"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Higgs Couplings in the NMSSM

Determining the Nature of BSM Physics

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

CERN, 01/2020

1. Motivation
2. (N)MSSM Higgs decays
3. BSM Higgs: what can we learn?
4. Conclusions

1. Motivation

Two Facts:

We have an SM-like Higgs discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

1. Motivation

Two Facts:

We have an SM-like Higgs discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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

1. Motivation

Two Facts:

We have an SM-like Higgs discovery!

The SM cannot be the ultimate theory!

Conclusion: It cannot be "the SM Higgs"!

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

A1: check changed properties

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

Higgs 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

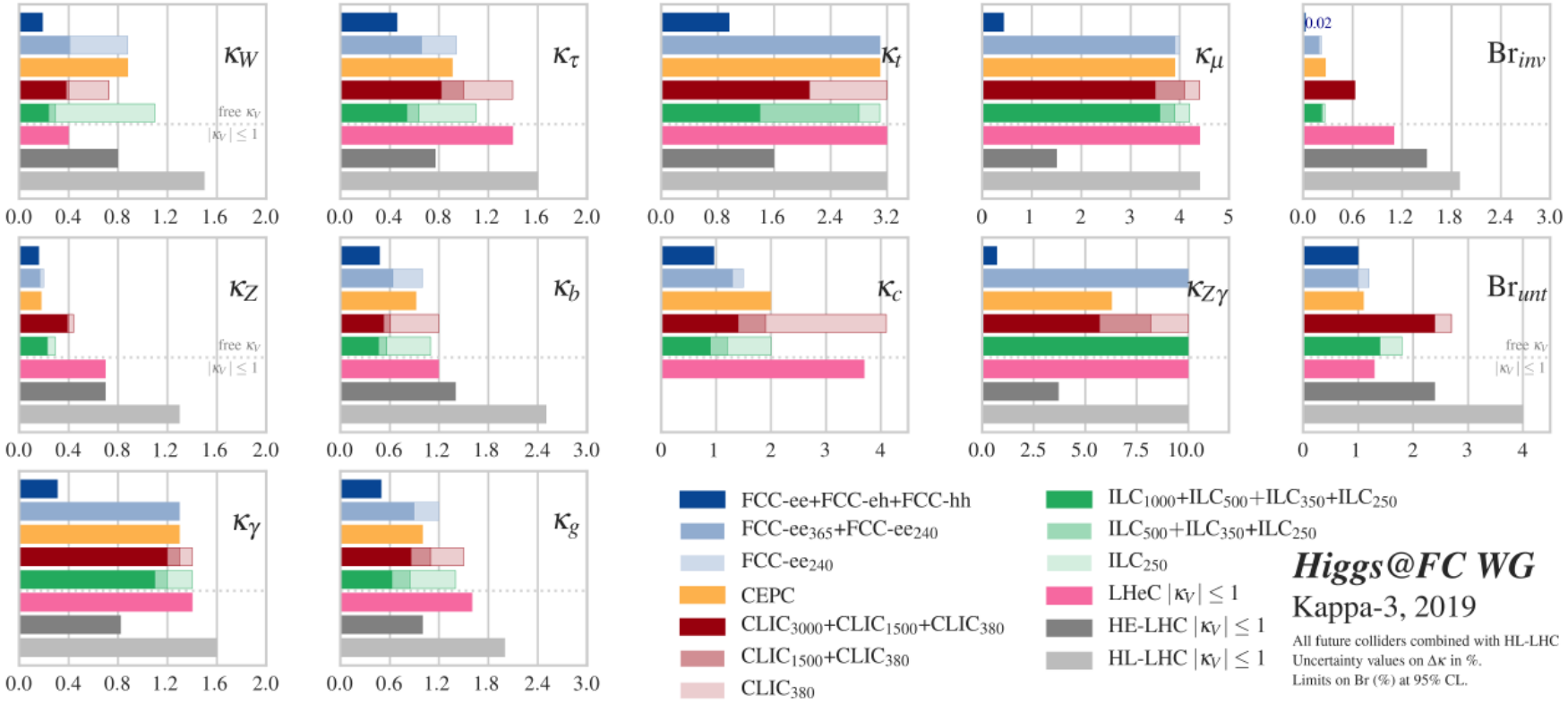
$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ indirect measurement of total width

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

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

Future expectations for κ (kappa-3 framework)



⇒ very roughly similar results

⇒ FCC-hh/-he/-ee appears better

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

⇒ also remember different time scales!

Intrinsic uncertainties for decay widths: [arXiv:1905.03764]

"ILC/CEPC/FCC-ee" = expected precision on g^2_{Hxx} (incl. HL-LHC meas.)

Partial width	QCD	electroweak	total	future	ILC/CEPC/FCC-ee
$H \to WW \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	0.6/1.9/0.8%
$H \to ZZ \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	0.4/0.4/0.3%
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$	1.7/2.2/1.8%
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	2.4/2.4/2.4%
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	22/13/20%
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	1.2/1.8/1.3%
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	2.4/4.0/2.6%
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	1.3/1.9/1.3%
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	7.8/7.8/7.8%
Γ_{tot}				$\sim 0.3\%$	1.1/1.8/1.2%

$\Rightarrow$ talk by S.H.

Needed for LHC/CLIC/ILC/CEPC/FCC-ee. . . physics:

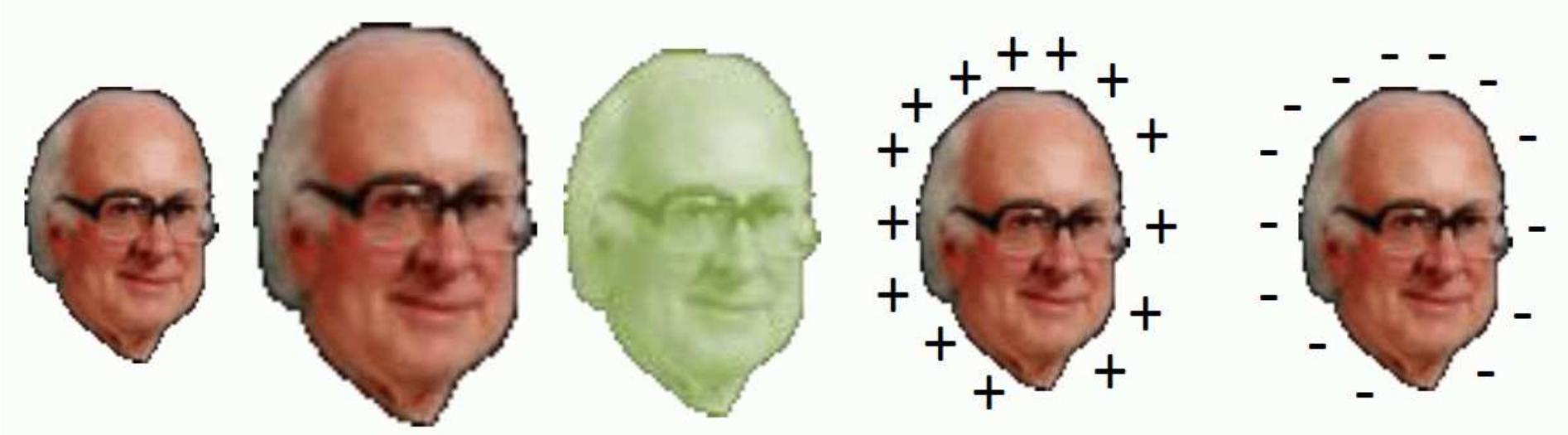
Precise and consistent prediction of

- Higgs boson masses
- Higgs boson mixings
- Higgs boson couplings
- Higgs boson production cross sections
- Higgs boson decay widths/branching ratios $\Leftarrow$ focus here
- . . .

$\Rightarrow$ (partially) provided by FeynHiggs

2. (N)MSSM Higgs Decays

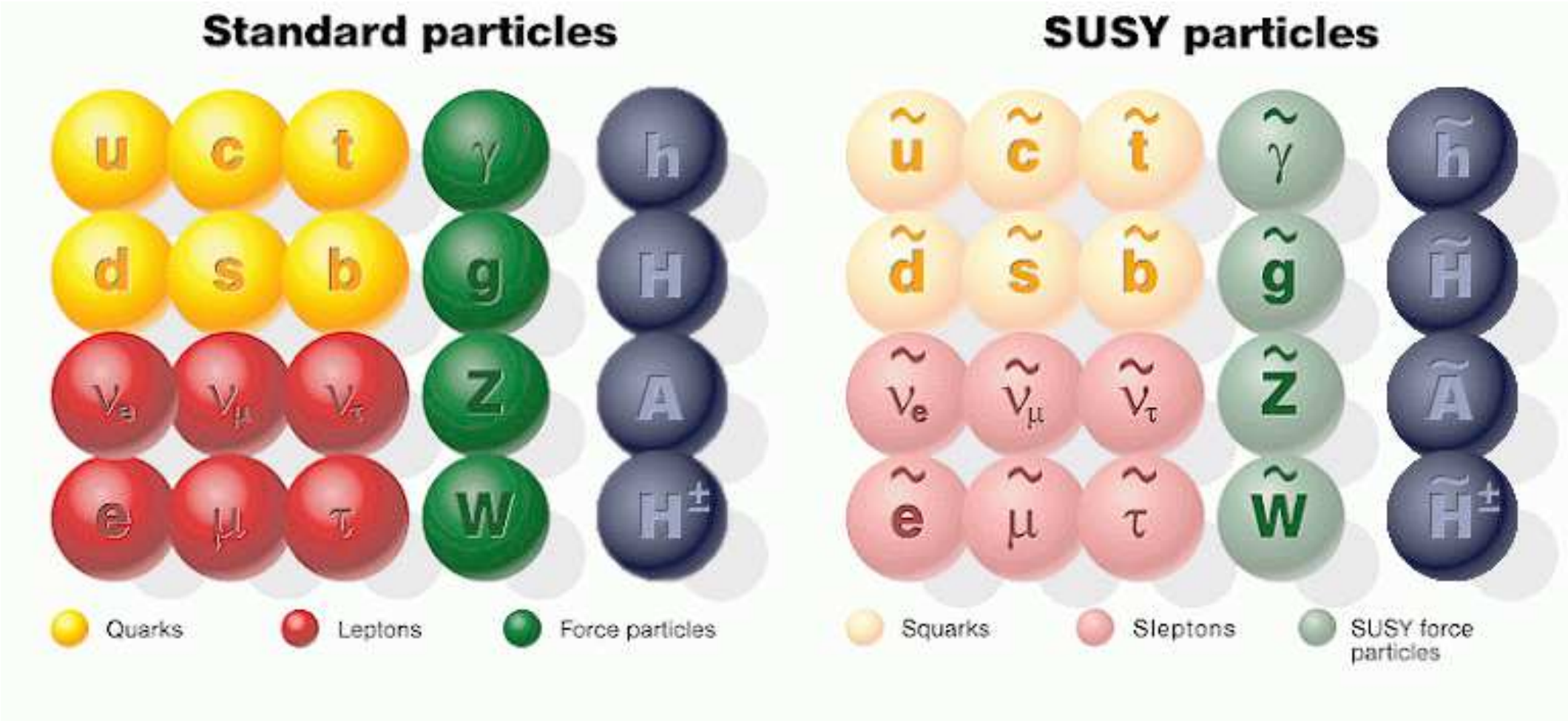
[F. Domingo, S.H. S. Passehr, G. Weiglein '18]



⇒ Please: repeat this excercise in your favorite model! Not EFT . . .

The MSSM:

⇒ Superpartners for Standard Model particles



Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ $\Rightarrow$ re-enters via loop corrections!

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Z_3 invariant NMSSM

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

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

Z_3 invariant NMSSM

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

$$
\begin{aligned}
V &= (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
&\quad + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\begin{aligned} \mathcal{CP}\text{−even} &: h_1, h_2, h_3 \\ \mathcal{CP}\text{−odd} &: a_1, a_2 \\ \text{charged} &: H^+, H^- \\ \text{Goldstones} &: G^0, G^+, G^- \end{aligned}$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM} : M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM} : \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM} : M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree},\text{NMSSM}} = m^2_{h,\text{tree},\text{MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM} : M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM} : \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM} : M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \leq M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \geq M_{H^\pm}^{\text{NMSSM,tree}}$

The FeynHiggs Ansatz for masses (taken from talk by [*P. Drechsel*])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2 = 0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

The FeynHiggs Ansatz for masses (taken from talk by [*P. Drechsel*])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2 = 0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

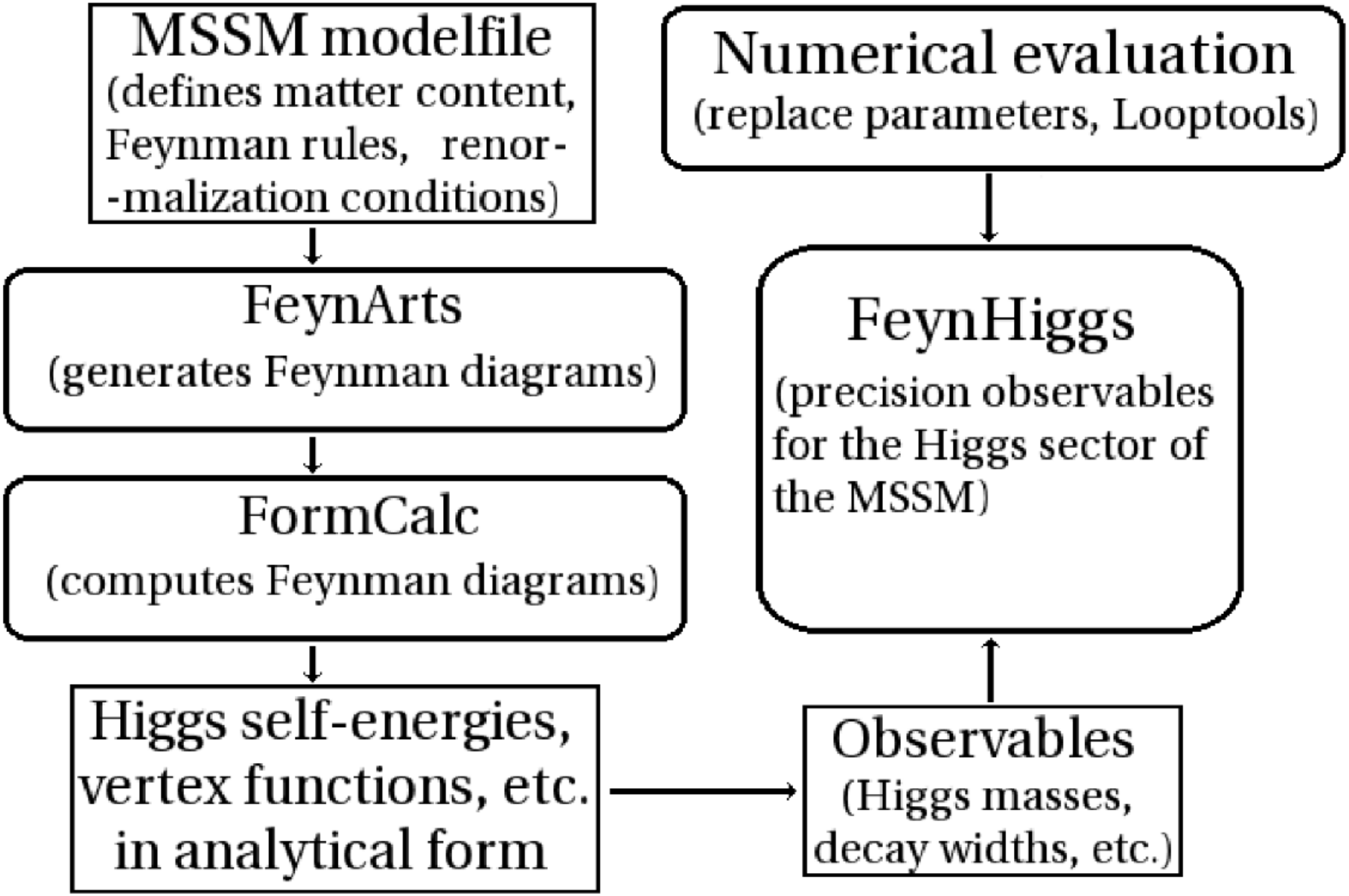
- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

⇒ **same Ansatz for Higgs decays!**

FeynHiggs "workflow":



Idea for this work:

[*slide from F. Domingo*]

- Renormalization of the CP-conserving Higgs-sector
  [Drechsel, Galeta, Heinemeyer, Weiglein, (2016)];
- CP-violating NMSSM, on-shell neutral Higgs *[Drechsel, F.D., Paßehr (2017)]*;
- Neutral Higgs decays into SM particles at full one-loop order
  [F.D., Heinemeyer, Paßehr, Weiglein, (2018)];
- Higgs-to-Higgs + Higgs-to-SUSY on-going...
- Inclusion within FeynHiggs in an unforseeable future...

Learn from MSSM and adapt to the NMSSM.
+ Re-juvenate MSSM from NMSSM.

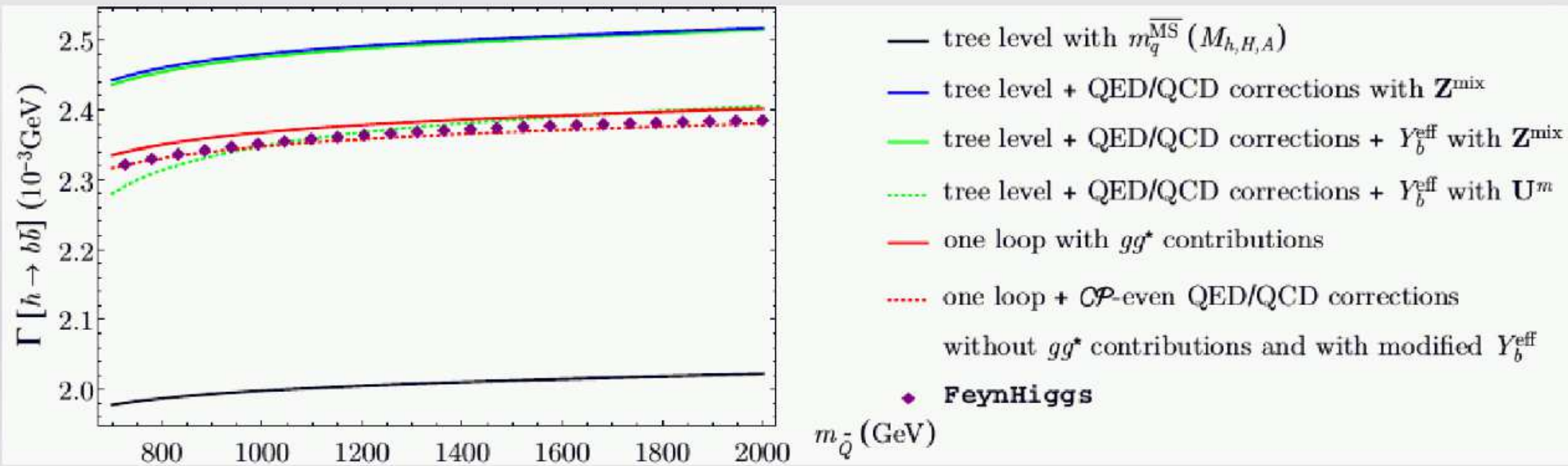
In the future: **FeynHiggs 3.0**

⇒ few numerical examples for the Higgs decays

⇒ Please: repeat this excercise in your favorite model! Not EFT ...

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

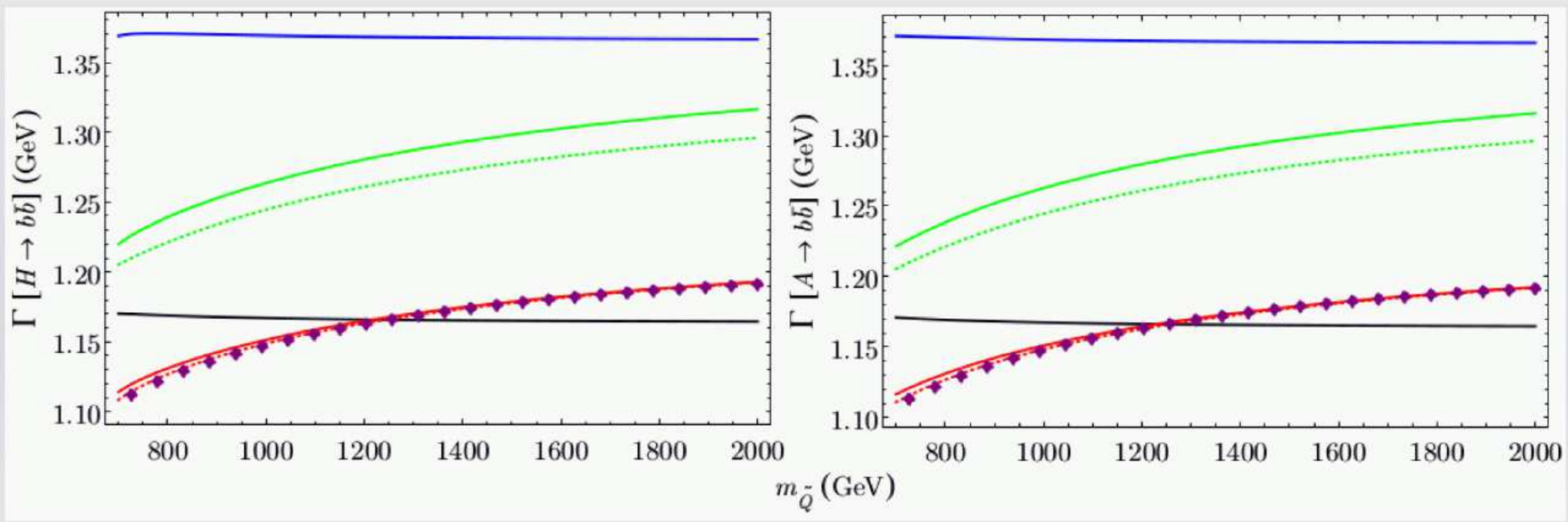


SM-like Higgs state

- Radiative corrections dominated by QCD-corrections;
- Unitary tree-level approximation works well;
- Difference wrt. FH (small): $h \to g(g^* \to b\bar{b})$
  (whether $h \to b\bar{b}$ or $h \to gg$ is an experimental question).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

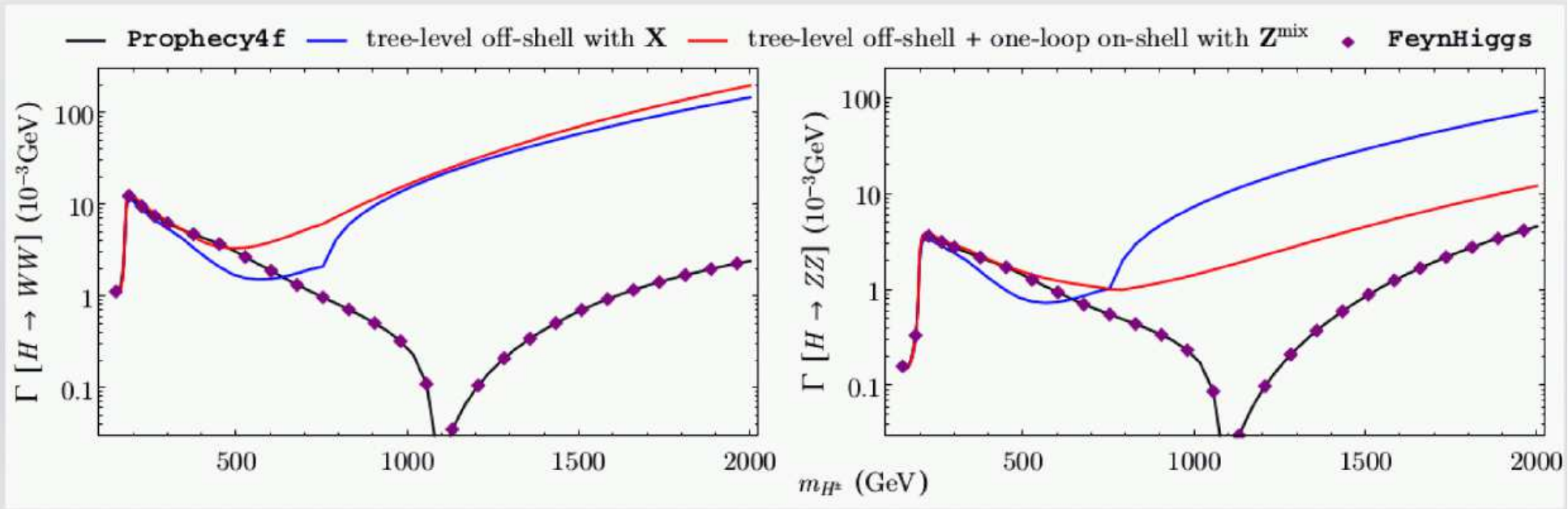


Heavy doublet Higgs states at ~ 1 TeV

- Sizable EW corrections due to Sudakov logarithms;
- Unitary tree-level approximation 'fails' ~ 10% off;
- Difference wrt. FH (minor): UV scale in Δ_b (higher-order).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]



Heavy CP-even doublet Higgs state

- black curve: SM 1L prediction of Prophecy4f rescaled (as FH);
- Red curve: full one-loop (on-shell);
- Rescaling procedure fails for a decoupling state $g^{HVV}/g^{H_{\rm SM}VV} \simeq 0$.

Overall (N)MSSM Higgs decay uncertainty estimates

- $h_i \to q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
  heavy: as SM-like, Sudakov logs: $\sim 5 - 10\%$

- $h_i \to \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
  heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$

- $h_i \to WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
  heavy: missing 2L (very small width): $\lesssim 50\%$

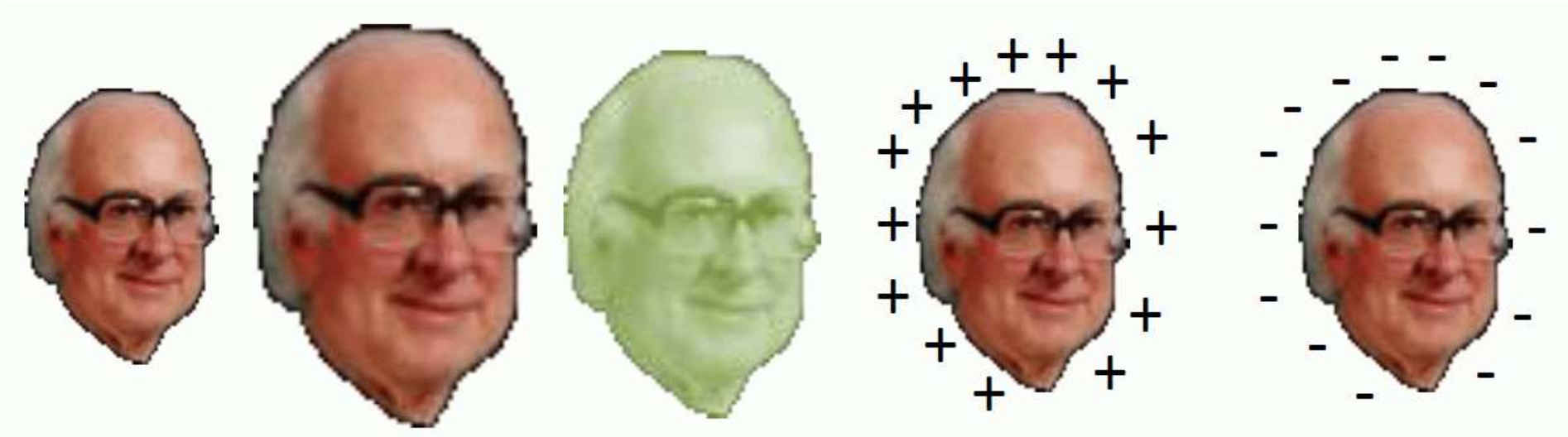
- $h_i \to \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NLO QCD, LO EW: $\lesssim 4\%$
  gg: NLO QCD, EW: $\lesssim 4\%$
  γZ: LO: $\sim 5\%$

- $h_i \to$ SUSY SUSY: [*S.H., C. Schappacher '14-'16*]
  1L effects $10 - 20\%$, 2L?

- all decays: $\mathbf{U}_{ij}$, $\mathbf{Z}_{ij}$: few %, effects close to threshold?

$\Rightarrow$ approaching e^+e^- prec. for SM-like Higgs (not for heavy Higgses yet)

3. BSM Higgs: what can we learn?



– let's assume that we do see a deviation

– **What do we learn from that?**

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

$\Rightarrow$ theory/experimental match?

Let us assume that we do see a deviation

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

⇒ We have to compare the observed deviation with predicted deviations

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

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

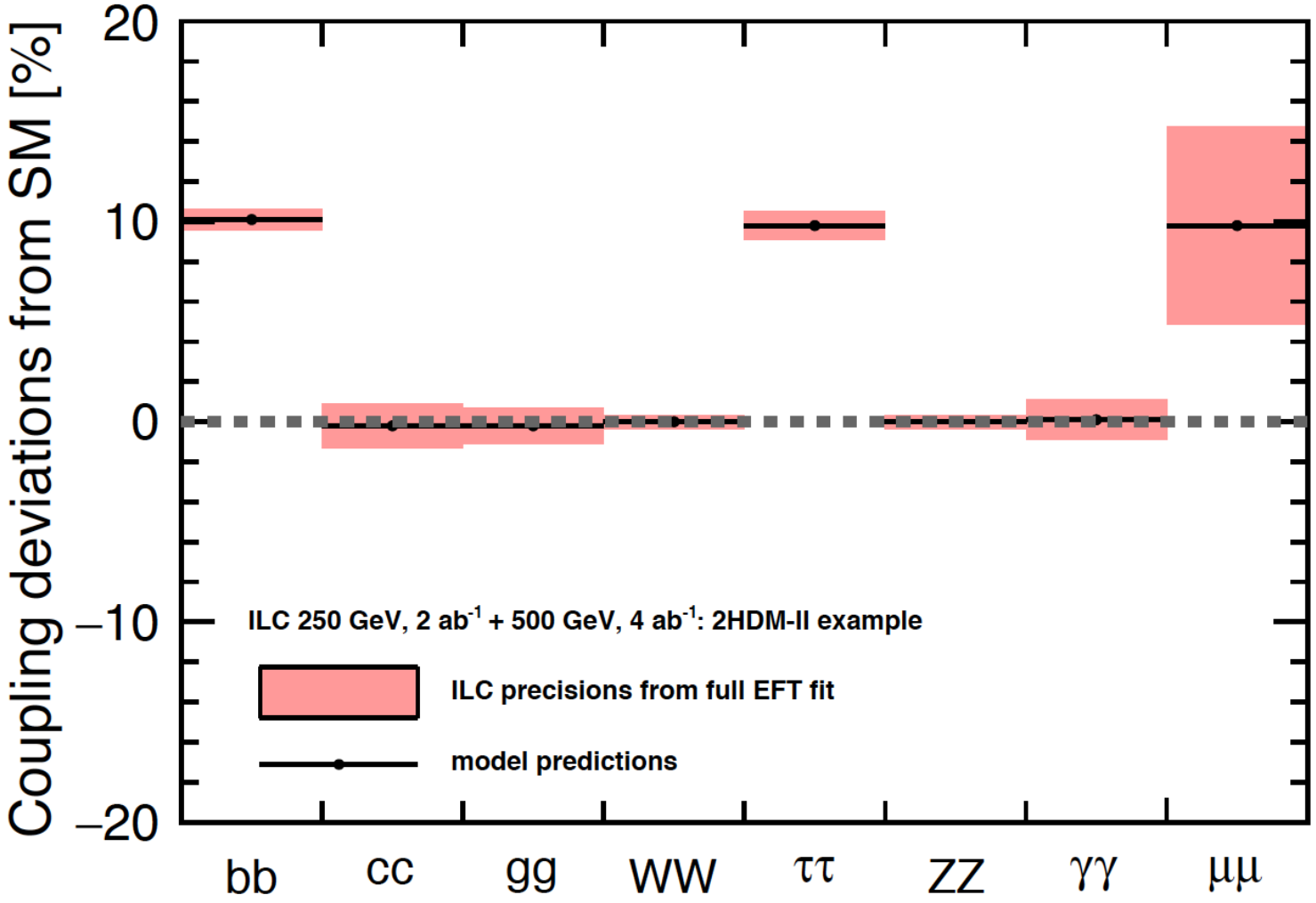
⇒ in the following:

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

⇒ "Wäscheleinen-Plots" (concrete: ILC500 – FCC-ee similar!)

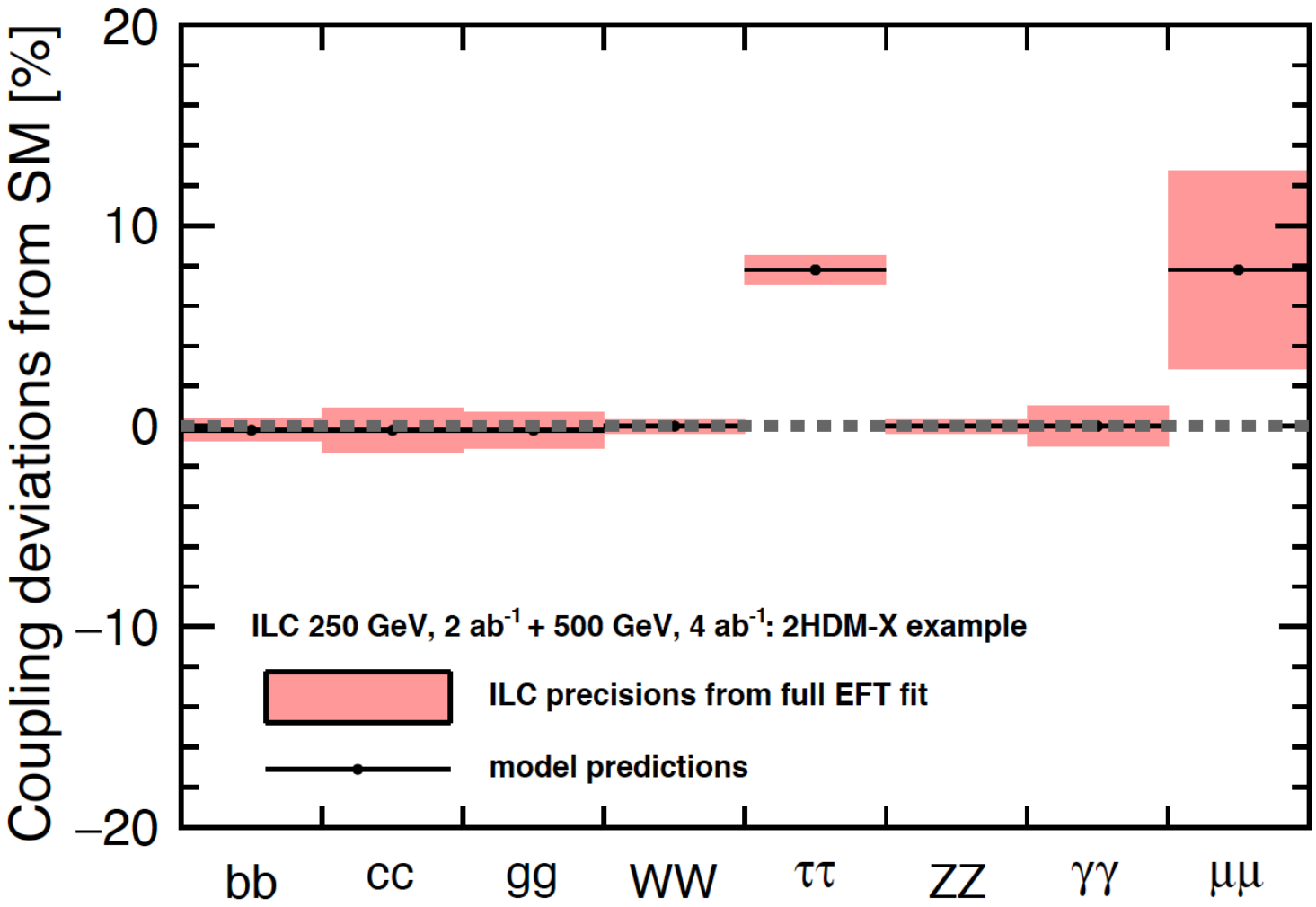
Wäscheleine I: e^+e^- precision vs. 2HDM type II prediction:

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



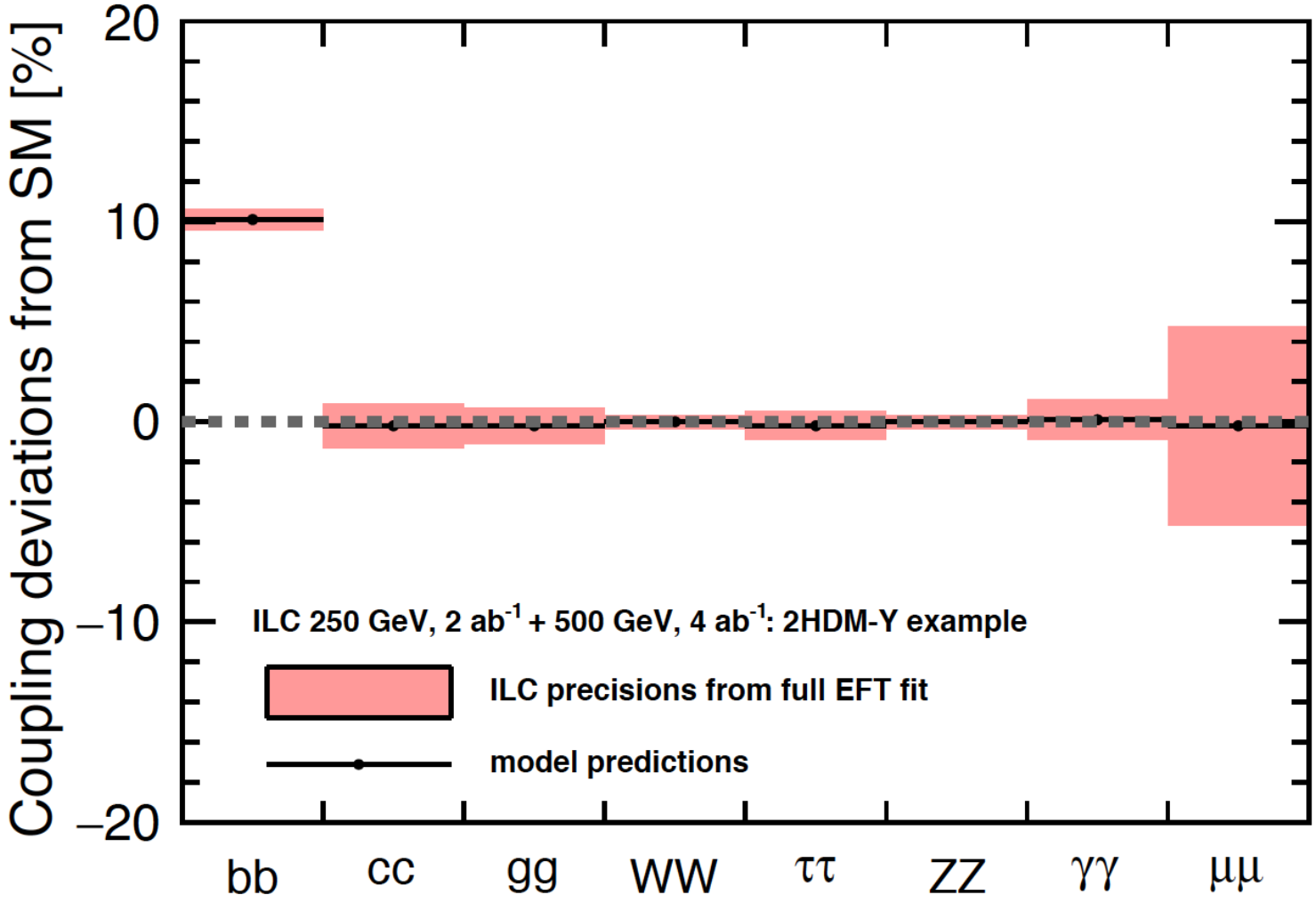
Wäscheleine II: e^+e^- precision vs. 2HDM type X prediction:

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



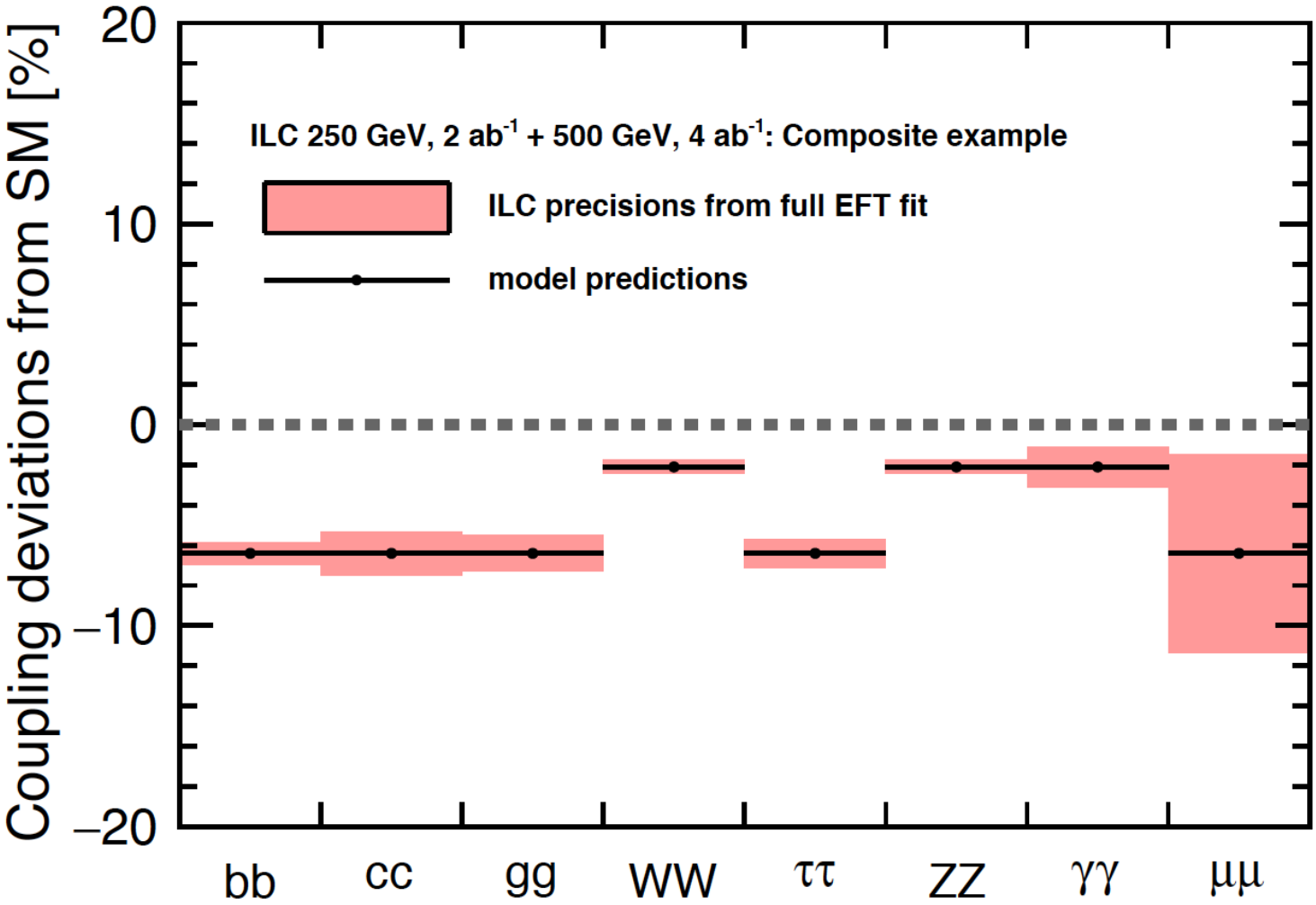
Wäscheleine III: e^+e^- precision vs. 2HDM type Y prediction:

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



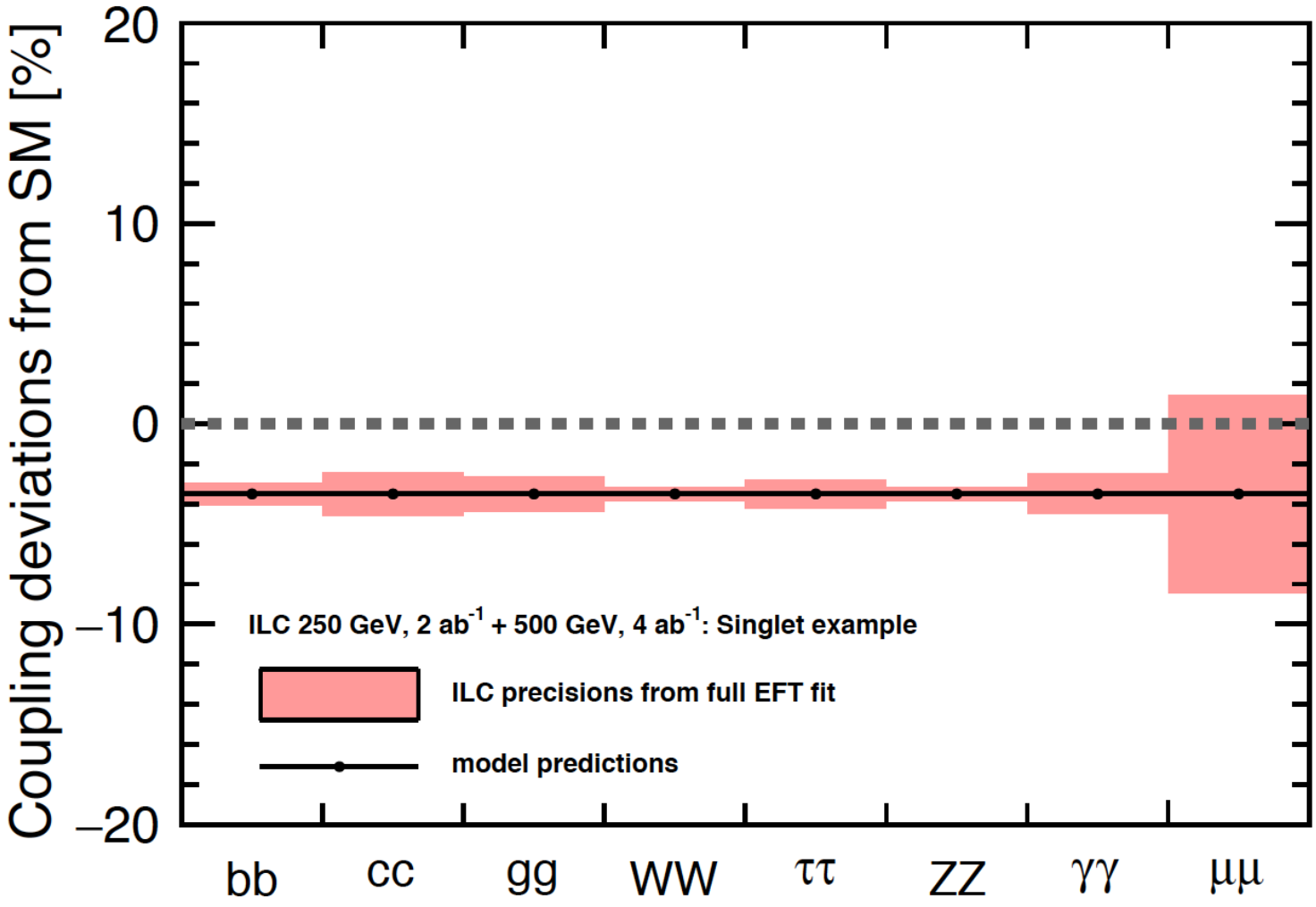
Wäscheleine IV: e^+e^- precision vs. Composite Higgs prediction:

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



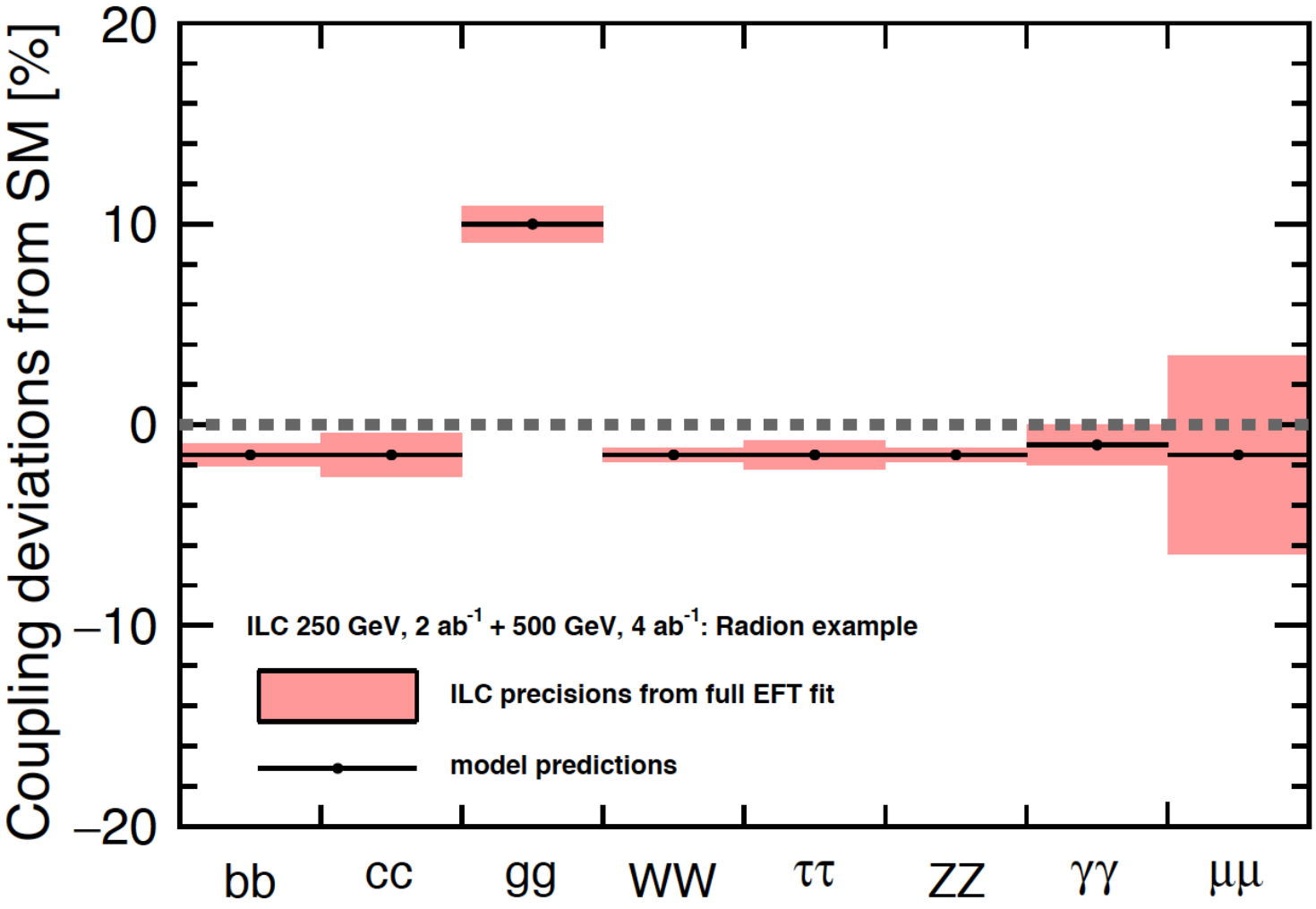
Wäscheleine V: e^+e^- precision vs. HxSM prediction:

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



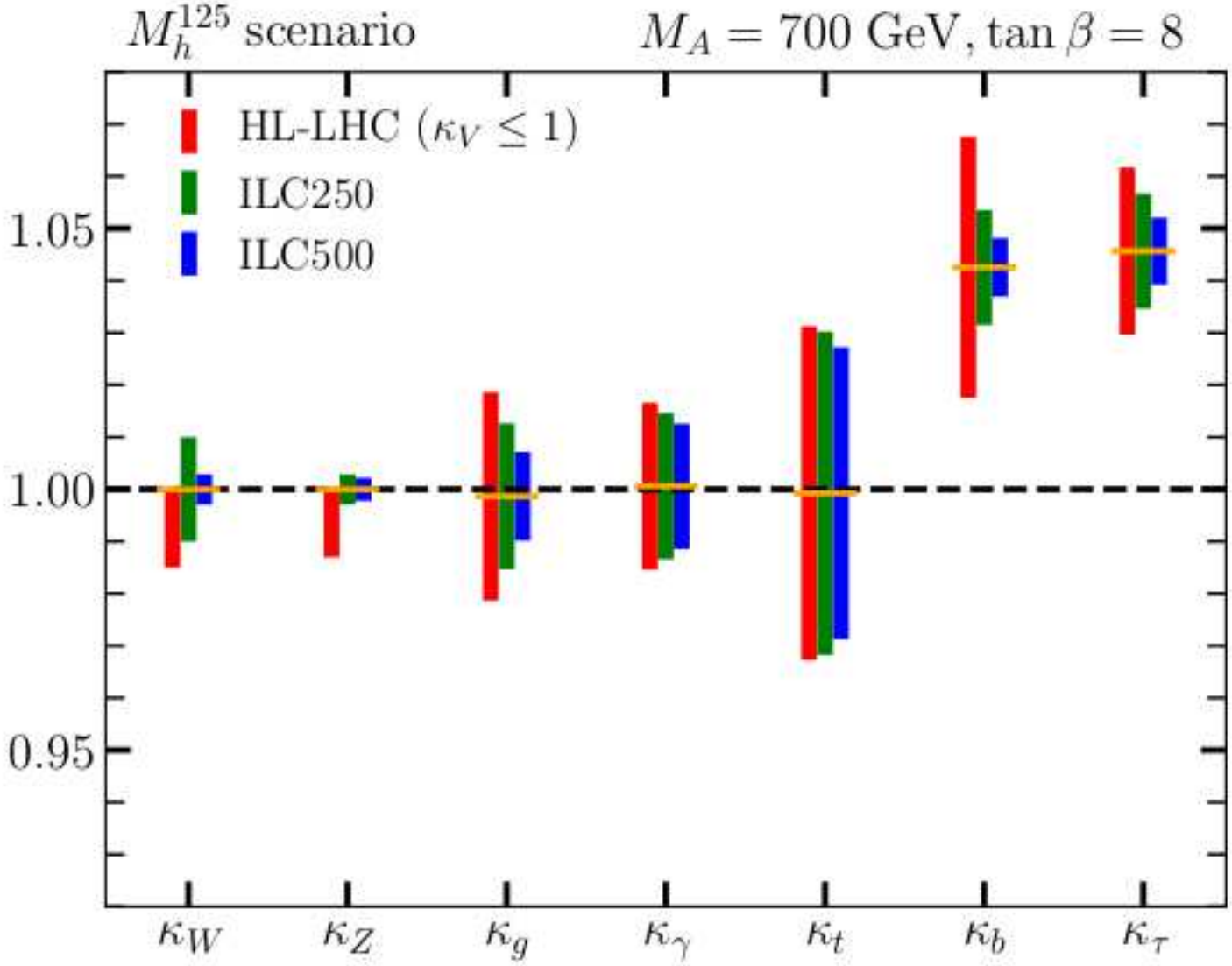
Wäscheleine VI: e^+e^- precision vs. Higgs-Radion prediction:

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



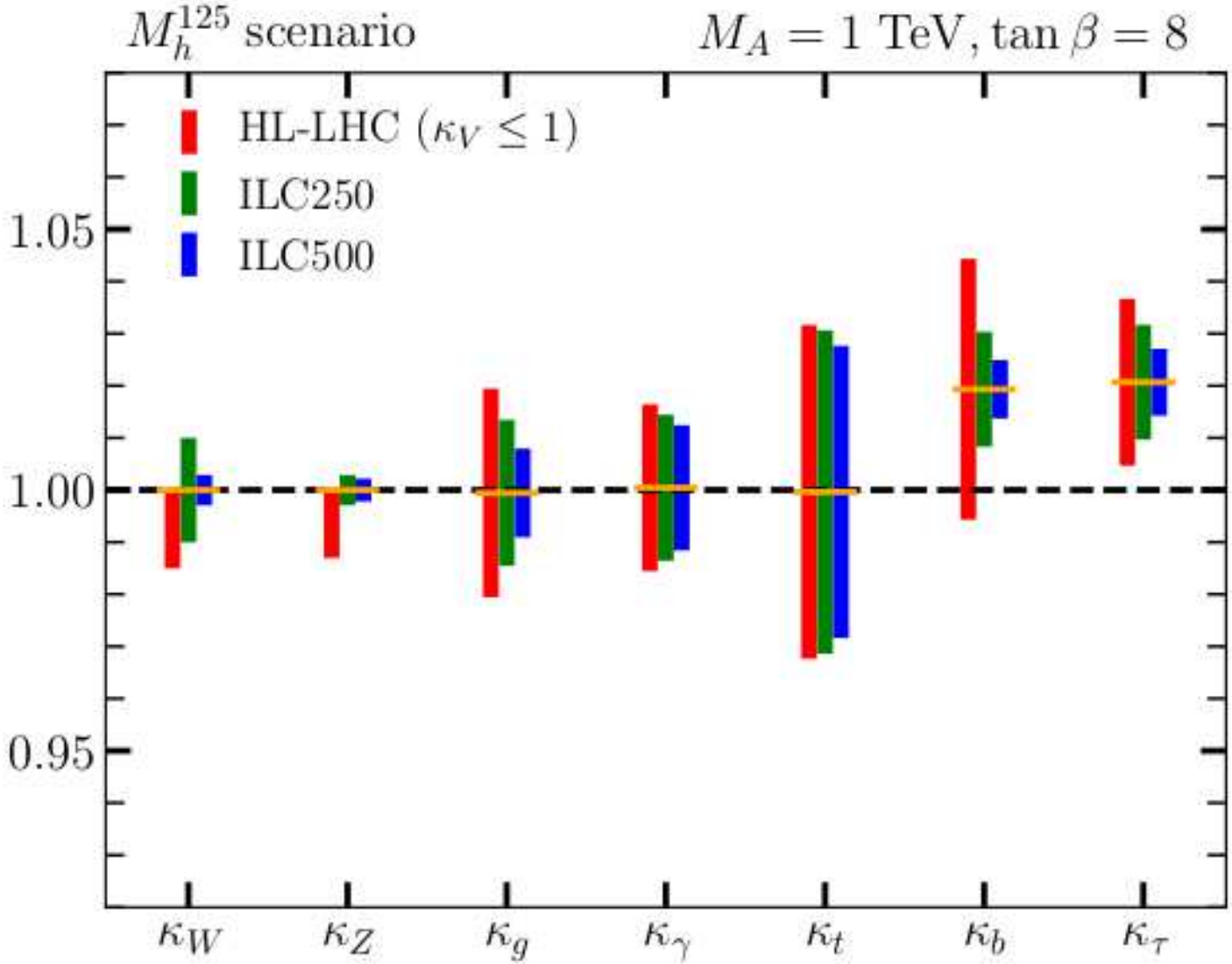
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

[*H. Bahl et al – PRELIMINARY*]



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

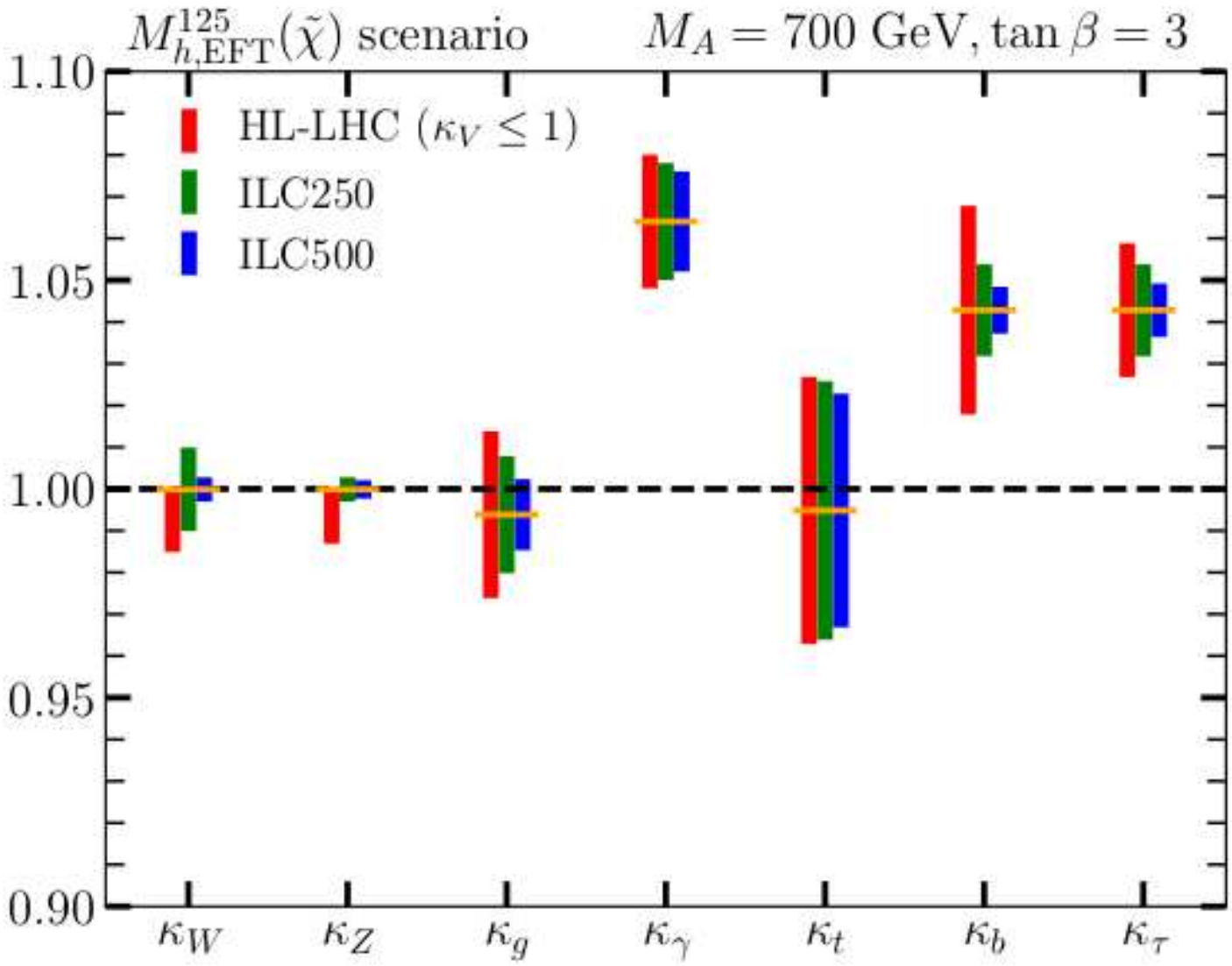
[*H. Bahl et al – PRELIMINARY*]



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

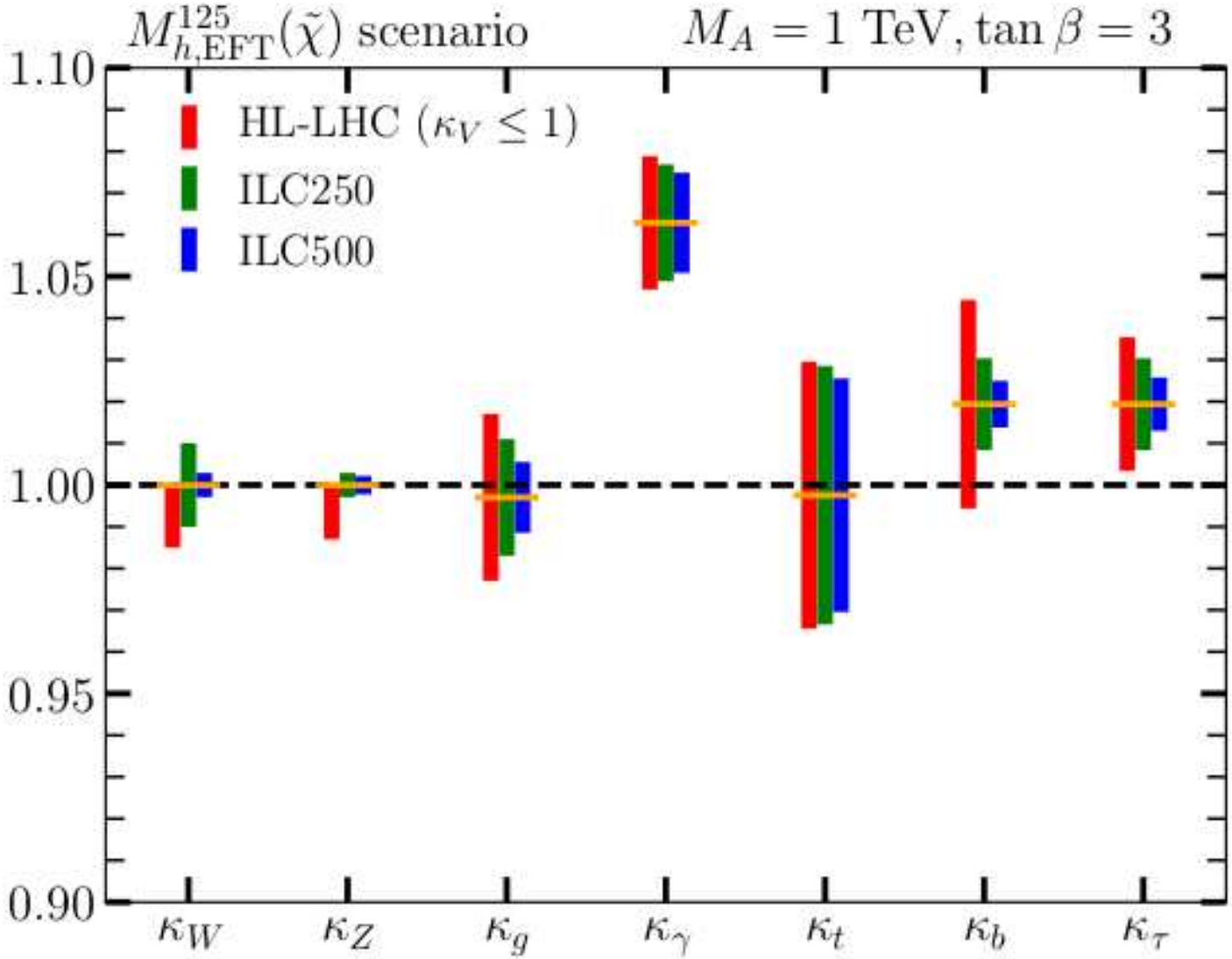
MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\mathrm{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

[*H. Bahl et al – PRELIMINARY*]



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

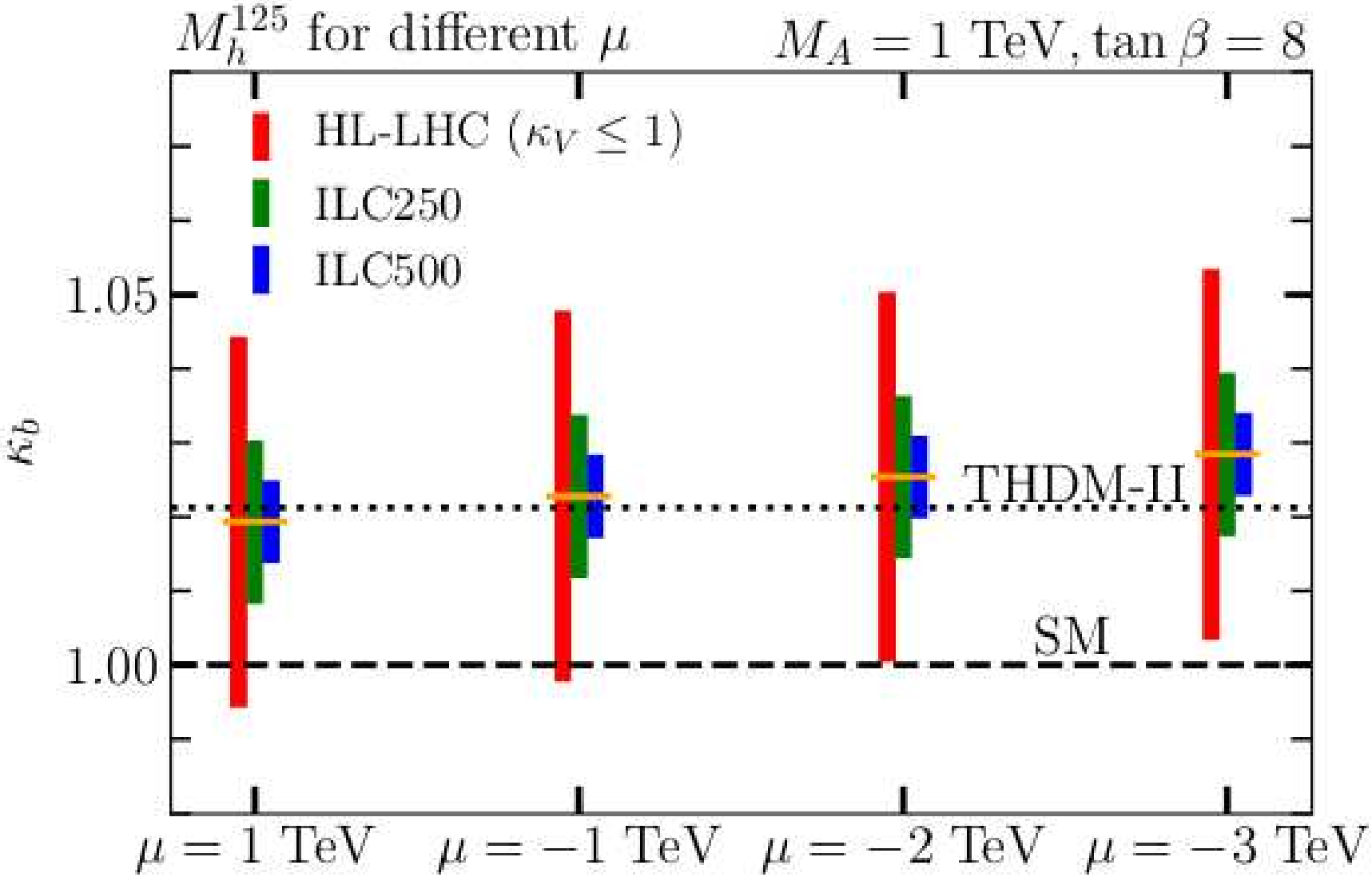
[*H. Bahl et al – PRELIMINARY*]



$\Rightarrow$ 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 – PRELIMINARY*]



$\Rightarrow$ MSSM vs. 2HDM: very challenging!

4. Conclusinos

- High precision prediction for cross sections and branching ratios are crucial for coupling constant determination

- Predictions (in the SM and BSM) needed at/below the per-cent level!

- (N)MSSM Higgs decays:
  SM-like Higgs: approaching e^+e^- precision
  heavy Higgses: much larger uncertainties (exp. situation unclear)

- Please: repeat this excercise in your favorite model! Not EFT . . .

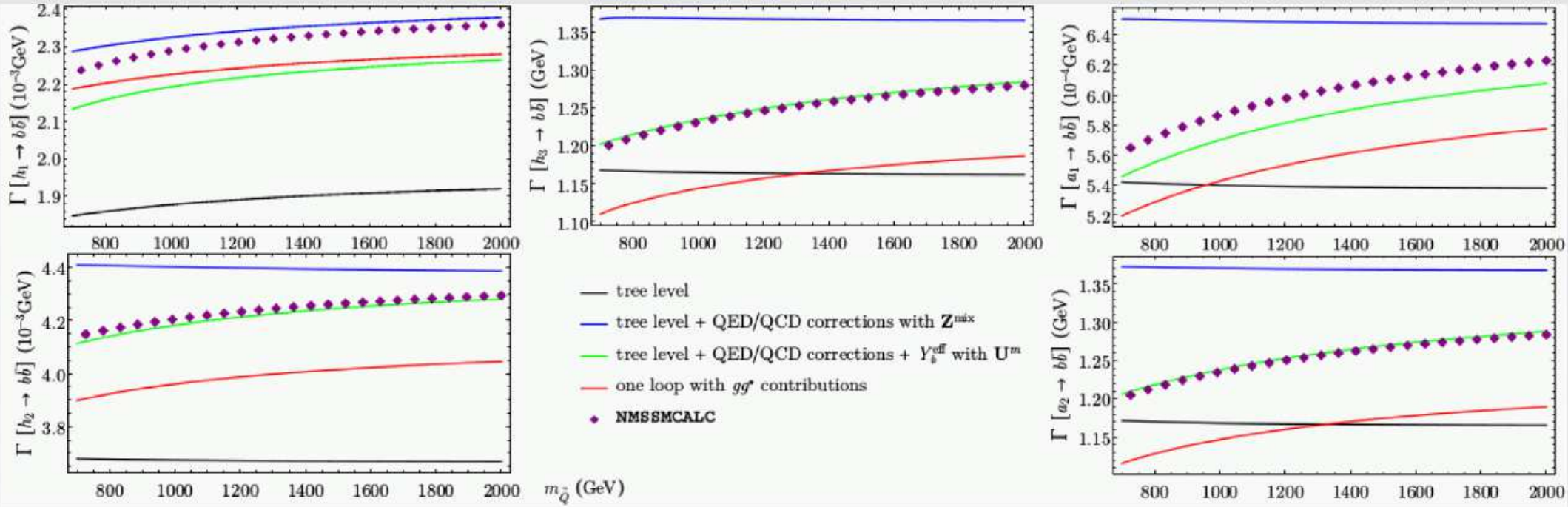
- BSM Higgs: deviations in per-cent range $\Rightarrow$ What can we learn?
  $\Rightarrow$ Compare e^+e^- precision with concrete BSM expectations
  $\Rightarrow$ Wäscheleinen-Plots (e^+e^- precision vs. BSM deviation)
  $\Rightarrow$ clear distinction between (selection of) models possible


Higgs Days at Santander 2020
Theory meets Experiment
28 September - 02 October
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Gervasio.Gomez@cern.ch
http://hdays.csic.es
UC
CSIC
IFCA
EXCELENCIA SEVERO OCHOA
EXCELENCIA MARÍA DE MAEZTU
European Commission
Horizon 2020
European Union funding for Research & Innovation
ifl
Instituto de Física Teórica


Further Questions?

Bringing the NMSSM to the same level: NMSSM

[slide from F. Domingo]

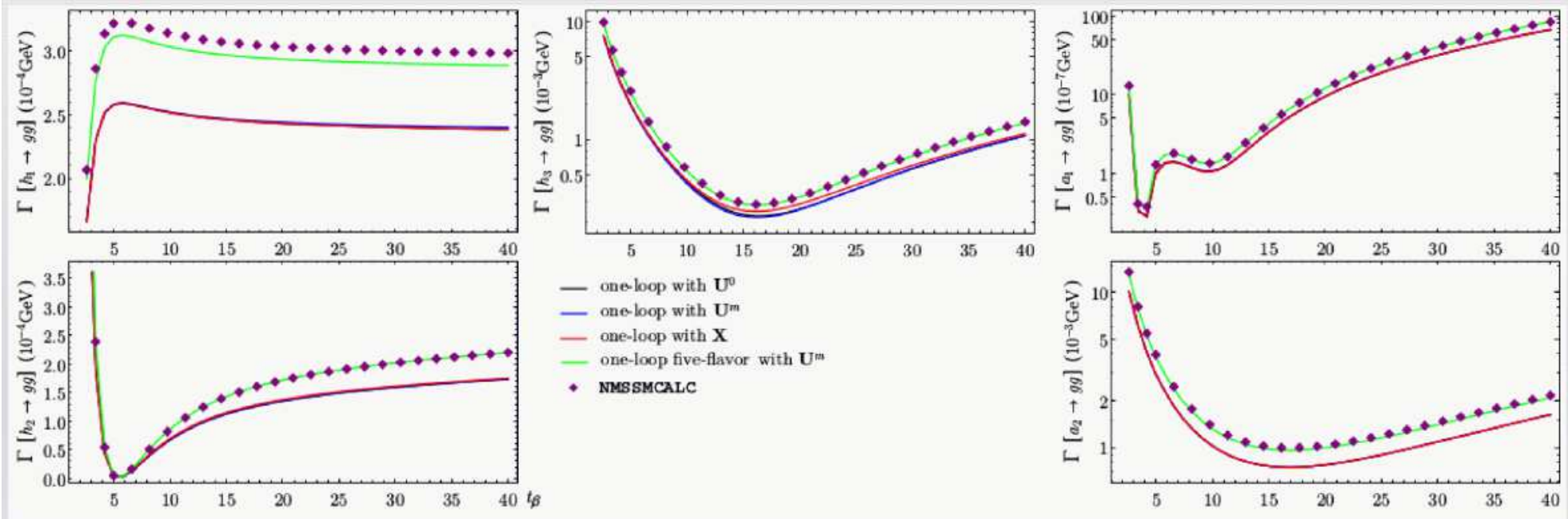


- HDECAY provides a QCD/large $\tan\beta$-corrected width (including SQCD) $\simeq$ our green line;
- Full one-loop shows EW Sudakov logarithms for heavy states.

Here: h_1 SM-like; h_2 (640 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).

Bringing the NMSSM to the same level: NMSSM

[slide from F. Domingo]



- HDECAY performs at the same order as us with 5-flavor radiation;
- $\sim 4\%$ deviation due to normalization factor (difference of EW 2-loop and QCD 3-loop order).

Here: h_1 SM-like; h_2 (650 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).