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BSM Higgs Lecture

Sven Heinemeyer, IFT (CSIC, Madrid)

Shanghai, 10/2025

1. Motivation for BSM Higgs & BSM Higgs sectors

2. BSM Higgs sectors: collider phenomenology & more

3. Tutorial: joint calculations

BSM Higgs Lecture

BSM Higgs sectors: collider phenomenology & more

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1. How to distinguish BSM Higgs sectors experimentally

2. Heavy BSM Higgs searches at the LHC

3. Triple Higgs Couplings (THCs) at the (HL-)LHC

4. m_{hh} measurements at the HL-LHC

5. BSM THCs at the ILC

1. How to distinguish BSM Higgs sectors experimentally

Remember:

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 of the h_{125}

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

⇒ let's take a look at A1

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 $\sim$ 125 GeV
- top/EW physics
- BSM searches
- ...

$\Rightarrow$ This new e^+e^- collider will come after,
or in the end phase of the HL-LHC

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

$\Rightarrow$ often e^+e^- expectations are shown in comparison to HL-LHC

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) considered 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)

LCF (Linear Collider Facillity (at CERN))
  e^+e^- collisions at 250 – 550 GeV (final stage open)

FCC-ee (Future Circular Collider e^+e^-)
  e^+e^- collisions up to 365 GeV

CEPC (Circular e^-e^+ Collider)
  e^+e^- collisions up to 365 GeV

FCC-hh (Future Circular Collider had-had)
  pp collisions at 100 TeV (possible?)

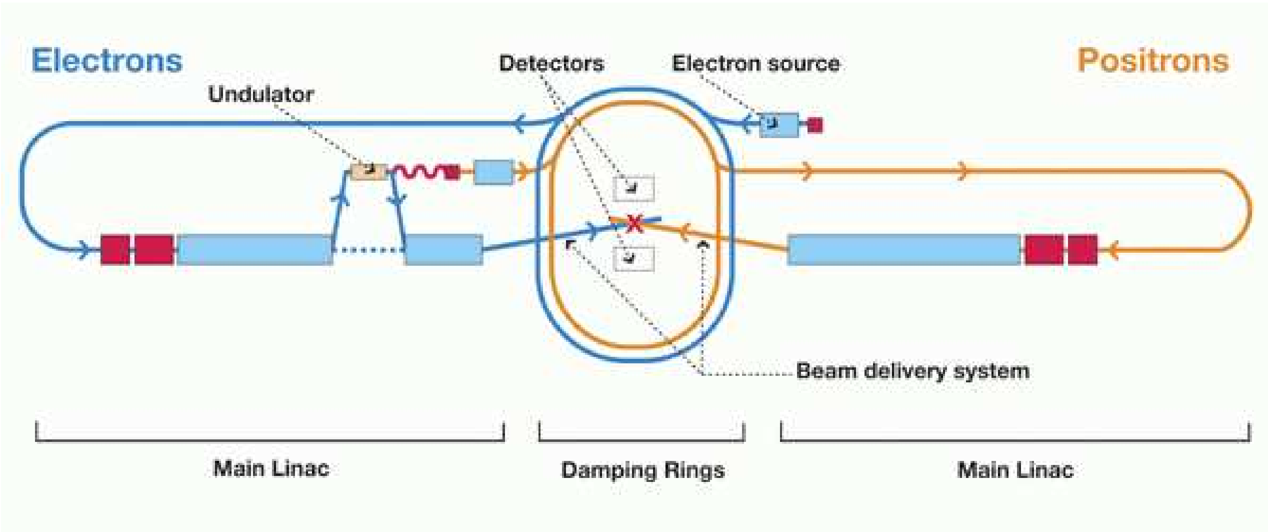
Mini overview of the International Linear Collider (ILC)

Mini overview of the International Linear Collider (ILC)

Linear e^+e^- collider, $\sqrt{s} = 250 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

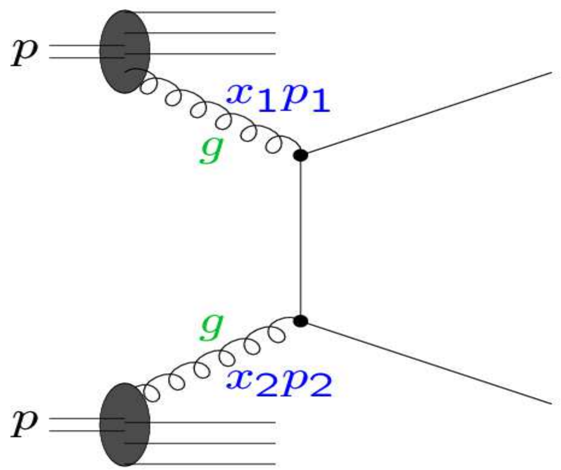
Schematic:



– two detectors in one interaction region (push-pull)
– undulator based e^+ source
– polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)
– tunable energy

Mini-comparison of LHC and ILC:

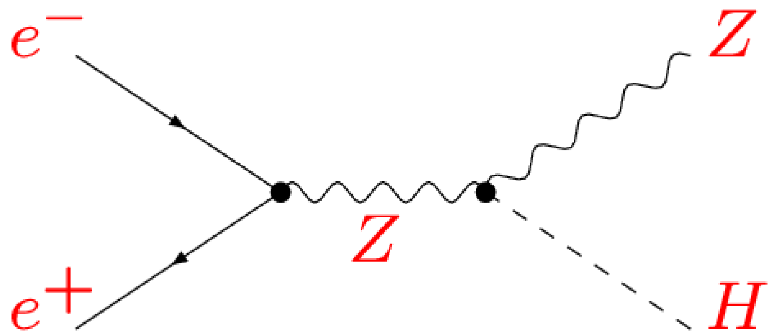
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

⇒ huge QCD backgrounds,
low signal–to–background ratios

ILC: e^+e^- scattering at ≈0.25–1 TeV

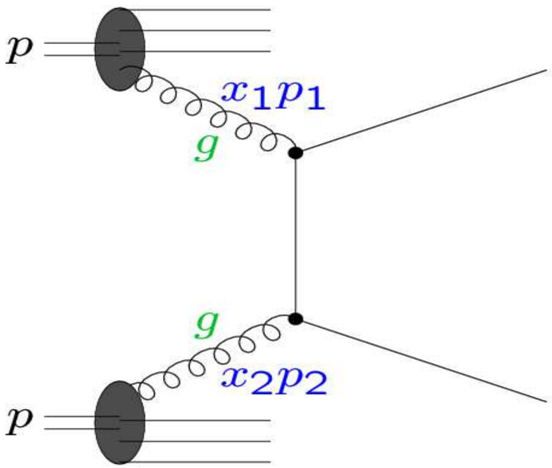


Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, ...

⇒ rel. small backgrounds
high-precision physics

Mini-comparison of LHC and ILC:

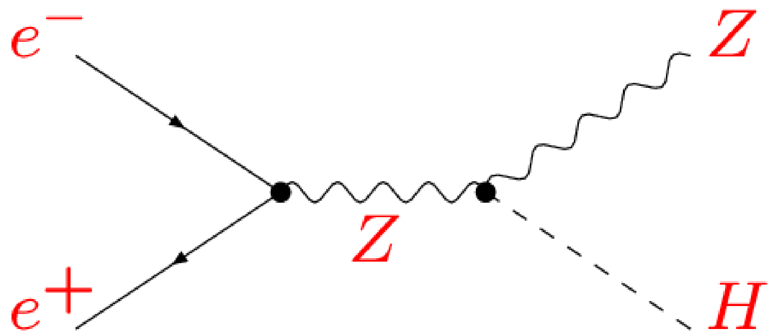
LHC: pp scattering at 14 TeV



interaction rate of 10^9 events$/s$

$\Rightarrow$ can trigger on only 1 event in 10^7

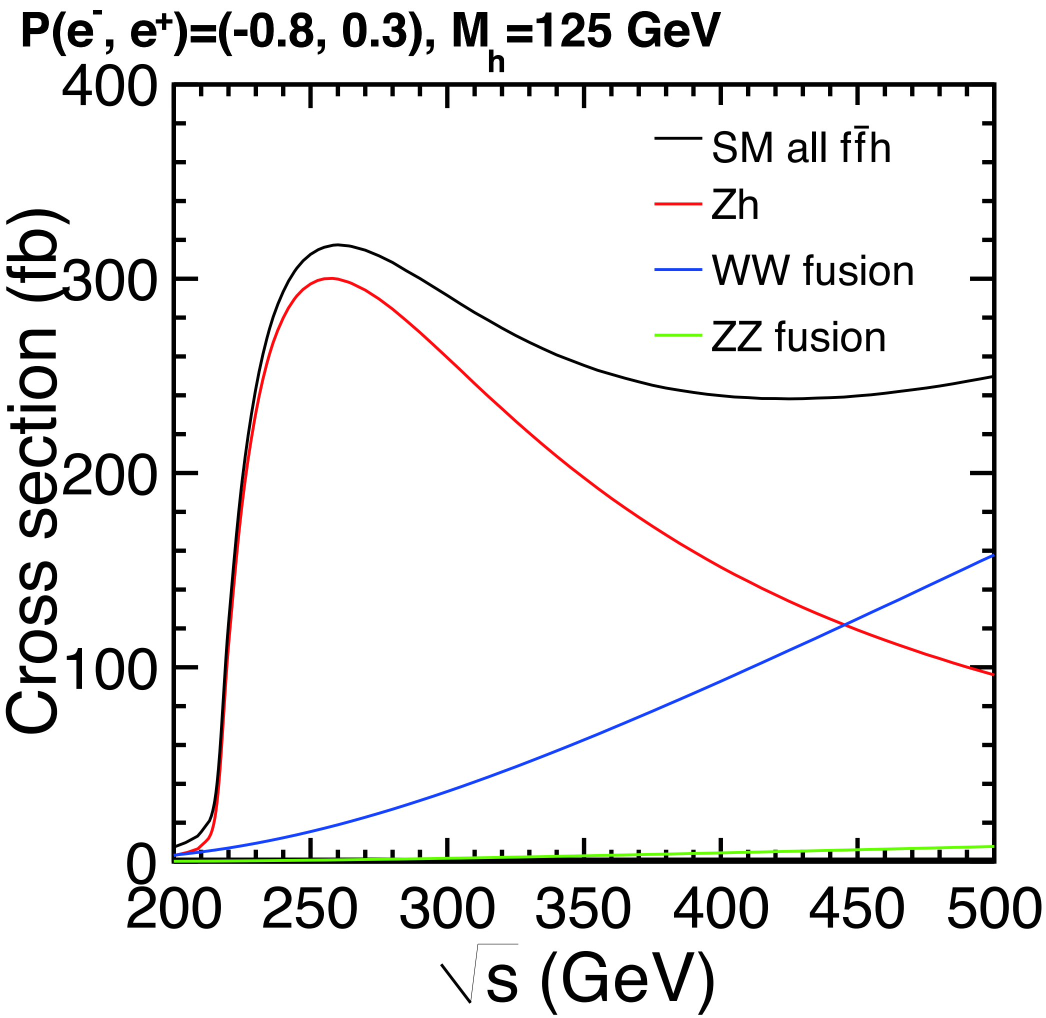
ILC: e^+e^- scattering at $\approx$0.25–1 TeV



untriggered operation

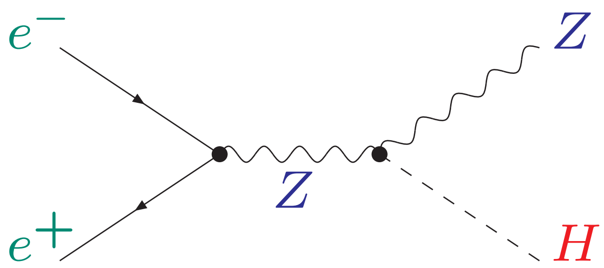
$\Rightarrow$ can find signals of unexpected new physics (direct production + large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

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



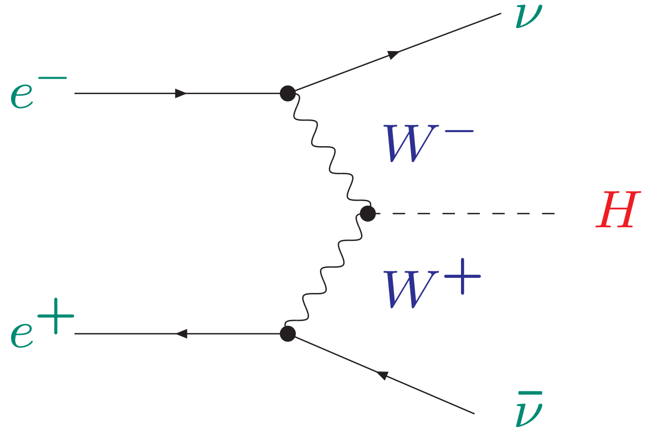
Higgs-strahlung:

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



weak boson fusion (WBF):

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



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

Measurement of Higgs couplings

LHCHWG recommendation: Higgs coupling strength scale factors: κ_i

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)

LHC always measures $\sigma \times$ BR

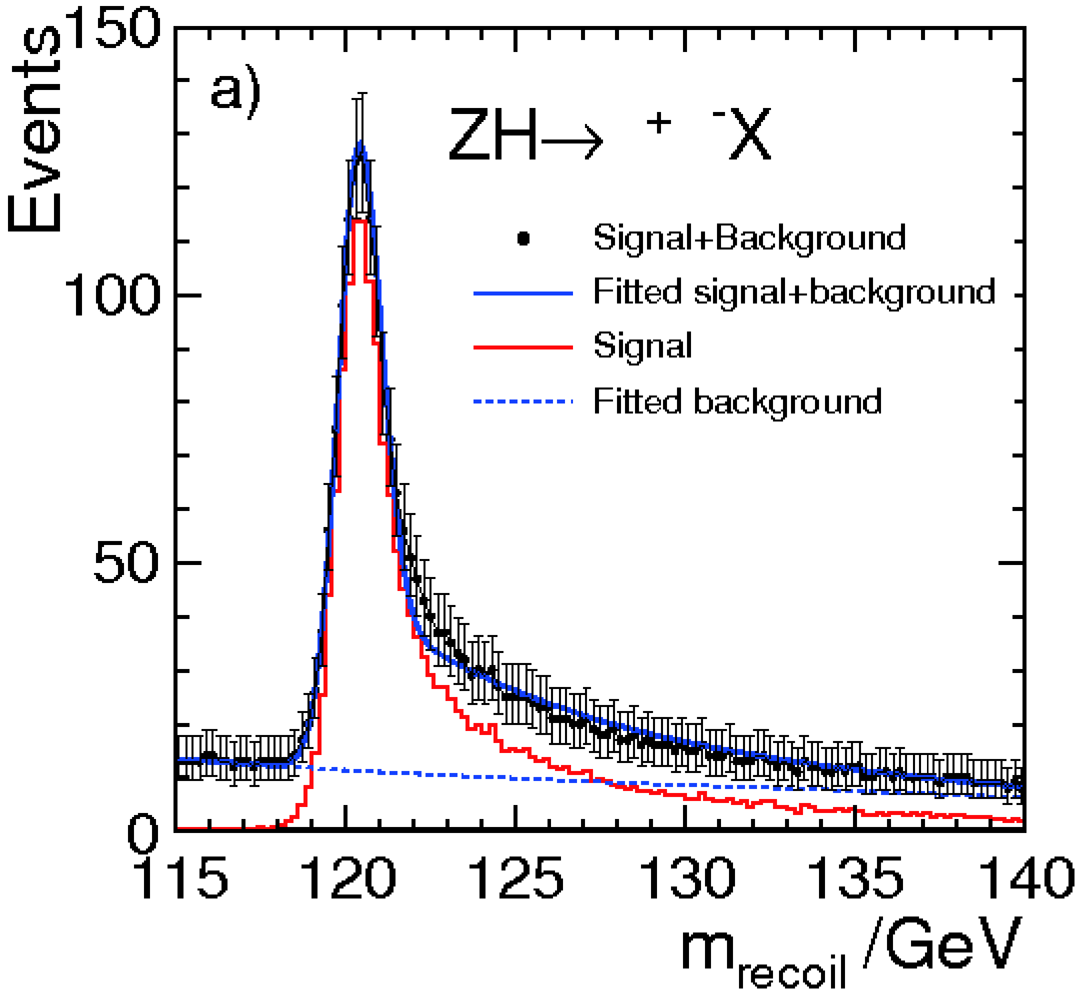
– no additional theory assumptions on your model:

$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

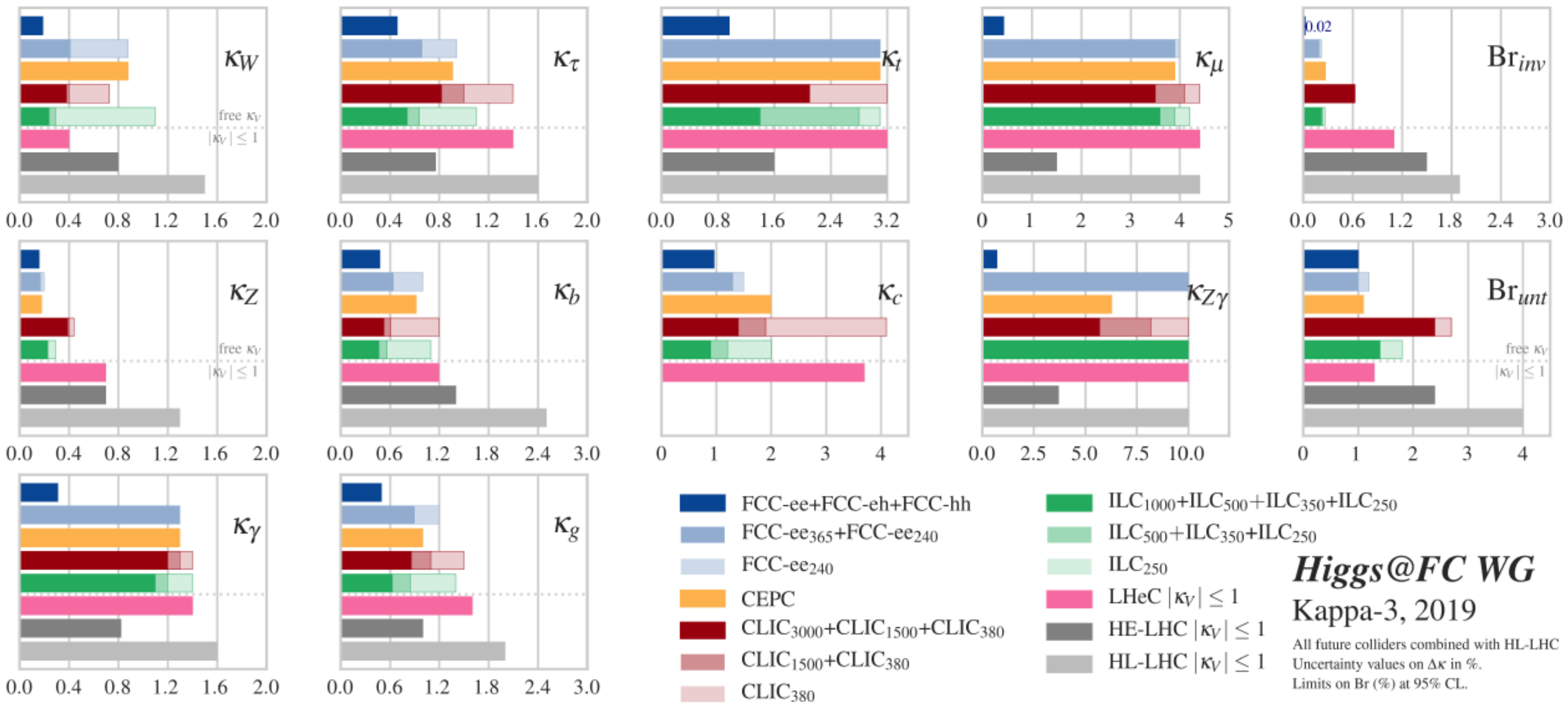
$\Rightarrow$ Determination of κ_i (evaluated to NLO QCD accuracy)

Z-recoil method: $e^+e^- \to ZH \to \mu^+\mu^- X$ $\Rightarrow$ "pure" cross section



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

Future expectations for κ (kappa-3 framework)



⇒ all e^+e^- options yield roughly similar results

⇒ FCC-hh/-he/-ee appears better

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

⇒ also remember different time scales!

BSM Higgs: what can we learn?

- let's assume that we do see a deviation in the measurements of the h_{125} couplings

- **What do we learn from that?** – "Higgs inverse problem"

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)

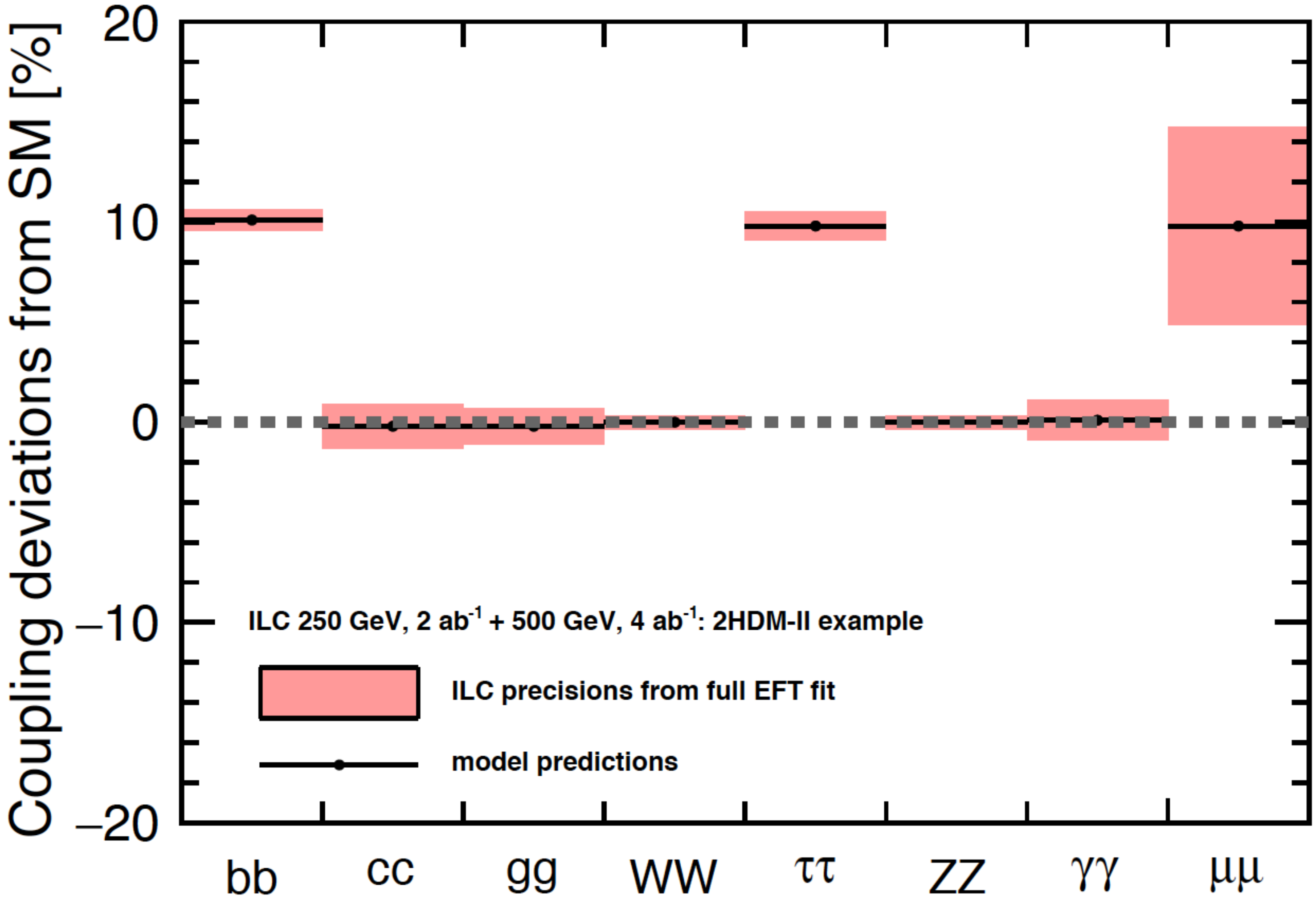
⇒ in the following:

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

⇒ “Wäscheleinen-Plots” (concrete: ILC500)

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

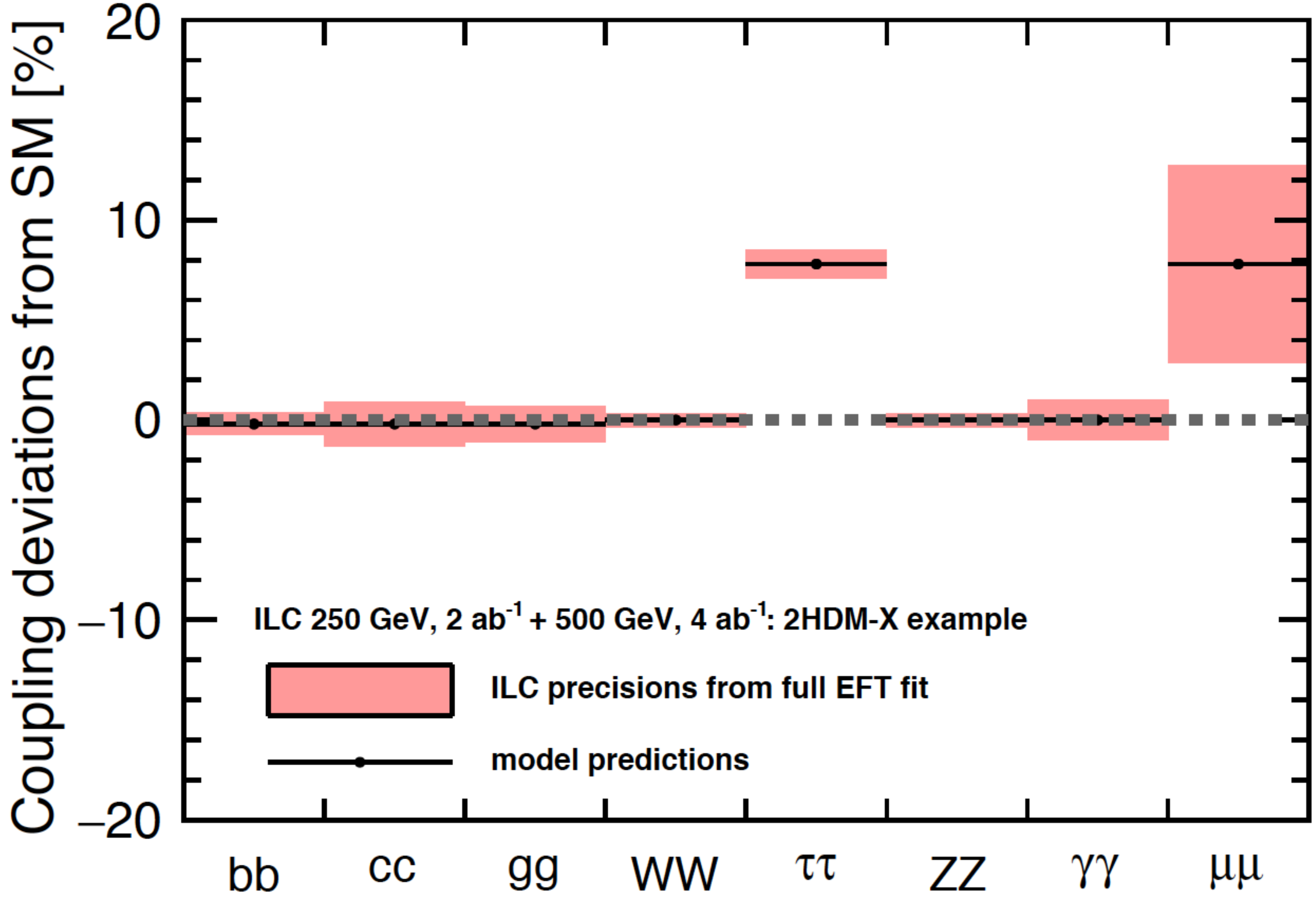
[*T. Barklow et al., '17*]



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

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

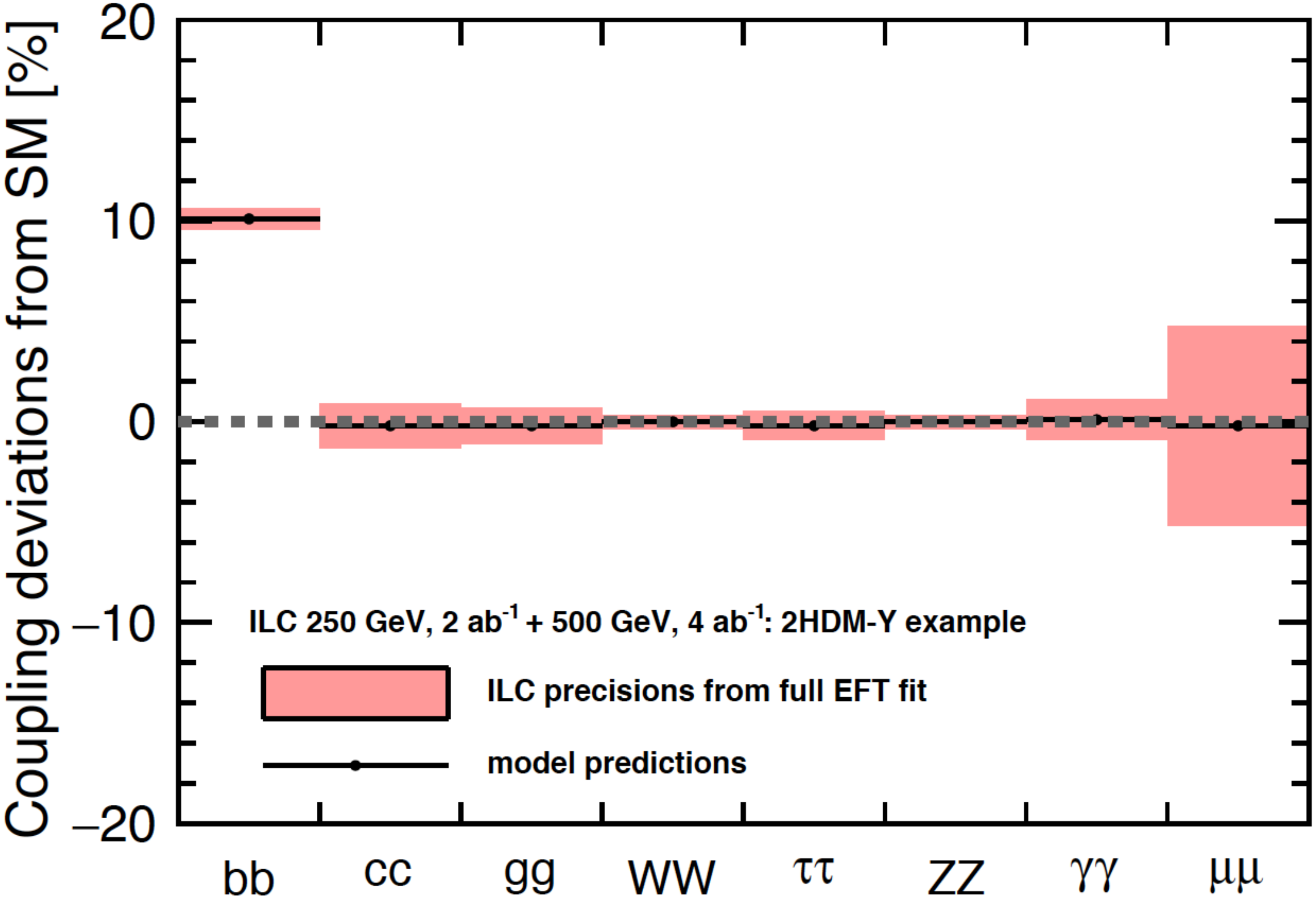
[*T. Barklow et al., '17*]



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

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

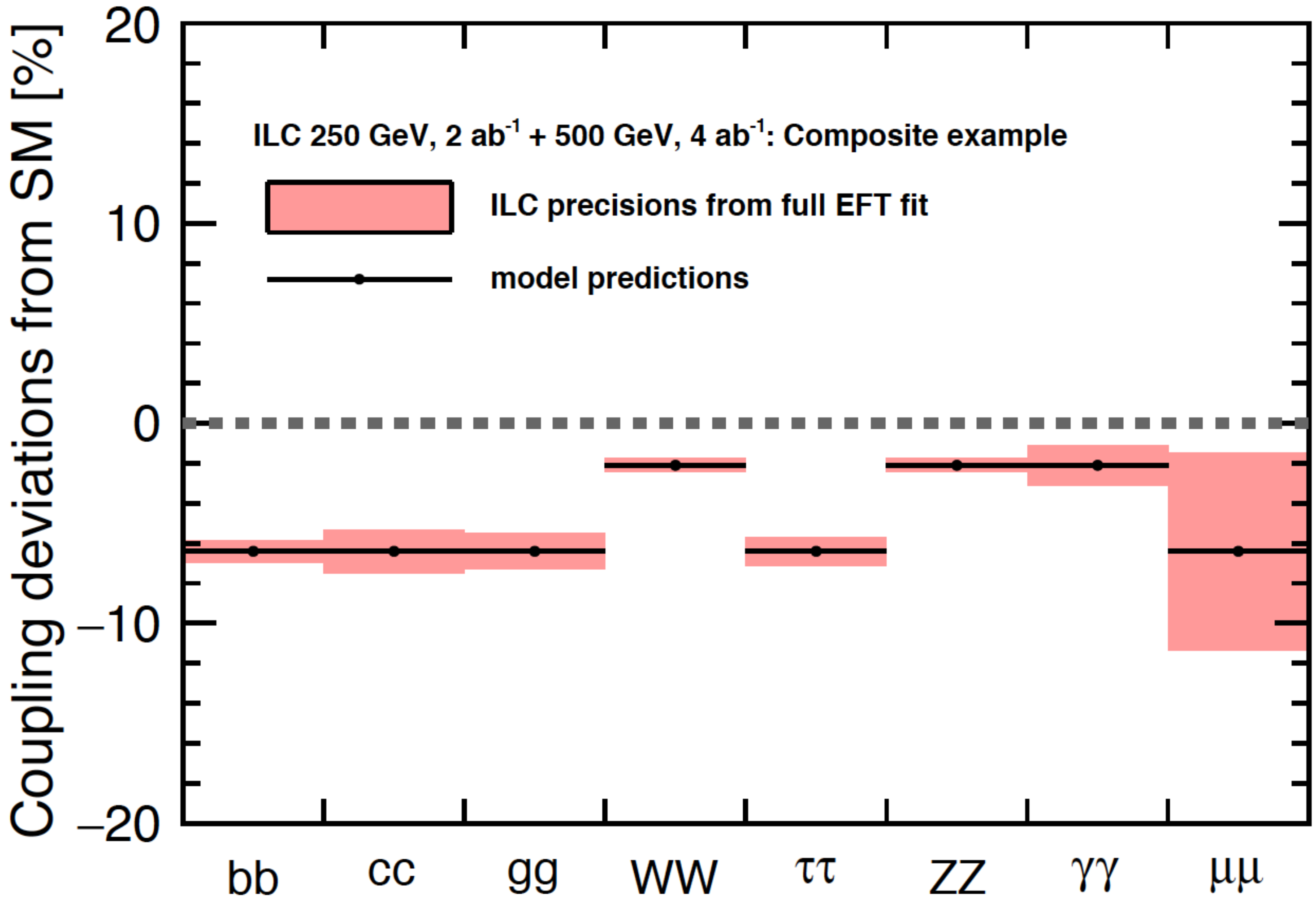
[*T. Barklow et al., '17*]



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

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

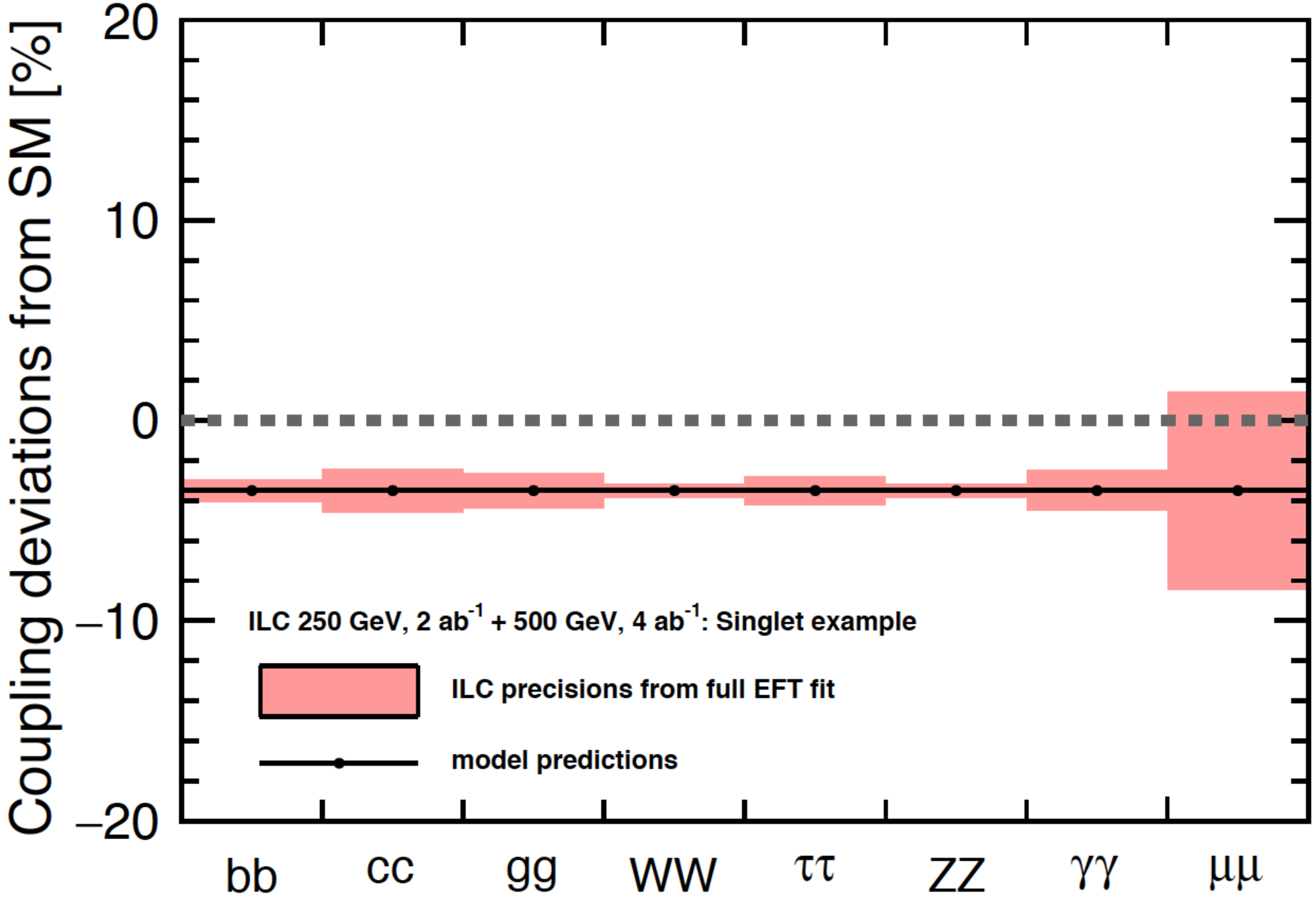
[*T. Barklow et al., '17*]



⇒ clear pattern, distinctive for Composite Higgs?!

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

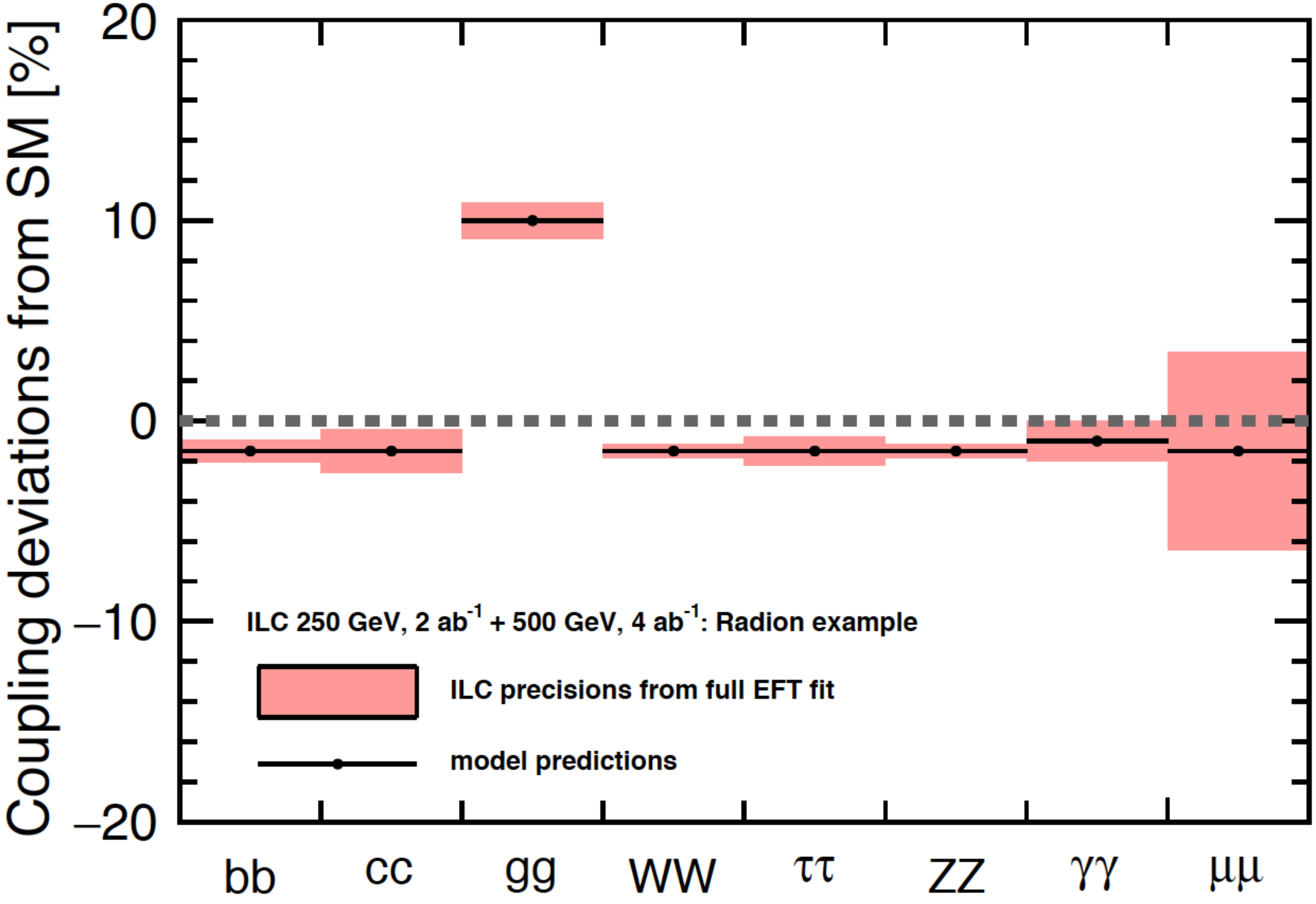
[*T. Barklow et al., '17*]



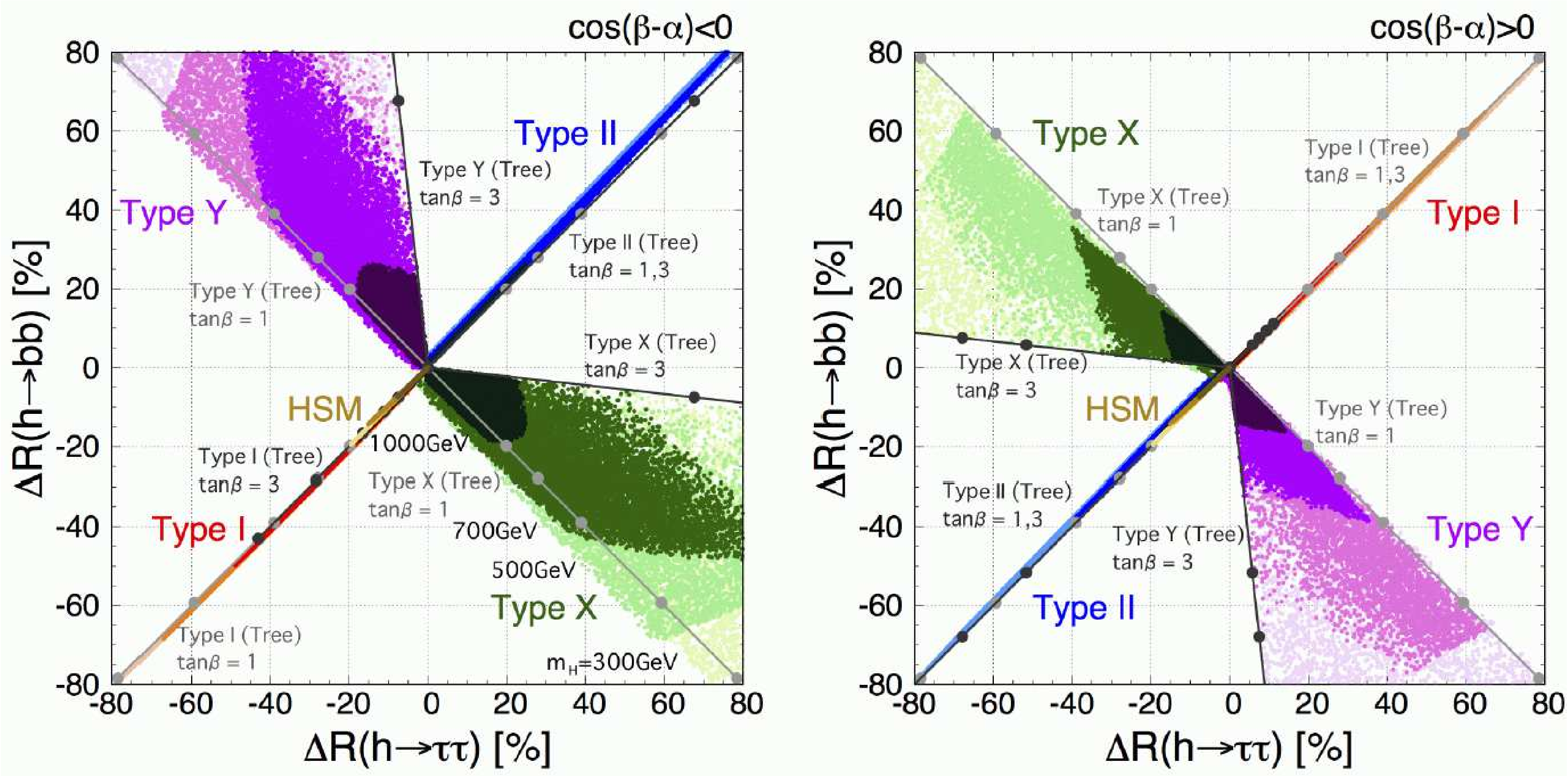
⇒ clear pattern, distinctive for RxSM?!

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

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



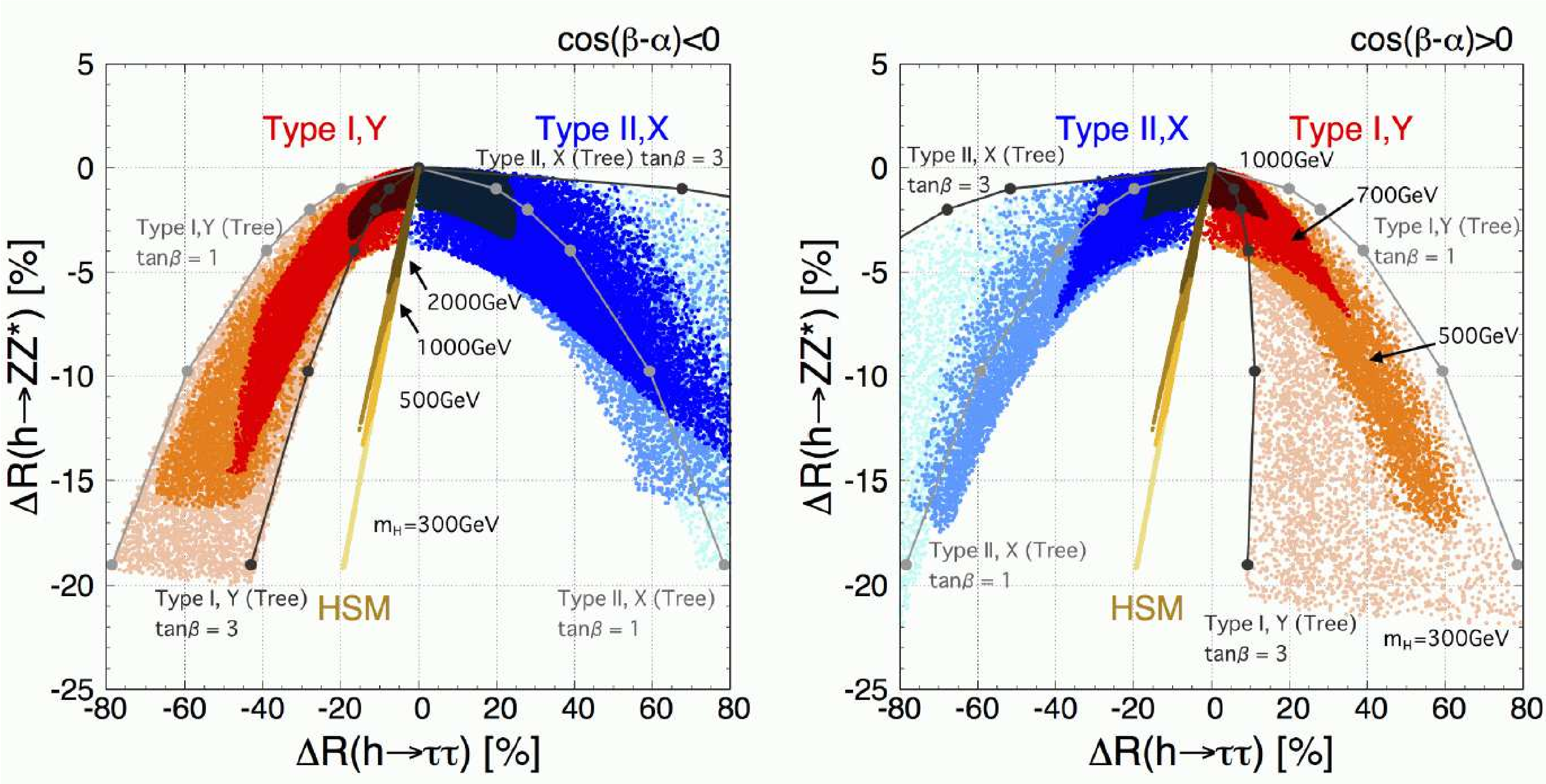
$\Rightarrow$ clear pattern, distinctive for Higgs Radion?!



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

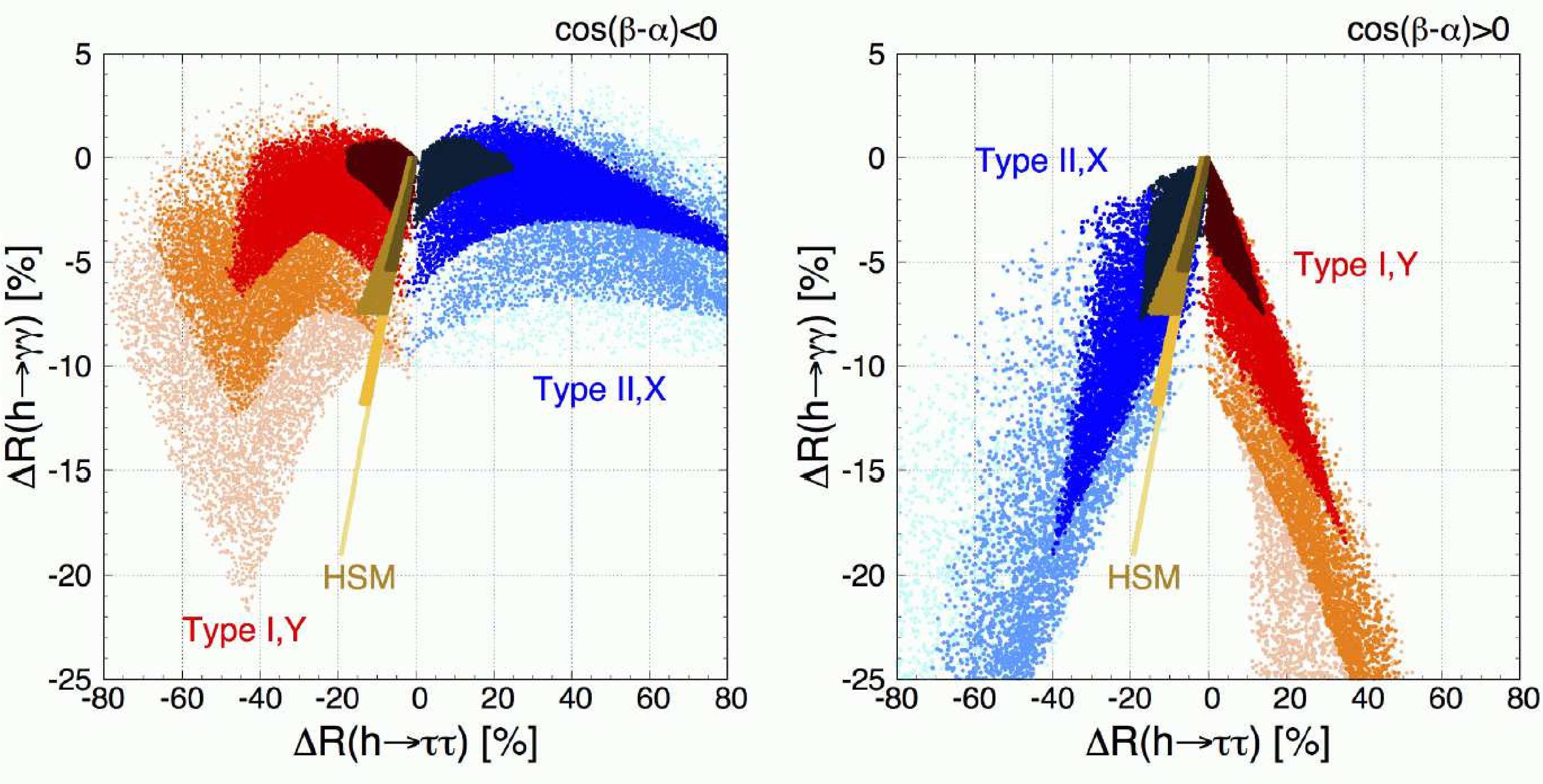
2HDM example (II):

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



$\Rightarrow$ LC precision has a great potential to discriminate the models!

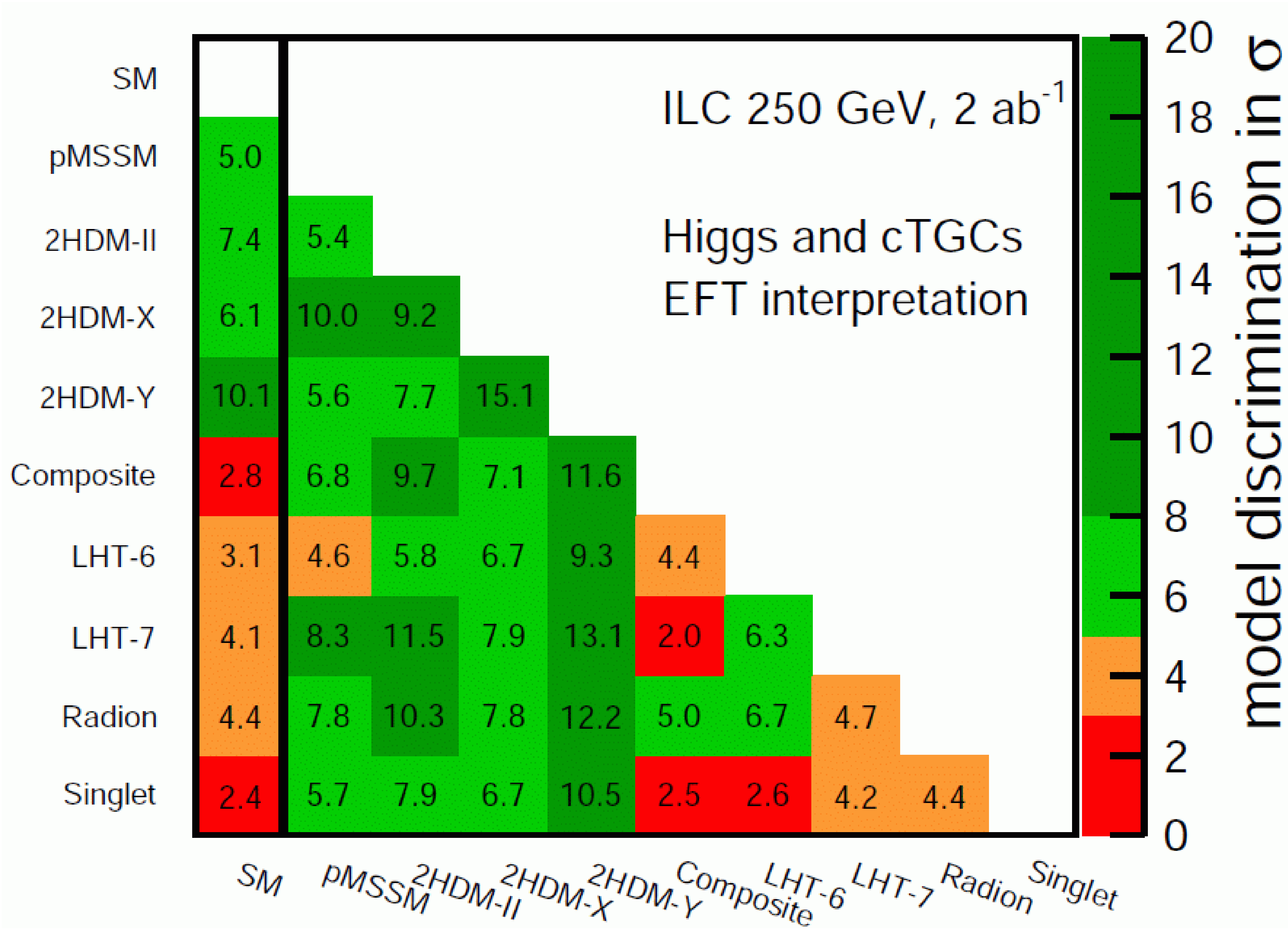
2HDM example (III): [S. Kanemura et al. '18]



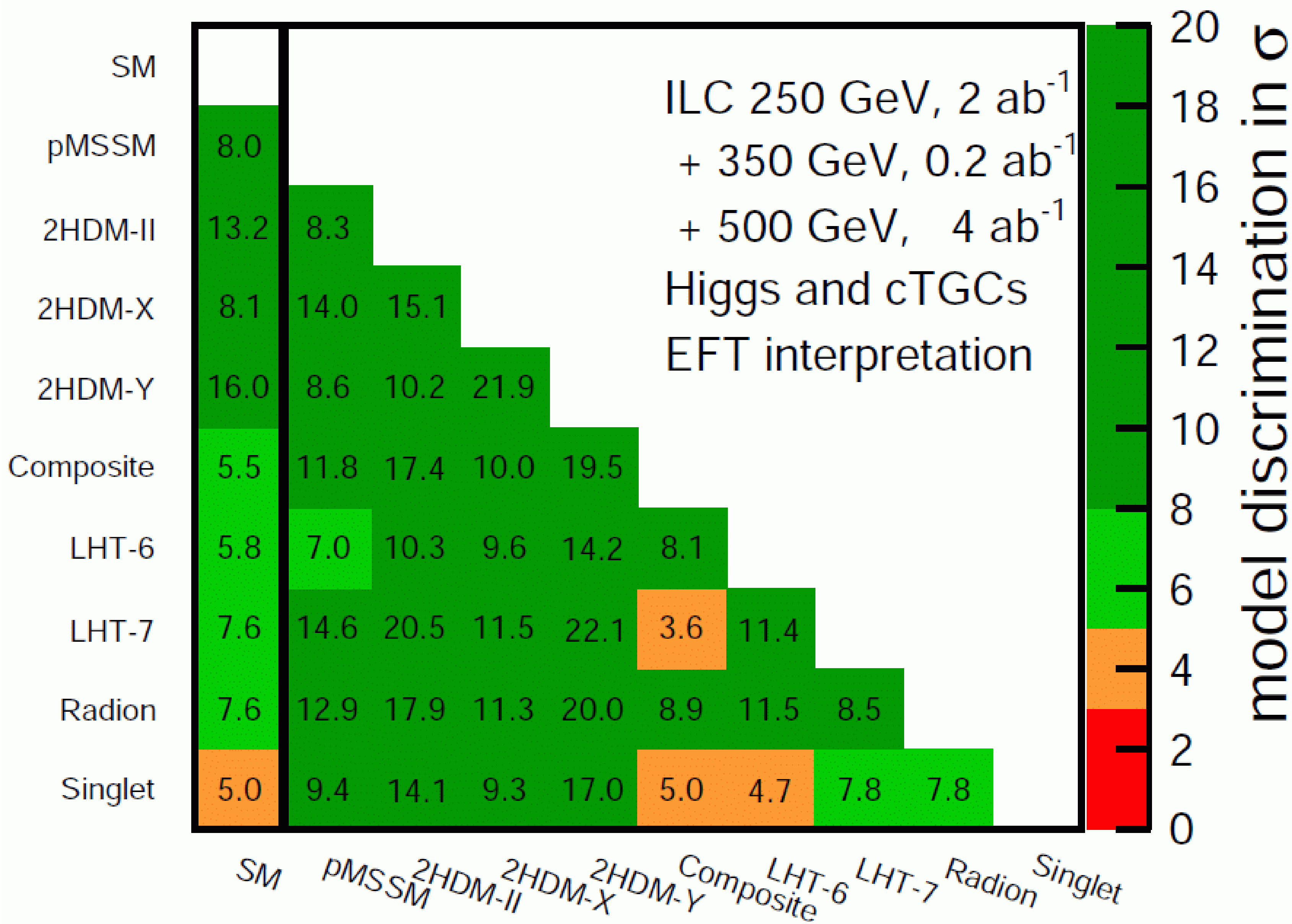
⇒ LC precision has a great potential to discriminate the models!

Model discrimination at ILC250:

[K. Fujii et al. '17]



[K. Fujii et al. '17]



Compare future colliders:

⇒ focus on Higgs searches and measurements

HL-LHC:

– will improve direct search limits
– will improve rate measurements (production $\times$ decay)
systematic/theory uncertainties: S2 scenario

[*M. Cepeda et al. '19 – YR18*]

ILC: (similar for FCC-ee/CEPC/CLIC)

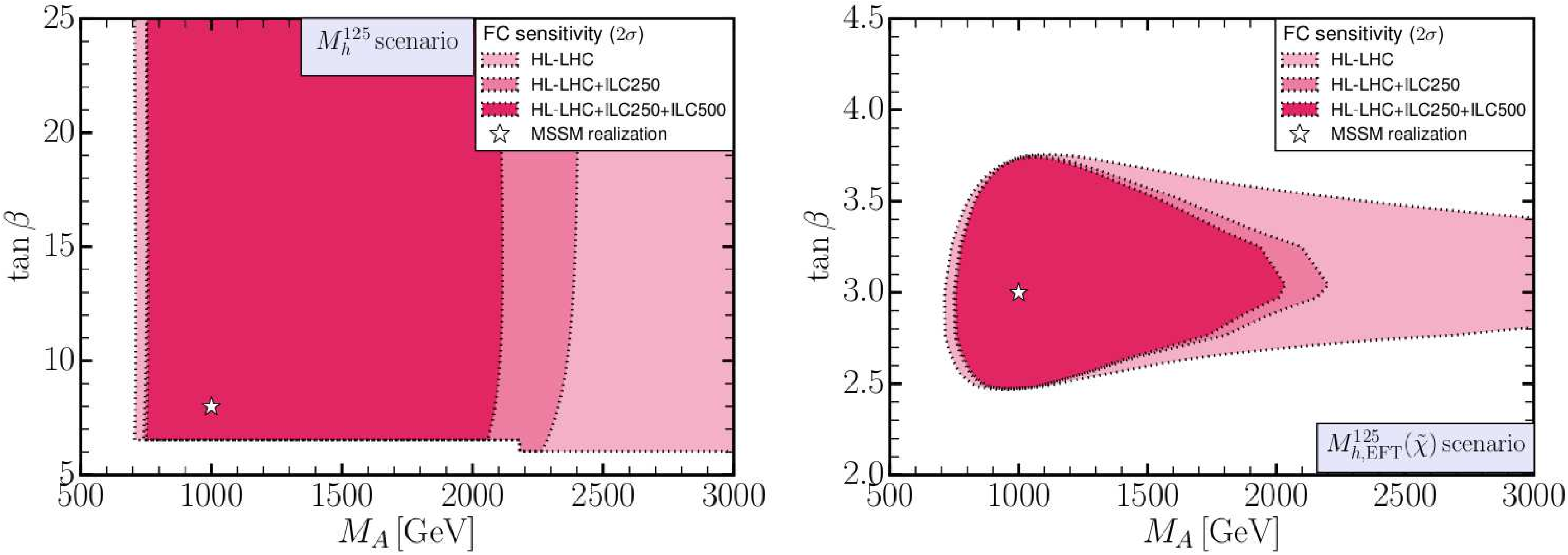
– will improve rate measurements (no theory assumptions!)
  – $250\,\text{fb}^{-1}$ at ILC250 $\oplus$ $500\,\text{fb}^{-1}$ at ILC500
  – polarization: $P(e^-, e^+) = (-80\%, +30\%)$

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

Relevance of ILC measurements:

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

- Assume a realization of an MSSM point: $M_A = 1$ TeV, $\tan\beta = 7/3$
- What limits can be set from rate/coupling measurements?

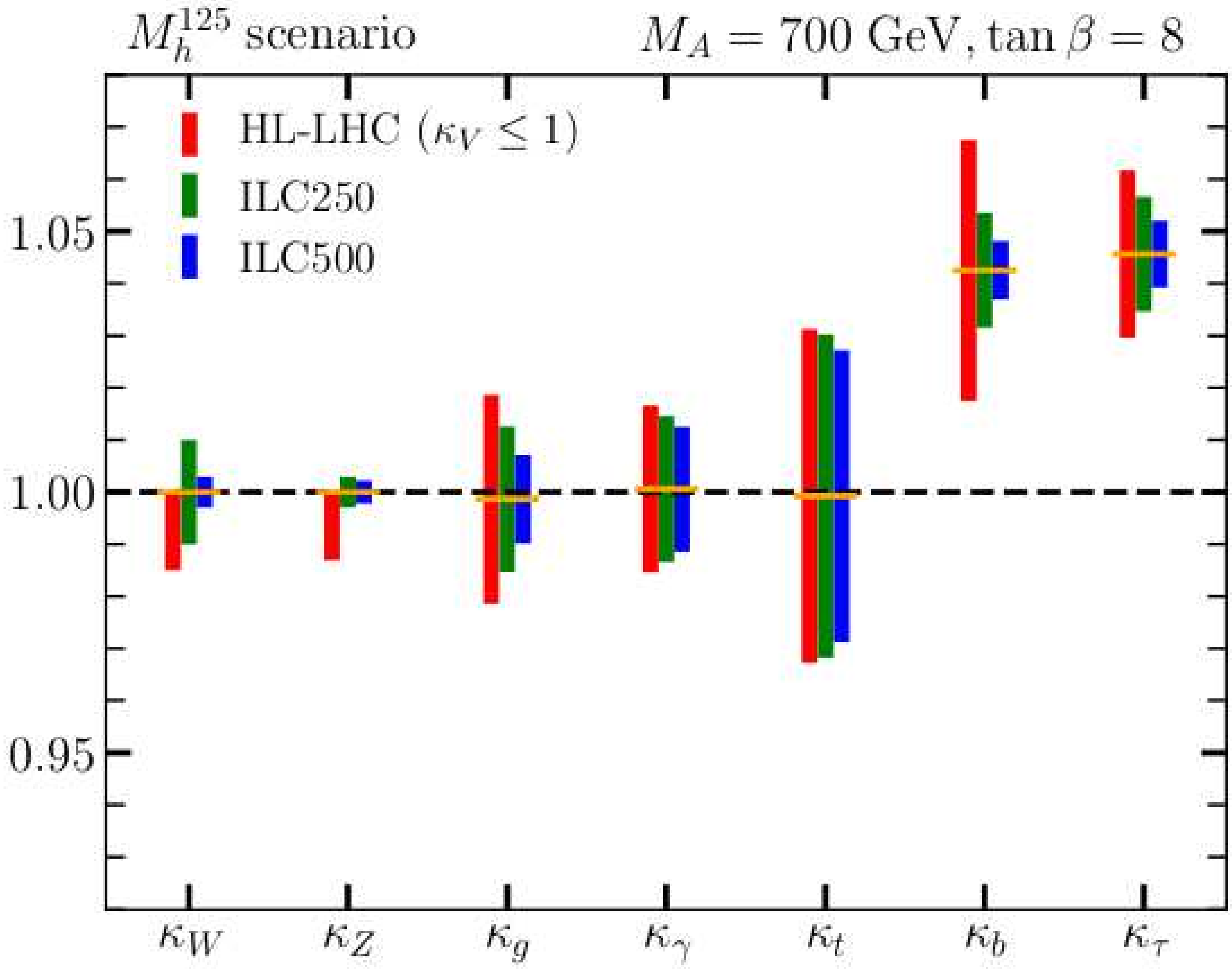


$\Rightarrow$ only ILC measurements give upper limit on M_A

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

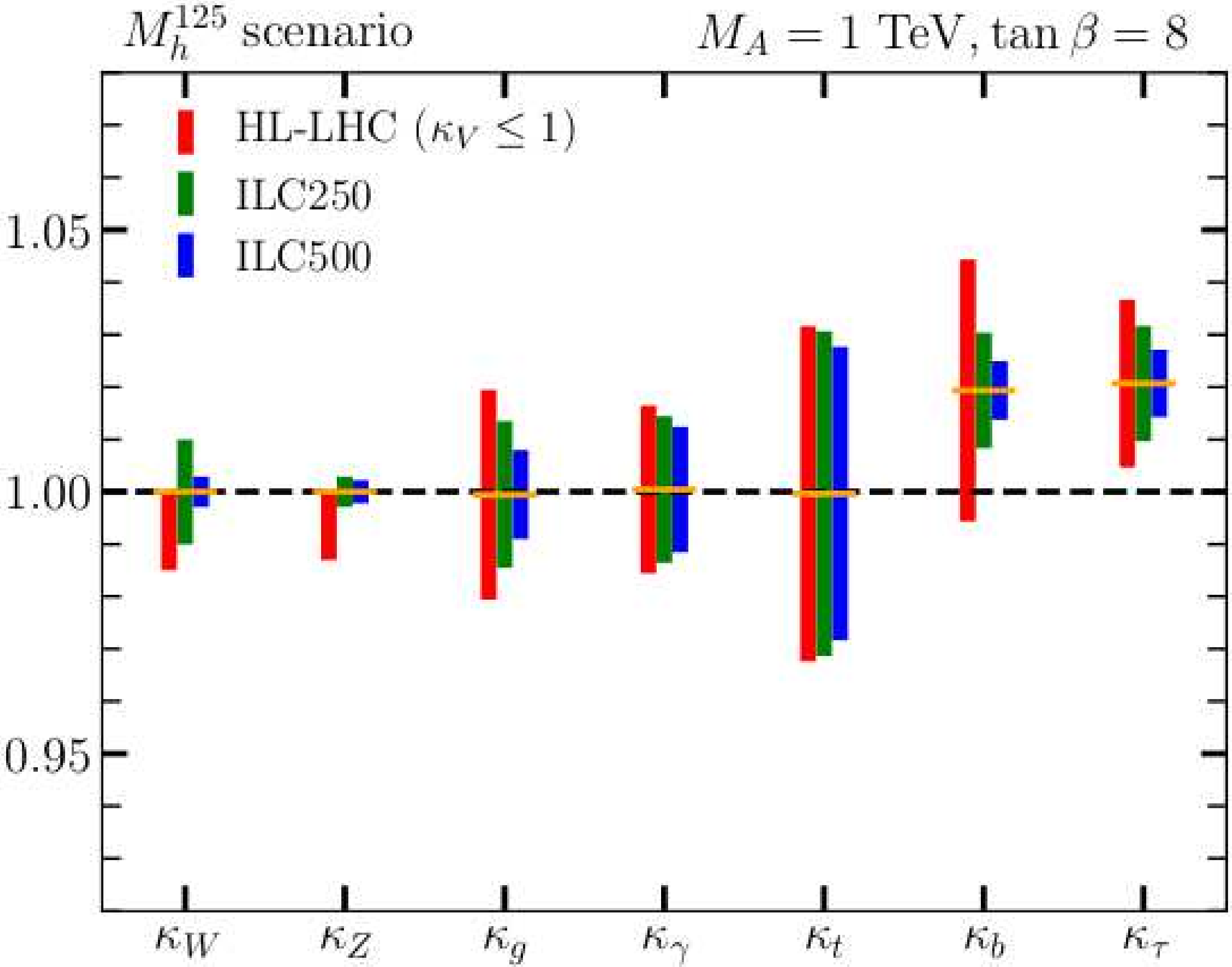
MSSM Wäscheleine I: e^+e^- precision vs. M_h^{125} ($M_A = 700$ GeV, $\tan\beta = 8$)

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



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

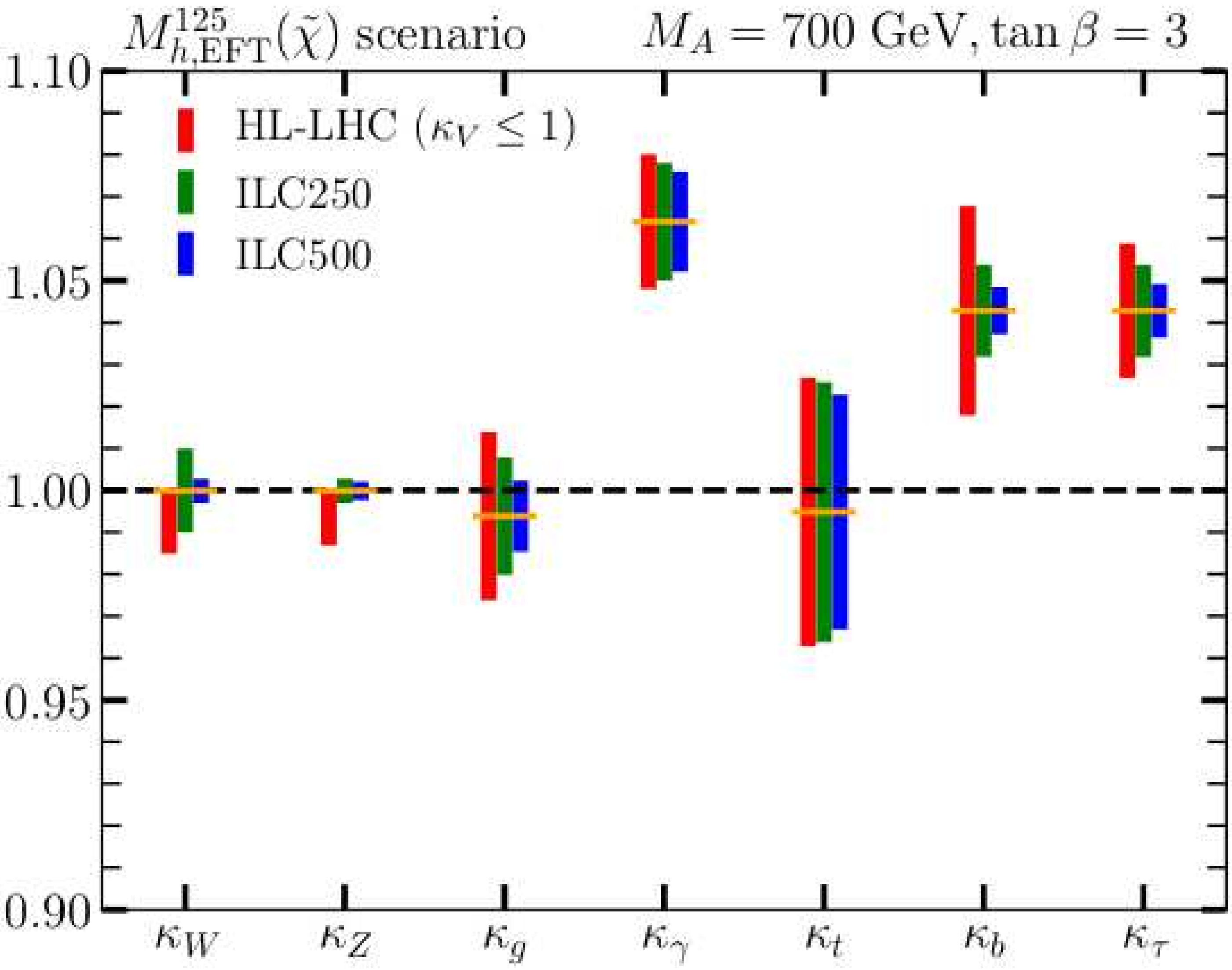
[*H. Bahl et al. '20*]



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

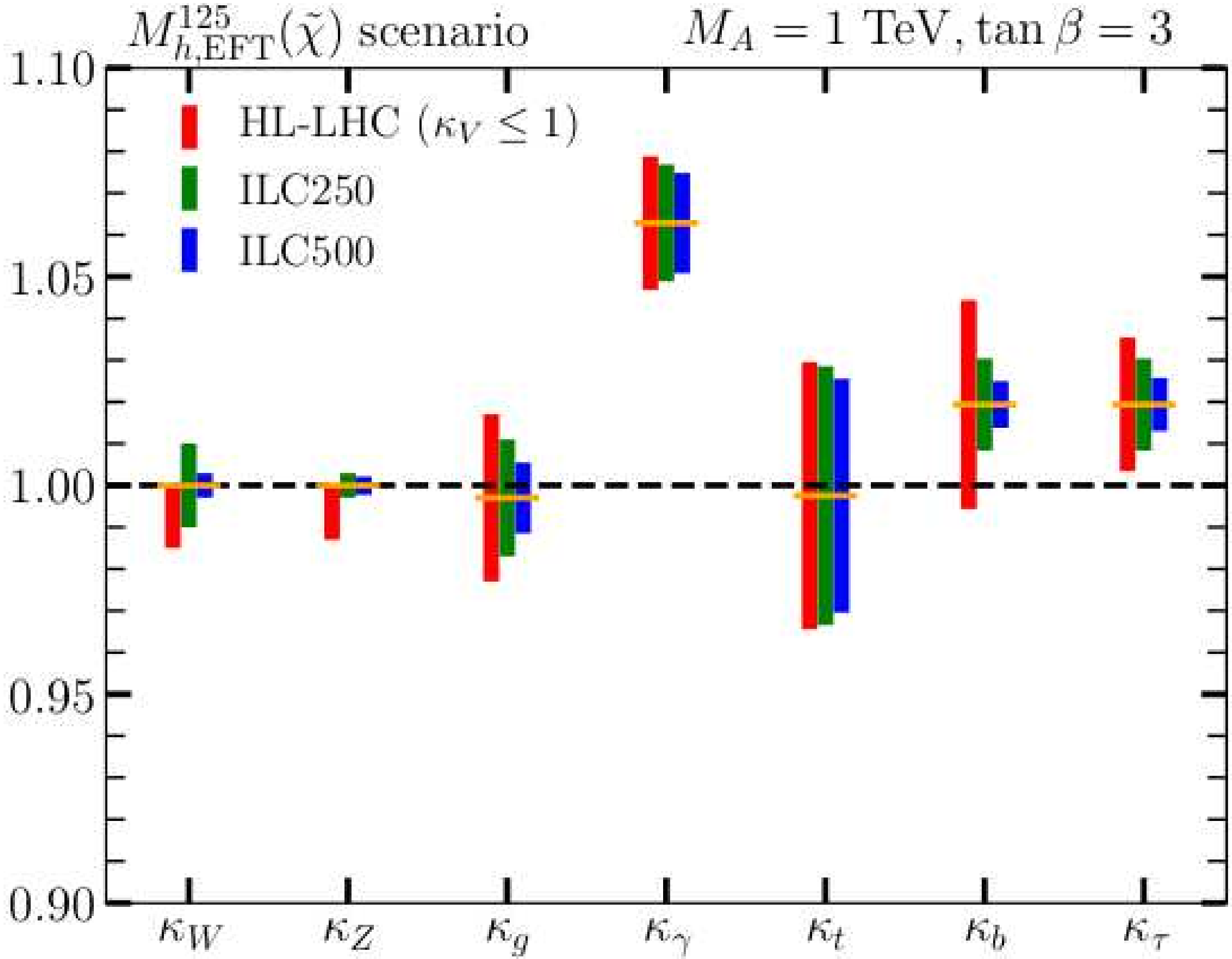
MSSM Wäscheleine III: e^+e^- vs. $M_h^{125,\text{EFT}}(\tilde{\chi})$ ($M_A = 700$ GeV, $\tan\beta = 3$)

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



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

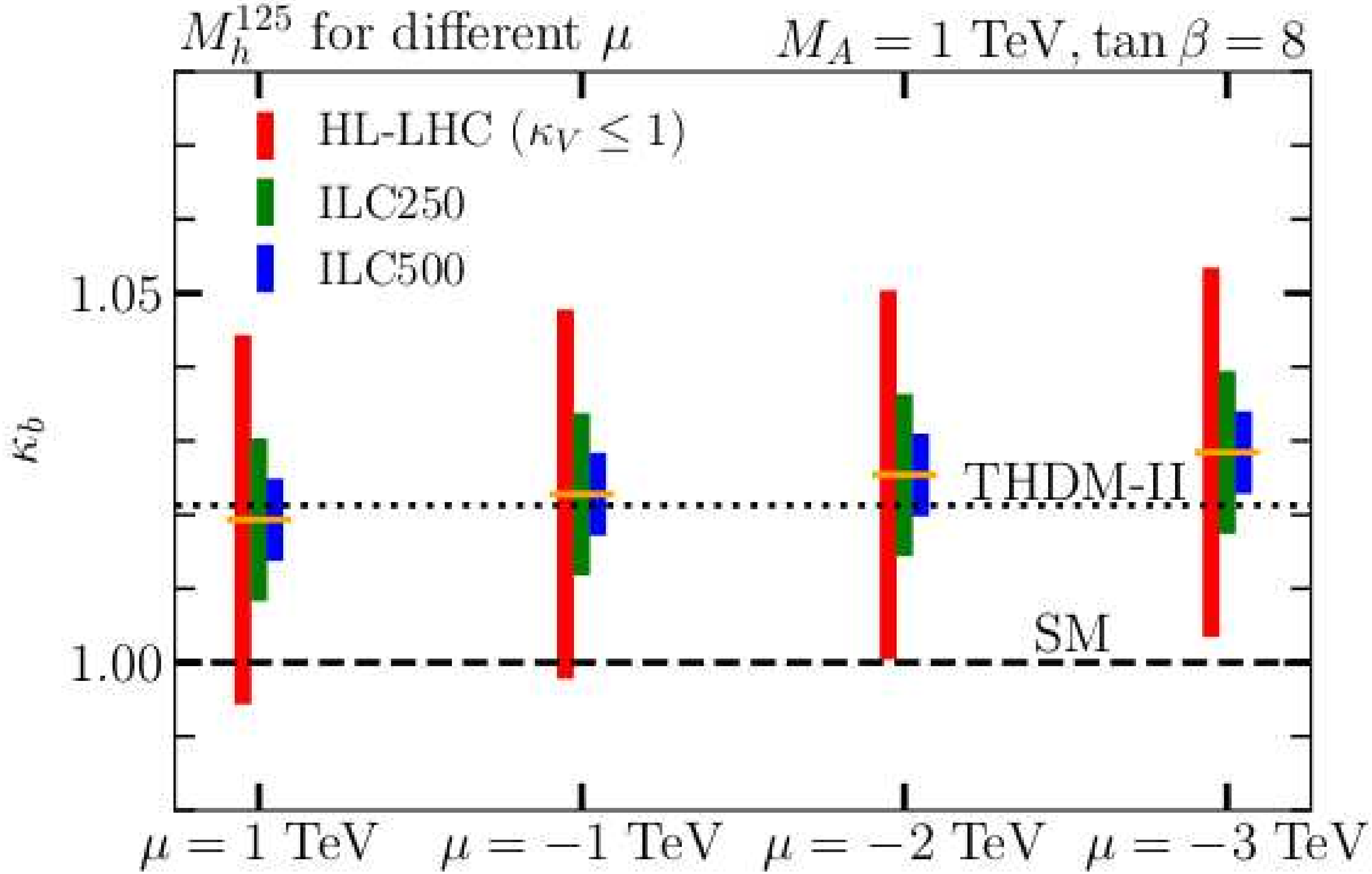
[*H. Bahl et al. '20*]



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

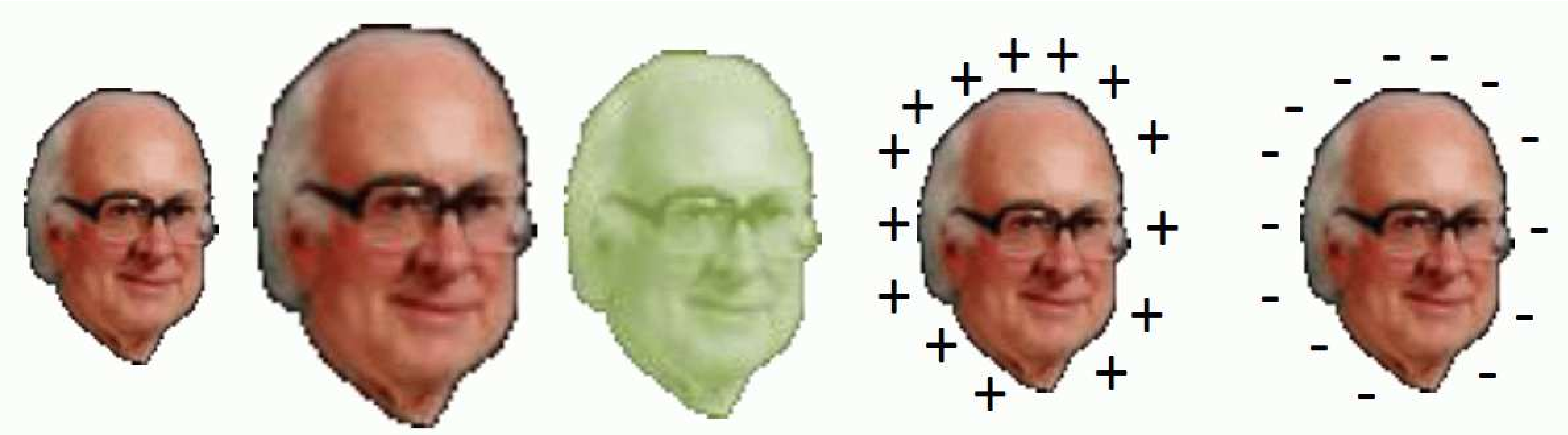
MSSM Wäscheleine V: e^+e^- vs. M_h^{125} ($M_A = 1000$ GeV, $\tan\beta = 8$)

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



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

2. Heavy BSM Higgs searches at the LHC



The MSSM Higgs sector:

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)

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

Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

$\to$ investigate benchmark scenarios:

$\to$ Vary only M_A and $\tan\beta$
$\to$ Keep all other SUSY parameters fixed

[E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel, P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18]

1. M_h^{125} scenario: 2HDM-like model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

Additional set for very heavy scalar tops:

Set of benchmarks for low $\tan\beta$

[*H. Bahl, S. Liebler, T. Stefaniak '19*]

– use 2HDM as low-energy model

– (mainly) EFT calculation, RGE running to M_{SUSY}

– implemented in FeynHiggs 2.16.0

7. $M_{h,\text{EFT}}^{125}$ scenario: all SUSY particles very heavy

8. $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario: SUSY particles very heavy, but light EW-inos

Data to be taken into account:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

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– Higgs boson signal strengths (LHC) $\Rightarrow$ HiggsSignals/SusHi

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– Higgs boson mass (LHC) ⇒ FeynHiggs

– Higgs boson signal strengths (LHC) ⇒ HiggsSignals/SusHi

– Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds

Data to be taken into account:

- Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs
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- SUSY searches (LHC)

Data to be taken into account:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

– Higgs boson signal strengths (LHC) $\Rightarrow$ HiggsSignals/SusHi

– Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds

– SUSY searches (LHC)

Data on purpose not to be taken into account:

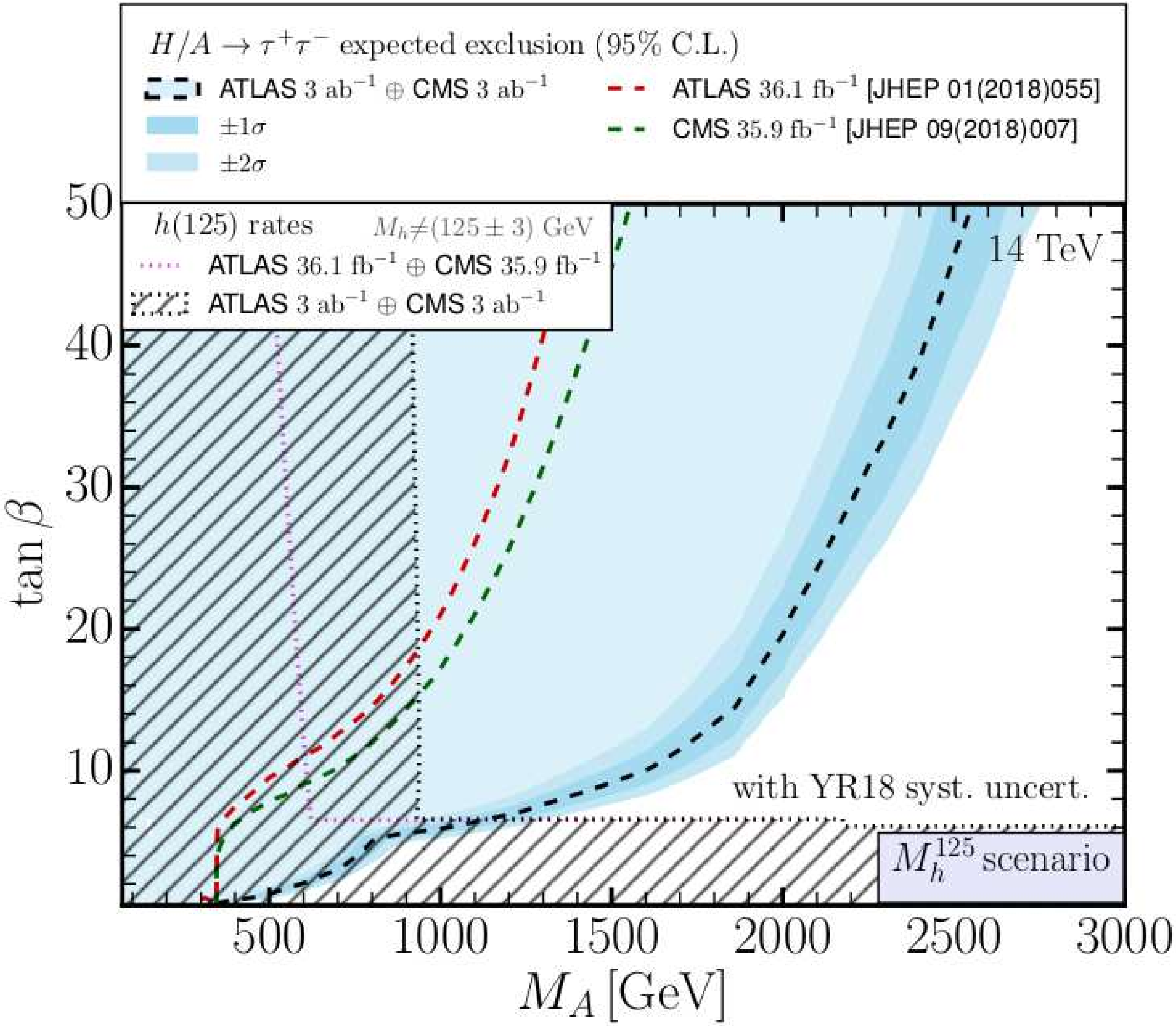
– electroweak precision data

– flavor data

– astrophysical data (DM properties)

HL-LHC reach in M_h^{125} scenario

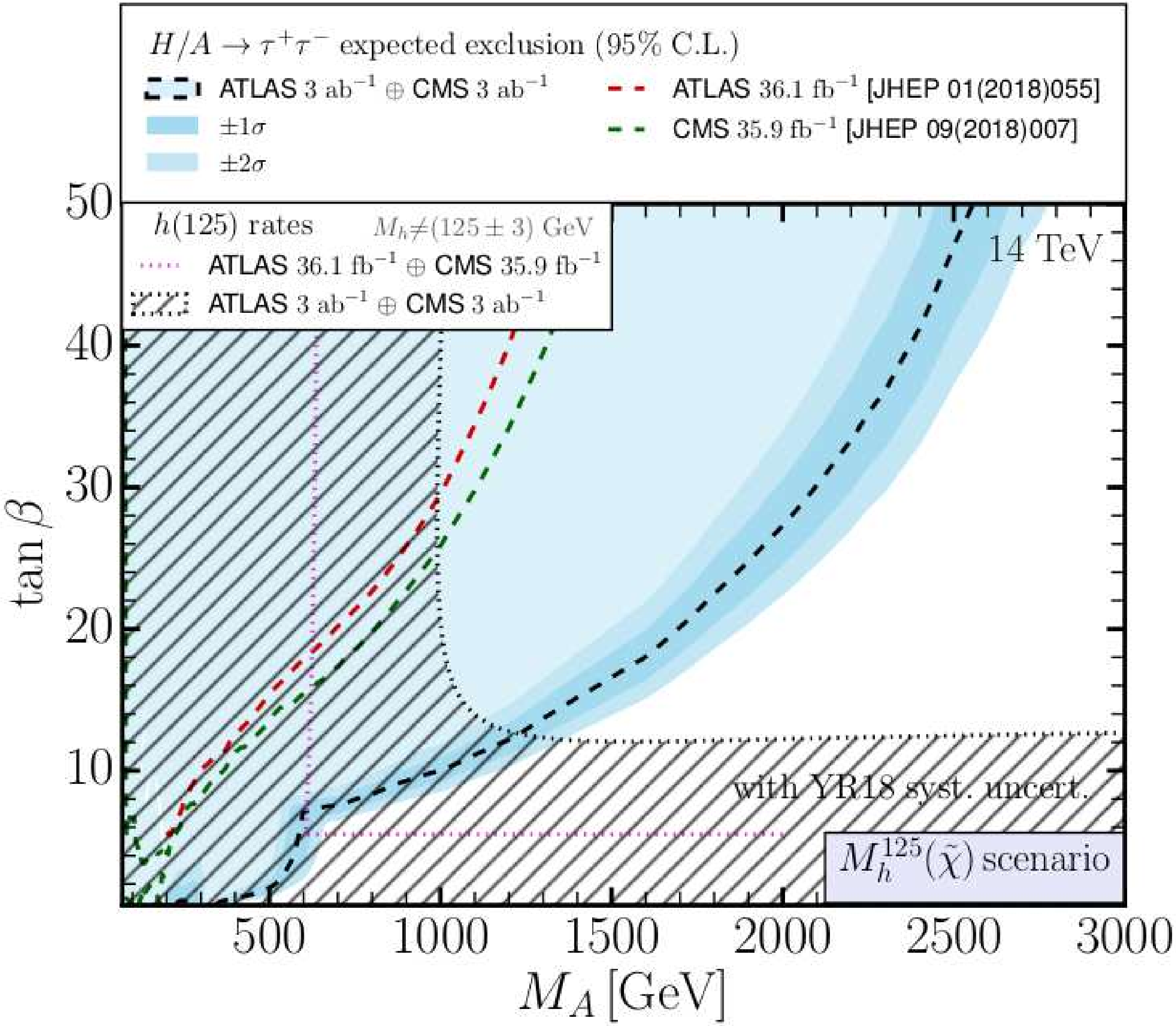
[*H. Bahl et al., '20*]



⇒ direct and indirect measurements: $M_A \gtrsim$ 1200 GeV

HL-LHC reach in $M_h^{125}(\tilde{\chi})$ scenario

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

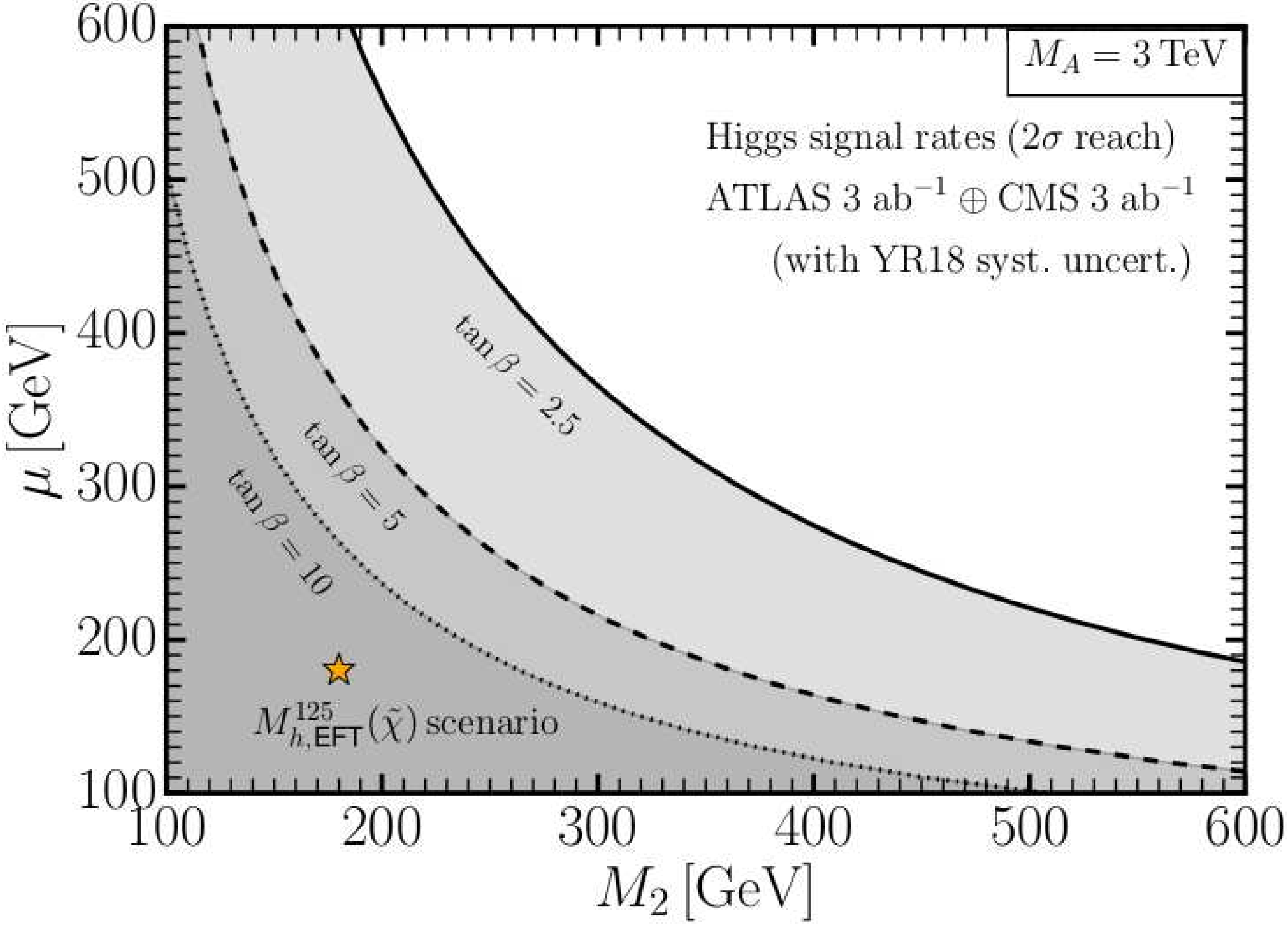


⇒ direct and indirect measurements: $M_A \gtrsim$ 1200 GeV

Indirect HL-LHC reach in $M_{h,\text{EFT}}^{125}(\tilde{\chi})$ scenario

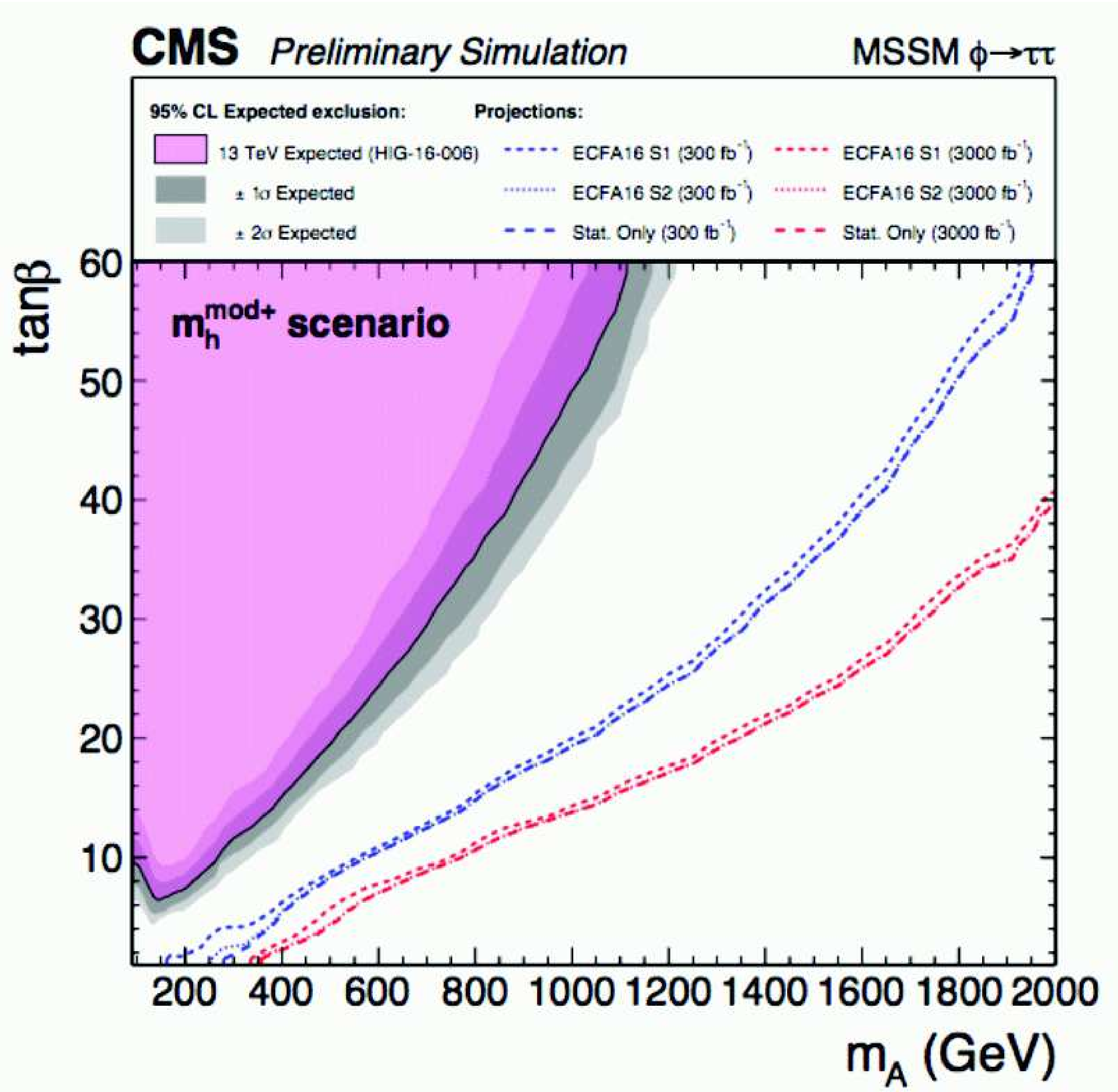
[H. Bahl et al., '20]

⇒ reach for charginos (mainly) via $h \to \gamma\gamma$:



⇒ strong reach for low tan β

Prospects for e^+e^- colliders

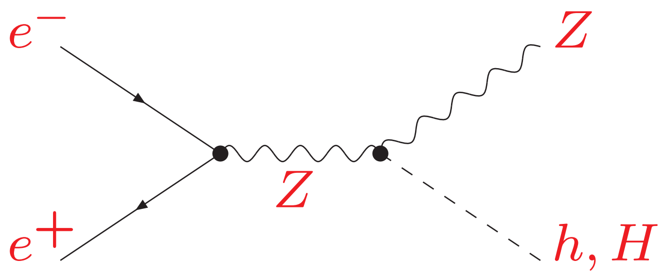


⇒ strong (HL-)LHC limits

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

Search for neutral SUSY Higgs bosons:

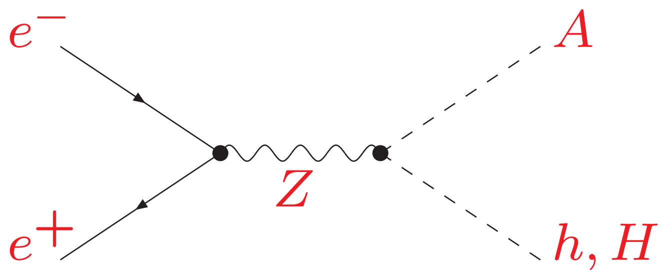
$e^+e^- \to Zh, ZH$



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

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

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

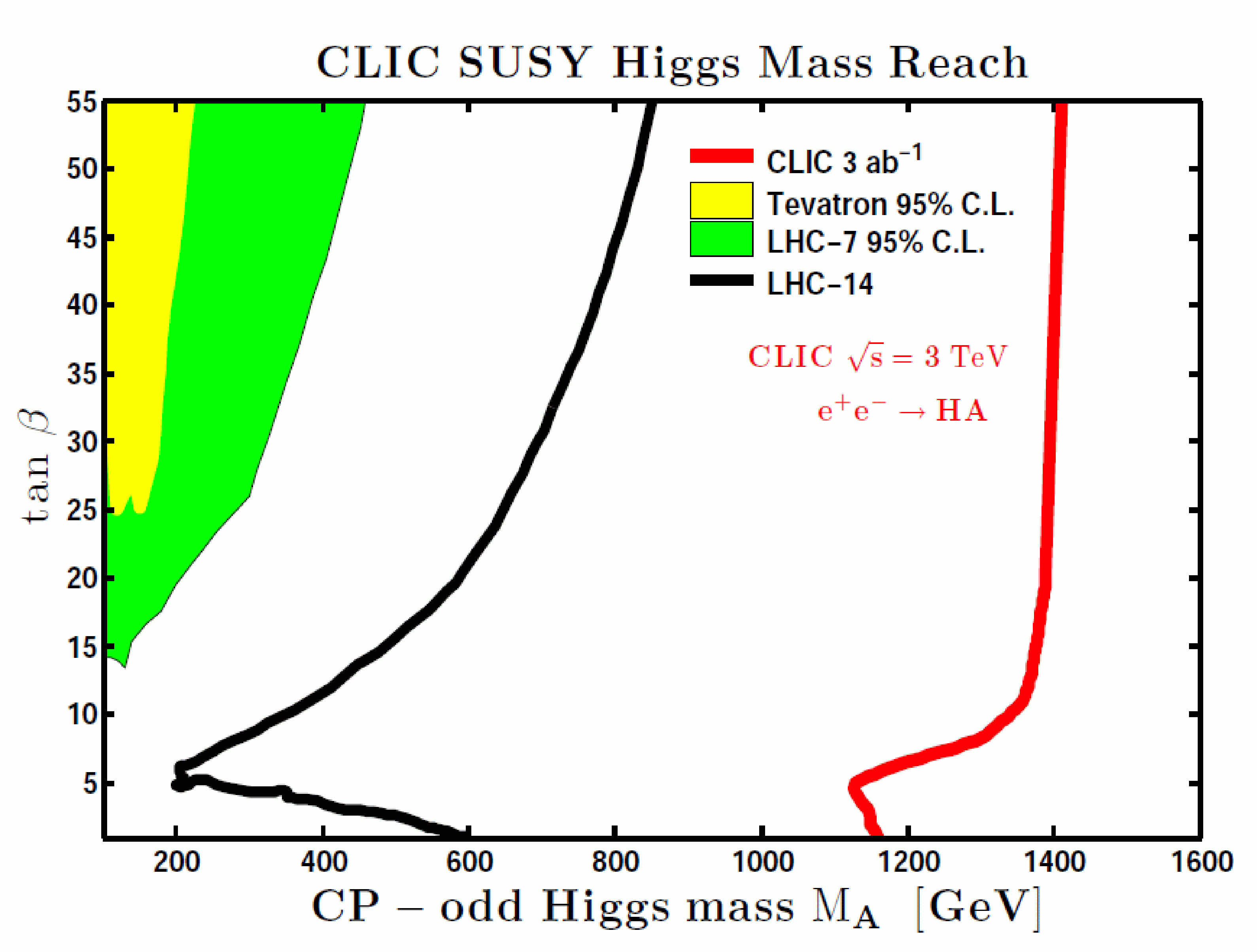


$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

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

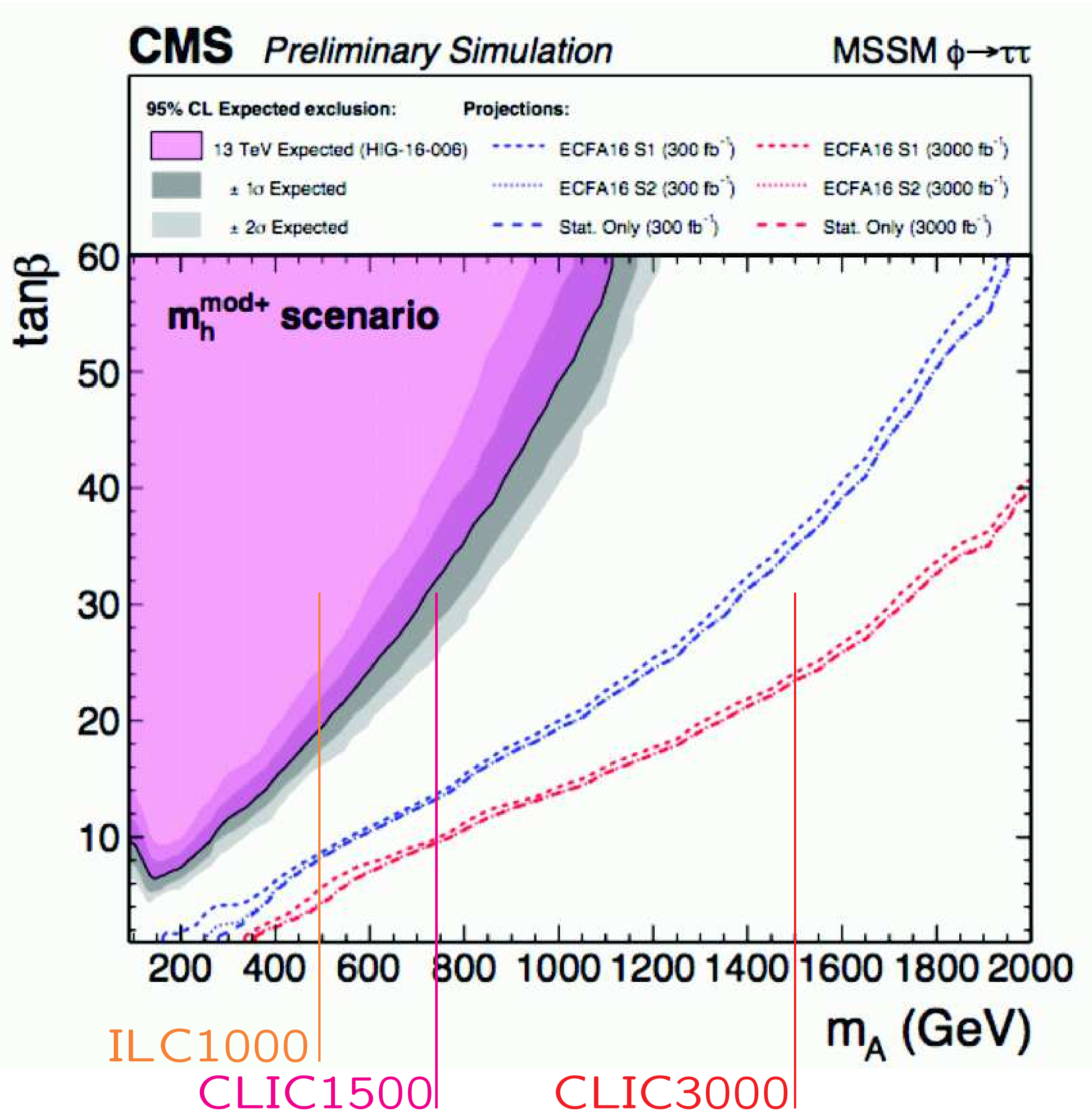
$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

CLIC reach: [*L. Linssen et al. '12*]



$\Rightarrow$ close to kinematic limit

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

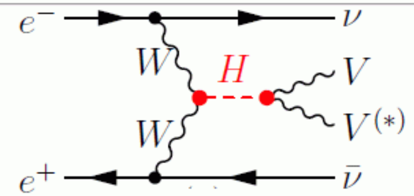


⇒ unique opportunities!

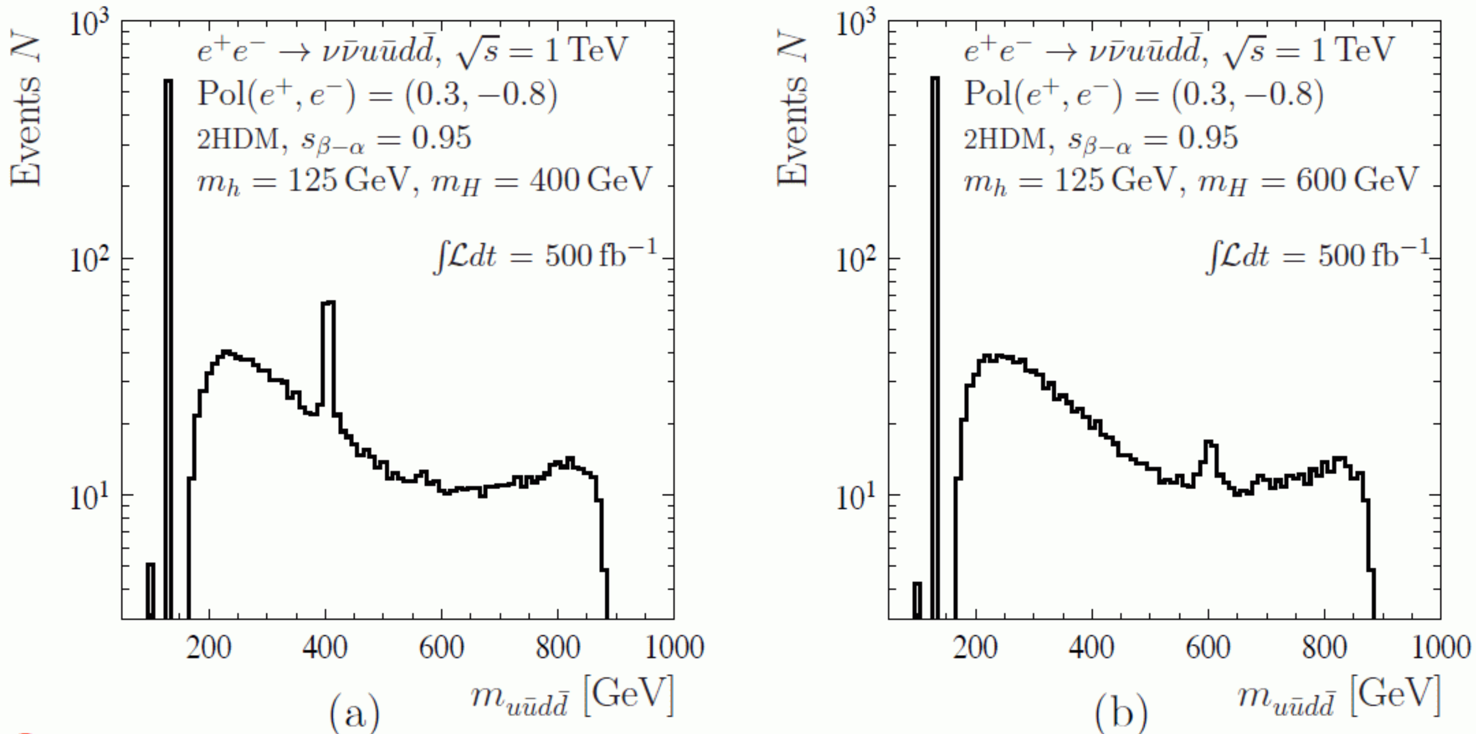
Single heavy Higgs production beyond kinematic reach:

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

[S. Liebler et al. '15]



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



$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[*Taken from G. Weiglein '18*]

3. Triple Higgs couplings (THCs) at the (HL-)LHC

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3. Triple Higgs couplings (THCs) at the (HL-)LHC

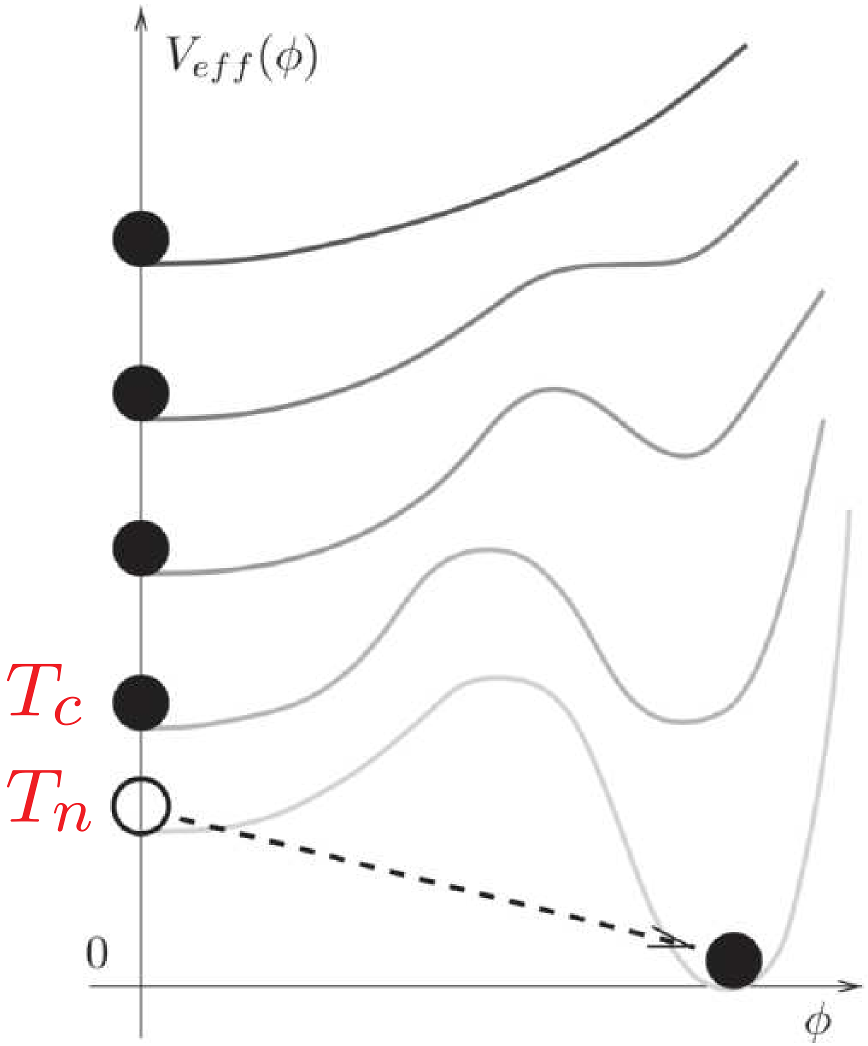
⇒ Why is there more matter than antimatter? ⇒ (EW) baryogenesis

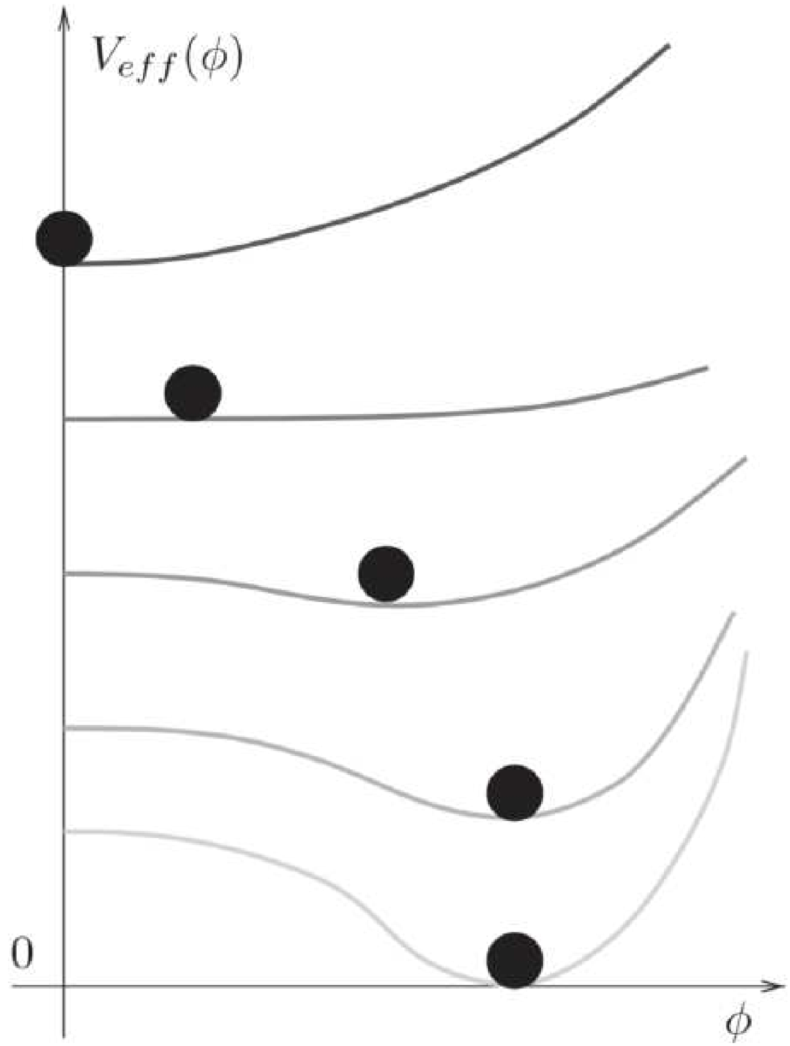
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

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

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

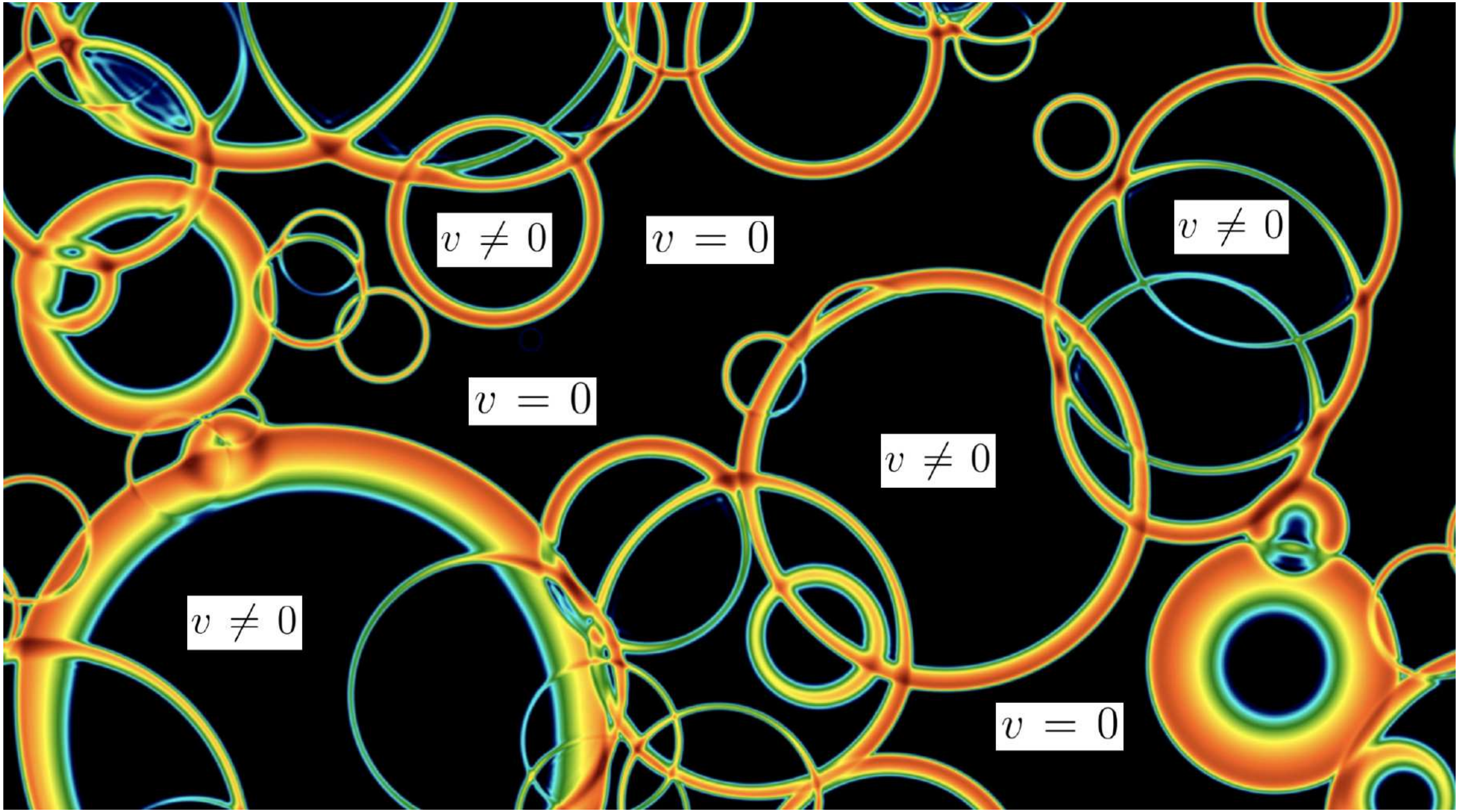




$\Rightarrow$ BSM Higgs sector required to realized FOEWPT

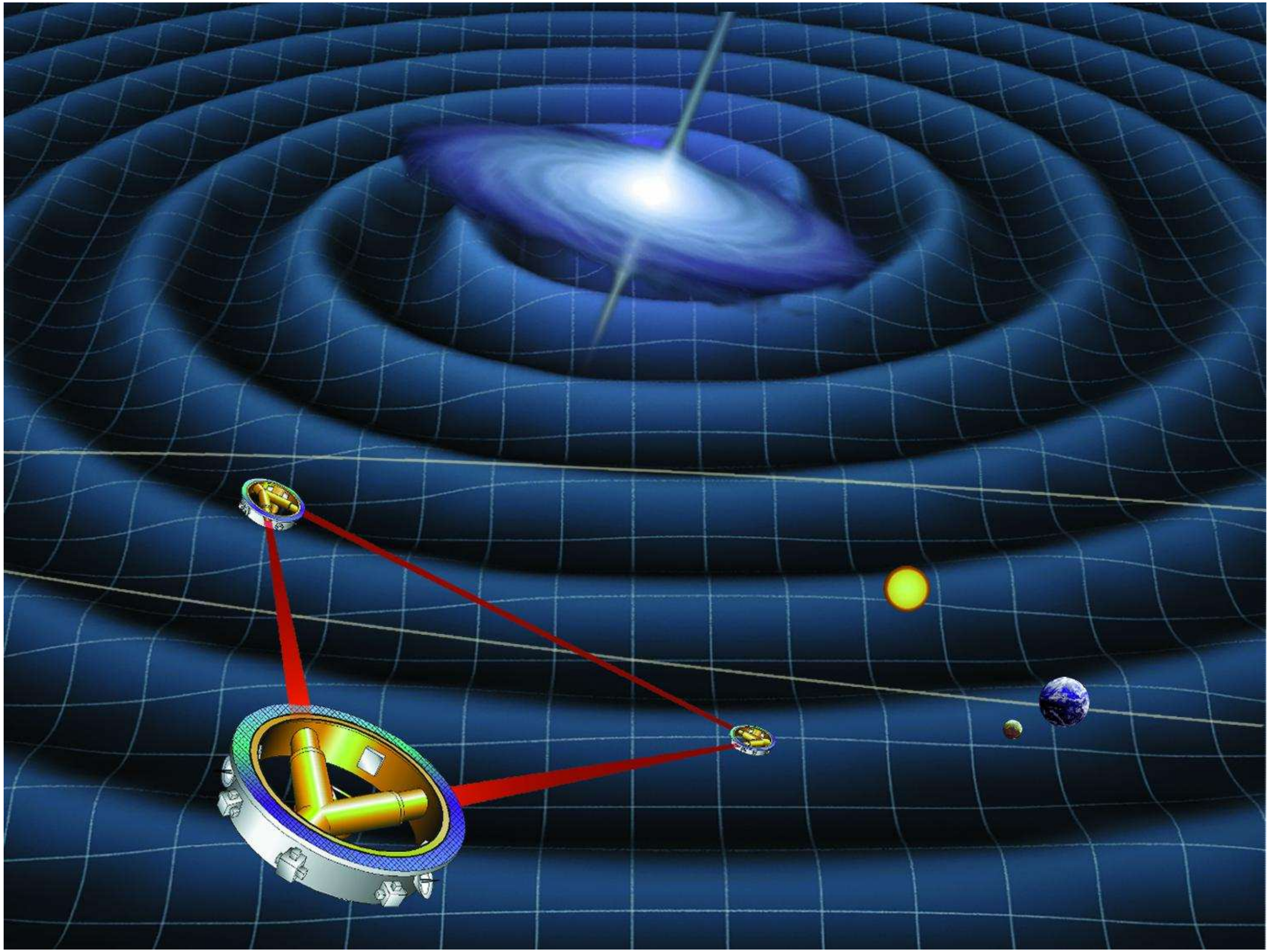
Bubble formation can lead to Gravitational Waves

[*taken from D. Weir*]



$\Rightarrow$ Interesting interplay of Higgs physics and Gravitational Waves!

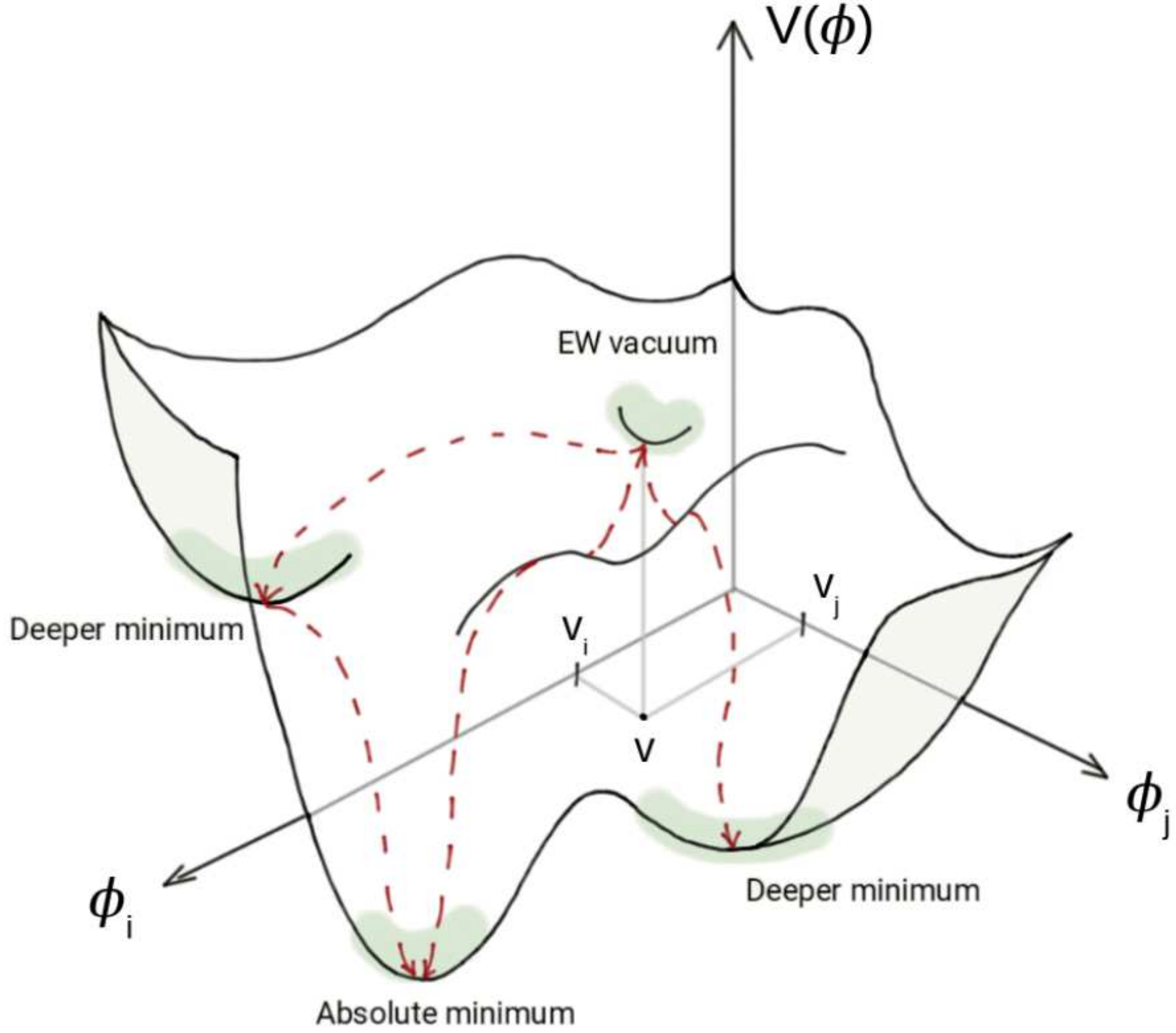
 [NASA]



Approved launch date: $\sim$ 2035

BSM Higgs sectors can (should) behave very different from SM Higgs

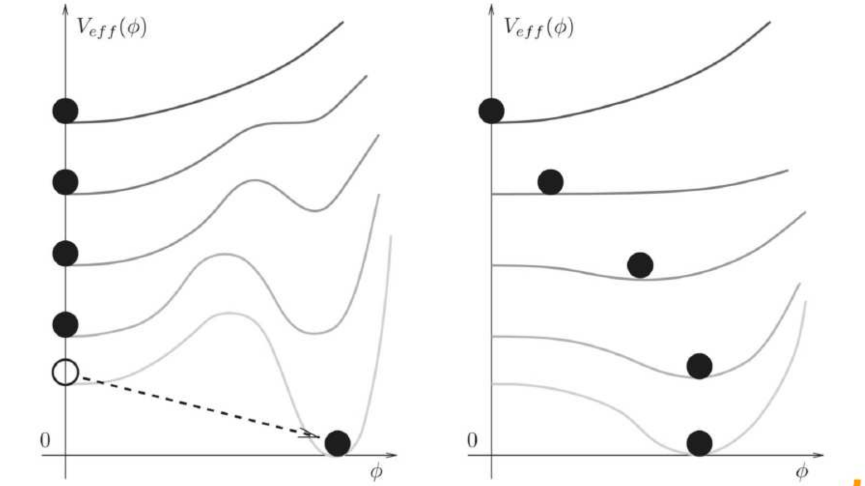
[*K. Radchenko '24*]



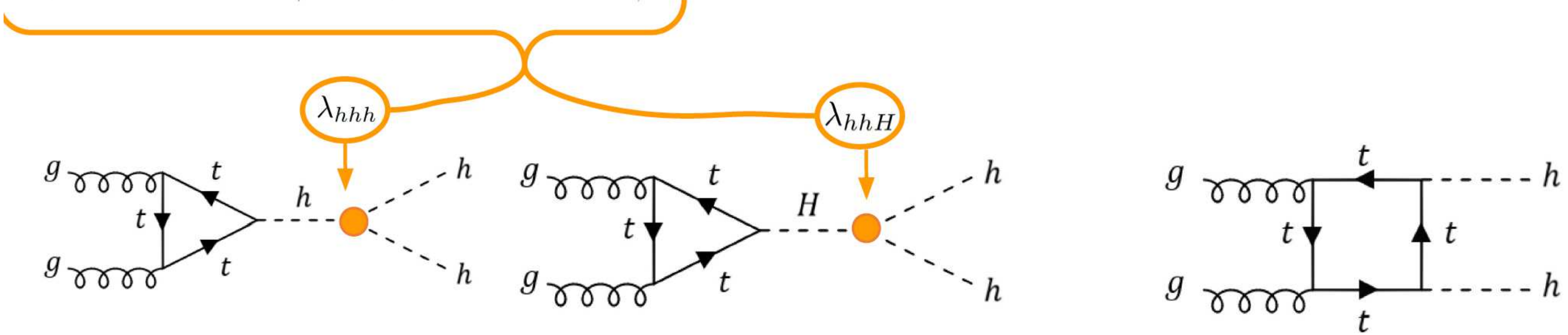
⇒ much more complicated structure, very^2 little known . . .

Extended Higgs sectors and Triple Higgs Couplings (THCs):

[taken from A. Verduras '24]



- THC determine the formation of the barrier
- The computation of the **EWPT dynamics is done at the one-loop level**
- To capture this effects in the di-Higgs production **we need one-loop THC**



$\Rightarrow$ Measurement of all THCs crucial!

$\Rightarrow \kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM}}, \quad \lambda_{hhH}, \ldots$

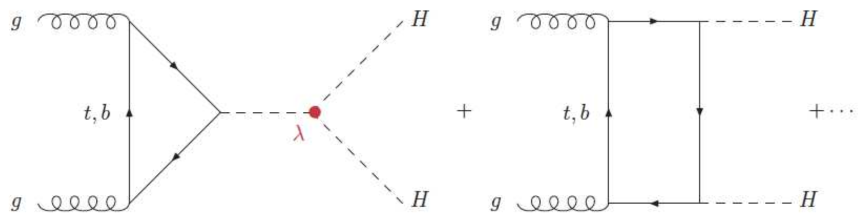
Calculation in the SM

Basics on di-Higgs production at the (HL-)LHC

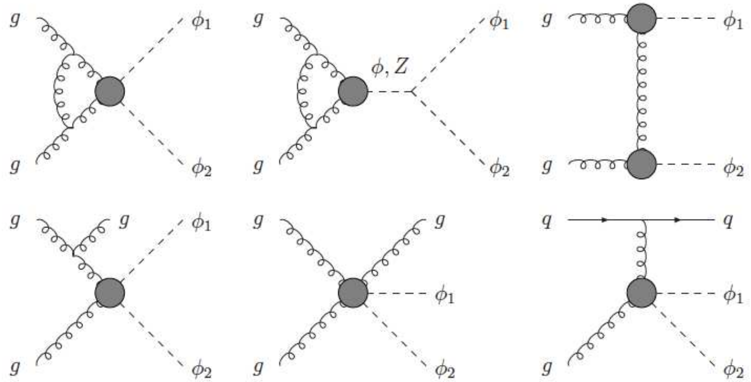
[taken from M. Spira]

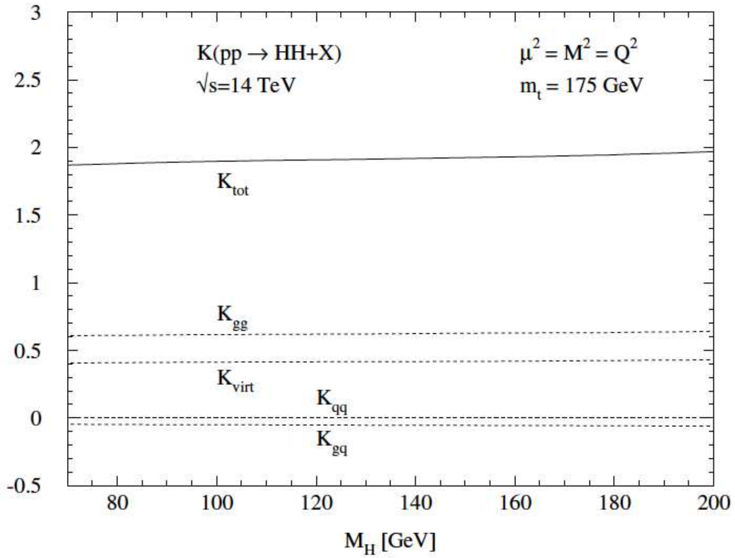
$gg \to HH$

(B)SM



- third generation dominant $\to t, b$
- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$



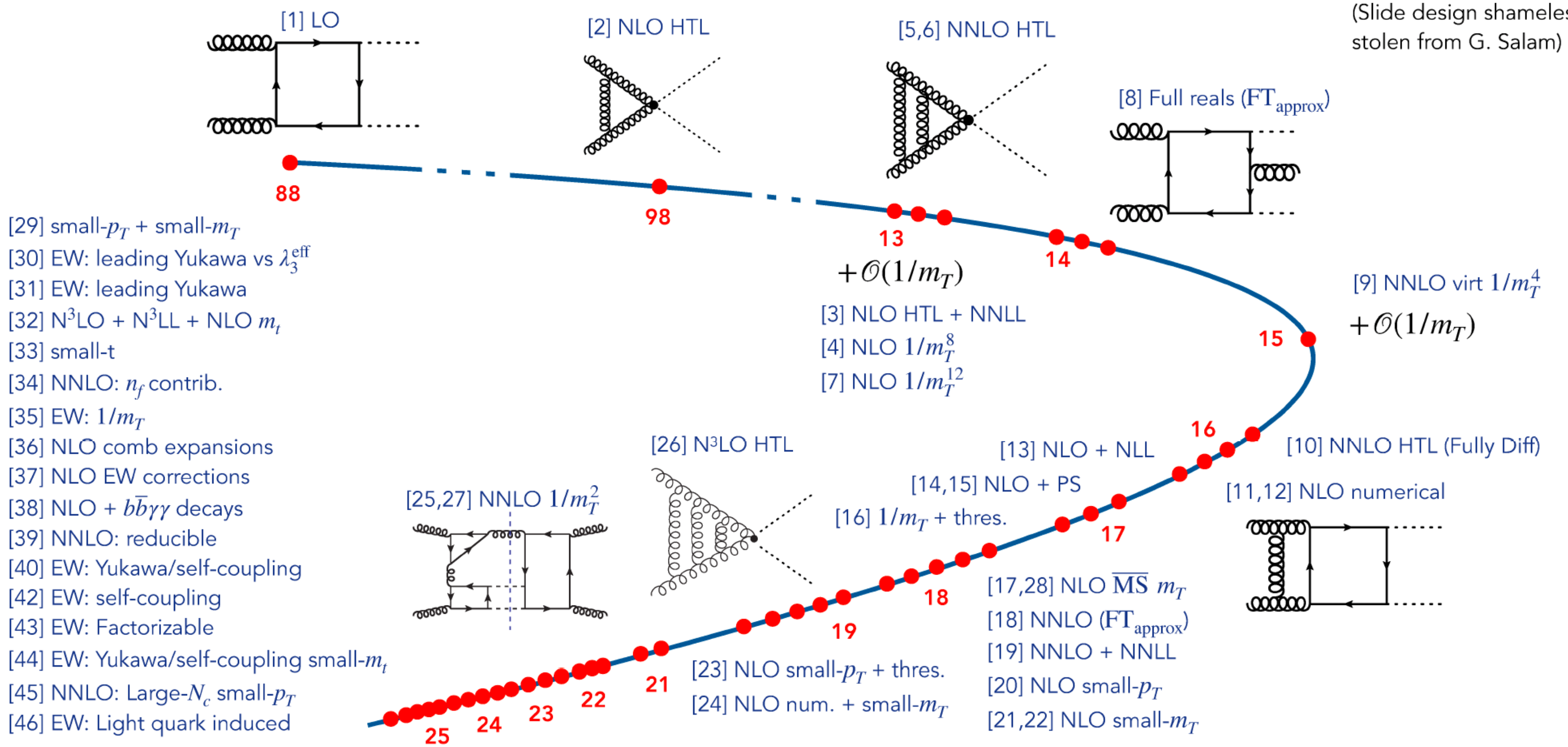


Dawson, Dittmaier, S.

$\Rightarrow$ predictions "easily" available in NLO QCD (heavy top limit)

In the SM there is much more available:

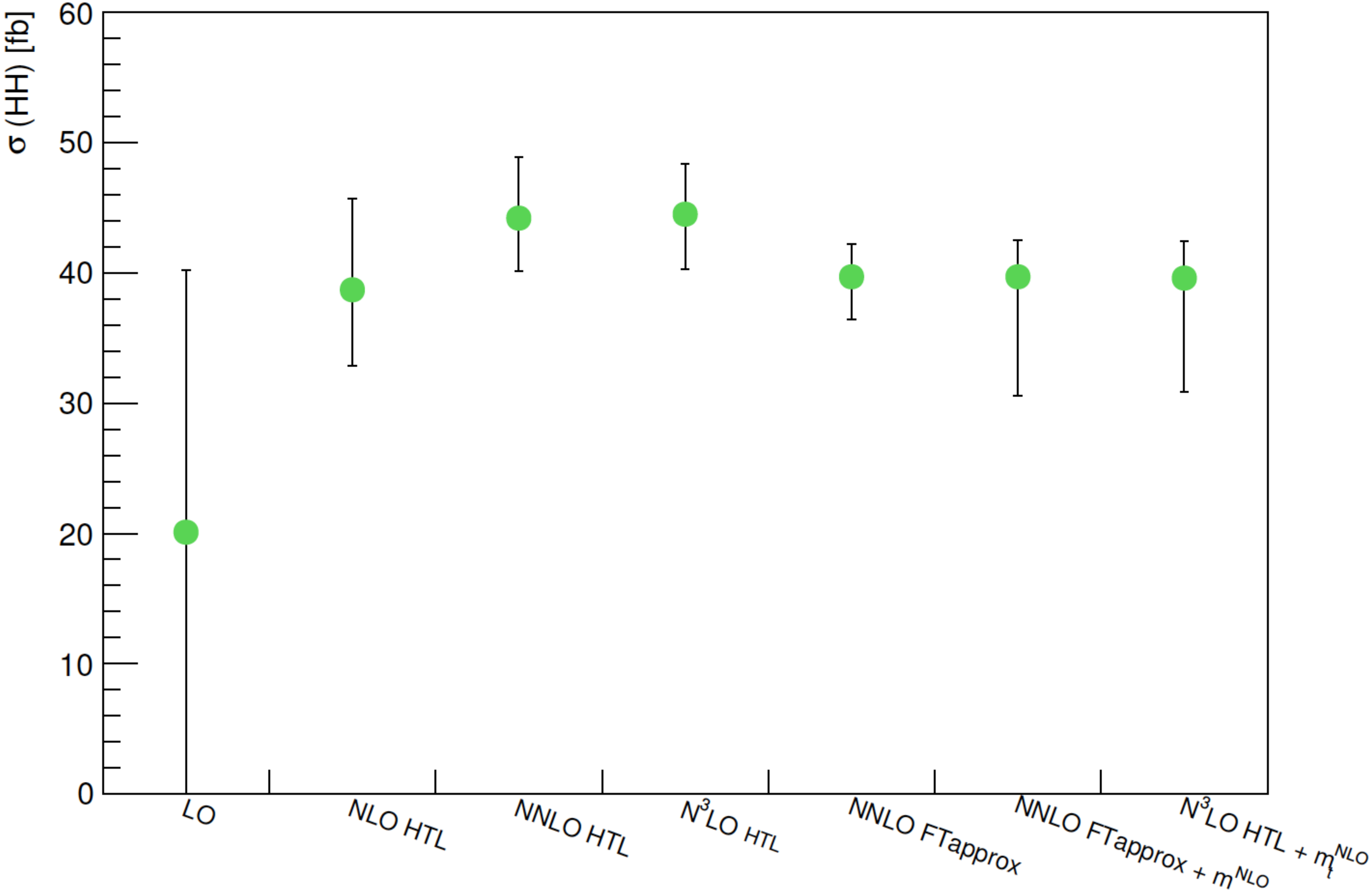
(Slide design shamelessly stolen from G. Salam)



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22; [30] Mühlleitner, Schlenk, Spira 22; [31] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [32] Ajjath, Shao 22; [33] Davies, Mishima, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser 23; [35] Davies, Schönwald, Steinhauser, Zhang 23; [36] Bagnaschi, Degrassi, Gröber 23; [37] Bi, Huang, Huang, Ma Yu 23 [38] Li, Si, Wang, Zhang, Zhao 24; [39] Davies, Schönwald, Steinhauser, Vitti 24; [40] Heinrich, SPJ, Kerner, Stone, Vestner [41] Li, Si, Wang, Zhang, Zhao 24; [42] Davies, Schönwald, Steinhauser, Zhang 24; [43] Davies, Schönwald, Steinhauser, Zhang 25; [44] Davies, Schönwald, Steinhauser 25; [45] Bonetti, Rendler, Bobadilla 25;

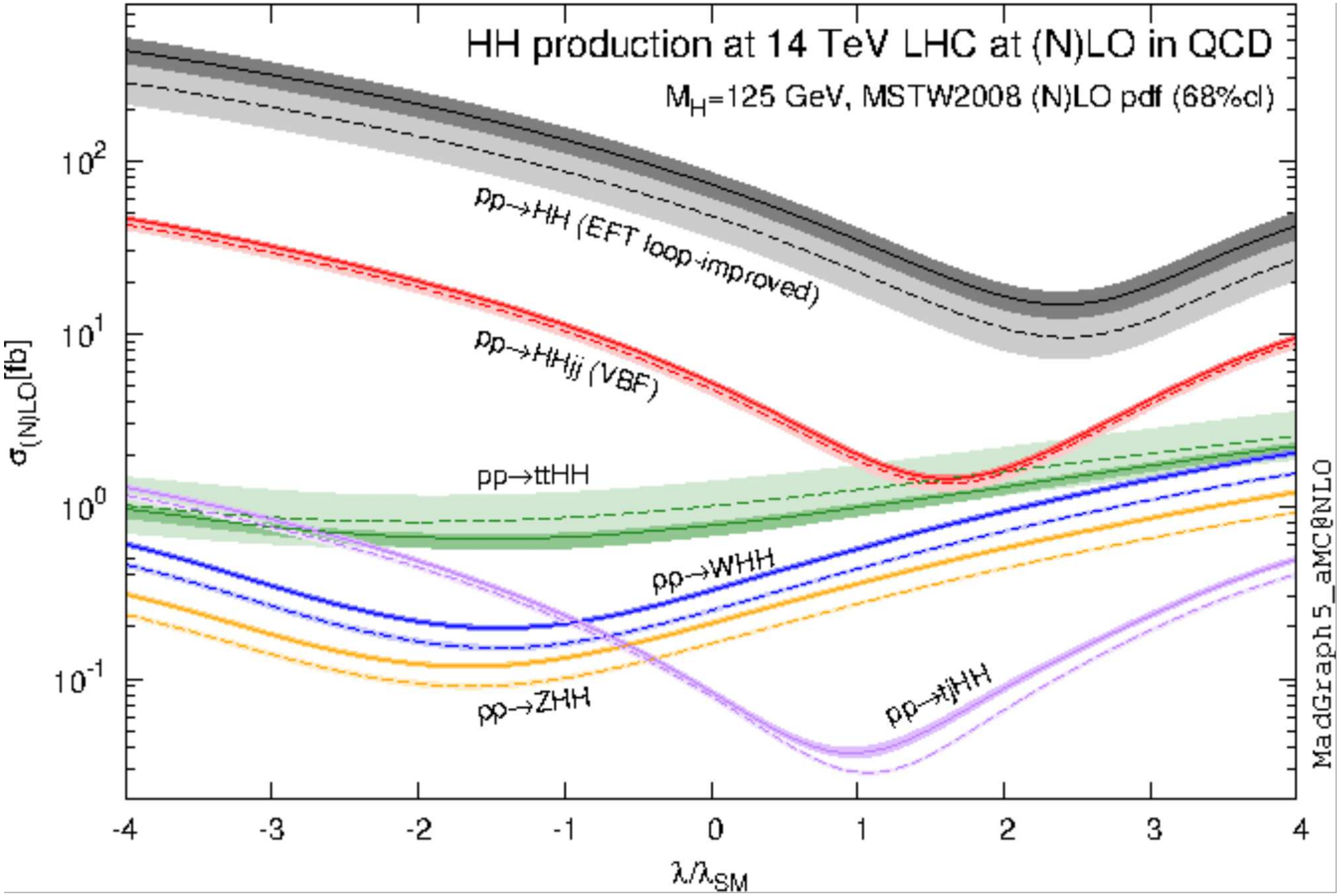
S. Jones

Size of the SM corrections has stabilized (albeit with uncertainties)



Di-Higgs production at the LHC: $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$

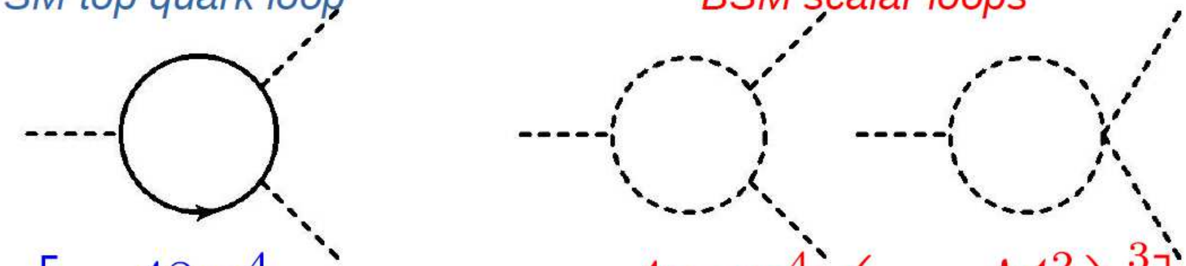
⇒ strong interference of "box" and "SM-like Higgs"



⇒ higher-order corrections to κ_λ potentially very important

One-loop non-decoupling effects

- **Leading one-loop** corrections to λ_{hhh} in models with extended sectors (like 2HDM):



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48 m_t^4}{v^3} + \sum_\Phi \frac{4 n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

First found in 2HDM: [Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\mathcal{M}$: **BSM mass scale**, e.g. soft breaking scale M of Z_2 symmetry in 2HDM
n_Φ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda} v^2$

$$\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3 \longrightarrow \begin{cases} 0, \text{ for } \mathcal{M}^2 \gg \tilde{\lambda} v^2 \\ 1, \text{ for } \mathcal{M}^2 \ll \tilde{\lambda} v^2 \end{cases}$$

→ **Huge BSM effects possible!**

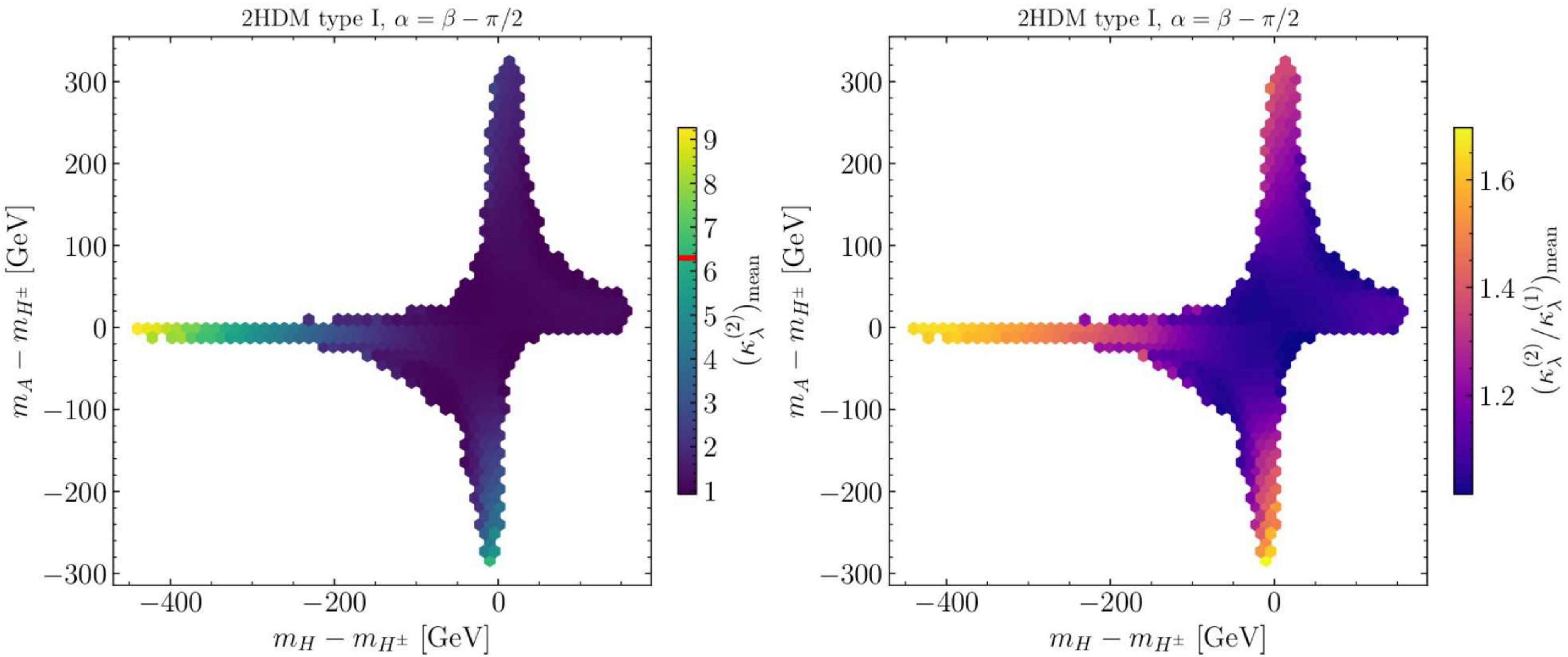
⇒ effects of 500% - 1000% found . . .

⇒ effects of 500% - 1000% found . . . ⇒ perturbativity??

Parameter scan results

[Bahl, JB, Weiglein 2202.03453]

Mean value for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(1)})^{2HDM}$ [right] in (m_H-$m_{H\pm}$, m_A-$m_{H\pm}$) plane



NB: all previously mentioned constraints are fulfilled by the points shown here

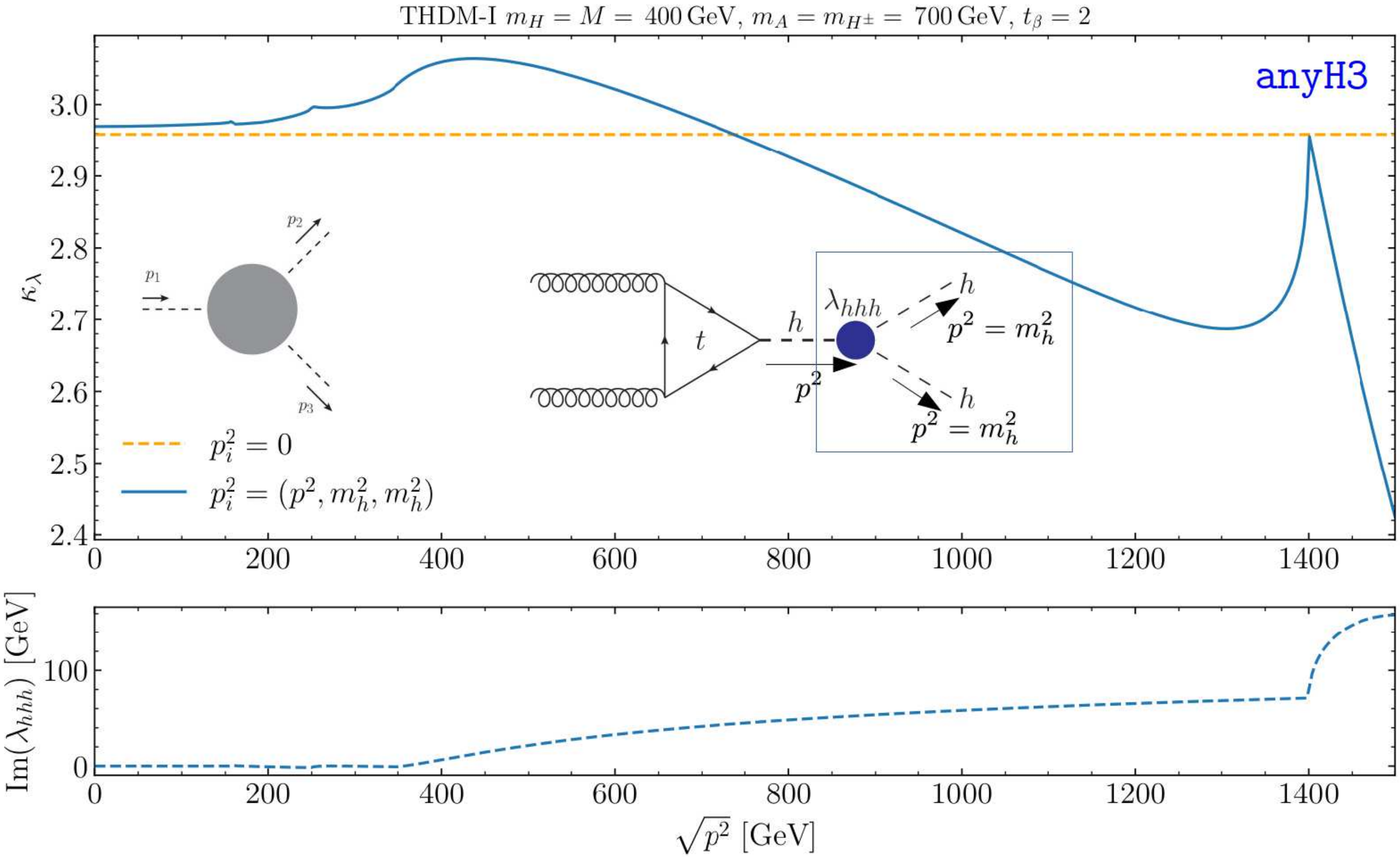
⇒ Perturbativity is found going from 1L to 2L

Details of possible higher-order correction to BSM THCs:

[*taken from J. Braathen*]

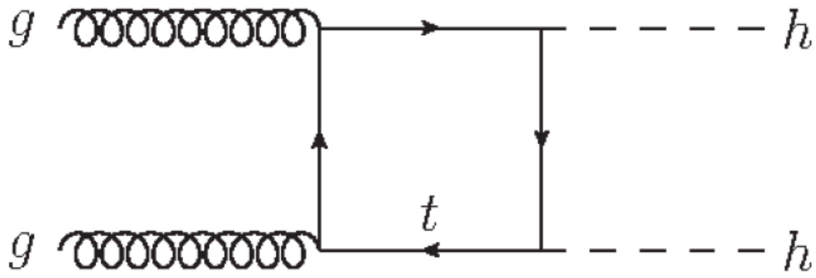
Momentum dependent effects:

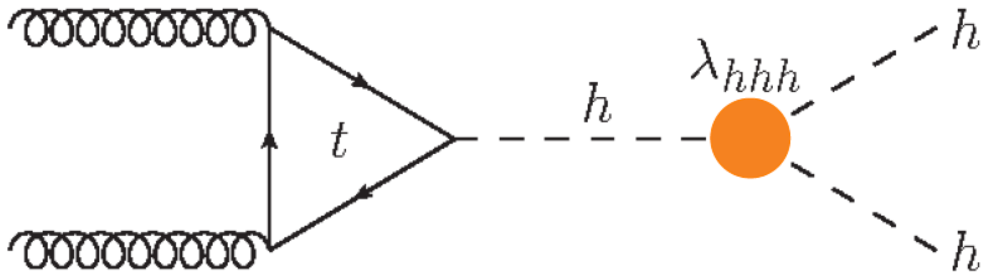
anyH3: momentum dependence in the 2HDM (1L)



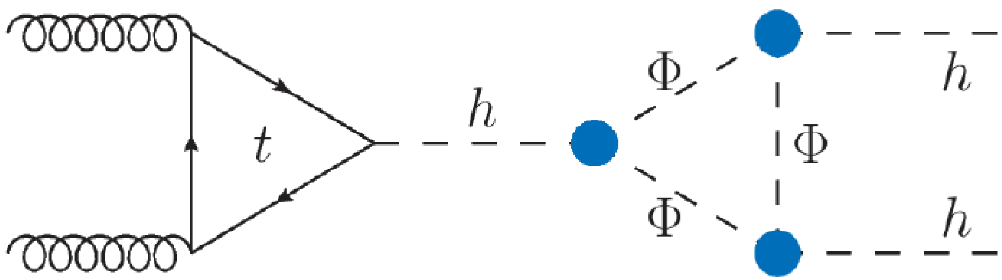
⇒ induce numerically sub-leading effect

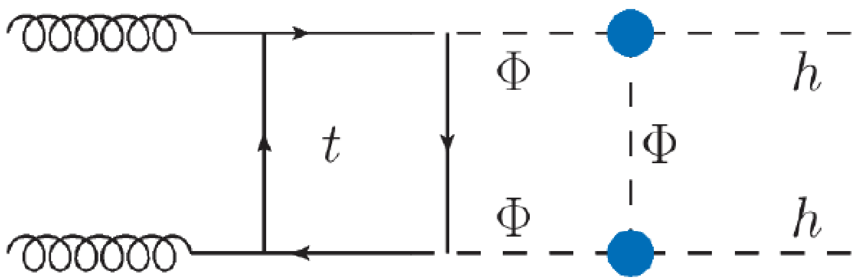
Box vs. s channel Higgs:





Inclusion of one-loop corrections to THCs:





$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$

Correction to $\lambda_{hhh} \rightarrow$ included

$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$

not included

$\Rightarrow$ always closed subset, dominant for large THCs

[*taken from J. Braathen '24*]

Generic predictions for λ_{hhh}

Based on

`arXiv:2305.03015` **(EPJC) + WIP**
in collaboration with Henning Bahl, Martin Gabelmann, Kateryna Radchenko Serdula and Georg Weiglein

⇒ crucially needed

⇒ links to MadGraph, . . .

New results I: mass-splitting effects in various BSM models

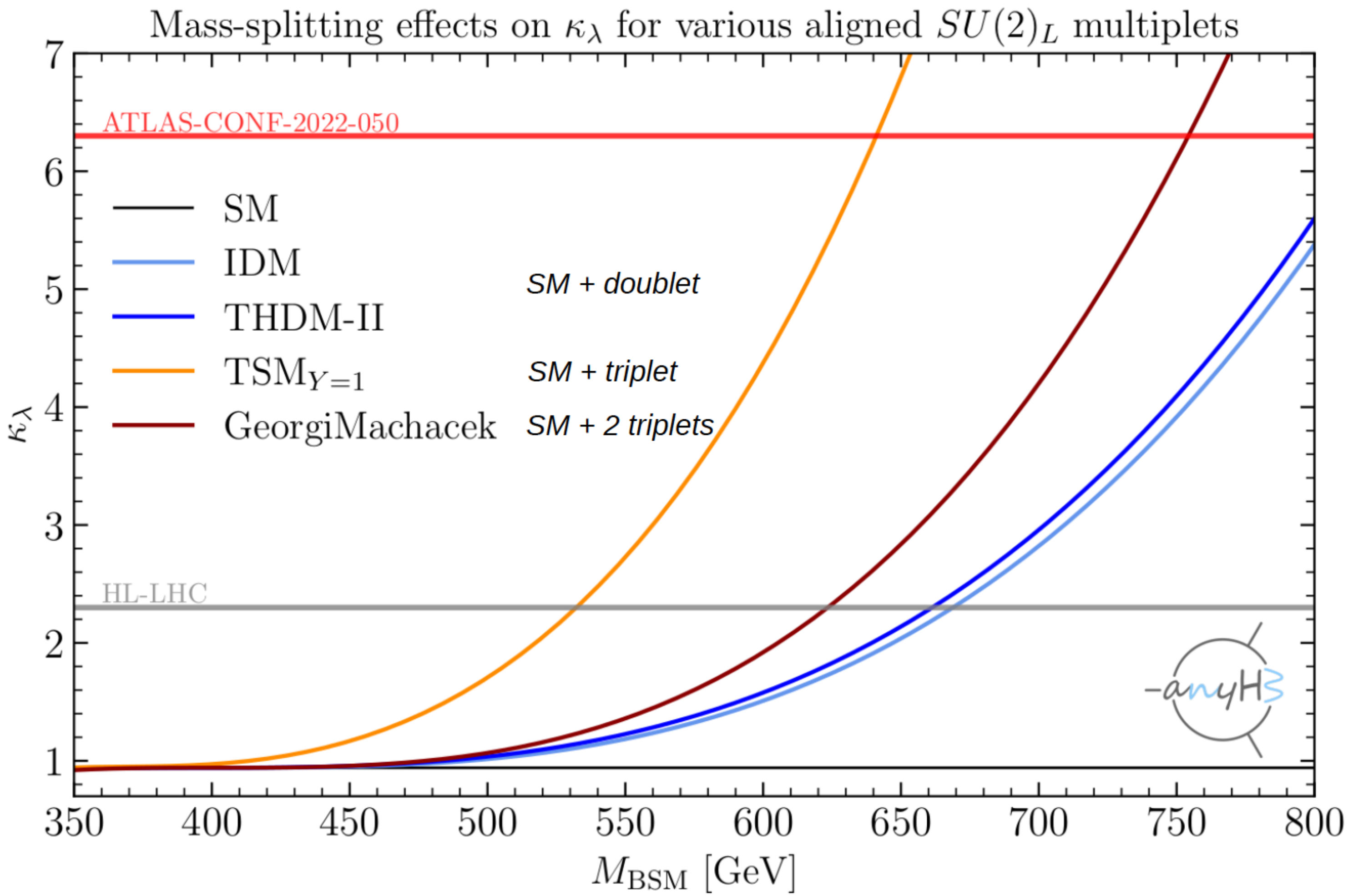
- Consider the non-decoupling limit in several BSM models

$$M^2_{\mathrm{BSM}} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

- Increase M_{BSM}, keeping $\mathcal{M}$ fixed
  → large mass splittings
  → **large BSM effects!**

- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**

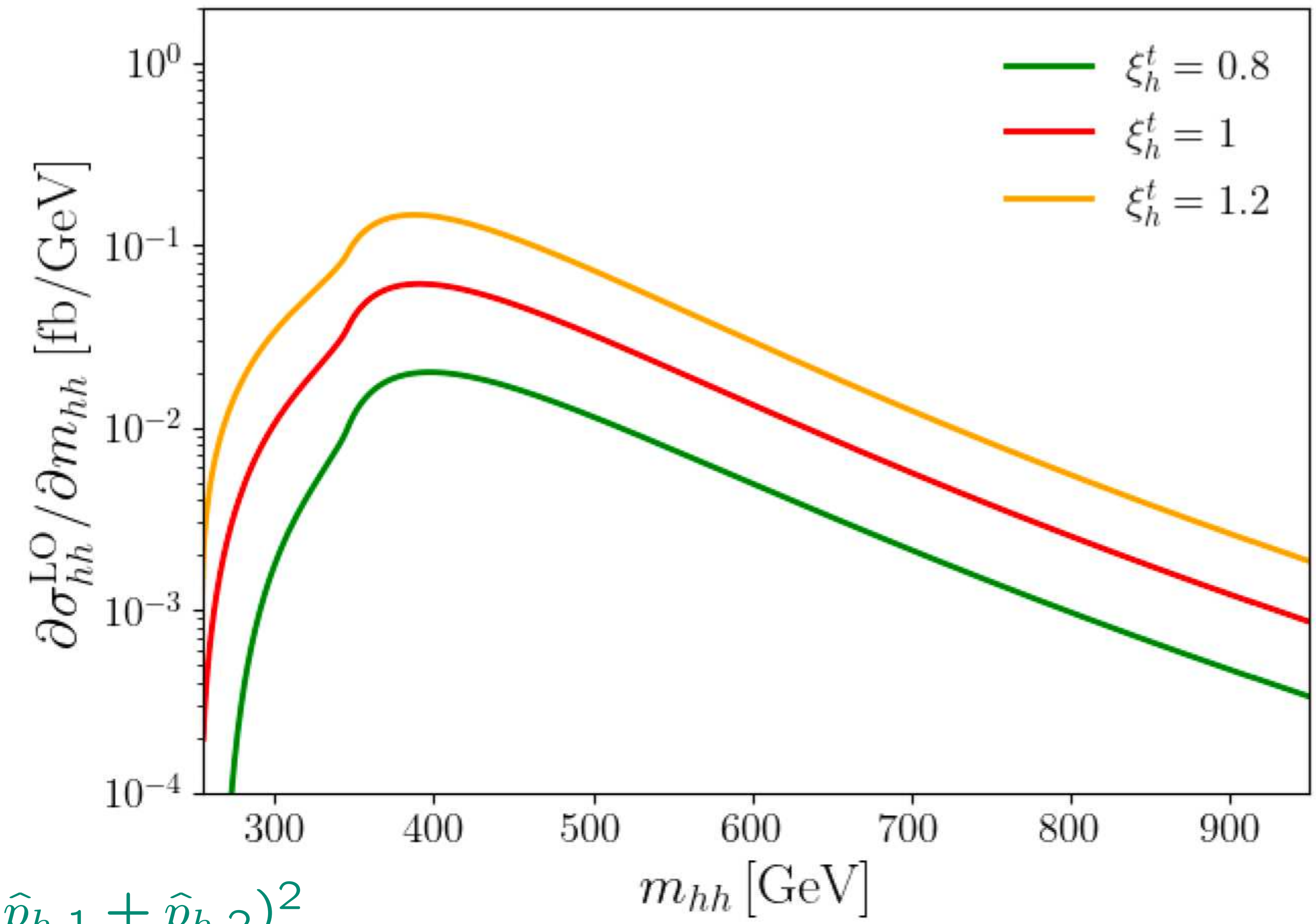


Here: scenarios with lightest BSM scalar mass + BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

(HL-)LHC di-Higgs searches rely on m_{hh} [PhD K. Radchenko '25]

m_{hh}: invariant mass distribution of the di-Higgs system

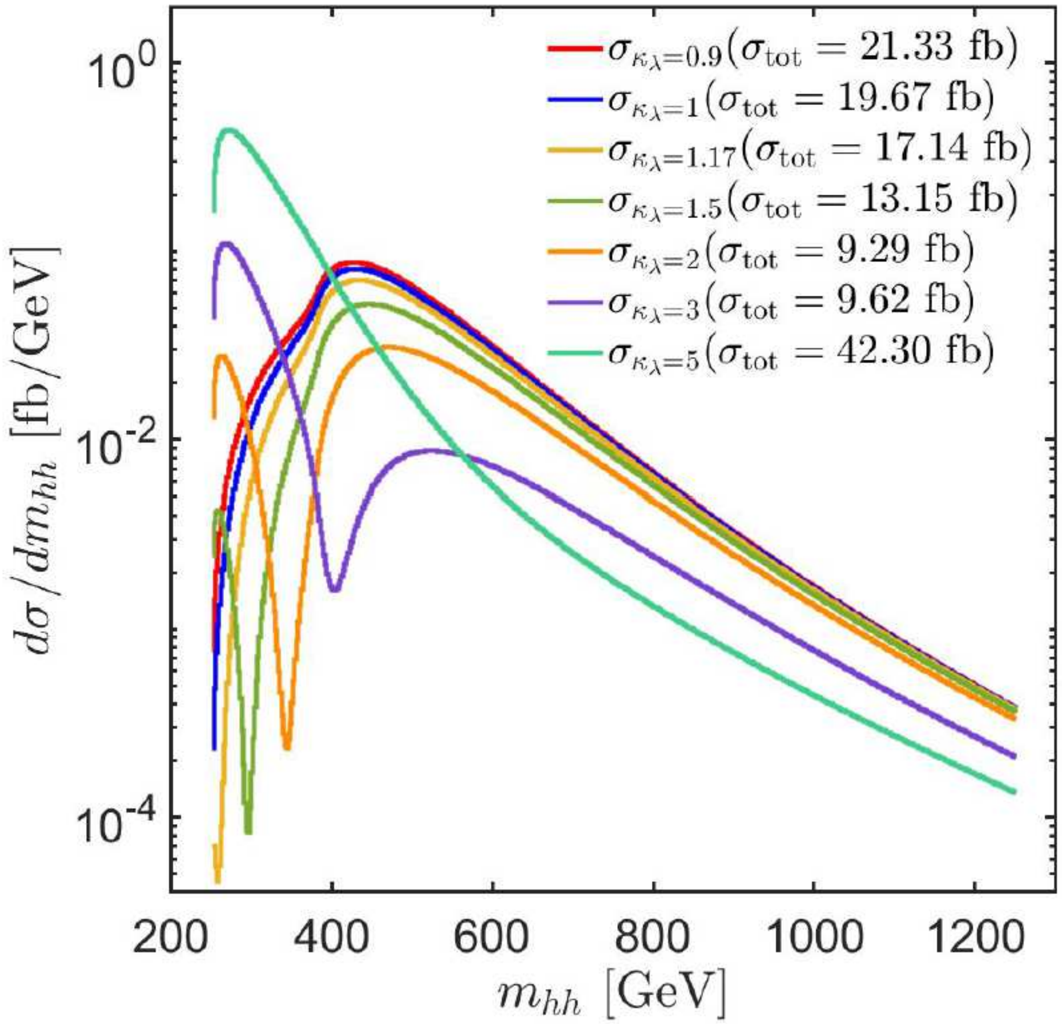
SM case with ξ_h^t varied:



$\Rightarrow m_{hh}^2 = (\hat{p}_{h,1} + \hat{p}_{h,2})^2$

Non-resonant BSM di-Higgs production ⇒ all calculated with HPAIR

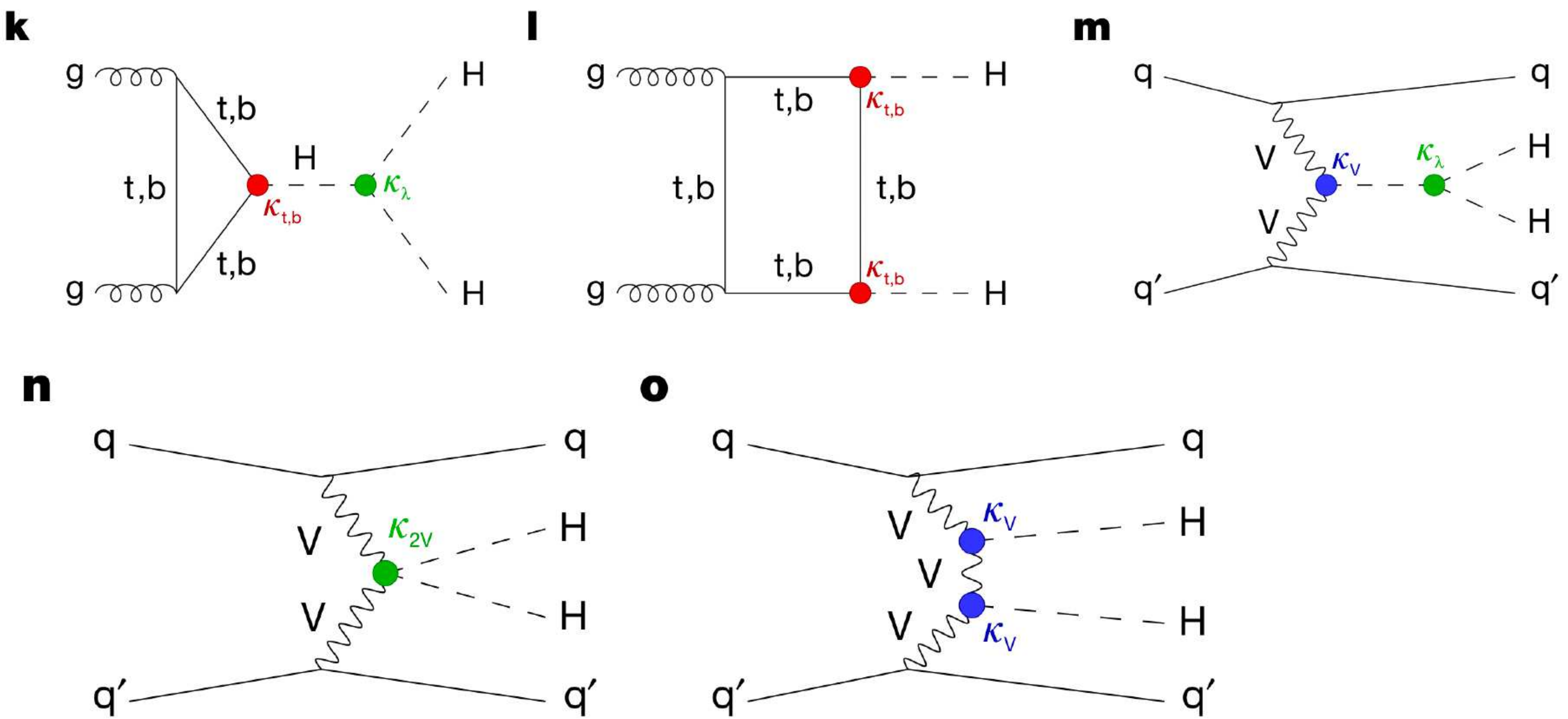
[*S.H., M. Mühlleitner, K. Radchendo, G. Weiglein – PRELIMINARY*]



⇒ higher-order effects in κ_λ

⇒ huge effects on m_{hh} distributions ⇒ effects on search limits?

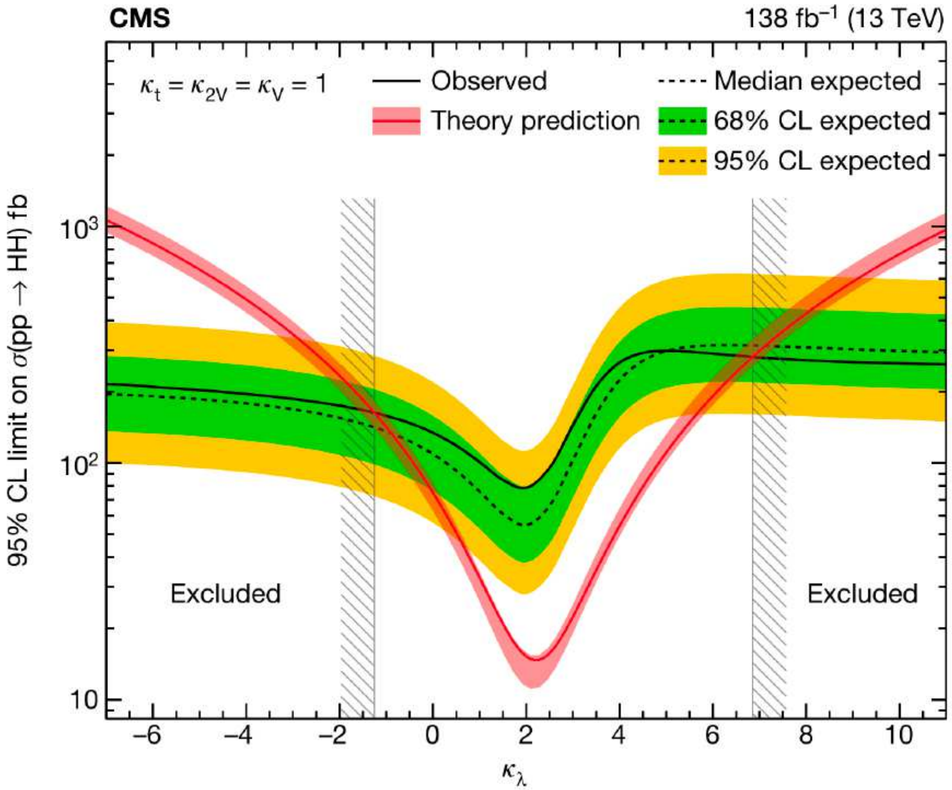
Experimental limits on κ_λ and κ_{2V}

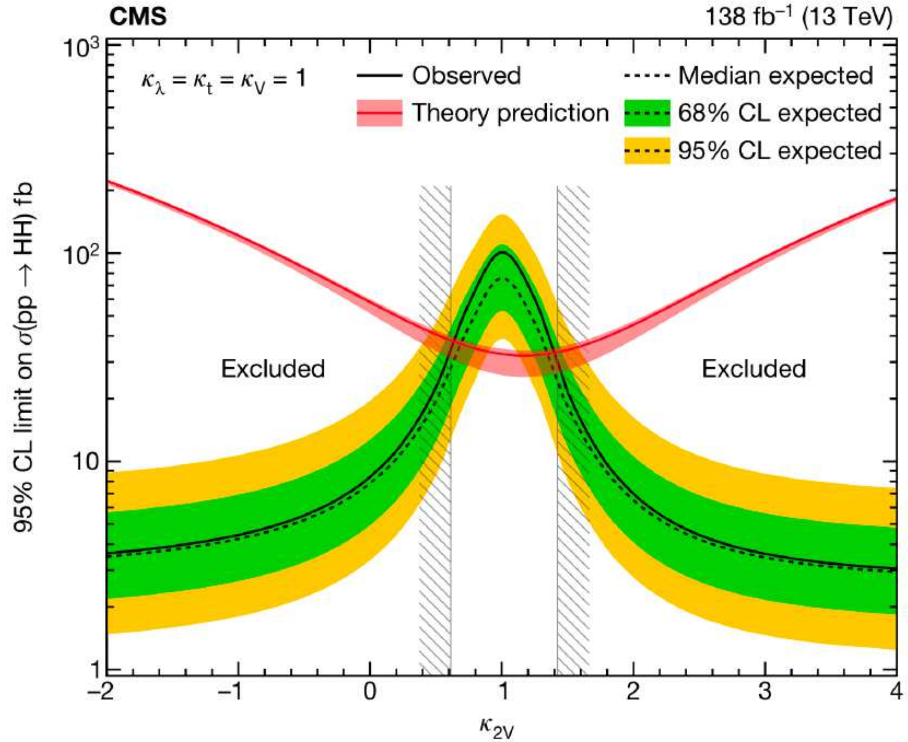


$\Rightarrow$ all κ's should be varied simultaneously

$\Rightarrow$ sensitivity to κ_λ and κ_{2V}?!

Experimental limits on κ_λ and κ_{2V}





$\Rightarrow$ shape of expected limits from m_{hh} distributions

$\Rightarrow$ limits getting stronger, improvement getting difficult

4. m_{hh} measurements at the HL-LHC

[*F. Arco, S.H., M. Mühlleitner, A. Parra Arnay, N. Rivero González, A. Verduras Schaeidt '25*]

Model: RxSM

Benchmark plane features:
– FOEWPT
– large "pure resonant di-Higgs production" at the LHC
based on [*M. Ramsey-Musolf et al. '19*]

⇒ first look at total cross section

⇒ then at differential cross section (m_{hh} distribution)

⇒ effects of $\kappa_\lambda \neq 1$

⇒ effects of H resonance, λ_{hhH}

Our model:

[*taken from A. Verduras '24*]

Real singlet extension of the SM (RxSM)

EW doublet: $\Phi = \begin{pmatrix} 0 \\ \frac{\phi+v}{\sqrt{2}} \end{pmatrix}$ Singlet: $S = s + v_S$

Potential:

$$V(\Phi, S) = \mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \kappa_{SH}(\Phi^\dagger\Phi)S + \frac{\lambda_{SH}}{2}(\Phi^\dagger\Phi)S^2 + \frac{M_S}{2}S^2 + \frac{\kappa_S}{3}S^3 + \frac{\lambda_S}{2}S^4$$

Gauge eigenstates:

$\phi, \; s$

Mass eigenstates:

$h, \; H$

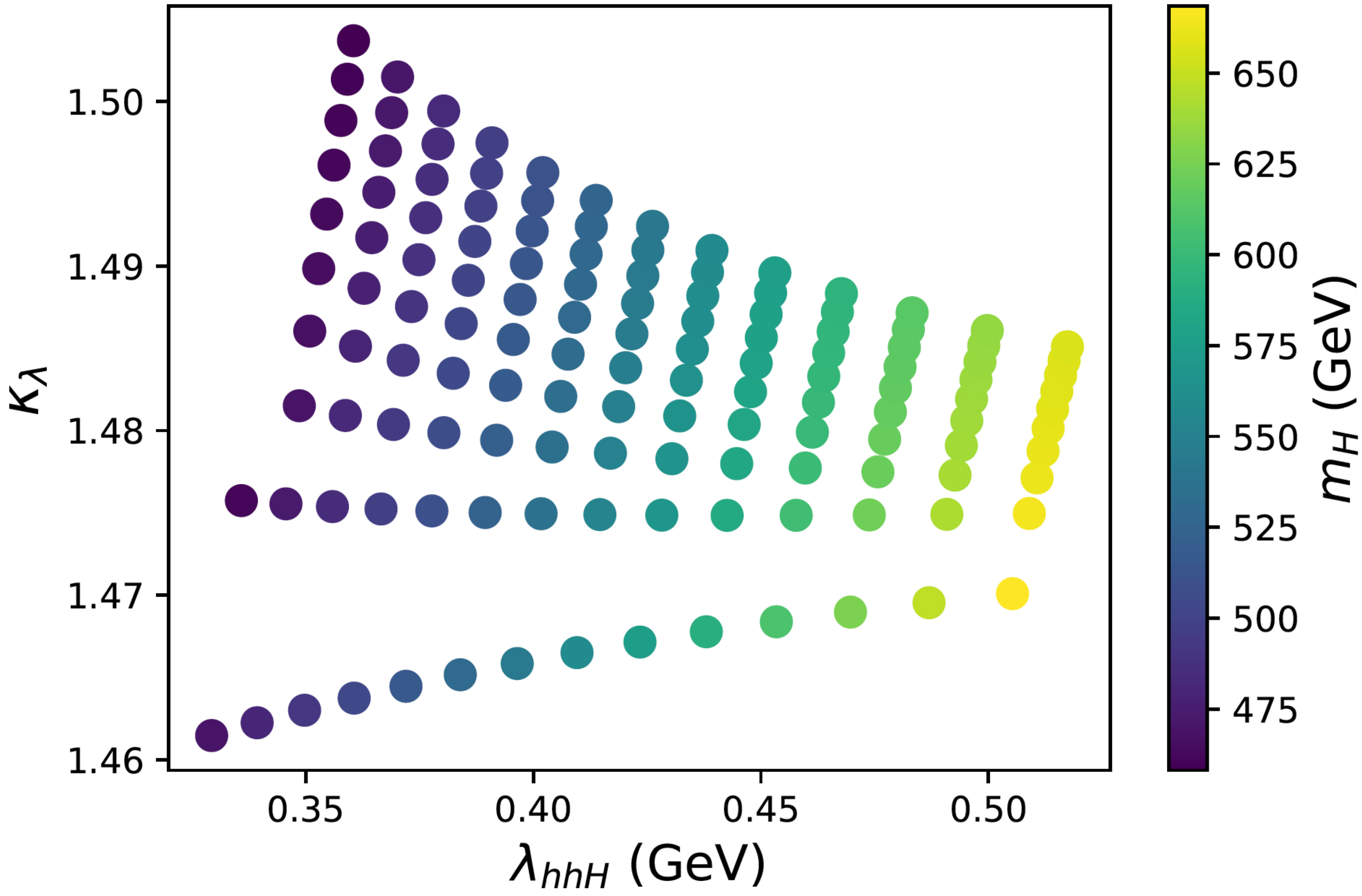
Masses & mixing angle:

$$m_h^2 = M_\phi^2 \cos^2(\alpha) + M_s^2 \sin^2(\alpha) + M_{\phi s}^2 \sin(2\alpha)$$
$$m_H^2 = M_\phi^2 \sin^2(\alpha) + M_s^2 \cos^2(\alpha) - M_{\phi s}^2 \sin(2\alpha)$$
$$\tan(2\alpha) = \frac{2M_{\phi s}^2}{M_\phi^2 - M_s^2}.$$

⇒ note slight difference w.r.t. RxSM introduced yesterday?

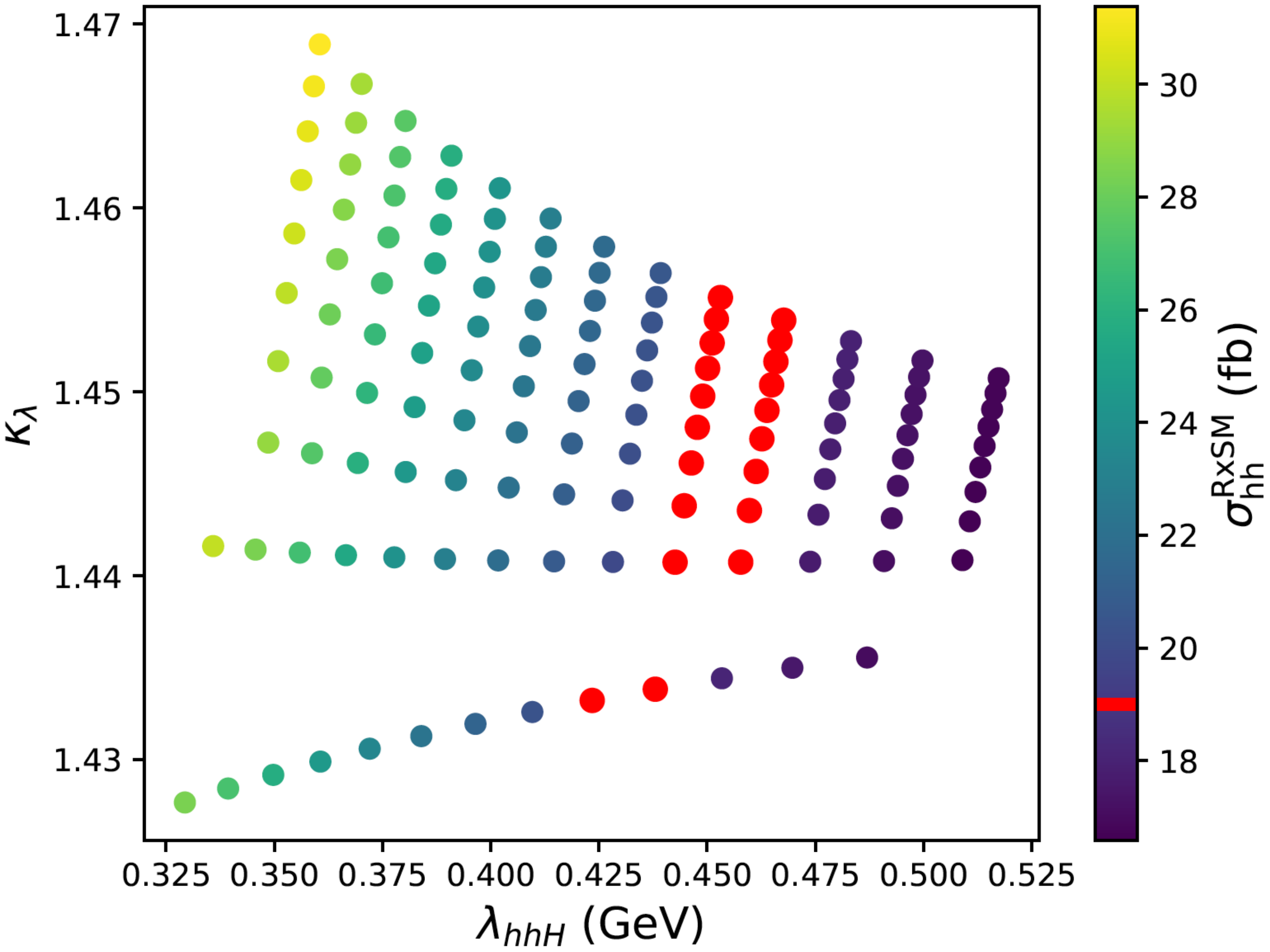
⇒ simplest Higgs-sector extension that features strong FOEWPT

RxSM anaysis in parameter plane featuring a FOEWPT



⇒ interesting range of m_H

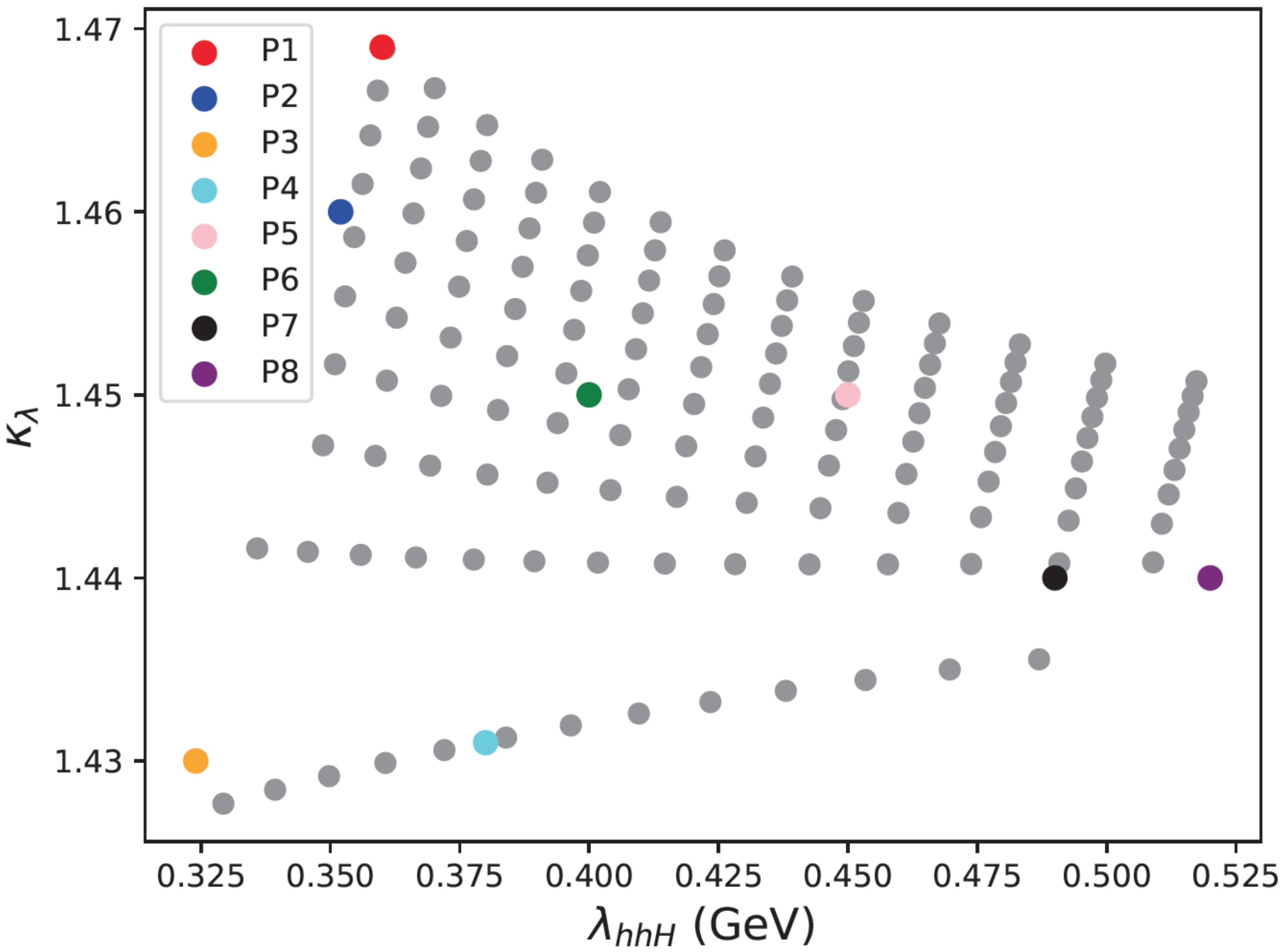
RxSM anaysis in parameter plane featuring a FOEWPT



⇒ deviations from SM possible, but not guaranteed

⇒ not alignment, but compensation of $\kappa_\lambda \approx 1.45$ and H contribution!

Define benchmark points for detailed analysis:



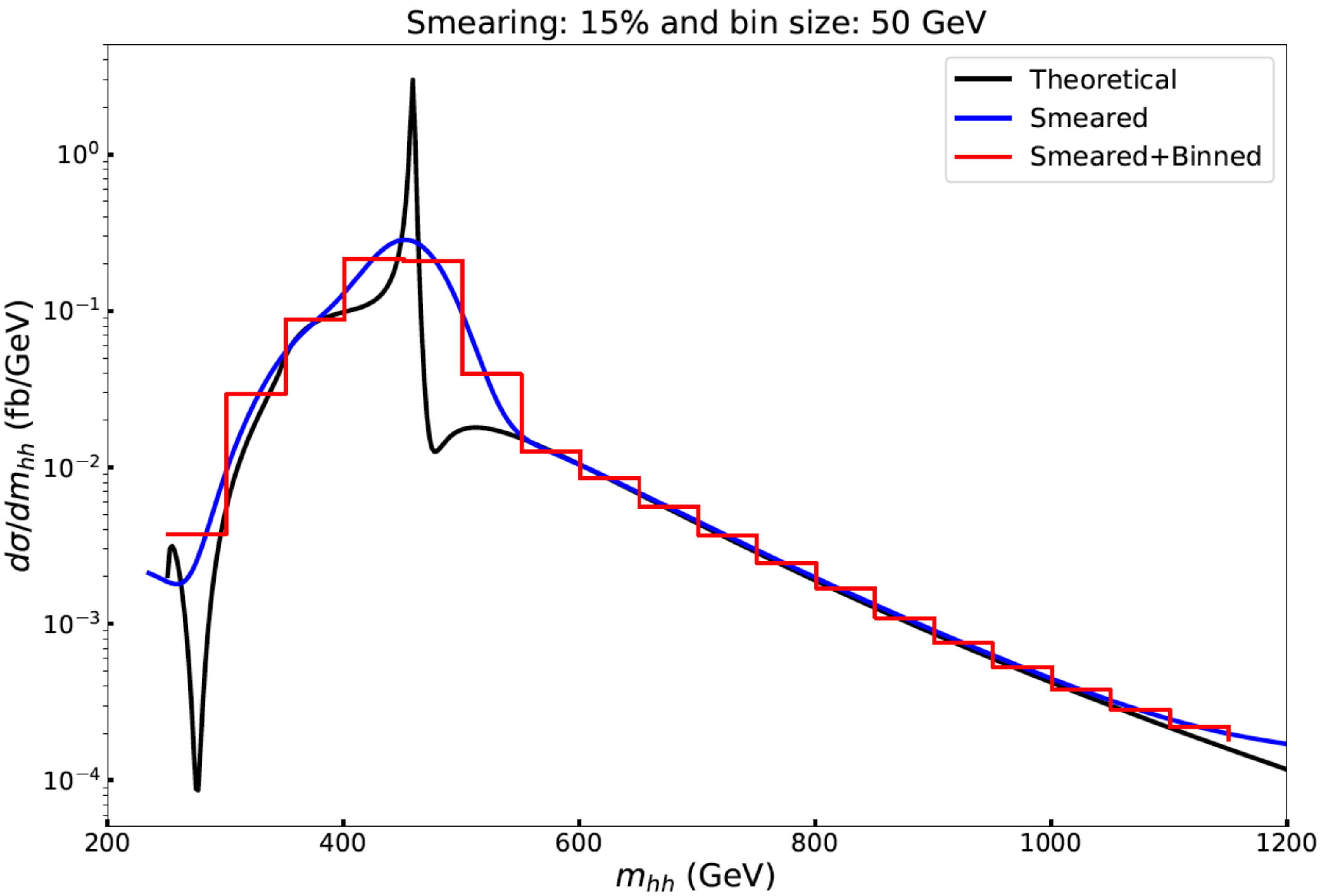
$\Rightarrow$ covering the whole plane/relevant phenomenology

Define benchmark points for detailed analysis:

Point	x [GeV]	λ	a_1 [GeV]	a_2	b_3 [GeV]	b_4	κ_λ	λ_{hhH}	λ_{hHH}	λ_{HHH}
P1	46.3	0.18	-691.10	4.50	-622.6	0.89	1.47	0.36	0.41	0.80
P2	46.3	0.18	-691.10	4.45	-442.70	0.45	1.46	0.35	0.46	0.37
P3	47.4	0.18	-675.10	4.11	0.00	0.00	1.43	0.33	0.44	0.67
P4	41.9	0.18	-763.70	5.23	0.00	0.00	1.43	0.38	0.55	0.82
P5	37.5	0.18	-853.30	6.65	-582.90	0.78	1.46	0.45	0.84	0.45
P6	40.8	0.18	-784.30	5.63	-442.70	0.45	1.45	0.40	0.60	0.42
P7	34.2	0.18	-935.70	7.85	-218.90	0.11	1.44	0.49	0.88	0.96
P8	33.1	0.18	-966.80	8.44	-582.90	0.78	1.44	0.52	0.92	0.98

Variation of:
- κ_λ: negligible
- λ_{hhH}: 50%
- λ_{hHH}: 100%
- λ_{HHH}: 100%

Analysis of m_{hh} distributions:



$\Rightarrow$ smearing and binning crucial - as expected

How to determine the significance of the H resonance?

Theoretical estimator:

$$R := \frac{\sum_i \left| N_i^R - N_i^C \right|}{\sqrt{\sum_i N_i^C}}$$

N_i^R : # of events in bin i under the resonance
N_i^C : # of events in bin i in the continuum/SM

under the condition:

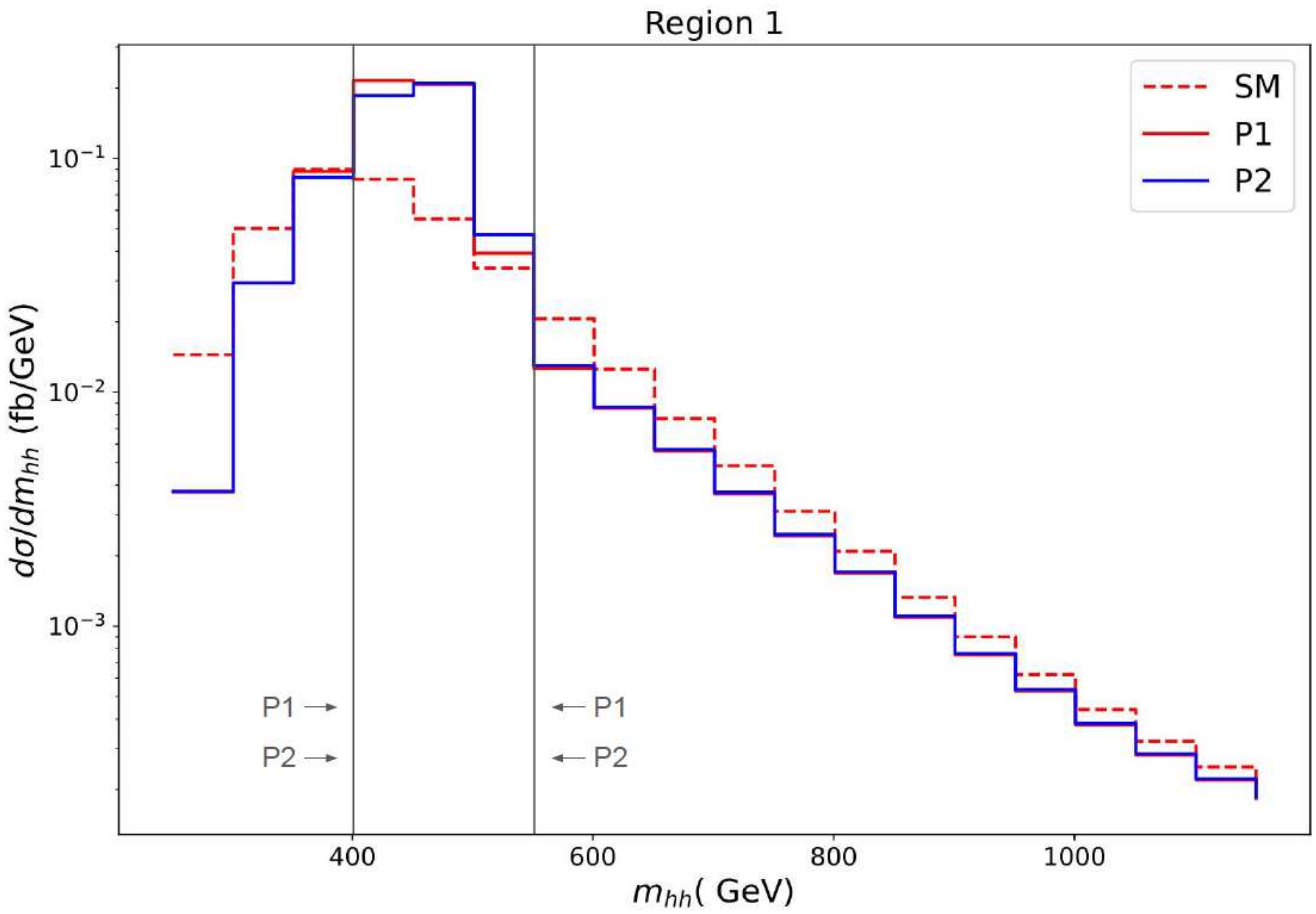
$$\left| N_i^R - N_i^C \right| \geq 100 \quad \text{in bin } i$$

Assumed final state: $gg \to hh \to b\bar{b}\, b\bar{b}$

Assumed luminosity: $\mathcal{L}_{\text{int}} = 3000\,\text{fb}^{-1} \times 2$ (for ATLAS $\oplus$ CMS)

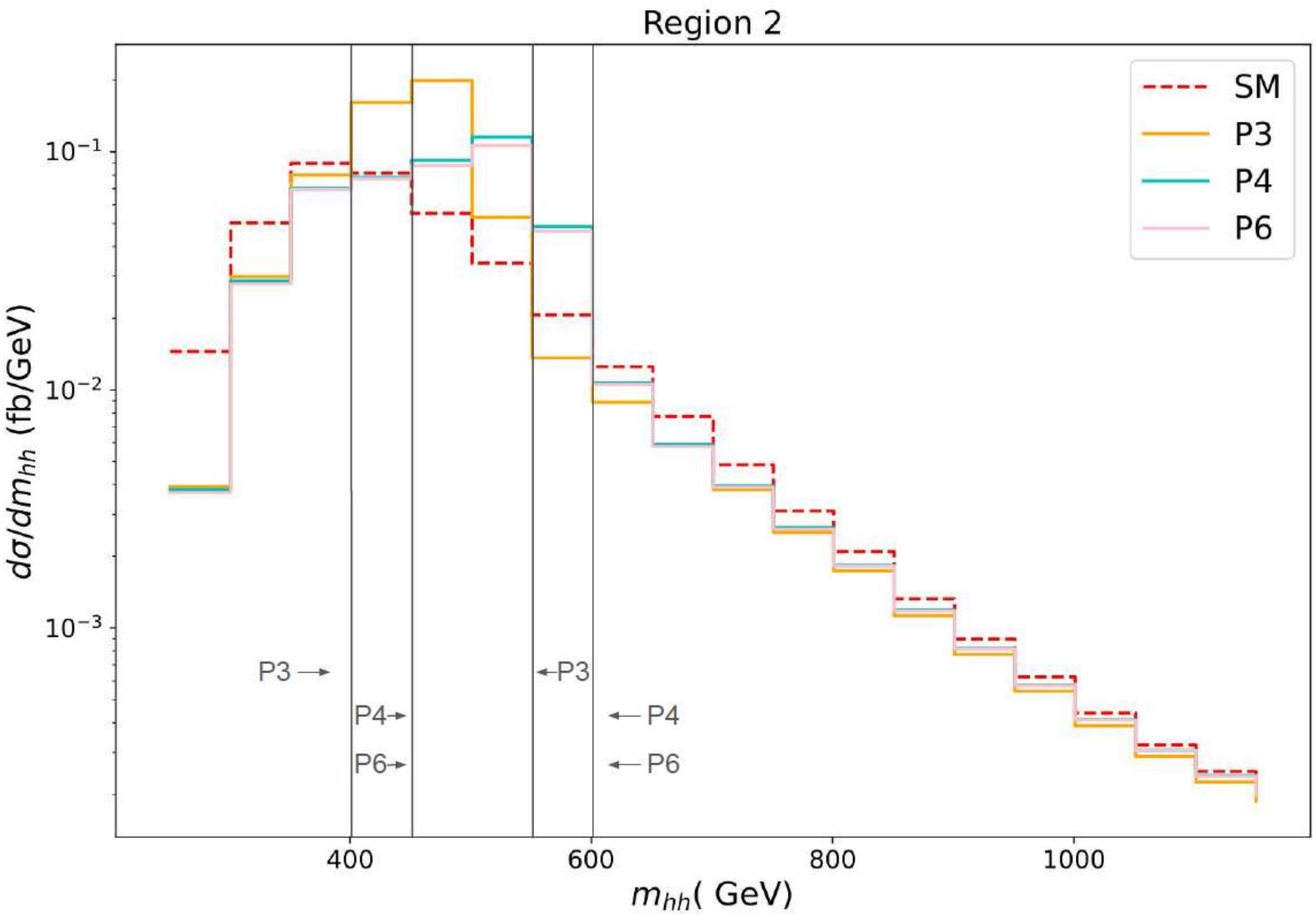
NOTE: this is to compare parameter points, it does NOT correspond to an experimental significance. But it helps. :-)

BPs with large deviation in $\sigma(gg \to hh)$ wrt. SM:



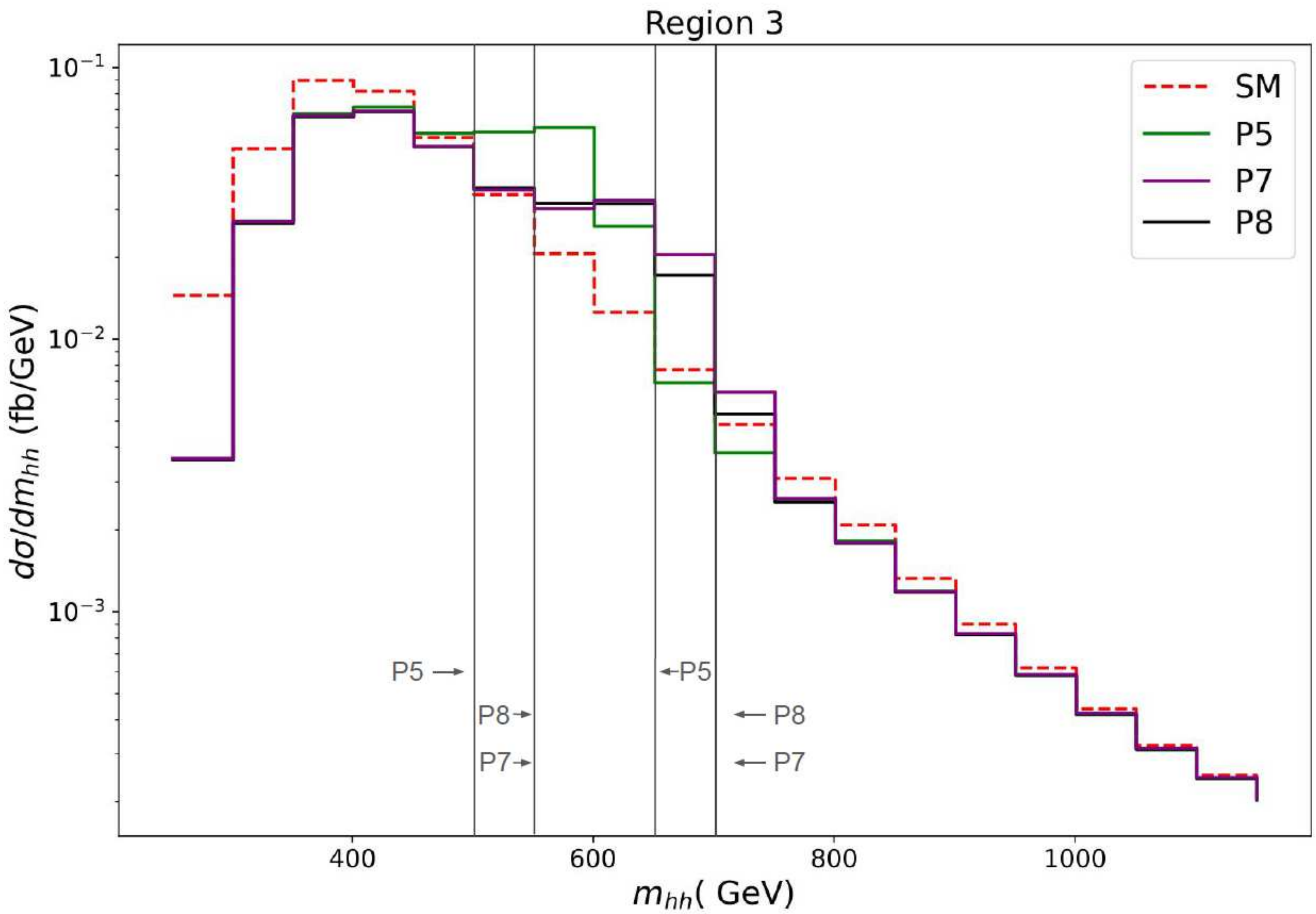
$\Rightarrow R_{1,2} \approx 230 \Rightarrow$ good prospects (full exp. analysis needed!)

BPs with small deviation in $\sigma(gg \to hh)$ wrt. SM:



$\Rightarrow R_{3,4,6} \approx 150..200 \Rightarrow$ good prospects?? (full exp. analysis needed!)

BPs with vanishing deviation in $\sigma(gg \to hh)$ wrt. SM:



$\Rightarrow R_{5,7,8} \approx 75..110 \Rightarrow$ good prospects???? (full exp. analysis needed!)

Mini-summary of BSM Higgs bosons/THCs at the LHC:

– large parameter spaces with relatively low masses allowed

– BSM Higgs sectors predict $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$ different from 1
FOEWPT favors $\kappa_\lambda \sim 1.5 - 2$

– BSM Higgs sectors predict BSM triple Higgs couplings: $\lambda_{hhH}, \ldots$

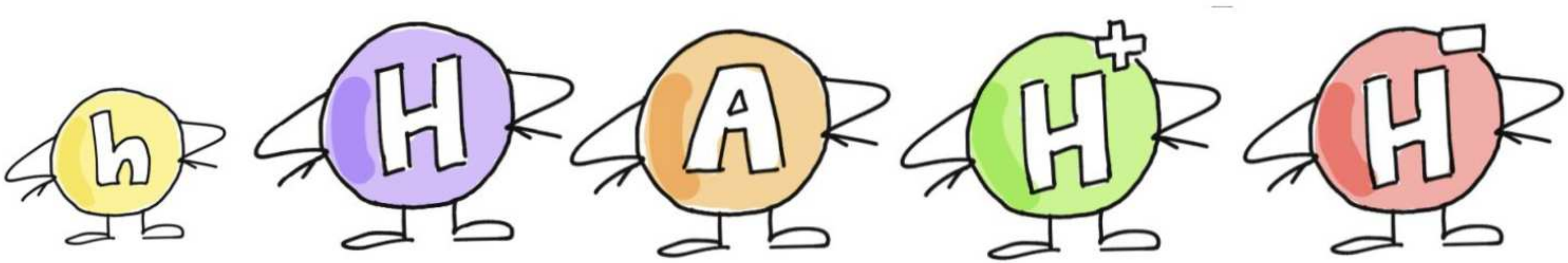
– access to κ_λ and λ_{hhH} via $gg \to hh$
crucial: m_{hh} distributions

– low m_{hh}: affected by changes in κ_λ

– $m_{hh} \sim m_H$: peak-dip resonance structure caused by λ_{hhH}
crucial: smearing and binning

– RxSM analysis suggests experimental sensitivity at the HL-LHC

5. BSM THCs at the ILC



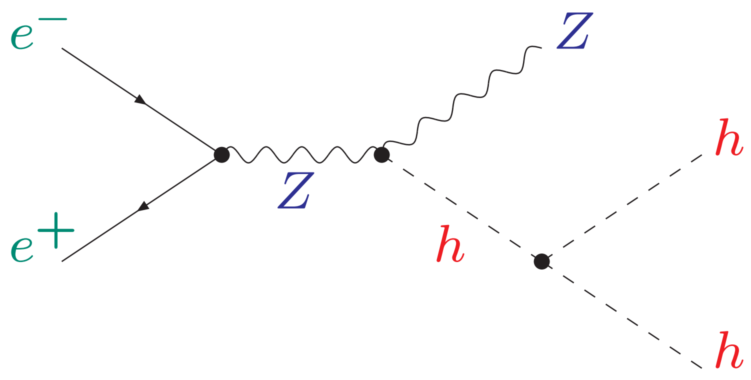
[*K. Radchenko*]


Einbahnstraße!
One Way Street!
Einbahnstraße

Di-Higgs production at e^+e^- colliders

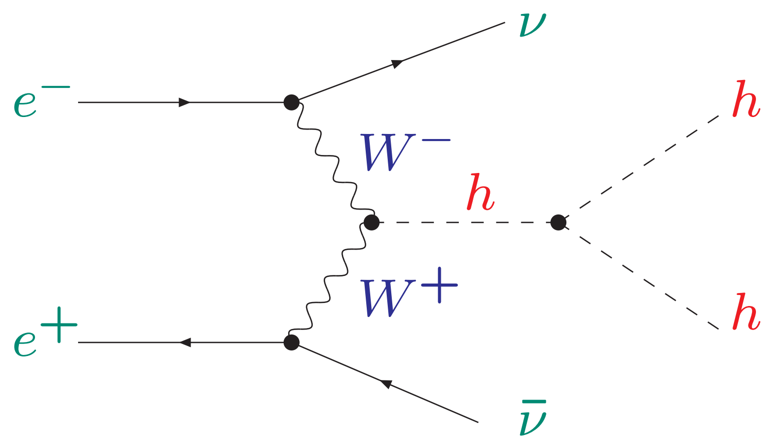
Higgs-strahlung:

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

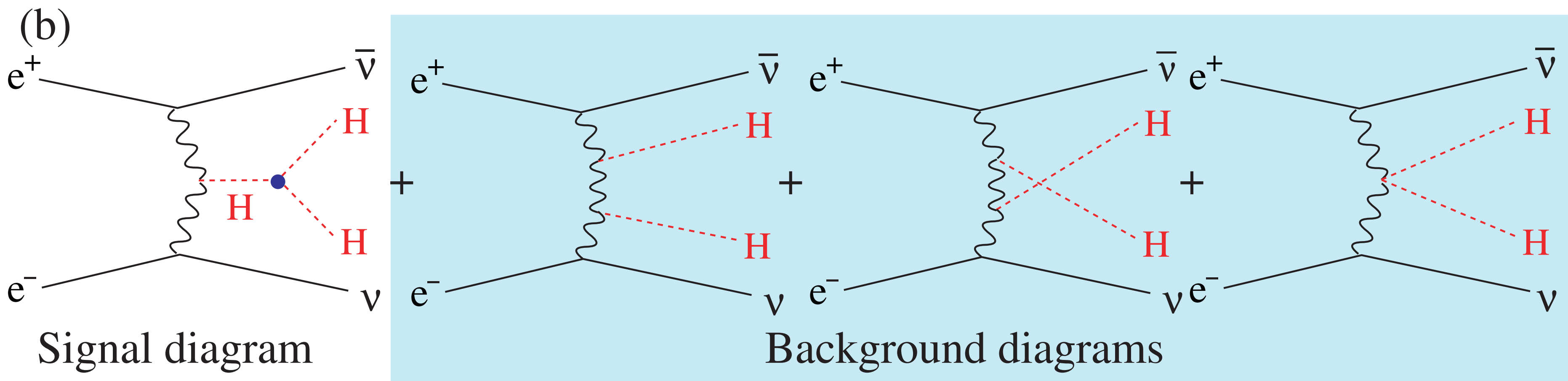


weak boson fusion (WBF):

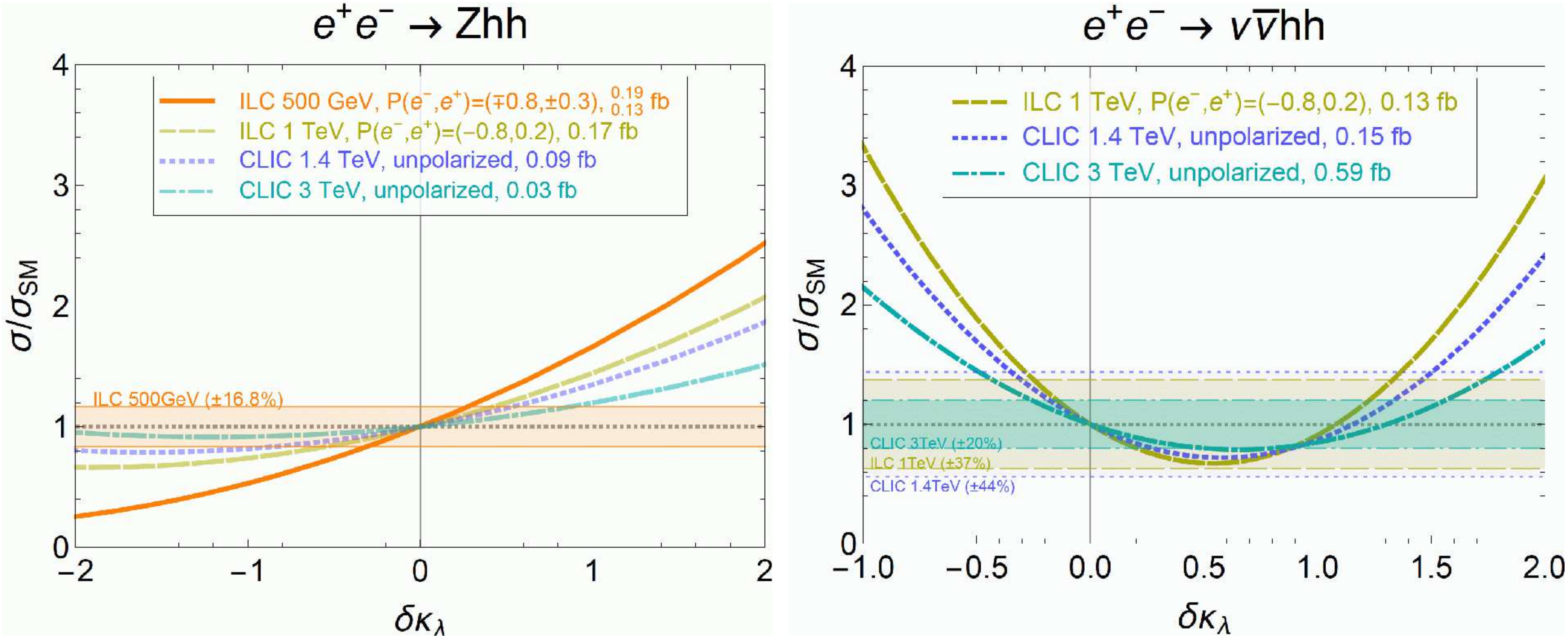
$e+e- \to \nu\bar{\nu}hh$



Signal and background interference:



Di-Higgs production at ILC/CLIC:

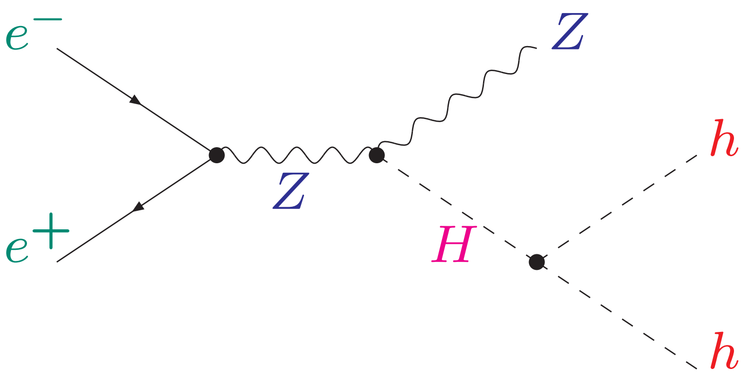


$\kappa_\lambda := 1 + \delta\kappa_\lambda$

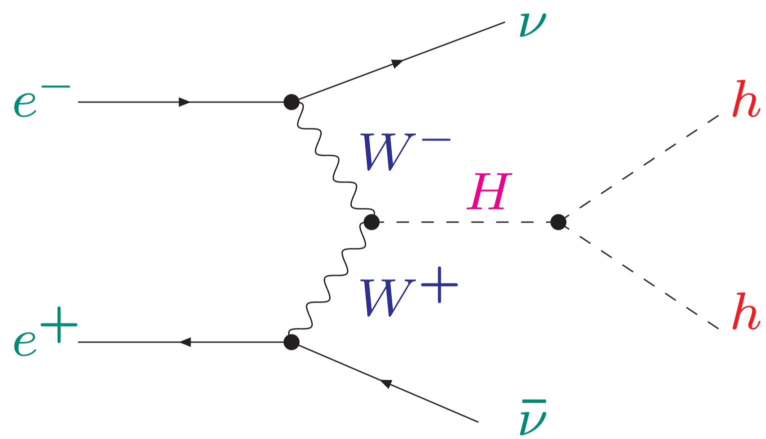
$\Rightarrow$ strong and different dependence on κ_λ

Heavy Higgs enters also in e^+e^- di-Higgs production:

Higgs-strahlung:
$e^+e^- \to Z^* \to Zhh$



weak boson fusion (WBF):
$e+e- \to \nu\bar{\nu}hh$



Difference w.r.t. $gg \to hh$:

– alignment limit gives the SM result for e^+e^-
– $\mathcal{CP}$-odd Higgs bosons enter into the calculation
(but not with THCs)

Two Higgs Doublet Model (2HDM):

Fields:

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

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \end{aligned}$$

Physical states: h, H, ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Mixing angles: α diag. $\mathcal{CP}$-even sector, β diag. $\mathcal{CP}$-odd/charged sector

"Physical" input parameters:

$$c_{\beta-\alpha}\,, \quad \tan\beta\,, \quad v\,, \quad M_h, \quad M_H\,, \quad M_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Assumption (often): $h \sim h_{125}$

Z_2 symmetry to avoid FCNC:

$$\Phi_1 \to \Phi_1 \, , \; \Phi_2 \to -\Phi_2$$

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons	
type I	Φ_2	Φ_2	Φ_2	
type II	Φ_2	Φ_1	Φ_1	$\to$ MSSM type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

Unitarity/perturbativity and EWPO: $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

SM/alignment limit: $c_{\beta-\alpha} \to 0$ for $h \sim h_{125}$
$s_{\beta-\alpha} \to 0$ for $H \sim h_{125}$

Possible effects (beyond tree-level) on 2HDM THCs:

[*taken from F. Arco '24*]

Parameter scan in the 2HDM (all types):

[*F. Arco, S.H., M. Mühlleitner '25*]

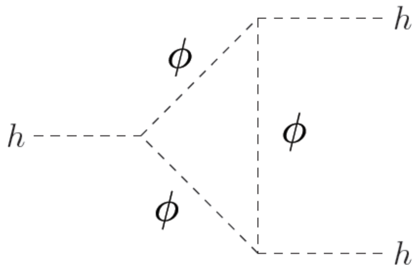
Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

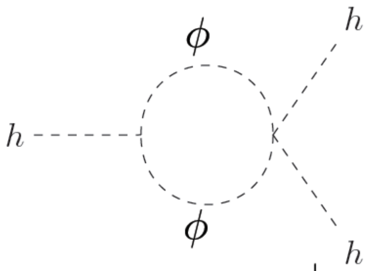
- Scan of the parameter space
- Applied ***constraints*** to the 2HDM
  - EWPO
  - Tree-level unitarity + potential stability
  - BSM Higgs boson searches
  - Properties of the SM-like Higgs boson
    - *Close to the alignment!*
  - Flavor Observables

[ScannerS + HiggsTools + HDECAY]

Parameter scan in the 2HDM (all types):

[F. Arco, S.H., M. Mühlleitner '25]





$\phi = H, A, H^{\pm}$

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
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FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the ***alignment limit*** !!!

(In the SM, top-loops are ~ -8%)

$\Rightarrow$ effect of the extended BSM Higgs sector!

Effects on THC determination at the ILC:

[*taken from F. Arco '24*]

[*F. Arco, S.H., M. Mühlleitner '25*]

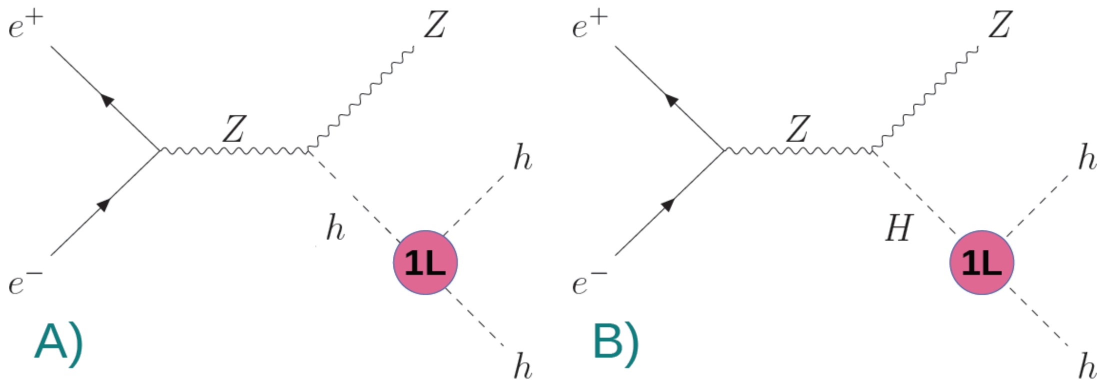
Effects from THCs at $e^+e^- \to hhZ$

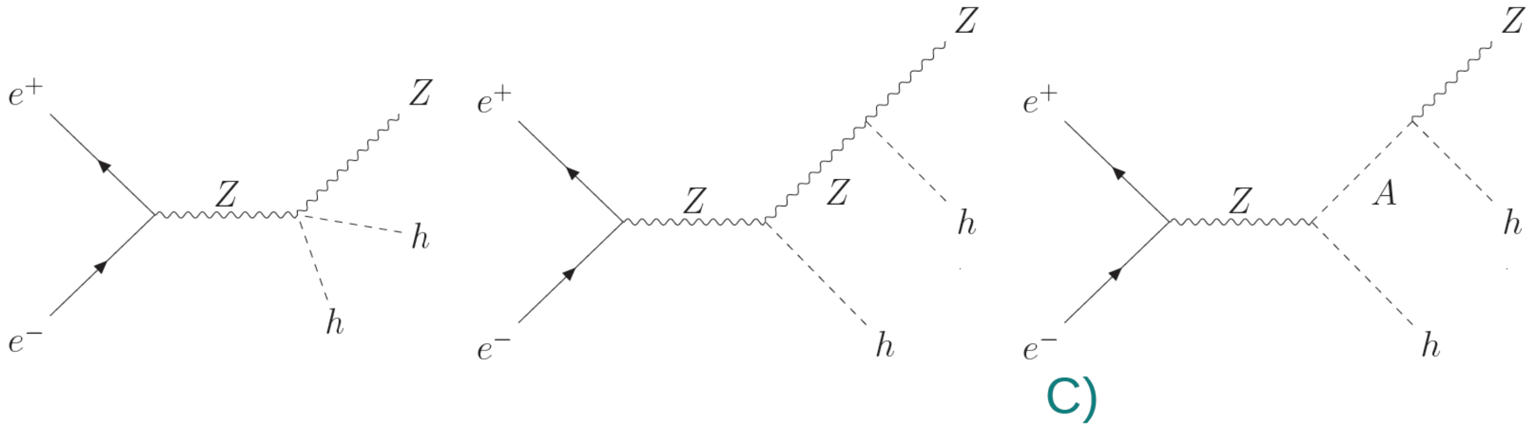
Karlsruhe Institute of Technology

A) **Non-resonant** diagram with κ_λ → at low m_{hh}

B) **Resonant H** diagram with λ_{hhH} → at $m_{hh} \simeq m_H$

C) Resonant A diagram (no THC)





13 13/06/2024 Francisco Arco – Impact of One-Loop Triple Higgs Couplings on di-Higgs Production at e^+e^- Colliders SUSY 2024 – IFT, Madrid

[F. Arco, S.H., M. Mühlleitner '25]

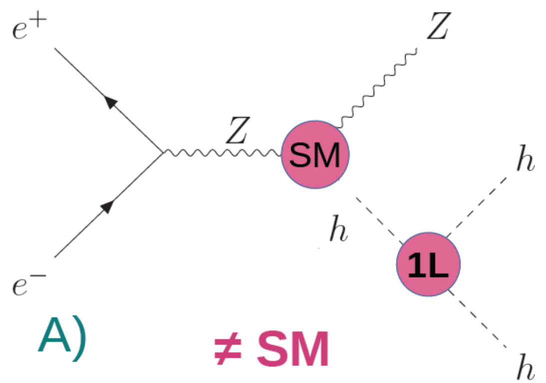
In the alignment limit ($c_{\beta-\alpha} = 0$)

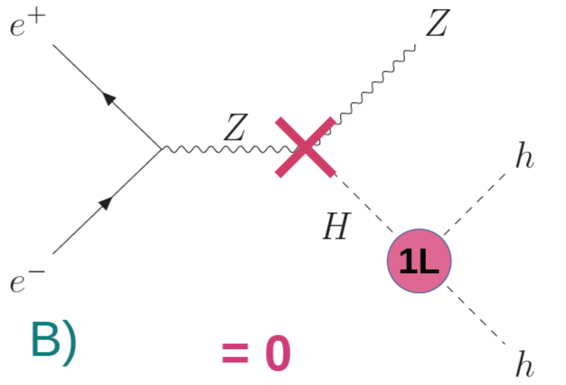
A) **Non-resonant** diagram
wit ... h

B) **R** ... am
wit ... $\simeq m_H$

C) R ... m
(no THC)

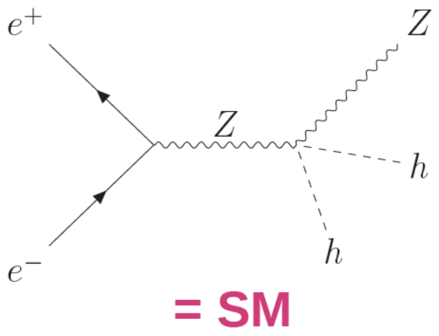
Only BSM effects in $\kappa_\lambda^{(1)}$

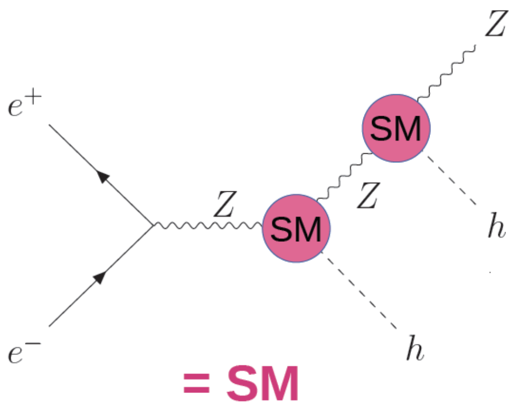


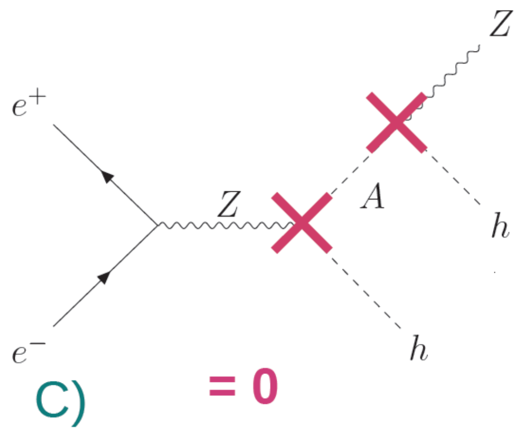


$\kappa_\lambda^{(0)} = 1,$

$\lambda_{hhH}^{(0)} = 0$







How to determine the significance of the H resonance?

Theoretical estimator:

$$R := \frac{\sum_i \left| \bar{N}_i^R - \bar{N}_i^C \right|}{\sqrt{\sum_i \bar{N}_i^C}}$$

$\bar{N}_i^R$: # of events in bin i under the resonance
$\bar{N}_i^C$: # of events in bin i in the continuum/SM

under the condition:

$$\left| \bar{N}_i^R - \bar{N}_i^C \right| \geq 2 \quad \text{in bin } i$$

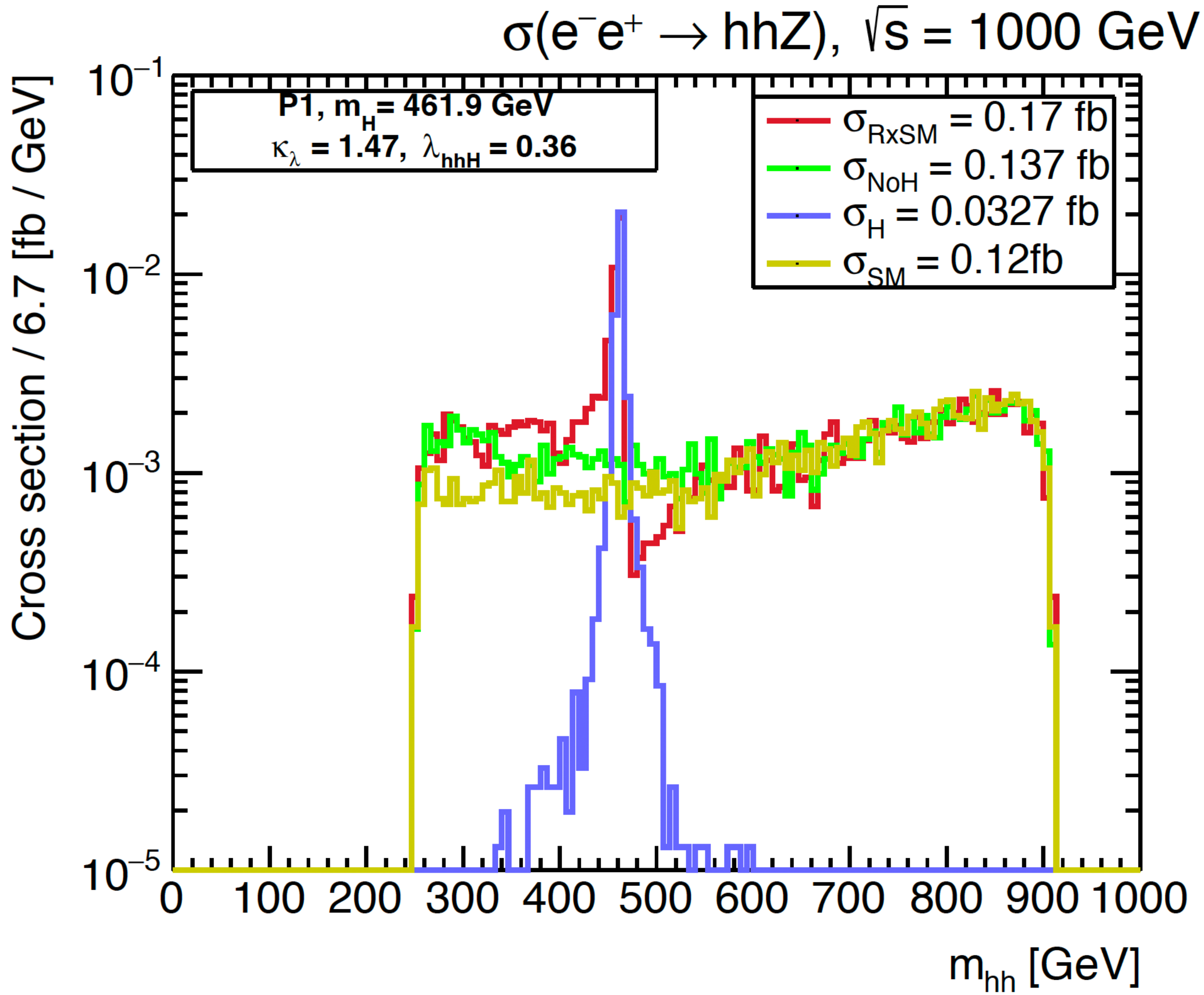
$$\bar{N} := N \times \left(\text{BR}(h \to b\bar{b})\right)^2 \times \mathcal{A} \times \varepsilon_b{}^4$$

$\mathcal{A}$: $p_T^Z > 20$ GeV, $p_T^b > 20$ GeV, $|\eta_b| > 2$, $\Delta R_{bb} > 0.4$ ≈ 0.75

$\varepsilon_b = 0.8$

$\mathcal{L} = 8\,\text{ab}^{-1}$

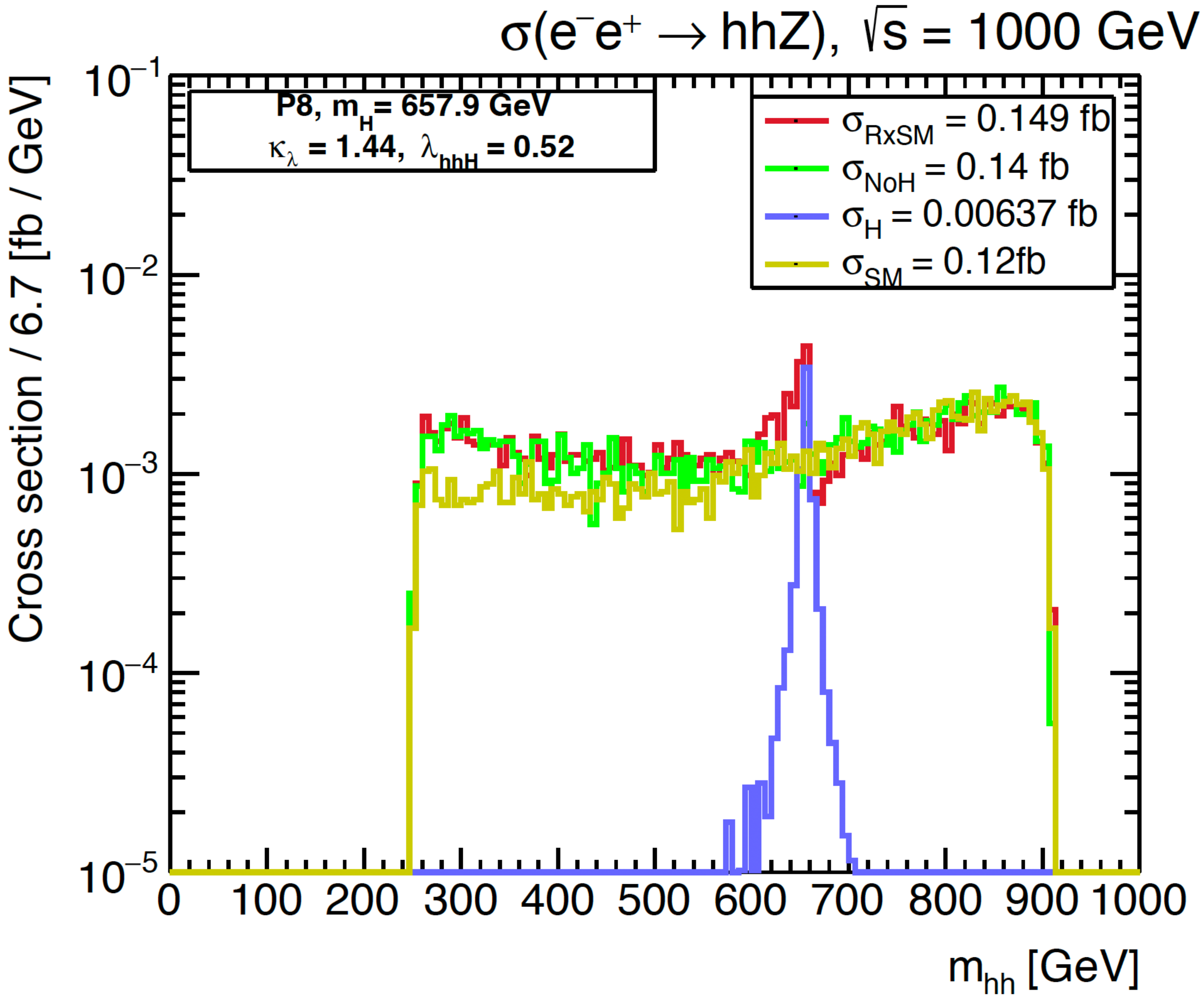
RxSM: m_{hh} for BP1 (lowest m_H)



Effects of κ_λ: low m_{hh}

Effects of λ_{hhH}: at $m_{hh} \sim m_H$ $\Rightarrow$ clear peak-dip structure

RxSM: m_{hh} for BP8 (highest m_H)



Effects of κ_λ: low m_{hh}

Effects of λ_{hhH}: at $m_{hh} \sim m_H$ $\Rightarrow$ less clear peak-dip structure

RxSM: Summary of sensitivities:

	P1	P2	P3	P4	P5	P6	P7	P8
R	13.59	14.35	10.54	7.16	5.75	7.26	3.39	3.70
m_H [GeV]	461.9	470.8	469.4	530.9	575.1	529.6	642.5	656.1
λ_{hhH}	0.36	0.35	0.33	0.38	0.45	0.40	0.49	0.52

Benchmark plane artefact:

lower λ_{hhH} $\Leftrightarrow$ lower m_H $\Leftrightarrow$ higher R

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Q: Can we actually measure λ_{hhH}?

RxSM: Summary of sensitivities:

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Benchmark plane artefact:

lower λ_{hhH} $\Leftrightarrow$ lower m_H $\Leftrightarrow$ higher R

Q: Can we actually measure λ_{hhH}?

A: Yes! Either with NNs , or at high-energy lepton colliders