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Higgs Physics at Future e^+e^- Colliders

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

zoom only, 10/2020

- Motivation
- Higgs precision measurements and BSM Physics scales
- The Higgs selfcoupling(s) at e^+e^- colliders
- BSM Higgs bosons below 125 GeV
- Conclusions

Higgs Physics at Future e^+e^- Colliders

in $\overbrace{\text{Spain}}$

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1. Motivation

Two Facts:

We have an SM-like Higgs discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

1. Motivation

Two Facts:

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Conclusion: It cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q': Which model?

A1: check changed properties

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

Higgs physics at future e^+e^- colliders:

- Measure precisely the h_{125} couplings to SM particles
  - consistency test of the SM
  - deviations from the SM
  - establish/measure new physics scales

- Measure precisely the Higgs selfcoupling(s)
  - deviations from the SM
  - performance if $\lambda_{hhh} \neq \lambda_{hhh}^{\text{SM}}$?
  - effects of additional Higgs bosons, enhanced triple Higgs couplings?

- Discovery of light BSM Higgs bosons
  - indirect discovery potential
  - direct discovery potential
  - precision measurements of BSM Higgs bosons

$\Rightarrow$ one example for each (currently investigated in Spain)

2. Higgs precision measurements and BSM Physics scales

What to expect from future colliders

$\Rightarrow$ focus on Higgs searches and measurements

HL-LHC:

– will improve direct search limits

– will improve rate measurements (production $\times$ decay)
systematic/theory uncertainties: S2 scenario

[*M. Cepeda et al. '19 – YR18*]

ILC:

– will improve rate measurements (no theory assumptions!)
- – $250\,\text{fb}^{-1}$ at ILC250 $\oplus$ $500\,\text{fb}^{-1}$ at ILC500
- – polarization: $P(e^-, e^+) = (-80\%, +30\%)$

[*T. Barklow et al. '17, '19*]

(roughly similar results at FCC-ee, CEPC, CLIC)

The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}
\end{aligned}
$$

$$
\begin{aligned}
V \;=\; & m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}\,|H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$
\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)
$$

Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

$\rightarrow$ investigate benchmark scenarios:

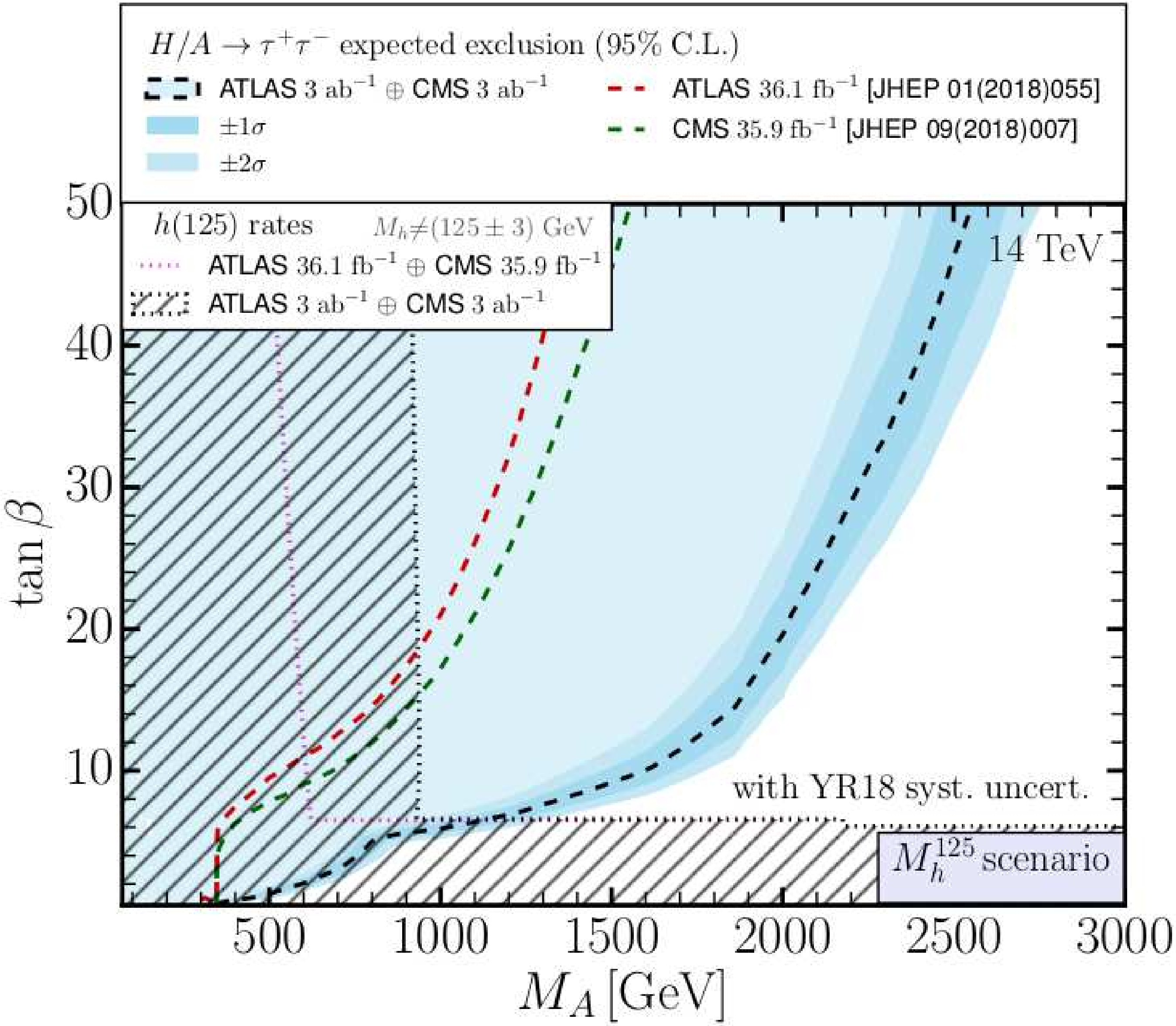
$\rightarrow$ Vary only M_A and $\tan\beta$
$\rightarrow$ Keep all other SUSY parameters fixed

[*E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel, P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18*]

1. M_h^{125} scenario: 2HDM-like model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^{\pm}\tilde{\chi}_l^{\mp}$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

HL-LHC reach in M_h^{125} scenario

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

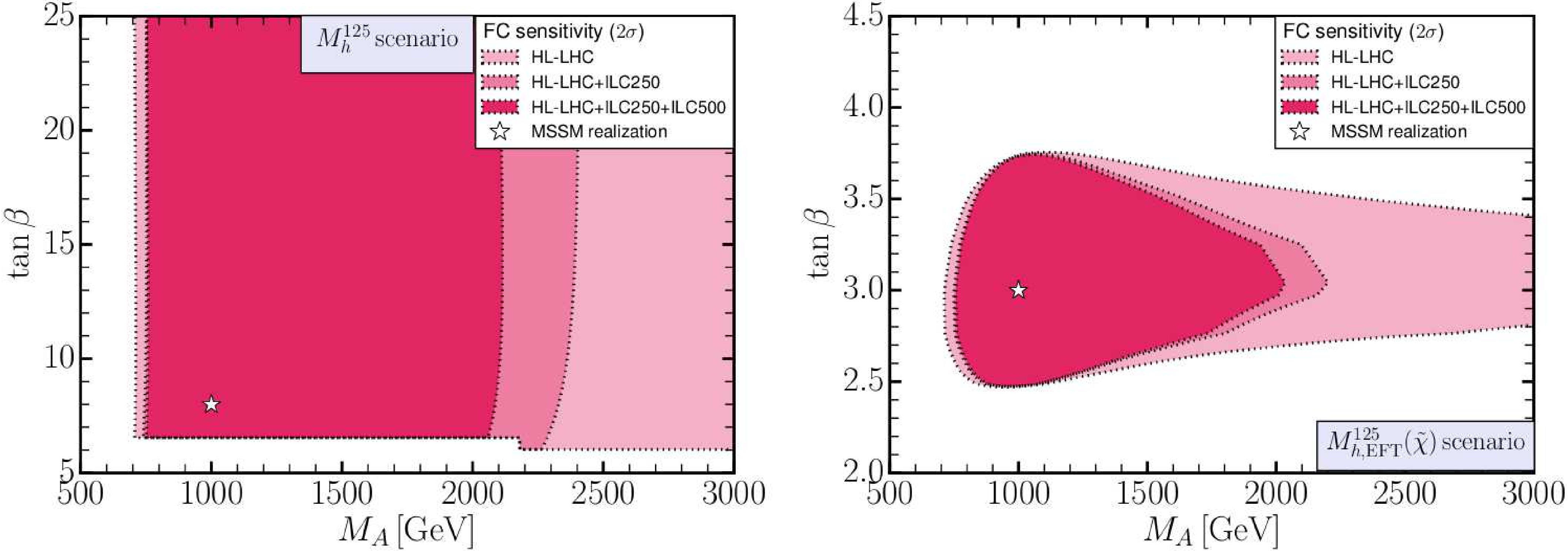


⇒ direct and indirect measurements: $M_A \gtrsim$ 1200 GeV

Relevance of ILC improvement:

[*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?



$\Rightarrow$ only ILC measurements give upper limit on M_A

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

Let us assume that we do see a deviation

What do we learn from that?
How do we learn something from that?

⇒ We have to compare the observed deviation with predicted deviations

⇒ Preferrably with the predicted deviations in a concrete models
(A comparison with an EFT result subsequently requires the mapping to concrete models anyway . . .)

⇒ Needed: sufficiently precise predictions in BSM model
close to ready: MSSM, NMSSM
(I am not aware of uncertainty estimates in other models)

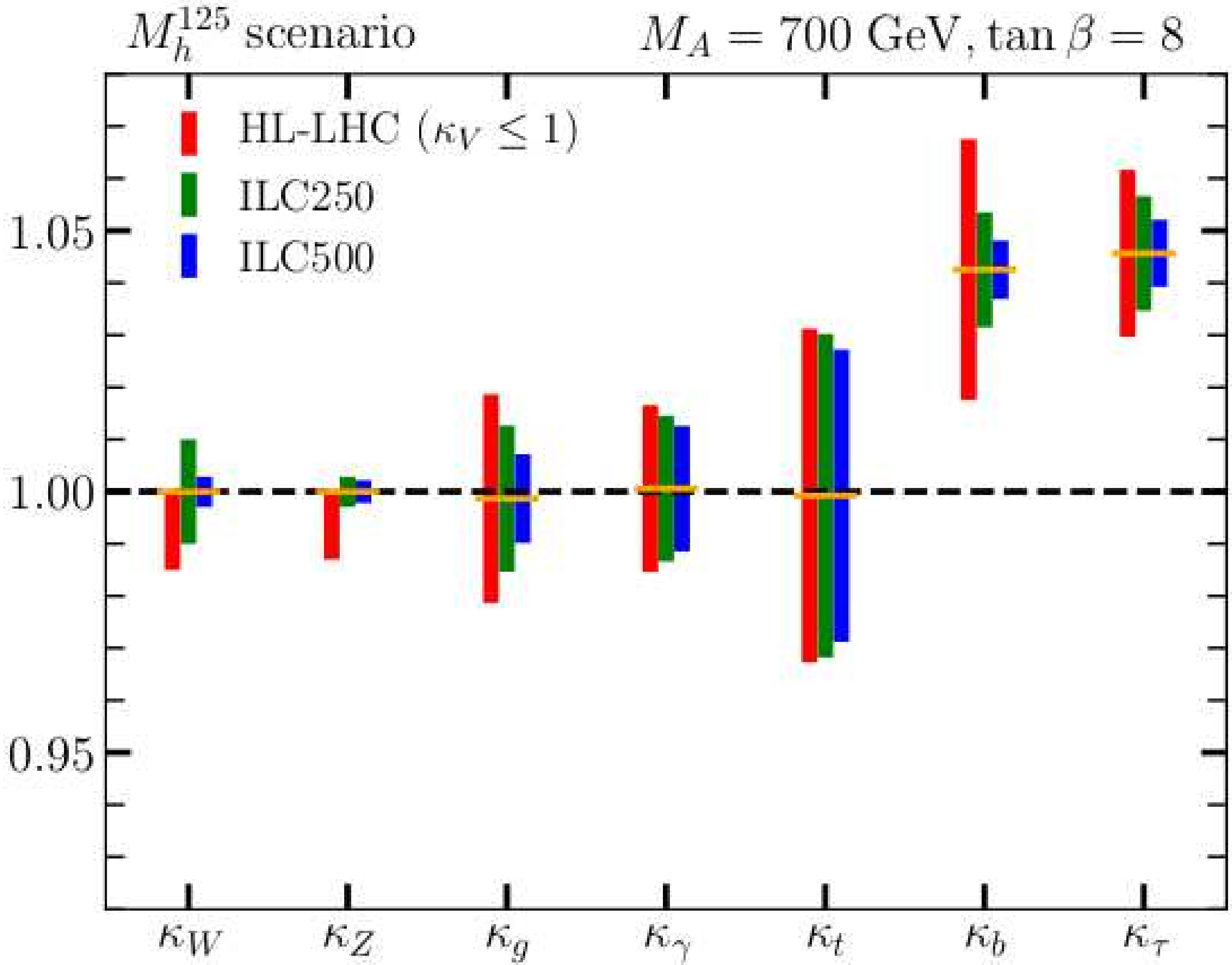
⇒ in the following:

model prediction (w/o TH unc.) ⇔ ILC precision (ILC500)

⇒ "Wäscheleinen-Plots" (Non-SUSY models in the back-up!)

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

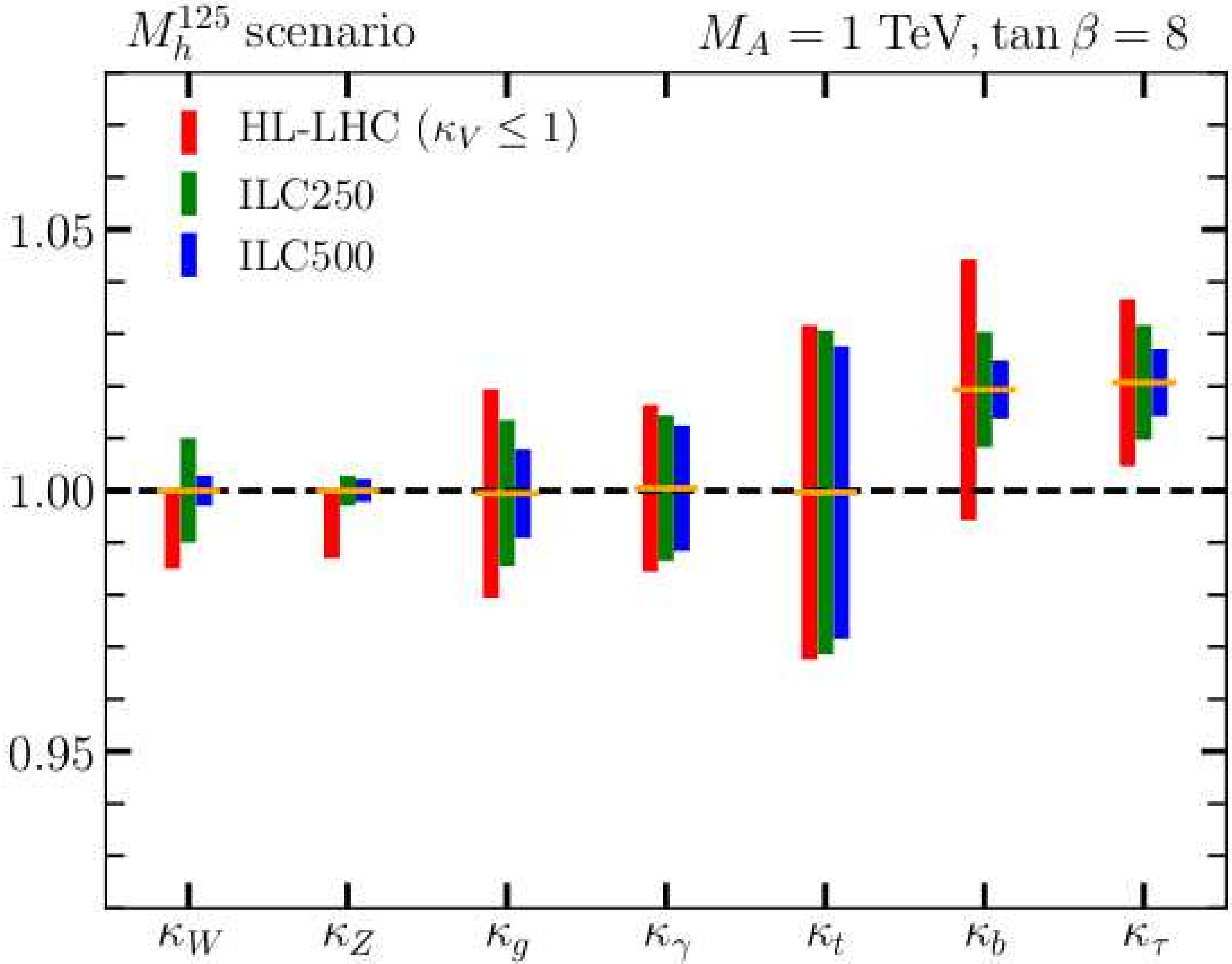
[*H. Bahl et al. '20*]



⇒ Type II deviations! Distinction from 2HDM possible?

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

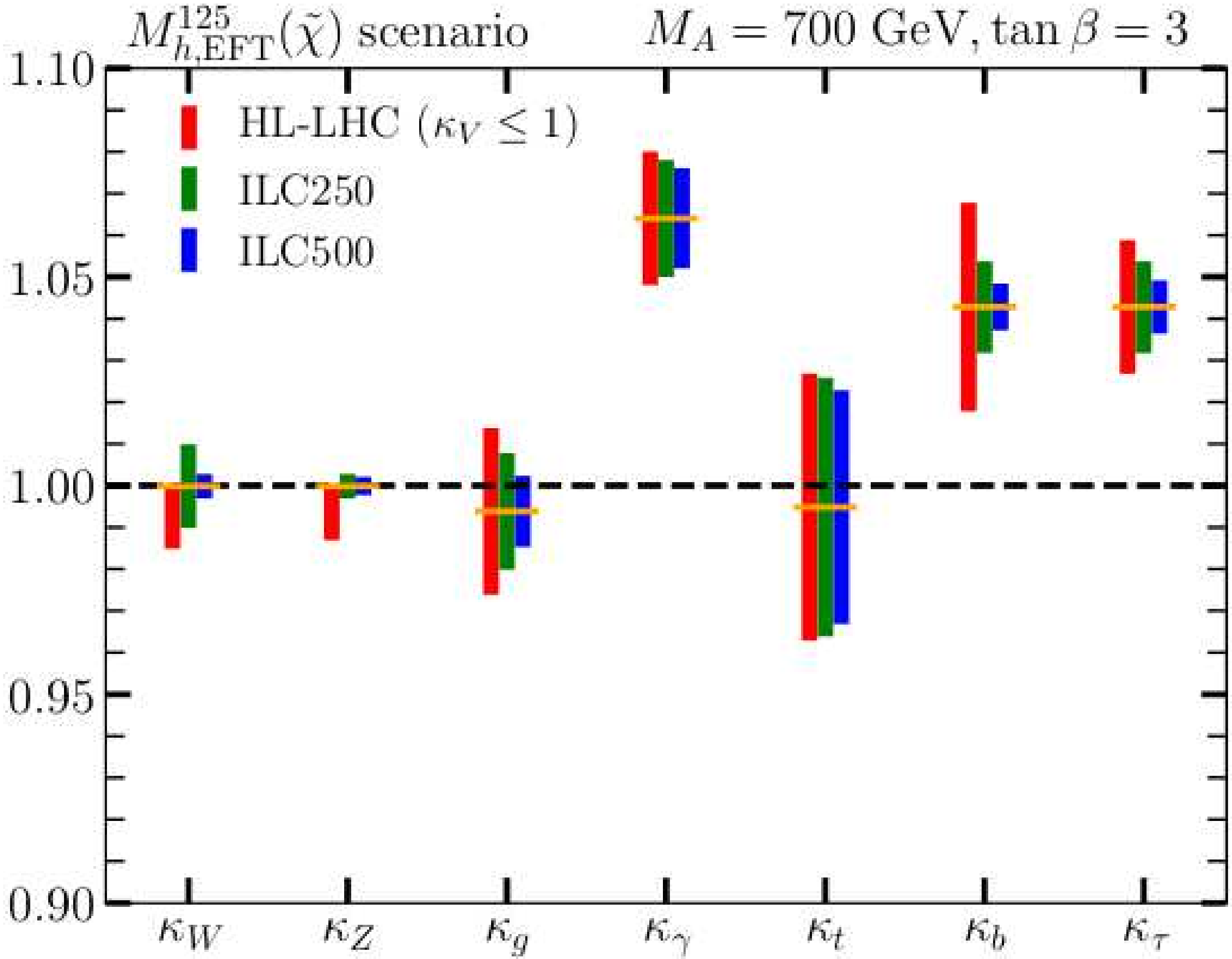
[*H. Bahl et al. '20*]



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

MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

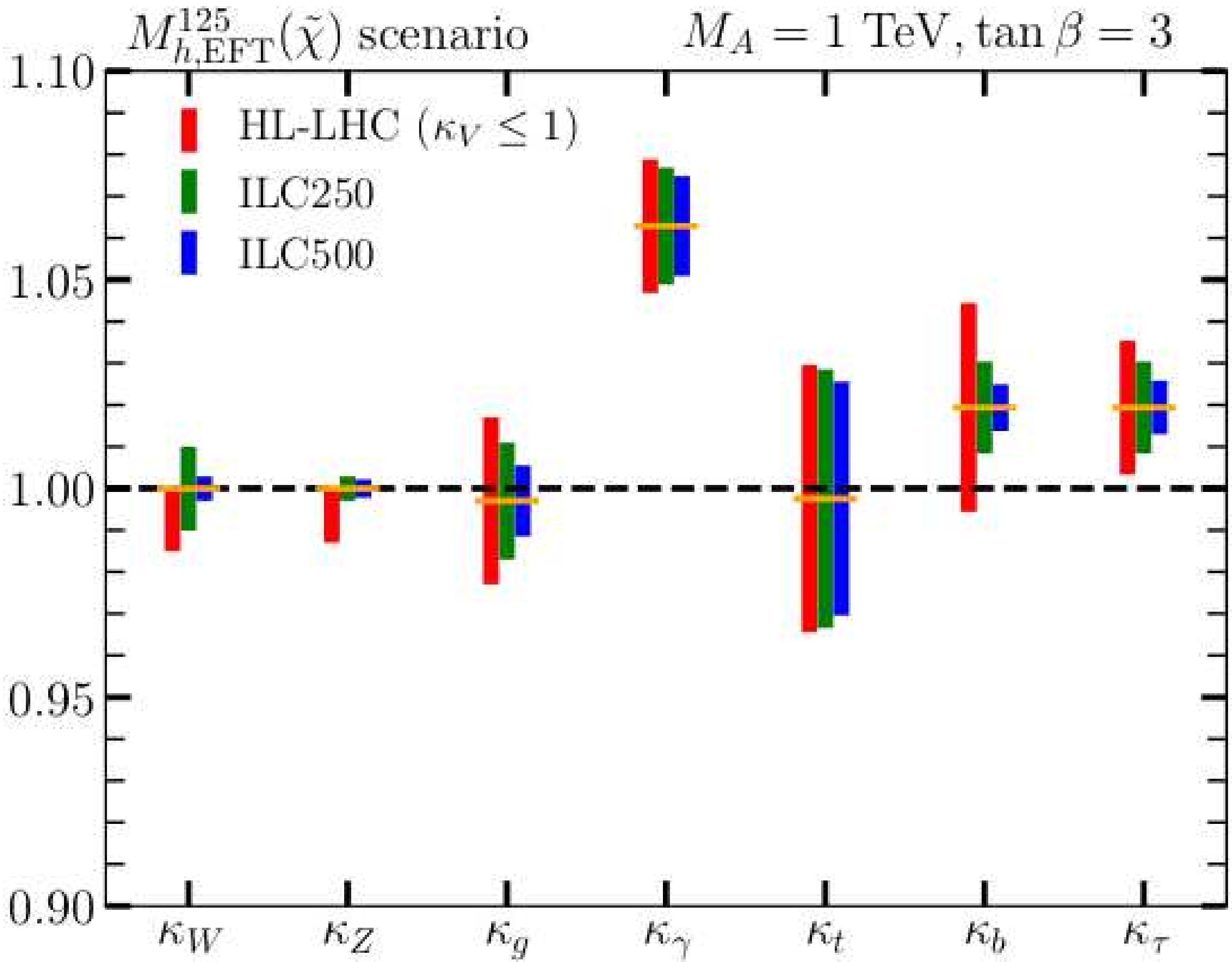
[*H. Bahl et al. '20*]



$\Rightarrow$ clear effect of light SUSY paticles

MSSM Wäscheleine IV: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 1000$ GeV, $\tan\beta = 3$)

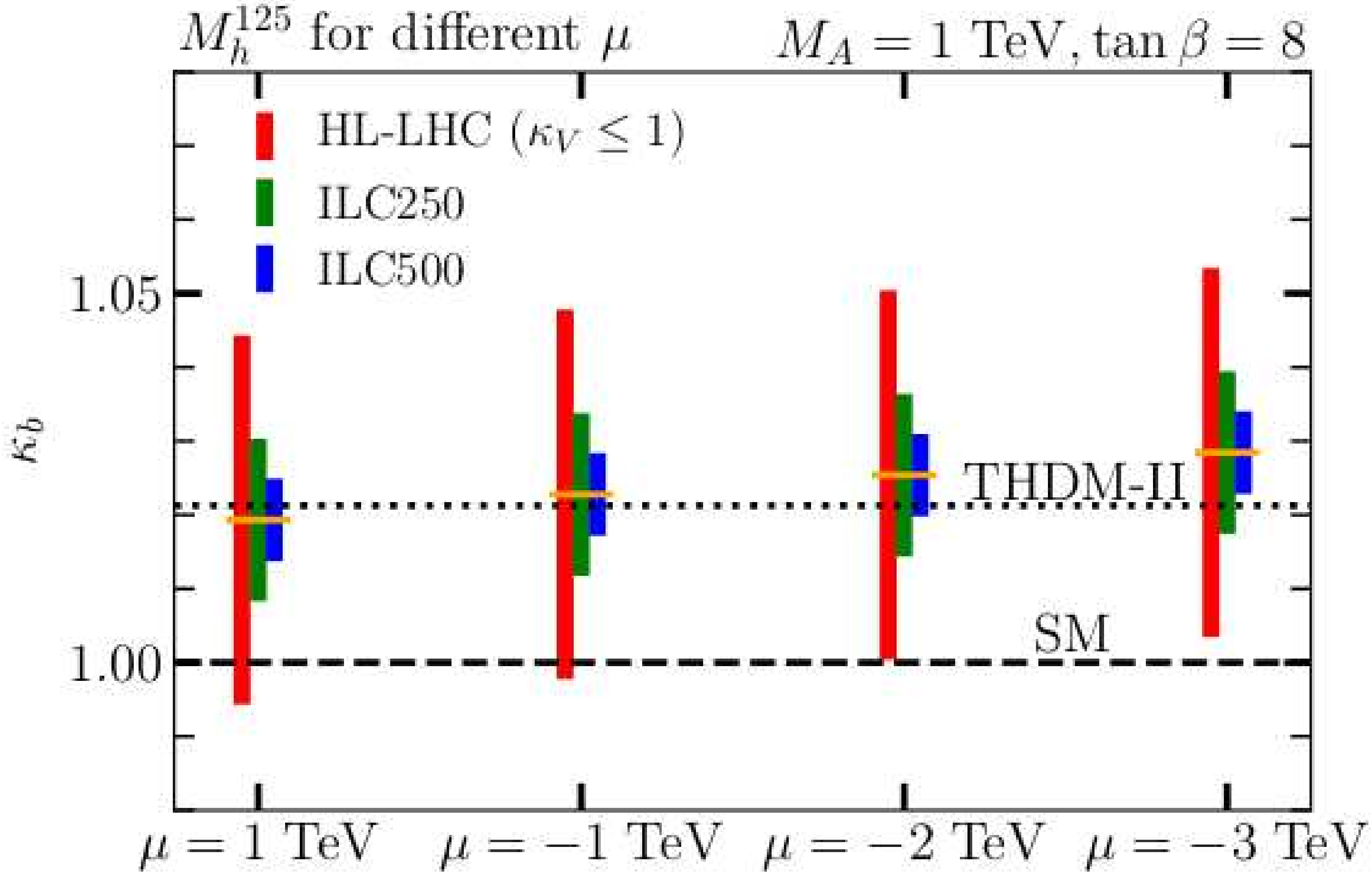
[*H. Bahl et al. '20*]



⇒ 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!

3. The Higgs selfcoupling(s) at e^+e^- colliders

Di-Higgs production: λ_{hhh} or $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM}}$

– deviations possible in BSM models
– which size is still allowed taking all constraints into account?
– implications for measurements at future colliders?

Di-Higgs production involving heavy Higgses: λ_{hhH}, λ_{hHH}, λ_{hAA}, $\lambda_{hH^+H^-}$

– large values of λ's possible?
– which size is still allowed taking all constraints into account?
– implications for searches at future colliders?

⇒ analysis in the 2HDM

[*F. Arco, S.H., M. Herrero '20*]

(several slides from F. Arco :-)

The 2HDM

Two Higgs Doublet Model *CP* conserving

The potential:
$$V = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

Considerations:

- ⋆ *CP* conserving $\longrightarrow$ all parameters are real
- ⋆ $\mathbb{Z}_2$ symmetry to avoid FCNC $\longrightarrow$ softly broken by m_{12}^2 **Very important!**
- ⋆ Four types of Yukawa structure (we will focus on type I and II)

CP odd

7 free parameters + 5 physical states: h, H, A, H^+ and H^-

CP even

Extension of Z_2 symmetry to fermions $\Rightarrow$ 4 types

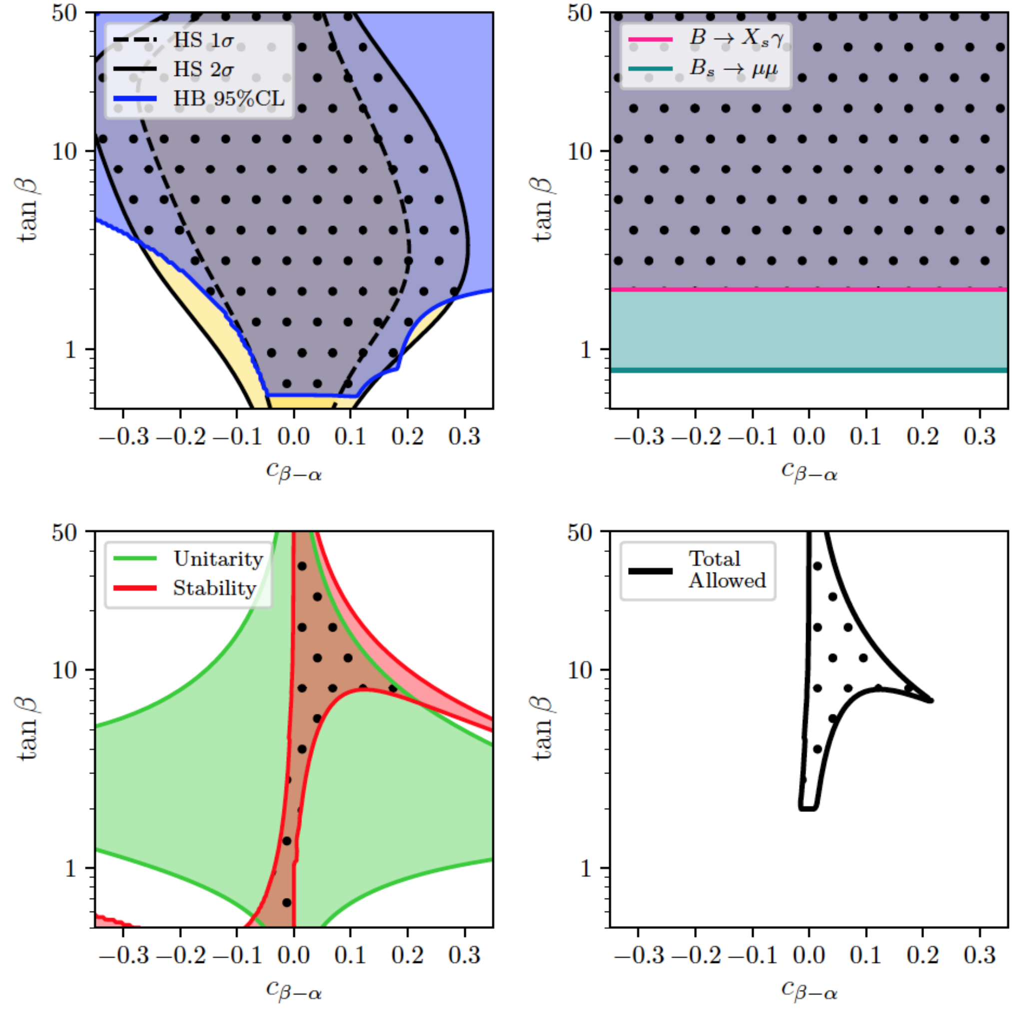
$\Rightarrow$ analyzed: type I and type II

The constraints:

$\rightarrow$ applied to every point analyzed/scanned/...

- Tree-level perturbativity
- Stability: potential is bounded from below
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds (2HDMC)
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (2HDMC)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso
- Electroweak precision data (S, T and U) $\Rightarrow$ 2HDMC

2HDM type I, scenario C

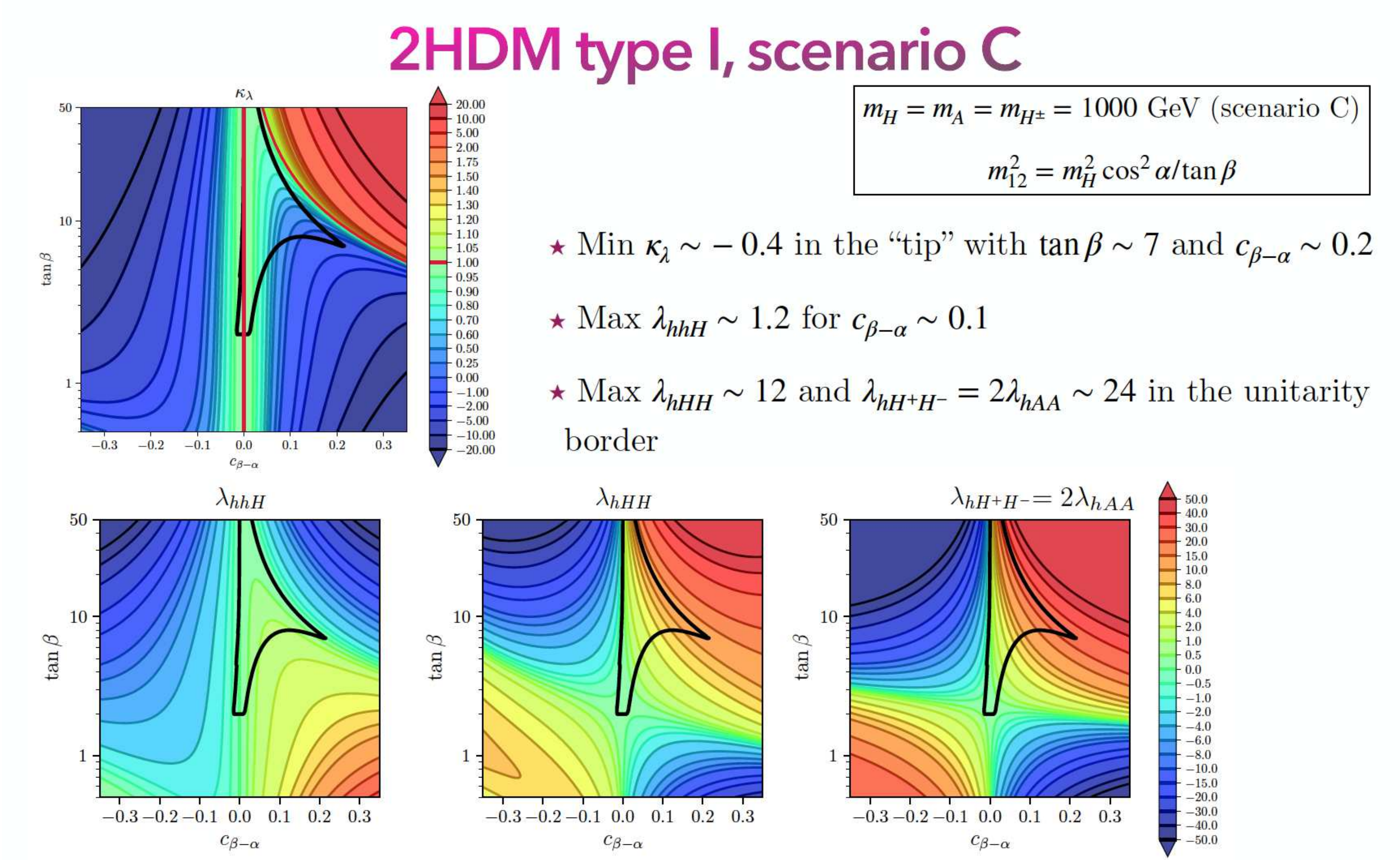


$m_H = m_A = m_{H^\pm} = 1000$ GeV (scenario C)

$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

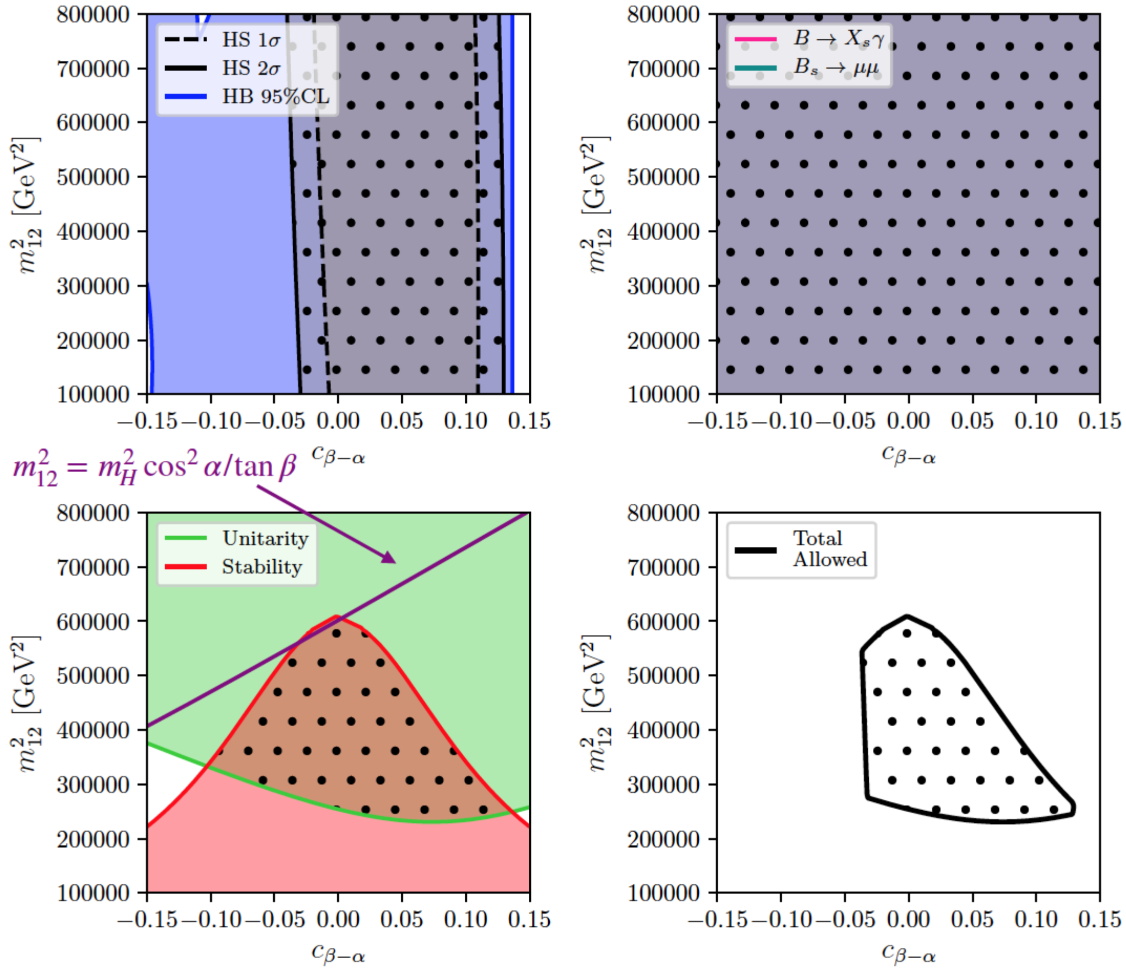
- ⋆ Collider searches imposes $|c_{\beta-\alpha}| \lesssim 0.3$
- ⋆ Low $\tan\beta$ disallowed by $B \to X_s\gamma$
- ⋆ Most stringent bounds from theoretical constraints, but helped by $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$

Example I: 2HDM type I: results



$\Rightarrow$ large deviations for κ_λ $\quad\Rightarrow$ large values for BSM λ's

2HDM type II, scenario C



$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ⋆ Collider measurements $c_{\beta-\alpha} \in [-0.05,\, 0.13]$ nearly independent of m_{12}^2
- ⋆ No bounds from flavor
- ⋆ Overlapped allowed region by unitarity and stability ($m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$ does not work here)

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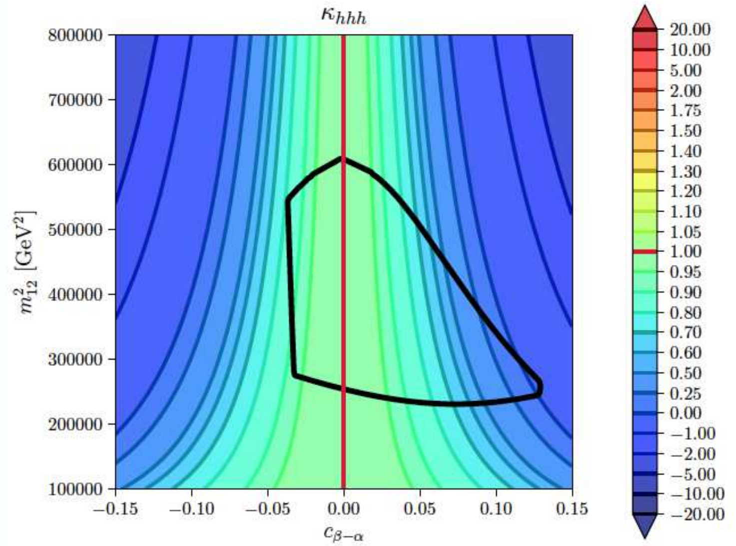
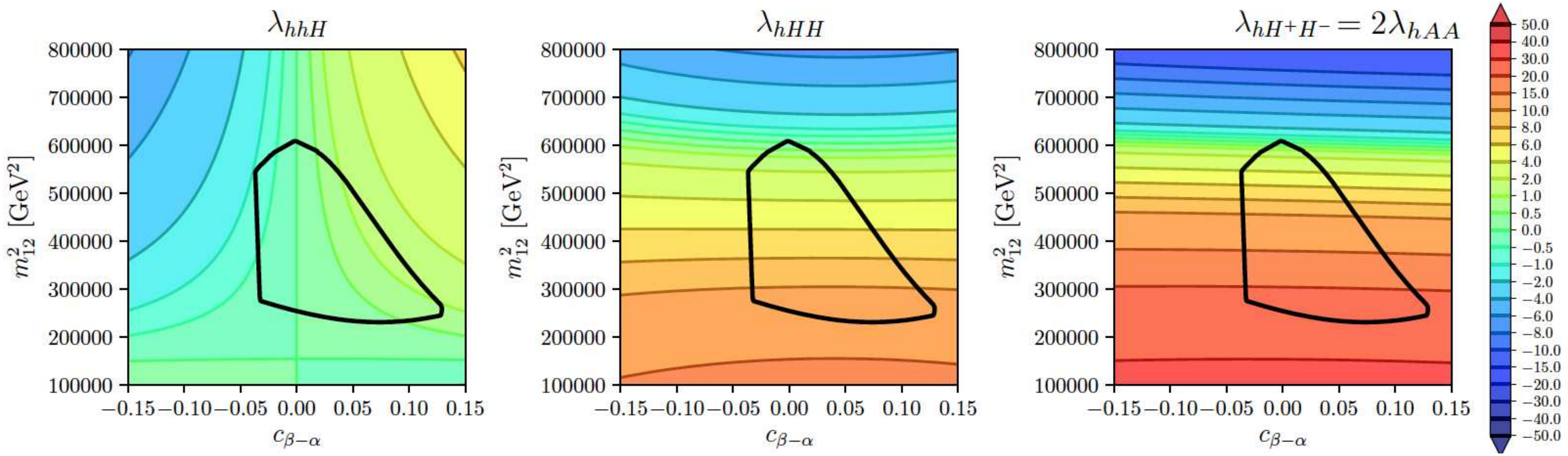
Example II: 2HDM type II: results

2HDM type II, scenario C



$$m_H = m_A = m_{H^\pm} = 1100 \text{ GeV (scenario C)}$$
$$\tan\beta = 0.9$$

- ⋆ Min $\kappa_\lambda \sim -1.0$ for max $c_{\beta-\alpha} \sim 0.13$
- ⋆ Allowed $\lambda_{hhH} \in [-1,\ 1.4]$
- ⋆ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ for min $m_{12}^2 \sim 2 \times 10^5$ GeV^2



$\Rightarrow$ large deviations for κ_λ $\Rightarrow$ large values for BSM λ's

Result overview:

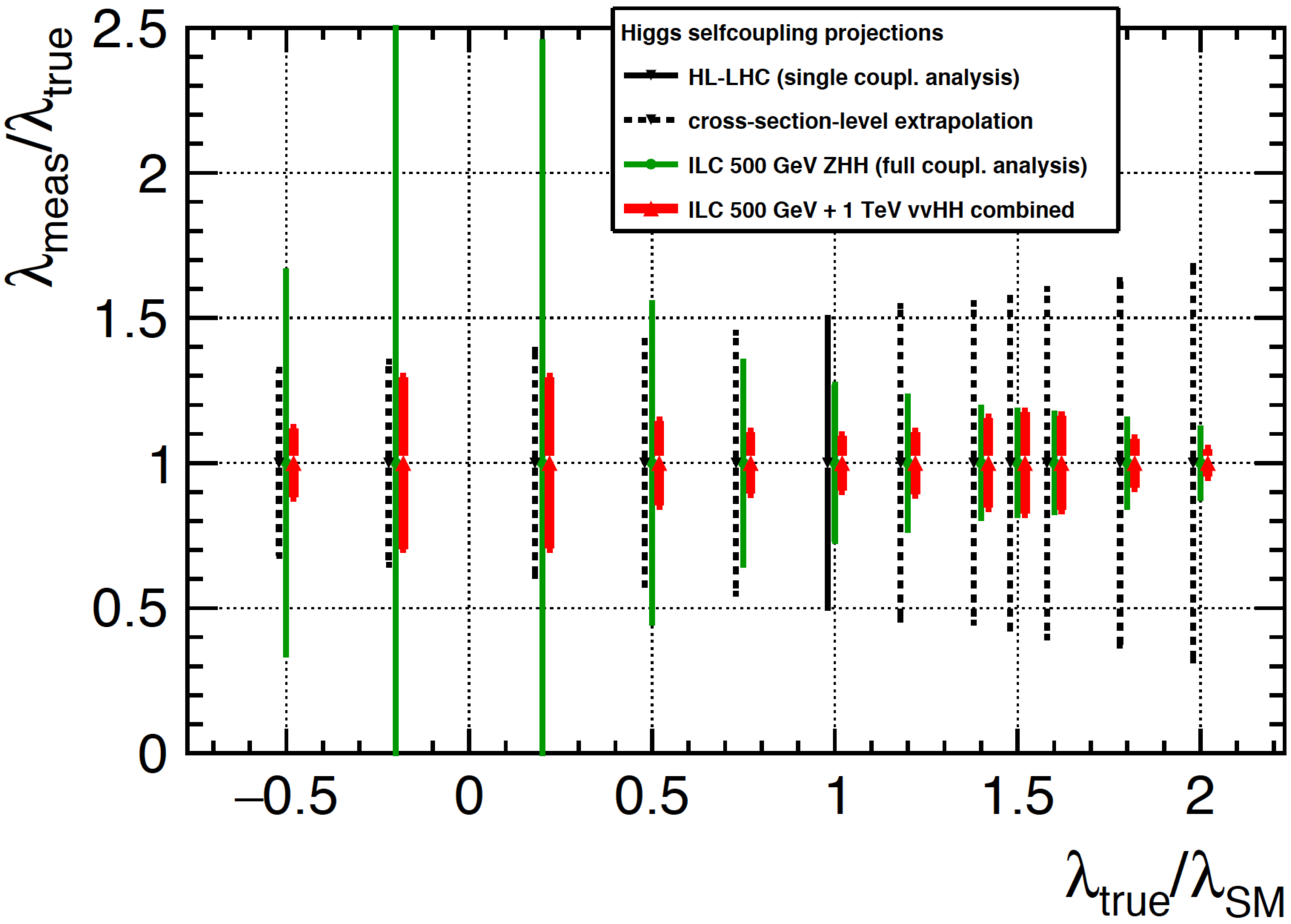
Final allowed ranges

Type I	Type II	
$\kappa_\lambda \in [-0.5,\ 1.5]$	$\kappa_\lambda \in [0.0,\ 1.0]$	→ Far from the alignment limit and playing with m_{12}^2
$\lambda_{hhH} \in [-1.4,\ 1.5]$	$\lambda_{hhH} \in [-1.6,\ 1.8]$	→ For $c_{\beta-\alpha} \sim \pm 0.05$
$\lambda_{hHH} \in [0,\ 15]$	$\lambda_{hHH} \in [0,\ 15]$	Large masses and nearly independent of $c_{\beta-\alpha}$ and scenario A or B
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$	
$\lambda_{hH^+H^-} \in [0,\ 32]$	$\lambda_{hH^+H^-} \in [0,\ 32]$	

✨ Interesting points are shown in our paper [arXiv:2005.10576] ✨

Measurement of the triple Higgs selfcoupling

[J. List et al. – PRELIMINARY]



$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

Production cross sections at (high-energy) e^+e^- colliders

[F. Arco, S.H., M. Herrero – PRELIMINARY]

⇒ many benchmark points proposed ⇒ example "point 6":

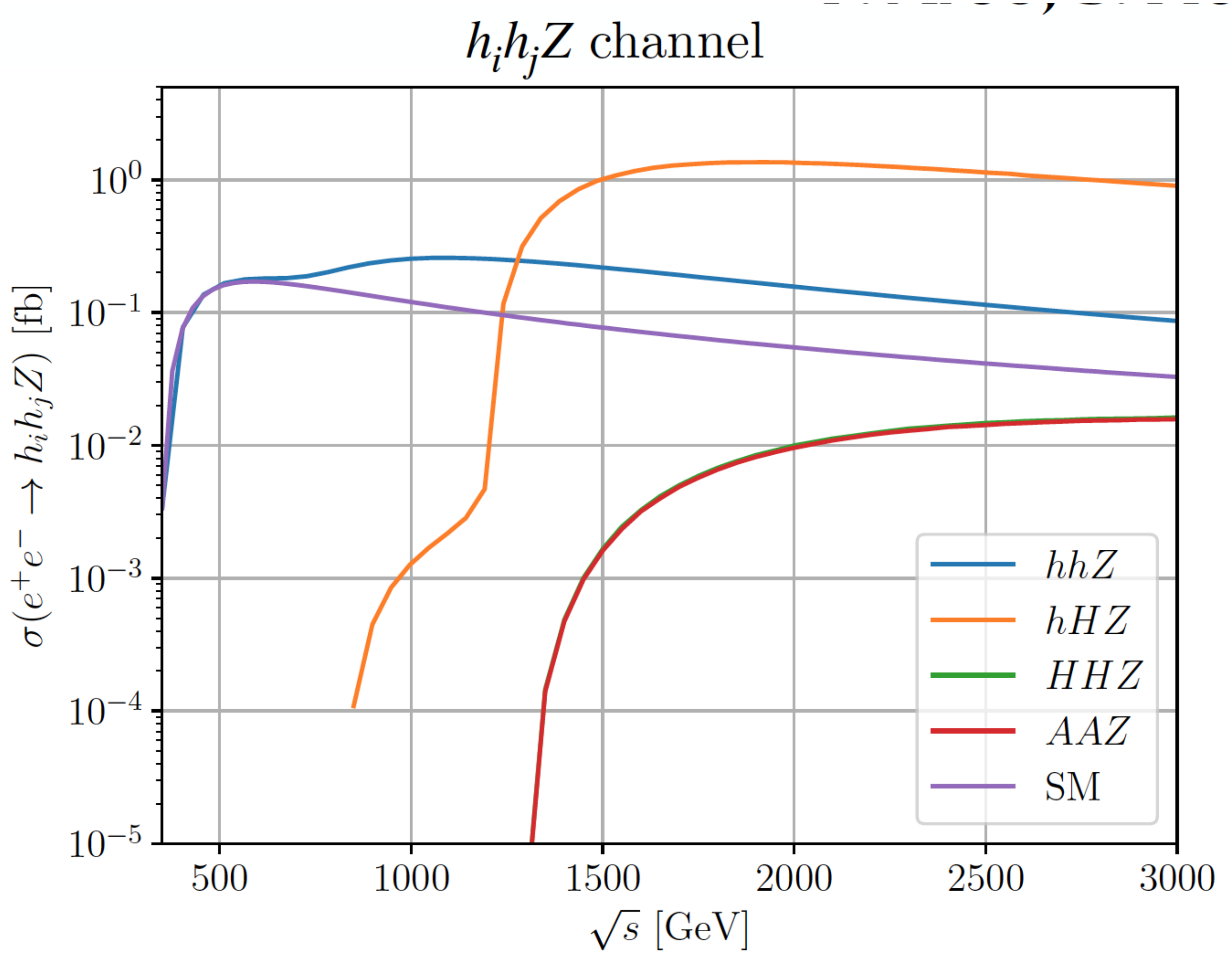
Proposed benchmark point: 2HDM type I

Input:	Output:
$m_h = 125$ GeV	$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM} \simeq 1$
$m_H = m_A = m_{H^\pm} = 600$ GeV	$\lambda_{hhH} = -0.5$
$\tan\beta = 10$	$\lambda_{hHH} = \lambda_{hAA} = 6$
$\cos(\beta - \alpha) = 0.2$	$\lambda_{hH^+H^-} = 12$
$m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta \simeq 36000$ GeV^2	

⇒ contribution to new Snowmass HH initiative

Various di-Higgs production cross sections I: (P6)

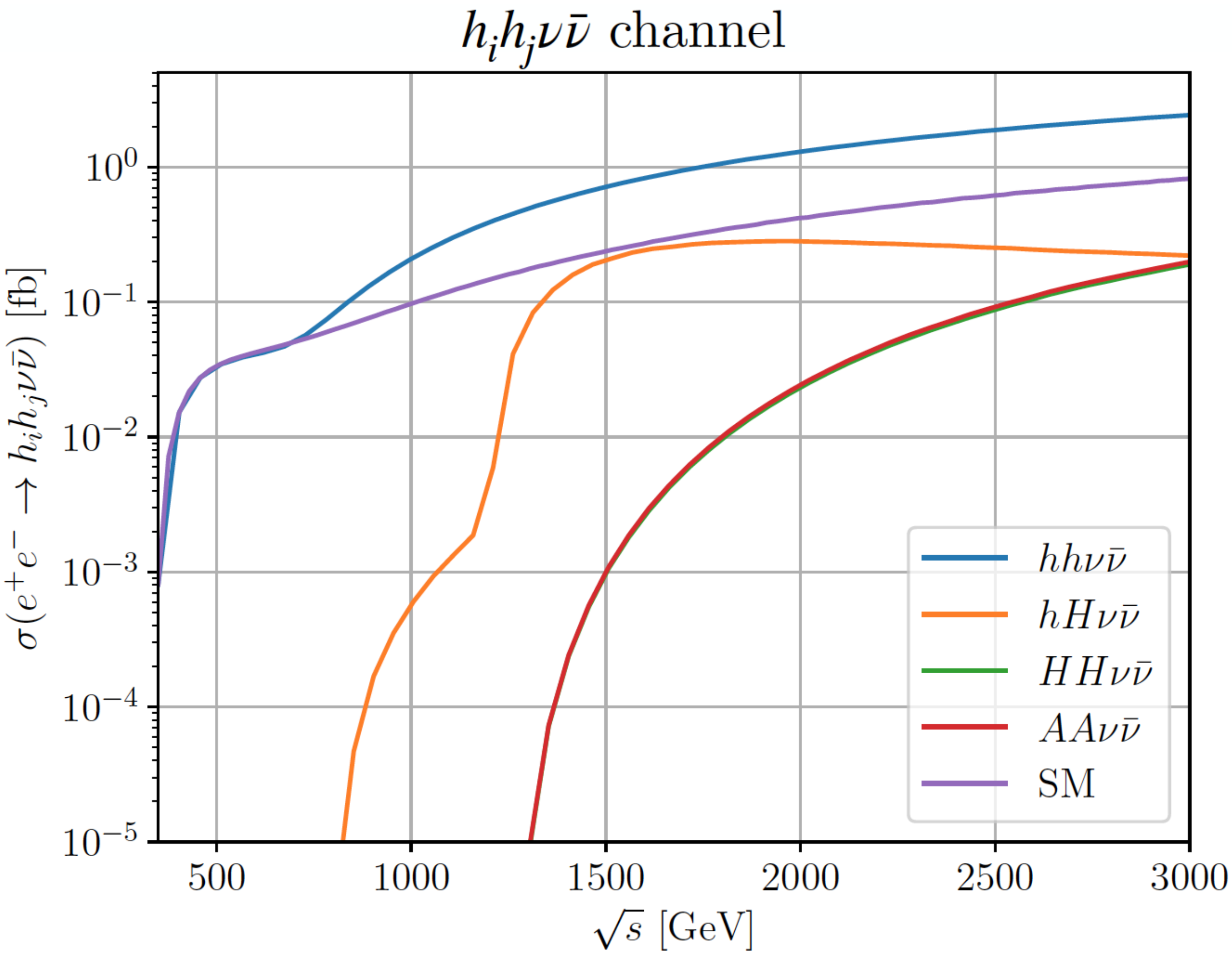
[*F. Arco, S.H., M. Herrero – PRELIMINARY*]



⇒ strong enhancement w.r.t. SM XS, large BSM XS's

Various di-Higgs production cross sections II: (P6)

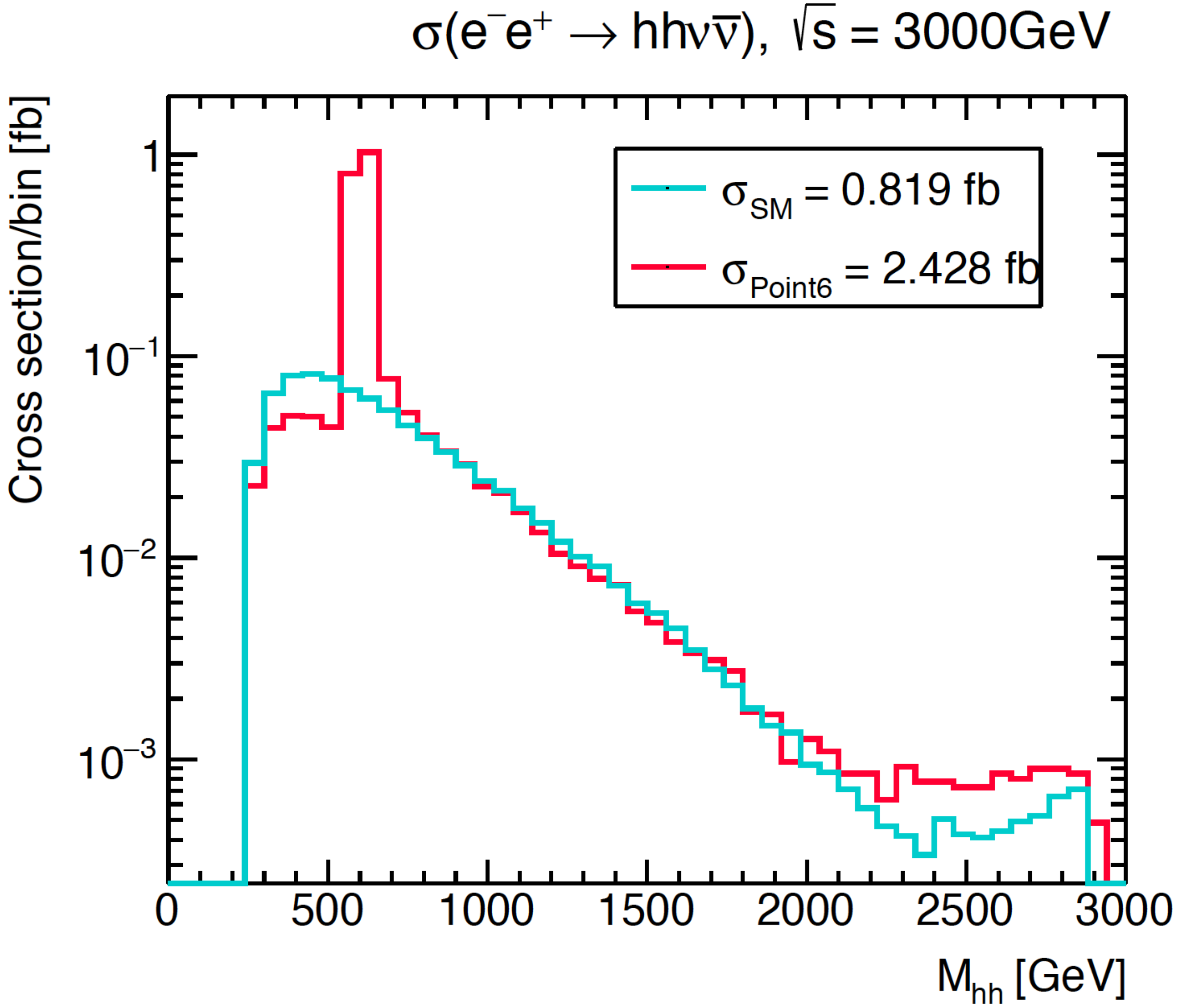
[F. Arco, S.H., M. Herrero – PRELIMINARY]



⇒ strong enhancement w.r.t. SM XS, large BSM XS's

Invariant mass distribution: (P6)

[F. Arco, S.H., M. Herrero – PRELIMINARY]



⇒ heavy Higgs boson in the s-channel strongly contributes

4. BSM Higgs bosons below 125 GeV

— Is there an excess?
  There are 2.5!

— Can this be explained?

— indirect HL-LHC/ILC opportunities
  (Similar for FCC-ee, CEPC! CLIC?)

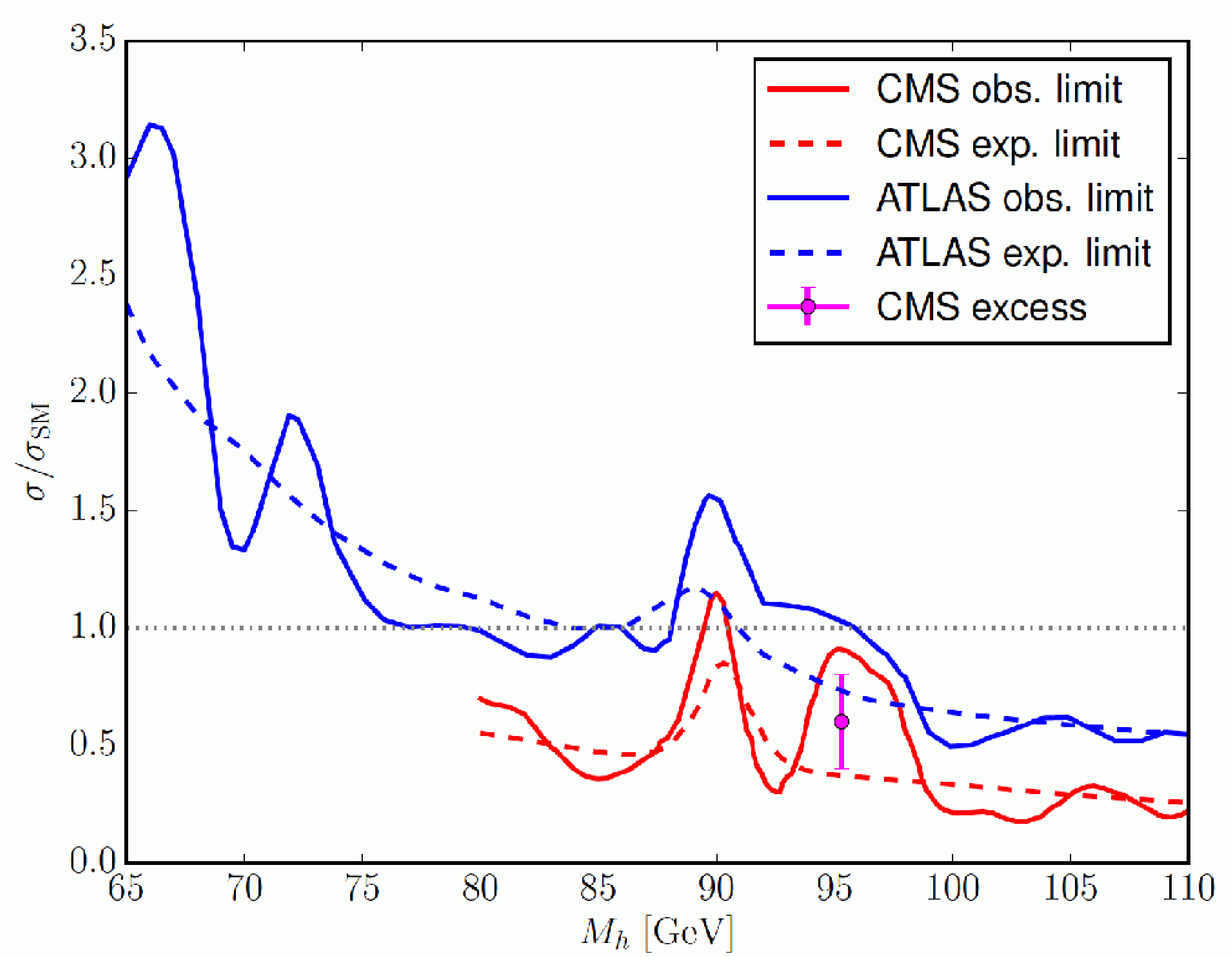
— direct ILC opportunities

What was seen at CMS and ATLAS?

[CMS '17, ATLAS '18, S.H., T. Stefaniak '18]

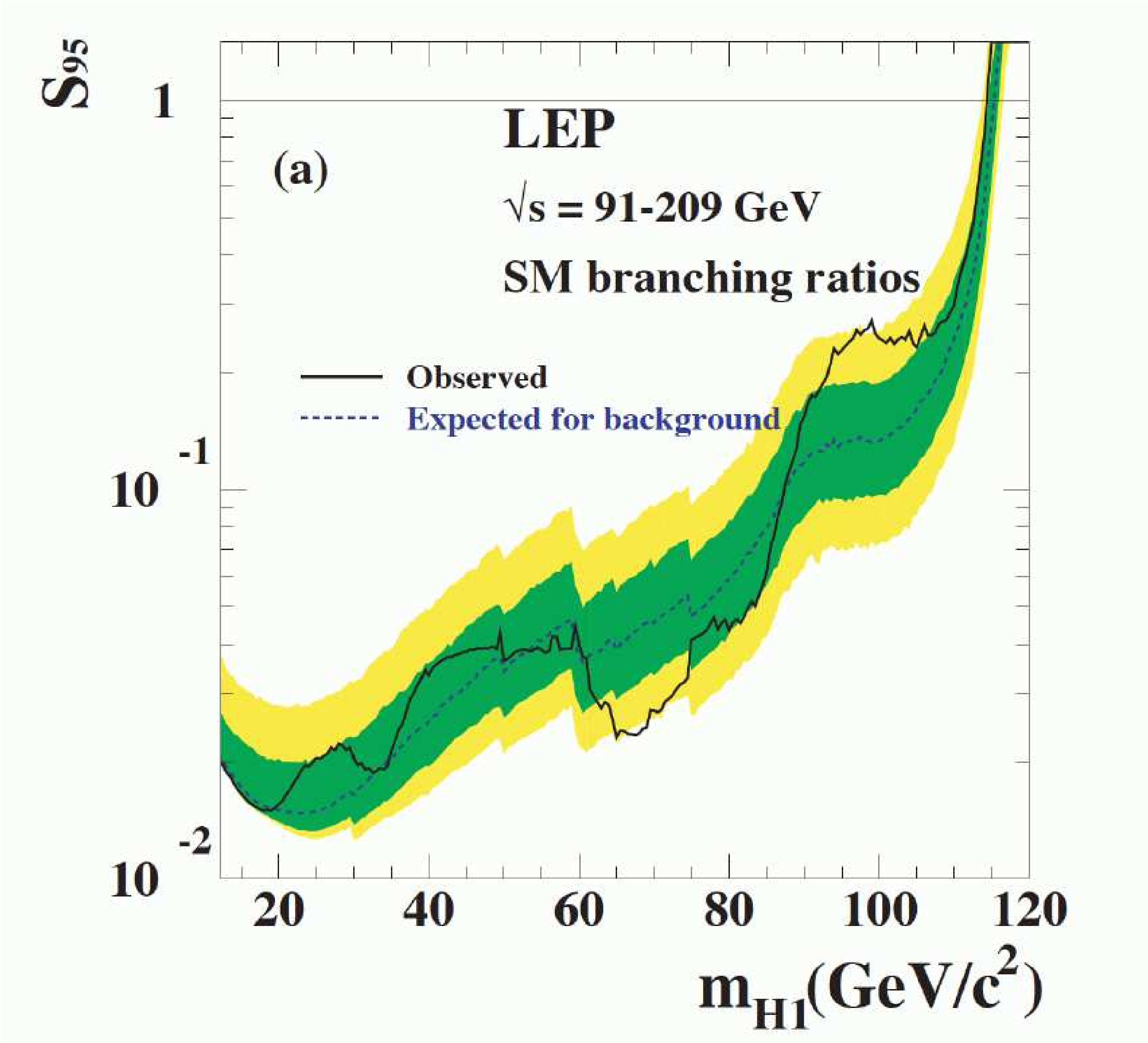
Search for $pp \to \phi \to \gamma\gamma$ with $m_\phi \leq 125$ GeV

$\mu_{\rm CMS} = 0.6 \pm 0.2$



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

What was seen at LEP?



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

Investigation in BSM Higgs models: **N2HDM**

[*T. Biekötter, M. Chakraborti, S.H. '19*]

Fields:

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

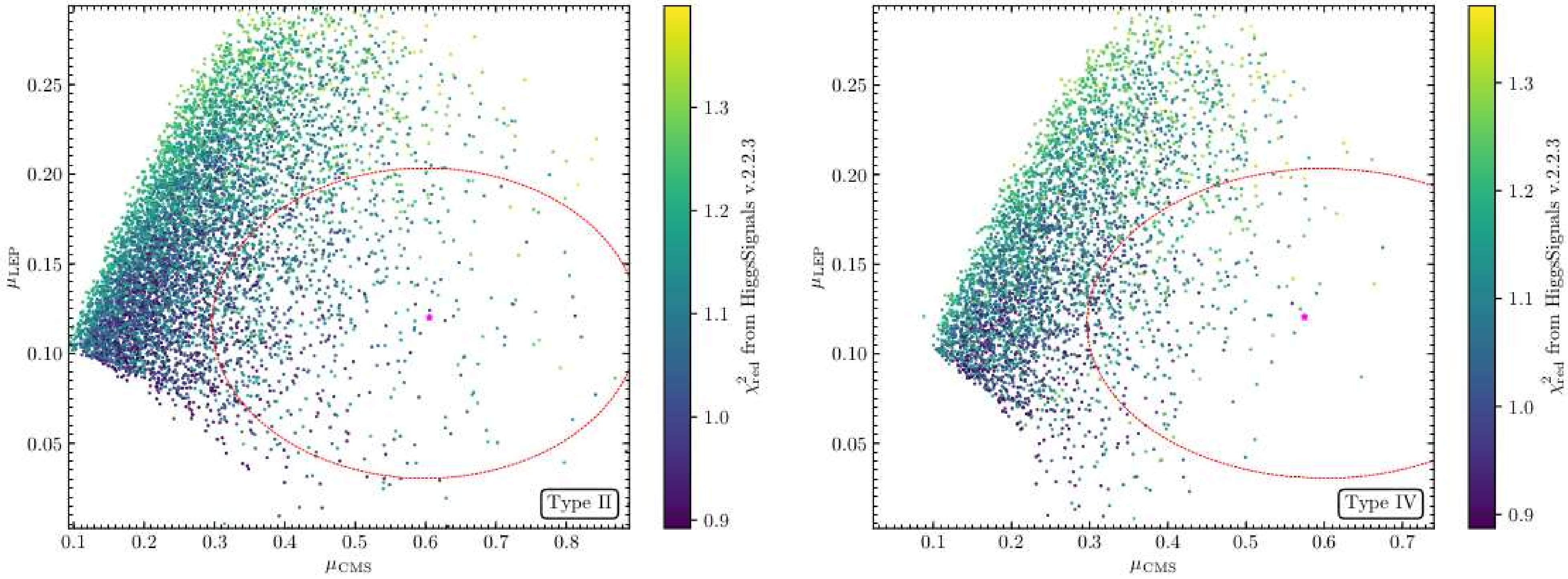
Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

	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

Fitting the excesses:

[*T. Biekötter, M. Chakraborti, S.H. '19*]



⇒ excesses well fitted, with good $\chi^2_{\rm red}$: 0.9 – 1.3

⇒ preferred $M_{H^\pm}$: 650 GeV – 950 GeV (lower limit: flavor constr.)
⇒ preferred $\tan\beta$: 0.8 – 3.8

What can we learn from future measurements?

– LHC h_{125} coupling measurements

– HL-LHC h_{125} coupling measurements

– ILC (or other e^+e^- coll.) h_{125} coupling measurements

– NEW: ILC (or other e^+e^- coll.) ϕ_{96} coupling measurements
[*S.H., P. Toledo '20*]

– direct production of ϕ_{96} at the LHC

– direct production of ϕ_{96} at the HL-LHC

– direct production of ϕ_{96} at the ILC (or other e^+e^- coll.)

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

What can we learn from future measurements?

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

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

- ILC (or other e^+e^- coll.) h_{125} coupling measurements $\Leftarrow$ focus

- NEW: ILC (or other e^+e^- coll.) ϕ_{96} coupling measurements $\Leftarrow$ focus
  [*S.H., P. Toledo '20*]

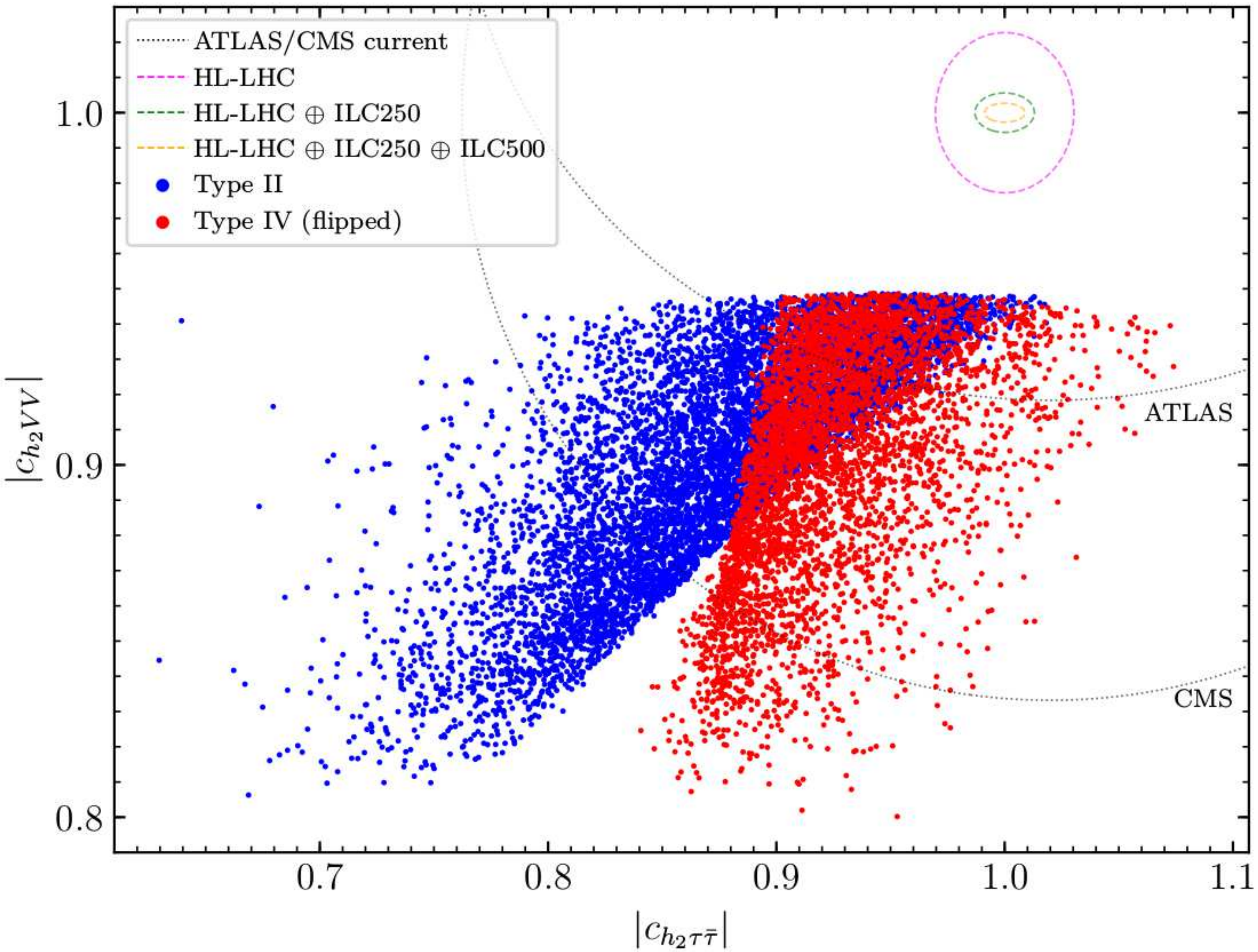
- direct production of ϕ_{96} at the LHC

- direct production of ϕ_{96} at the HL-LHC

- direct production of ϕ_{96} at the ILC (or other e^+e^- coll.) $\Leftarrow$ focus

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

Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

Probes of the 96 GeV Higgs at the ILC

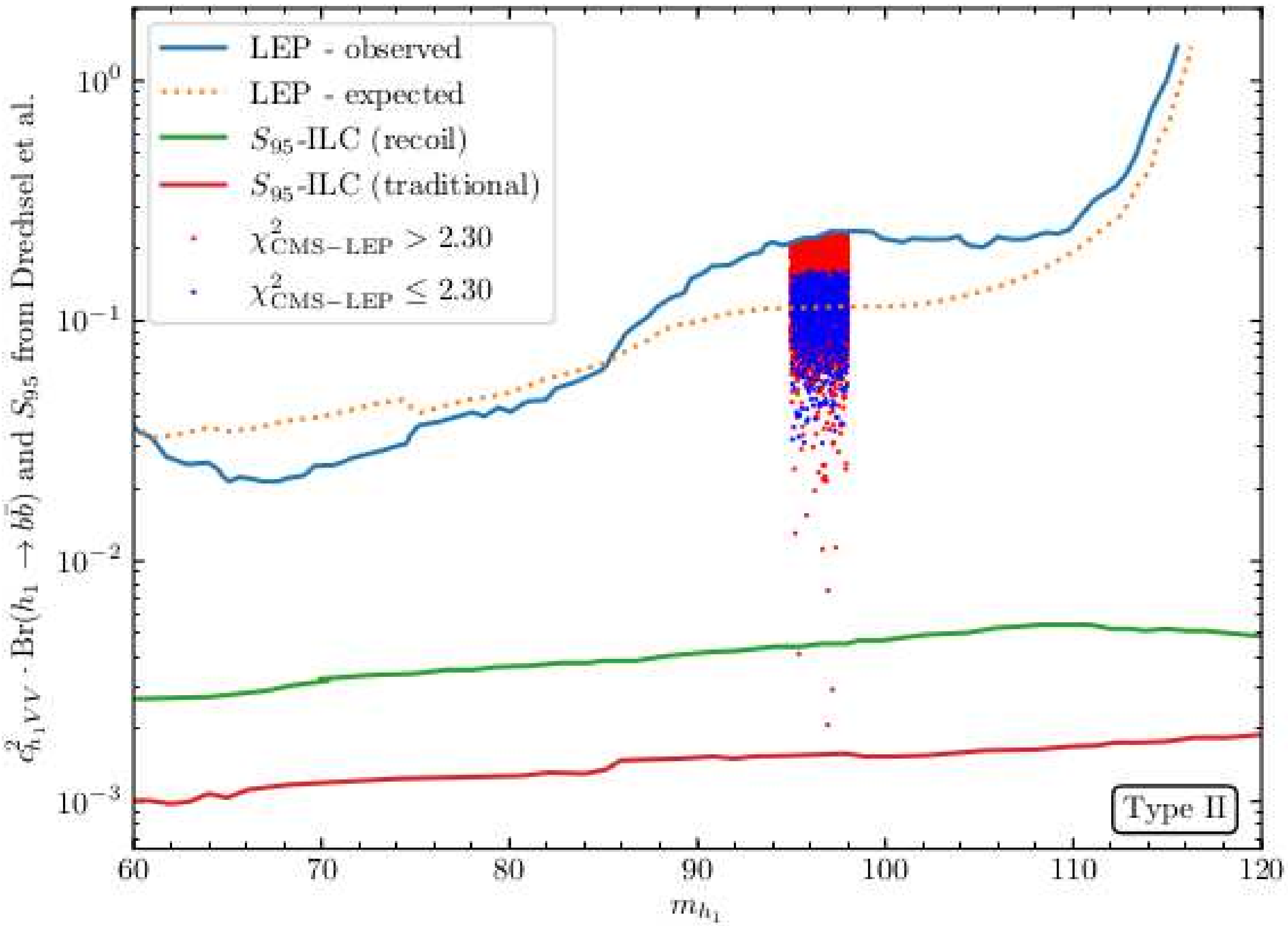
– Direct production at the ILC
  Uses work by:
  [*P. Drechsel, G. Moortgat-Pick, G. Weiglein '18*]
  [*Y. Wang, M. Berggren, J. List '20*]

– Coupling measurements at the ILC [*S.H., P. Toledo '20*]
  Thanks go to:
  – T. Biekötter (for the data and discussions)
  – M. Cepeda (for her help with the formulas)
  – J. List (for help on S/B in BSM models)
  – J. Tian (for help on S/B in the SM)
  – C. Schappacher (for some production cross sections)

$\Rightarrow$ focus on "good" points with $\chi^2_{\text{CMS}-\text{LEP}} < 2.3$

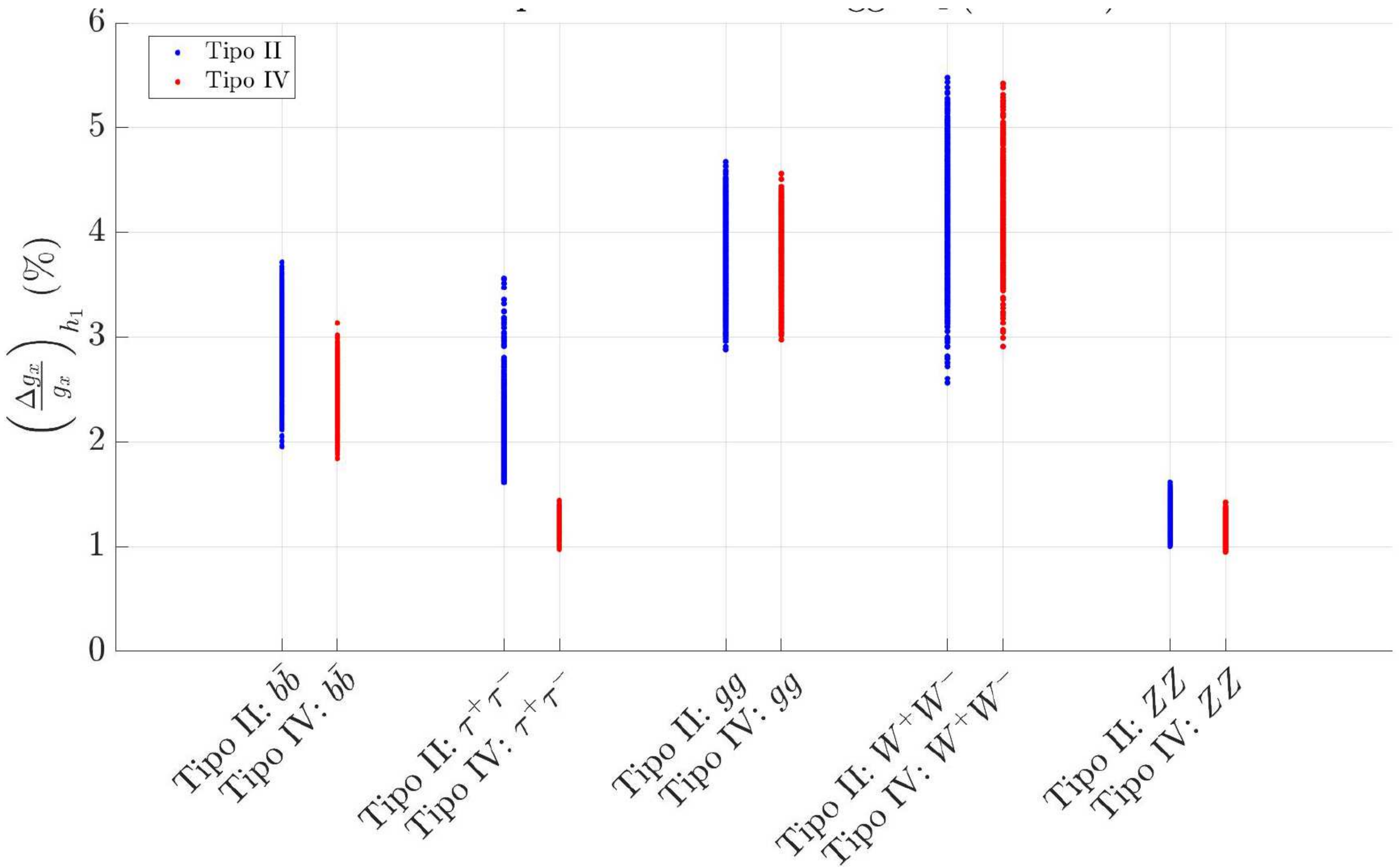
Next project? ⇒ ILC production of the light scalar

[*T. Biekötter, M. Chakraborti, S.H. '19*]



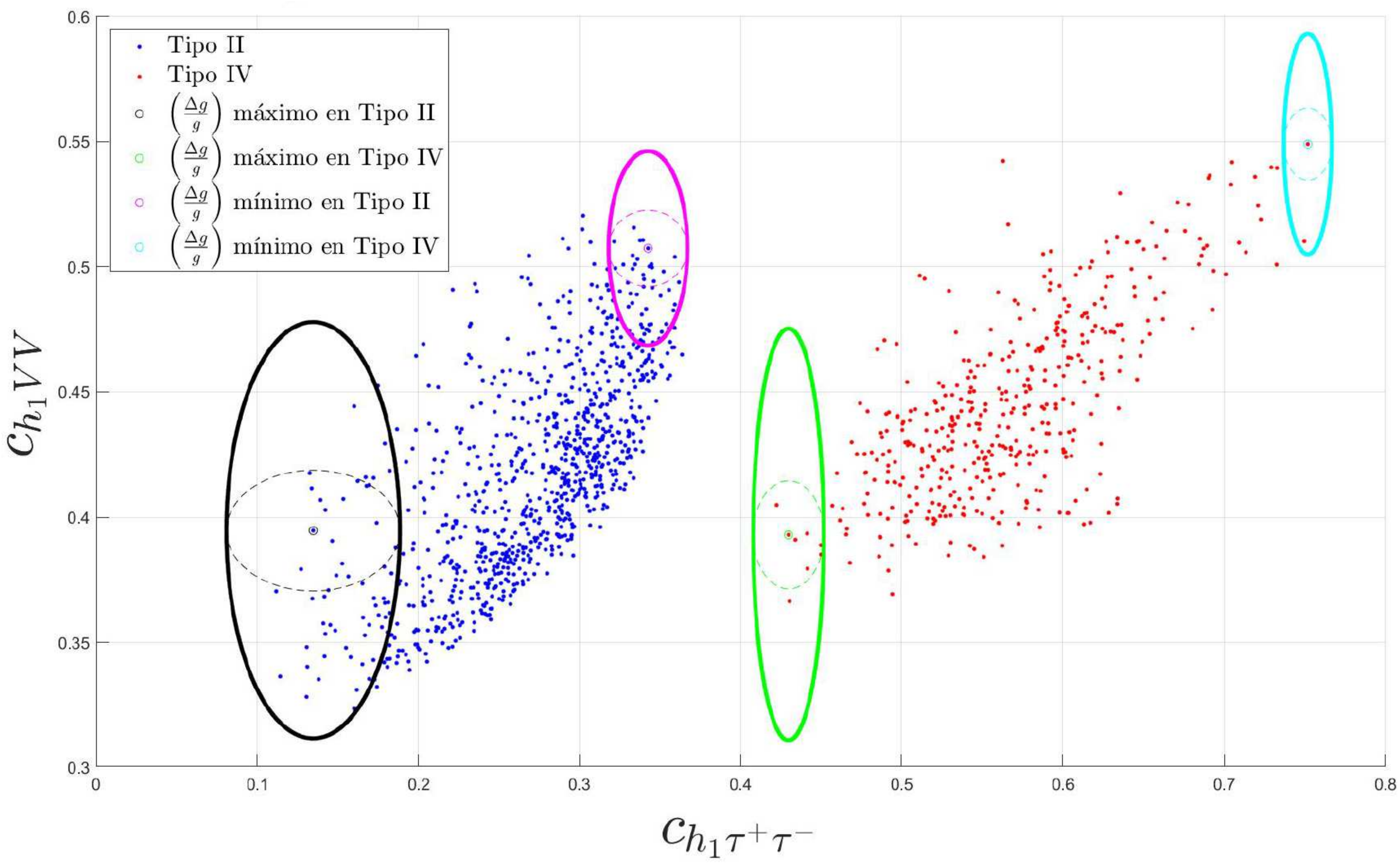
⇒ new state easily in the reach of the ILC ⇒ coupling measurements

N2HDM: precision of ILC coupling measuements [S.H., P. Toledo '20]



$\Rightarrow \mathcal{O}(1-5\%)$: g_Z best from production, g_τ very precise in type IV

N2HDM: $\tau\tau$ vs. WW/ZZ: [S.H., P. Toledo '20]



$\Rightarrow$ model distinction possible via coupling measurements

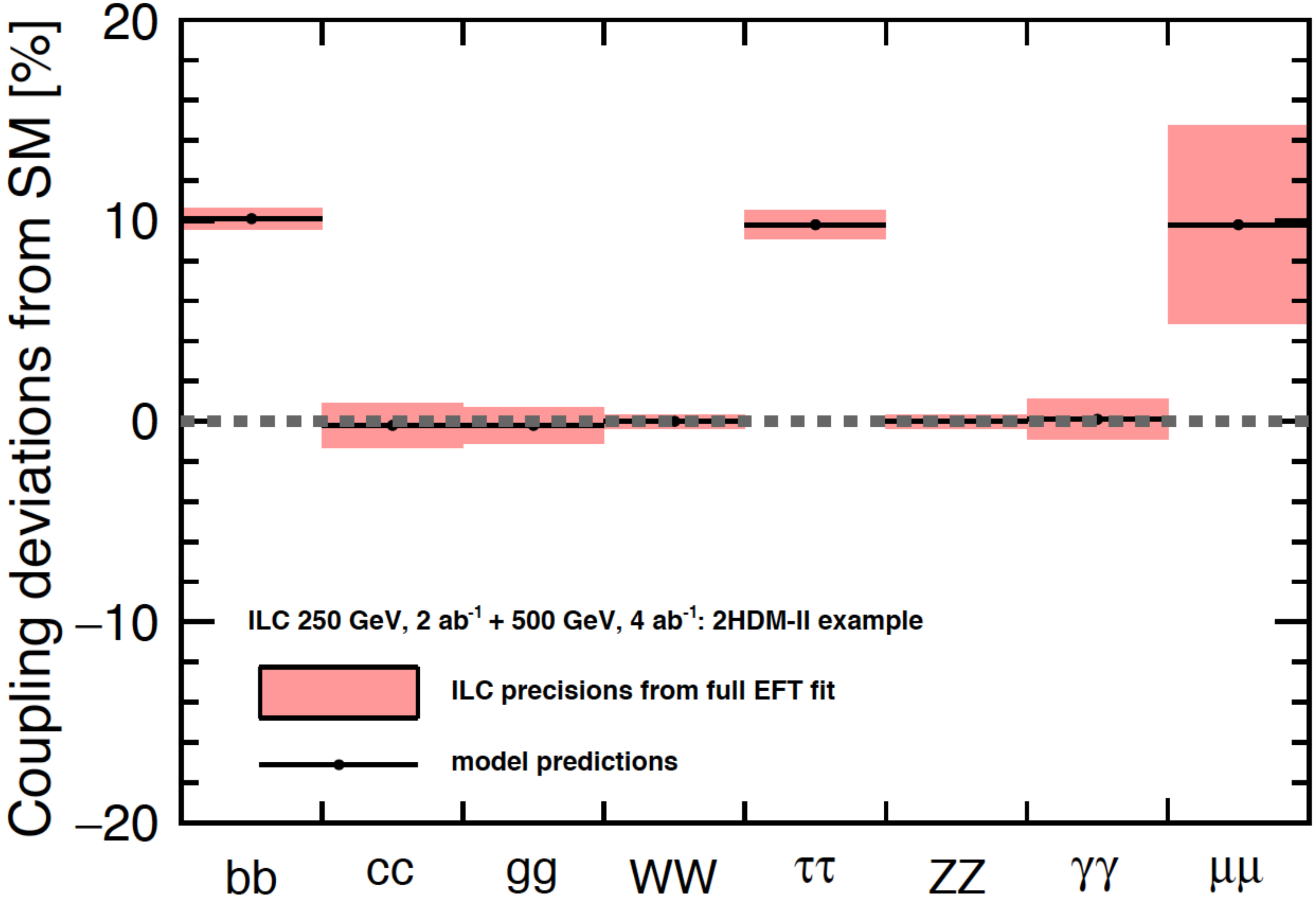
5. Conclusions: There is BSM physics! Extended Higgs sector likely?!

- Higgs precision meas. and BSM physic (ILC, CLIC, FCC-ee, CEPC)
  - MSSM is taken as a showcase
  - HL-LHC can test M_A up to ~ 1.2 TeV
  - ILC can set upper limit on undiscovered mass scales
  - light SUSY particles can have a strong impact $\Rightarrow$ parameter det.?!
  - difficult to disentangle SUSY effects from Higgs effects
- Higgs selfcoupling(s) at e^+e^- colliders (ILC, CLIC)
  - Analysis in the 2HDM type I, II
  - all constraints (theo/exp) are taken into account
  - large deviations in λ_{hhh} still possible (more in type I)
  - over most of the parameter space ILC is clearly superior to HL-LHC
  - large BSM triple Higgs couplings possible
  - large SM-like and BSM di-Higgs production cross sections
- BSM Higgs bosons below 125 GeV (ILC, FCC-ee, CEPC; CLIC?)
  - analysis of a 96 GeV Higgs within the N2HDM
  - $pp \to \phi_{96} \to \gamma\gamma$ excess at CMS, not excluded by ATLAS
  - $e^+e^- \to Z\,\phi_{96} \to Z\,b\bar{b}$ excess at LEP
  - ϕ_{96} can be produced at the ILC abundantly
  - coupling measurements can distinguish various BSM solutions


Further Questions?

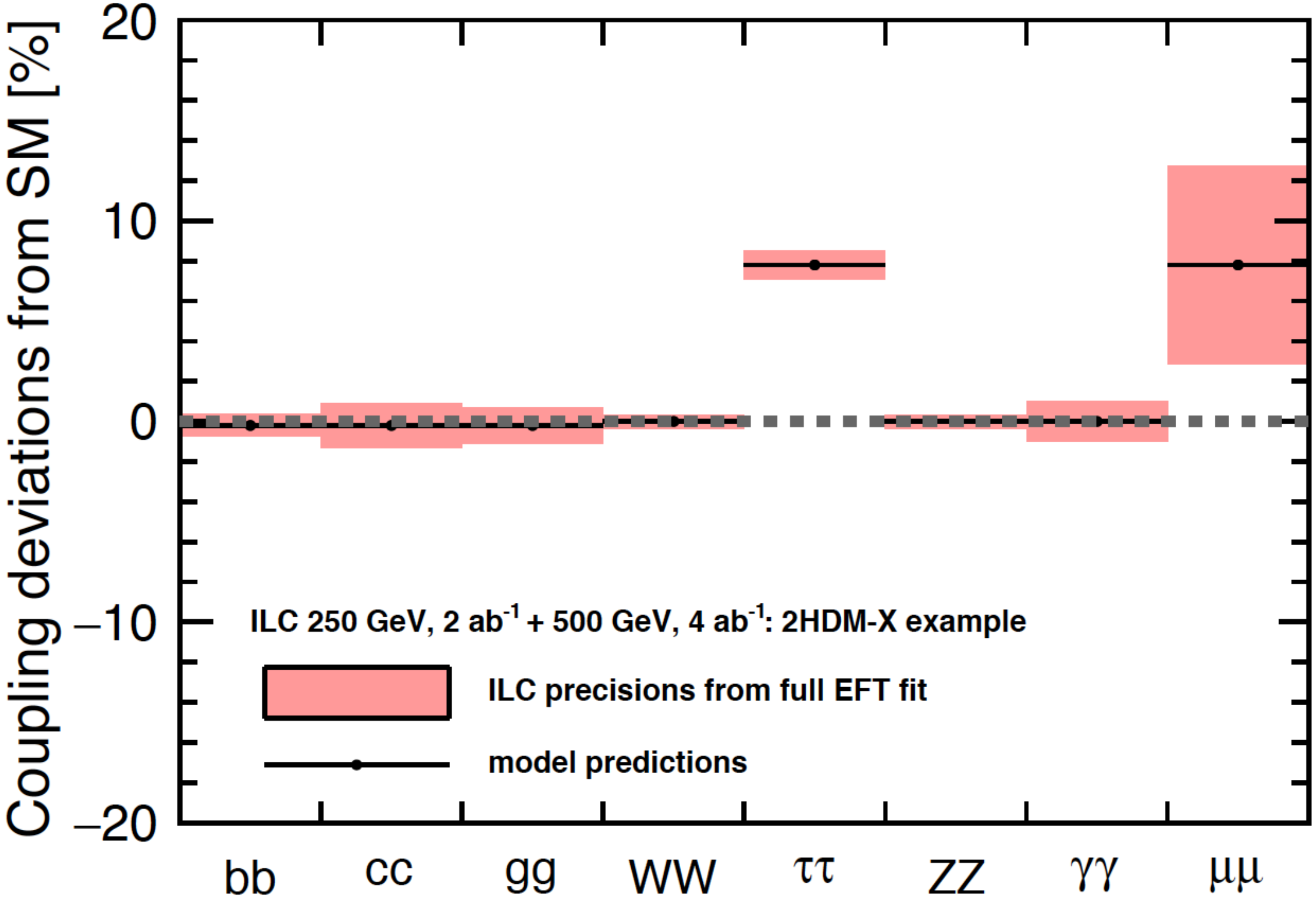
BSM Wäscheleine I: ILC precision vs. 2HDM type II prediction:

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



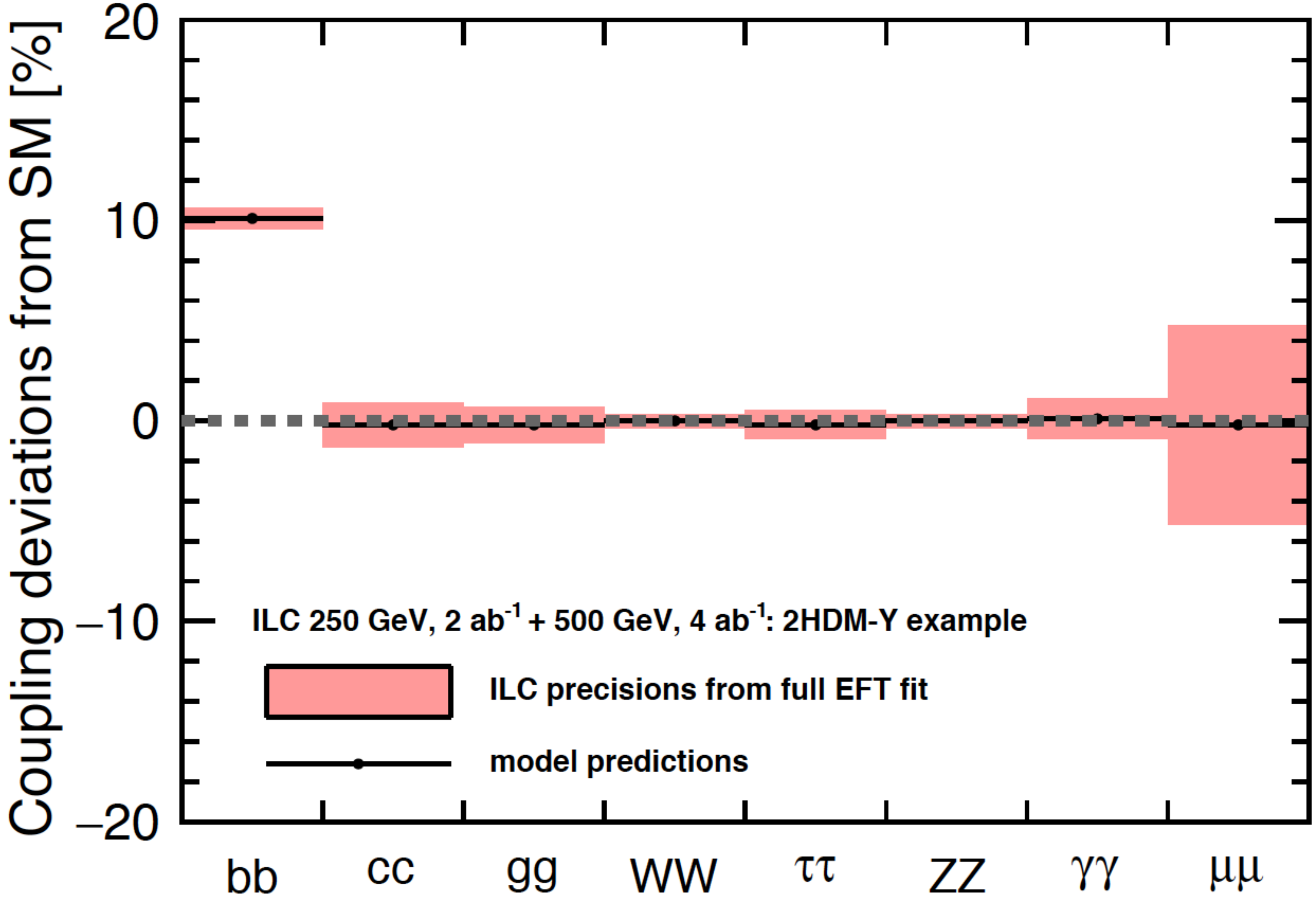
BSM Wäscheleine II: ILC precision vs. 2HDM type X prediction:

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



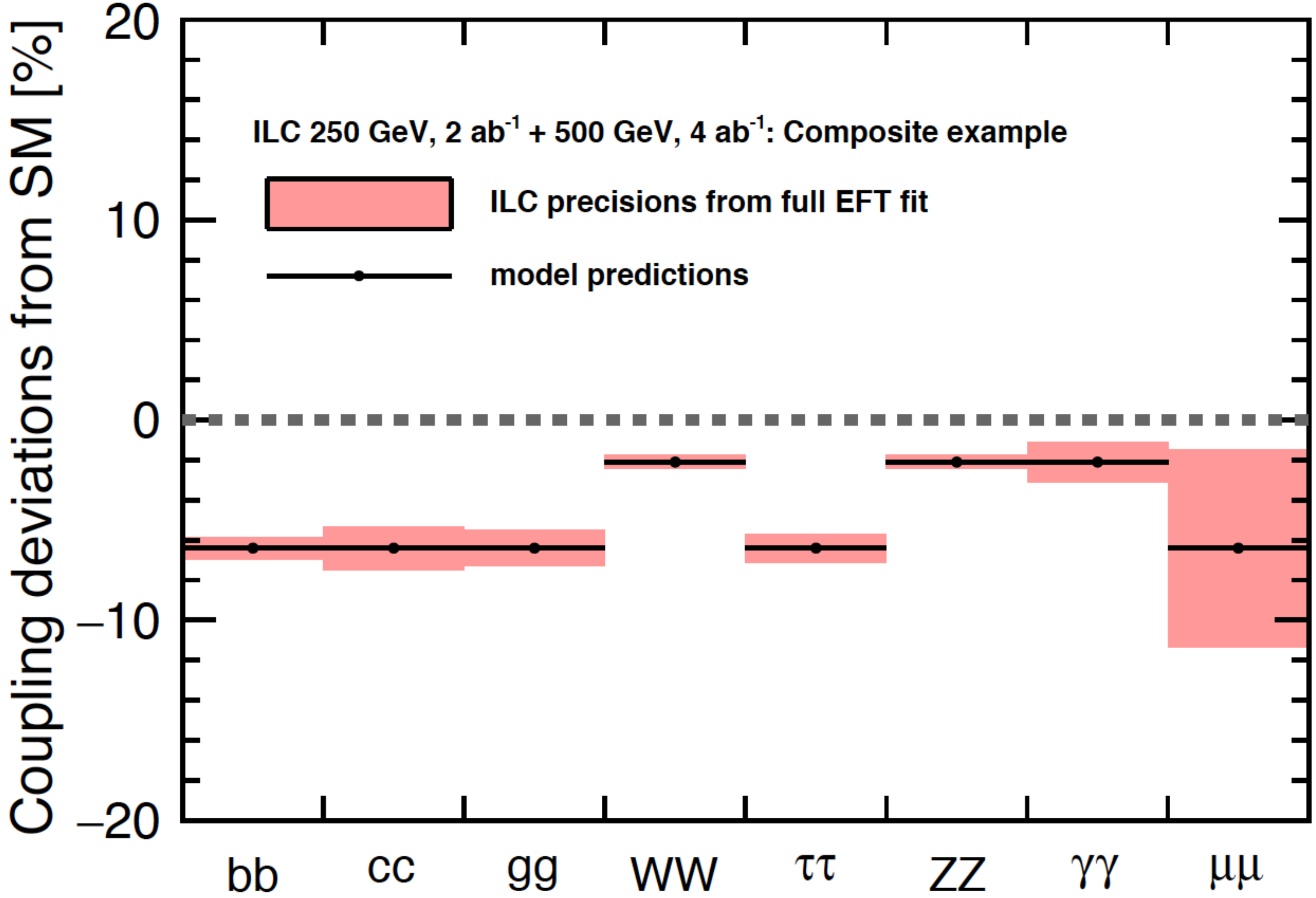
BSM Wäscheleine III: ILC precision vs. 2HDM type Y prediction:

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



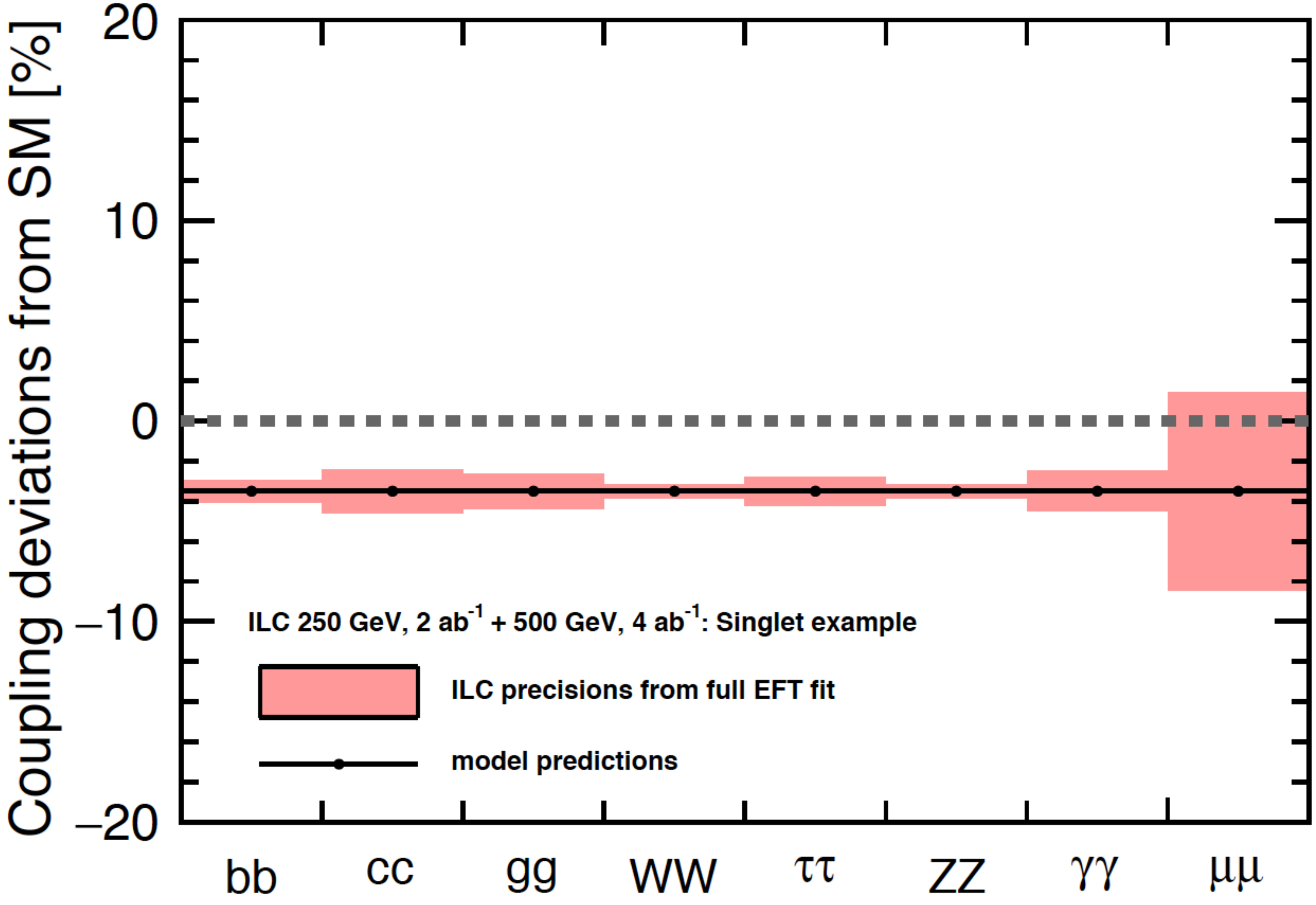
BSM Wäscheleine IV: ILC precision vs. Composite Higgs prediction:

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



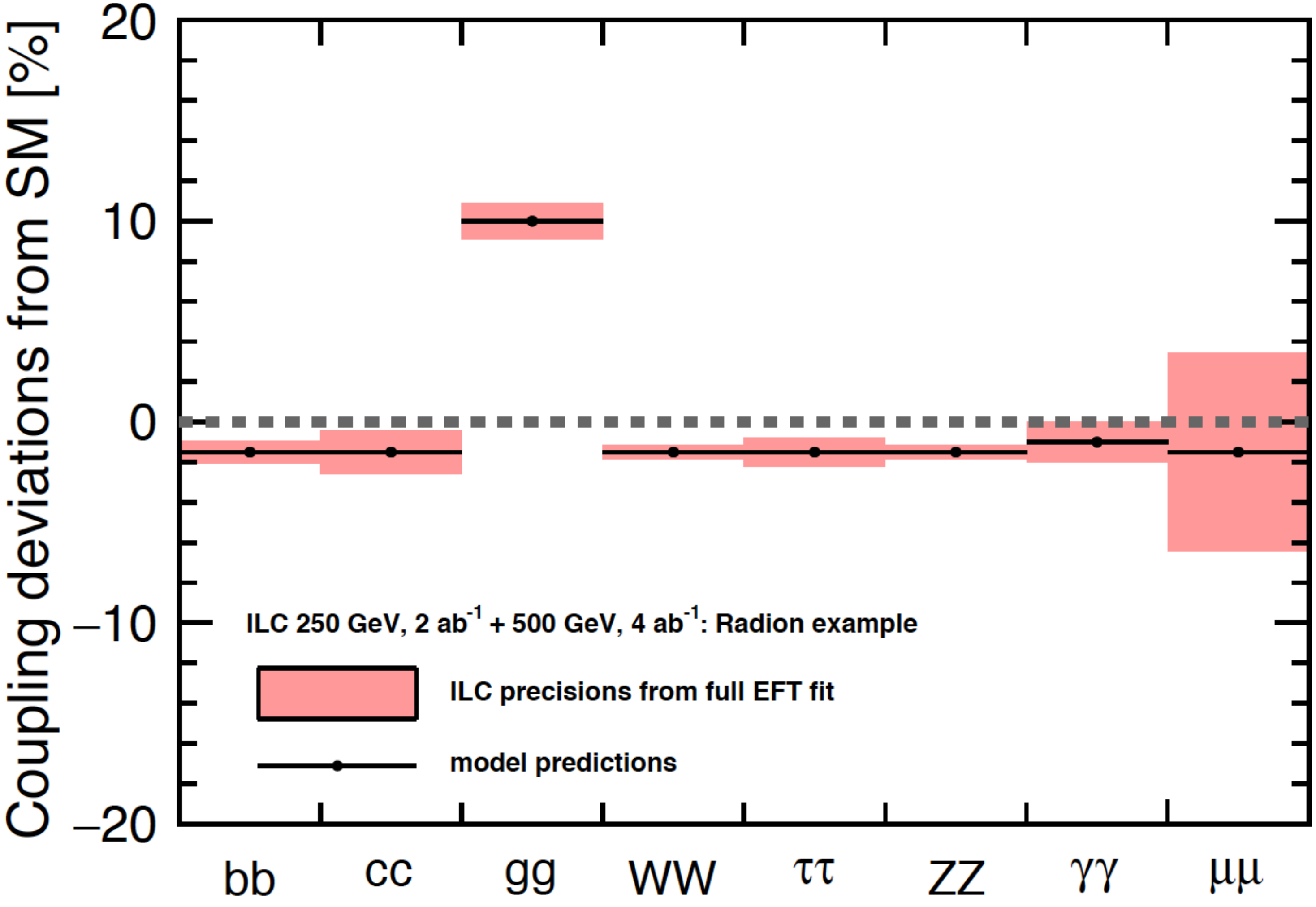
BSM Wäscheleine V: ILC precision vs. HxSM prediction:

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



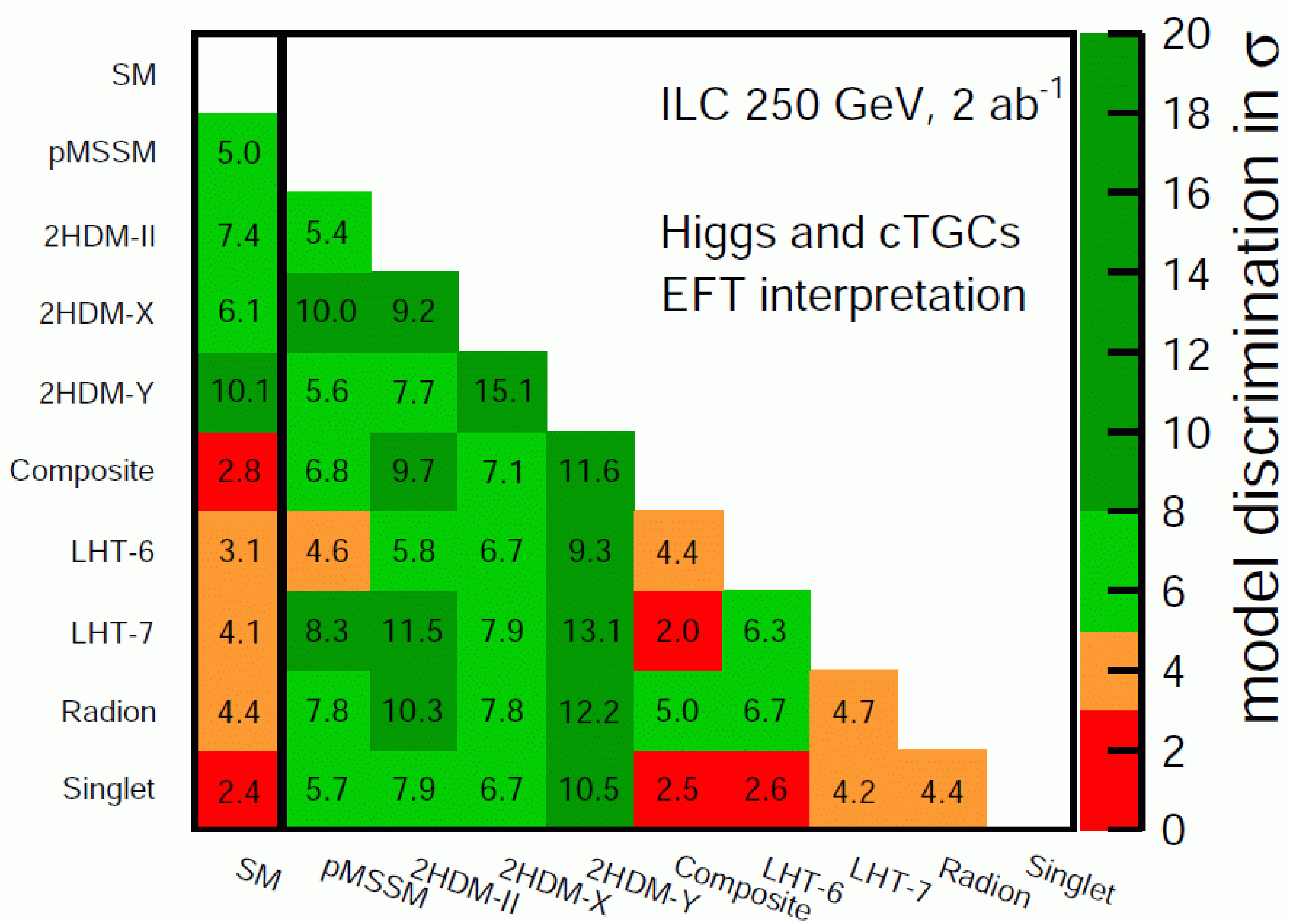
BSM Wäscheleine VI: ILC precision vs. Higgs-Radion prediction:

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

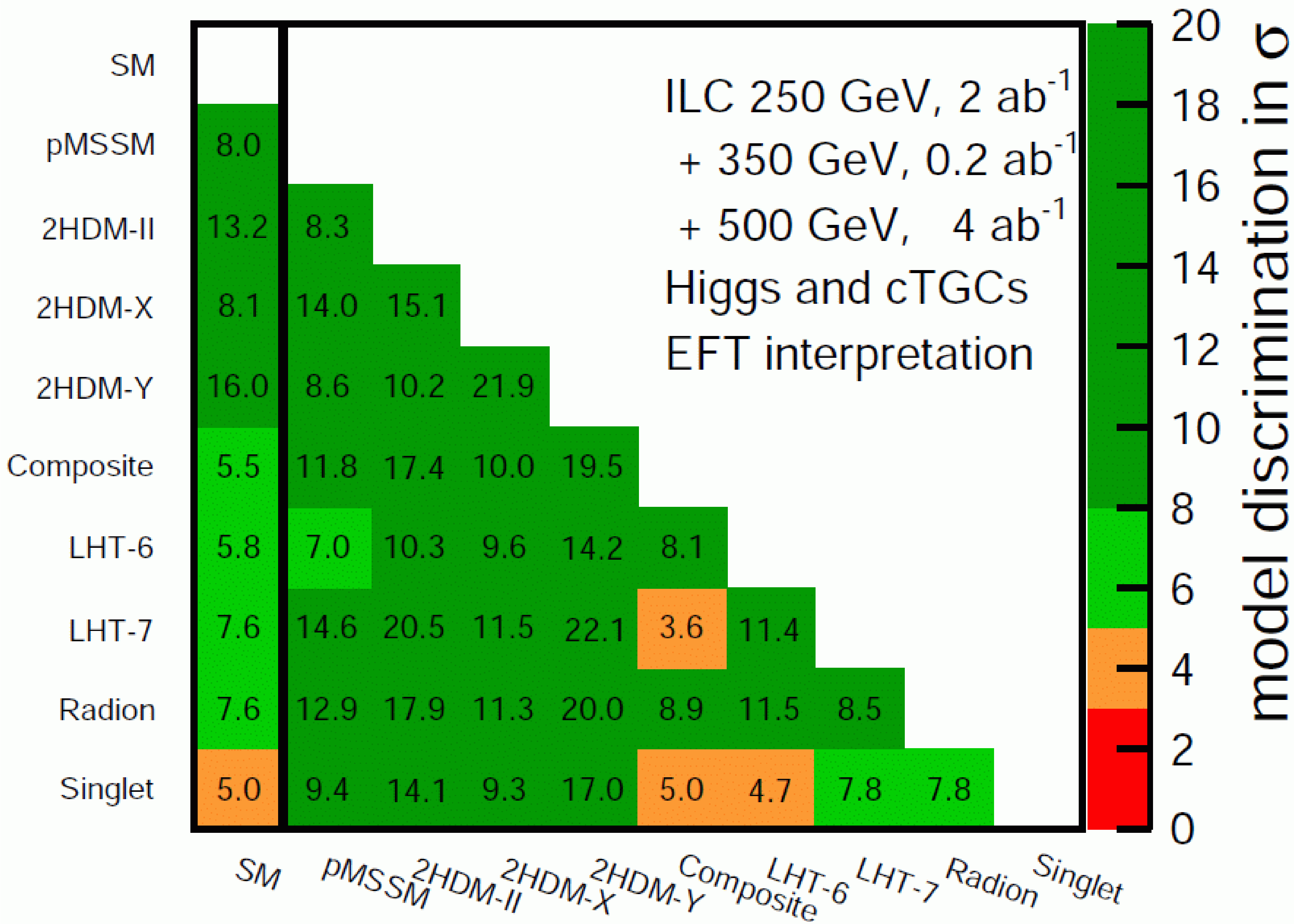


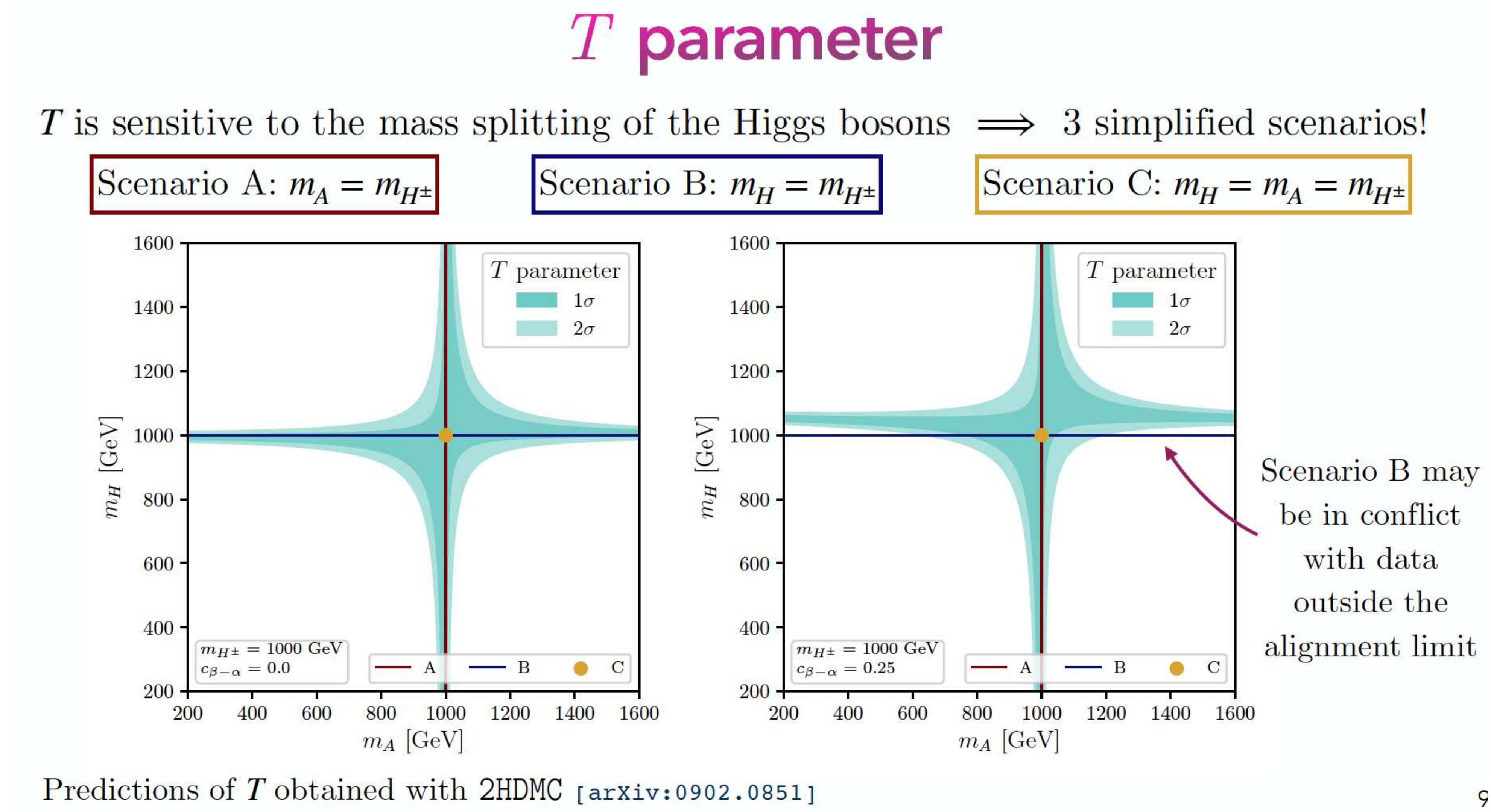
Model discrimination at ILC250:

[*K. Fujii et al. '17*]



Model discrimination at ILC500: [*K. Fujii et al. '17*]

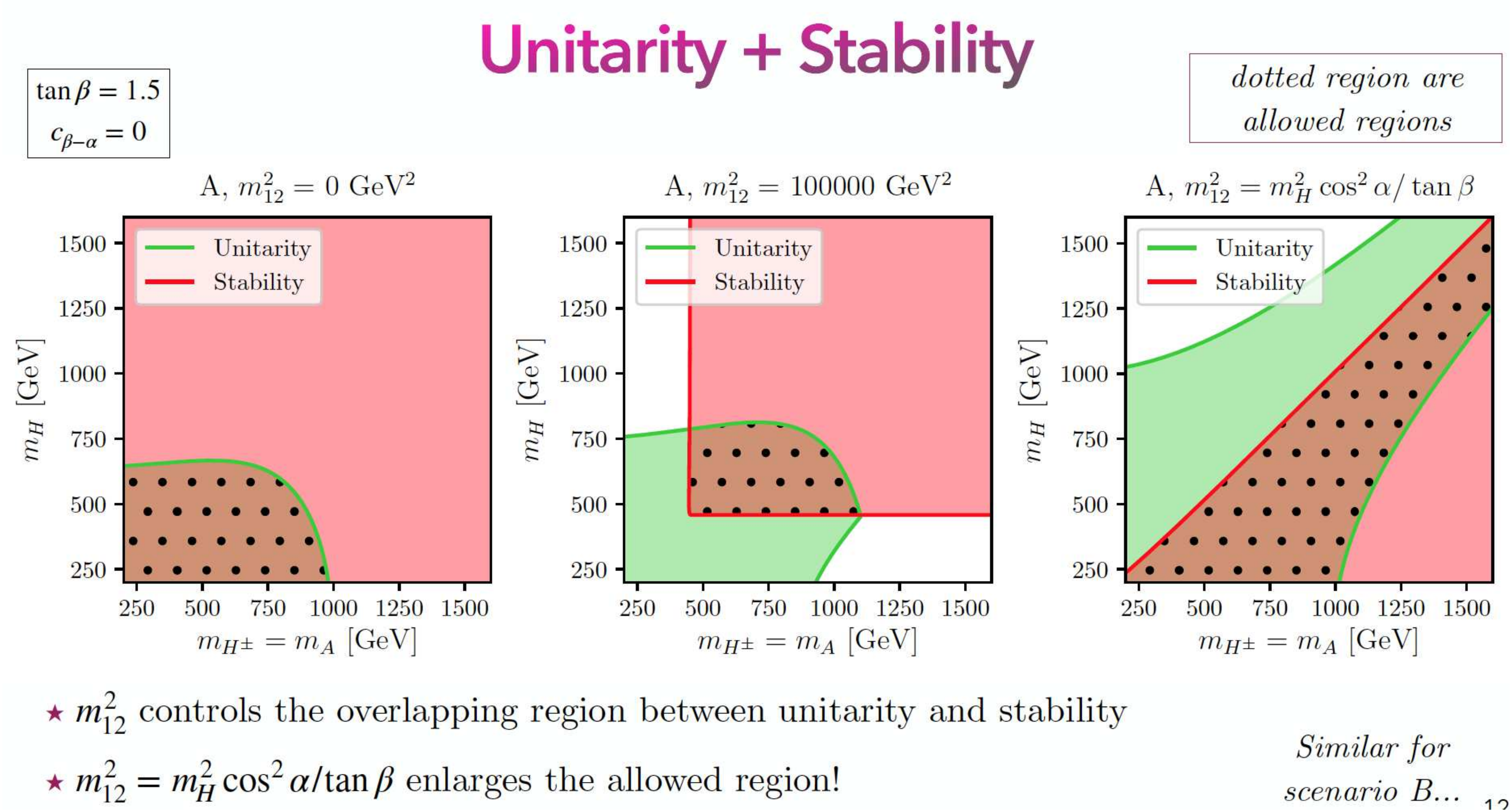




⇒ definition of Scenario A, B, C

⇒ Once T is satisfied, also S and U are satisfied

Unitarity vs. Stability:



⇒ special condition for m_{12}^2 helps

What about SUSY??

SUSY realizations

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⇒ type II fits best, type II is needed for SUSY ⇒ no surprize! ;-)

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

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– NMSSM
– $\mu\nu$SSM
– . . .

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

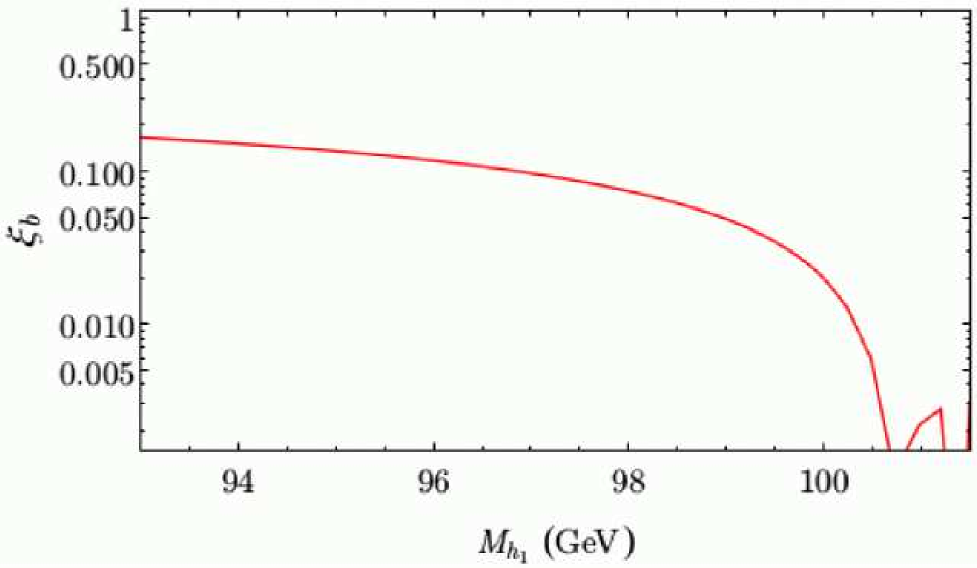
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

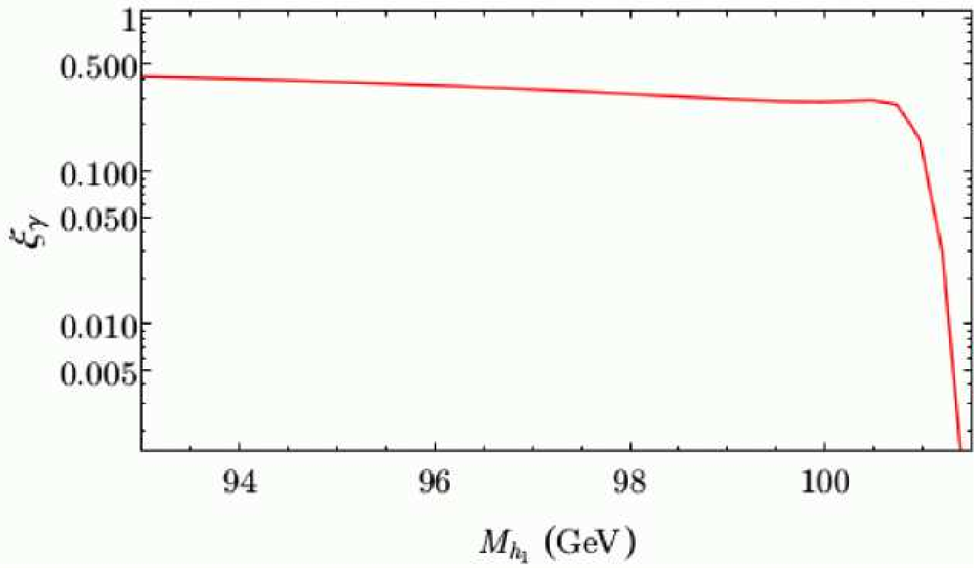
Parameters:

$\lambda = 0.6,\ \kappa = 0.035,\ \tan\beta = 2,\ \mu_{\text{eff}} = (397 + 15x)$ 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	$m^2_{\tilde{Q}_{iL}}$	$m^2_{\tilde{u}_{iR}}$	$m^2_{\tilde{d}_{iR}}$	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

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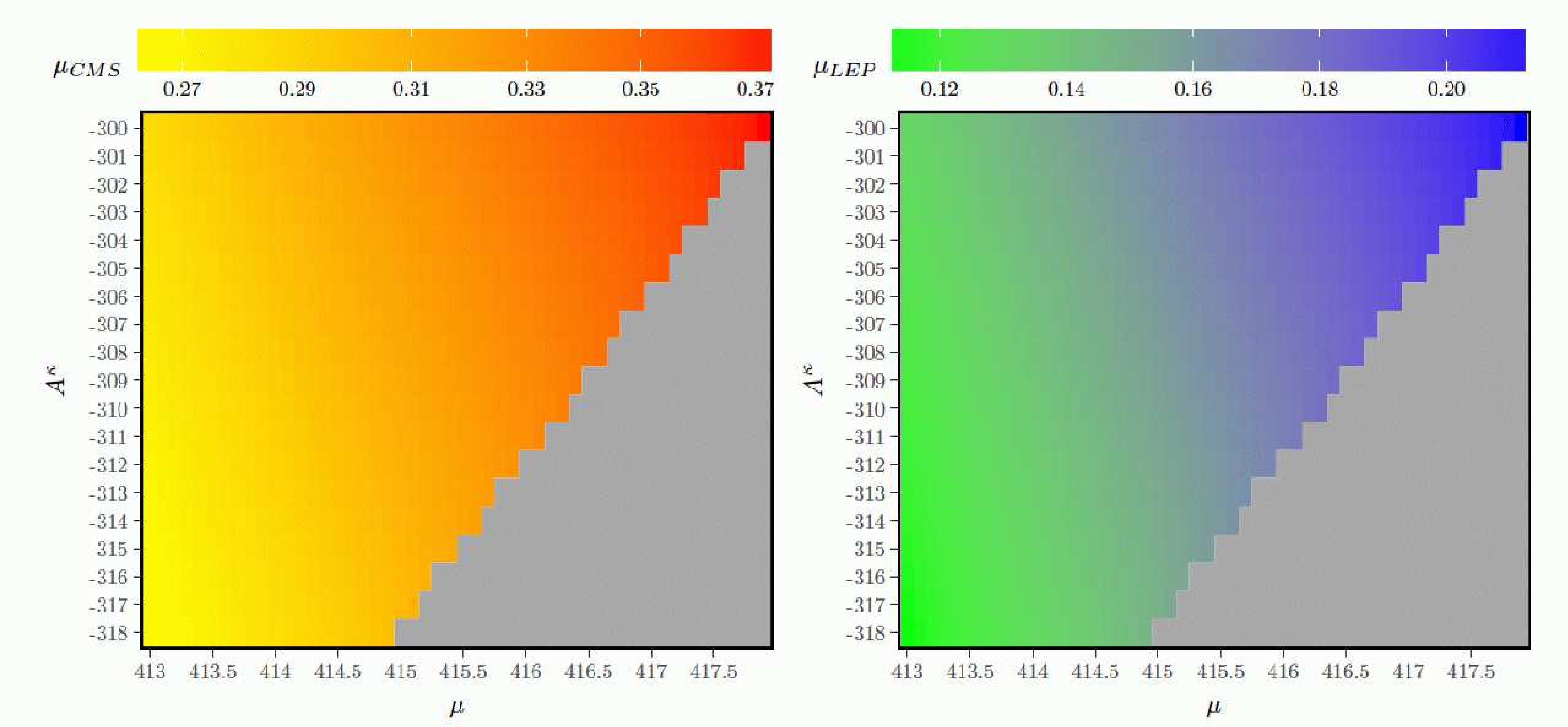
[*T. Biekötter, S.H., C. Muñoz '17*]

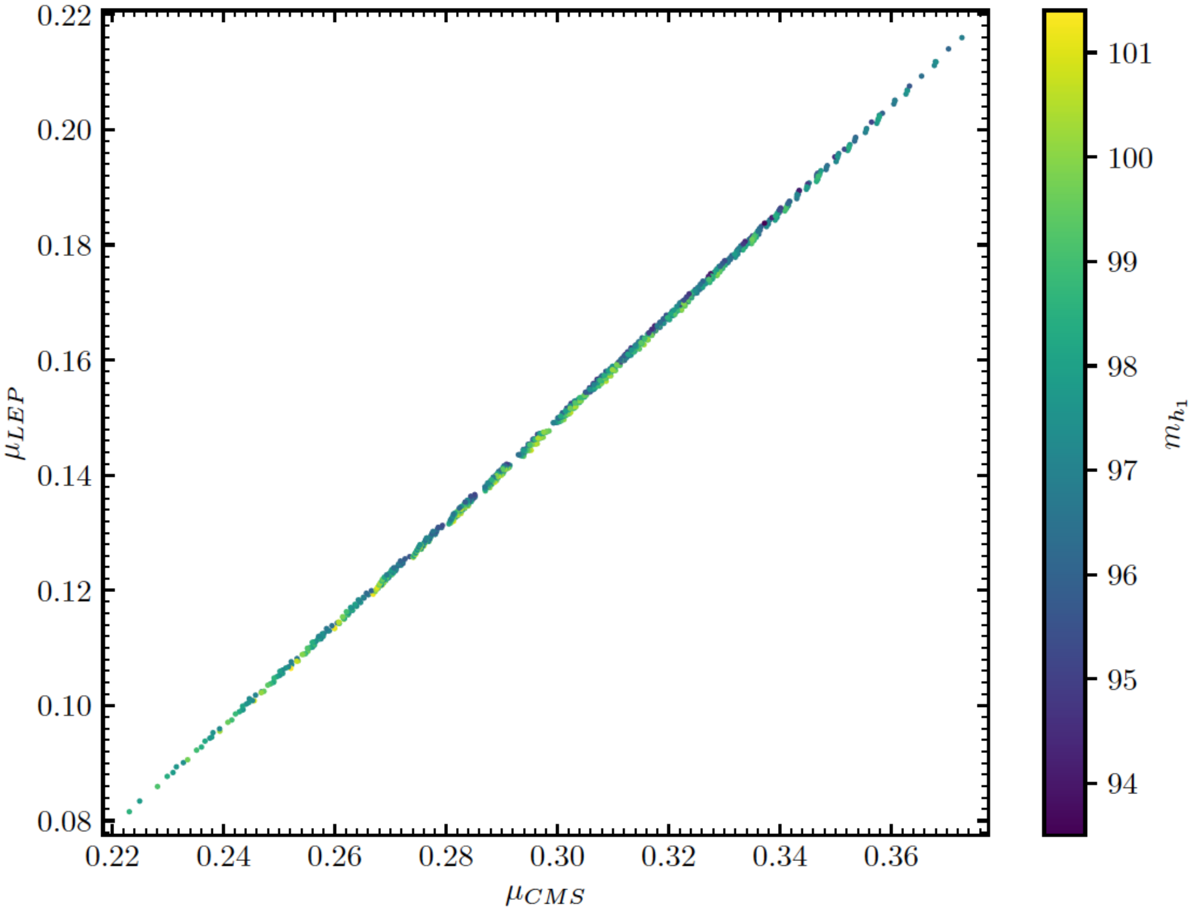


$\Rightarrow$ YES, WE CAN! :-)

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 μ_{LHC}!

Fitting the excesses:

$$\mu_{\text{LEP}} = 0.117 \pm 0.057, \qquad \mu_{\text{CMS}} = 0.6 \pm 0.2$$

$$\mu_{\text{LEP}} = \frac{\sigma_{\text{N2HDM}}(e^+e^- \to Zh_1)}{\sigma_{\text{SM}}(e^+e^- \to ZH)} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$
$$= \left|c_{h_1VV}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}$$

$$\mu_{\text{CMS}} = \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$
$$= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}$$

$$\chi^2_{\text{CMS-LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

$\Rightarrow$ “best-fit point”

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 $\text{BR}(h_1 \to \gamma\gamma)$
- $c_{h_1 tt}$ not reduced for μ_{CMS}
- $c_{h_1 \tau\tau}$ possibly reduced to enhance $\text{BR}(h_1 \to \gamma\gamma)$

	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 bonus: $c_{h_1 \tau\tau}$ can be suppressed (together with $c_{h_1 bb}$)

$\Rightarrow$ only type II and IV can fit CMS and LEP excesses

Best-fit point in type II:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
96.5263	125.09	535.86	712.578	737.829	

$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.26287	1.26878	-1.08484	-1.24108	80644.3	272.72

$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.5048	0.2682	$5.09 \cdot 10^{-2}$	$2.582 \cdot 10^{-3}$	$1.37 \cdot 10^{-2}$	$1.753 \cdot 10^{-3}$

$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5916	0.0771	$6.36 \cdot 10^{-2}$	$2.153 \cdot 10^{-3}$	0.2087	$2.610 \cdot 10^{-3}$

$\Rightarrow$ surprizingly large $\text{BR}_{h_1}^{\gamma\gamma}$

Best-fit point in type IV:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
97.8128	125.09	485.998	651.502	651.26	

$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.3147	1.27039	-1.02829	-1.32496	41034.1	647.886

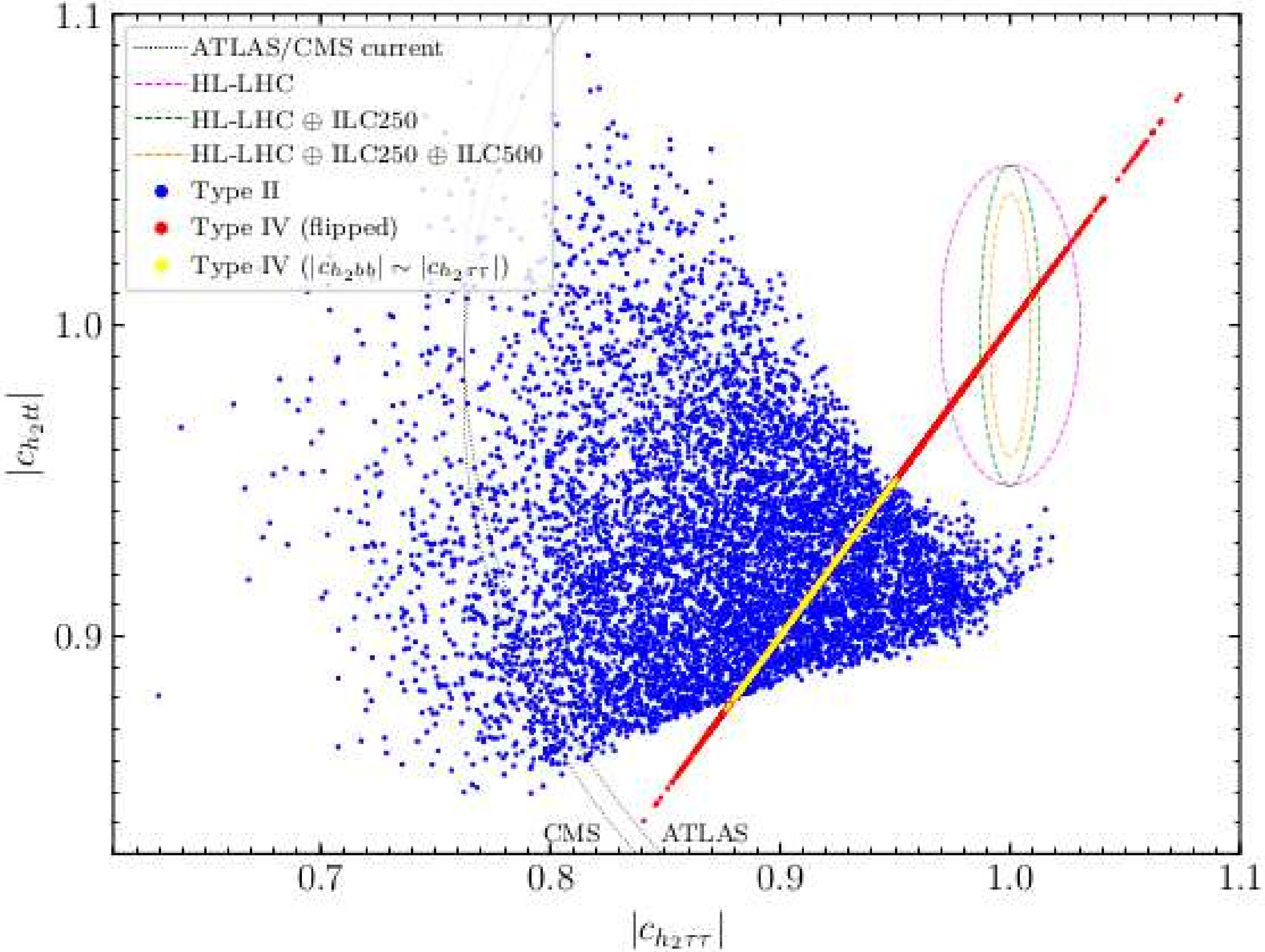
$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.4074	0.20714	0.248324	$2.139 \cdot 10^{-3}$	$1.347 \cdot 10^{-2}$	$1.579 \cdot 10^{-3}$

$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5363	0.09388	$7.58 \cdot 10^{-2}$	$2.247 \cdot 10^{-3}$	0.2267	$2.836 \cdot 10^{-2}$

$\Rightarrow$ substantially larger $\text{BR}_{h_1}^{\tau\tau}$ than in type II

Probes of the 125 GeV Higgs

Future measurements: ⇒ HL-LHC/ILC Higgs coupling measurements



⇒ type II shows deviation from SM

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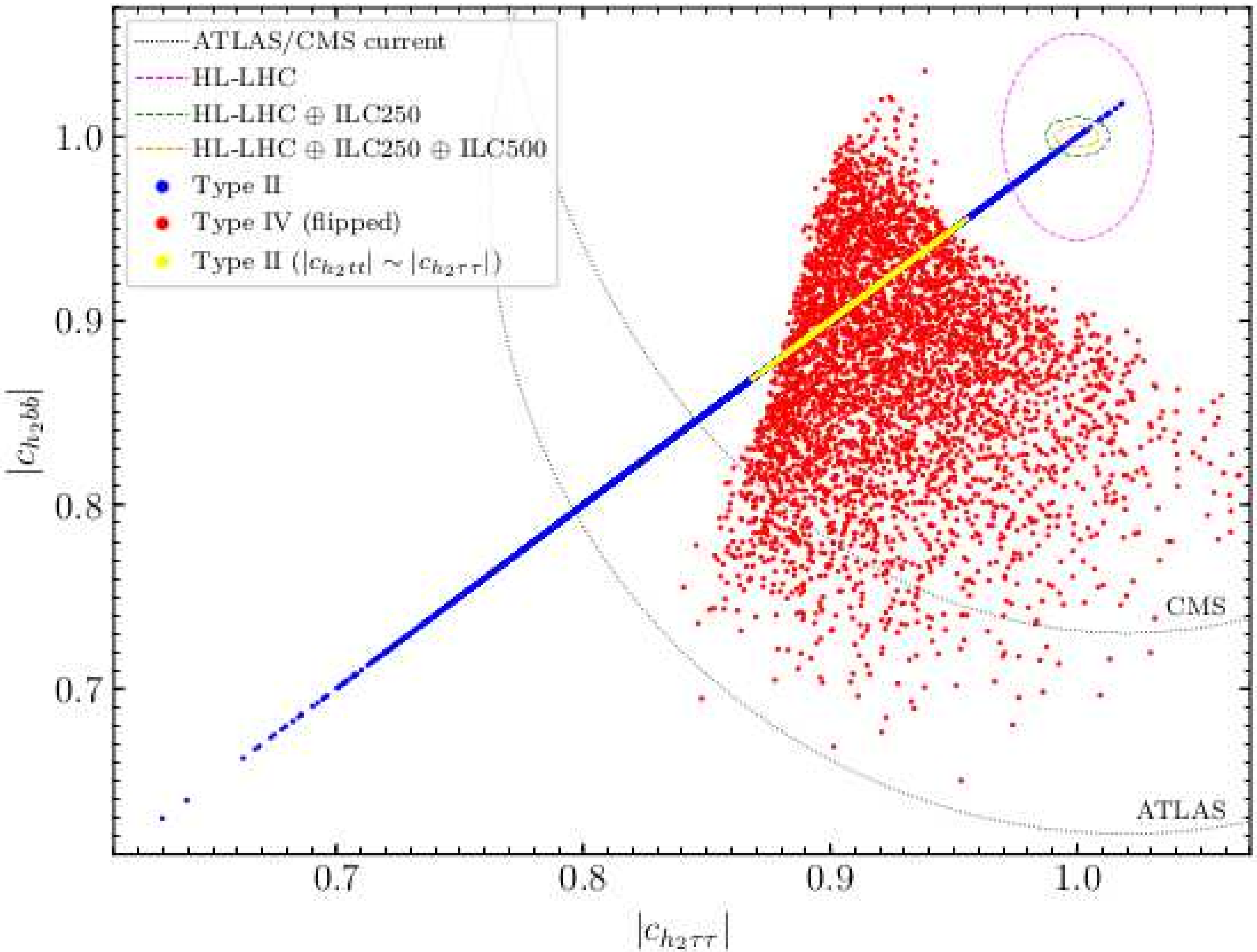


⇒ type IV shows deviations from SM

⇒ N2HDM can always be distinguished from SM!

How to evaluate the precision of ϕ_{96} coupling measurements?

Start with data of the SM Higgs:

SM Higgs BRs: [YR4 LHCHXSWG]

final state	$b\bar{b}$	gg	$\tau^+\tau^-$	WW^*	σ_{ZH}
BR	0.582	0.082	0.063	0.214	206 fb

SM Higgs coupling uncertainties:
ILC, $\mathcal{L}_{\rm int} = 2\,{\rm ab}^{-1}$ 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	$H \to b\bar{b}$	$H \to gg$	$H \to \tau^+\tau^-$	$H \to WW$	σ_{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 ϕ_{96}:

$$\sigma(e^+e^- \to \phi Z) = \sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 96}) \times |c_{\phi VV}|^2$$

$$\sigma_{\text{SM}}(e^+e^- \to Z\, H_{\text{SM}}^{\phi 96}) = 0.332\,\text{pb}$$

$\Rightarrow \mathcal{O}\left(10^5\right)$ ϕ'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 ϕ couples with g_x to xx

$$\Gamma(\phi \to xx) \propto g_x^2$$

$$\text{BR}(\phi \to xx) =: 1/p$$

$$\frac{\Delta N_S}{N_S} = 2\,\frac{\Delta g_x}{g_x}\left(1 - \frac{1}{p}\right)$$

- 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 $D = 2$ as starting point

Evaluating uncertainties of ϕ_{96}:

- Coupling is measured via decay

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

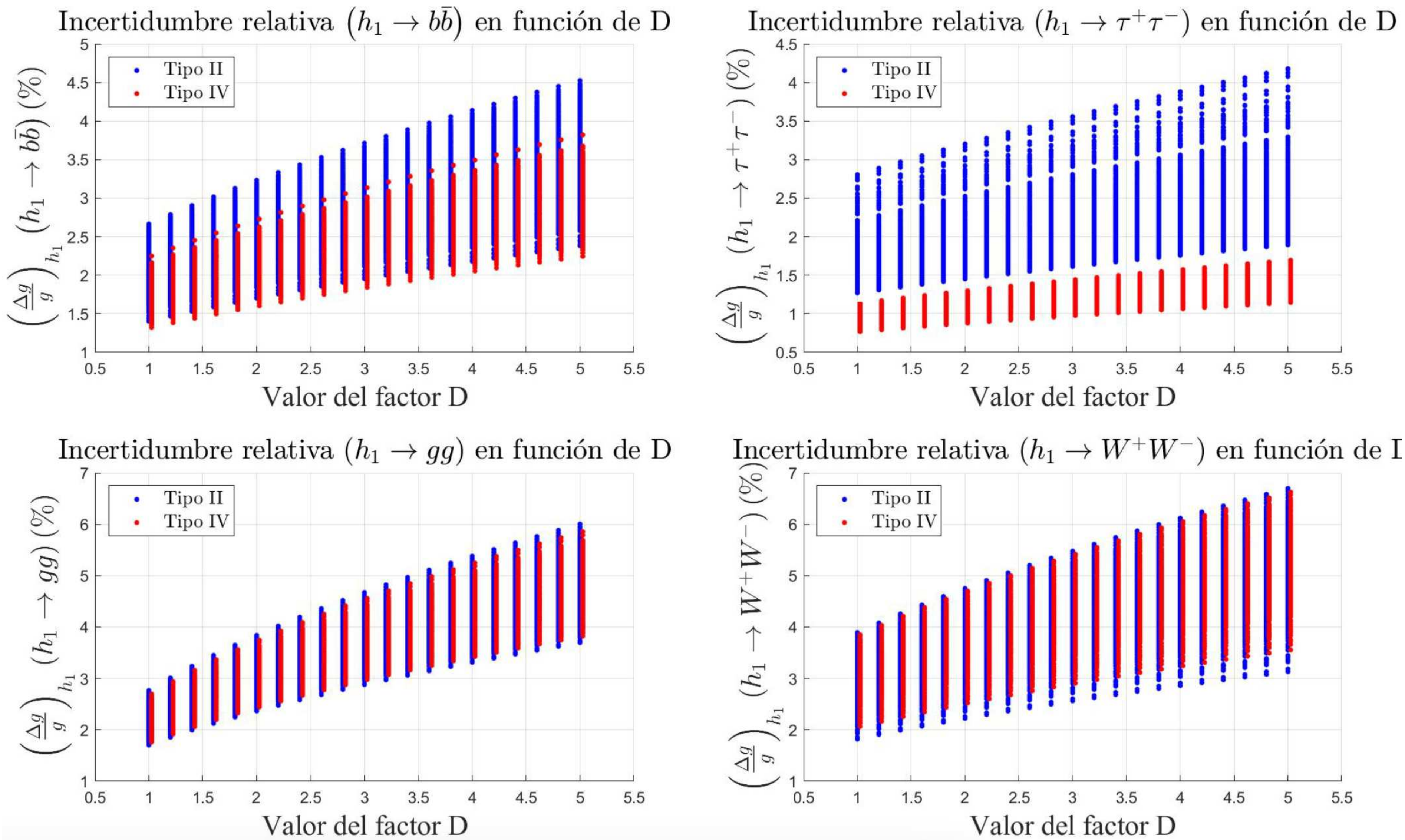
$$\to \sqrt{\frac{D+f_H}{1+f_H}} \times \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}} \times \sqrt{\frac{\mathrm{BR}(H \to xx)}{\mathrm{BR}(\phi \to xx)}} \times \frac{(1-\mathrm{BR}(H \to xx))}{(1-\mathrm{BR}(\phi \to xx))}$$

- Coupling is measured via production: g_Z (S/B does not change)

$$\left(\frac{\Delta g_Z}{g_Z}\right)_\phi = \left(\frac{\Delta g_Z}{g_Z}\right)_H \times \frac{\left(\frac{\Delta N_S}{N_S}\right)_\phi}{\left(\frac{\Delta N_S}{N_S}\right)_H}$$

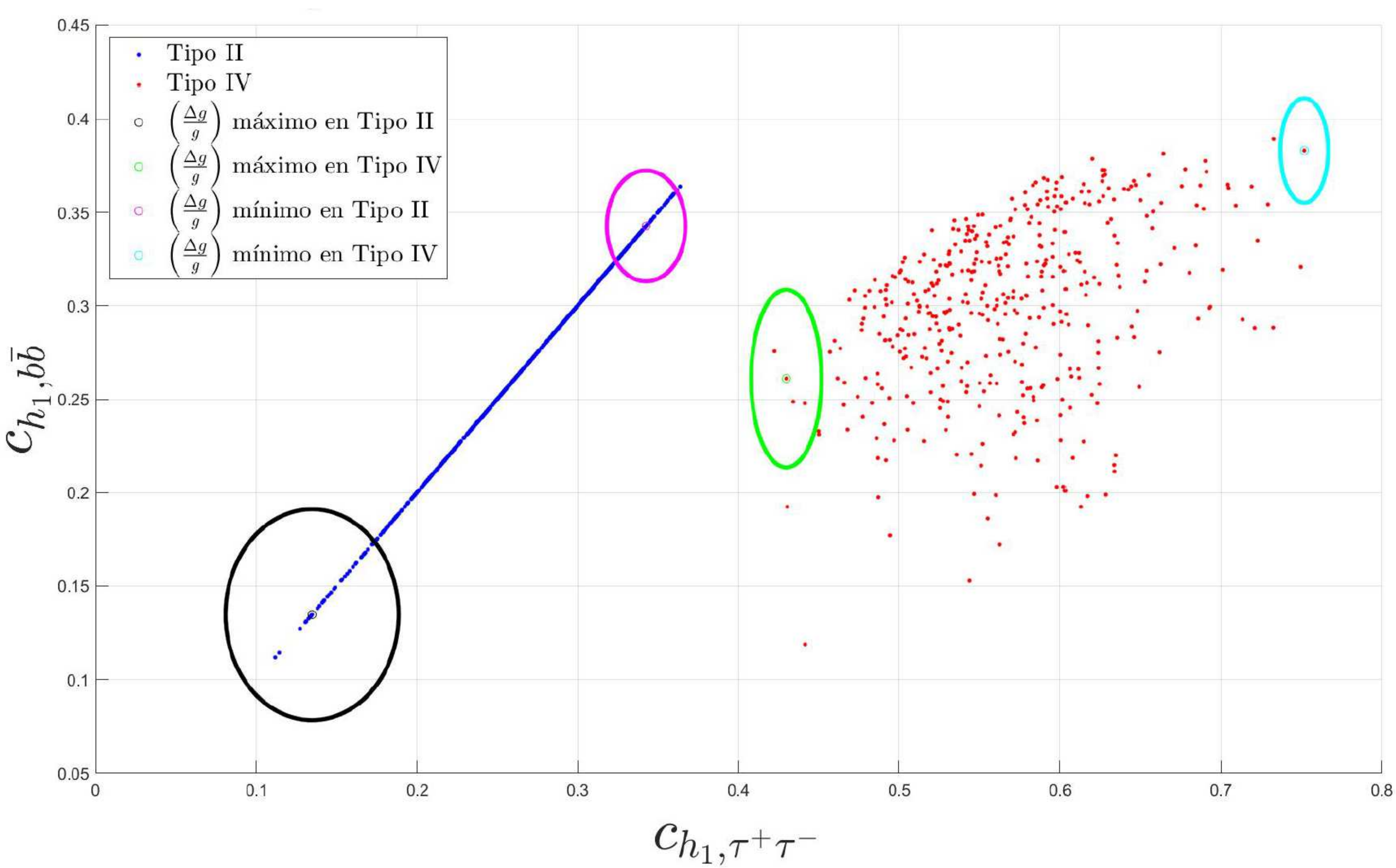
$$\to \sqrt{\frac{\sigma(e^+e^- \to ZH)}{\sigma(e^+e^- \to Z\phi)}}$$

N2HDM: dependence on $D = f_H/f_\phi$: [S.H., P. Toledo '20]



$\Rightarrow$ non-negligible, but small $\Rightarrow$ "robust" result

N2HDM: $\tau\tau$ vs. $b\bar{b}$ coupling: [S.H., P. Toledo '20]



⇒ model distinction possible via coupling measurements