
WILL EXPLAIN
HIGGS-BOSON
PARTICLE
FOR
FOOD
HM

# FOEWPT, THCs and GWs in the 2HDM

*Sven Heinemeyer, IFT (CSIC, Madrid)*

Nanjing/zoom, 05/2024

# 1. Introduction

# 1. Introduction

# 1. Introduction


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

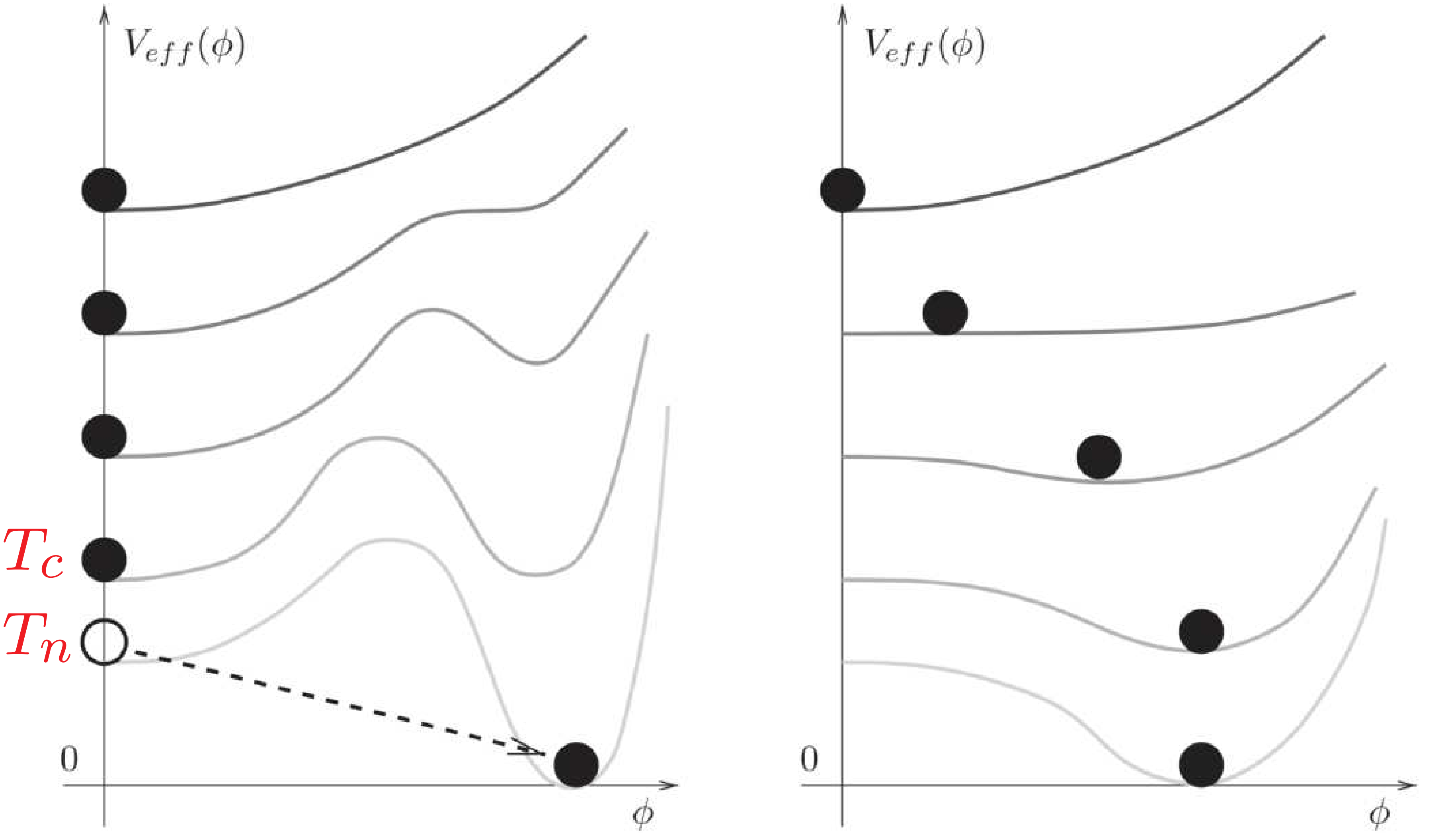
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

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

# Phase transition: BSM vs. SM

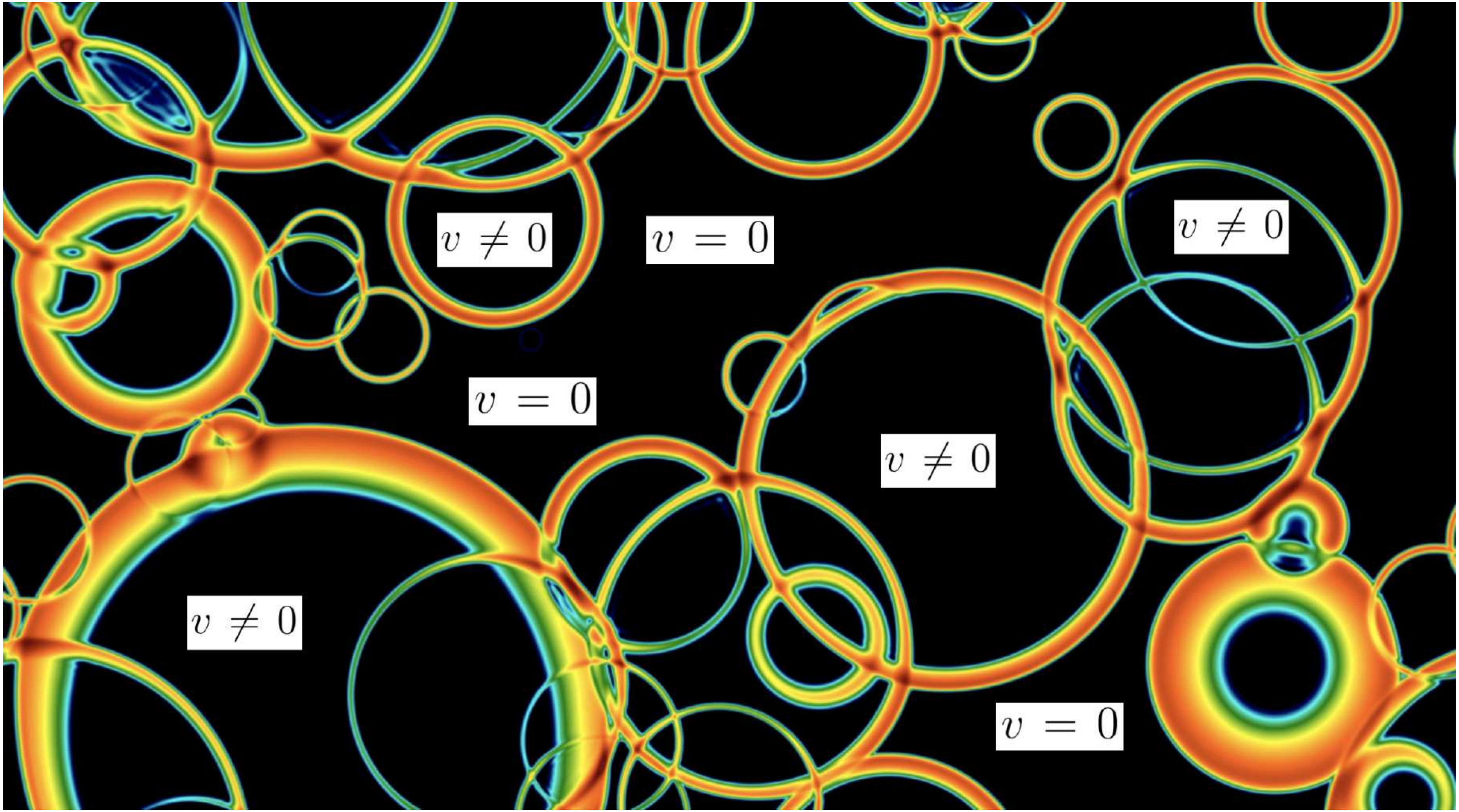
[*taken from V. A. Rubakov and D. S. Gorbunov*]




⇒ BSM Higgs sector required to realized FOEWPT

# Bubble formation can lead to Gravitational Waves

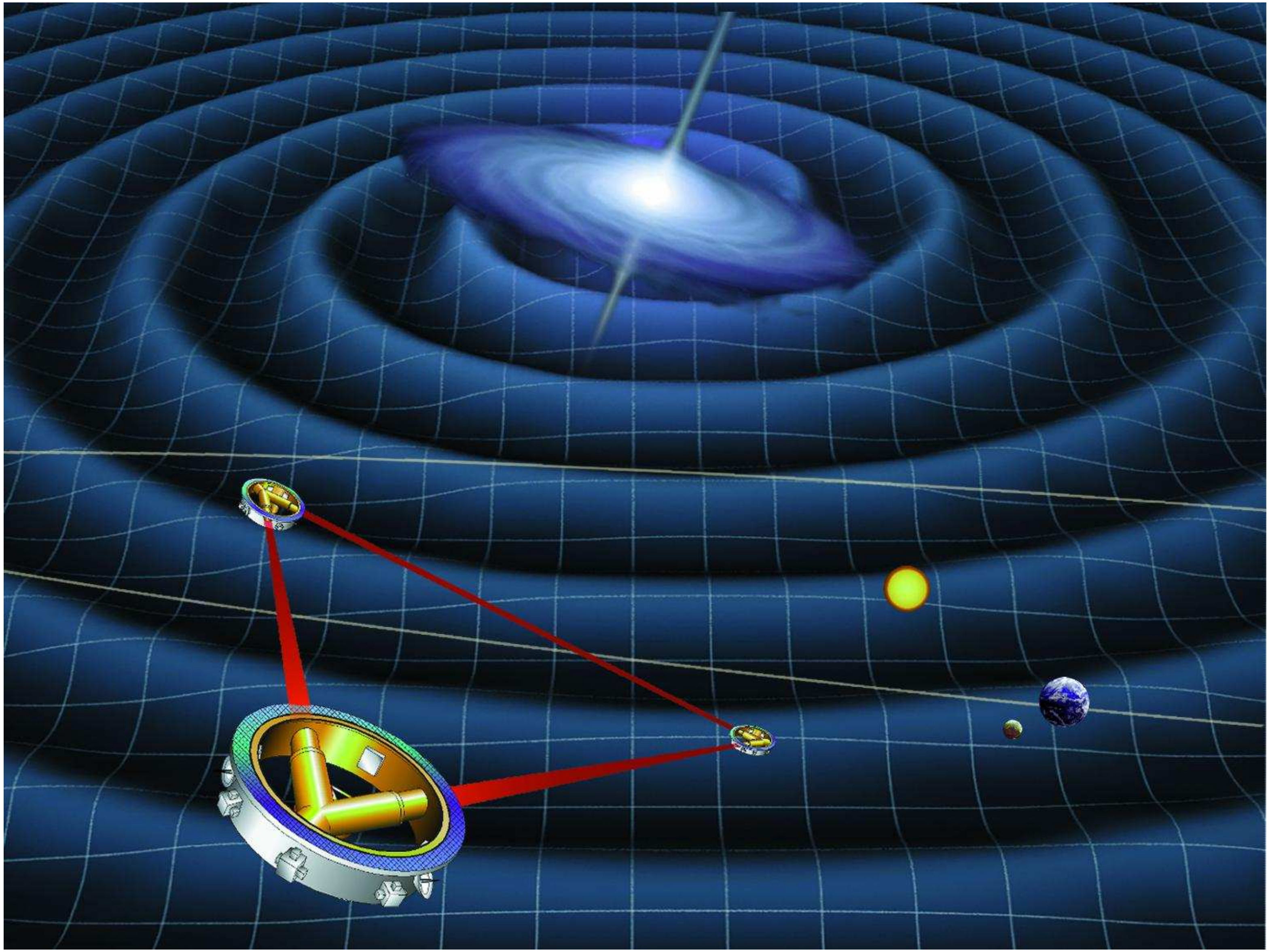
[*taken from D. Weir*]




$\Rightarrow$ Can this happen in the 2HDM? Implications for THCs?

# GW observatory: LISA

[*NASA*]



Approved launch date: $\sim$ 2035

## 2. FOEWPT and GWs in the 2HDM

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: $\lambda_{hhh}$, $\lambda_{hhH}$, $\lambda_{hHH}$, $\lambda_{hH^+H^-}$, $\lambda_{HAA}$, ...

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 | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ | |
| type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ | $\to$ SUSY type |
| type III (lepton-specific) | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ | |
| type IV (flipped) | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ | |

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

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

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

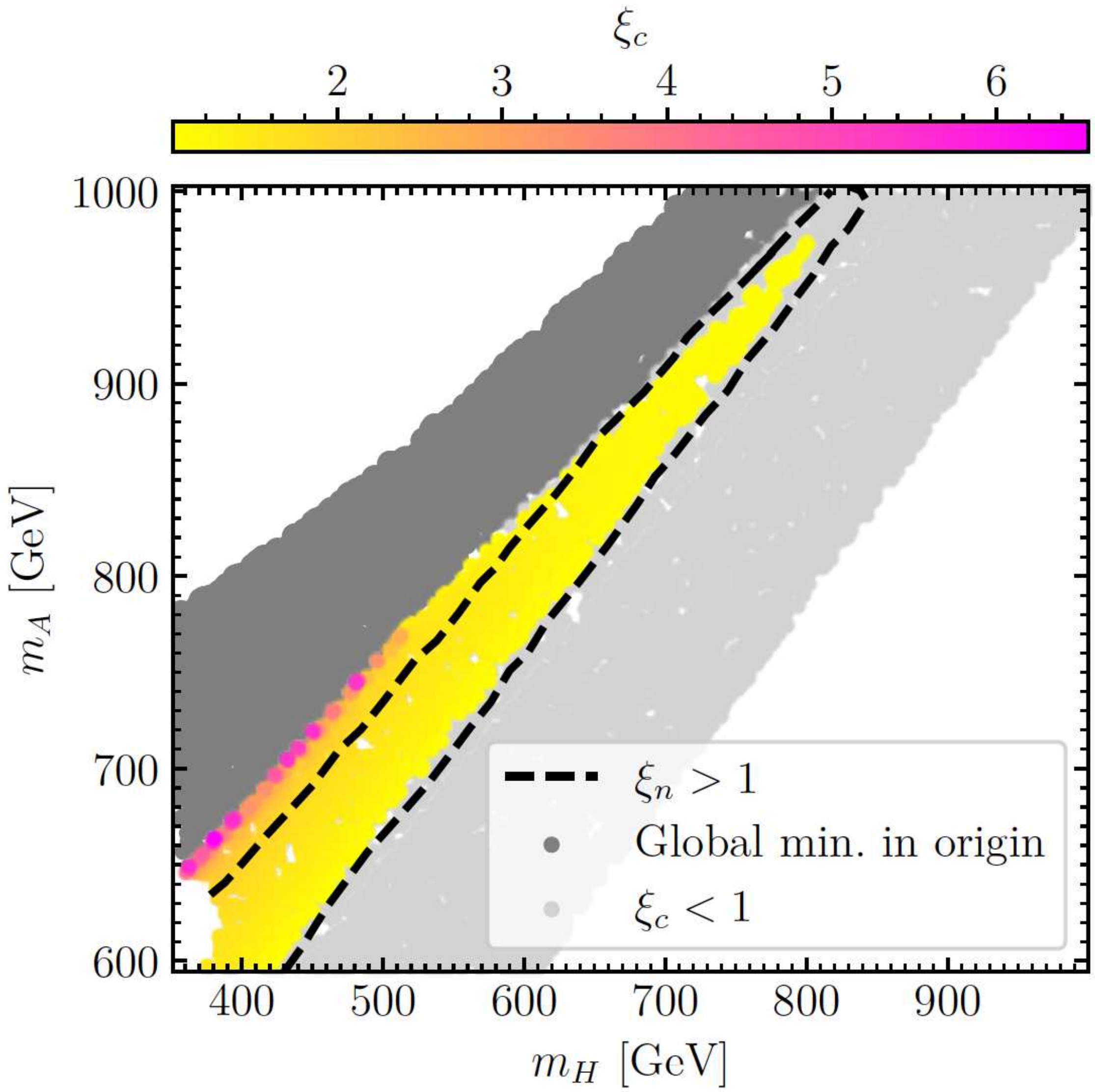
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\leq m_H \leq$ 1 TeV, 0.6 TeV $\leq m_A = m_{H^\pm} \leq$ 1.2 TeV

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($B_s \to X_s\gamma$), $\Delta M_{B_s}$) $\Rightarrow$ SuperIso bounds
- Electroweak precision data ($T$ and $S$) $\Rightarrow$ ScannerS
- $\lambda_{hhh}$ at one-loop $\Rightarrow$ BSMPT

# FOEWPT/GWs in the 2HDM: $\xi_c := v_c/T_c \gtrsim 1$

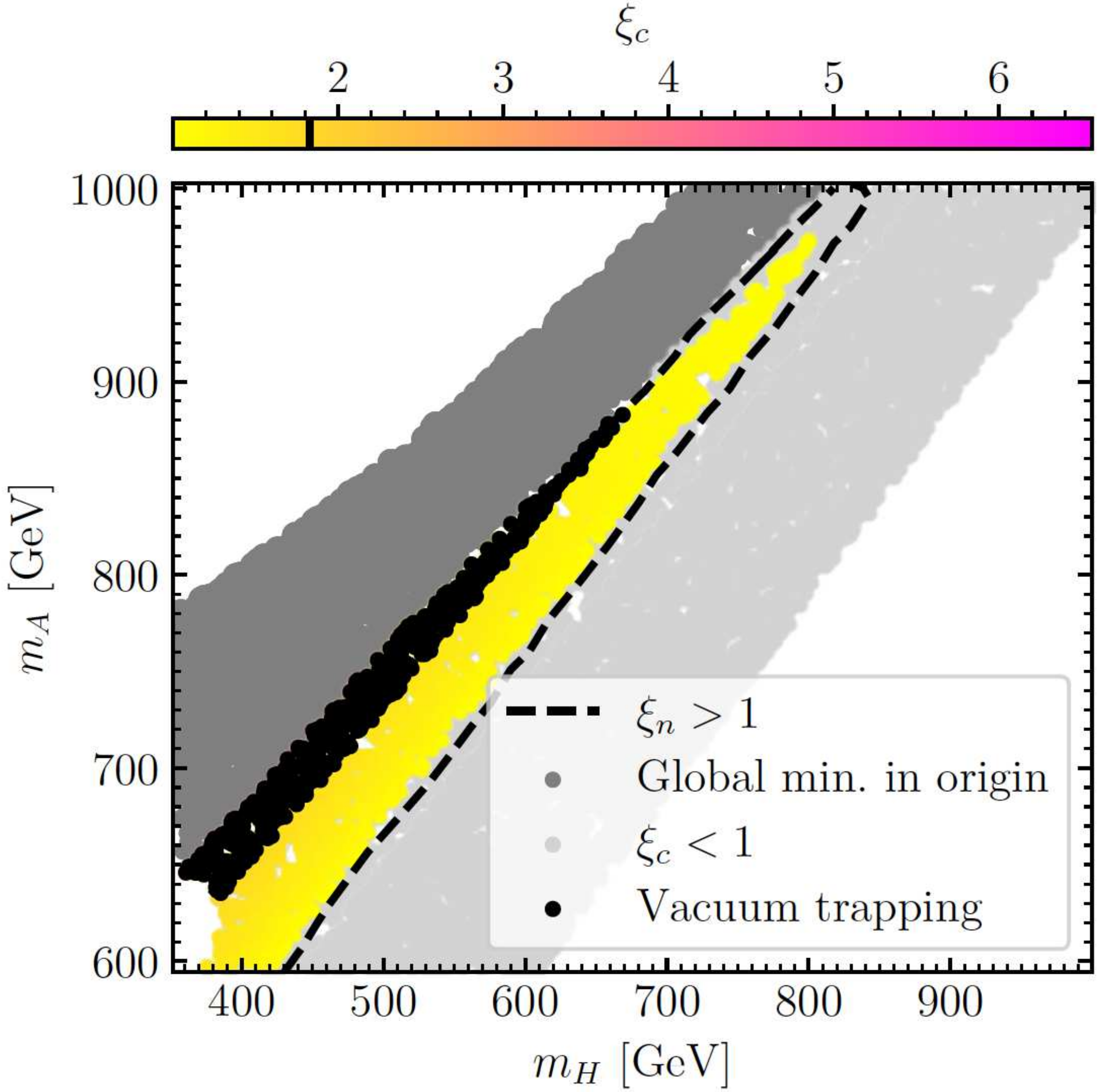
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]




$\Rightarrow$ large $\xi_c$ found in the 2HDM $\Rightarrow$ strong GW signal?

# FOEWPT/GWs in the 2HDM: $\xi_n := v_n/T_n \gtrsim 1$

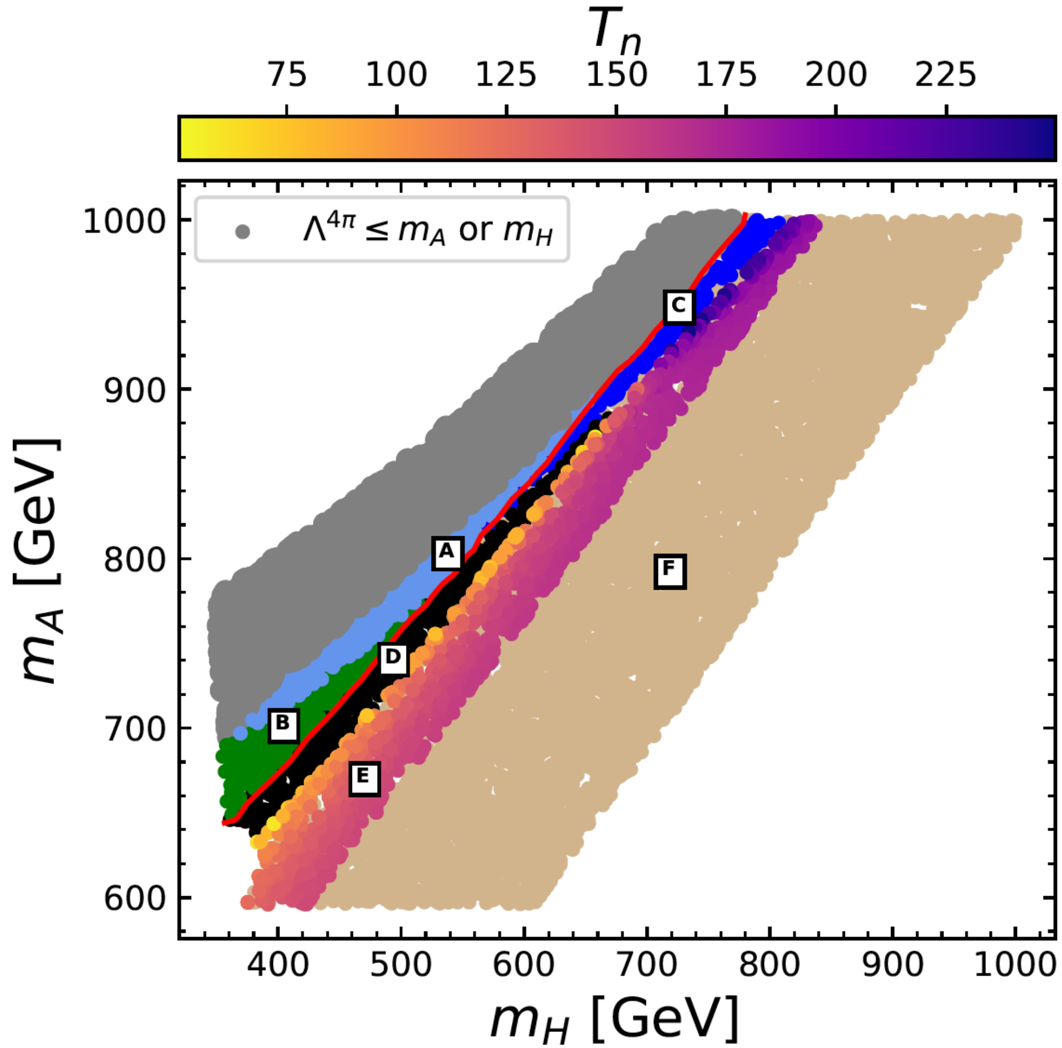
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]




⇒ potentially strongest GW signal: forbidden by vacuum trapping

# Six thermal histories in the 2HDM:

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

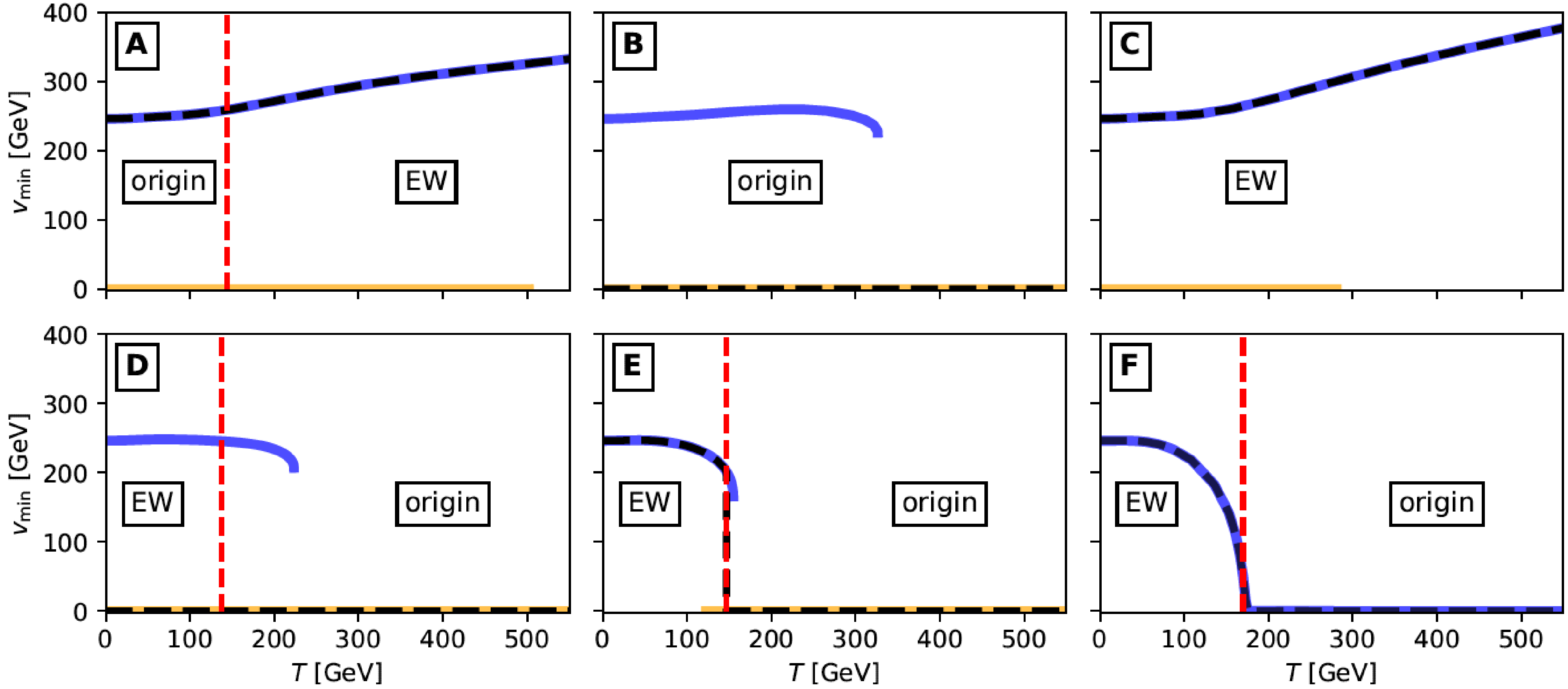



E: viable for FOEWPT, GWs are induced (detectable?)

F: no FOEWPT, no GWs are induced

# Six thermal histories in the 2HDM:

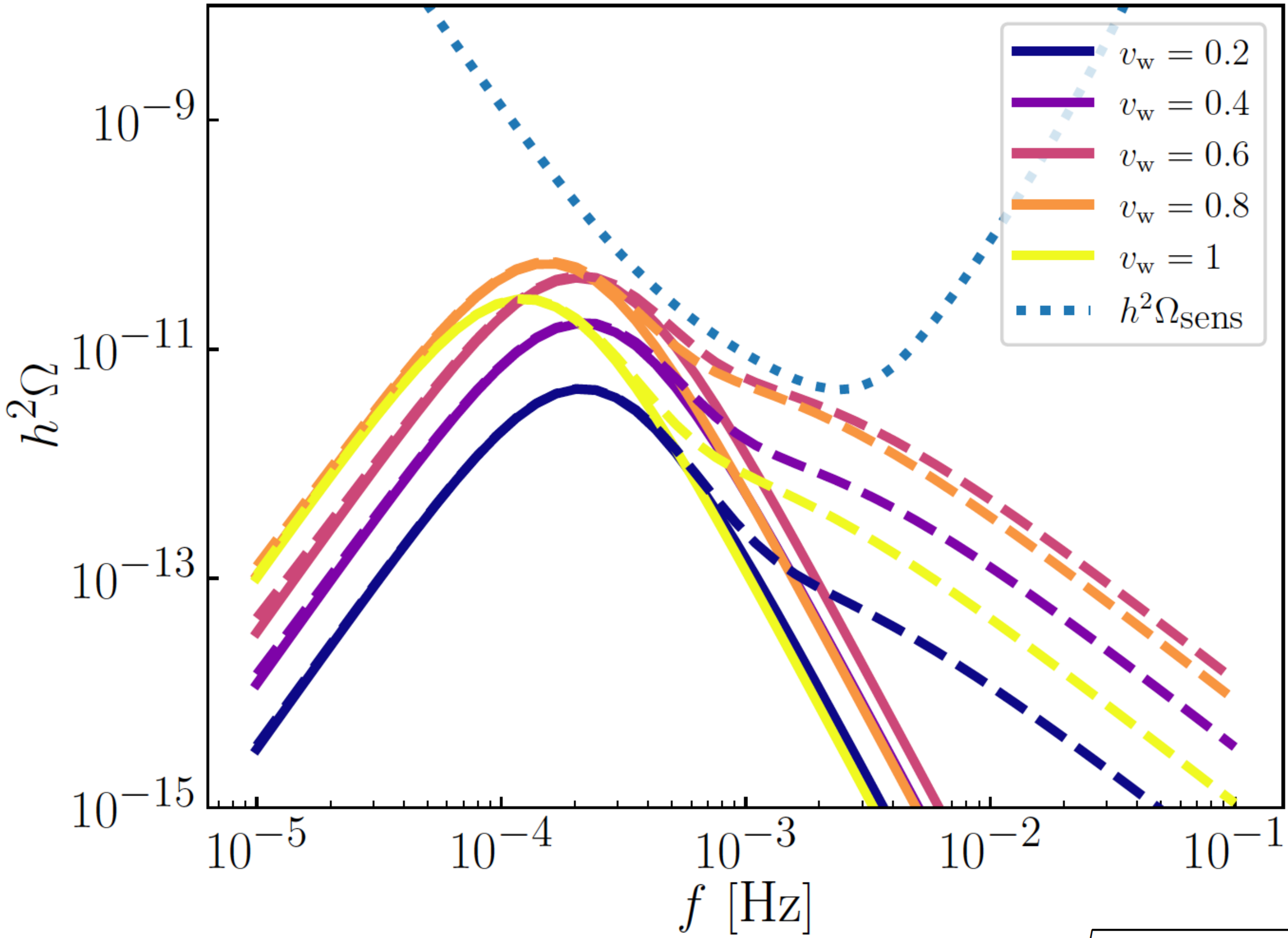
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]




⇒ Zone E preferred by phenomenology/FOEWPT

# GWs vs. LISA: ($m_H = 419$ GeV, $m_A = m_{H^\pm} = 663$ GeV)

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

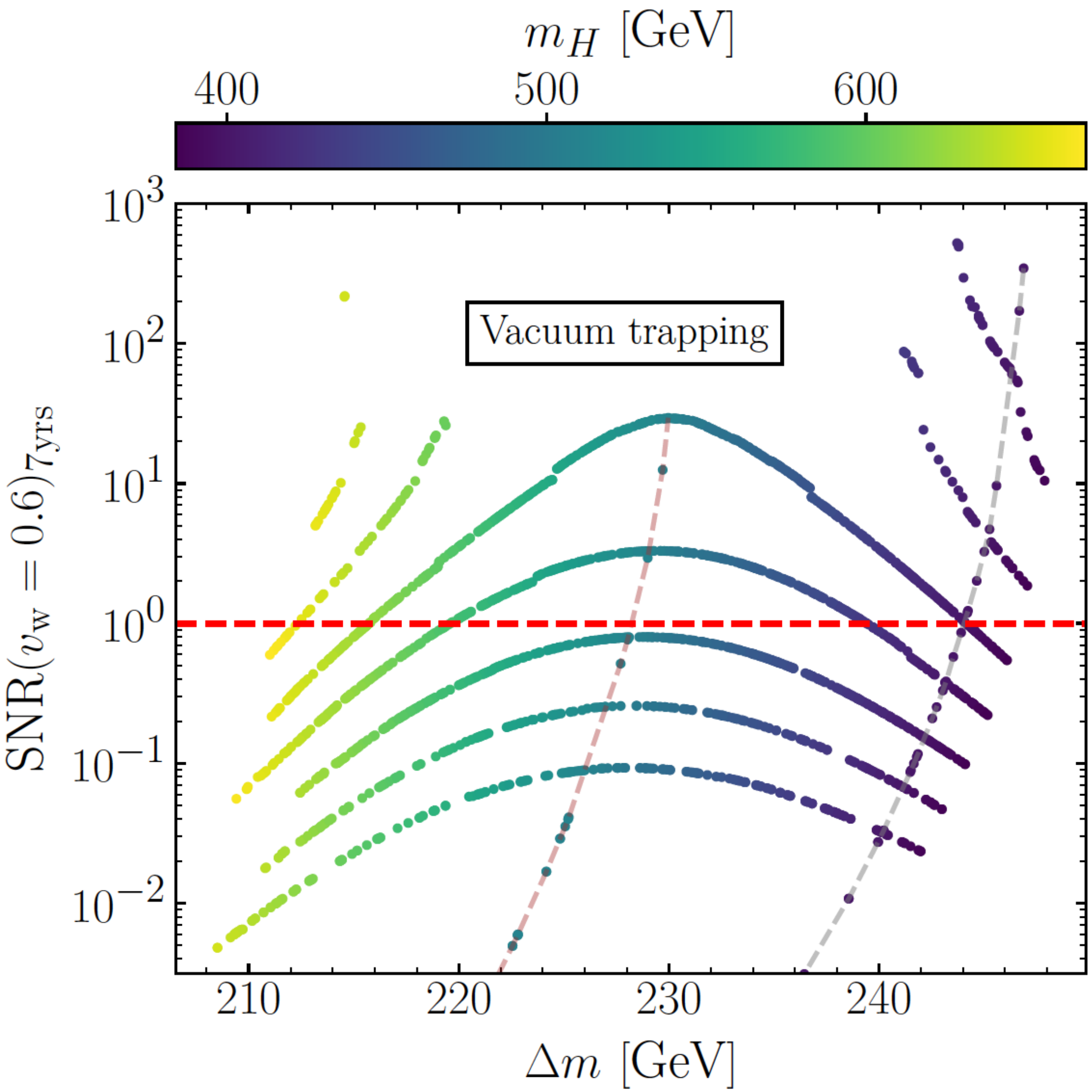



$$\mathrm{SNR} = \sqrt{\mathcal{T} \int_{-\infty}^{+\infty} \mathrm{d}f \left[\frac{h^2\Omega_{\mathrm{GW}}(f)}{h^2\Omega_{\mathrm{Sens}}(f)}\right]^2}$$

⇒ bubble wall velocity and turbulence important

## GWs vs. LISA: ($v_W = 0.6$, 7 years of LISA data)

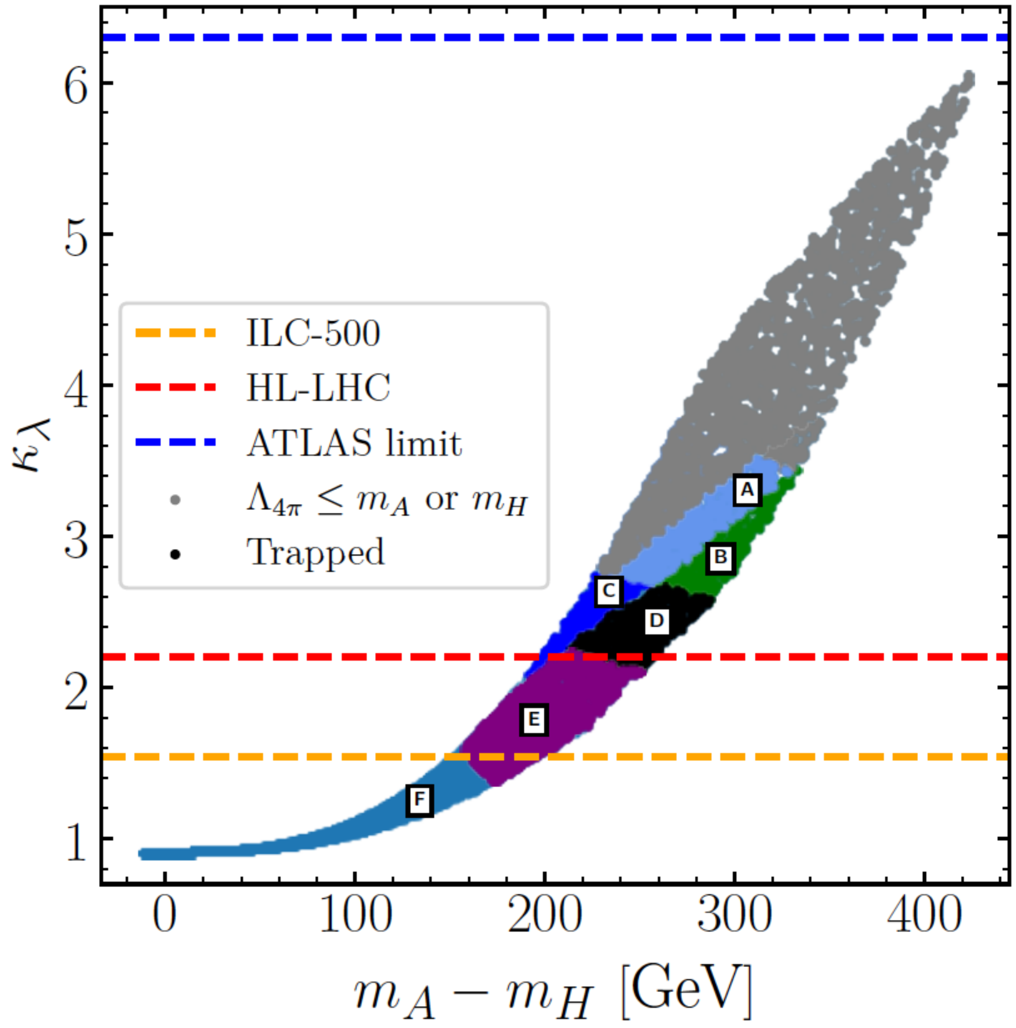
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

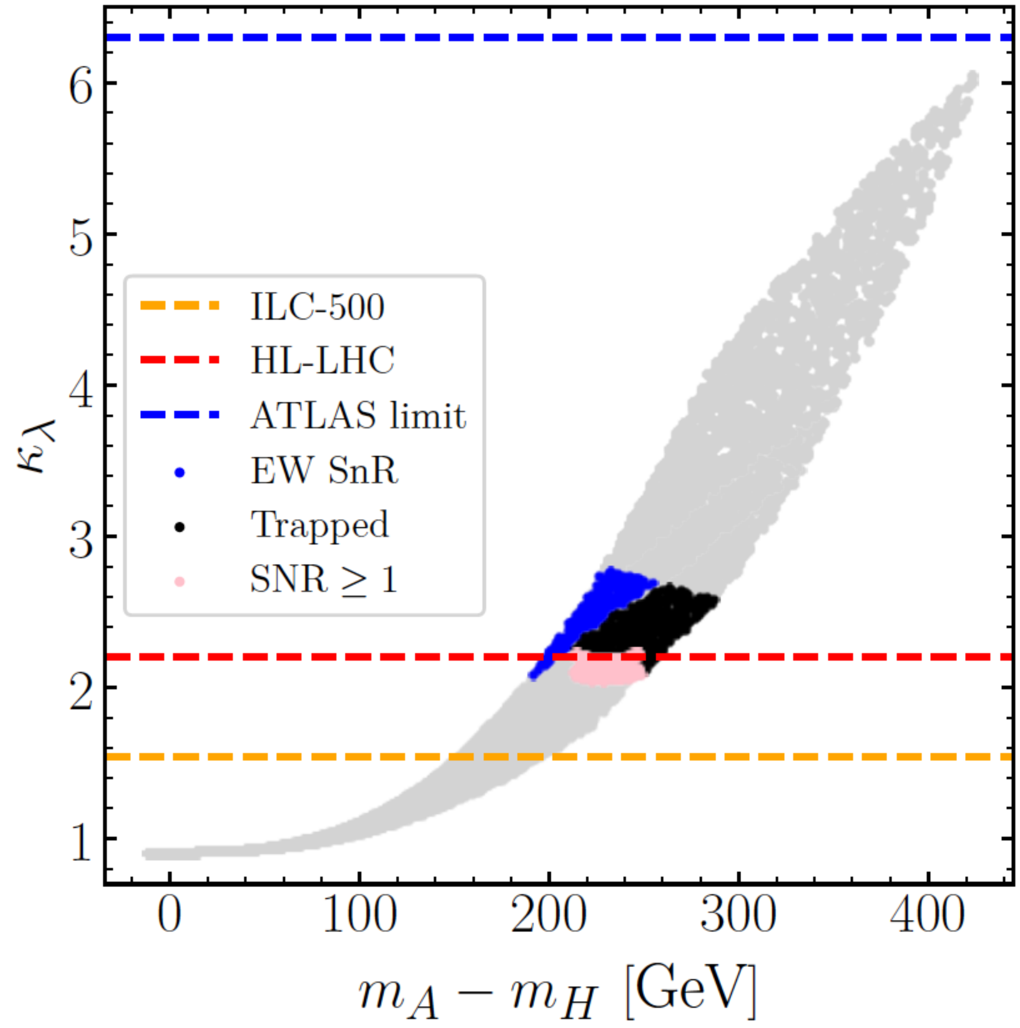



⇒ detectable GWs only in a very small zone close to VT

# 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*]



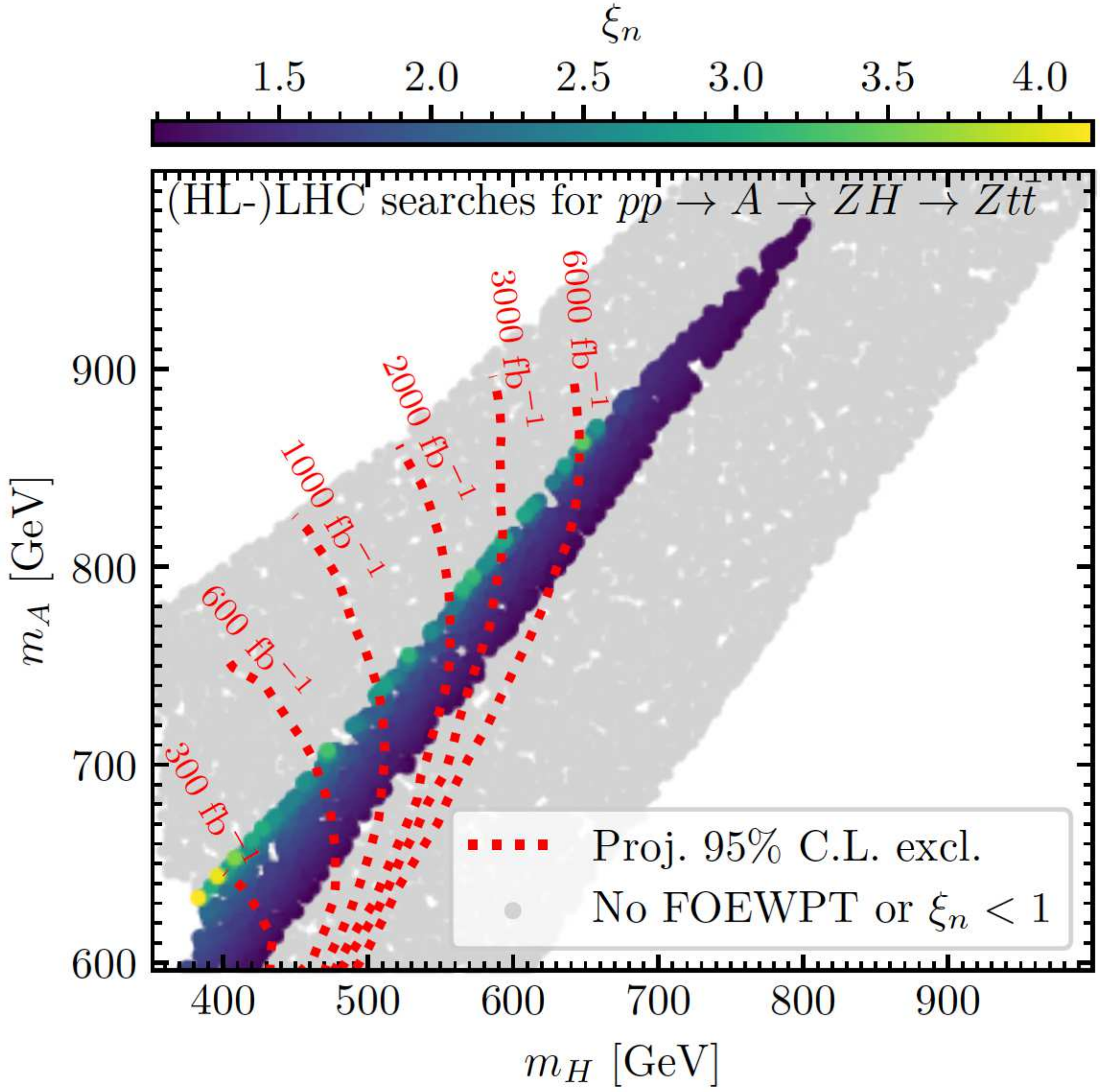




$\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$ and $m_A - m_H \sim 200$ GeV

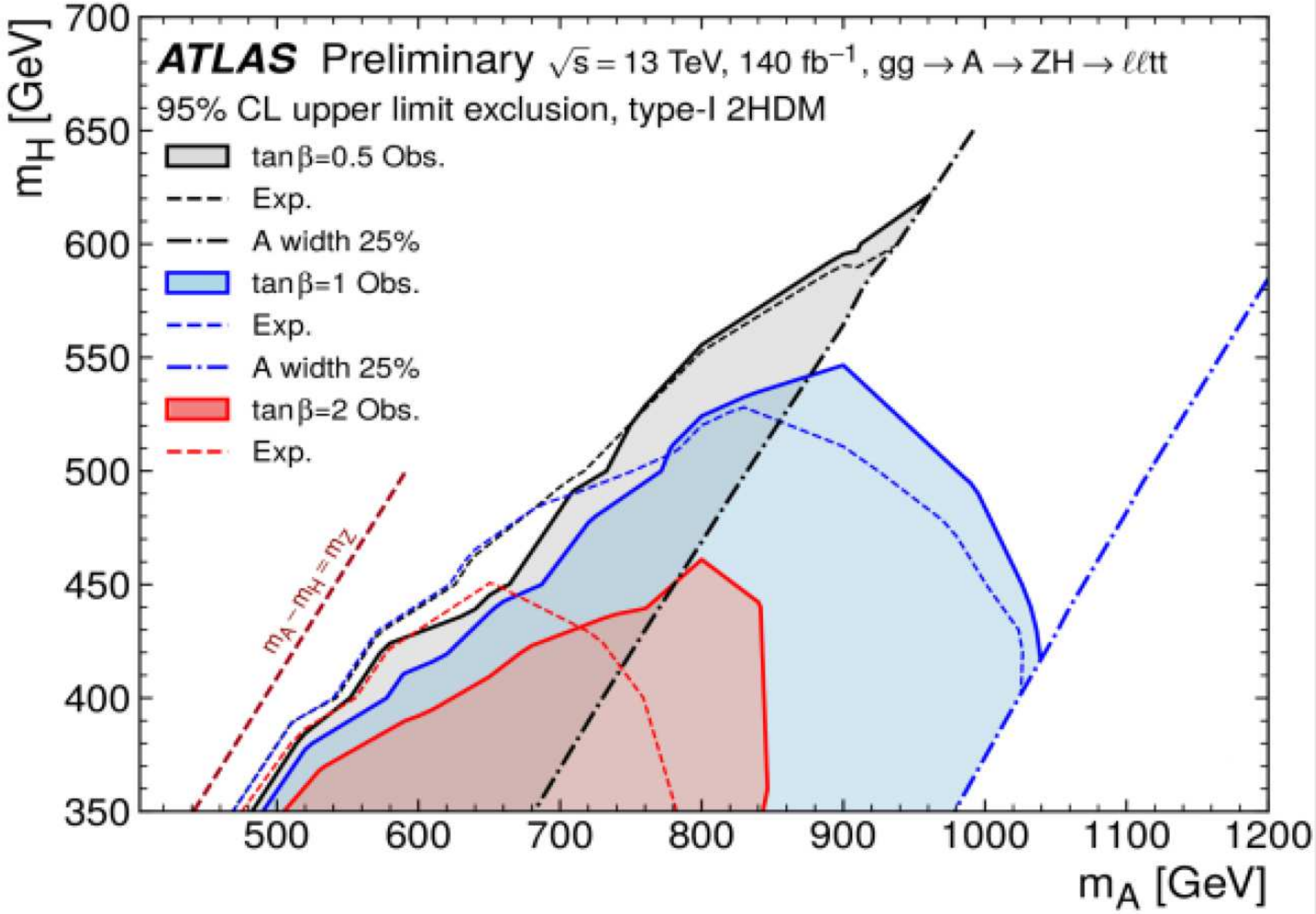
$\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$ and $m_A - m_H \gtrsim 200$ GeV

## Smoking gun signature: gap between $m_A$ and $m_H$: $pp \to A \to ZH \to Z\,t\bar{t}$

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



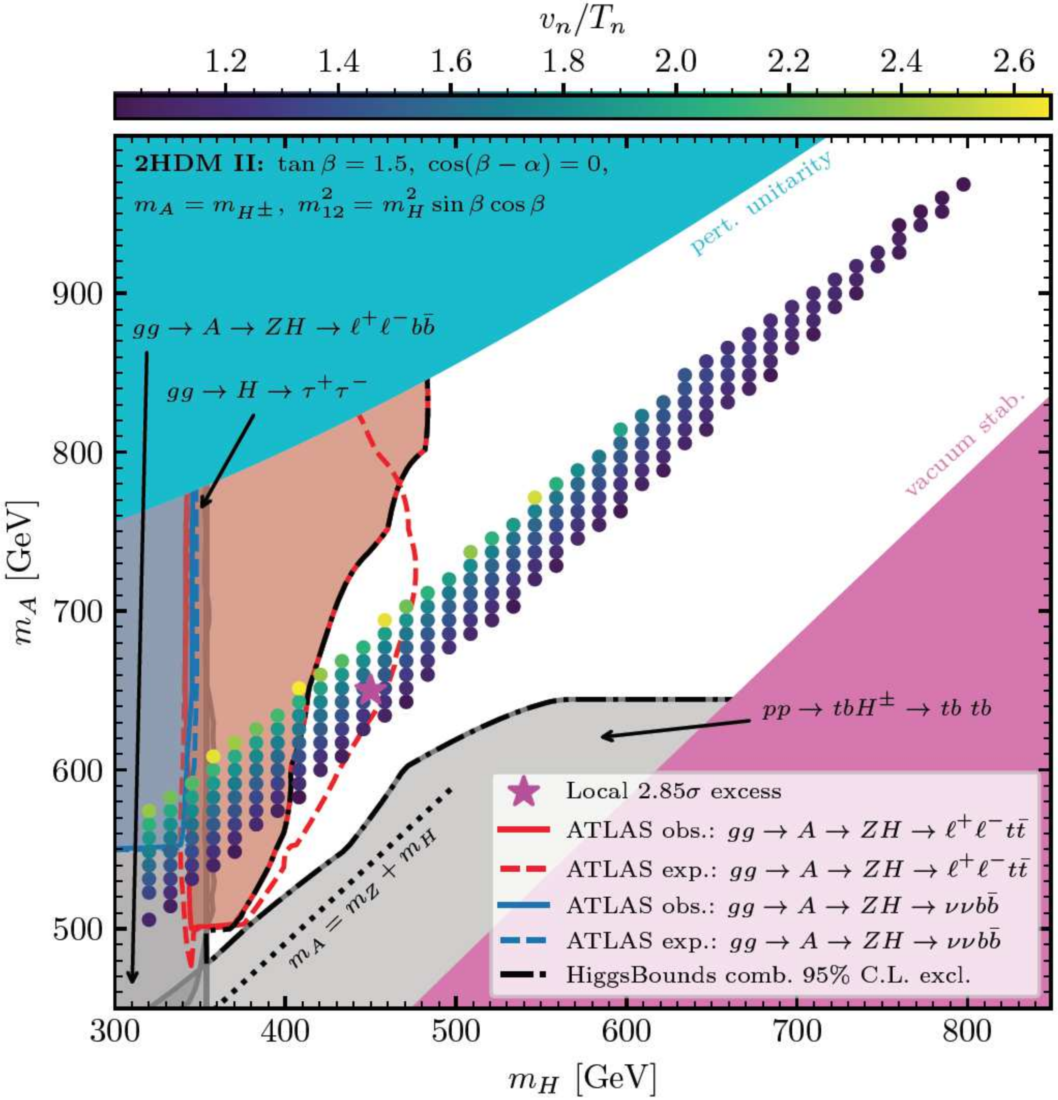

$\Rightarrow$ GW zone can be covered at the HL-LHC




⇒ interesting excess in the "right spot" :-) ($m_H$ = 450 GeV, $m_A$ = 650 GeV)

# Smoking gun signature: highest excess for $\tan\beta = 1.5$

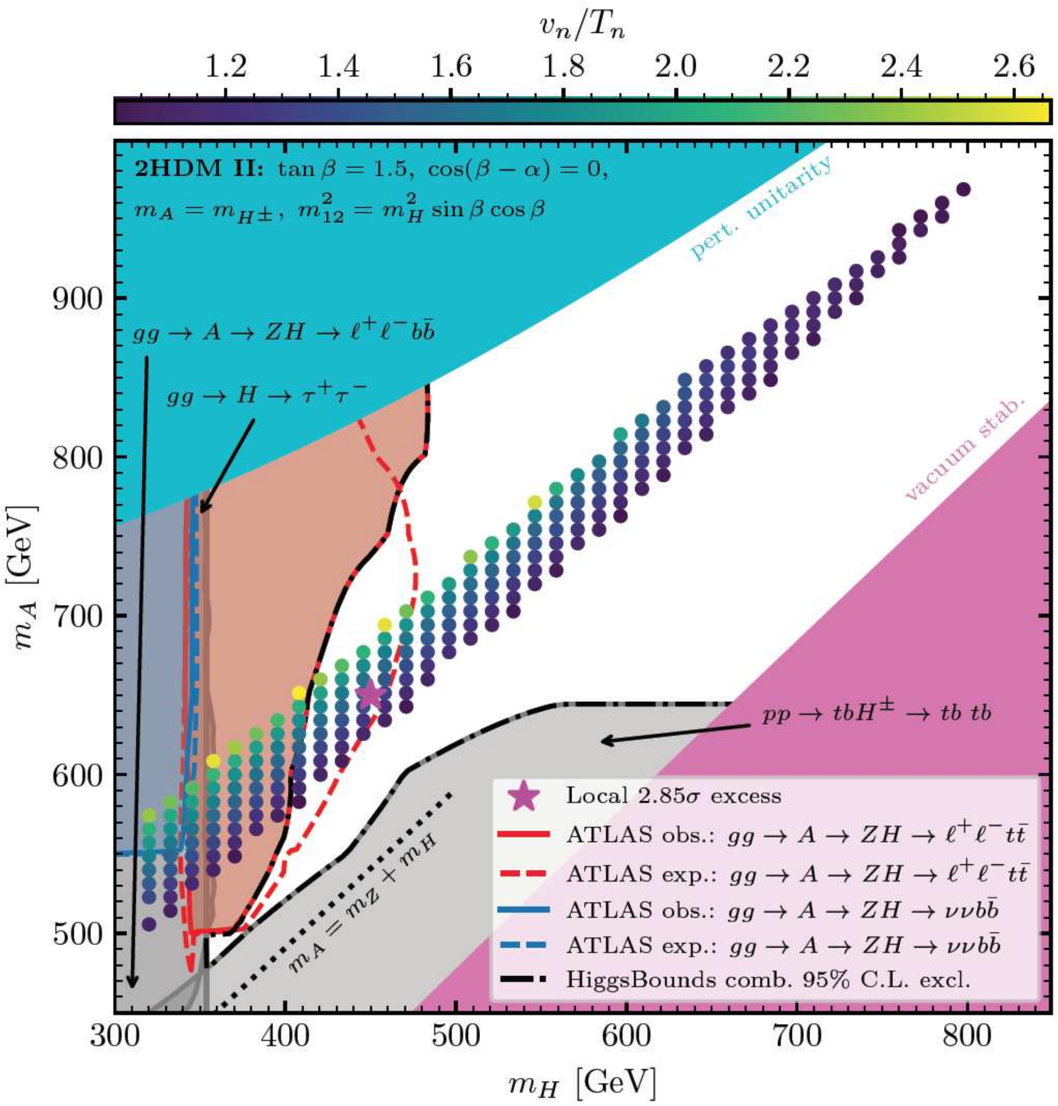
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]




$\Rightarrow$ excess in the sweet spot

# Smoking gun signature: highest excess for $\tan\beta = 1.5$

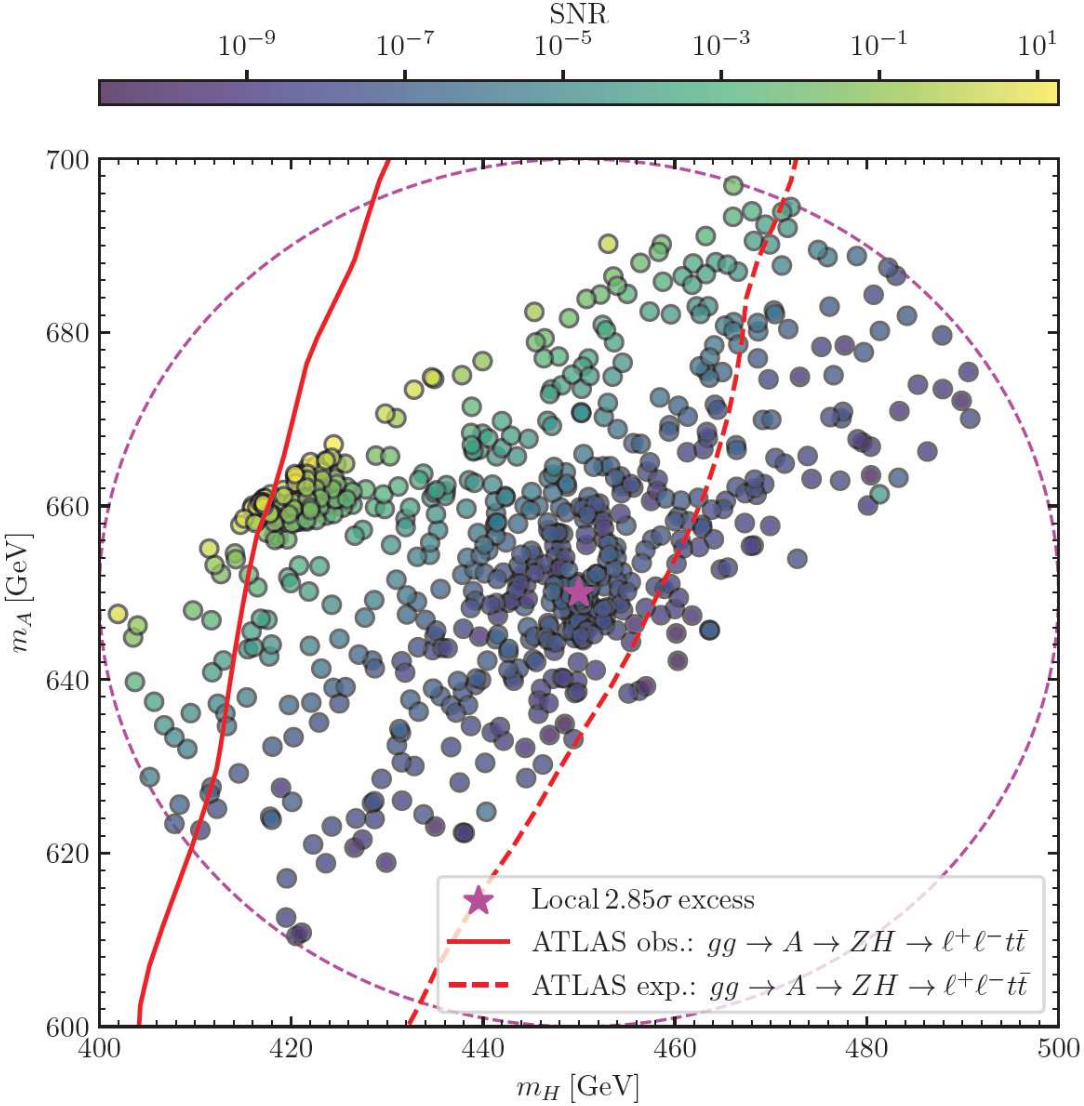
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]




⇒ excess in the sweet spot ⇒ not confirmed by CMS Run 2 analysis :-(

# Smoking gun signature: GW signal at LISA?

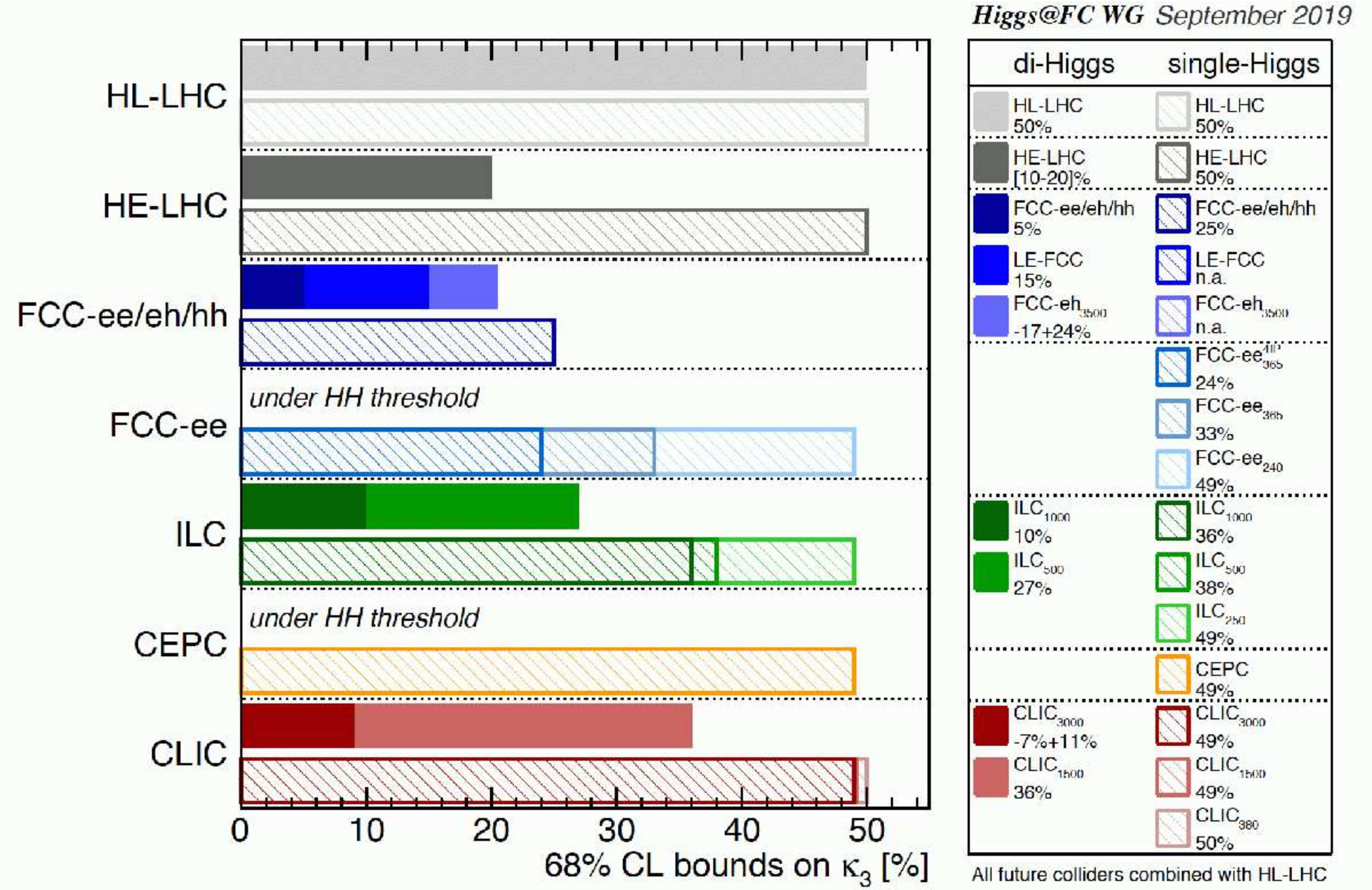
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]




⇒ GW signal at LISA possible, but not guaranteed

# 3. THCs in the 2HDM at the HL-LHC and the ILC

## SM triple Higgs coupling: comparison of all colliders:

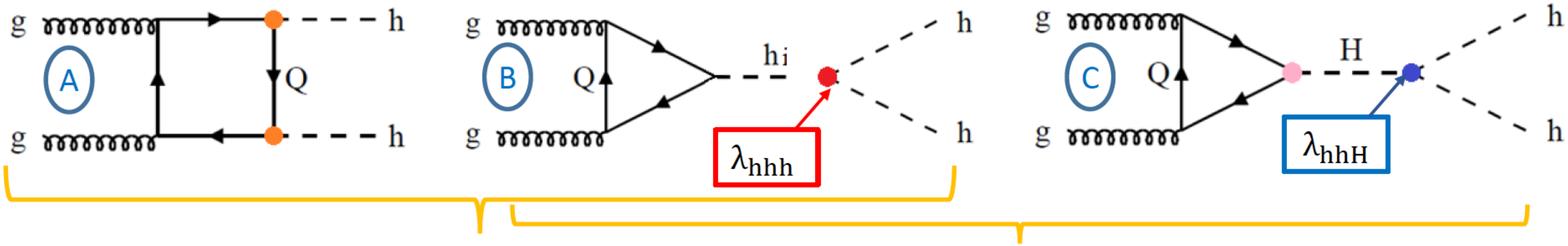



⇒ focus on “SM triple Higgs coupling”, $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM,tree}}$

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

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

# Di-Higgs production at the LHC:

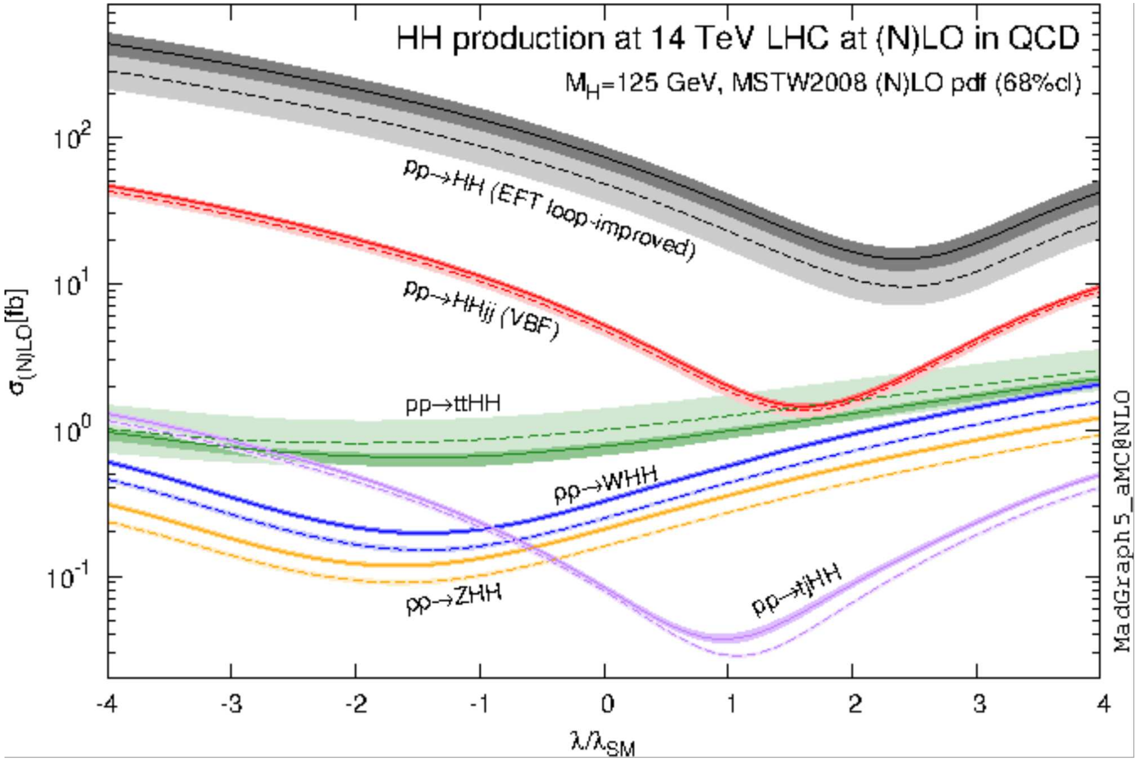



$\sigma_{SM} \sim$ 38 fb at NLO

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

Diagrams that are sensitive
to triple Higgs couplings

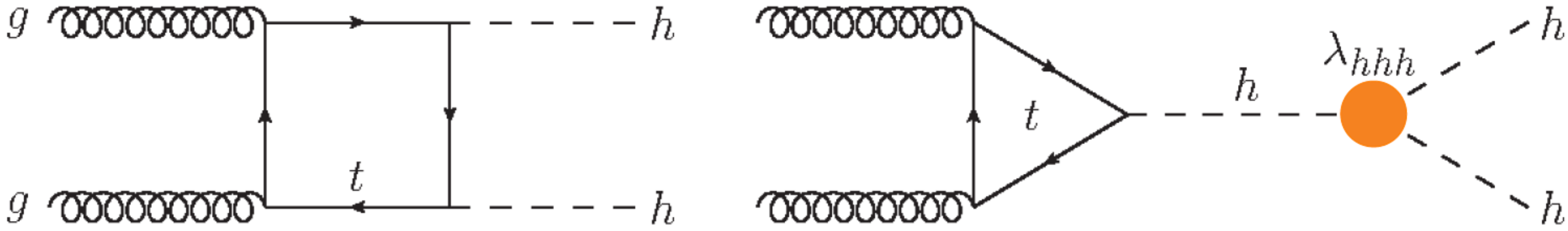
$\Rightarrow$ strong interference of "box" and "SM-like Higgs"



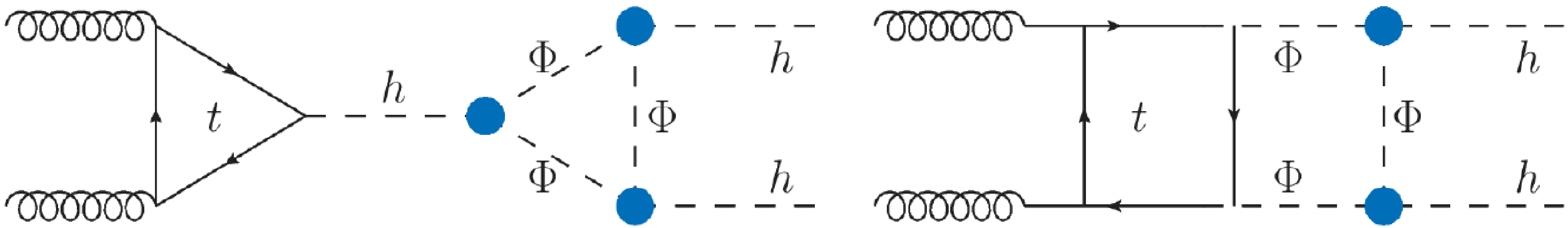
## Higher-order correction to the THCs:

[*taken from J. Braathen*]

### Box vs. $s$-channel Higgs:




### Inclusion of one-loop corrections to THCs:




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

***Correction to $\lambda_{hhh}$ → included***

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

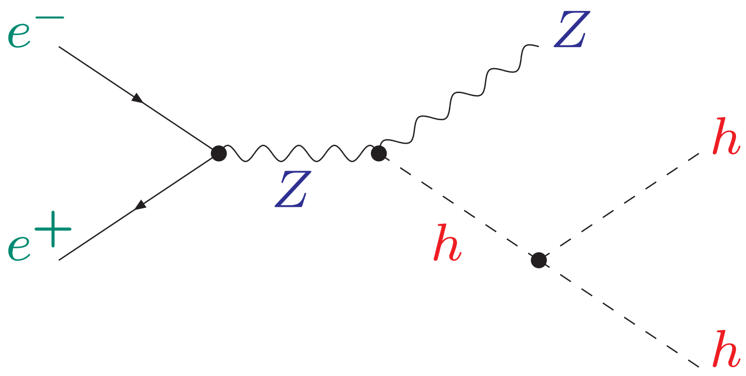
***not included***

⇒ always closed subset, dominant for large THCs

# Di-Higgs production at ILC/CLIC:

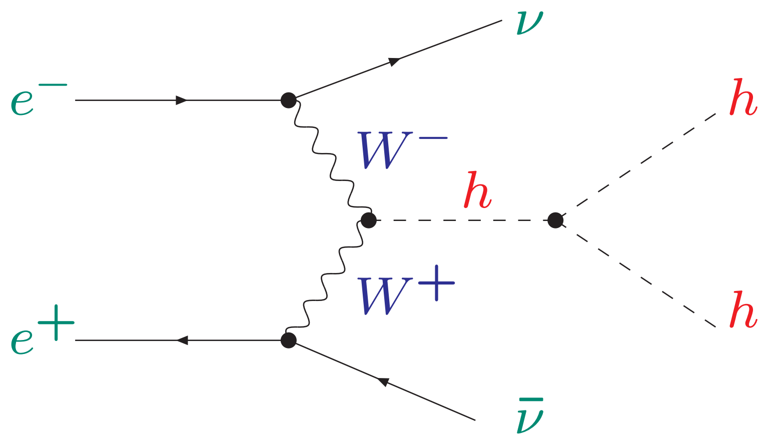
Higgs-strahlung:

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

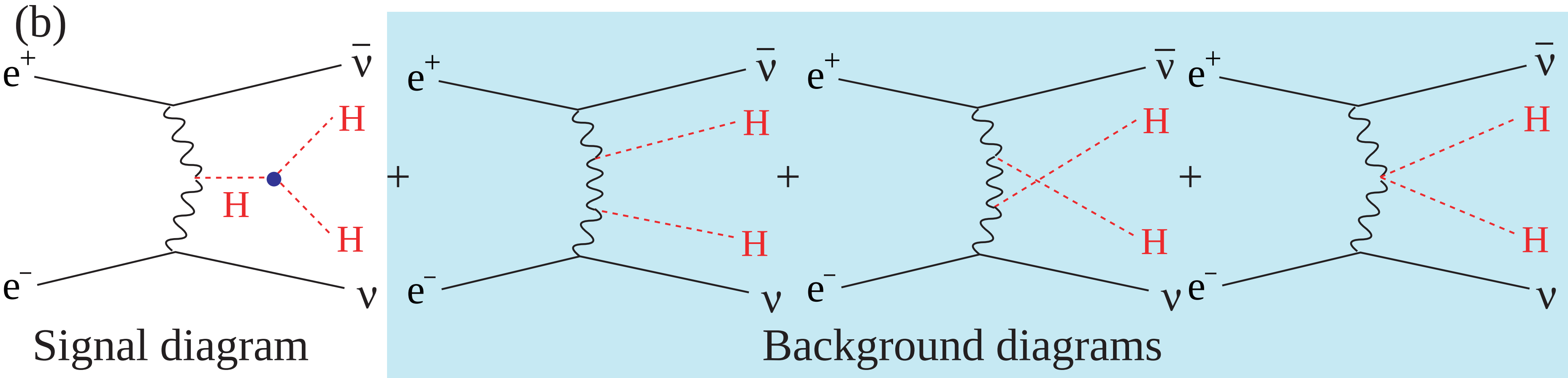



weak boson fusion (WBF):

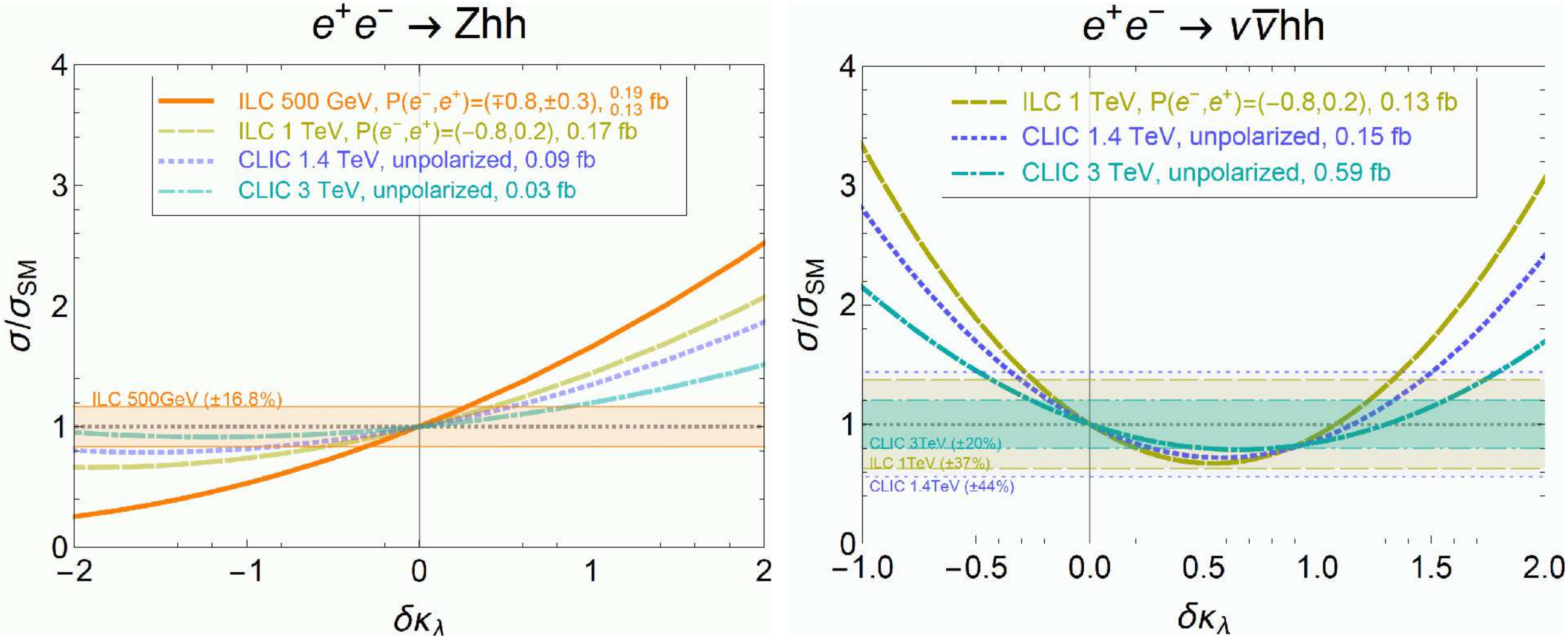
$e+e- \to \nu\bar{\nu}hh$




Signal and background interference:



# Di-Higgs production at ILC/CLIC:

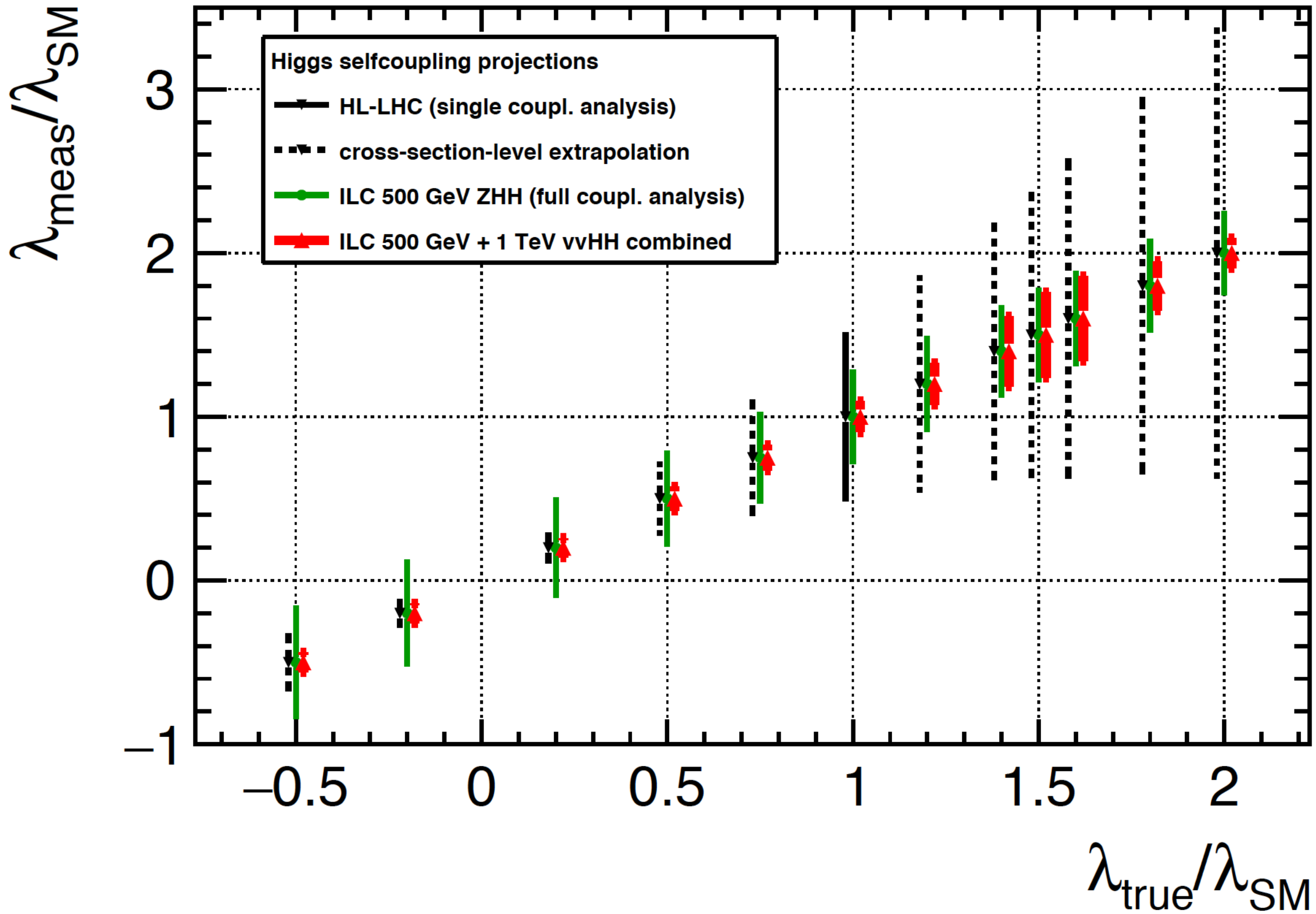



$\kappa_\lambda := 1 + \delta\kappa_\lambda$

$\Rightarrow$ strong and different dependence on $\kappa_\lambda$

## Measurement of $\kappa_\lambda$ selfcoupling at HL-LHC/ILC:

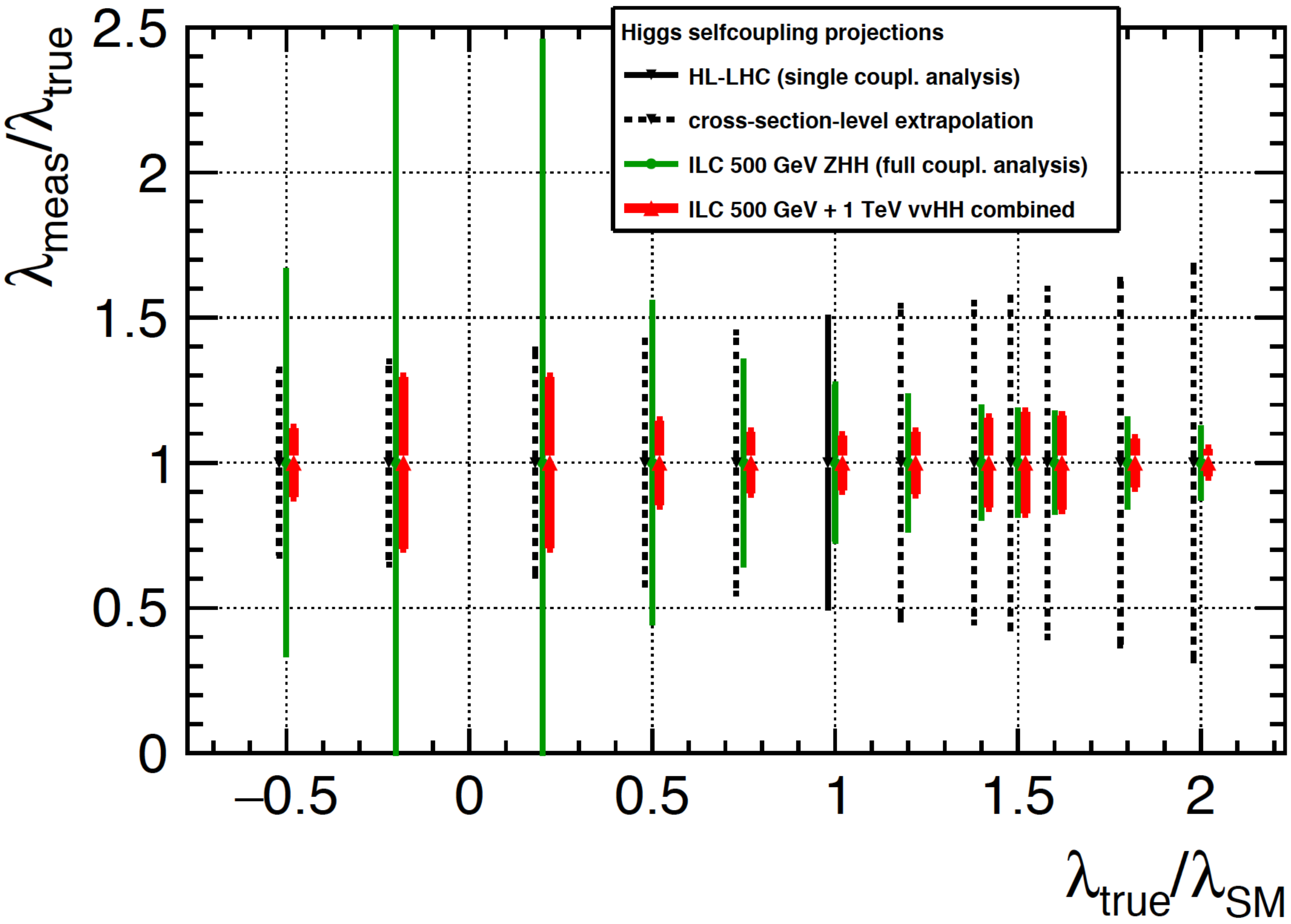
*[J. List et al. – PRELIMINARY]*




FOEWPT/GW: $\lambda_{hhh} \lesssim 2 \Rightarrow$ bad for HL-LHC, good for ILC

# Measurement of $\kappa_\lambda$ selfcoupling at HL-LHC/ILC:

[*J. List et al. – PRELIMINARY*]

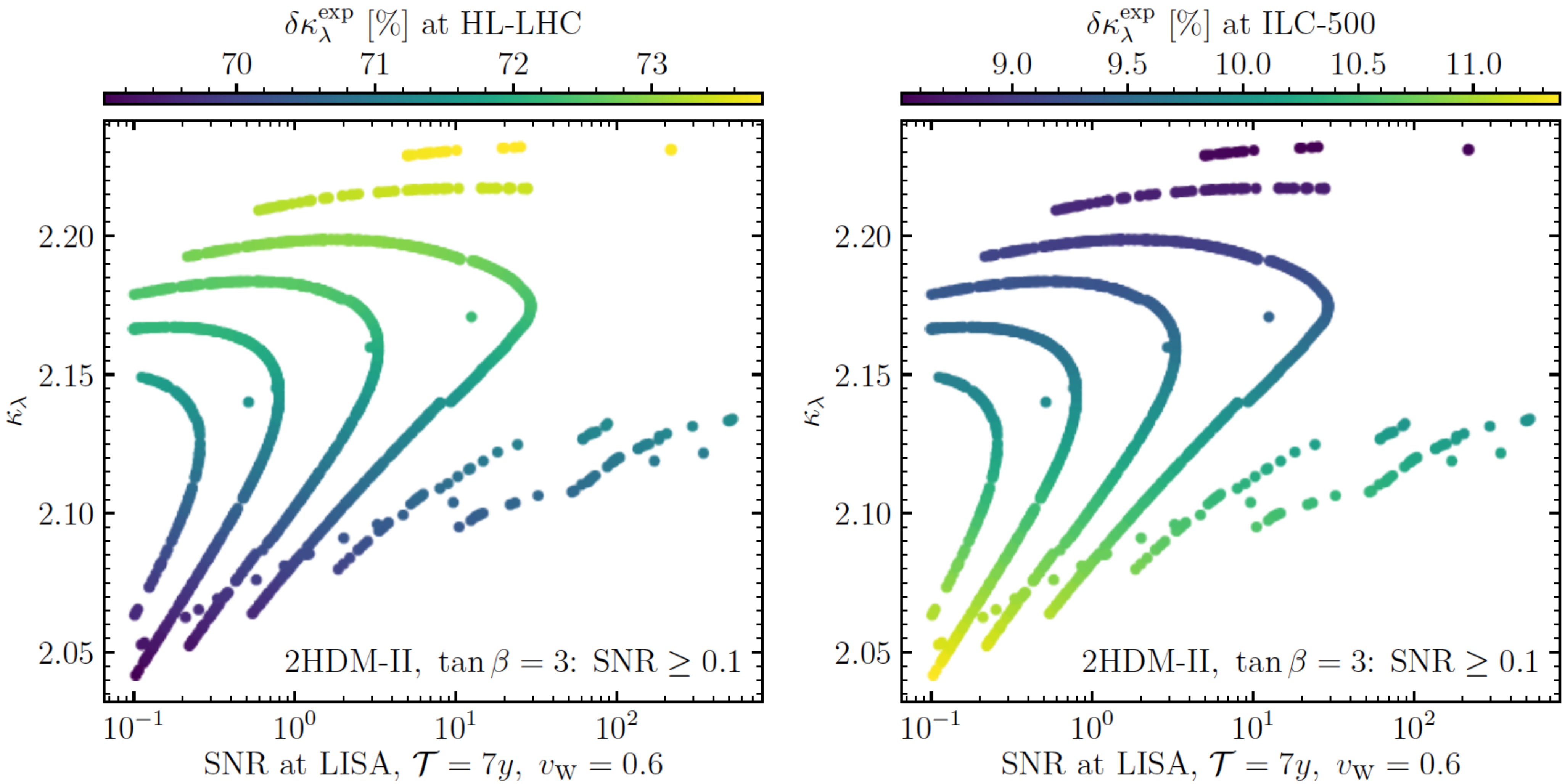



$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

# Example: 2HDM ⇒ FOEWPT ⇒ GW's

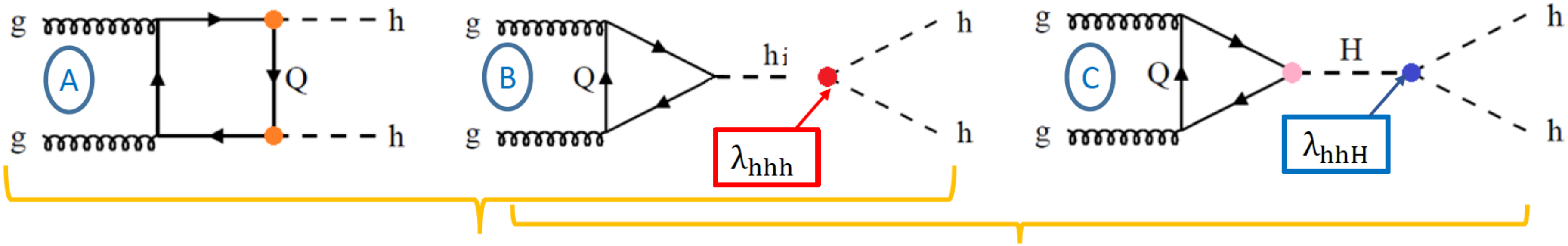
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

⇒ Synergies: collider: $\lambda_{hhh}$ ⇔ LISA: GW signals




⇒ FOEWPT requires large $\lambda_{hhh}$ and can induce GW signals

# BSM THCs at the HL-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

⇒ possible strong resonance with BSM Higgs

Important: experimental limtis are obtained for

– non-resonant production

– purely resonant production

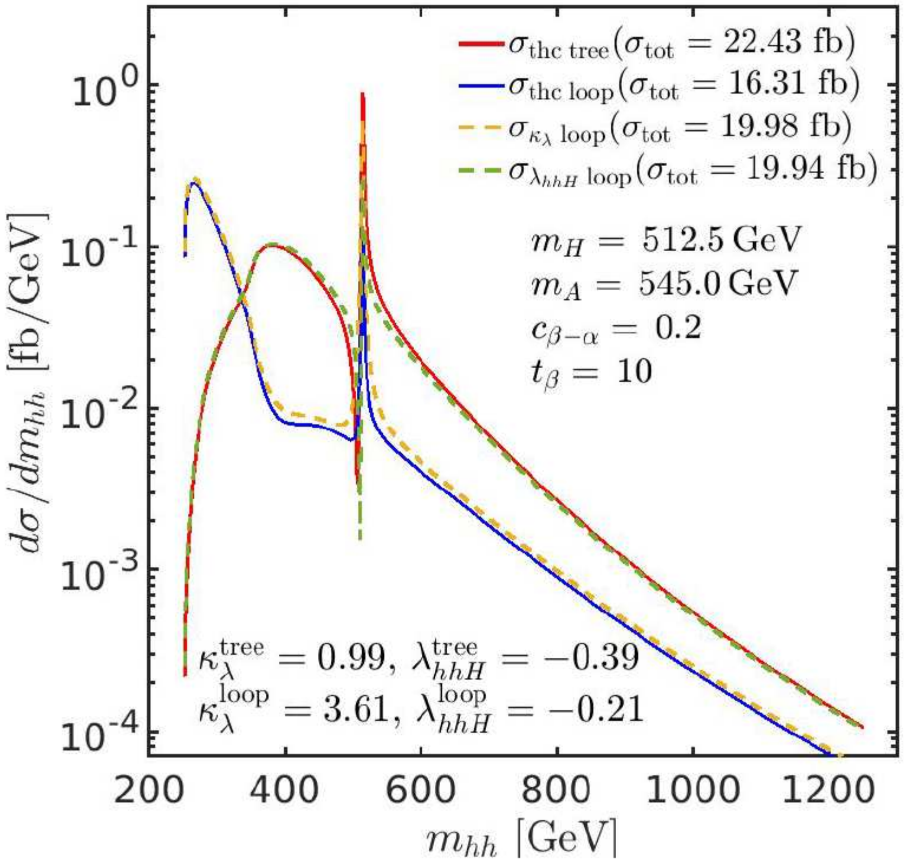
⇒ no limits available for mixed scenarios :-(

⇒ existing exclusion bounds questionable!

## Two types of BSM effects:

⇒ 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: $\lambda_{hhH}, \ldots$

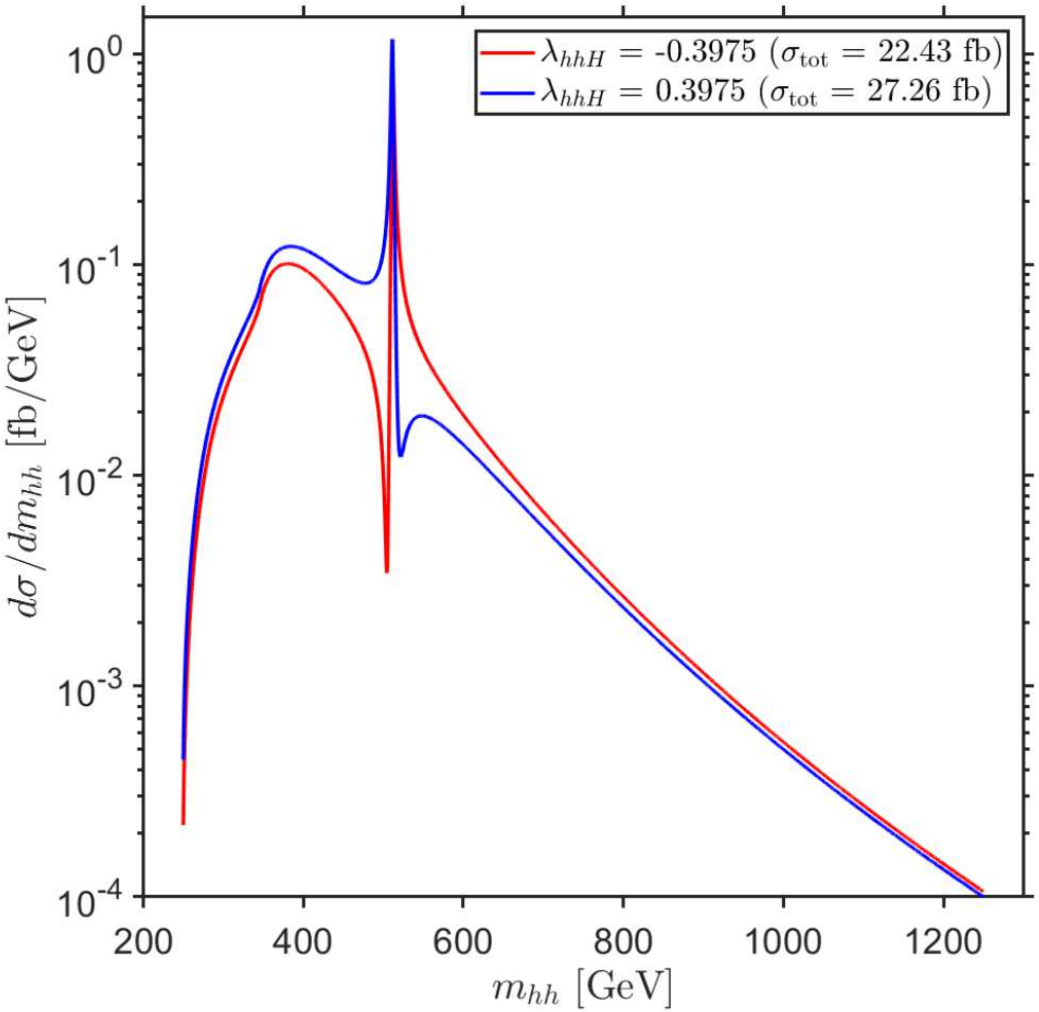
Example of $m_{hh}$ distortions: [S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]



# Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV$, m_H = 515$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

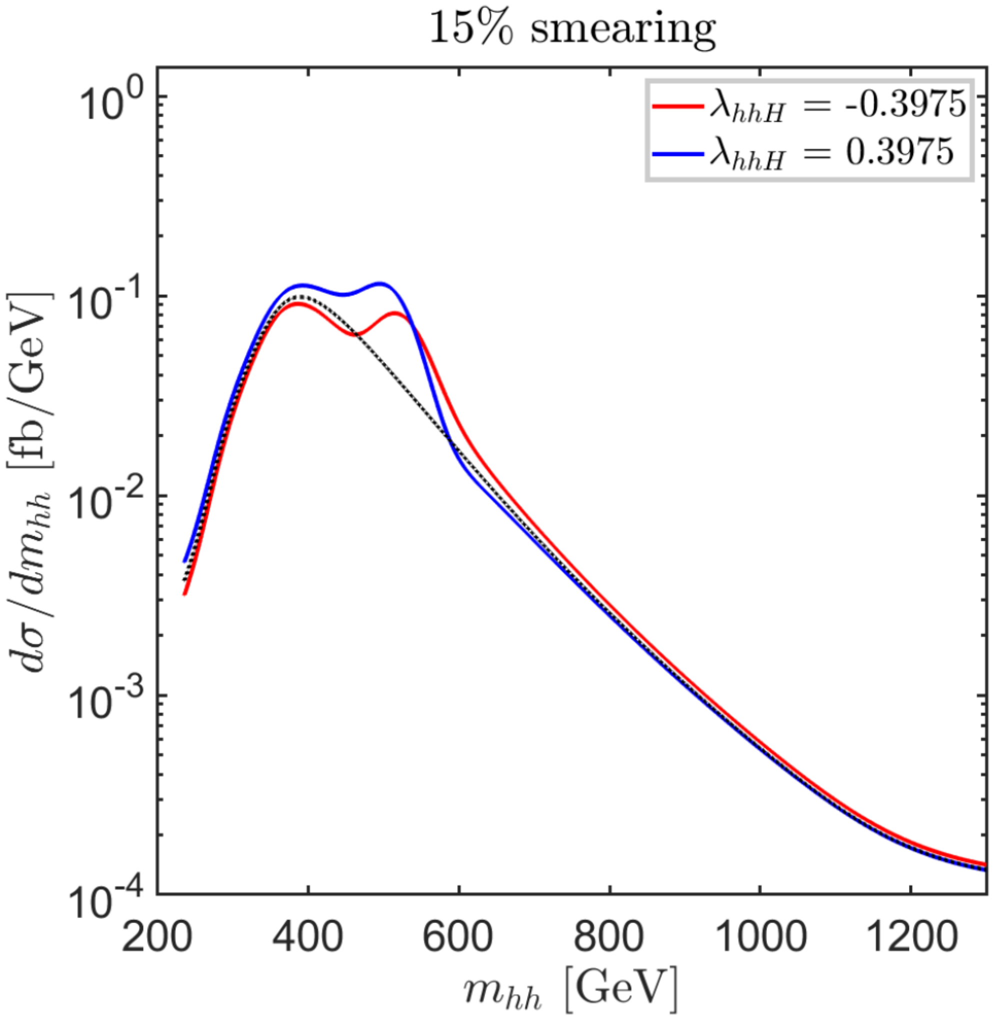



⇒ dip-peak / peak-dip from resonant $H$-exchange ⇒ access to $\lambda_{hhH}$?

# Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV, $m_H = 515$ GeV, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

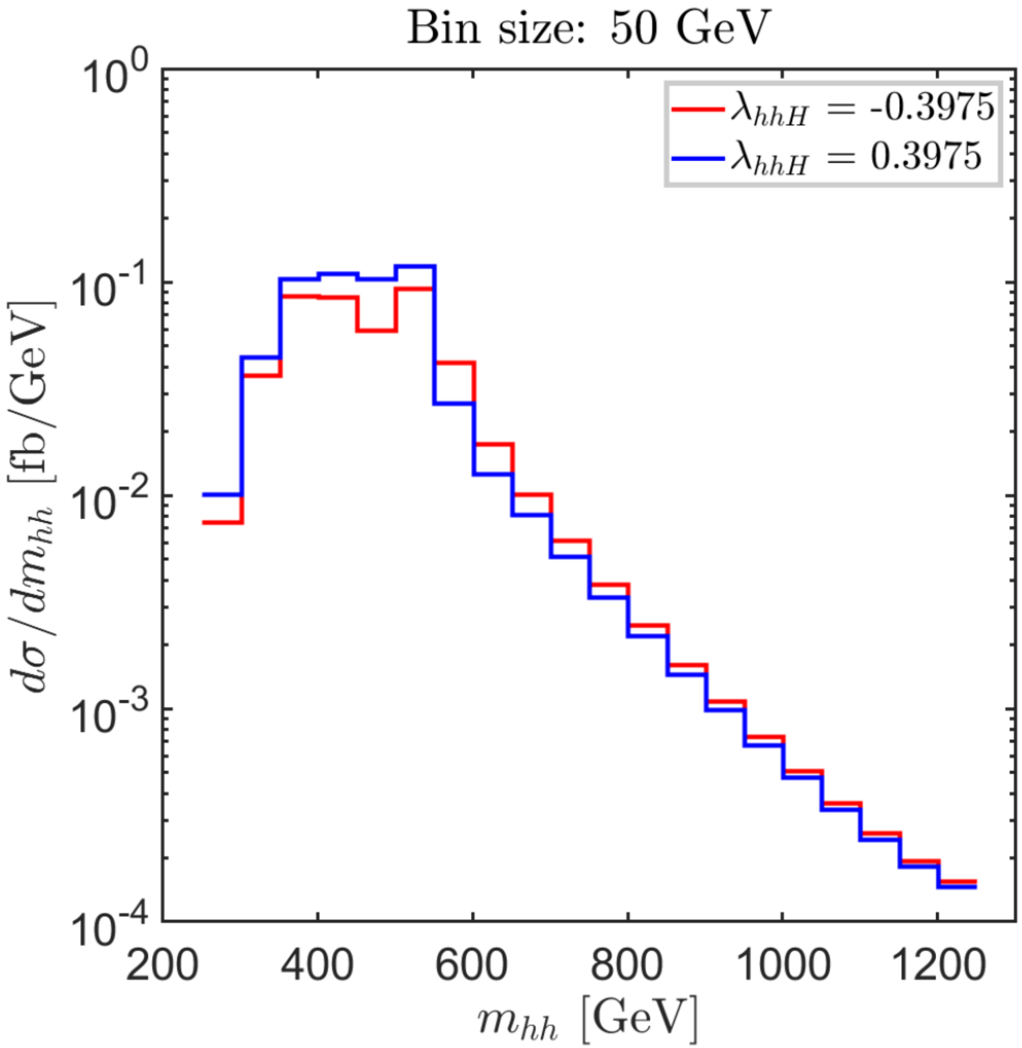



⇒ smearing of 15% applied (optimistic?) ⇒ access to $\lambda_{hhH}$?

## Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV, $m_H = 515$ GeV, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

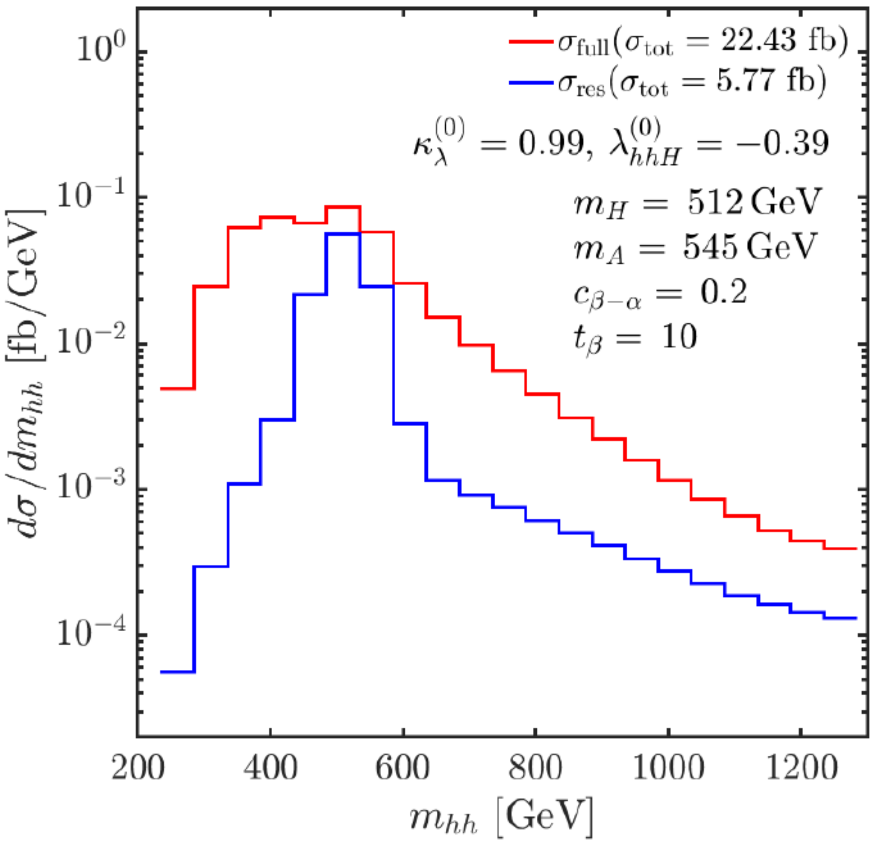



⇒ binning of 50 GeV applied (realistic?) ⇒ access to $\lambda_{hhH}$?

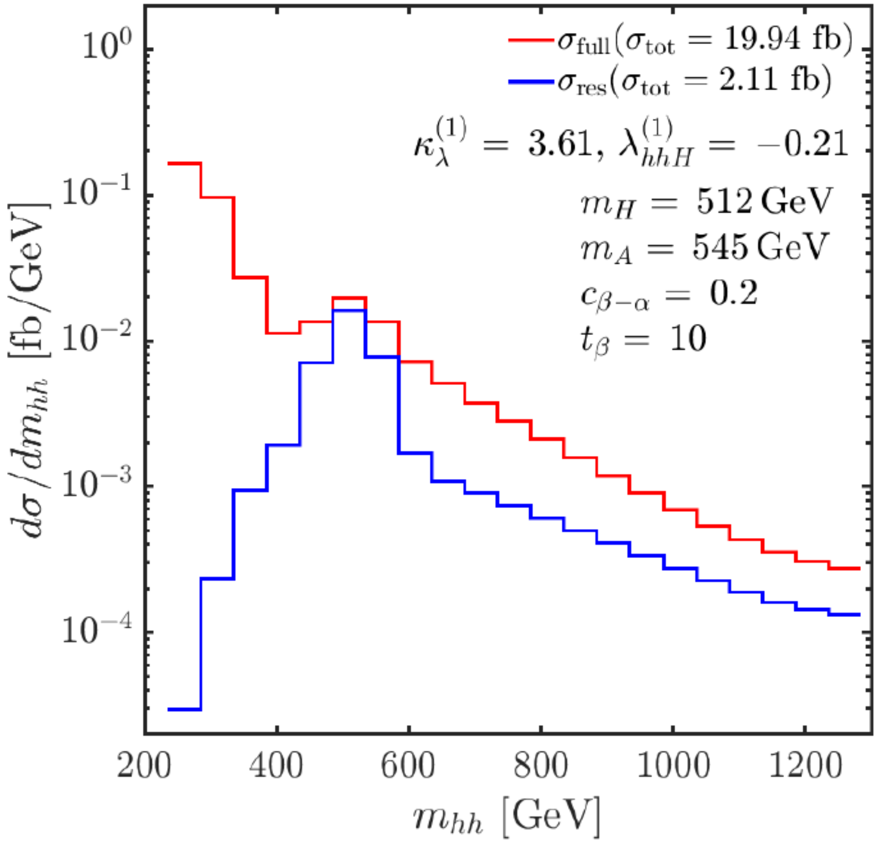
## Experimental analysis vs. reality:

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

THC tree-level



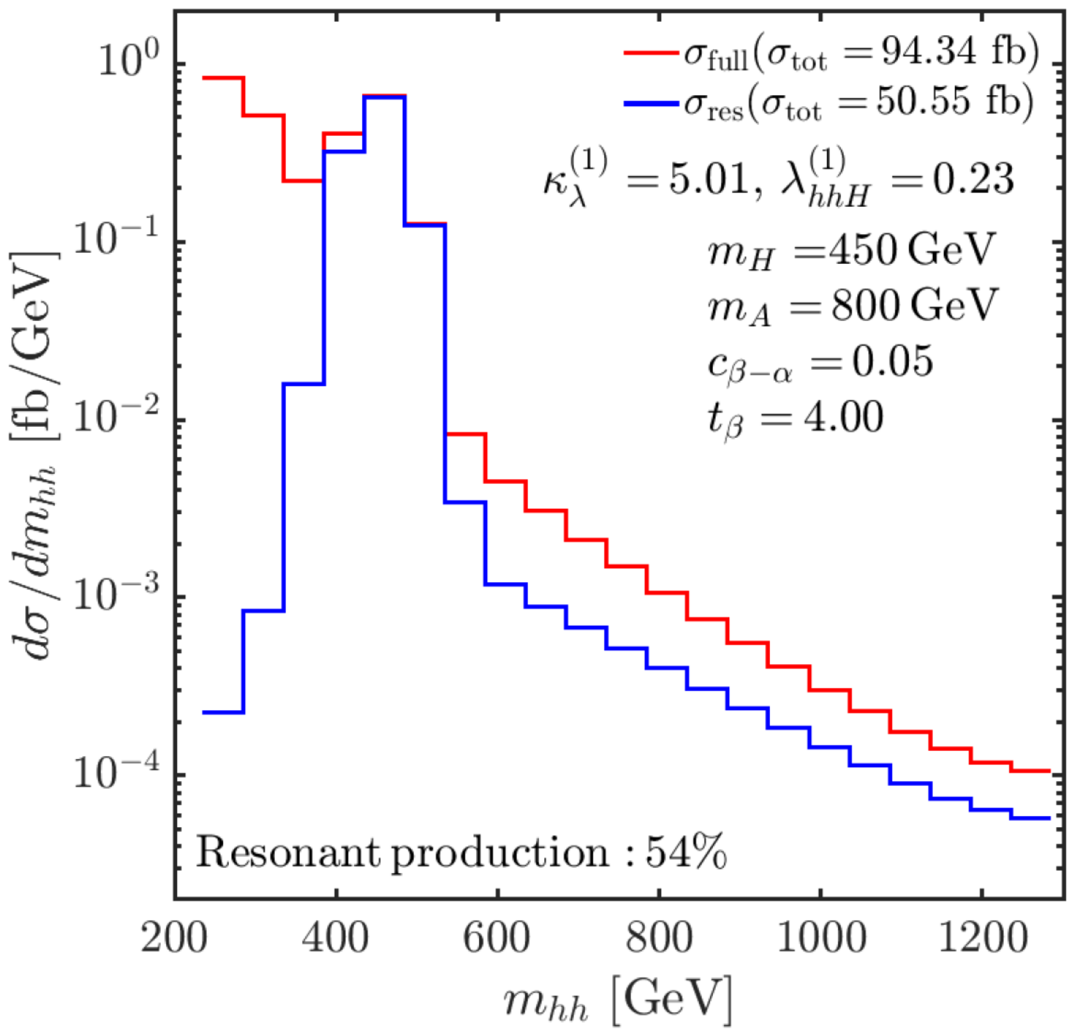

THC one-loop




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

## Experimental analysis vs. reality:

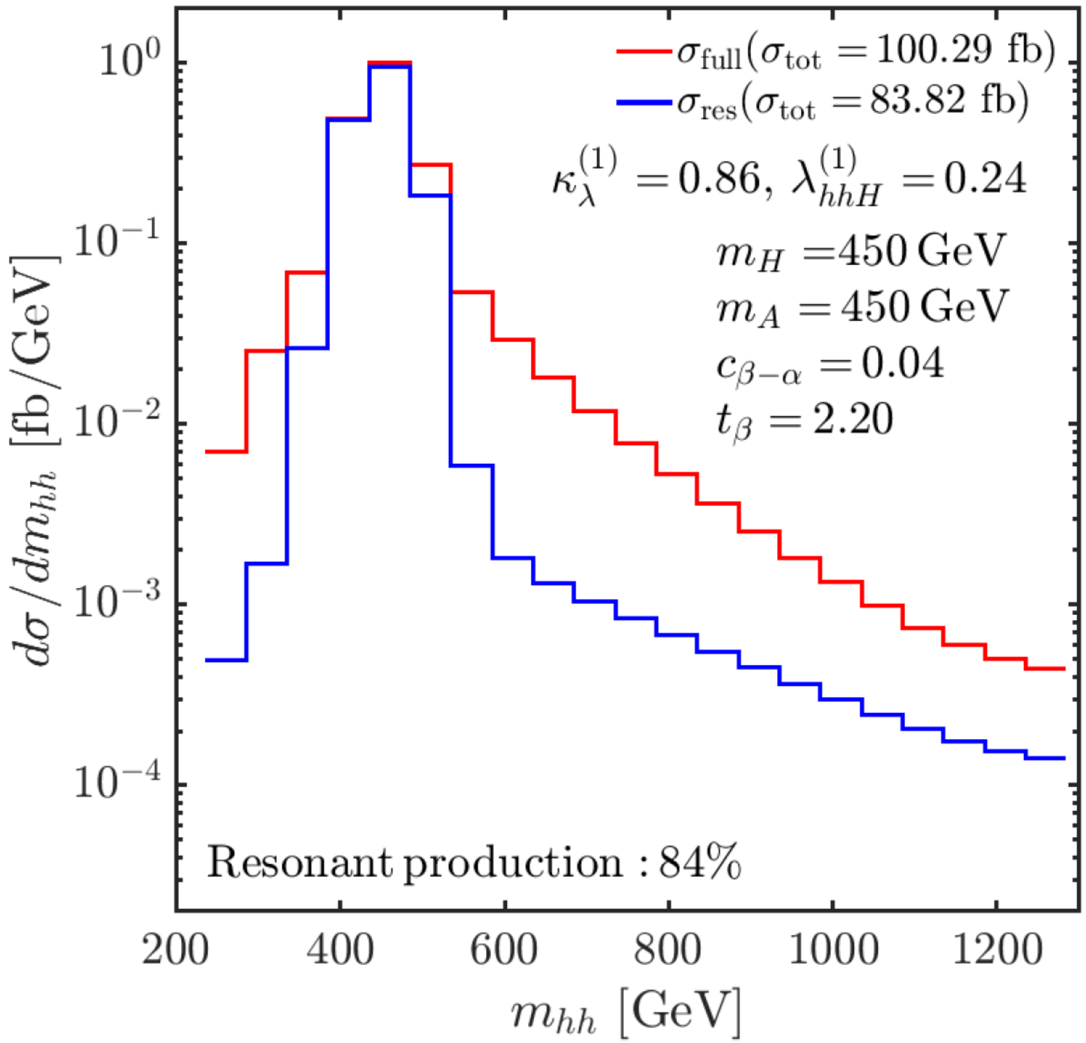
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]




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

# Experimental analysis vs. reality:

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



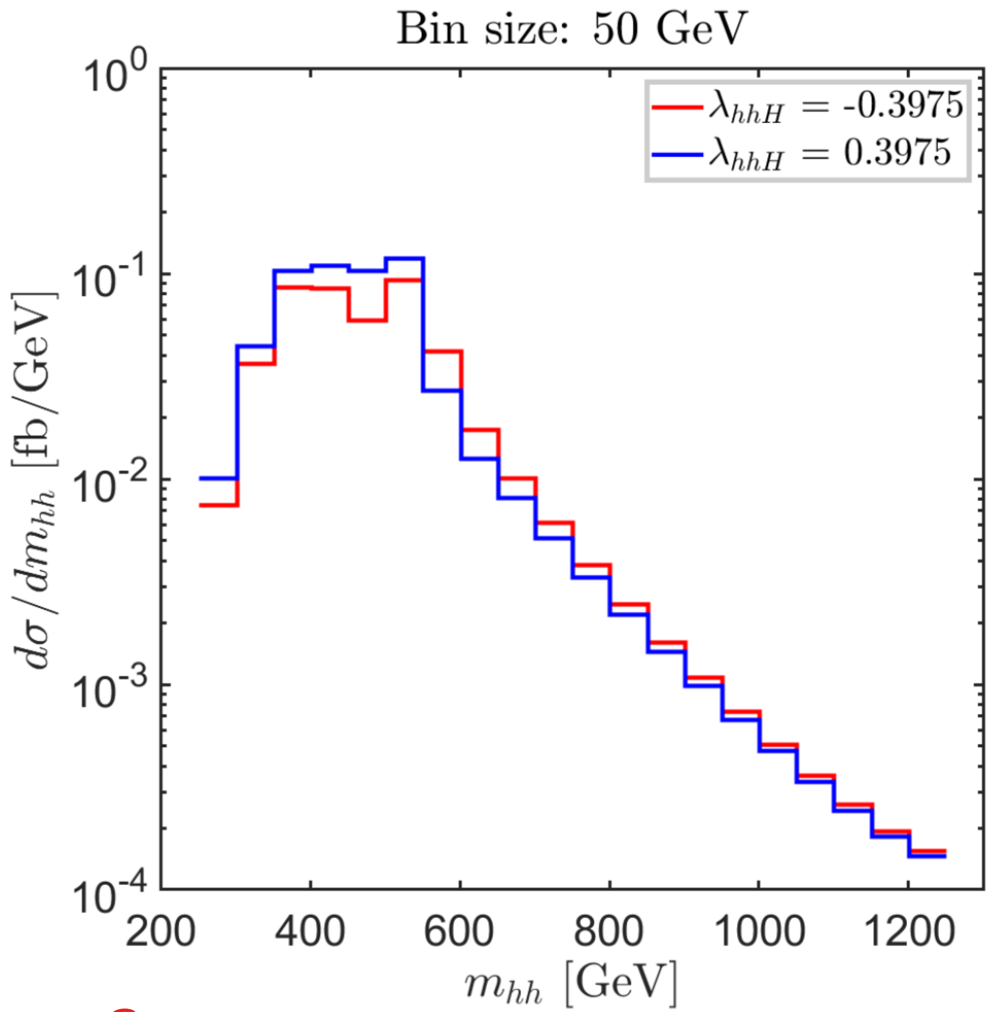

$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

# 4. My first neural network analysis

## Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

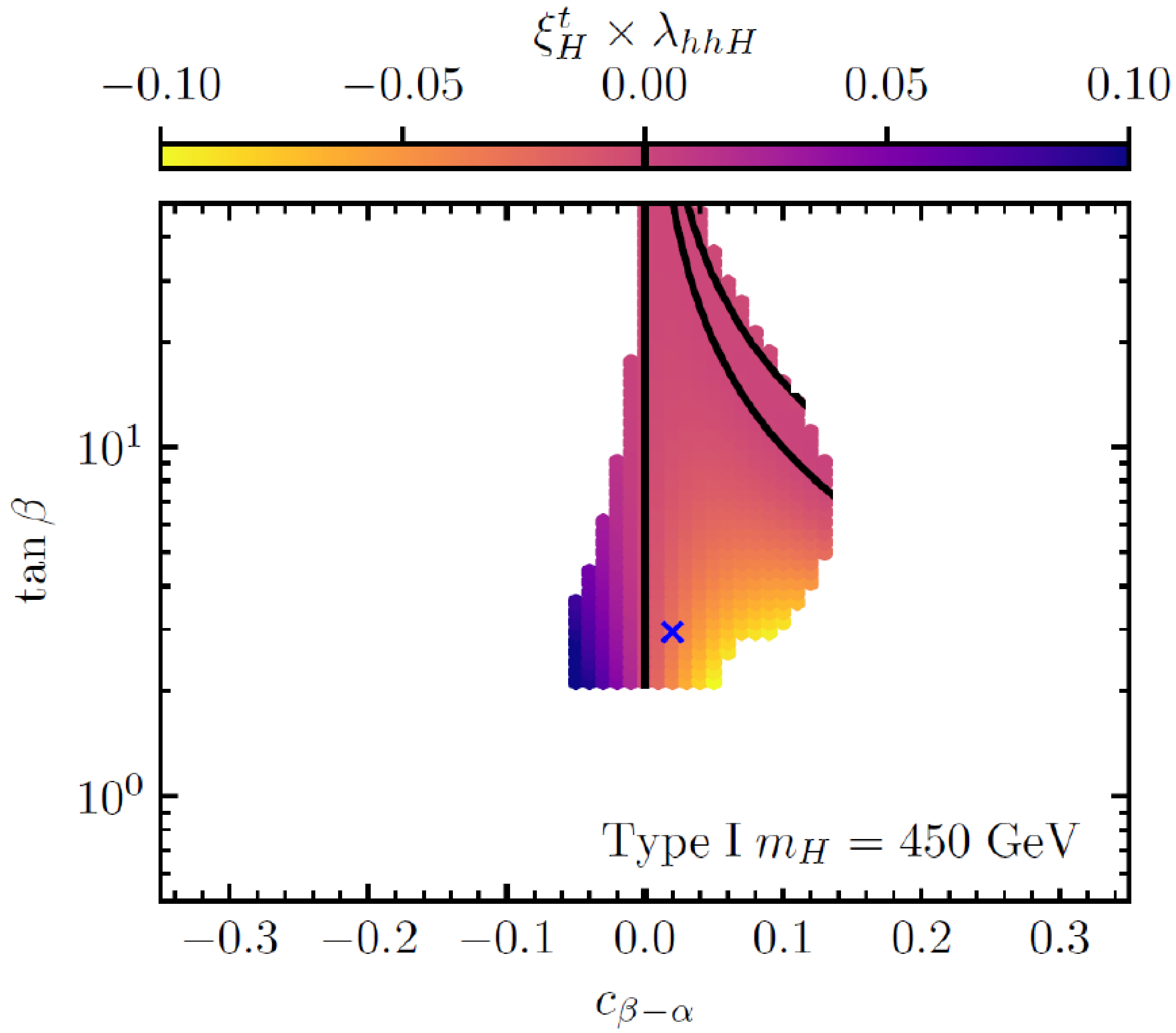
$m_{A,H^\pm} = 545$ GeV, $m_H = 515$ GeV, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$




$\Rightarrow$ access to $\xi_H^t \times \lambda_{hhH}$?

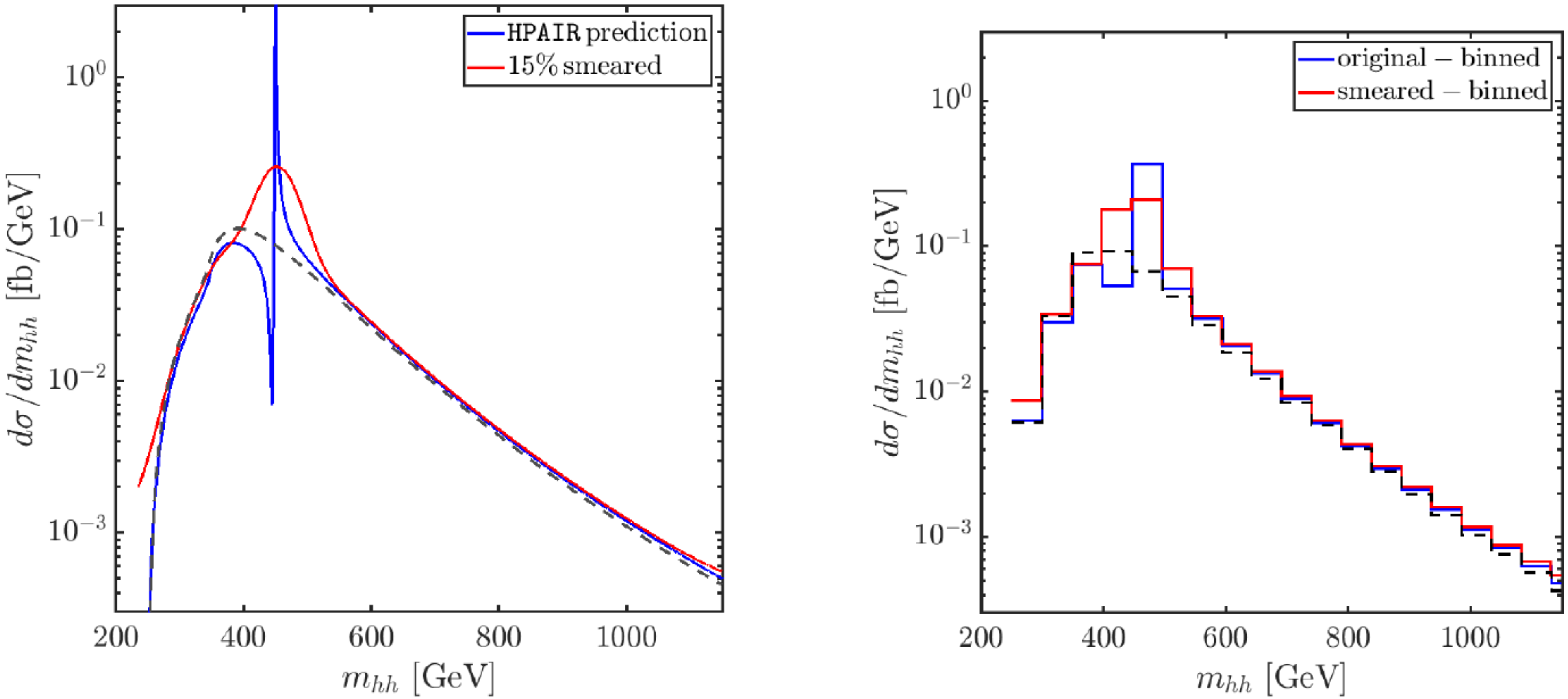
# Parameter plane to train the NN:

*[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]*



# Each point yields an $m_{hh}$ distribution $\Rightarrow$ fed to the NN

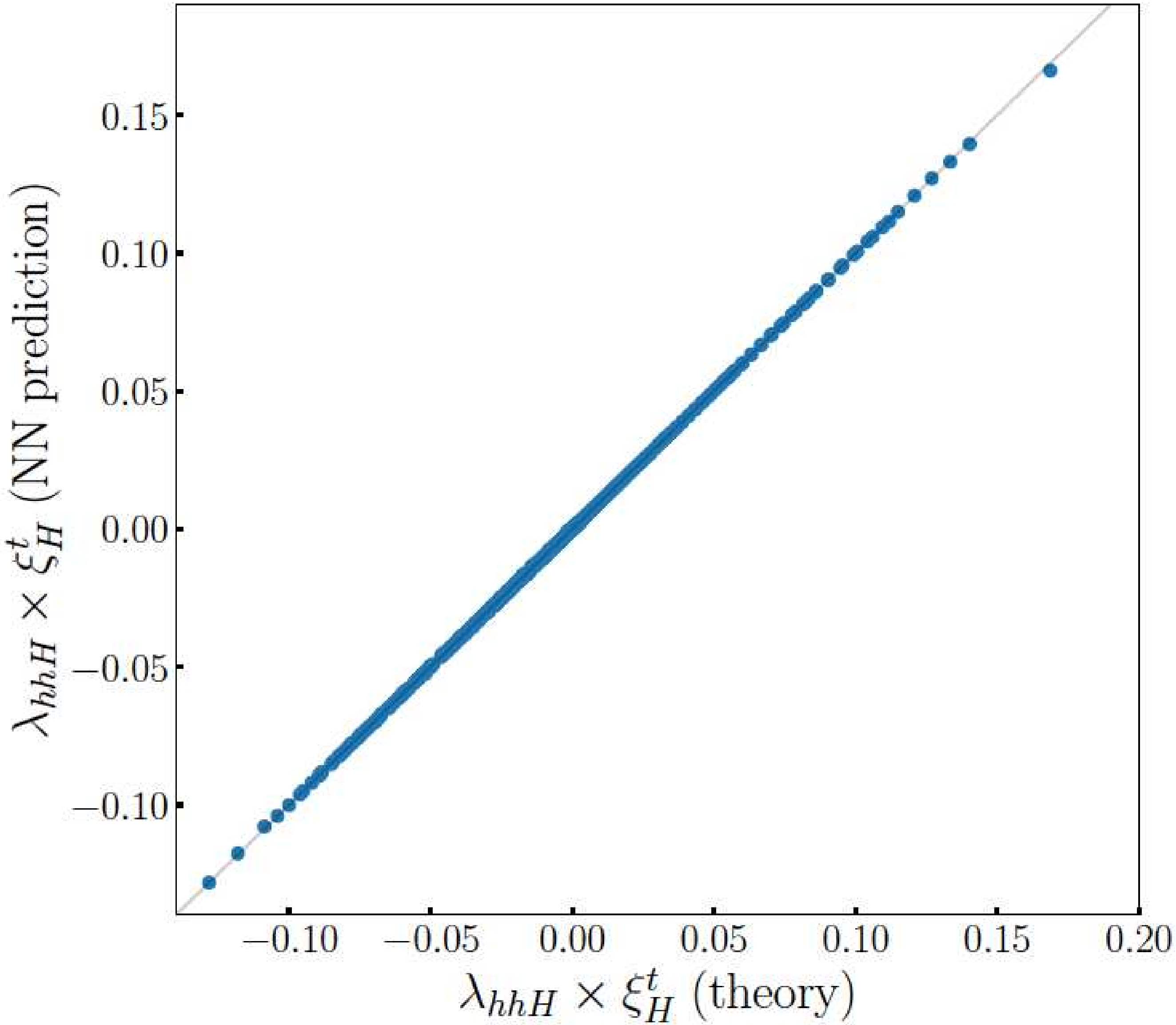
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]




- 16 input values (smeared and binned)
- 4 hidden layers with 128 nodes
- output layer to yield $\xi_H^t \times \lambda_{hhH}$
- training with 3/4 of $m_{hh}$ distribution (randomly chosen)
- "measure" the remaining 1/4 (or . . . )

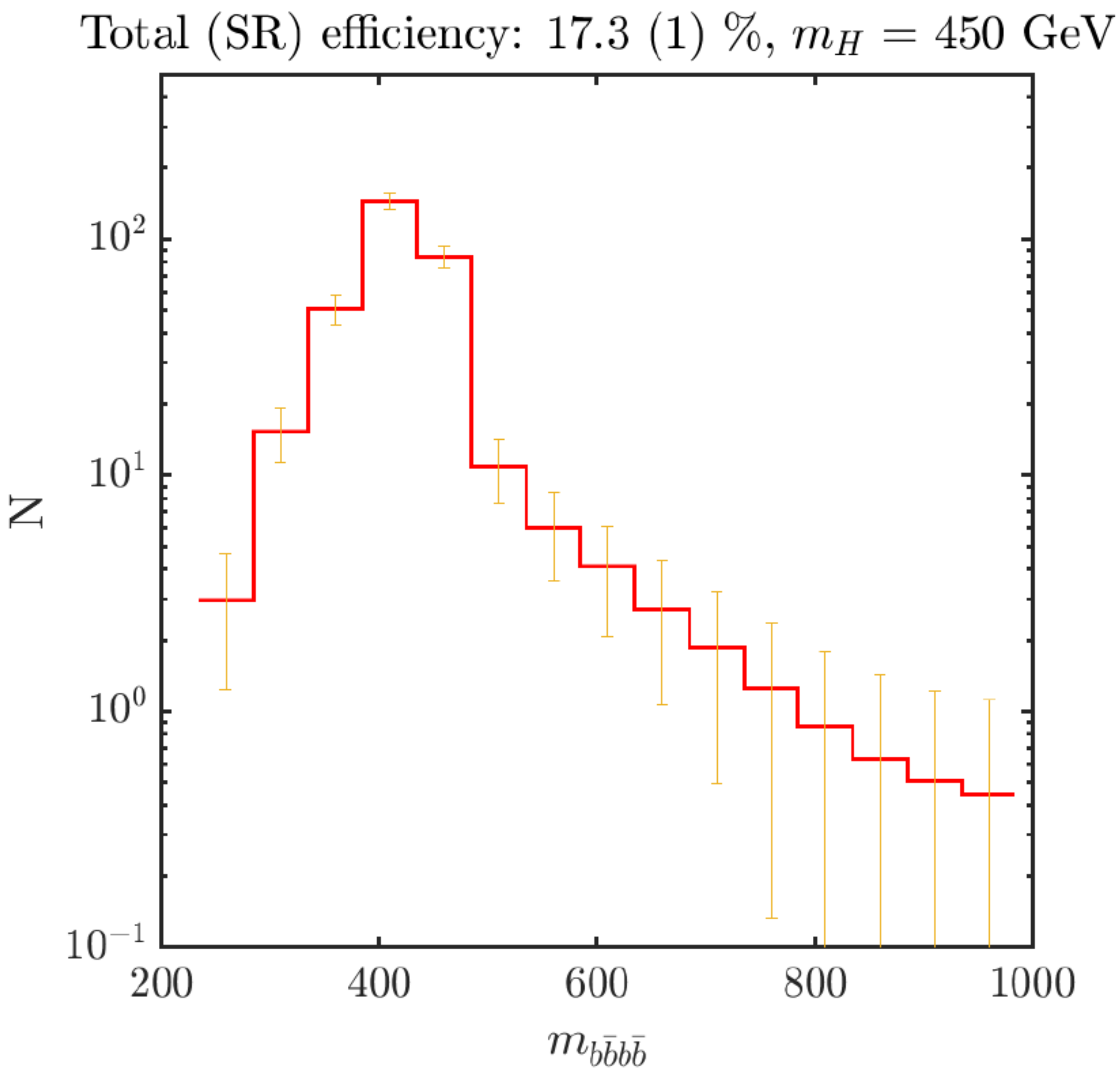
## Train with the correct $m_{hh}$ distributions: $\Rightarrow$ perfect result

*[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]*



# “Realistic result” has statistical uncertainties ($b\bar{b}\,b\bar{b}$ final state):

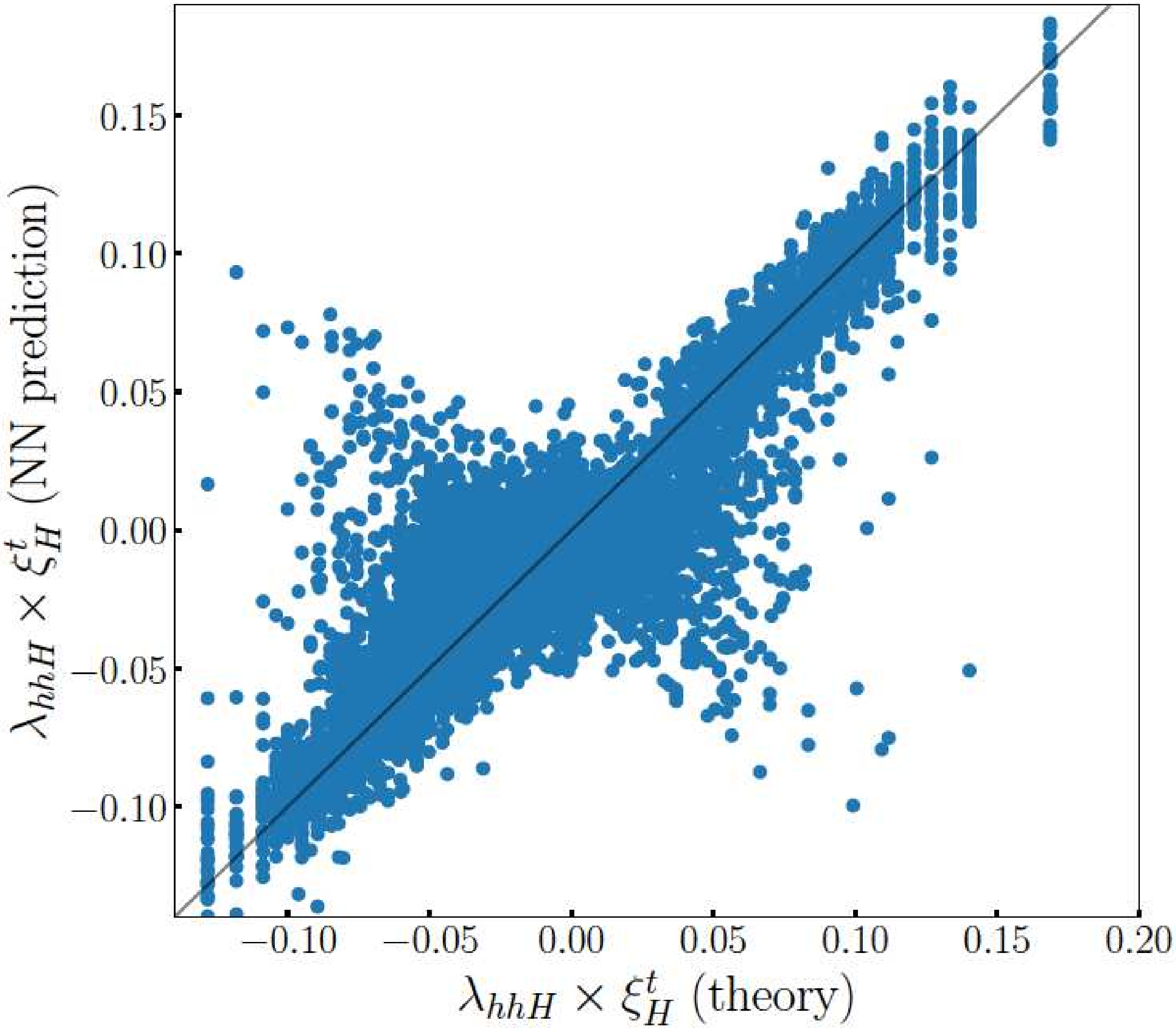
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]




$\Rightarrow$ for each point in the plane test an $m_{hh}$ distribution statistically smeared

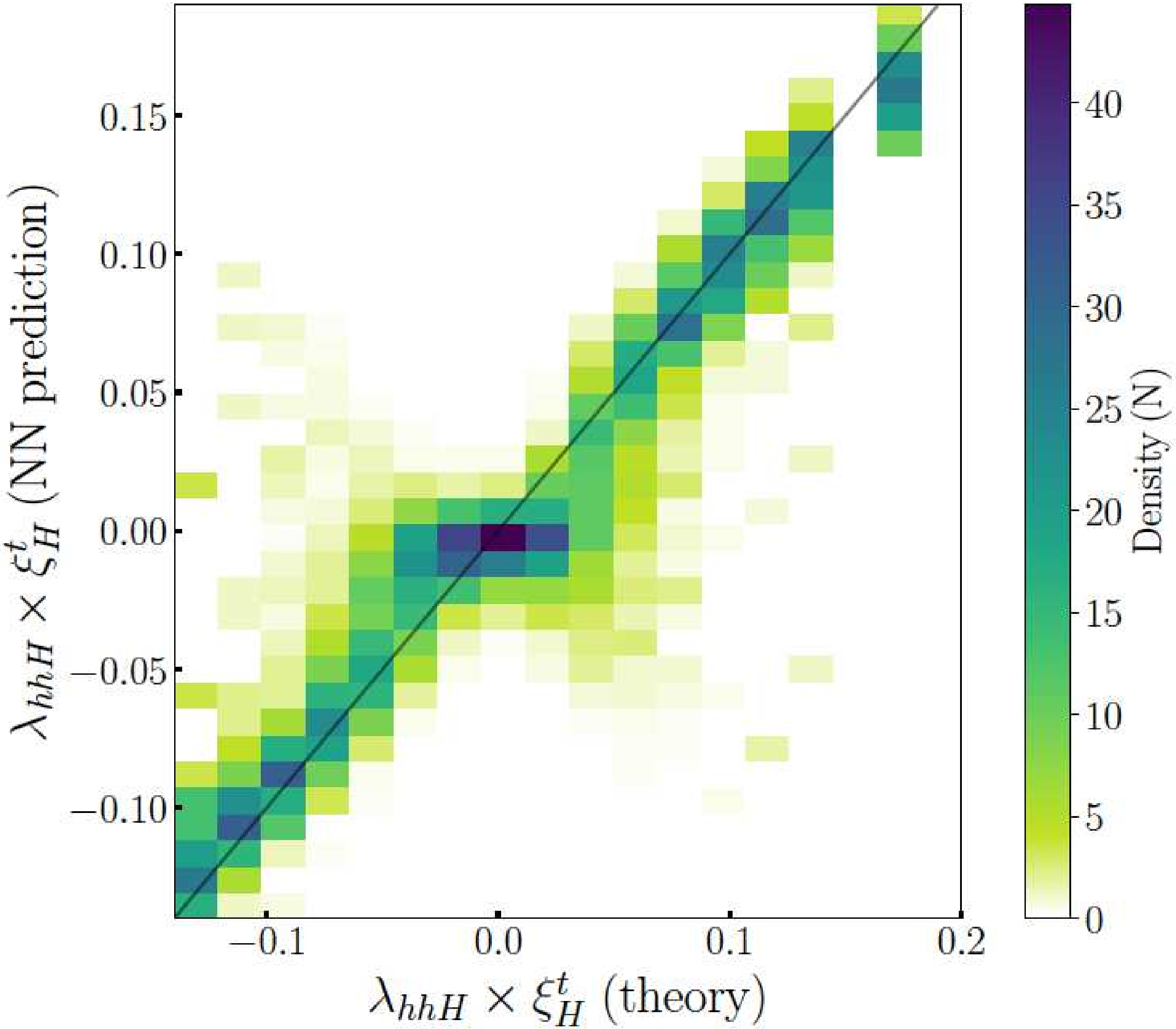
## “Realistic” determination of $\lambda_{hhH} \times \xi^t_H$:

[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]



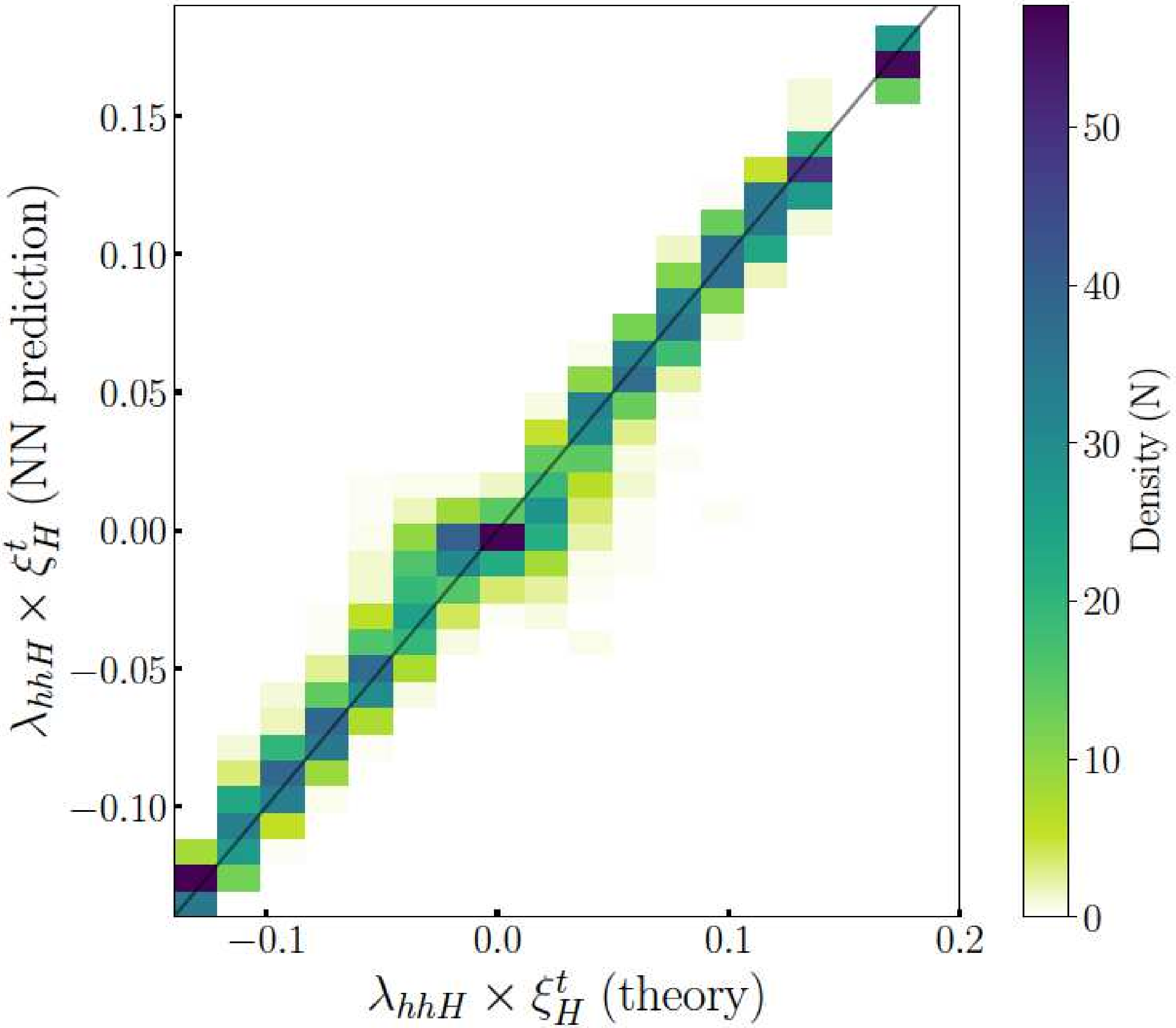
## “Realistic” determination of $\lambda_{hhH} \times \xi_H^t$:

[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



# Hypothetical improvement in the efficiencies by $\times 2$:

[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



## 5. Conclusions

- ⇒ 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
  **Q:** Can this happen in the 2HDM? Implications for THCs?

- 2HDM: ⇒ FOEWPT requires $\kappa_\lambda \lesssim 2$ ⇒ GW signal requires $\kappa_\lambda \sim 2$
  ⇒ bad for HL-LHC ($\delta\lambda_{hhh} \sim 70\%$), good for ILC ($\delta\lambda_{hhh} \sim 10\%$)
  ⇒ FOEWPT favors $A$-$H$ mass gap ⇒ Smoking gun: $A \to ZH \to Zt\bar{t}$
  ⇒ 2.9 $\sigma$ excess ($m_H = 450$ GeV, $m_A = 650$ GeV) ⇒ possible GW det. at LISA

- Tripe Higgs couplings are in the focus of current and future colliders
  ⇒ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$
  BSM case 1: $\kappa_\lambda \neq 1$ (particularly via 1-loop corrections)
  BSM case 2: THC that involves BSM Higgses: $\lambda_{hhH}, \ldots$

- Searches for resonant di-Higgs production:
  ⇒ exp. analyses leave out interferences ⇒ results not reliable

- Acces to $\lambda_{hhH} \times \xi_H^t$ at the HL-LHC:
  ⇒ NN analysis shows remarkable sensitivity


Further Questions?