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HM

Higgs Physics: Opportunities for the ILC in the Light of HL-LHC Results

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virtual, 07/2021

1. Introduction
2. h_{125} measurements
3. BSM Higgs
4. Conclusions

1. Introduction

ILC timeline (optimistic?):

Pre-preparatory Phase

Main Preparatory Phase

Construction Phase

2020.8

(2022)

About 4 years

(2026)

About 9 years

(2035)

LCB/LCC

International Development Team

ILC Pre-Lab

ILC Laboratory

⇒ The ILC will come after or in the end phase of the HL-LHC

⇒ physics potential of the new e^+e^- collider must be viewed in the context of HL-LHC results

⇒ show e^+e^- expectations in comparison to HL-LHC

Two facts:

I: We have a discovery!

II: 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?

Two facts:

I: We have a discovery!

II: The SM cannot be the ultimate theory!

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 of the h_{125}

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

Extended Higgs sectors

Compatibility with the experimental results requires:

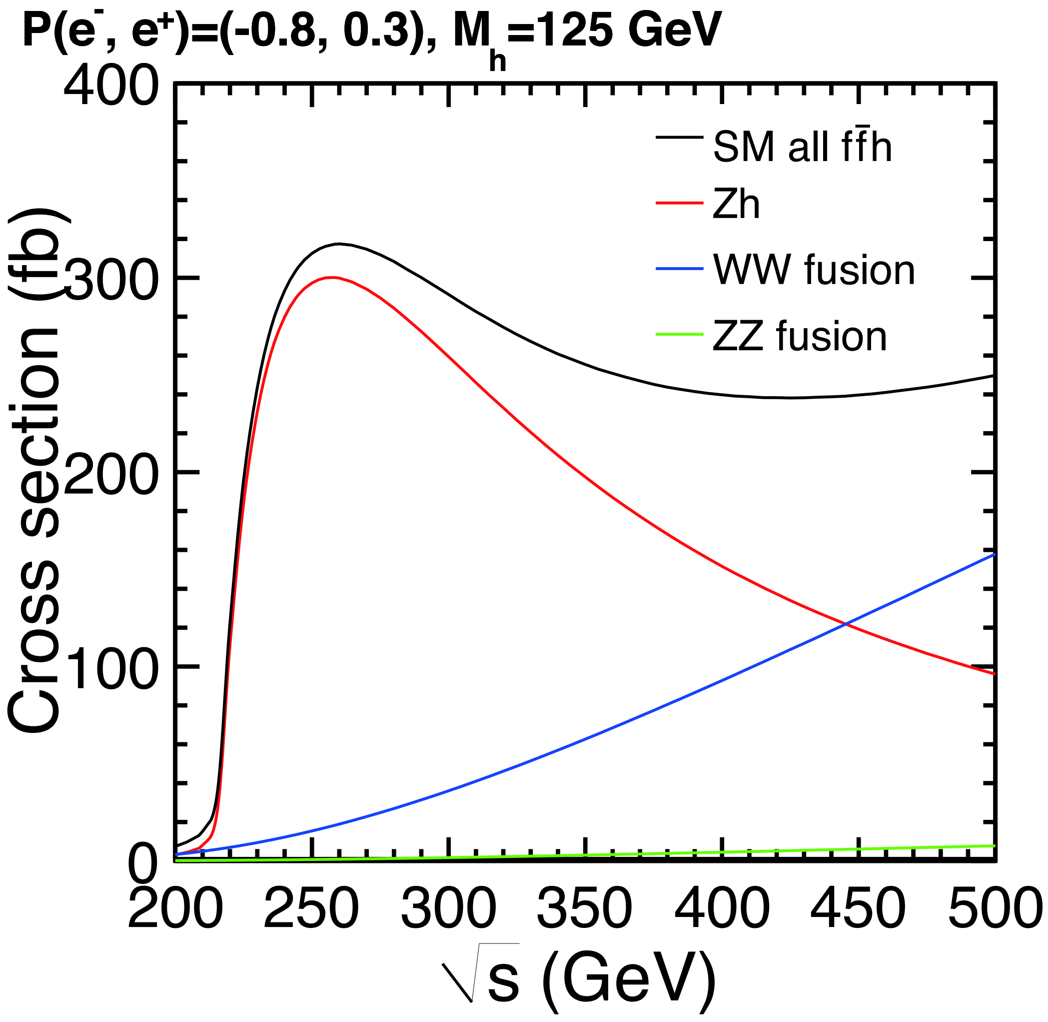
- A SM-like Higgs at $\sim$ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,. . .) have to be such that they are in agreement with the present bounds

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

Prediction for the mass of the SM-like Higgs vs. exp. result:

- Important constraints on parameter space of the model
- Limited by remaining theoretical uncertainties
- Very accurate Higgs-mass predictions needed

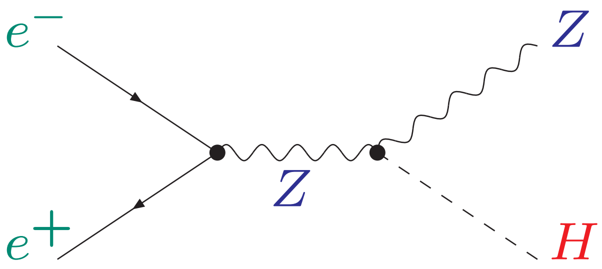
2. h_{125} measurements



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

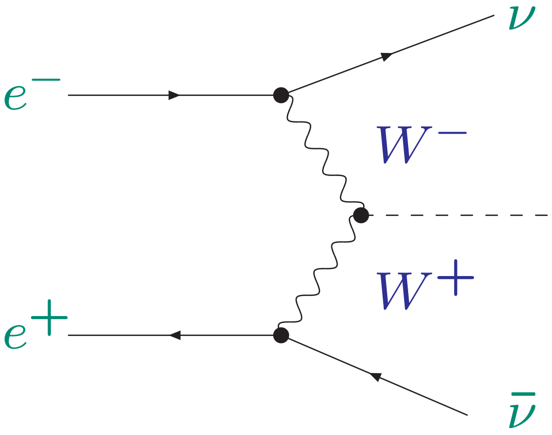
Higgs-strahlung:

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



weak boson fusion (WBF):

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



Higgs coupling measurements at e^+e^- colliders

Initial measurement: $\sigma \times$ BR

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

⇒ measurement of the Higgs production cross section

⇒ NO additional theoretical assumptions needed for absolute determination of partial widths – in contrast to LHC measurements!

⇒ indirect measurement of total width

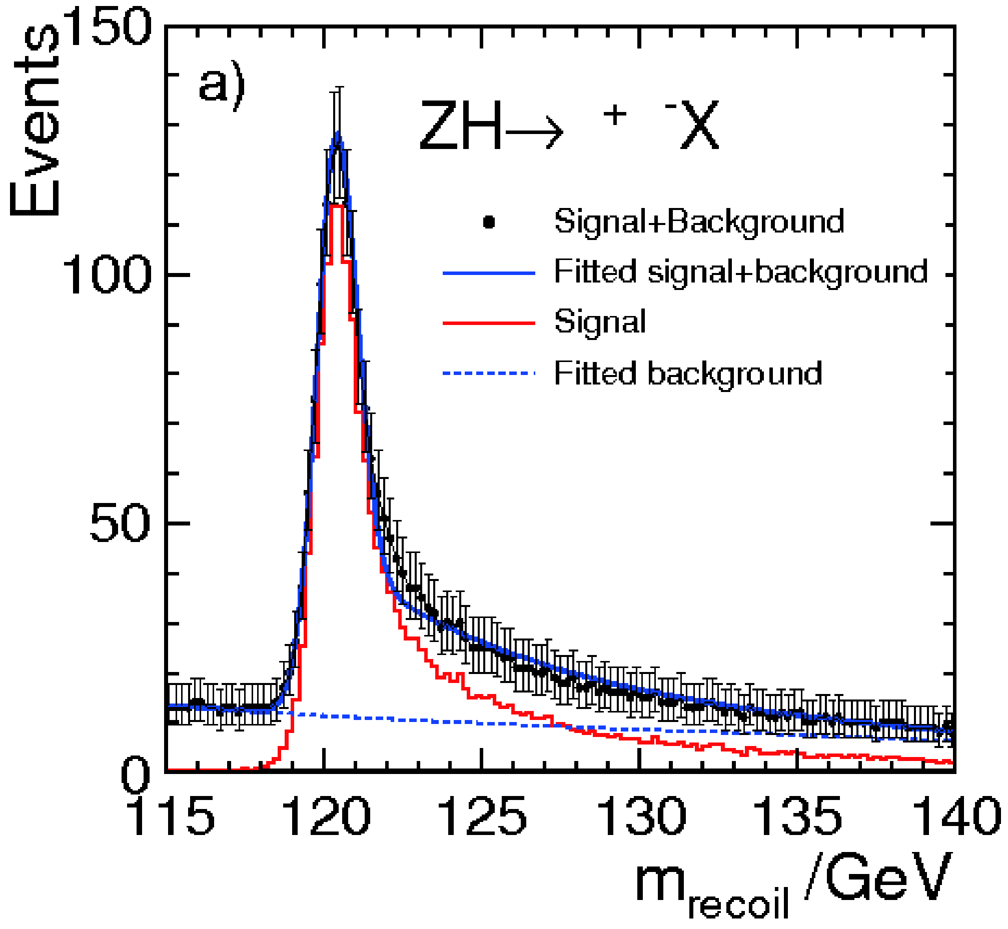
⇒ direct extraction of partial widths (couplings)

⇒ search for deviations from the SM
⇒ distinction between different models

Model independent cross section measurement

[ILC TDR '13]

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$



⇒ crucial for a model independent coupling measurement! $\delta M_H^{\text{exp}} \lesssim 0.05$ GeV

Required precision for M_H?

- M_H is fundamental parameter
  $\Rightarrow$ high precision measurement on its own right

- M_H is input parameter for Higgs physics:

$$\delta M_H = 0.2 \text{ GeV} \quad \Rightarrow \quad \frac{\delta \text{BR}(H \to ZZ^*)}{\text{BR}(H \to ZZ^*)} \sim 2.5\%$$

$$\frac{\delta \text{BR}(H \to WW^*)}{\text{BR}(H \to WW^*)} \sim 2.2\%$$

$\Rightarrow \delta M_H \lesssim 0.02$ GeV desirable

$\Rightarrow$ only reachable at the ILC (or other e^+e^- colliders)

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:

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

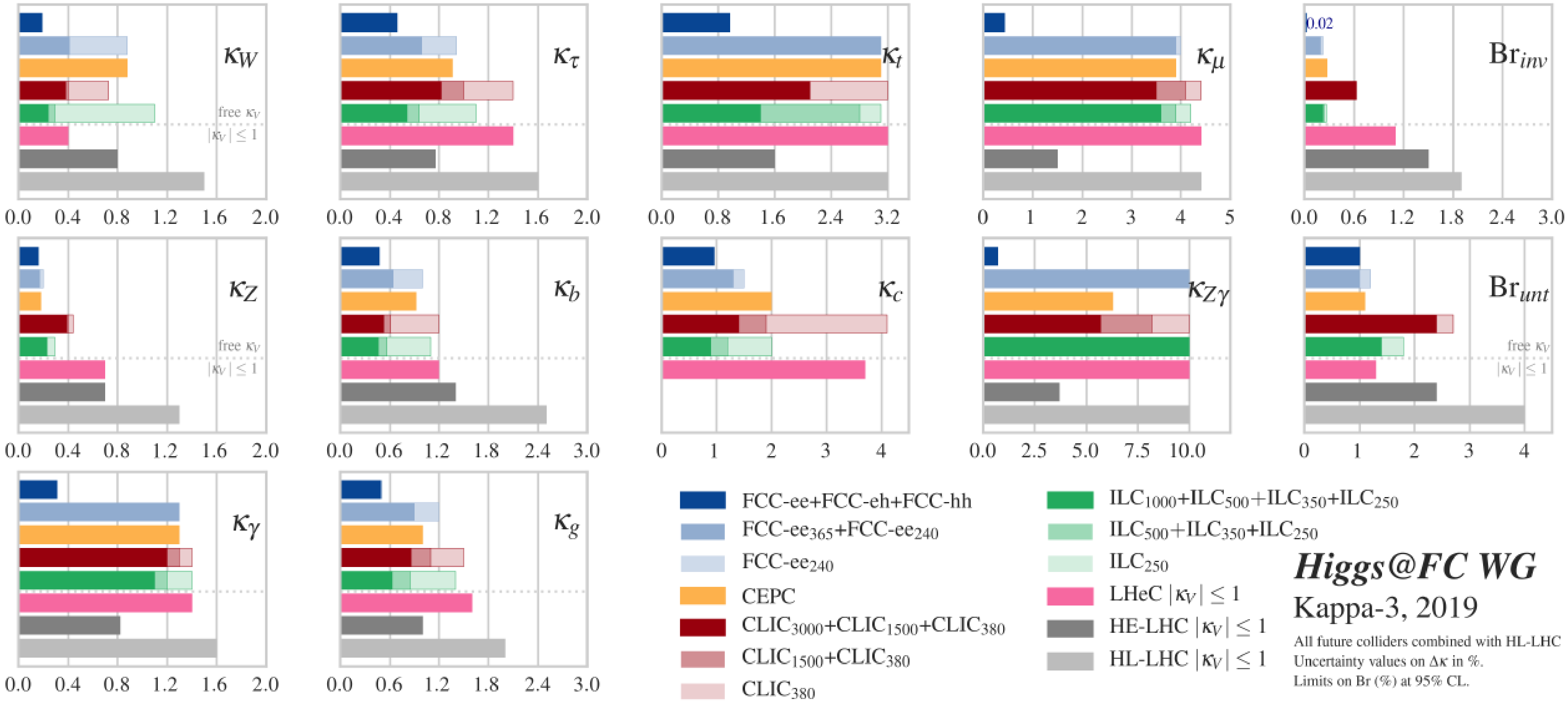
$$\kappa_F \approx 1 - (3 - 9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

⇒ 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)



Higgs@FC WG

Kappa-3, 2019

All future colliders combined with HL-LHC
Uncertainty values on $\Delta\kappa$ in %.
Limits on Br (%) at 95% CL.

⇒ ILC shows strong improvement over HL-LHC in many cases

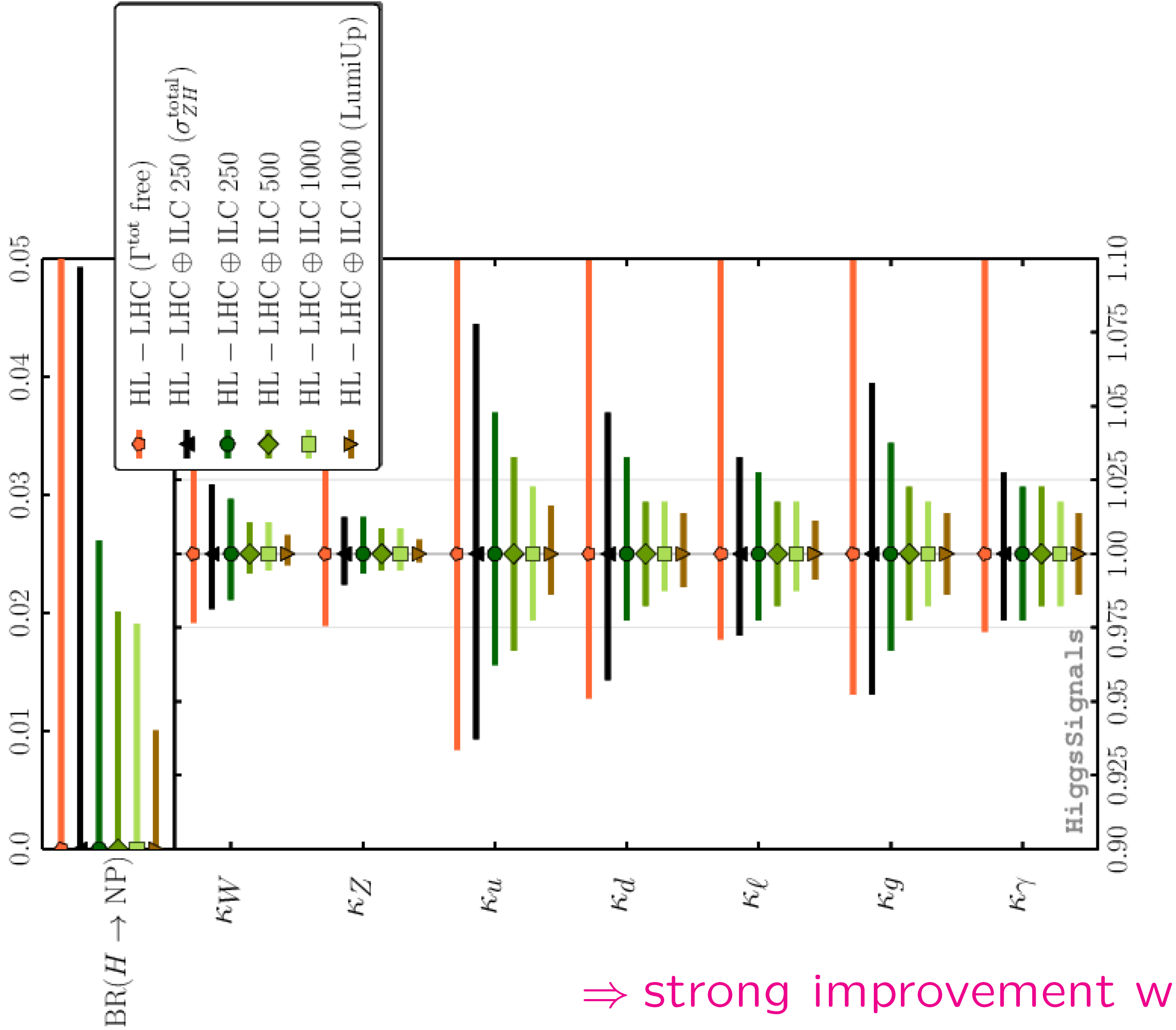
⇒ . . . and without theory assumptions

⇒ and this improvement could be decisive!

HL-LHC vs. ILC in the most general κ framework:

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14]

no theory assumptions, full fit



⇒ strong improvement with the ILC

What if nature is more complicated than κ's?

Assumptions for κ-framework:

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM
4. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i
   ($\kappa_i = 1$ corresponds to the SM case)

Broader class of models covered: EFT

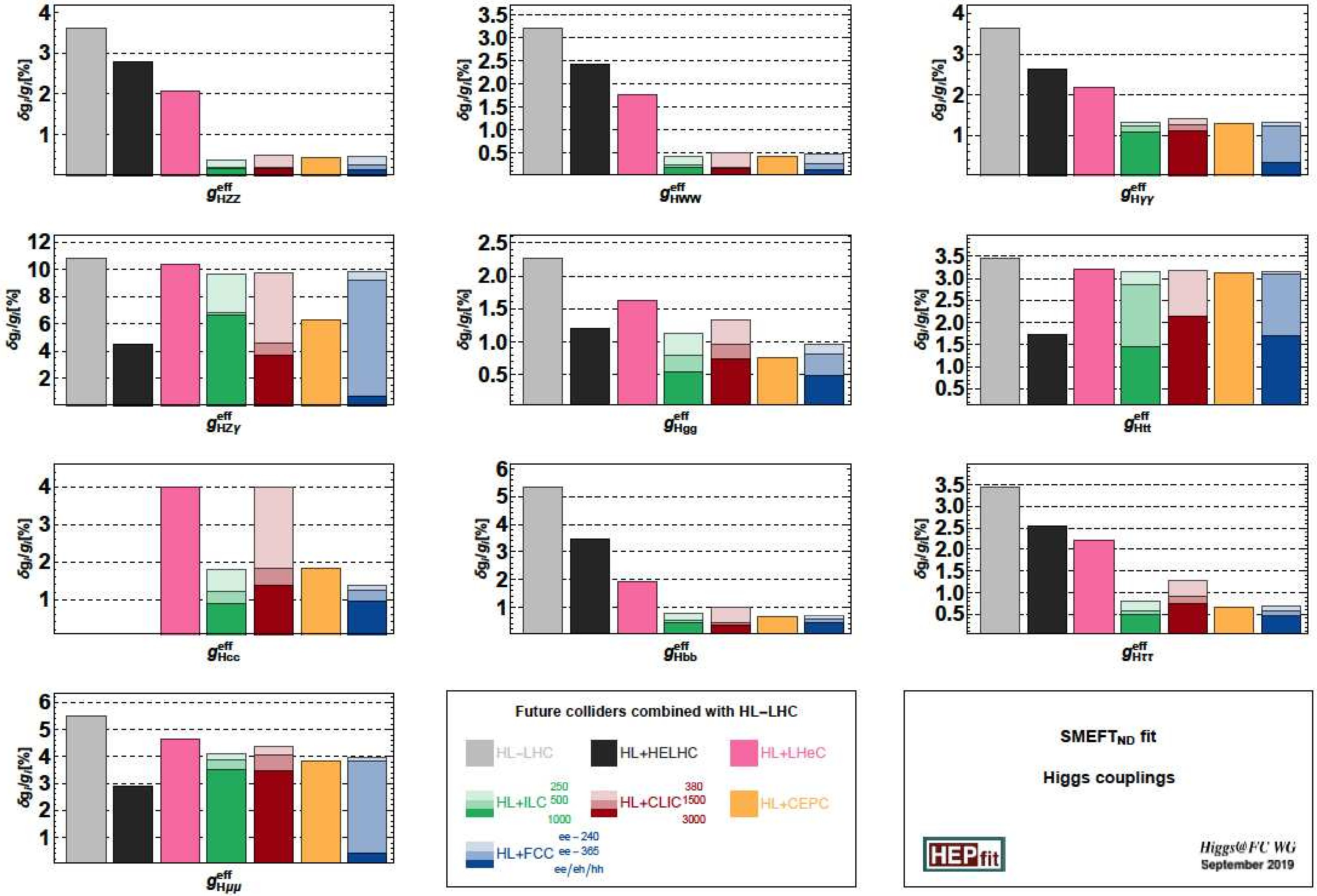
– no light new states

– non-SM-like coupling structures

Note: also EFT does NOT cover all models

⇒ investigate in addition "realistic" (UV-complete) models!

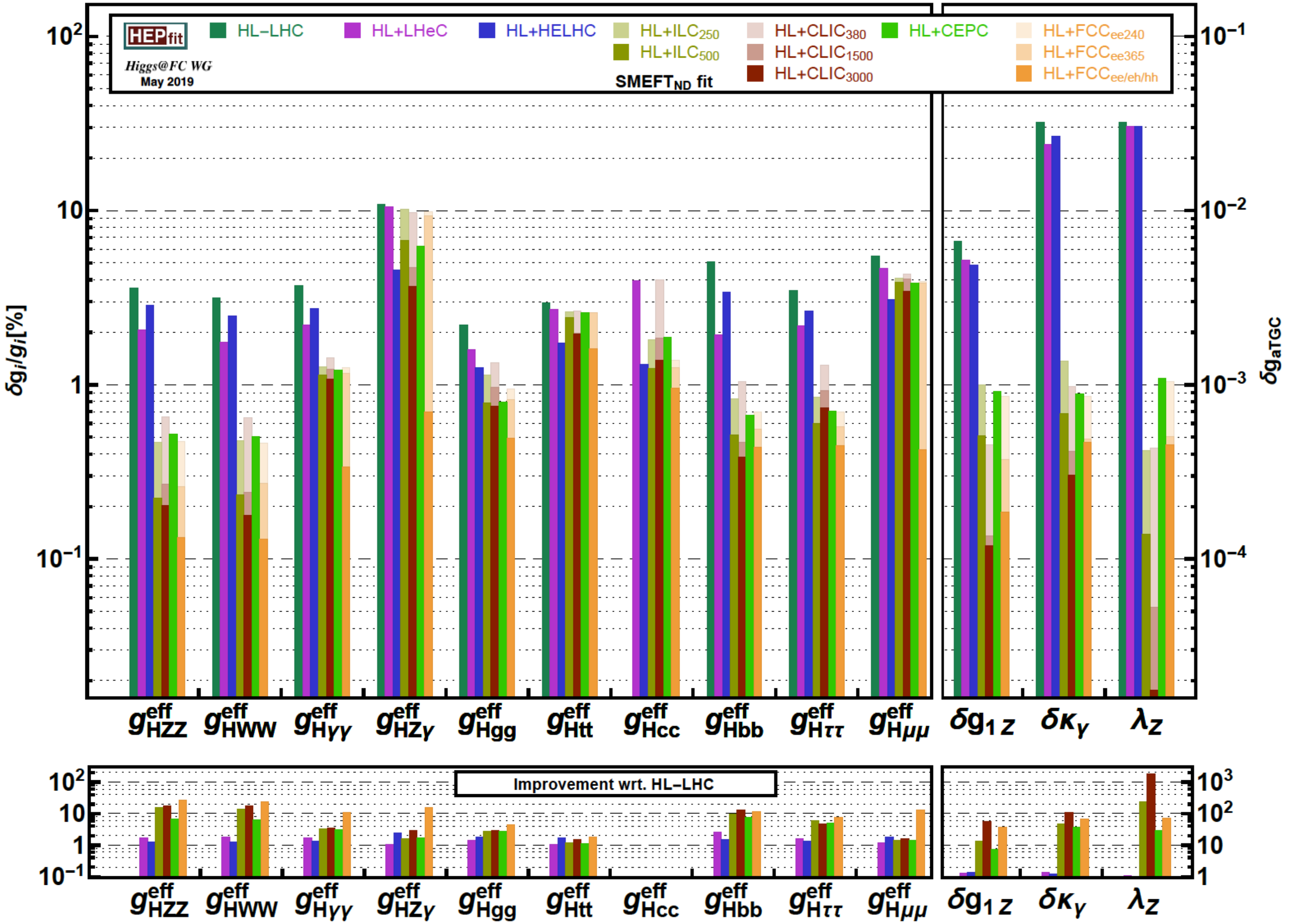
Future expections for Higgs couplings in SMEFT (I)



⇒ clear improvement with the ILC!

⇒ polarization important to disentangle BSM coupling structures

Future expections for Higgs couplings in SMEFT (II)



⇒ clear improvement with the ILC!

⇒ polarization important to disentangle BSM coupling structures

Most challenging: $\lambda_{hhh}^{\text{BSM}}$ measurements

Possibilities for $\lambda_{hhh}^{\text{BSM}}$ measurements:

$\boxed{\kappa_\lambda := \lambda_{hhh}^{\text{BSM}}/\lambda_{hhh}^{\text{SM}} \neq 1 \text{ possible!}}$

1. measurement of di-Higgs production
   → (HL-)LHC, FCC-hh, ILC500, CLIC

2. single Higgs production in an EFT
   → (HL-)LHC, FCC-hh, ILC, CLIC, FCC-ee, CEPC

3. EWPO measurements in an EFT
   → ILC (GigaZ, radiative return), FCC-ee (TeraZ), CEPC

⇒ focus on (1), (2)

Desired precision in λ?

$\Rightarrow$ highly model dependent

Examples: [*R. Gupta, H. Rzehak, J. Wells '13*]

- Higgs singlet extension: $(\Delta\lambda/\lambda)^{\rm max} \sim -18\%$
- Composite Higgs models: $(\Delta\lambda/\lambda)^{\rm max} \sim +20\%$
- MSSM: $(\Delta\lambda/\lambda)^{\rm max} \lesssim -15\%$
- NMSSM: $(\Delta\lambda/\lambda)^{\rm max} \lesssim -25\%$
- 2HDM: NEW: detailed analysis [*F. Arco, S.H., M. Herrero '20*]

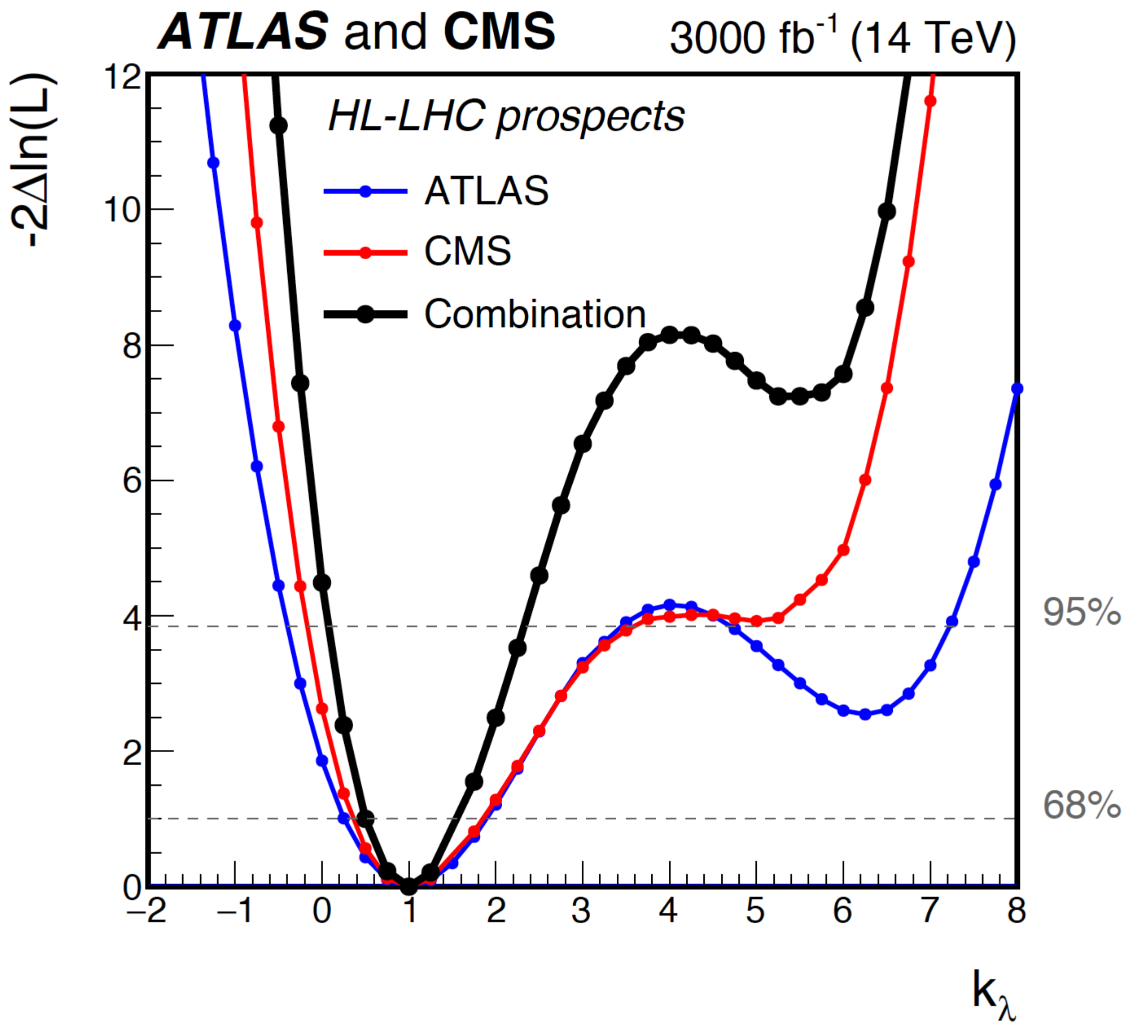
Result overview:

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
$\lambda_{hAA} \in [0,\ 16]$	$\lambda_{hAA} \in [0,\ 16]$	
$\lambda_{hH^+H^-} \in [0,\ 32]$	$\lambda_{hH^+H^-} \in [0,\ 32]$	

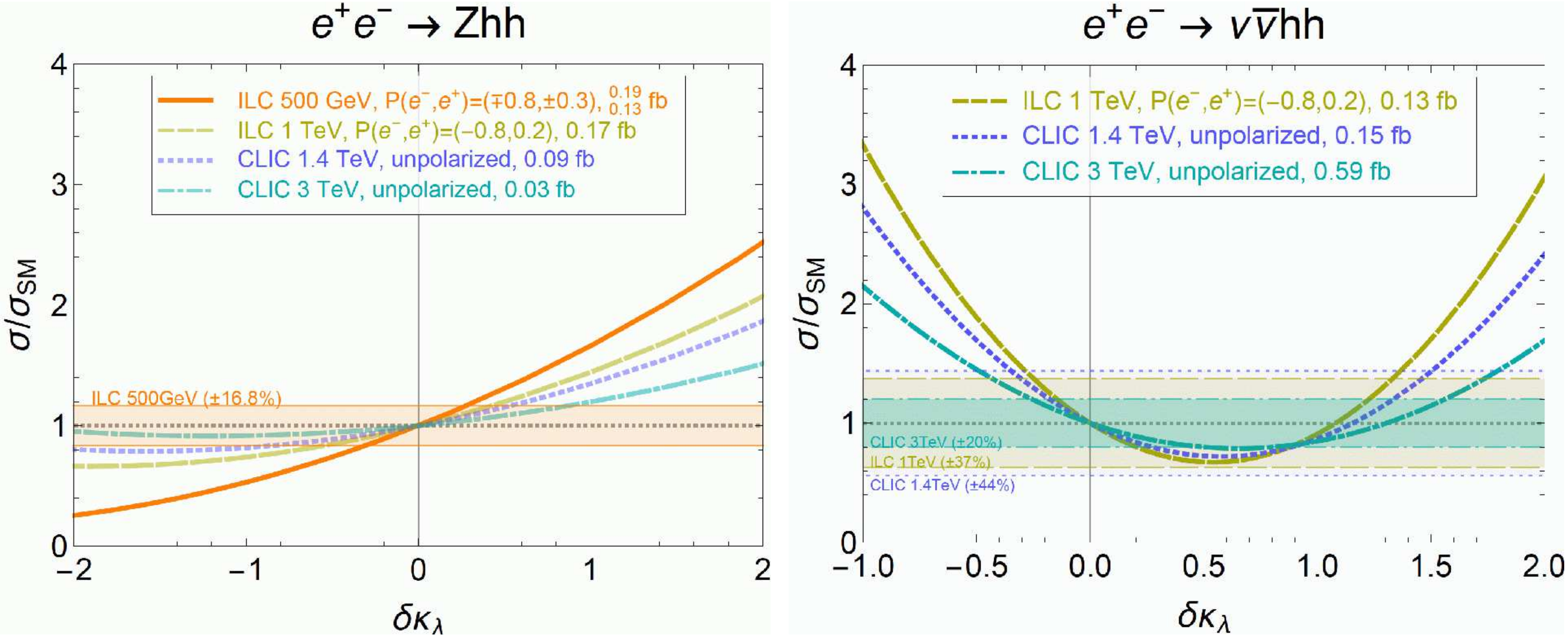
✨ Interesting points are shown in our paper [arXiv:2005.10576] ✨

Results for HL-LHC: $[\kappa_\lambda = -0.5 \ldots +1.5]$



⇒ only evaluated for $\kappa_\lambda = 1$

Di-Higgs production at ILC/CLIC: $[\kappa_\lambda = -0.5 \ldots +1.5]$

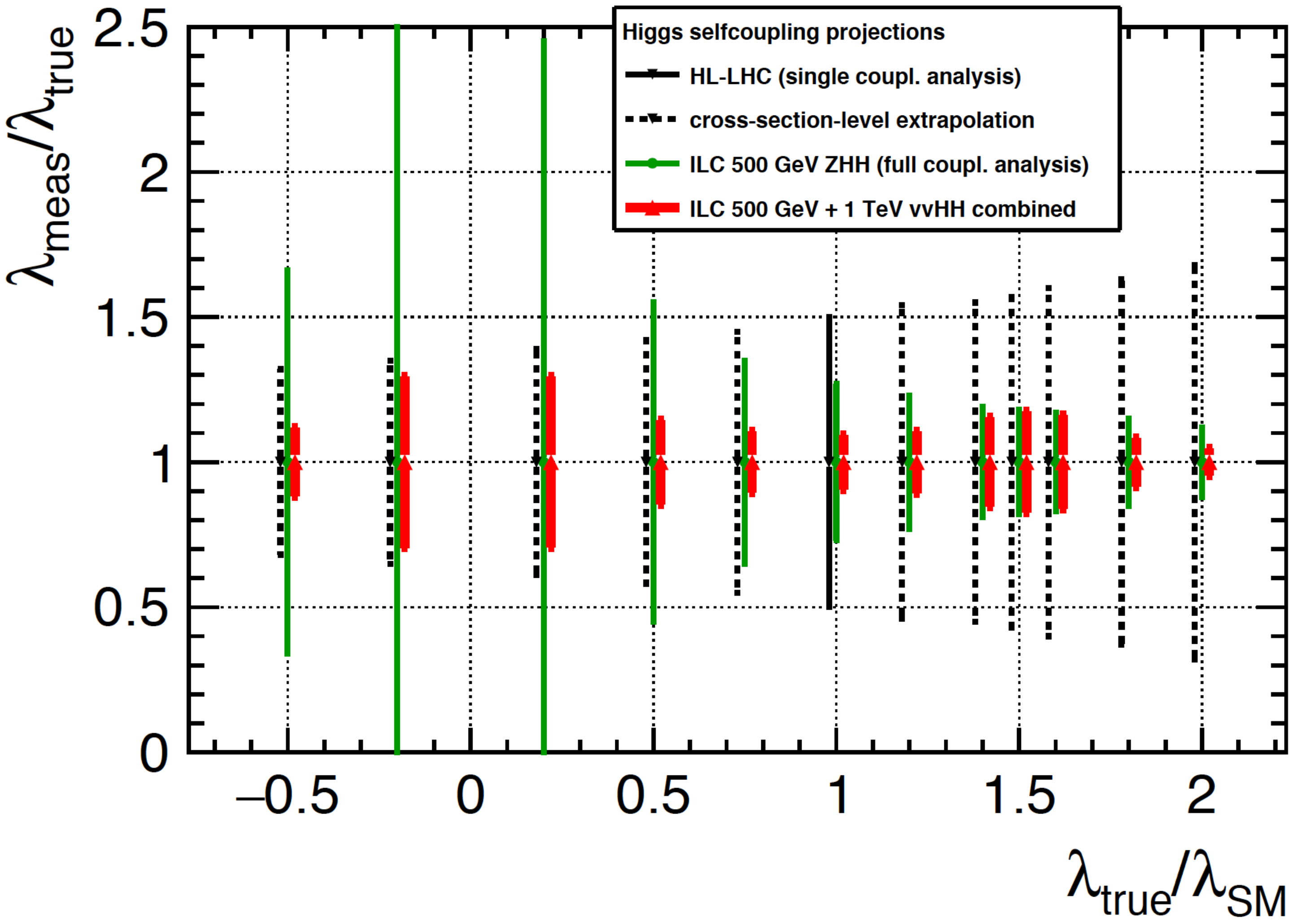


⇒ strong and different dependence on κ_λ

⇒ not all $\kappa_\lambda = 1 + \delta\kappa_\lambda$ range covered (but one can imagine . . .)

Measurement of κ_λ selfcoupling at ILC/HL-LHC: $[\kappa_\lambda = -0.5 \ldots + 1.5]$

[J. List et al. – PRELIMINARY]



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

Measurement of κ_λ selfcoupling at ILC/HL-LHC: $[\kappa_\lambda = -0.5 \ldots +1.5]$

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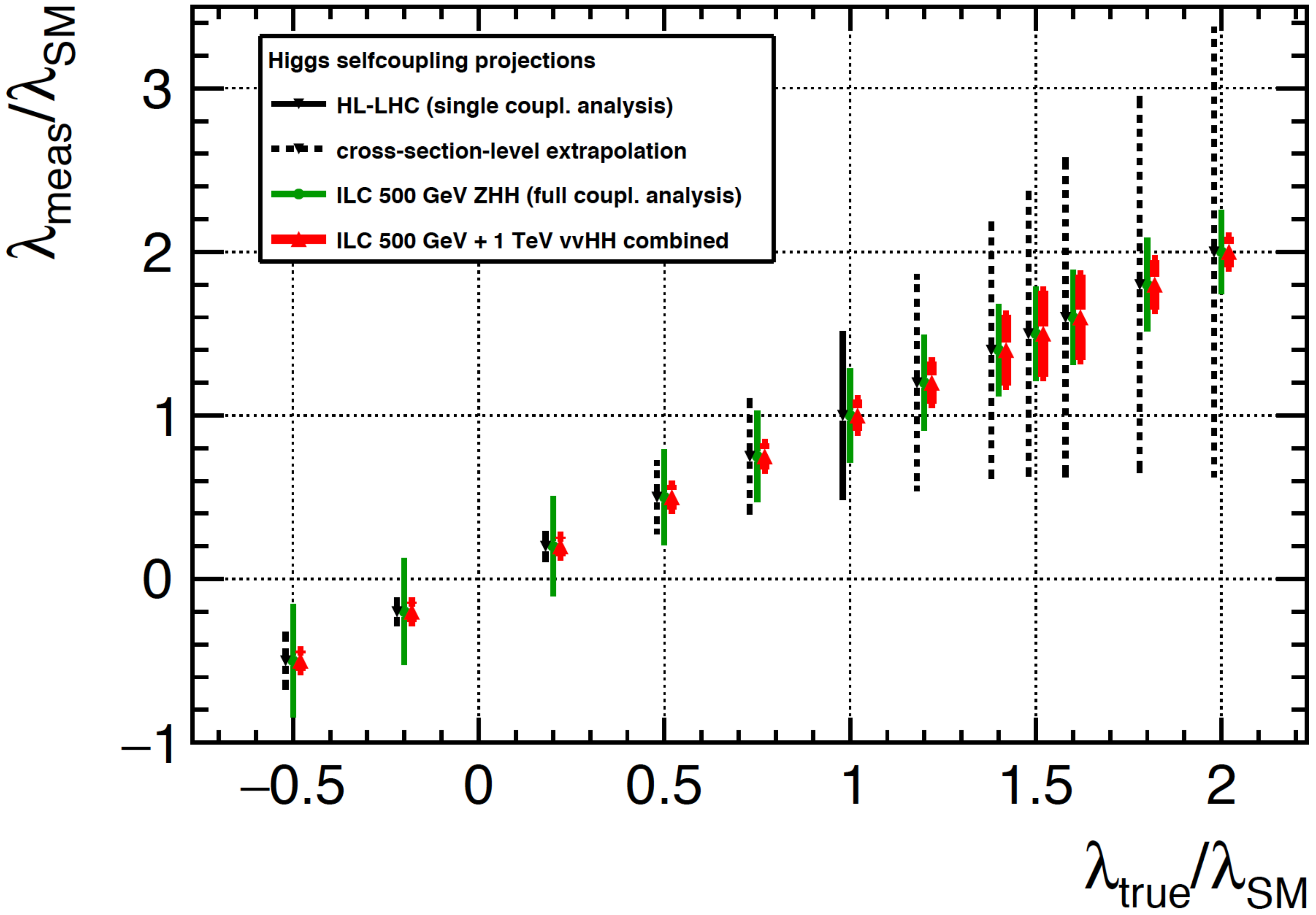
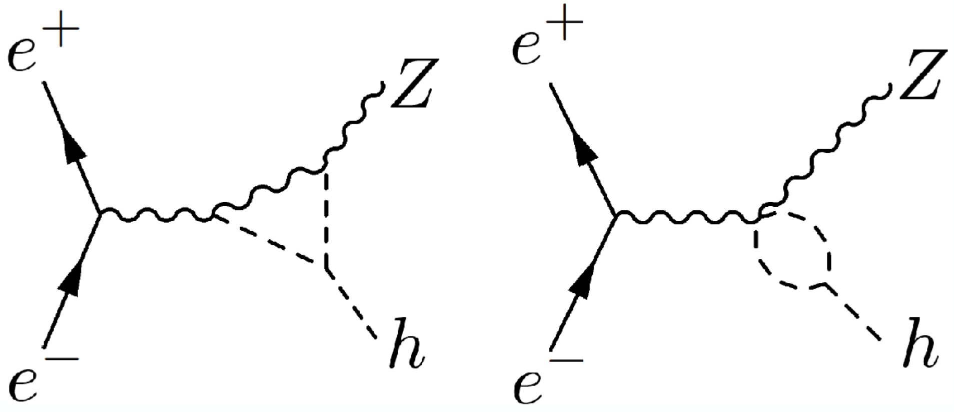
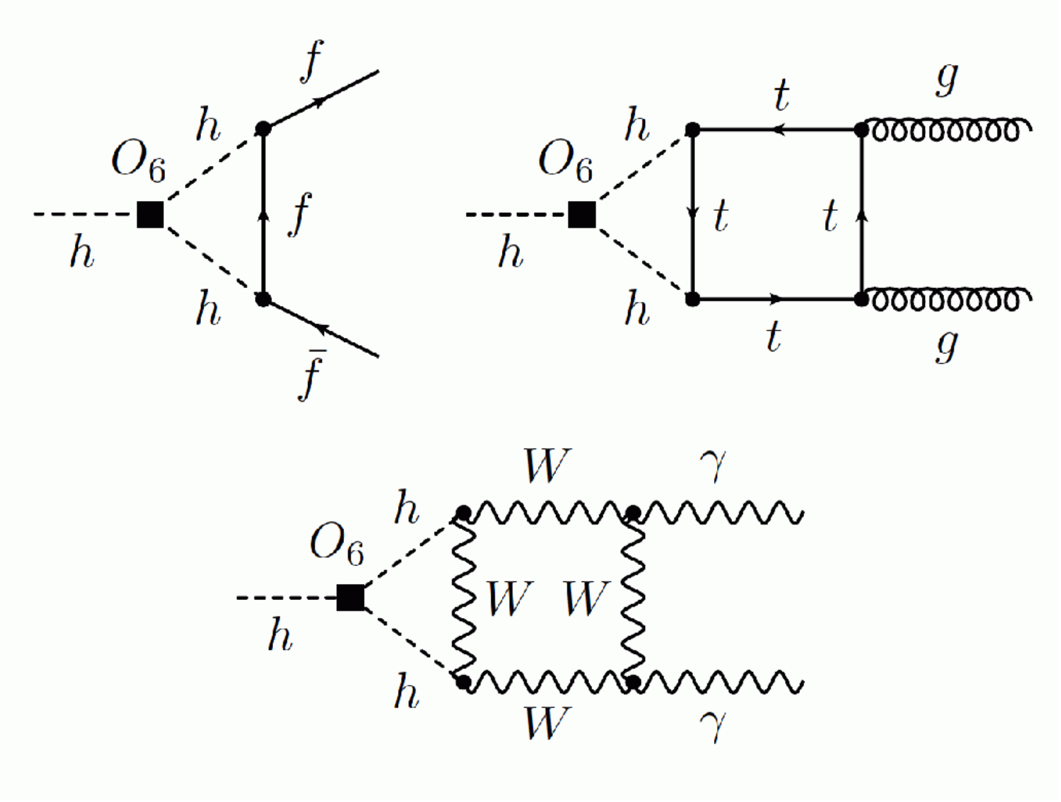


⇒ over most of the parameter space ILC is clearly superior to HL-LHC

Single-Higgs production:

$[\kappa_\lambda = -0.5 \ldots +1.5]$



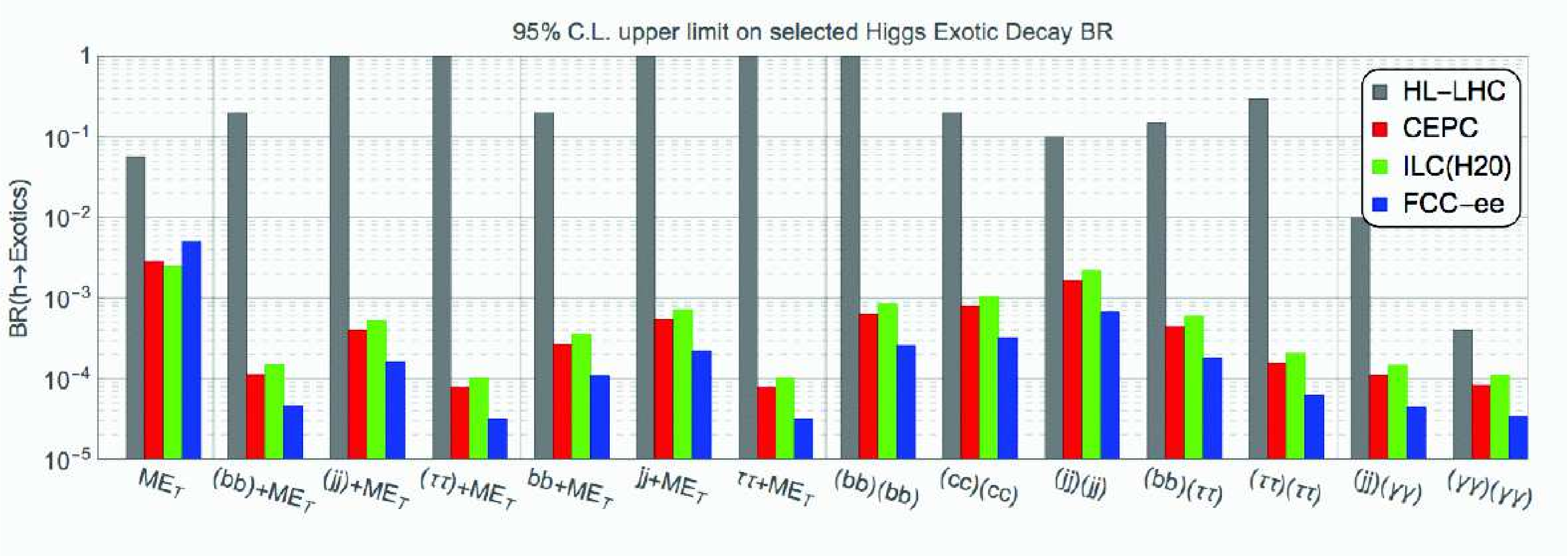


EFT analysis performed only for $\kappa_\lambda = 1$

⇒ prospects for single production unclear!

Exotic Higgs decays:

[*Z. Liu, L.-T. Wang, H. Zhang '17*]



⇒ strong improvement at the ILC

⇒ sensitivity to BSM physics?!

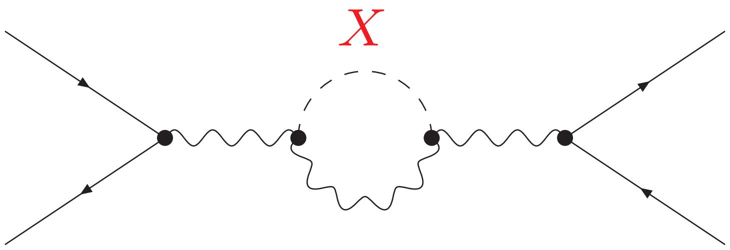
Higgs consistency tests via EWPO:

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\text{eff}}, a_\mu, \; M_h$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H, BSM: limits on M_X

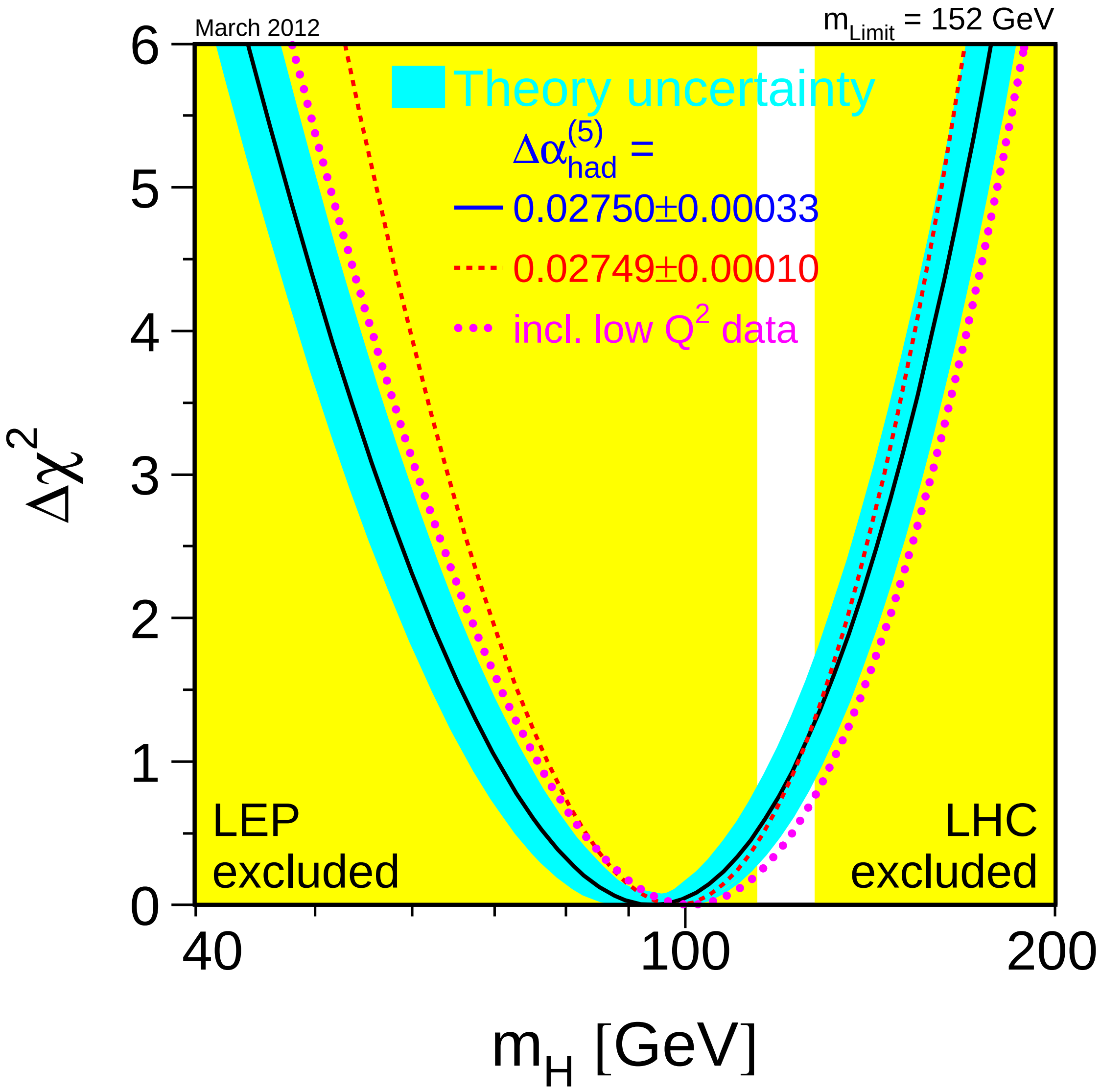
Very high accuracy of measurements and theoretical predictions needed
$\Rightarrow$ models “ready” so far: SM, MSSM, “pure multi-Higgs” models (?)

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

⇒ no confirmation of
Higgs mechanism

⇒ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

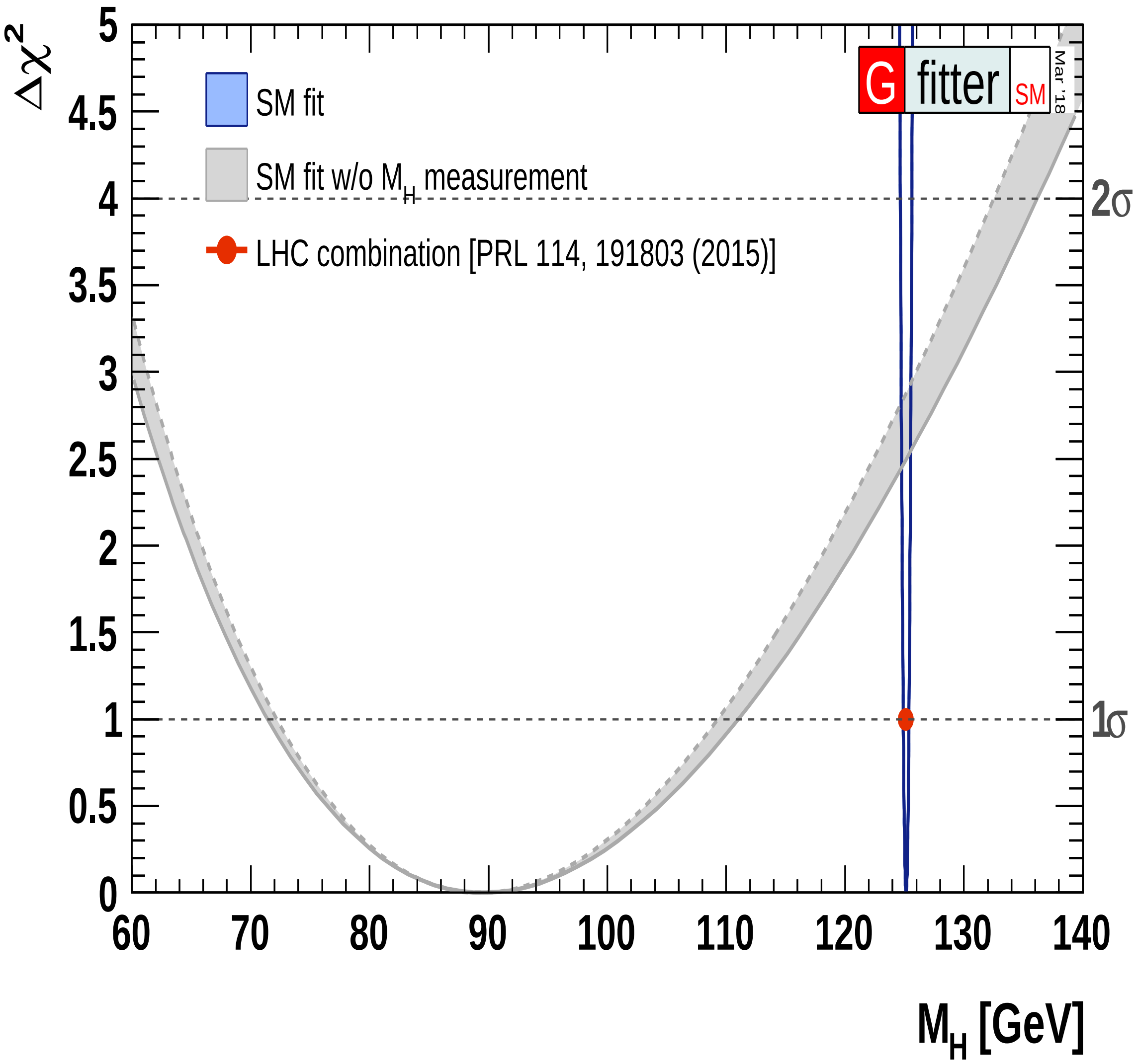
Latest global fit to all SM data:
[*GFitter '18*]

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

“agreement” at $1.8\,\sigma$

Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism



$\Rightarrow$ slightly rising “tension” over the last years . . .

Improvements with the HL-LHC and ILC

Experimental errors of the precision observables:

	today	HL-LHC	ILC/GigaZ
$\delta\sin^2\theta_{\rm eff}(\times 10^5)$	15	$\lesssim 15$	1.3
δM_W [MeV]	12	$\lesssim 12$	2-3
δm_t [GeV]	0.6	$\lesssim 0.5$	0.05

M_W: from direct reconstruction and threshold scan

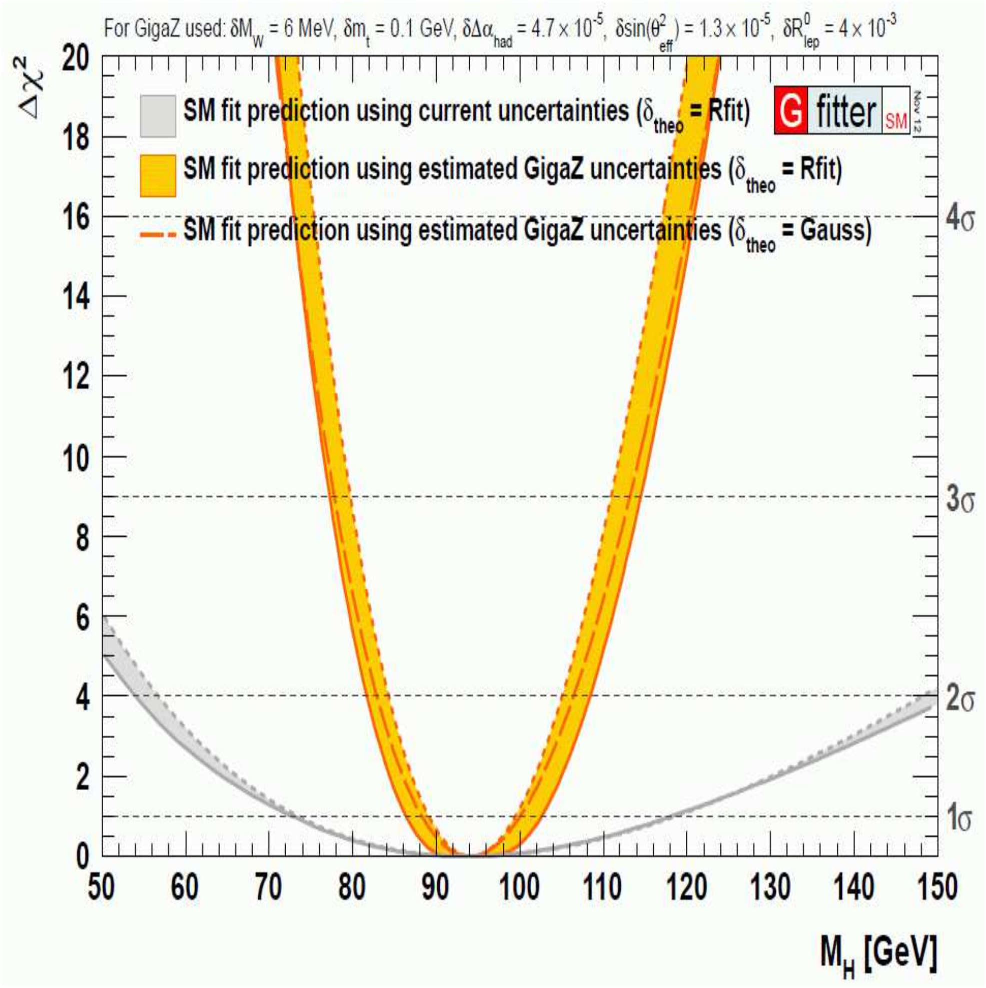
$\sin^2\theta_{\rm eff}$: 1/2 year GigaZ run (polarization important)

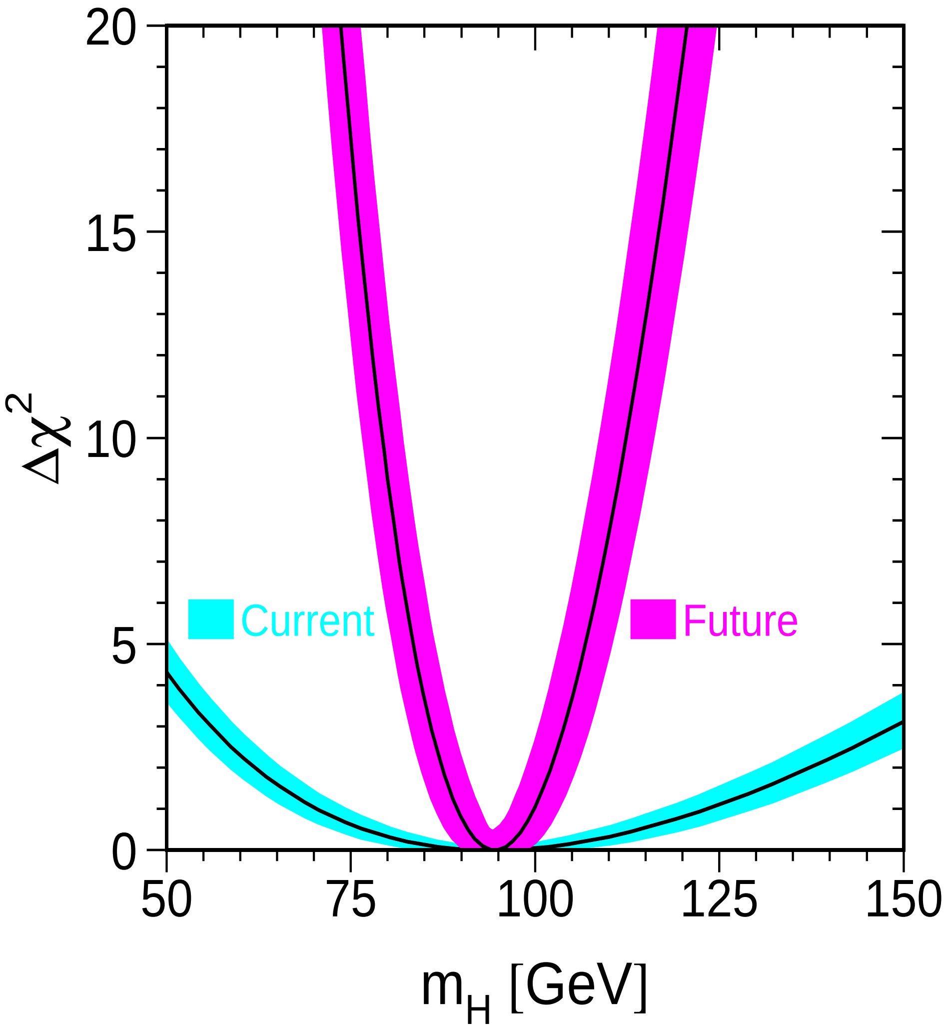
α_s : Improvement from GigaZ run via R_l

⇒ no theory uncertainties included here . . .

Most precise M_H test with the ILC:

[*GFitter '13*] [*LEPEWWG '13*]





$\Rightarrow \delta M_H^{\text{ind}} \lesssim 6$ GeV

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible

Let us assume that we do see a deviation in the h_{125} couplings

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)

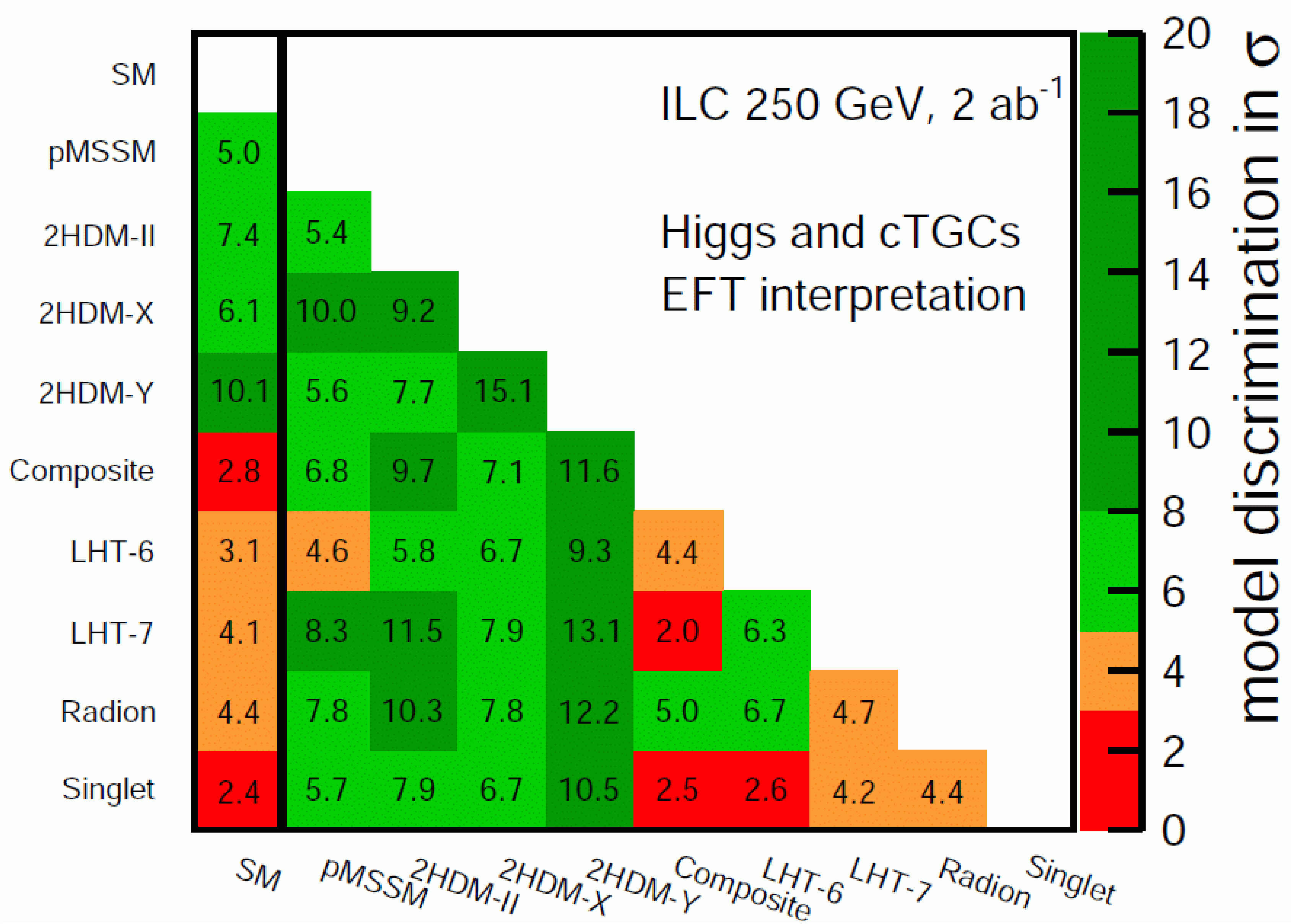
⇒ in the following:

$$\boxed{\text{model prediction (w/o TH unc.)} \Leftrightarrow e^+e^- \text{ precision}}$$

⇒ “Wäscheleinen-Plots” (concrete: ILC250/500)

Model discrimination at ILC250:

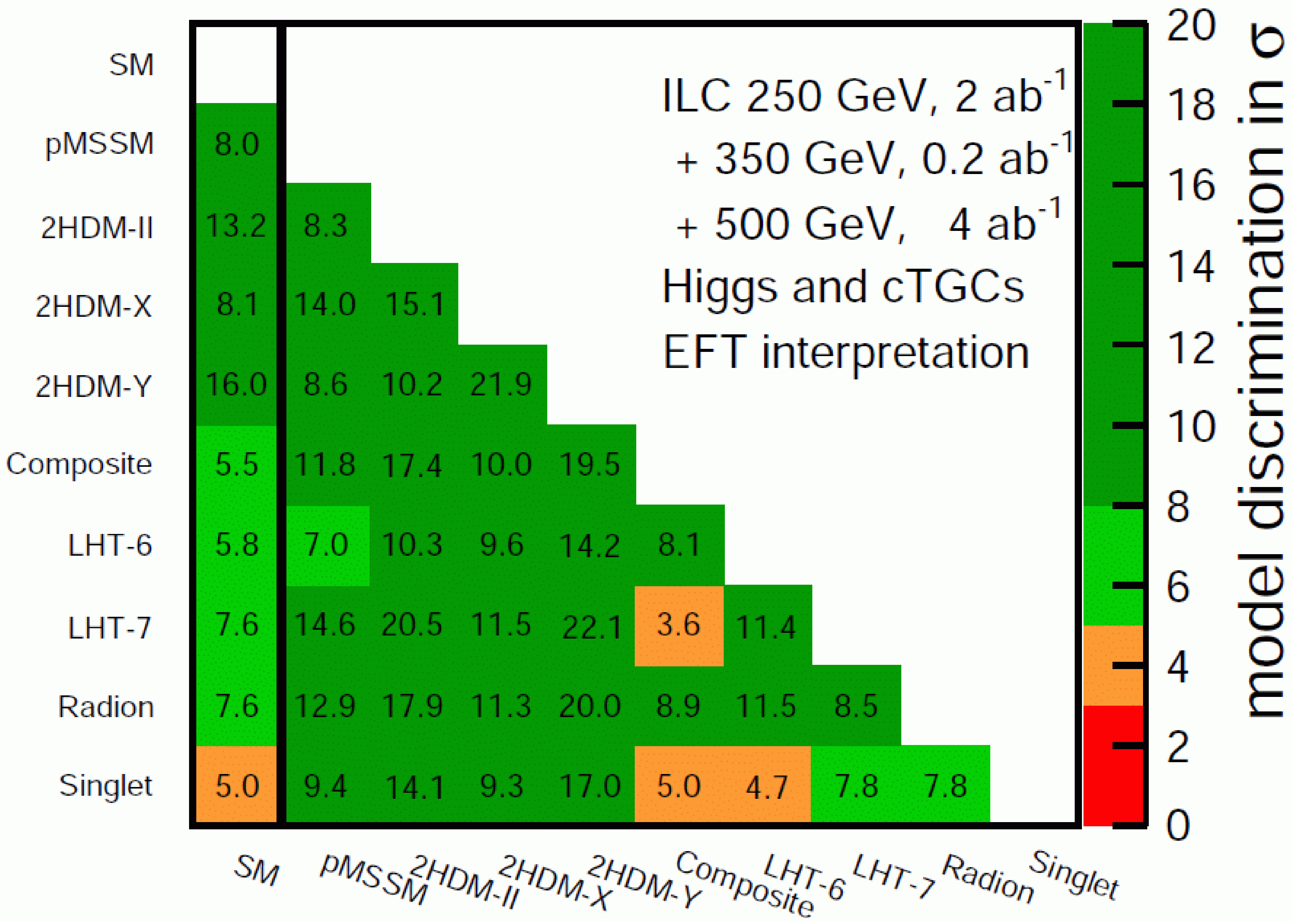
[*K. Fujii et al. ’17*]



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

Model discrimination at ILC500:

[K. Fujii et al. '17]



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

Compare future colliders:

⇒ focus on Higgs searches and measurements

HL-LHC:

– will improve direct search limits

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

[*M. Cepeda et al. '19 – YR18*]

ILC:

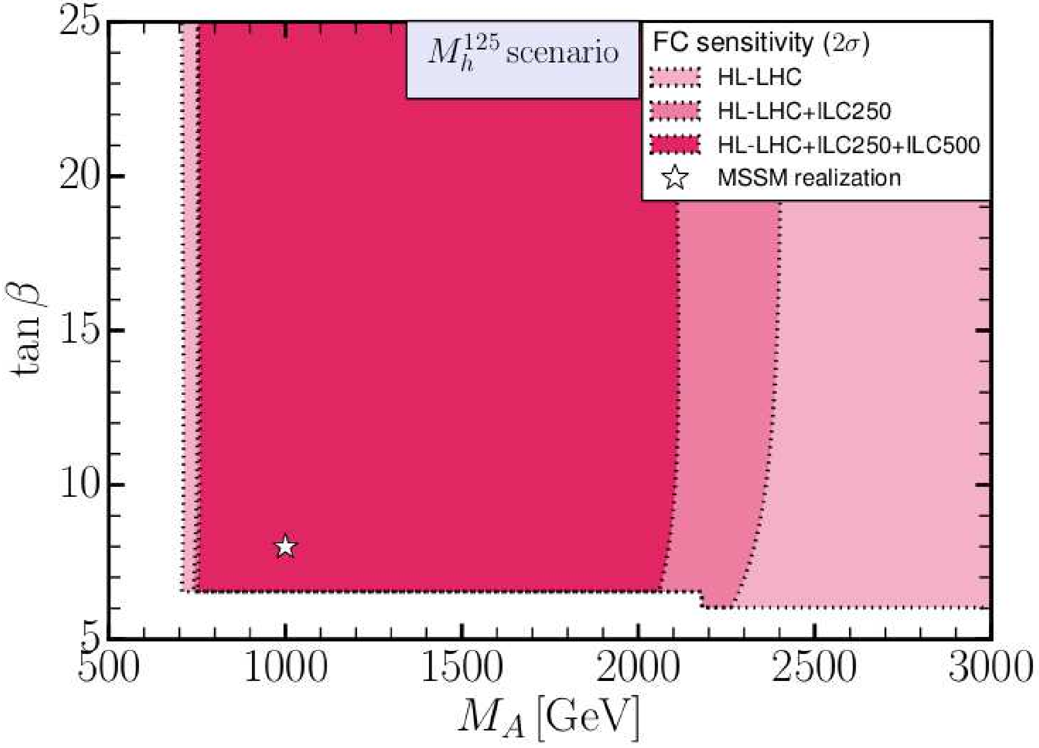
– will improve rate measurements (no theory assumptions!)
  - 250 fb^{-1} at ILC250 $\oplus$ 500 fb^{-1} at ILC500
  - polarization: $P(e^-, e^+) = (-80\%, +30\%)$

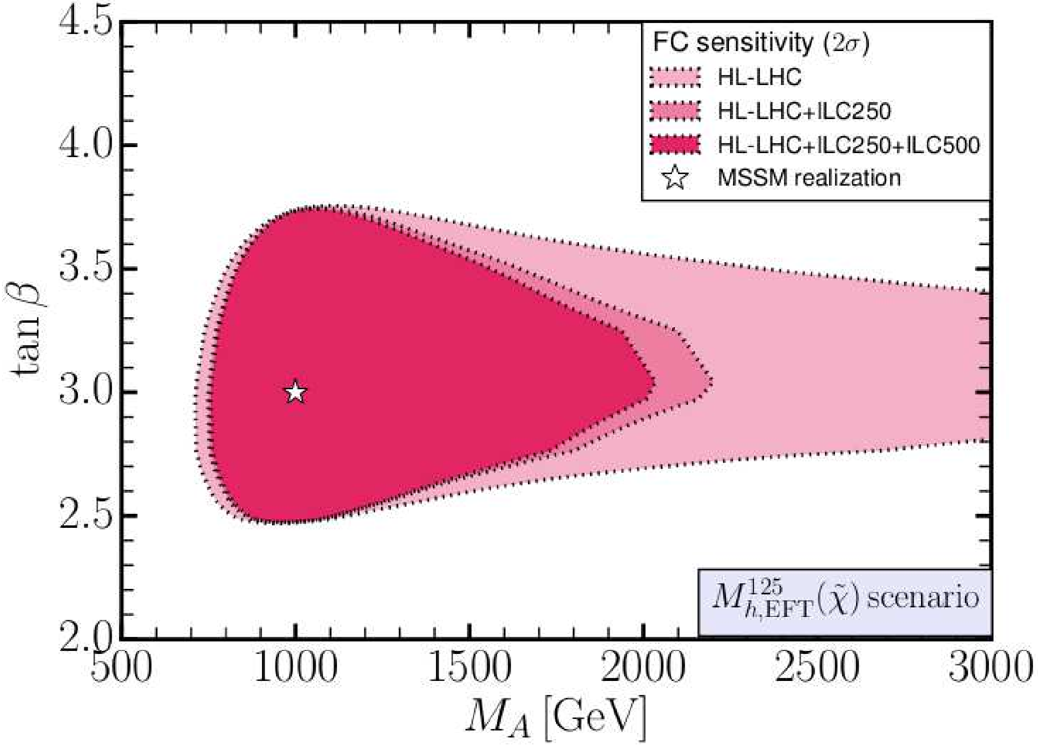
[*T. Barklow et al. '17, '19*]

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?



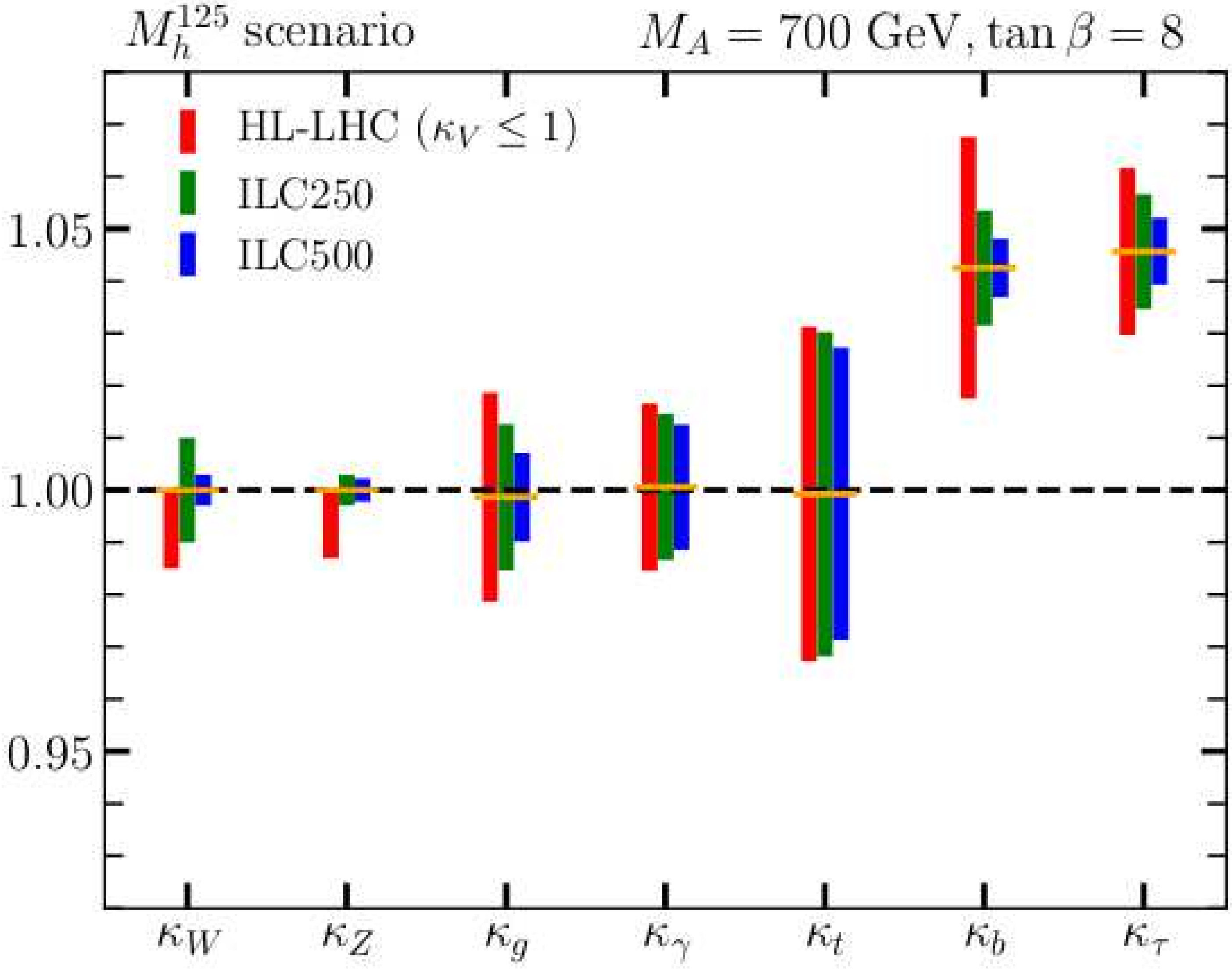


⇒ only ILC measurements give upper limit on M_A

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

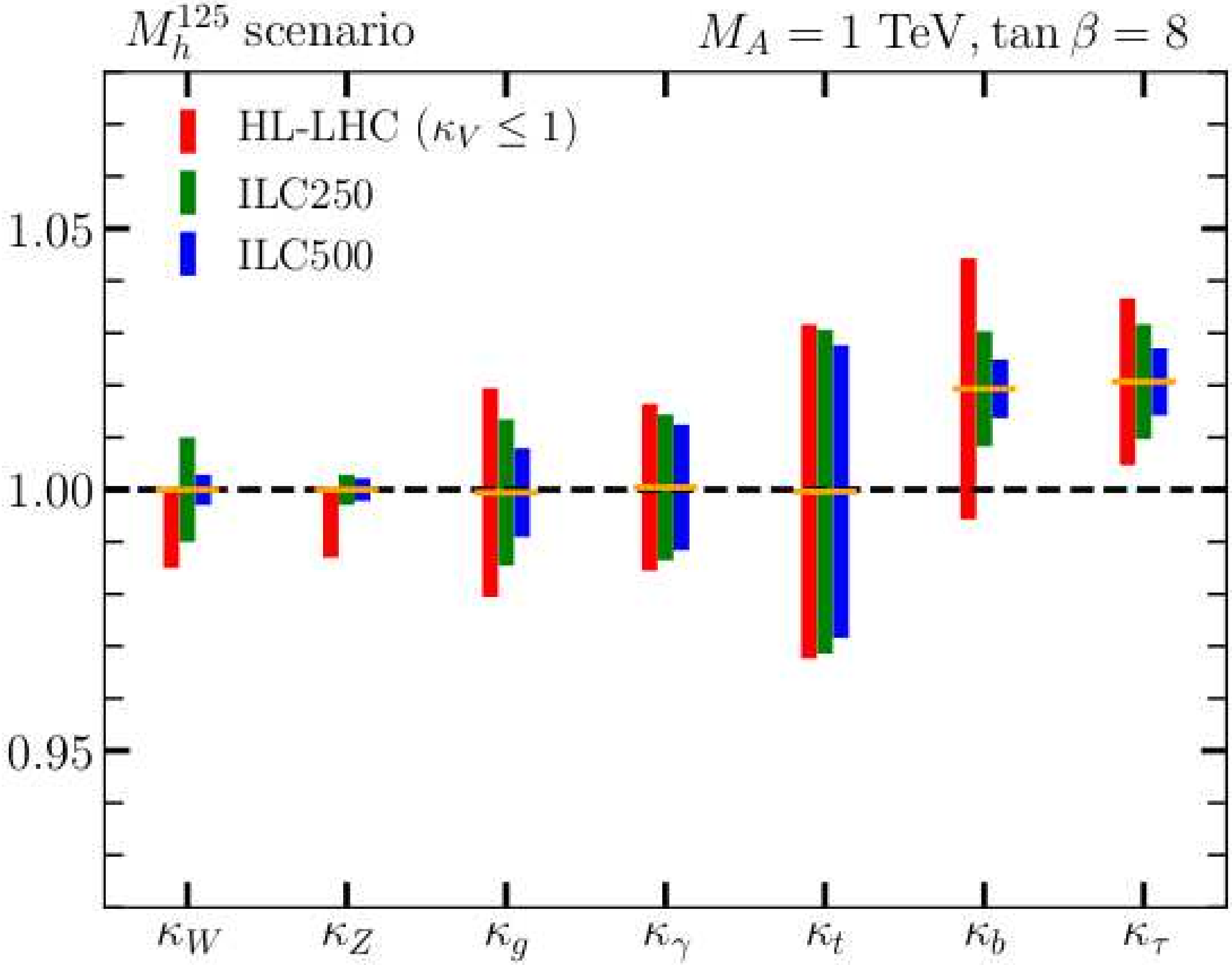
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

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



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

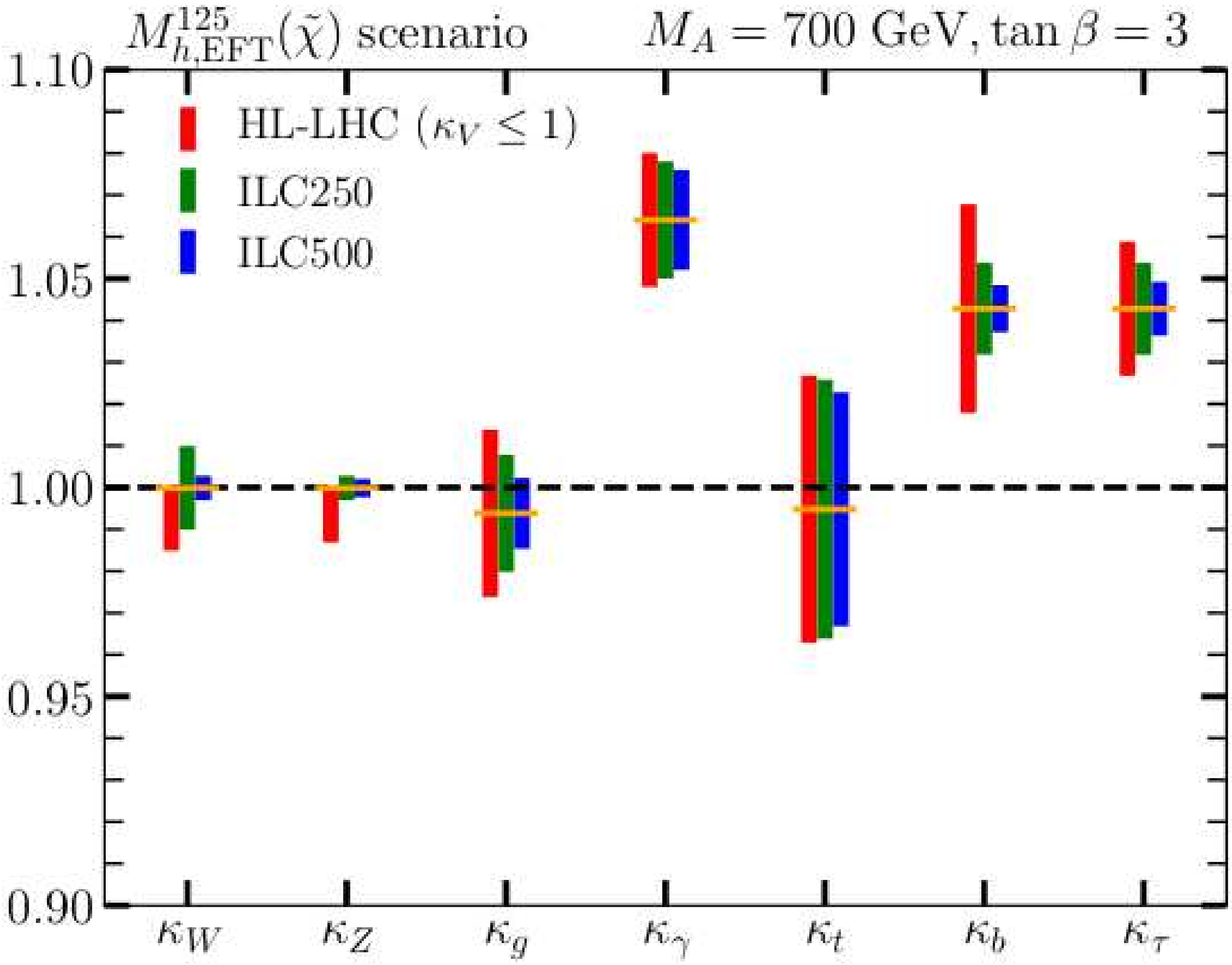
[*H. Bahl et al. '20*]



⇒ only e^+e^- measurements allows to set upper limit on M_A

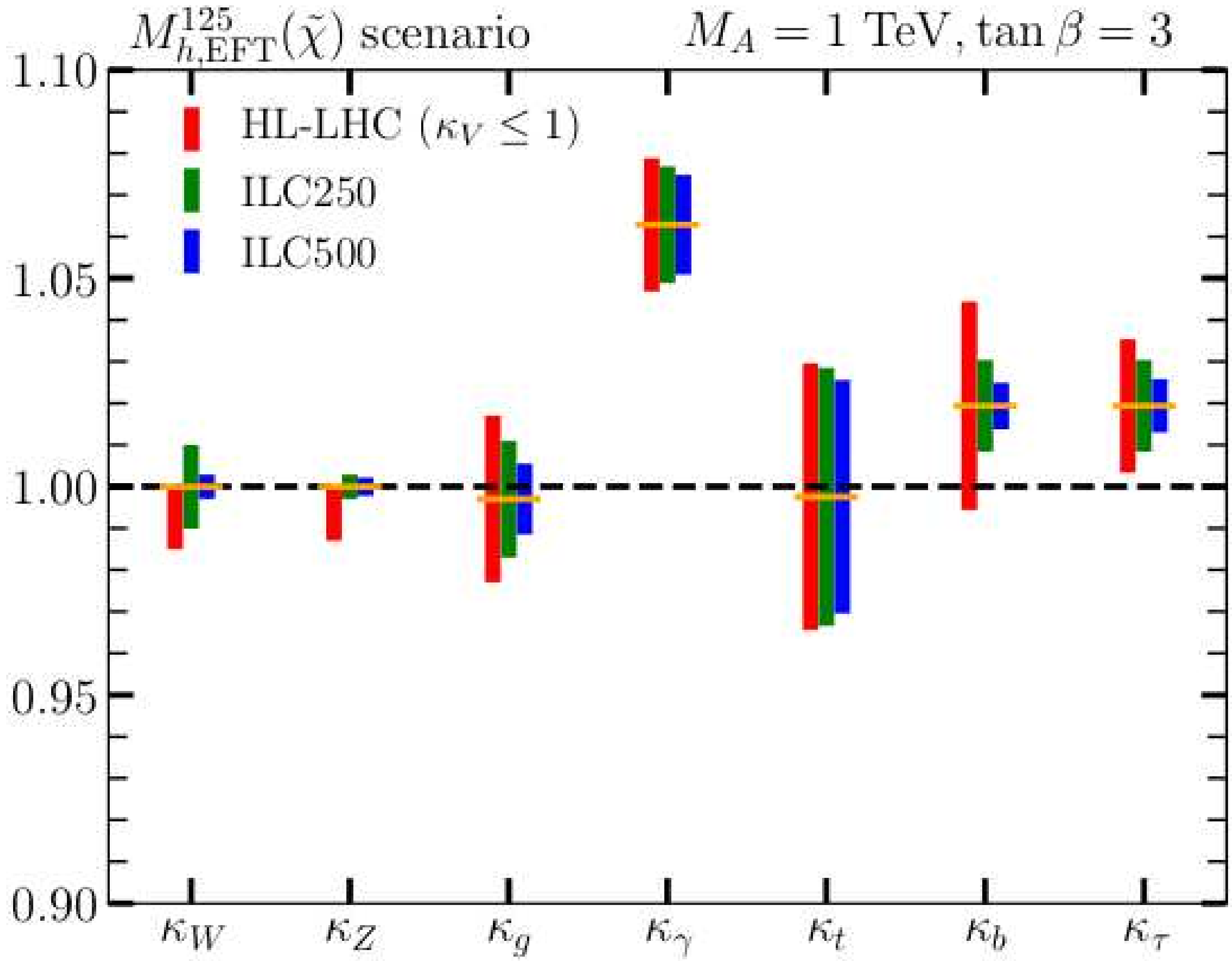
MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

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



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

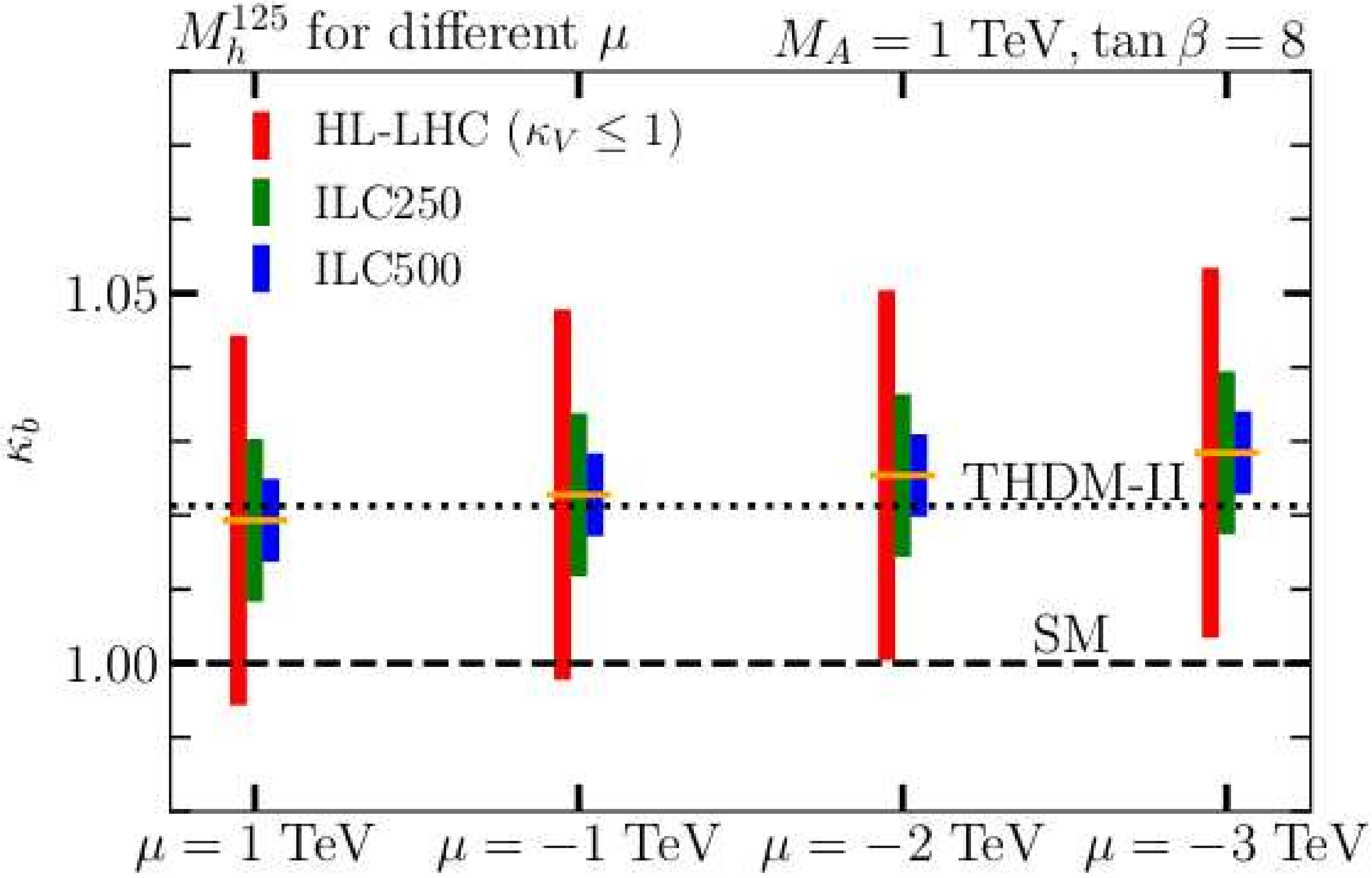
[*H. Bahl et al. '20*]



⇒ only e^+e^- measurements allows to set upper limit on M_A

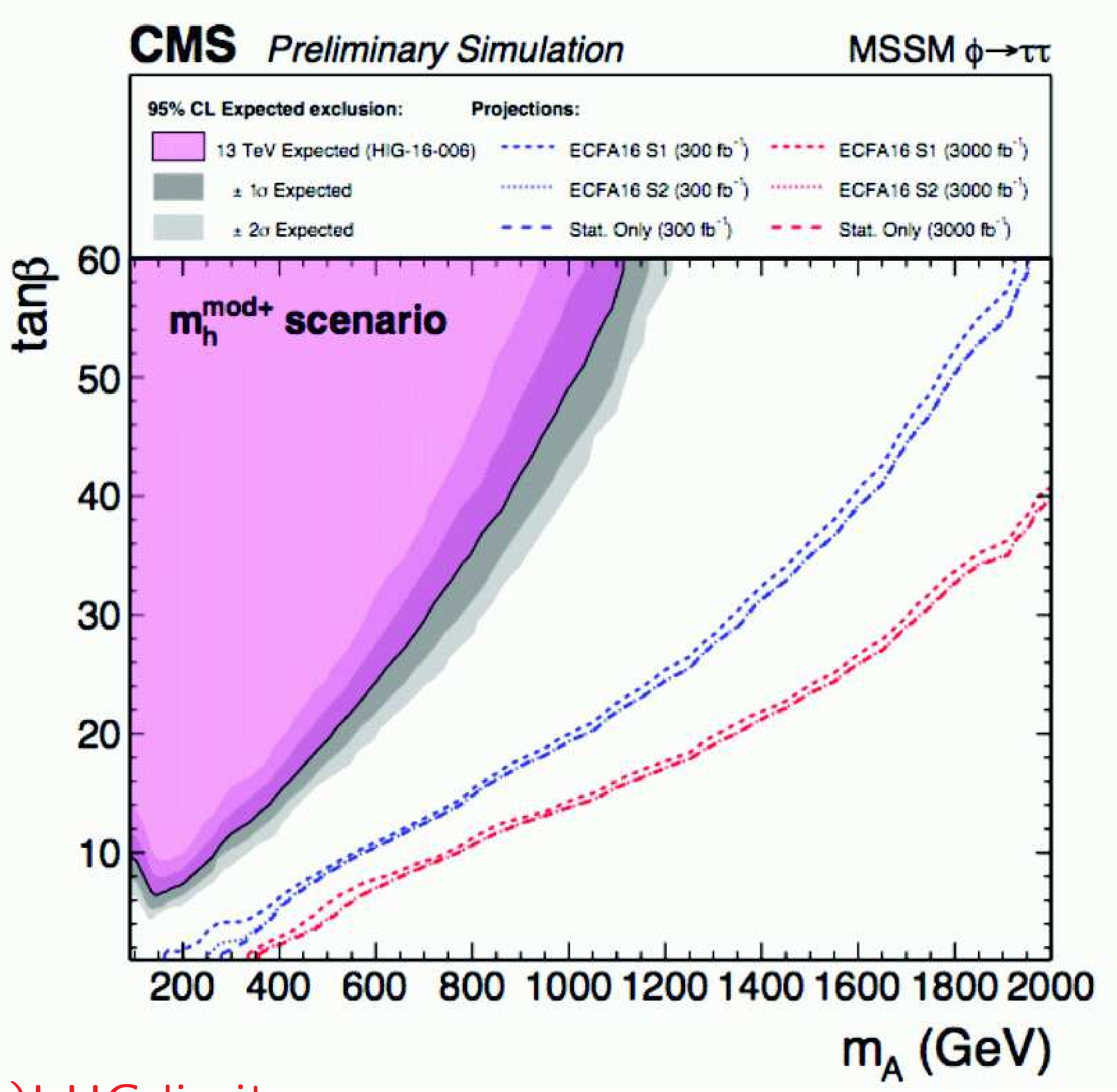
MSSM Wäscheleine V: e^+e^- vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

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



⇒ MSSM vs. 2HDM: very challenging!

3. A) BSM Higgs Bosons above 125 GeV

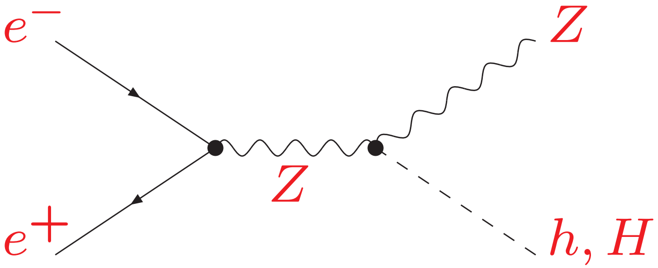


⇒ strong (HL-)LHC limits

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

Search for neutral SUSY Higgs bosons:

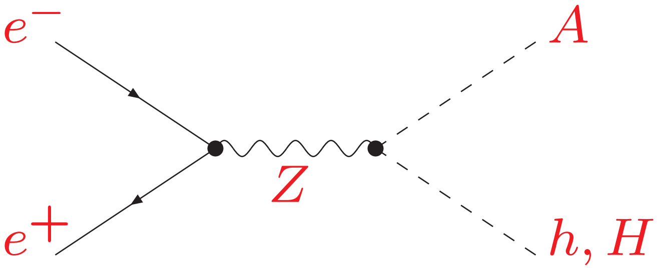
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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



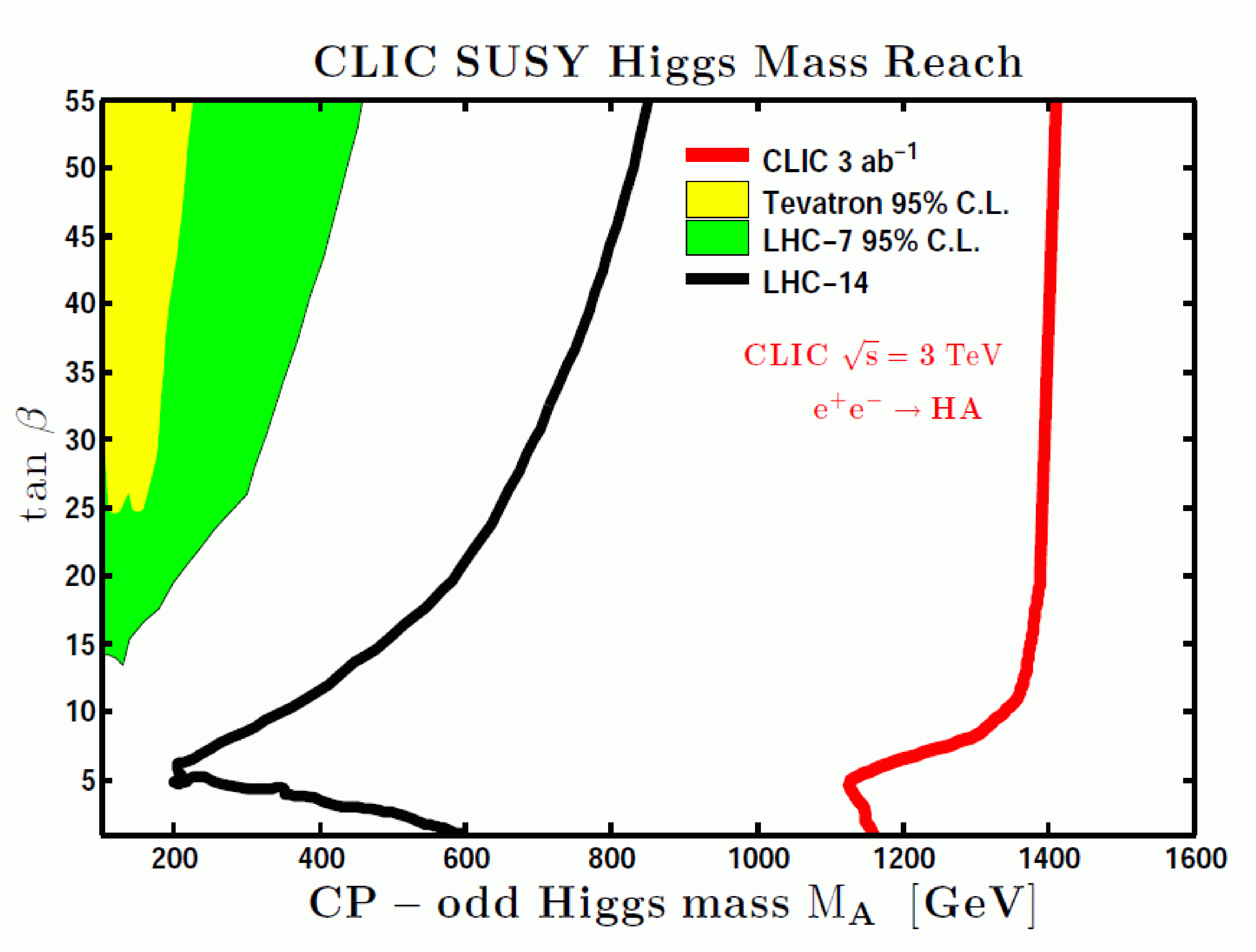
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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

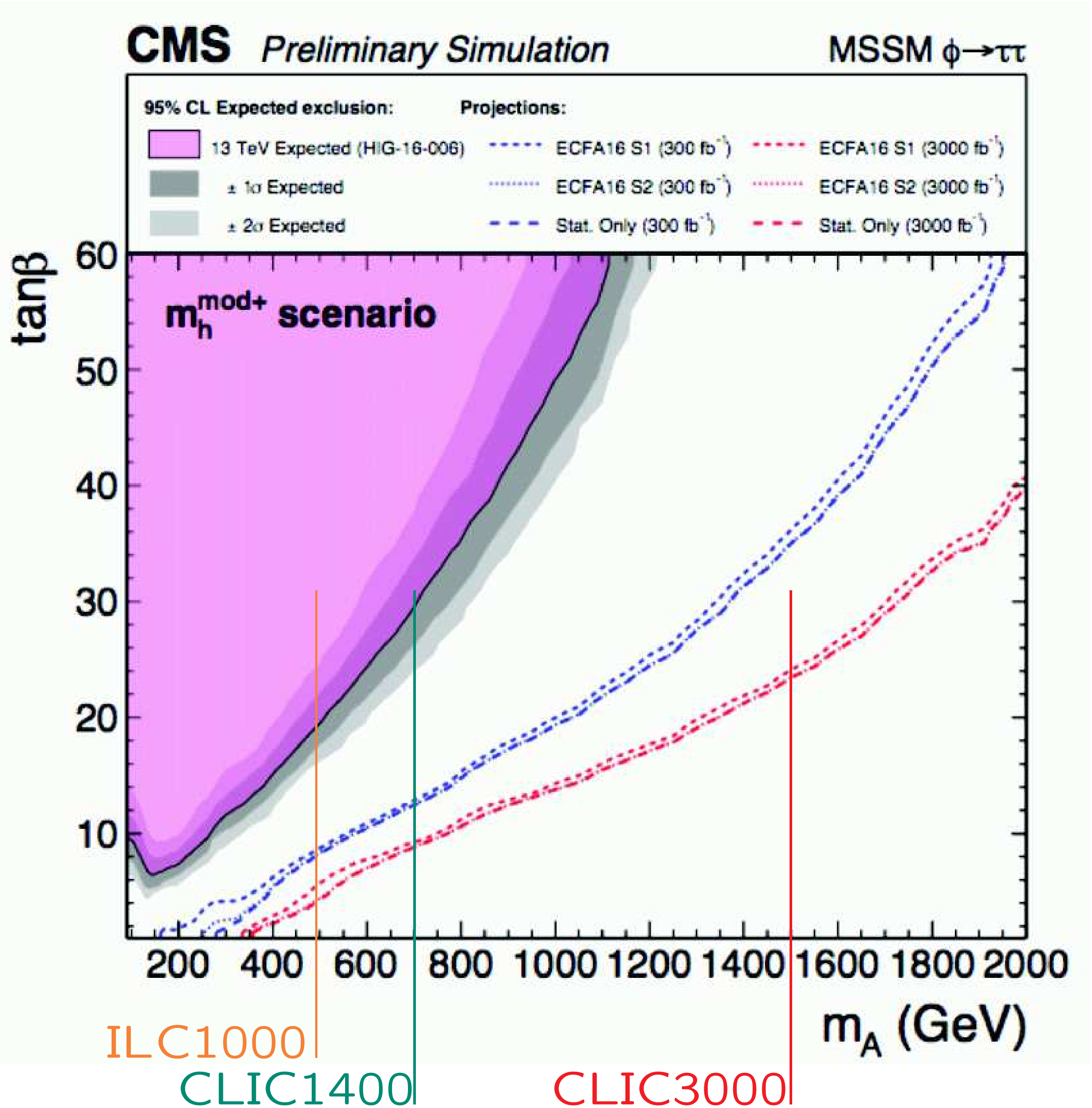
CLIC reach:

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



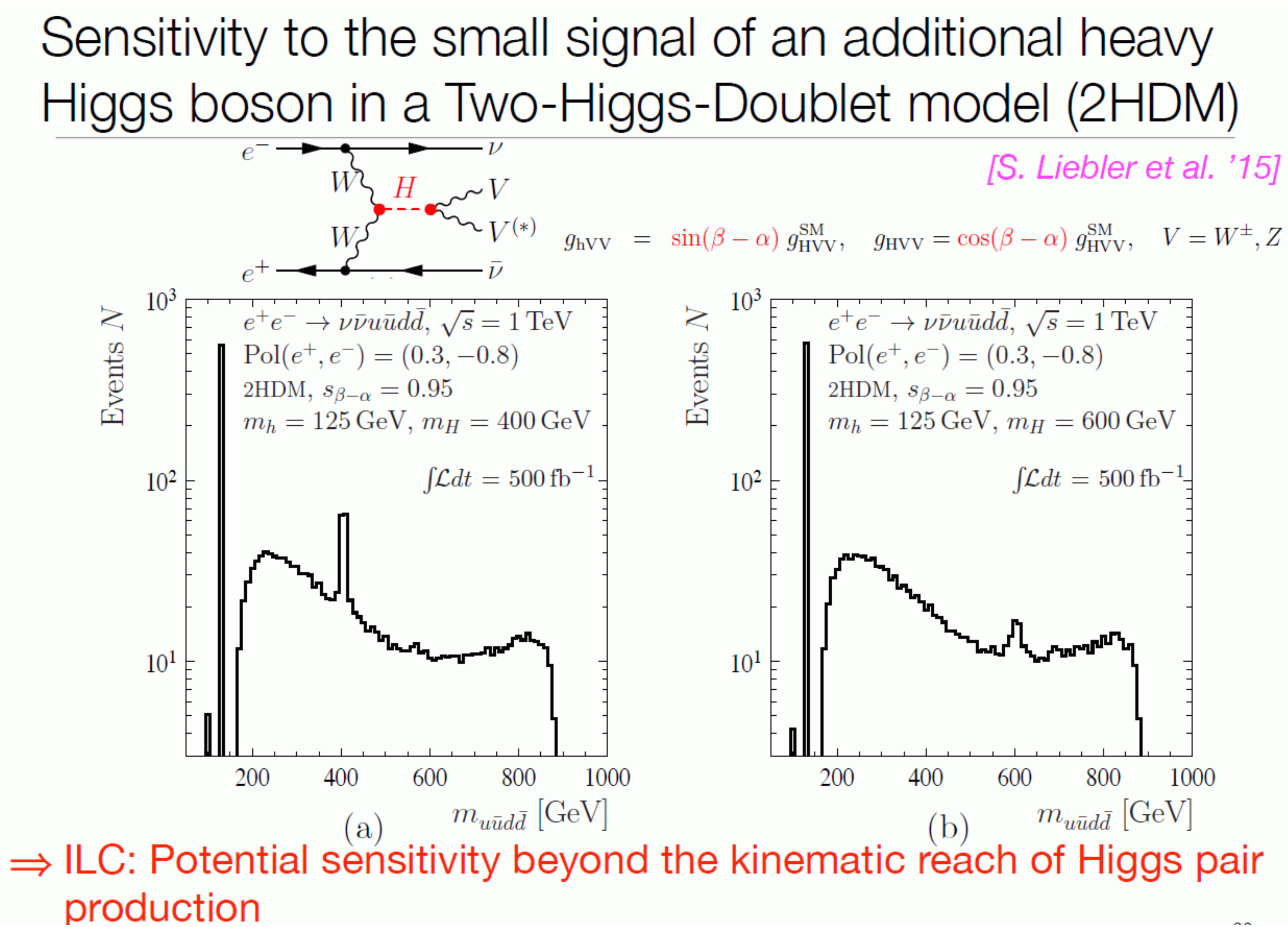
⇒ close to kinematic limit

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



⇒ opportunities clearly $\sqrt{s}$ dependent . . .

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)

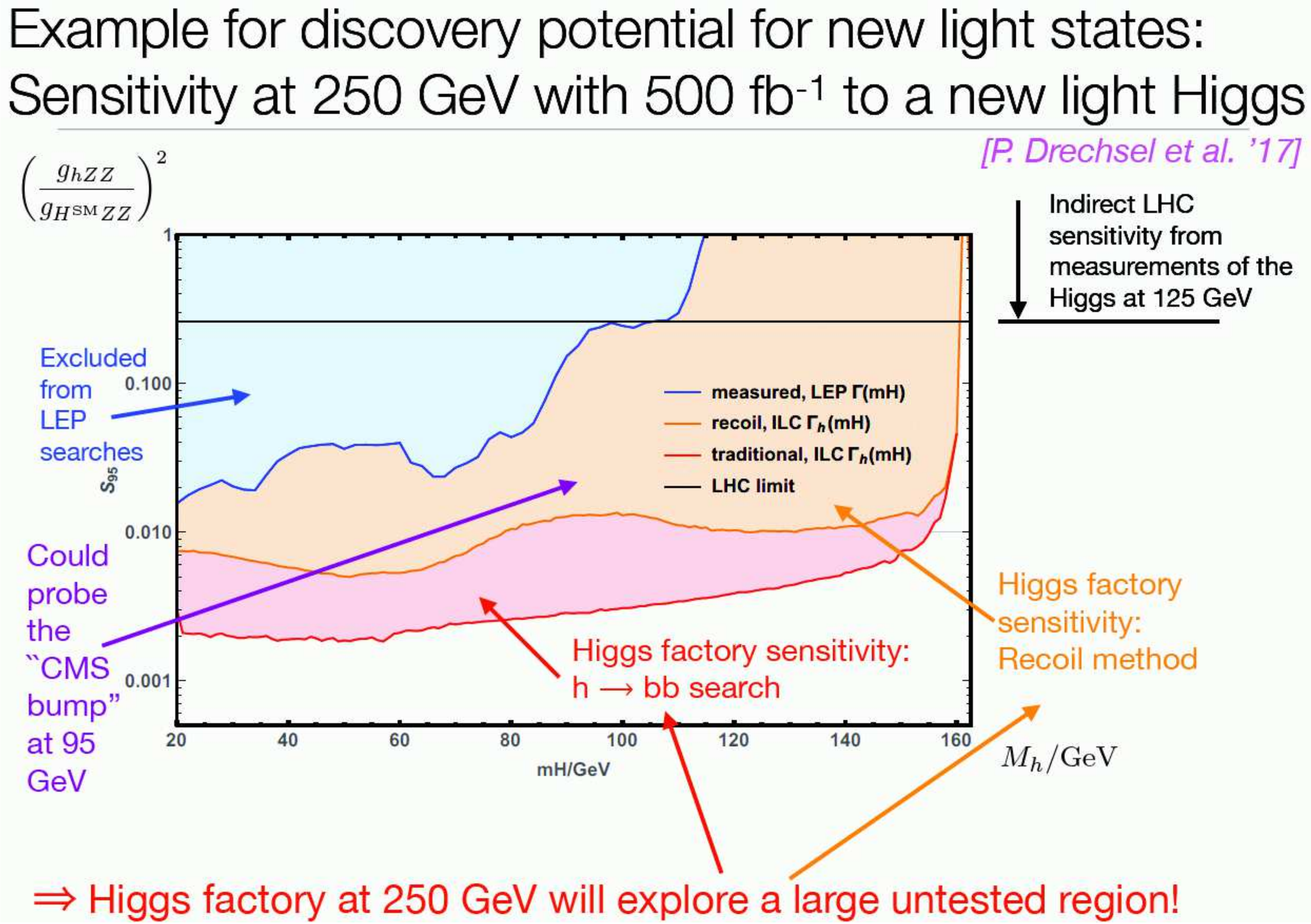
[S. Liebler et al. ’15]

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

⇒ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[Taken from G. Weiglein ’18]

3. B) BSM Higgs Bosons below 125 GeV



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

[P. Drechsel et al. '17]

Indirect LHC sensitivity from measurements of the Higgs at 125 GeV

Excluded from LEP searches

Could probe the "CMS bump" at 95 GeV

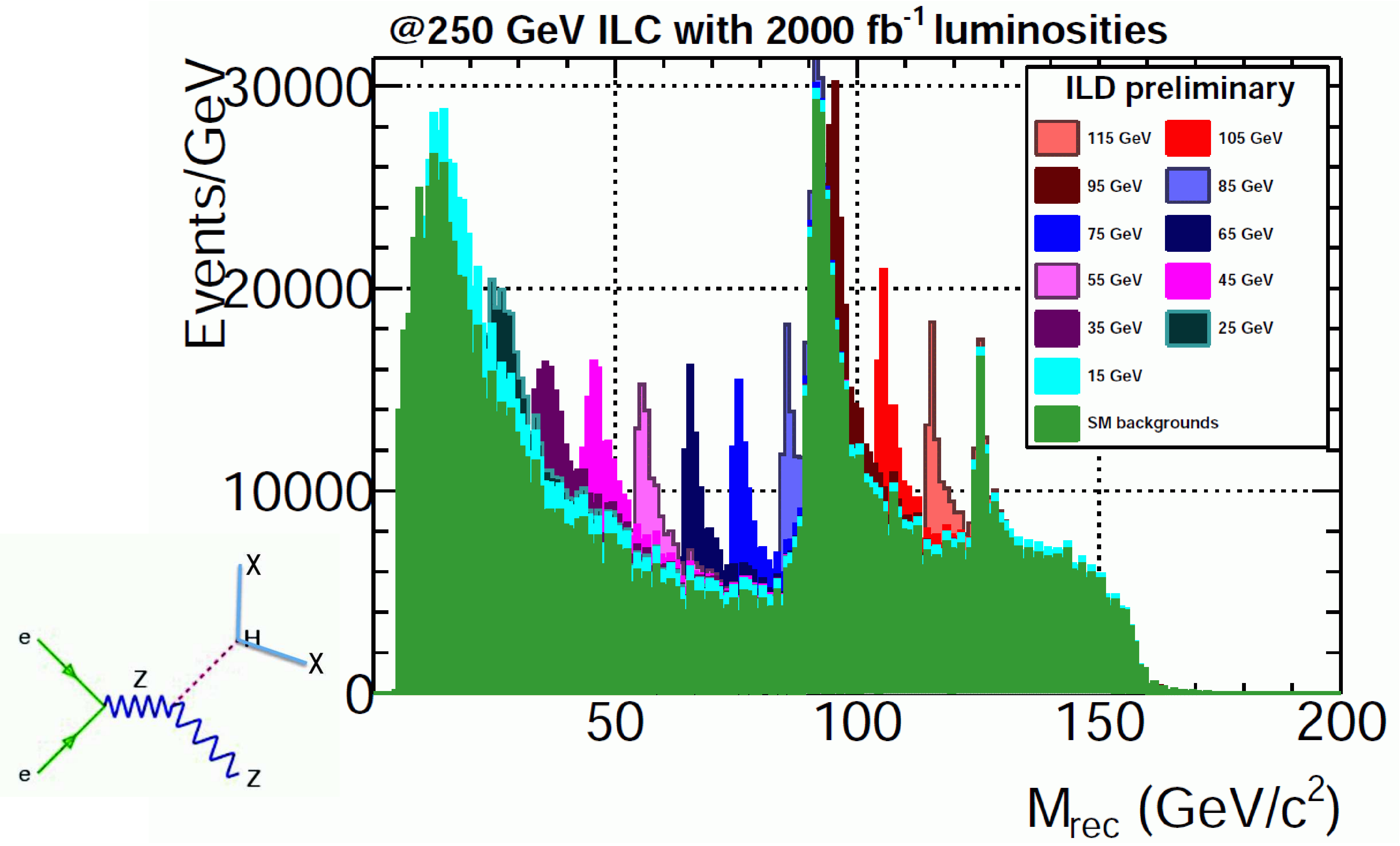
Higgs factory sensitivity: h ⟶ bb search

Higgs factory sensitivity: Recoil method

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

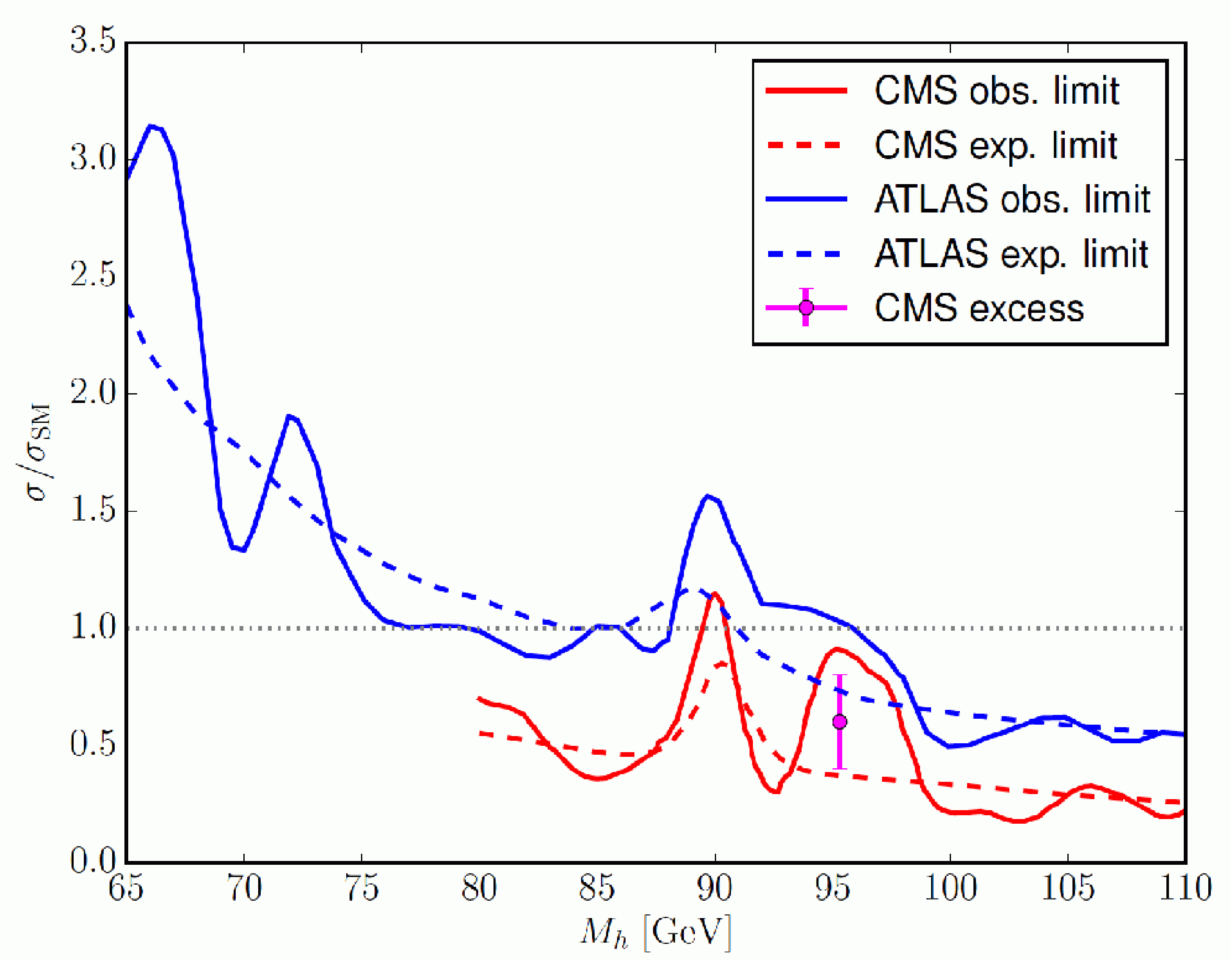
[*Taken from G. Weiglein '18*]

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



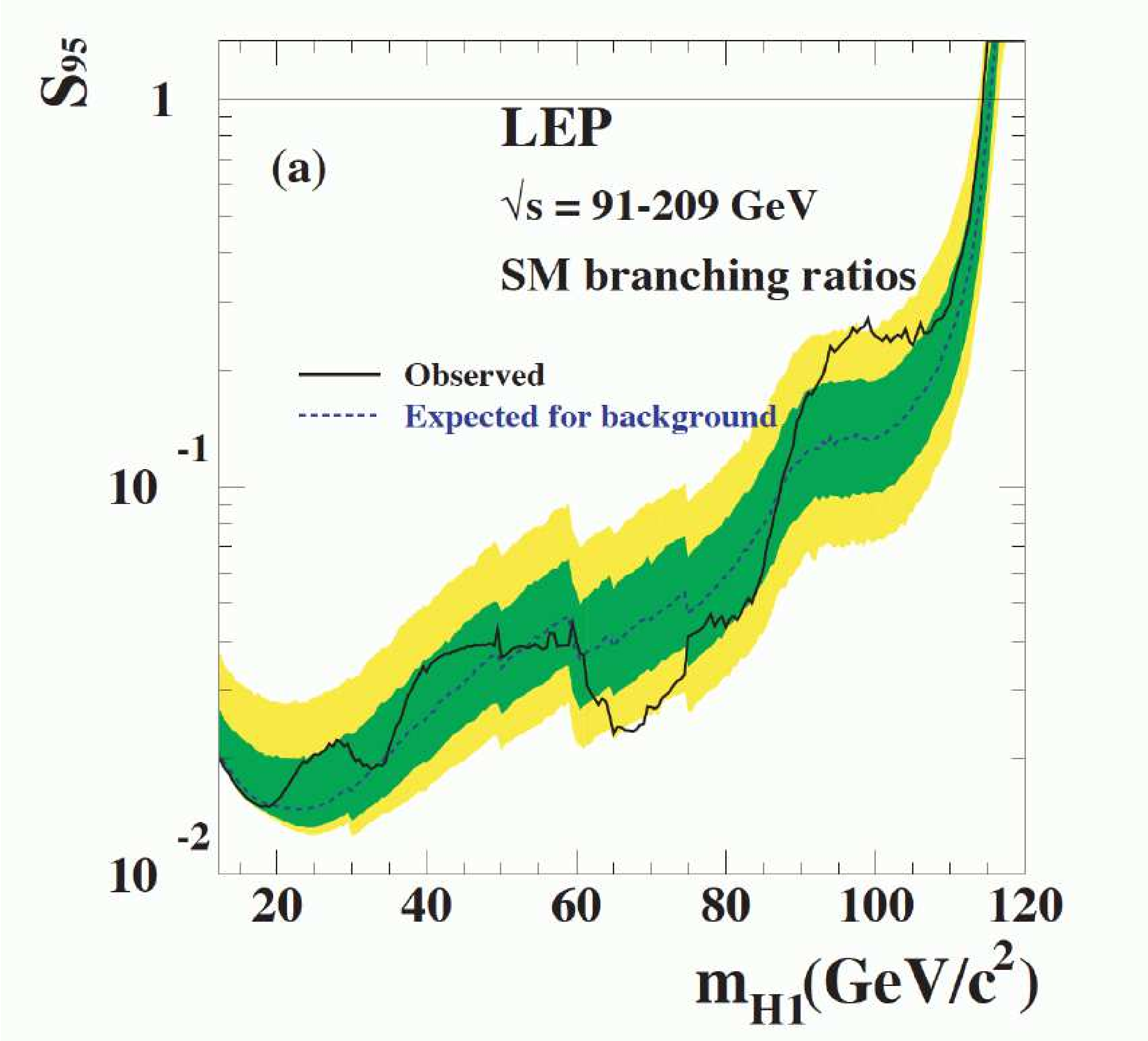
Case study: Search for $pp \to \phi \to \gamma\gamma$ with $m_\phi \leq 125$ GeV

[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!

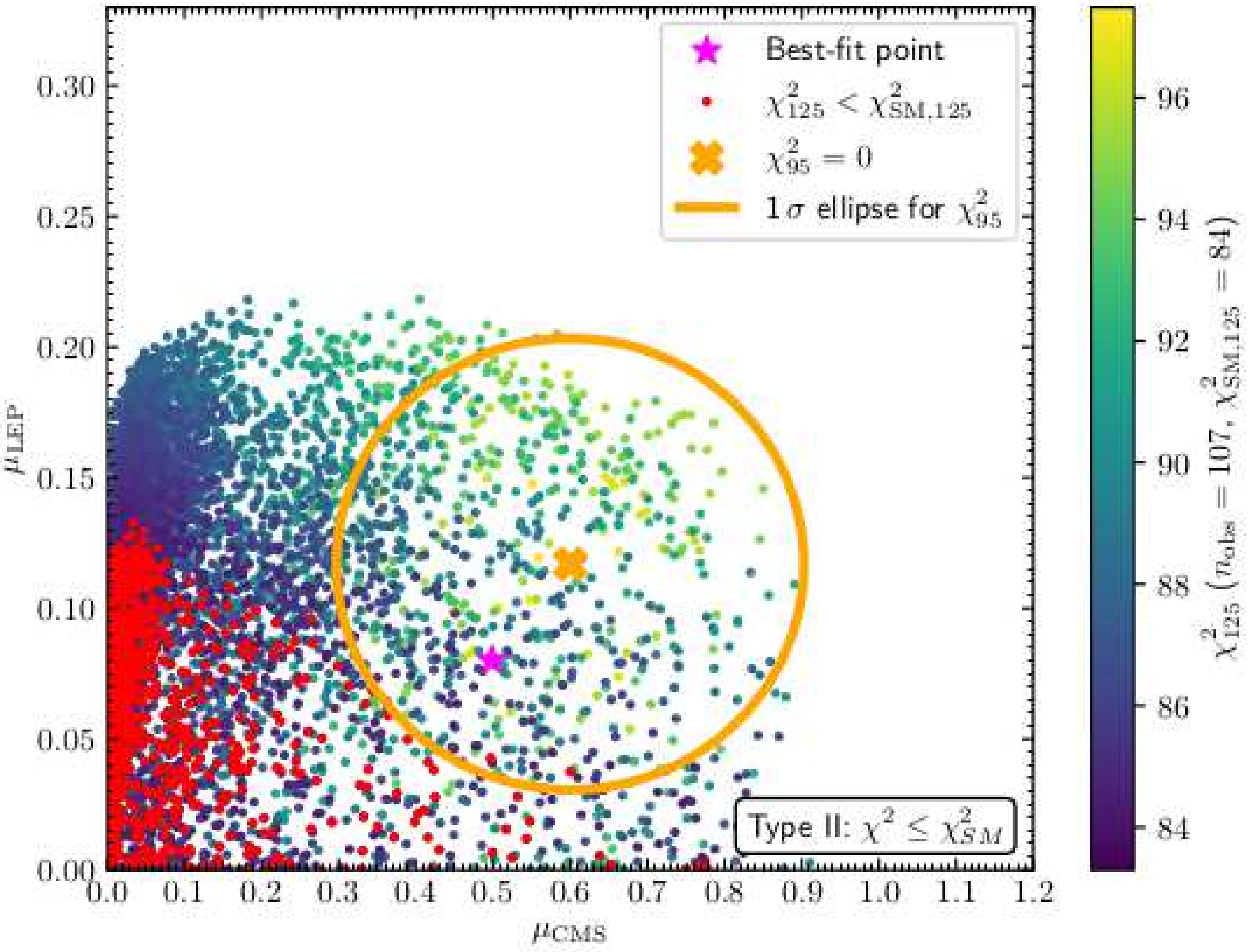
Remember the LEP excess?



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

Fitting the excesses in the N2HDM: [*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]

type I: NO type II: BEST type III: NO type IV: OK ⇒ SUSY?

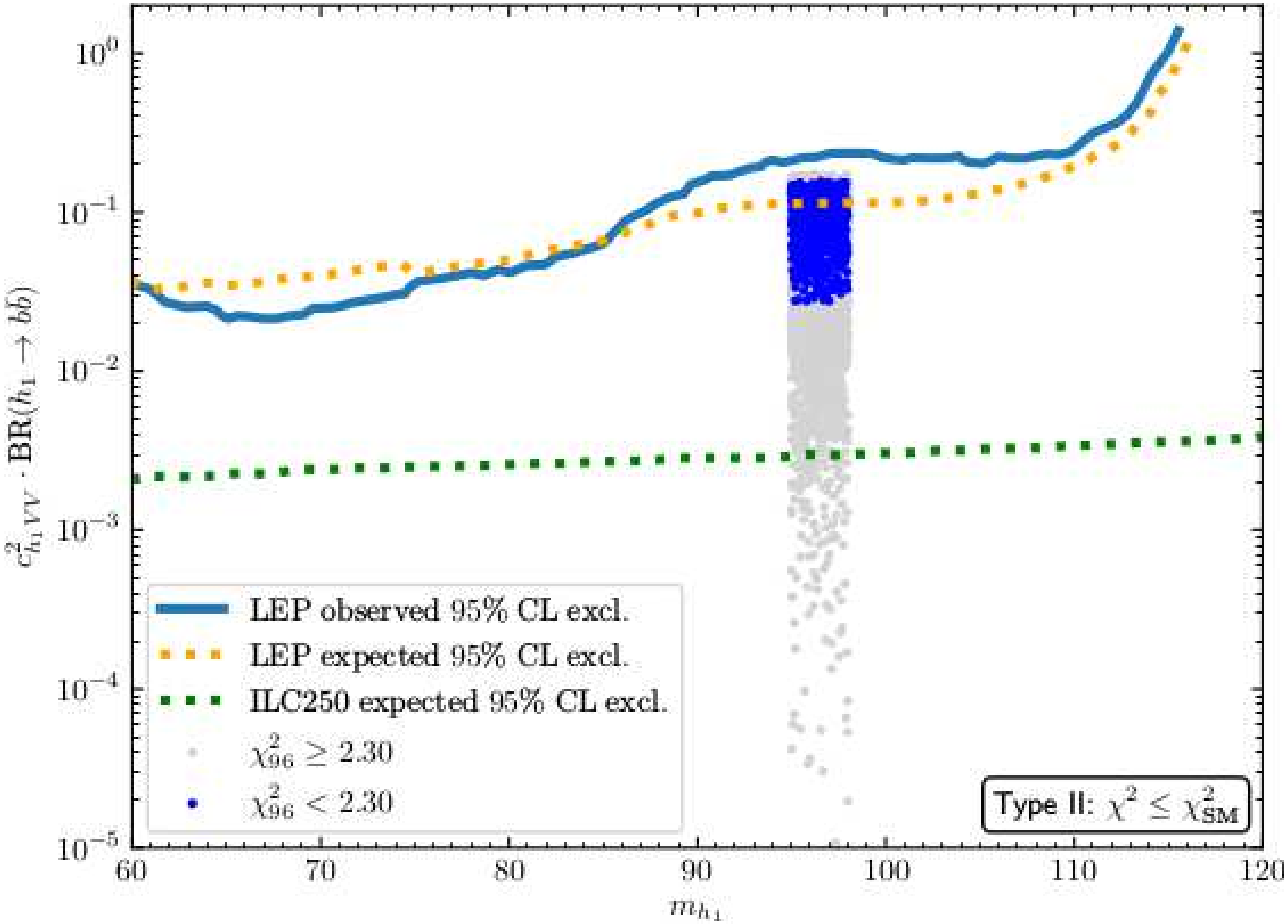


⇒ excesses well fitted, with good χ^2_{125}

red points have $\chi^2_{125} < \chi^2_{\rm SM,125}$

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

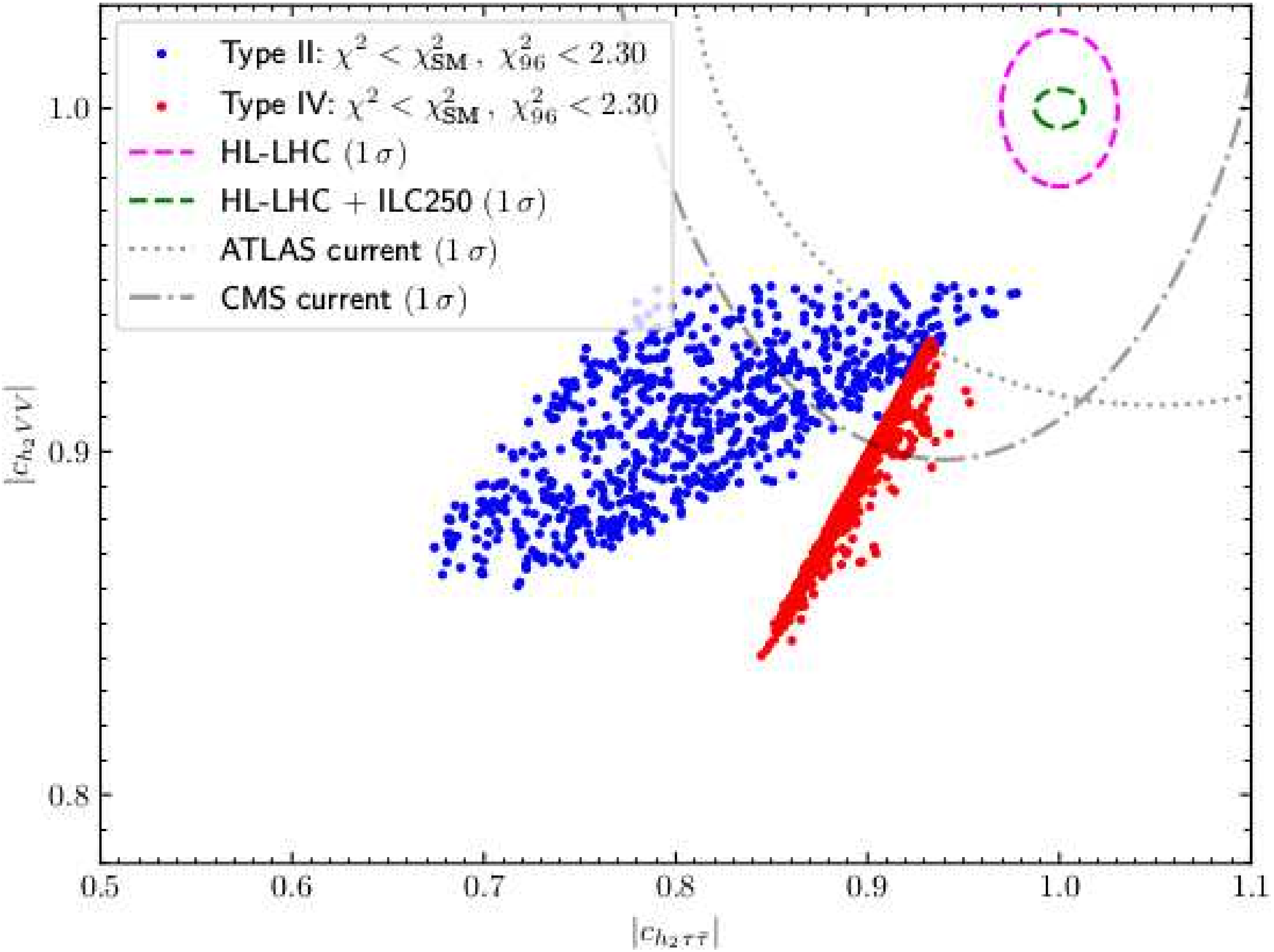
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



⇒ 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]



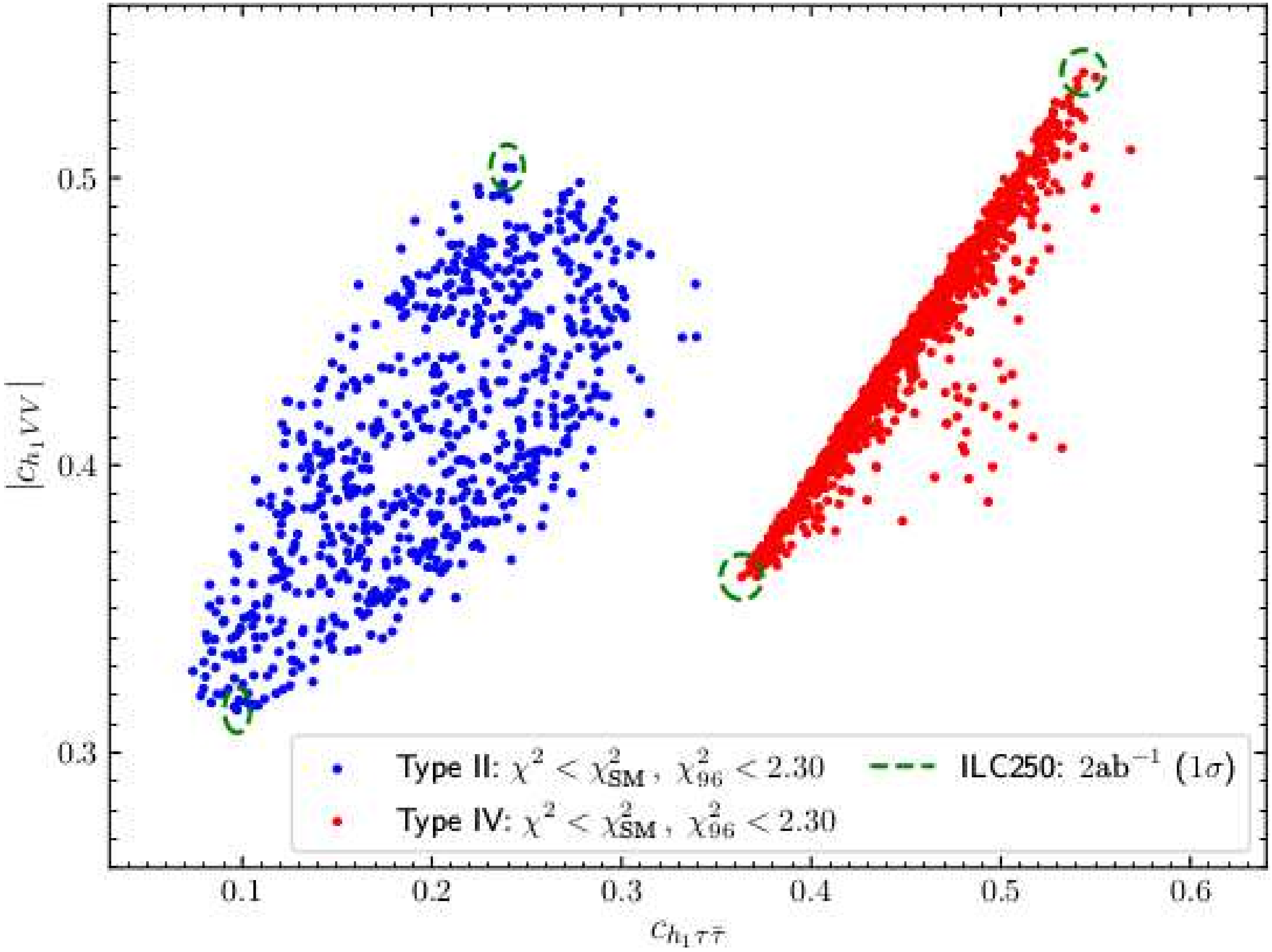
⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM at the ILC

HL-LHC/ILC ϕ_{96} coupling measurements at the ILC

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

green circles: ϕ_{96} coupling precision at the ILC250



⇒ model distinction possible via coupling measurements at the ILC

4. Conclusions

[sorry for mis-using the cartoon!]

artwork by F. Simon

⇒ clear Higgs physics potential for the ILC after HL-LHC

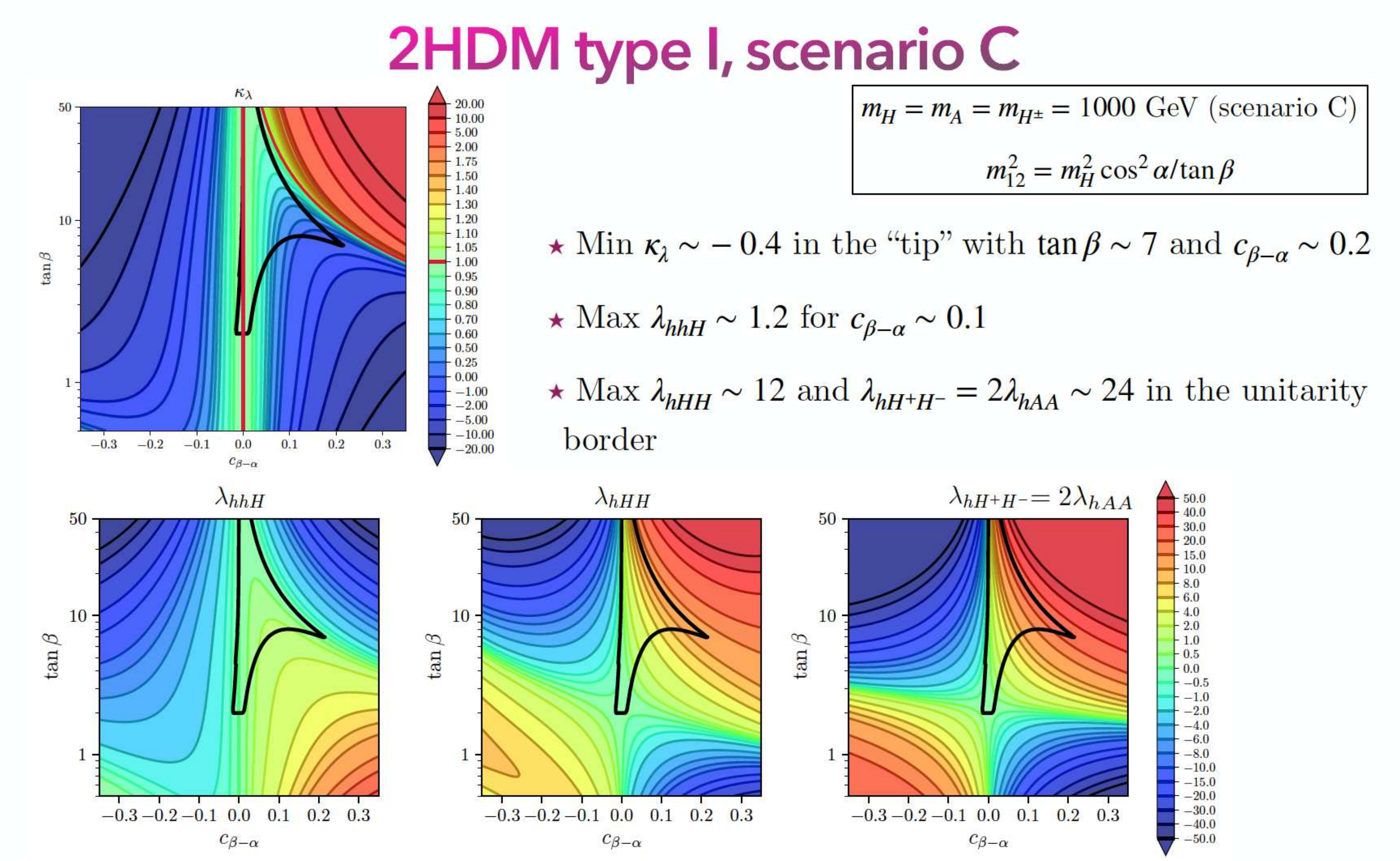

Further Questions?

For any BSM (Higgs) analysis: the constraints:

→ applied to every point analyzed/scanned/. . .

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

Example I: 2HDM type I: results



2HDM type I, scenario C

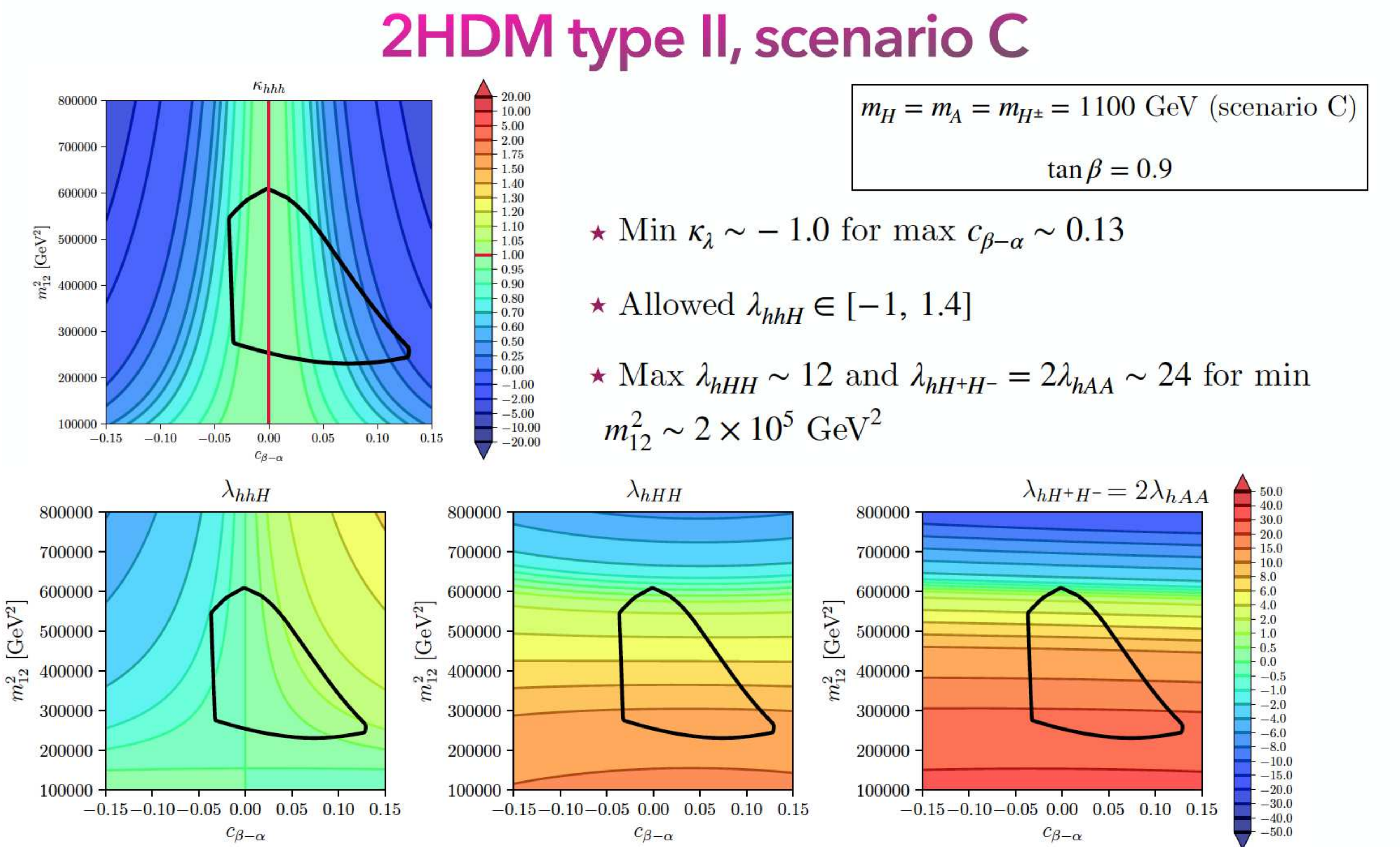
$$m_H = m_A = m_{H^\pm} = 1000 \text{ GeV (scenario C)}$$

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

- ★ Min $\kappa_\lambda \sim -0.4$ in the "tip" with $\tan\beta \sim 7$ and $c_{\beta-\alpha} \sim 0.2$
- ★ Max $\lambda_{hhH} \sim 1.2$ for $c_{\beta-\alpha} \sim 0.1$
- ★ Max $\lambda_{hHH} \sim 12$ and $\lambda_{hH^+H^-} = 2\lambda_{hAA} \sim 24$ in the unitarity border

⇒ large deviations for κ_λ ⇒ large values for BSM λ's

Example II: 2HDM type II: results



2HDM type II, scenario C

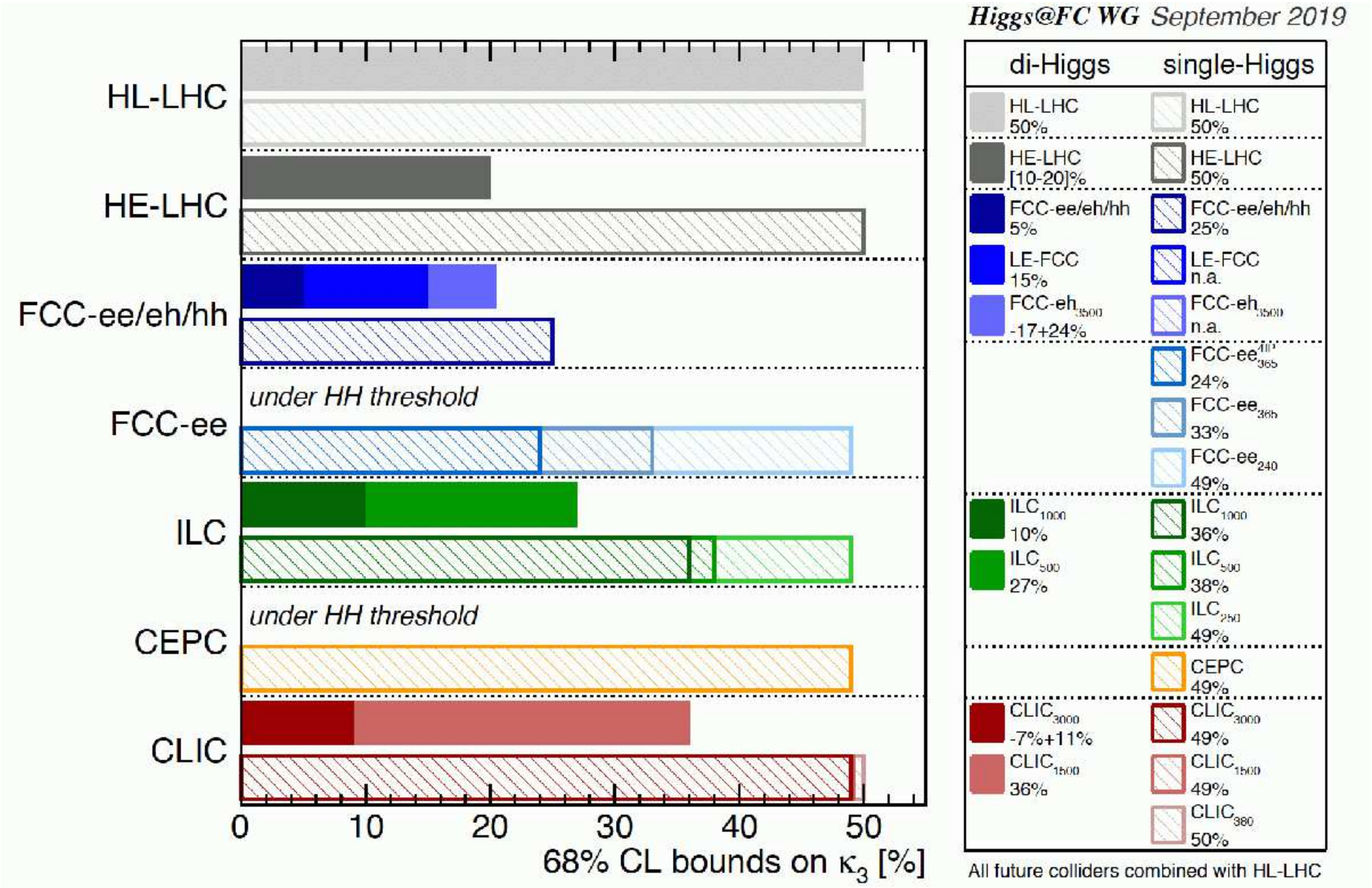
$m_H = m_A = m_{H^\pm} = 1100$ GeV (scenario C)

$\tan\beta = 0.9$

- ⋆ 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

⇒ large deviations for κ_λ ⇒ large values for BSM λ's

Comparison of all colliders: $[\kappa_\lambda = -0.5 \ldots +1.5]$

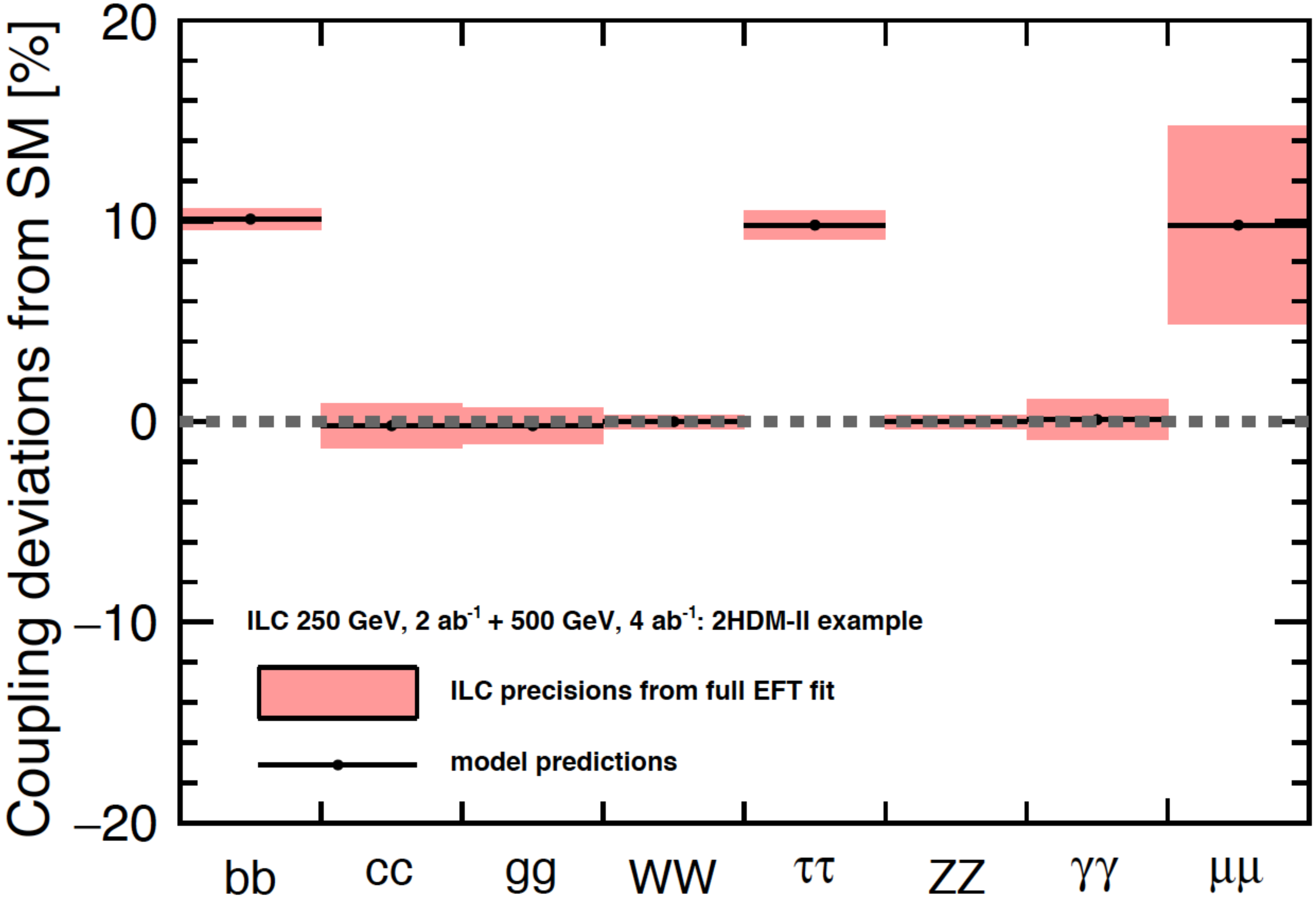


Analysis/comparison performed only for $\kappa_\lambda = 1$

$\Rightarrow$ prospects unclear for single Higgs production!

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

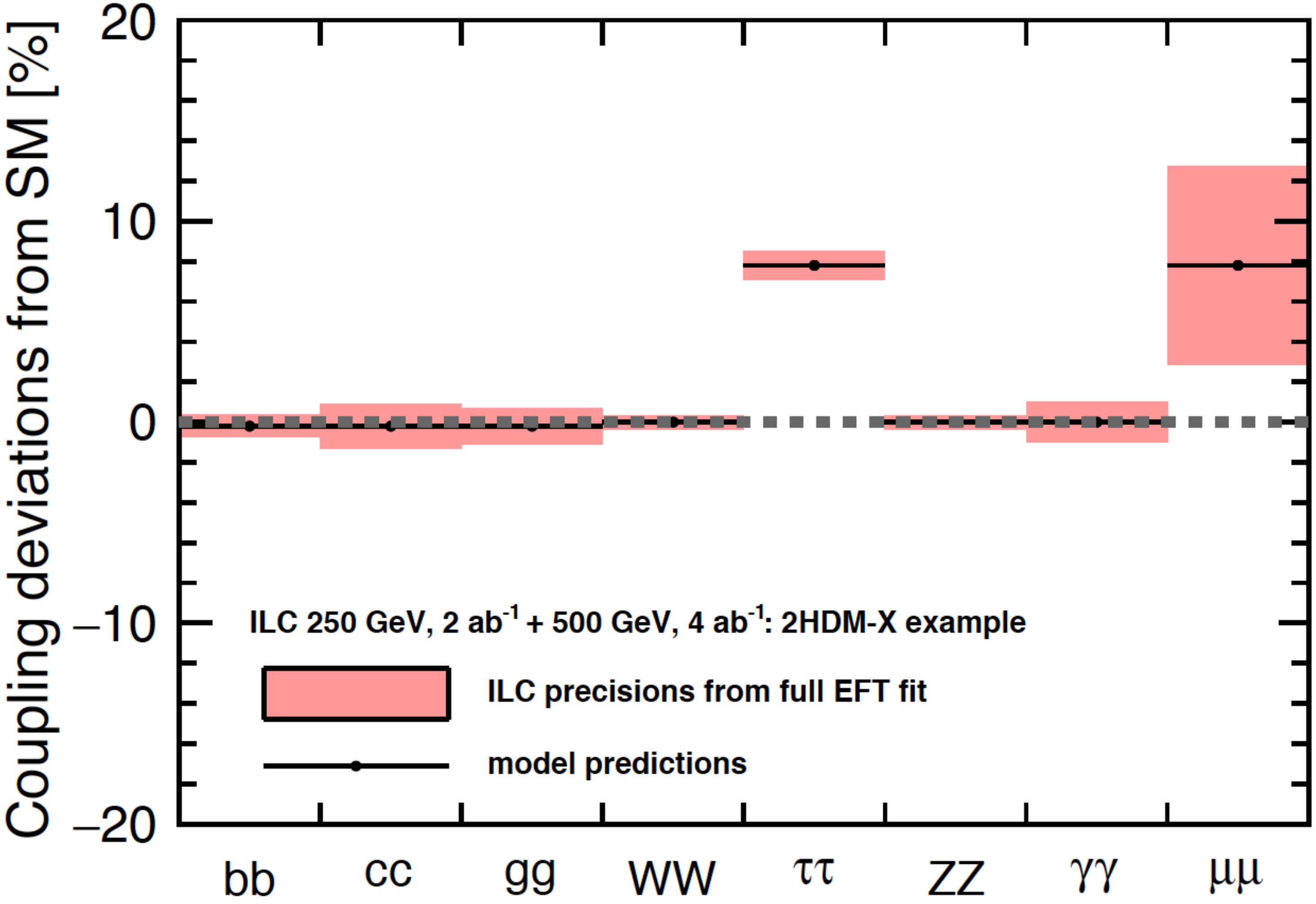
[*T. Barklow et al., '17*]



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

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

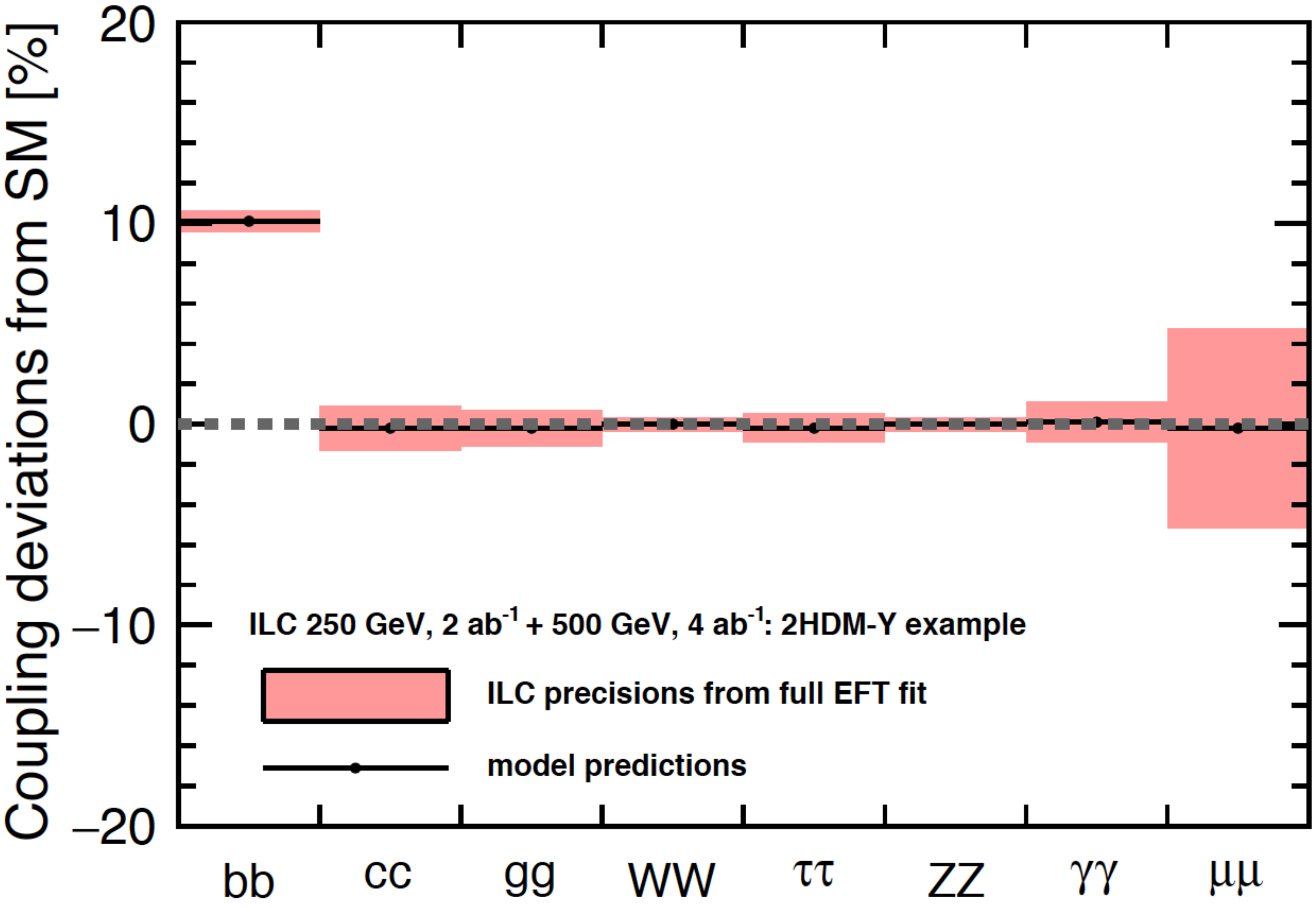
[*T. Barklow et al., '17*]



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

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

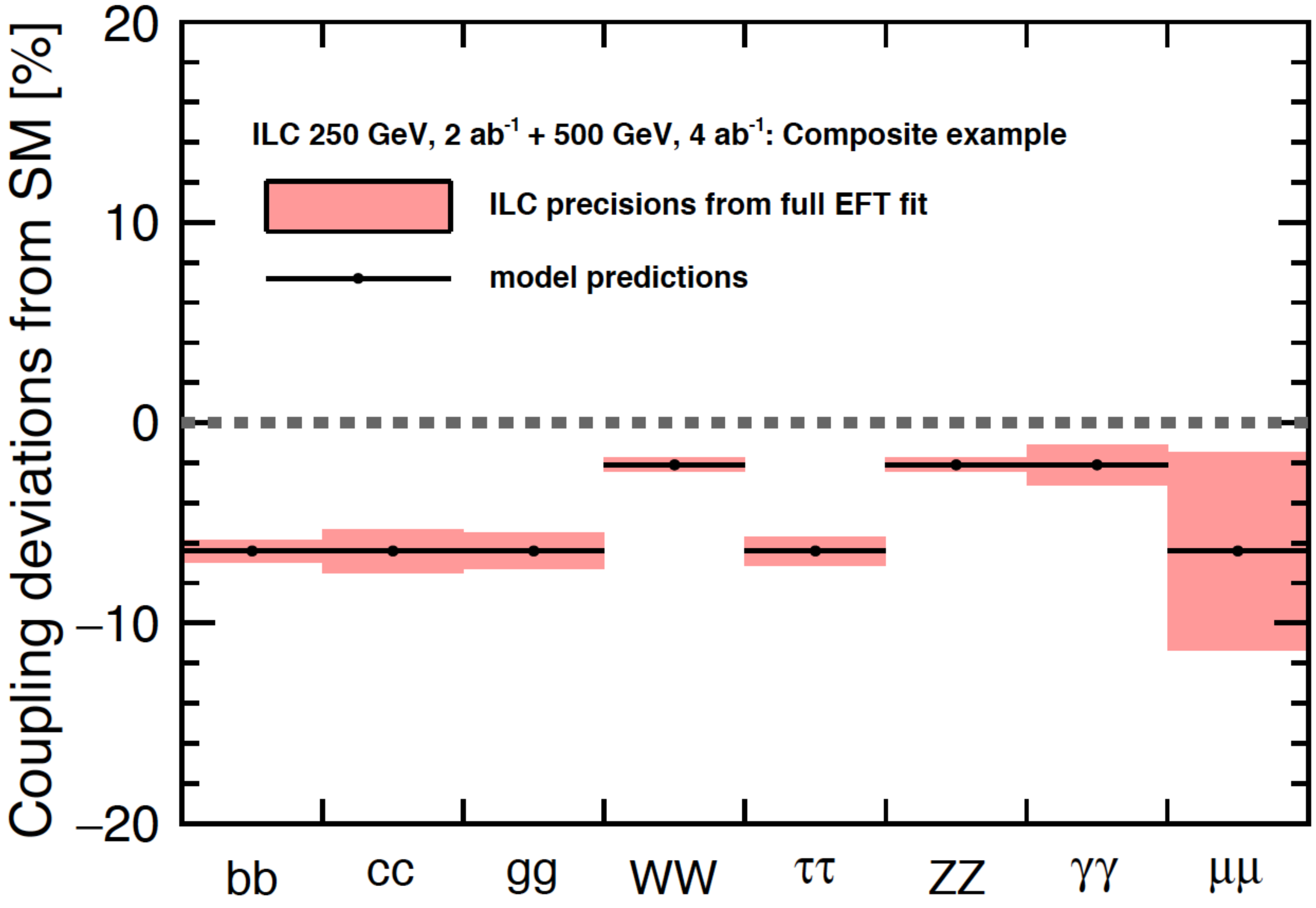
[*T. Barklow et al., '17*]



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

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

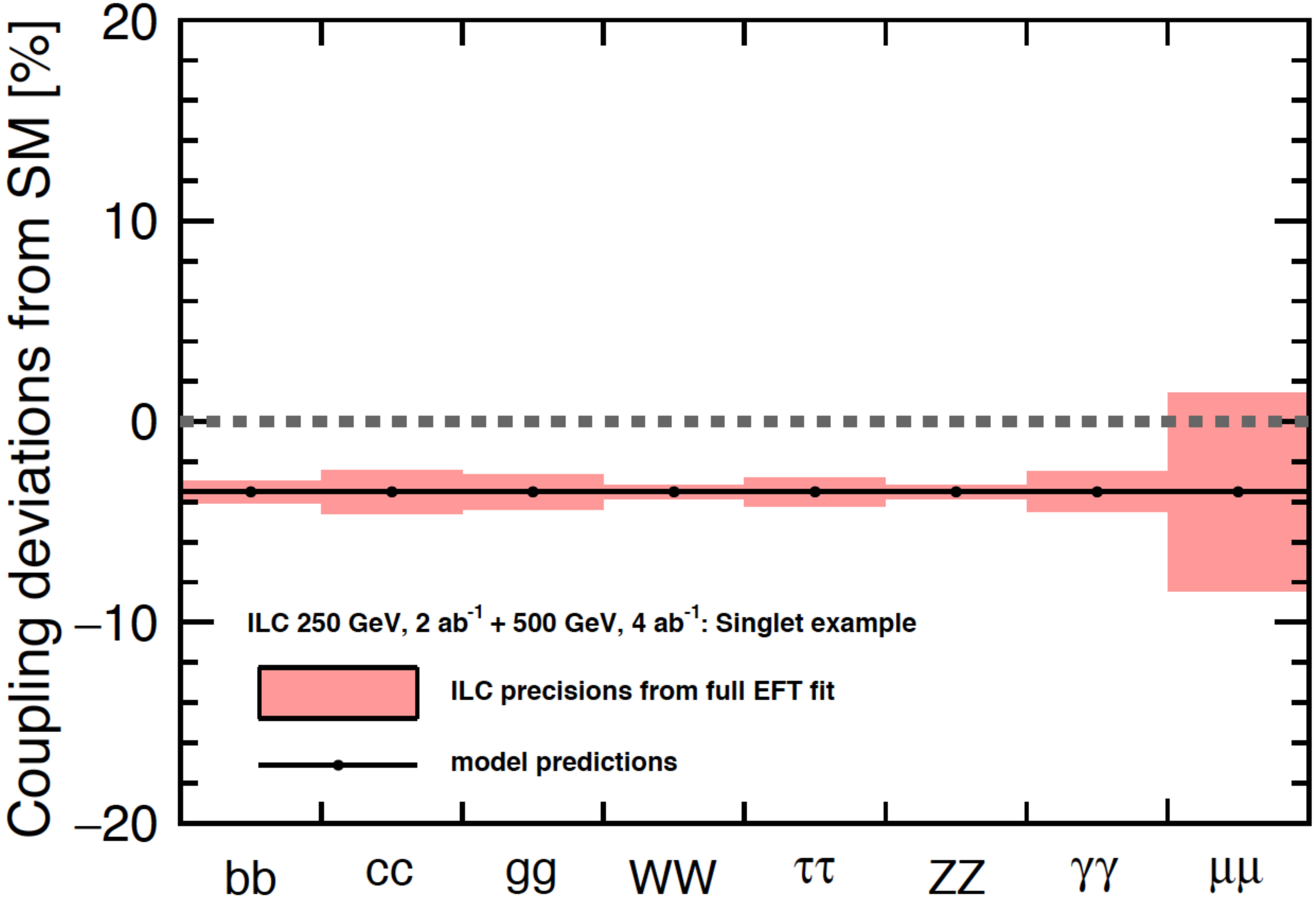
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Composite Higgs?!

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

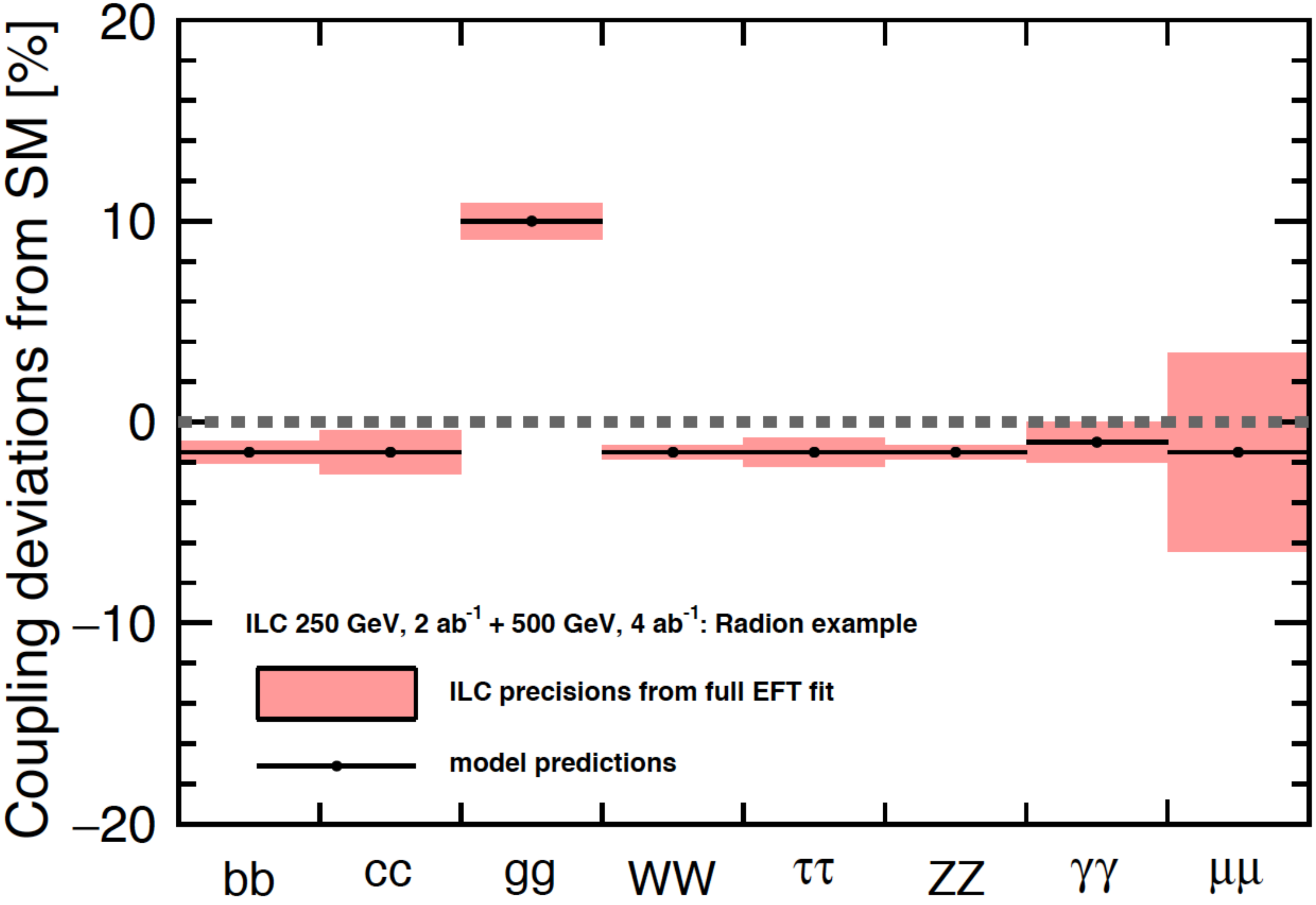
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for HxSM?!

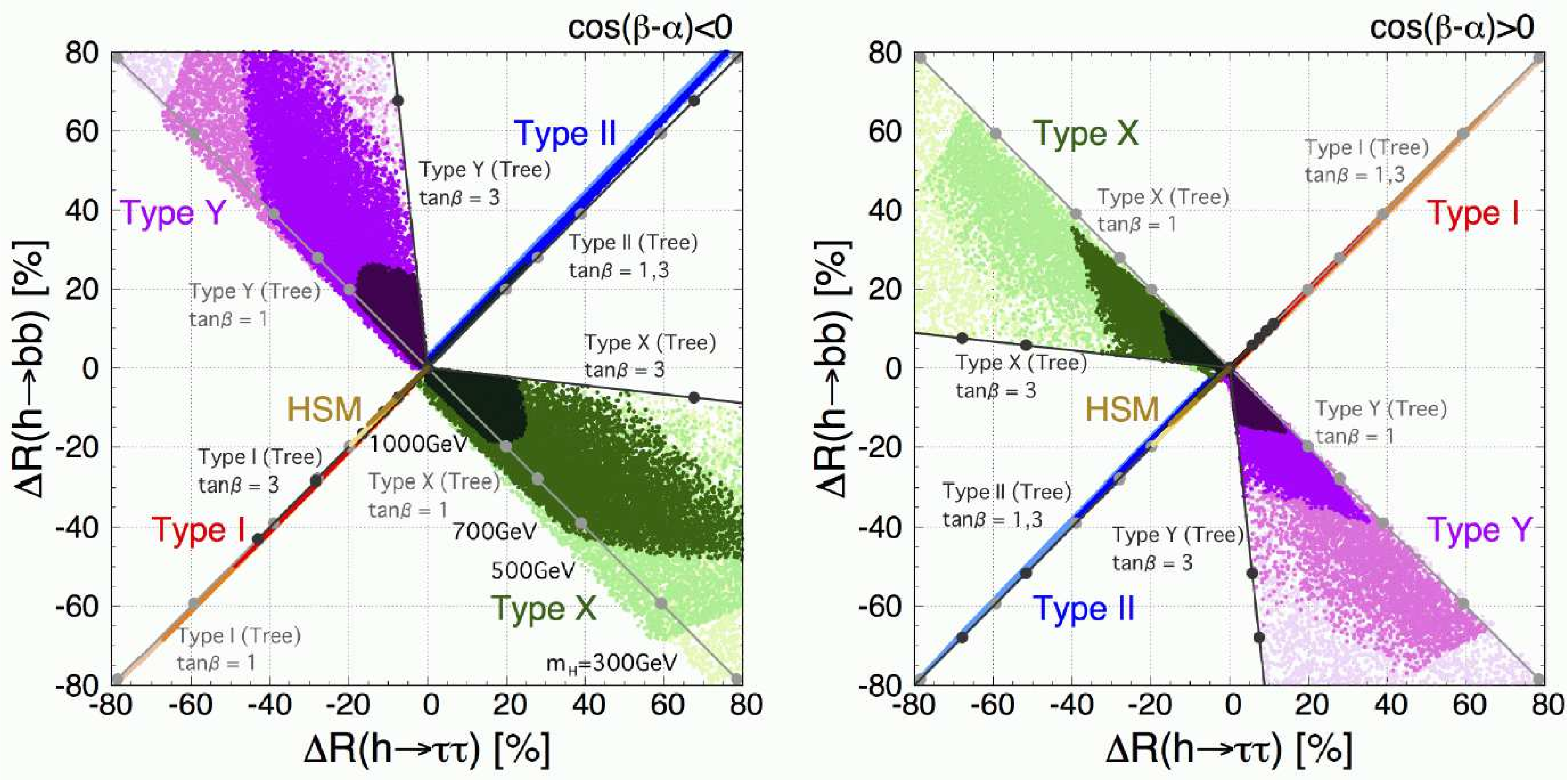
Wäscheleine VI: e^+e^- precision vs. Higgs-Radion prediction:

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



⇒ clear pattern, distinctive for Higgs Radion?!

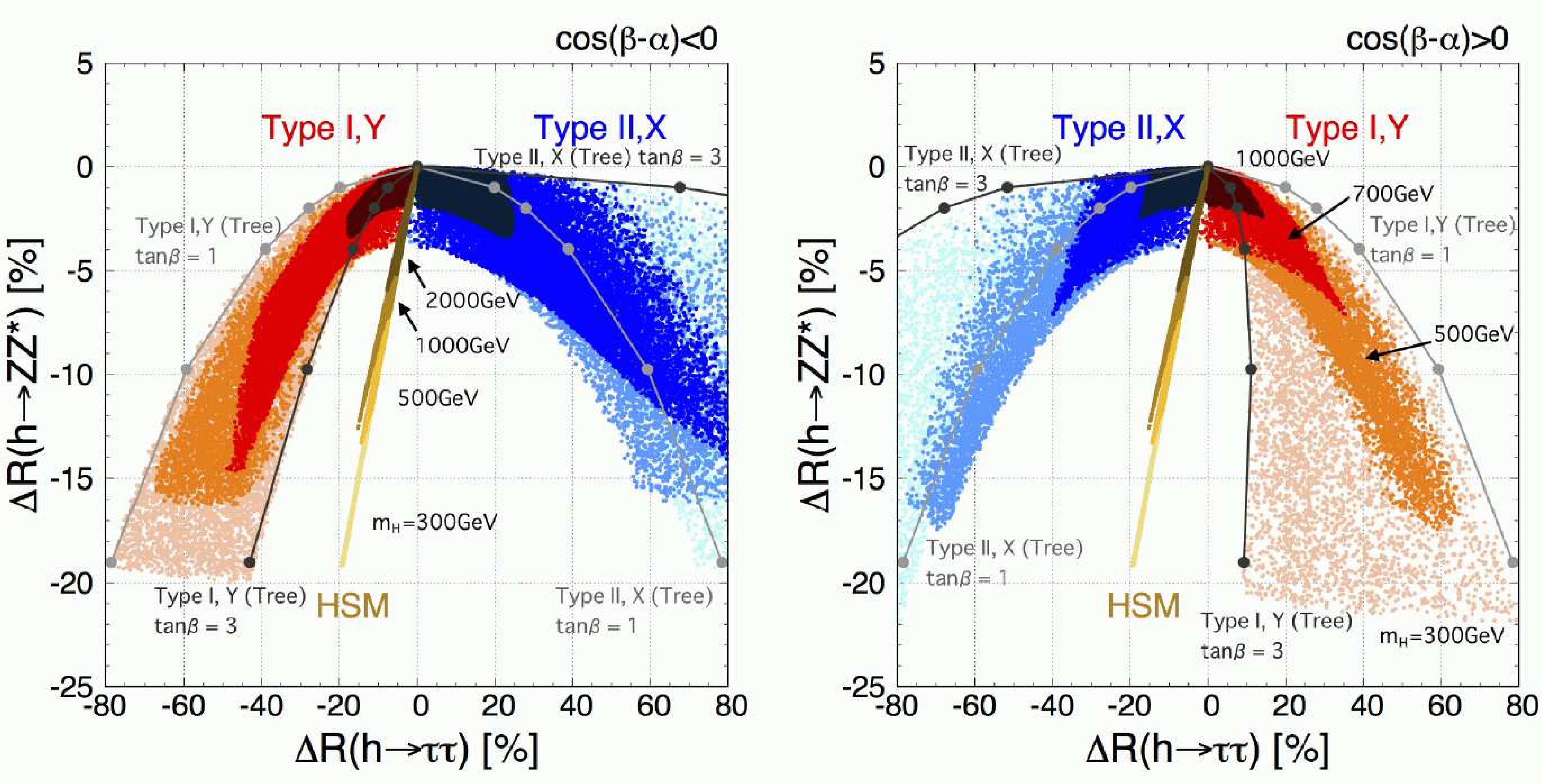
2HDM example (I): [*S. Kanemura et al. '18*]



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

2HDM example (II):

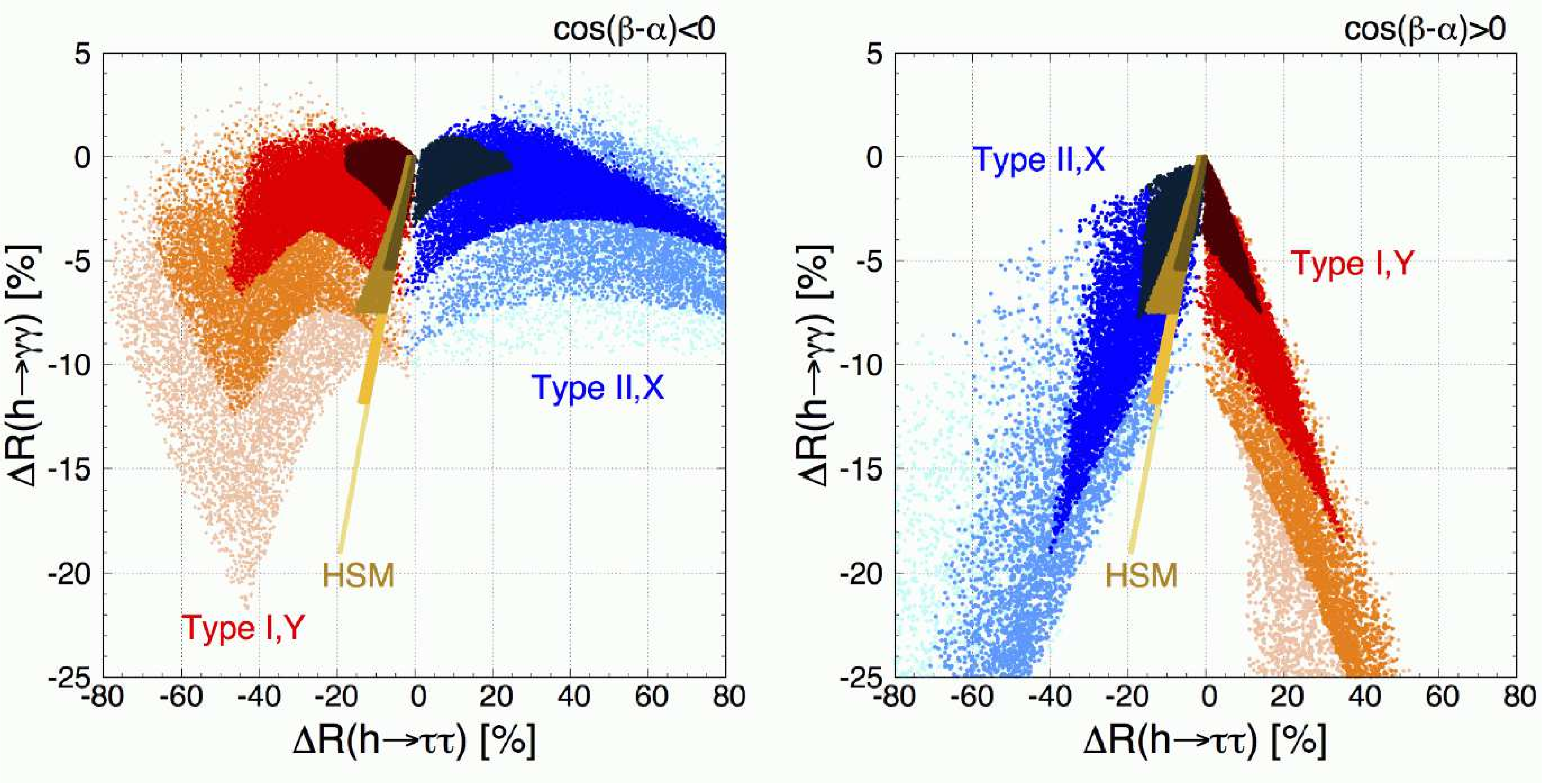
[*S. Kanemura et al. '18*]



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

2HDM example (III):

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



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

Investigation in BSM Higgs models: **N2HDM**

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

Fields:

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

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

SUSY realizations

What about SUSY??

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

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$\Rightarrow$ models with an additional singlet??

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– NMSSM
– $\mu\nu$SSM
– . . .

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

⇒ models with an additional singlet??

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

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

What about the NMSSM?

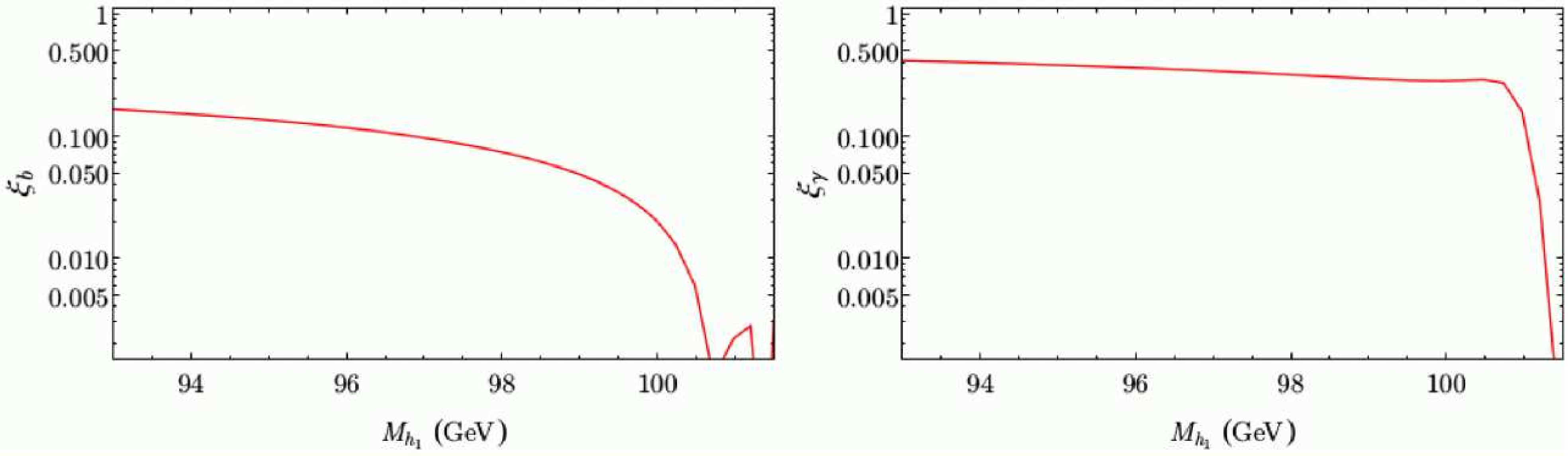
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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



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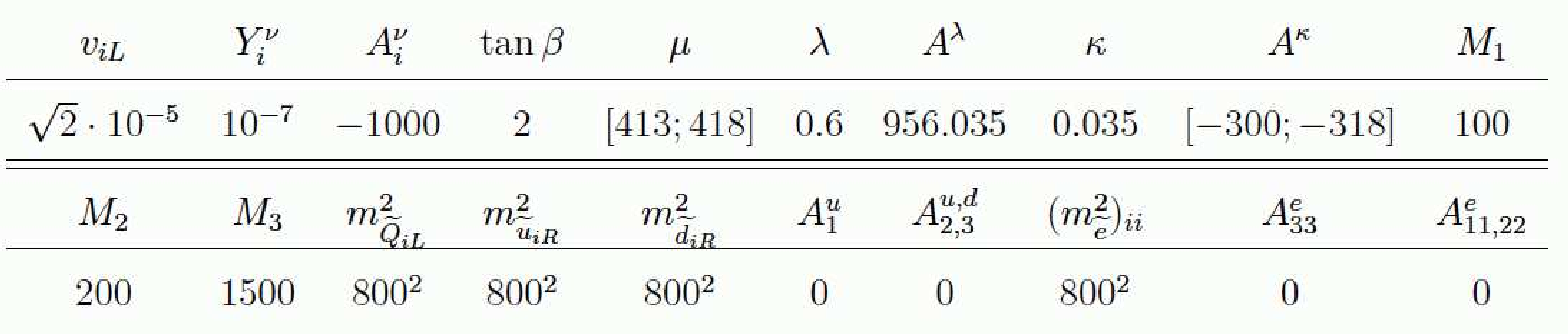
Can the $\mu\nu$SSM explain the two excesses?

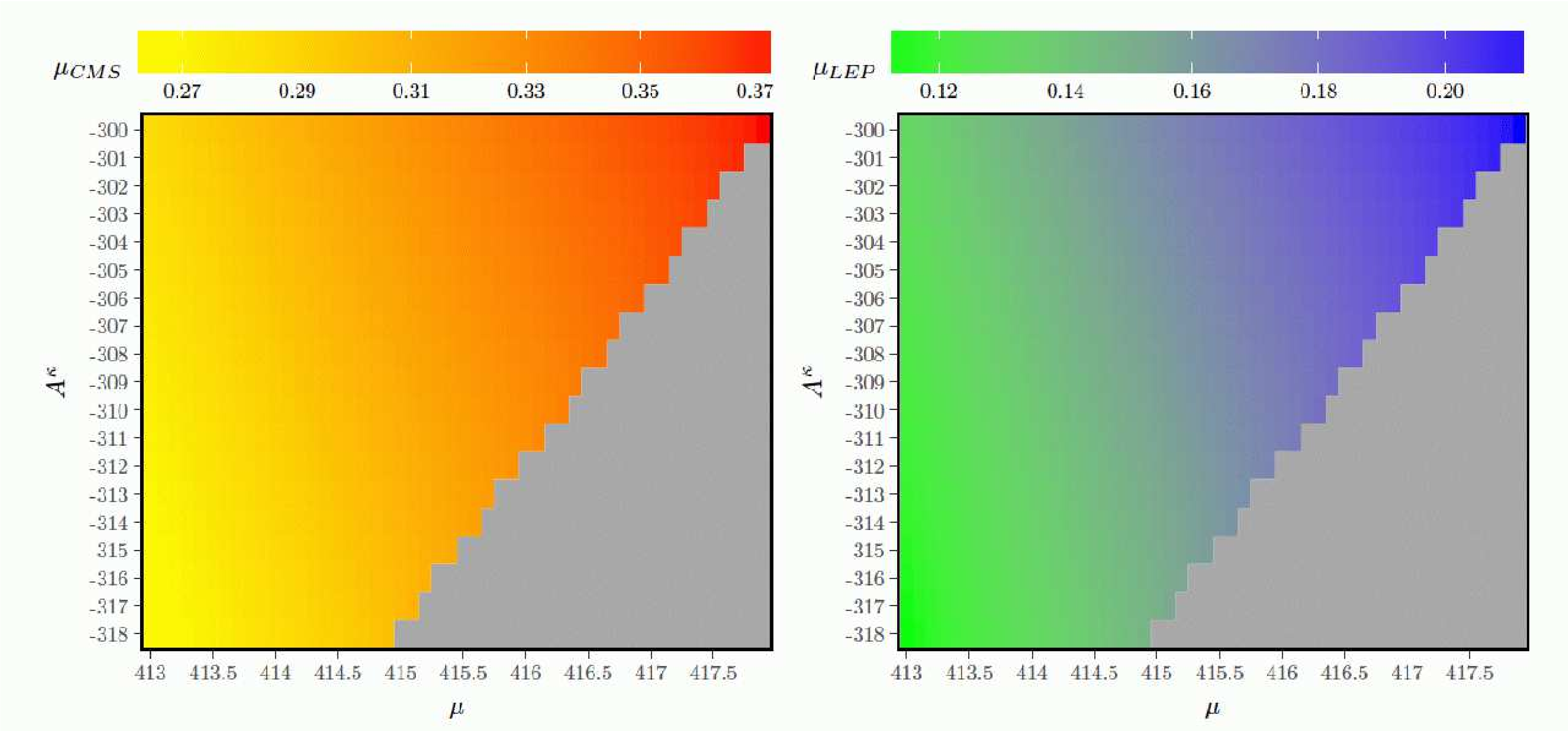
[*T. Biekötter, S.H., C. Muñoz '17*]



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*]

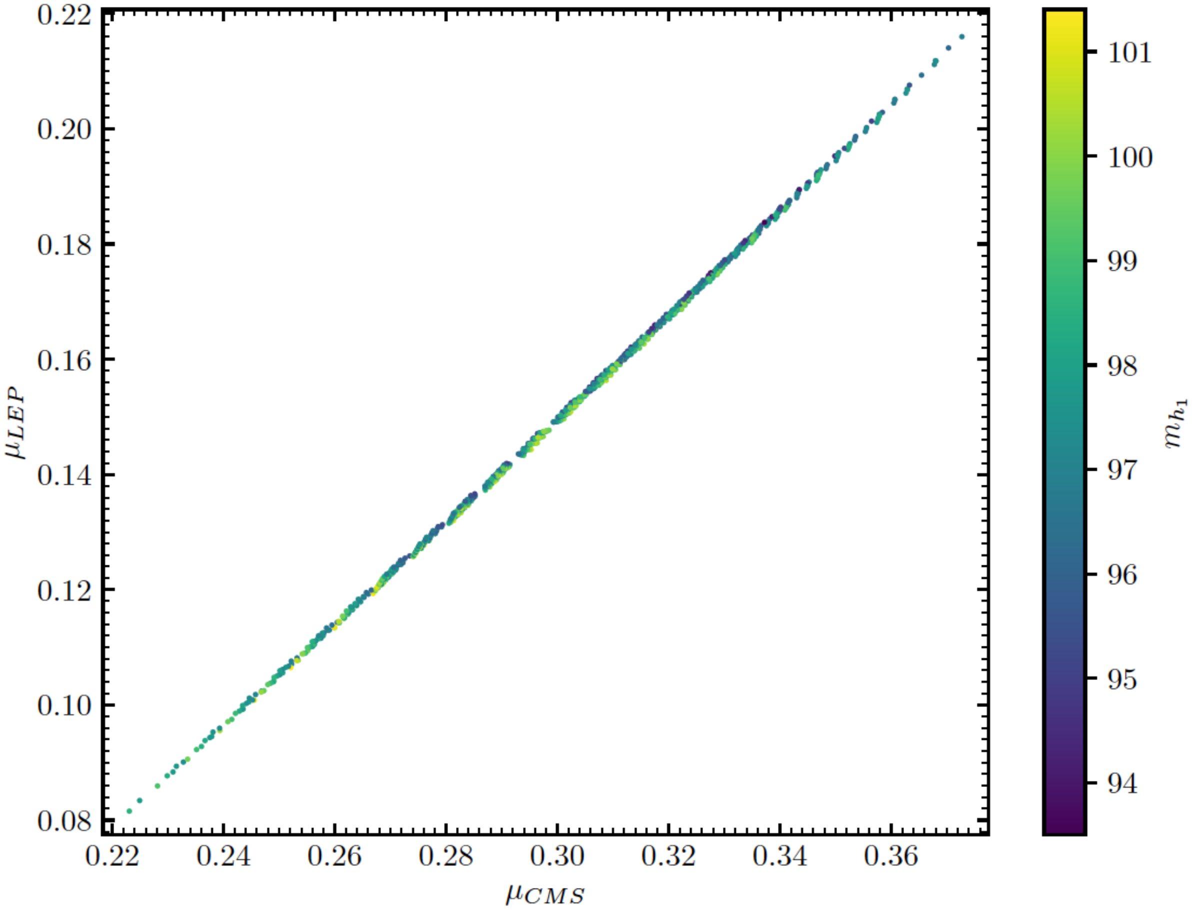


⇒ YES, WE CAN! :-)

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 $\mu_{\rm LHC}$!