSM Higgs bosons
4. Direct detection of “light” BSM Higgs bosons
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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Q': Which model?

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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

Extended Higgs sectors

Compatibility with the experimental results requires:

- A SM-like Higgs at ~ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,...) have to be such that they are in agreement with the present bounds

The "sum rule": $\sum_i g^2_{h_i VV} = g^2_{H_{\rm SM} VV}$ – and we know $g^2_{h_{125} VV} \sim g^2_{H_{\rm SM} VV}$

$\Rightarrow$ not much room left for BSM Higgs couplings to gauge bosons

Sum rule "violated" only by triplets or higher representations . . .

Toy example:

Two Higgs Doublet Model (2HDM):

Fields:

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

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): $\rightarrow$ (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:

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

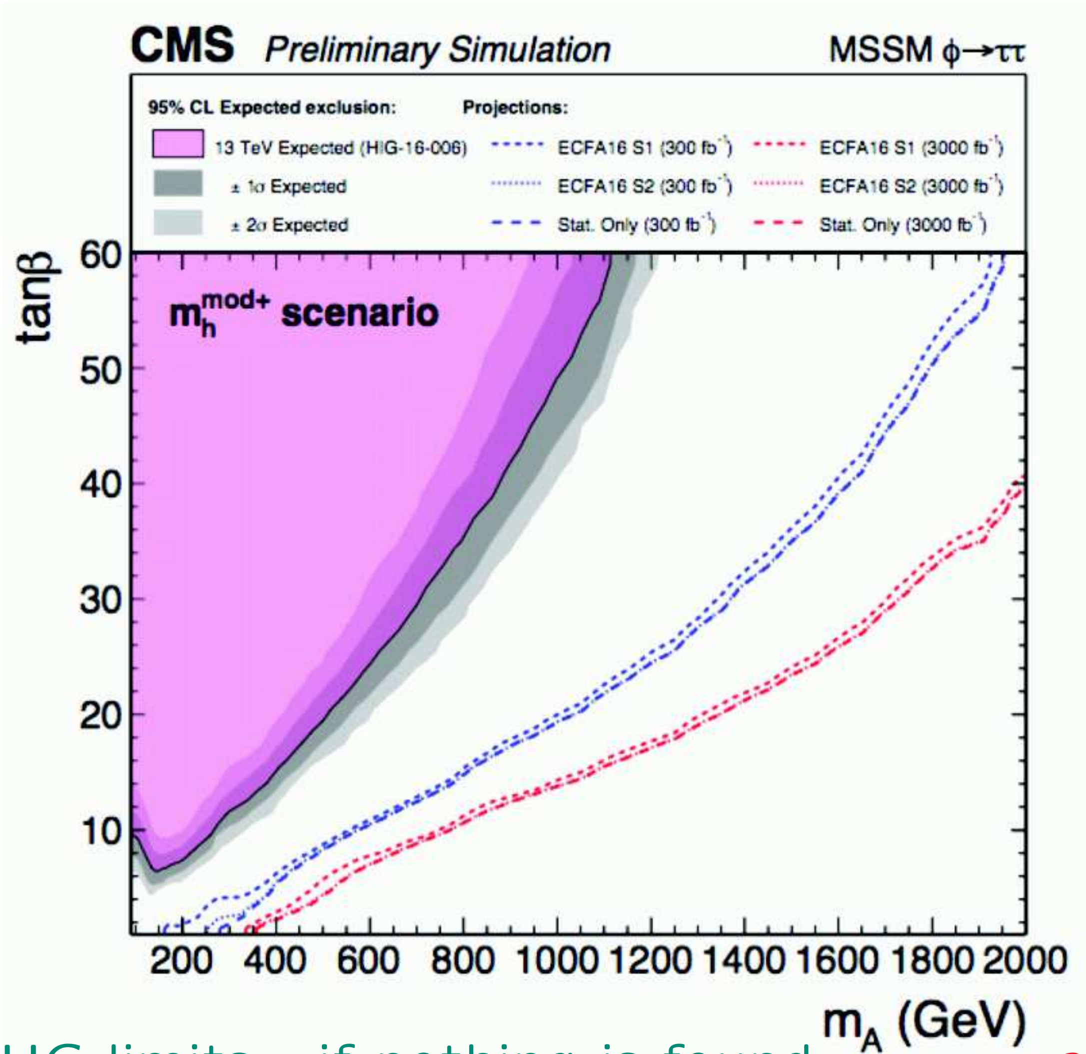
Z_2 symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_S \to \Phi_S$

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. Direct Detection of “heavy” BSM Higgs bosons

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

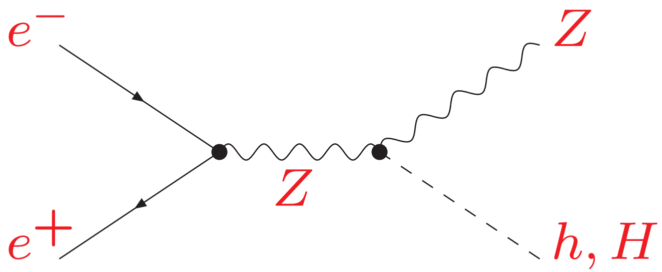


⇒ strong (HL-)LHC limits - if nothing is found

⇒ but if there is something in the kinematical e^+e^- reach, it can be analyzed in detail

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

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



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

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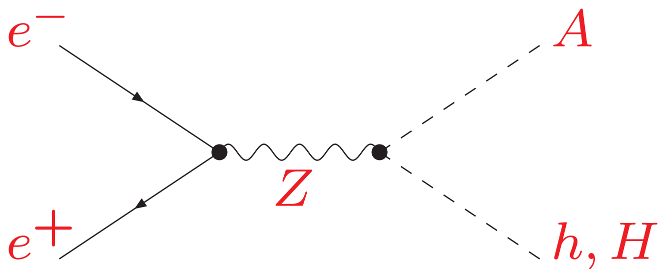
$e^+e^- \to Ah, AH$



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

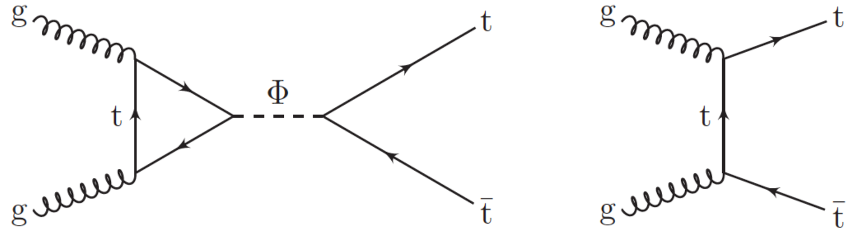
$\sigma_{HA} \propto \sin^2(\beta - \alpha)\sigma_{hZ}^{\rm SM}$

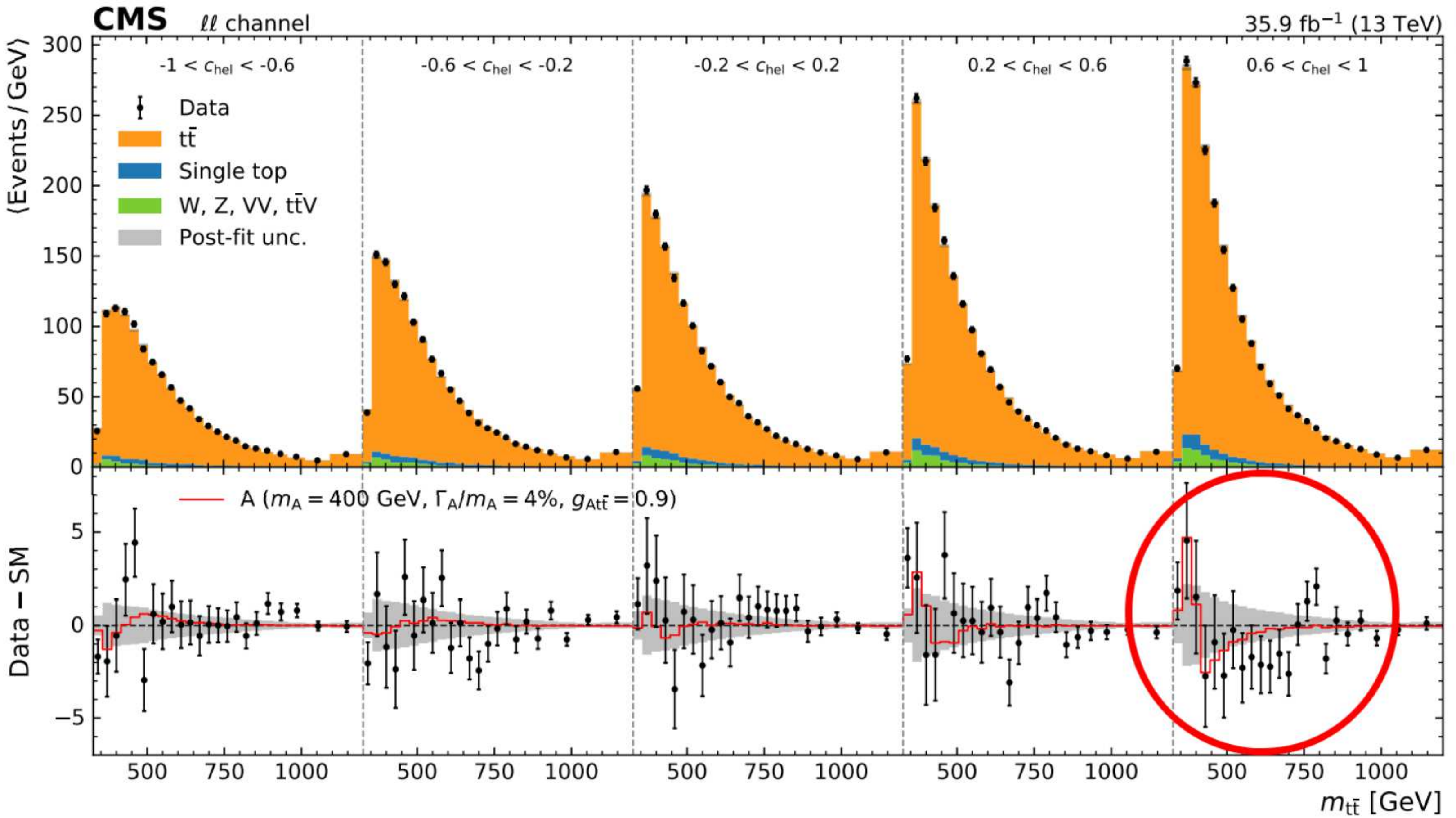
$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

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

Possible hint for heavy Higgses at the LHC:

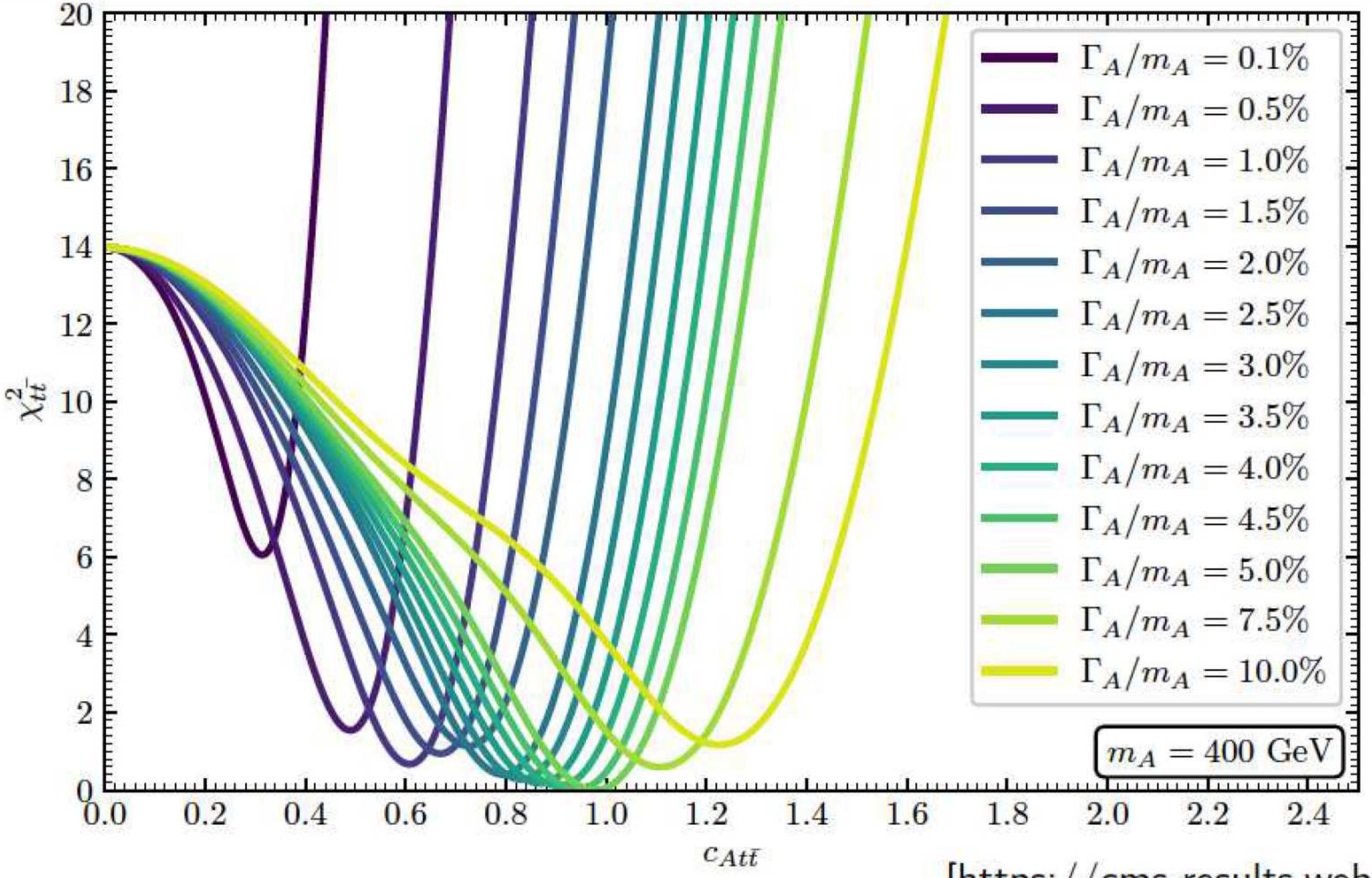
CMS Higgs-boson search in $pp \to \phi \to t\bar{t}$ at $m_\phi \sim 400$ GeV





[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*]

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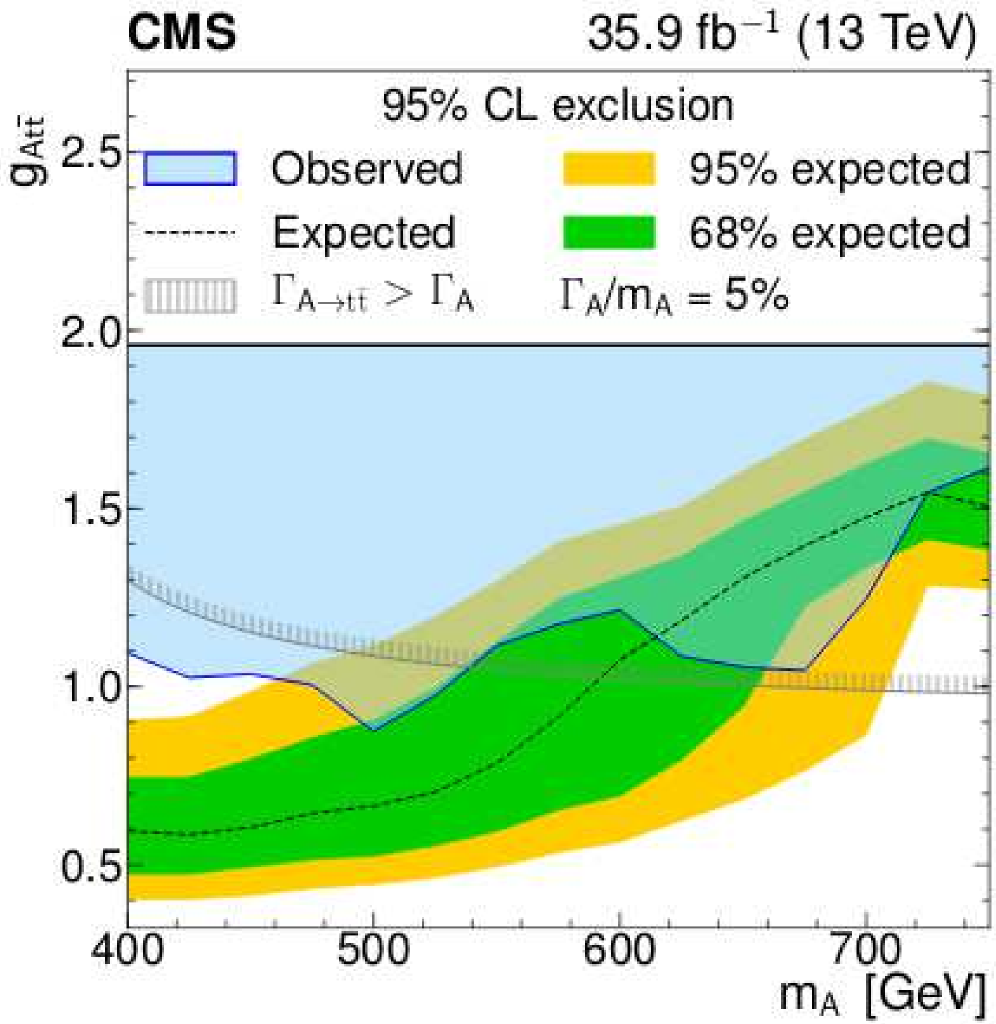

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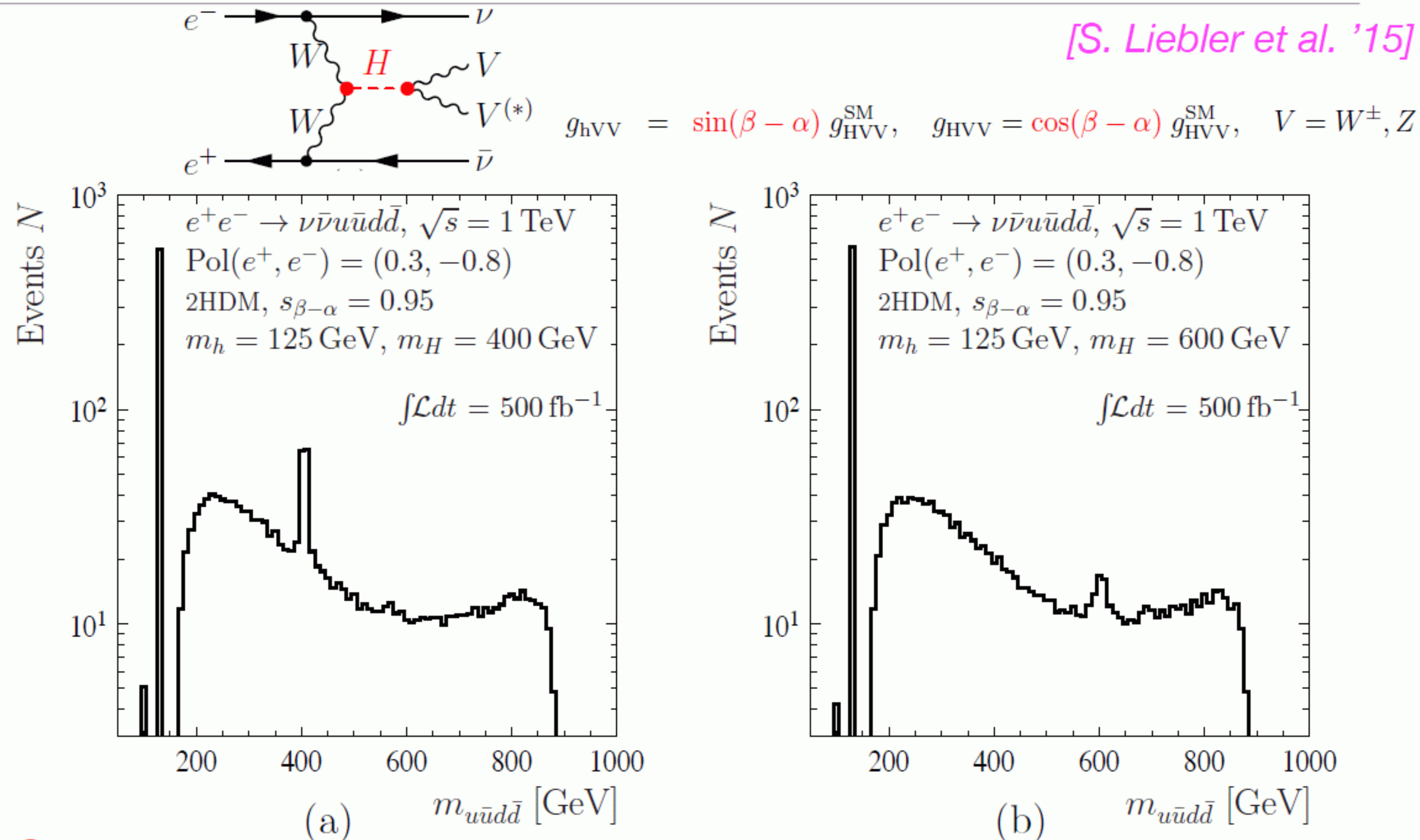
[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]

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]

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

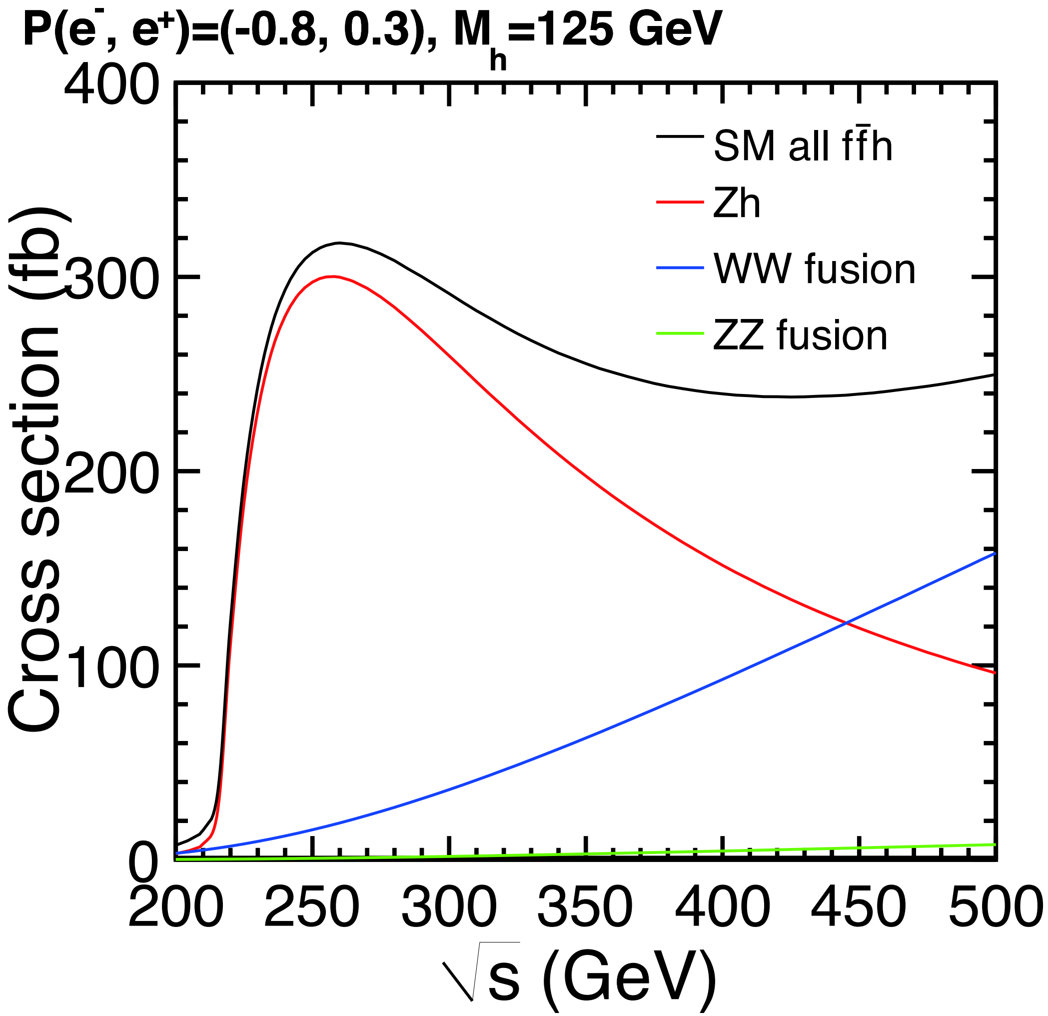


$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[*Taken from G. Weiglein '18*]

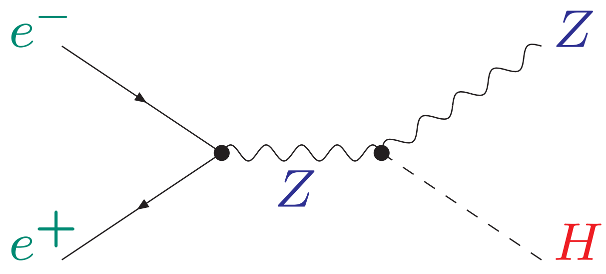
3. Indirect Detection of “heavy” BSM Higgs bosons

⇒ via h_{125} coupling measurements



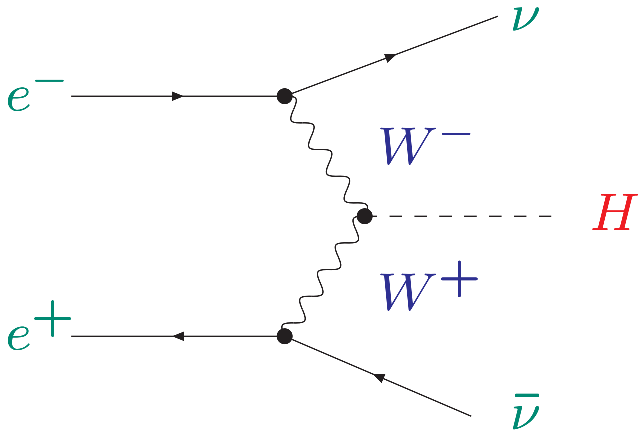
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



$\sqrt{s} \sim 250$ GeV, Higgs-strahlung dominated

Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}\,(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}\,(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$$

Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

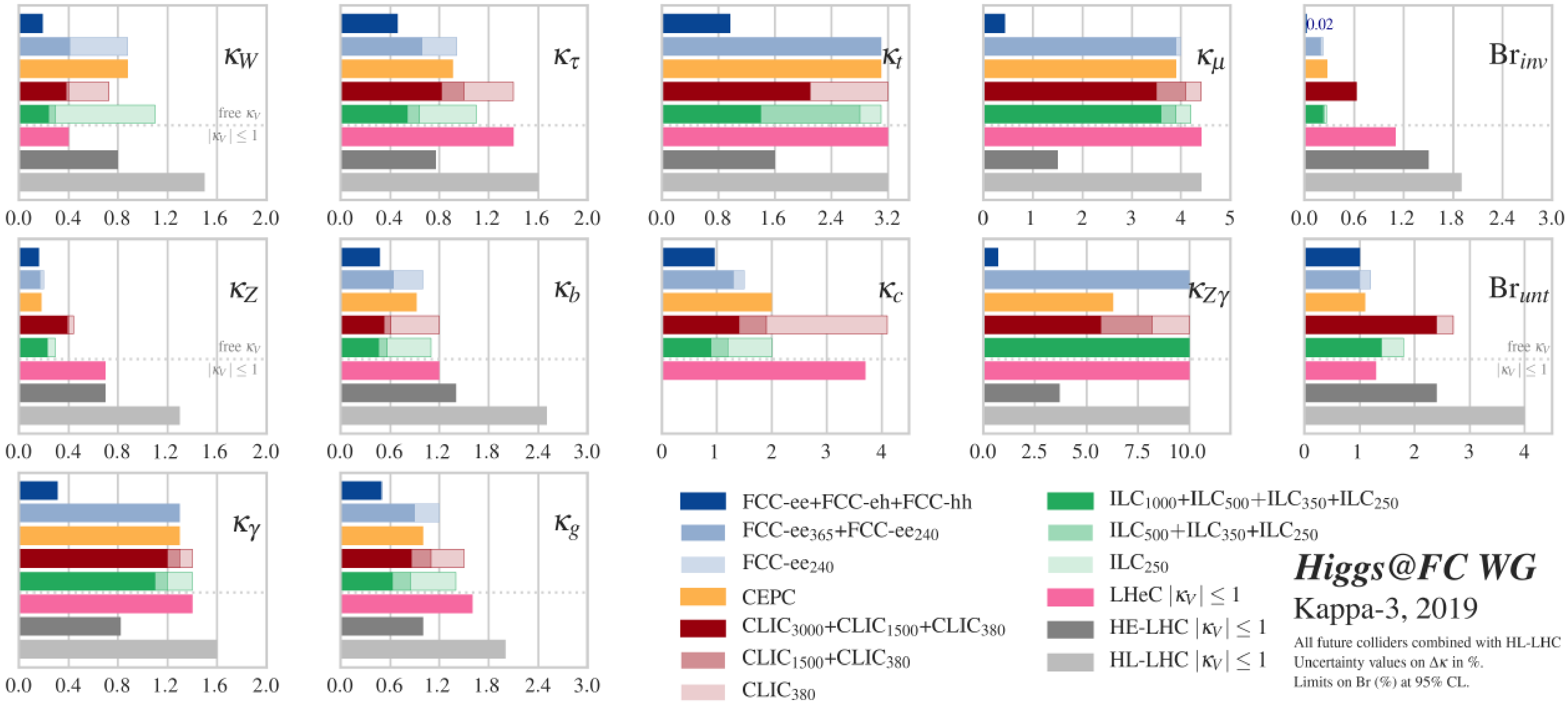
$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

⇒ couplings to bosons in the per mille range

⇒ couplings to fermions in the per cent range

⇒ at which collider can this be reached?

Future expectations for κ (kappa-3 framework)



$\Rightarrow$ ILC shows strong improvement over HL-LHC in many cases

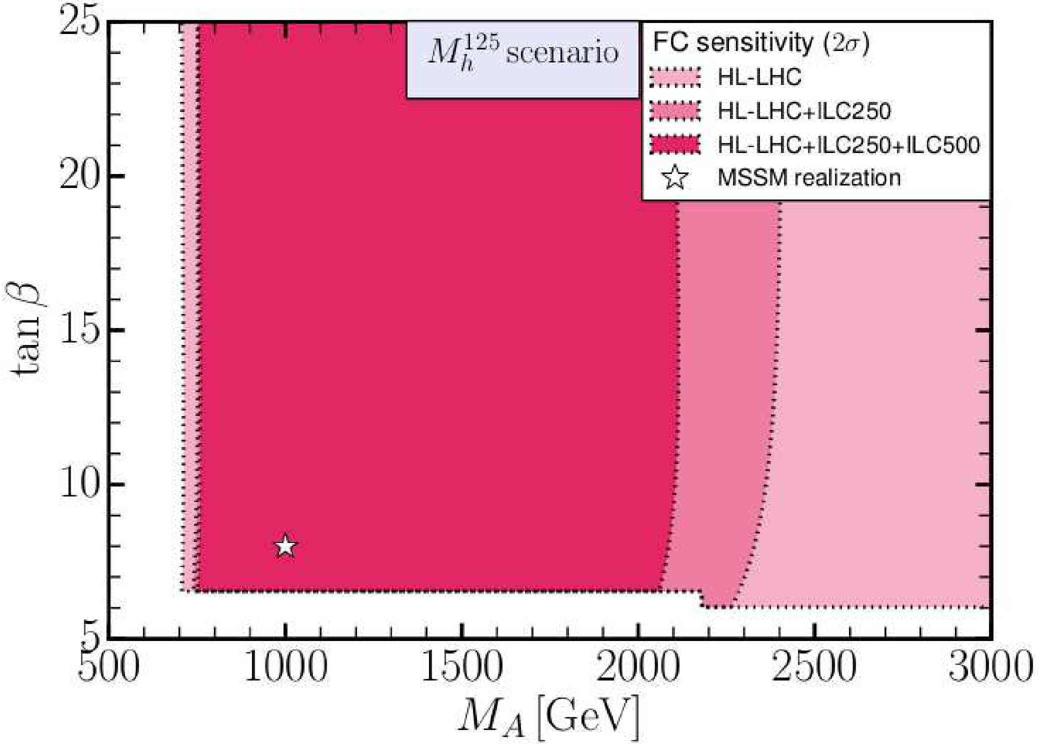
$\Rightarrow$ . . . and without theory assumptions

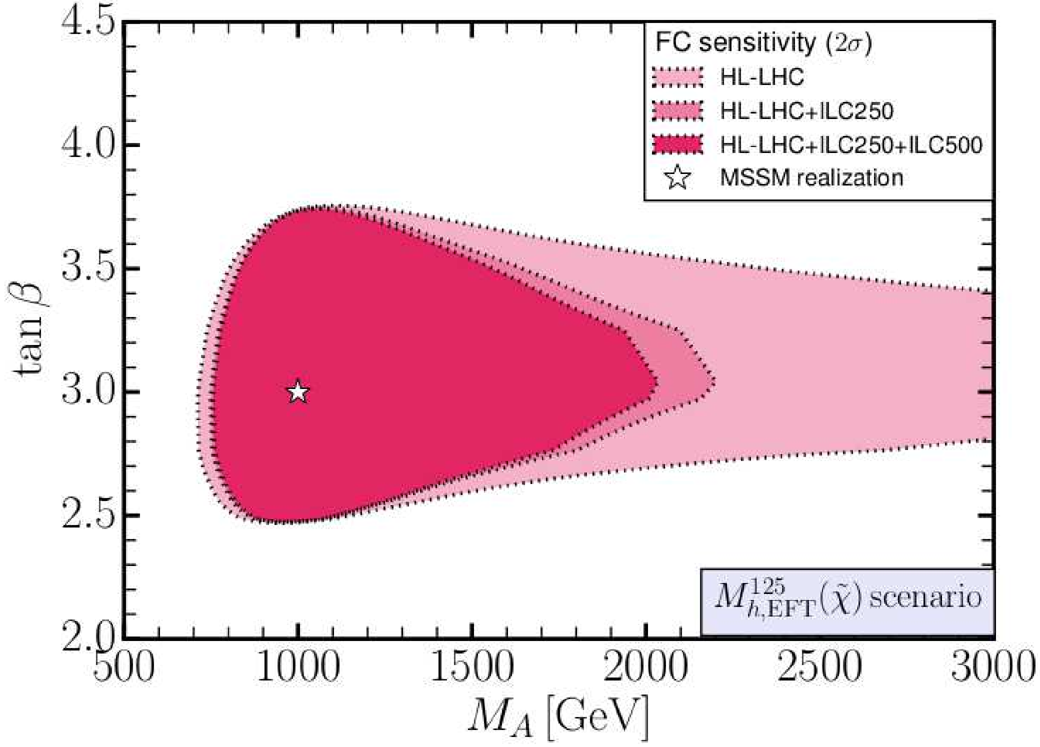
$\Rightarrow$ and this improvement could be decisive!

Relevance of ILC measurements:

[H. Bahl et al., '20]

- Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7/3$
- What limits can be set from rate/coupling measurements?



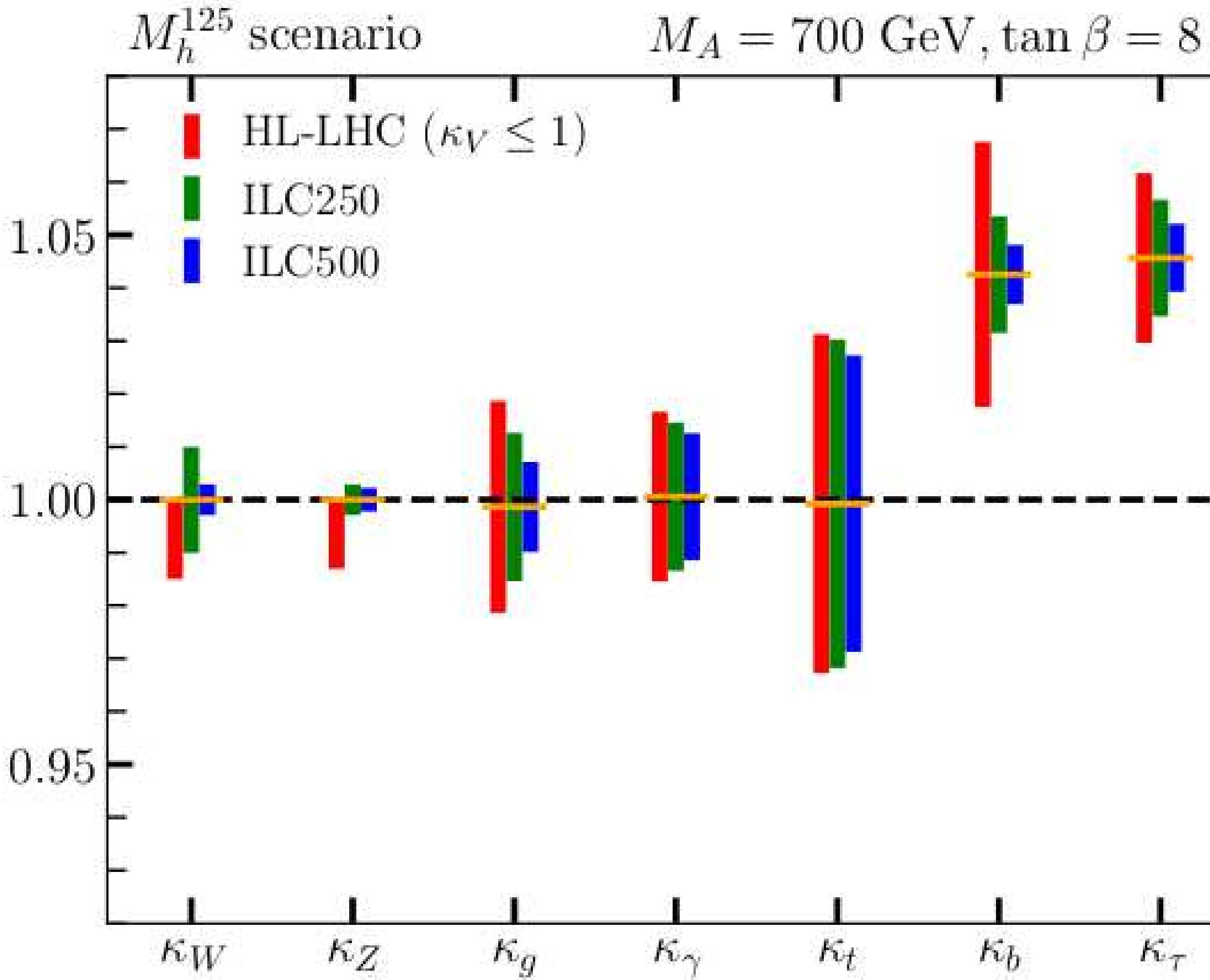


⇒ only ILC measurements give upper limit on M_A

⇒ limits on $\tan\beta$ only for small(er) $\tan\beta$

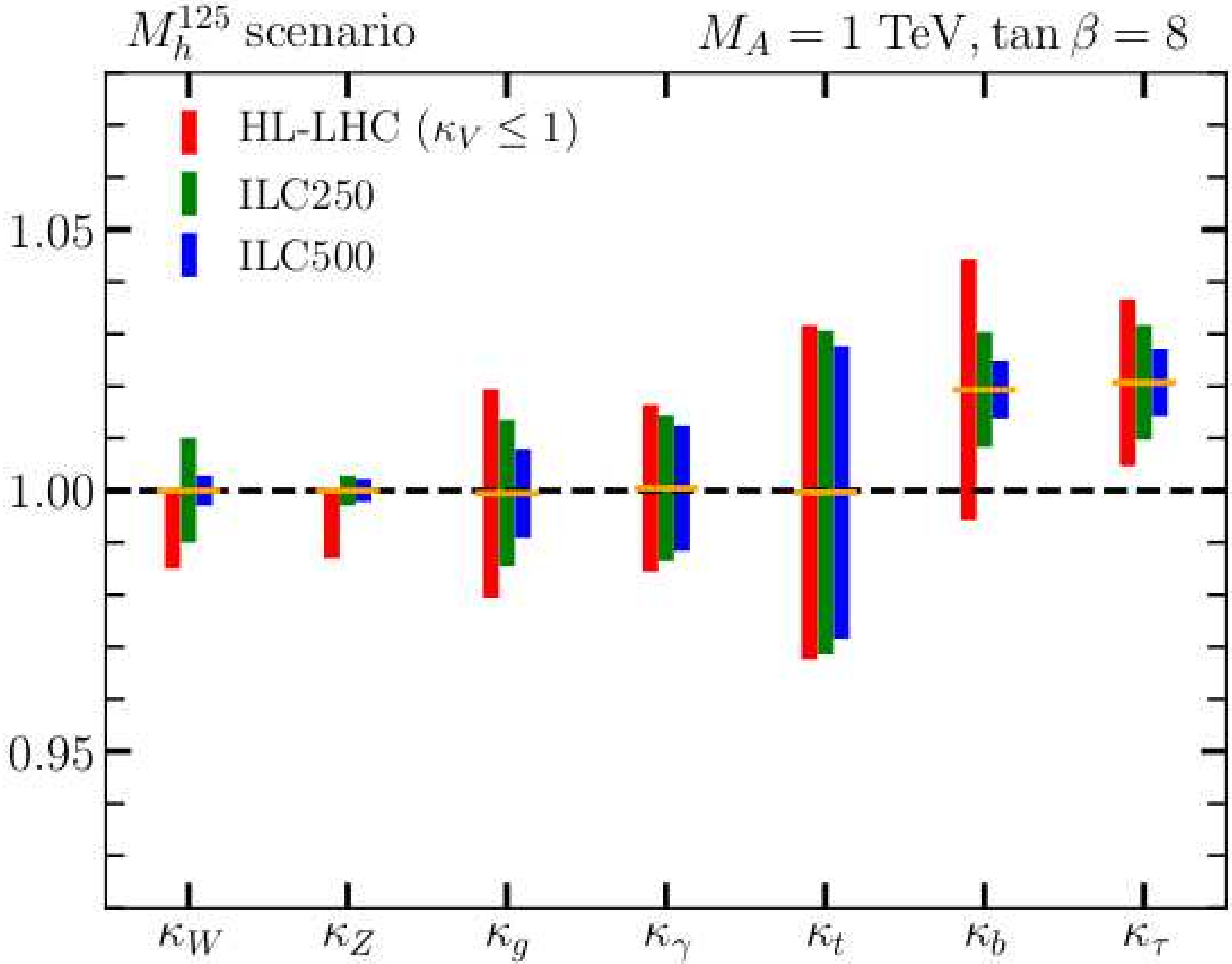
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

[*H. Bahl et al. '20*]



MSSM Wäscheleine II: e^+e^- precision vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

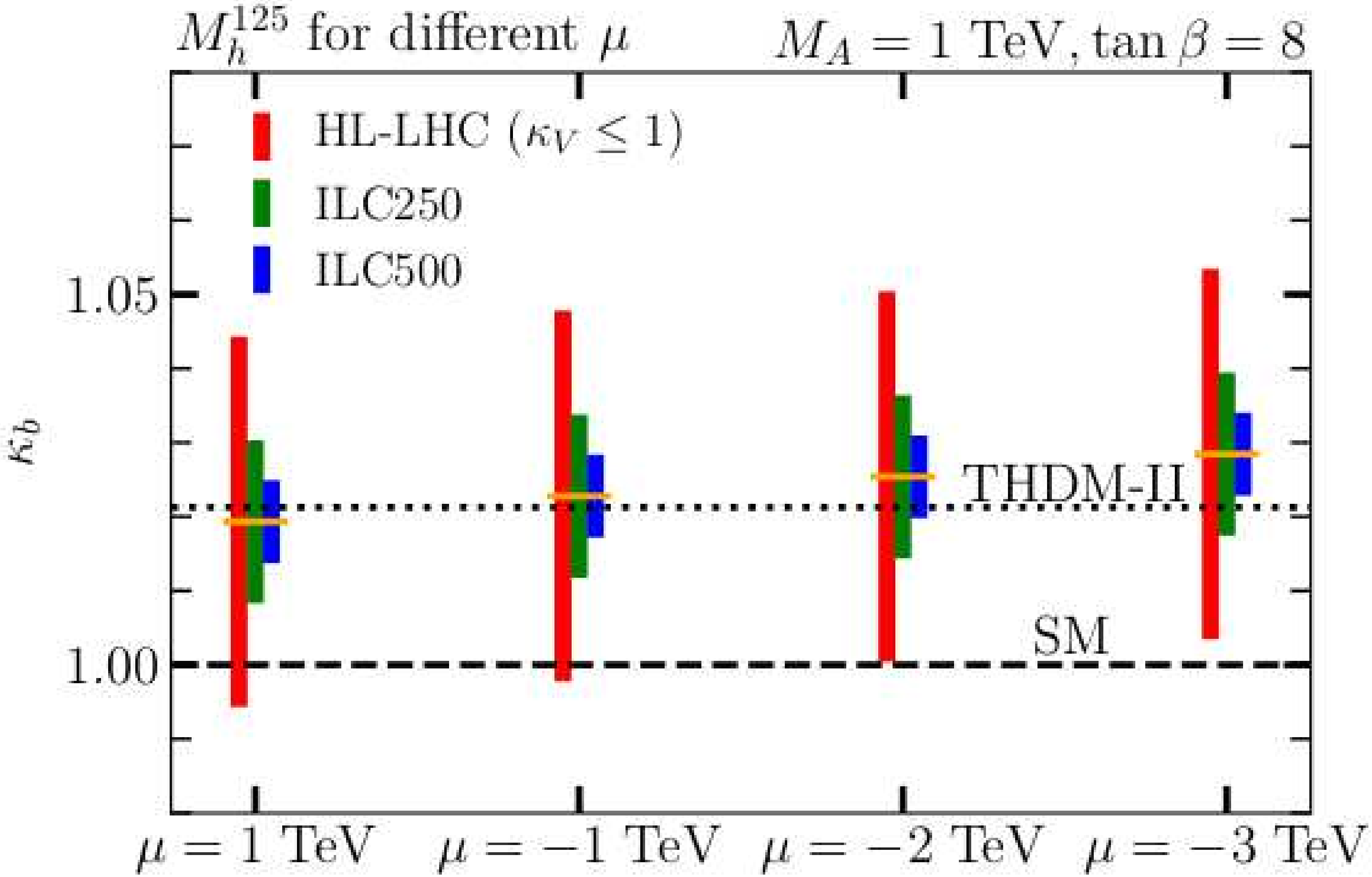
[*H. Bahl et al. '20*]



$\Rightarrow$ only e^+e^- measurements allows to set upper limit on M_A

MSSM Wäscheleine V: e^+e^- vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

[*H. Bahl et al. '20*]



⇒ MSSM vs. 2HDM: very challenging!

What about the “real hints” at $\sim$ 400 GeV? $\rightarrow$ N2HDM: (NMSSM similar)

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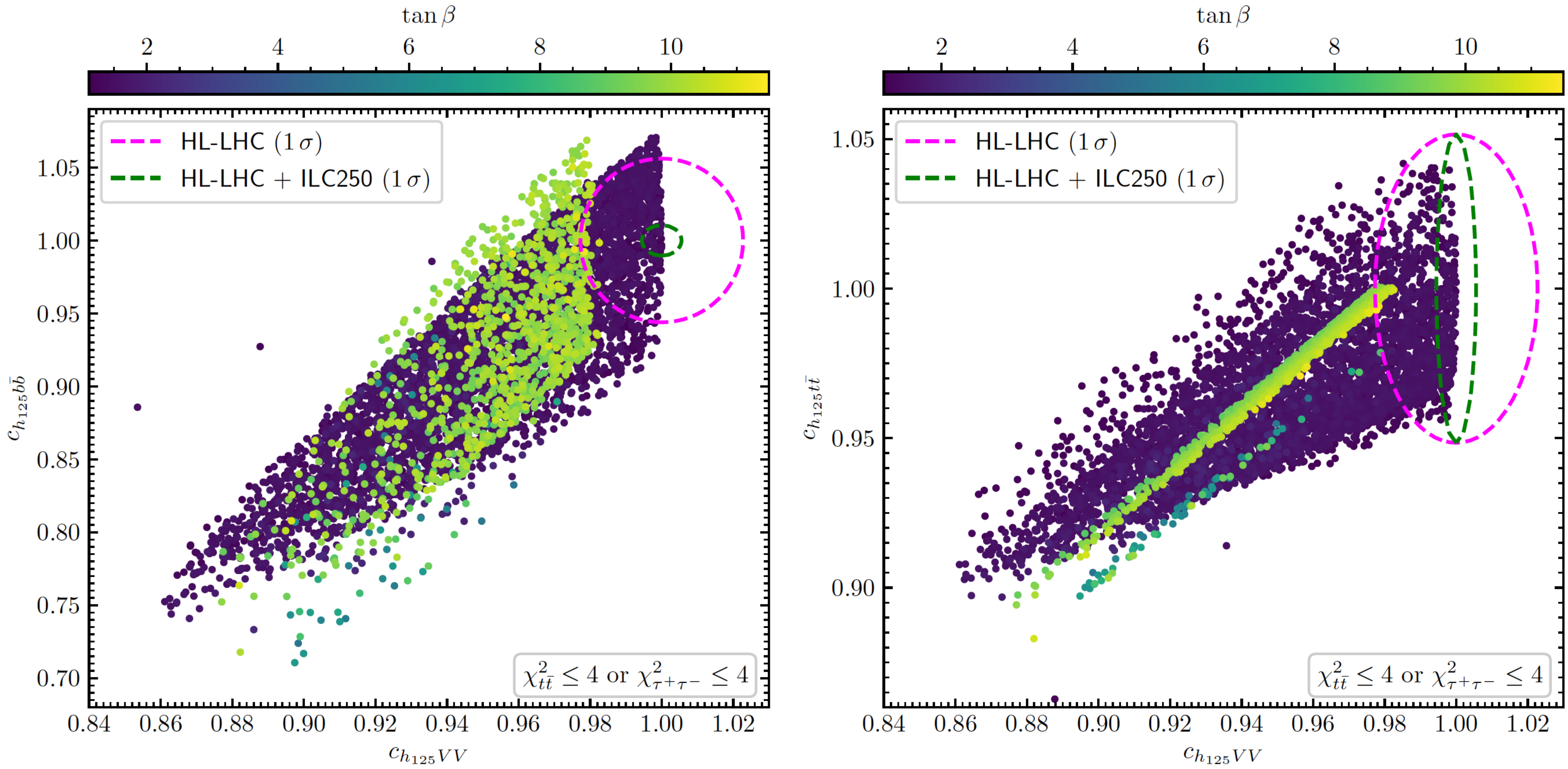
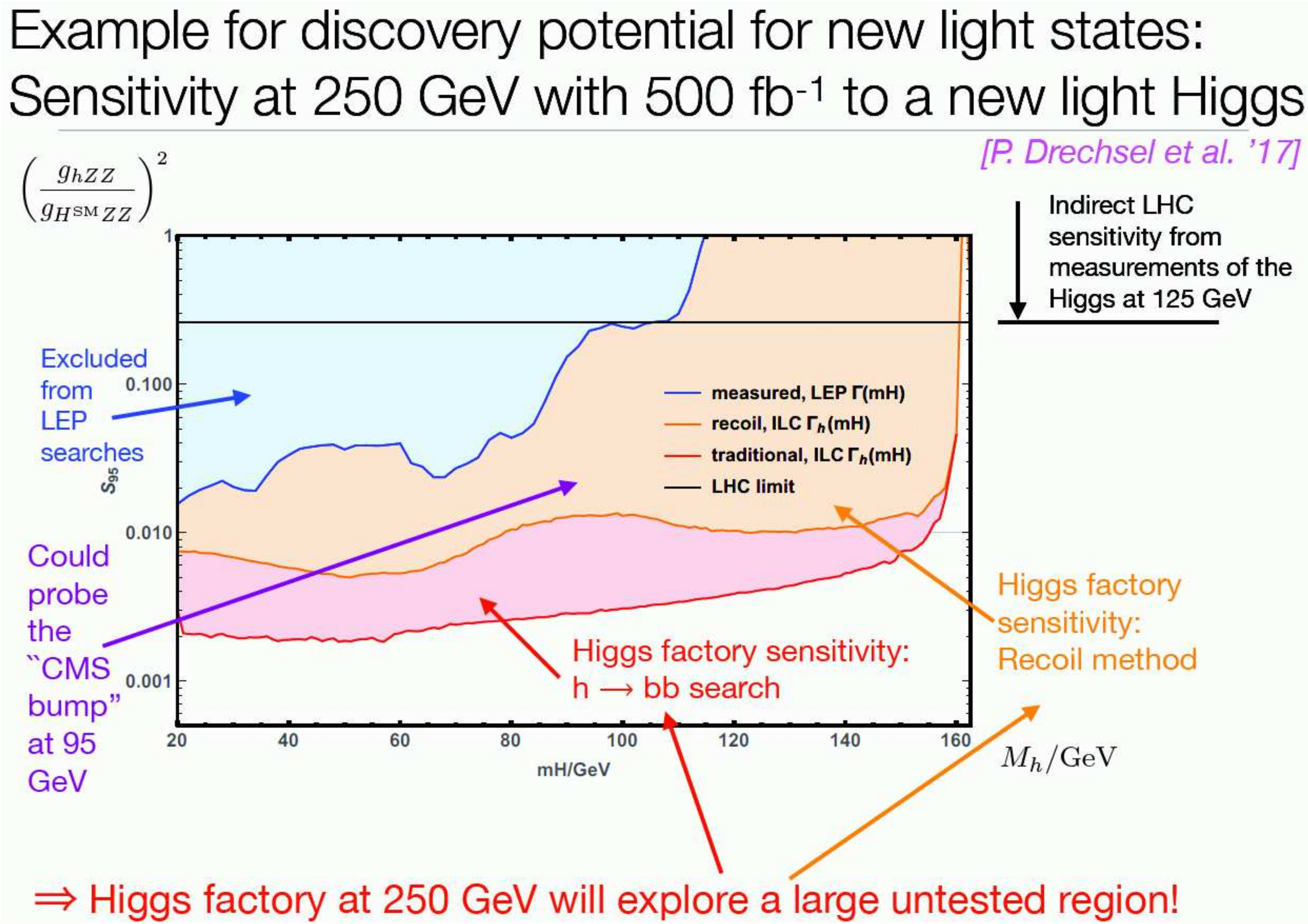
[*T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21*]



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

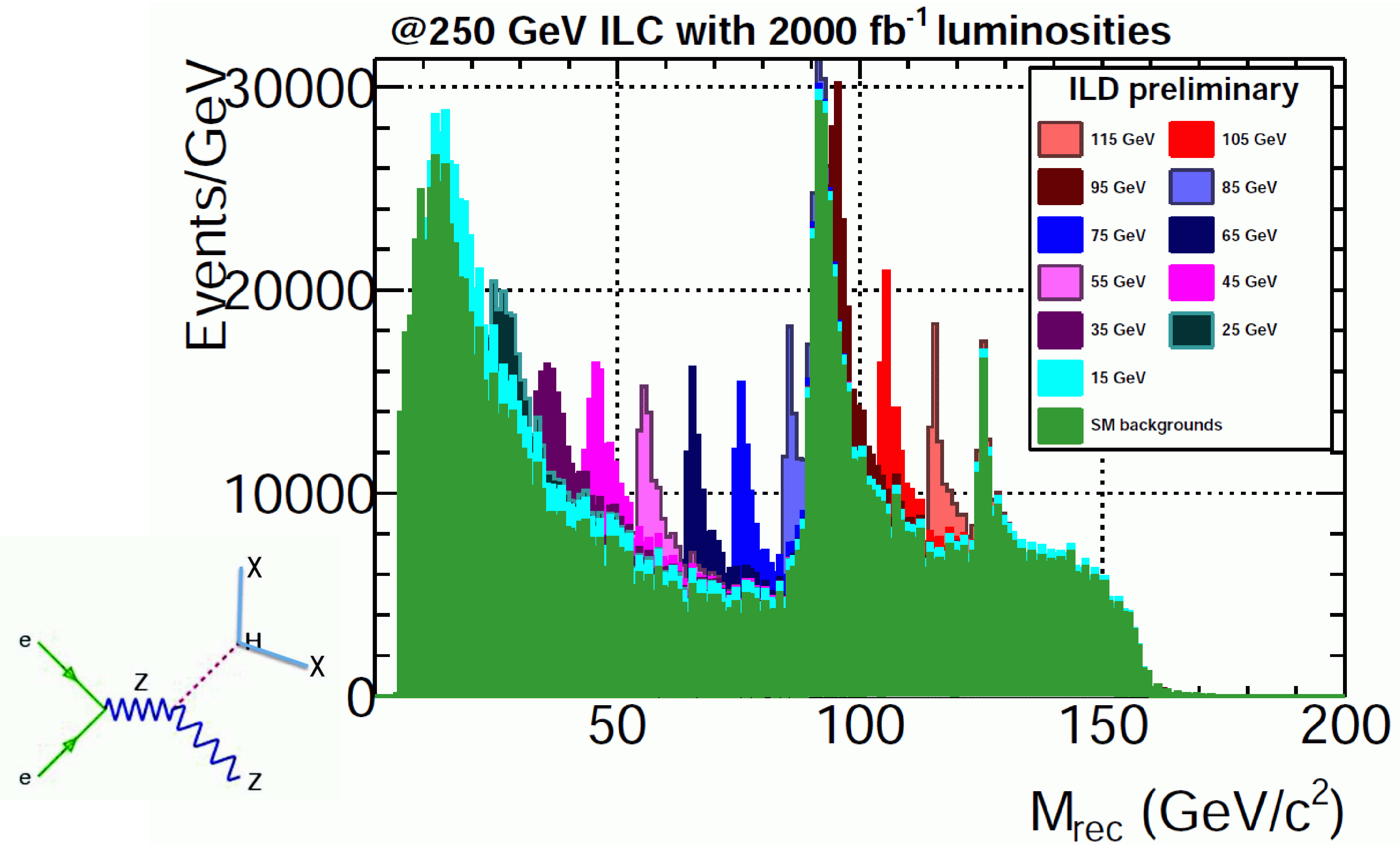
high $\tan\beta$ ($\tau^+\tau^-$): ILC can always distinguish the SM from the N2HDM

4. Direct detection of “light” BSM Higgs bosons



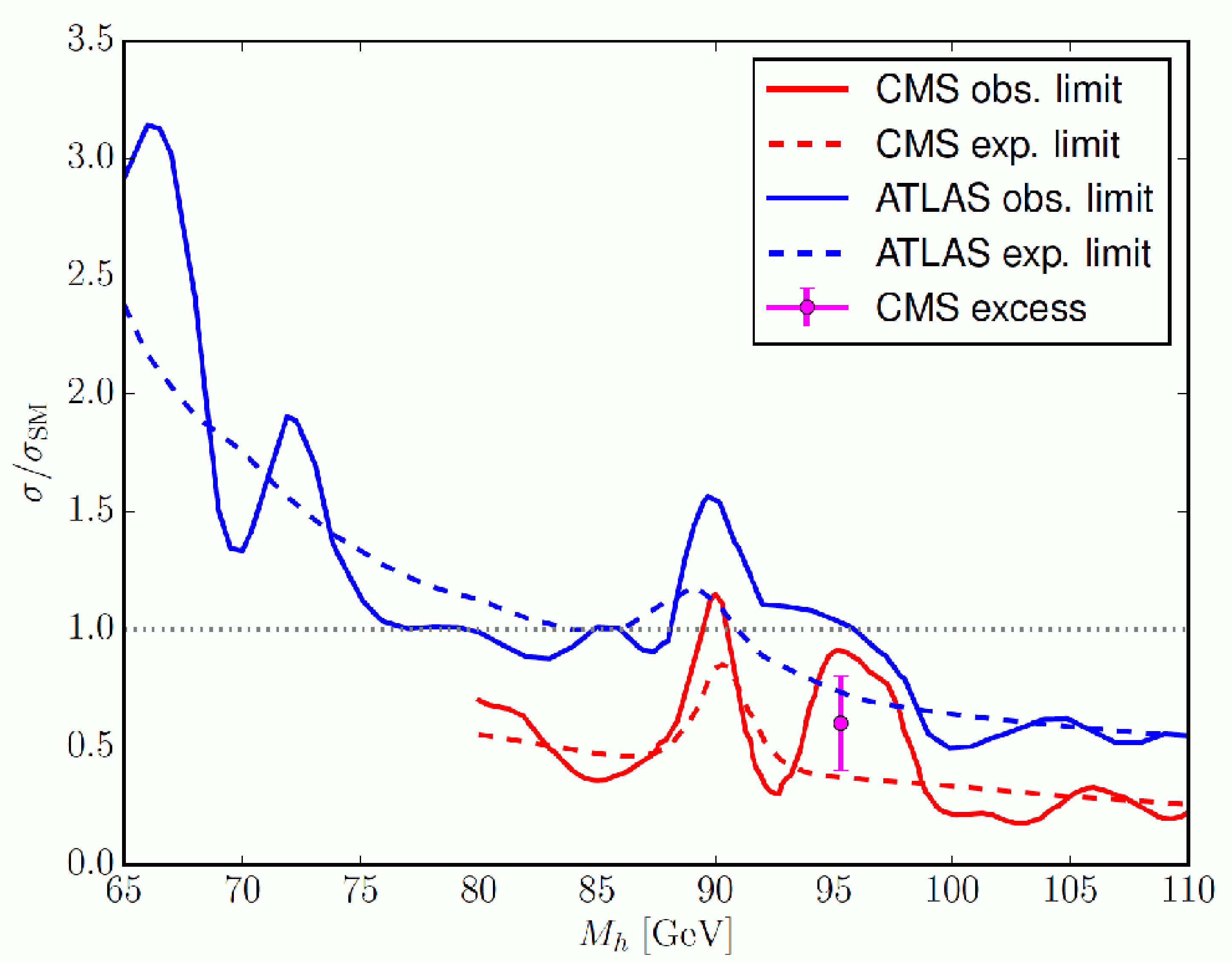
[*Taken from G. Weiglein '18*]

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



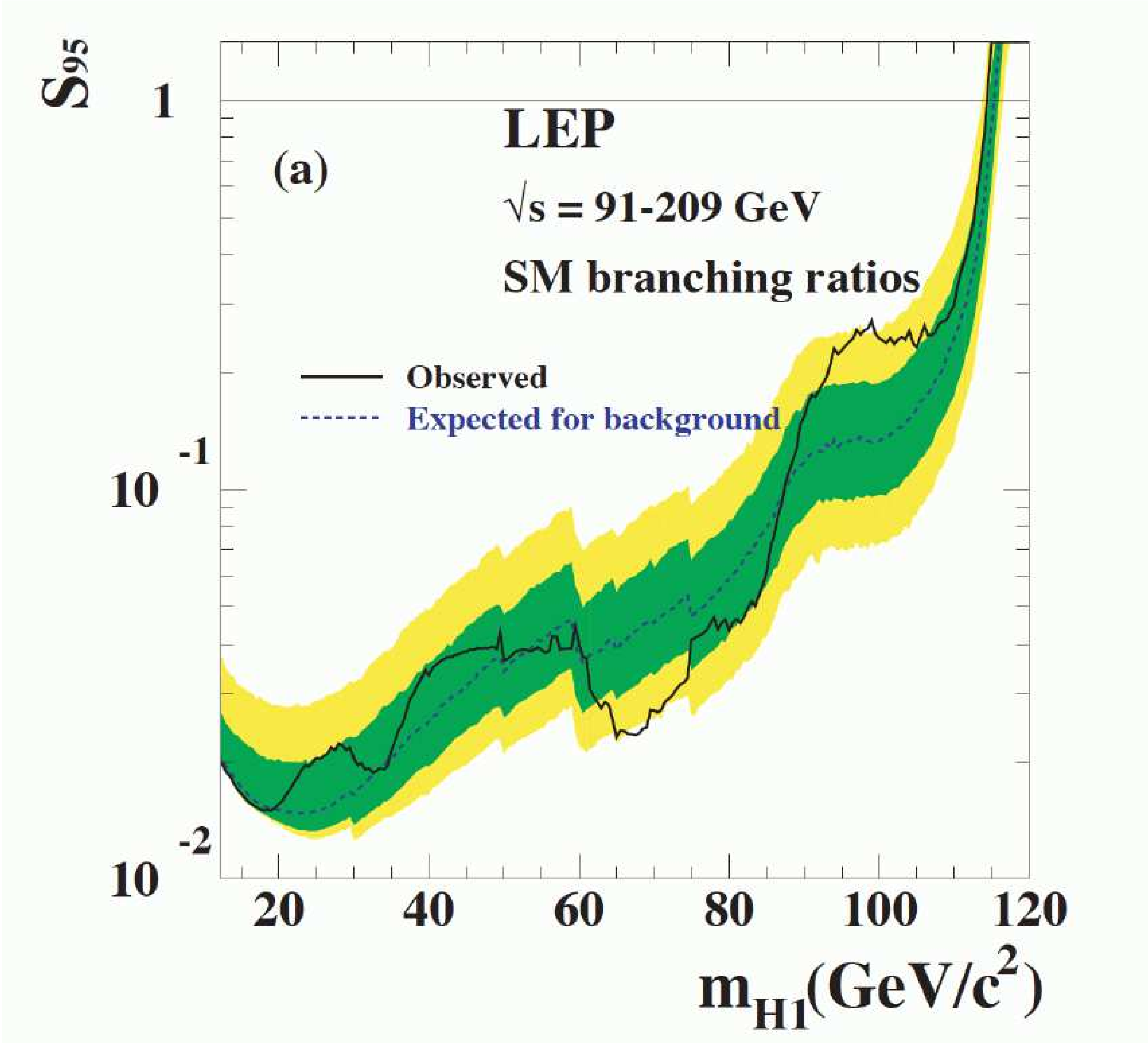
Case study: Search for $pp \to \phi \to \gamma\gamma$: excess at $m_\phi \sim 95$ GeV

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



⇒ if there is something, it would look exactly like this!

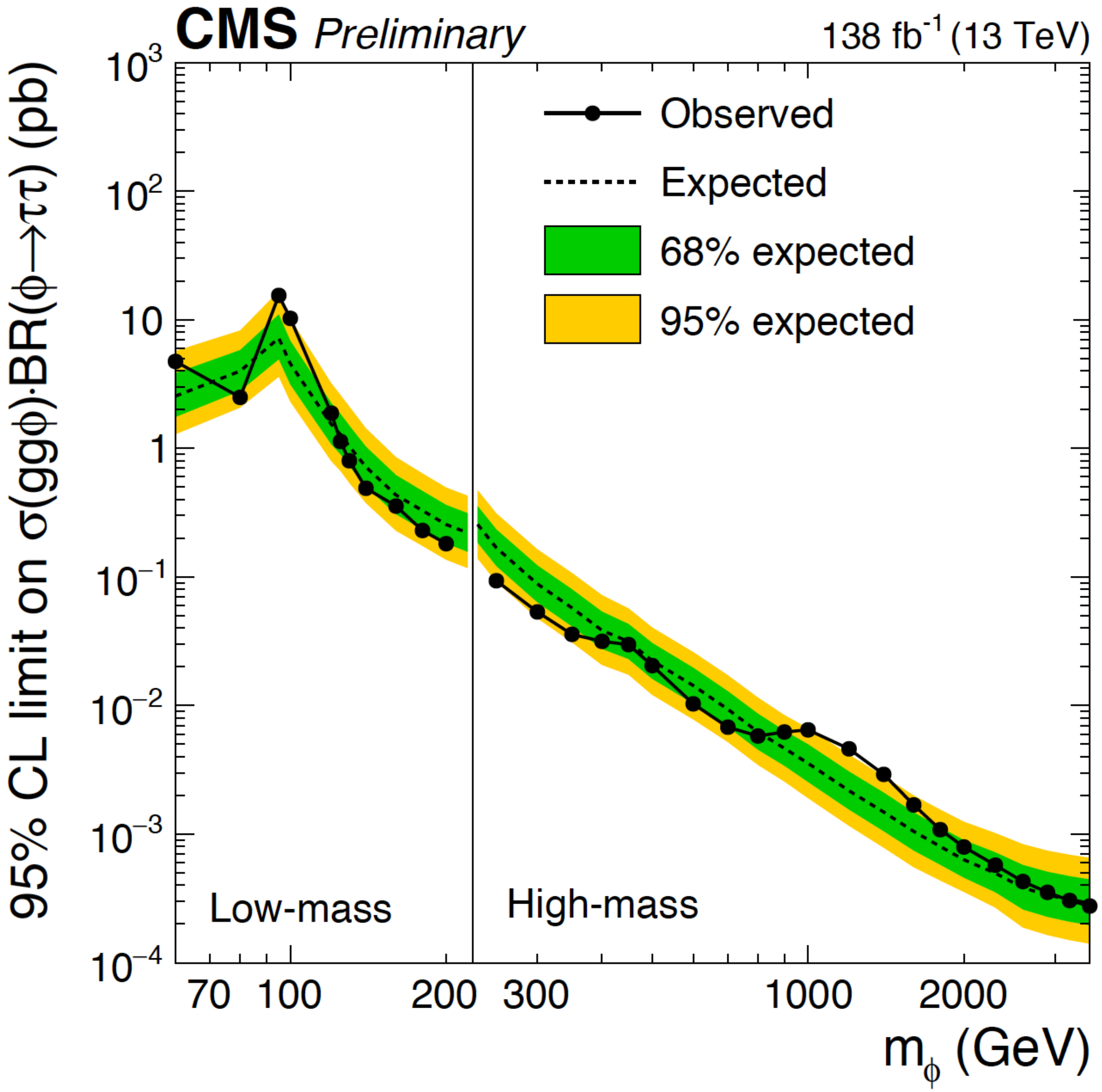
Remember the LEP excess?



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

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

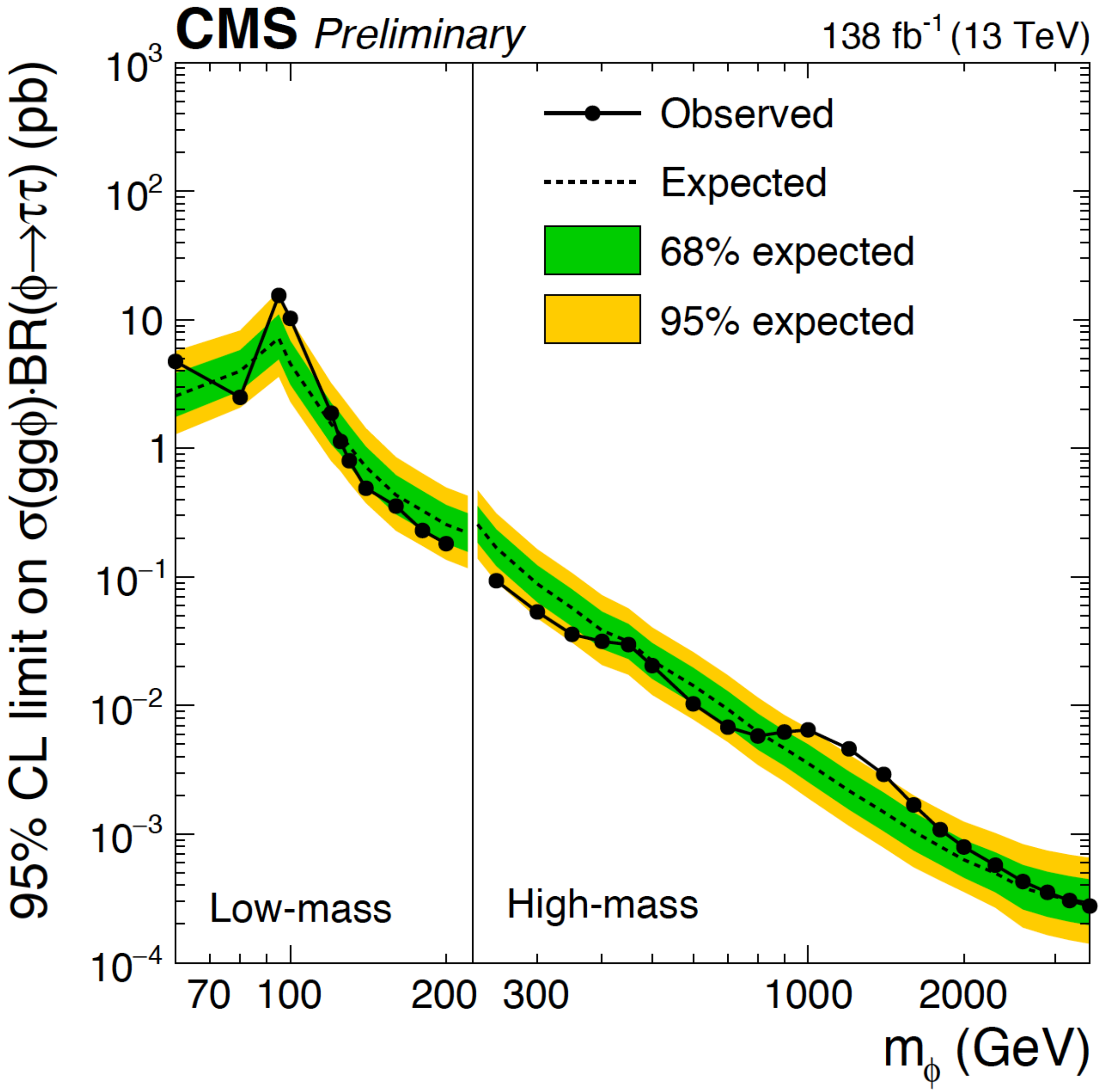
[*CMS '22*]



Can you spot the excess?

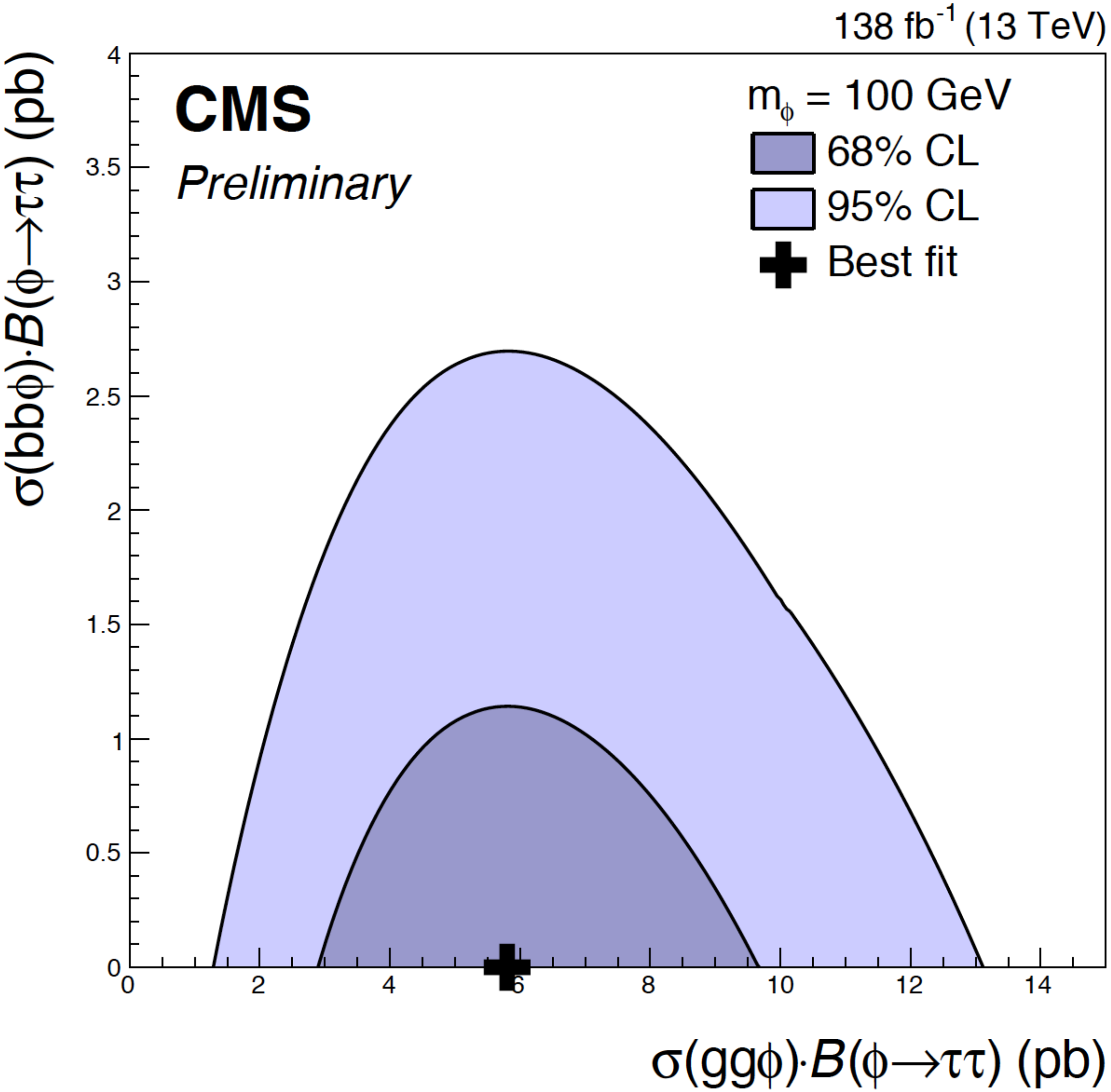
The new $\tau^+\tau^-$ excess

[*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

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

corresponding to

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

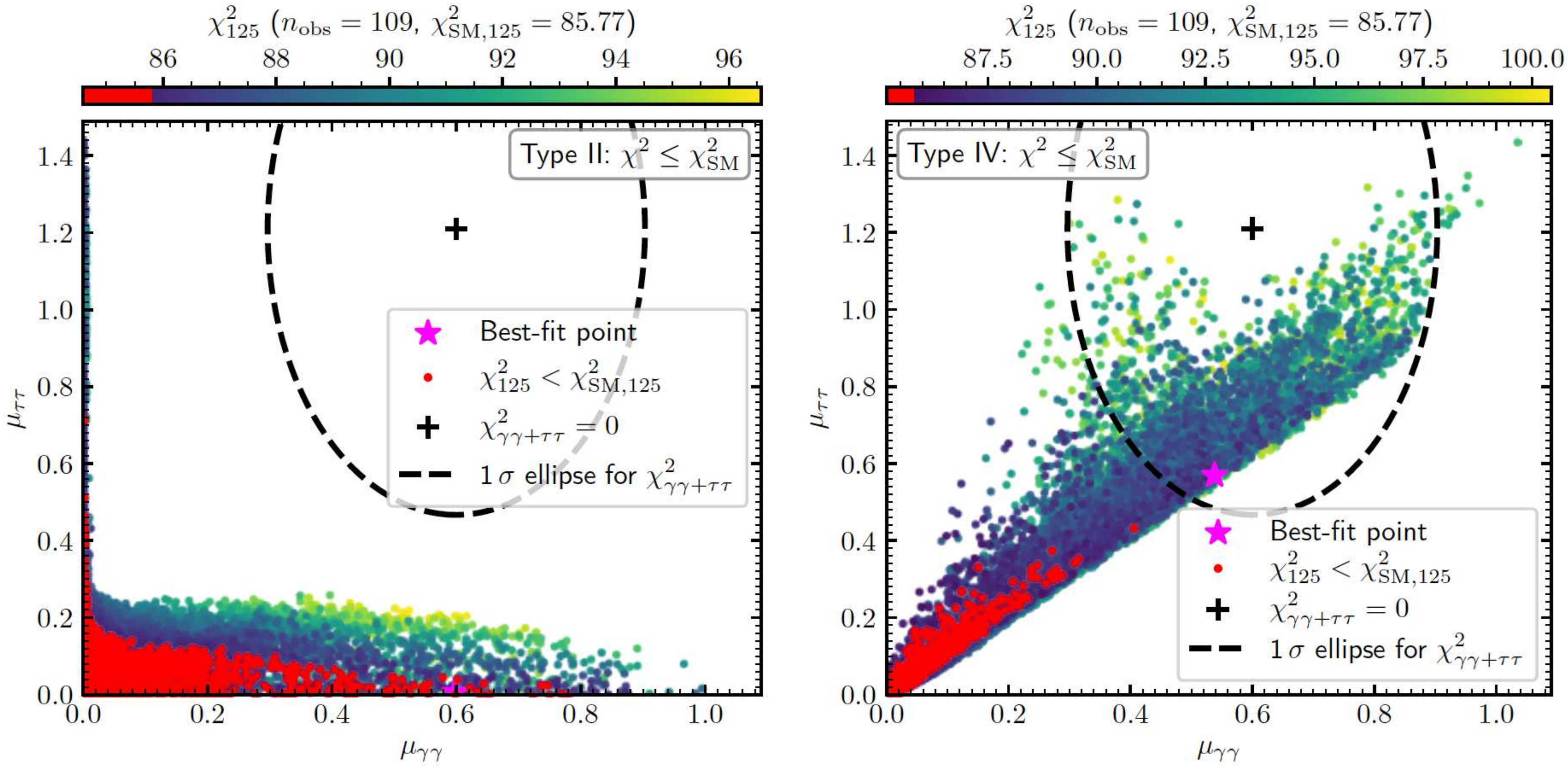
Three (effectively) independent channels
$\Rightarrow$ no LEE (as theorist I am allowed to add naively)

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

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

Can we fit all excesses together?

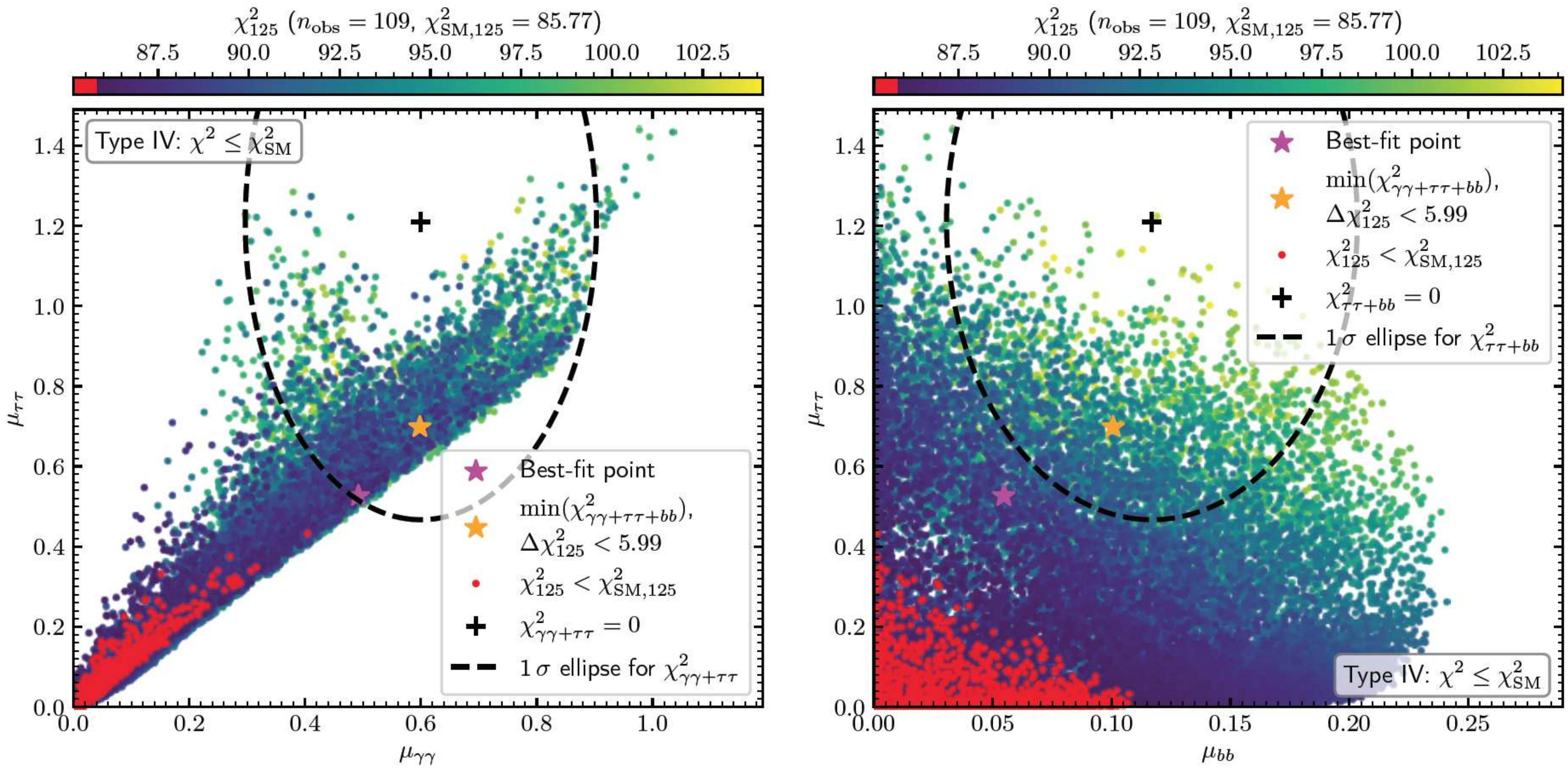
 [*T. Biekötter, S.H., G. Weiglein '22*]



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*]

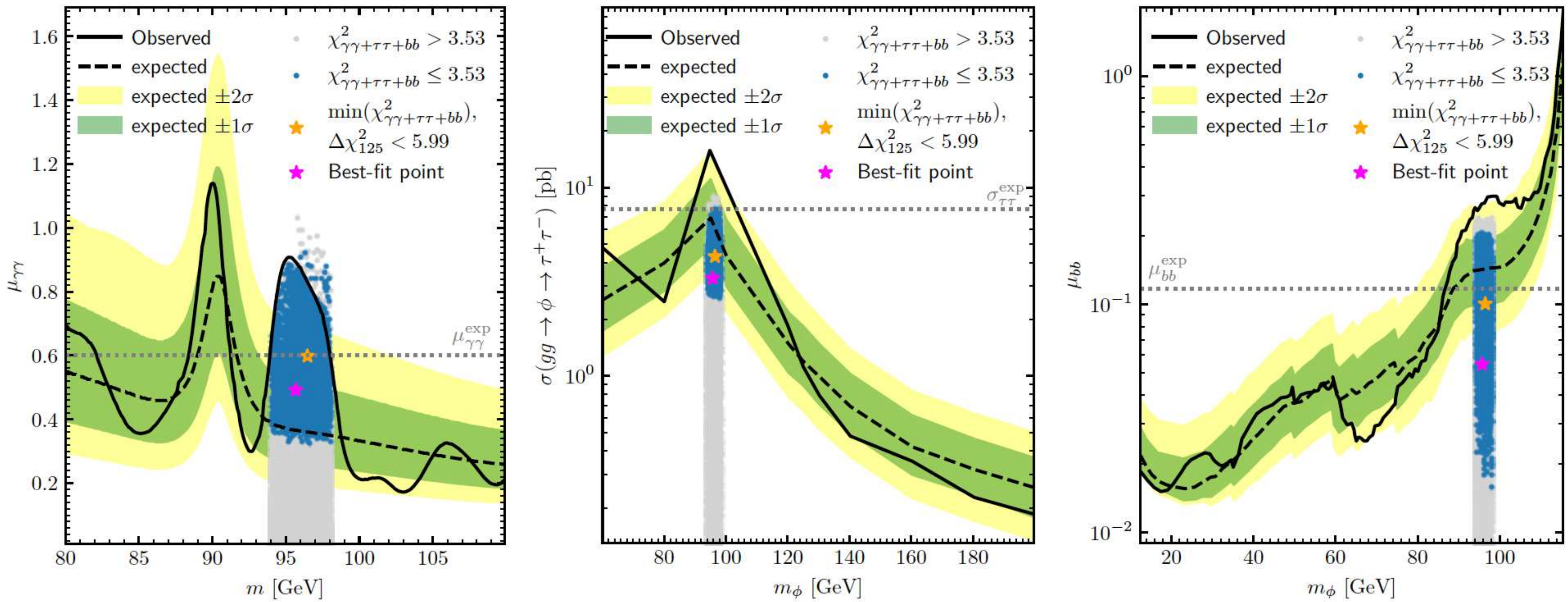


Color coding: χ^2_{125} from HiggsSignals

⇒ 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*]

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

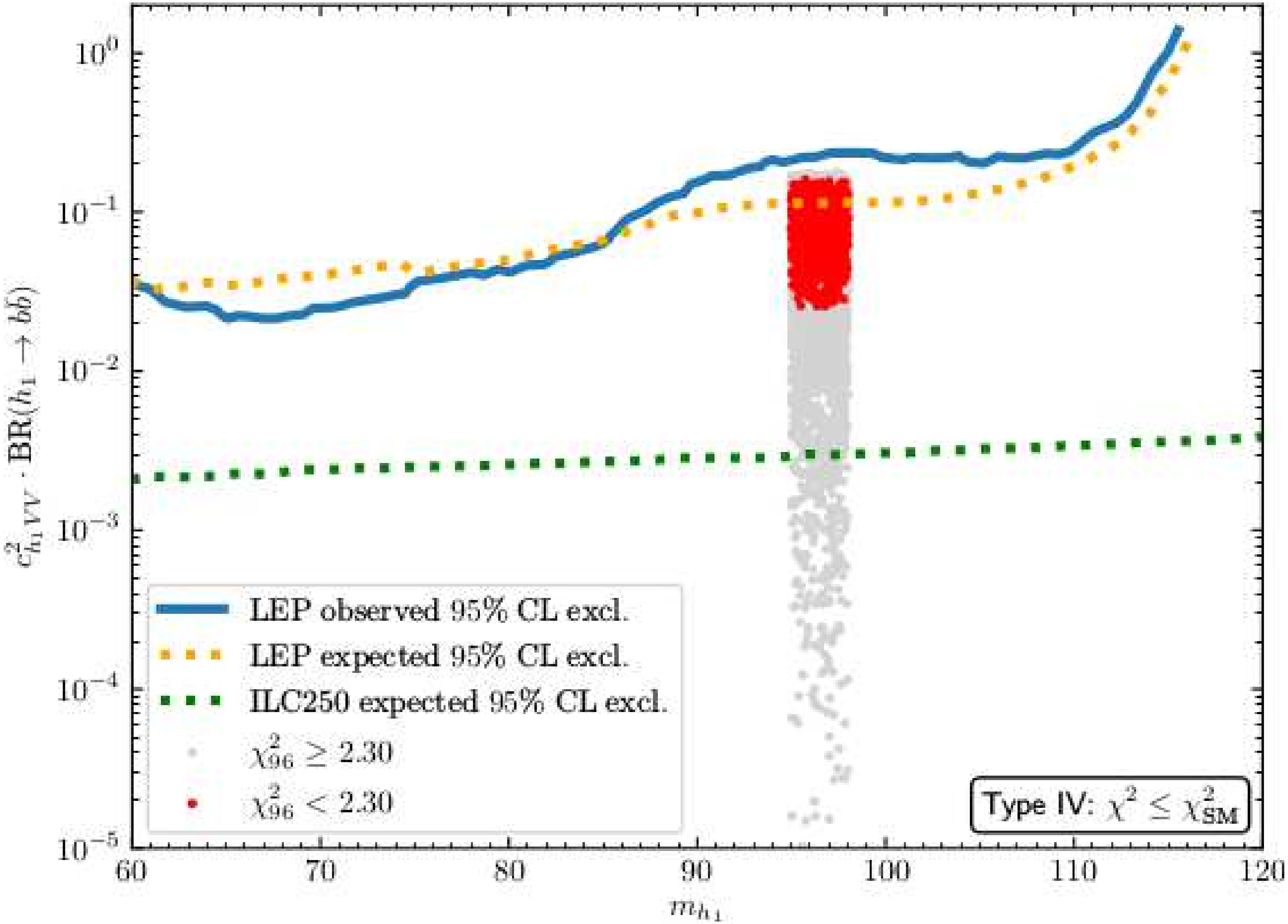


gray lines: central values of excesses

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

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

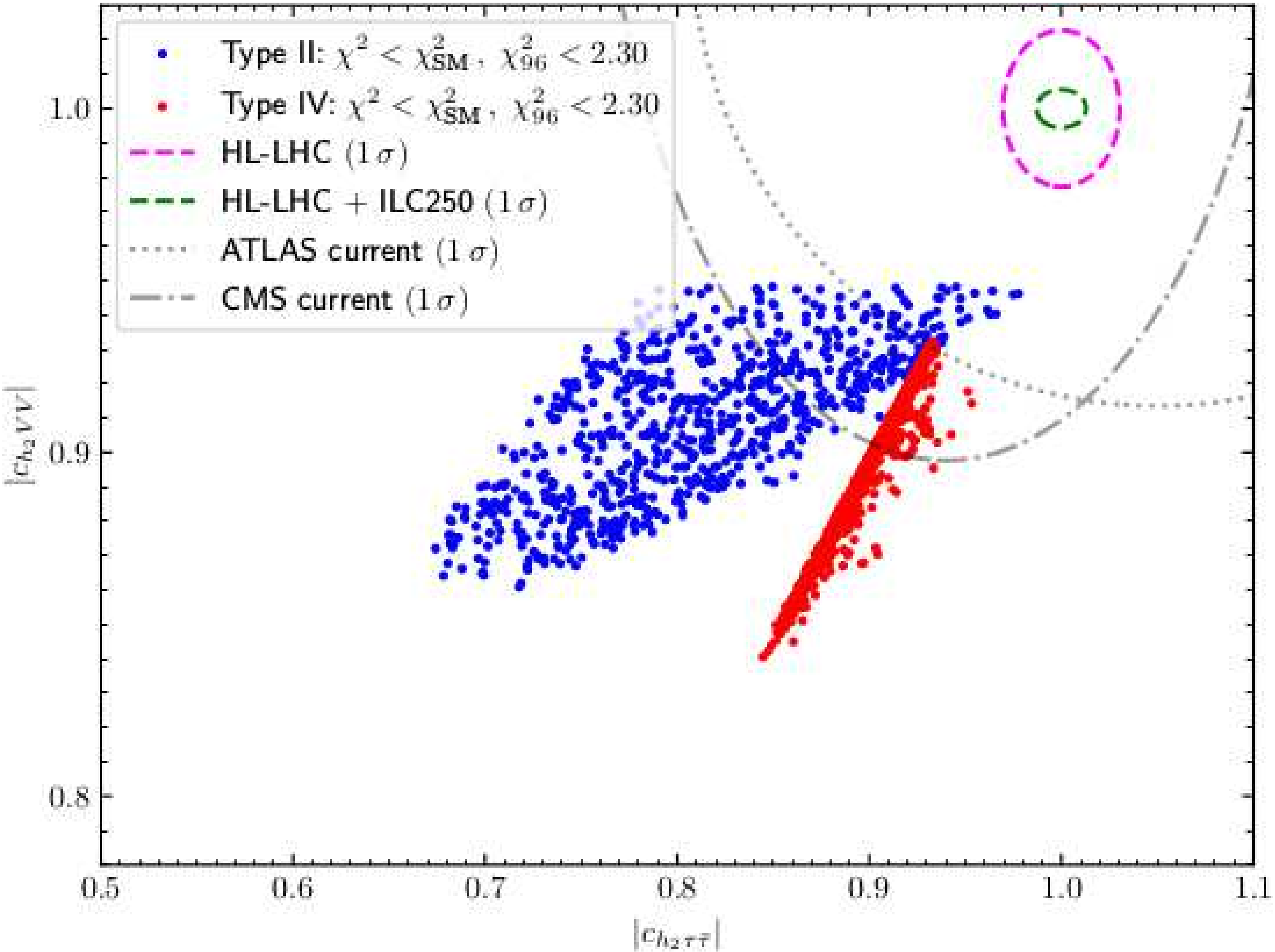
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



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

HL-LHC/ILC h_{125} coupling measurements

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



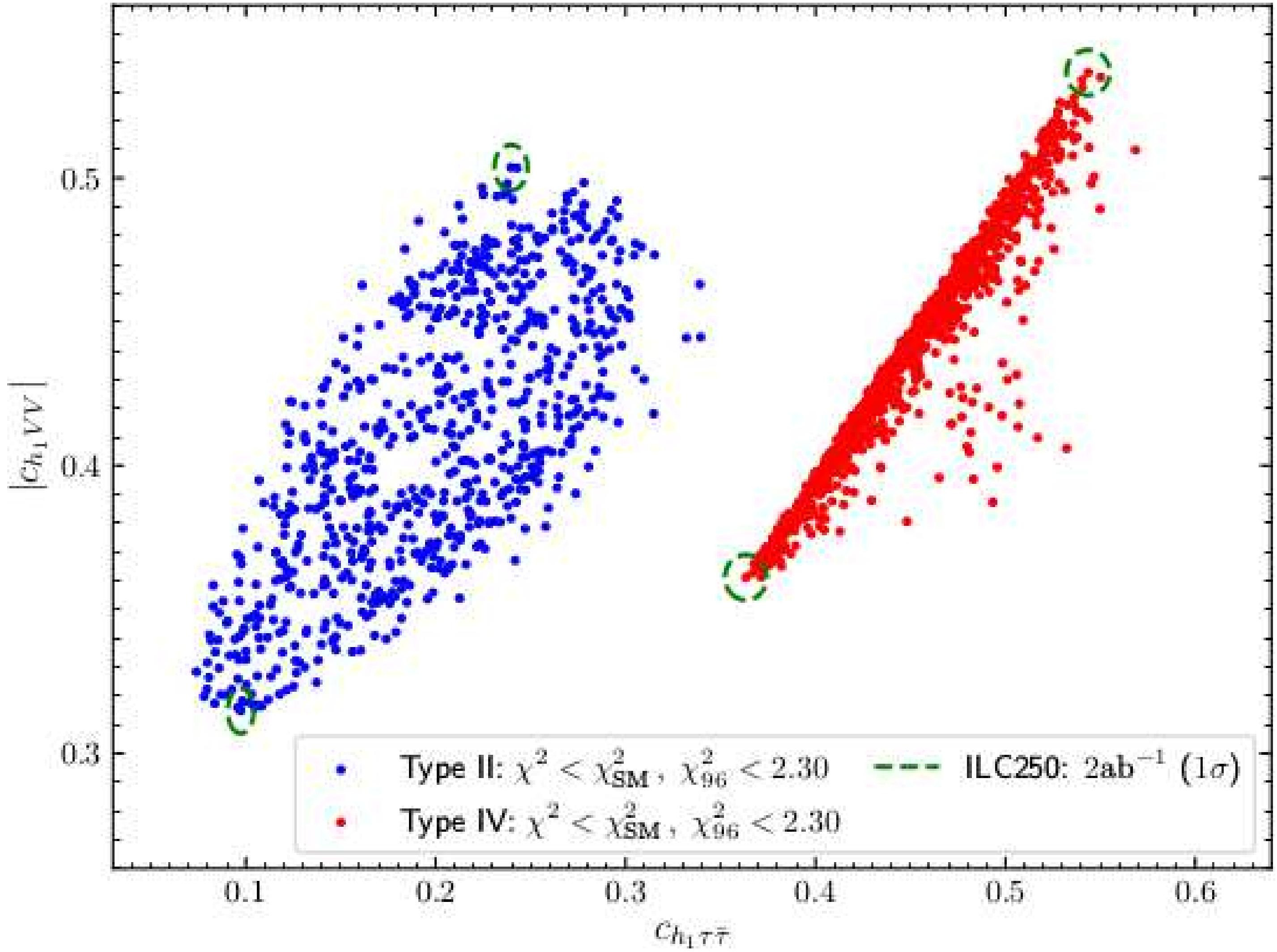
⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM at the ILC

ILC ϕ_{95} coupling measurements at the ILC

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

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



⇒ model distinction possible via coupling measurements at the ILC

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 :-)
  - ILC250: light Higgs bosons up to $\sim$ 160 GeV detectable
  - ILC250/500: h_{125} coupling meas. are likely to see a deviation
    $\Rightarrow$ ILC can set upper limits on NP scales
  - ILC250: precision study of light Higgs bosons possible
    $\Rightarrow$ to disentangle the underlying model
- No time for BSM triple Higgs couplings . . .


Higgs Days at Santander 2022
Theory meets Experiment
5 – 9 September
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Gervasio.Gomez@cern.ch
http://hdays.csic.es
UC
CSIC
EXCELENCIA SEVERO OCHOA
European Commission
ift

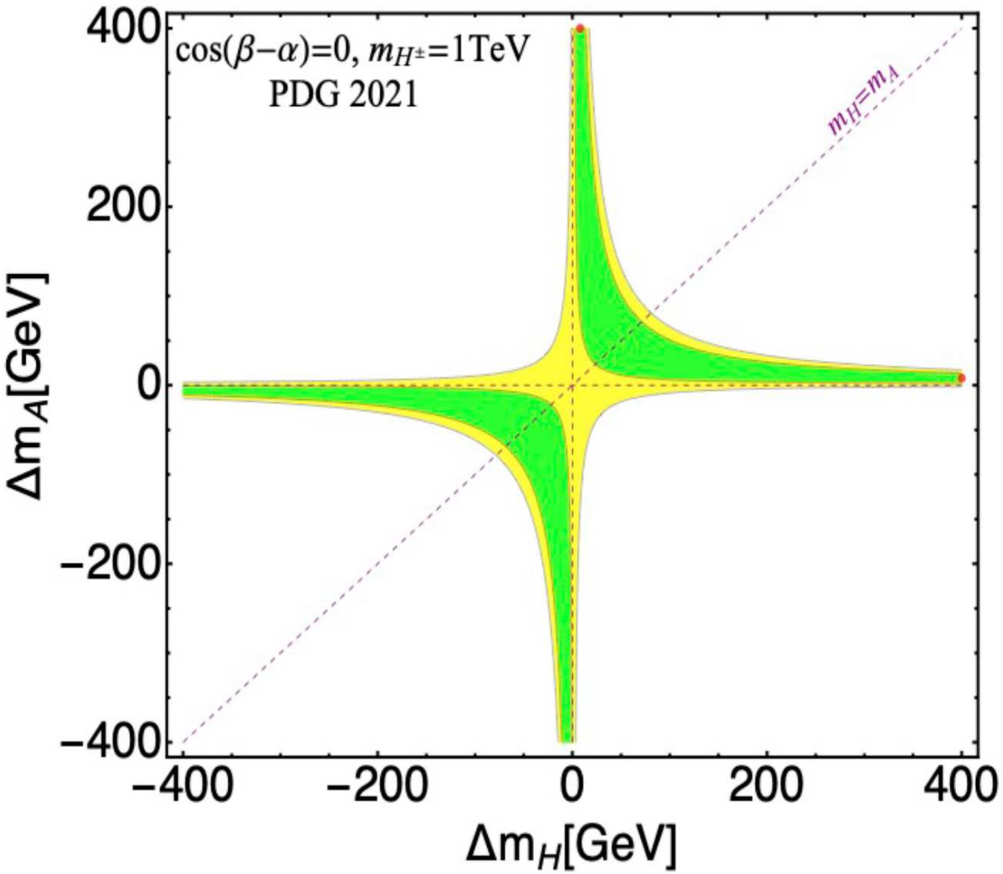

Further Questions?

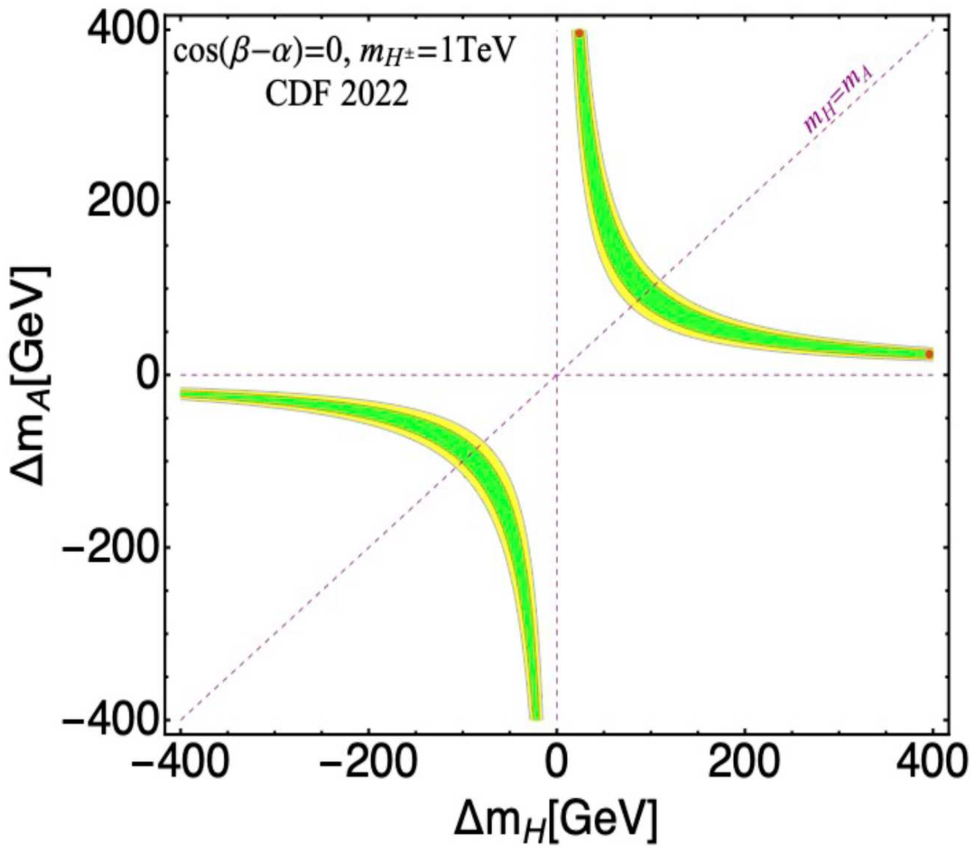
Example: $m_{H^\pm} = 1000$ GeV, $\cos(\beta - \alpha) = 0$

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

PDG 2021

M_W^{CDF}





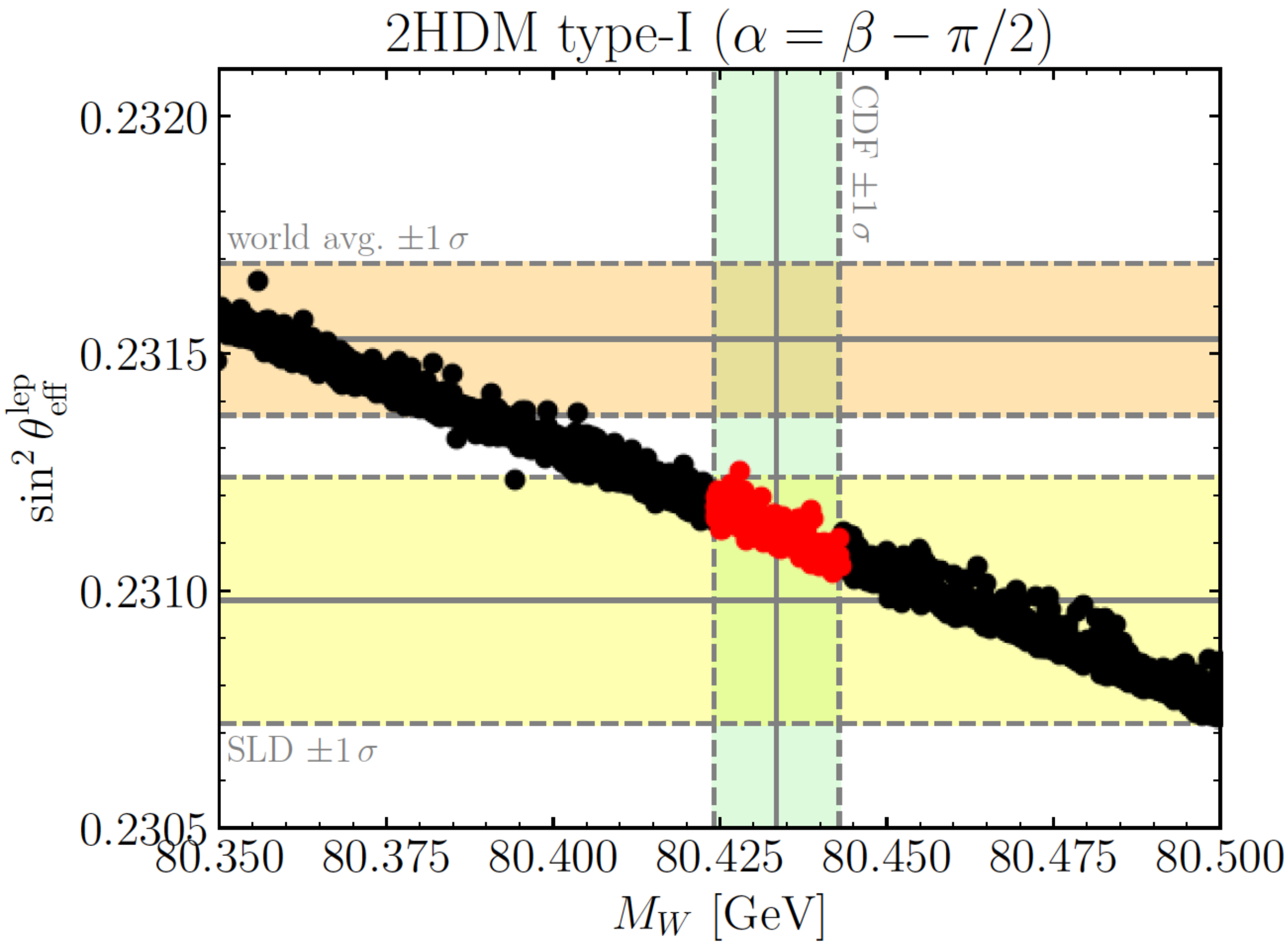
⇒ nearly no overlap of the 2σ regions

⇒ new CDF value requires relatively large BSM Higgs mass splitting

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

M_W^{CDF} vs. $\sin^2\theta_{\text{eff}}$ in the 2HDM

[H. Bahl, J. Braathen, G. Weiglein '22]

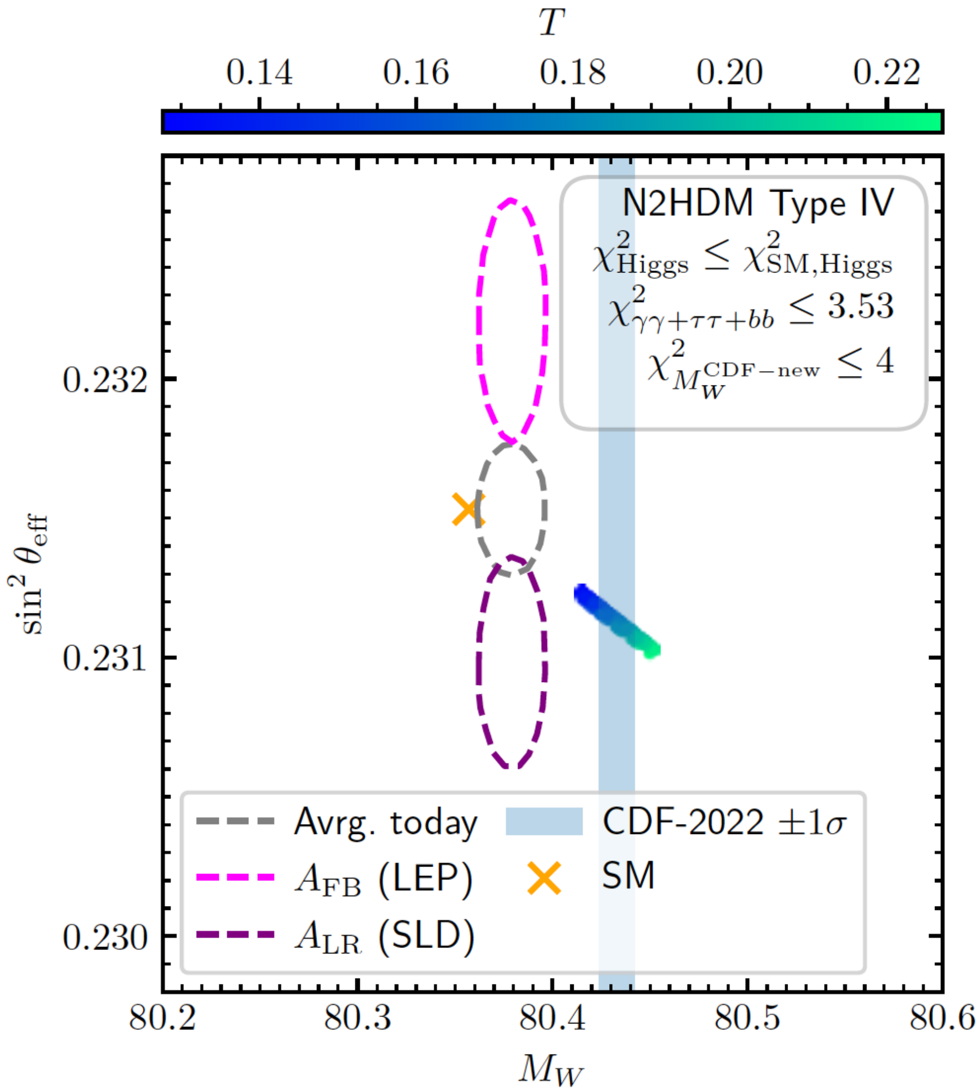


Remember: $\Delta\rho$ goes up $\Rightarrow$ M_W goes up, $\sin^2\theta_{\text{eff}}$ goes down
$\Rightarrow$ agreement only with SLD value of $\sin^2\theta_{\text{eff}}$

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

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

$\Rightarrow$ N2HDM favored by 3 independent excesses in Higgs searches at ~ 95 GeV



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

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Possible hint for heavy Higgses in the N2HDM:

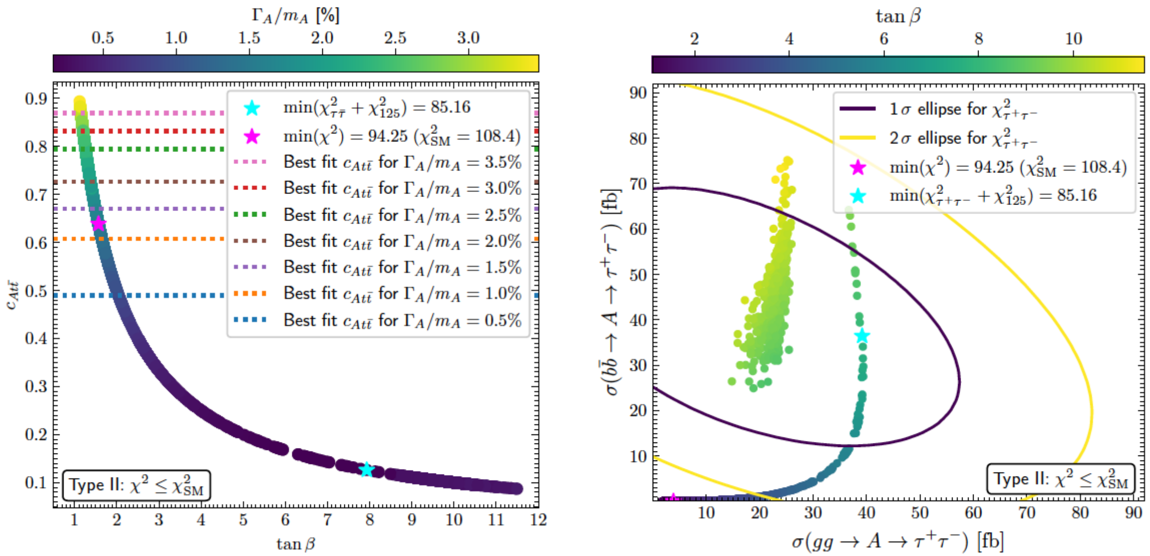
[*taken from T. Biekötter '21*]

A 400 GeV pseudoscalar in the type II N2HDM

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

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

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



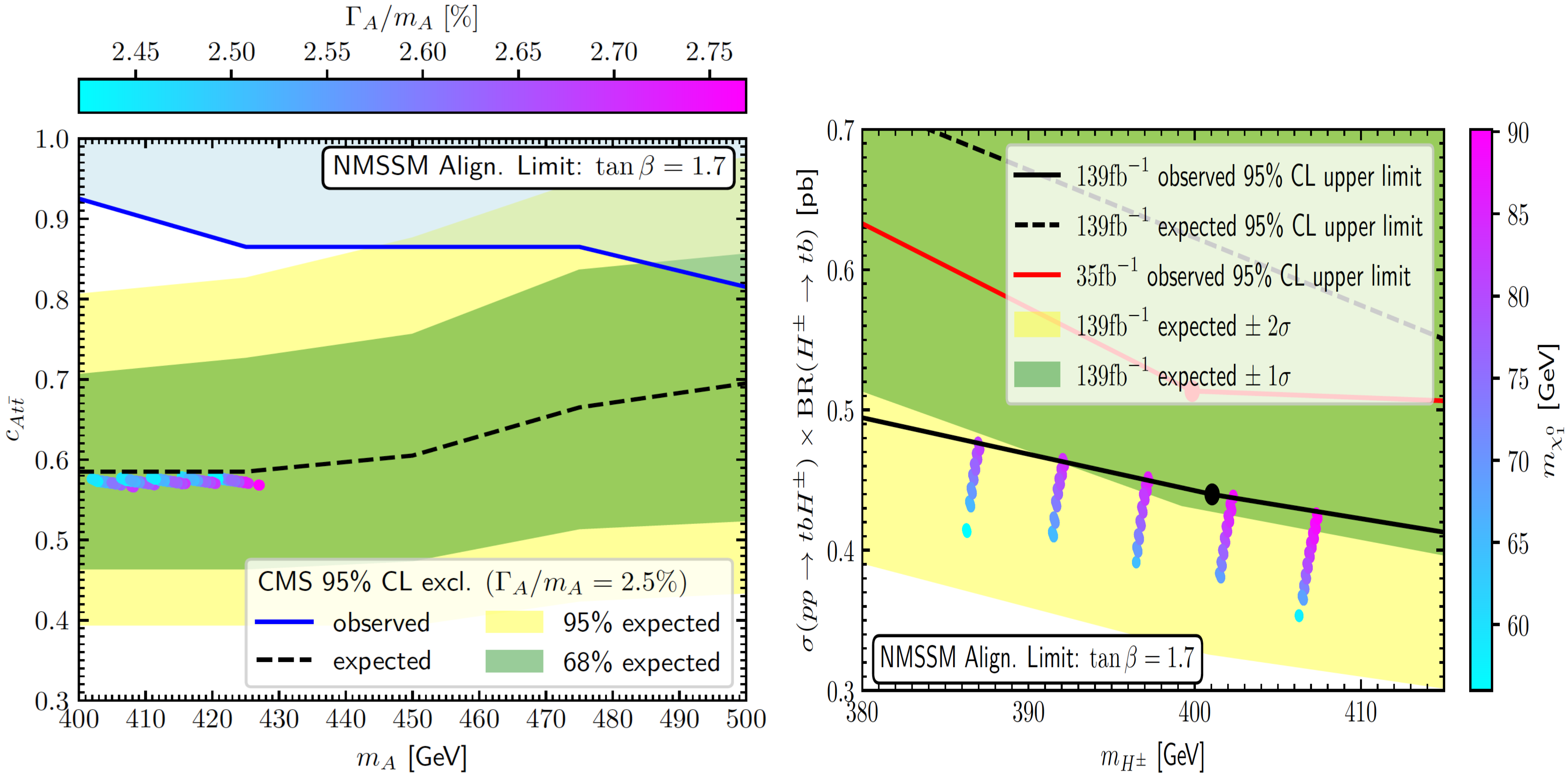
(Also the "$A \to Zh$" excess can be realized)
$\to$ Later

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 $\tan\beta \sim 1.7$)

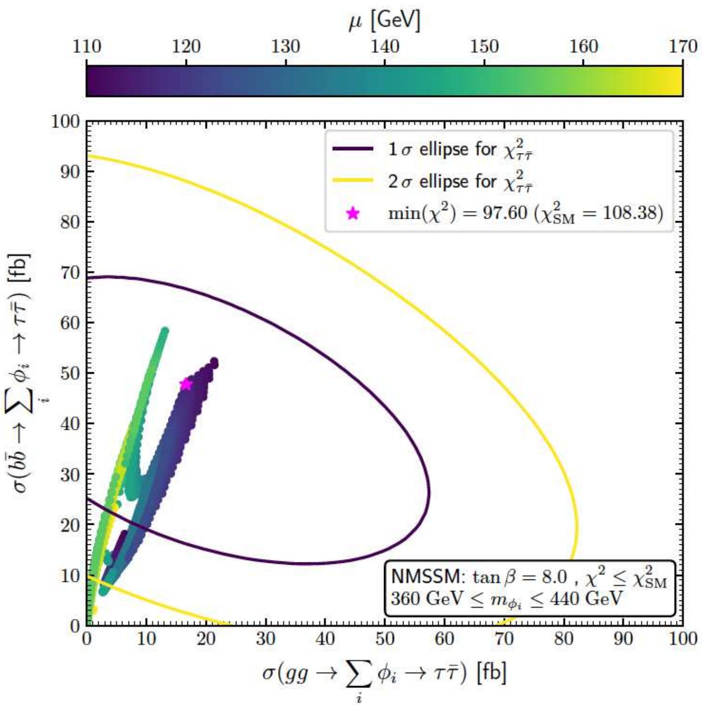
[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]

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

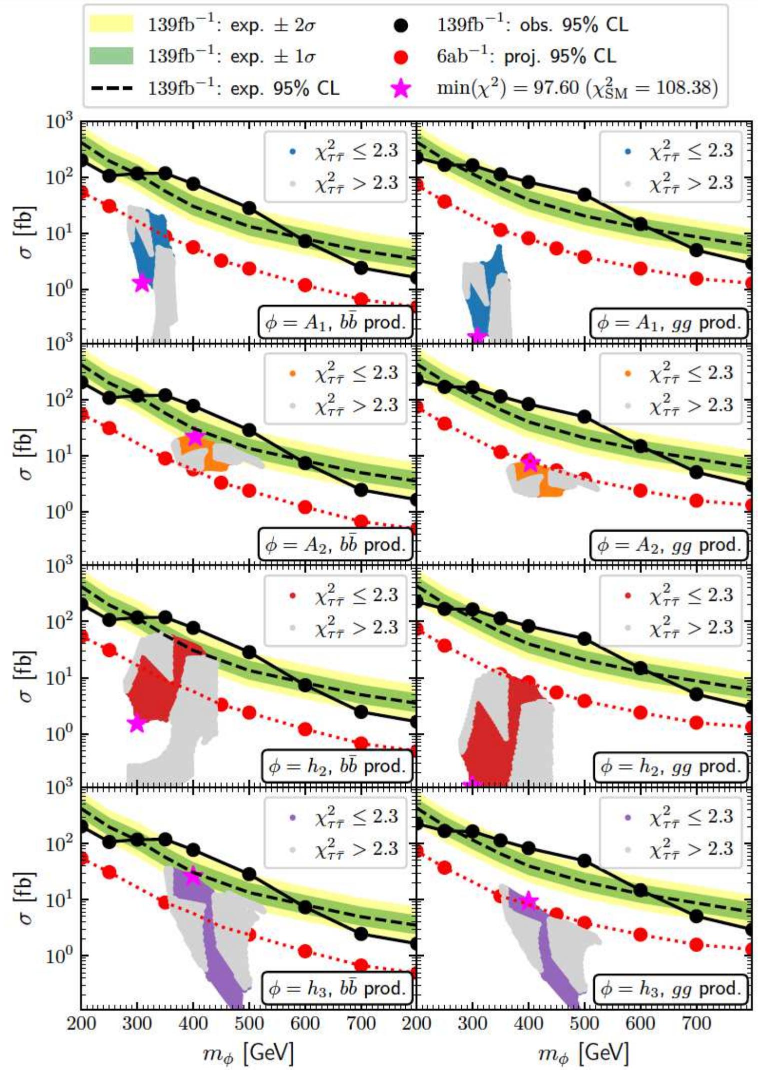
$\tau^+\tau^-$ **excess** $\to$ moderate $\tan\beta = 8$



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*]

What about the "real hints" at ~ 400 GeV? $\rightarrow$ NMSSM:

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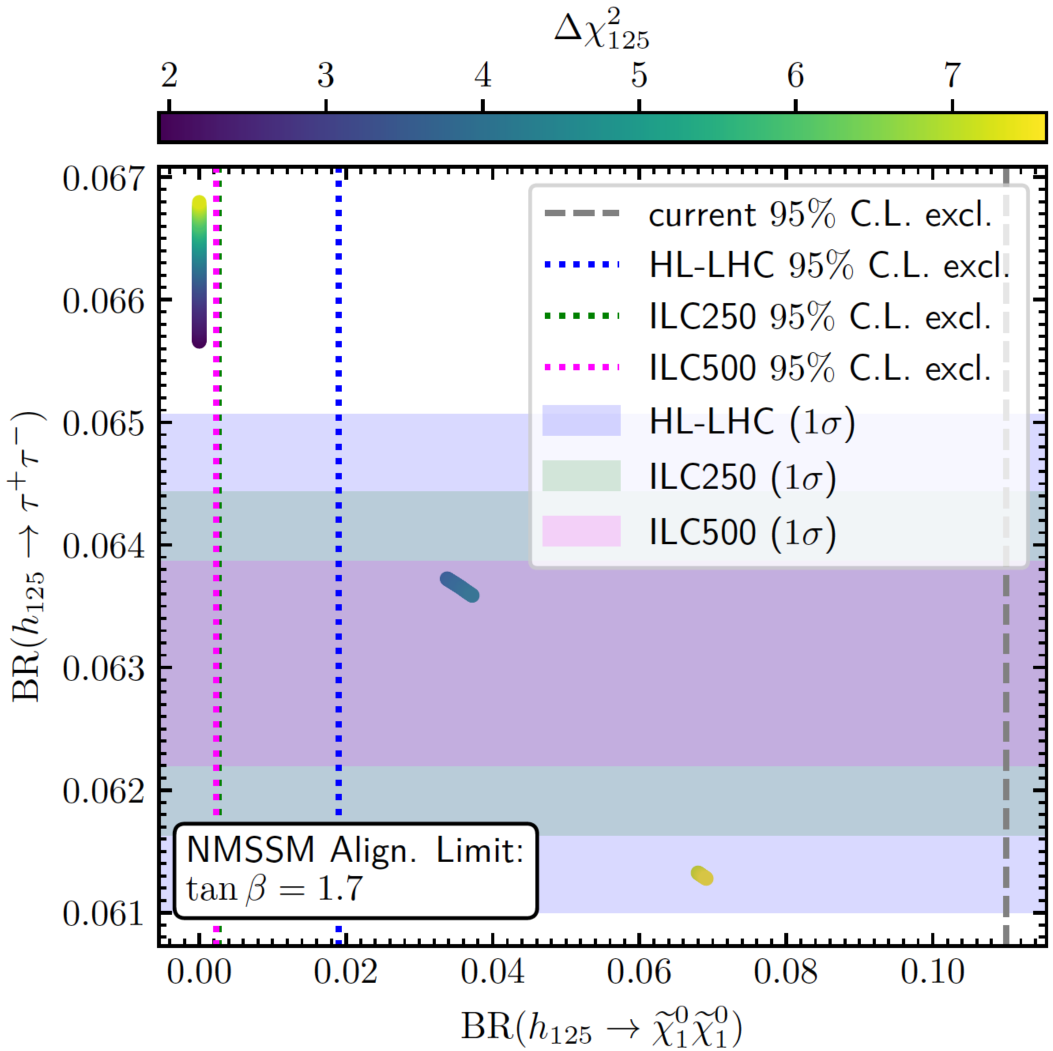
[T. Biekötter, A. Grohsjean, S.H., C. Schwanenberger, G. Weiglein '21]

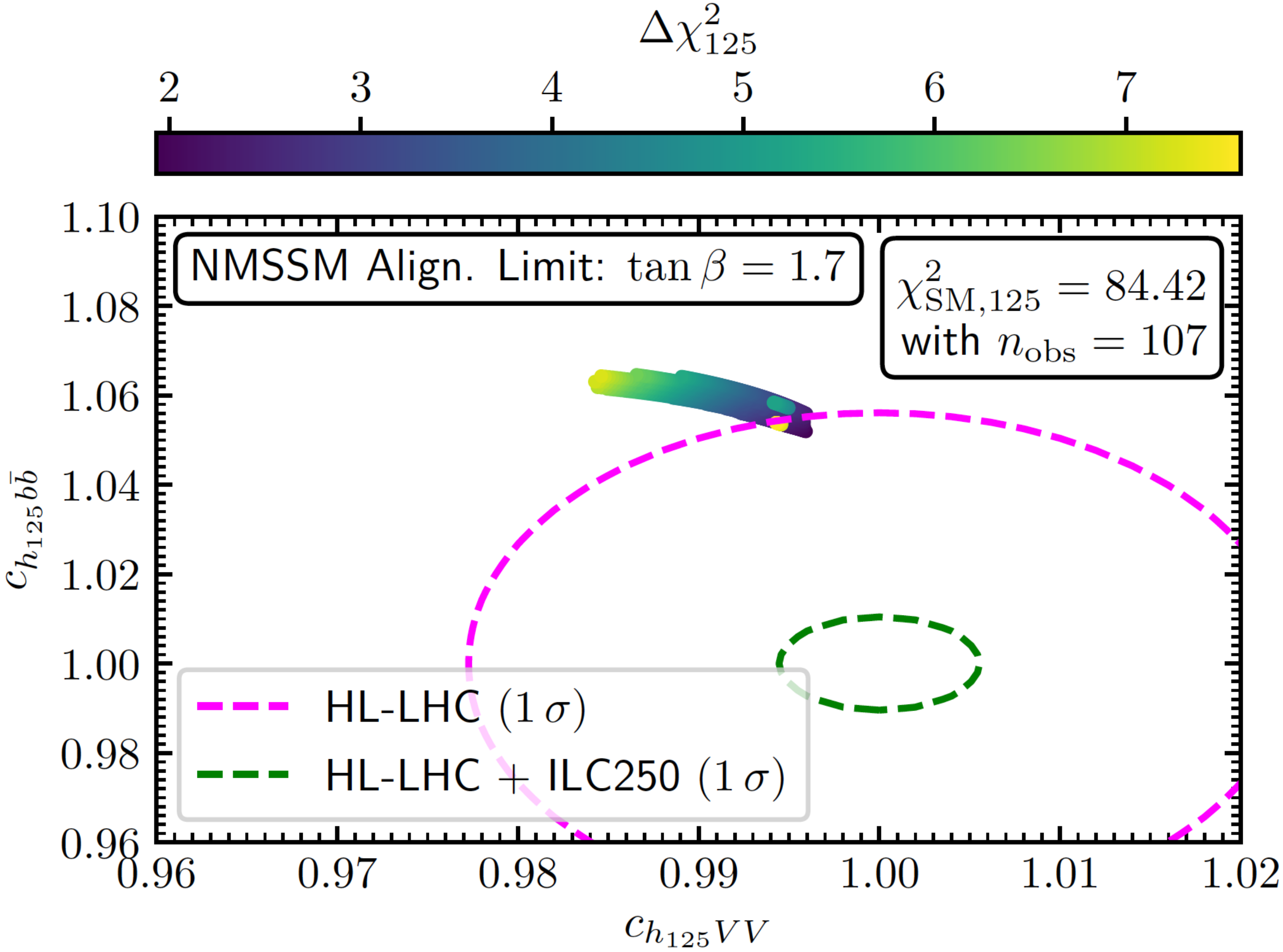


$\Rightarrow$ HL-LHC can test $h_{125} \to \tilde{\chi}^0_1\tilde{\chi}^0_1$ (small part of allowed parameter space)

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

What about the “real hints” at ~ 400 GeV? $\rightarrow$ 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 $c_{h_{125}bb}$

SUSY realizations

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- ...

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

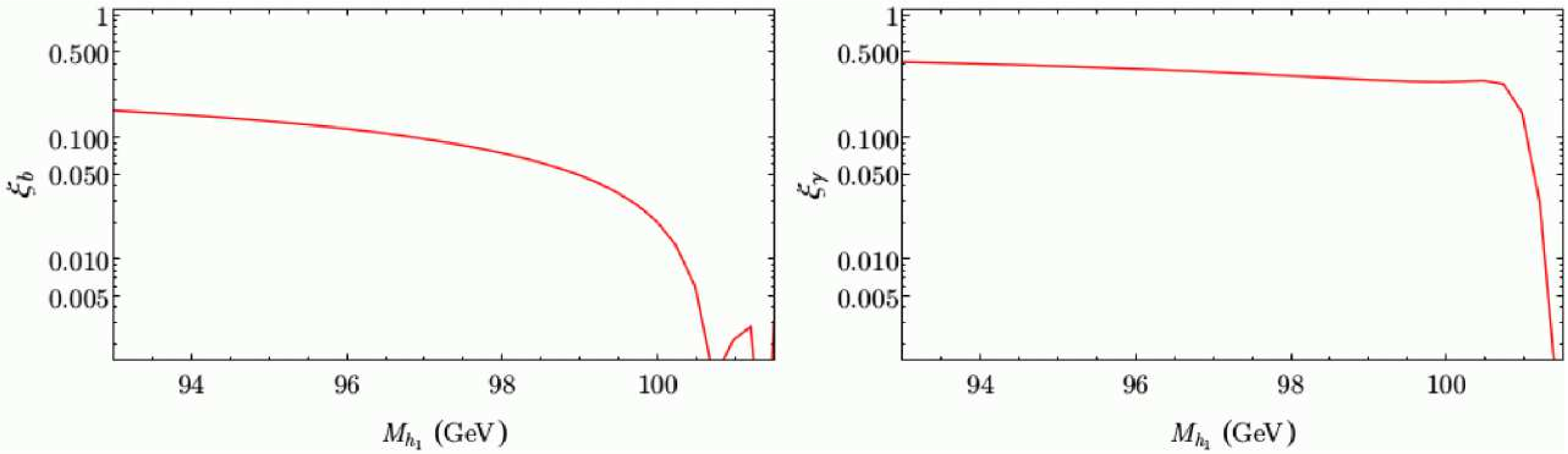
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

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 (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?

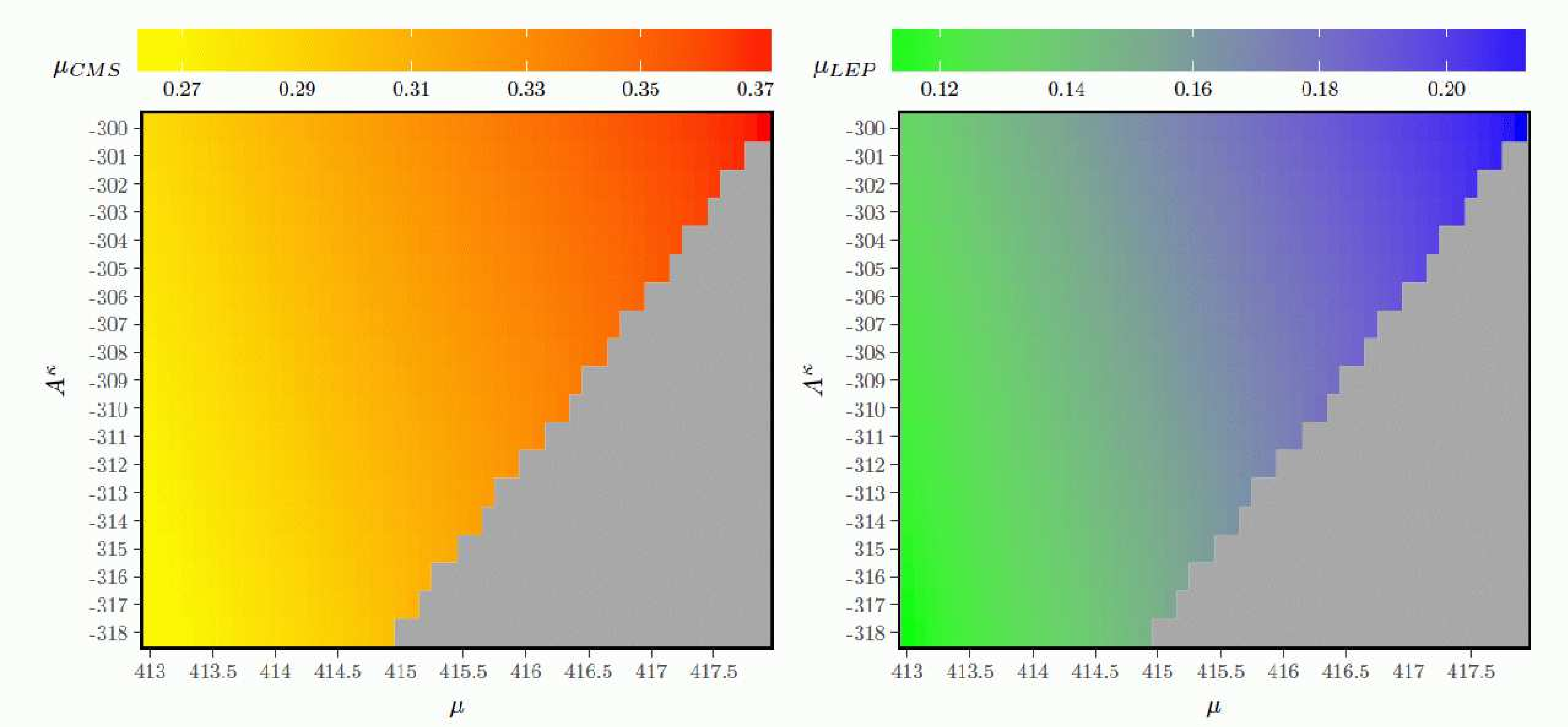
[*T. Biekötter, S.H., C. Muñoz '17*]

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*]

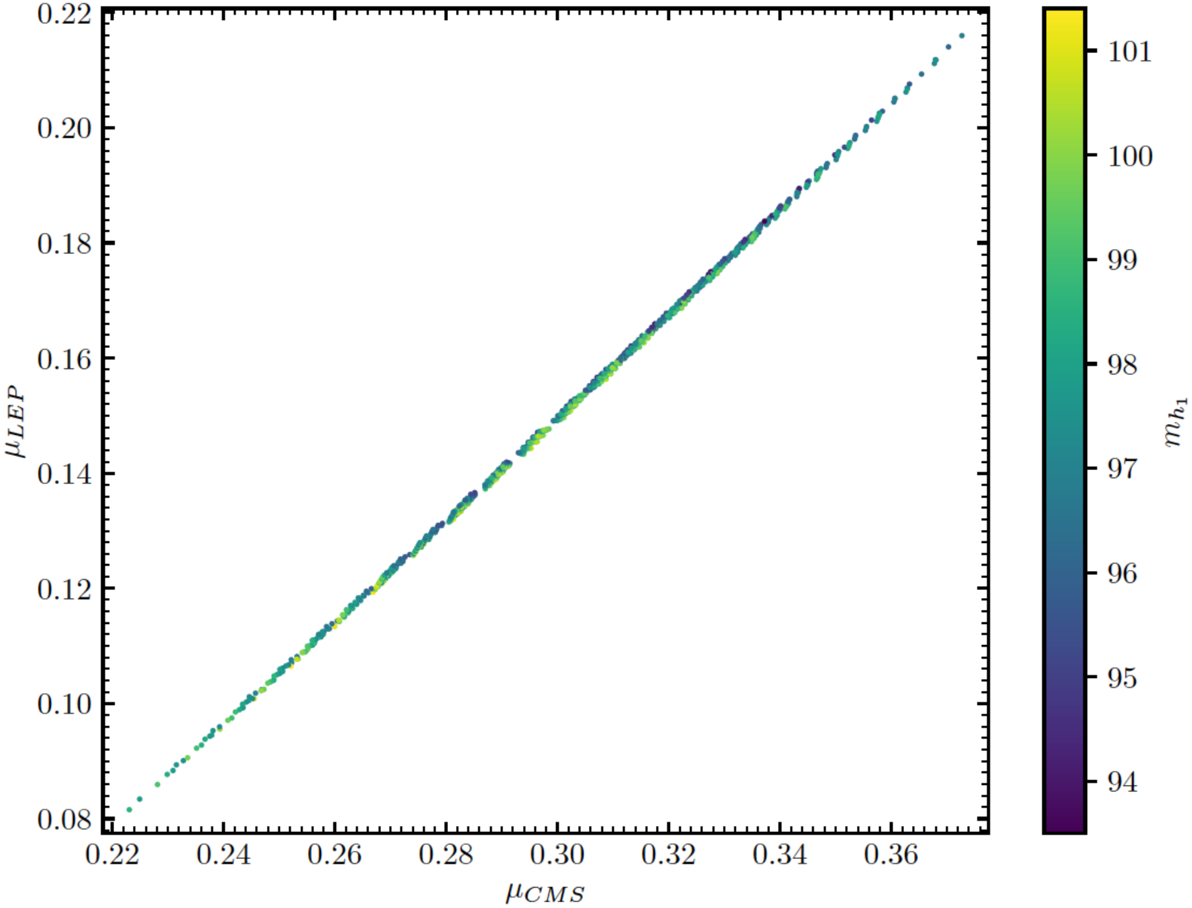


⇒ YES, WE CAN! :-)

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?

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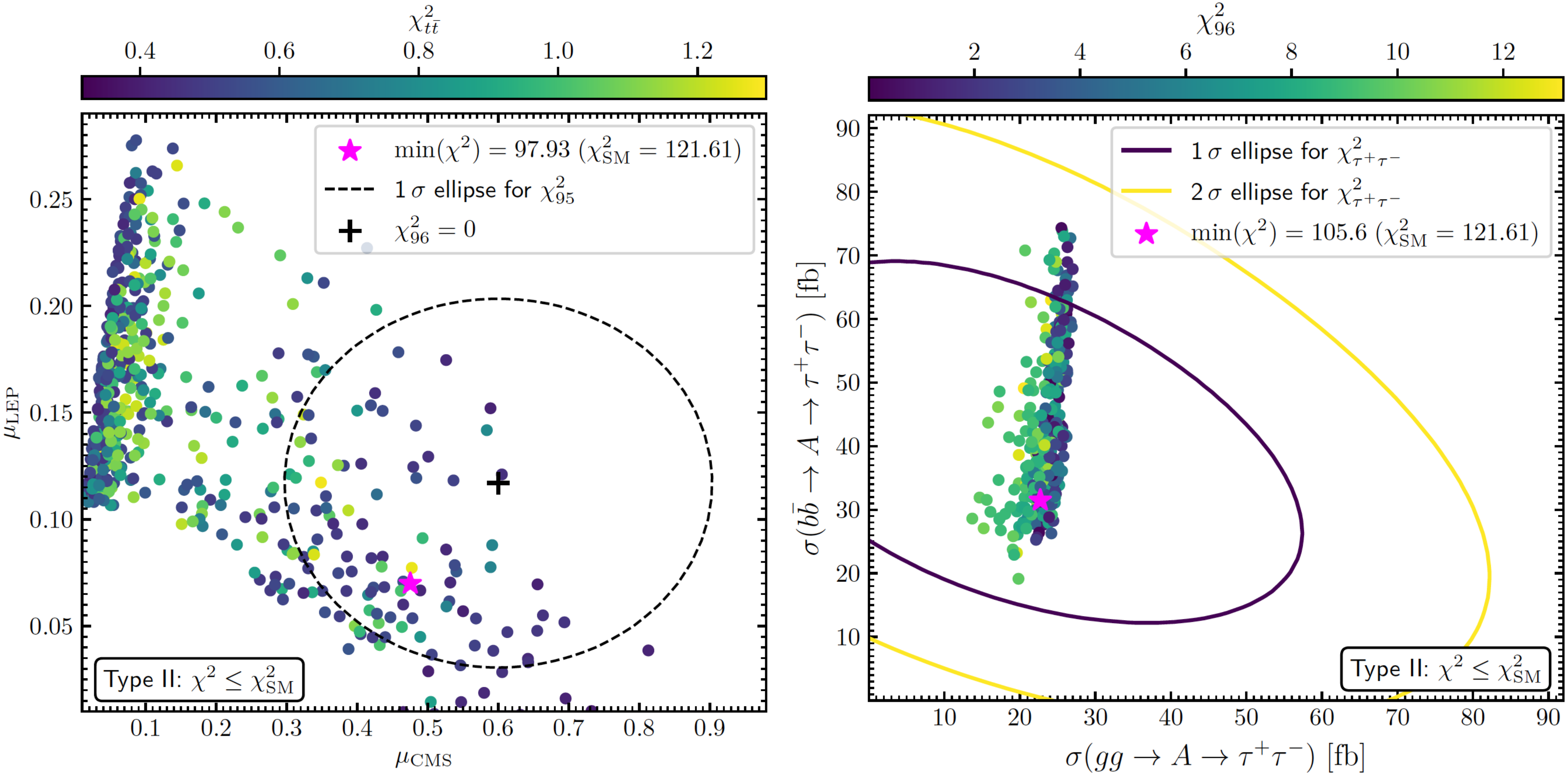
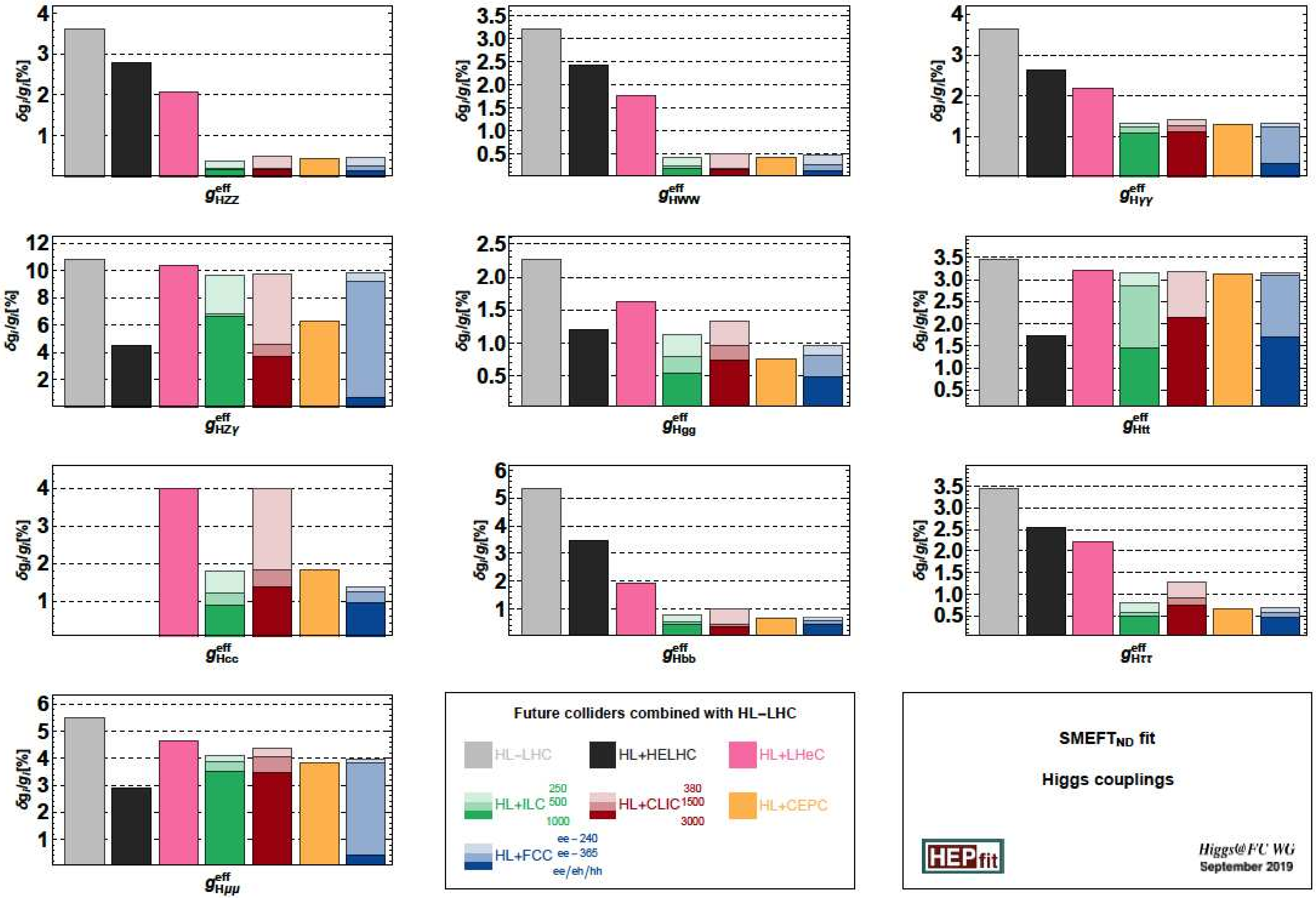
can the excesses at 400 GeV and 96 GeV be explained simultaneously?

$\Rightarrow$ Yes, in the N2HDM



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

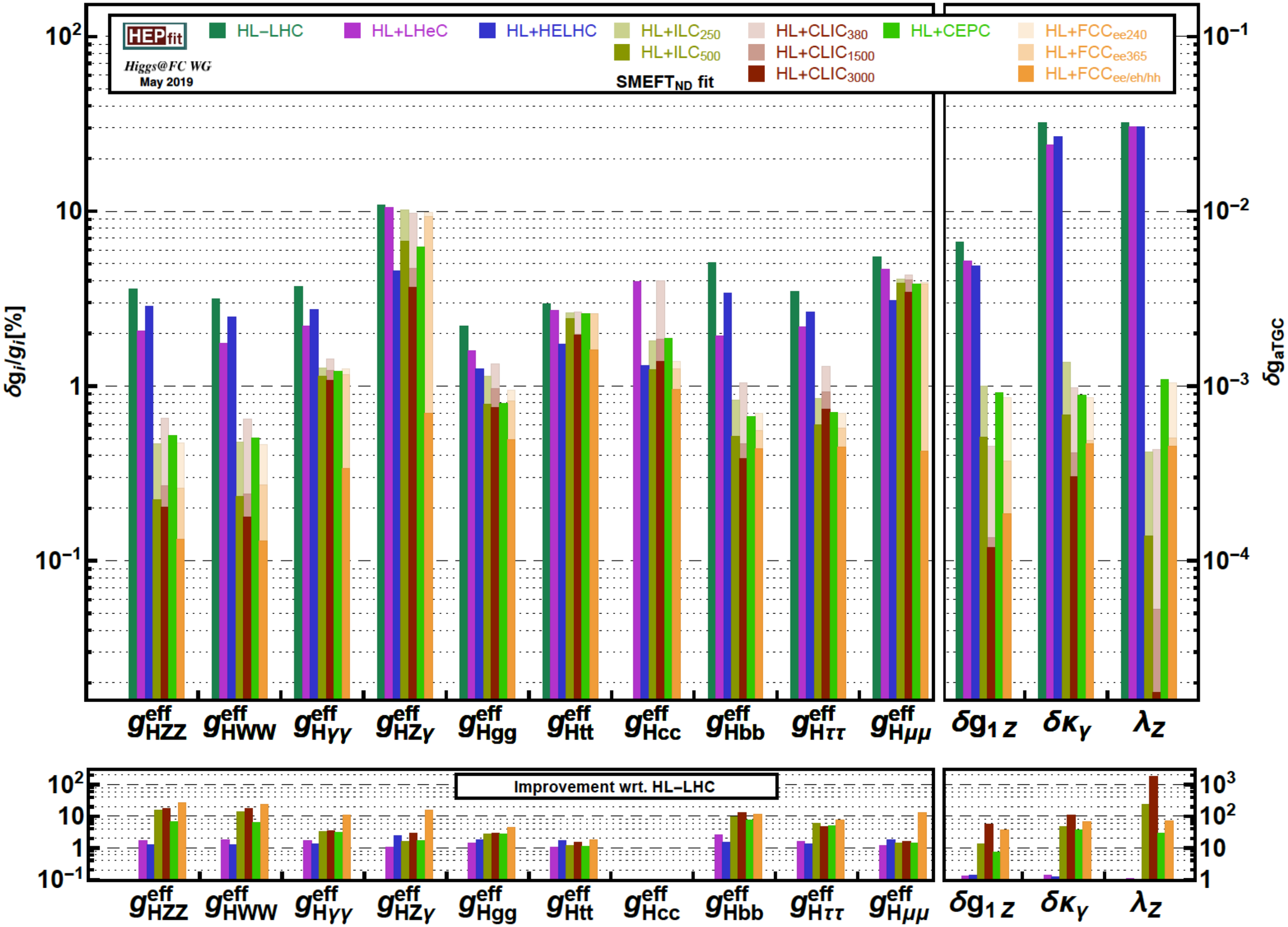
Future expections for Higgs couplings in SMEFT (I)



⇒ clear improvement with the ILC!

⇒ polarization important to disentangle BSM coupling structures

Future expections for Higgs couplings in SMEFT (II)



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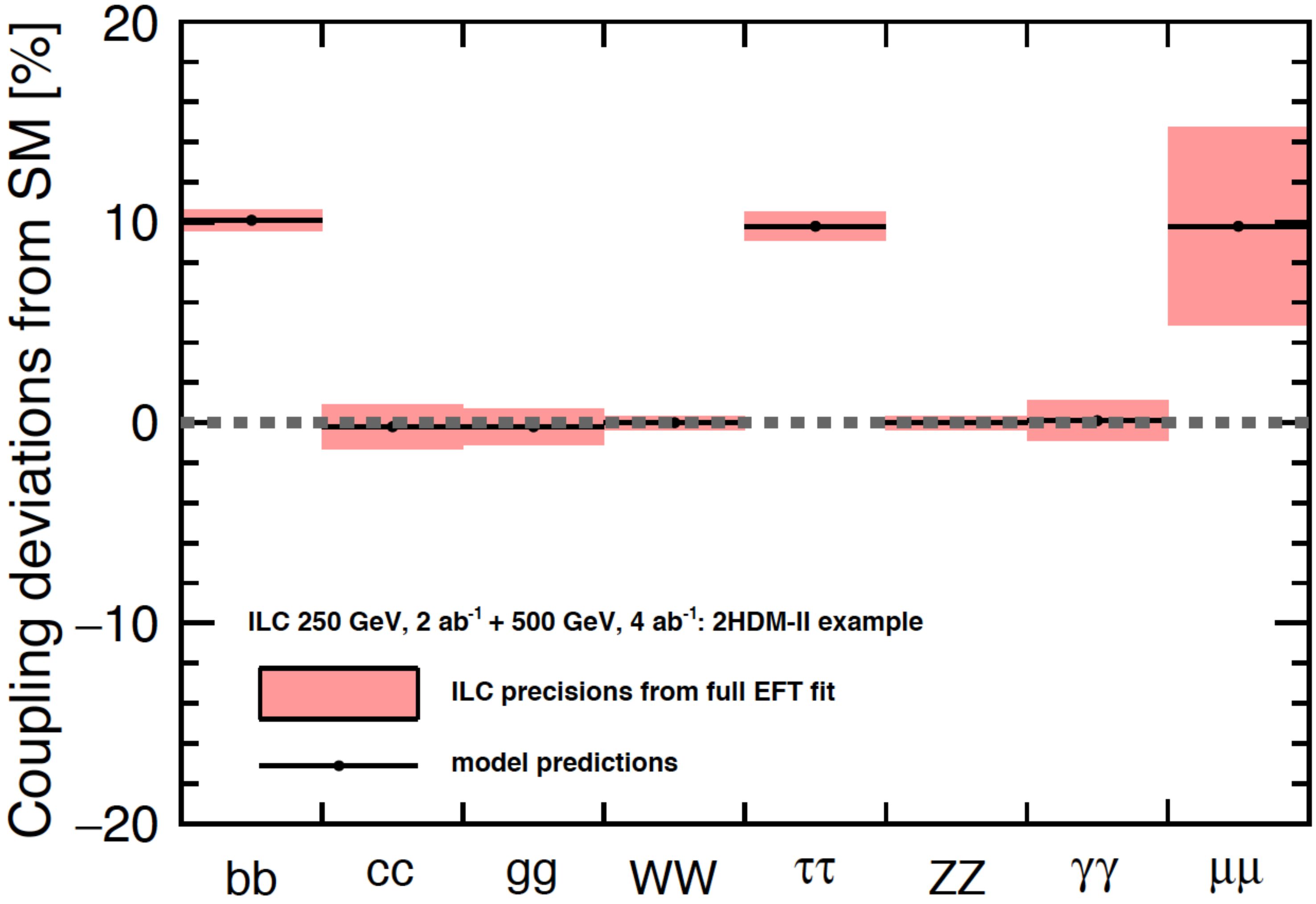
Wäscheleine I: e^+e^- precision vs. 2HDM type II prediction:

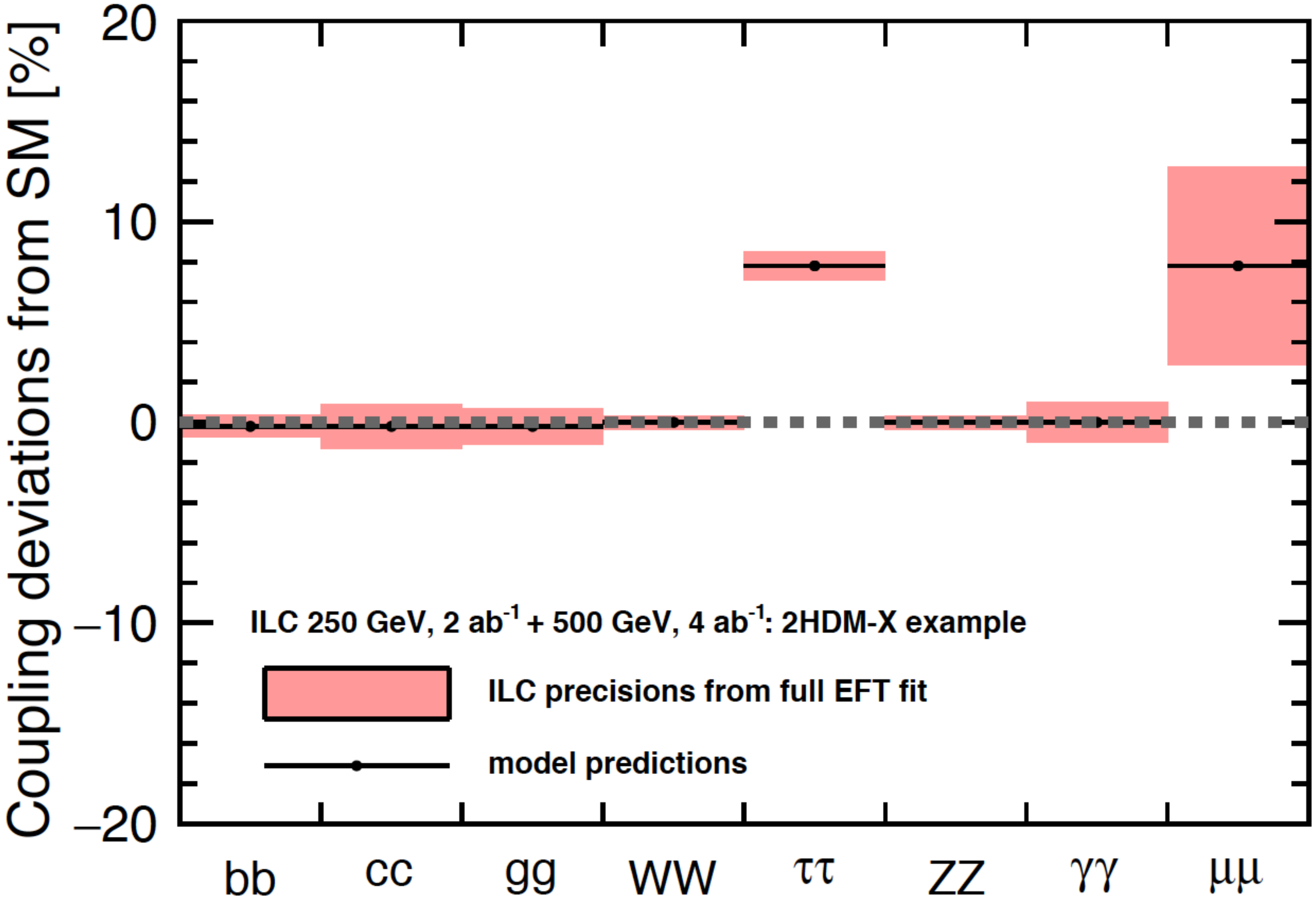
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type II?!

Wäscheleine II: e^+e^- precision vs. 2HDM type X prediction:

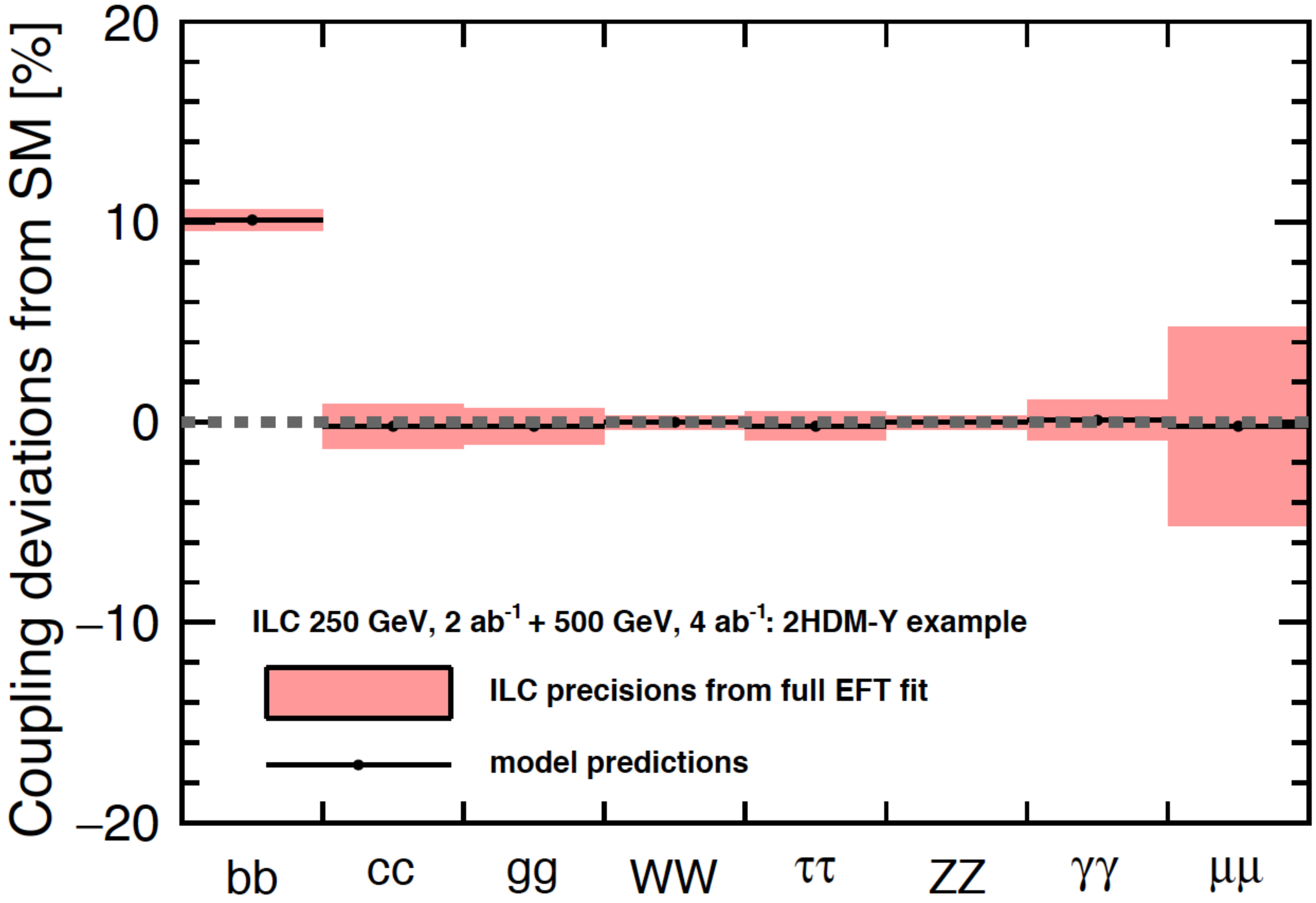
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type X?!

Wäscheleine III: e^+e^- precision vs. 2HDM type Y prediction:

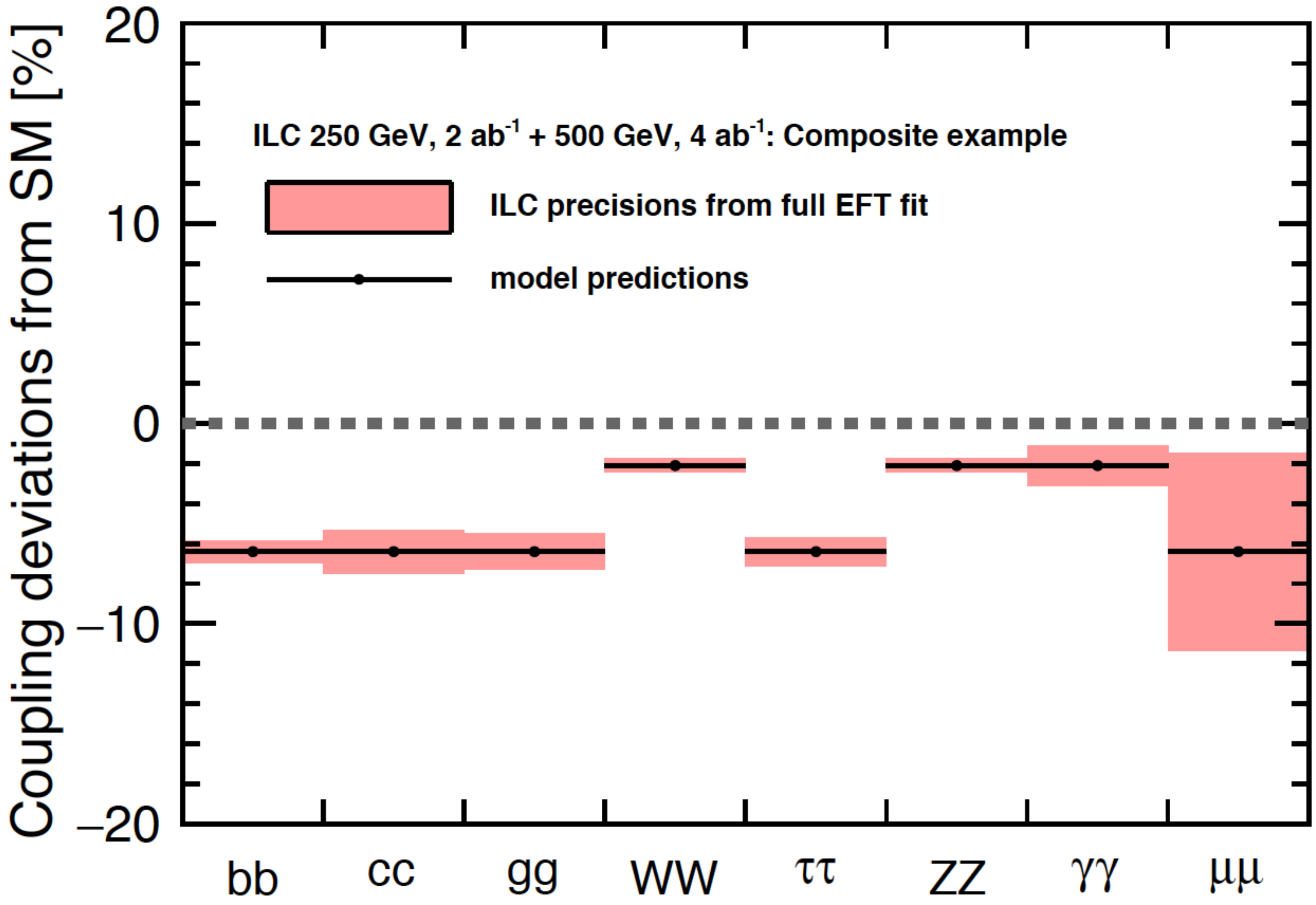
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for 2HDM type Y?!

Wäscheleine IV: e^+e^- precision vs. Composite Higgs prediction:

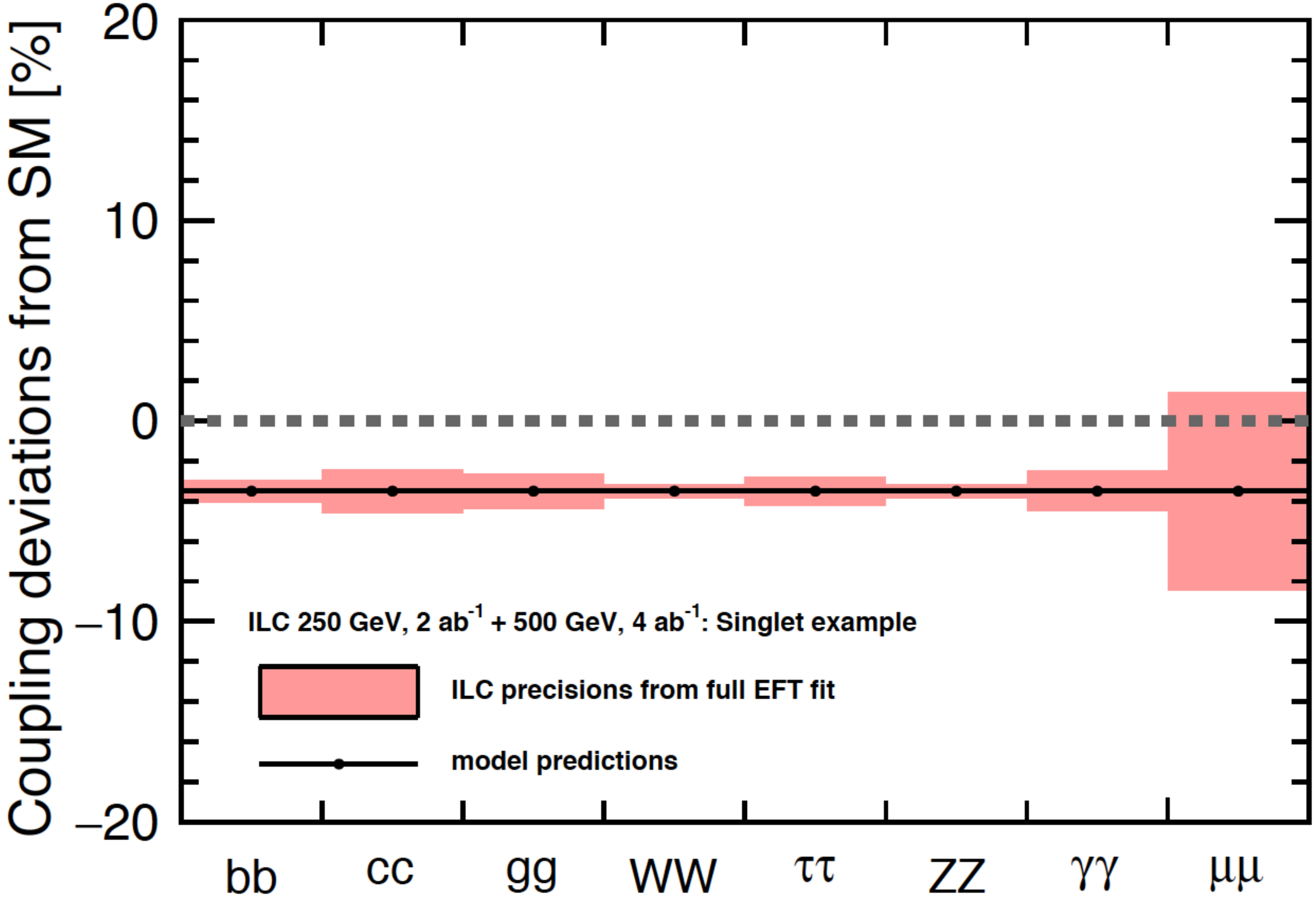
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Composite Higgs?!

Wäscheleine V: e^+e^- precision vs. HxSM prediction:

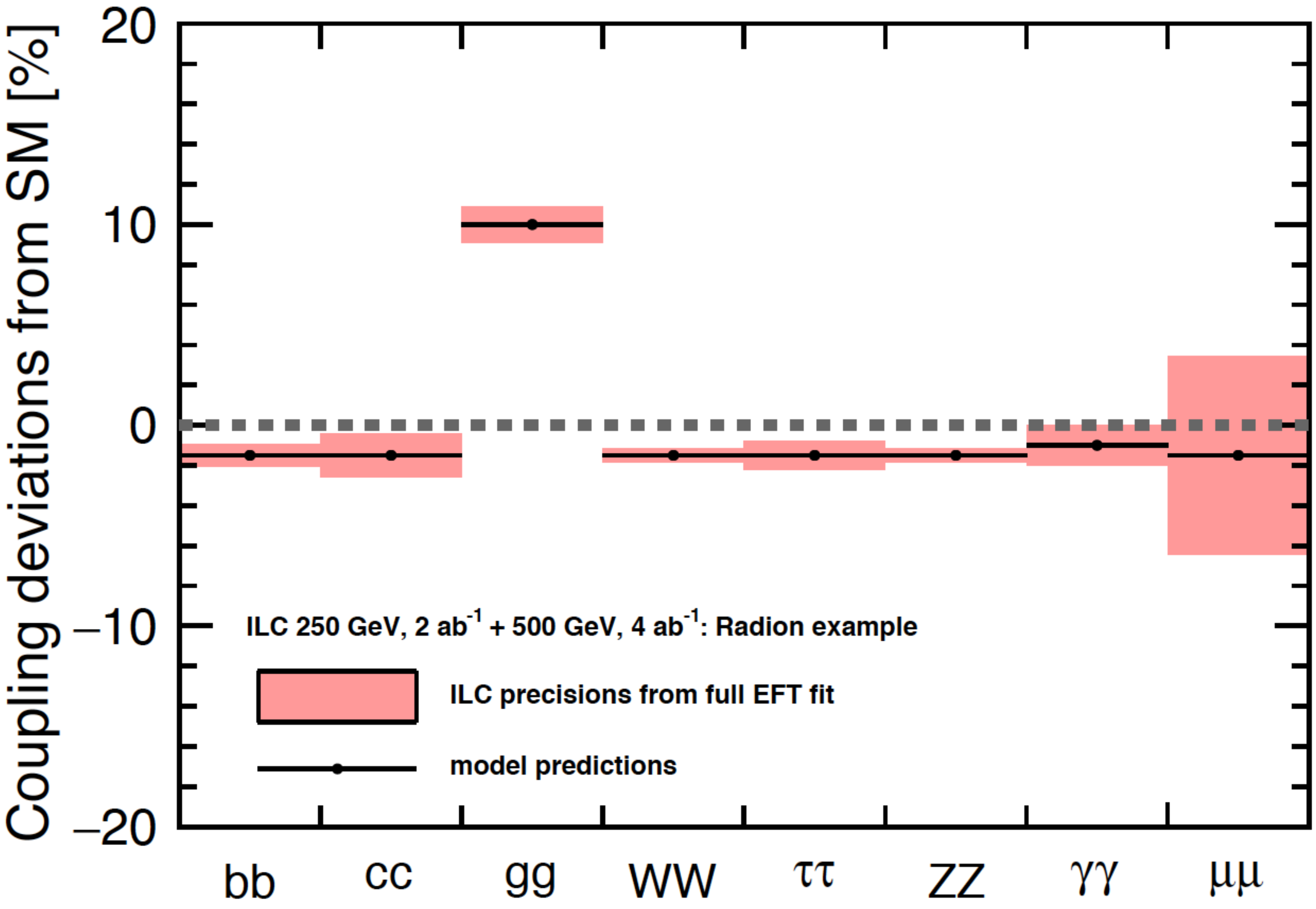
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for HxSM?!

Wäscheleine VI: e^+e^- precision vs. Higgs-Radion prediction:

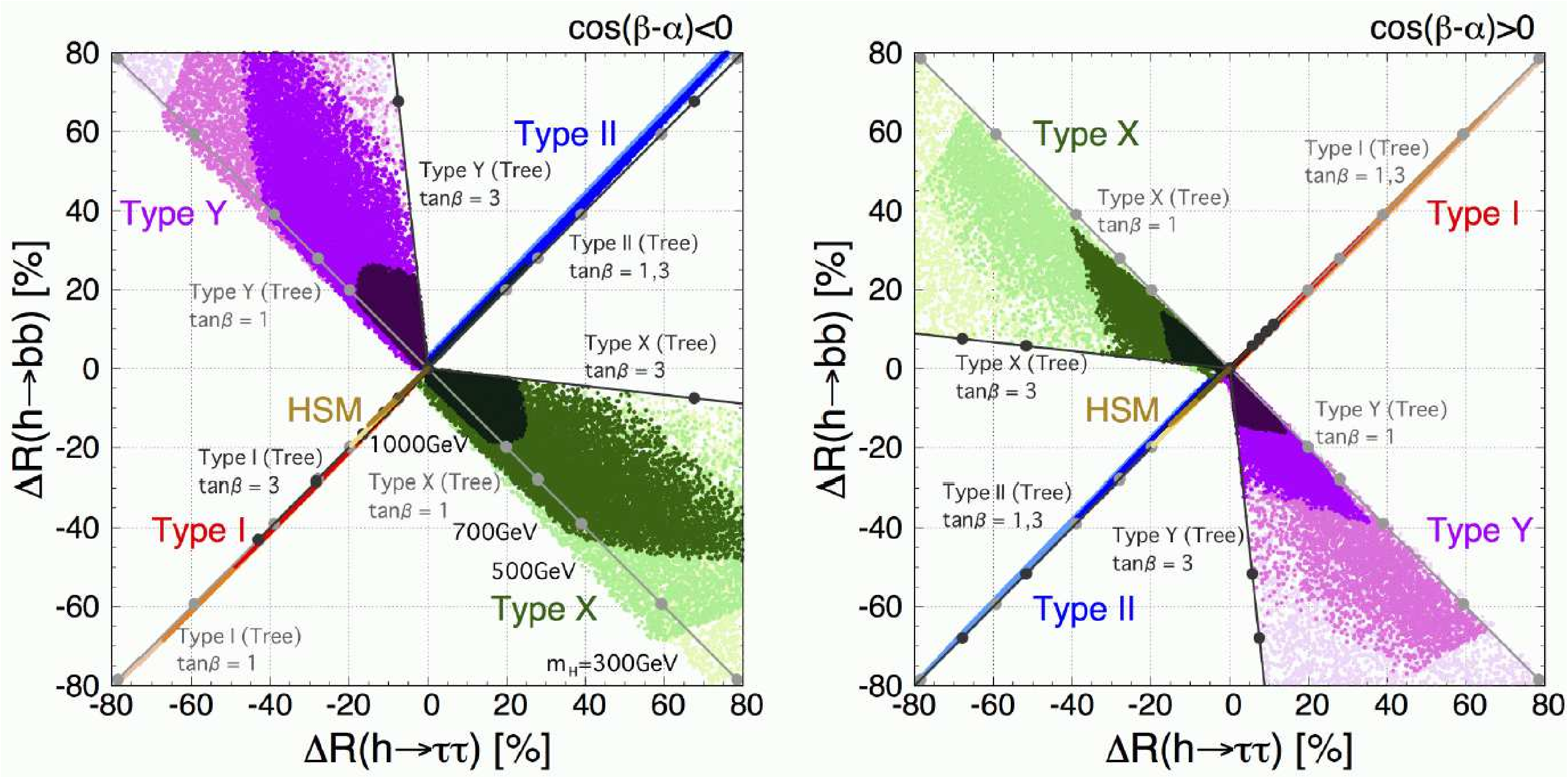
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Higgs Radion?!

2HDM example (I):

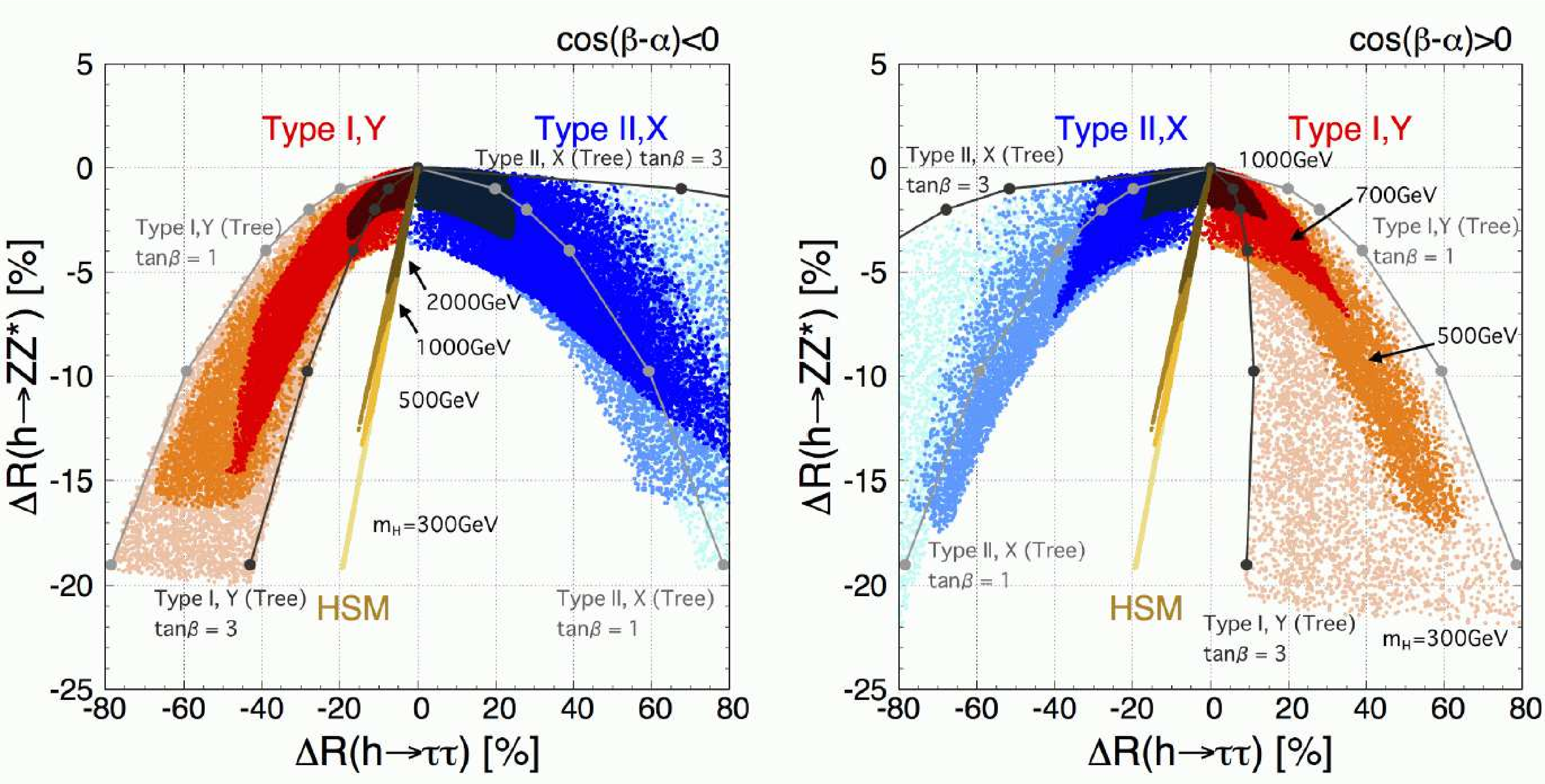
[*S. Kanemura et al. '18*]



⇒ LC precision has a great potential to discriminate the models!

2HDM example (II):

[*S. Kanemura et al. '18*]



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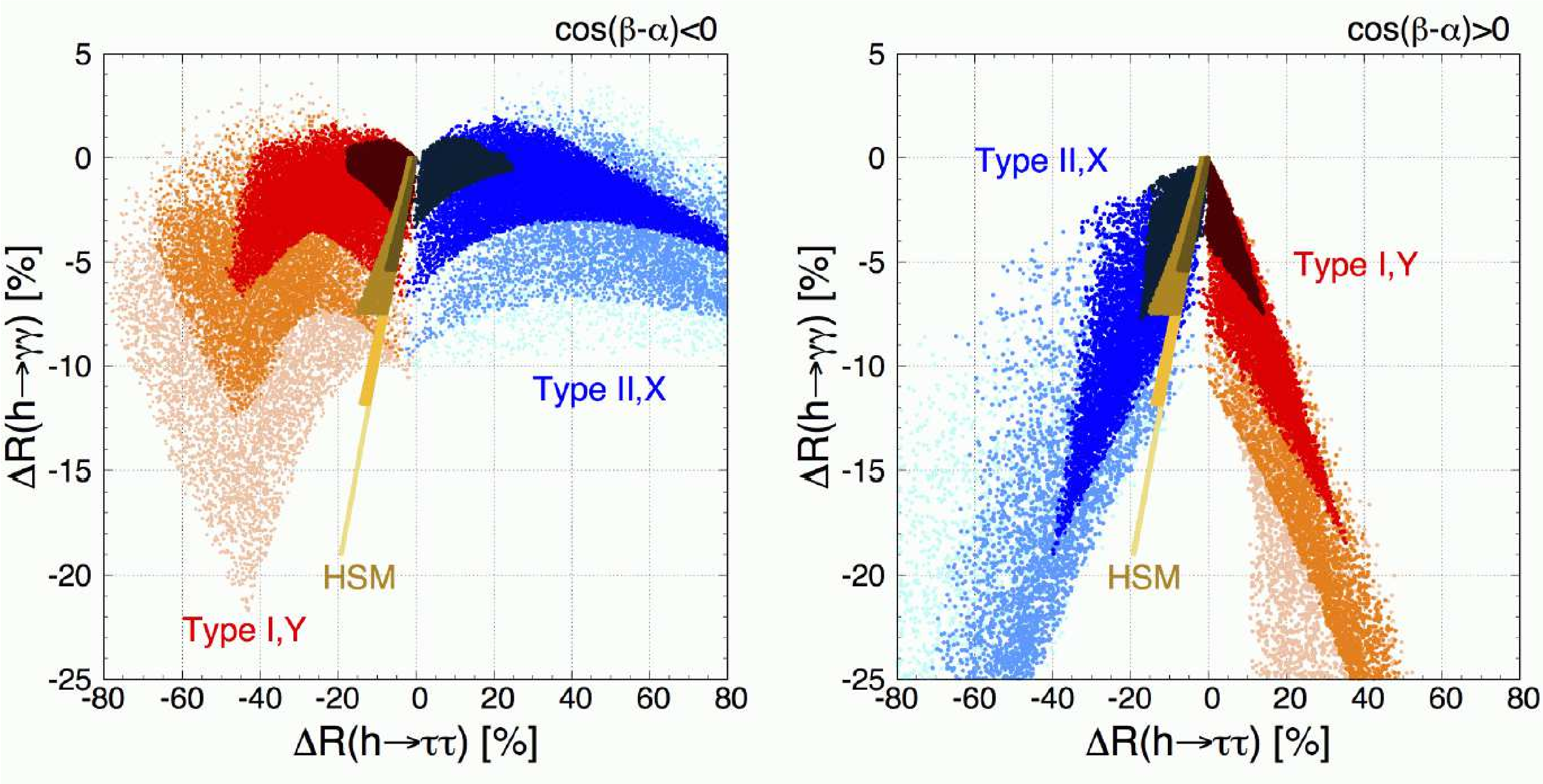
2HDM example (III): [S. Kanemura et al. '18]



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