



# BSM Higgs Bosons at the LC

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

Fukuoka, 05/2018

1. Why it is not the SM Higgs
2. BSM Higgs Bosons above 125 GeV
3. BSM Higgs Bosons below 125 GeV
4. BSM Higgs Boson at 125 GeV
5. Conclusions

# BSM Higgs Bosons at the LC

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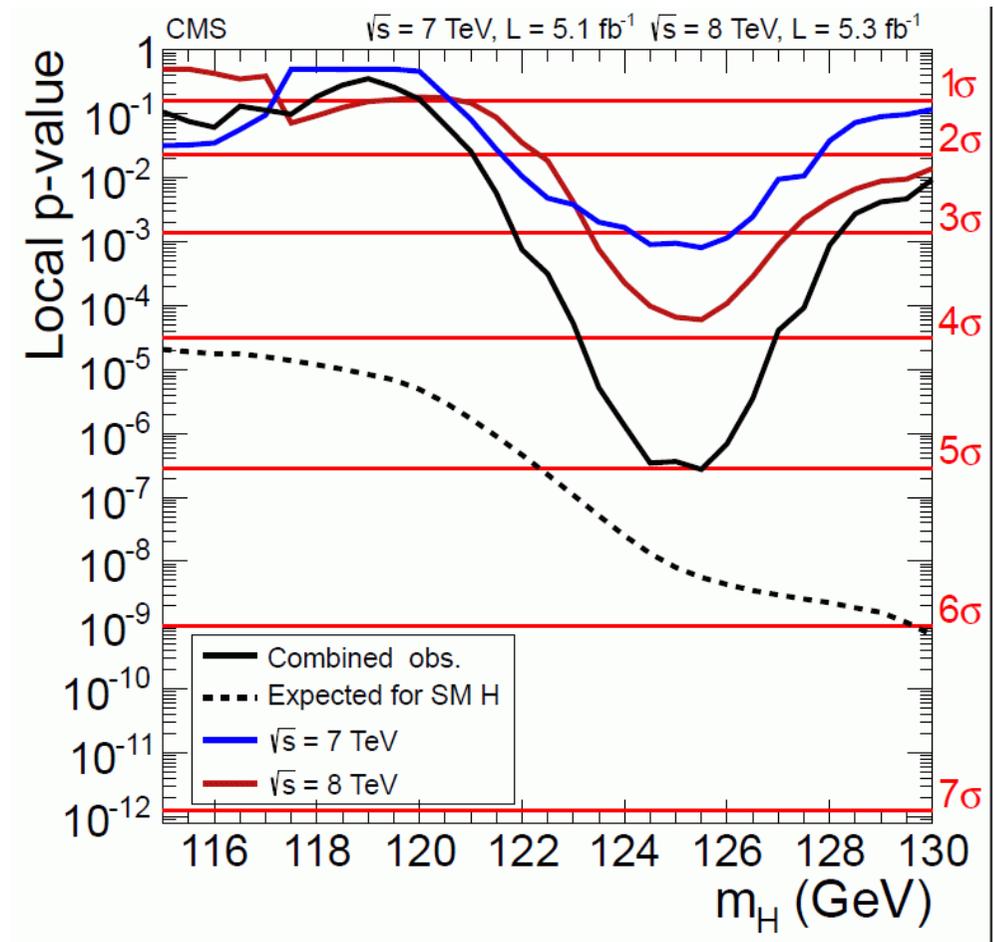
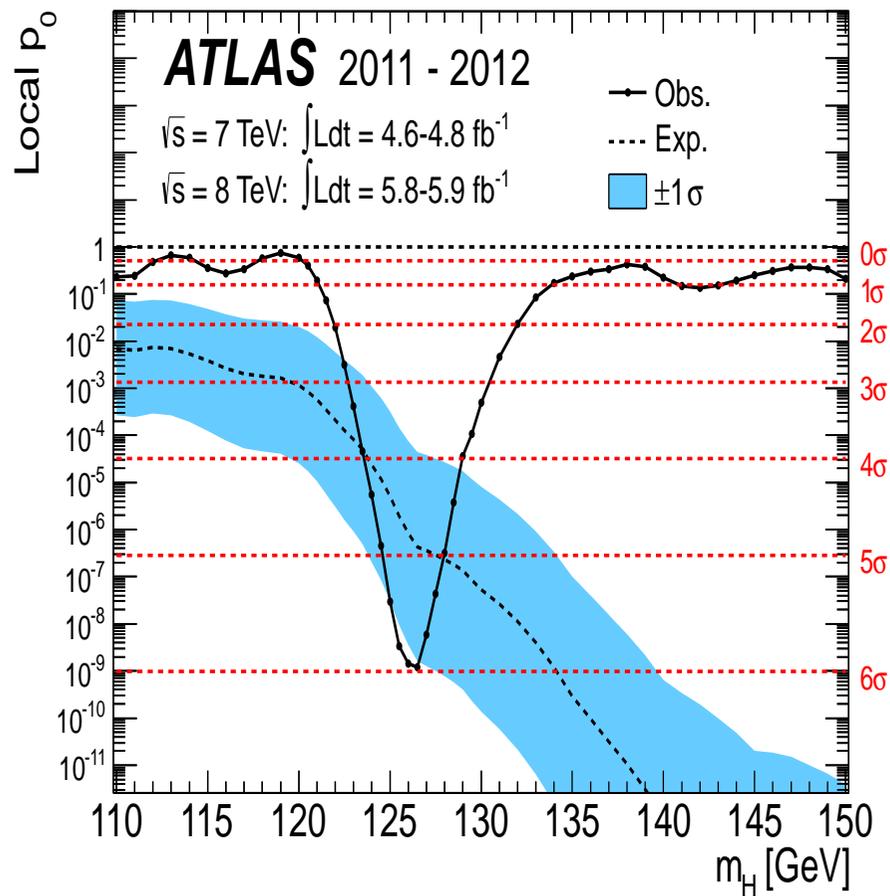
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1. Why it is not the SM Higgs
2. BSM Higgs Bosons above 125 GeV
3. BSM Higgs Bosons below 125 GeV  $\Leftarrow$  at ILC250
4. BSM Higgs Boson at 125 GeV  $\Leftarrow$  at ILC250
5. Conclusions

# 1. Why it is not the SM Higgs

## Fact I:

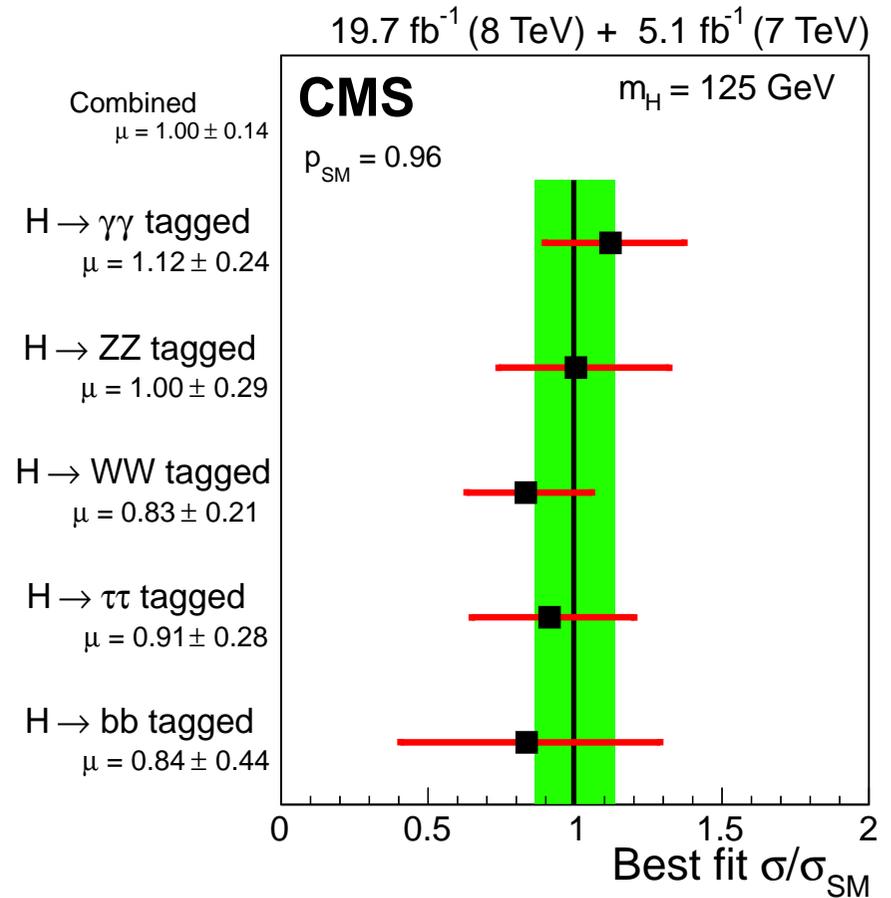
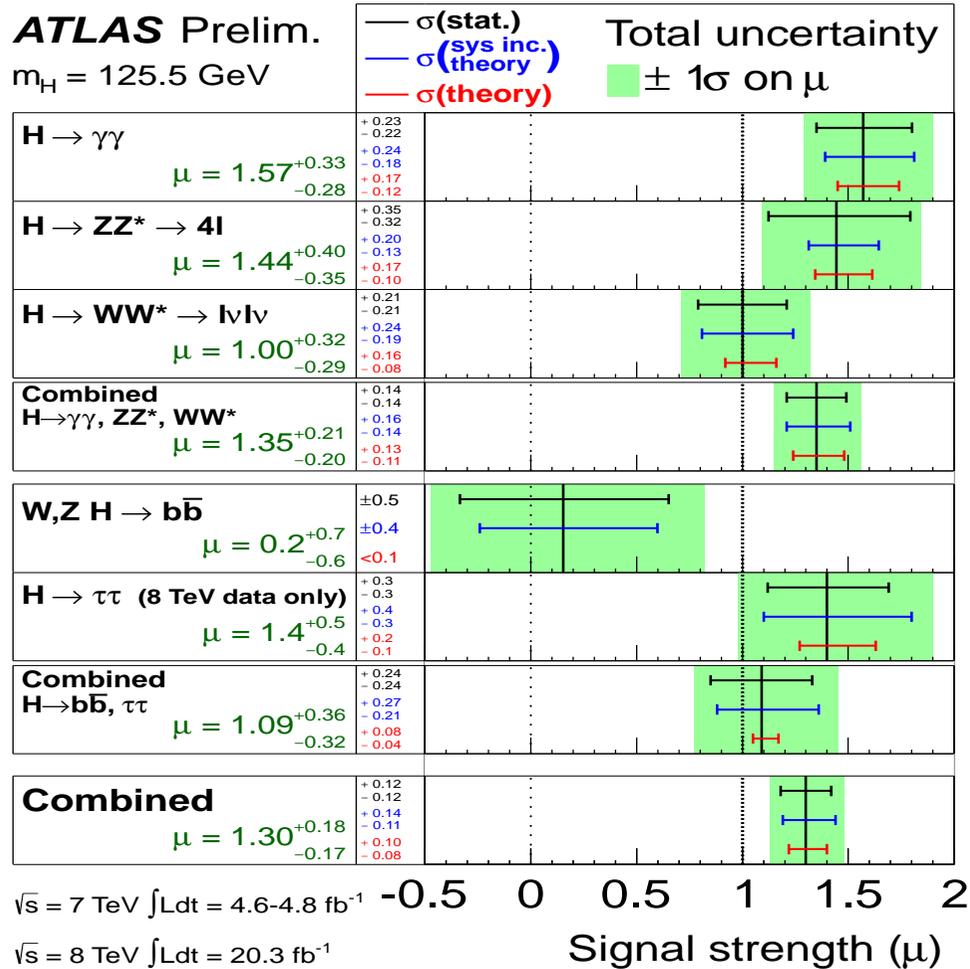
We have a discovery!



# 1. Why it is not the SM Higgs

## Fact I:

We have an SM-like discovery!



## Fact II:

The SM cannot be the ultimate theory!

### Some facts:

1. gravity is not included
2. the hierarchy problem
3. Dark Matter is not included
4. neutrino masses are not included
5. anomalous magnetic moment of the muon shows a  $\sim 4\sigma$  discrepancy

## Fact I & II:

We have a 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?

## Fact I & II:

We have a discovery!

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

**A2:** check for additional Higgs bosons

**A2':** 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  $CP$**  properties of this particle? Are there additional sources of  **$CP$  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/ldots**?  
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
  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, ...

## 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

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

## The “sum rule”:

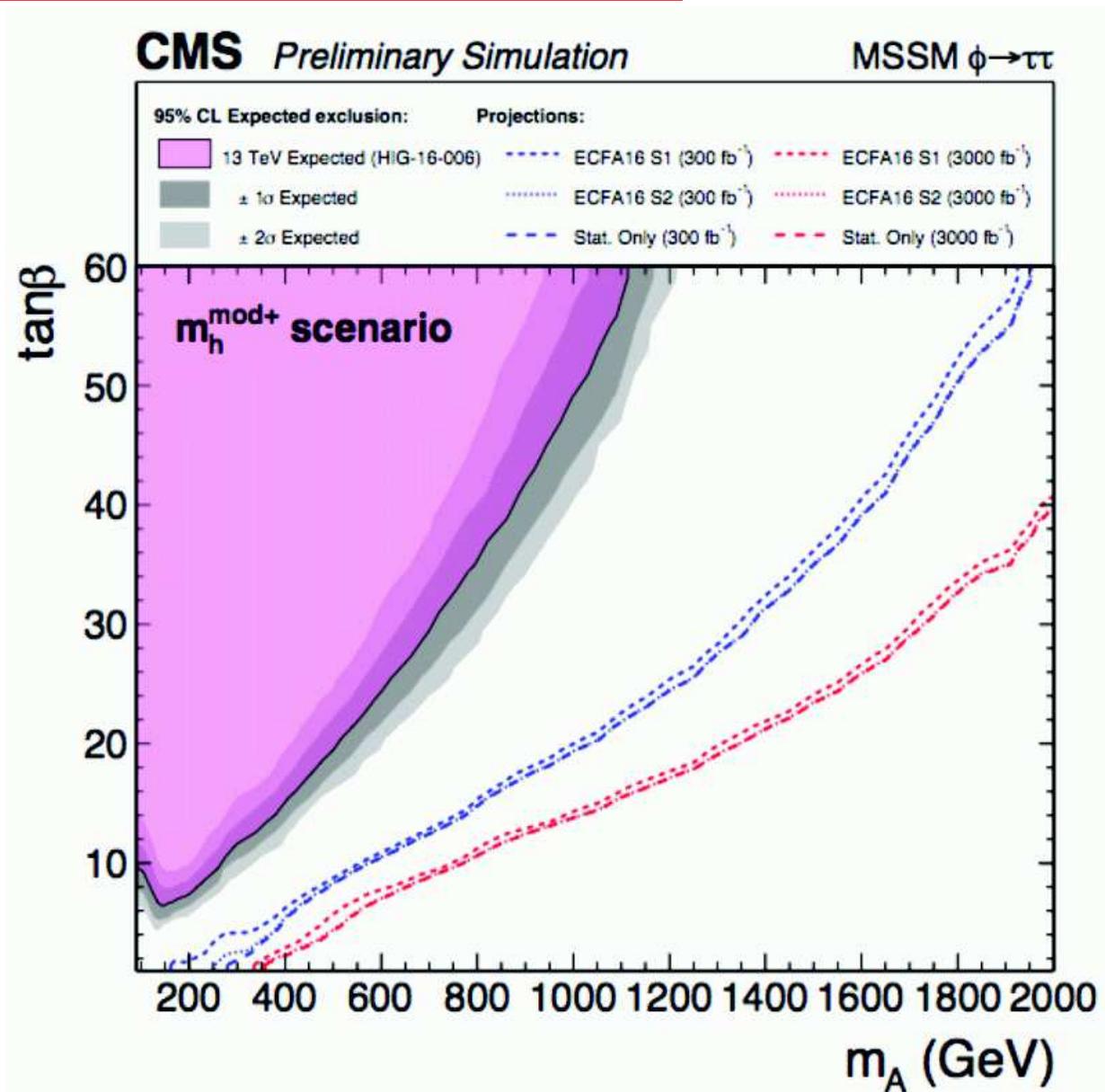
In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a “sum rule”:

$$\sum_i g_{H_i V V}^2 = (g_{H V V}^{\text{SM}})^2$$

- ⇒
- The SM coupling strength is “**shared**” between the Higgses of an extended Higgs sector,  $\kappa_V \leq 1$
  - The **more SM-like** the couplings of the state at 125 GeV turn out to be, the **more suppressed** are the couplings of the other Higgses to gauge bosons; heavy Higgses usually have a **much smaller width** than a SM-like Higgs of the same mass
  - **Searches for additional Higgs bosons need to test compatibility with the observed signal at 125 GeV!**

[Taken from G. Weiglein '18]

## 2. BSM Higgs Bosons above 125 GeV

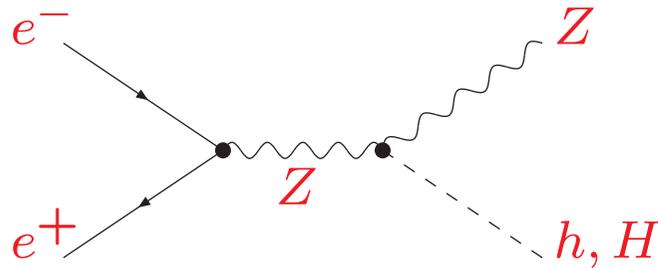


⇒ strong (HL-)LHC limits

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:

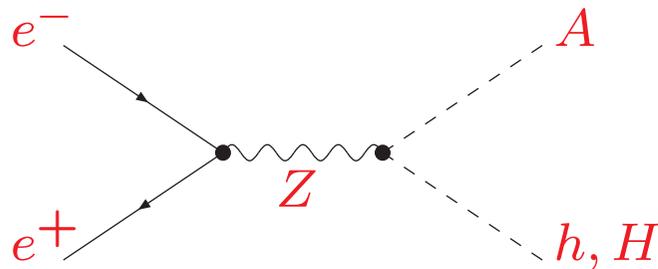
$e^+e^- \rightarrow Zh, ZH$



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

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

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

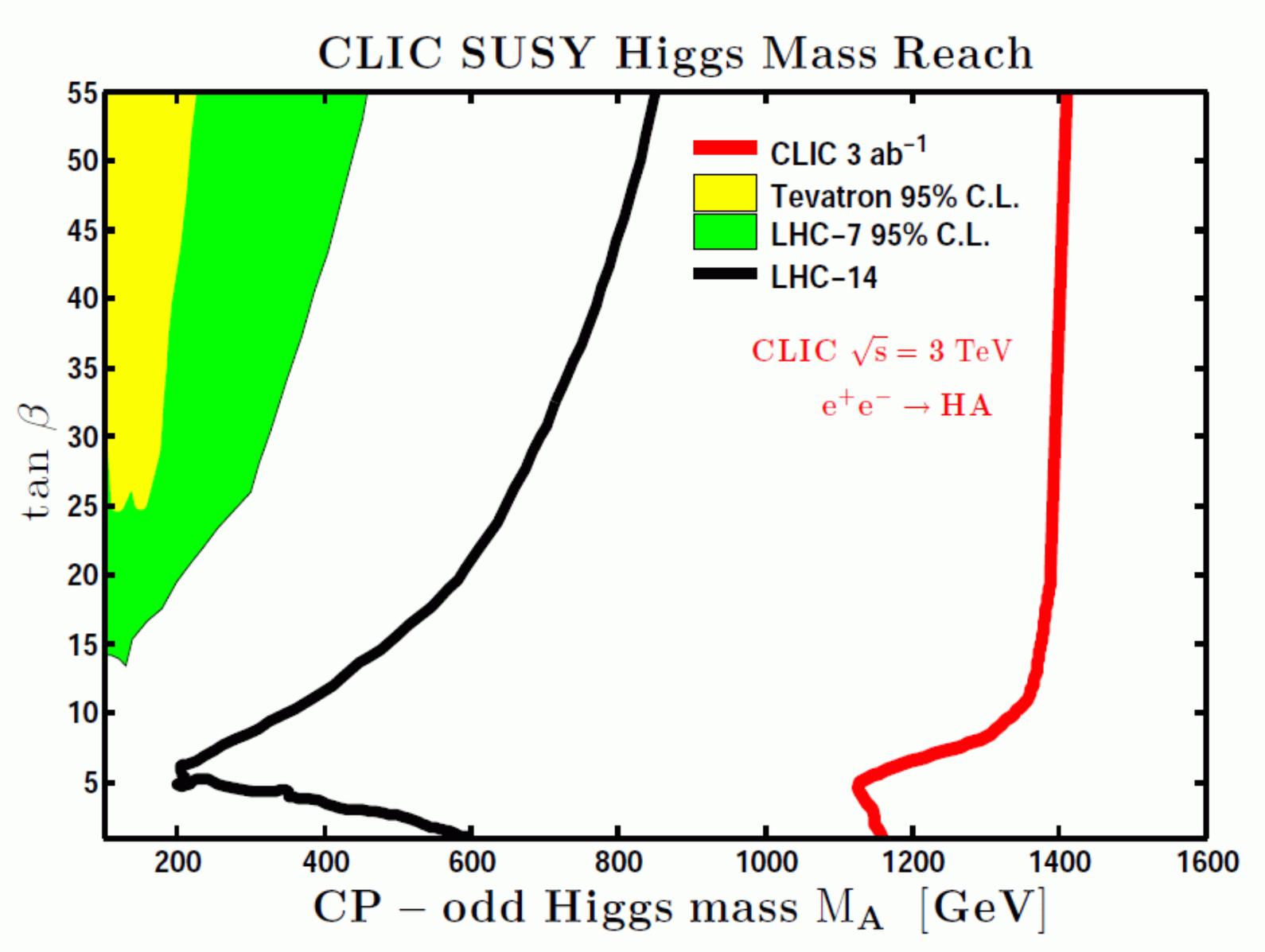


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$$

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

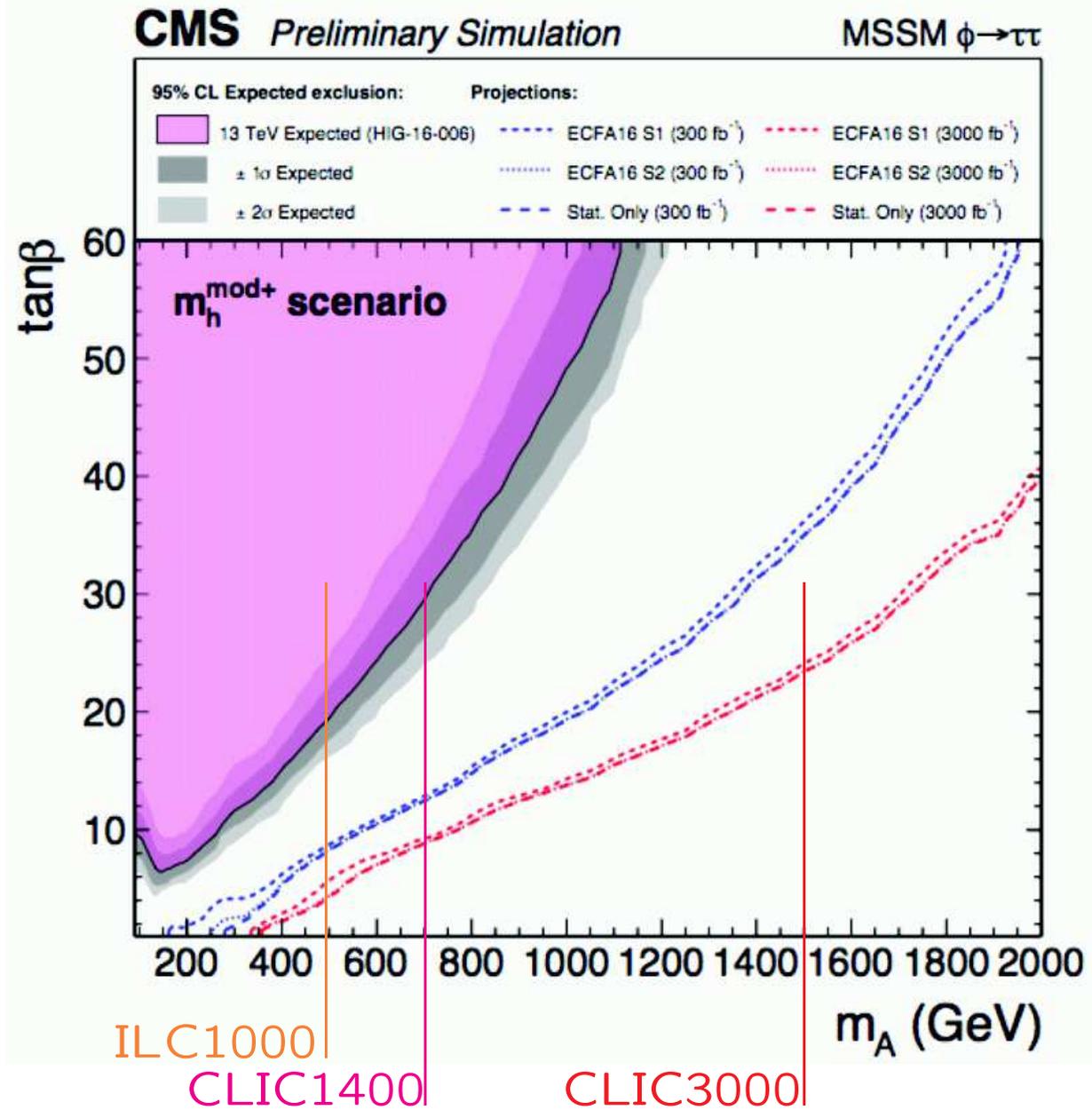
$\Rightarrow$  only pair production of heavy Higgs bosons!

reach:  $M_A \lesssim \sqrt{s}/2$



⇒ close to kinematic limit

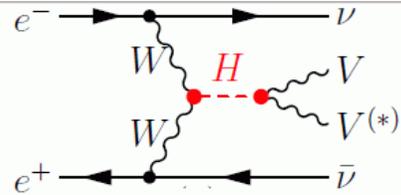
# “Simple” LC reach in the MSSM (neglecting $t\bar{t}$ final states)



⇒ unique opportunities!

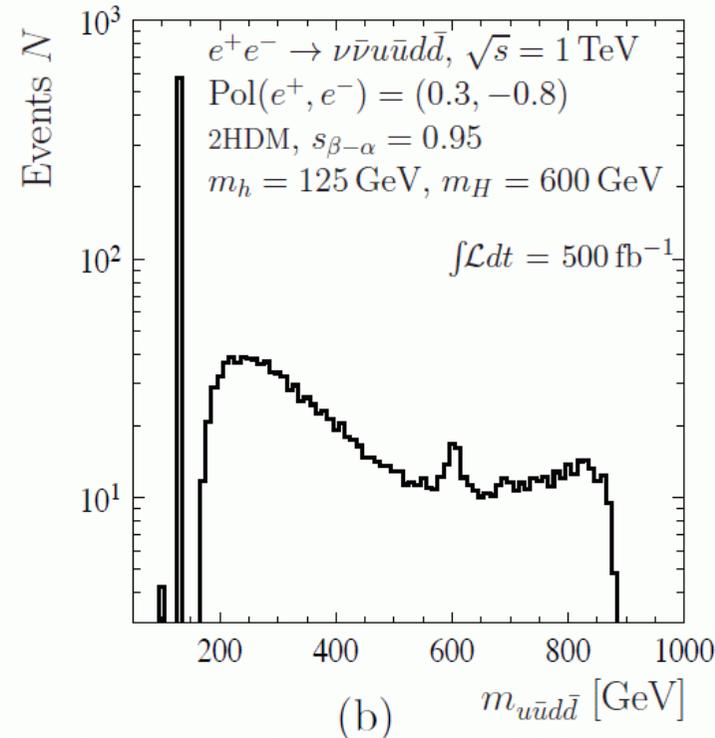
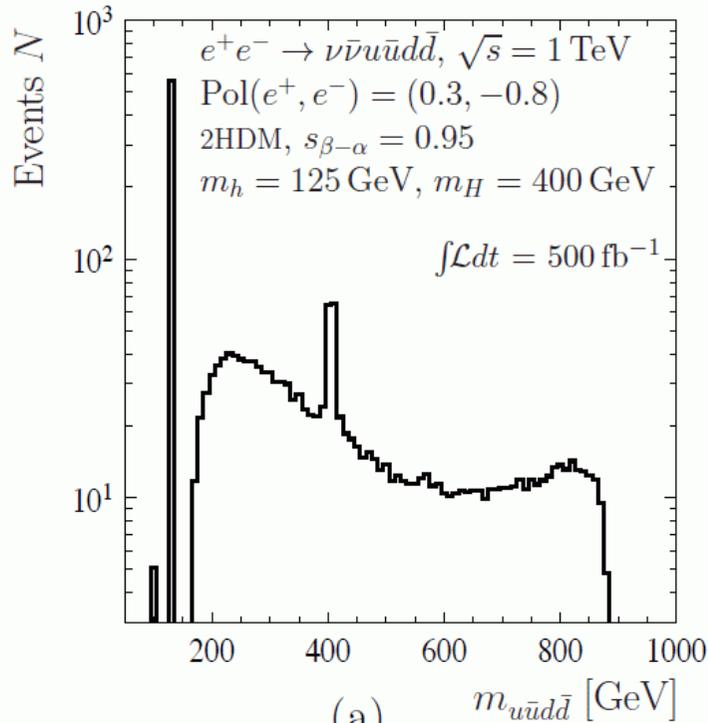
# Single heavy Higgs production beyond kinematic reach:

## Sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)



[S. Liebler et al. '15]

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



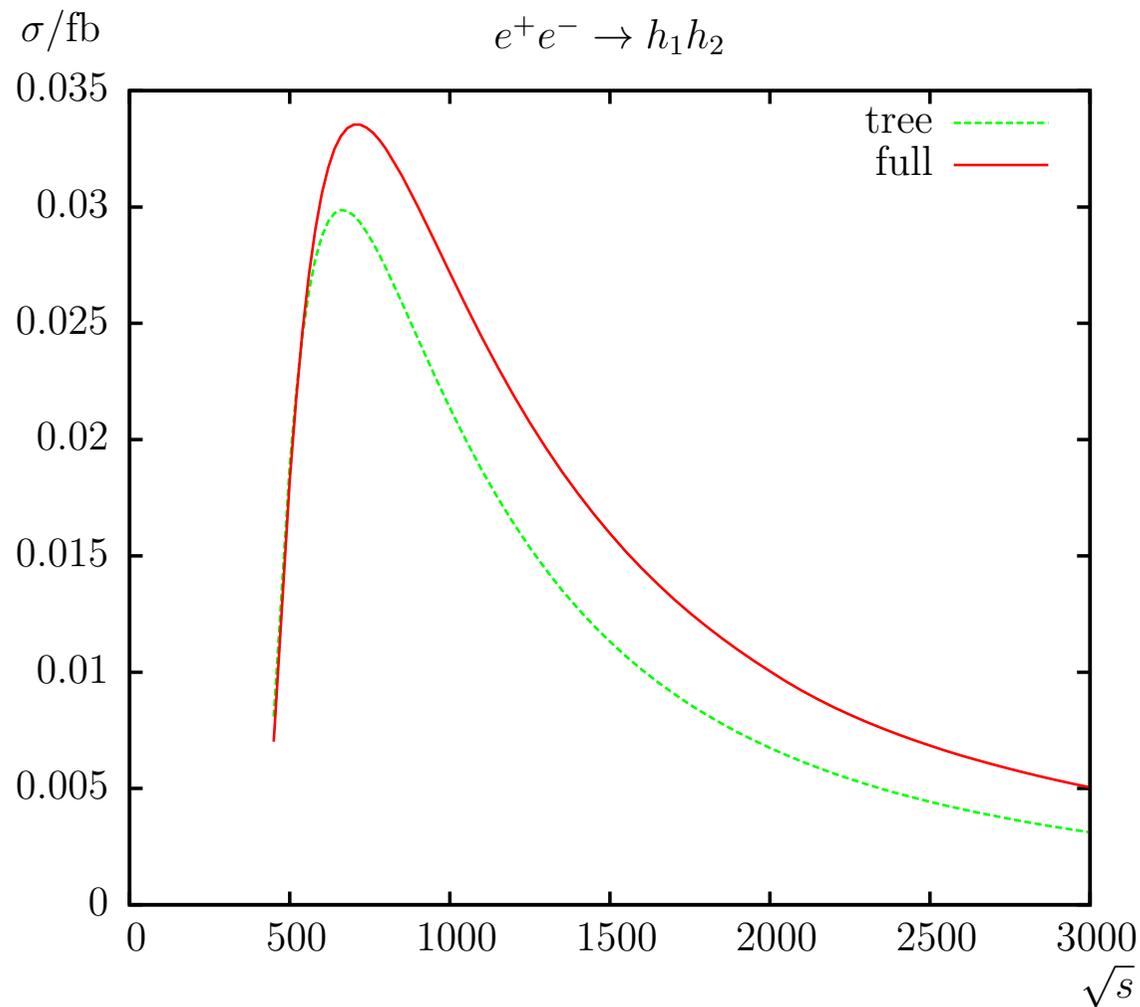
⇒ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[Taken from G. Weiglein '18]

# Are the theory predictions under control? MSSM example (I):

[S.H., C. Schappacher '15]

$e^+e^- \rightarrow h_1h_2$ :

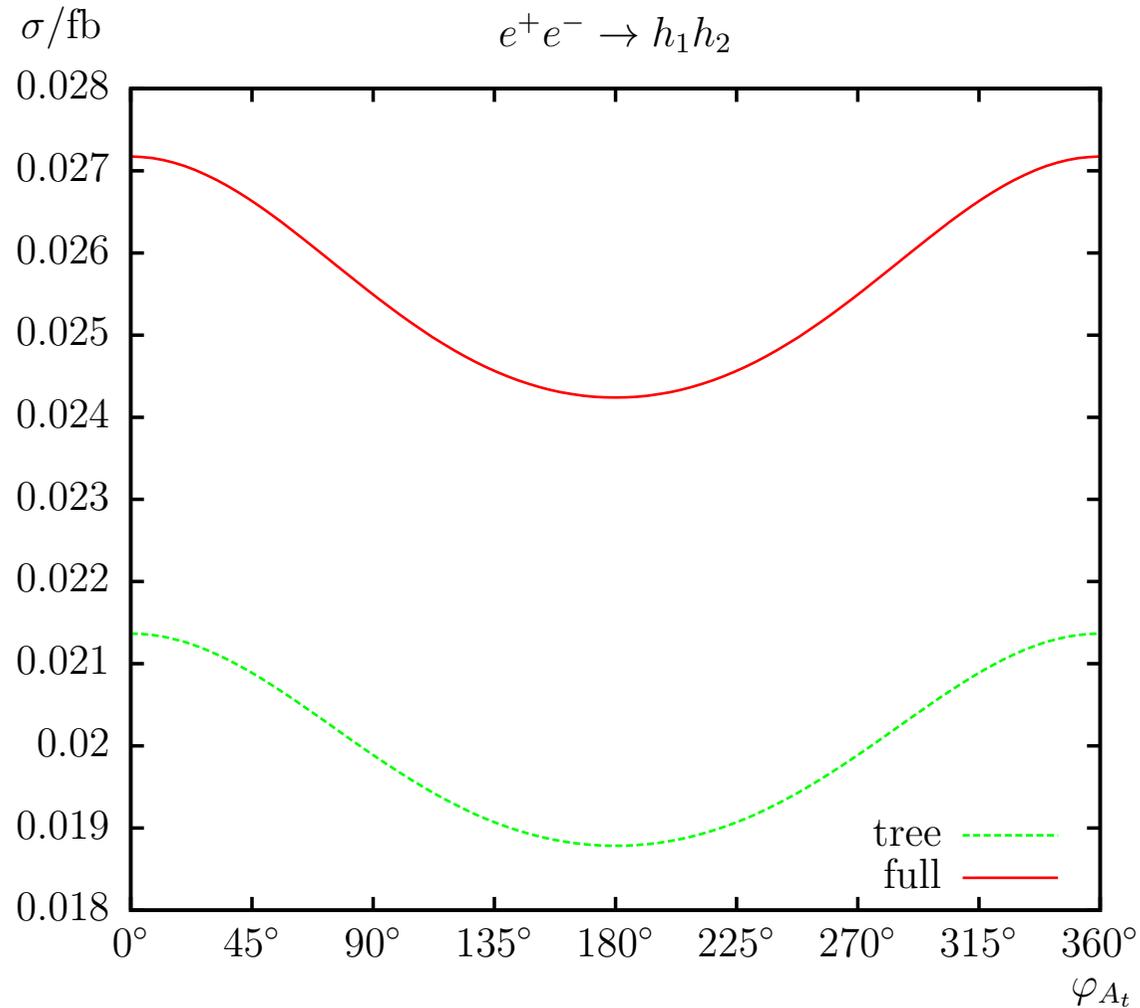


$\Rightarrow$  loop corrections crucial!

## Are the theory predictions under control? MSSM example (II):

[S.H., C. Schappacher '15]

$e^+e^- \rightarrow h_1h_2$ :

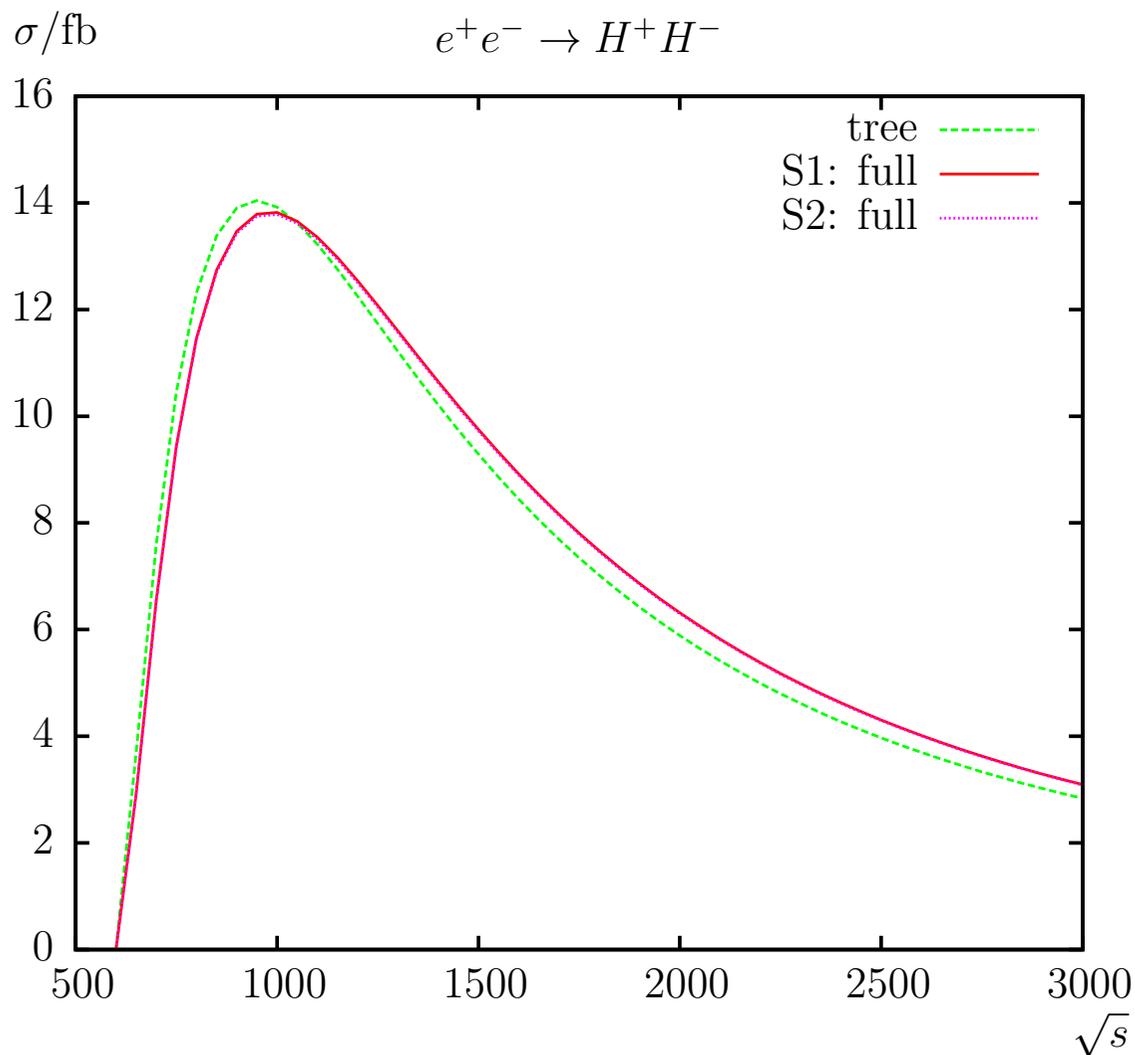


$\Rightarrow$  phase dependence more pronounced at loop-level

# Are the theory predictions under control? MSSM example (III):

[S.H., C. Schappacher '16]

$e^+e^- \rightarrow H^+H^-$ :

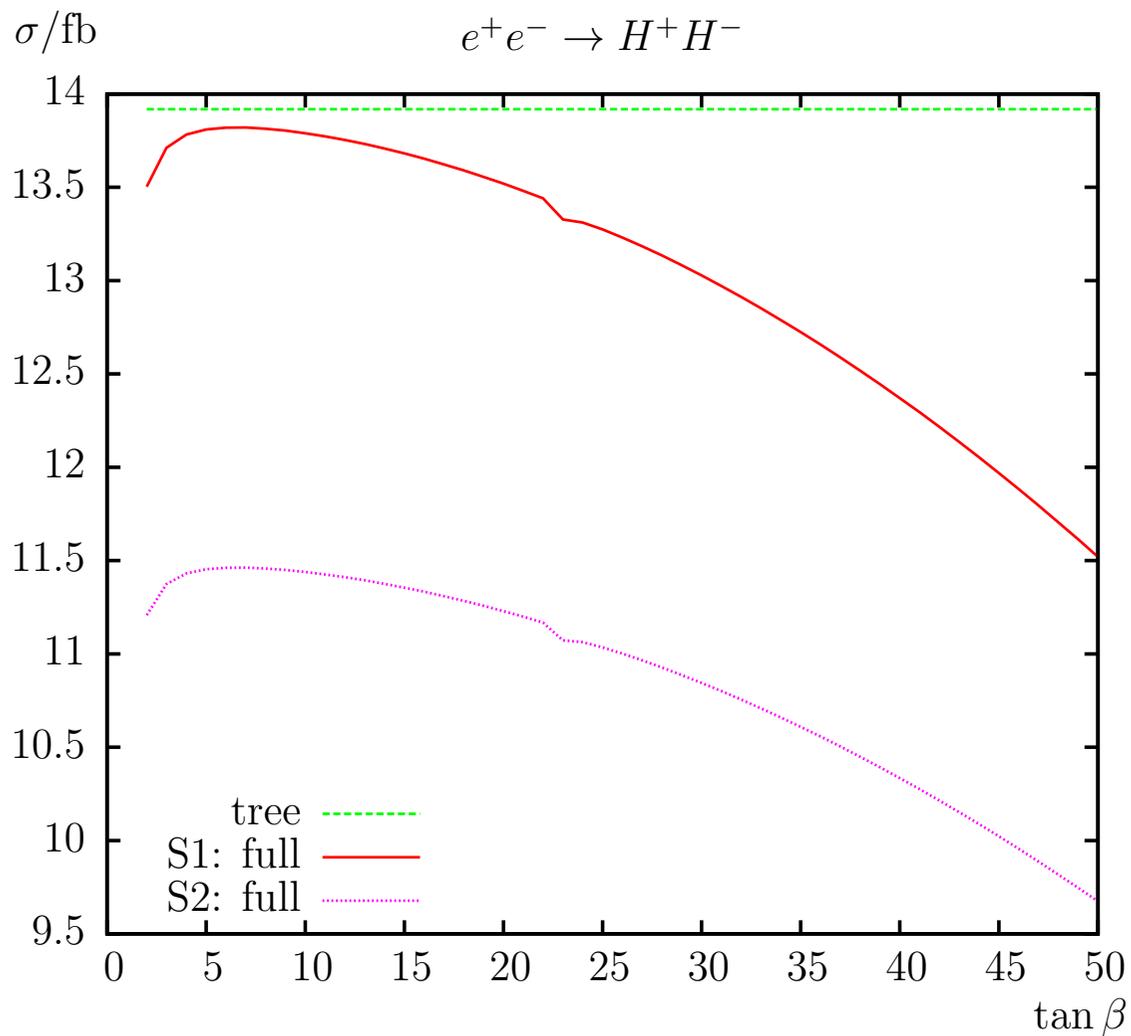


$\Rightarrow$  loop corrections non-negligible!

# Are the theory predictions under control? MSSM example (IV):

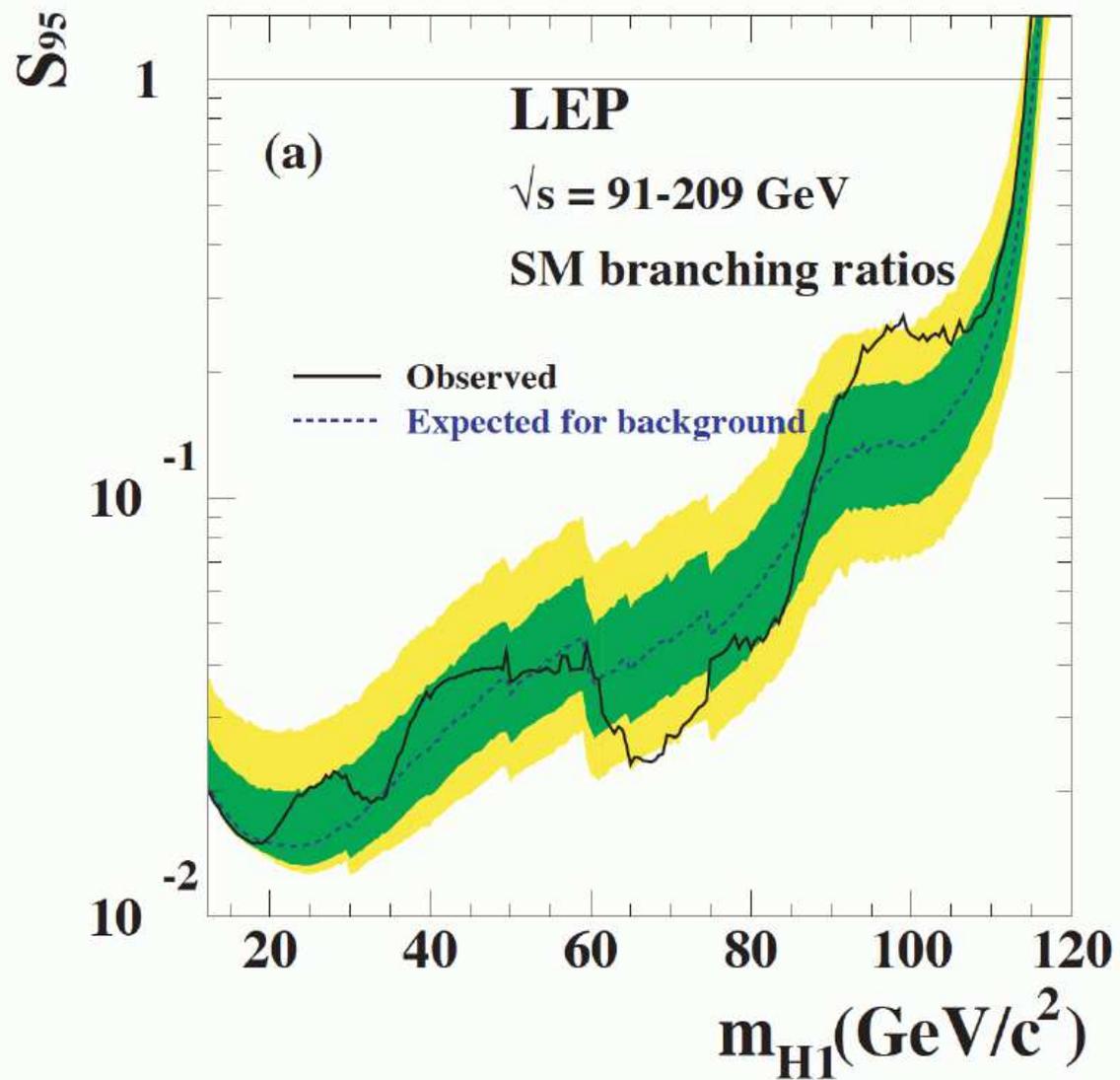
[S.H., C. Schappacher '15]

$$\underline{e^+e^- \rightarrow H^+H^-}$$



$\Rightarrow$  loop corrections sizable for large  $\tan \beta$

### 3. BSM Higgs Bosons below 125 GeV

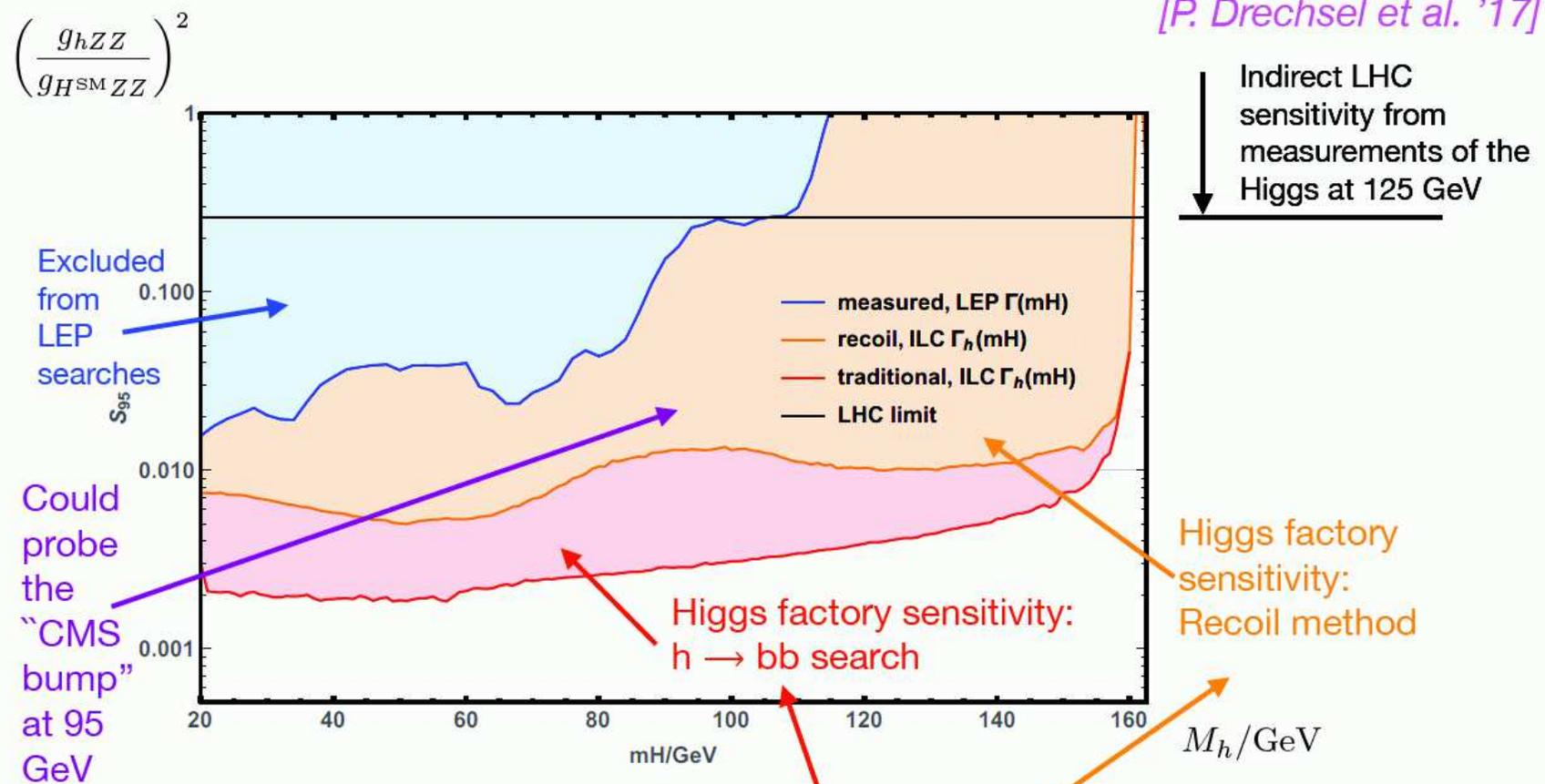


⇒ LEP limits!

⇒ ILC limits?

## ILC reach for light Higgs bosons:

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

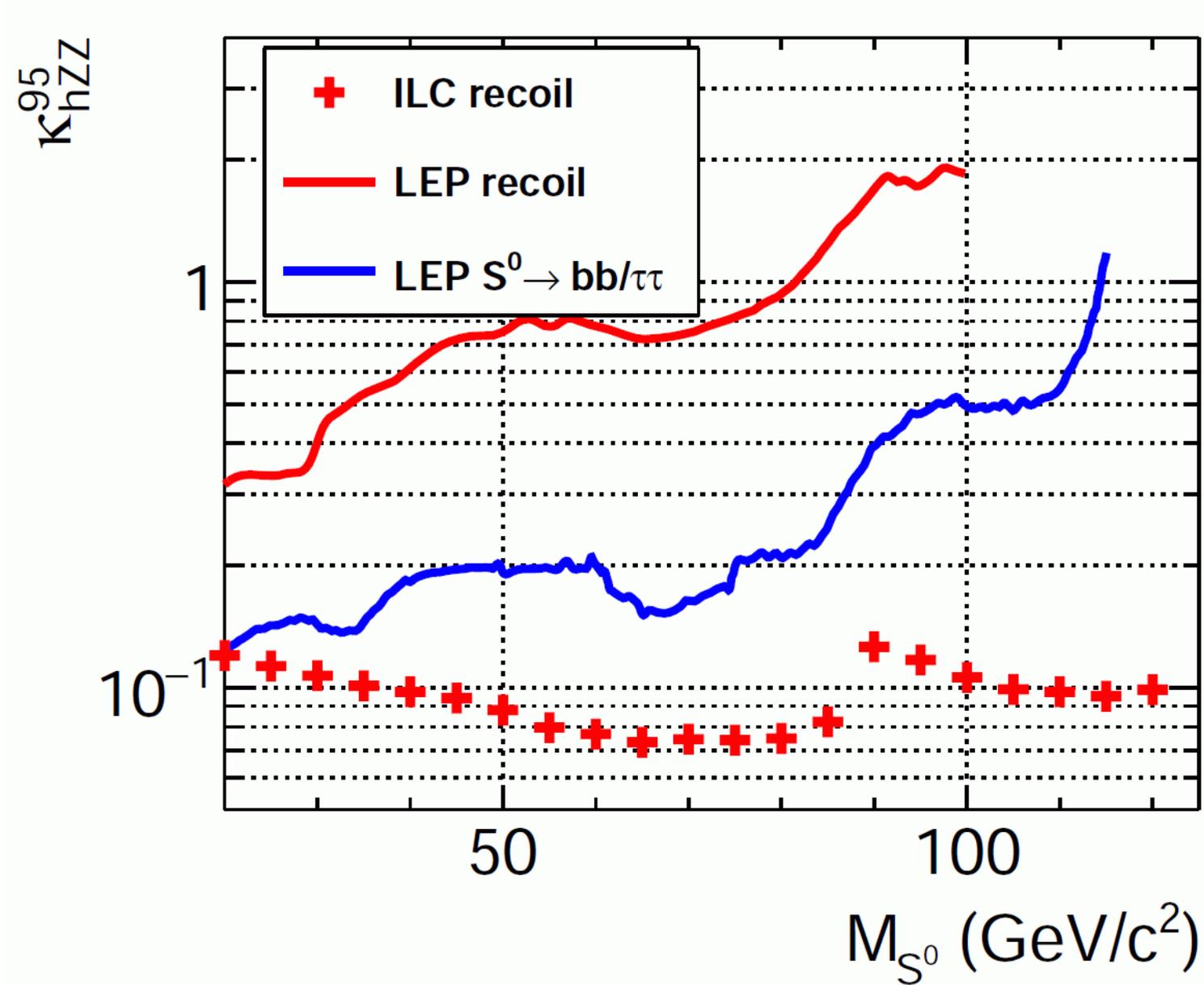


**⇒ Higgs factory at 250 GeV will explore a large untested region!**

[Taken from G. Weiglein '18]

Theory study confirmed by experimental analysis:

[Y. Wang et al. '18]



Interesting case: light singlet

Singlet does not couple to SM particles!

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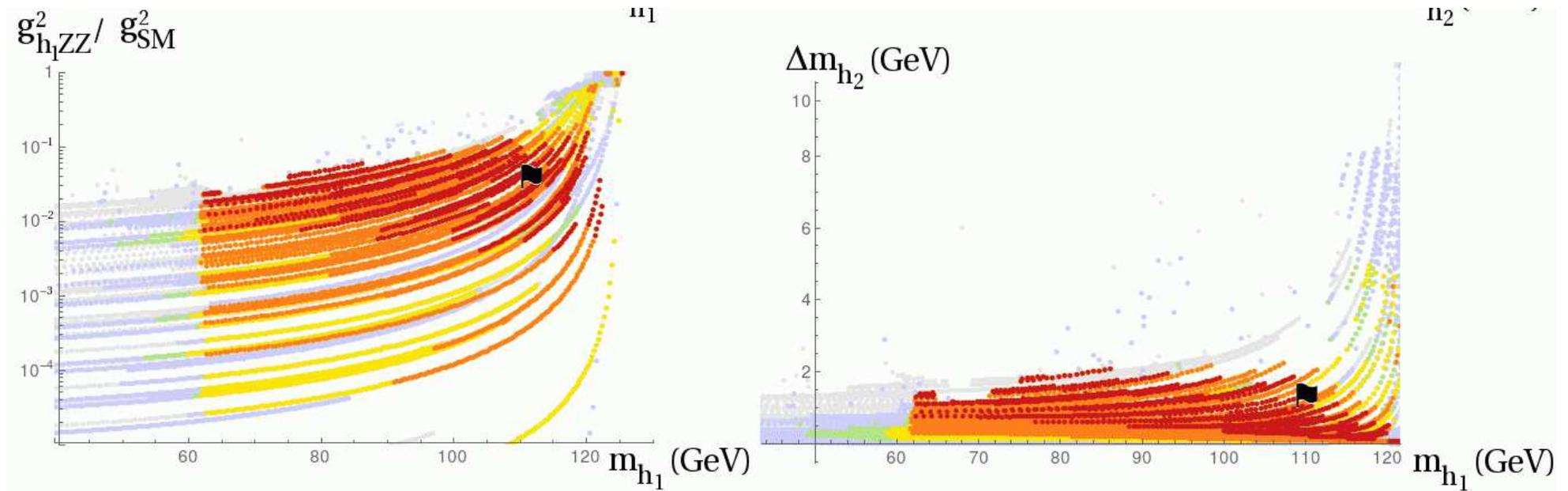
“Easily” possible in the NMSSM:

Light, singlet-like Higgs below 125 GeV

Can the ILC find them?

Parameters:

$\tan \beta = 8$ ,  $M_A = 1$  TeV,  $A_\kappa = -2 \dots 0$  TeV,  $\mu = 120 \dots 2000$  GeV,  
 $2M_1 = M_2 = 500$  GeV,  $M_3 = 1.5$  TeV,  $m_{\tilde{Q}_3} = 1$  TeV,  $m_{\tilde{Q}_{1,2}} = 1.5$  TeV,  
 $A_t = -2$  TeV,  $A_{b,\tau} = -1.5$  TeV



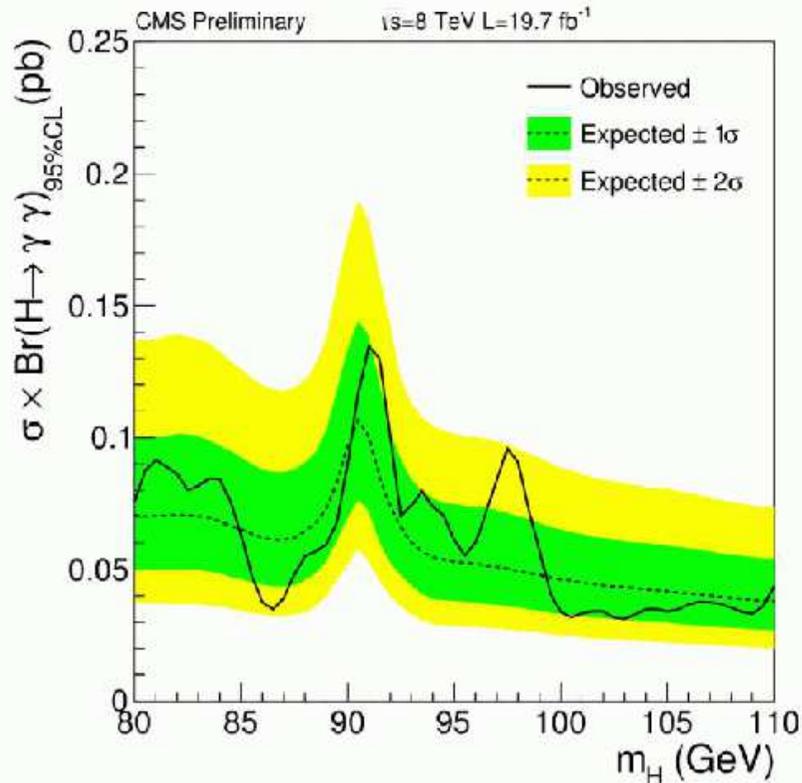
- ⇒ light Higgs below 125 GeV
- ⇒ strongly reduced couplings to gauge bosons!
- ⇒ possibly within ILC reach!

# $h \rightarrow \gamma\gamma$ (65-110 GeV) Run 1

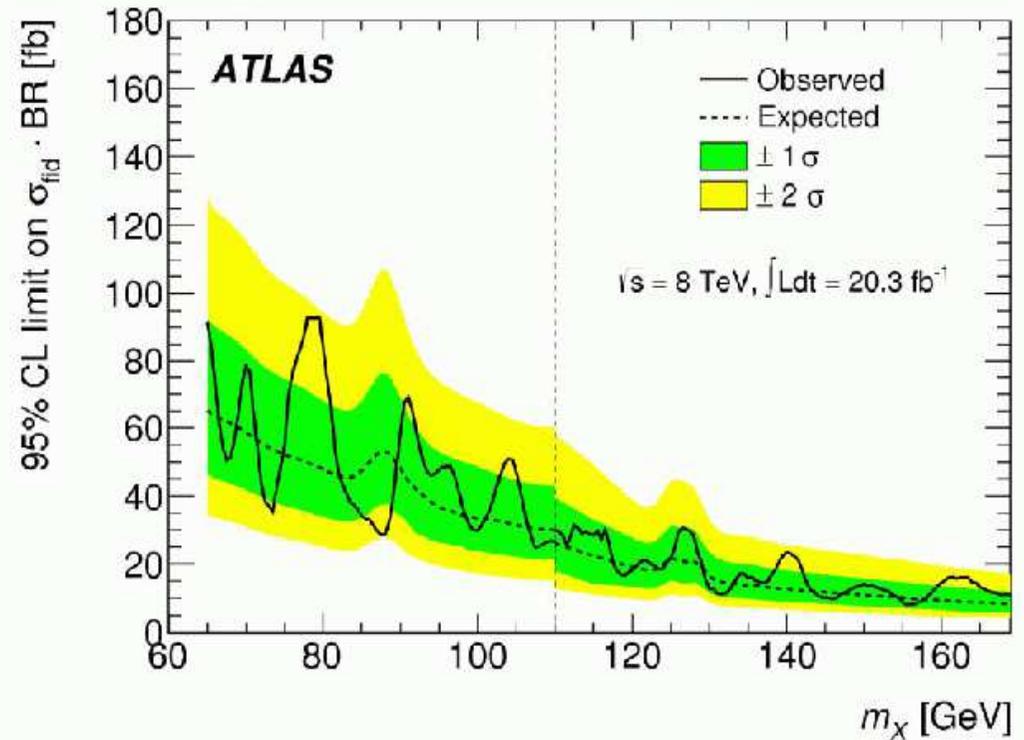


CMS PAS HIG-14-037

PRL 113 171801 (2014)



•  $\sim 2\sigma$  excursion @  $\sim 97.5$  GeV



•  $\sim 2\sigma$  excursion @  $\sim 80$  GeV

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

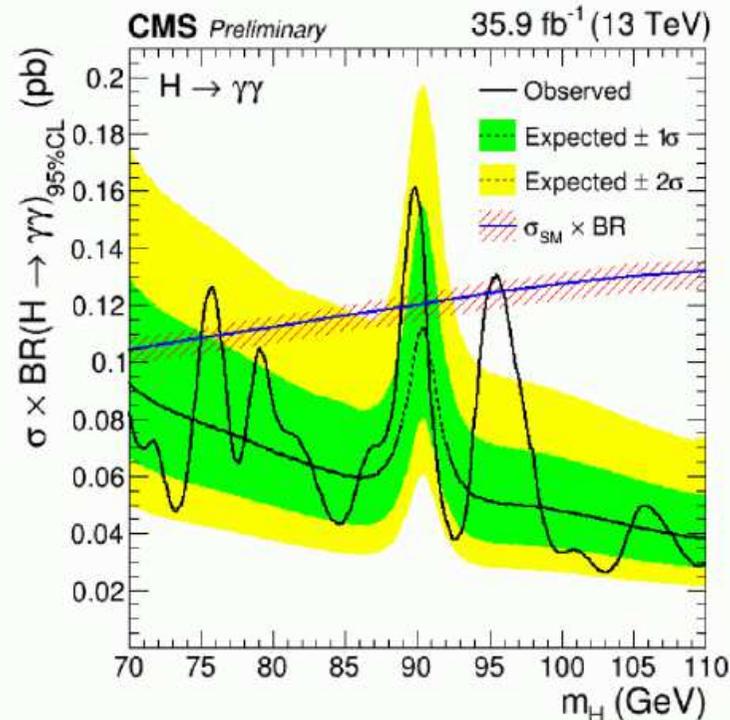
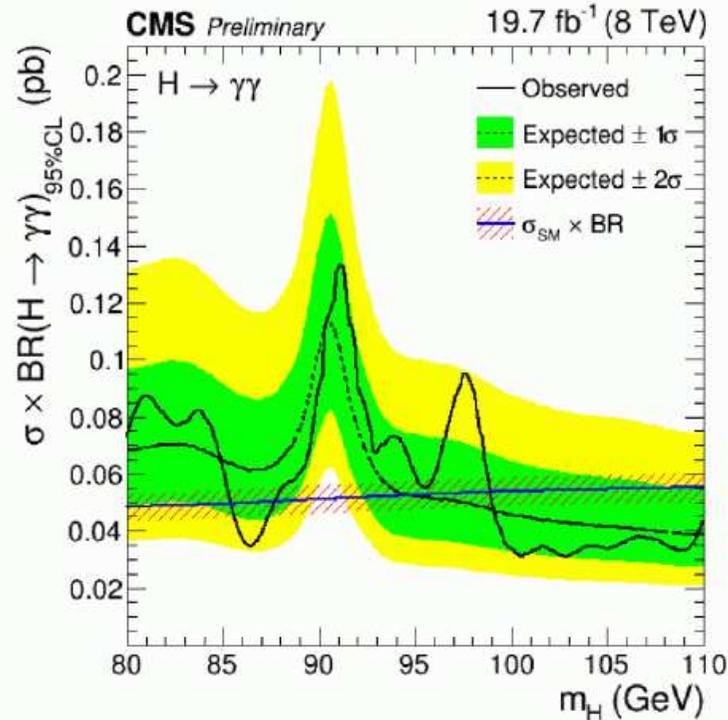
18



# $h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+2



CMS PAS HIG-17-013



8 TeV:  
 minimum(maximum)  
 limit on  $\sigma \times Br$  :  
 31(133) fb at  
 $m=102.8(91.1)$  GeV

13 TeV:  
 minimum(maximum)  
 limit on  $\sigma \times Br$  :  
 26(161) fb at  
 $m=103.0(89.9)$  GeV

- 8 TeV limits on  $\sigma \times Br$  redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

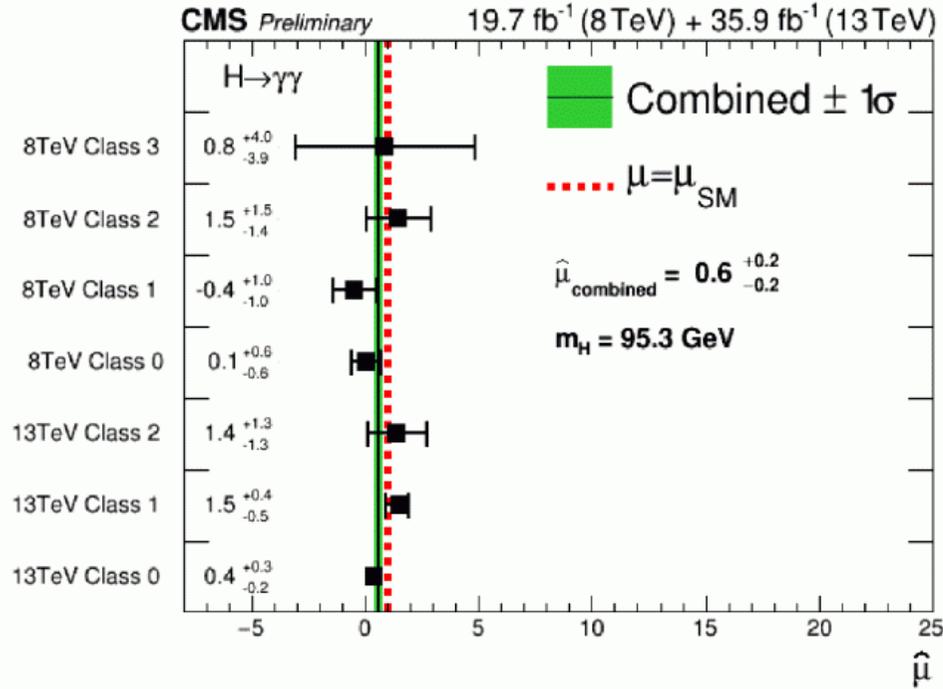
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017



# $h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+2



CMS PAS HIG-17-013



Excess here mostly driven by class 1 (&2) at 13 TeV

$\chi^2$  probability for the seven individual values to be compatible with a single signal hypothesis: 41%

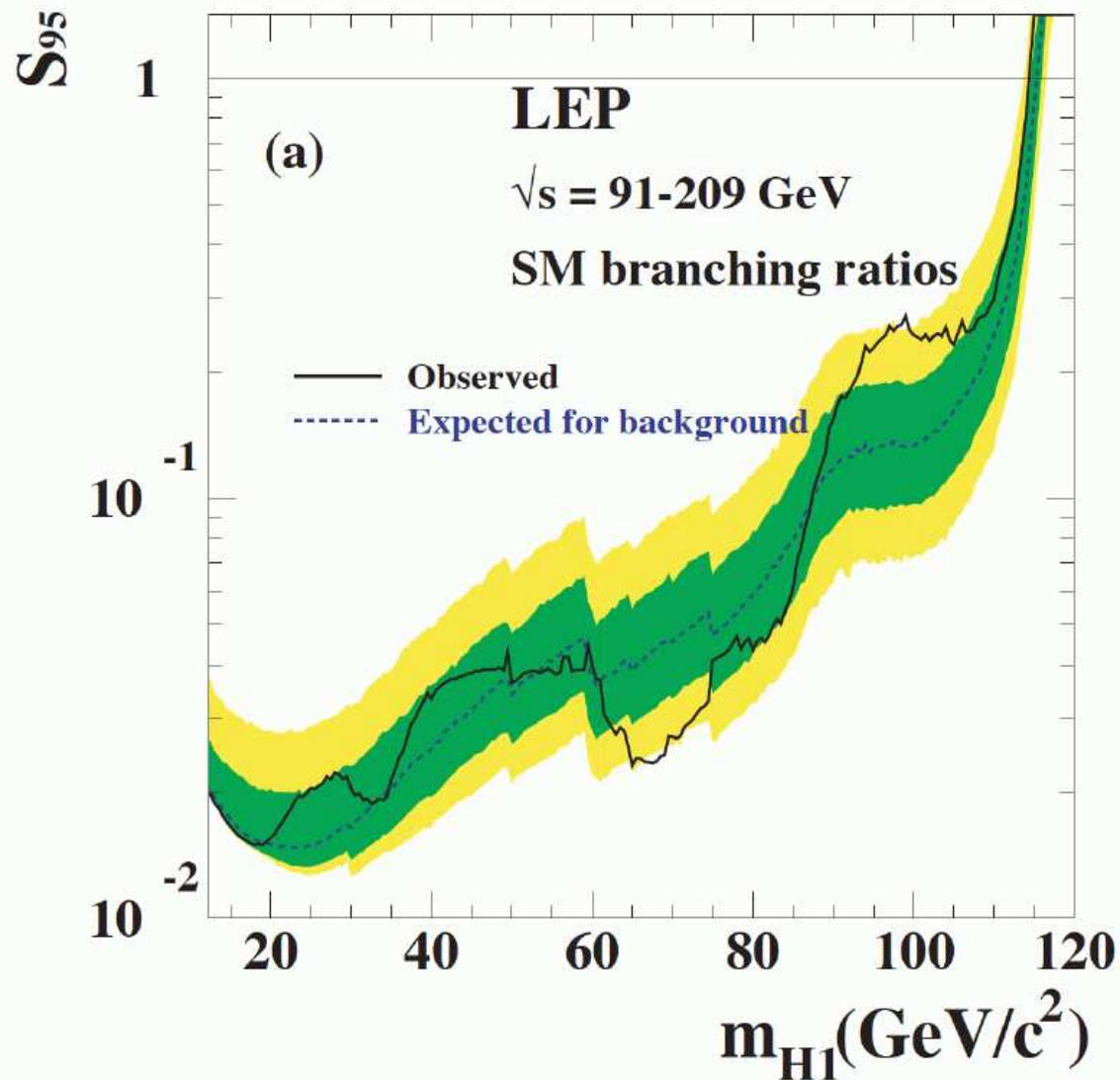
- ‘Signal’ strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing  $m_H=95.3 \text{ GeV}$
- More data are required to ascertain the origin of this excess

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55

$$\mu_{\text{CMS}}(96 \text{ GeV}) = [\sigma(pp \rightarrow h_1) \times \text{BR}(h_1 \rightarrow \gamma\gamma)]_{\text{exp/SM}} = 0.6 \pm 0.2$$

## “96 GeV excess”: what was seen at LEP?



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

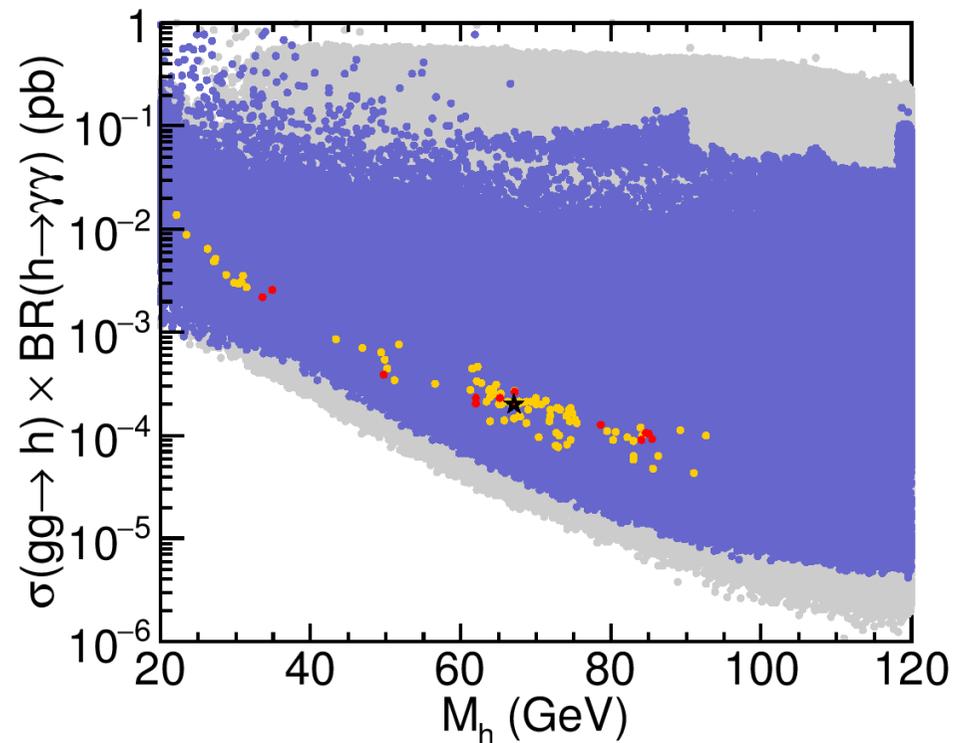
Should we get excited?

⇒ according to CMS no!

⇒ let's wait for ATLAS, ETA summer '18

Which model fits?

[P. Bechtle, H. Haber, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '16]



⇒ not the MSSM

⇒ 2HDM? NMSSM?

## Check 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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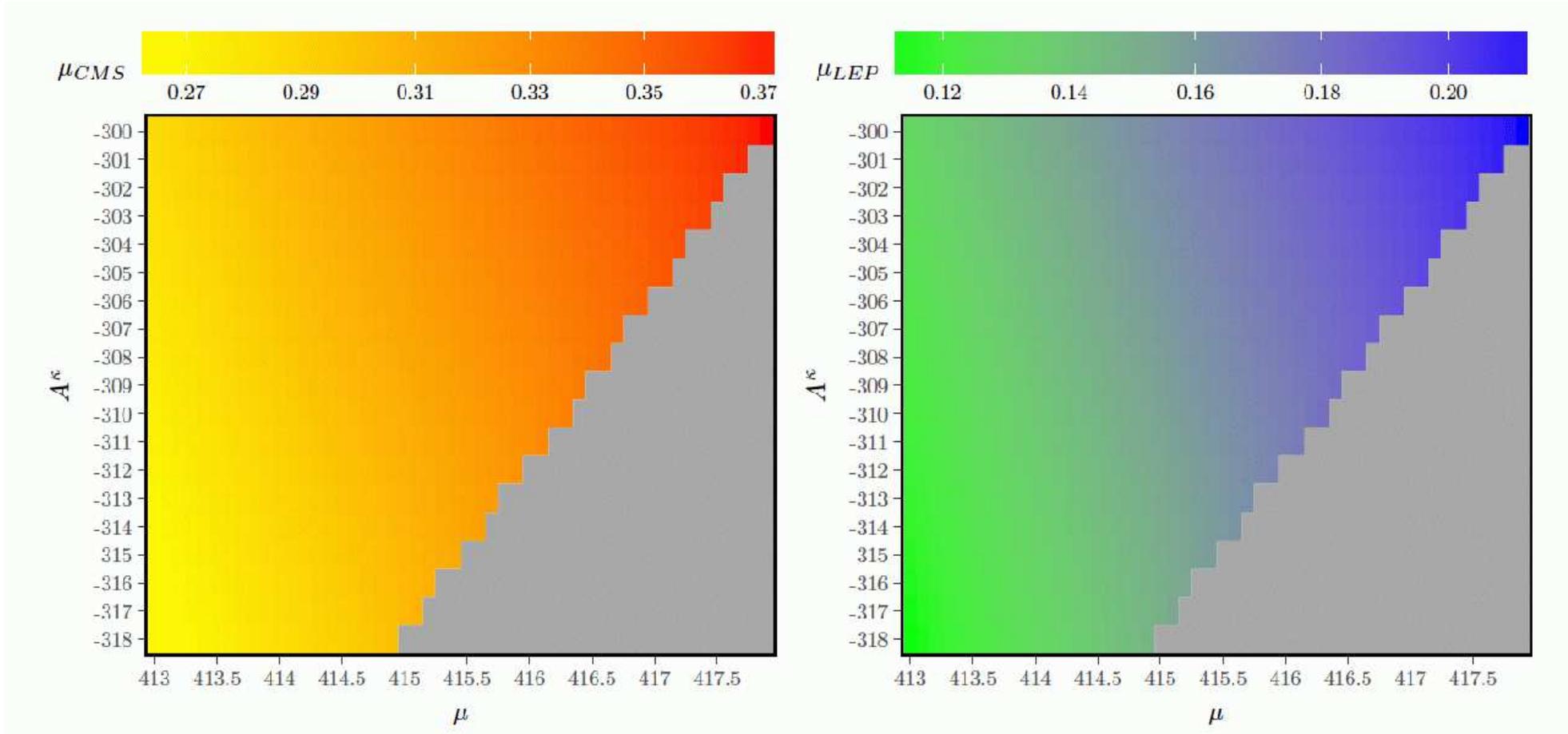
Can the  $\mu\nu$ SSM explain the two “excesses”?

[T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475]

$v_{iL}$	$Y_i^\nu$	$A_i^\nu$	$\tan\beta$	$\mu$	$\lambda$	$A^\lambda$	$\kappa$	$A^\kappa$	$M_1$
$\sqrt{2} \cdot 10^{-5}$	$10^{-7}$	-1000	2	[413; 418]	0.6	956.035	0.035	[-300; -318]	100
$M_2$	$M_3$	$m_{\tilde{Q}_{iL}}^2$	$m_{\tilde{u}_{iR}}^2$	$m_{\tilde{d}_{iR}}^2$	$A_1^u$	$A_{2,3}^{u,d}$	$(m_e^2)_{ii}$	$A_{33}^e$	$A_{11,22}^e$
200	1500	$800^2$	$800^2$	$800^2$	0	0	$800^2$	0	0

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[*T. Biekötter, S.H., C. Muñoz, arXiv:1712.07475*]

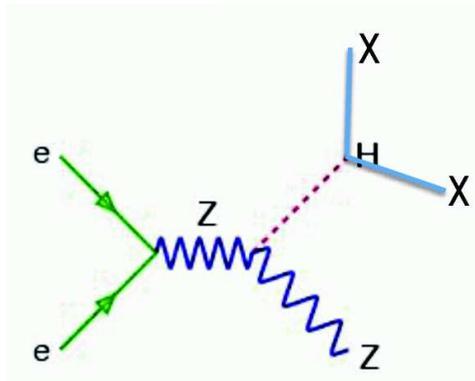
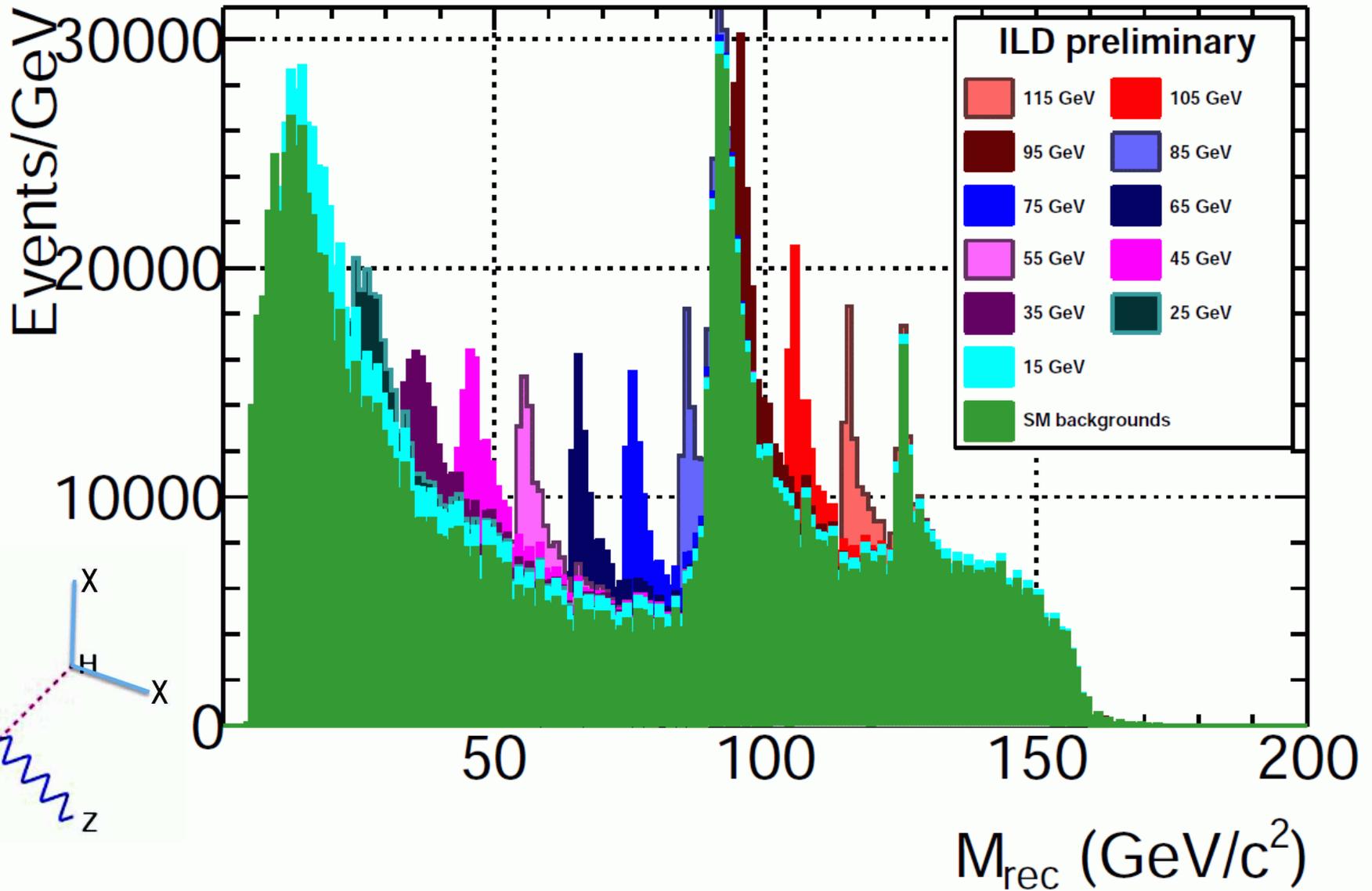


⇒ YES, WE CAN! :-)

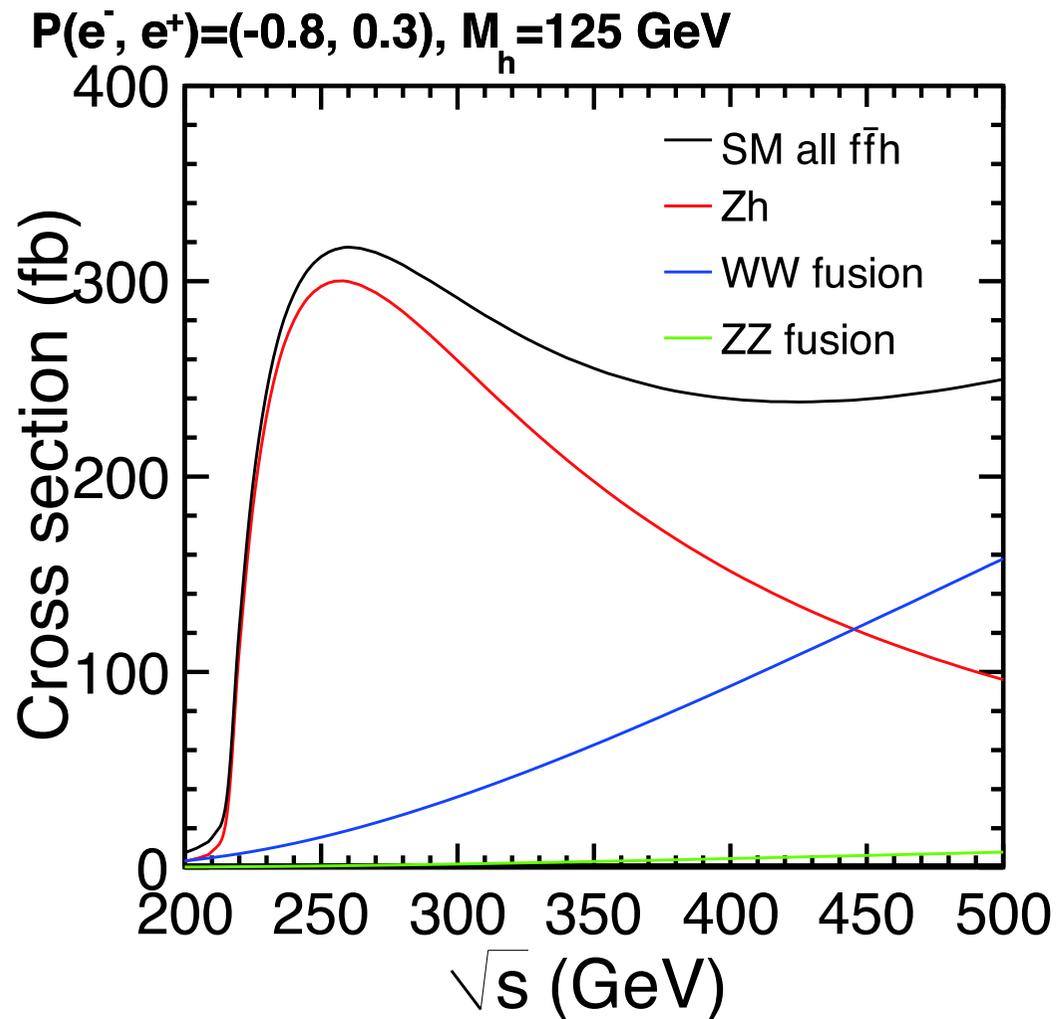
(at the 1 – 1.5  $\sigma$  level)

⇒ Easily tested at the ILC!

@250 GeV ILC with 2000 fb<sup>-1</sup> luminosities

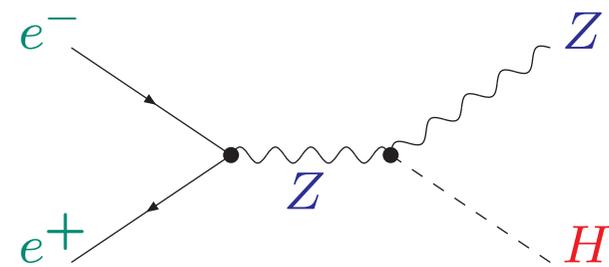


## 4. BSM Higgs Boson at 125 GeV



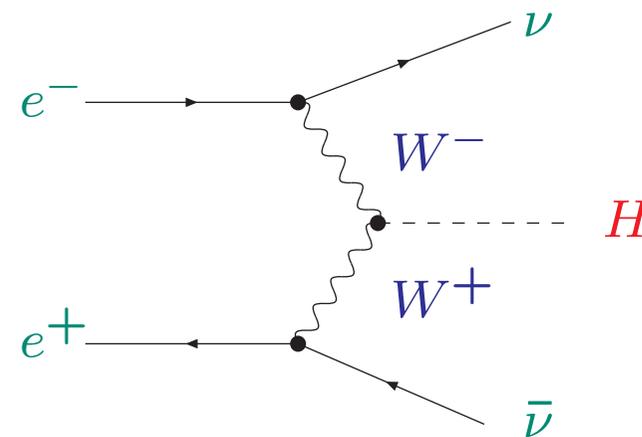
Higgs-strahlung:

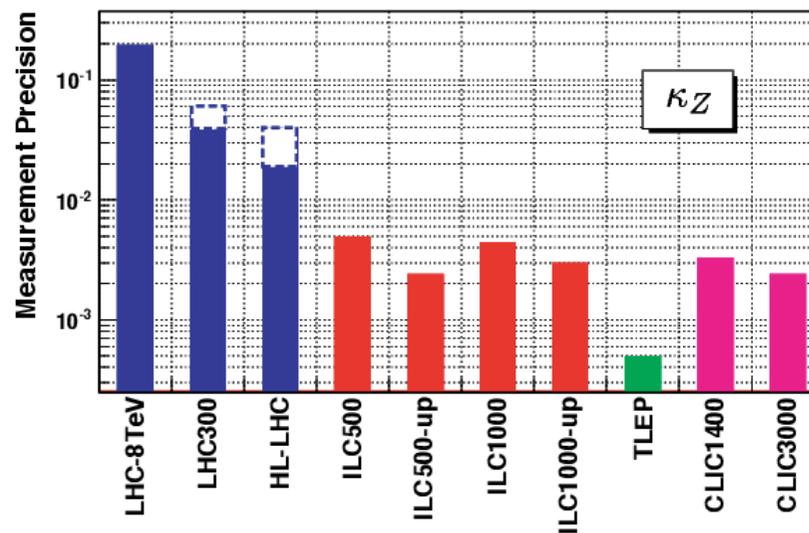
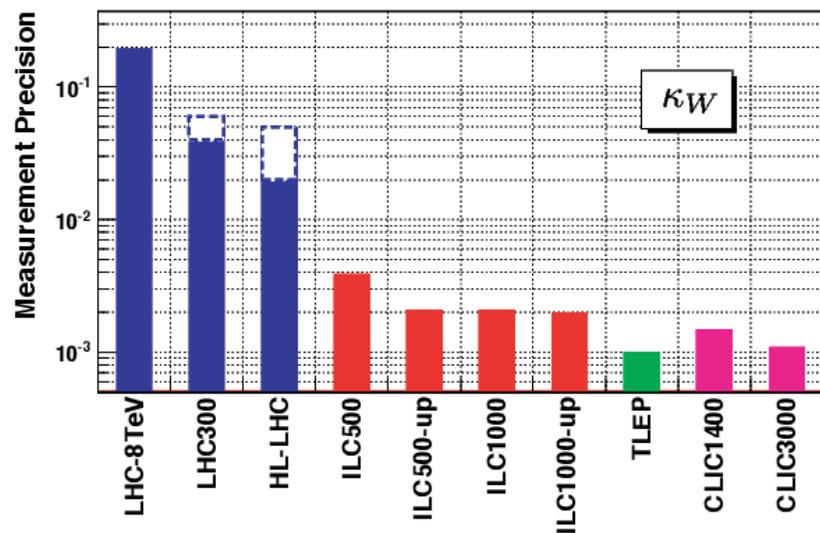
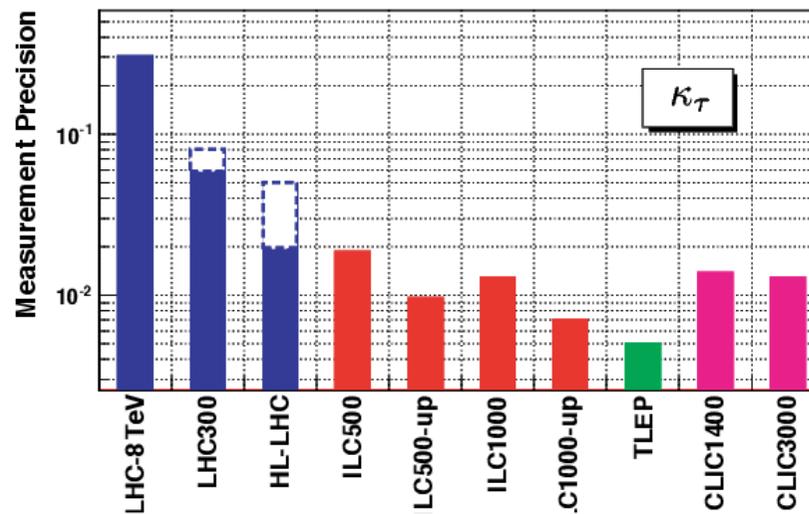
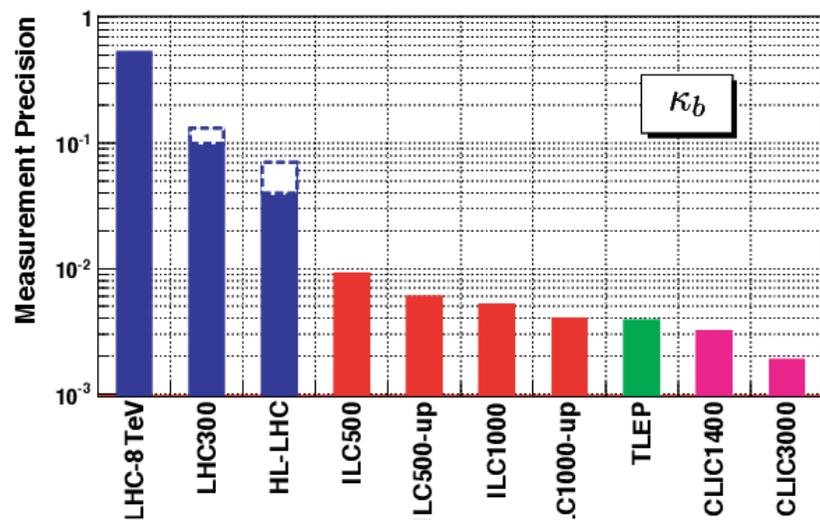
$$e^+e^- \rightarrow Z^* \rightarrow ZH$$



weak boson fusion (WBF):

$$e^+e^- \rightarrow \nu\bar{\nu}H$$



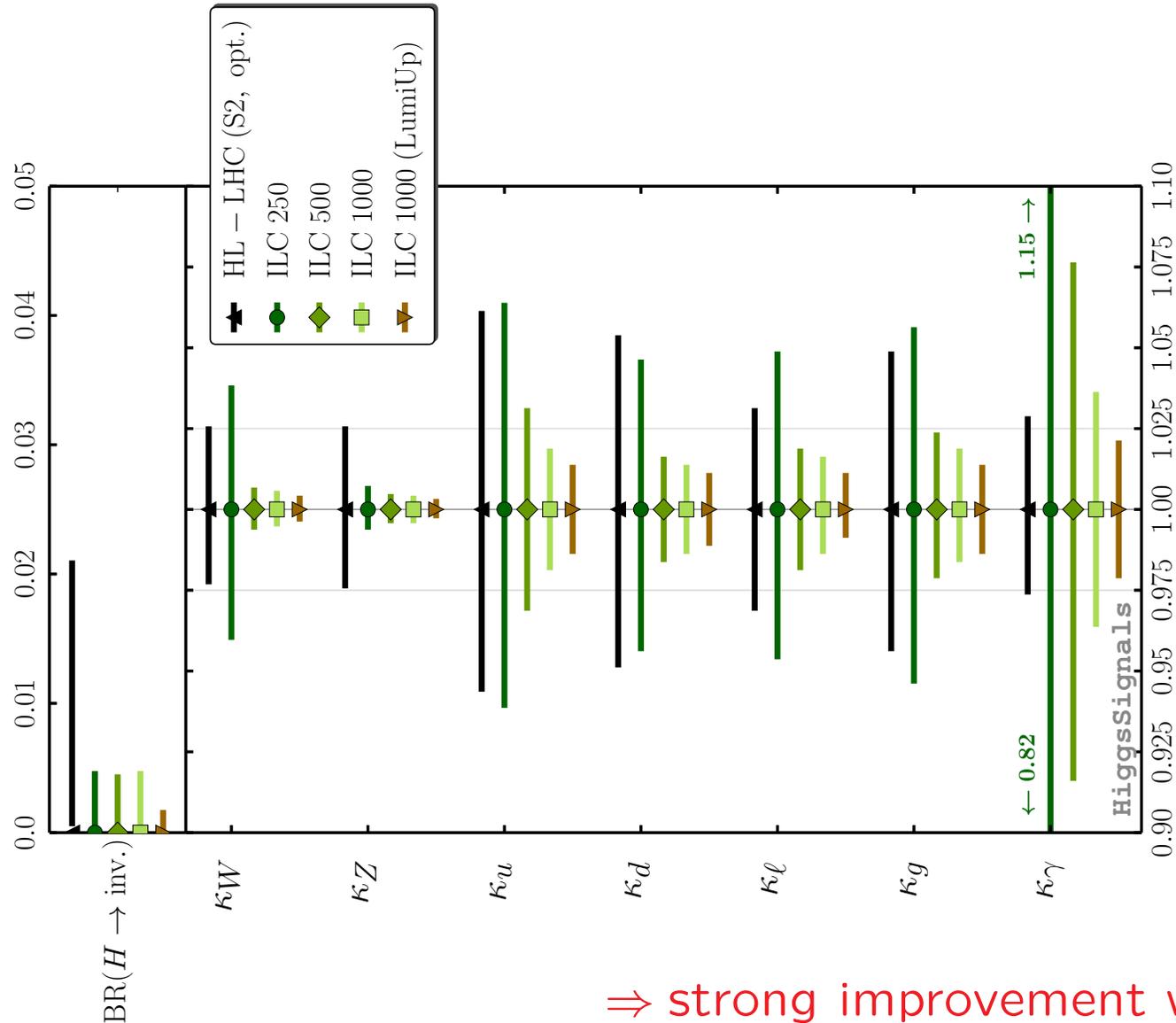


⇒ can the sub-percent/permille level be matched by theory?

# HL-LHC vs. ILC in the most general $\kappa$ framework:

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

assumption:  $BR(H \rightarrow NP) = BR(H \rightarrow inv.)$

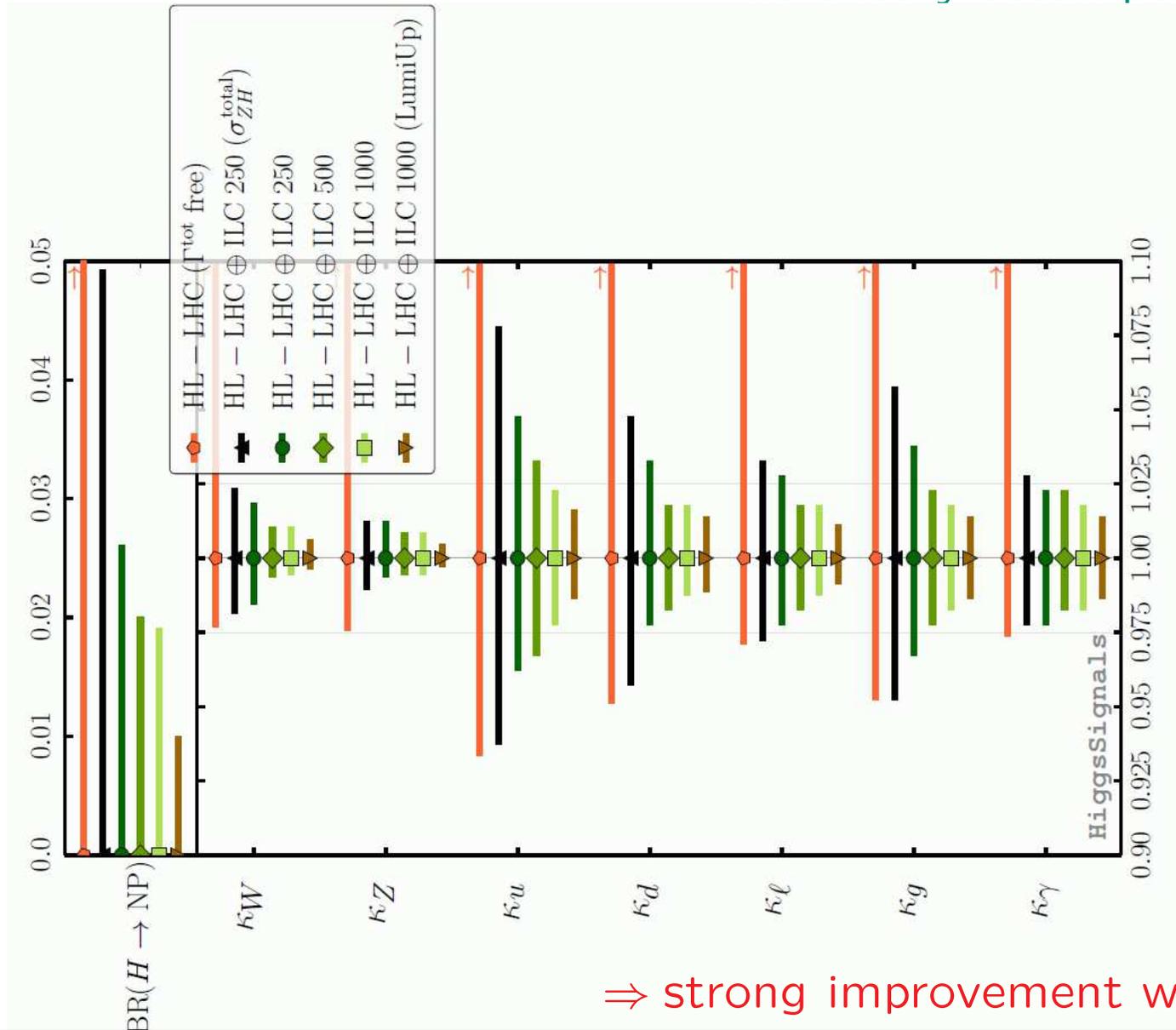


$\Rightarrow$  strong improvement with the ILC

# HL-LHC vs. ILC in the most general $\kappa$ framework:

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

no theory assumptions, full fit



$\Rightarrow$  strong improvement with the ILC

## 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:

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

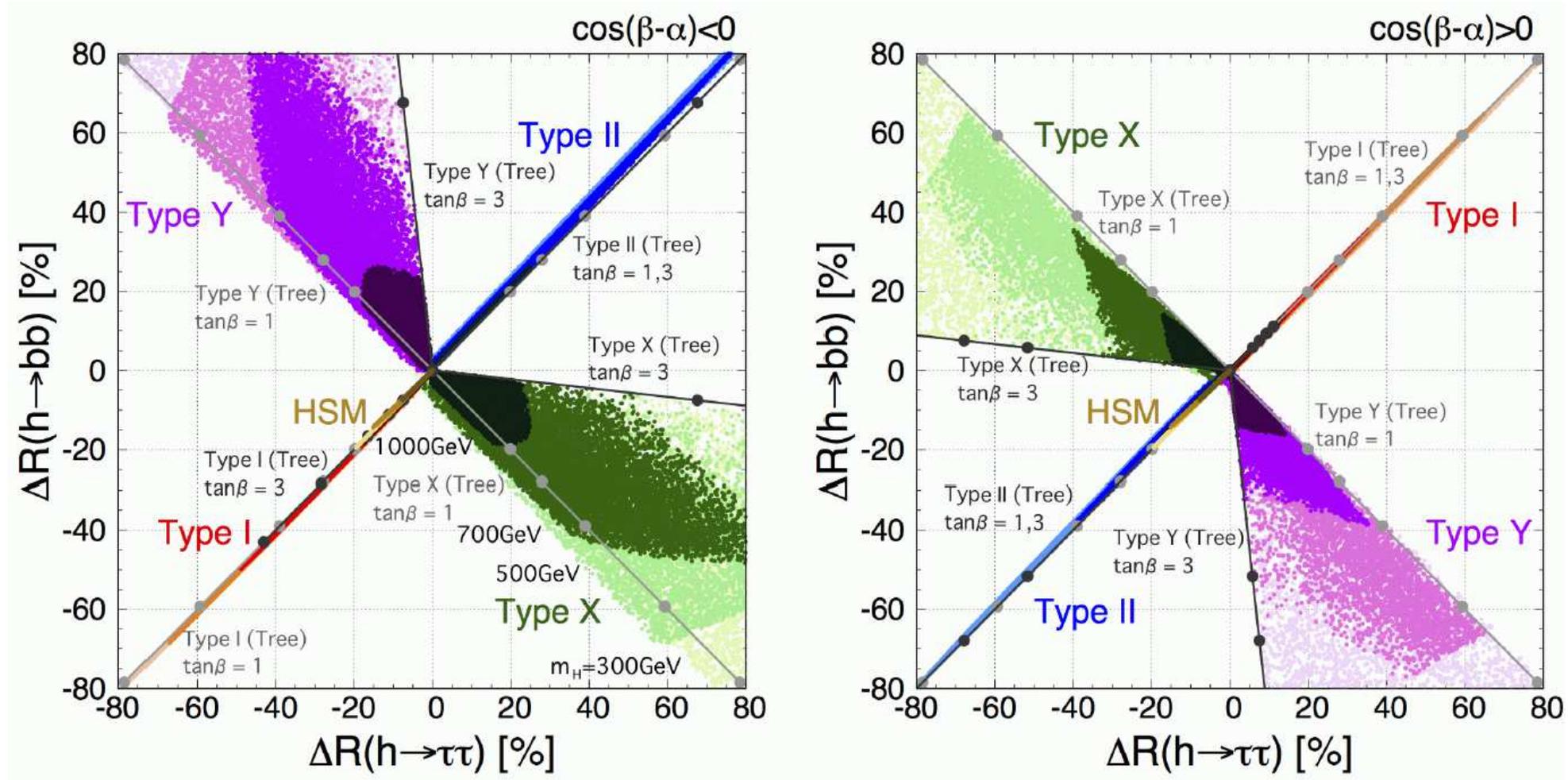
$$\kappa_F \approx 1 - (3 - 9)\% \left( \frac{1 \text{ TeV}}{f} \right)^2$$

⇒ couplings to bosons in the **per mille** range

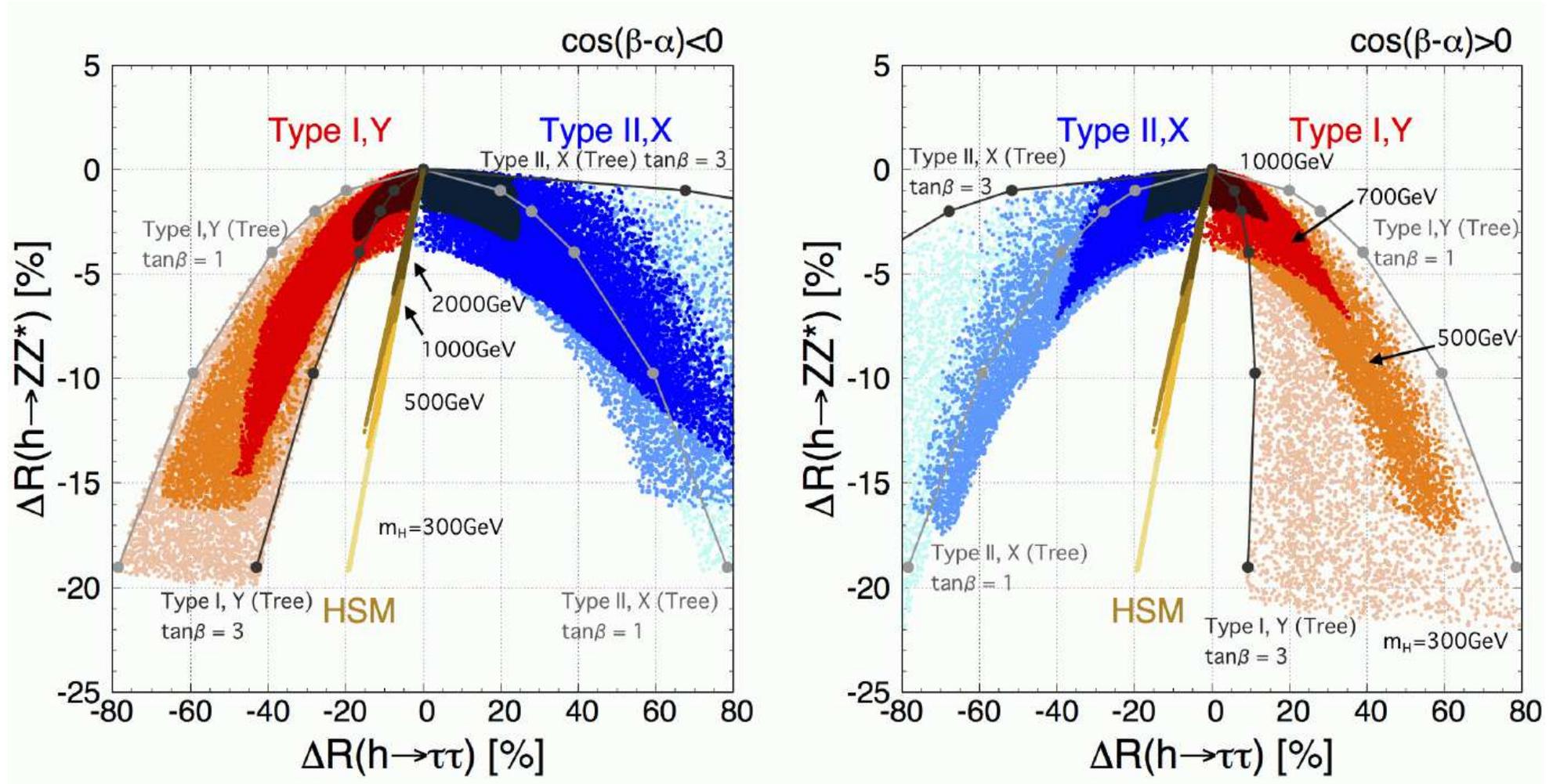
⇒ couplings to fermions in the **per cent** range

⇒ the more precise the better

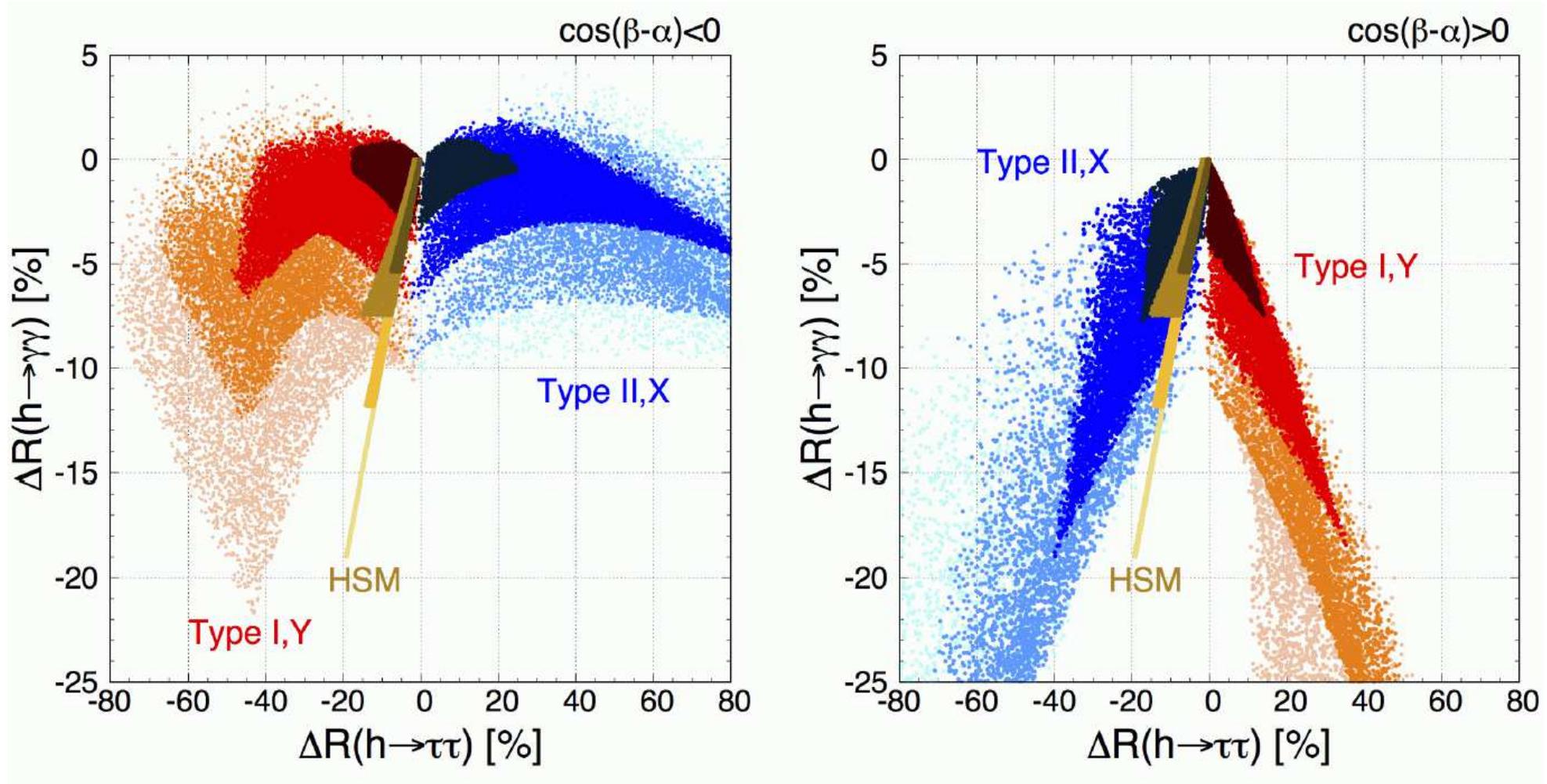
⇒ **ILC/CLIC can discriminate (many) models!**



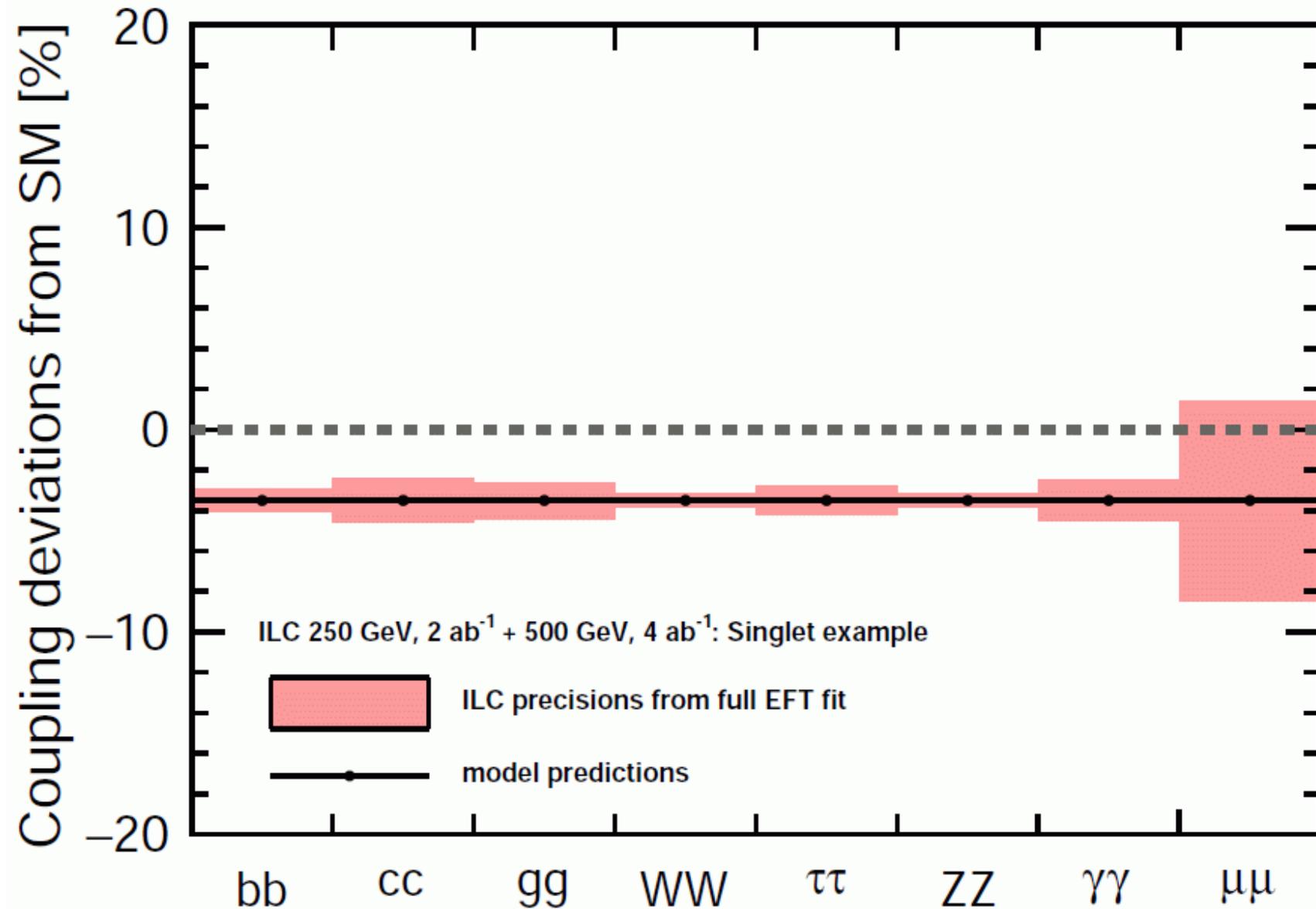
⇒ LC precision has a great potential to discriminate the models!

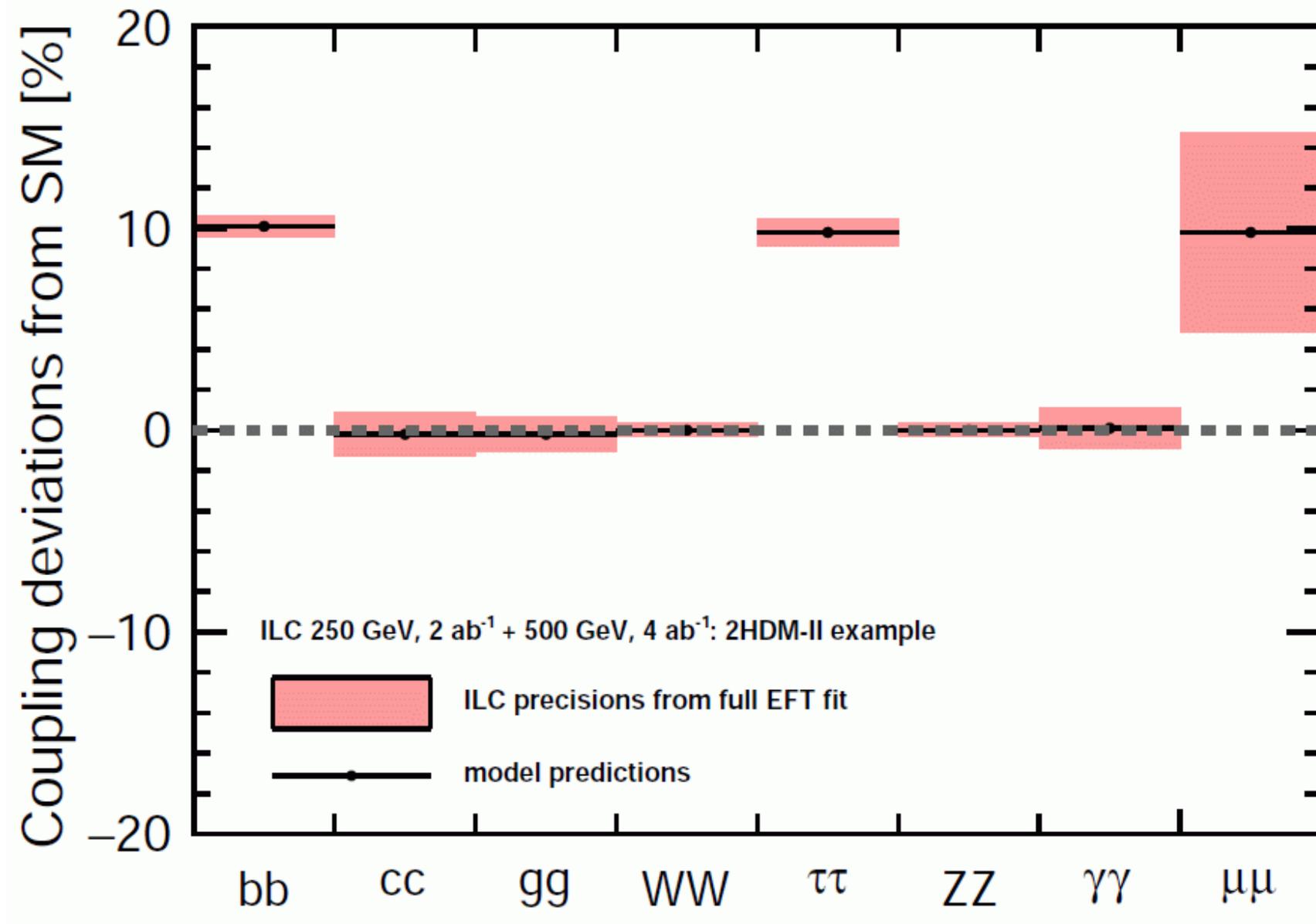


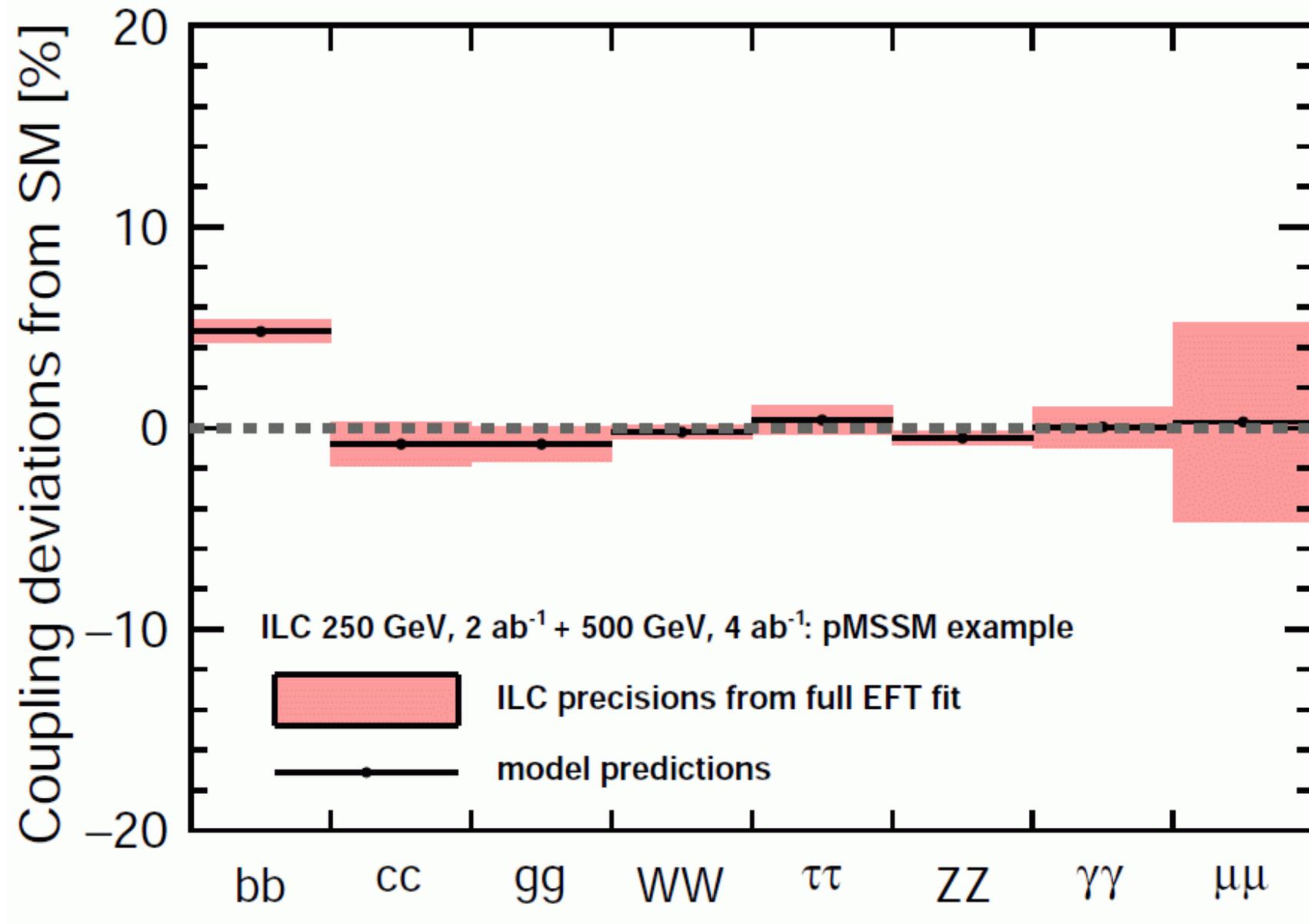
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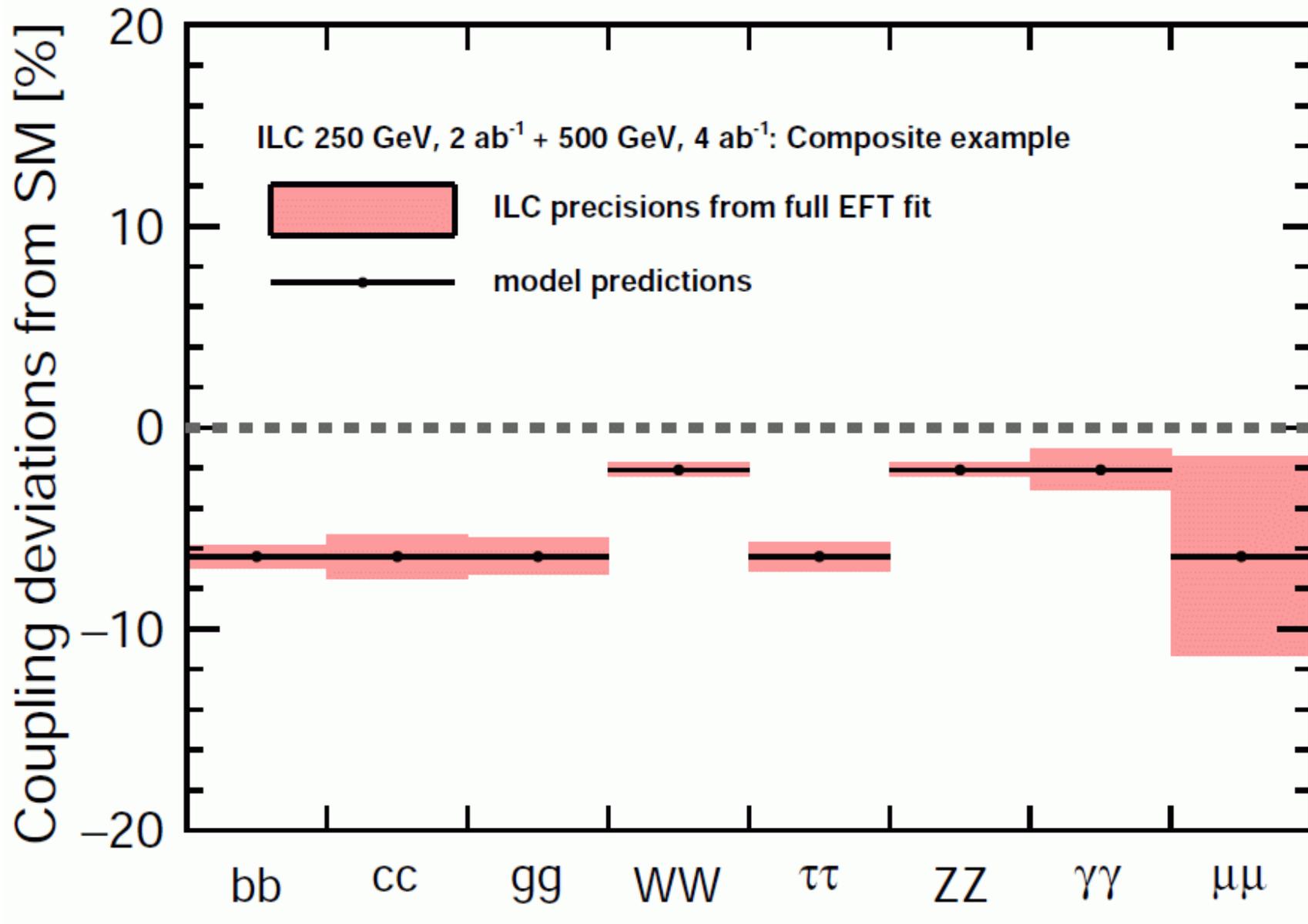


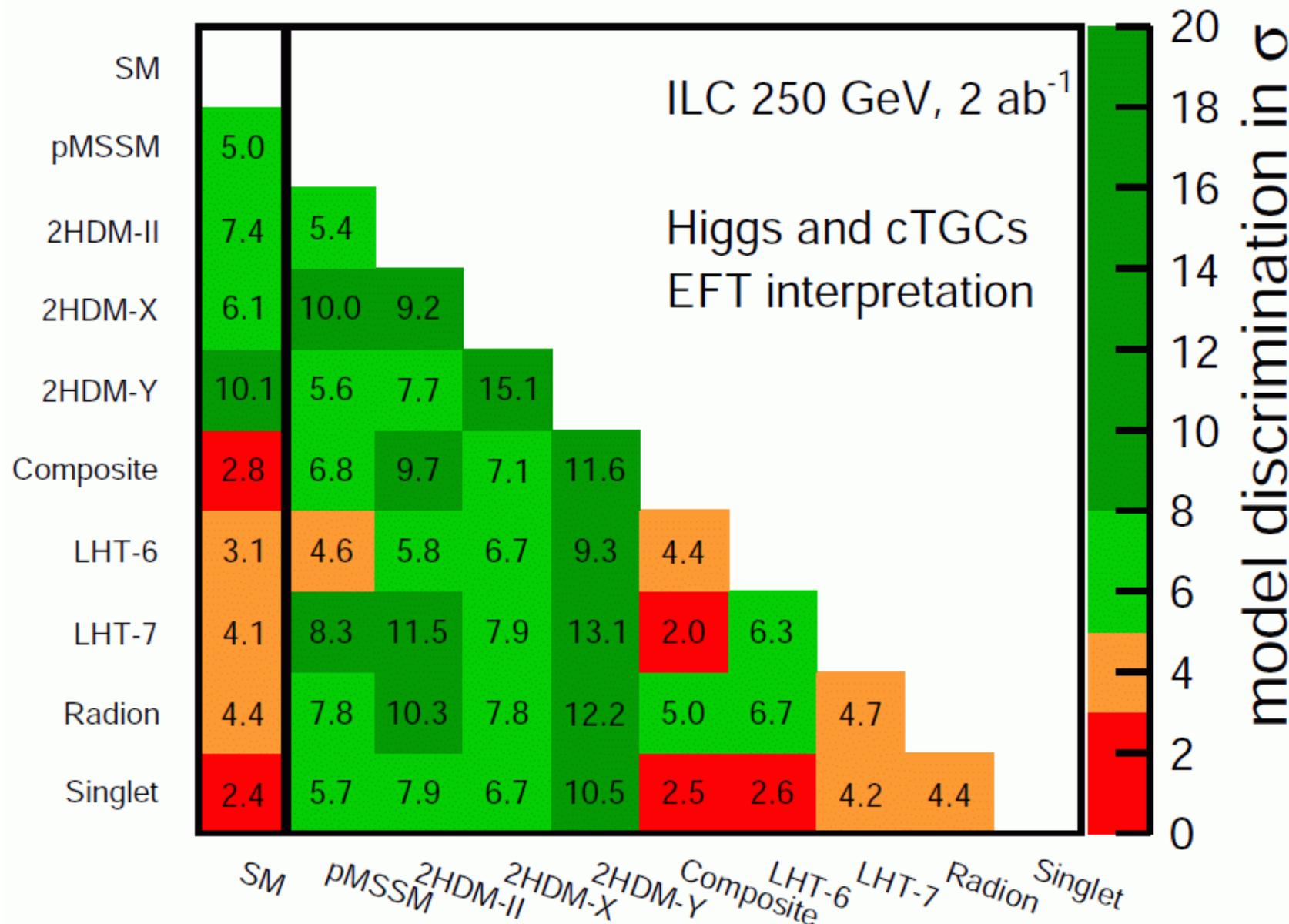
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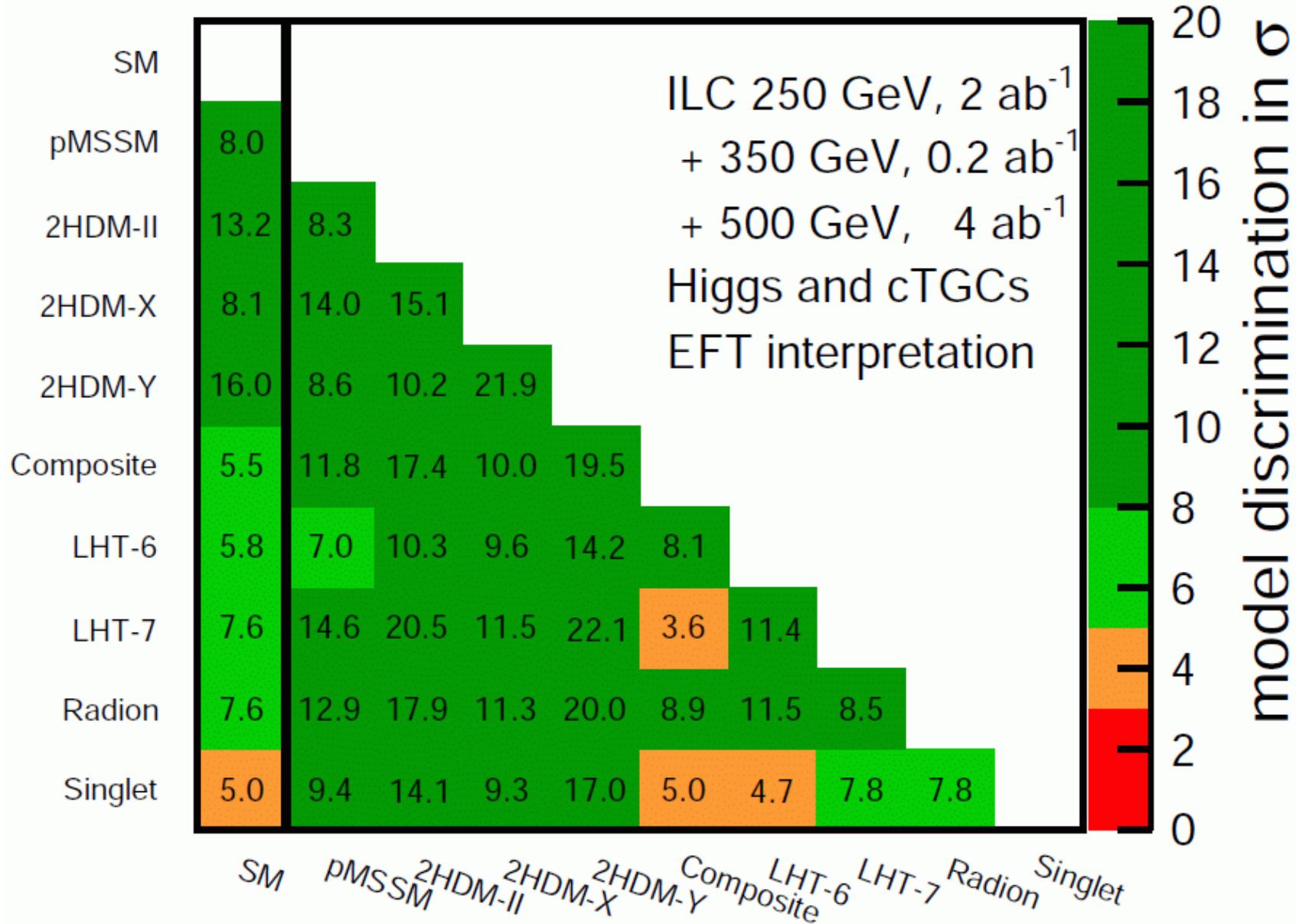












## Required precision for $\mathcal{CP}$ -admixture?

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

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

$$\mathcal{A}(X \rightarrow f\bar{f}) = \frac{m_f}{v} \bar{u}_2 (b_1 + ib_2 \gamma_5) u_1$$

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

Desired precision:

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

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

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ILC precision:

[*Snowmass Higgs report '13*]

gauge bosons:  $f_{\mathcal{CP}} \sim 7 \cdot 10^{-4}, 4 \cdot 10^{-5}, 8 \cdot 10^{-6}$

$\sqrt{s} = 250 \text{ GeV}, 500 \text{ GeV}, 1000 \text{ GeV}$

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

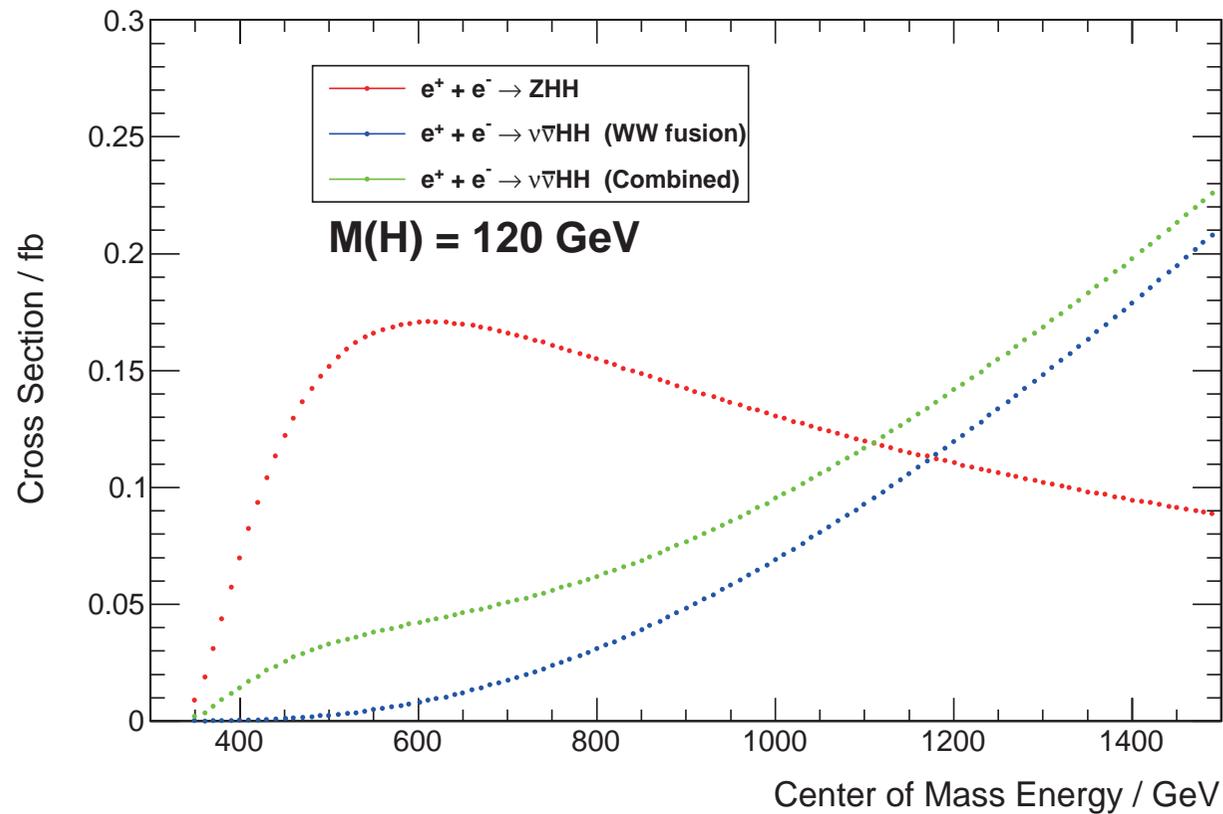
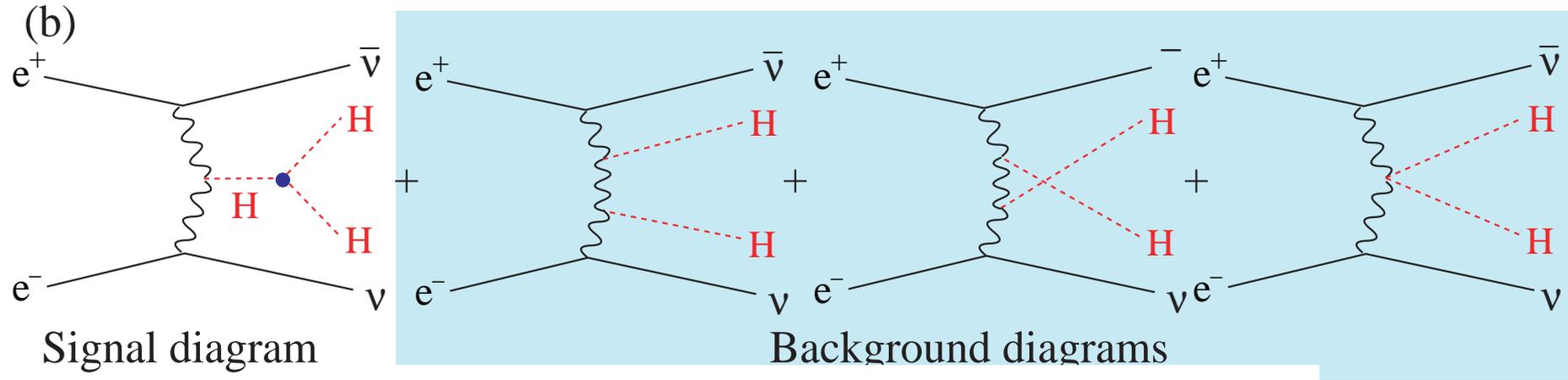
$\sqrt{s} = 250 \text{ GeV}$

⇒ potential to test  $\mathcal{CP}$ -admixture

⇒ complementary energy dependences

# Particularly challenging: Higgs self-coupling

[ILC TDR '13]



## Desired precision in $\lambda$ ?

⇒ highly model dependent

Examples:

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

- Higgs singlet extension:  $(\Delta\lambda/\lambda)^{\max} \sim -18\%$
- Composite Higgs models:  $(\Delta\lambda/\lambda)^{\max} \sim +20\%$
- MSSM:  $(\Delta\lambda/\lambda)^{\max} \lesssim -15\%$
- NMSSM:  $(\Delta\lambda/\lambda)^{\max} \lesssim -25\%$

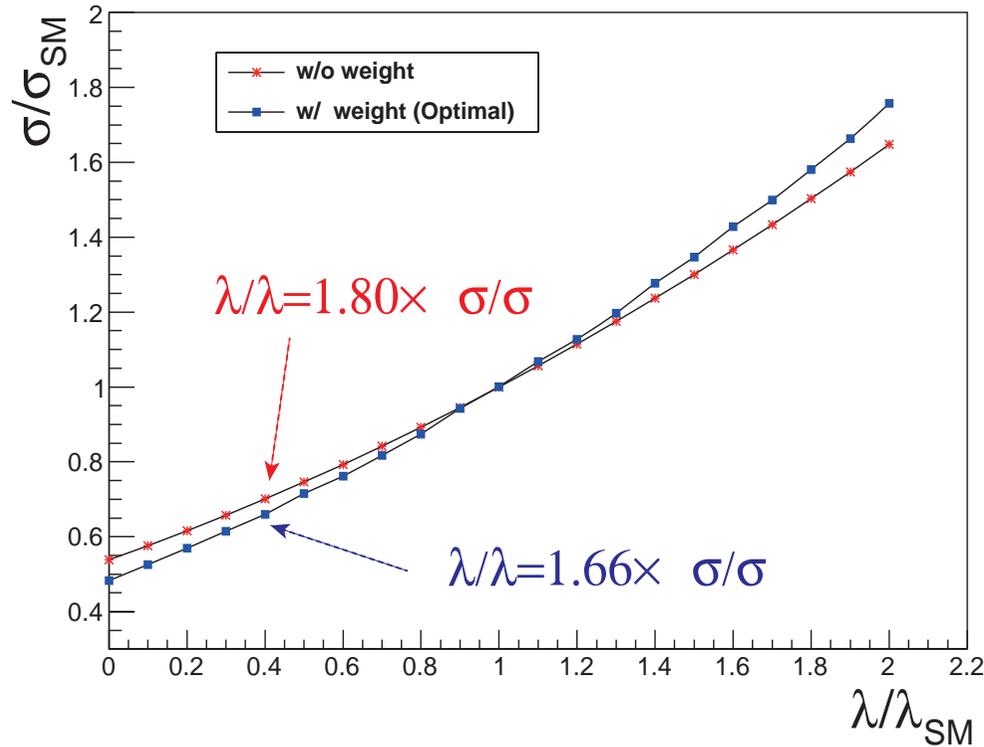
Decoupling leads to non-vanishing effects!

But we want to test “confirm” the SM value in the first place!

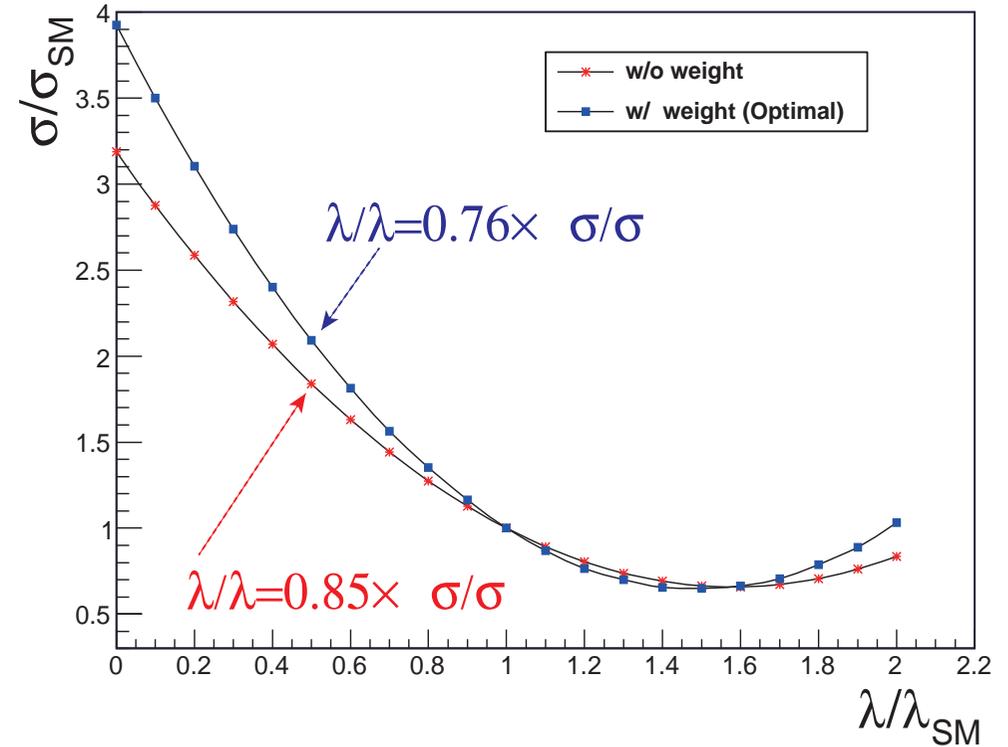
# Sensitivity to triple Higgs coupling $\lambda$ :

[taken from K. Fuji '13]

## $ZHH@500$ GeV



## $\nu\bar{\nu}HH@1000$ GeV



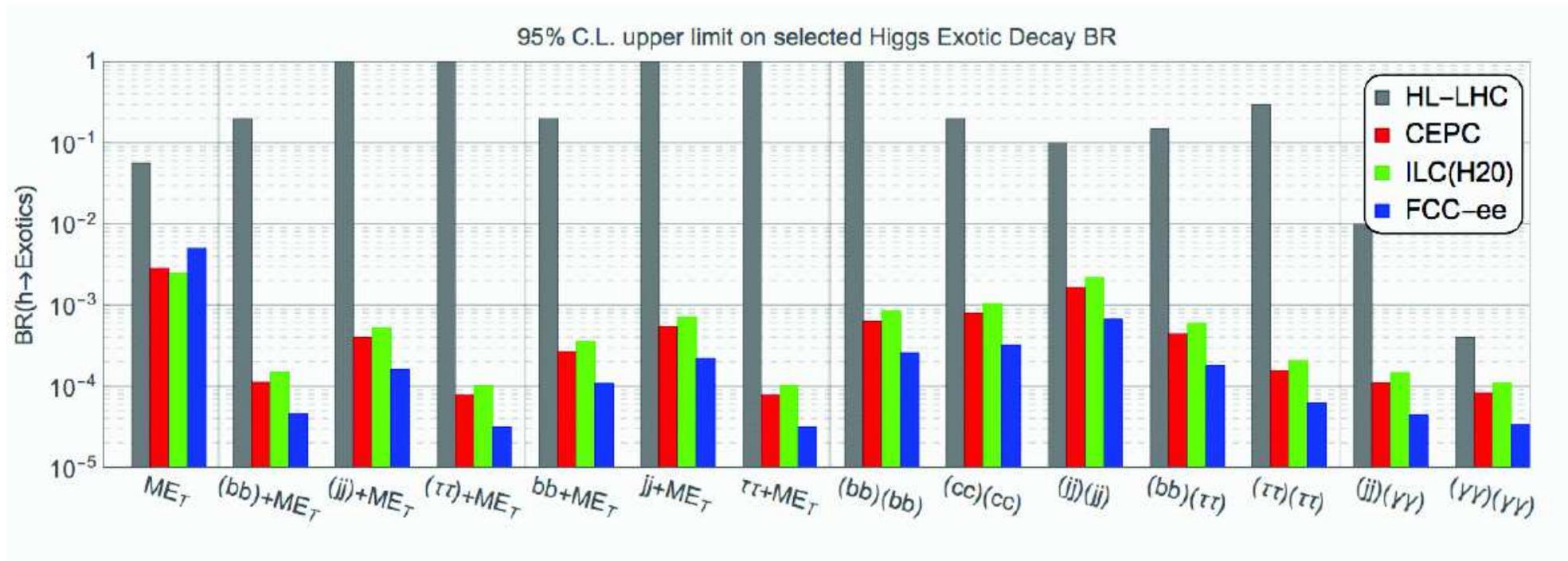
	ILC500	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	1000	1000	1400	3000
$\int \mathcal{L} dt$ ( $\text{fb}^{-1}$ )	4000	2000	5000	1500	+2000
$P(e^-, e^+)$	( $\mp 0.8, \pm 0.3$ )	( $\mp 0.8, \pm 0.2$ )	( $\mp 0.8, \pm 0.2$ )	( $-0.8, 0$ )	( $-0.8, 0$ )
$\Delta\lambda/\lambda$	27%	16%	10%	40%	19%

$\Rightarrow$  BSM models can be tested

[C. Dührig '17, H. Abramovicz et al. '16]

# Exotic Higgs decays:

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



⇒ strong improvement at the ILC

⇒ sensitivity to BSM physics?!

## 5. Conclusions

- The discovered Higgs boson is **not the SM Higgs boson**
- Test for **changed properties**  
Test for **additional Higgs bosons**  
Test for additional Higgs bosons **above and below 125 GeV**
- BSM Higgs bosons above 125 GeV:  
**LCs** have a unique potential to **discover BSM Higgs boson**  
possibly **beyond kinematical reach**
- BSM Higgs bosons below 125 GeV:  
**LCs** have a unique potential to **discover BSM Higgs boson**  
**⇒ envisaged scenarios well covered**
- BSM Higgs boson at 125 GeV:  
precise coupling measurement can **distinguish models**

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- BSM Higgs boson at 125 GeV:  
precise coupling measurement can **distinguish models**

**Let's go and build this machine!**

# Higgs Days at Santander 2018

Theory meets Experiment

10.-14. September



Contact: [Sven.Heinemeyer@cern.ch](mailto:Sven.Heinemeyer@cern.ch)

Local: [Gervasio.Gomez@cern.ch](mailto:Gervasio.Gomez@cern.ch)

<http://hdays.csic.es>

Further Questions?



## cMSSM parameters for neutral Higgs production:

**Table 2:** MSSM default parameters for the numerical investigation; all parameters (except of  $t_\beta$ ) are in GeV (calculated masses are rounded to 1 MeV). The values for the trilinear sfermion Higgs couplings,  $A_{t,b,\tau}$  are chosen such that charge- and/or color-breaking minima are avoided [76], and  $A_{b,\tau}$  are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead  $A_f = 0$ ,  $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$  GeV and  $M_{\tilde{L},\tilde{E}} = 500$  GeV.

Scen.	$\sqrt{s}$	$t_\beta$	$\mu$	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$ A_{t,b,\tau} $	$M_1$	$M_2$	$M_3$
<b>S</b>	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

$m_{h_1}$	$m_{h_2}$	$m_{h_3}$
123.404	288.762	290.588

with  $\sqrt{s}$ ,  $M_{H^\pm}$ ,  $\tan \beta$ ,  $\phi_{A_t}$  varied

- Scenario chosen such that many processes are possible at the same time
- not chosen to maximize loop corrections

## cMSSM parameters for charged Higgs production:

**Table 1:** MSSM default parameters for the numerical investigation; all parameters (except of  $t_\beta$ ) are in GeV. The values for the trilinear sfermion Higgs couplings,  $A_{t,b,\tau}$  are chosen such that charge- and/or color-breaking minima are avoided [64], and  $A_{b,\tau}$  are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead  $A_f = 0$ ,  $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$  GeV and  $M_{\tilde{L},\tilde{E}} = 500$  GeV.

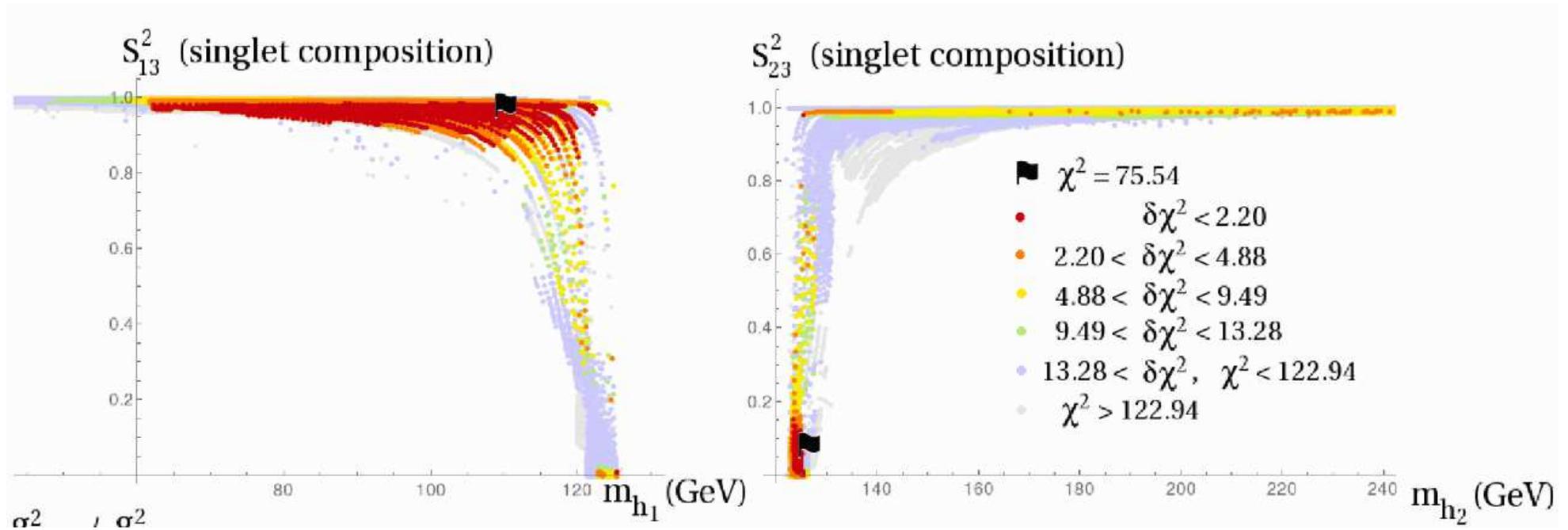
Scen.	$\sqrt{s}$	$t_\beta$	$\mu$	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$ A_{t,b,\tau} $	$M_1$	$M_2$	$M_3$
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

with  $\sqrt{s}$ ,  $M_{H^\pm}$ ,  $\tan \beta$ ,  $\phi_{A_t}$  varied

- Scenario chosen such that many processes are possible at the same time
- not chosen to maximize loop corrections

Parameters:

$\tan \beta = 8$ ,  $M_A = 1$  TeV,  $A_\kappa = -2 \dots 0$  TeV,  $\mu = 120 \dots 2000$  GeV,  
 $2M_1 = M_2 = 500$  GeV,  $M_3 = 1.5$  TeV,  $m_{\tilde{Q}_3} = 1$  TeV,  $m_{\tilde{Q}_{1,2}} = 1.5$  TeV,  
 $A_t = -2$  TeV,  $A_{b,\tau} = -1.5$  TeV



⇒ light Higgs below 125 GeV has large singlet component

⇒ second Higgs is SM-like

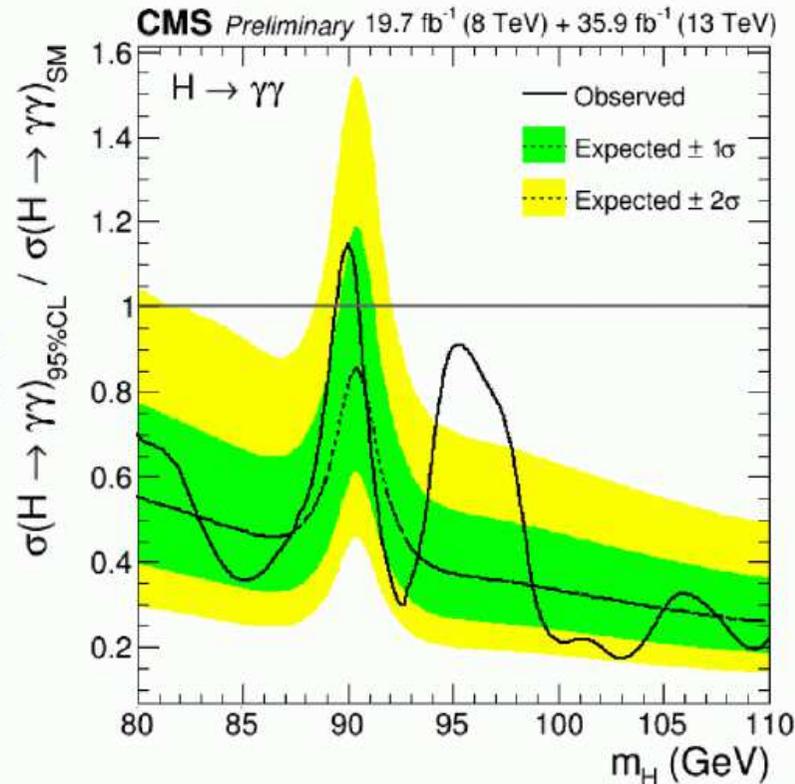


# $h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+ 2



CMS PAS HIG-17-013

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).



8 TeV+13 TeV:  
 minimum(maximum) limit  
 on  $(\sigma \times Br) / (\sigma \times Br)_{SM}$  :  
 0.17(1.15) at  
 $m=103.0(90.0)\text{GeV}$

- Combined 8 TeV+13 TeV  $\sigma \times Br$  limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.

29

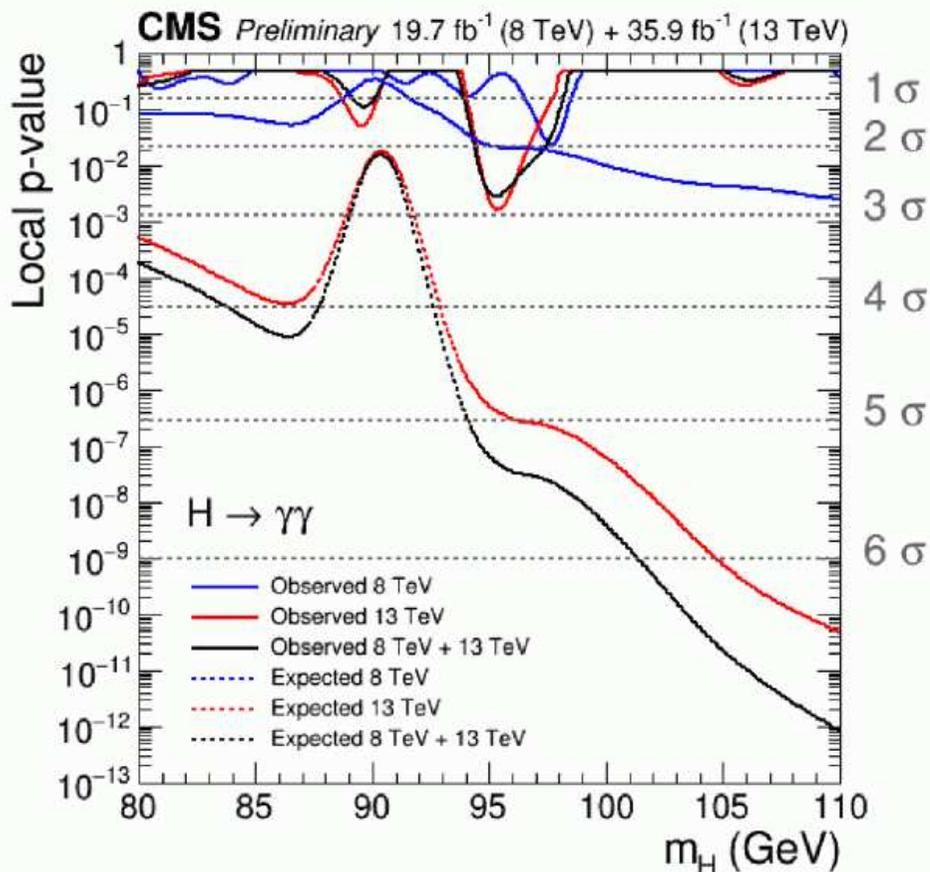
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017



# $h \rightarrow \gamma\gamma$ (70-110 GeV) Runs 1+ 2



CMS PAS HIG-17-013



8 TeV: Excess with  $\sim 2.0 \sigma$  local significance at  $m=97.6$  GeV

13 TeV: Excess with  $\sim 2.9 \sigma$  local ( $1.47 \sigma$  global) significance at  $m=95.3$  GeV

8TeV+13 TeV: Excess with  $\sim 2.8 \sigma$  local ( $1.3 \sigma$  global) significance at  $m=95.3$  GeV

More data are required to ascertain the origin of this excess

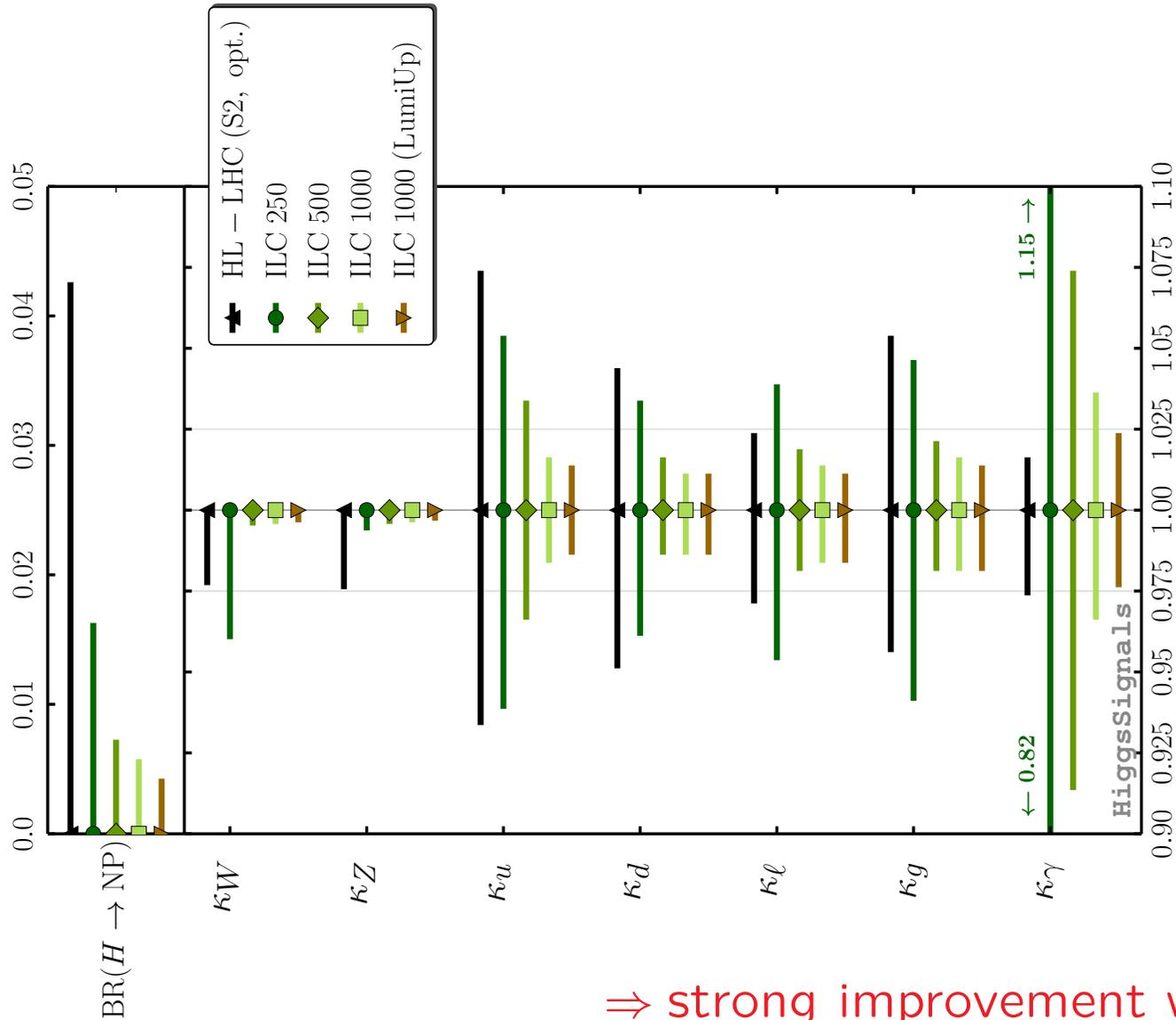
- Expected and observed local p-values for 8 TeV, 13 TeV and their combination

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

# HL-LHC vs. ILC in the most general $\kappa$ framework:

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

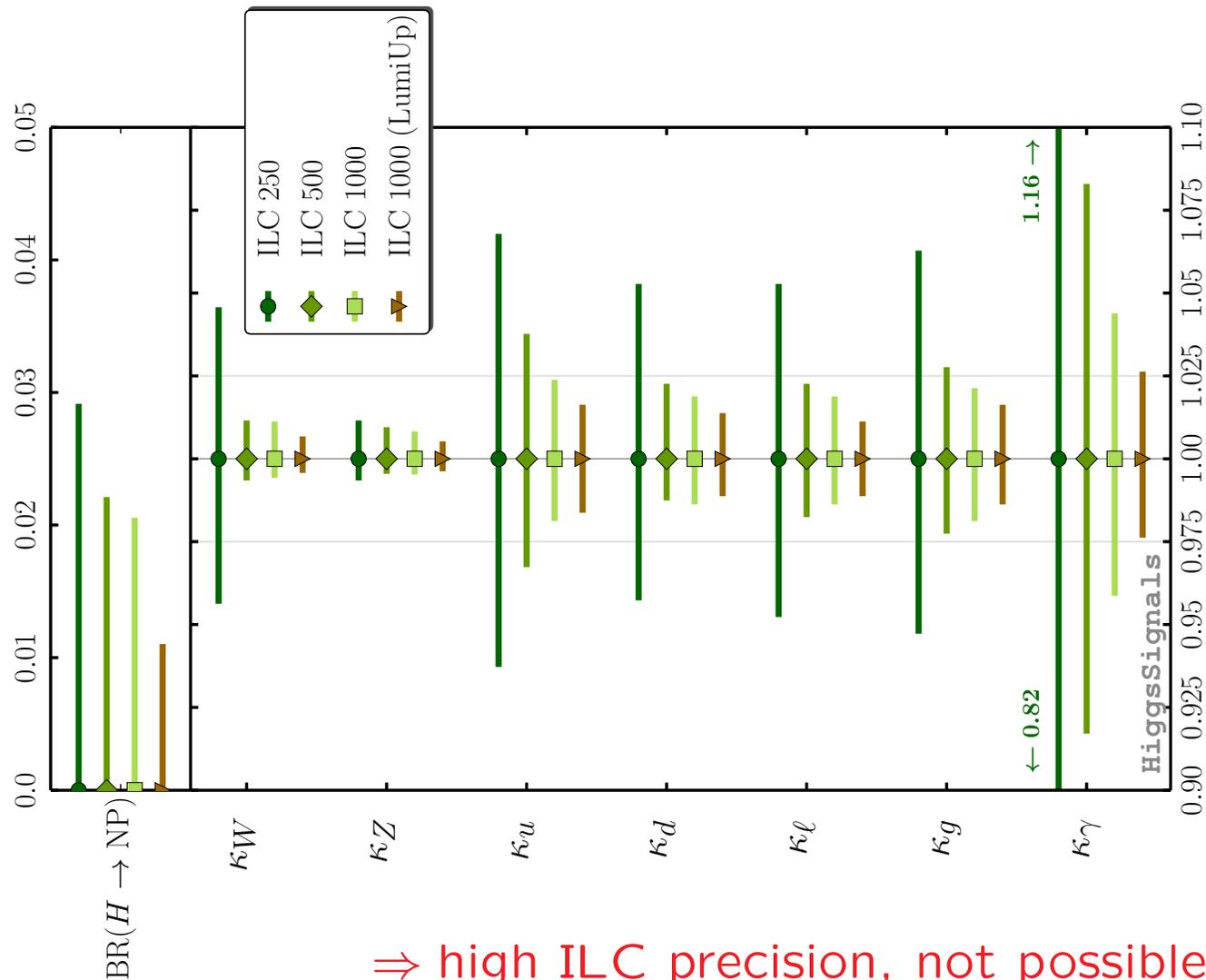
assumption:  $\kappa_V \leq 1$



# HL-LHC vs. ILC in the most general $\kappa$ framework:

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

no theory assumptions, full fit



⇒ high ILC precision, not possible at the LHC

$$\sigma_{Zh} = \left| \text{tree-level diagram} \right|^2 + 2 \operatorname{Re} \left[ \text{tree-level diagram} \cdot \left( \text{loop diagram with } g_{zzh} \right) + \left( \text{loop diagram with } \lambda \right) \right]$$

$\delta_{\sigma}^{240} = 100 (2\delta_Z + 0.014\delta_h) \%$

⇒ sensitivity to  $\lambda_{HHH}$  goes down for higher  $\sqrt{s}$

⇒ percent precision possible on  $\sigma_{ZH}$ ,  $\lambda_{HHH}$

⇒ indirect and model dependent measurement

(to be included in a global coupling fit - within a model)

⇒  $\mathcal{O}(10\%)$  measurement of  $\lambda_{HHH}$  needed  
to measure  $\sigma_{HZ}$  at the percent level!