
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD

Triple Higgs Couplings at Current and Future Experiments

Sven Heinemeyer, IFT (CSIC, Madrid)

Taipei, 10/2024

1. Introduction
2. Resonant di-Higgs production: theory vs. experiment
3. Triple Higgs couplings at the HL-LHC and the ILC
4. Conclusions

1. Introduction

Q: Higgs potential: barely known

⇒ measure triple Higgs couplings

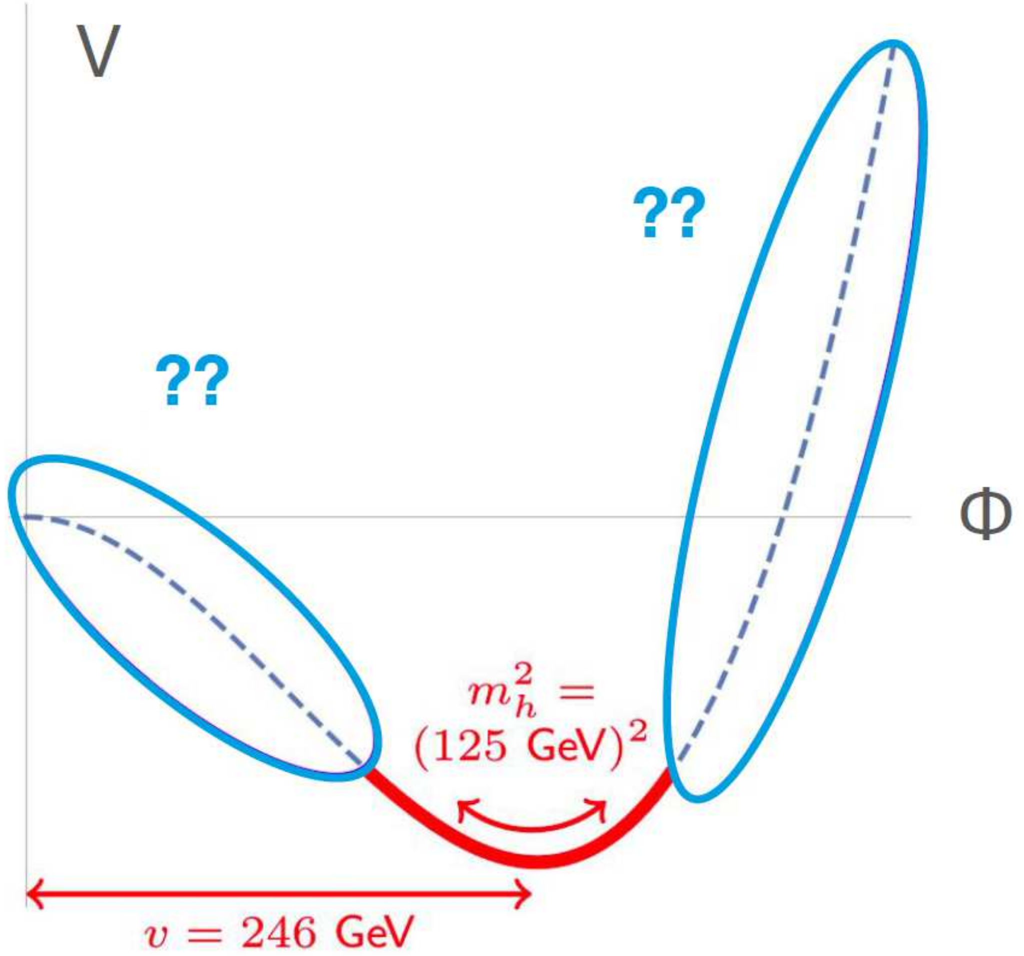
Q2: Why is there
more matter than antimatter?
⇒ (EW) baryogenesis

⇒ requires First Order EW Phase Transition (FOEWPT)

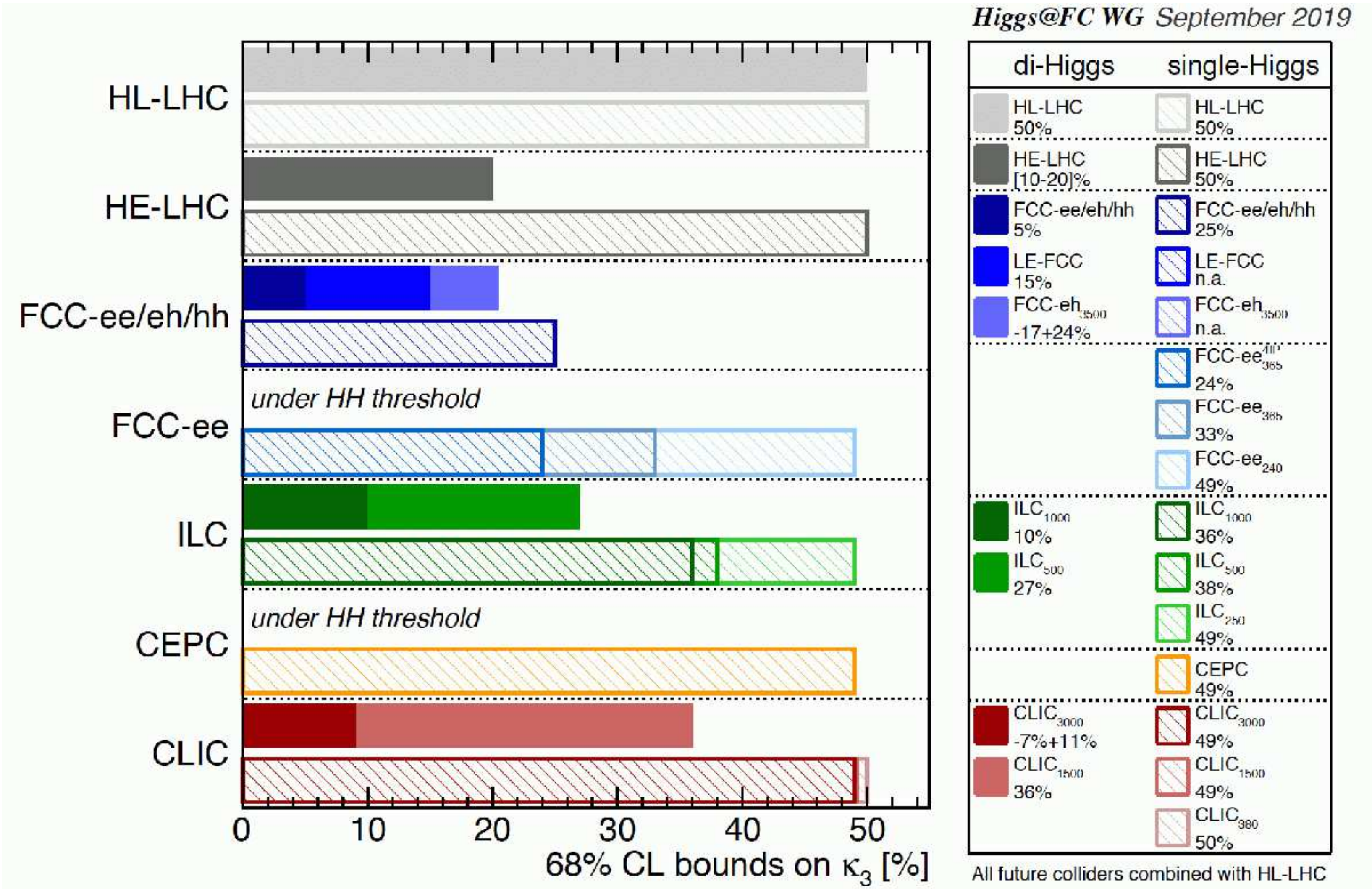
not possible in the SM
⇒ BSM Higgs sector required

⇒ new Higgs bosons below $\sim 800 - 1000$ GeV

⇒ new phenomena:
– resonant di-Higgs production
– BSM triple Higgs couplings



SM triple Higgs coupling: comparison of all colliders:

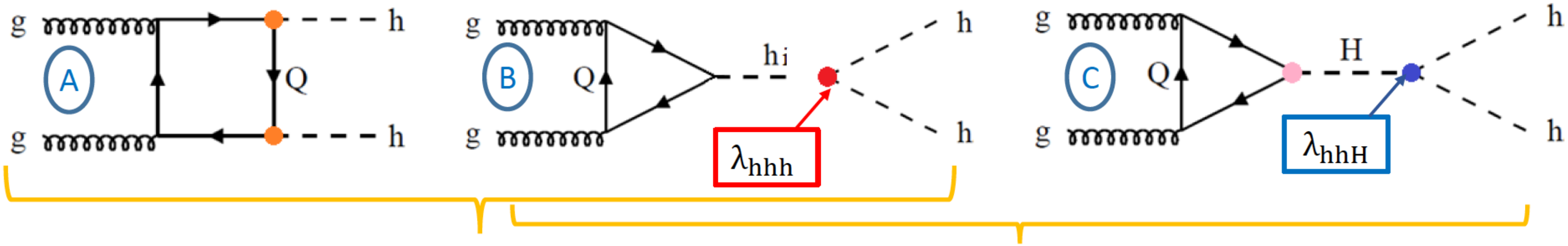


⇒ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM,tree}$

BSM case 1: $\kappa_\lambda \neq 1$

BSM case 2: THC that involves BSM Higgses: $\lambda_{hhH}, \ldots$

Di-Higgs production at the LHC:

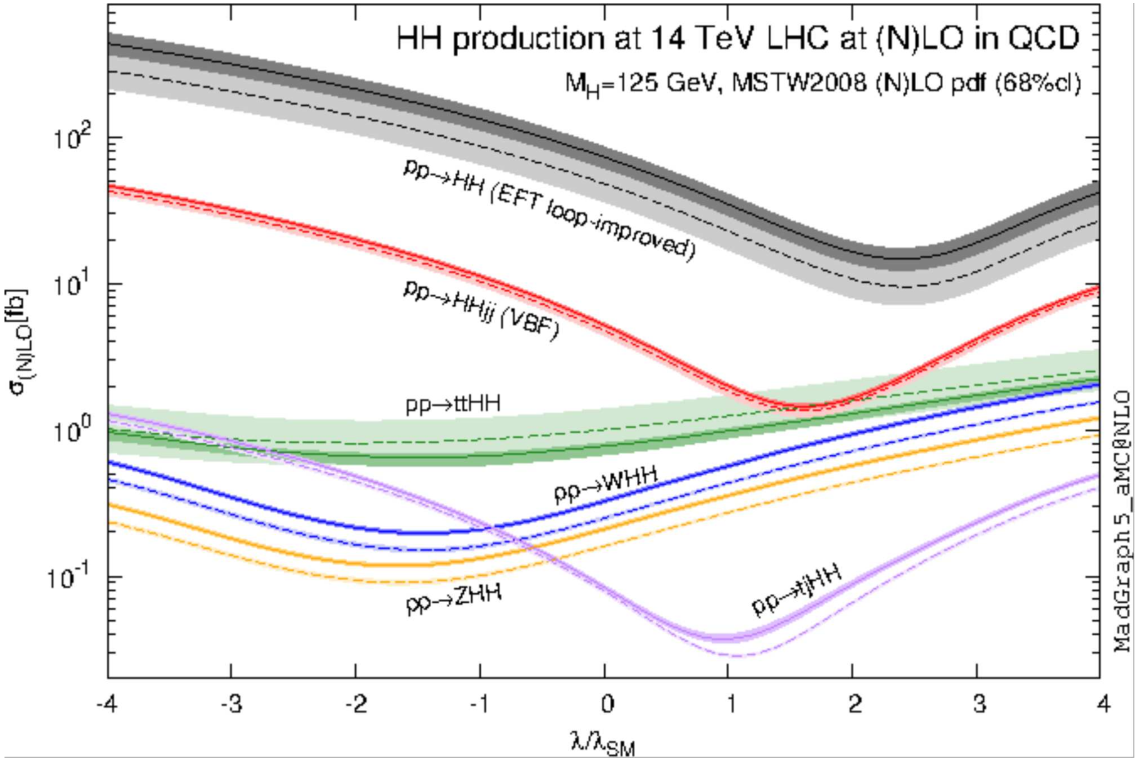


$\sigma_{SM} \sim$ 38 fb at NLO

Diagrams that exist in the SM:
They have a negative interference

Diagrams that are sensitive
to triple Higgs couplings

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



Resonant di-Higgs production requires BSM physics

Resonant di-Higgs production requires BSM physics

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)

"Physical" input parameters:

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

Alignment limit: $c_{\beta-\alpha} \to 0$ (for $M_h \sim 125$ GeV)

Many triple Higgs couplings: λ_{hhh}, λ_{hhH}, λ_{hHH}, $\lambda_{hH^+H^-}$, λ_{HAA}, ...

Assumption: $h \sim h_{125}$

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:

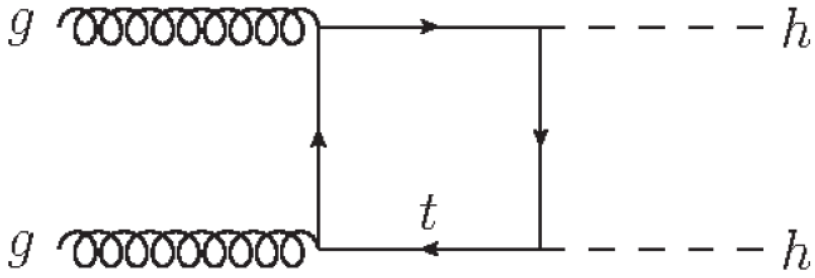
	u-type	d-type	leptons	
type I	Φ_2	Φ_2	Φ_2	
type II	Φ_2	Φ_1	Φ_1	$\to$ SUSY type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

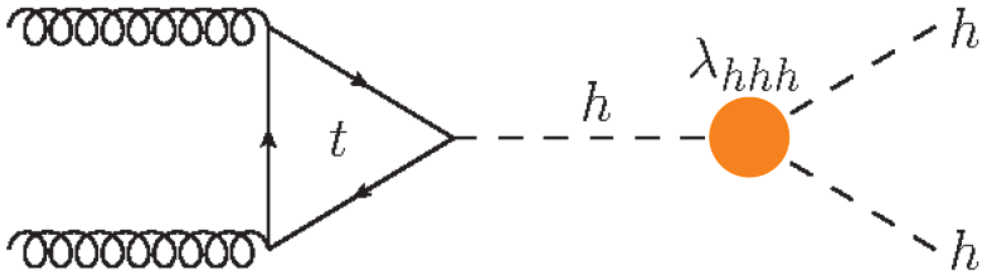
Sum rule (with h SM-like): $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) \approx 0$

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

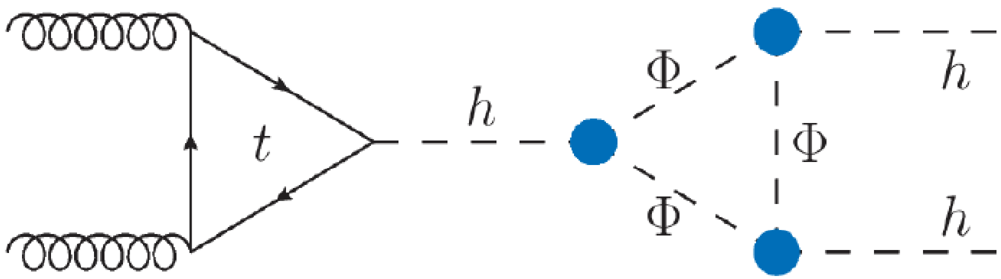
 [*taken from J. Braathen*]

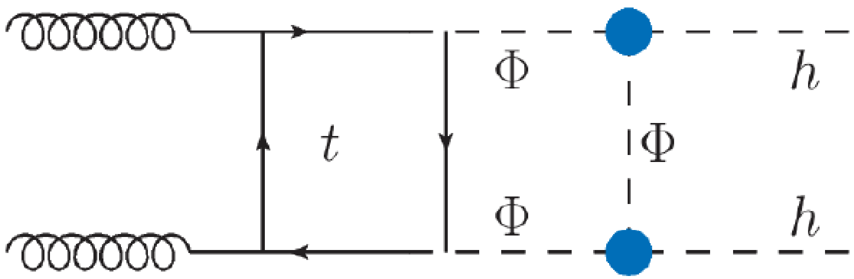
Box vs. s-channel Higgs:





Inclusion of one-loop corrections to THCs:





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

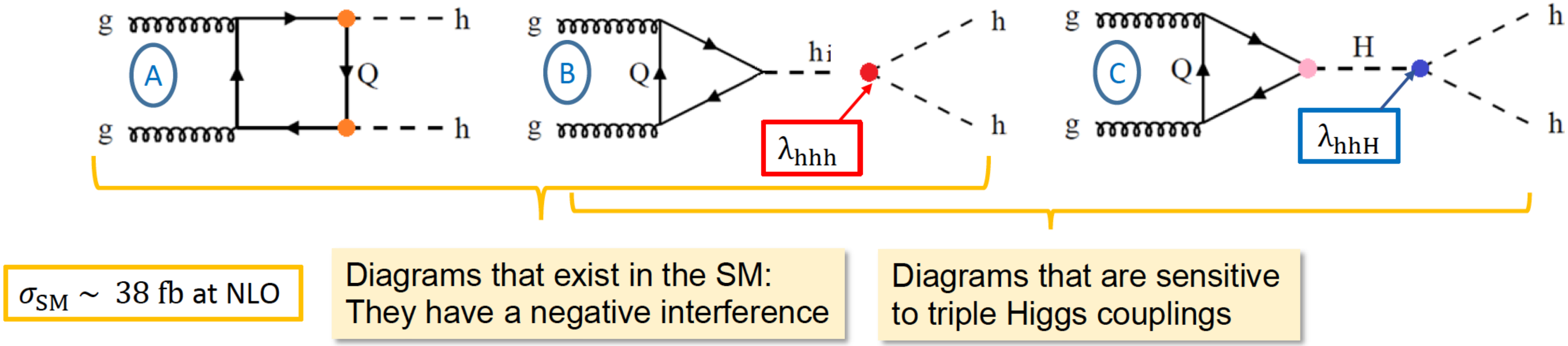
Correction to $\lambda_{hhh} \rightarrow$ included

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

not included

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

BSM THCs at the HL-LHC



⇒ possible strong resonance with BSM Higgs

Important: experimental limtis are obtained for

– non-resonant production

– purely resonant production

⇒ no limits available for mixed scenarios :-(

⇒ existing exclusion bounds questionable!

Example model in this talk: 2HDM

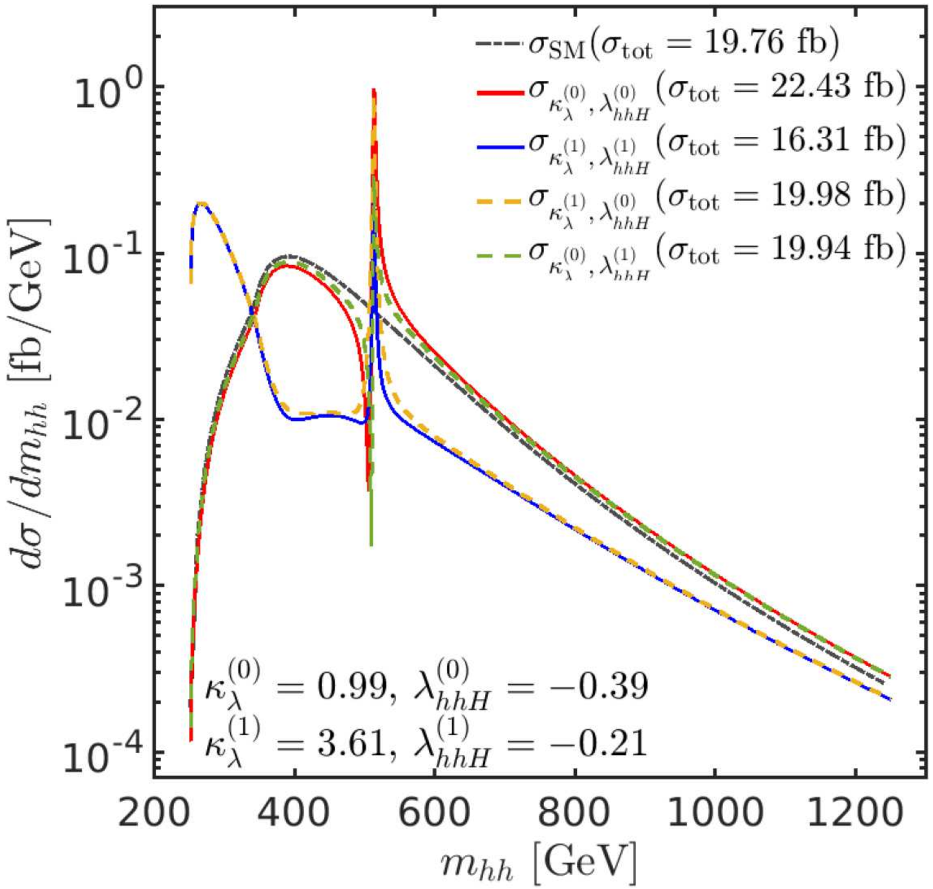
Similar results exist also for RxSM (Higgs singlet extension)

[S.H., A. Verduras PRELIMINARY]

2. Resonant di-Higgs production: theory vs. experiment:

$\Rightarrow$ analyses so far focus on "SM THC": $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM,tree}} \equiv 1$
BSM case 1: $\kappa_\lambda \neq 1$
BSM case 2: THC that involves BSM Higgses: $\lambda_{hhH}, \ldots$

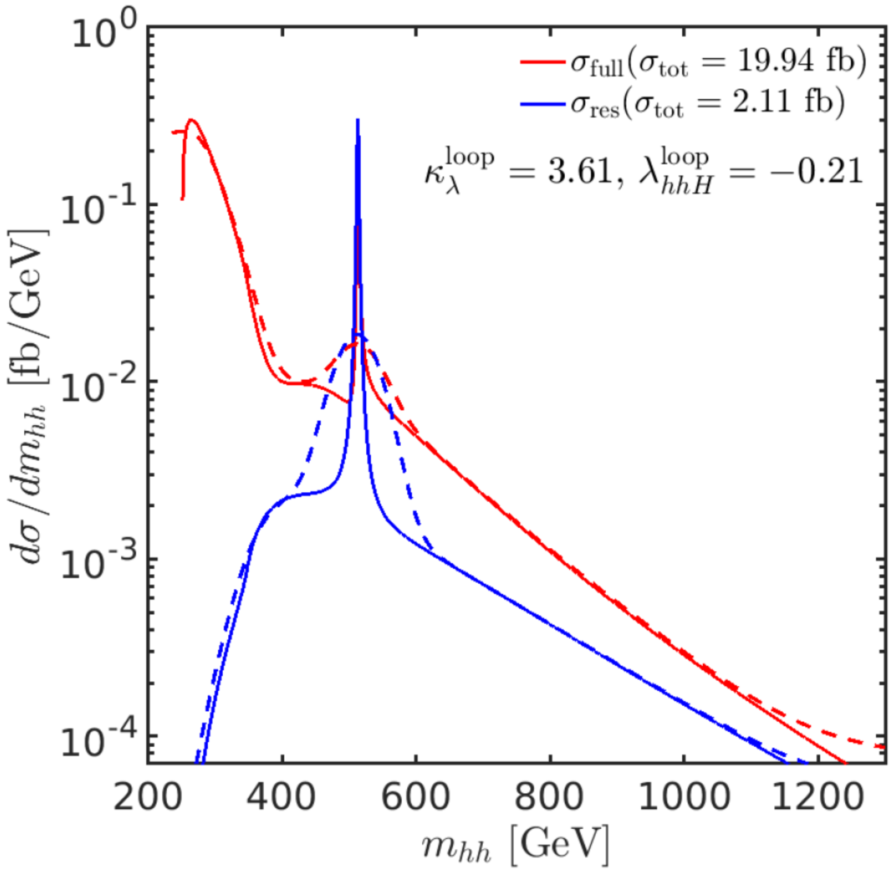
Example of m_{hh} distortions: [S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]



Experimental analysis vs. reality: including exp. uncertainties

[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]

smeared



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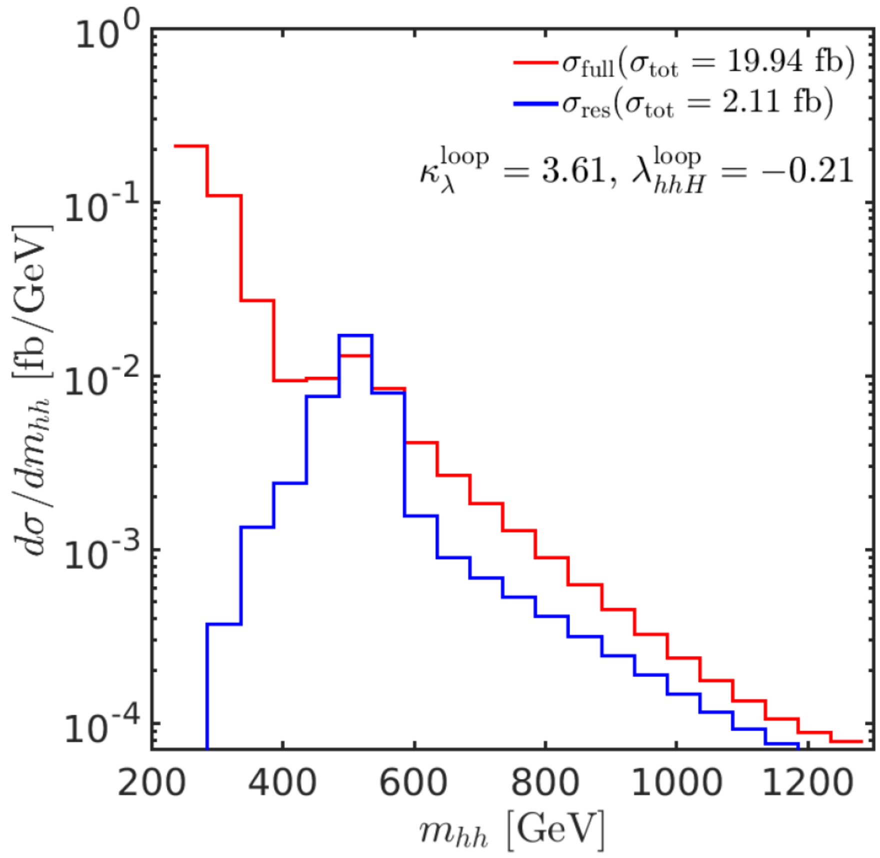
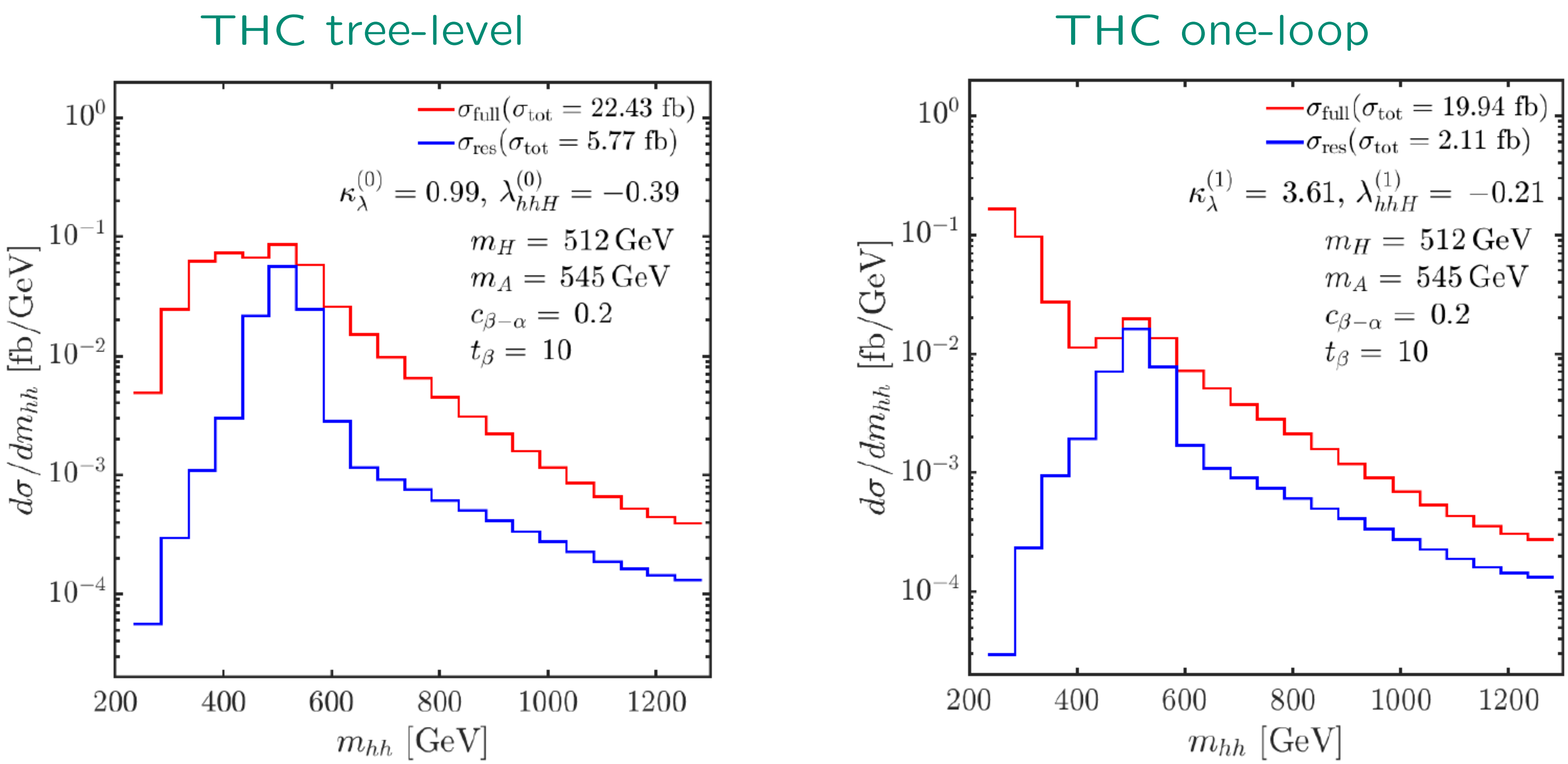


⇒ experimental analysis ⇒ full calculation

Experimental analysis vs. reality: relevance of loop corrections

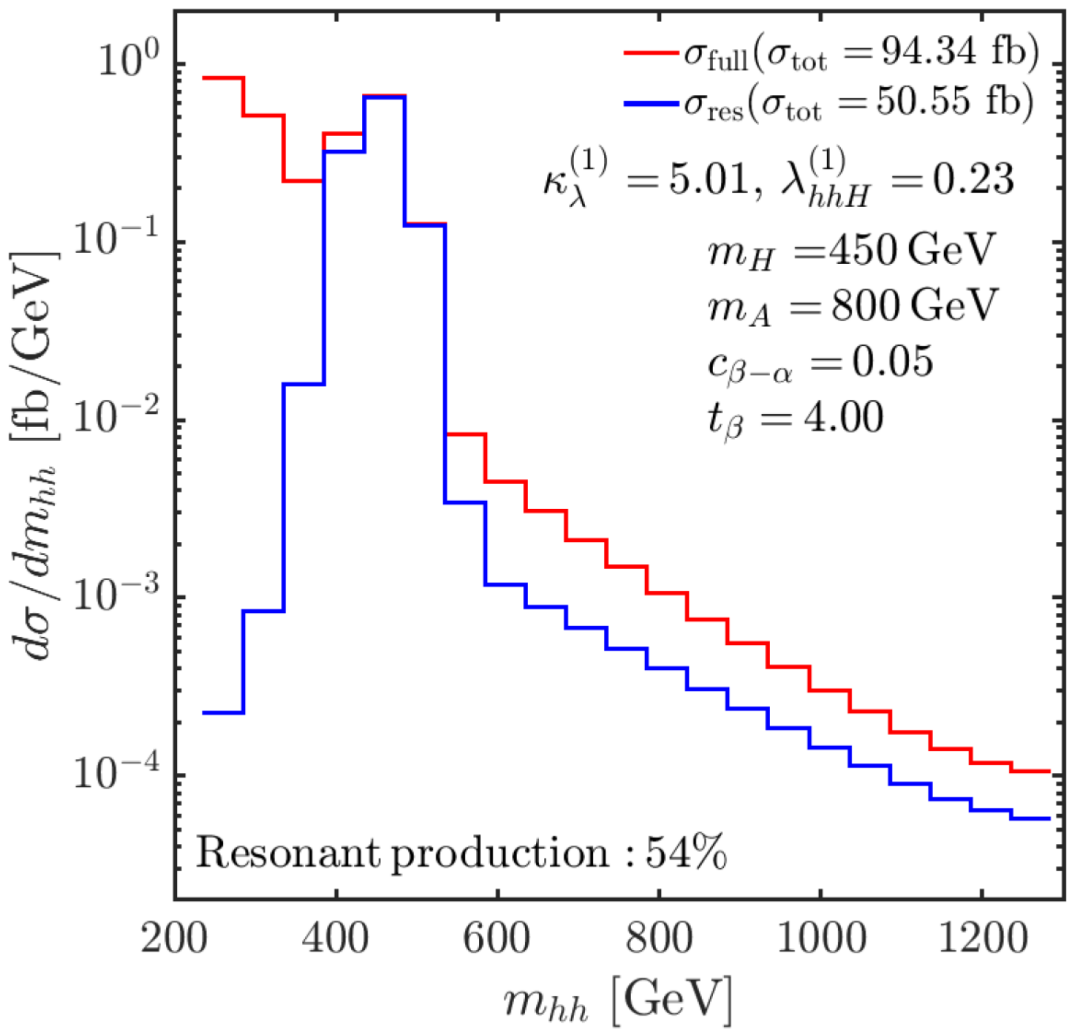
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



$\Rightarrow$ experimental analysis $\Rightarrow$ full calculation

Experimental analysis vs. reality: real point (I)

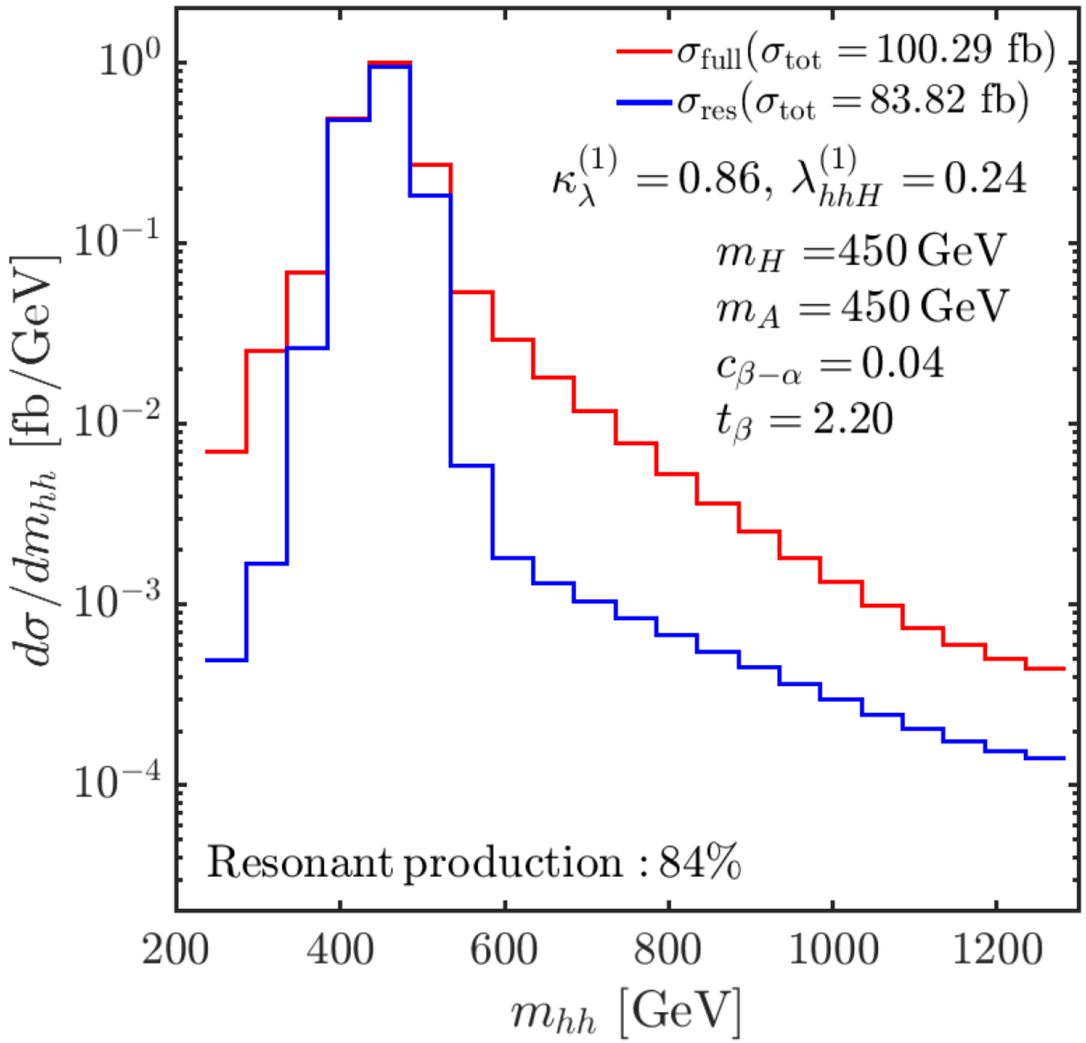
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

Experimental analysis vs. reality: real point (II)

[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

3. THCs at the HL-LHC and the ILC

⇒ 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, . . .

"Realistic" model analysis in the 2HDM

Q: where do we find a FOEWPT?

Q: implications for λ_{hhh} measurements?

Q: implications for BSM Higgs bosons?

- resonant di-Higgs production
- BSM triple Higgs couplings

$\Rightarrow$ Parameter scan in the 2HDM type II $\Rightarrow$ ScannerS

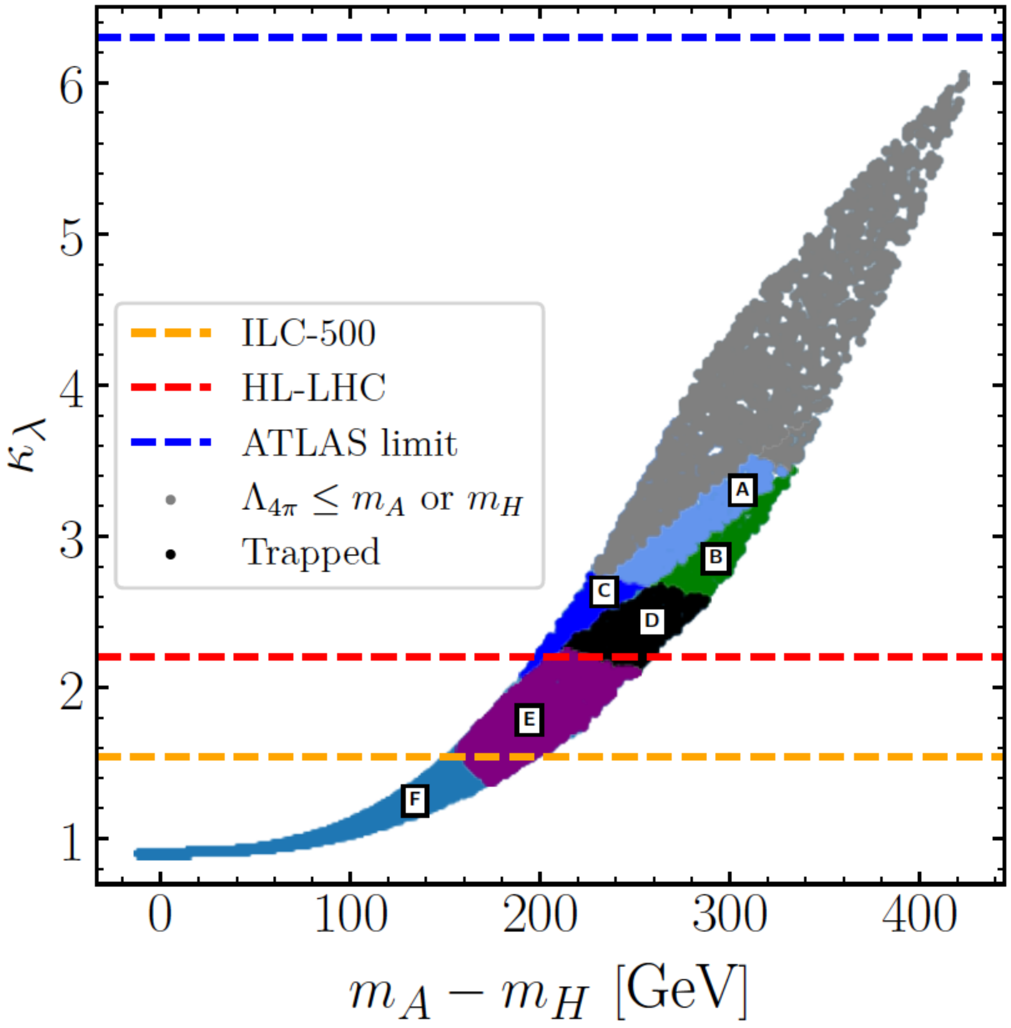
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\leq m_H \leq$ 1 TeV, 0.6 TeV $\leq m_A = m_{H^\pm} \leq$ 1.2 TeV

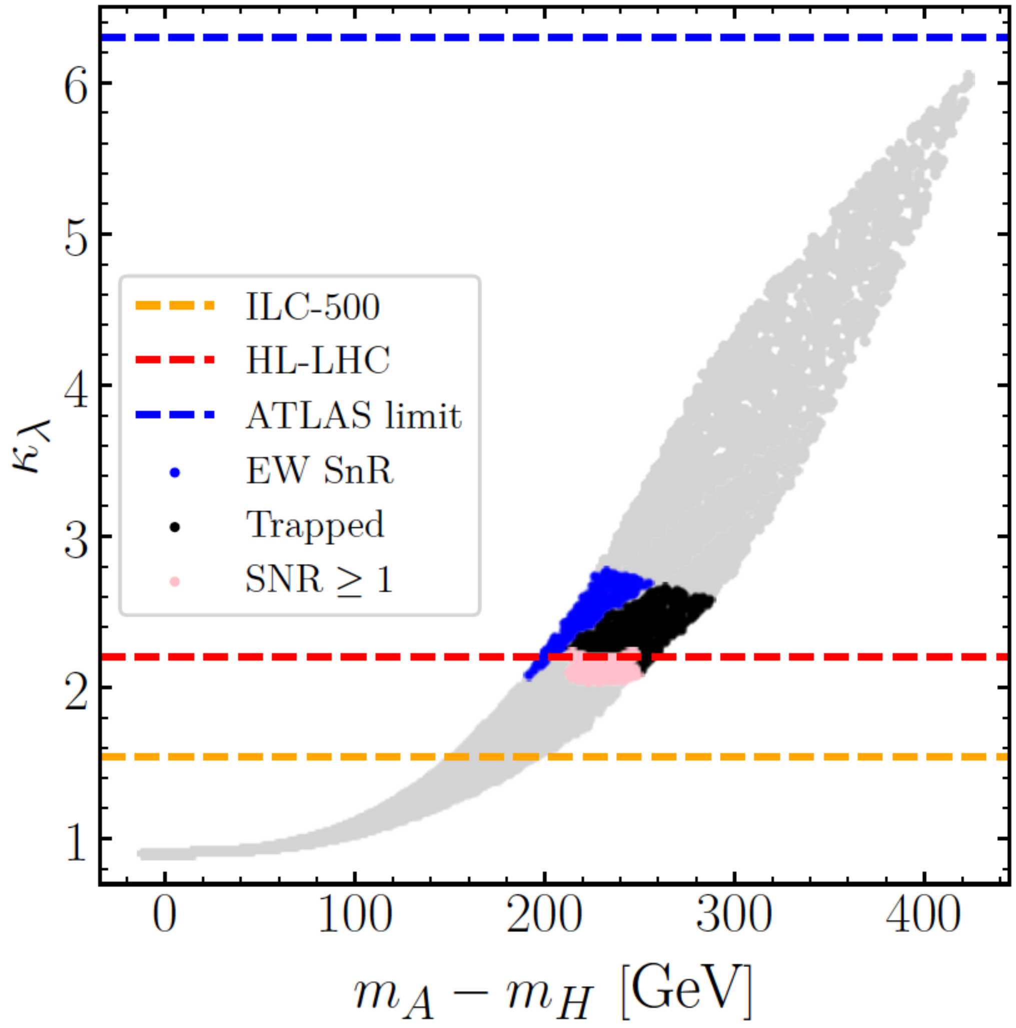
Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
  . . . or sufficiently long-lived $\Rightarrow$ Evade
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties $\Rightarrow \chi^2_{125} \Rightarrow$ HiggsSignals (2HDECAY, SusHi)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS
- λ_{hhh} at one-loop $\Rightarrow$ BSMPT

2HDM parameter scan to yield FOEWPT: $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM,tree}}$

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

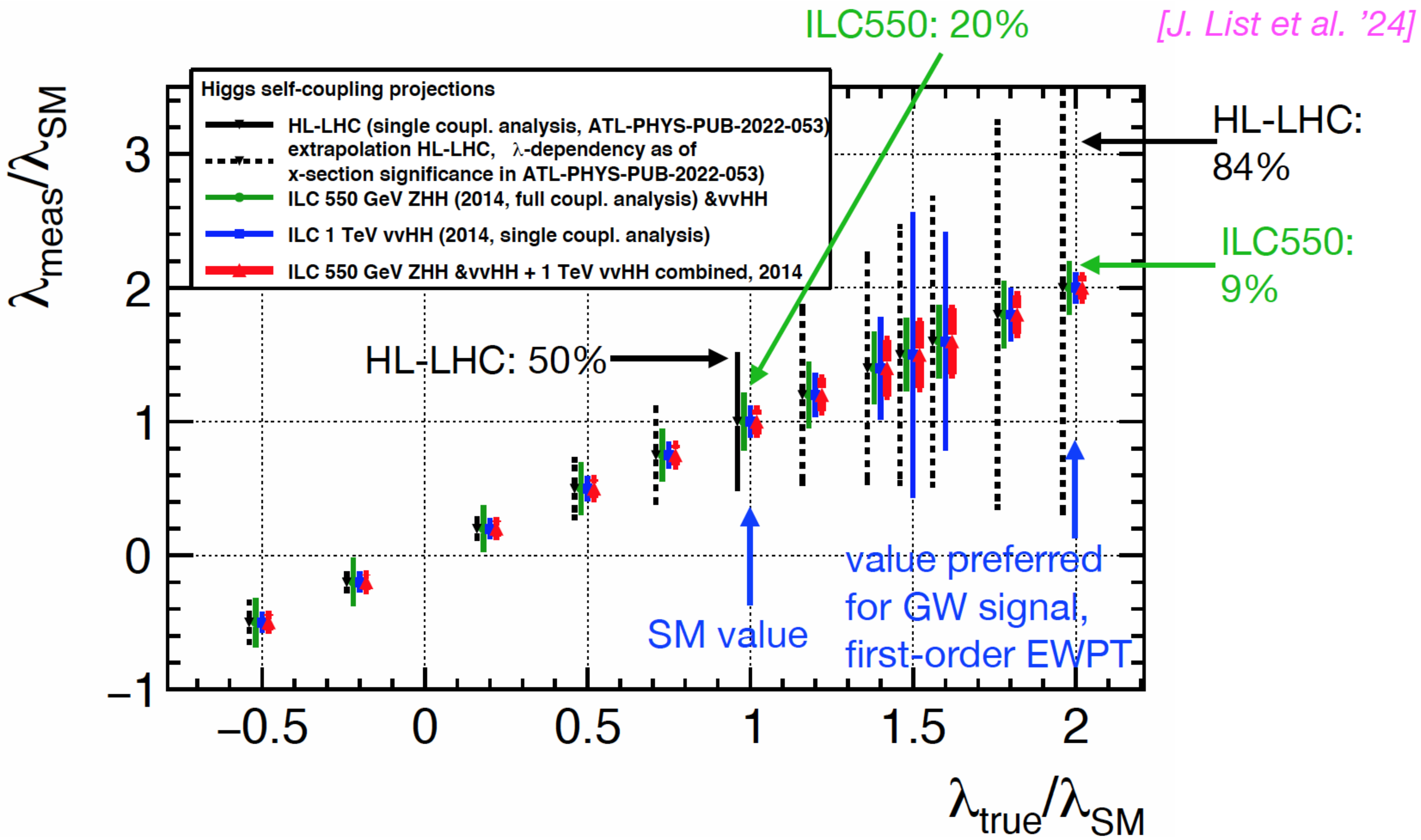




$\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$ and $m_A - m_H \sim 200$ GeV

$\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$ and $m_A - m_H \gtrsim 200$ GeV

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

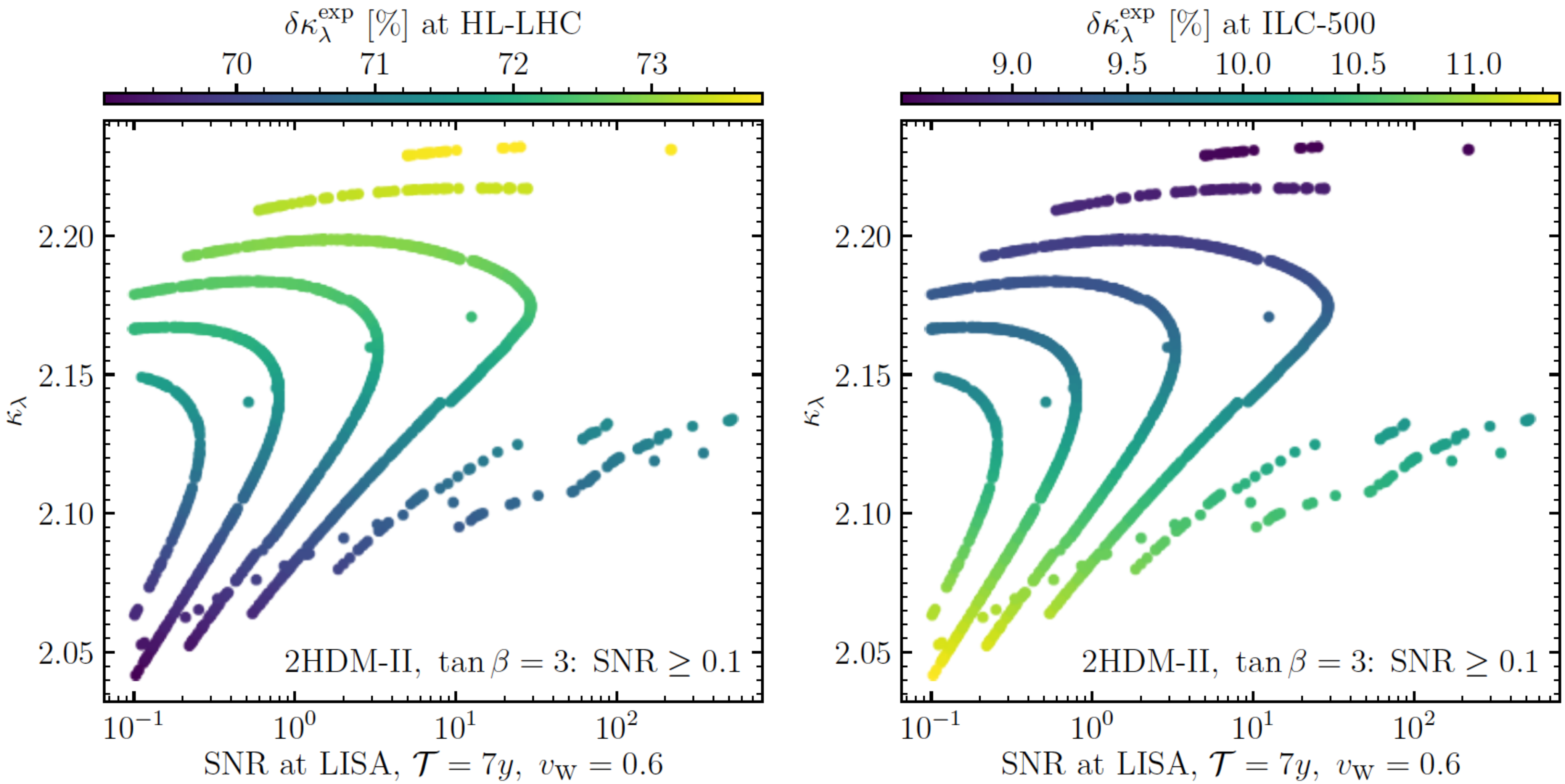


⇒ over most of the parameter space ILC is clearly superior to HL-LHC

Example: 2HDM ⇒ FOEWPT ⇒ GW's

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

⇒ Synergies: collider: λ_{hhh} ⇔ LISA: GW signals



⇒ FOEWPT requires large λ_{hhh} and can induce GW signals

Accessing BSM THCs in the 2HDM at ILC500:

[*taken from F. Arco '24*]

Parameter scan in the 2HDM (all types):

[*F. Arco, S.H., M. Mühlleitner - PRELIMINARY*]

-

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

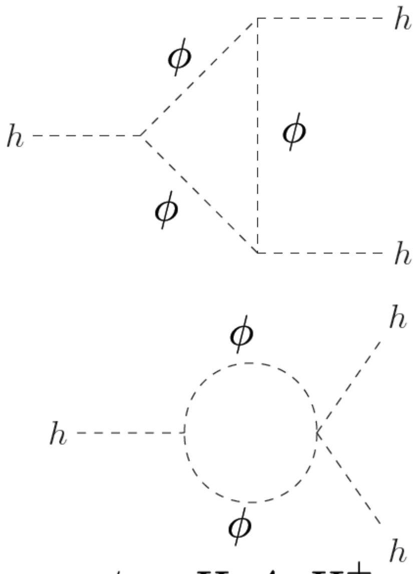
[ScannerS + HiggsTools + HDECAY]

Concrete example: 2HDM:

[*taken from F. Arco '24*]

Parameter scan in the 2HDM (all types):

[*F. Arco, S.H., M. Mühlleitner - PRELIMINARY*]



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

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]
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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]

(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!

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

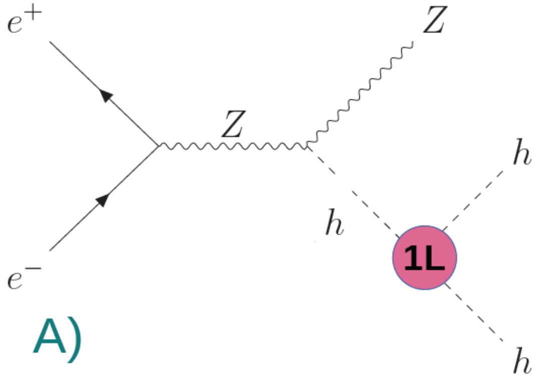
Effects from THCs at $e^+e^- \to hhZ$

Karlsruhe Institute of Technology

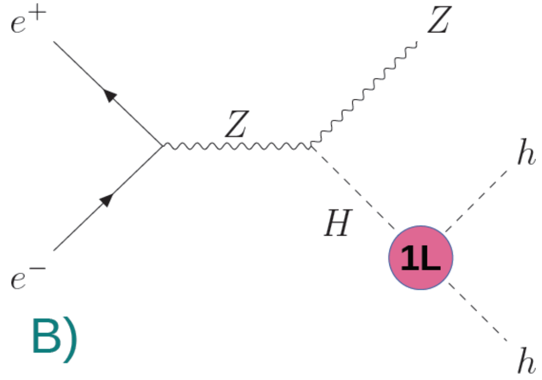
A) **Non-resonant** diagram
with κ_λ → at low m_{hh}

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

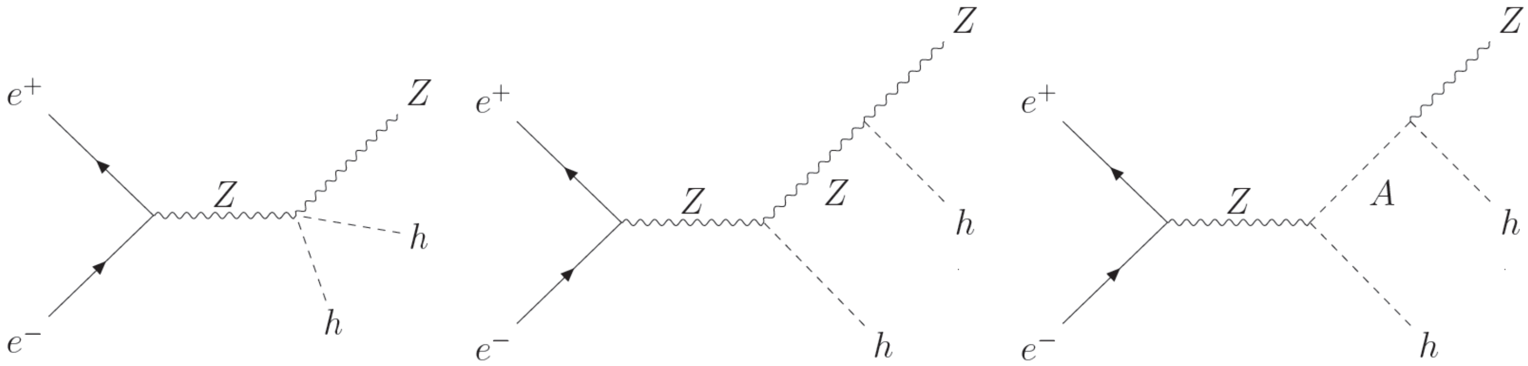
C) Resonant A diagram
(no THC)



A)



B)



C)

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[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

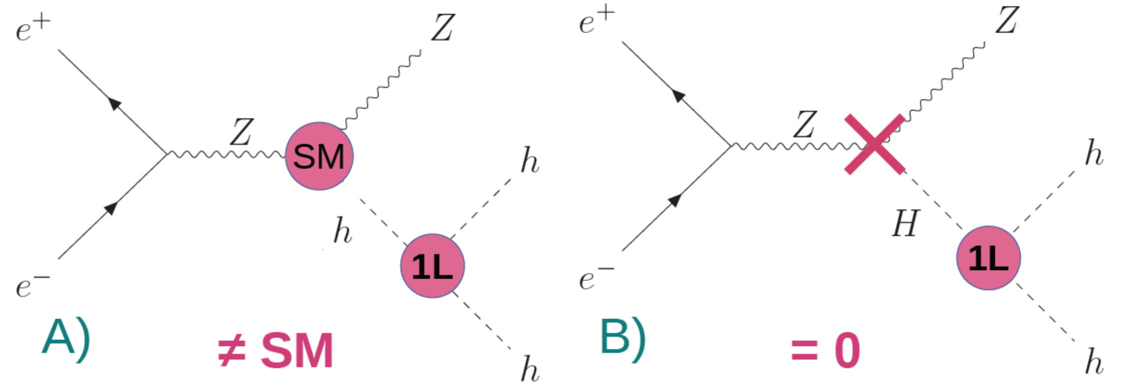
In the alignment limit ($c_{\beta-\alpha}=0$)

A) **Non-resonant** diagram
wit… h

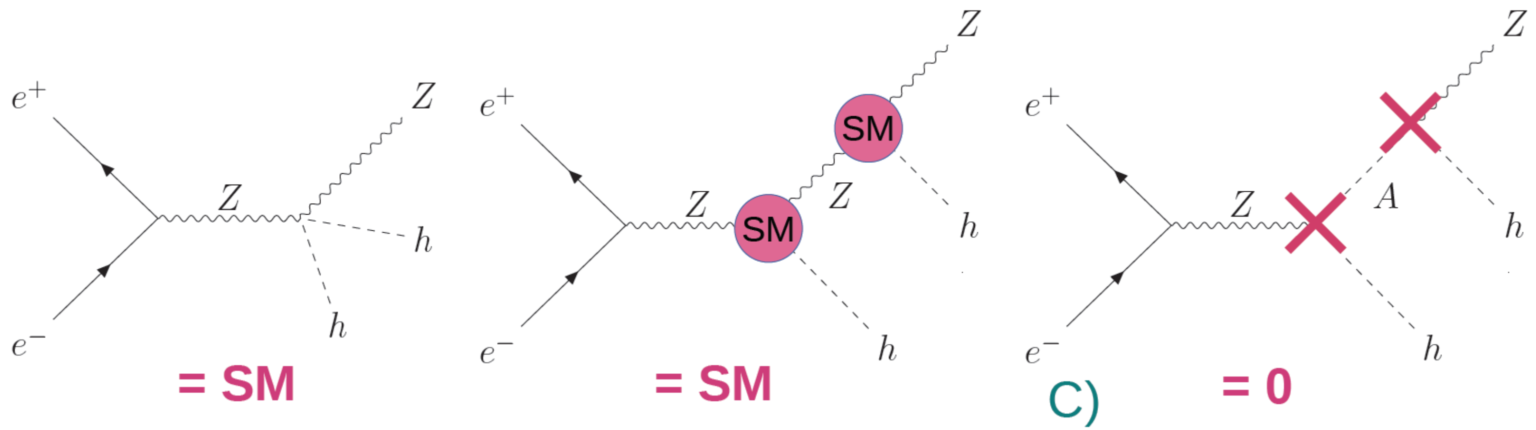
B) **R**… am
wit… $\simeq m_H$

C) R… diagram
(no THC)

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



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



[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

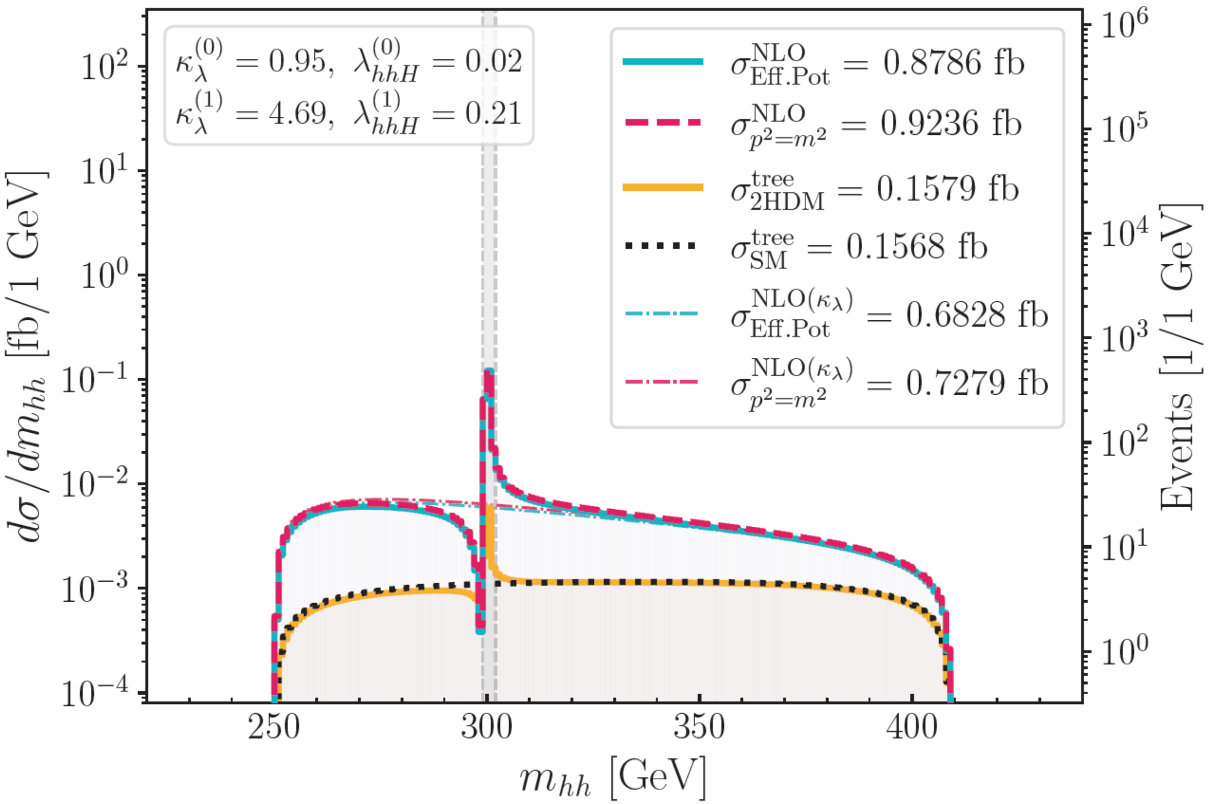
Large 1L λ_{hhH} @ILC500GeV

BPlahhH-1, type I

$m_H = \bar{m} = 300$ GeV,

$m_A = m_{H^\pm} = 650$ GeV,

$\tan\beta = 12, \ \cos(\beta - \alpha) = 0.12$



- Large effect from $\kappa_\lambda^{(1)}$
- For this point $\lambda_{hhH}^{(0)} \ll \lambda_{hhH}^{(1)}$

  $\Rightarrow$ the H resonance is more prominent

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$\Rightarrow$ individual effects of $\lambda_{hhh}^{(1)}$ and $\lambda_{hhH}^{(1)}$ $\Rightarrow$ extraction possible? $\Rightarrow$ WIP

Effects on THC determination at the ILC:

[taken from F. Arco '24]

[F. Arco, S.H., M. Mühlleitner - PRELIMINARY]

1L λ_{hhH} with different sign @ILC500

Karlsruhe Institute of Technology

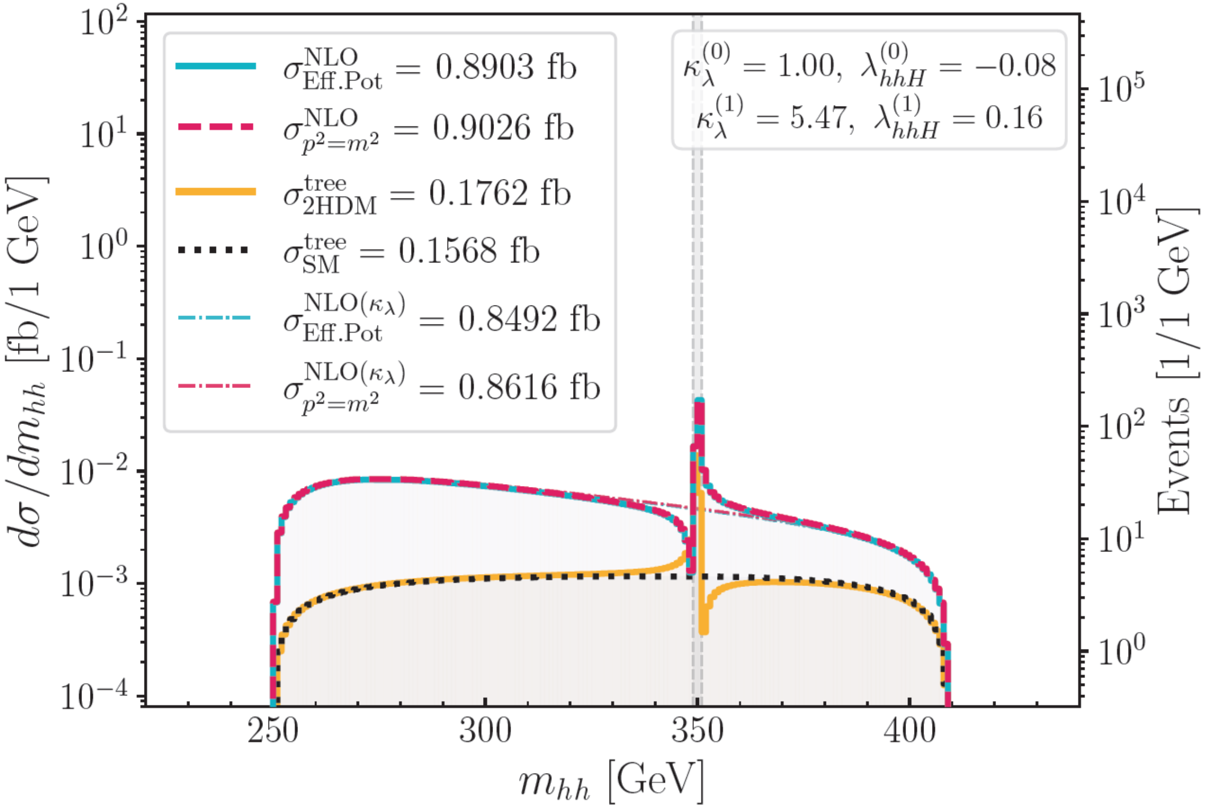
BPsign, type I

$m_H = \bar{m} = 350$ GeV,

$m_A = m_{H^\pm} = 650$ GeV,

$\tan\beta = 20,\ \cos(\beta - \alpha) = 0.1$

- In this point: $\text{sign}\left(\lambda^{(1)}_{hhH}\right) \neq \text{sign}\left(\lambda^{(0)}_{hhH}\right)$
- $\Rightarrow$ changes the dip-peak structure of the resonance !
- Large effect from $\kappa_\lambda^{(1)}$



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$\Rightarrow$ individual effects of $\lambda^{(1)}_{hhh}$ and $\lambda^{(1)}_{hhH}$ $\Rightarrow$ extraction possible? $\Rightarrow$ WIP

4. Conclusions

- Triple Higgs couplings are in the focus of current and future colliders
  $\Rightarrow$ focus so far on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$
  BSM case 1: $\kappa_\lambda \neq 1$
  BSM case 2: THC that involves BSM Higgses: $\lambda_{hhH}, \ldots$

  $\Rightarrow$ Both can have a strong impact on $\sigma(gg \to hh)$ and m_{hh}

- BSM model: 2HDM: spectrum: h, H, A, $H^\pm$ with λ_{hhh}, $\lambda_{hhH}, \ldots$
  $\Rightarrow$ large one-loop corrections to κ_λ of 100% . . . 1000%

- Experimental searches for resonant di-Higgs production:

  $\Rightarrow$ exp. analyses leave out interferences with non-res. diagrams
  $\Rightarrow$ strong impact on m_{hh} $\Rightarrow$ results not reliable

- κ_λ in the 2HDM:

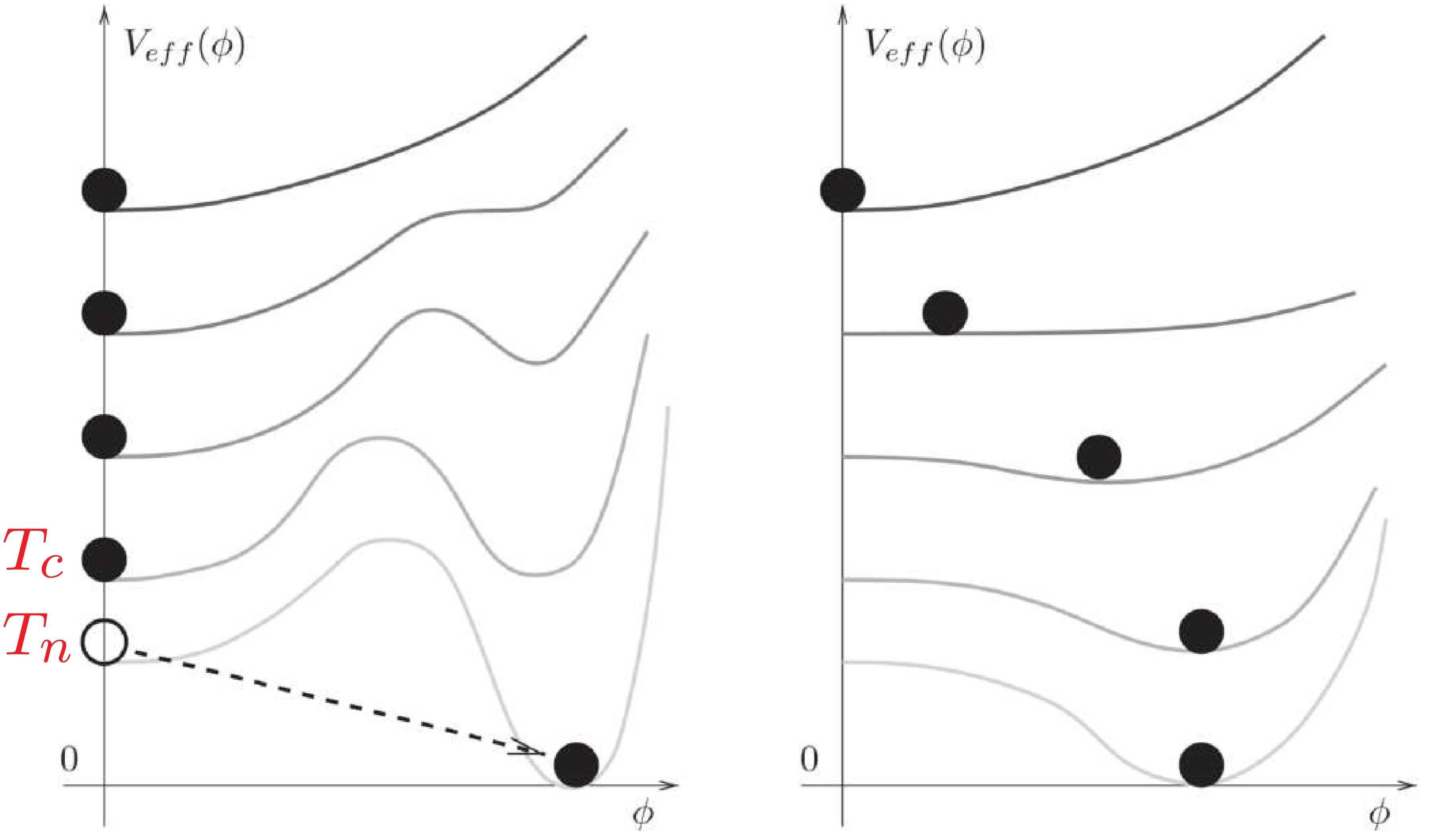
  $\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$ $\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$
  $\Rightarrow$ bad for HL-LHC ($\delta\lambda_{hhh} \sim 70\%$), good for ILC500 ($\delta\lambda_{hhh} \sim 10\%$)

- BSM THCs in the 2HDM: $\Rightarrow$ FOEWPT requires $m_H \lesssim 800$ GeV

  $\Rightarrow$ ILC500, ILC1000 are unique laboratories to study these scenarios
  $\Rightarrow$ extraction of λ_{hhH} appears possible $\Rightarrow$ WIP


Further Questions?

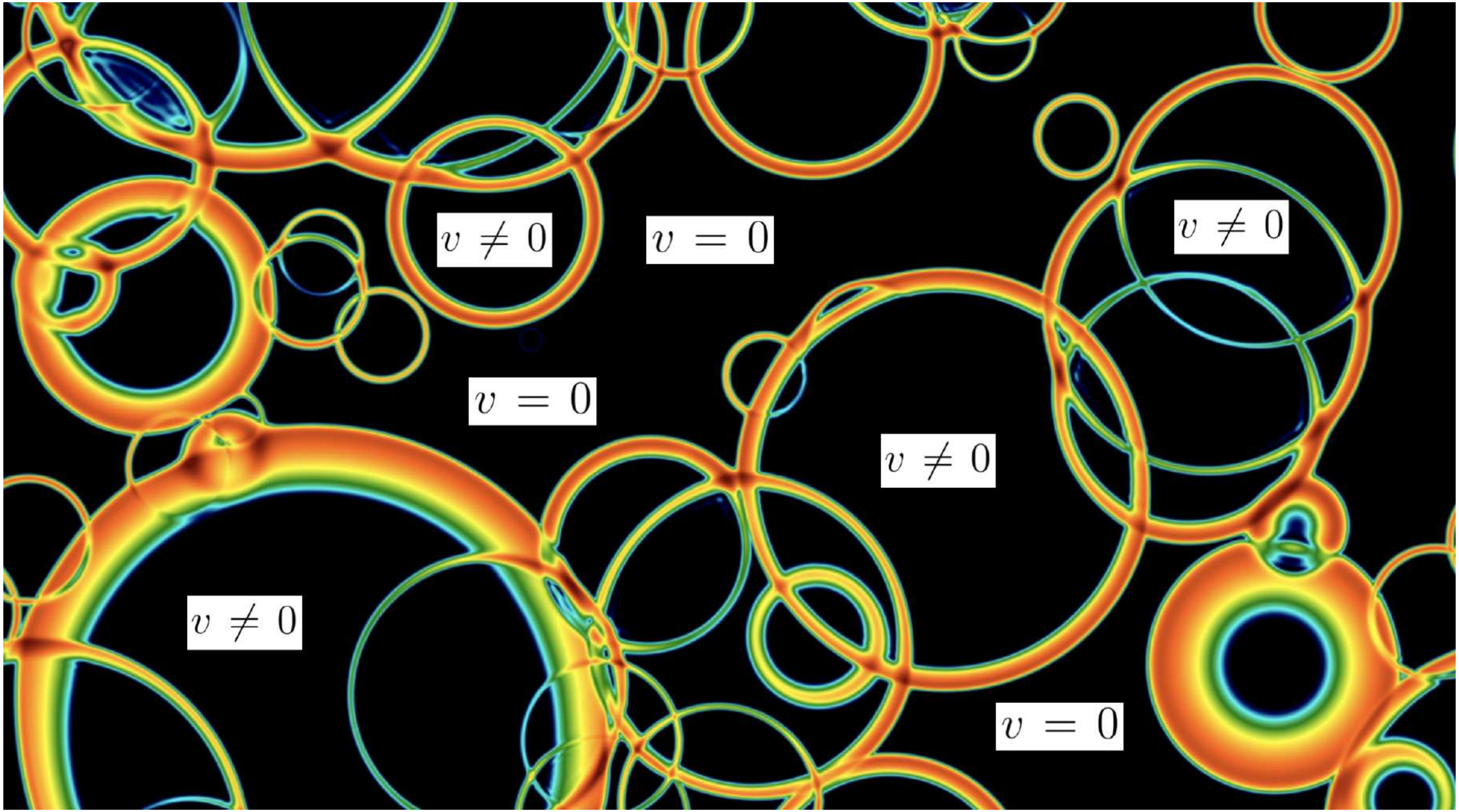
[*taken from V. A. Rubakov and D. S. Gorbunov*]



$\Rightarrow$ BSM Higgs sector required to realized FOEWPT

Bubble formation can lead to Gravitational Waves

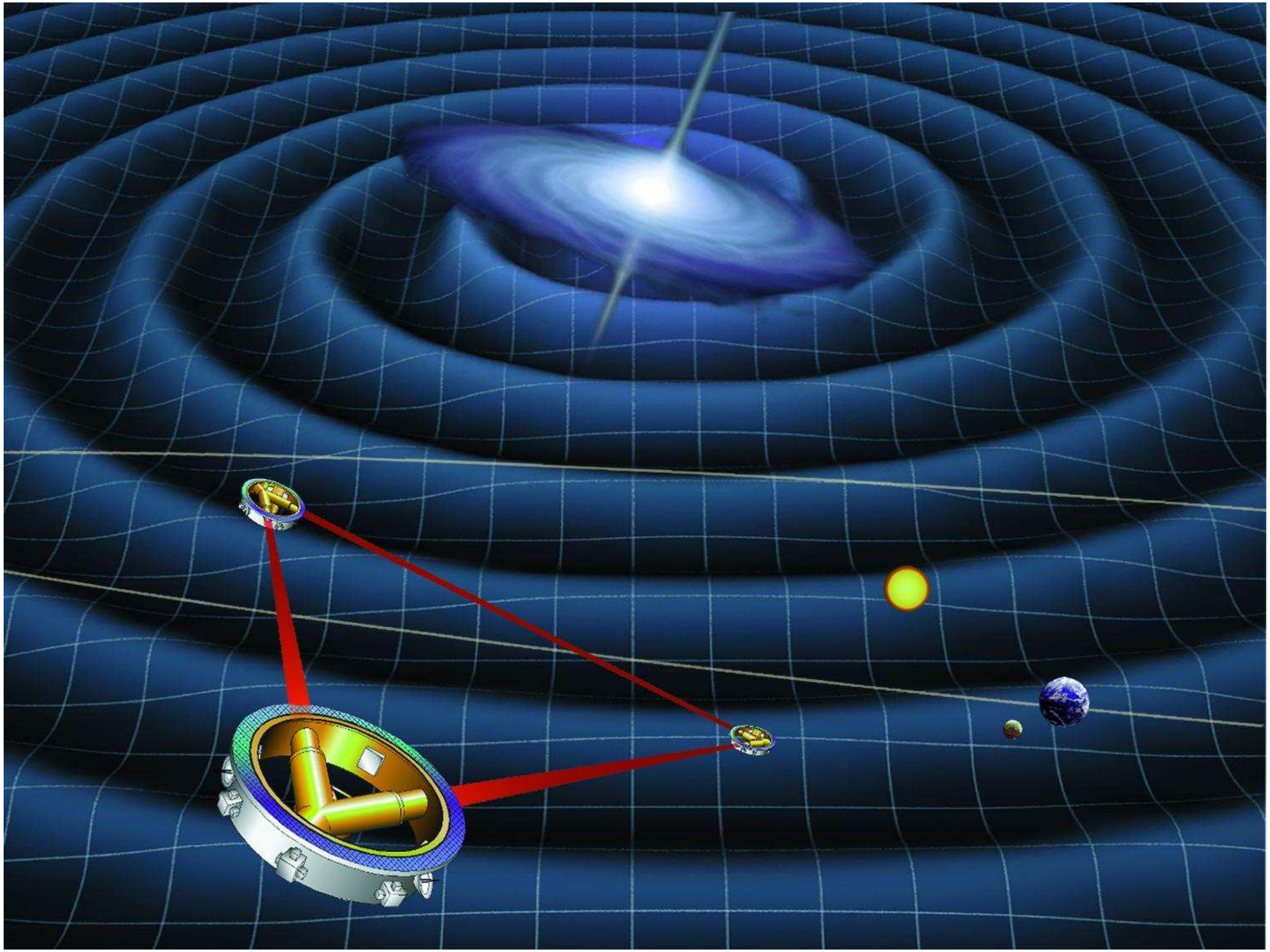
[*taken from D. Weir*]



⇒ Can this happen in the 2HDM? Implications for THCs?

GW observatory: LISA

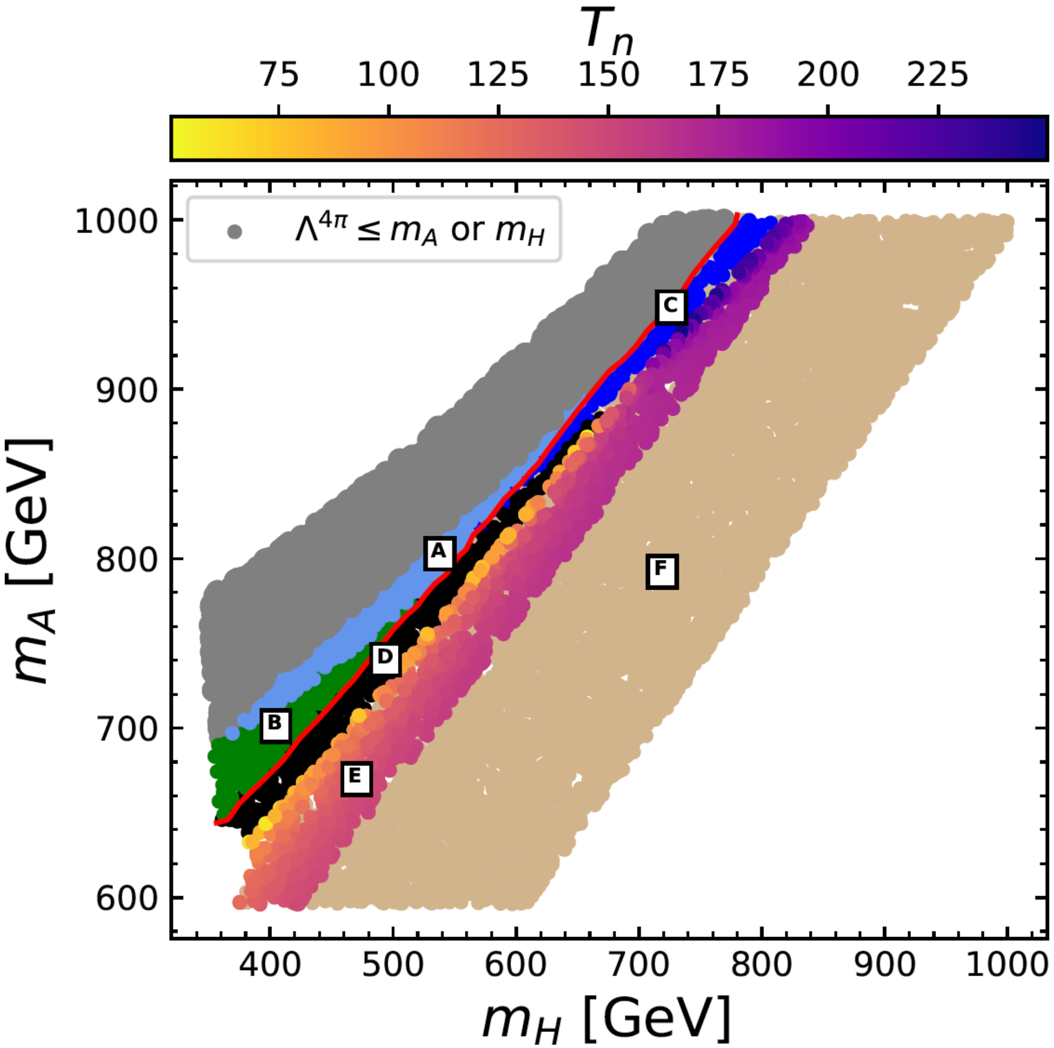
[*NASA*]



Approved launch date: $\sim$ 2035

Six thermal histories in the 2HDM:

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

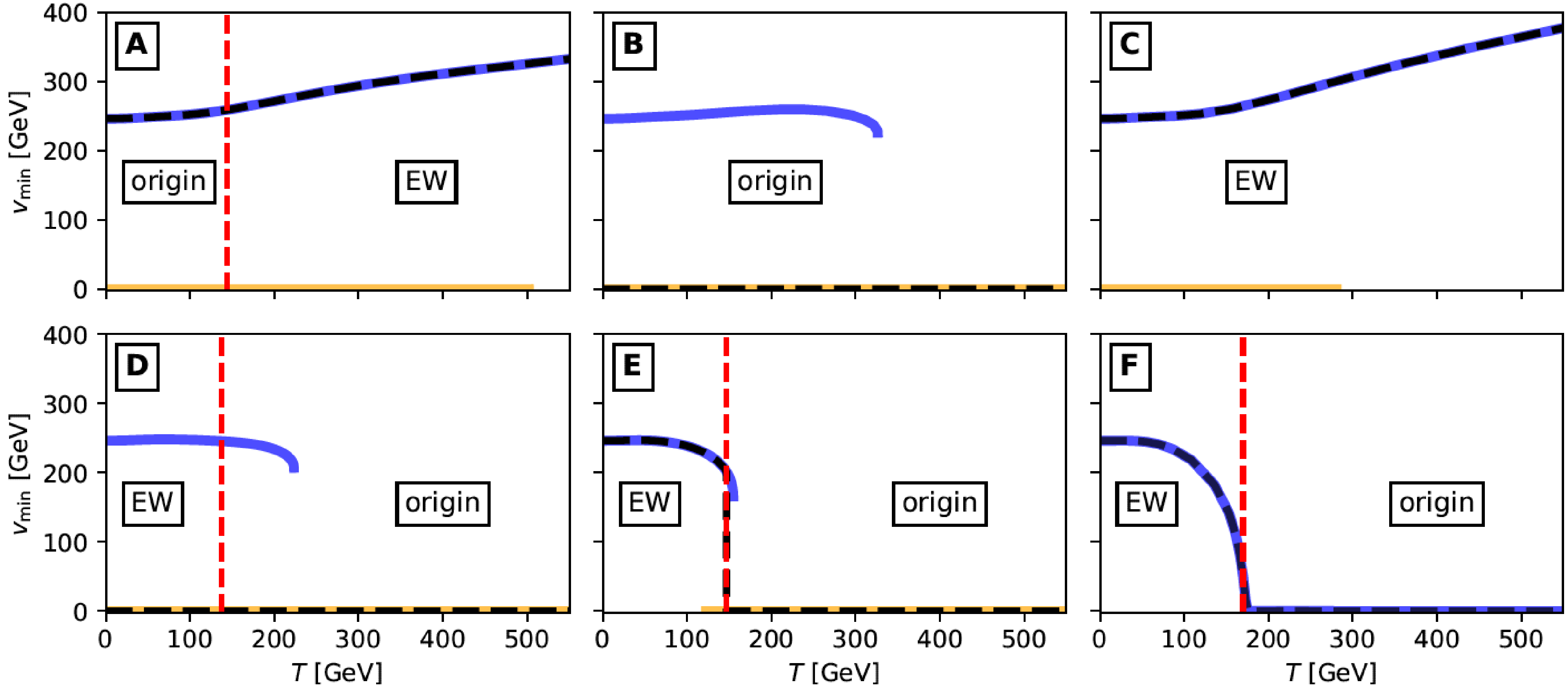


E: viable for FOEWPT, GWs are induced (detectable?)

F: no FOEWPT, no GWs are induced

Six thermal histories in the 2HDM:

[T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22]



⇒ Zone E preferred by phenomenology/FOEWPT