
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

CEPC Higgs Physics Opportunities after the HL-LHC

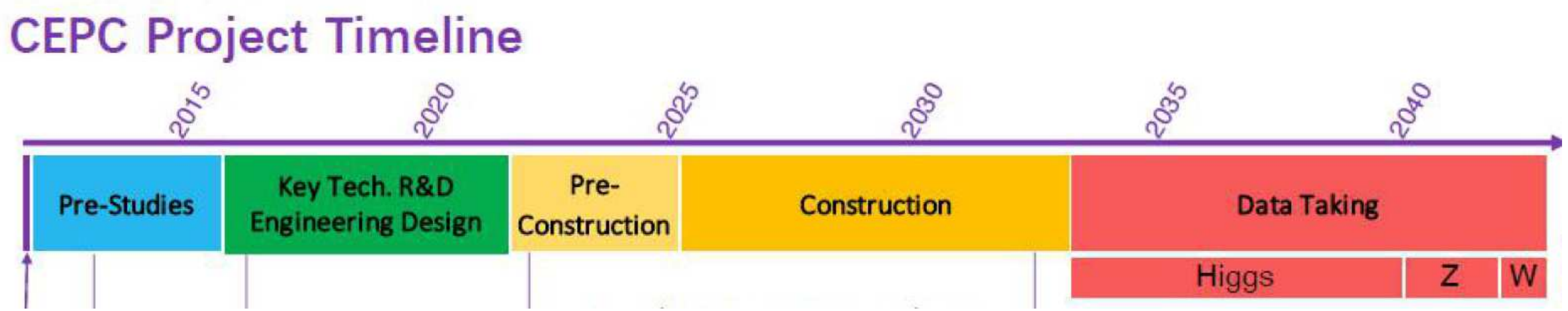
Sven Heinemeyer, IFT (CSIC, Madrid)

virtual, 07/2021

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

1. Introduction

CEPC timeline (optimistic?): [*talk by J. Gao '21*]



⇒ The CEPC will come in the end phase of (or after?) 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

Disclaimer:
CEPC(250) Higgs results roughly similar to FCC-ee(250)/ILC250
⇒ also FCC-ee/ILC results will be used for CEPC projection

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': Which model?

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 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:

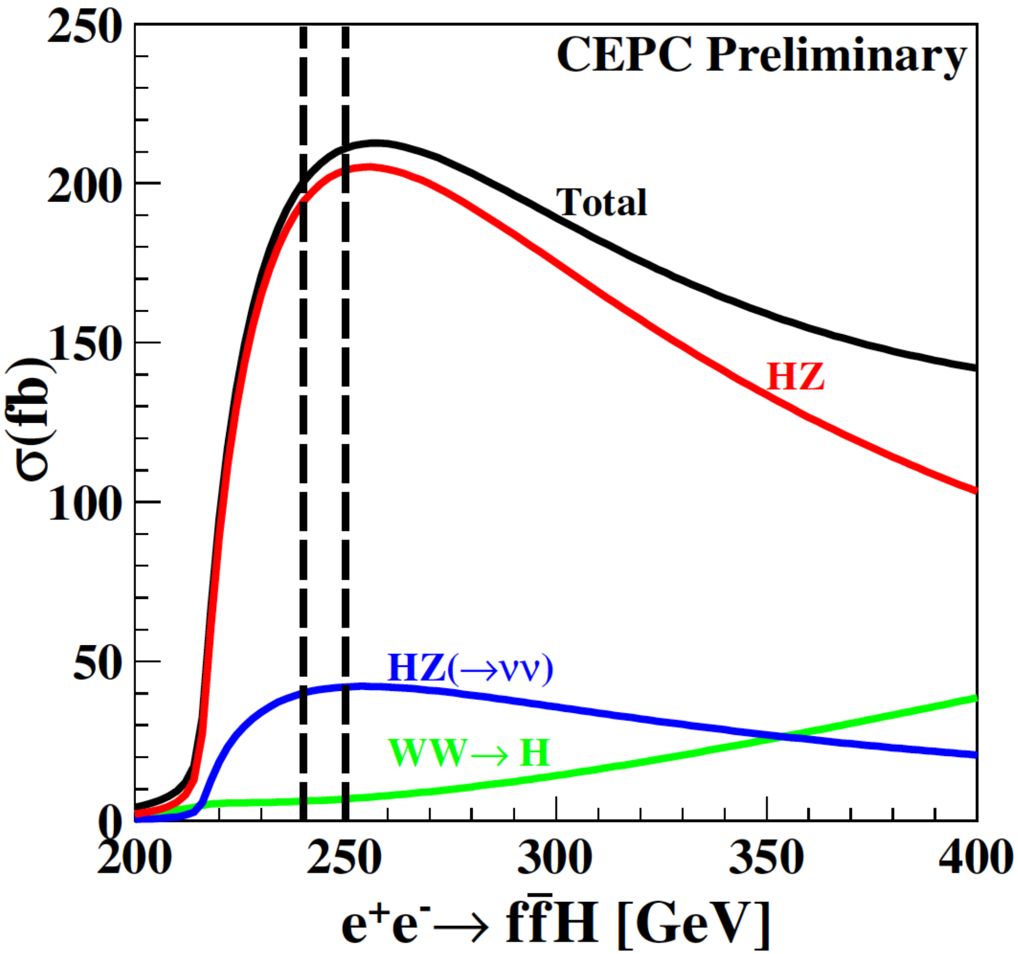
- A SM-like Higgs at ~ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,. . .) have to be such that they are in agreement with the present bounds

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

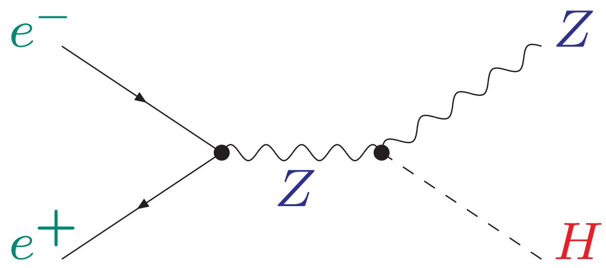
$\Rightarrow$ not much room left for BSM Higgs couplings to gauge bosons

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

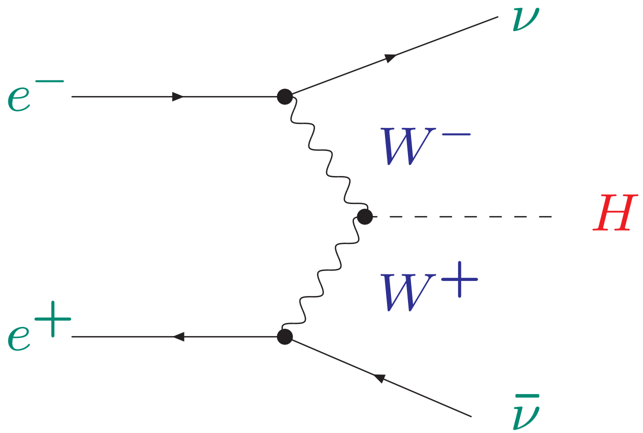
2. h_{125} measurements



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

Higgs coupling measurements at e^+e^- colliders

Initial measurement: $\sigma \times$ BR

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

$\Rightarrow$ measurement of the Higgs production cross section

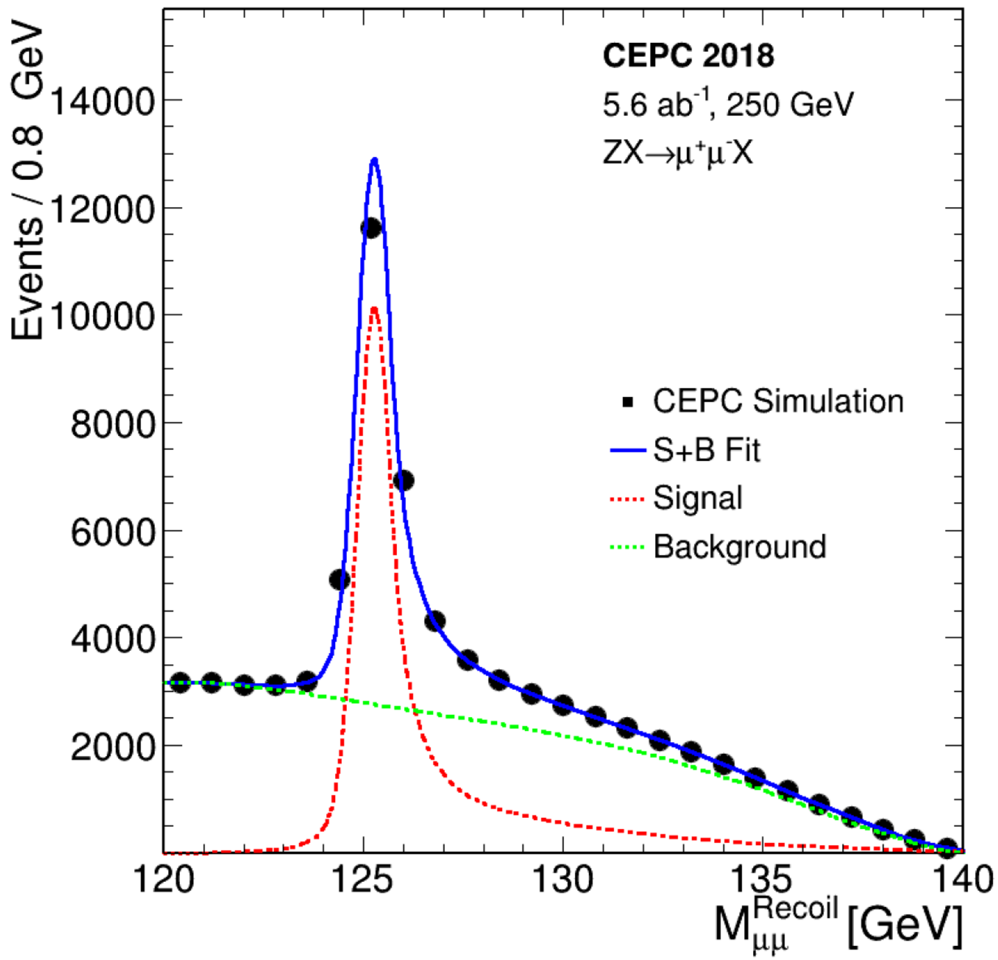
$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths – in contrast to LHC measurements!

$\Rightarrow$ indirect measurement of total width

$\Rightarrow$ direct extraction of partial widths (couplings)

$\Rightarrow$ search for deviations from the SM
$\Rightarrow$ distinction between different models

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



⇒ crucial for a model independent coupling measurement! $\delta M_H^{\text{exp}} \lesssim 0.01$ 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 CEPC (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:

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

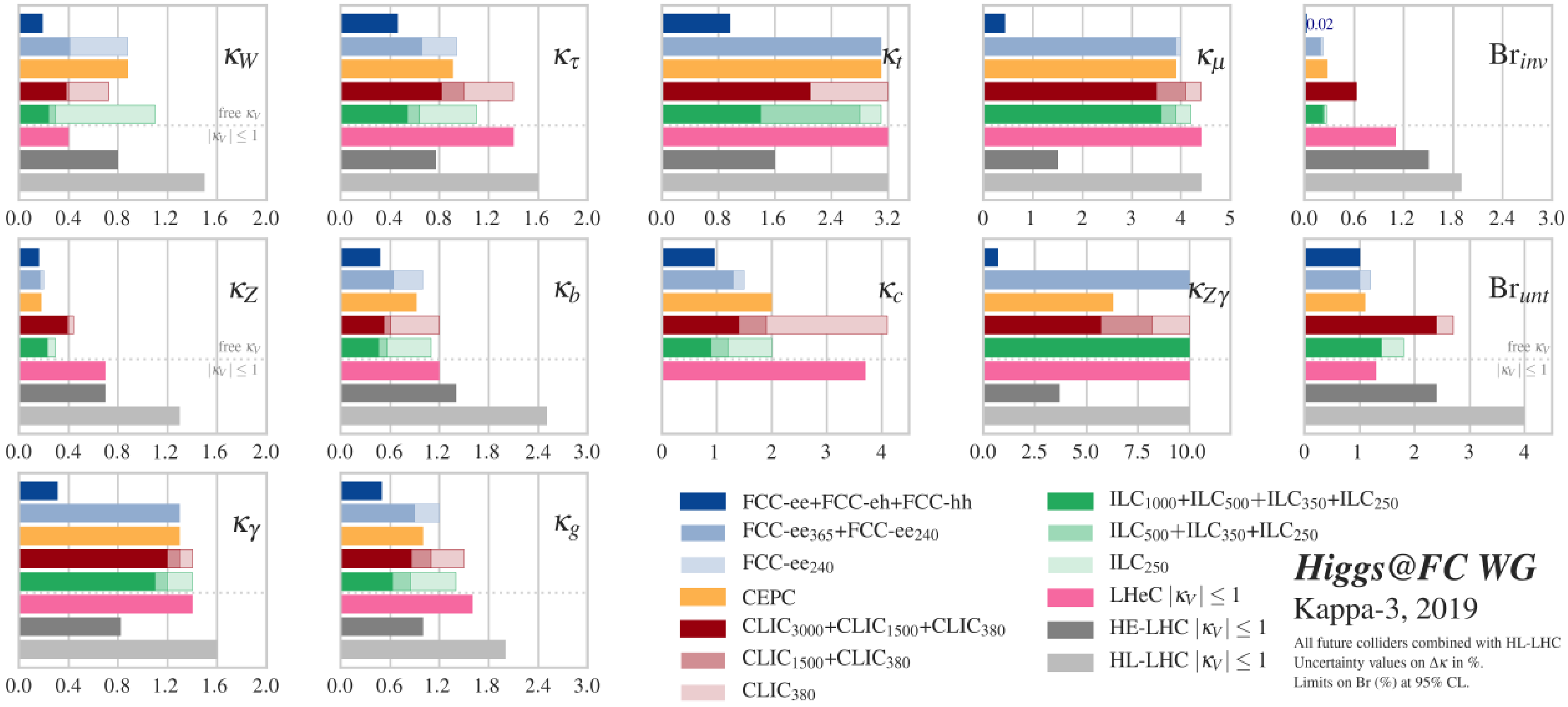
$$\kappa_F \approx 1 - (3 - 9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$\Rightarrow$ couplings to bosons in the per mille range

$\Rightarrow$ couplings to fermions in the per cent range

$\Rightarrow$ at which collider can this be reached?

Future expectations for κ (kappa-3 framework)



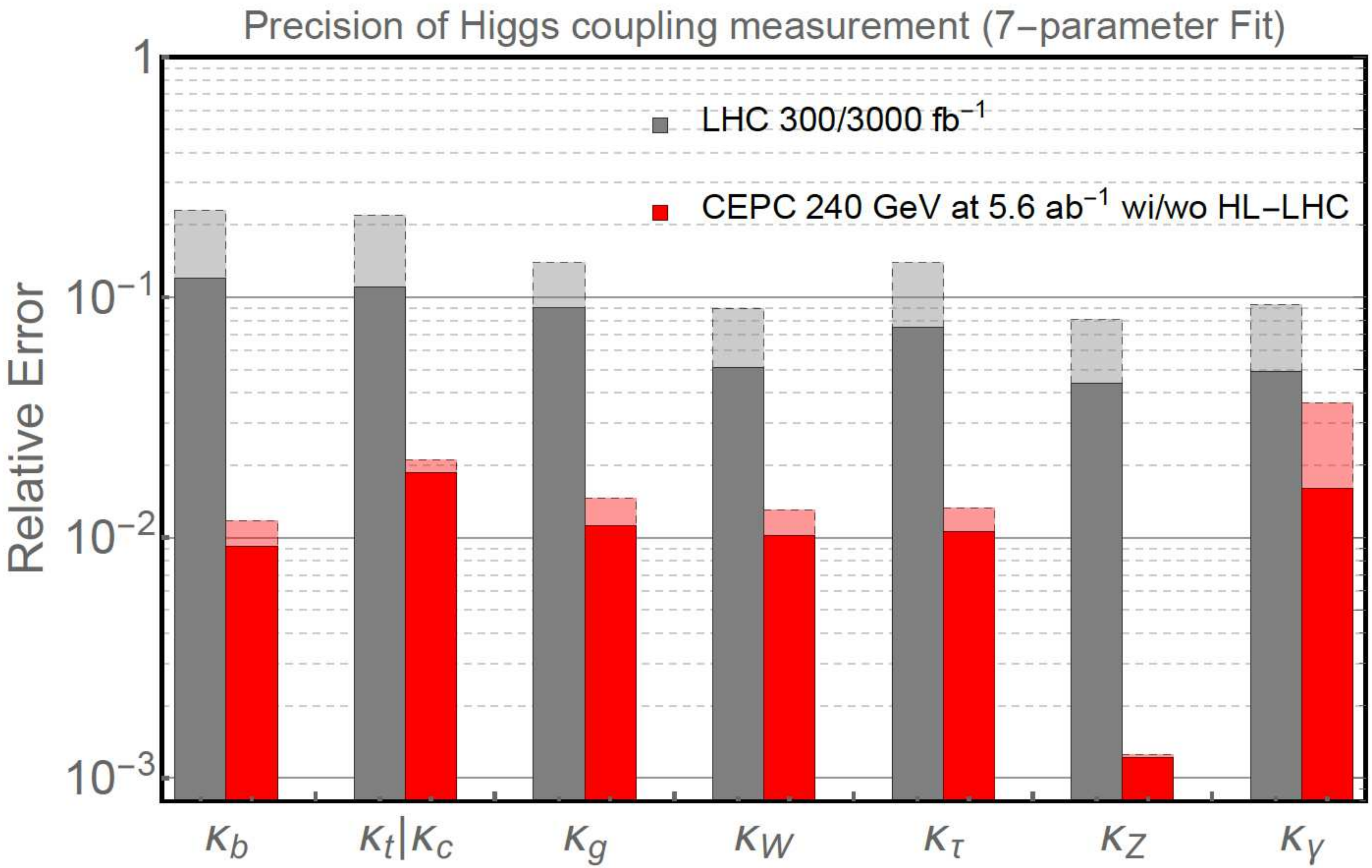
⇒ CEPC shows strong improvement over HL-LHC in many cases

⇒ . . . and without theory assumptions

⇒ and this improvement could be decisive!

HL-LHC vs. CEPC:

[F. An et al. '18]



$\Rightarrow$ improvement by ~ 10

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

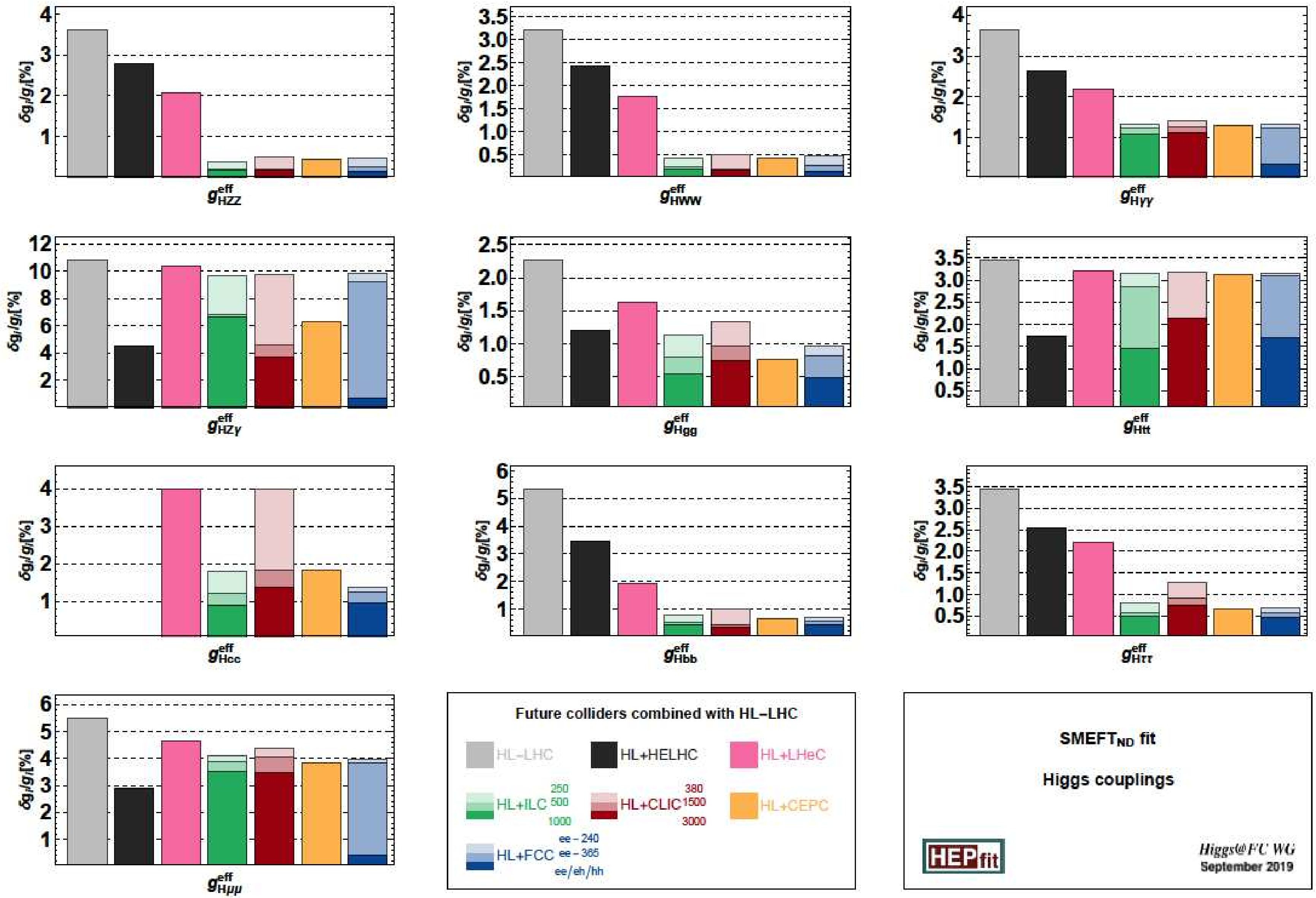
3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM

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

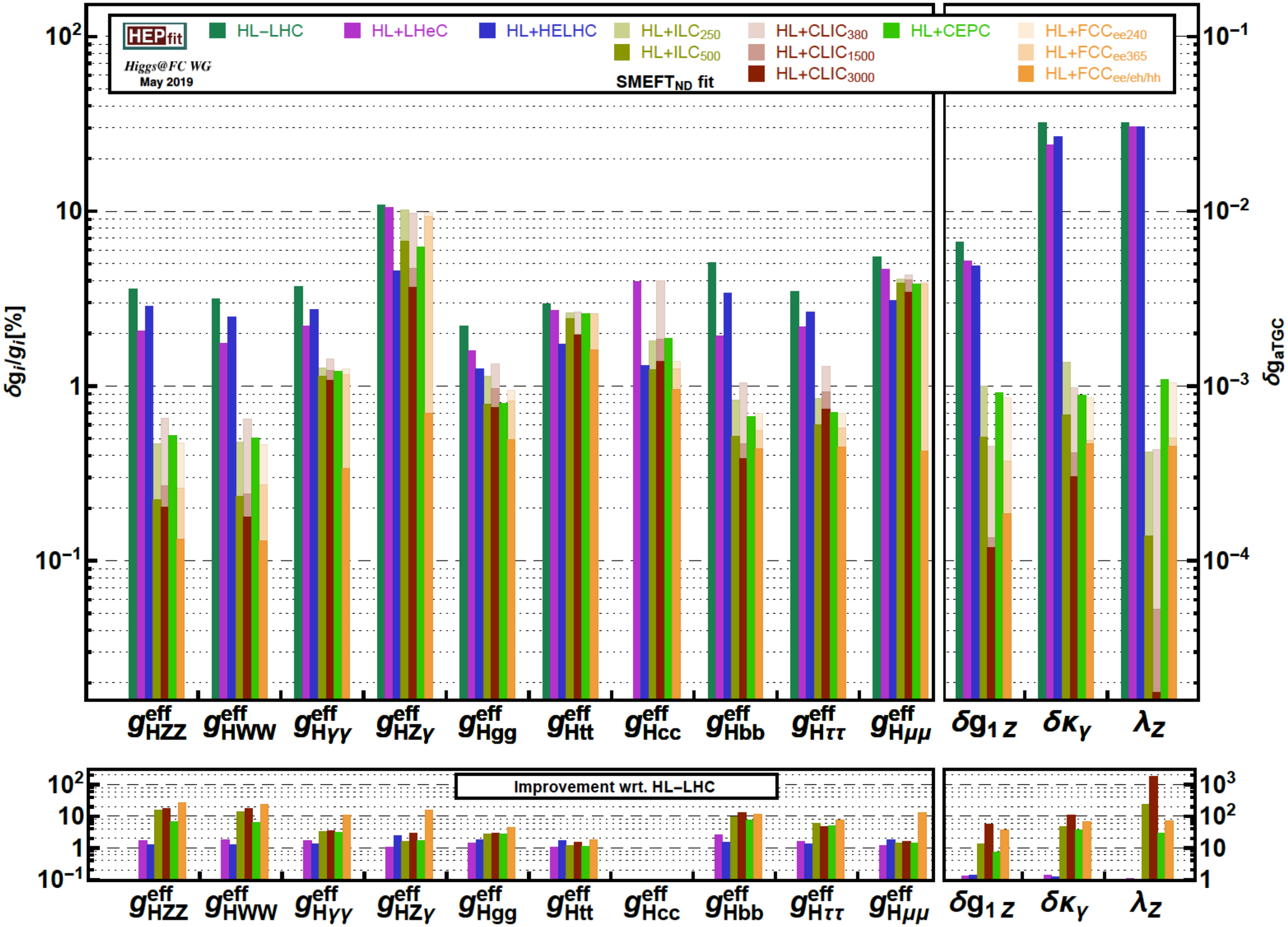
Note: also EFT does NOT cover all models
⇒ investigate in addition "realistic" (UV-complete) models!

Future expections for Higgs couplings in SMEFT (I)



⇒ clear improvement with the CEPC!

Future expections for Higgs couplings in SMEFT (II)



⇒ clear improvement with the CEPC!

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

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

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

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

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

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

$\Rightarrow$ focus on (2)

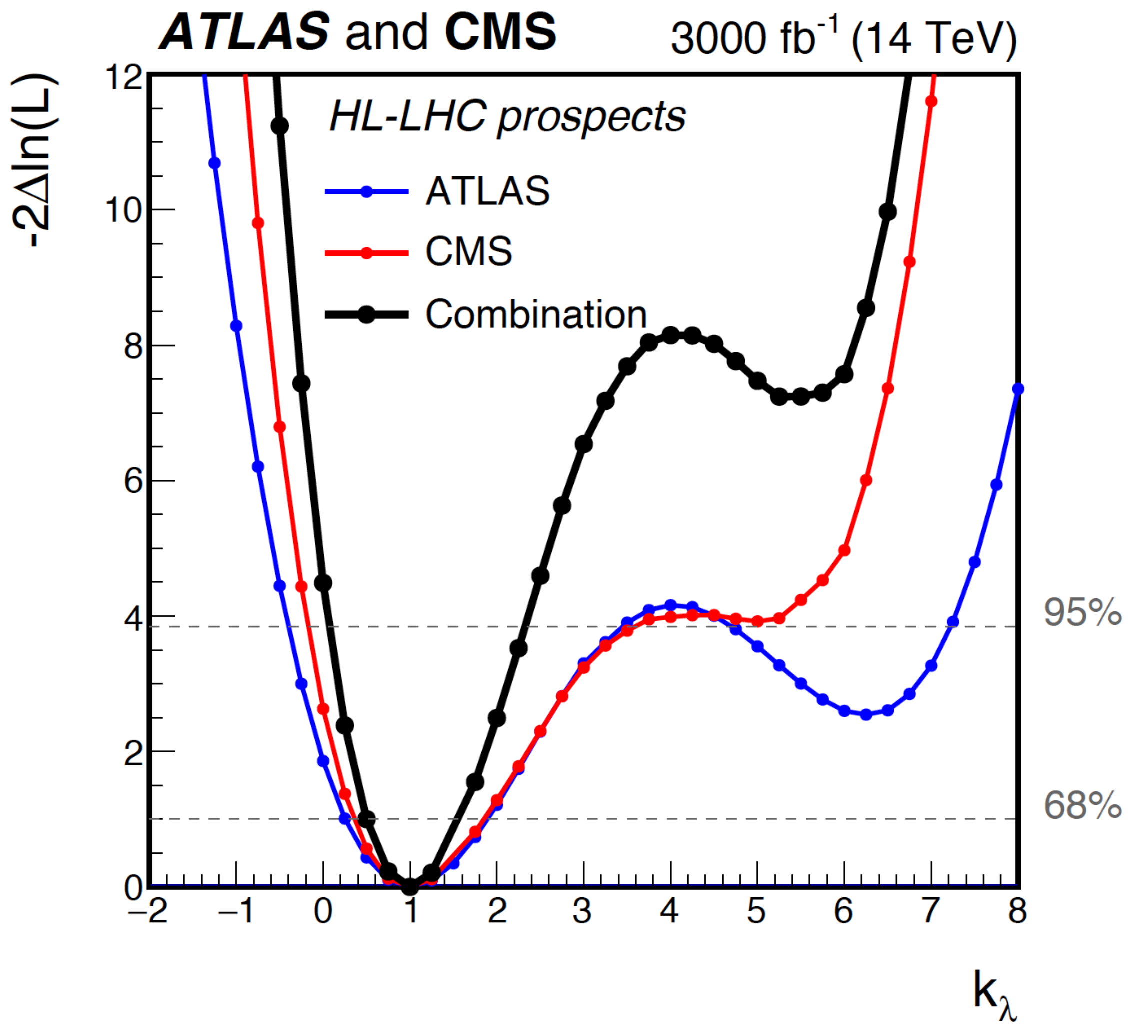
Desired precision in λ?

$\Rightarrow$ highly model dependent

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

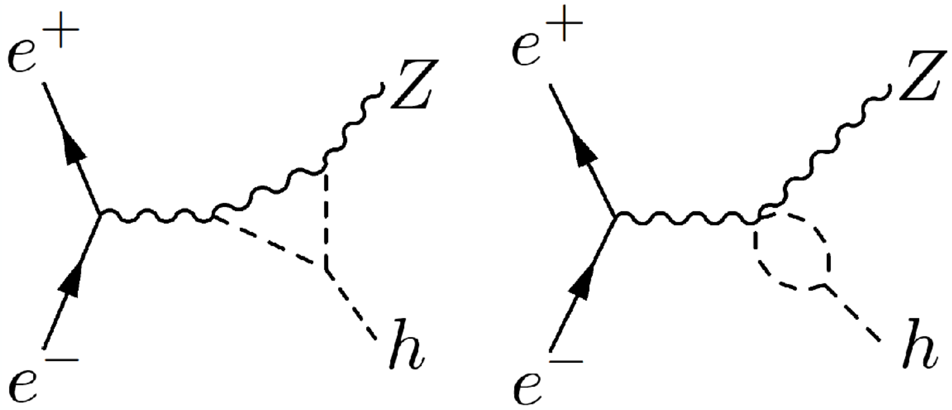
- Higgs singlet extension: $(\Delta\lambda/\lambda)^{\text{max}} \sim -18\%$
- Composite Higgs models: $(\Delta\lambda/\lambda)^{\text{max}} \sim +20\%$
- MSSM: $(\Delta\lambda/\lambda)^{\text{max}} \lesssim -15\%$
- NMSSM: $(\Delta\lambda/\lambda)^{\text{max}} \lesssim -25\%$
- 2HDM: NEW: $\kappa_\lambda = -0.5 \ldots +1.5$ (largest deviations for type I)
  [*F. Arco, S.H., M. Herrero '20, '21*]

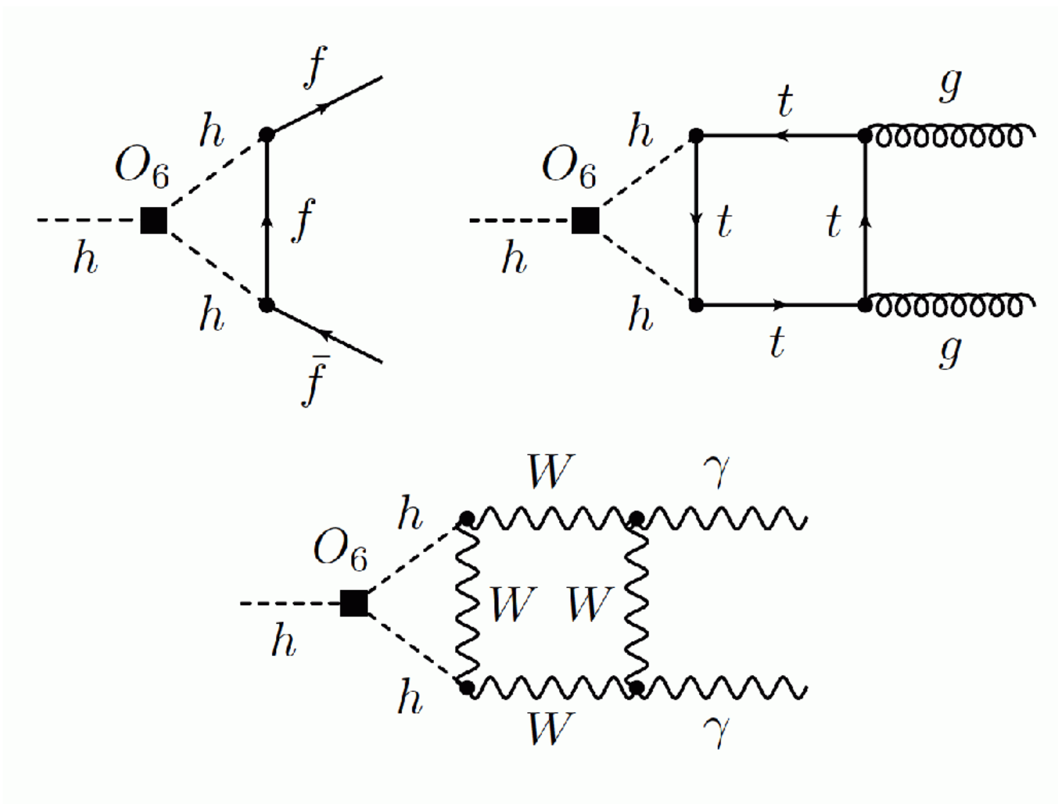
Results for HL-LHC: $[\kappa_\lambda = -0.5 \ldots +1.5]$



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

Single-Higgs production: $[\kappa_\lambda = -0.5 \ldots + 1.5]$

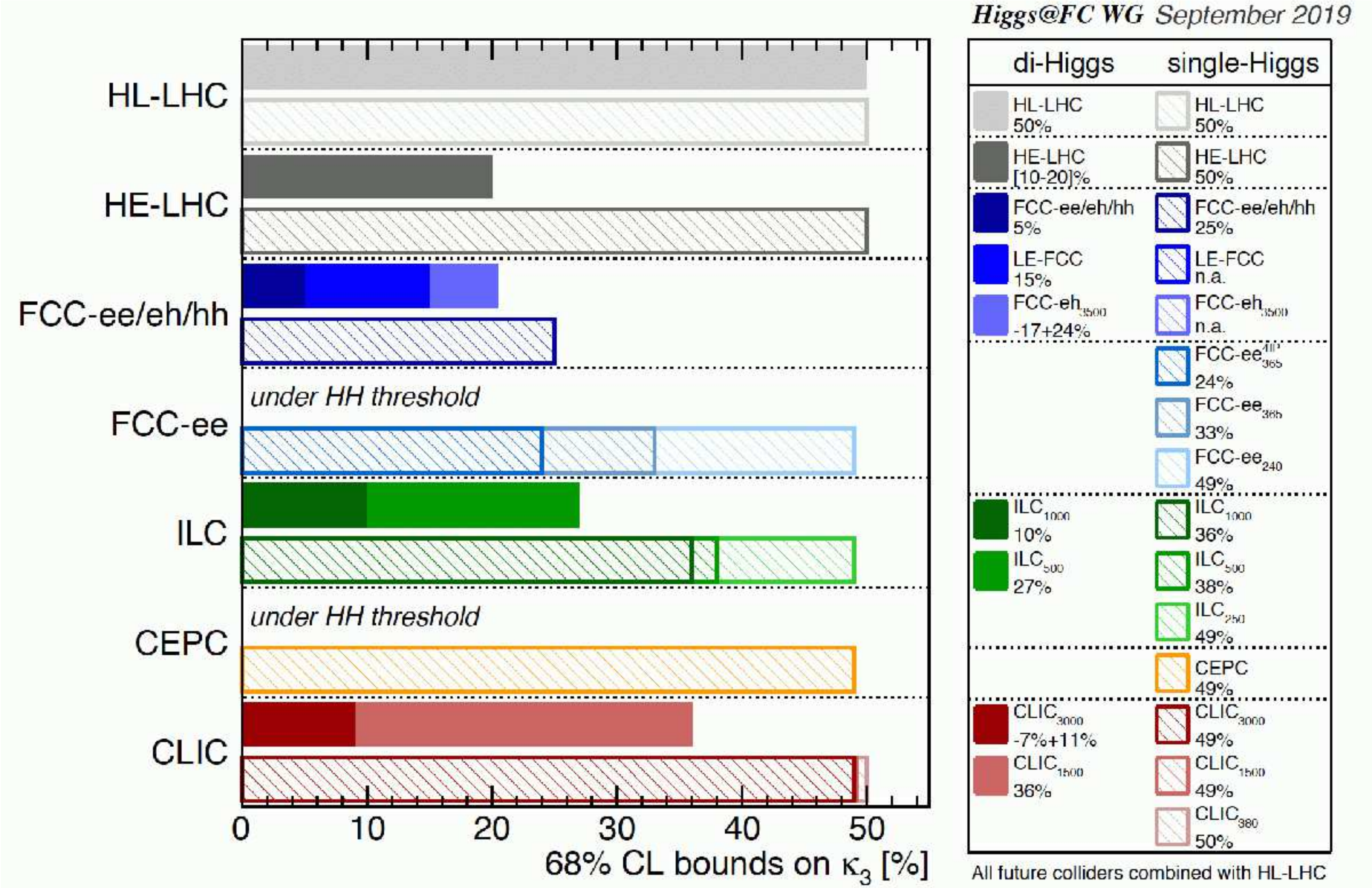




EFT analysis performed only for $\kappa_\lambda = 1$

$\Rightarrow$ prospects for single production unclear!

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



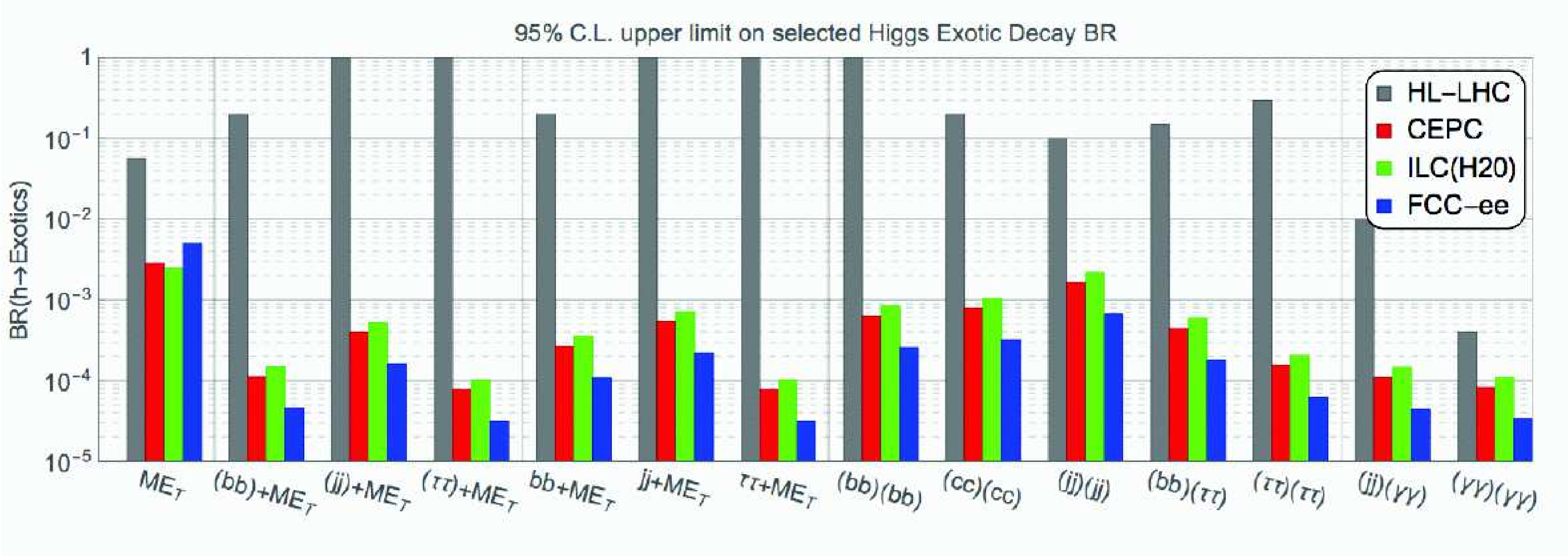
Analysis/comparison performed only for $\kappa_\lambda = 1$

$\Rightarrow$ prospects unclear for single Higgs production!

CEPC results can improve with $\sqrt{s} \sim 350$ GeV $\Rightarrow$ analysis?

Exotic Higgs decays:

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



⇒ strong improvement at the CEPC

⇒ sensitivity to BSM physics?!

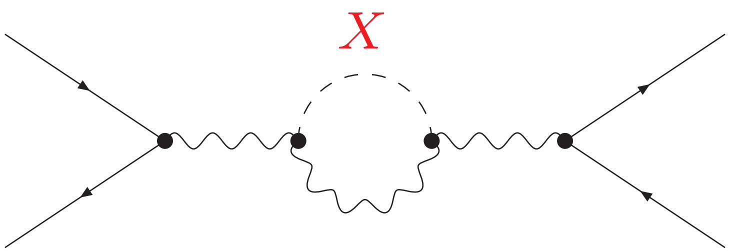
Higgs consistency tests via EWPO:

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, M_h$	$\leftrightarrow$	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

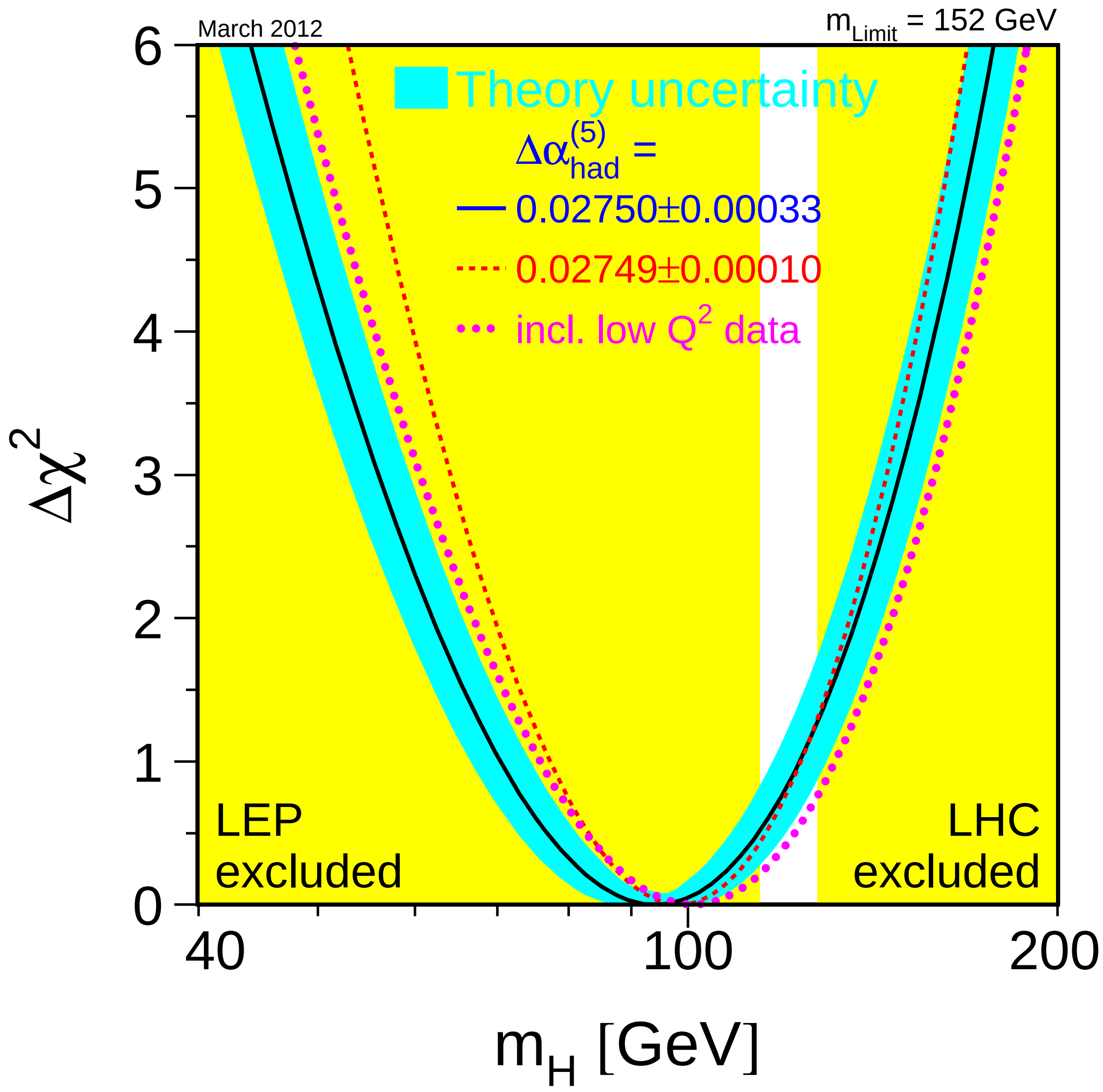
Very high accuracy of measurements and theoretical predictions needed
$\Rightarrow$ models "ready" so far: SM, MSSM, "pure multi-Higgs" models (?)

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

$\Rightarrow$ no confirmation of
Higgs mechanism

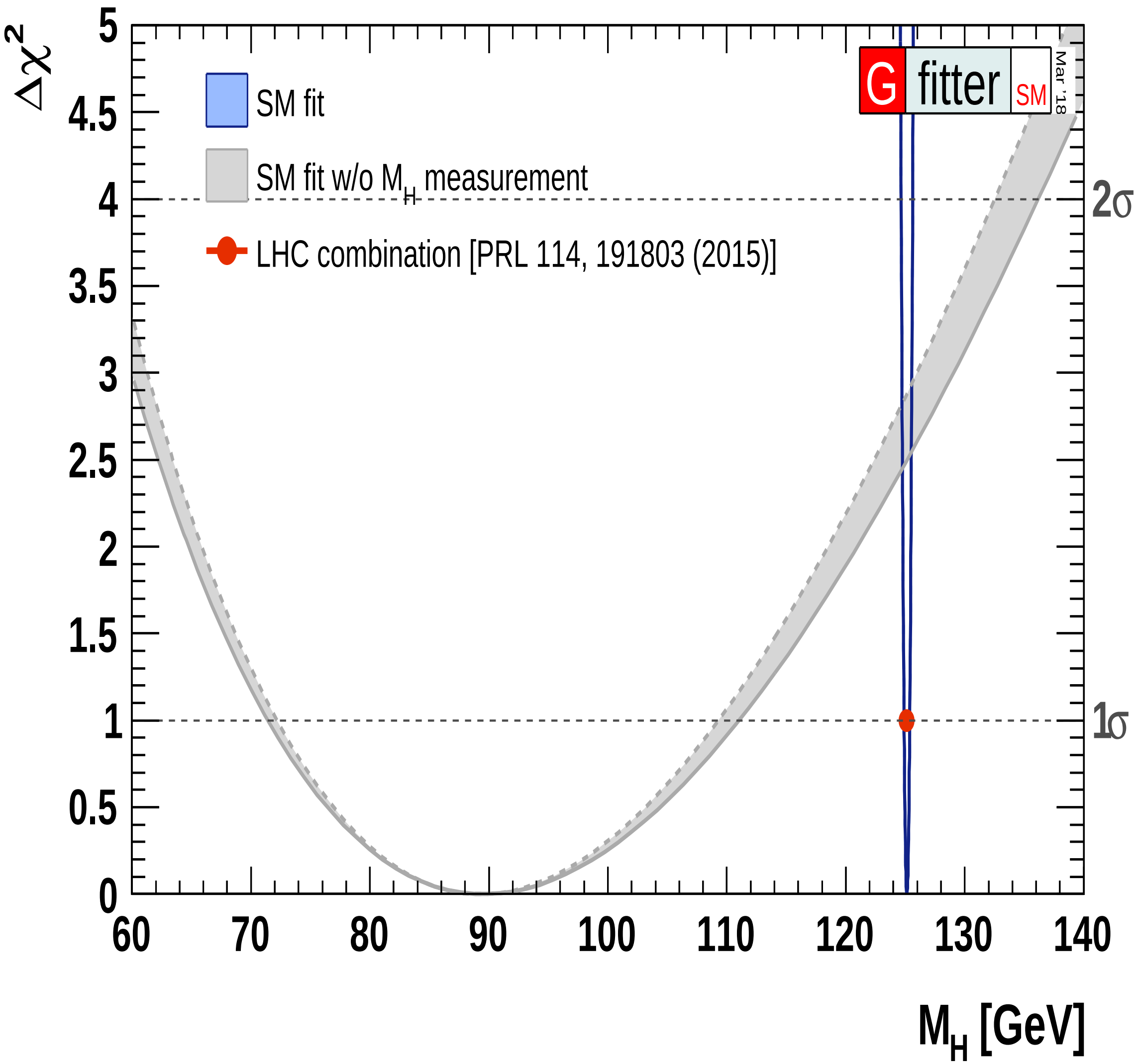
$\Rightarrow$ Prediction before discovery: in the SM: $M_H \lesssim 160$ GeV

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 CEPC

Experimental errors of the precision observables:

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

M_W: from direct reconstruction and threshold scan

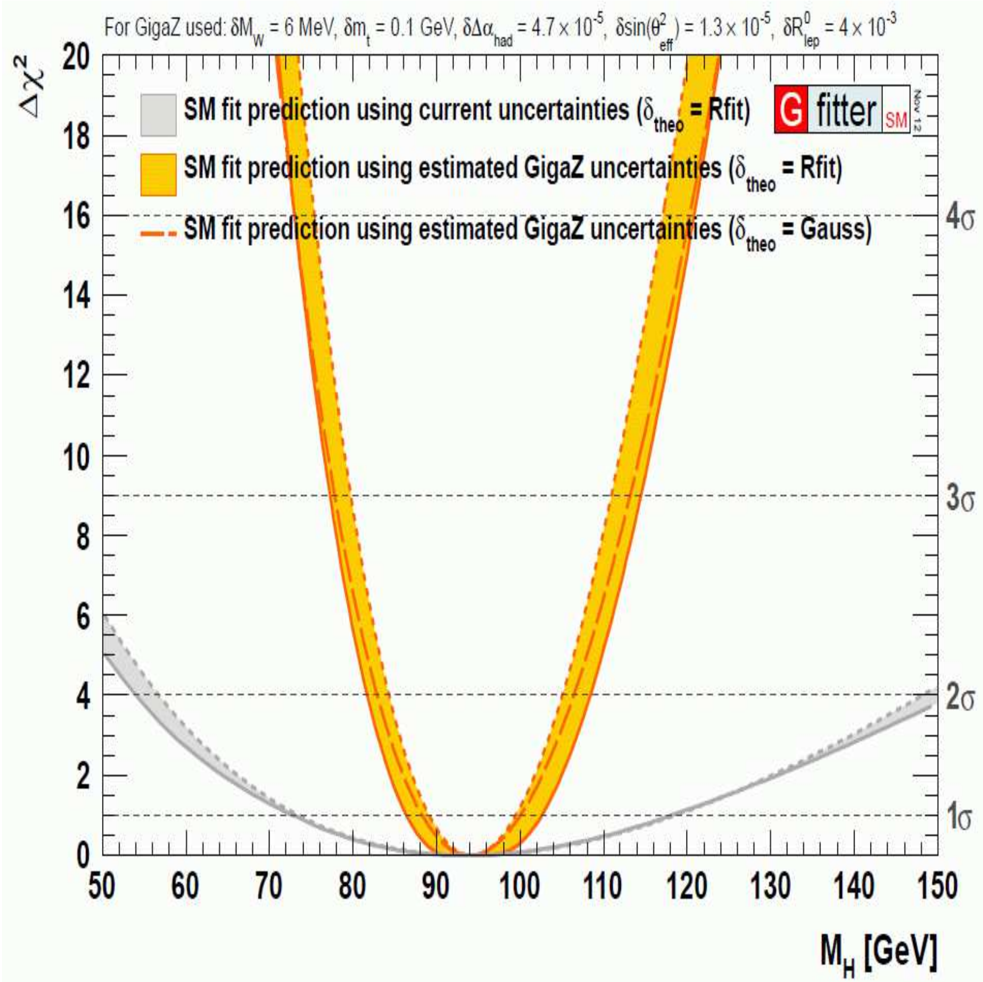
$\sin^2\theta_{\rm eff}$: $> 150\,\text{fb}^{-1}$ at the Z-pole needed

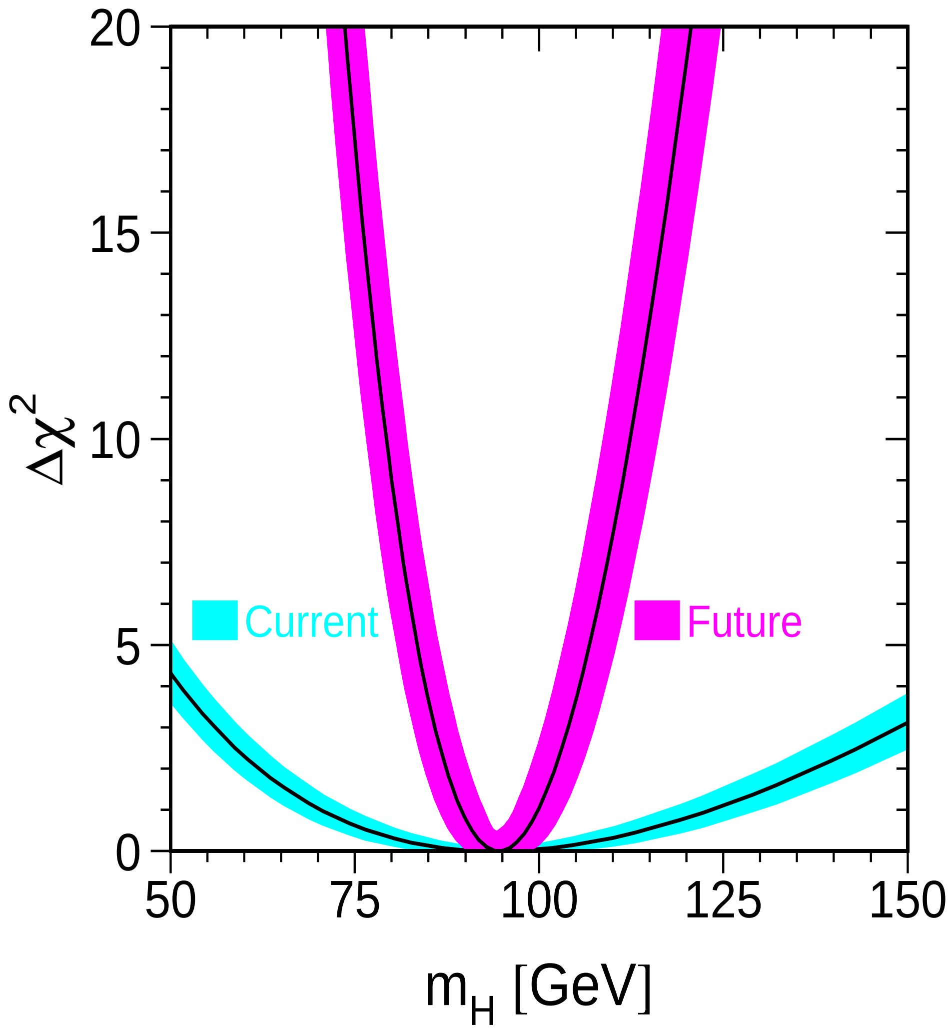
α_s : Improvement from Z-pole running via R_l

$\Rightarrow$ no theory uncertainties included here . . .

Most precise M_H test with the CEPC:

[*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:

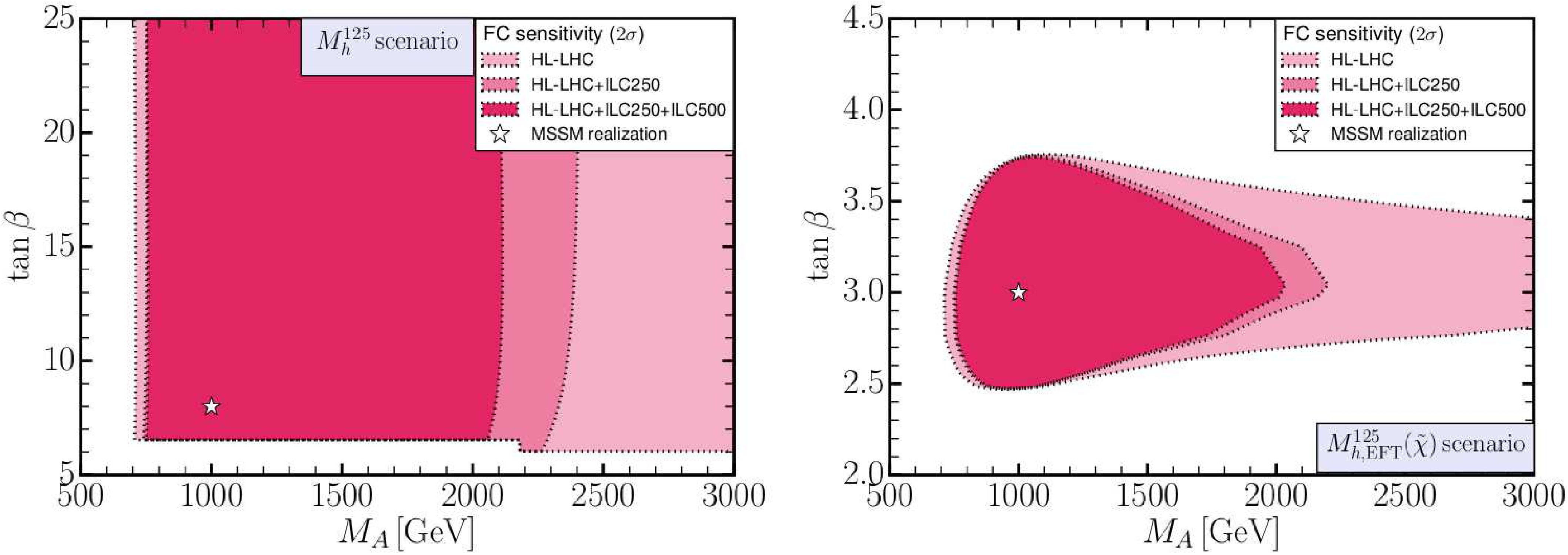
model prediction (w/o TH unc.) ⇔ e^+e^- precision

⇒ "Higgs inverse" problem

Relevance of CEPC 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?

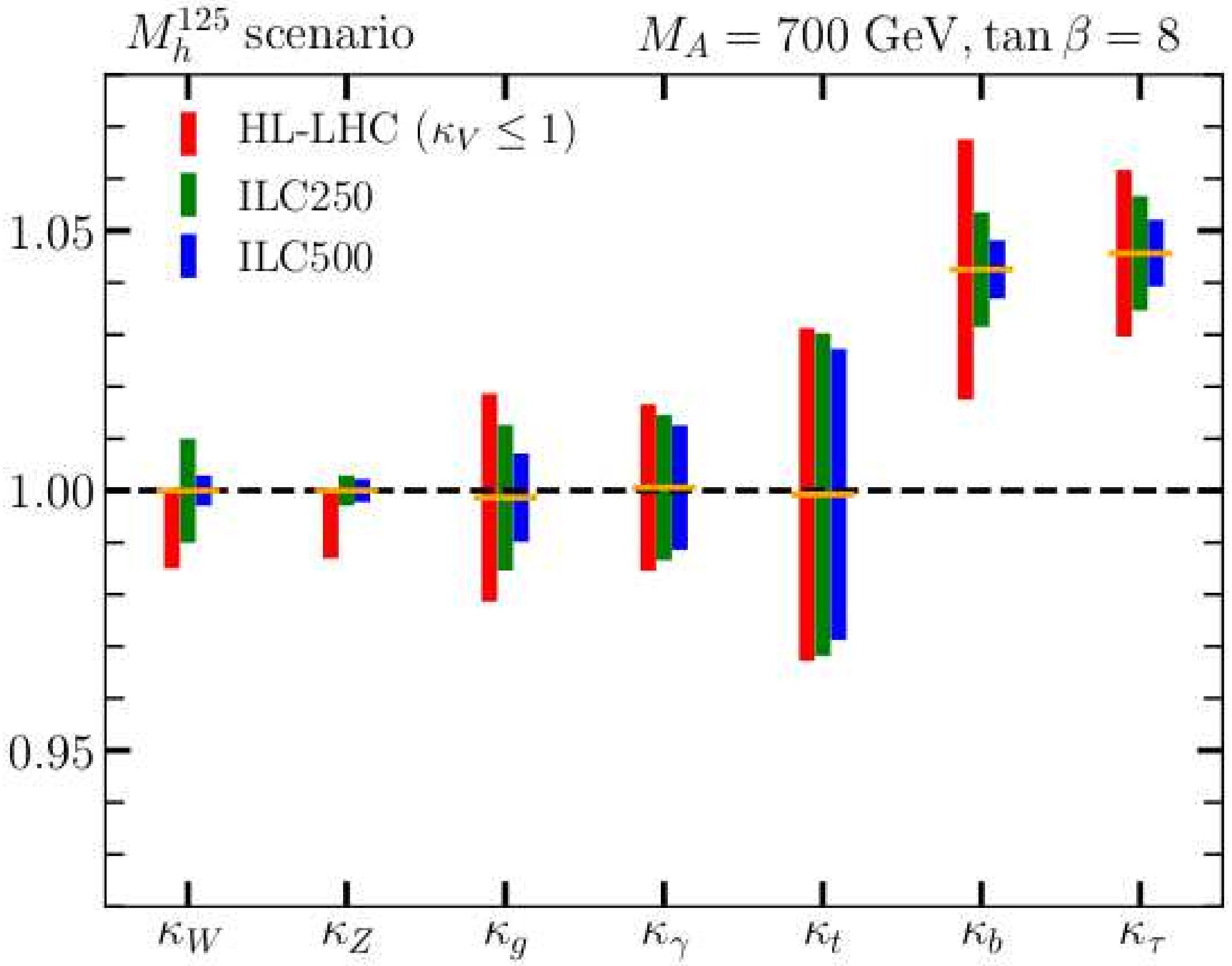


⇒ only CEPC measurements give upper limit on M_A

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

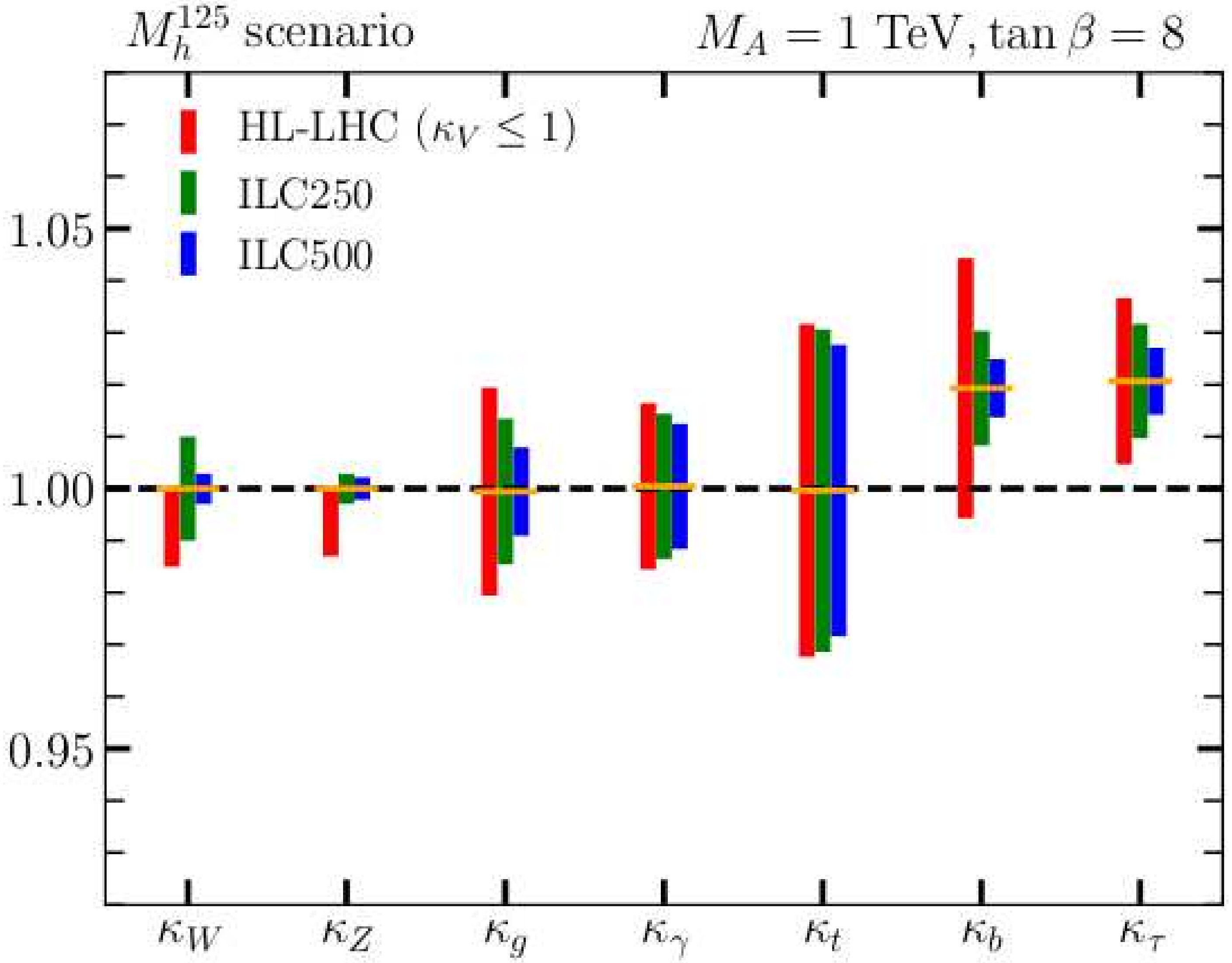
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

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



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

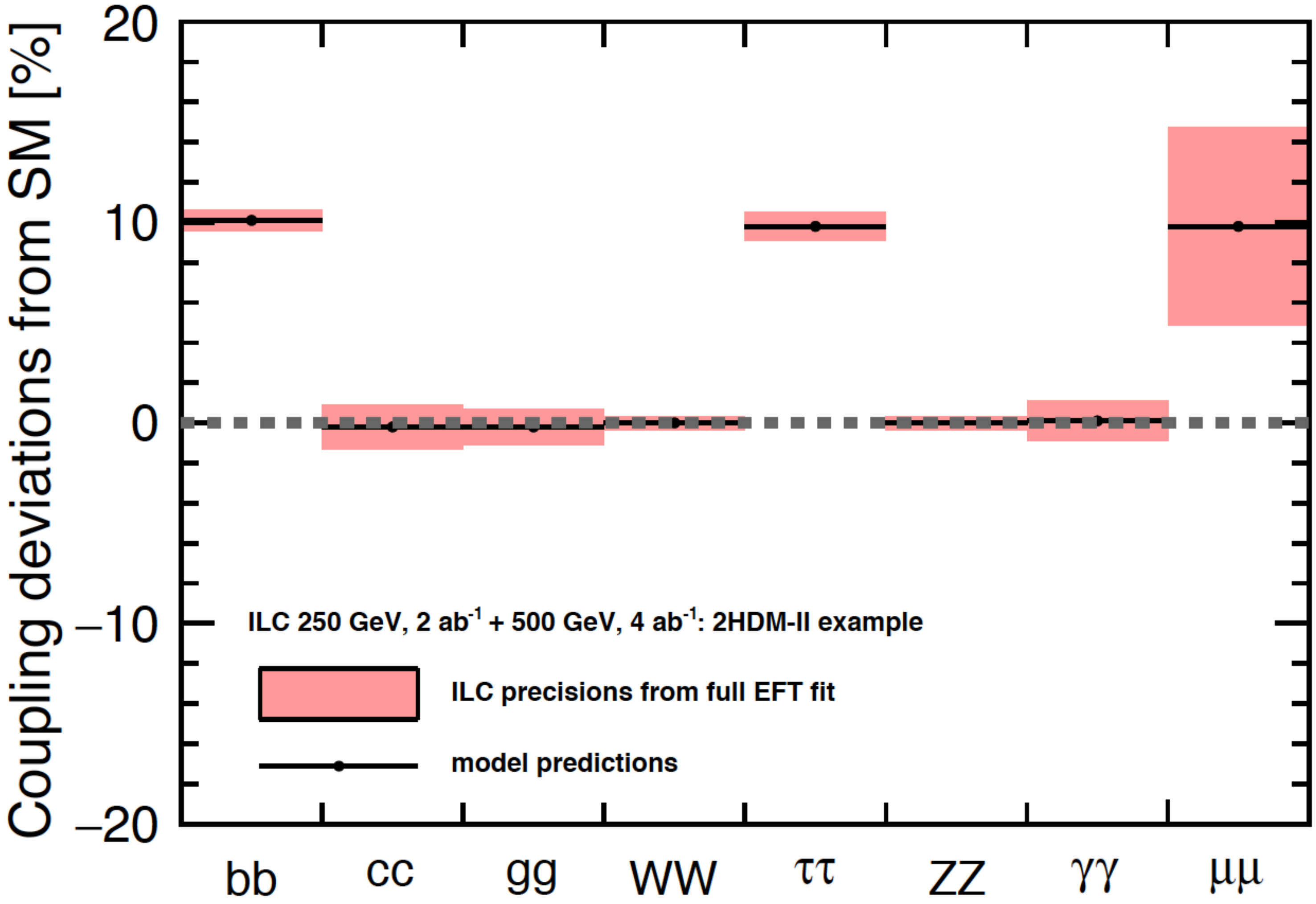
[*H. Bahl et al. '20*]



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

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

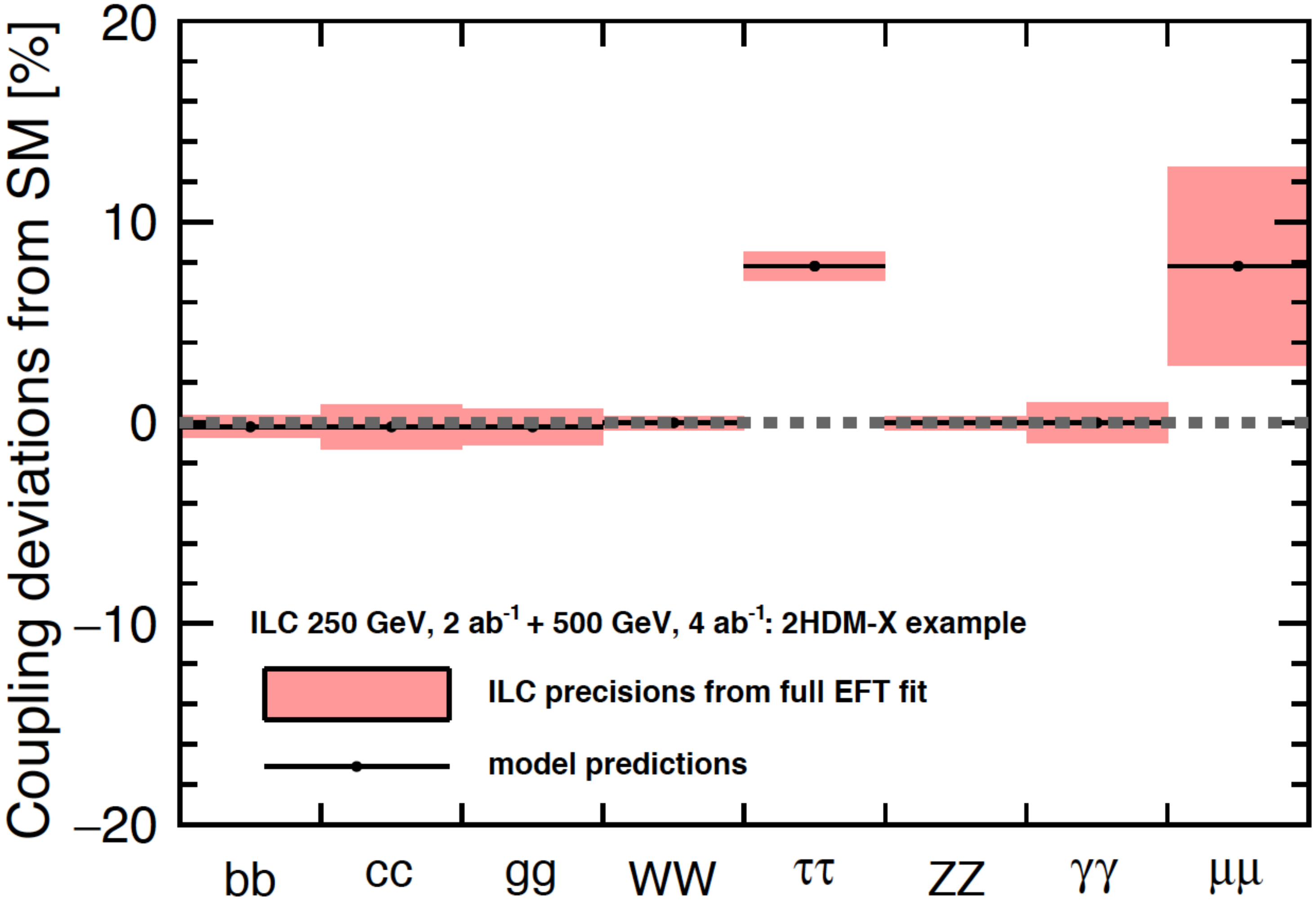
[*T. Barklow et al., '17*]



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

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

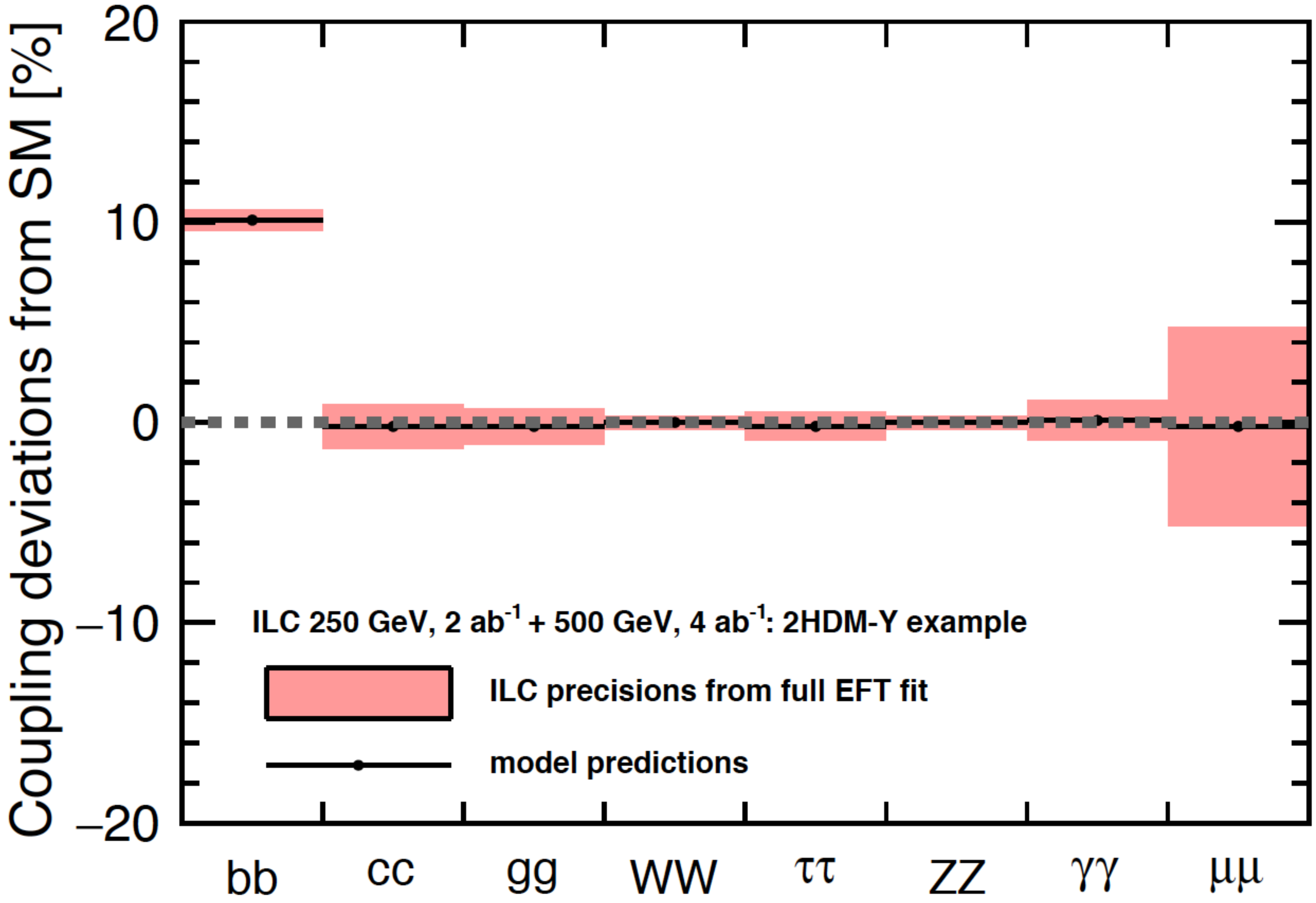
[*T. Barklow et al., '17*]



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

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

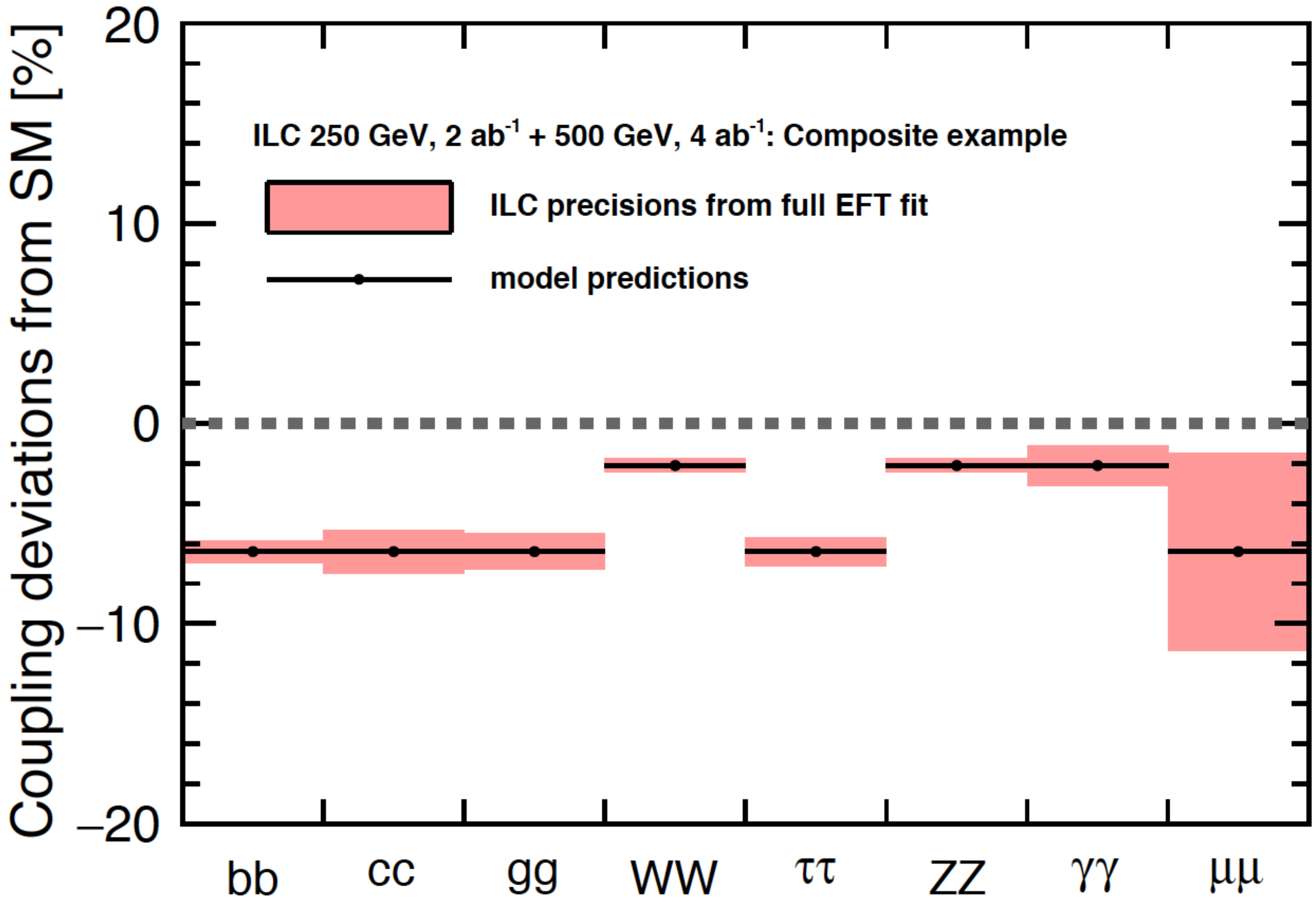
[*T. Barklow et al., '17*]



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

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

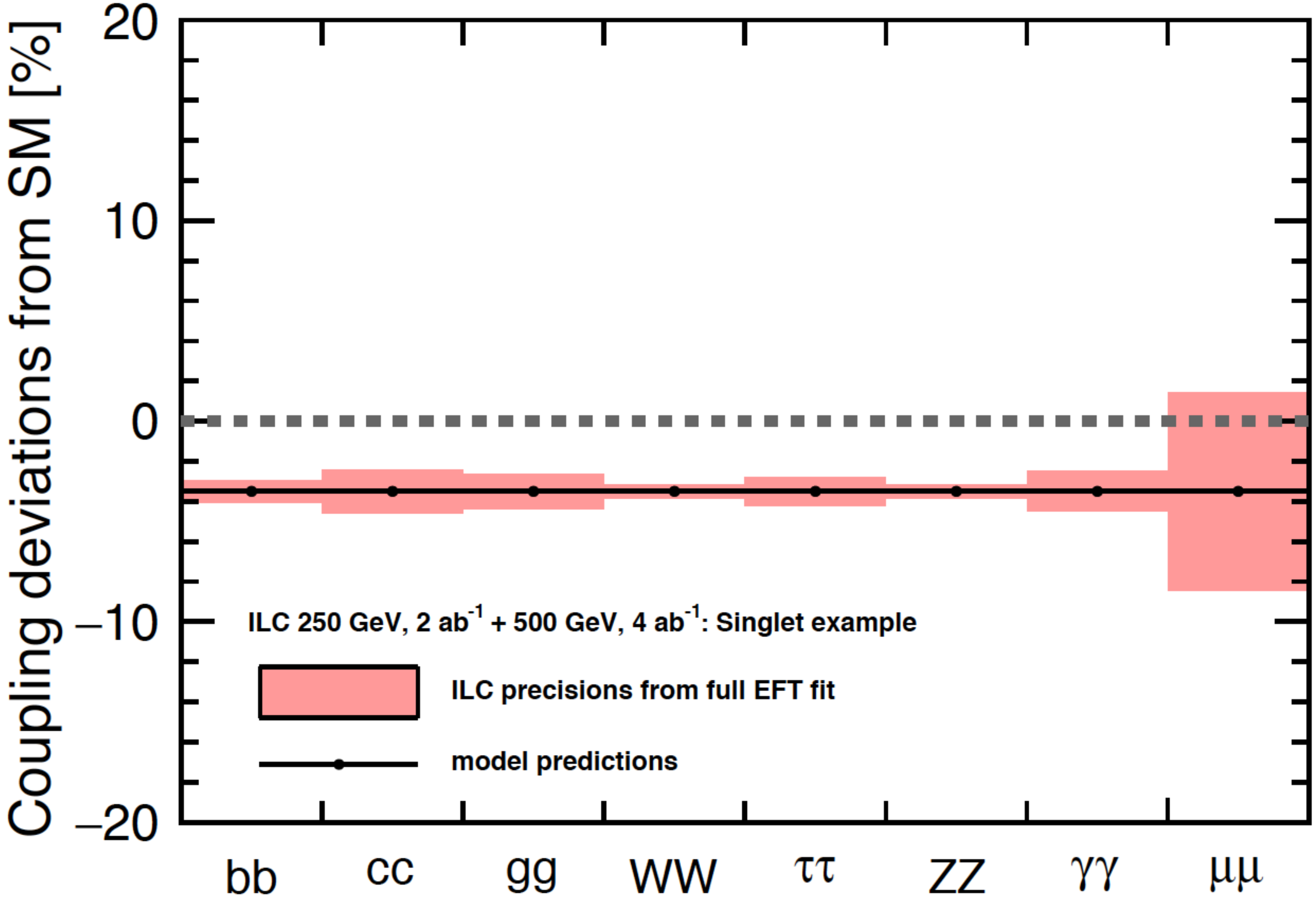
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Composite Higgs?!

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

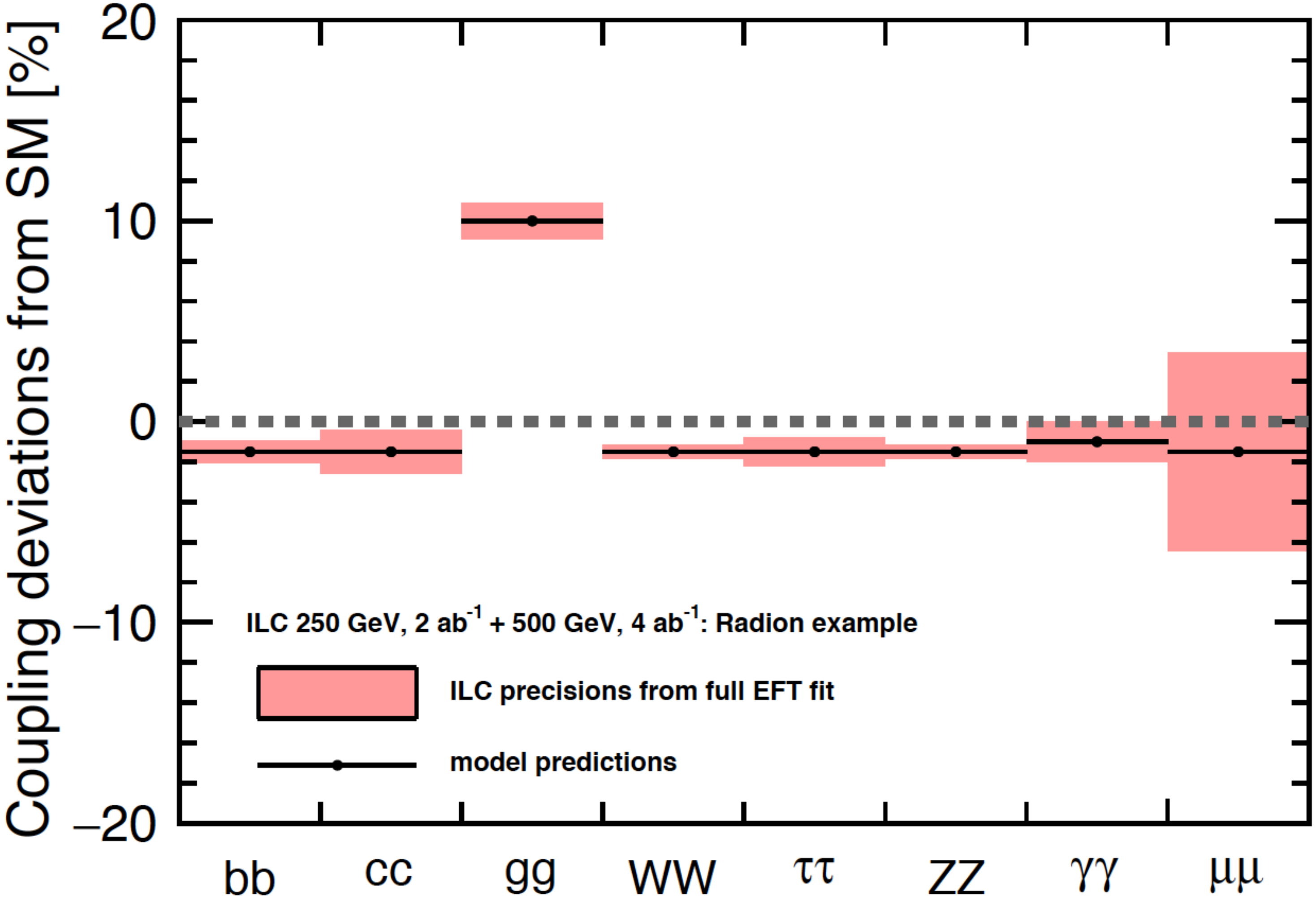
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for HxSM?!

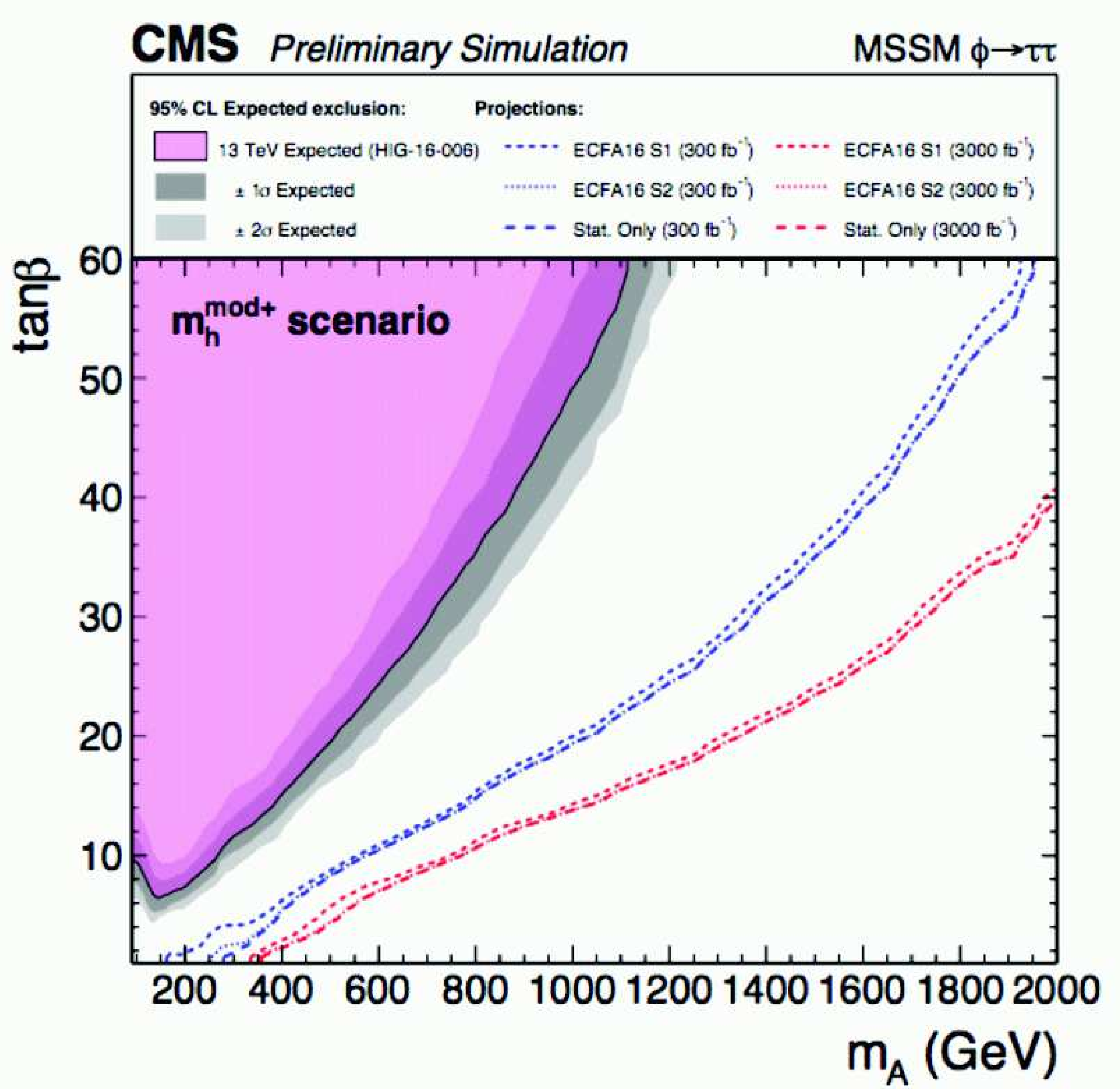
Wäscheleine VI: e^+e^- precision vs. Higgs-Radion prediction:

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



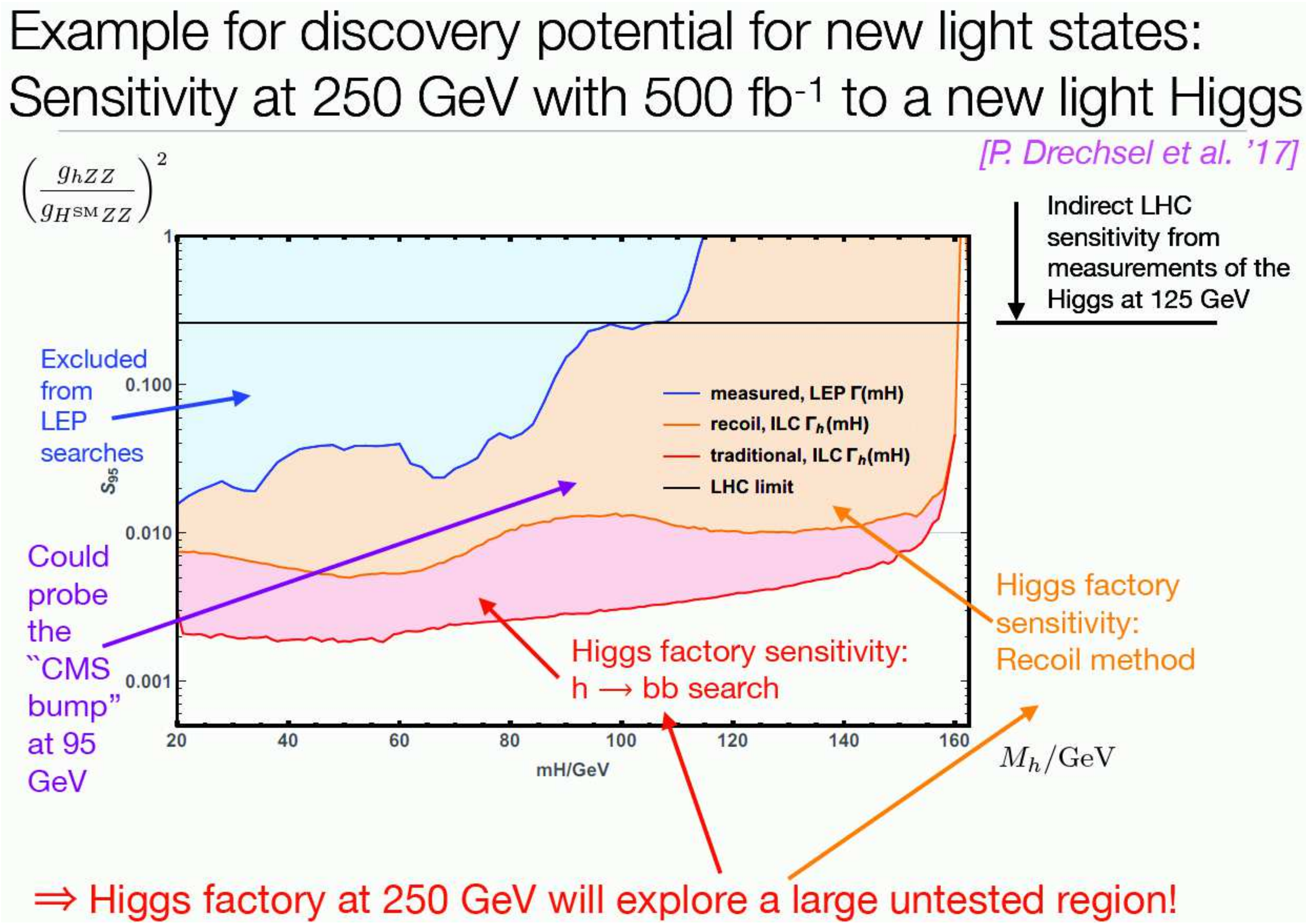
⇒ clear pattern, distinctive for Higgs Radion?!

3. BSM Higgs Bosons



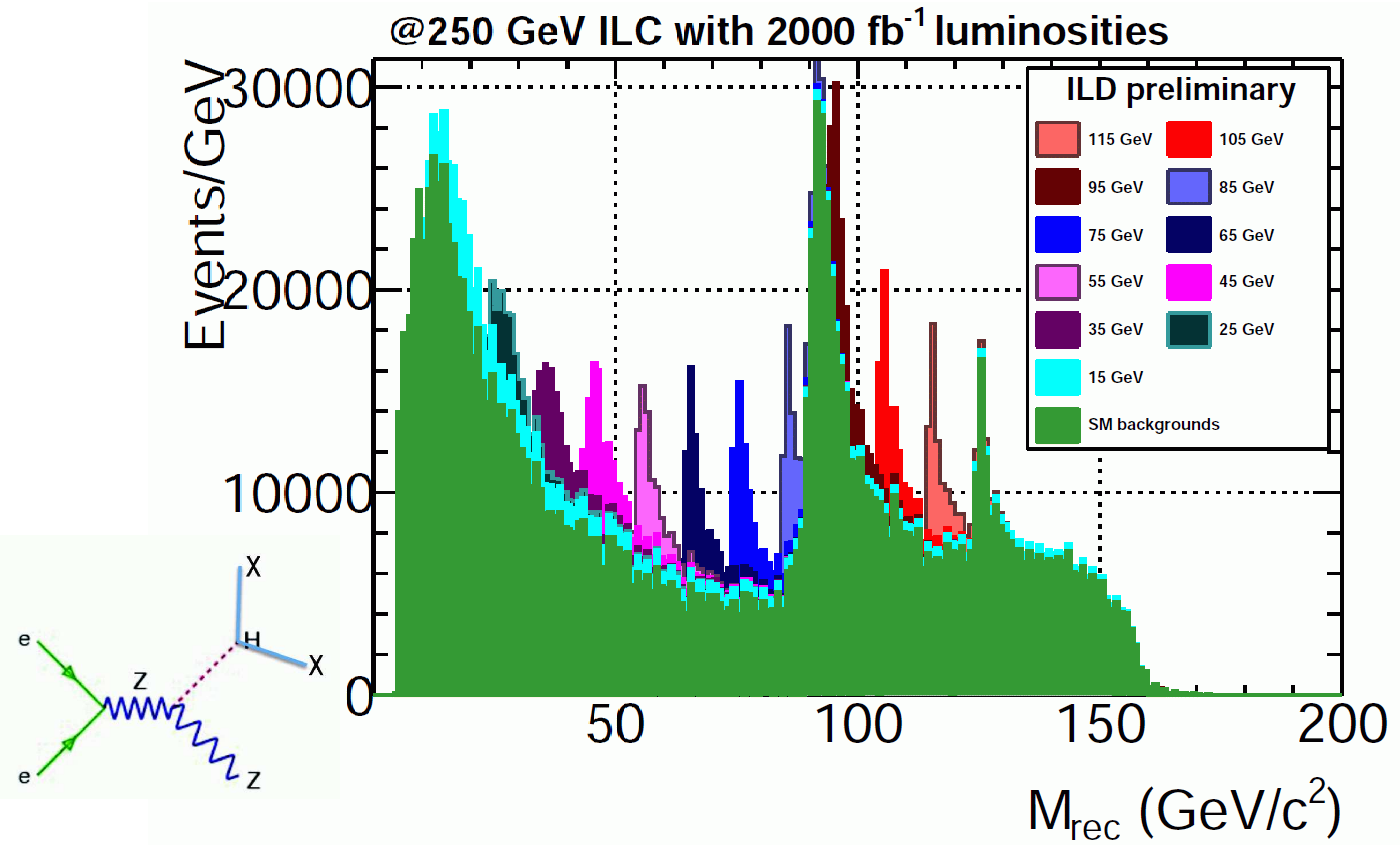
⇒ strong (HL-)LHC limits ⇒ not much space left for $\sqrt{s} \lesssim 350$ GeV

BSM Higgs Bosons below 125 GeV



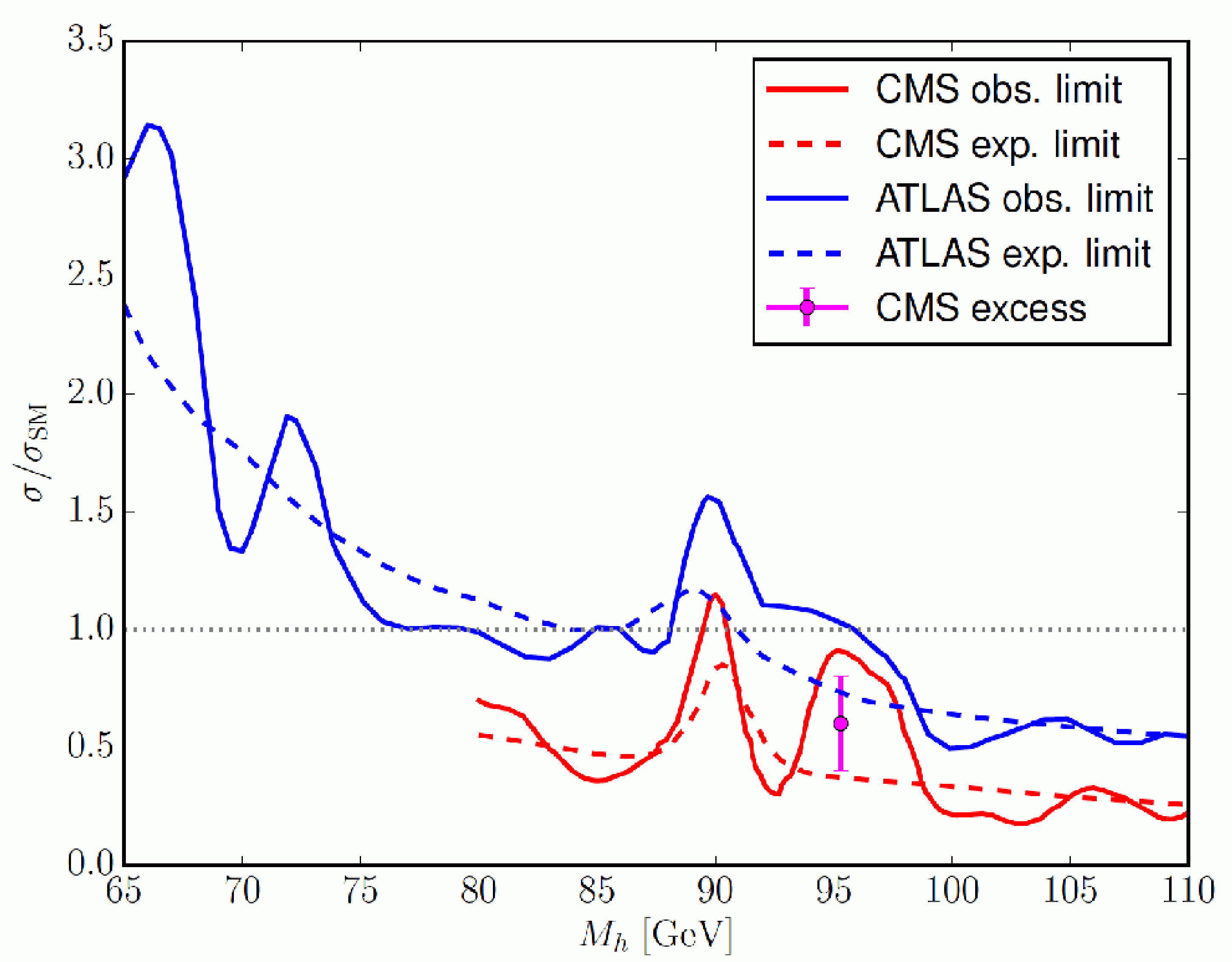
[*Taken from G. Weiglein '18*]

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



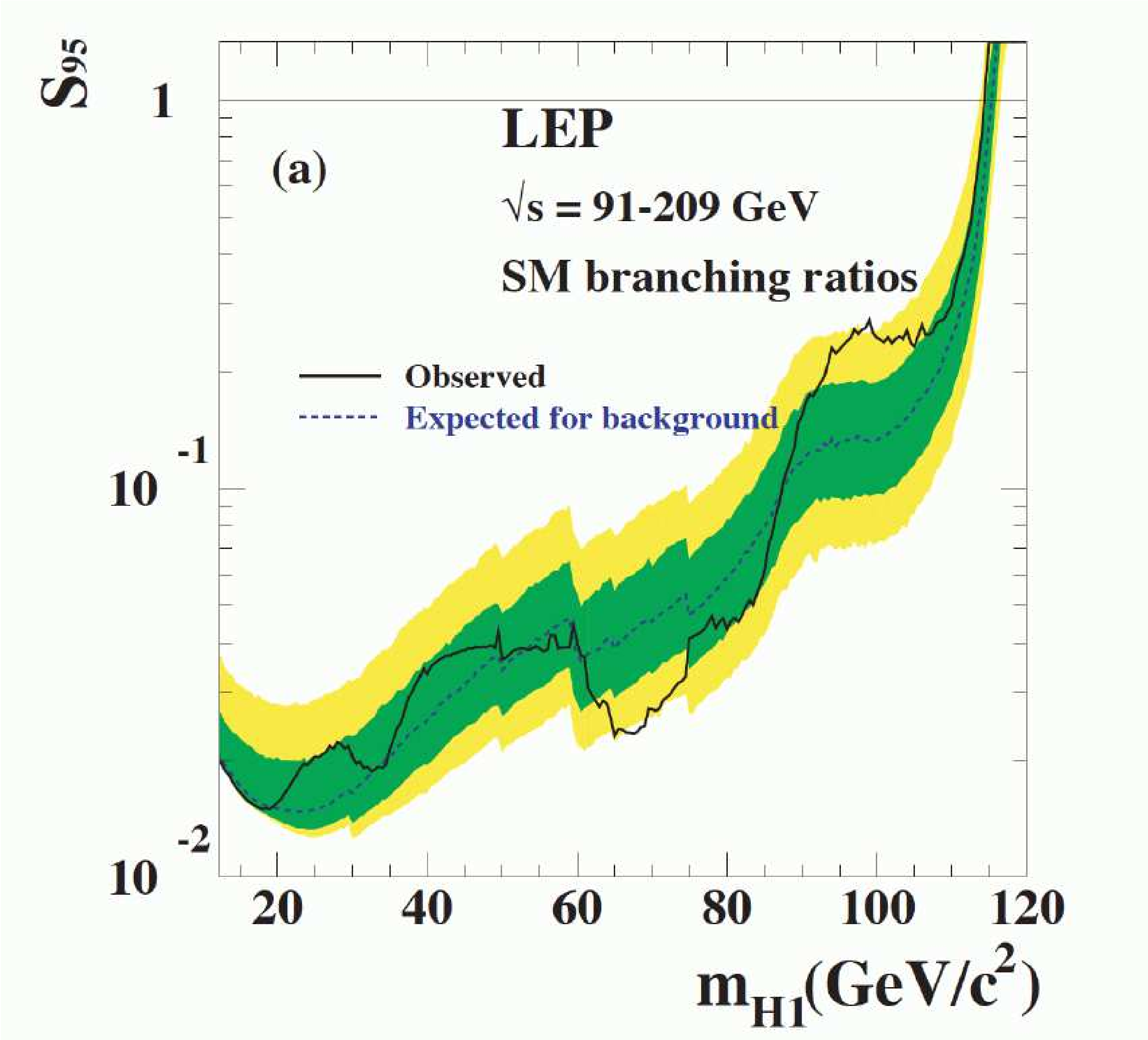
Case study: Search for $pp \to \phi \to \gamma\gamma$ with $m_\phi \leq 125$ GeV

[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!

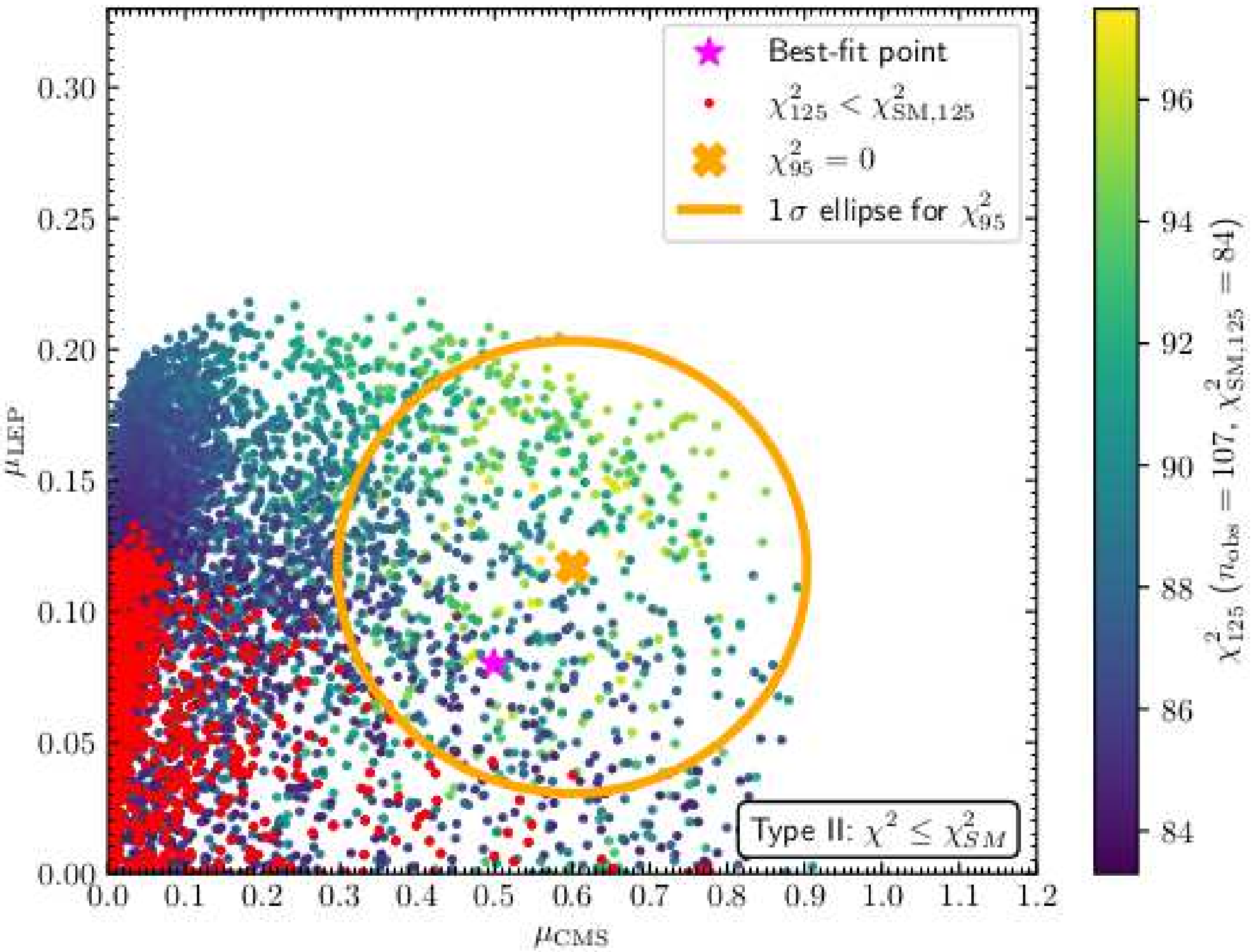
Remember the LEP excess?



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

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?

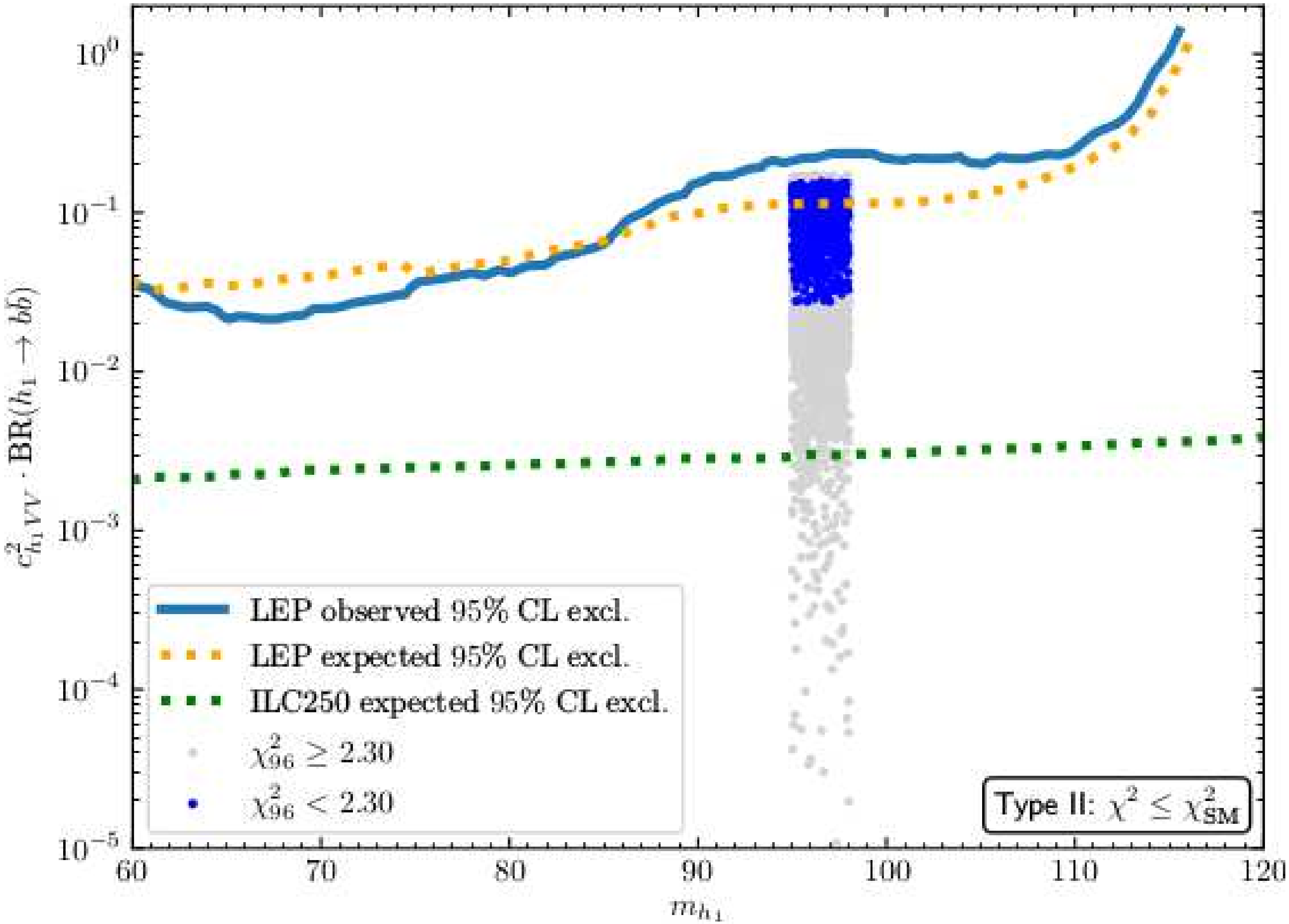


⇒ excesses well fitted, with good χ^2_{125}

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

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

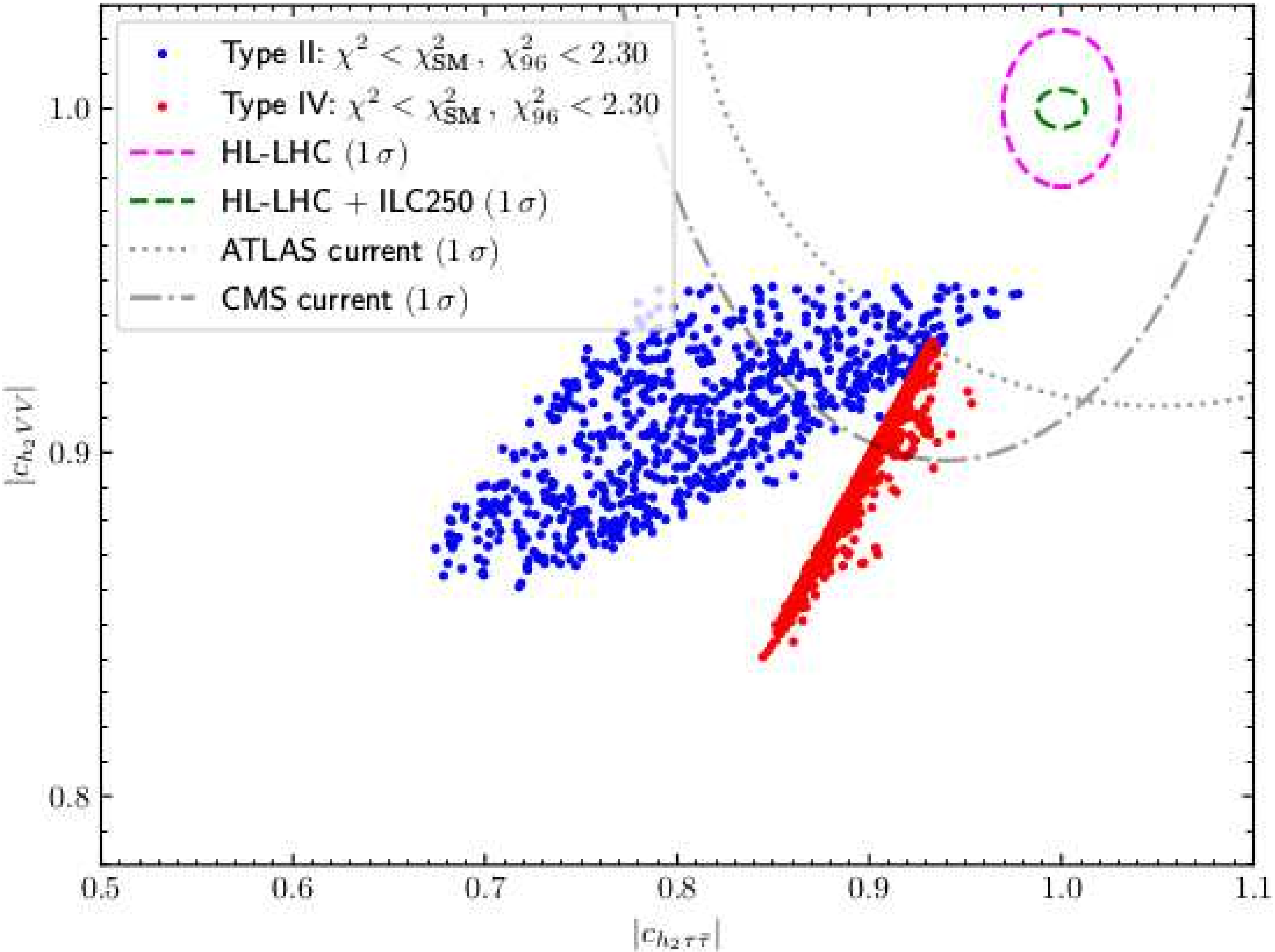
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]



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

HL-LHC/CEPC h_{125} coupling measurements

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



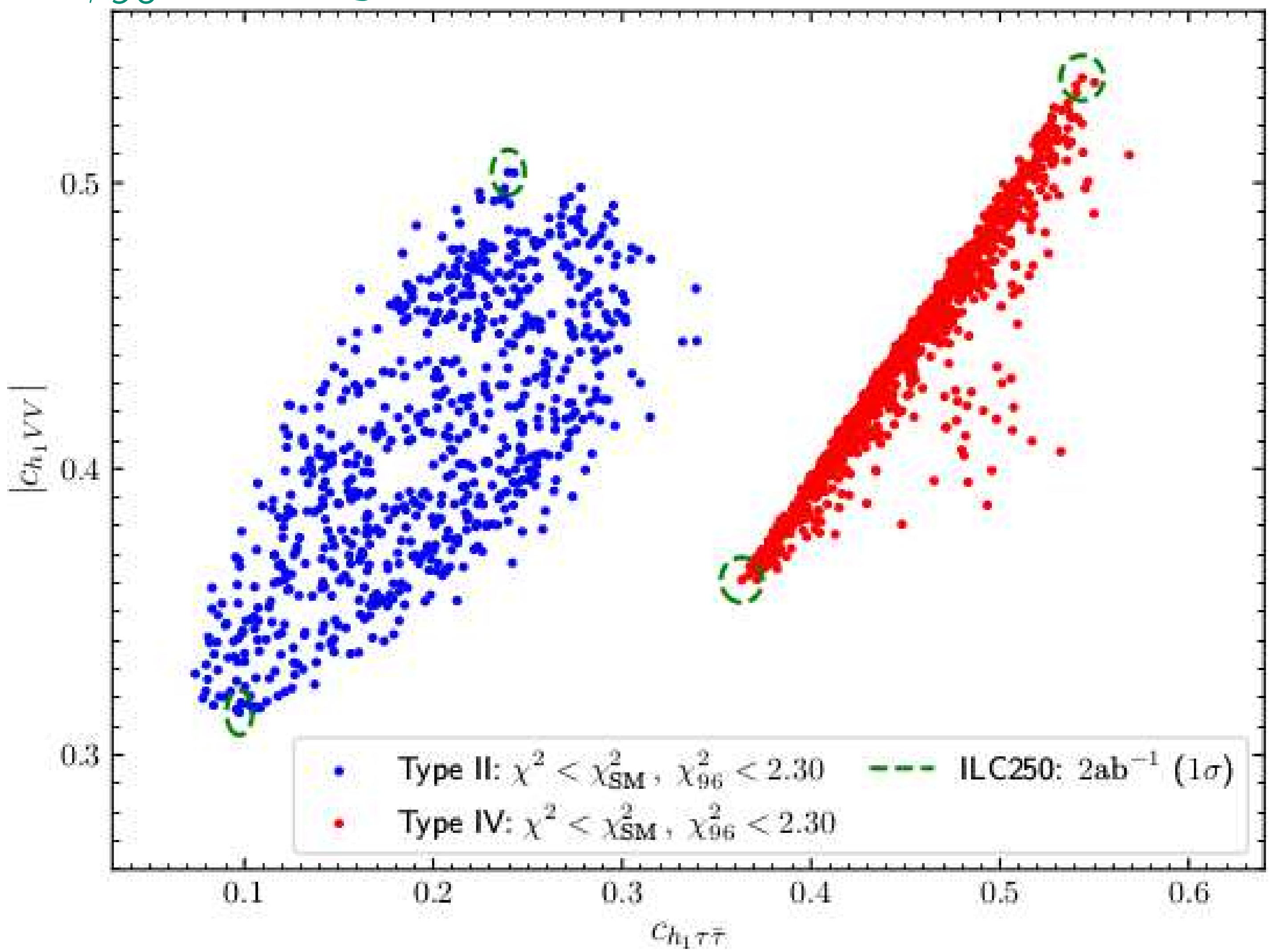
⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM at the CEPC

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

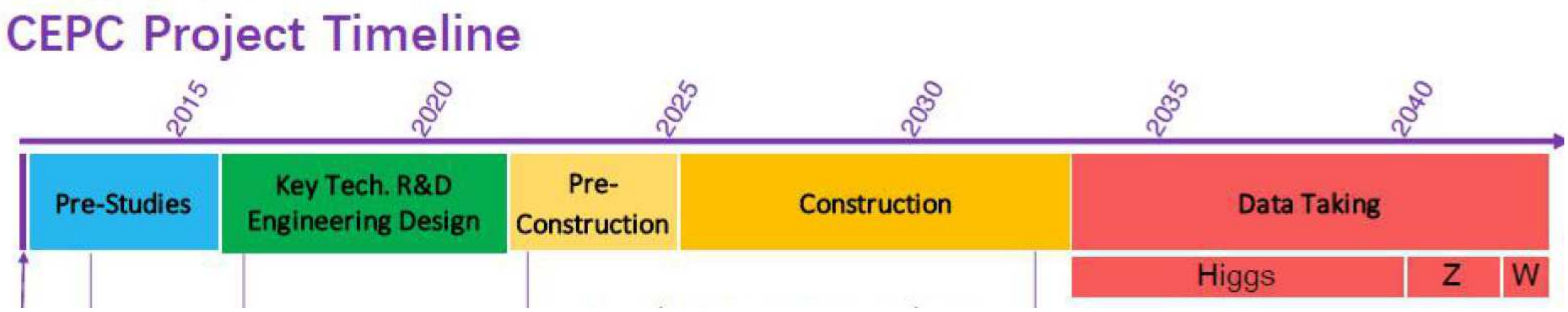
[*T. Biekötter, S.H., G. Weiglein – PRELIMINARY*]

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



⇒ model distinction possible via coupling measurements at the CEPC

4. Conclusions



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

- clear case: h_{125} mass and coupling measurements
  → solving the "Higgs inverse" problem
- clear case: Precision observables and indirect Higgs mass fit
- clear case: Higgs bosons below 125 GeV
- Situation not clear for λ_{hhh} ⇒ more analyses needed


Further Questions?

SUSY realizations

What about SUSY??

SUSY realizations

What about SUSY??

$\Rightarrow$ type II fits best, type II is needed for SUSY $\Rightarrow$ no surprize! ;-)

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?

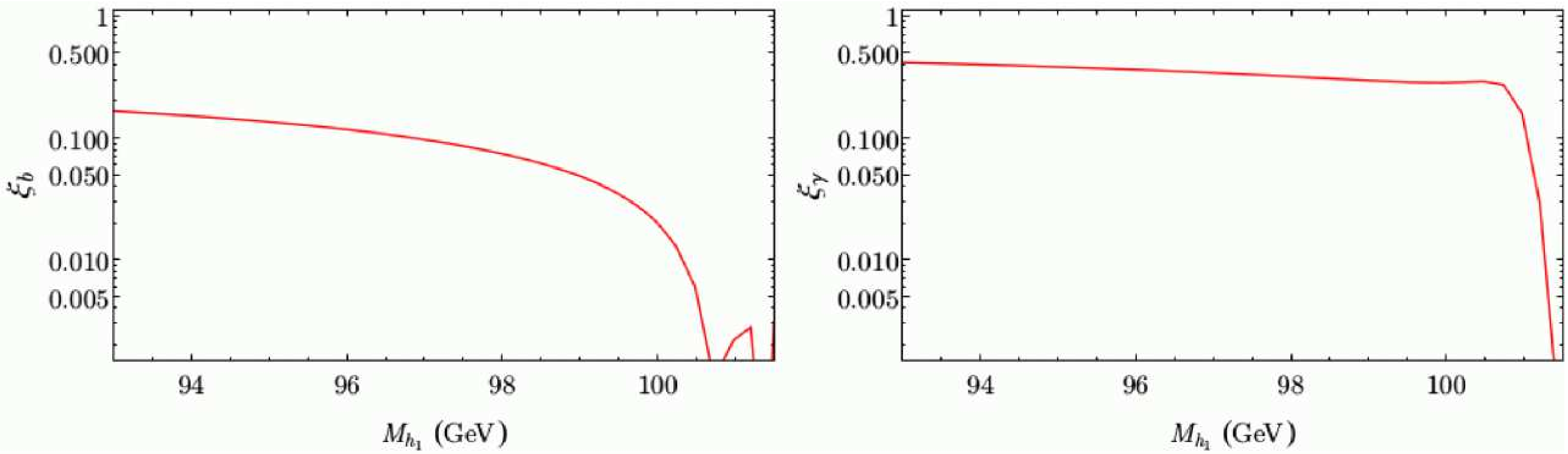
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

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, $A_t = A_b = 0$

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

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



⇒ 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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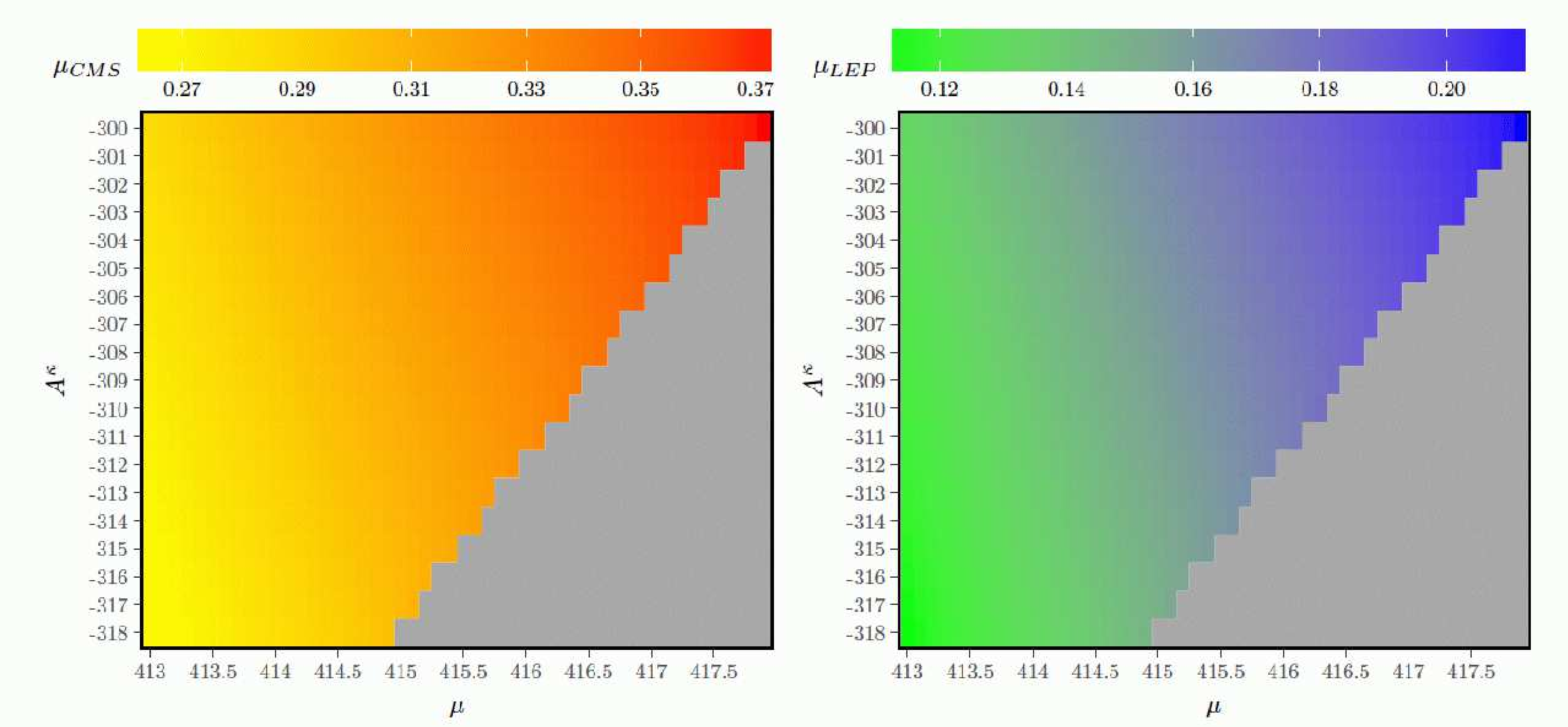
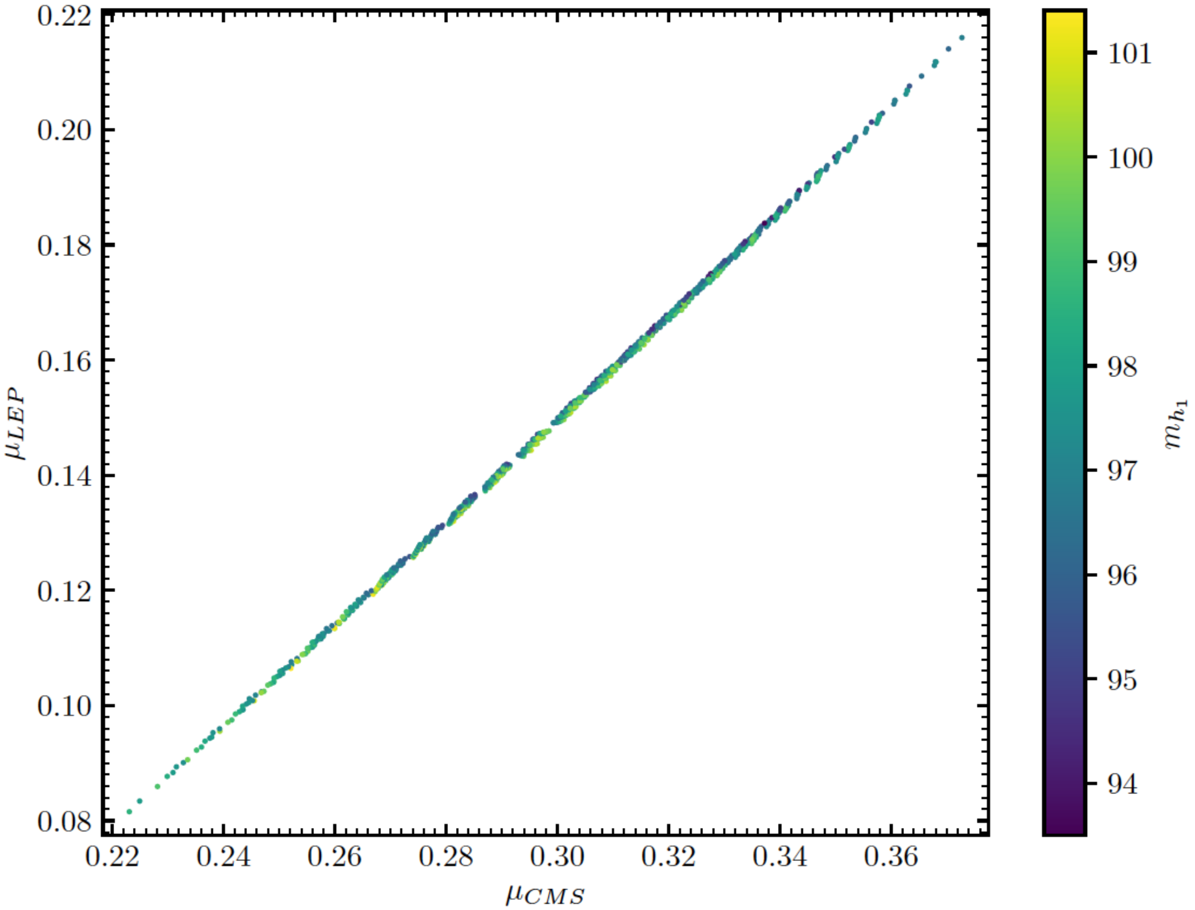


$\Rightarrow$ YES, WE CAN! :-)

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}!