SUSY 2024

Theory meets Experiment

Madrid, 10 – 14 June 2024

Pre-SUSY school: 3 – 7 June 2024

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Signs for a FOEWPT at the LHC?!

Sven Heinemeyer, IFT (CSIC, Madrid)

Dublin, 05/2024

1. Introduction
2. FOEWPT and GWs in the 2HDM
3. Signs of a FOEWPT at the LHC?
4. THCs at the HL-LHC and the ILC
5. Conclusions

1. Introduction

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

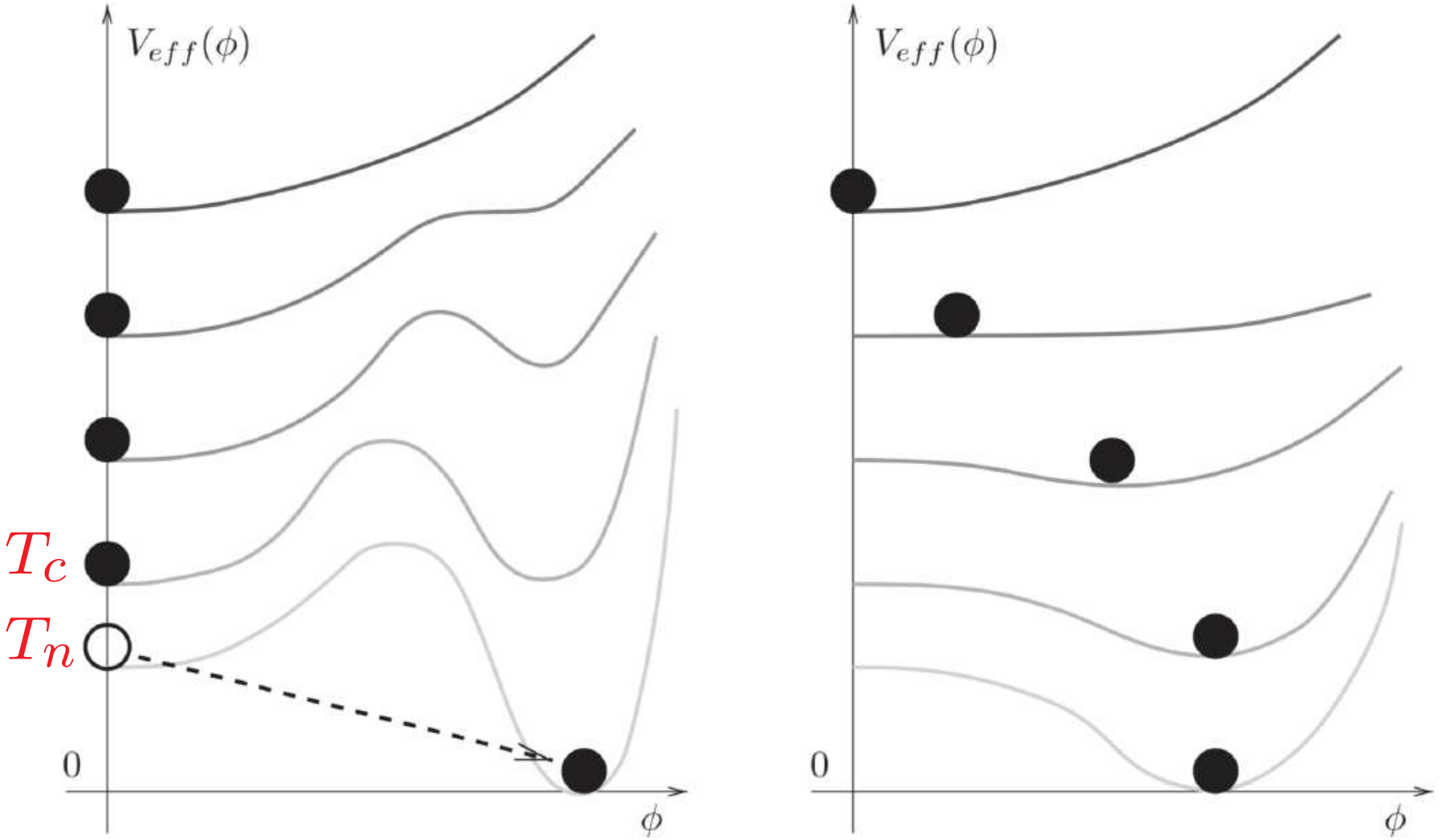
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

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

Phase transition: BSM vs. SM

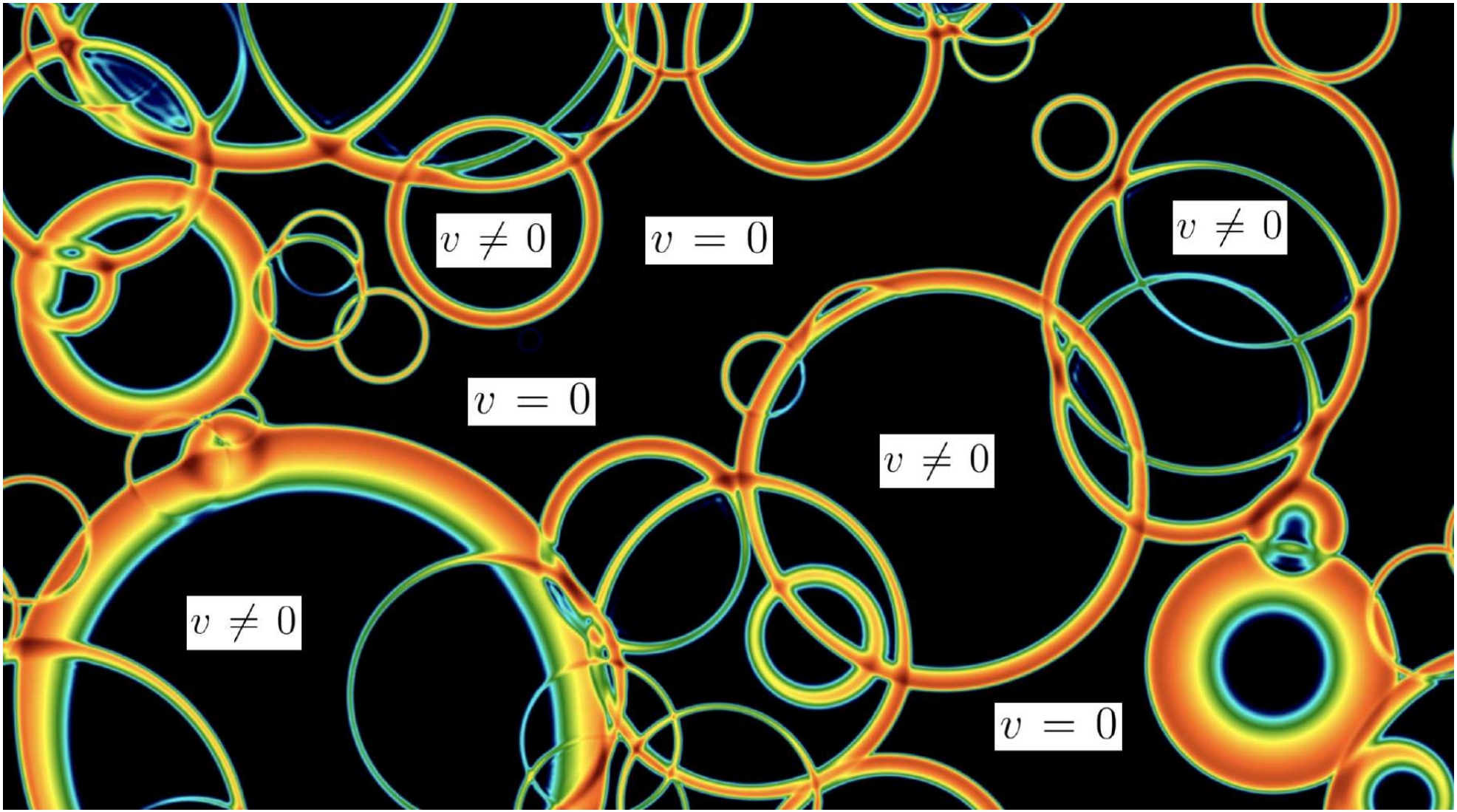
[taken from V. A. Rubakov and D. S. Gorbunov]



$\Rightarrow$ 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?

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: 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 : $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

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

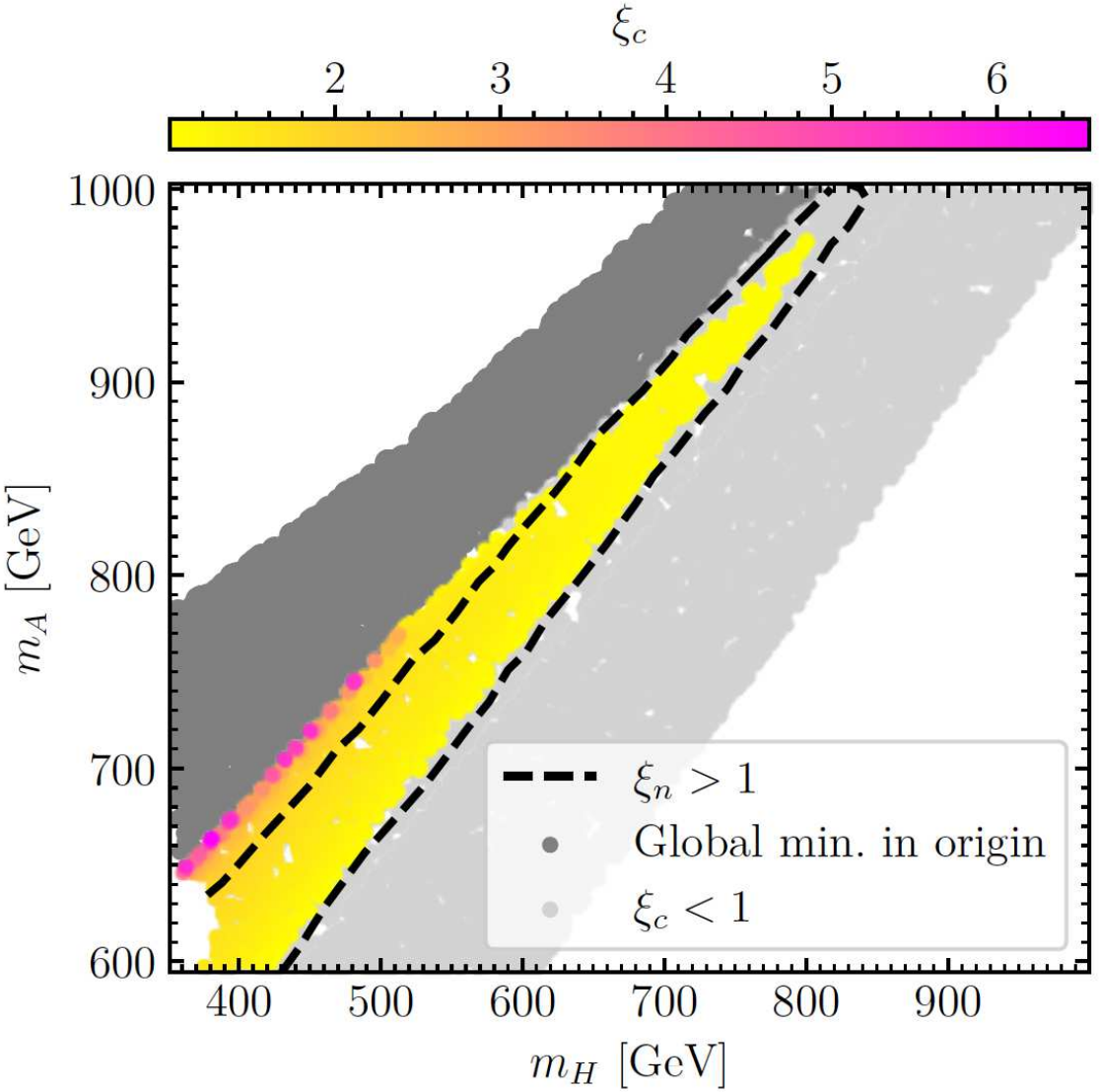
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\leq m_H \leq$ 1 TeV, 0.6 TeV $\leq m_A = m_{H^\pm} \leq$ 1.2 TeV

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 $\Rightarrow$ HiggsSignals (2HDECAY, SusHi)
  $\Rightarrow \chi^2_{125}$ (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

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

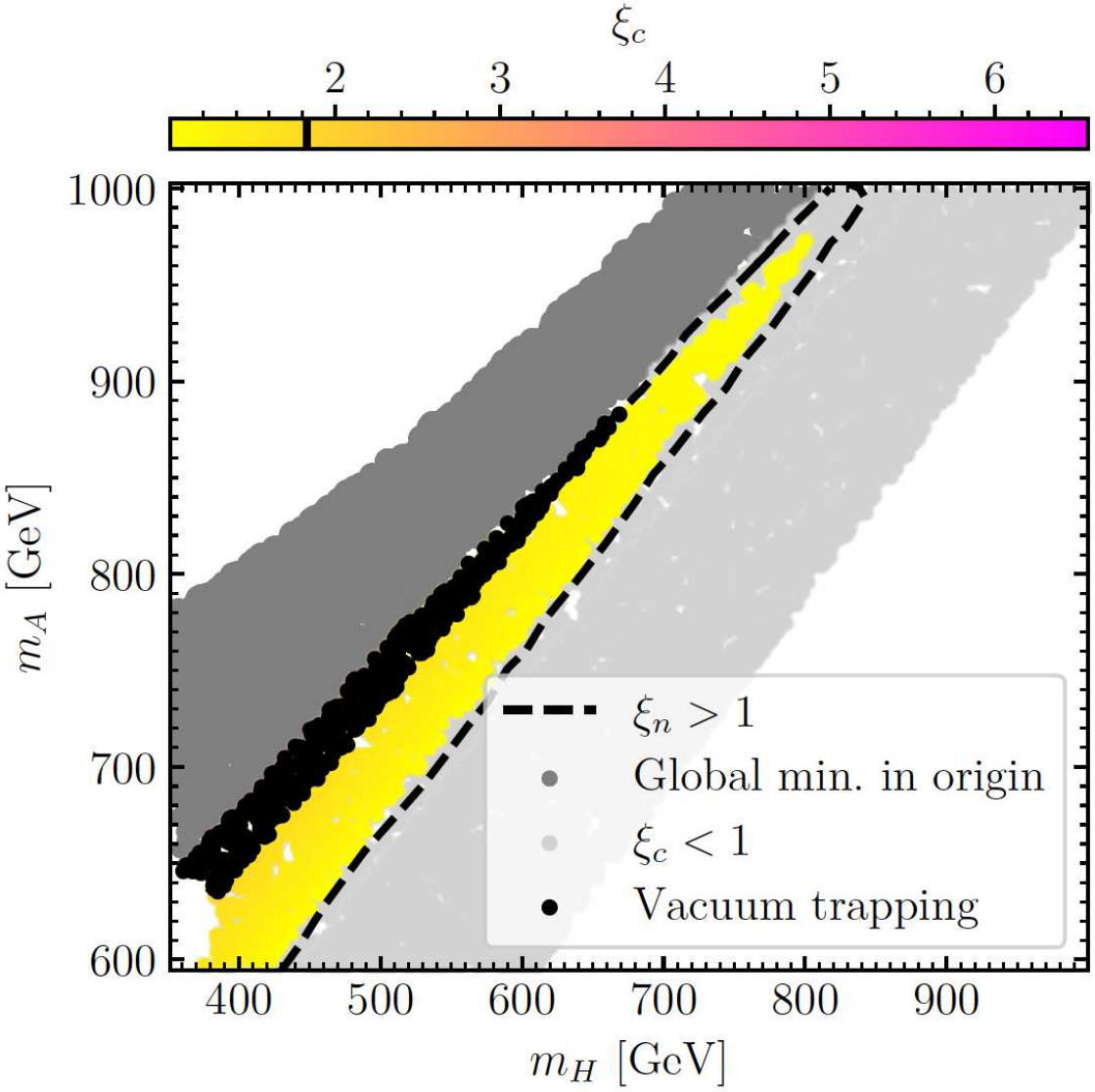
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



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

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

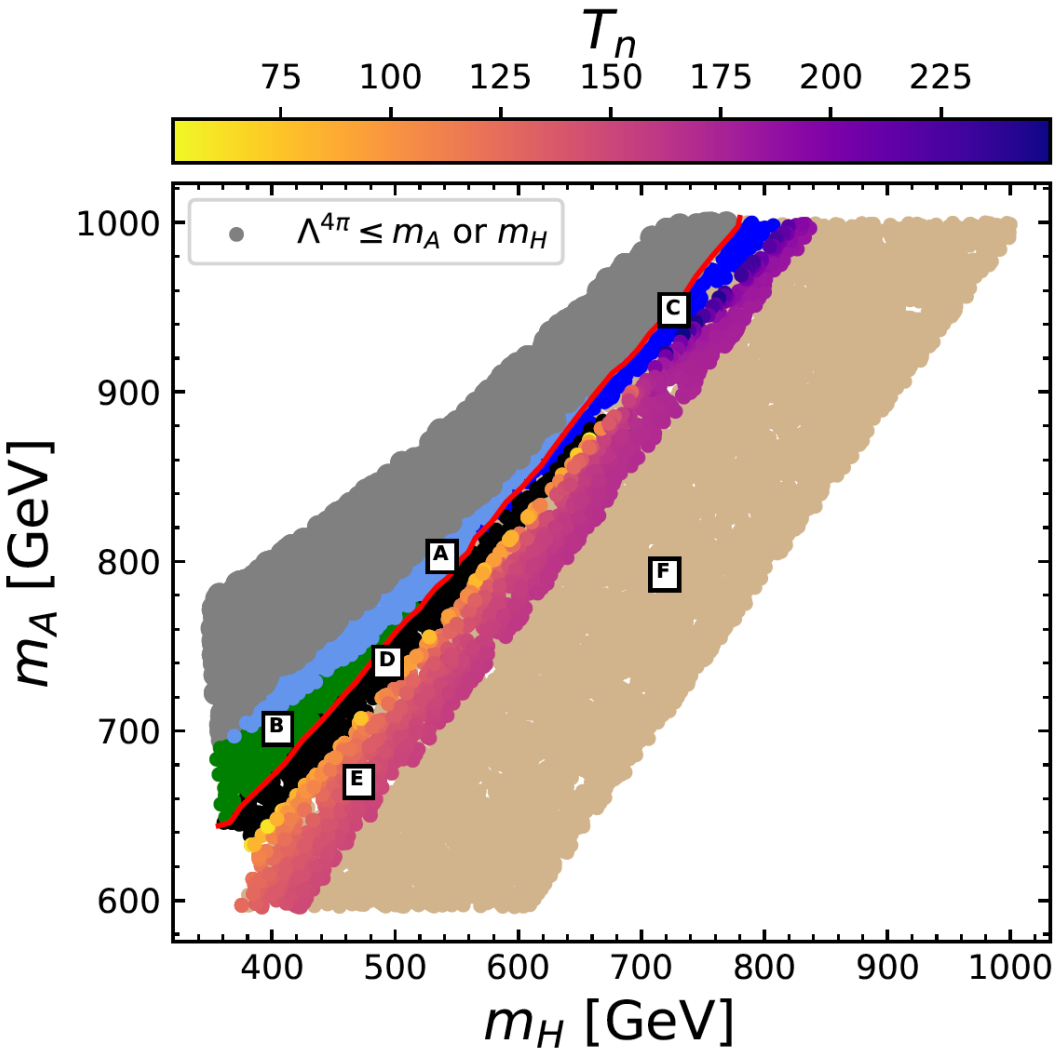
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



$\Rightarrow$ 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:

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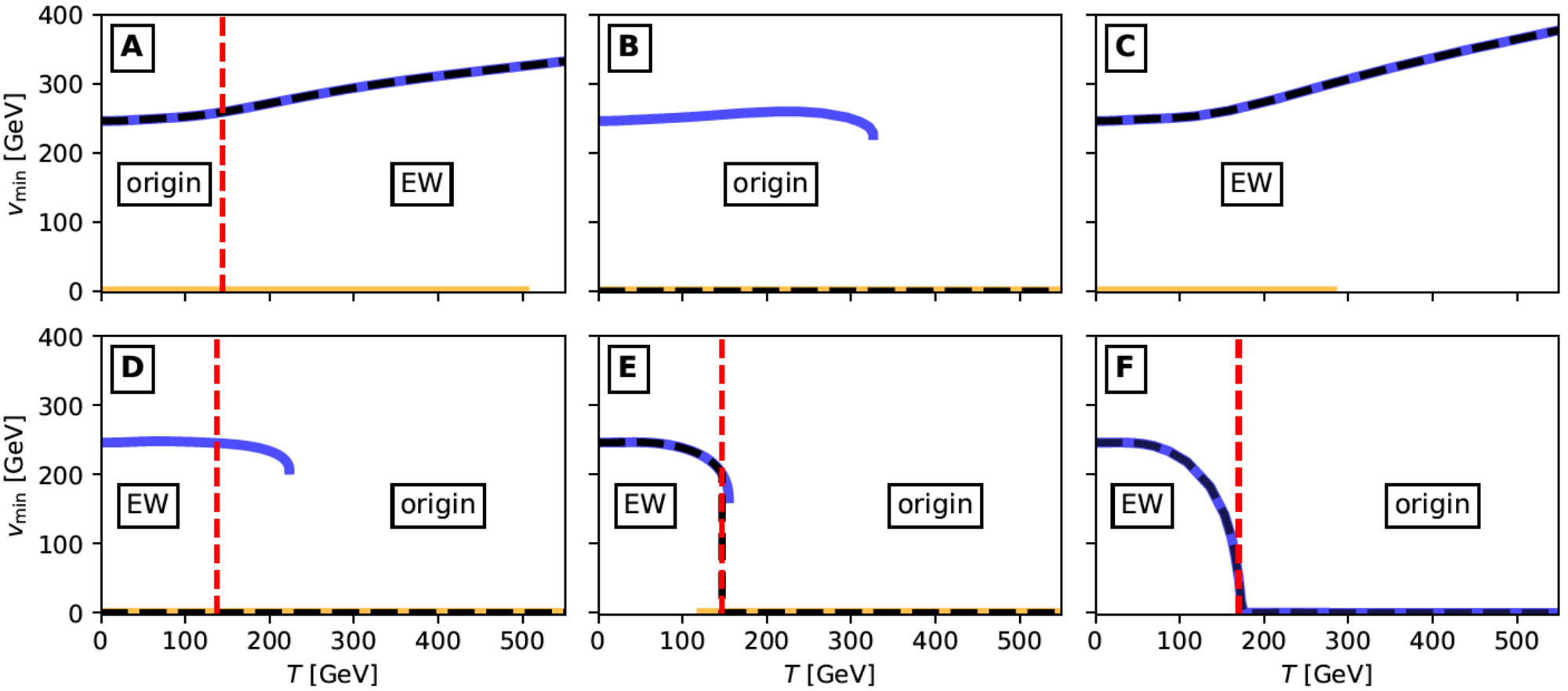
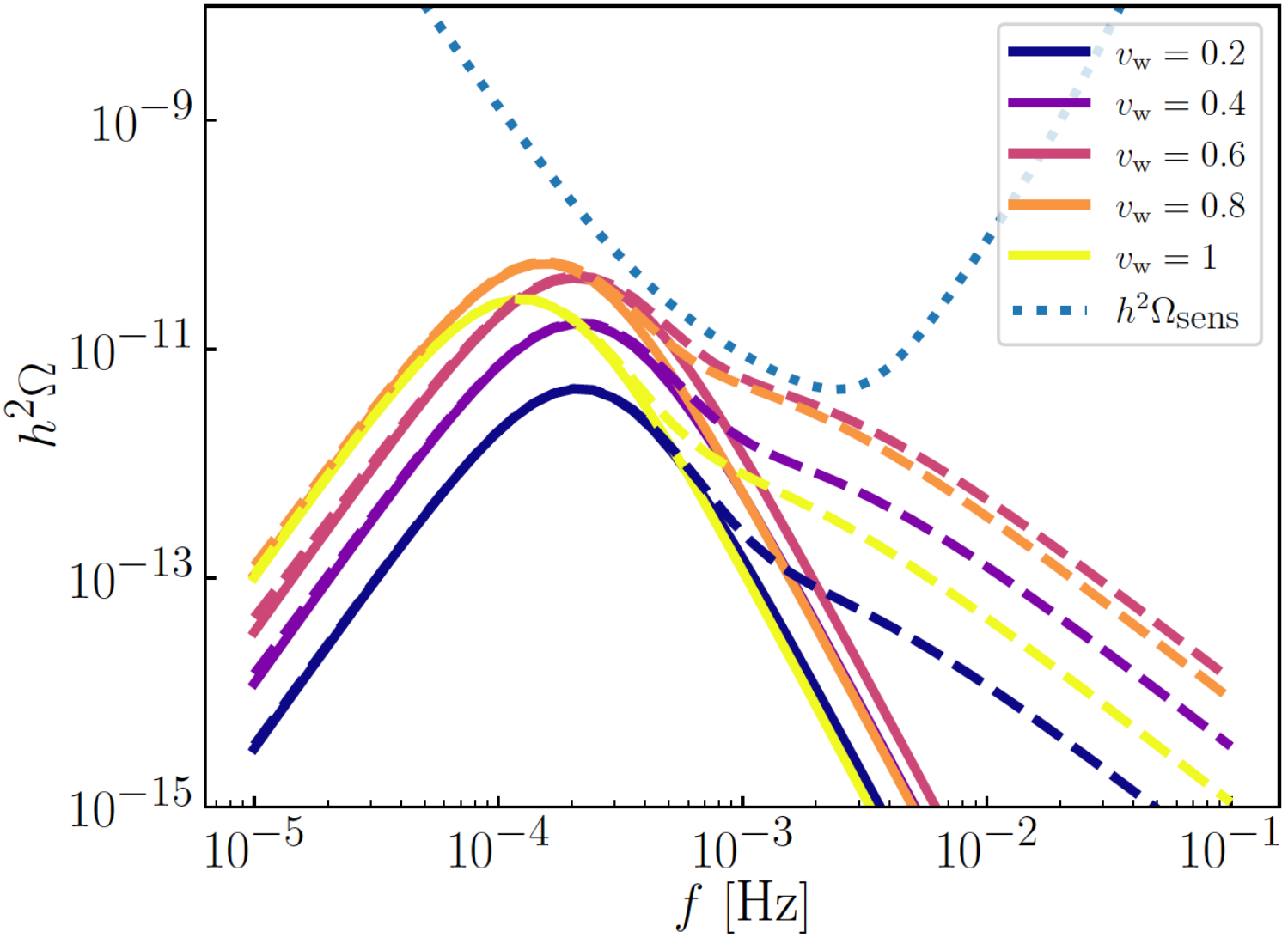


⇒ Zone E preferred by phenomenology/FOEWPT

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

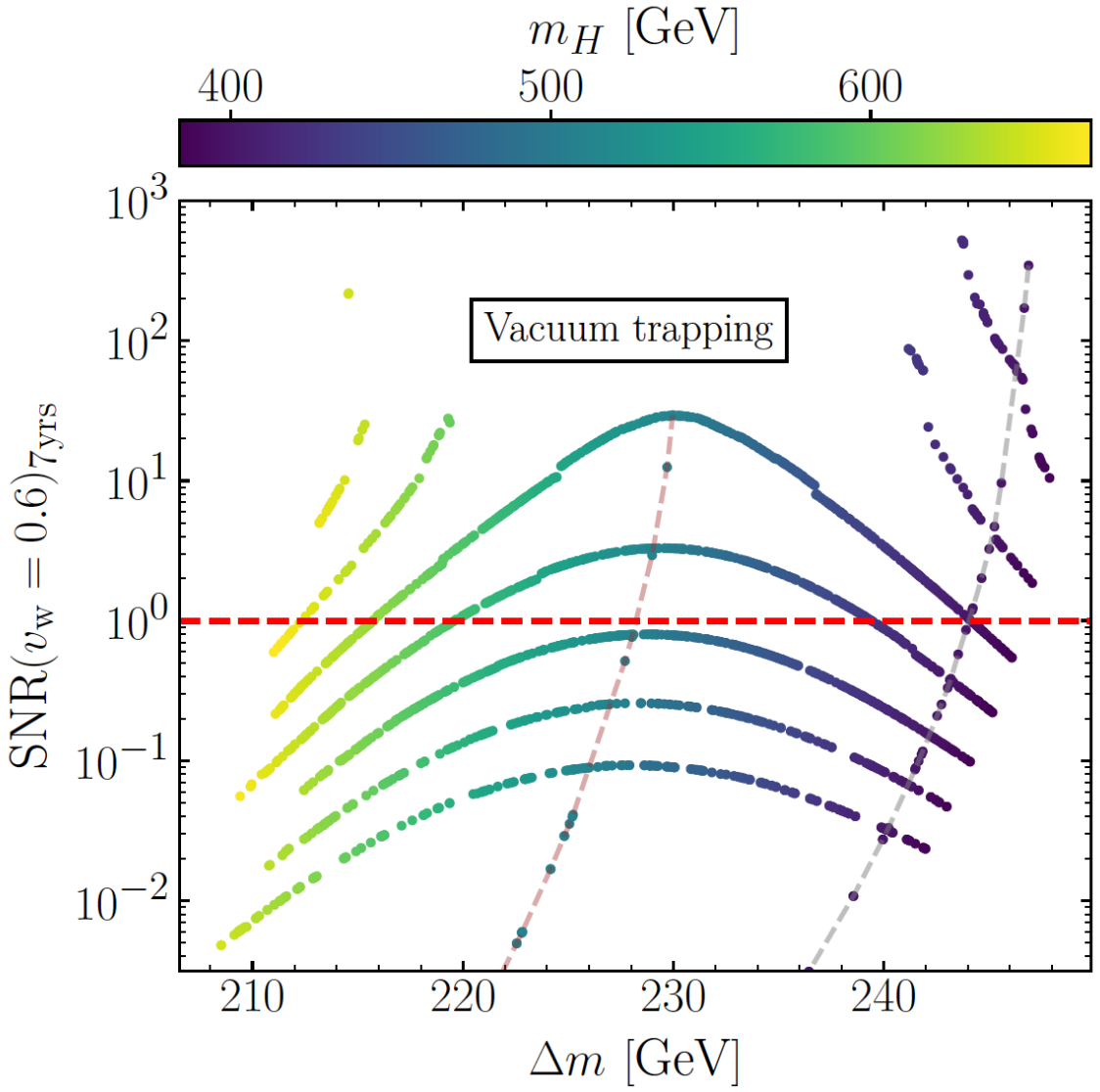
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



⇒ 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*]

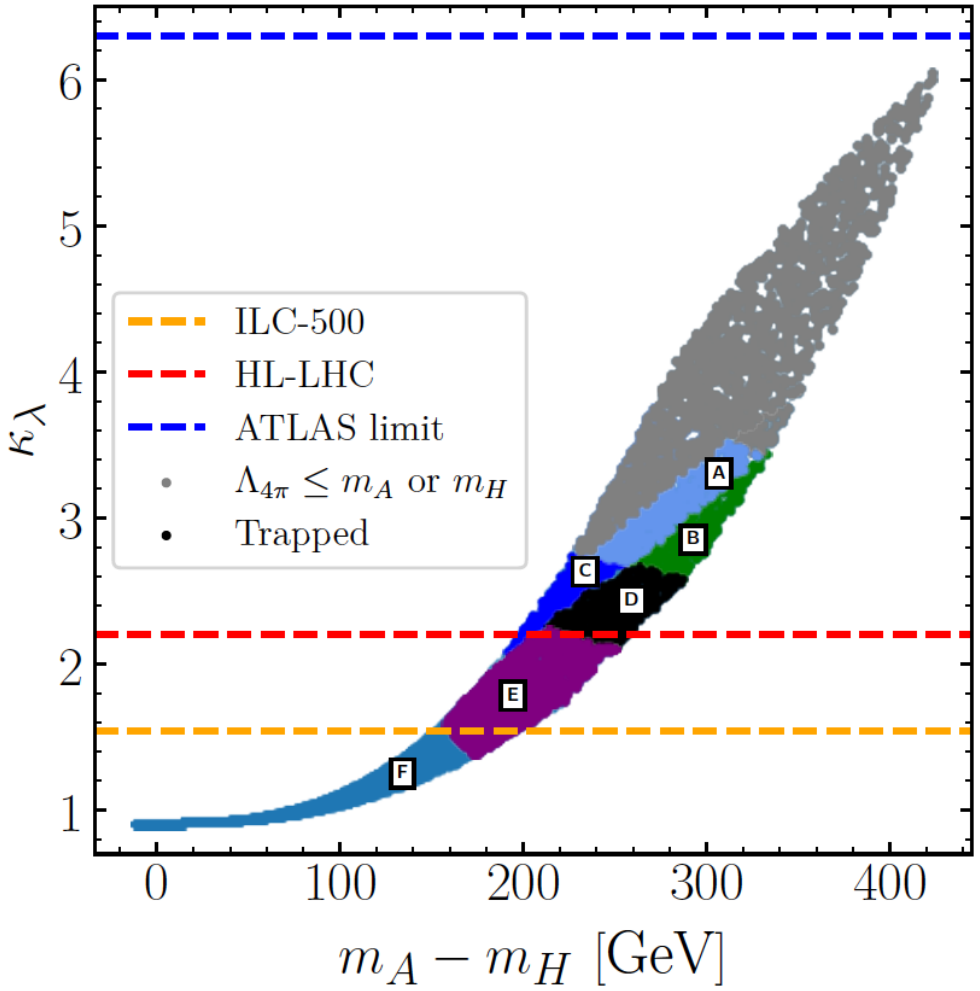


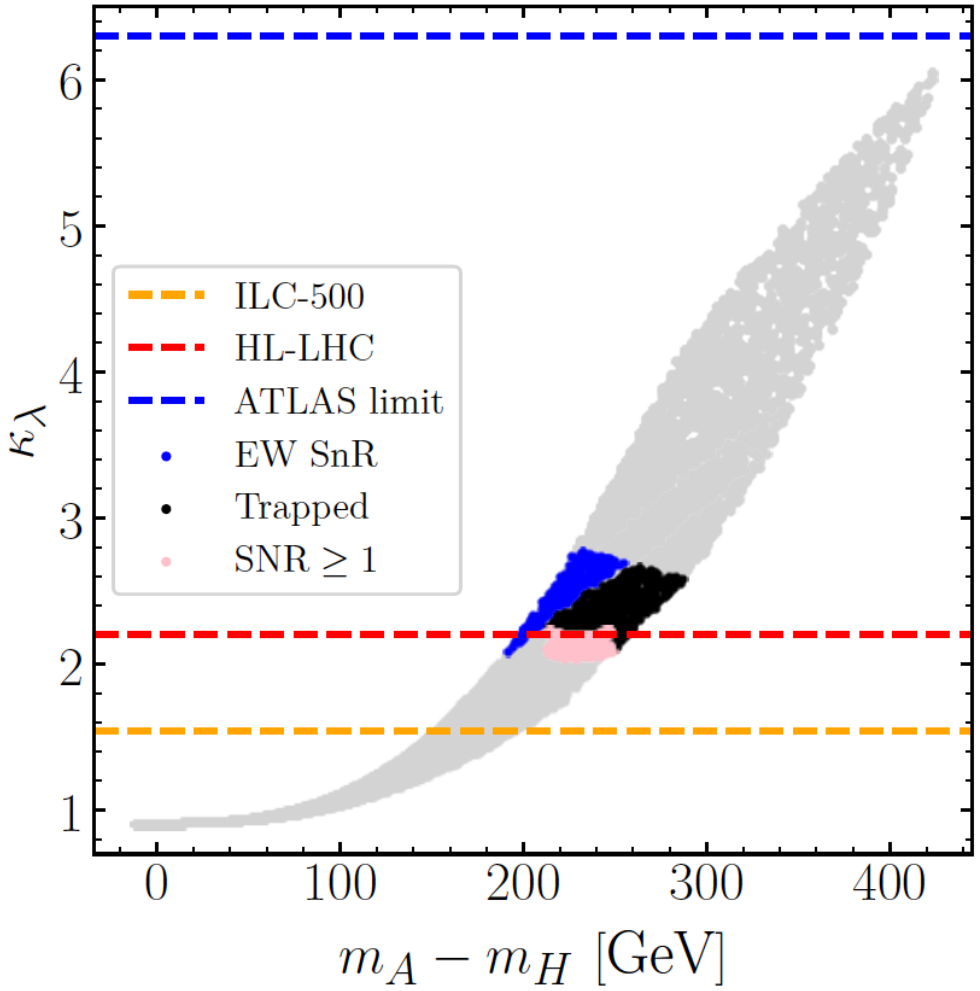
$\Rightarrow$ detectable GWs only in a very small zone close to VT

3. Signs of a FOEWPT at the LHC?

2HDM parameter scan to yield FOEWPT:

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



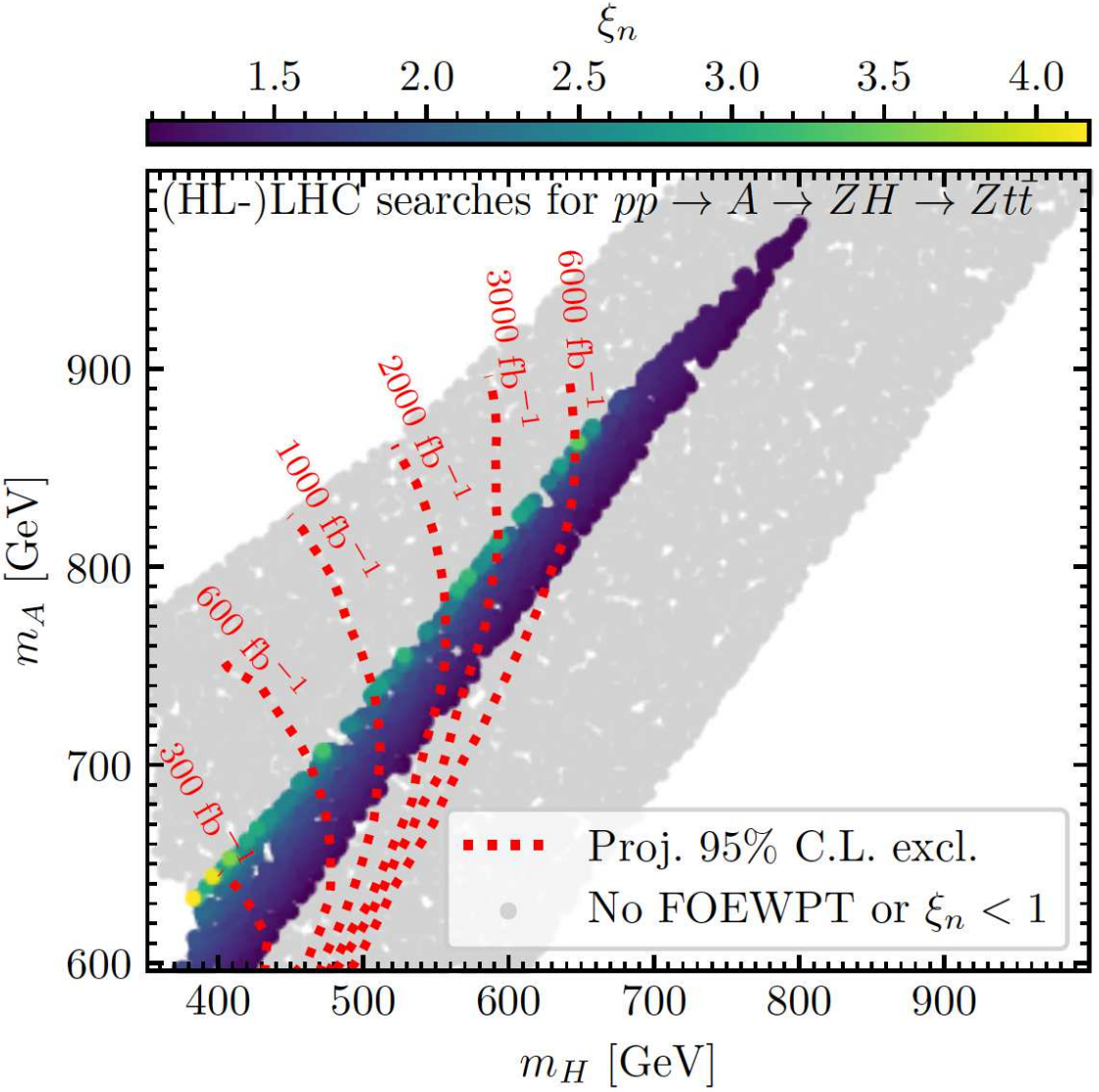


$\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$

$\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$

Smoking gun signature: gap between m_A and m_H

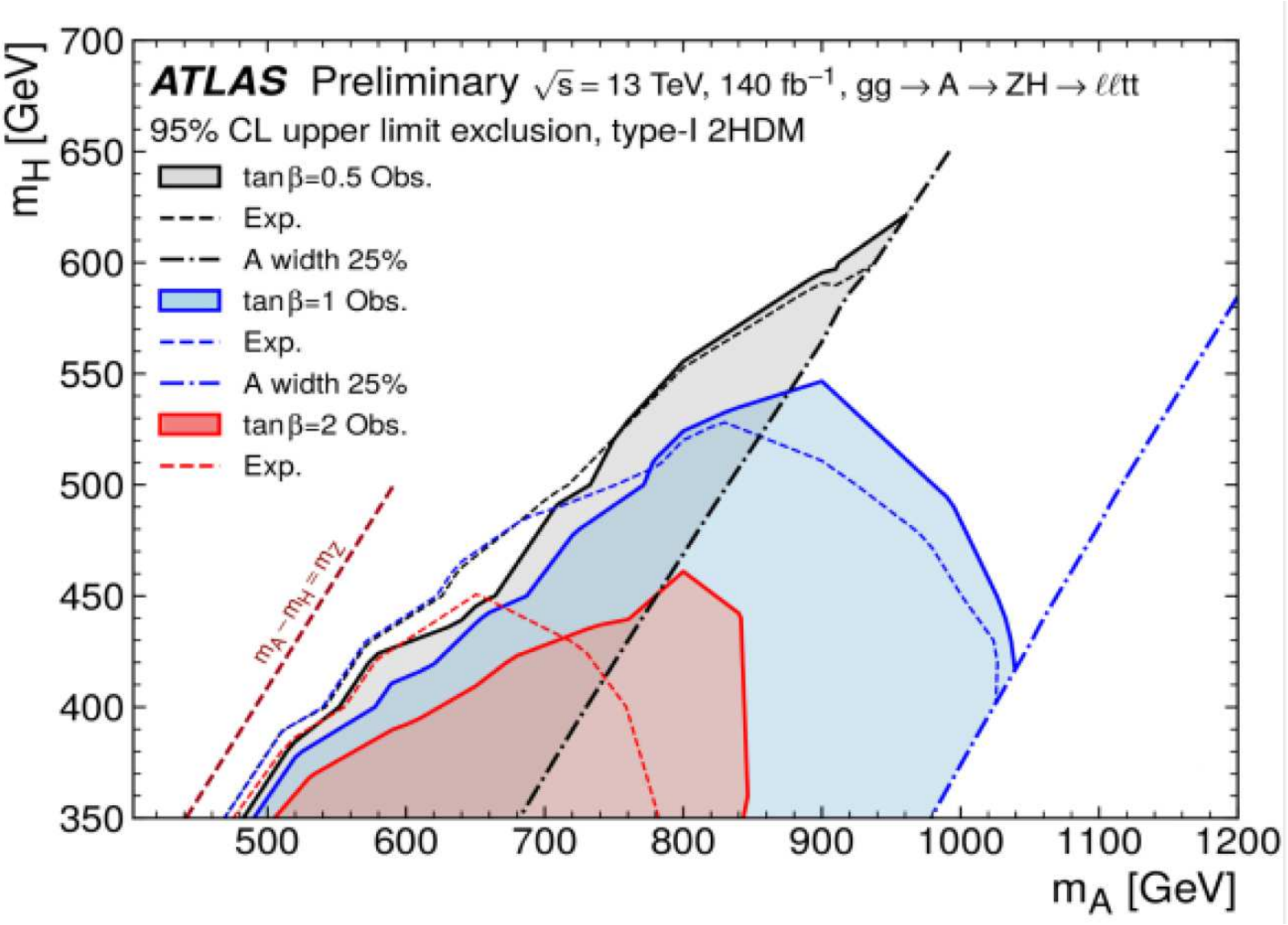
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



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

Latest experimental results: ATLAS at LHCP23

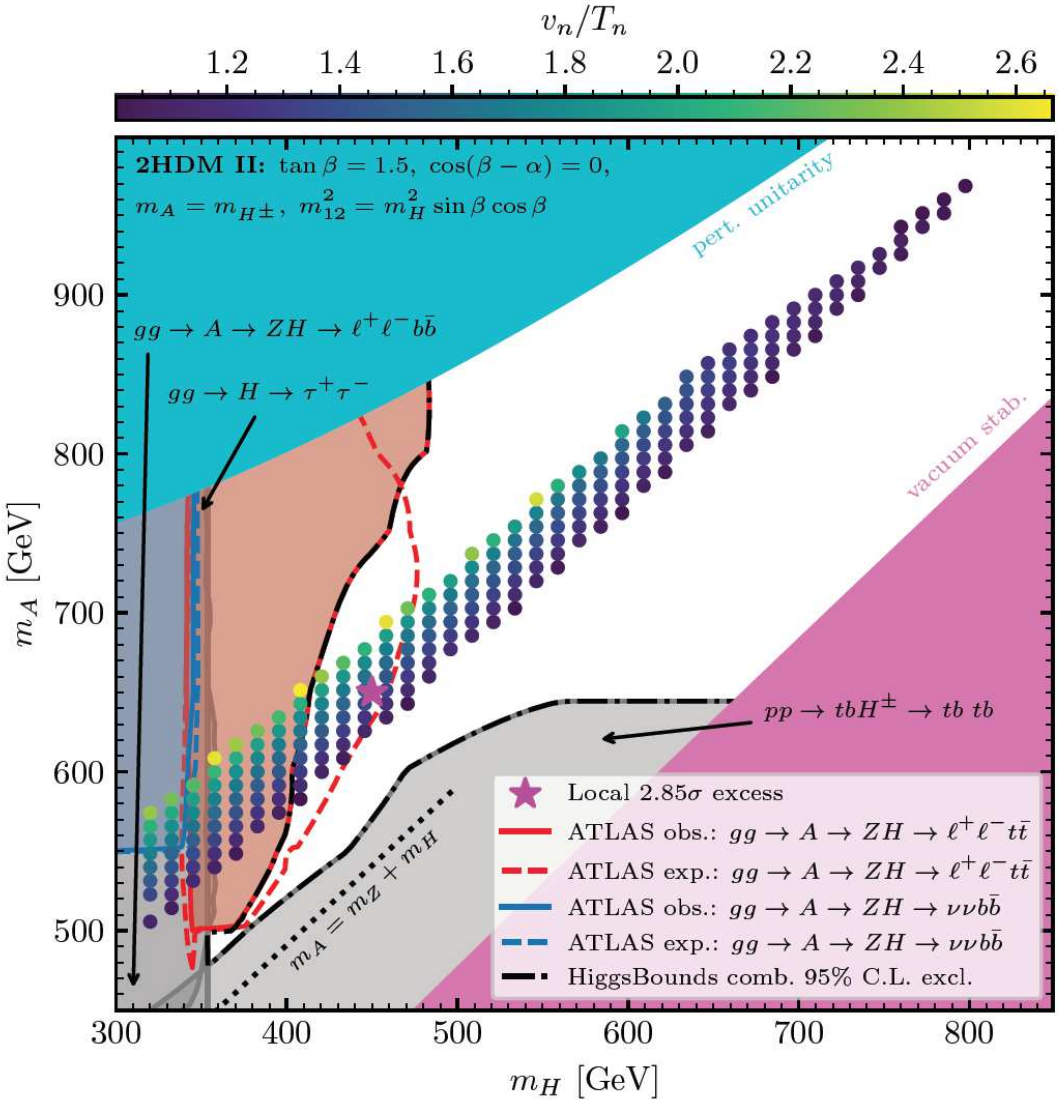
[*ATLAS '23*]



⇒ 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 $\tan\beta = 1.5$

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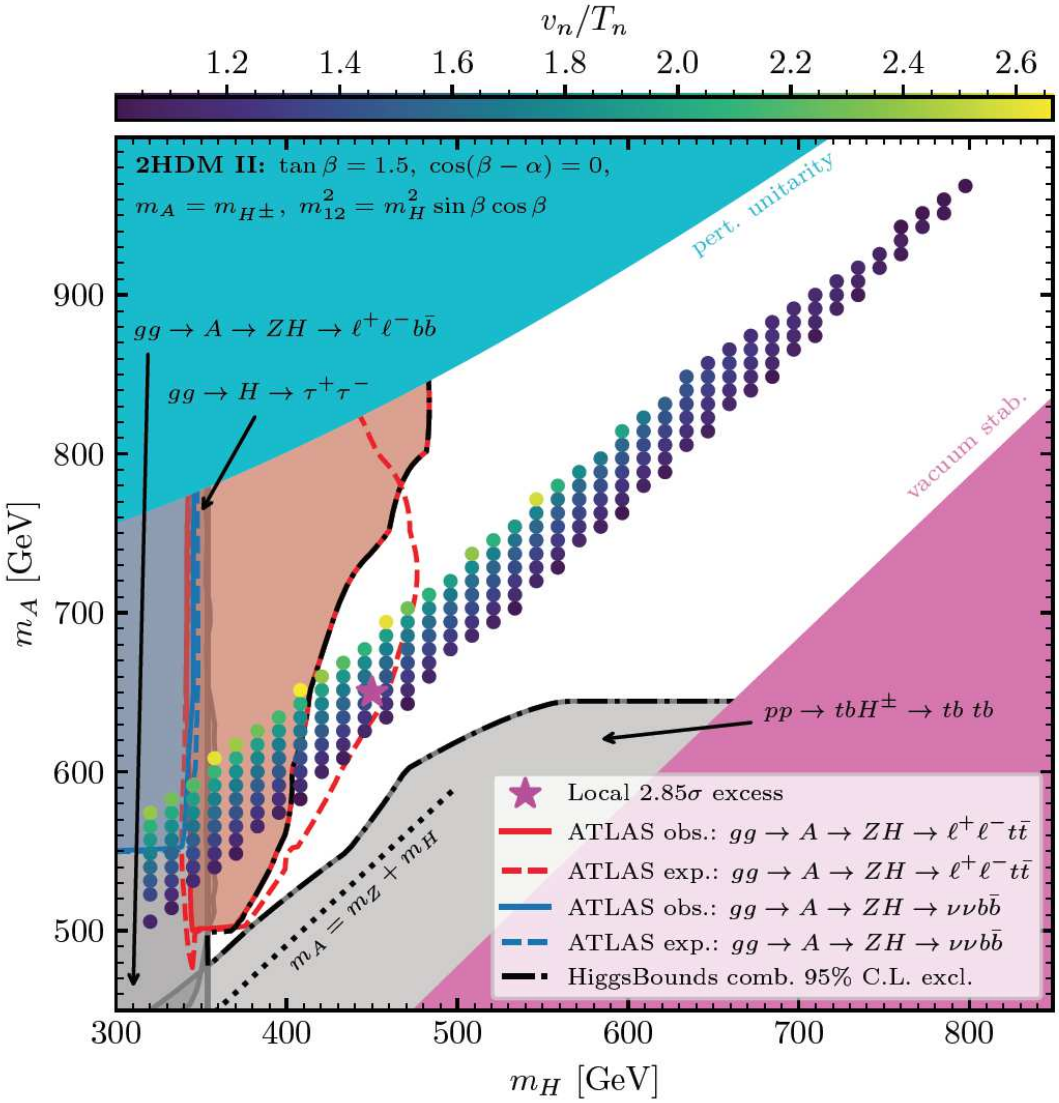
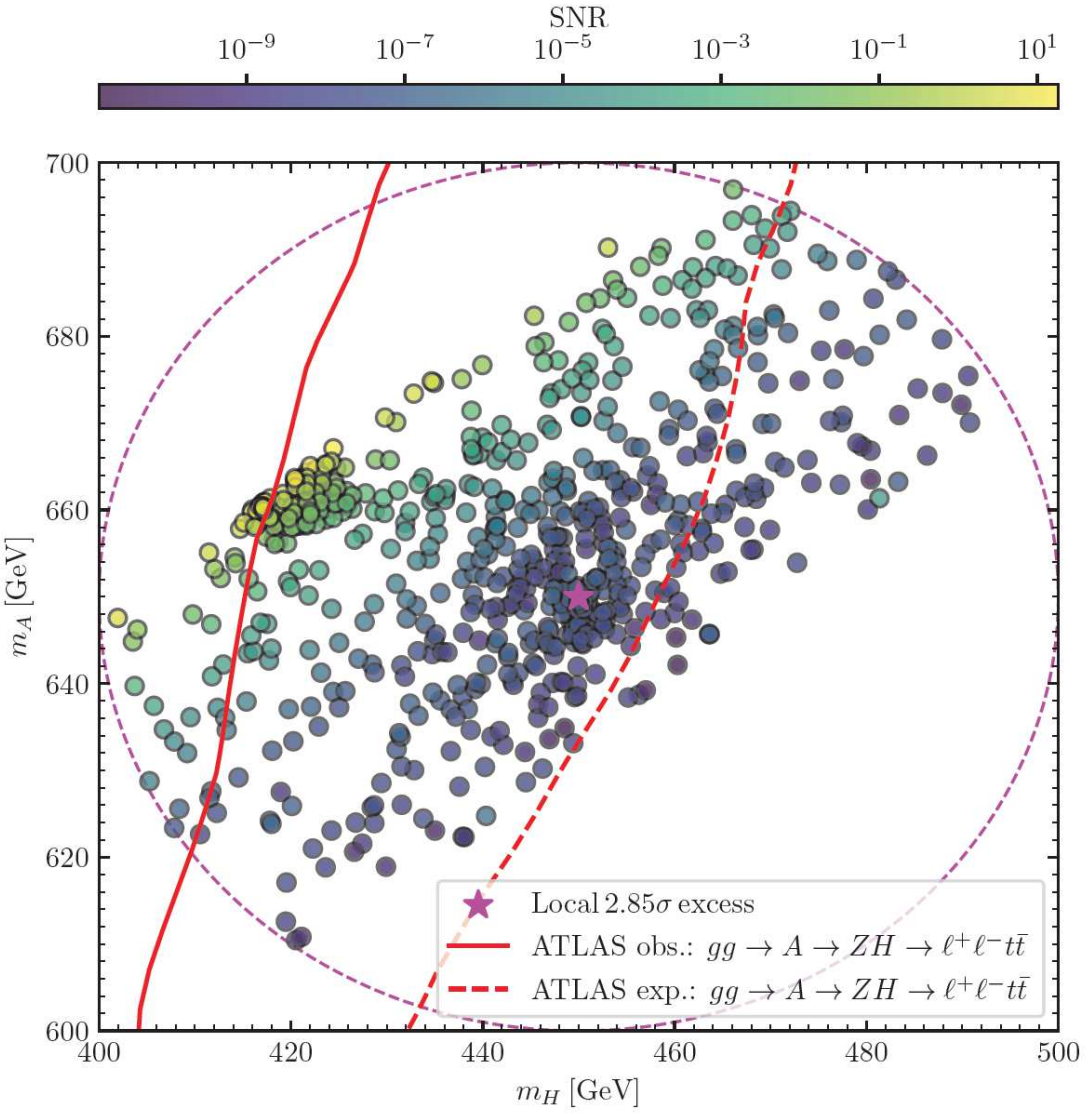


$\Rightarrow$ excess in the sweet spot $\Rightarrow$ not confirmed by CMS Run 2 analysis :-(

Smoking gun signature: GW signal at LISA?

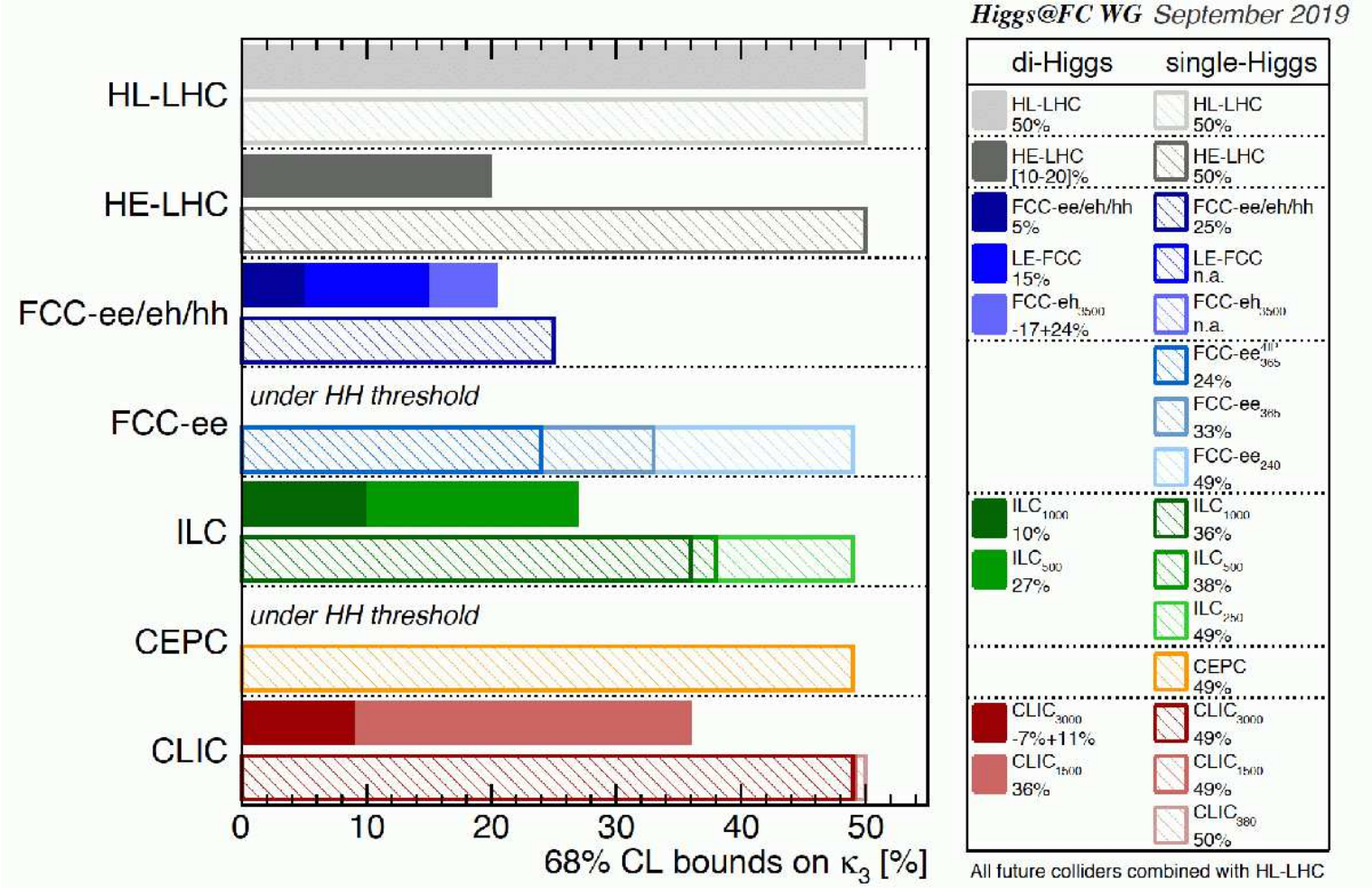
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]



$\Rightarrow$ GW signal at LISA possible, but not guaranteed

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

SM triple Higgs coupling: comparison of all colliders:



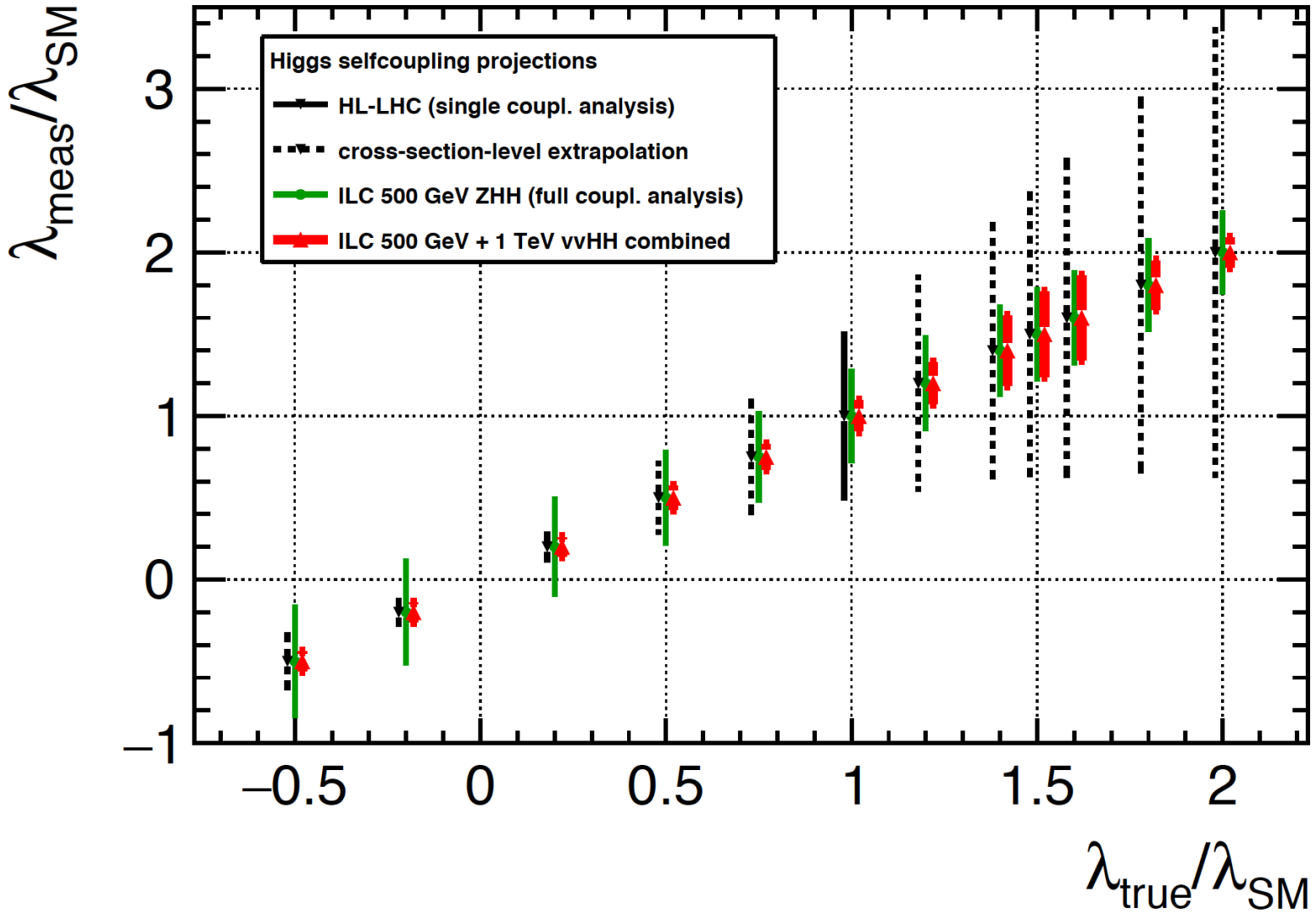
$\Rightarrow$ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda^{\text{SM}}_{hhh}$

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

BSM case 2: THC that involves BSM Higgses: λ_{hhH}, ...

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

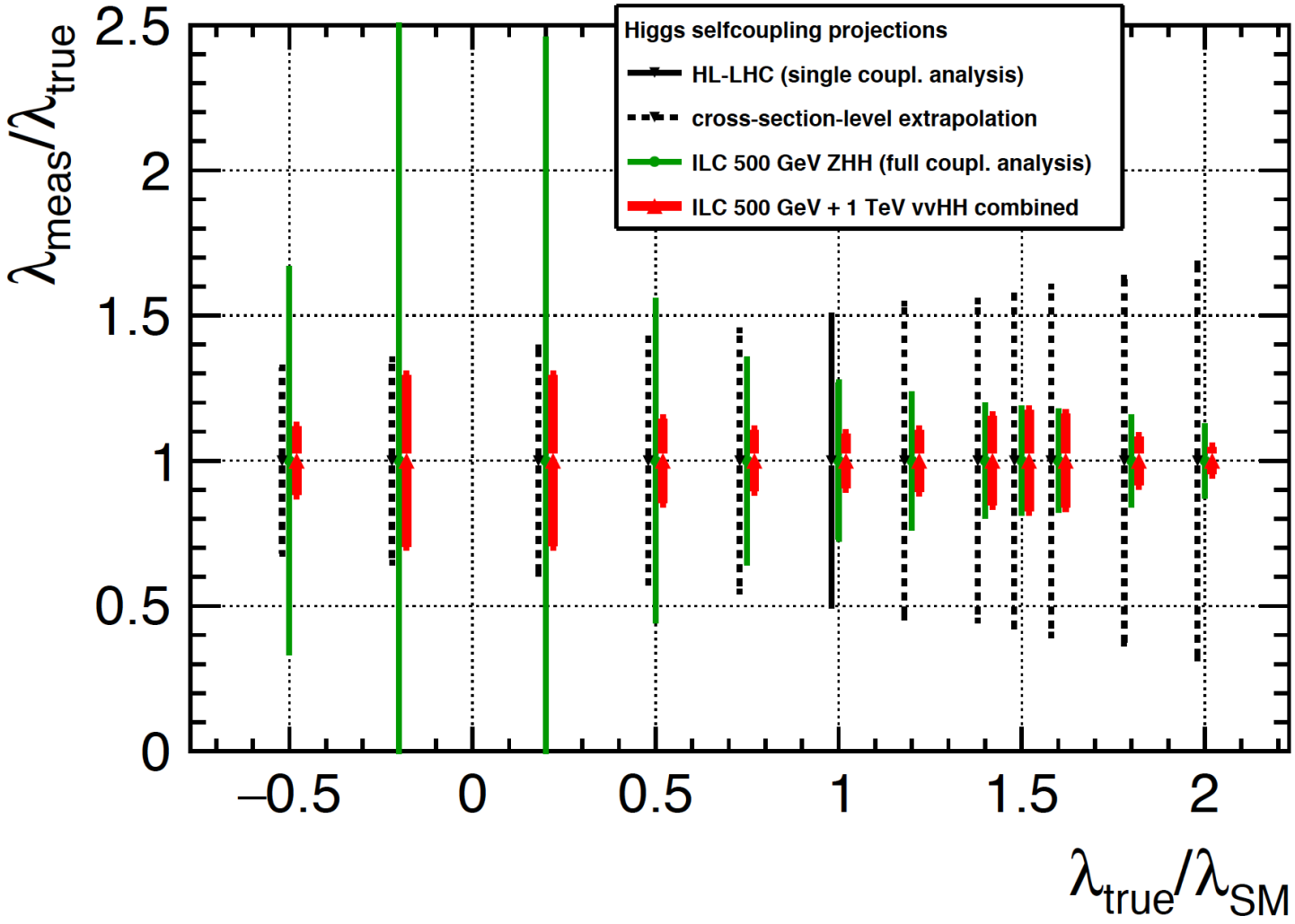
[J. List et al. – PRELIMINARY]



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

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

[J. List et al. – PRELIMINARY]

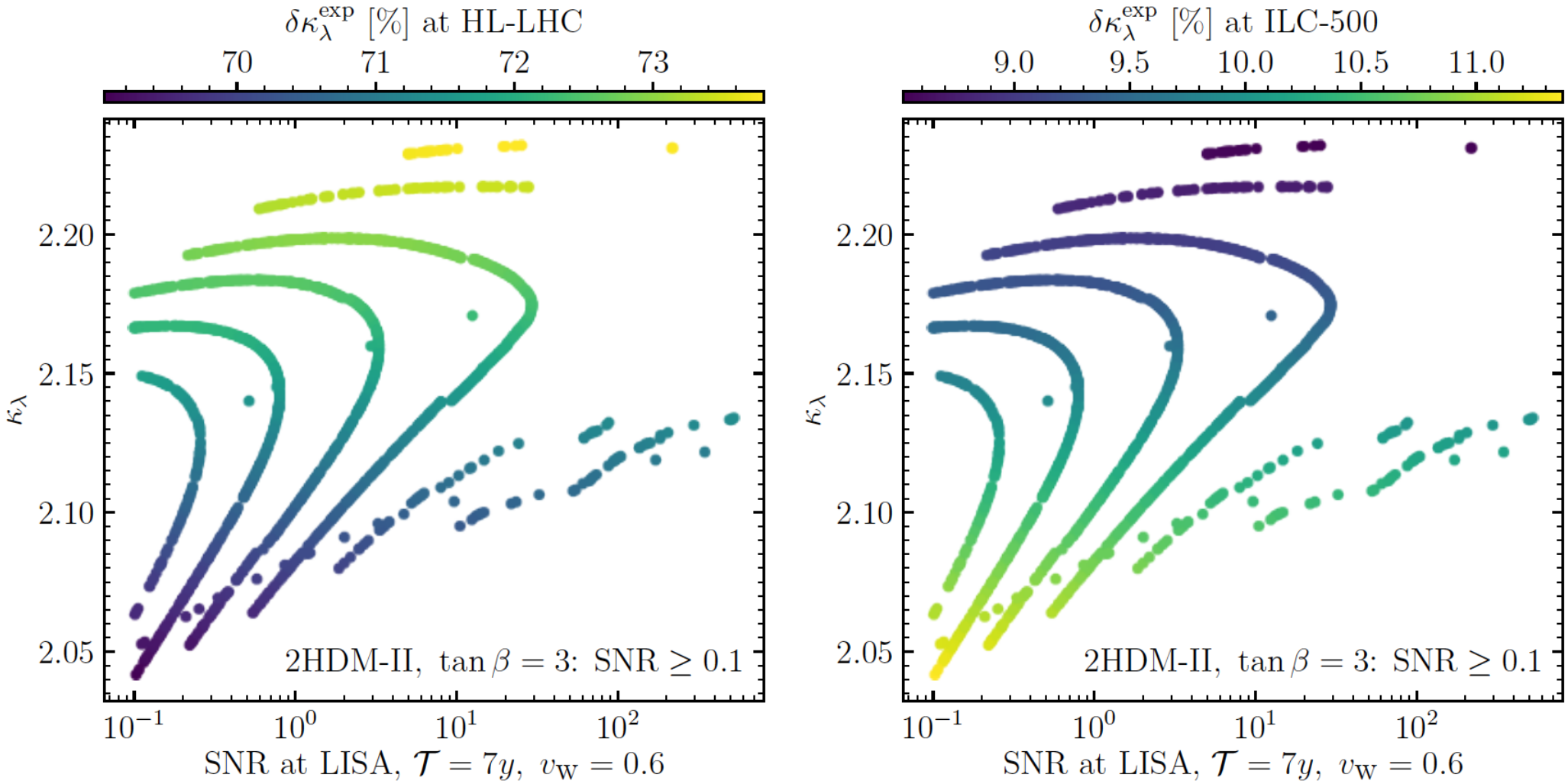


⇒ over most of the parameter space ILC is clearly superior to HL-LHC

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

5. Conclusions

- $\Rightarrow$ Why is there more matter than antimatter? $\Rightarrow$ (EW) baryogenesis
  $\Rightarrow$ requires First Order EW Phase Transition (FOEWPT)
  FOEWPT not possible in the SM $\Rightarrow$ BSM Higgs sector required
  FOEWPT can cause Gravitational Waves (GW), detectable with LISA
  Implications for the (HL-)LHC?

- Model under investigation: 2HDM
  Many triple Higgs couplings: λ_{hhh}, λ_{hhH}, λ_{hHH}, $\lambda_{hH^+H^-}$, λ_{HAA}, ...
  $\Rightarrow$ talk by Kateryna Radchenko on Sunday

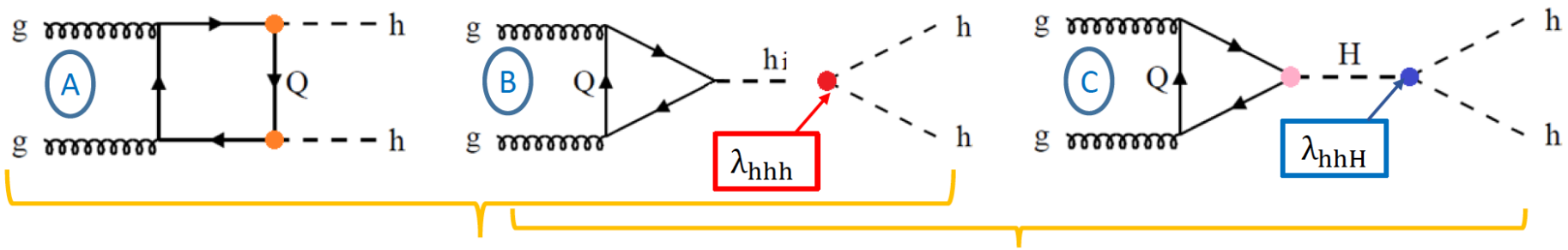
- 2HDM:
  $\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$ $\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$
  $\Rightarrow$ bad for HL-LHC ($\delta\lambda_{hhh} \sim 70\%$), good for ILC ($\delta\lambda_{hhh} \sim 10\%$)

- $\Rightarrow$ FOEWPT favors A-H mass gap $\Rightarrow$ Smoking gun: $A \to ZH \to Zt\bar{t}$
  $\Rightarrow$ ATLAS: $2.9\,\sigma$ excess ($m_H = 450$ GeV, $m_A = 650$ GeV)
  $\Rightarrow$ possible GW det. at LISA
  $\Rightarrow$ not confirmed by CMS ...
  $\Rightarrow$ but this remains an interesting possibility!


Higgs Days at Santander 2024
Theory meets Experiment
9 – 13 September
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Gervasio.Gomez@cern.ch
http://hdays.csic.es


Further Questions?

Di-Higgs production at the LHC:

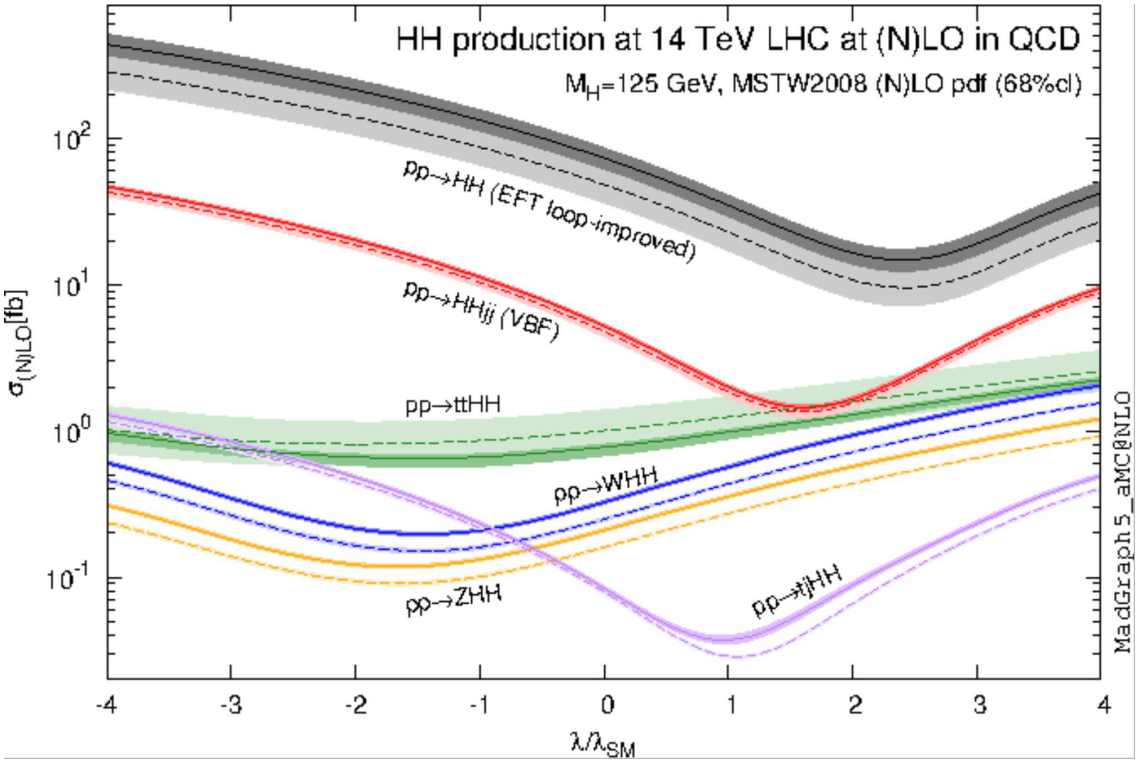


$\sigma_{SM} \sim$ 38 fb at NLO

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

Diagrams that are sensitive
to triple Higgs couplings

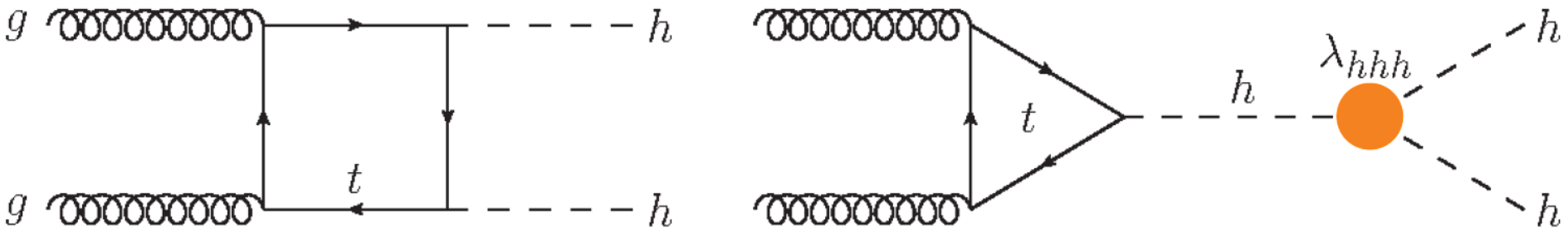
$\Rightarrow$ strong interference of "box" and "SM-like Higgs"



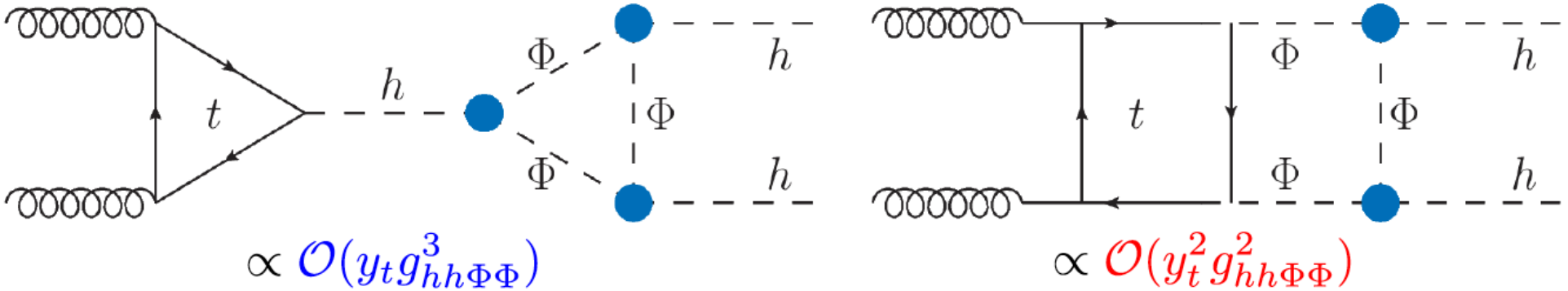
Higher-order correction to the THCs:

[*taken from J. Braathen*]

Box vs. s channel Higgs:



Inclusion of one-loop corrections to THCs:



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

Correction to λ_{hhh} → included

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

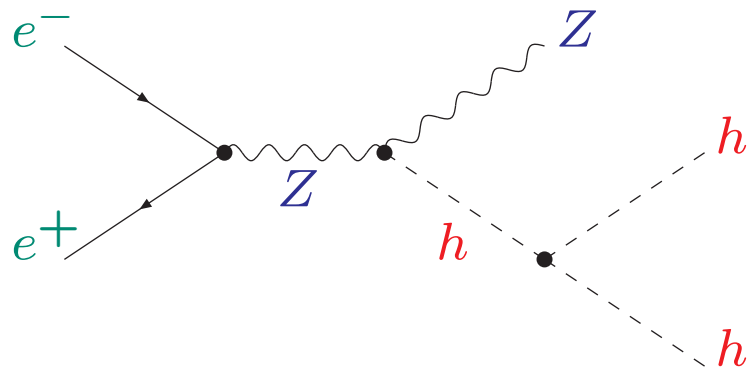
not included

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

Di-Higgs production at ILC/CLIC:

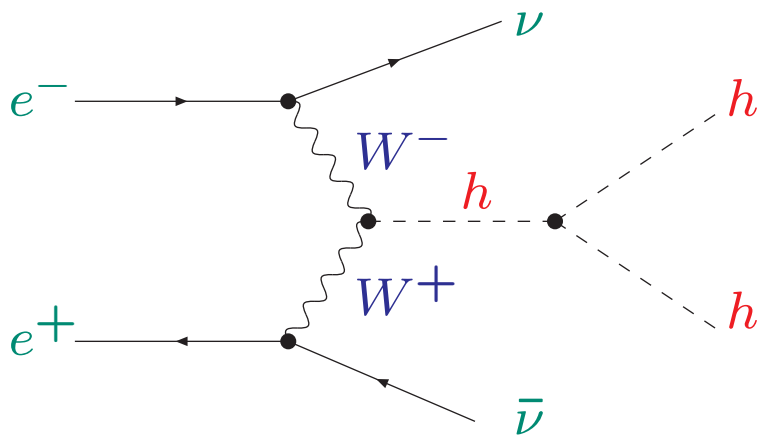
Higgs-strahlung:

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

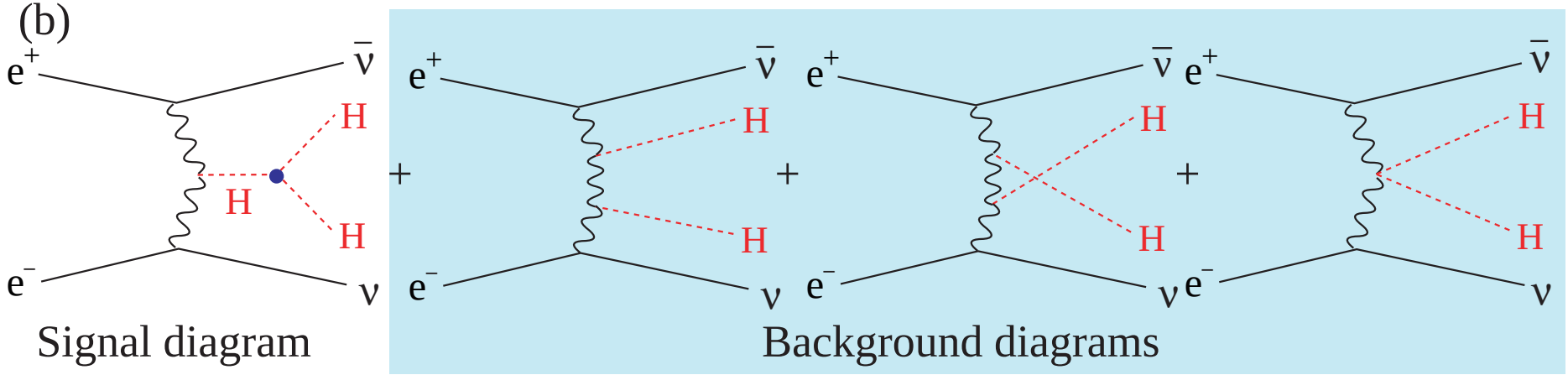


weak boson fusion (WBF):

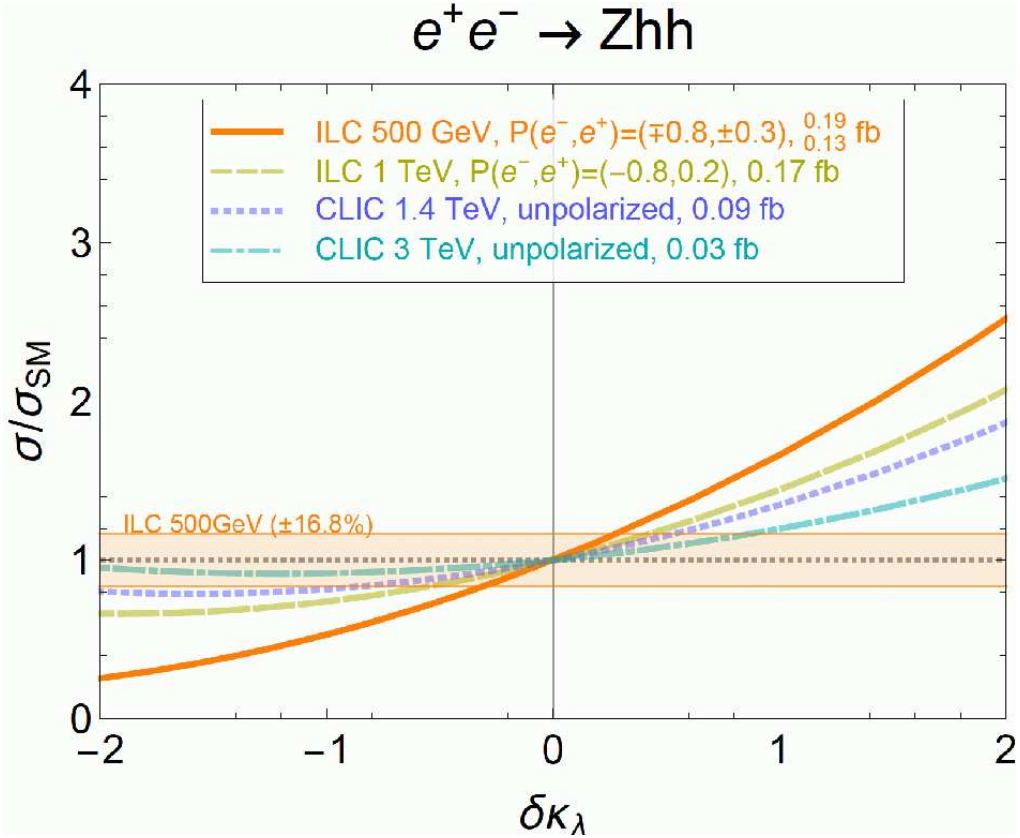
$e + e- \to \nu\bar{\nu}hh$

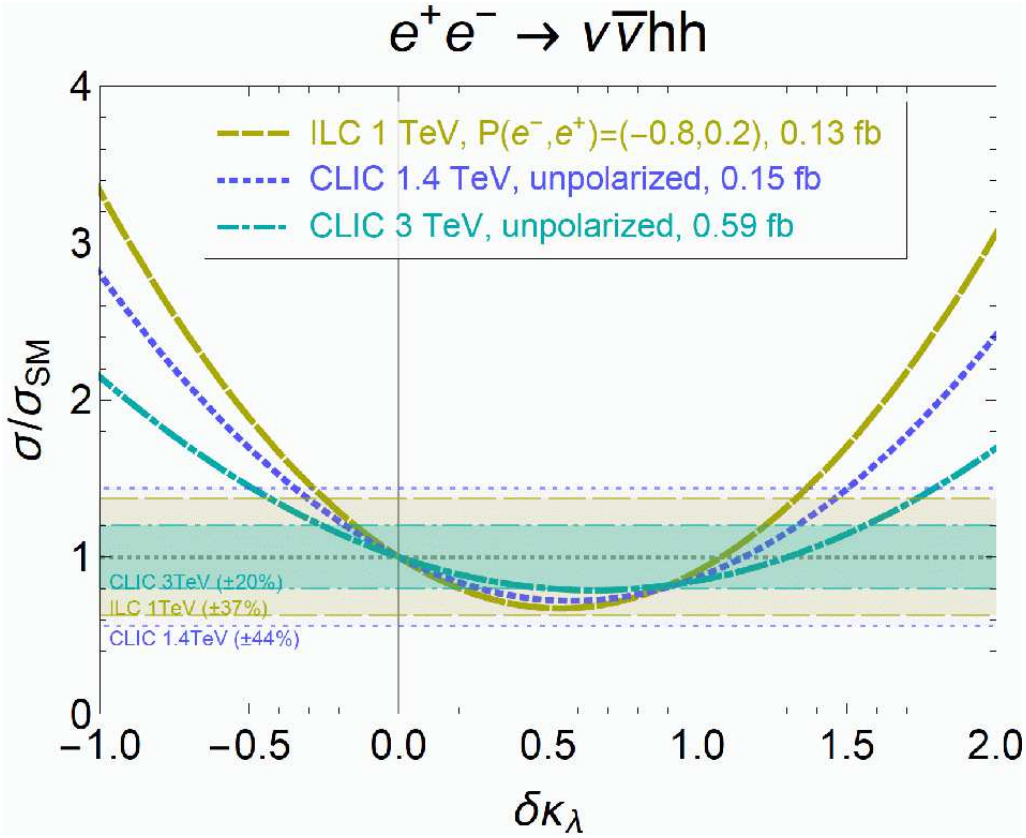


Signal and background interference:



Di-Higgs production at ILC/CLIC:





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

$\Rightarrow$ strong and different dependence on κ_λ