

artwork by F. Simon

Future Perspectives for Higgs Physics

Sven Heinemeyer, IFT (CSIC, Madrid)

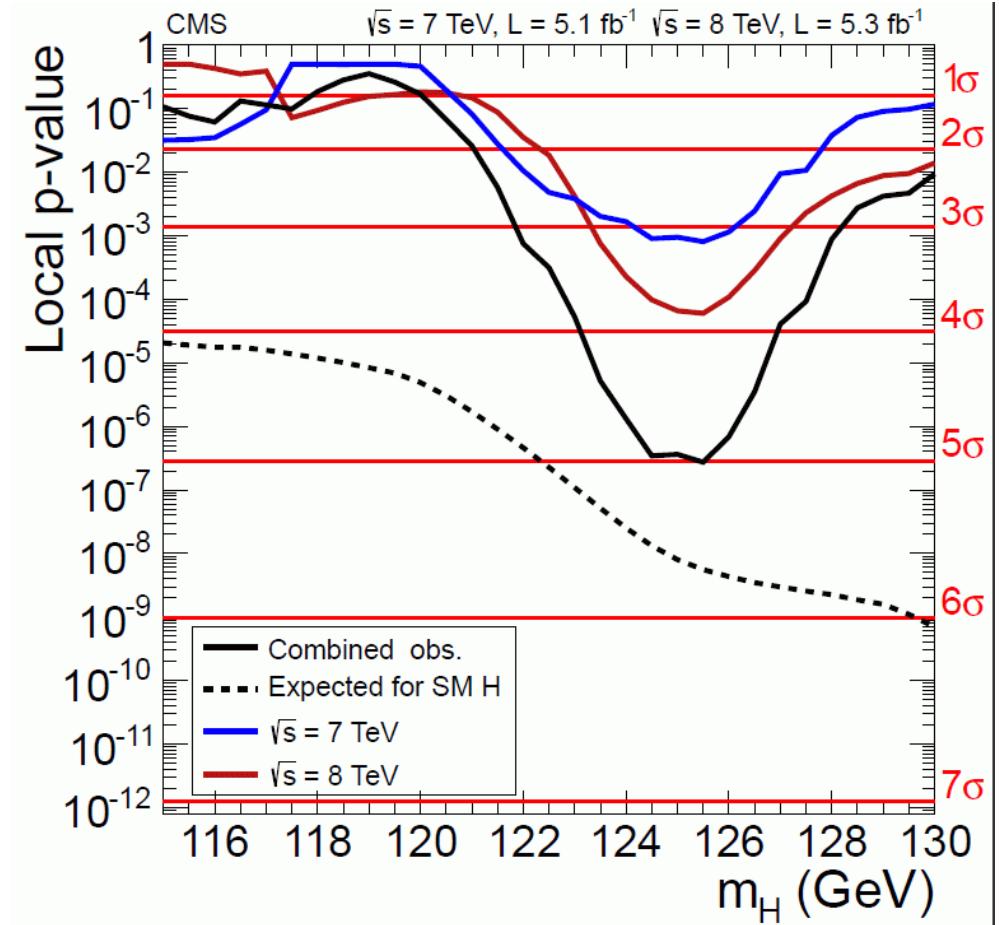
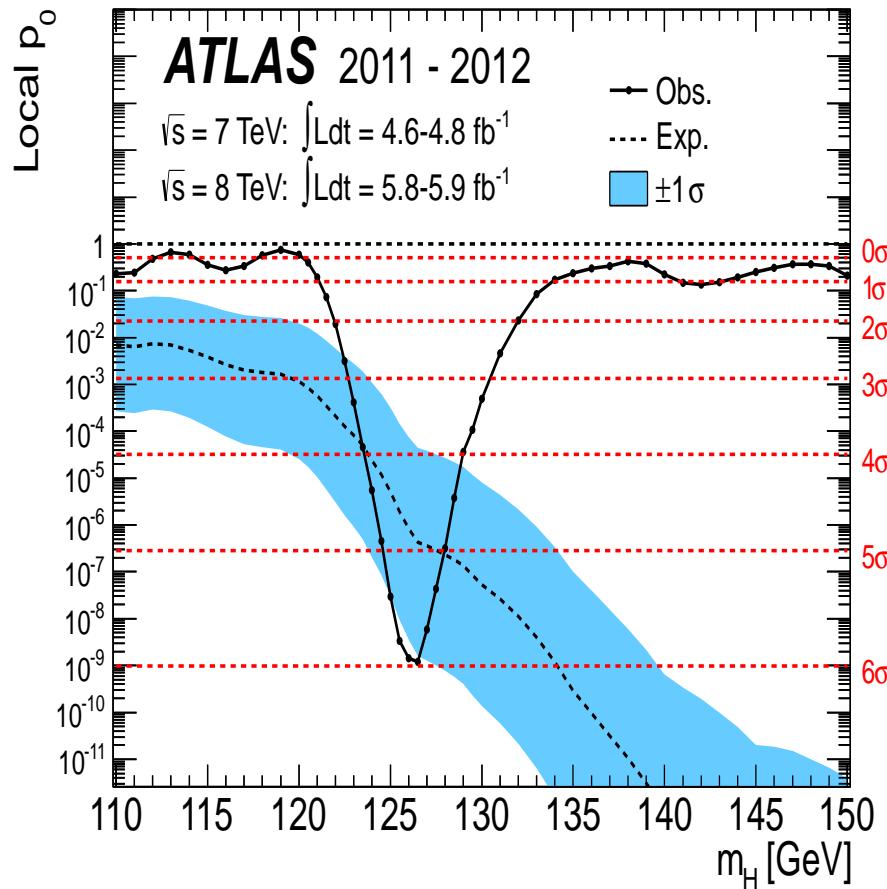
Bologna, 07/2022

1. Introduction
2. The secure future: HL-LHC
3. The agreed upon future (the no-brainer)
4. Theory meets Experiment
5. Important Complementarities
6. Conclusions

1. Introduction

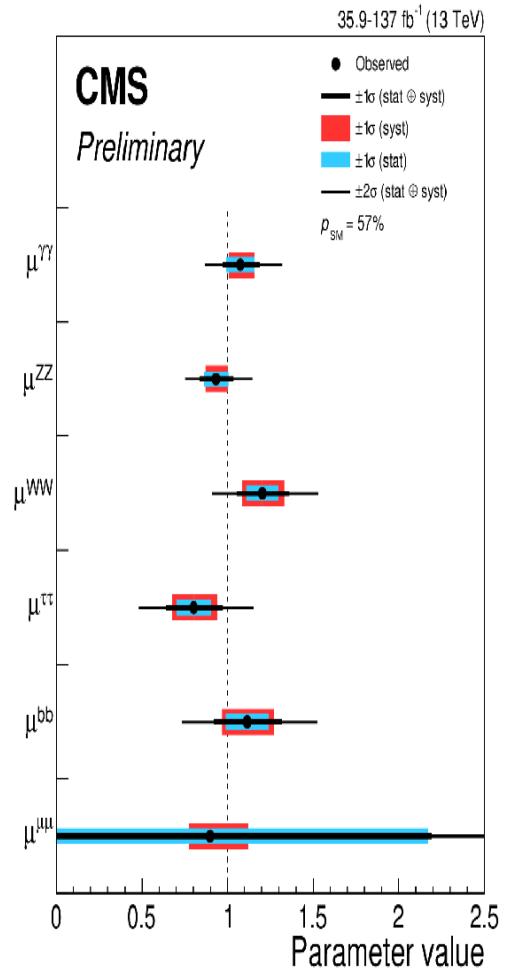
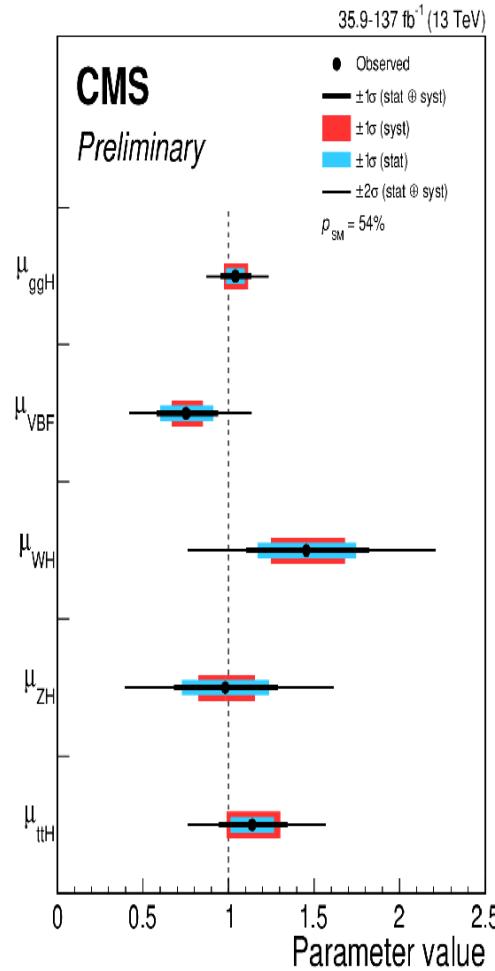
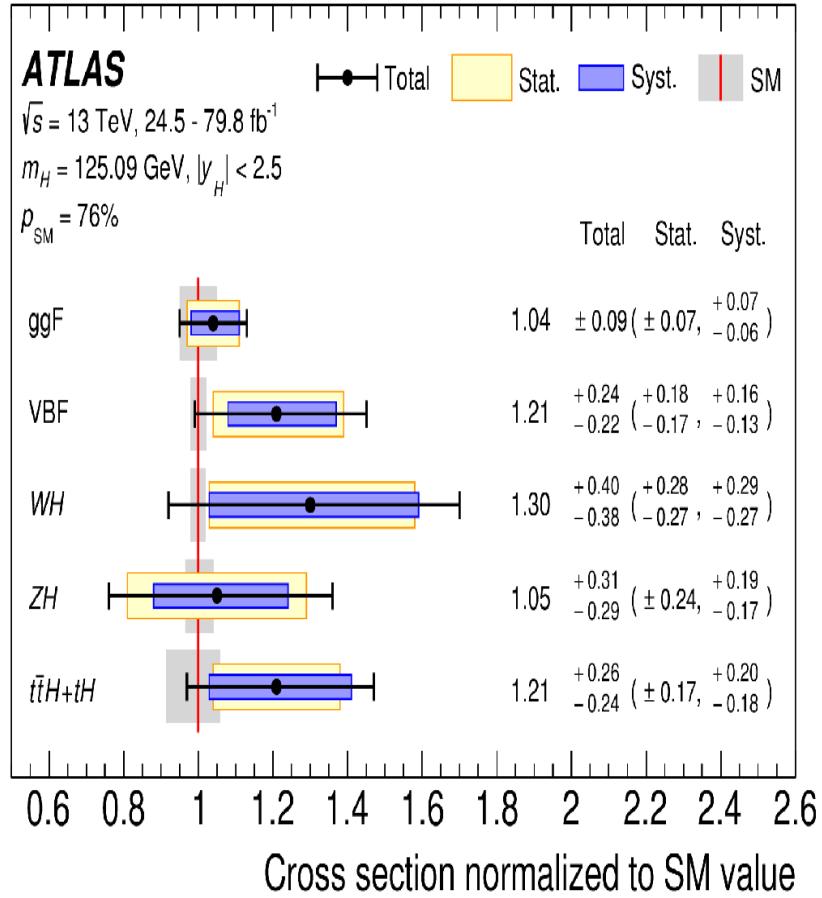
Fact I: The physics world changed on 04.07.2012:

We have a discovery!



Fact I: The physics world changed on 04.07.2012:

We have an SM-like discovery!



Fact II:

The SM cannot be the ultimate theory!

Some sub-facts:

1. gravity is not included
2. the hierarchy problem
3. no unification of the three forces
4. Dark Matter is not included
5. Baryon Asymmetry of the Universe cannot be explained
6. neutrino masses are not included
7. anomalous magnetic moment of the muon shows a $\sim 4\sigma$ discrepancy

Fact I & II:

We have discovered 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: Does the BSM physics have any (relevant) impact on the Higgs?
⇒ any hints from LHC results (as guideline/toy example)?

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

The main questions:

- What are the **couplings** of this particle to other known elementary particles? Is its coupling to each particle proportional to that particles mass, as required by the BEH mechanism?
- What are the **mass**, **total width**, **spin** and **\mathcal{CP}** properties of this particle? Are there additional sources of **\mathcal{CP} violation** in the Higgs sector?
- What is the value of the particles **self-coupling**? Is this consistent with the expectation from the symmetry-breaking potential?
- Is this particle a single, **fundamental scalar** as in the SM, or is it part of a larger structure? Is it part of a model with **additional scalar singlets/doublets/Idots**?
Or, could it be a **composite** state, bound by new interactions?
- Does this particle couple to **new particles** with no other couplings to the SM (“Higgs portal”)? Is the particle **mixed with new scalars** of exotic origin, for example, the radion of extra-dimensional models?

Models with extended Higgs sectors:

1. SM with additional Higgs singlet(s)
 2. Two Higgs Doublet Model (THDM): type I, II, III, IV
 3. Minimal Supersymmetric Standard Model (MSSM)
 4. MSSM with one extra singlet (NMSSM)
 5. MSSM with more extra singlets
 6. SM/MSSM with Higgs triplets
 7.
- ⇒ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)
- ⇒ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, ...

Overview of current at possible future collider experiments:

LHC (Large Hadron Collider): running

pp collisions at 13(14) TeV

HL-LHC final high-luminosity phase: approved

HE-LHC new magnets \Rightarrow 27 TeV (possible?)

ILC (International Linear Collider) decision 202n in Japan

e^+e^- collisions at 250 GeV (final stage 1000 GeV)

CLIC (Compact LInear Collider)

e^+e^- collisions at 380 GeV (final stage 3000 GeV)

FCC-ee (Future Circular Collider e^+e^-) feasibility study on-going

e^+e^- collisions up to 350 GeV

CEPC (Chinese e^-e^+ Collider)

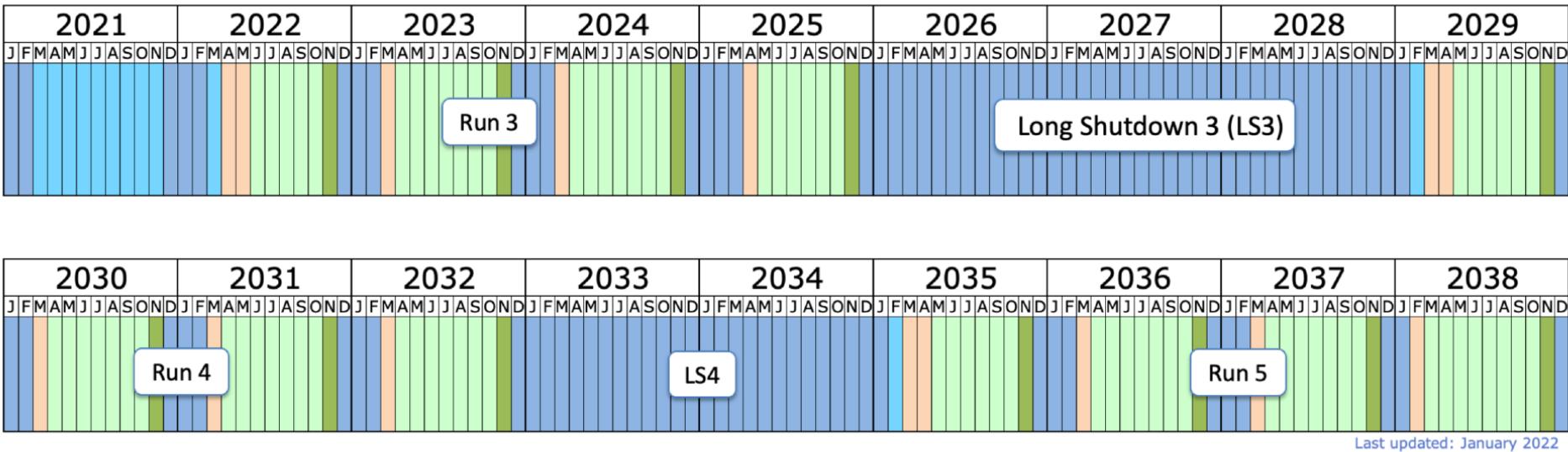
e^+e^- collisions up to 250 GeV

FCC-hh (Future Circular Collider had-had)

pp collisions at 100 TeV (possible?)

2. The secure future: HL-LHC

Projected time line:

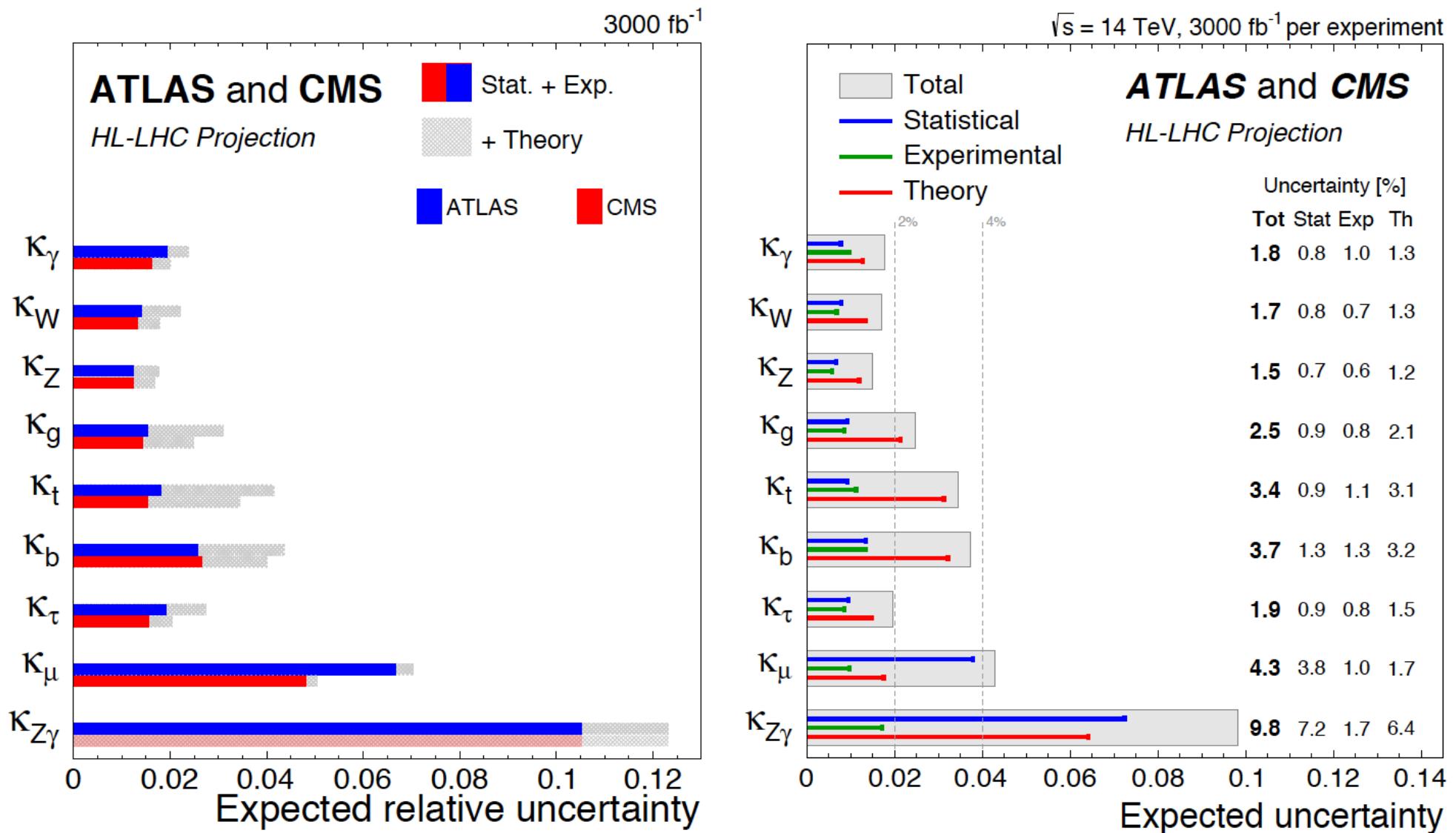


⇒ we can expect ~ 20 times more integrated luminosity

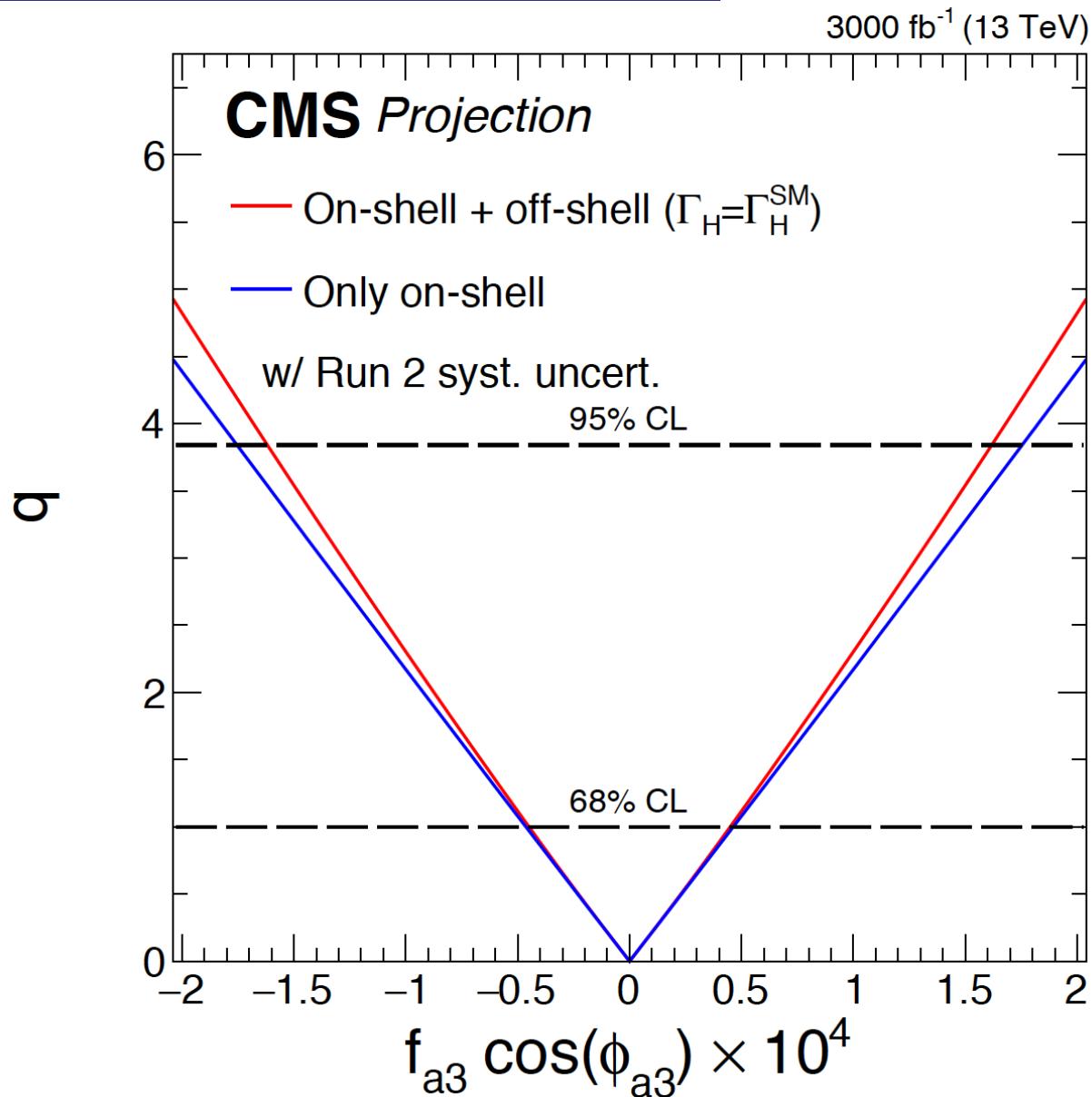
- precision measurements
- rare processes
- discoveries
- ...

Strong improvement in Higgs couplings:

(do not forget the caveats)

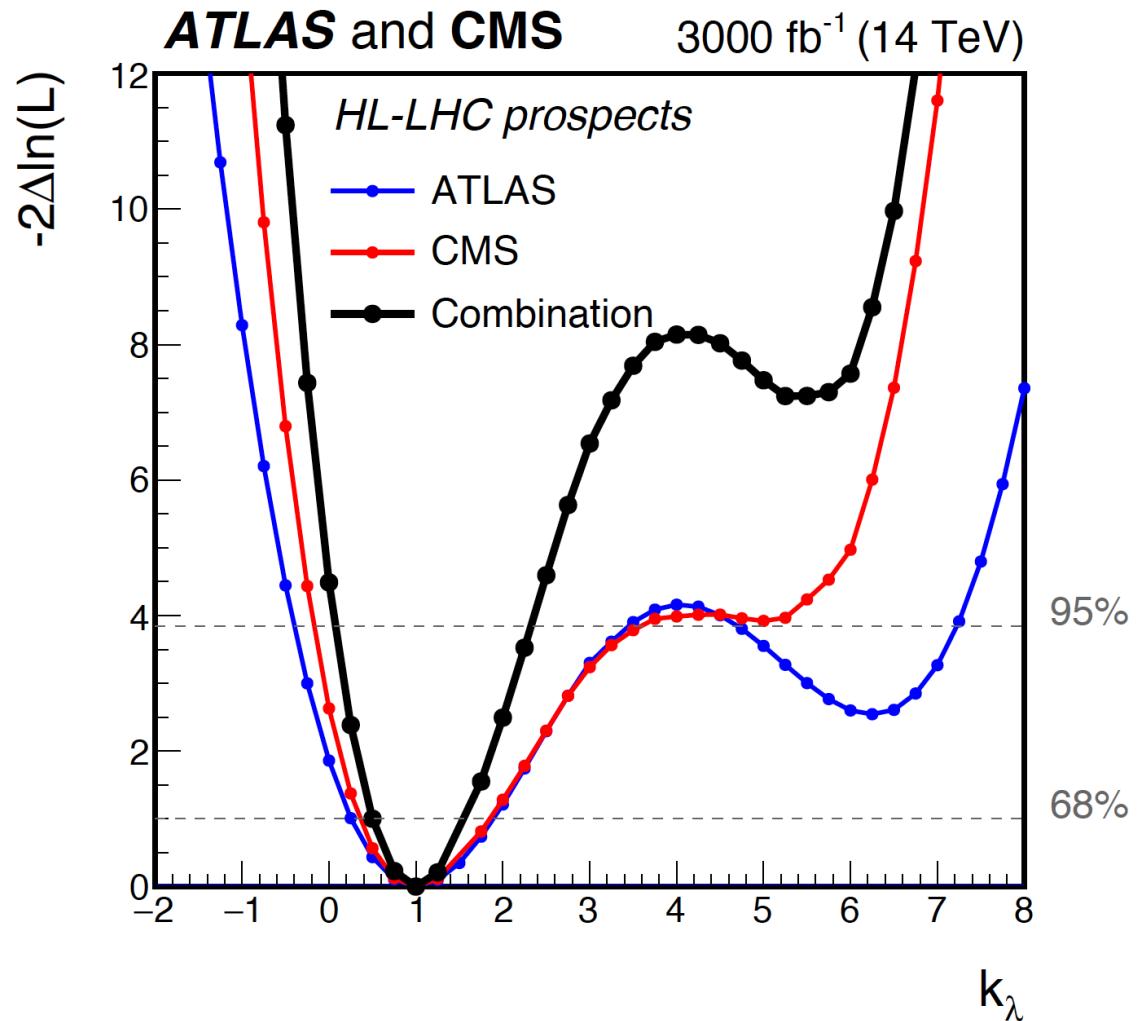


Strong improvement in the Higgs \mathcal{CP} limits:



→ sufficient?? $f_{a3} \lesssim 10^{-5}$ needed ...

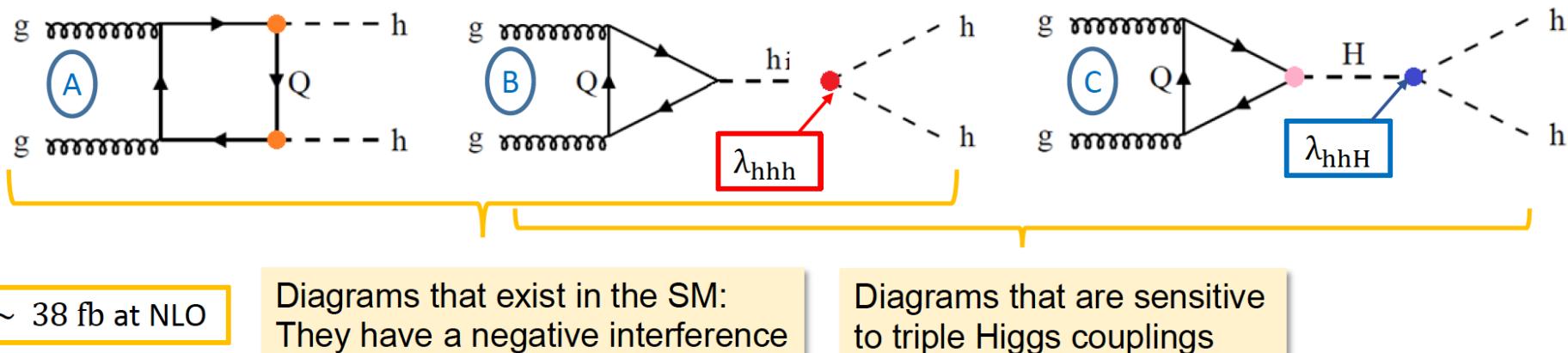
“Measurement” of triple Higgs coupling:



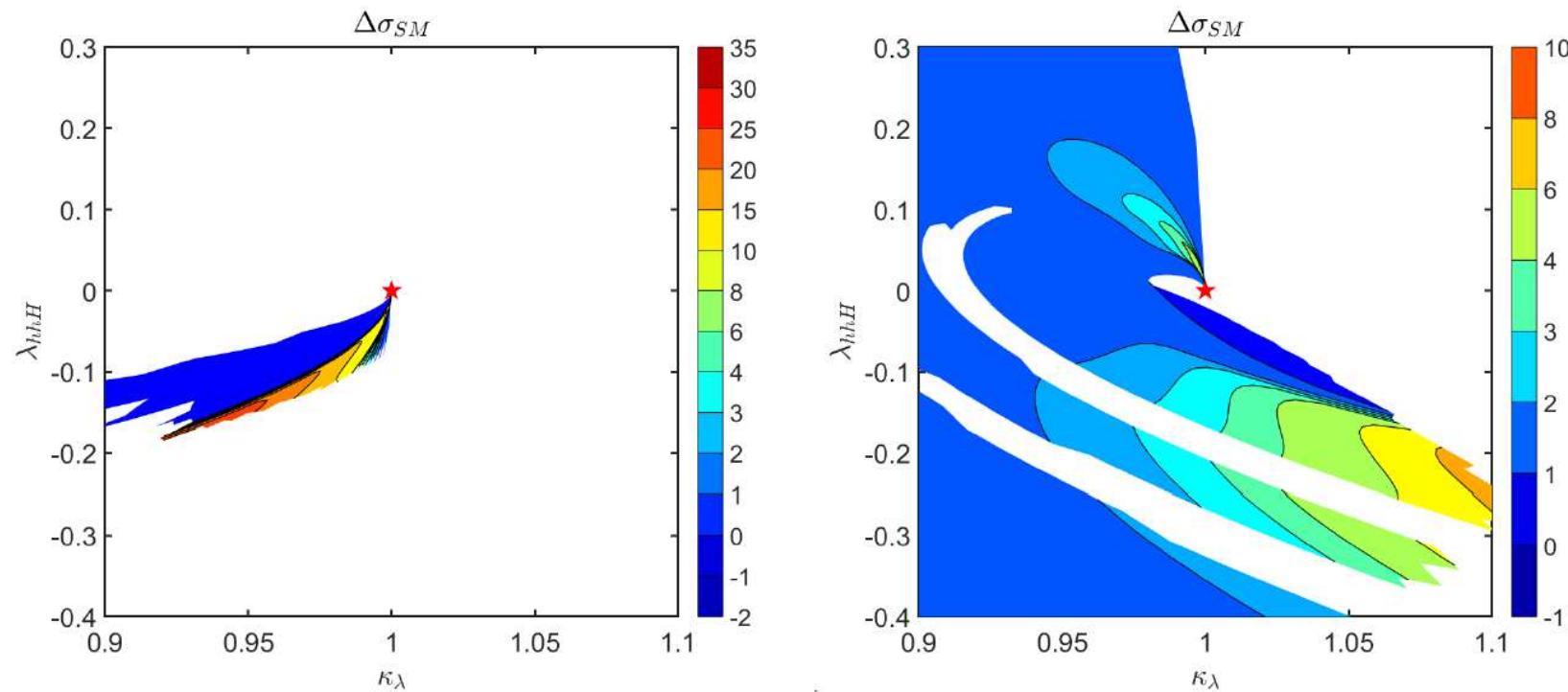
⇒ only evaluated for $\kappa_\lambda = \lambda_{hhh}/\lambda_{hhh}^{\text{SM}} = 1$

⇒ measurement at the 50% level

Possible access to BSM triple Higgs couplings: [S.H., M. Mühlleitner, K. Radchenko '22]



Benchmark plane: 2HDM type I, $m_{12}^2 = (m_H^2 \cos^2 \alpha) / \tan \beta$, $\tan \beta = 10$



3. The agreed upon future (the no-brainer)

Recommendation of the ESPPU:

(European Strategy for Particle Physics Update)

The next large facility after the (HL-)LHC
for particle physics should be an e^+e^- collider.

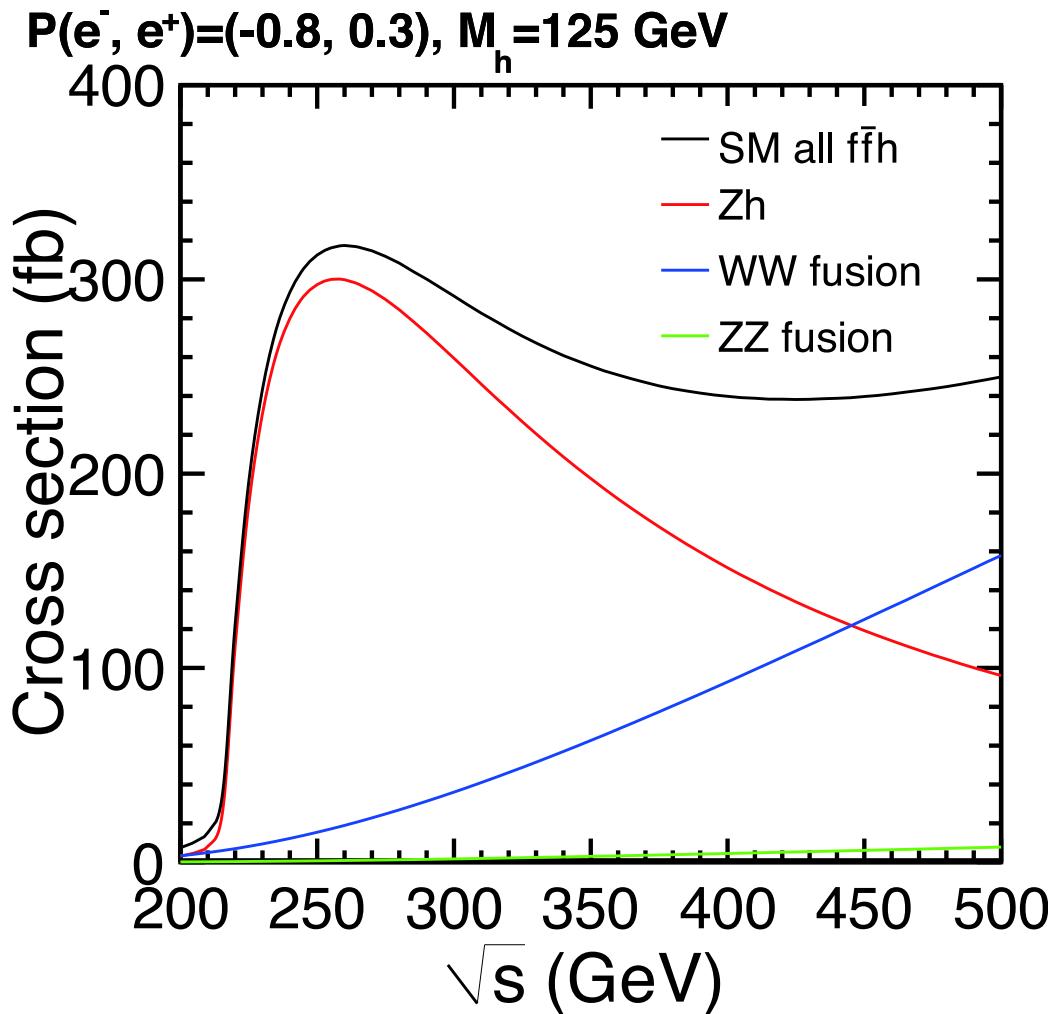
- to study the Higgs at ~ 125 GeV
- top/EW physics
- BSM searches
- ...

⇒ This new e^+e^- collider 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

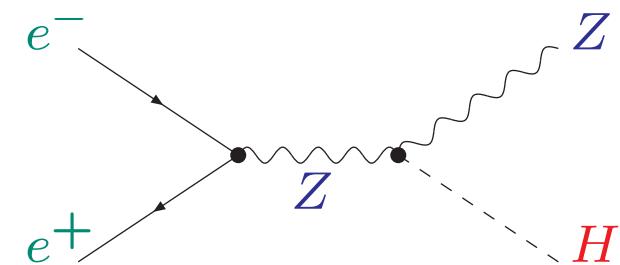
⇒ often e^+e^- expectations are shown in comparison to HL-LHC

Higgs production cross sections at e^+e^- colliders:

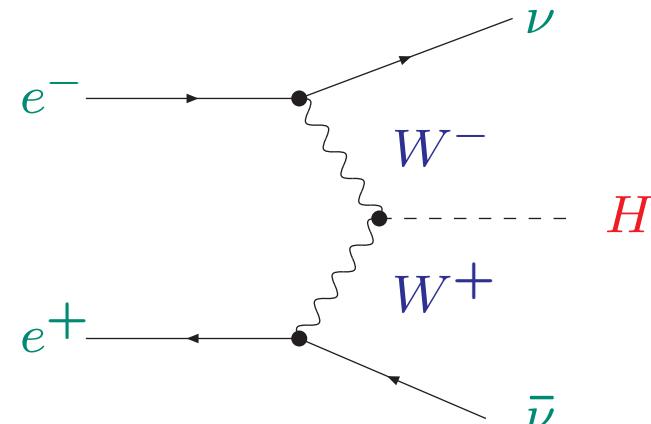


$\sqrt{s} \sim 250 \text{ GeV}$, Higgs-strahlung dominated

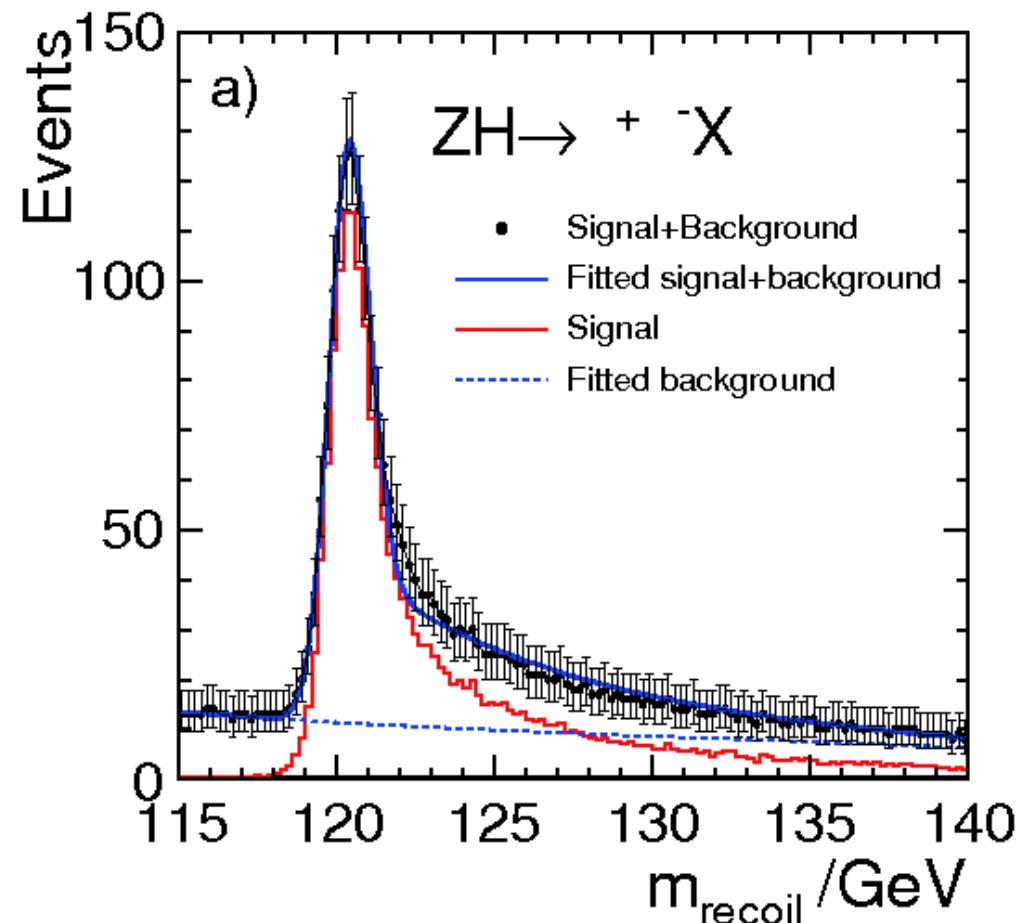
Higgs-strahlung:
 $e^+e^- \rightarrow Z^* \rightarrow ZH$



weak boson fusion (WBF):
 $e^+e^- \rightarrow \nu\bar{\nu}H$

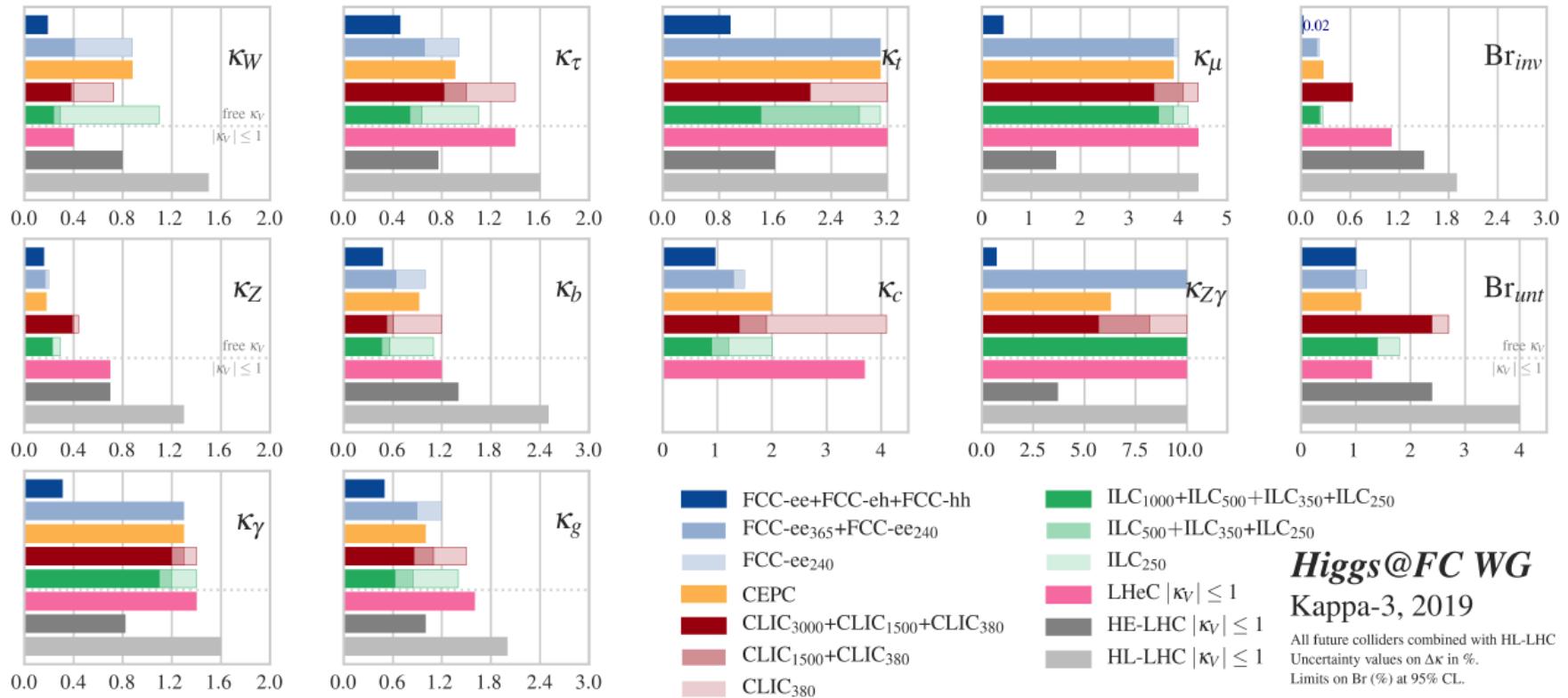


Z-recoil method: $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$



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

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.

→ very roughly similar results for different e^+e^- options

→ FCC-hh/-he/-ee appears better

→ FCC-hh uses different theory assumptions, uncertainties $\lesssim 1\%$

→ also remember different time scales!

Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400 \text{ GeV}}{M_A} \right)^4$$
$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}(10\%) \left(\frac{400 \text{ GeV}}{M_A} \right)^2 \cot^2 \beta$$
$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}(10\%) \left(\frac{400 \text{ GeV}}{M_A} \right)^2$$

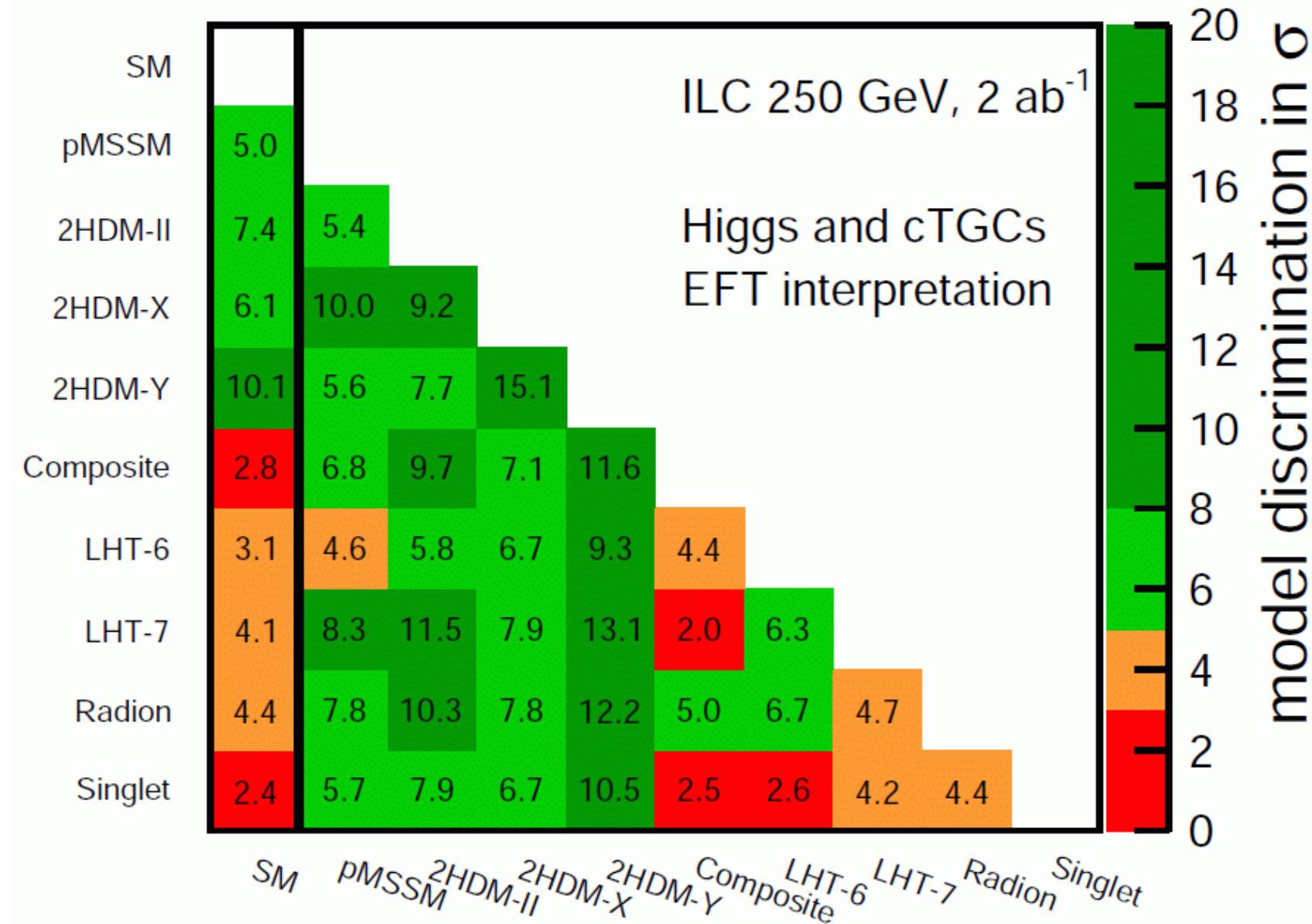
Composite Higgs example:

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

- ⇒ couplings to bosons in the **per mille** range
- ⇒ couplings to fermions in the **per cent** range
- ⇒ only e^+e^- colliders yield the (likely) required precision

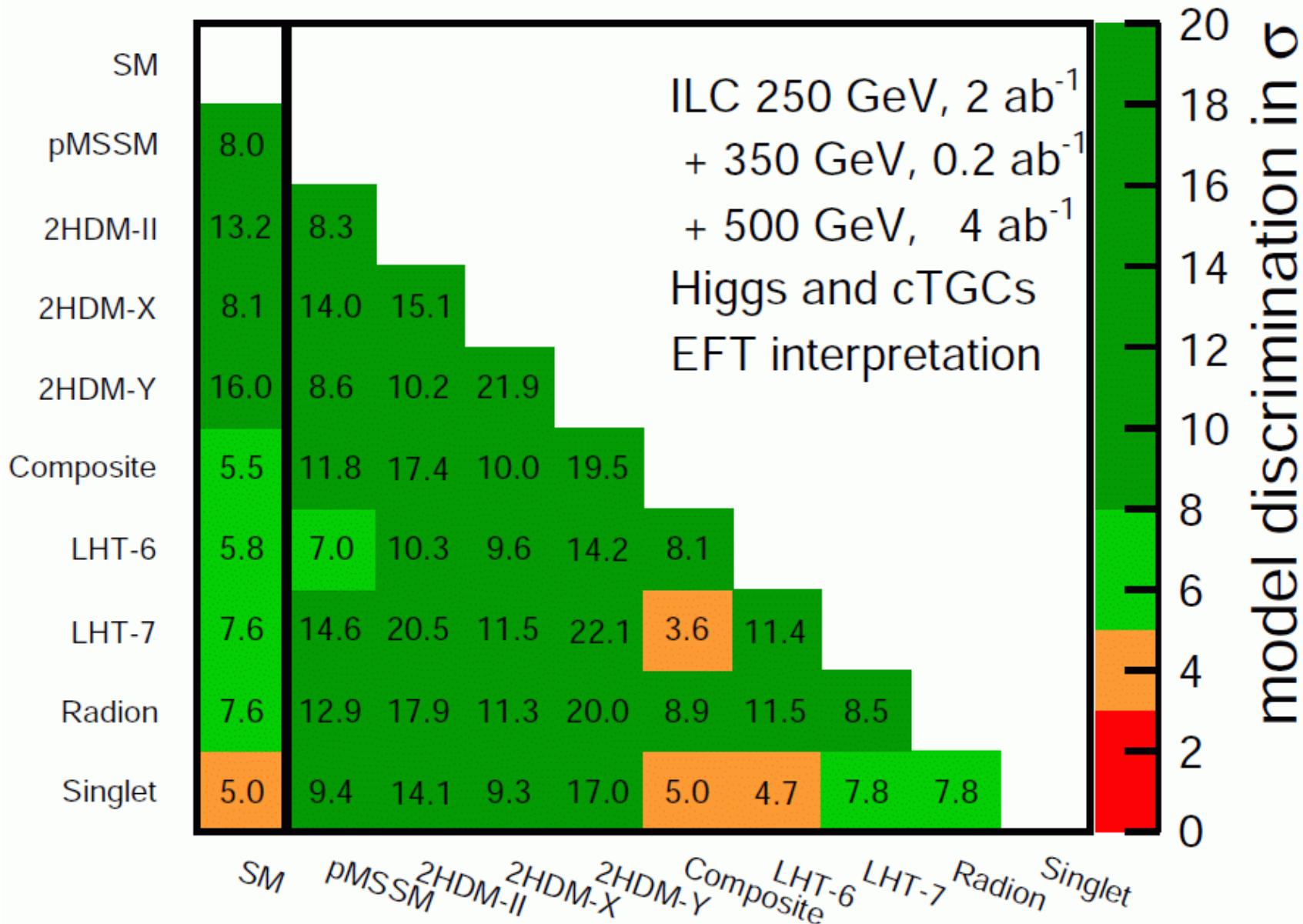
Model discrimination at ILC250:

[K. Fujii et al. '17]



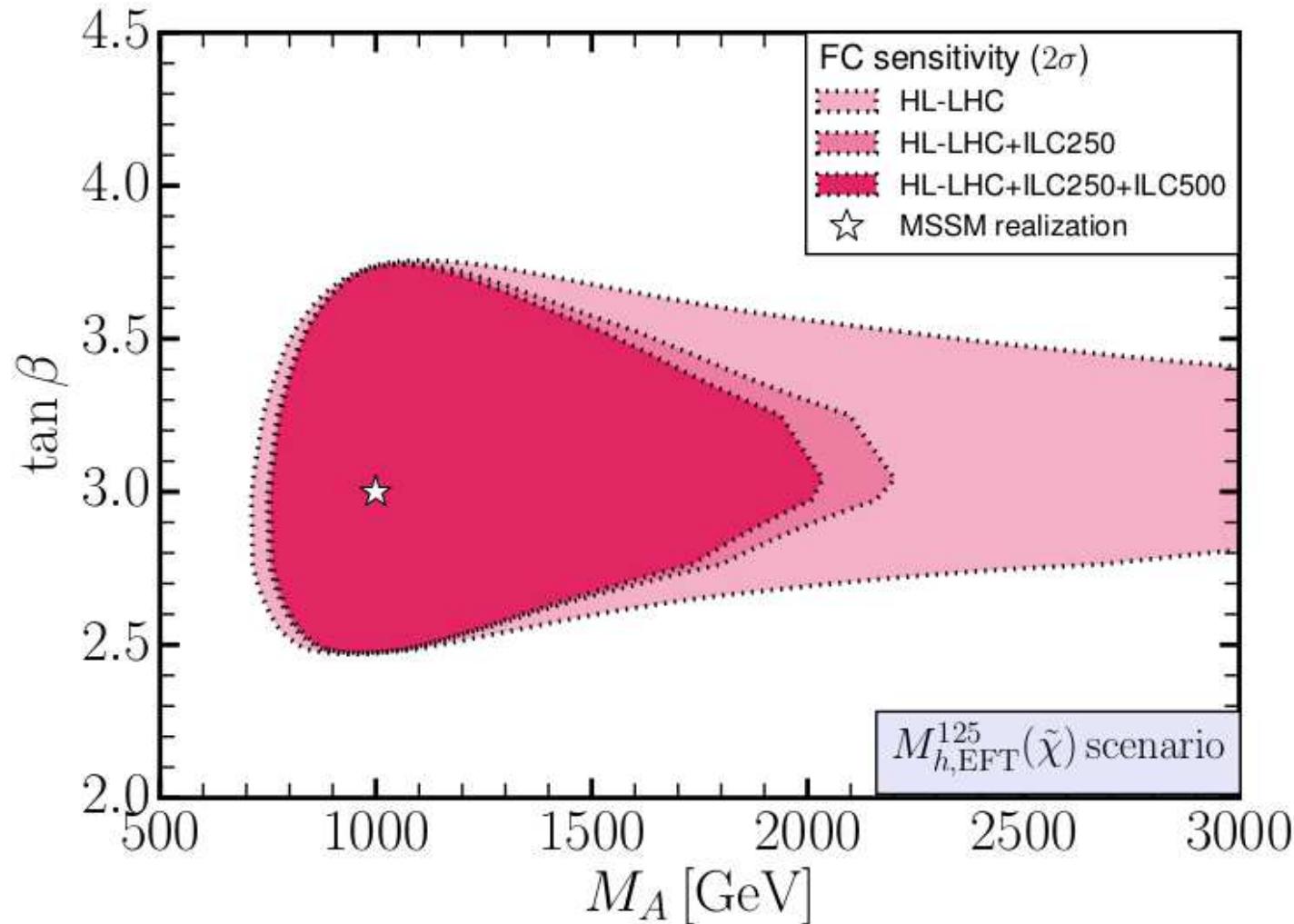
Model discrimination at ILC500:

[K. Fujii et al. '17]



Relevance of e^+e^- Higgs measurements:

[H. Bahl et al., '20]

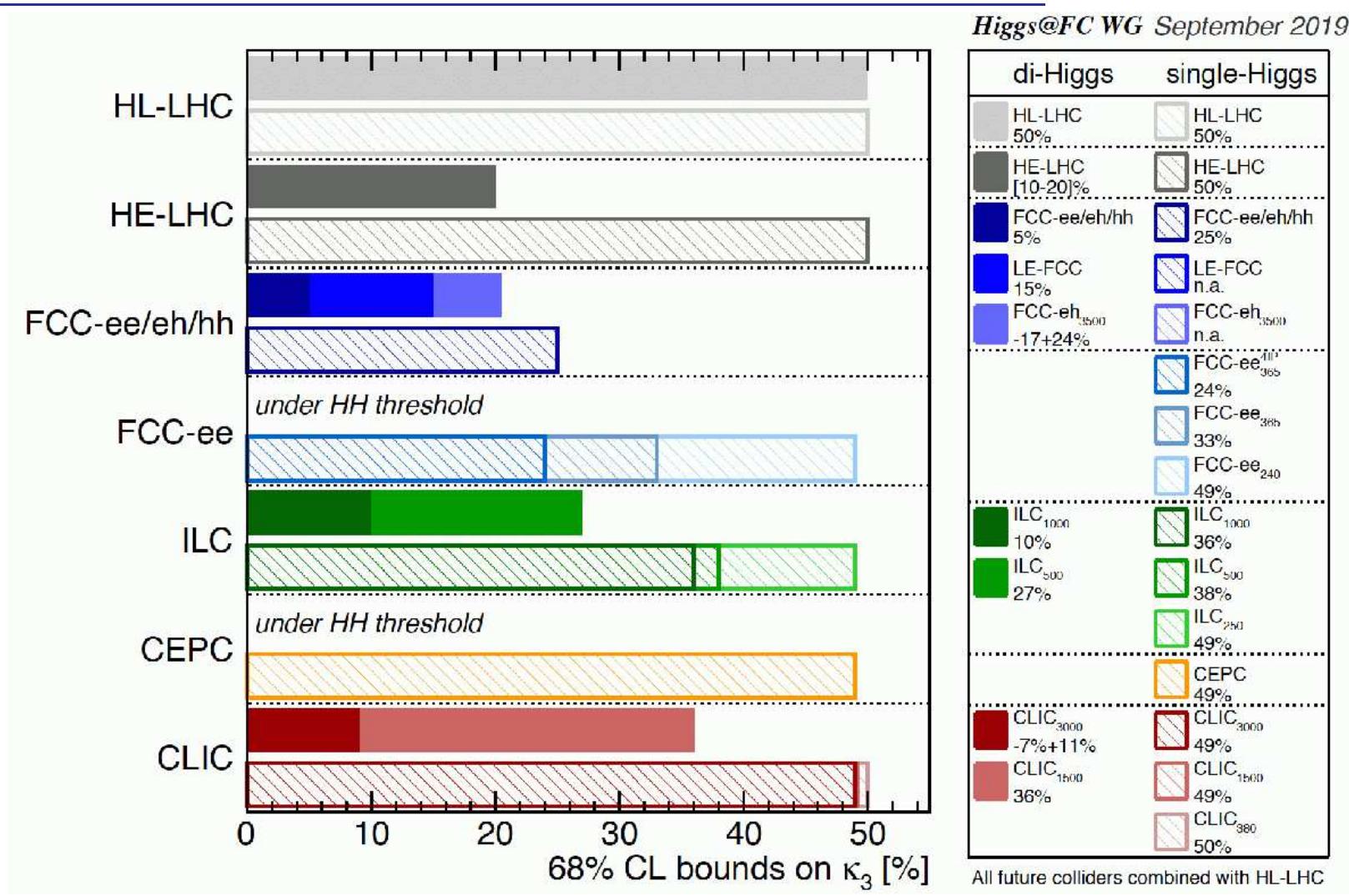


HL-LHC: no upper limit on BSM Higgs scales

e^+e^- : can set upper limits on BSM Higgs scales

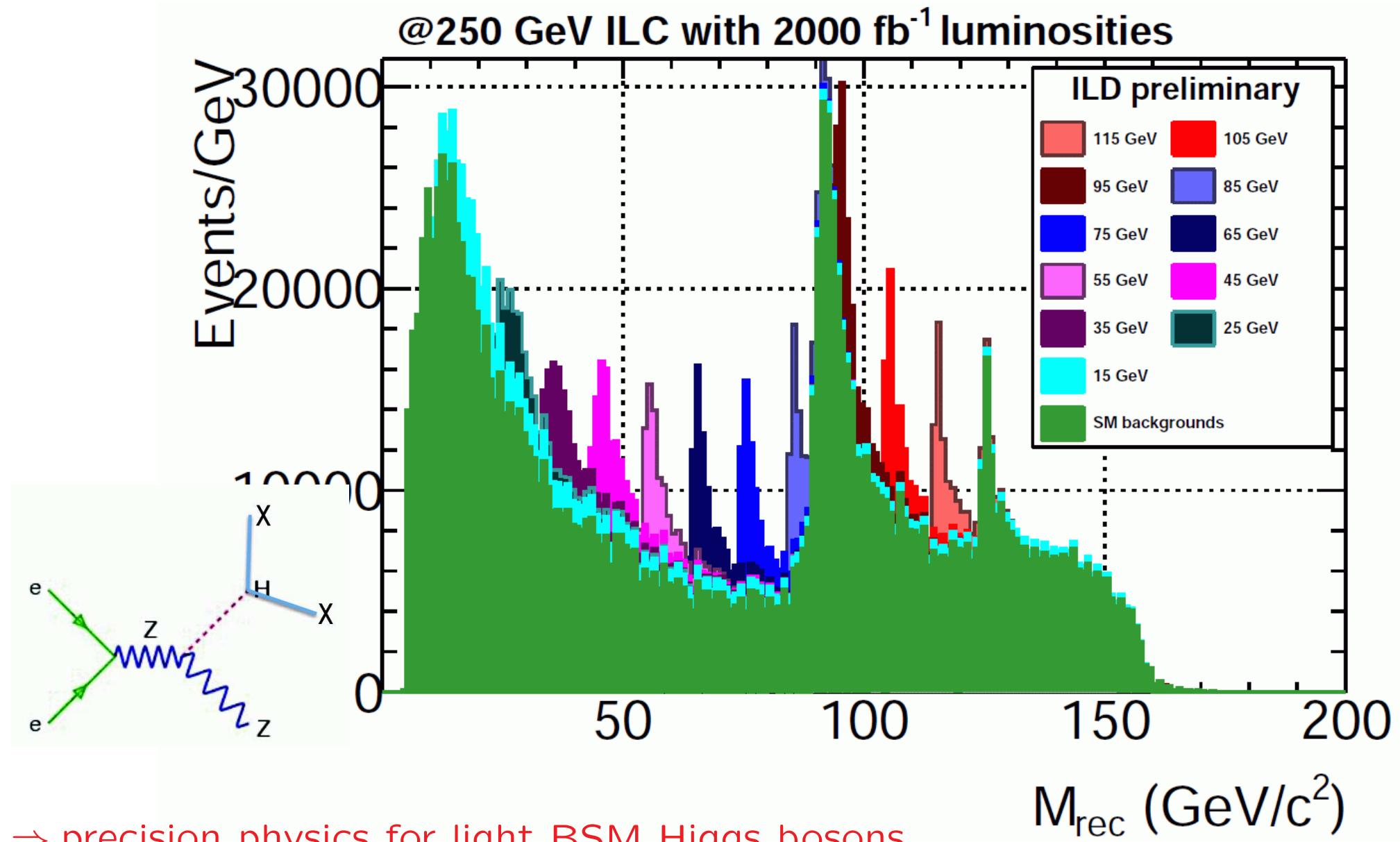
⇒ clear target for future collider searches

SM triple Higgs coupling: comparison of all colliders:



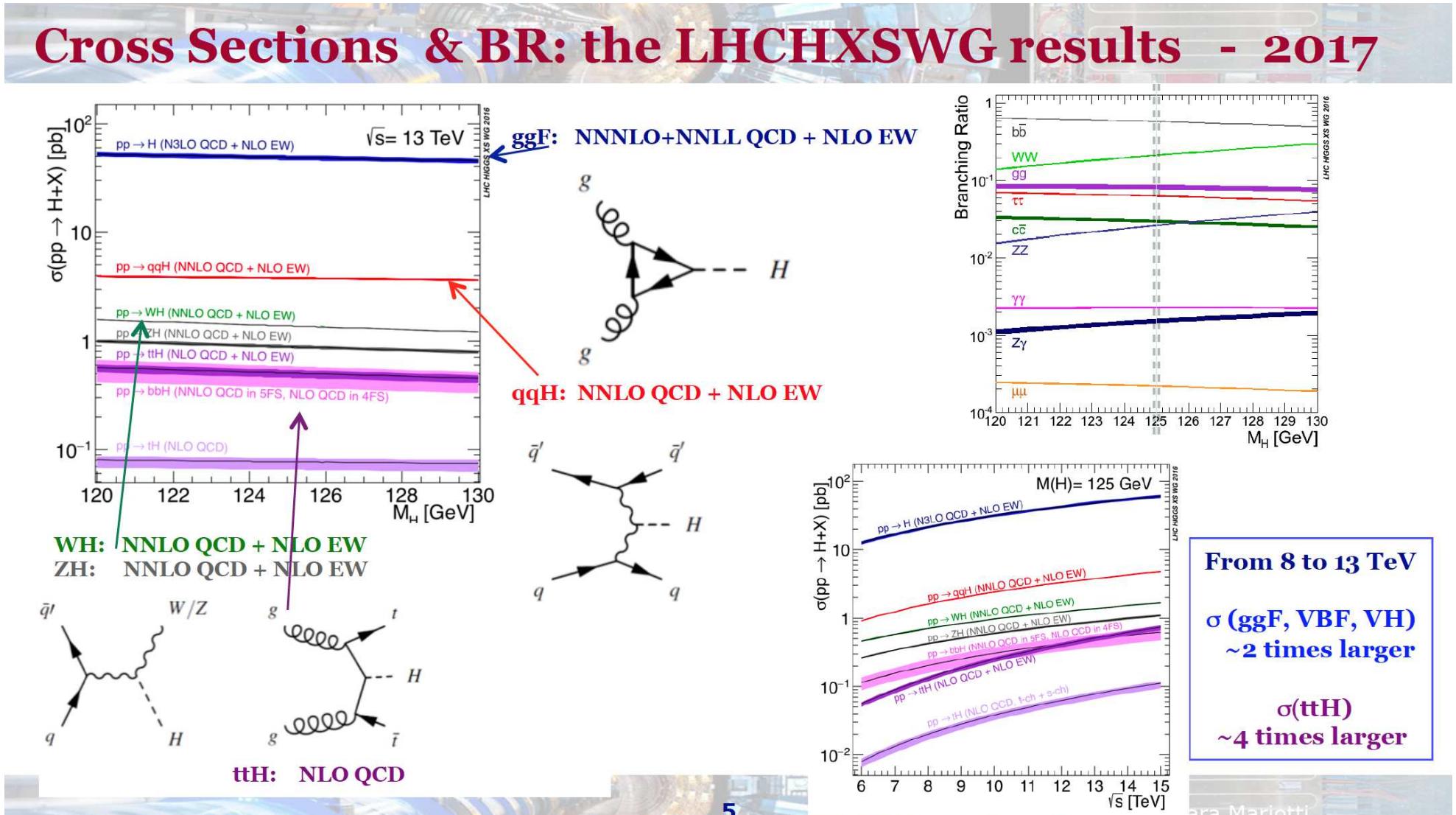
Analysis/comparison performed only for $\kappa_\lambda = 1$

BSM triple Higgs couplings? \Rightarrow back-up



4. Theory meets Experiment

[taken from C. Mariotti, previous talk]



⇒ Crucial contribution from the LHCH(XS)WG

Experimental situation:

(HL-)LHC/ILC/CLIC/FCC-ee/CEPC/...
will provide (high!) accuracy **measurements**!

Theory situation:

- Measurements are performed using theory predictions
- measured observables have to be compared with theoretical predictions
(in various models: SM, THDM, (N)MSSM, EFTs, ...)

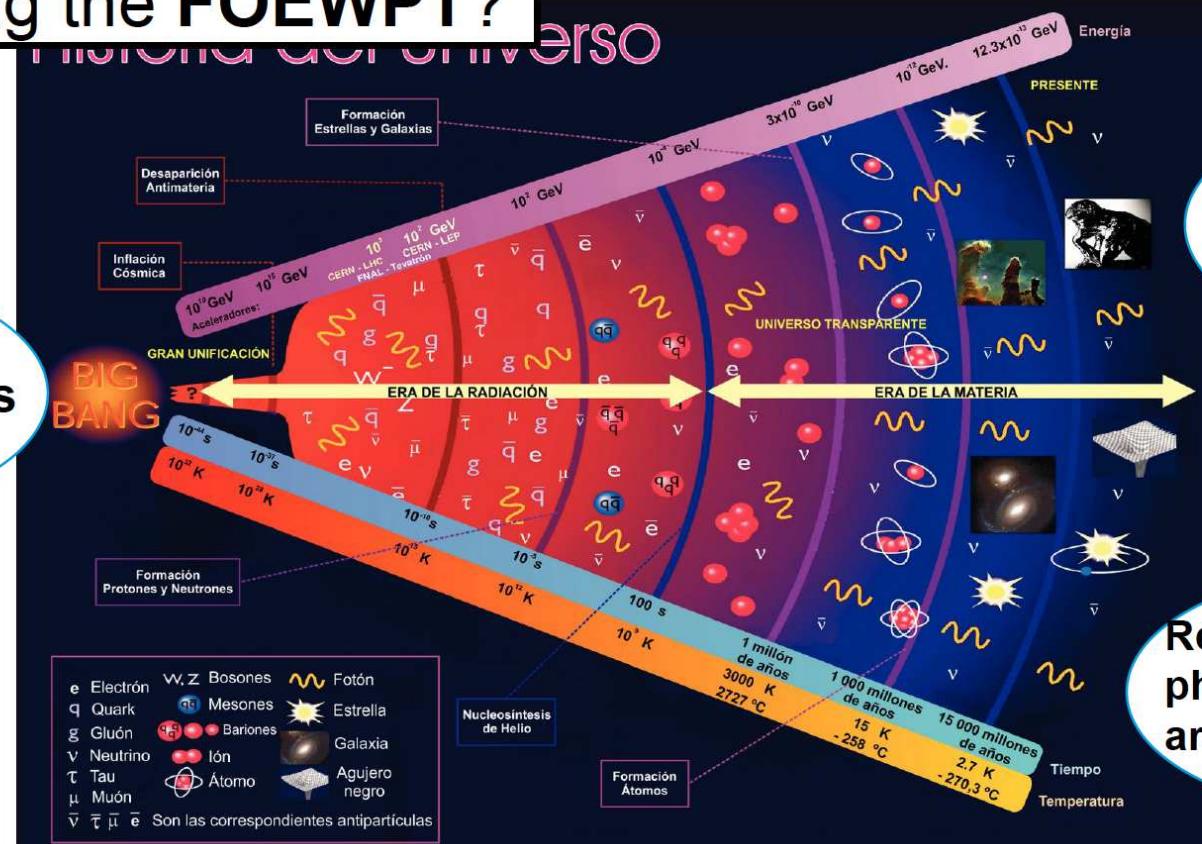
Full uncertainty is given by the (linear) sum of
experimental and theoretical uncertainties!

⇒ Experimental precision can only fully be exploited
with theory uncertainties at the same level of accuracy!

⇒ Theory effort should be seen as an integral part
of any (future) Higgs (or SM/BSM) physics program!

5. Important complementarities

Why studying the FOEWPT?



EW Baryogenesis

GW predictions

Requires new
physics
around the EW scale

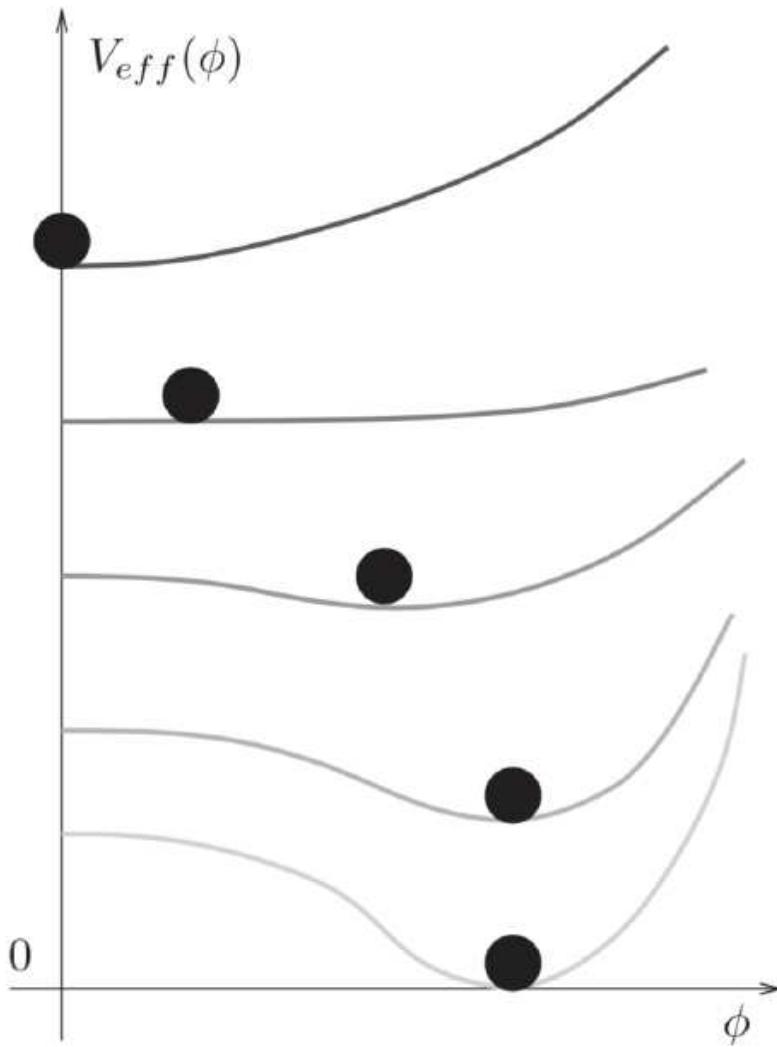
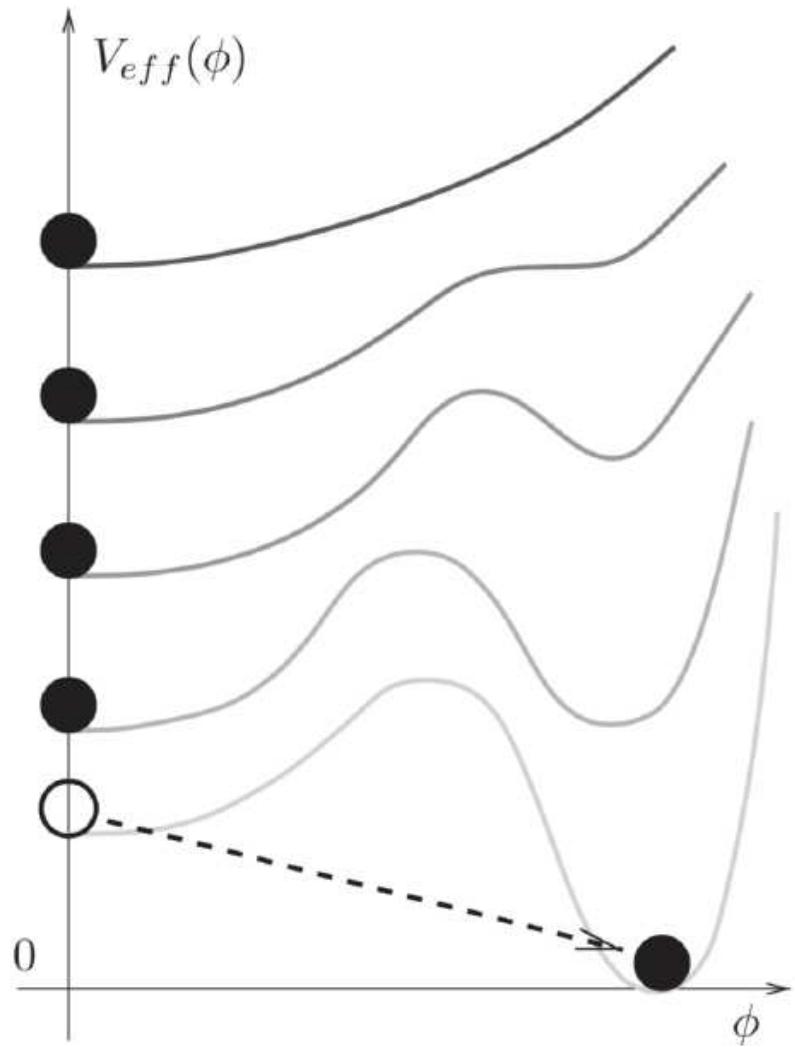
EW baryogenesis possible during First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM \Rightarrow BSM Higgs sector required

FOEWPT can cause Gravitational Waves (GW), detectable with LISA, . . .

Phase transition: BSM vs. SM

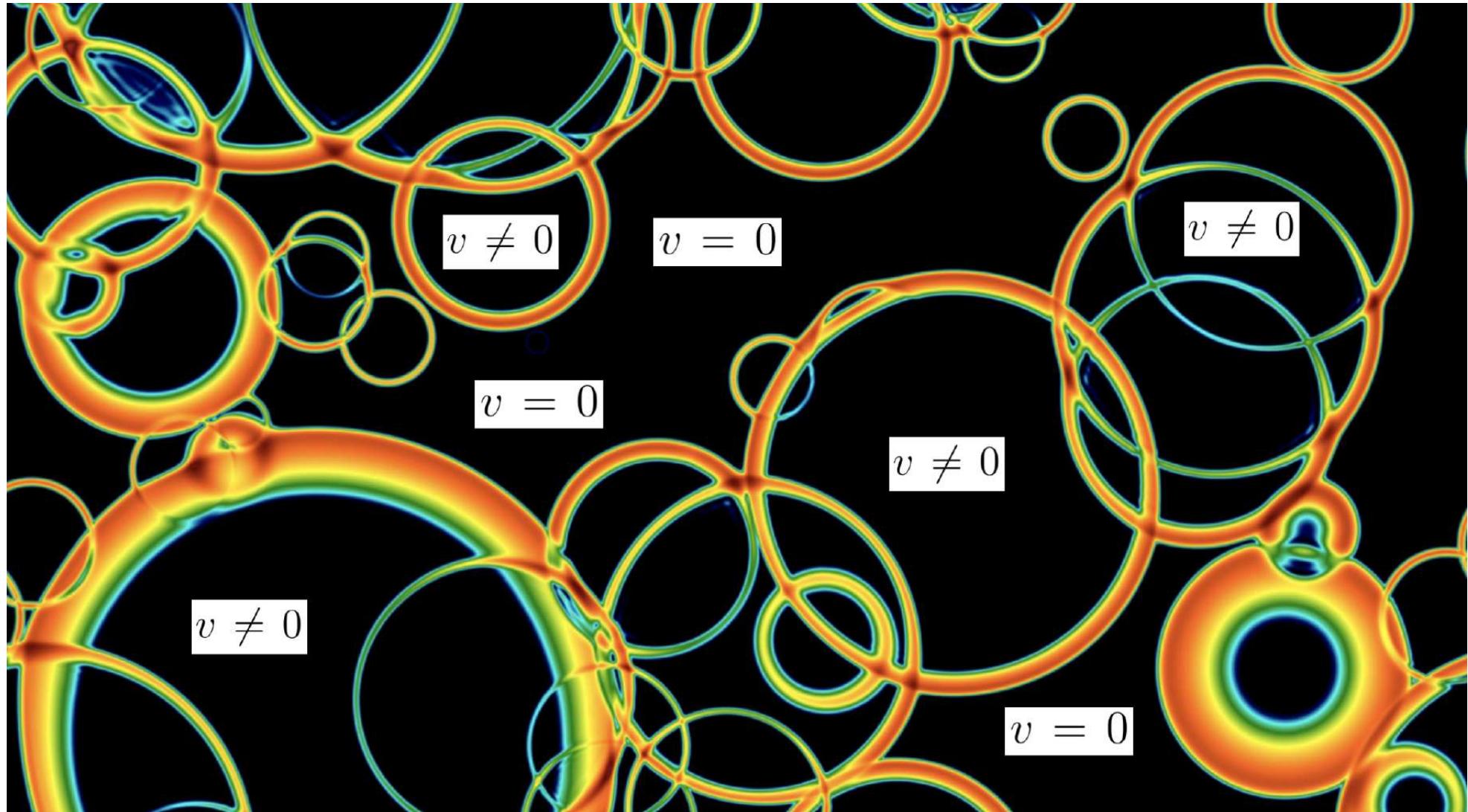
[taken from V. A. Rubakov and D. S. Gorbunov]



→ BSM Higgs sector required to realize FOEWPT

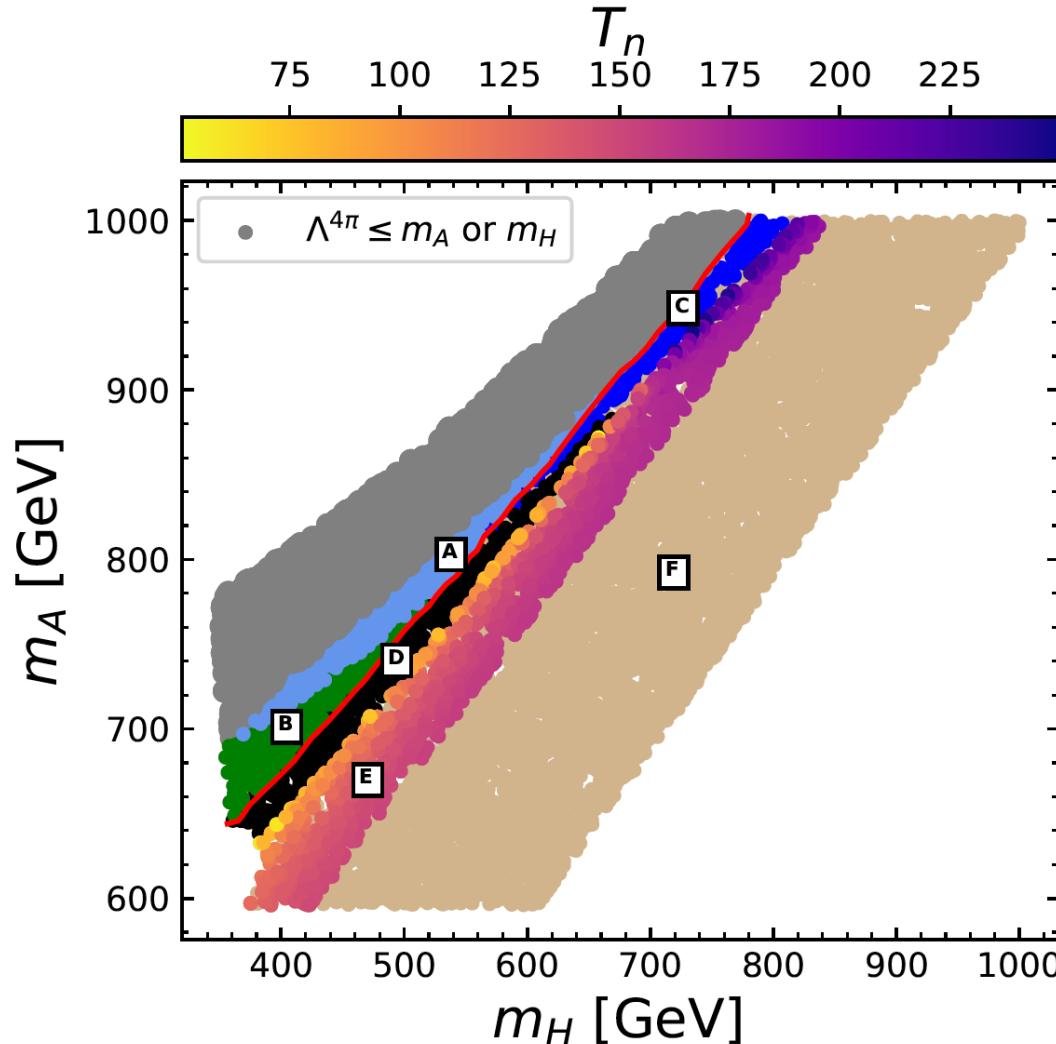
Bubble formation can lead to Gravitational Waves

[taken from D. Weir]



Example: 2HDM, FOEWPT and GW's

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein – PRELIMINARY*]



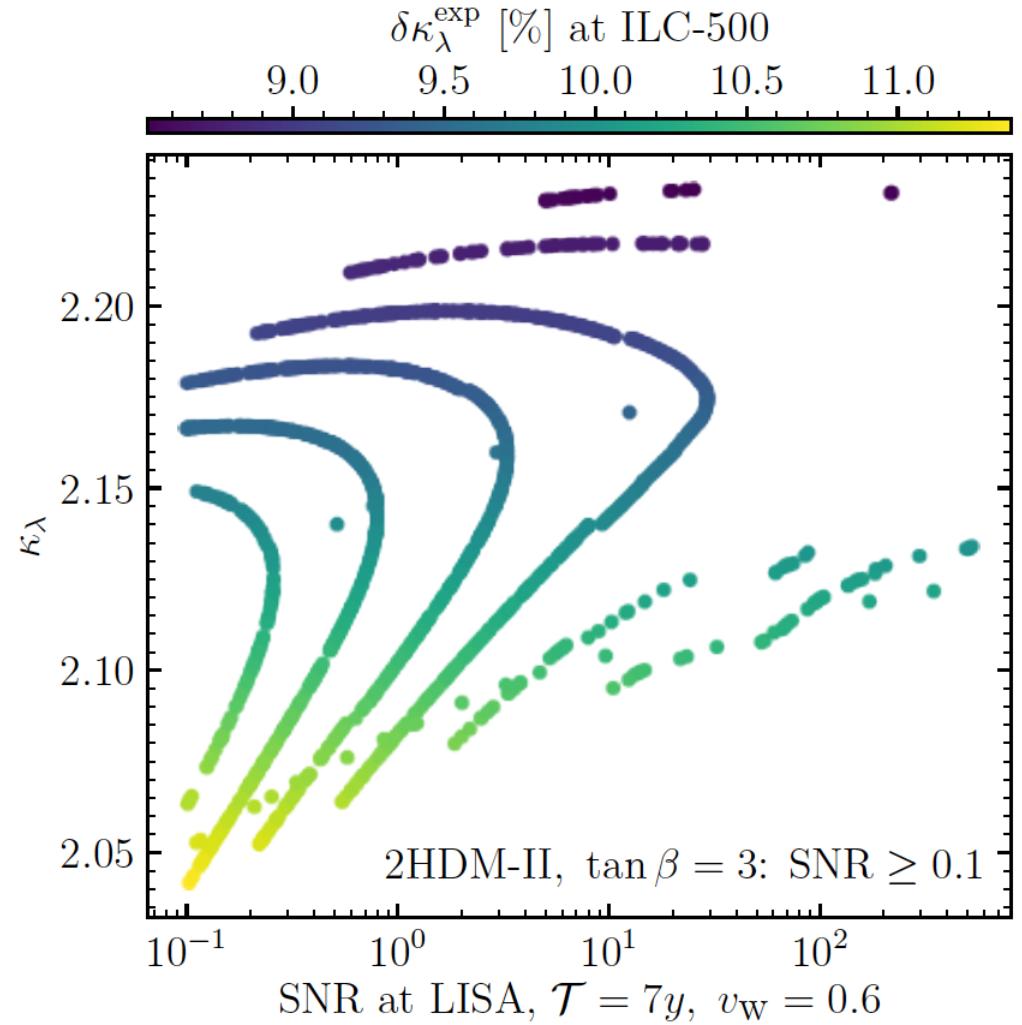
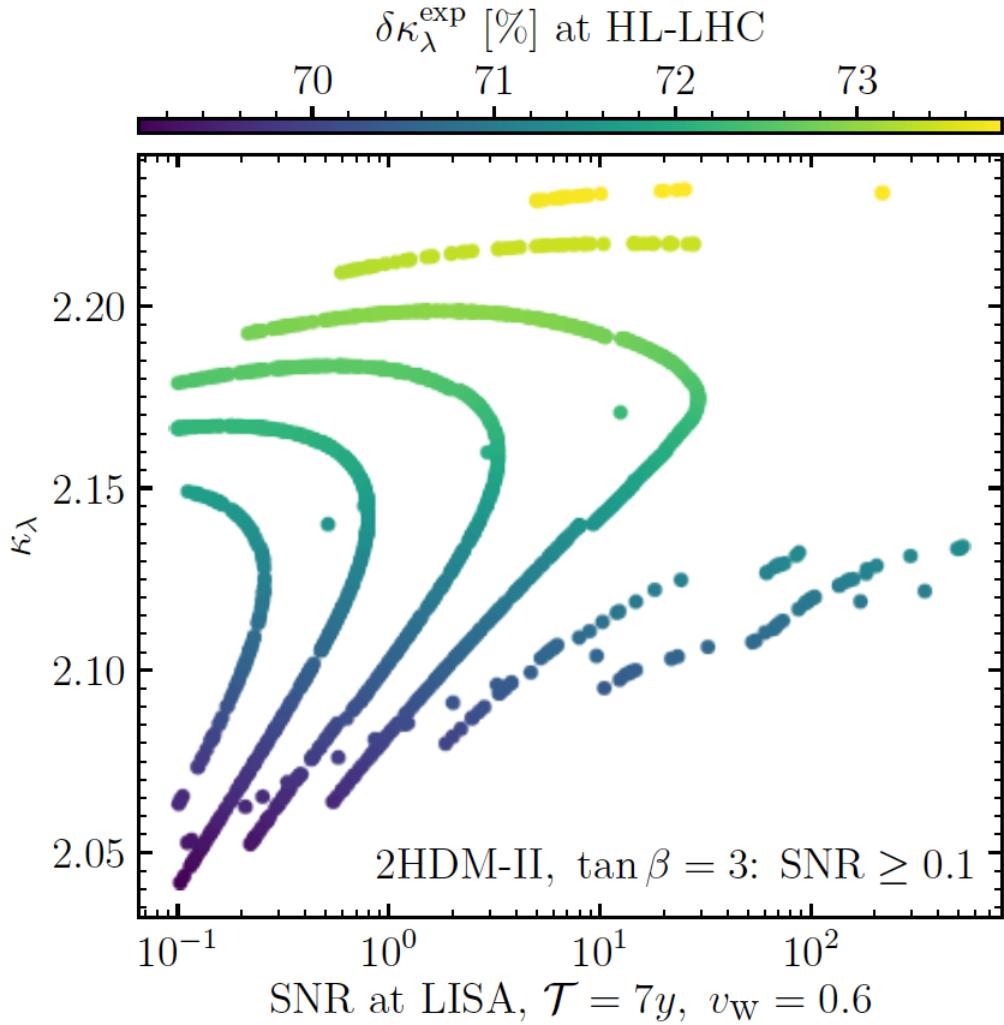
E: viable for **FOEWPT**, **GWs** are induced (detectable?)

F: no **FOEWPT**, no **GWs** are induced

Example: 2HDM, FOEWPT and GW's

[T. Biekötter, S.H., J. No, O. Olea, G. Weiglein – PRELIMINARY]

⇒ complementarity with λ_{hhh} measurements



⇒ FOEWPT requires large λ_{hhh} , deviations from SM measurable

6. Conclusion: Let's go for e^+e^- as quickly as possible :-)



artwork by F. Simon

... and work out the GW complementarity



Further Questions?

Required precision for \mathcal{CP} -admixture?

$$H = \cos \alpha \text{ } \mathcal{CP}\text{-even} + \sin \alpha \text{ } \mathcal{CP}\text{-odd}$$

$$\mathcal{A}(X \rightarrow VV) = \frac{1}{v} \left(a_1 m_V^2 \varepsilon_1^* \varepsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

$$\mathcal{A}(X \rightarrow f\bar{f}) = \frac{m_f}{v} \bar{u}_2 (b_1 + i b_2 \gamma_5) u_1$$

$$f_{\mathcal{CP}} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

Desired precision:

gauge bosons: $f_{\mathcal{CP}} \lesssim 10^{-5}$ (loop suppressed)

fermions: $f_{\mathcal{CP}} \lesssim 10^{-2}$

What if nature is more complicated than κ 's?

Assumptions for κ -framework:

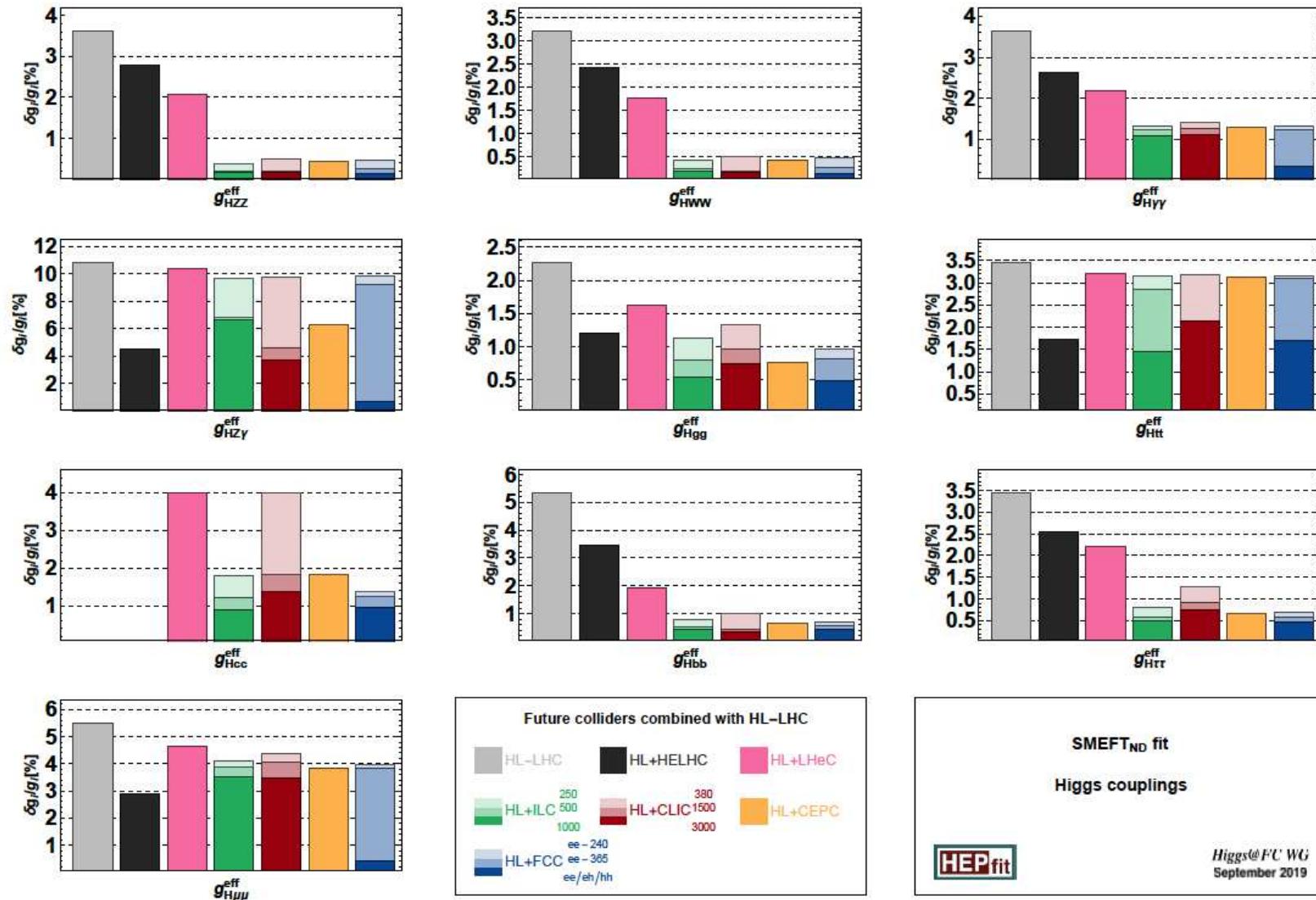
1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of **coupling strength** (absolute values of couplings) but not of **tensore structure** wrt. to SM
4. Use state-of-the-art predictions in the SM and rescale the predictions with “leading 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
- UV-complete model: consistent higher-order calculations possible

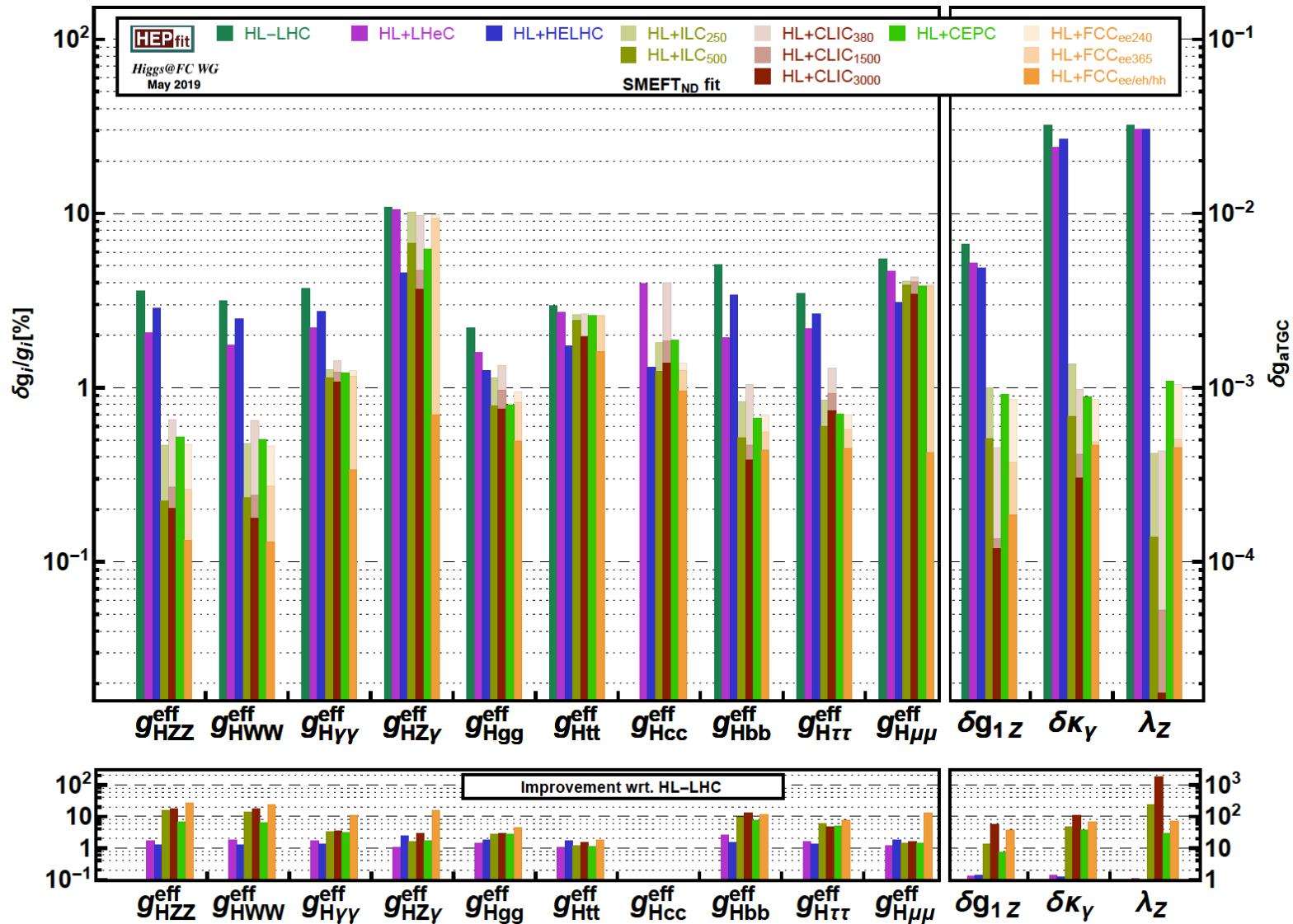
Note: also EFT does NOT cover all models
⇒ investigate in addition “realistic” models!

Future expectations for Higgs couplings in SMEFT (I)



⇒ clear improvement with e^+e^- colliders!
 ⇒ similar performance (polarization vs. luminosity)

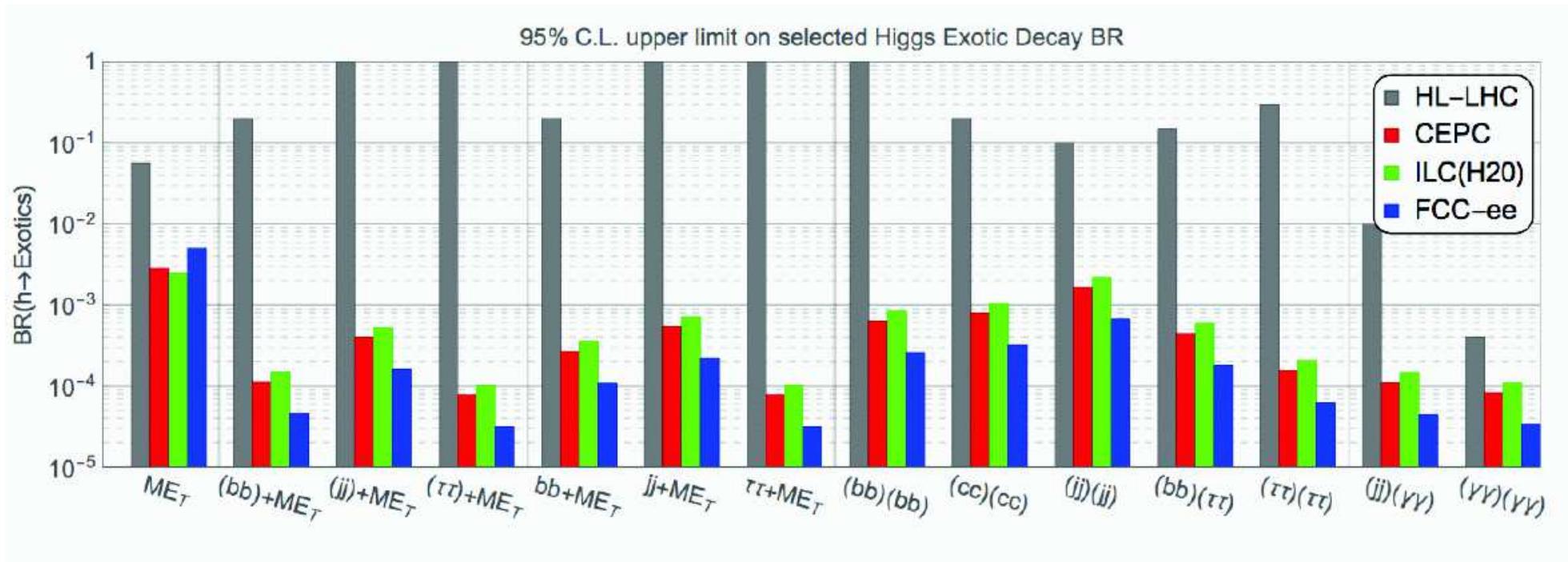
Future expectations for Higgs couplings in SMEFT (II)



⇒ clear improvement with e^+e^- colliders!
 ⇒ similar performance (polarization vs. luminosity)

Exotic Higgs decays:

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



⇒ strong improvement at e^+e^- colliders

⇒ sensitivity to BSM physics?!

Let us assume that we do see a deviation

What do we learn from that?

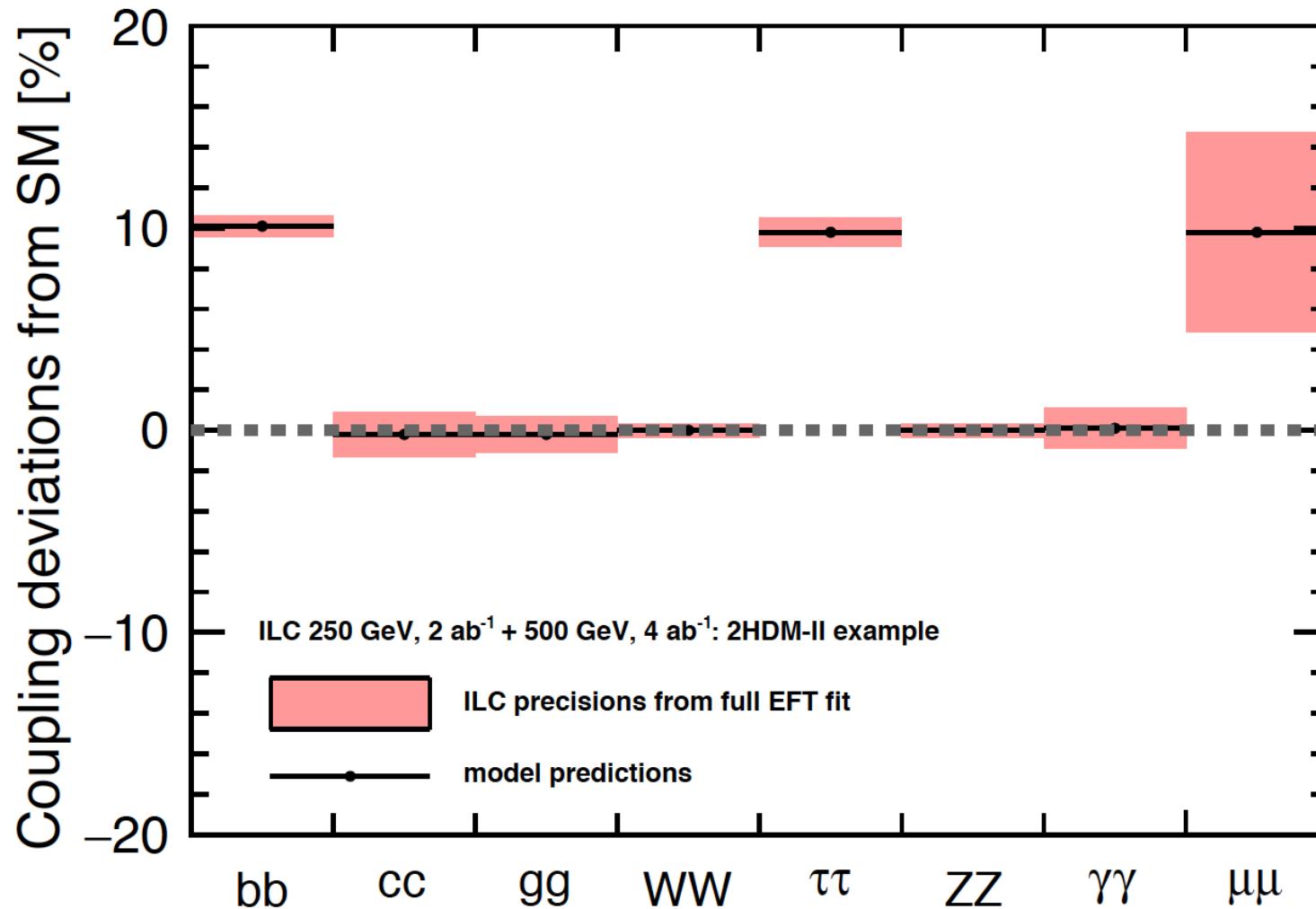
How do we learn something from that?

- ⇒ We have to compare the **observed** deviation with **predicted** deviations
- ⇒ Preferably 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.) $\Leftrightarrow e^+e^-$ precision
- ⇒ “Wäscheleinen-Plots” (concrete: ILC500 – FCC-ee similar!)

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

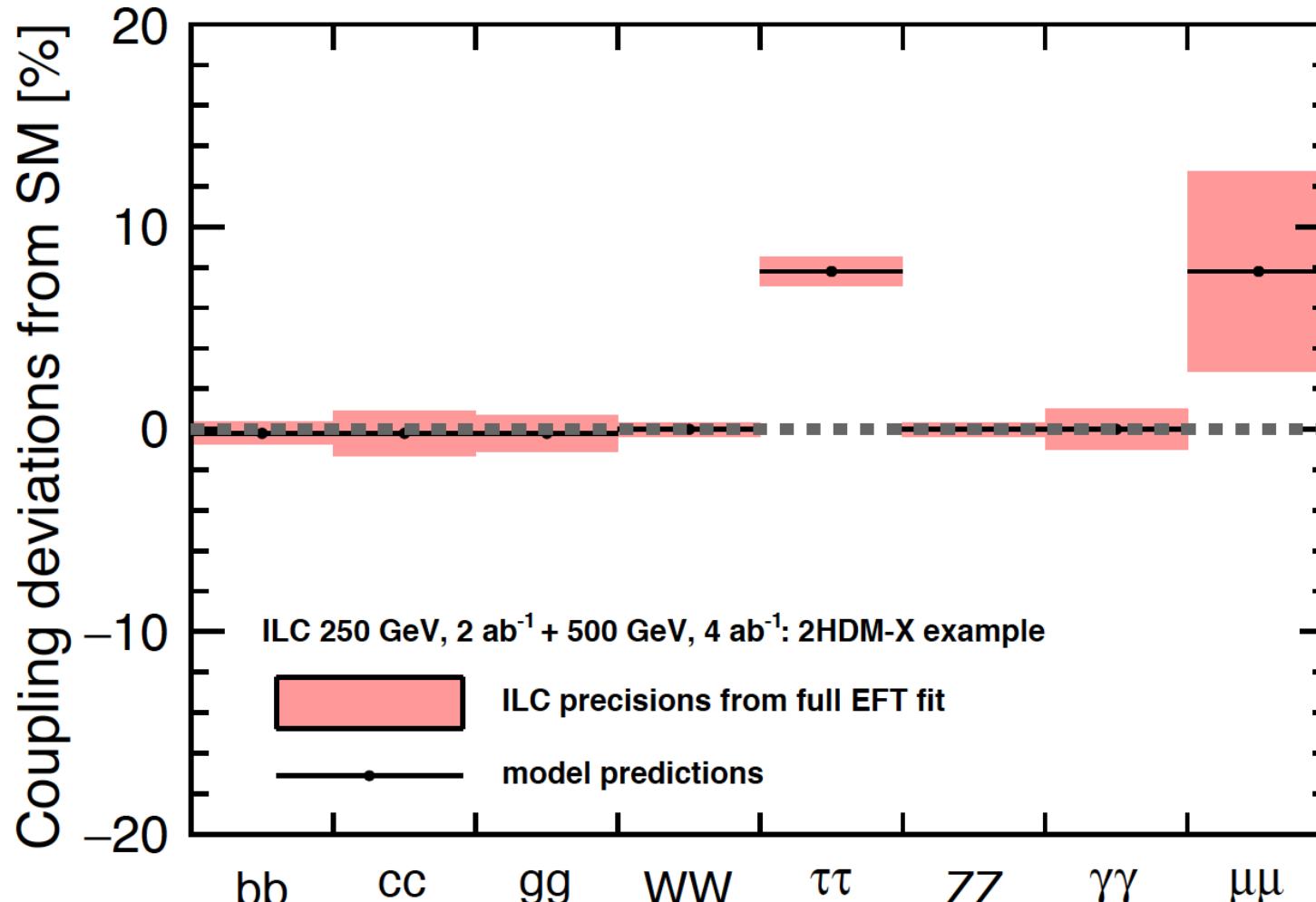
[T. Barklow et al., '17]



⇒ clear pattern, distinctive for 2HDM type II?

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

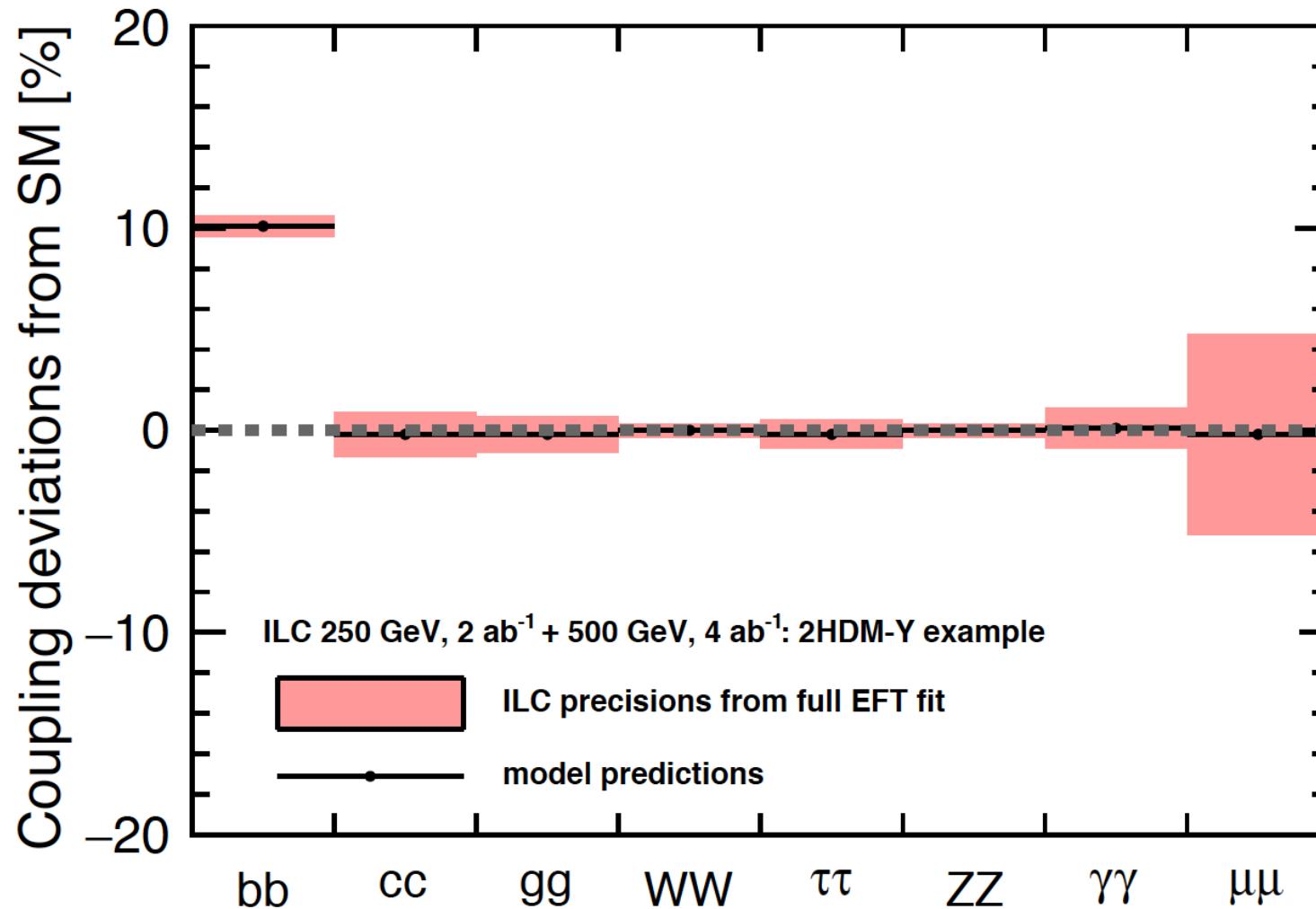
[T. Barklow et al., '17]



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

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

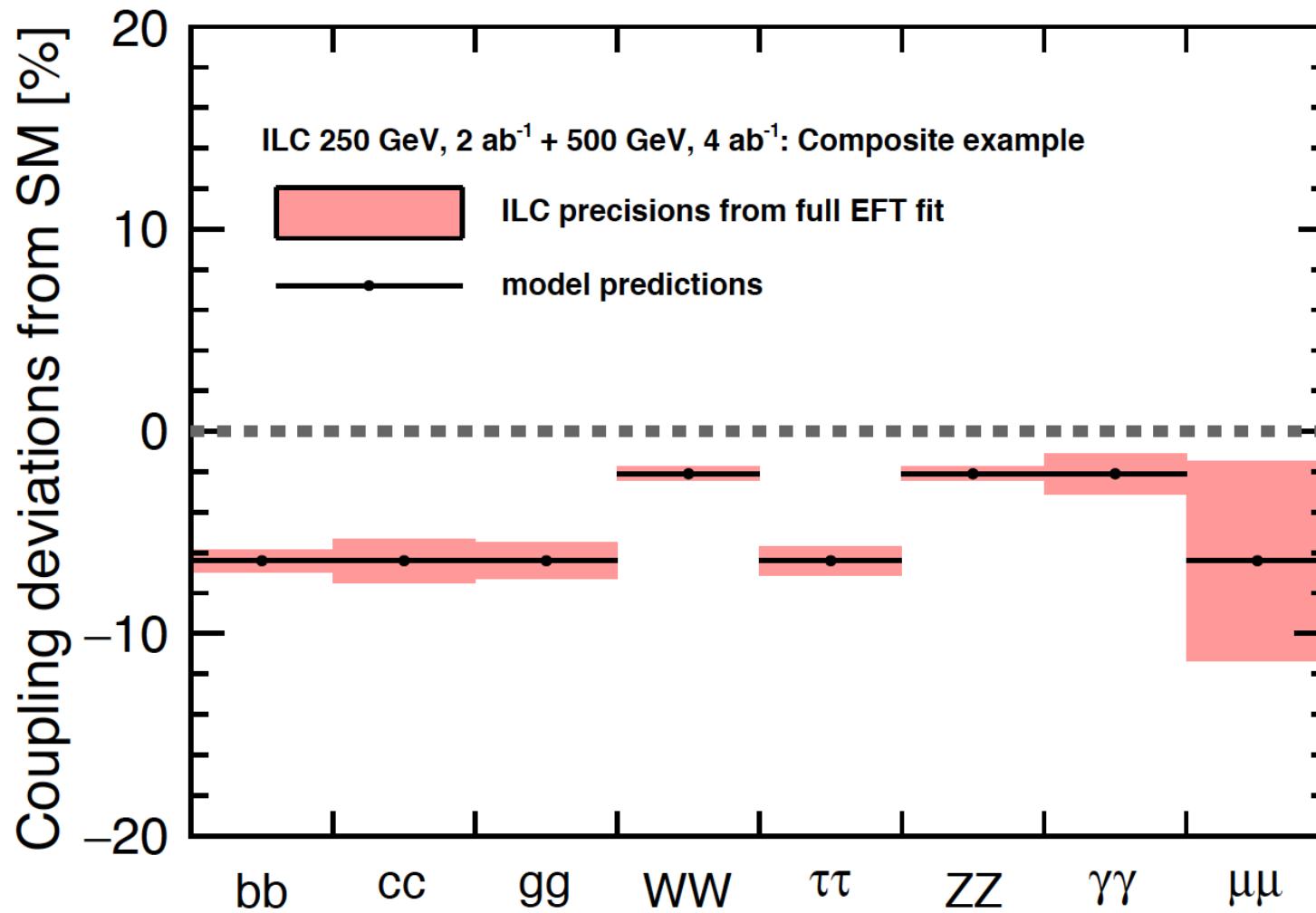
[T. Barklow et al., '17]



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

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

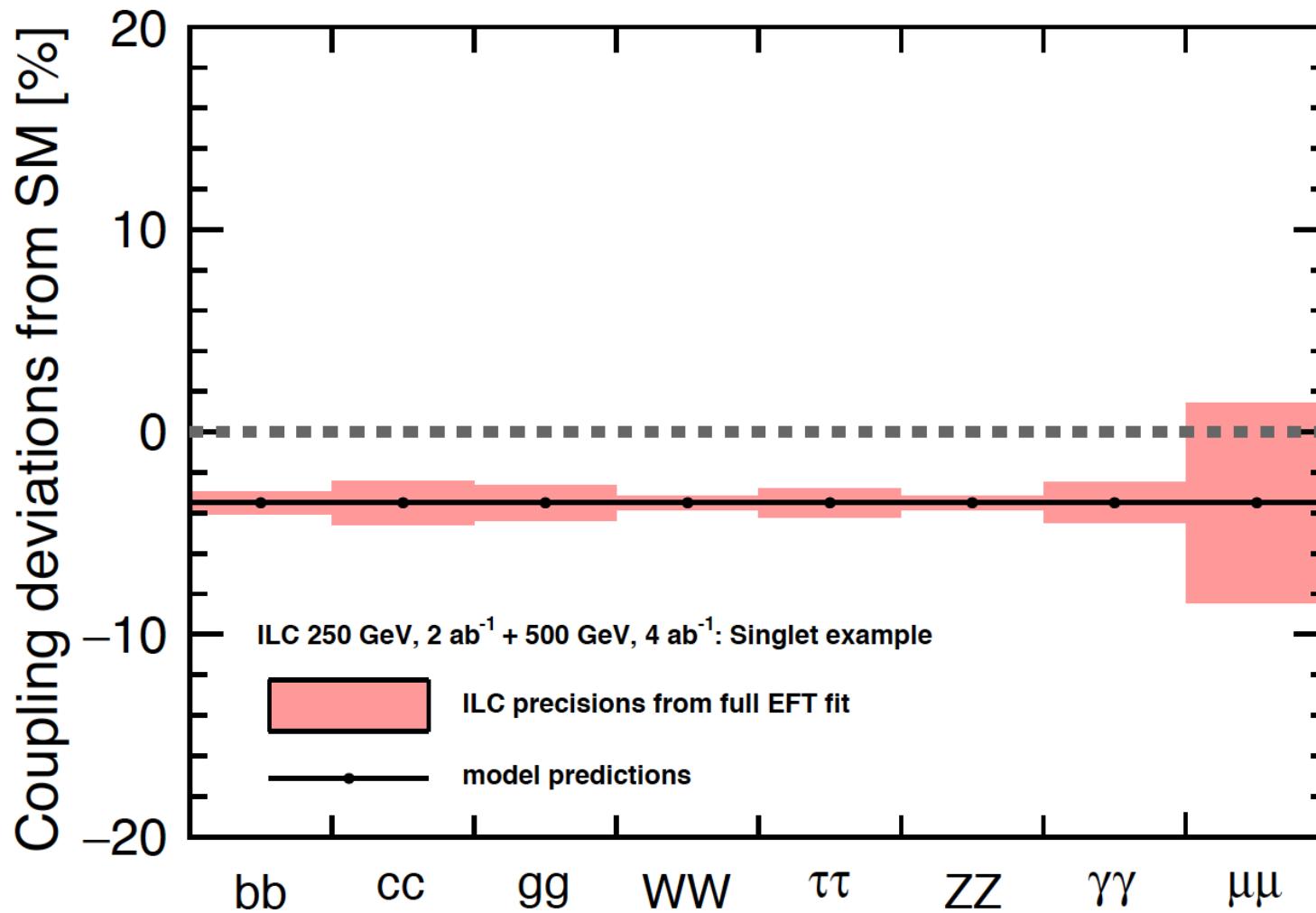
[T. Barklow et al., '17]



⇒ clear pattern, distinctive for Composite Higgs?!

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

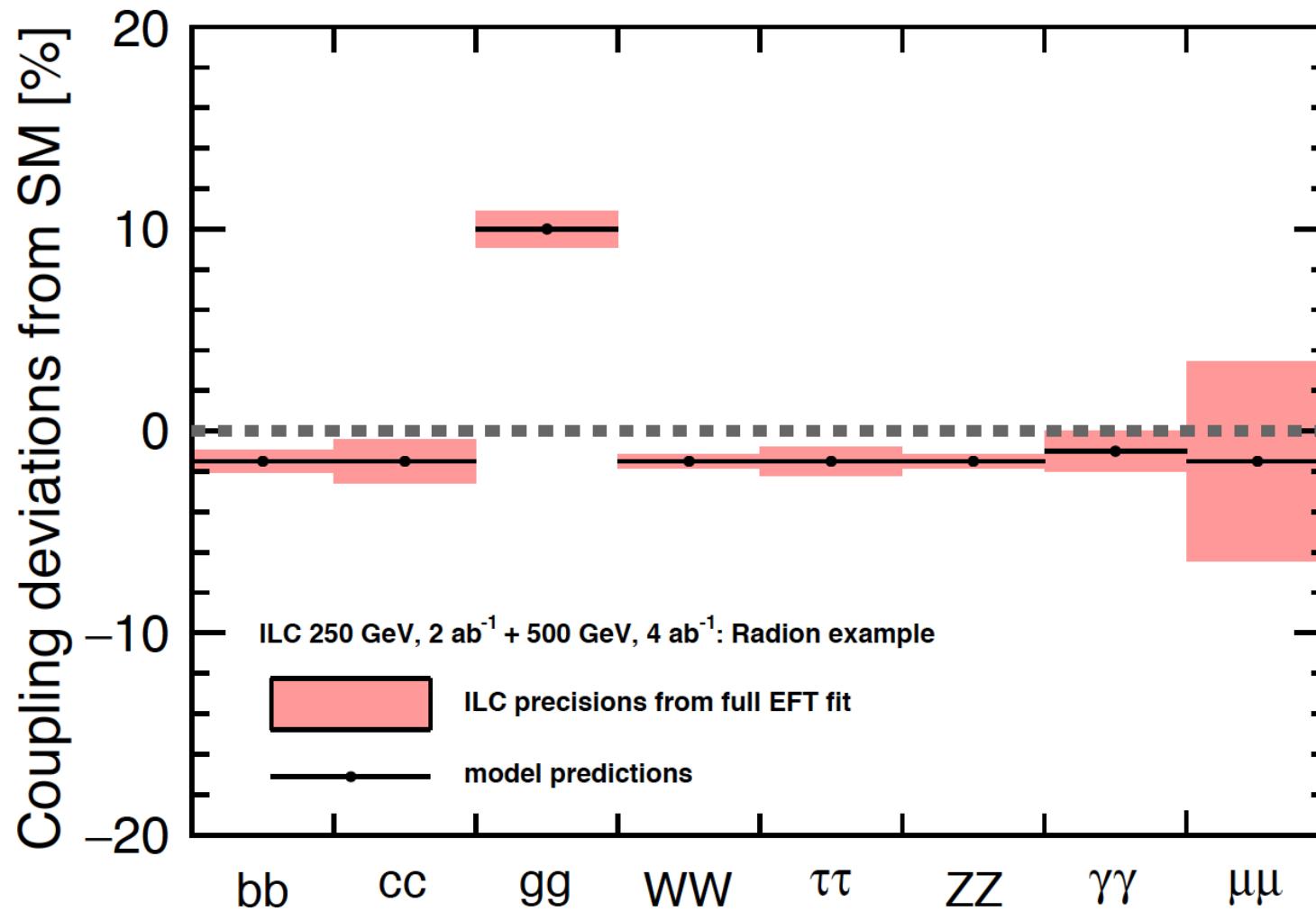
[T. Barklow et al., '17]



⇒ clear pattern, distinctive for HxSM?!

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

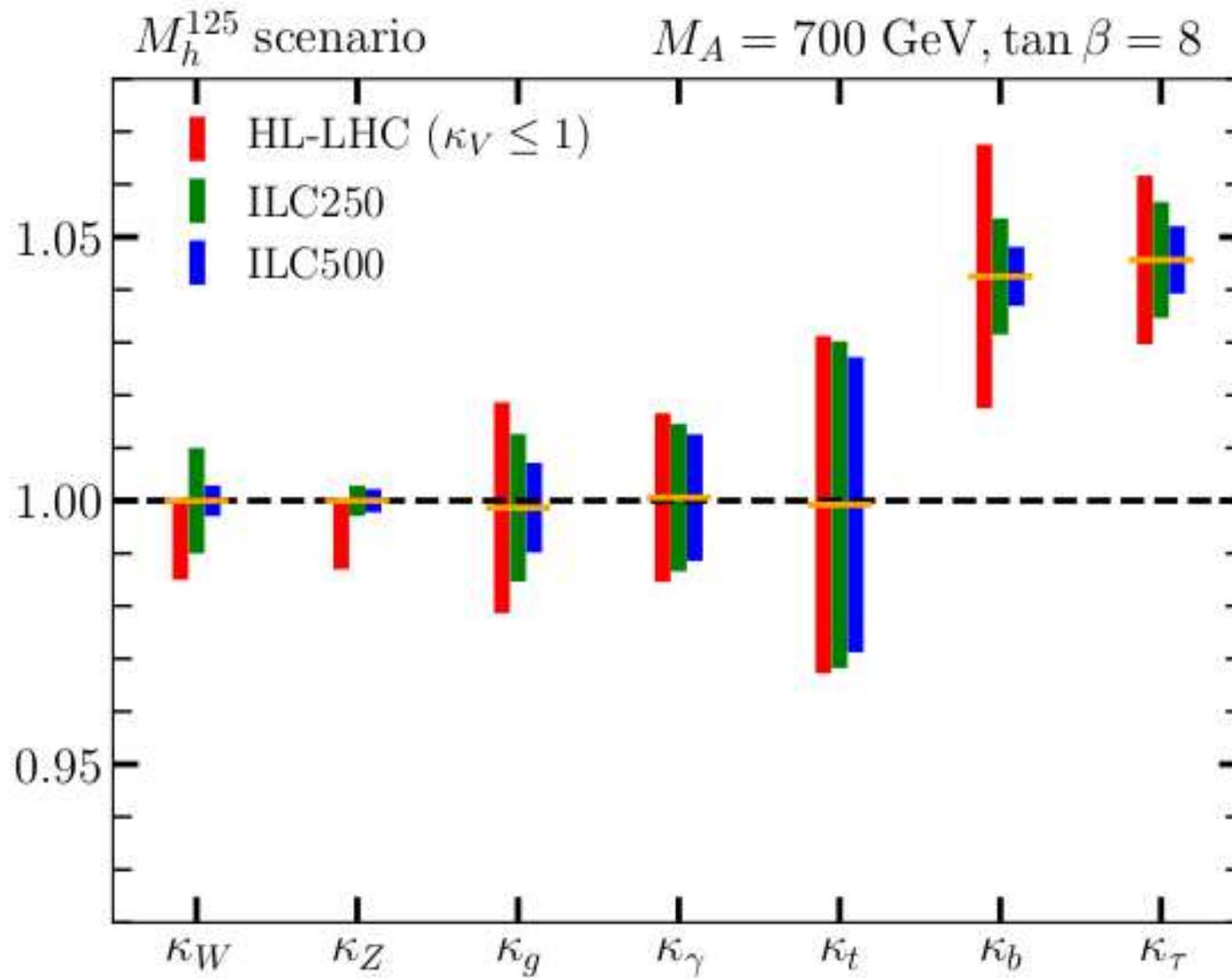
[T. Barklow et al., '17]



⇒ clear pattern, distinctive for Higgs Radion?!

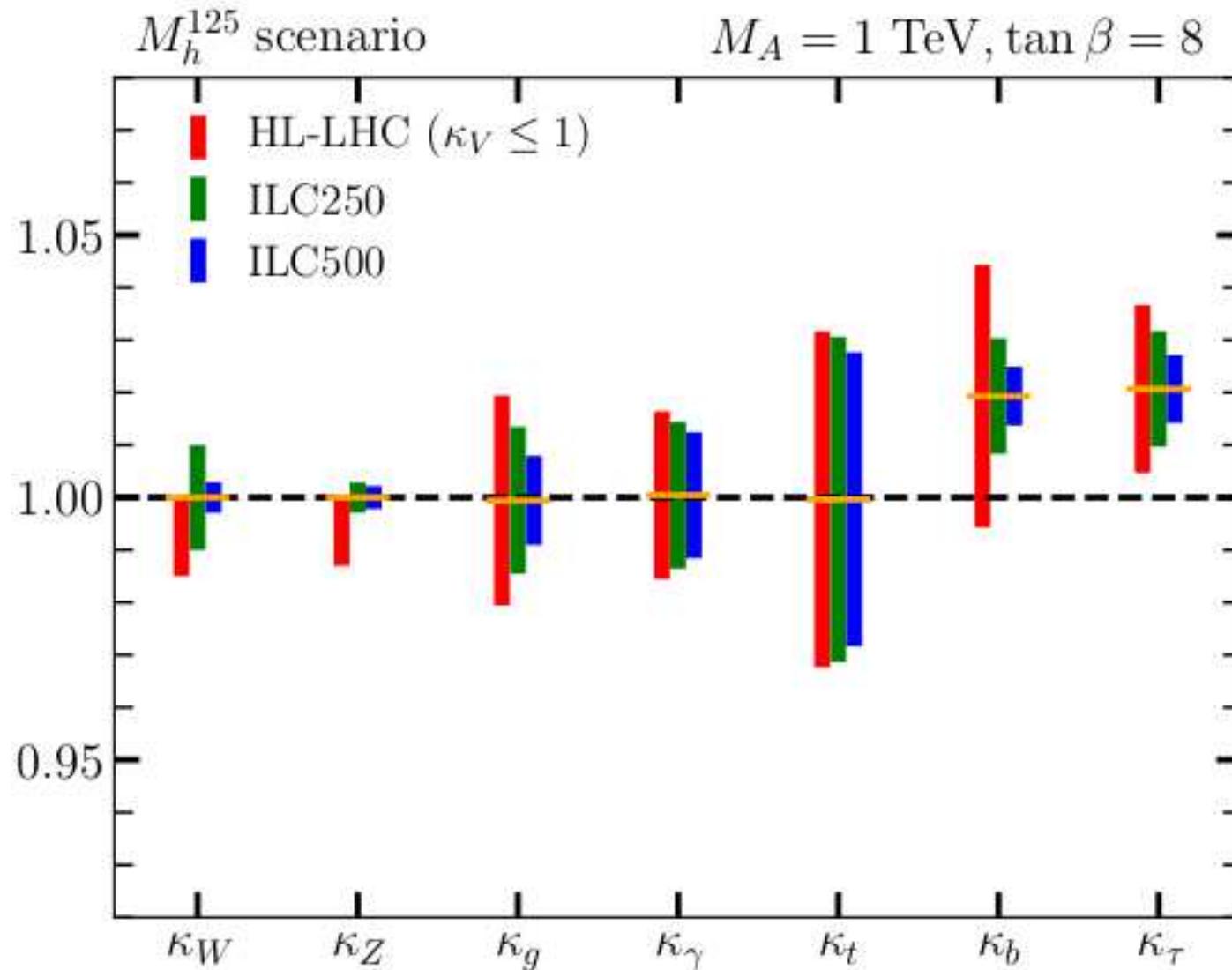
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

[H. Bahl et al. '20]



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

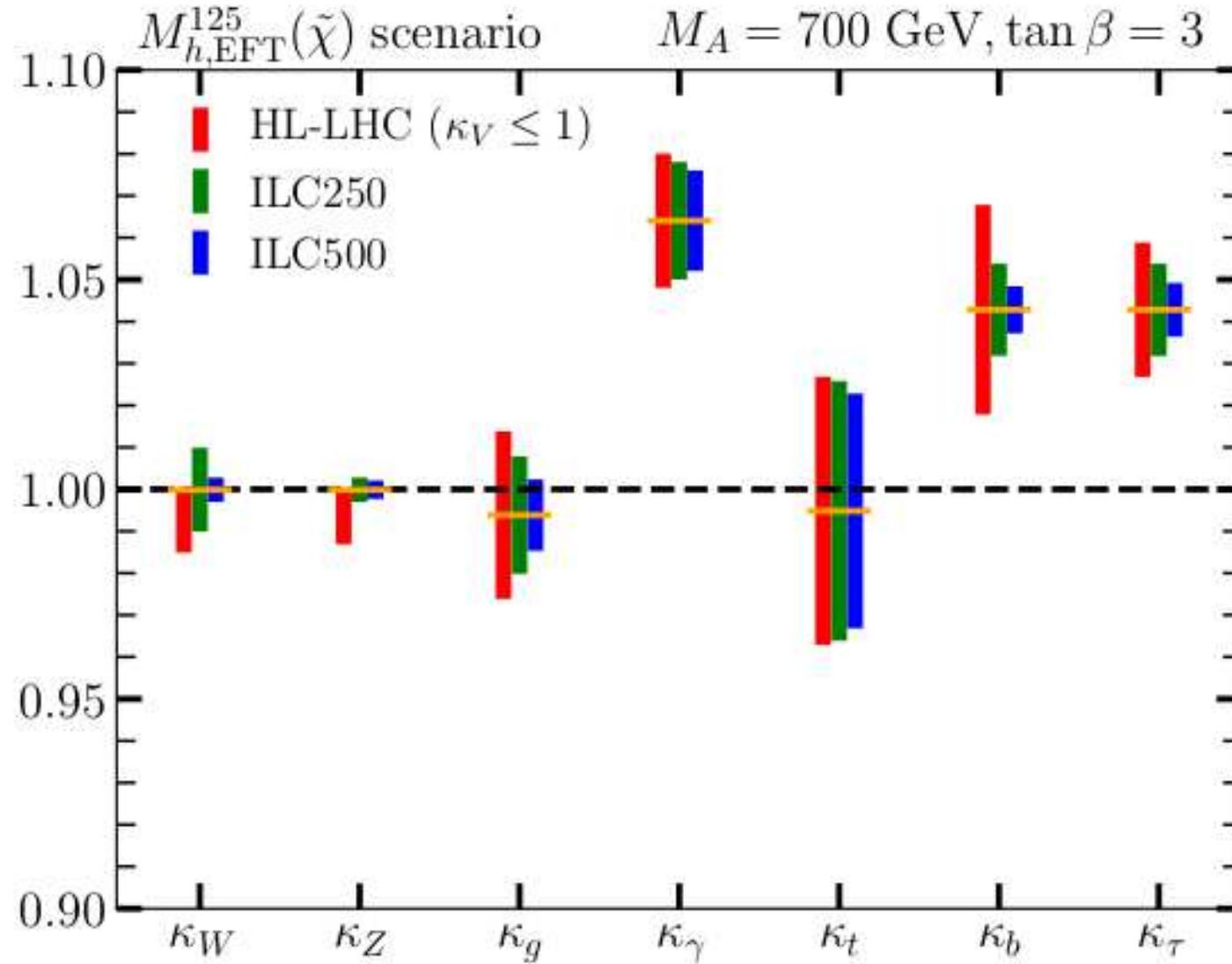
[H. Bahl et al. '20]



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

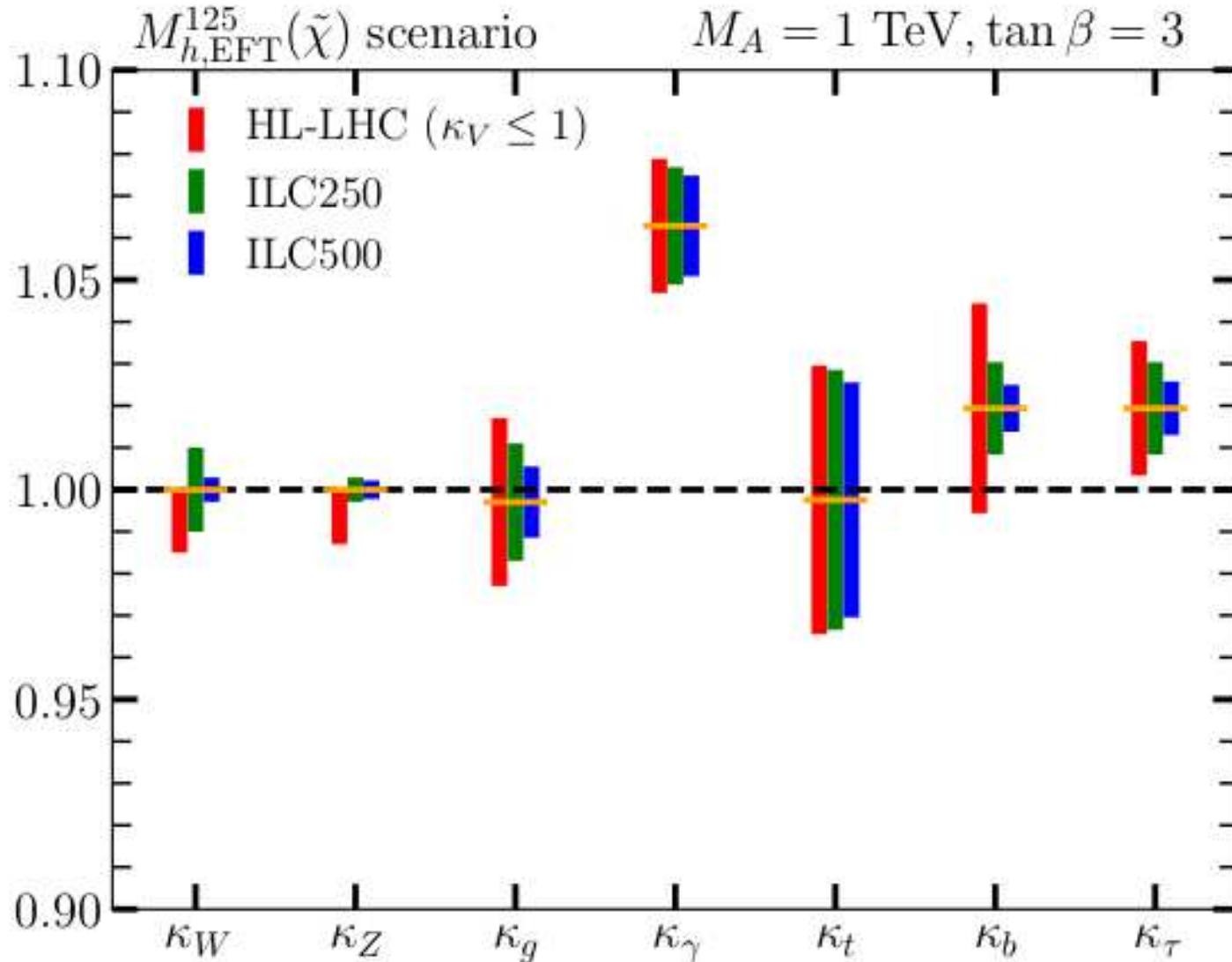
MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan \beta = 3$)

[H. Bahl et al. '20]



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

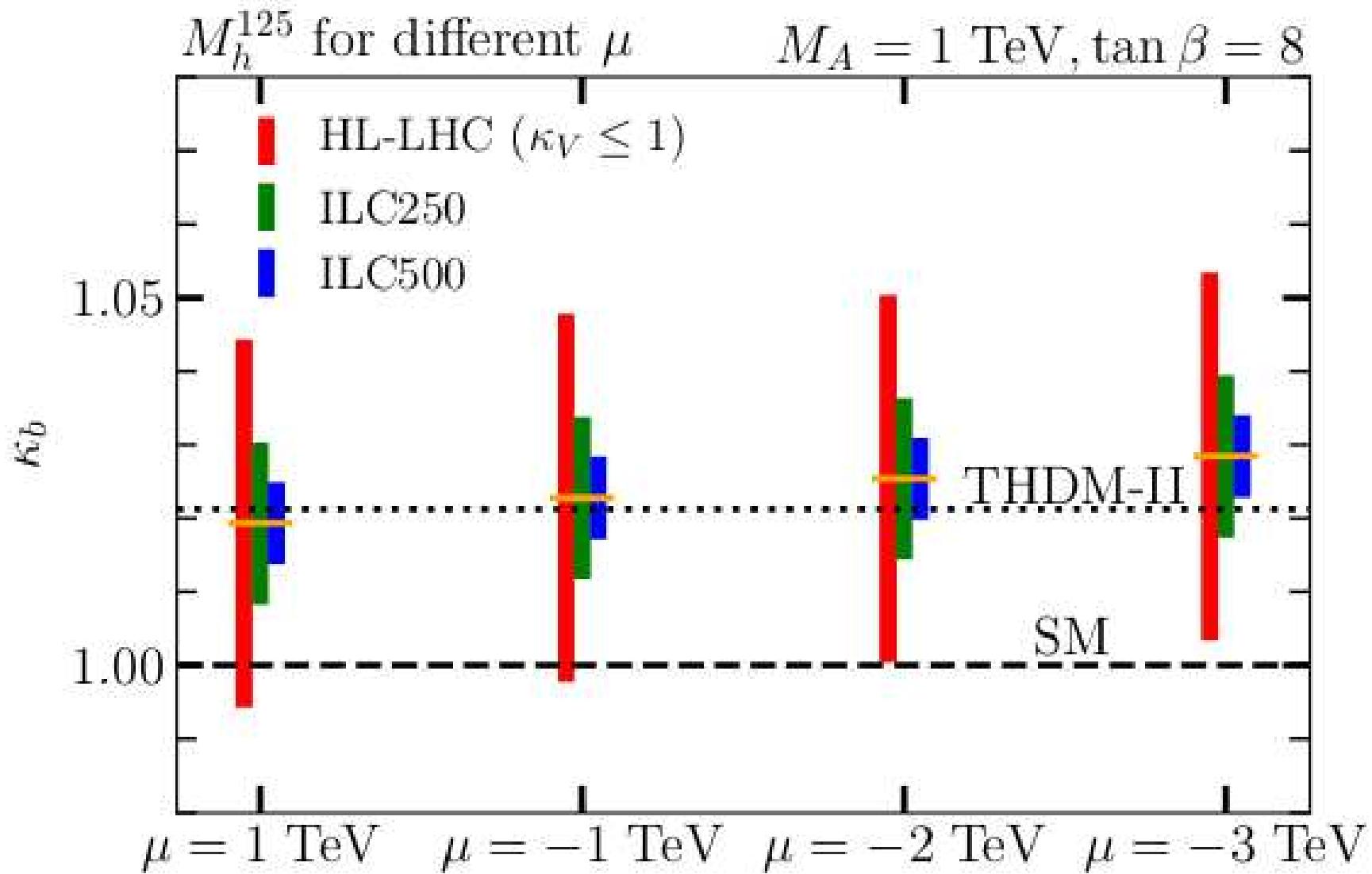
[H. Bahl et al. '20]



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

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

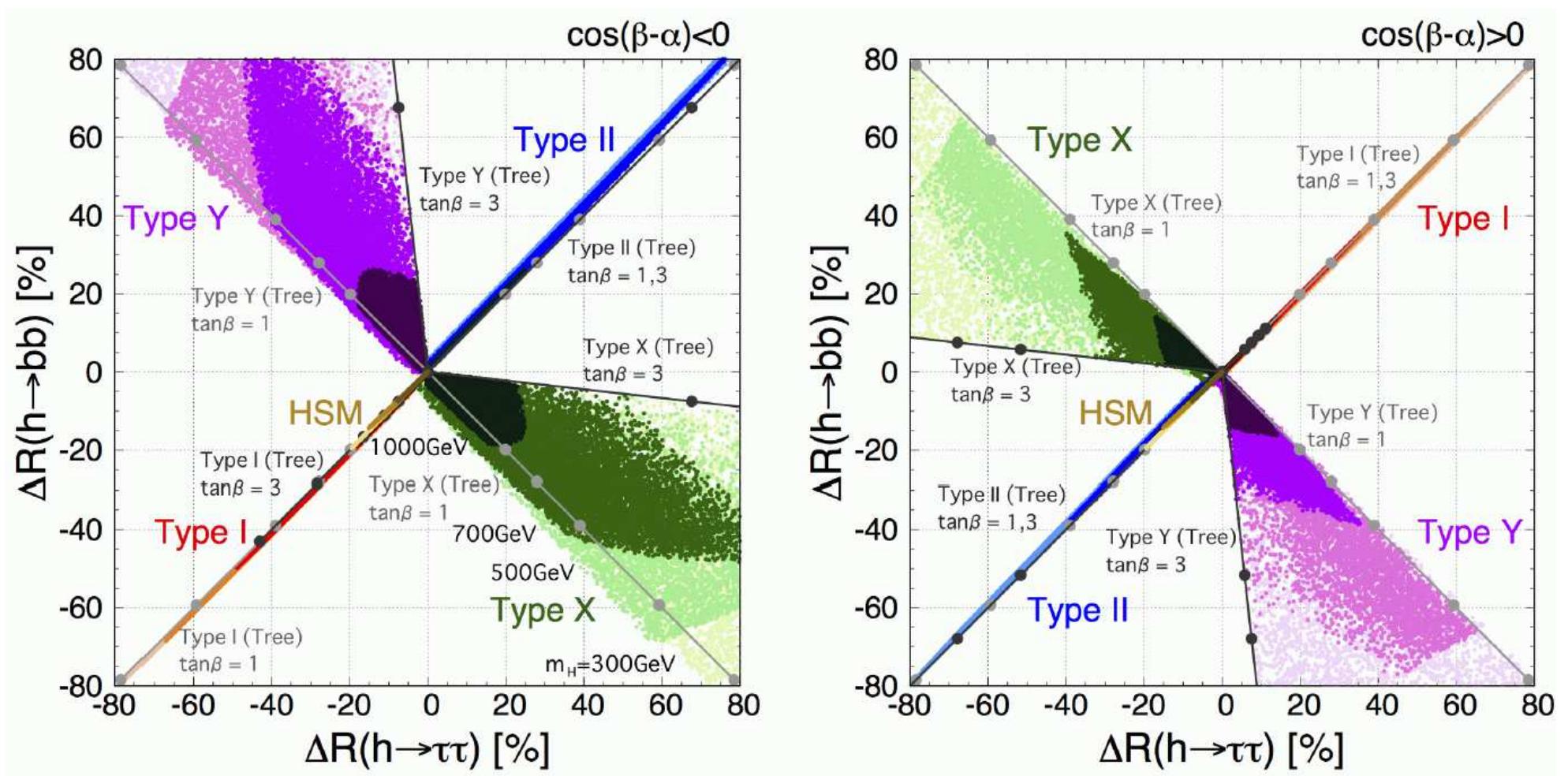
[H. Bahl et al. '20]



⇒ MSSM vs. 2HDM: very challenging!

2HDM example (I):

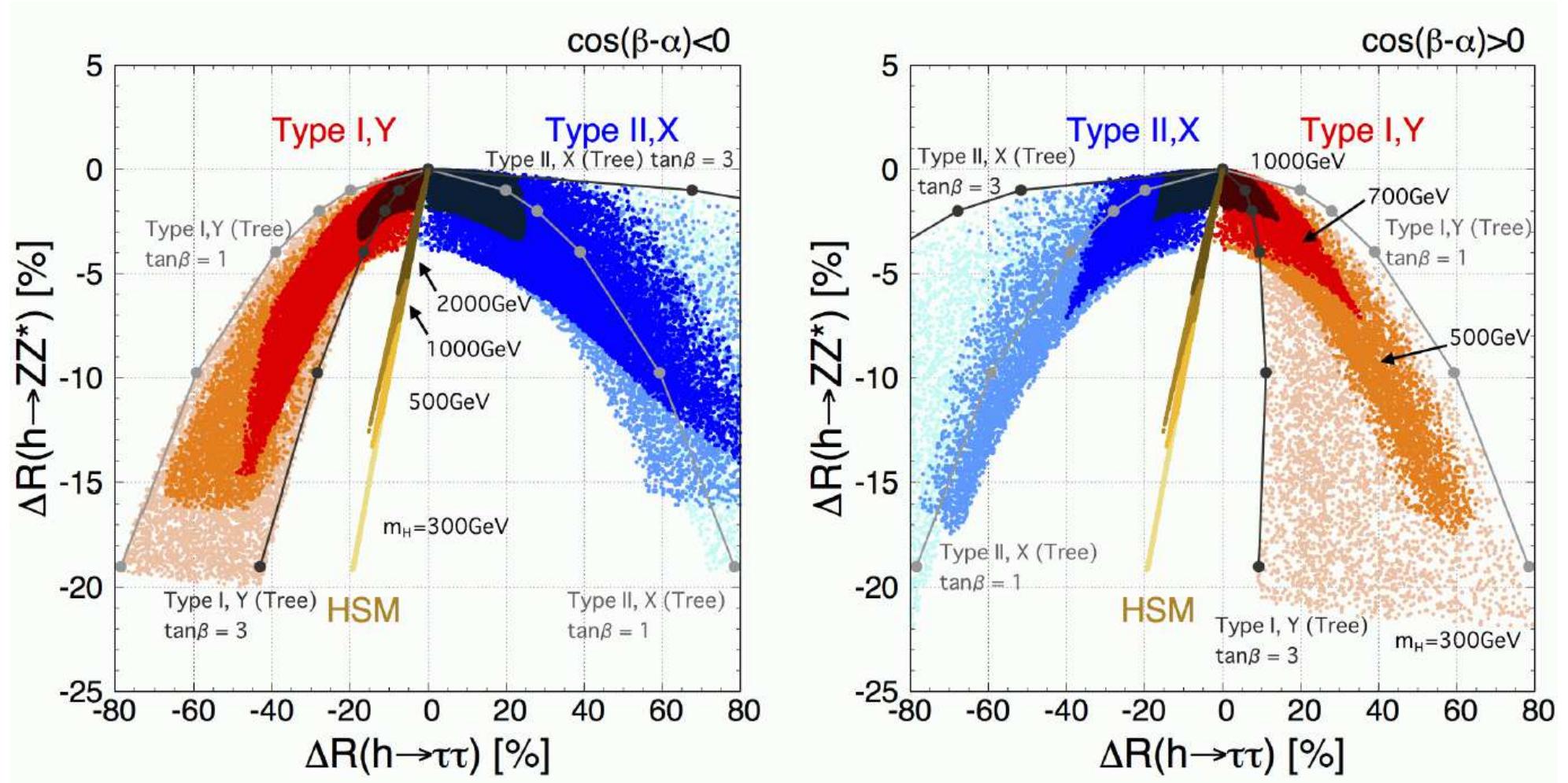
[S. Kanemura et al. '18]



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

2HDM example (II):

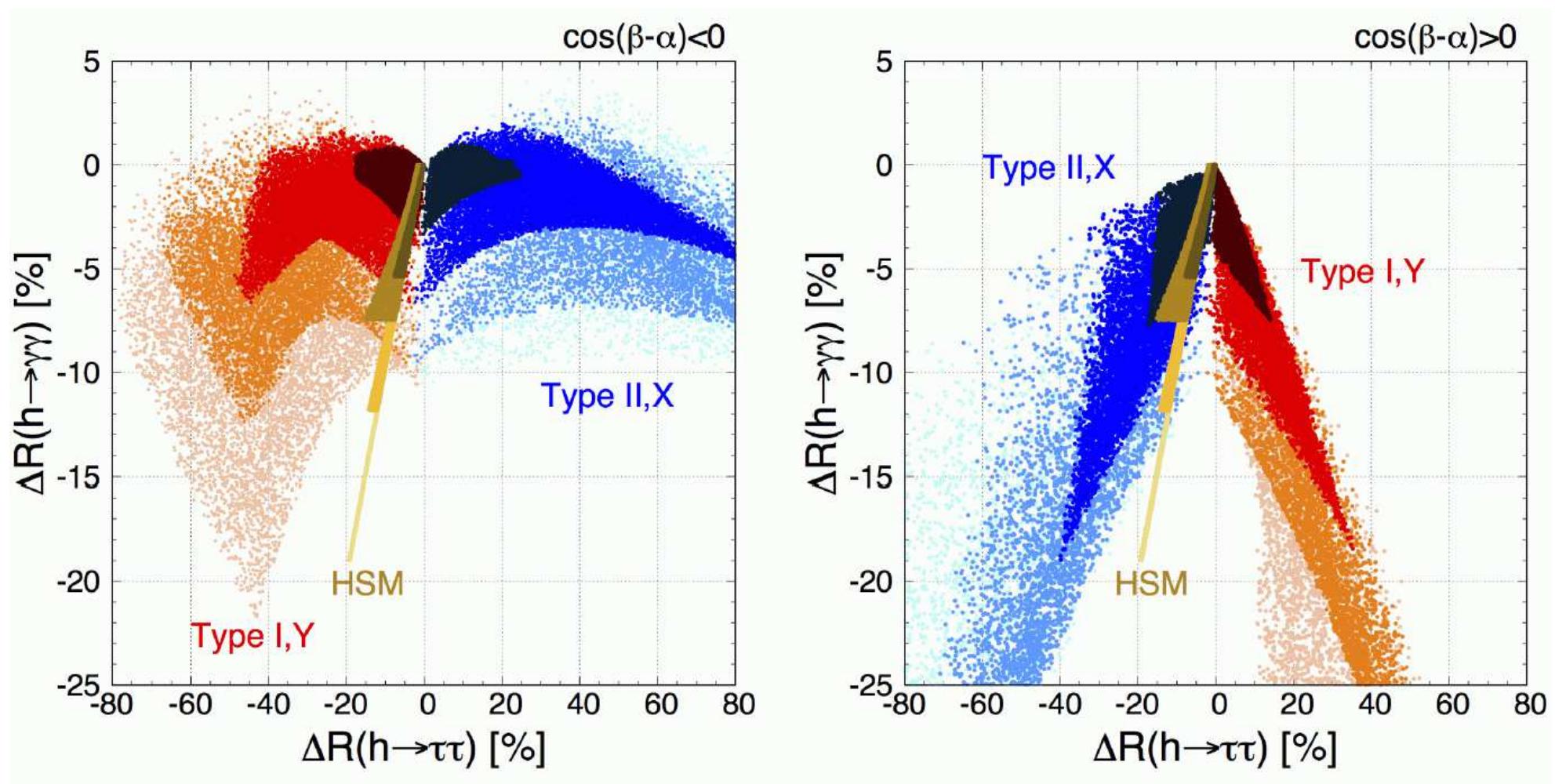
[S. Kanemura et al. '18]



→ 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!

Final allowed ranges

Type I

$$\kappa_\lambda \in [-0.5, 1.5]$$

$$\lambda_{hhH} \in [-1.4, 1.5]$$

$$\lambda_{hHH} \in [0, 15]$$

$$\lambda_{hAA} \in [0, 16]$$

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

Type II

$$\kappa_\lambda \in [0.0, 1.0]$$

$$\lambda_{hhH} \in [-1.6, 1.8]$$

$$\lambda_{hHH} \in [0, 15]$$

$$\lambda_{hAA} \in [0, 16]$$

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



Far from the alignment limit
and playing with m_{12}^2

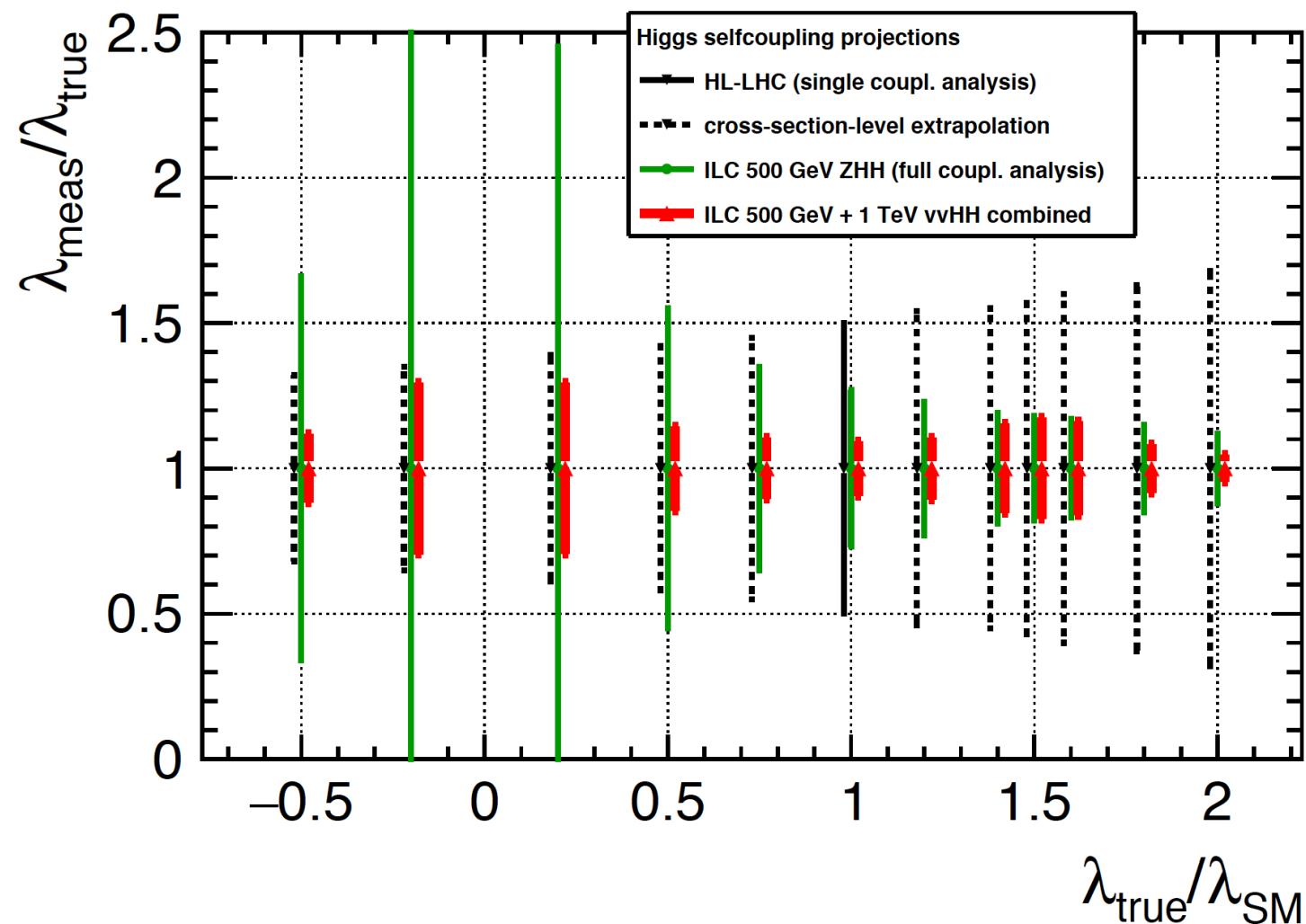
For $c_{\beta-\alpha} \sim \pm 0.05$

Large masses and nearly
independent of $c_{\beta-\alpha}$ and
scenario A or B

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

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

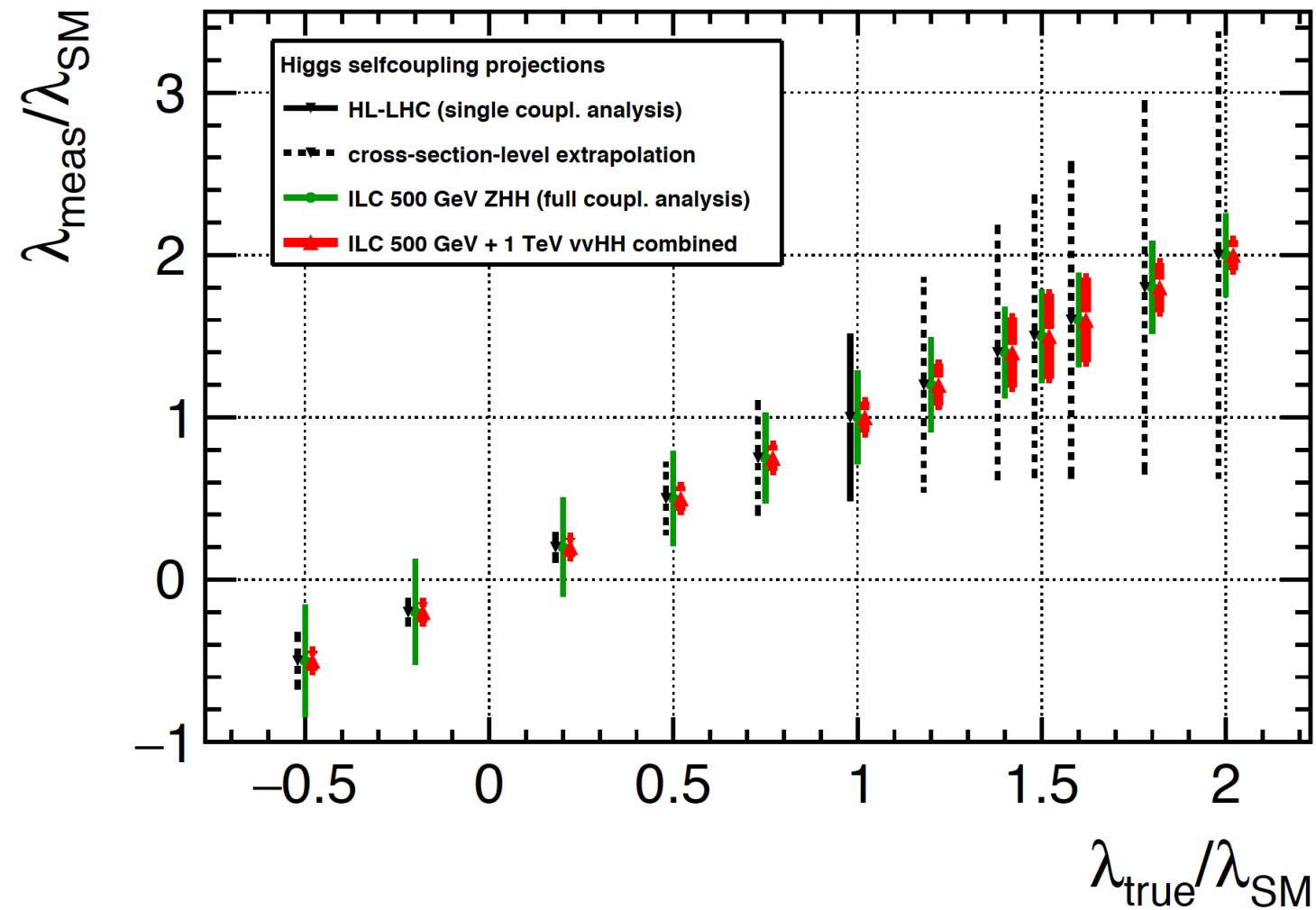
[J. List et al. – PRELIMINARY]



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

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

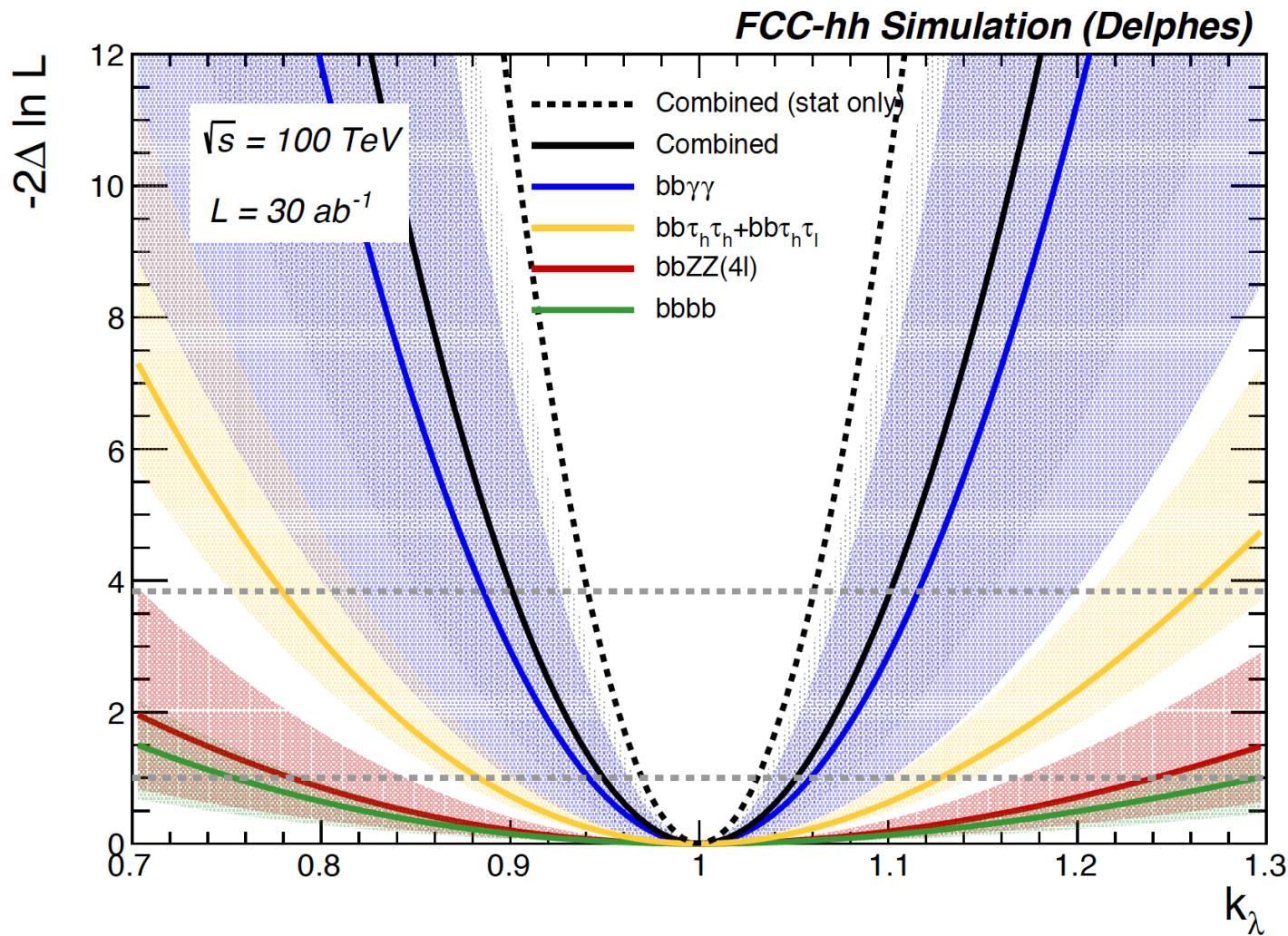
[J. List et al. – PRELIMINARY]



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

Measurement of κ_λ at the FCC-hh:

[Mangano, Ortona, Selvaggi '20]



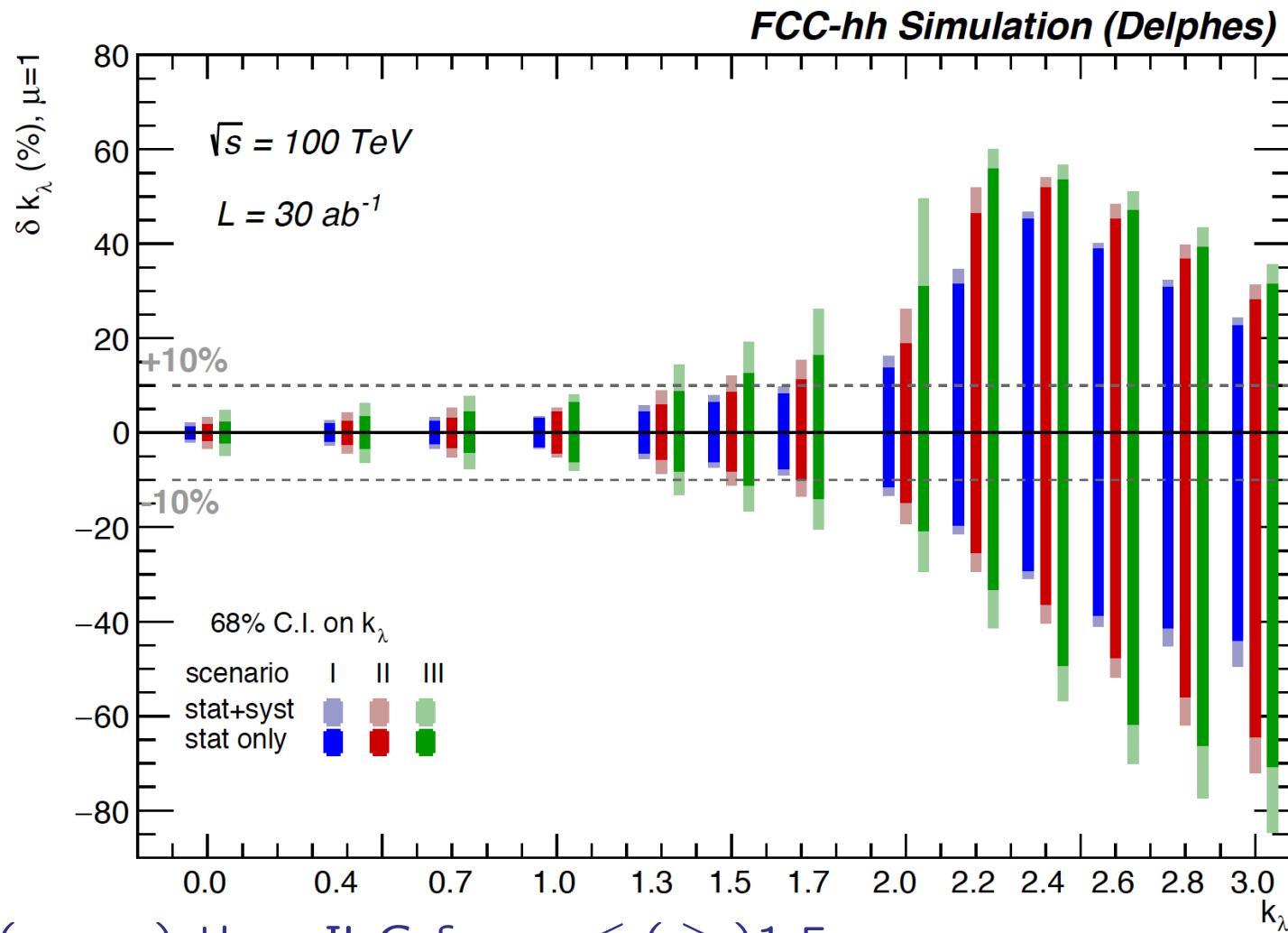
⇒ result only for $\kappa_\lambda = 1$

⇒ pile-up neglected ...

Measurement of κ_λ at the FCC-hh:

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

[Mangano, Ortona, Selvaggi '20]



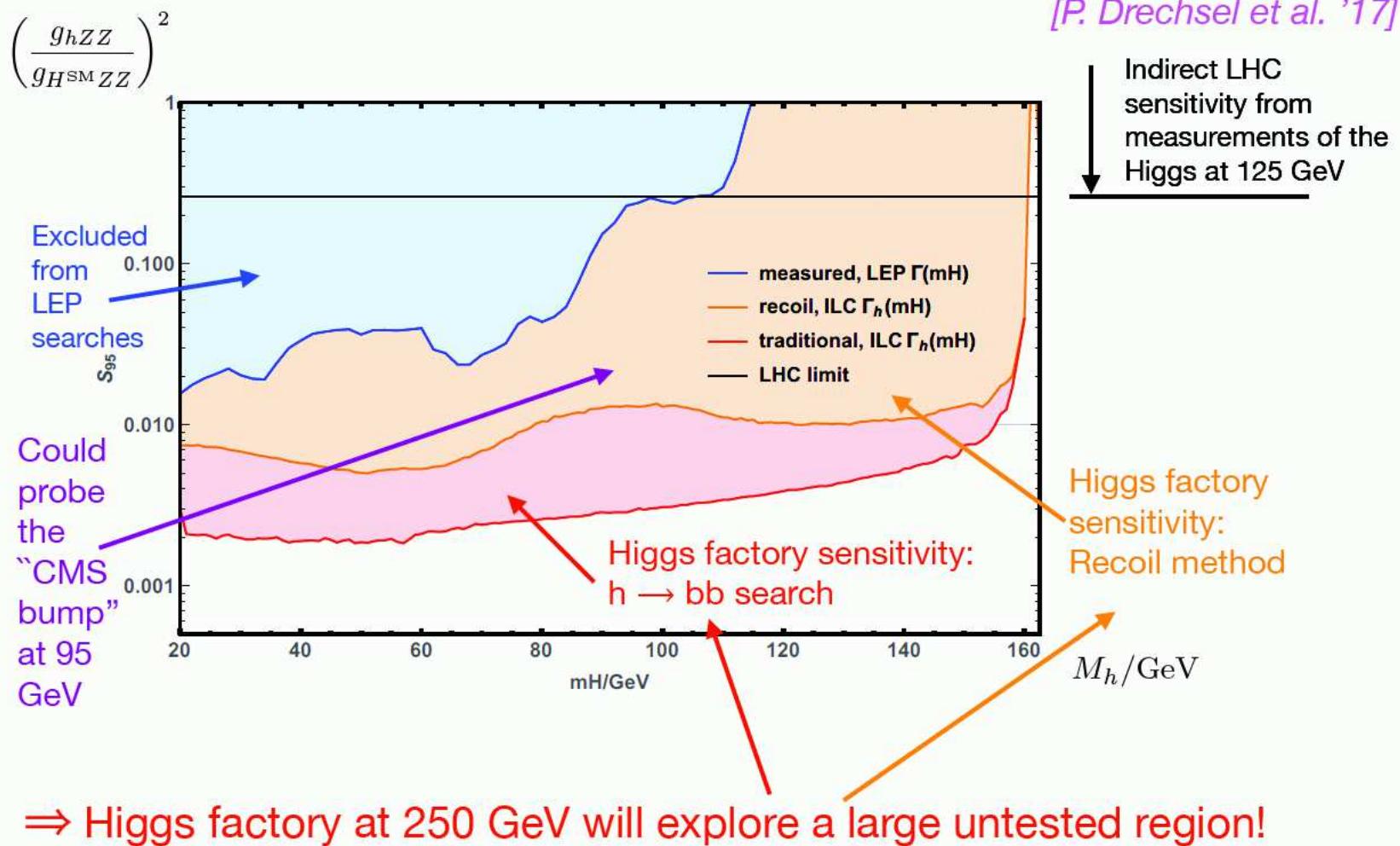
→ better (worse) than ILC for $\kappa_\lambda \lesssim (\gtrsim) 1.5$

→ no results for $\kappa_\lambda \leq 0$

→ pile-up neglected . . .

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



[Taken from G. Weiglein '18]

Example: 2HDM, FOEWPT and GW's

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein – PRELIMINARY*]

