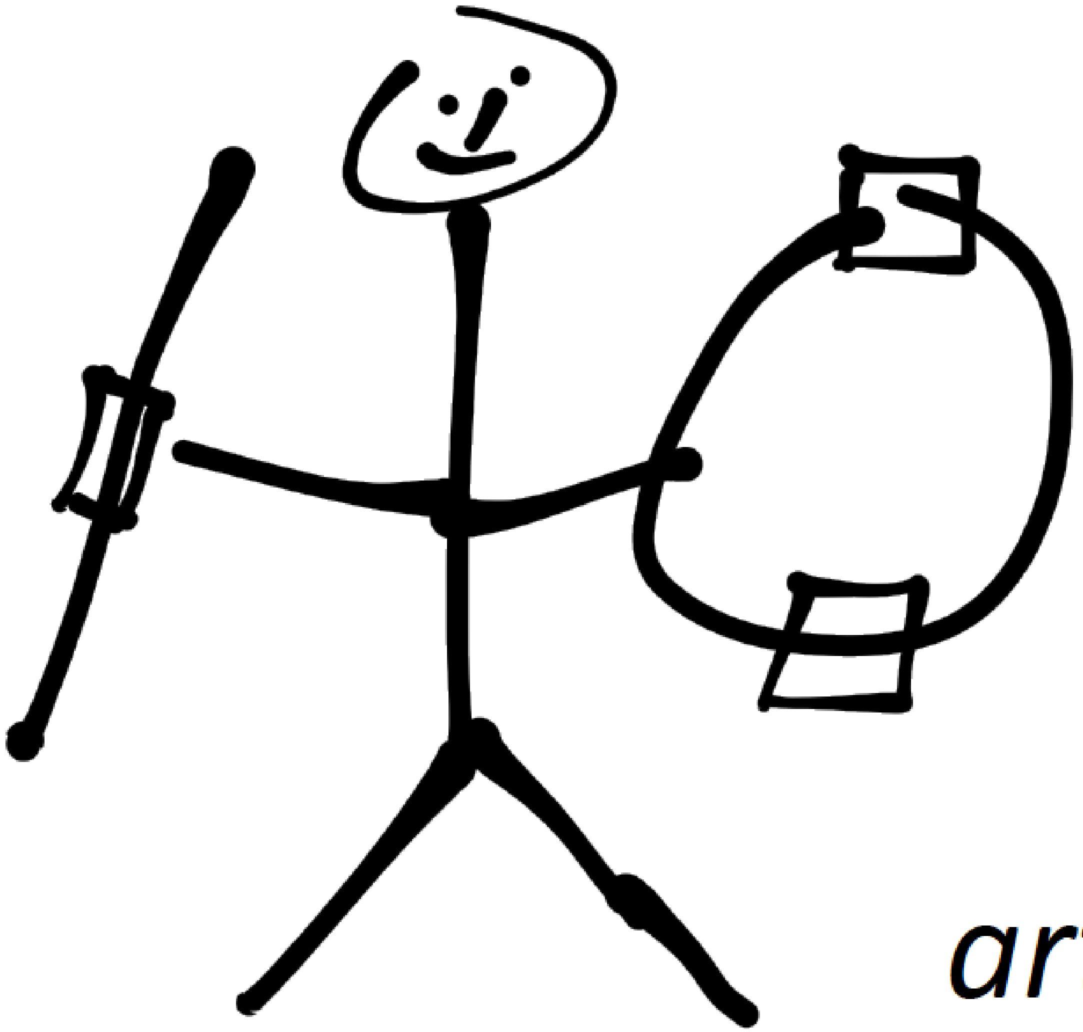


artwork by F. Simon

BSM Triple Higgs Couplings at ILC/CLIC

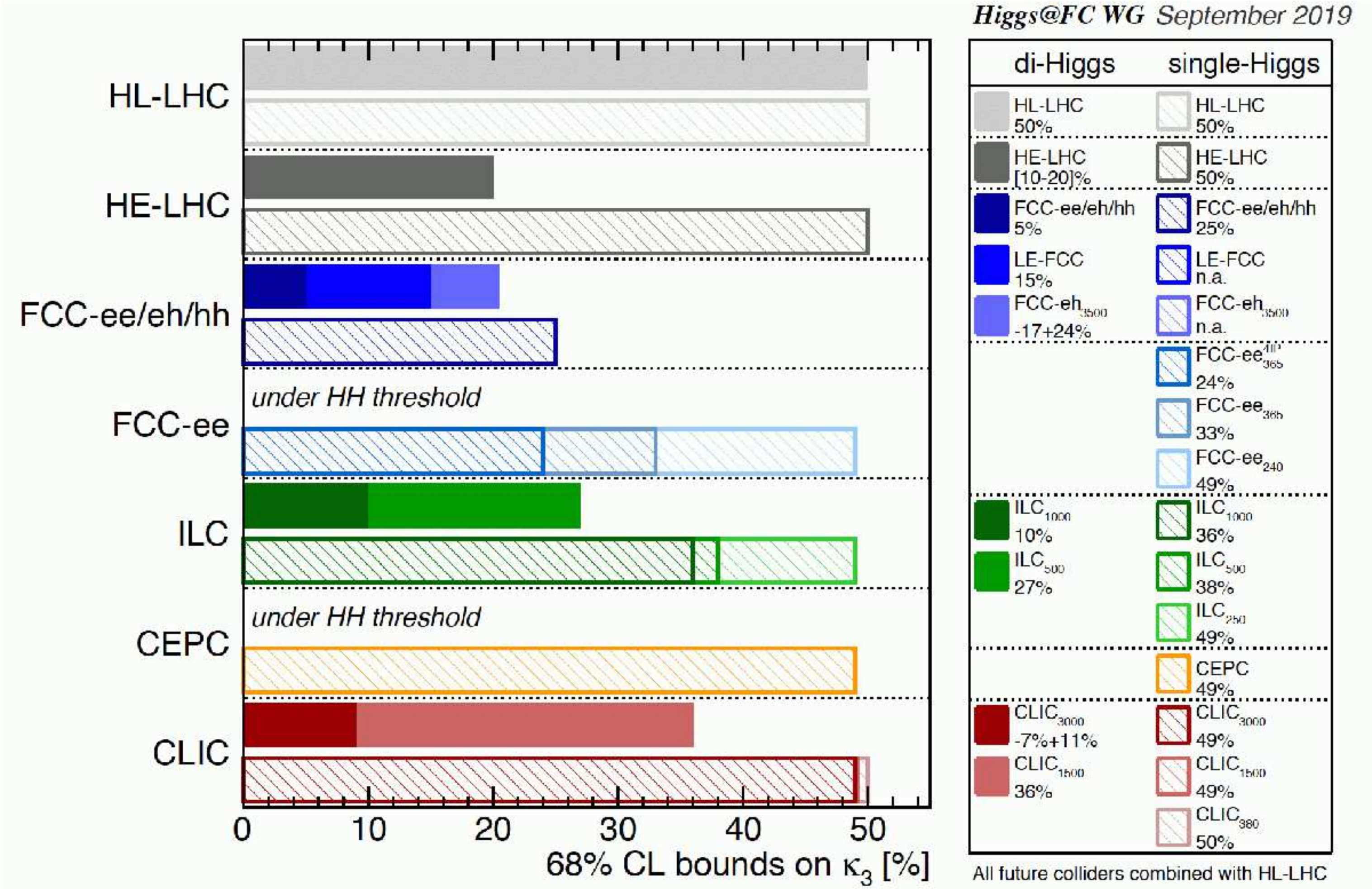
Sven Heinemeyer, IFT (CSIC, Madrid)

Paestum, 10/2023

1. Introduction
2. FOEWPT and THCs in the 2HDM
3. THCs in the 2HDM at the ILC/CLIC
4. Conclusions

1. Introduction

SM triple Higgs coupling: comparison of all colliders:



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

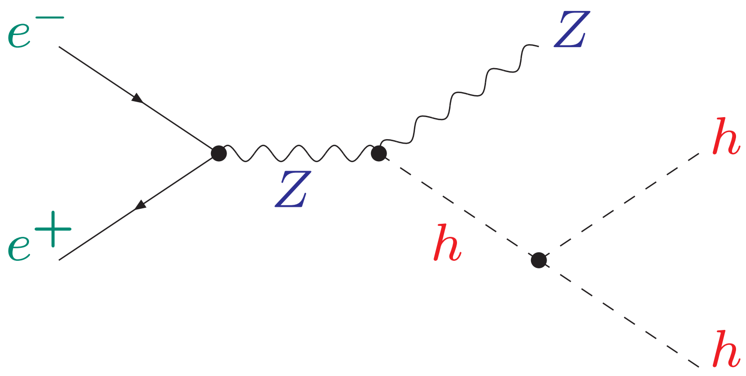
BSM case 1: $\kappa_\lambda \neq 1$

BSM case 2: genuine BSM THCs: λ_{hhH}, . . . ⇒ all must be measured

Di-Higgs production at ILC/CLIC:

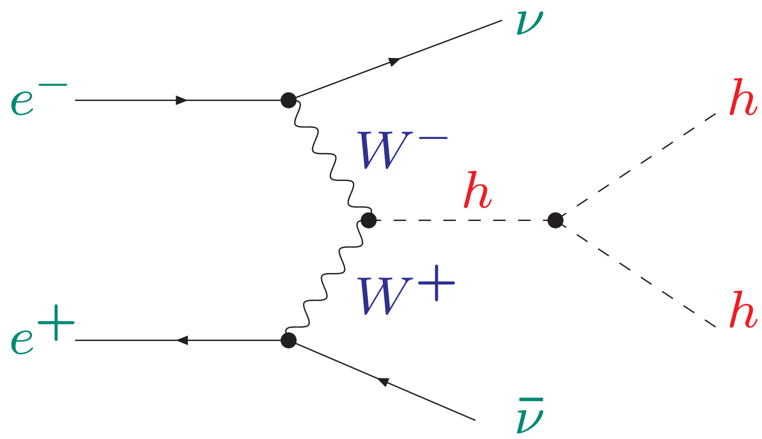
Higgs-strahlung:

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

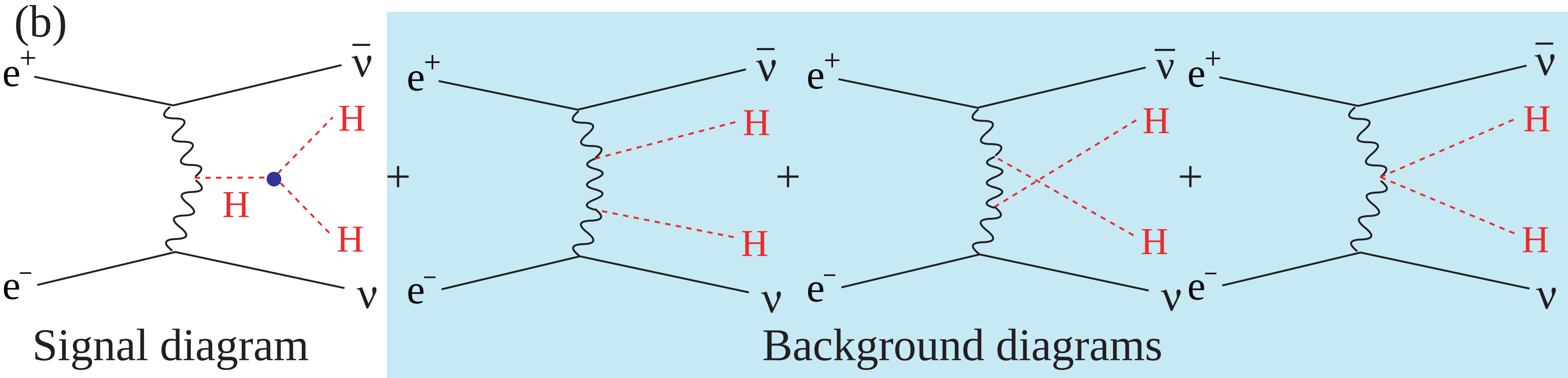


weak boson fusion (WBF):

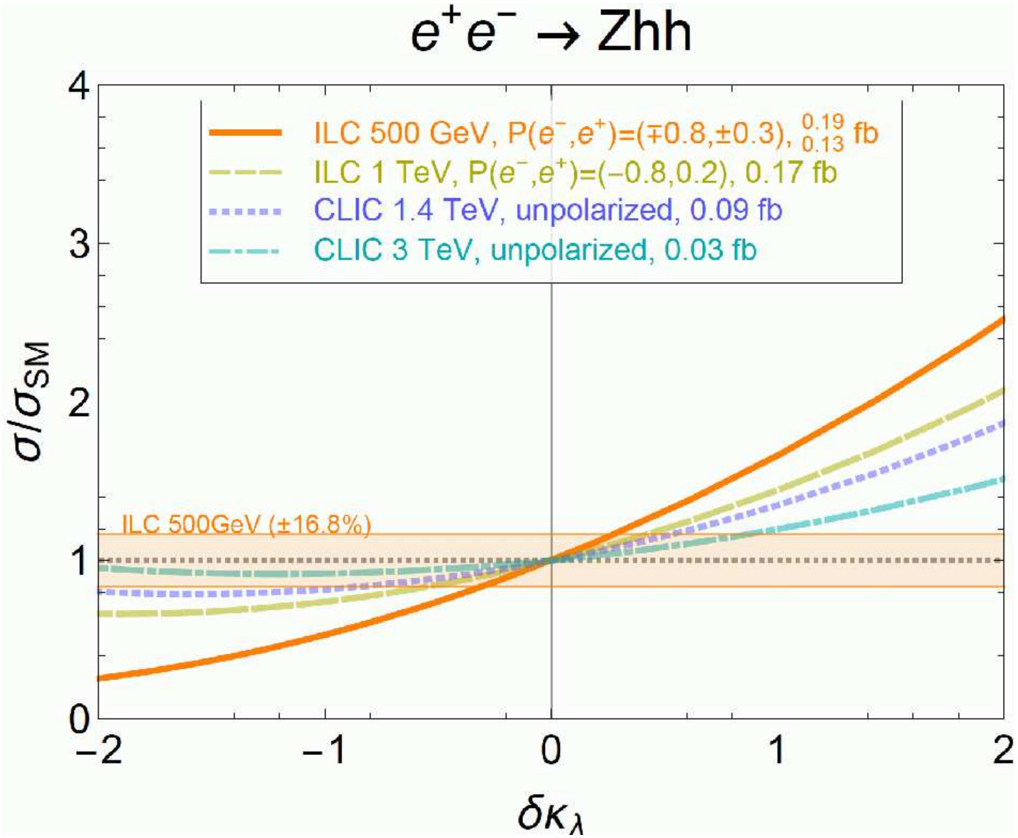
$e+e- \to \nu\bar{\nu}hh$

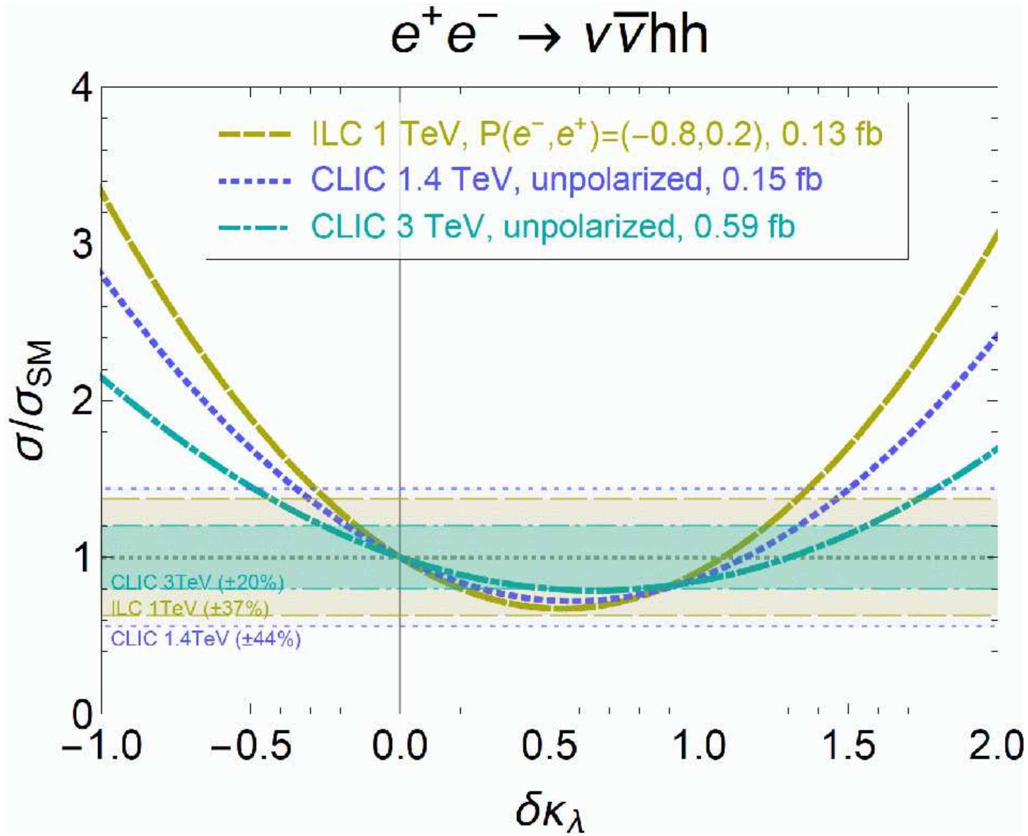


Signal and background interference:



Di-Higgs production at ILC/CLIC:



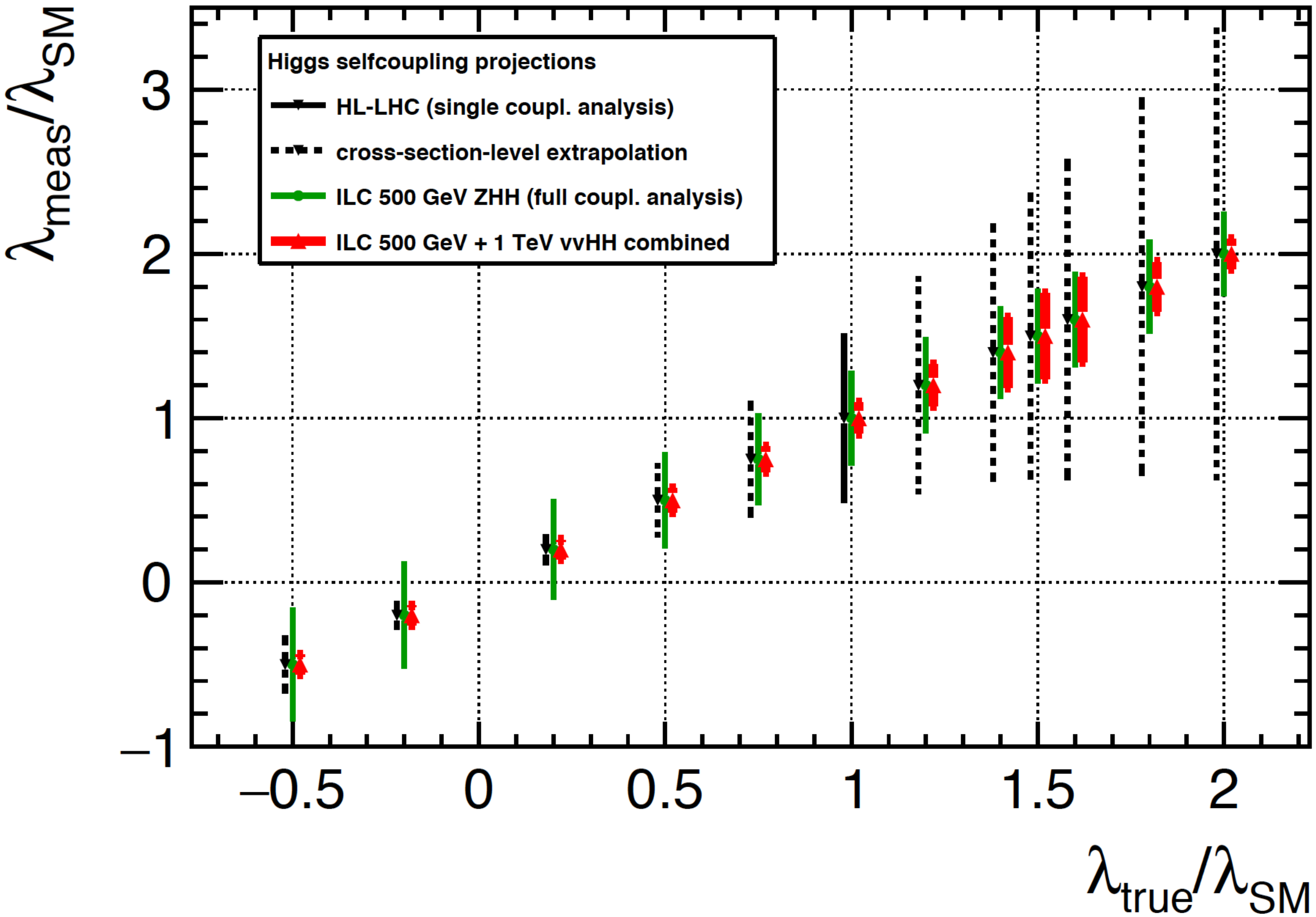


$\kappa_\lambda := 1 + \delta\kappa_\lambda$

$\Rightarrow$ strong and different dependence on κ_λ

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

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

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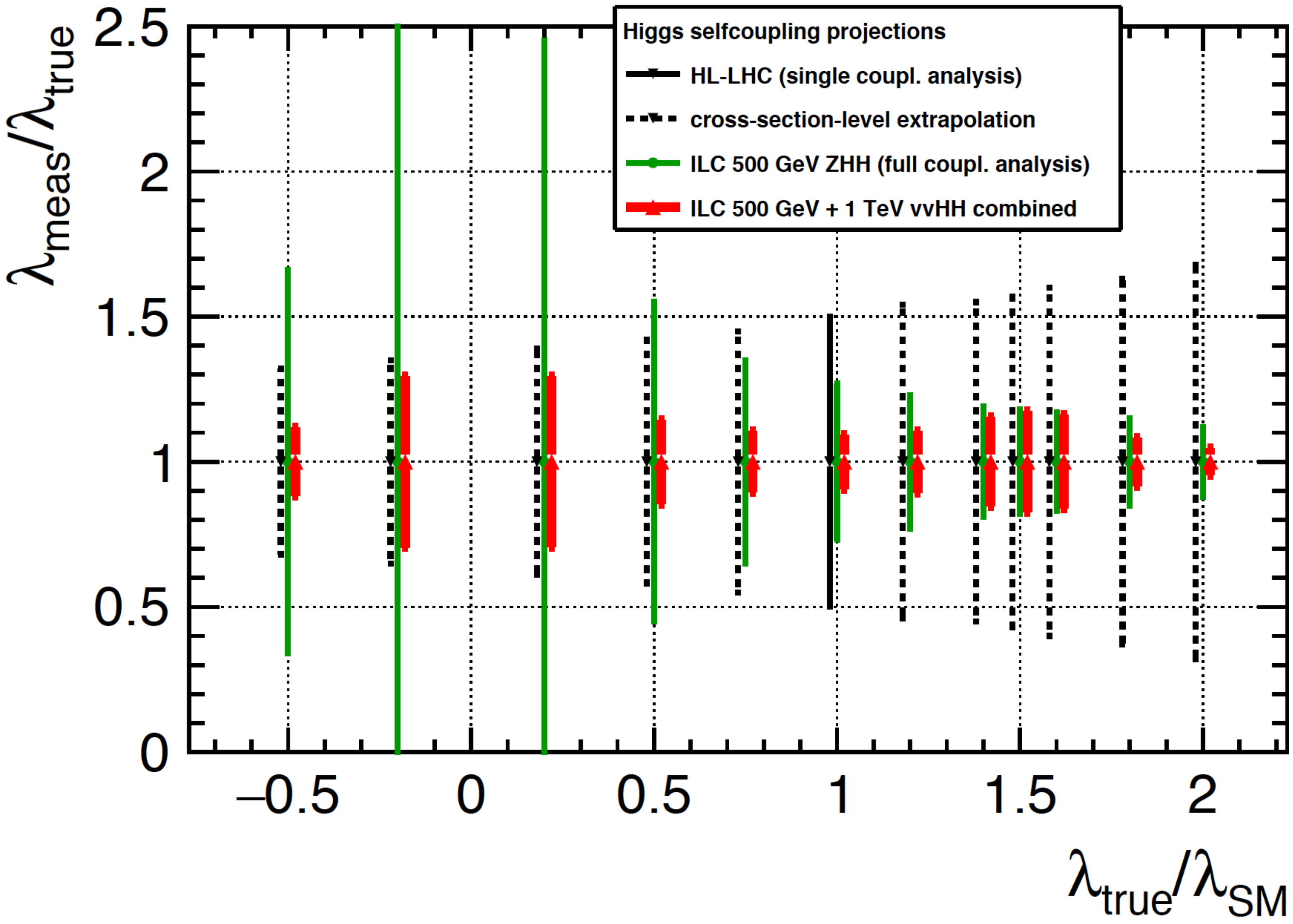


$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

"Our" model: 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:

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

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:

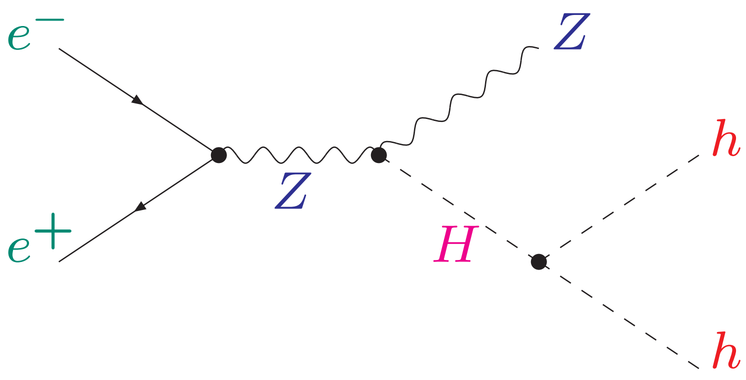
	u-type	d-type	leptons	
type I	Φ_2	Φ_2	Φ_2	
type II	Φ_2	Φ_1	Φ_1	$\to$ SUSY type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

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

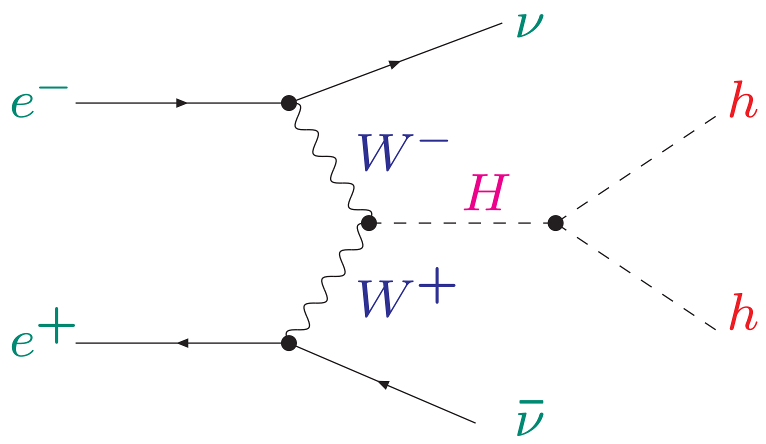
Unitarity/perturbativity and EWPO : $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

Di-Higgs production with BSM Higgses at ILC/CLIC:

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



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



⇒ λ_{hhH} enters

⇒ resonant enhancement for $m_H > 2m_h$

2. FOEWPT and THCs in the 2HDM

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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, . . .

⇒ Parameter scan in the 2HDM type II ⇒ ScannerS

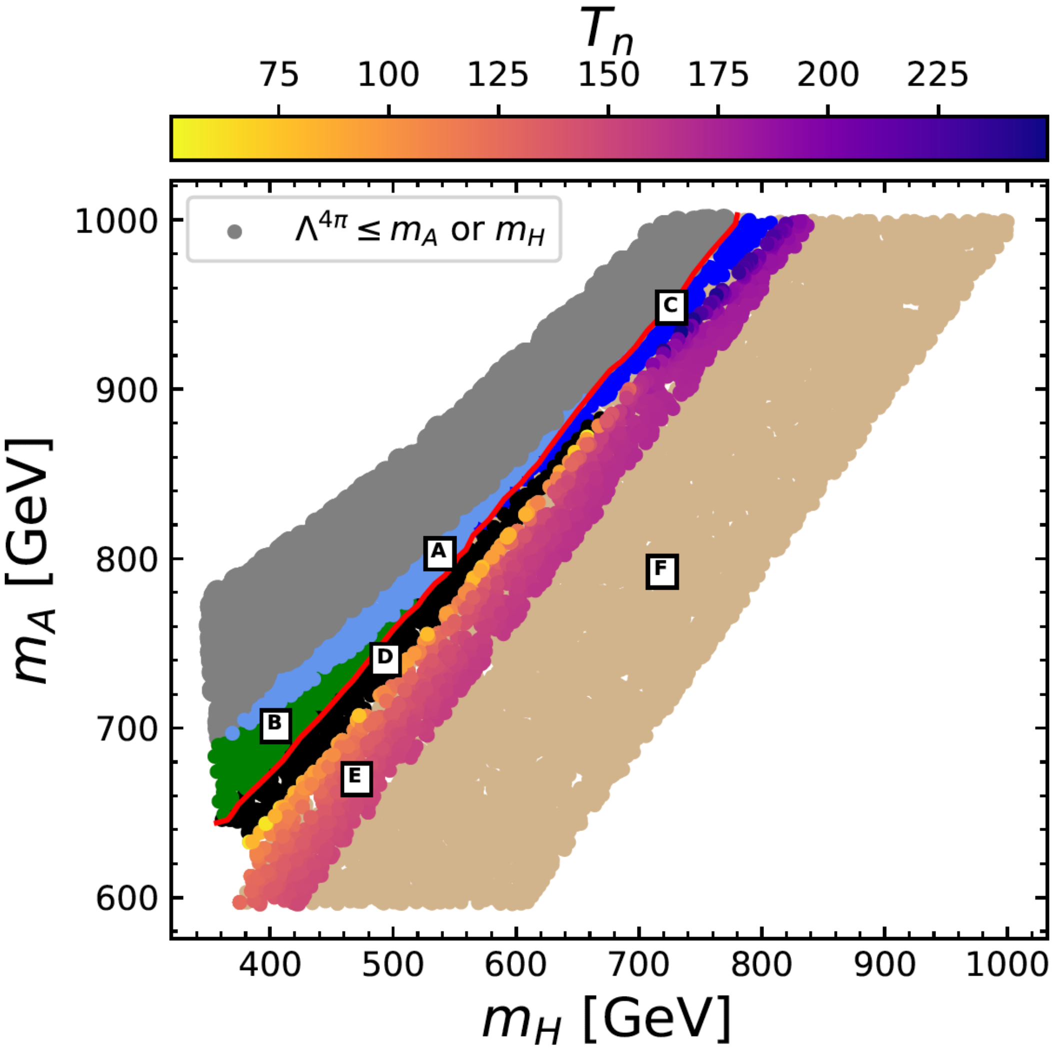
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
$0.2\ \text{TeV} \le m_H \le 1\ \text{TeV}$, $0.6\ \text{TeV} \le m_A = m_{H^\pm} \le 1.2\ \text{TeV}$

Constraints:

- Tree-level perturbativity ⇒ ScannerS
- Minimum of potential is global minimum ⇒ ScannerS
  ... or sufficiently long-lived ⇒ Evade
- Higgs searches at LEP, Tevatron, LHC ⇒ HiggsBounds
- SM-like Higgs properties ⇒ HiggsSignals (2HDECAY, SusHi)
  ⇒ χ^2_{125} (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) ⇒ SuperIso bounds
- Electroweak precision data (T and S) ⇒ ScannerS

Six thermal histories in the 2HDM:

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

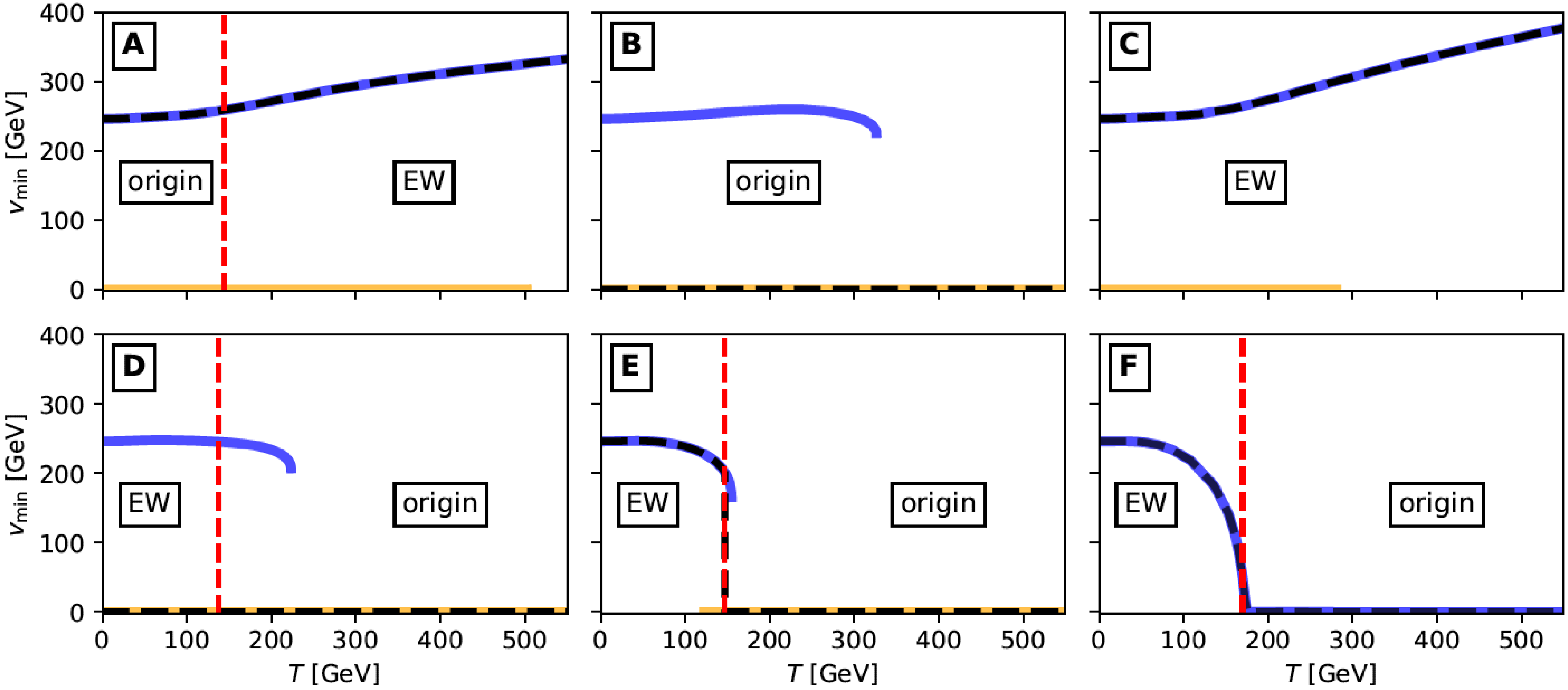


E: viable for FOEWPT $\Rightarrow$ effects for THCs? GWs?

smoking gun signature: $A \to Z\,H \to Z\,t\bar{t}$ $\Rightarrow$ ATLAS: 2.9 σ excess

Six thermal histories in the 2HDM:

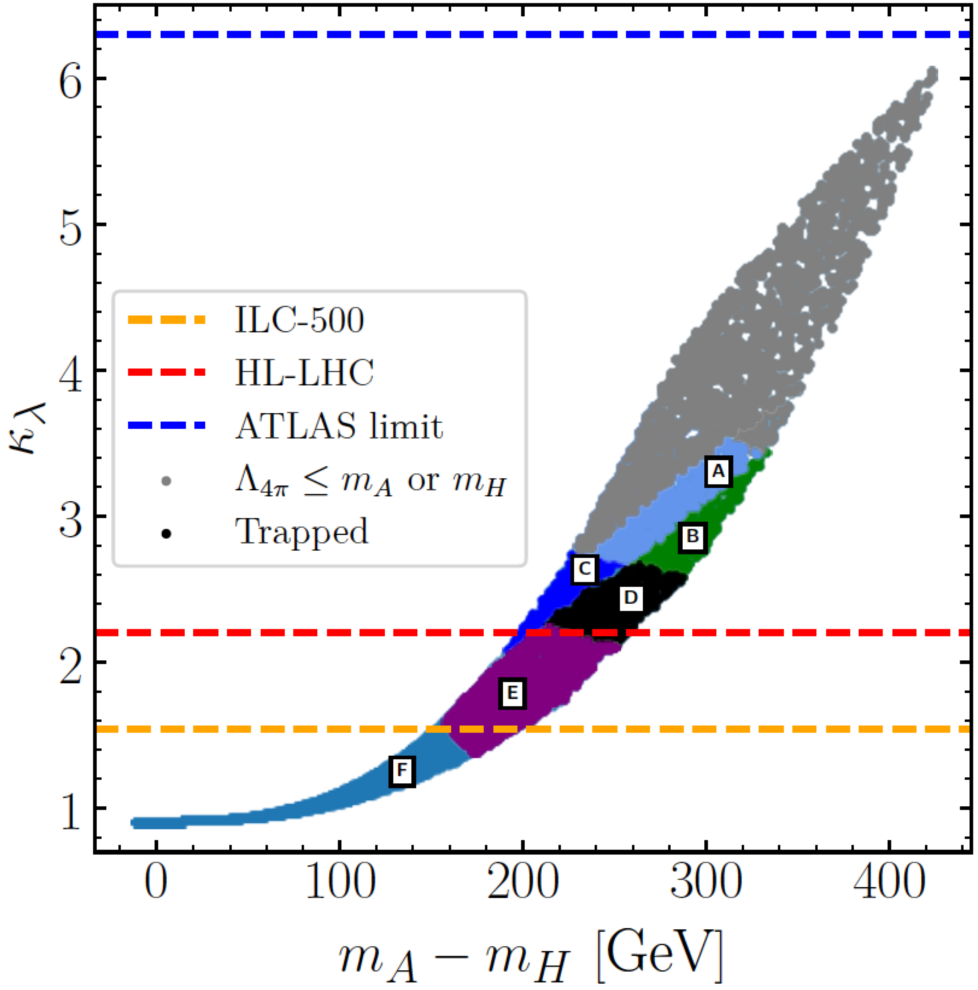
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

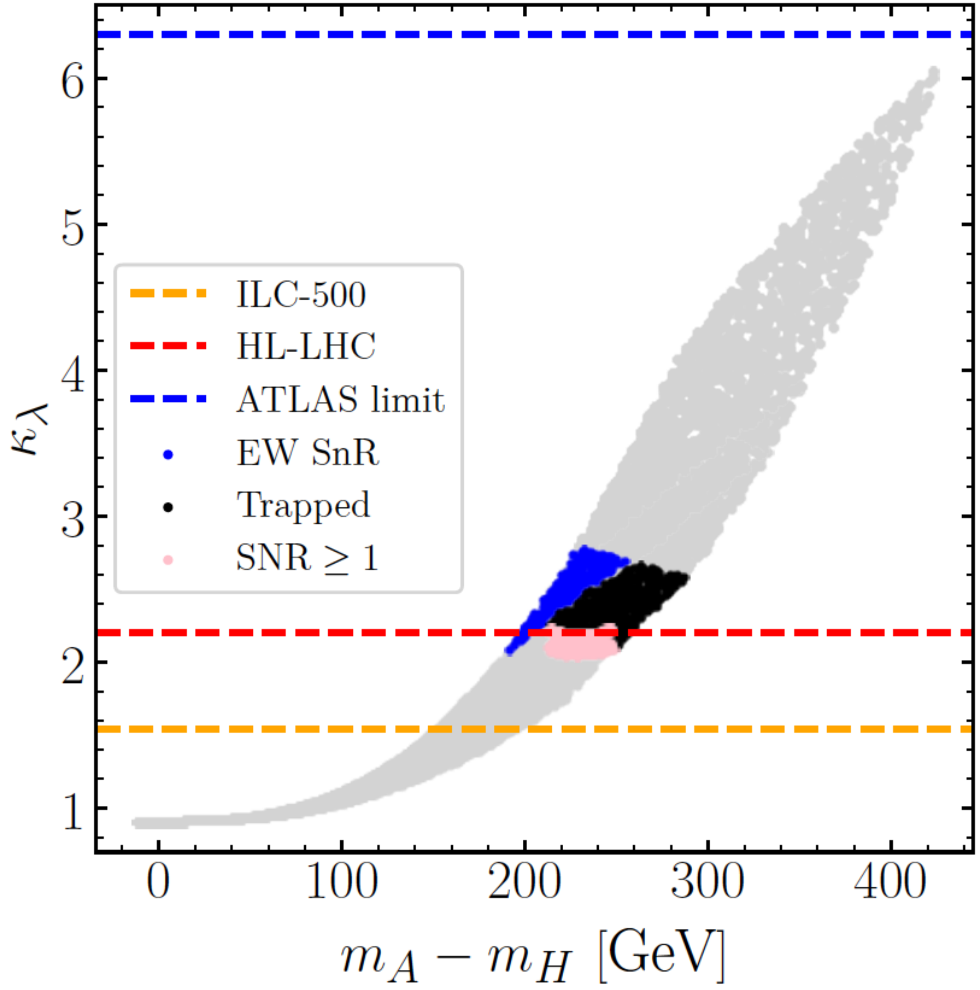


⇒ Zone E preferred by phenomenology/FOEWPT

2HDM parameter scan to yield FOEWPT:

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





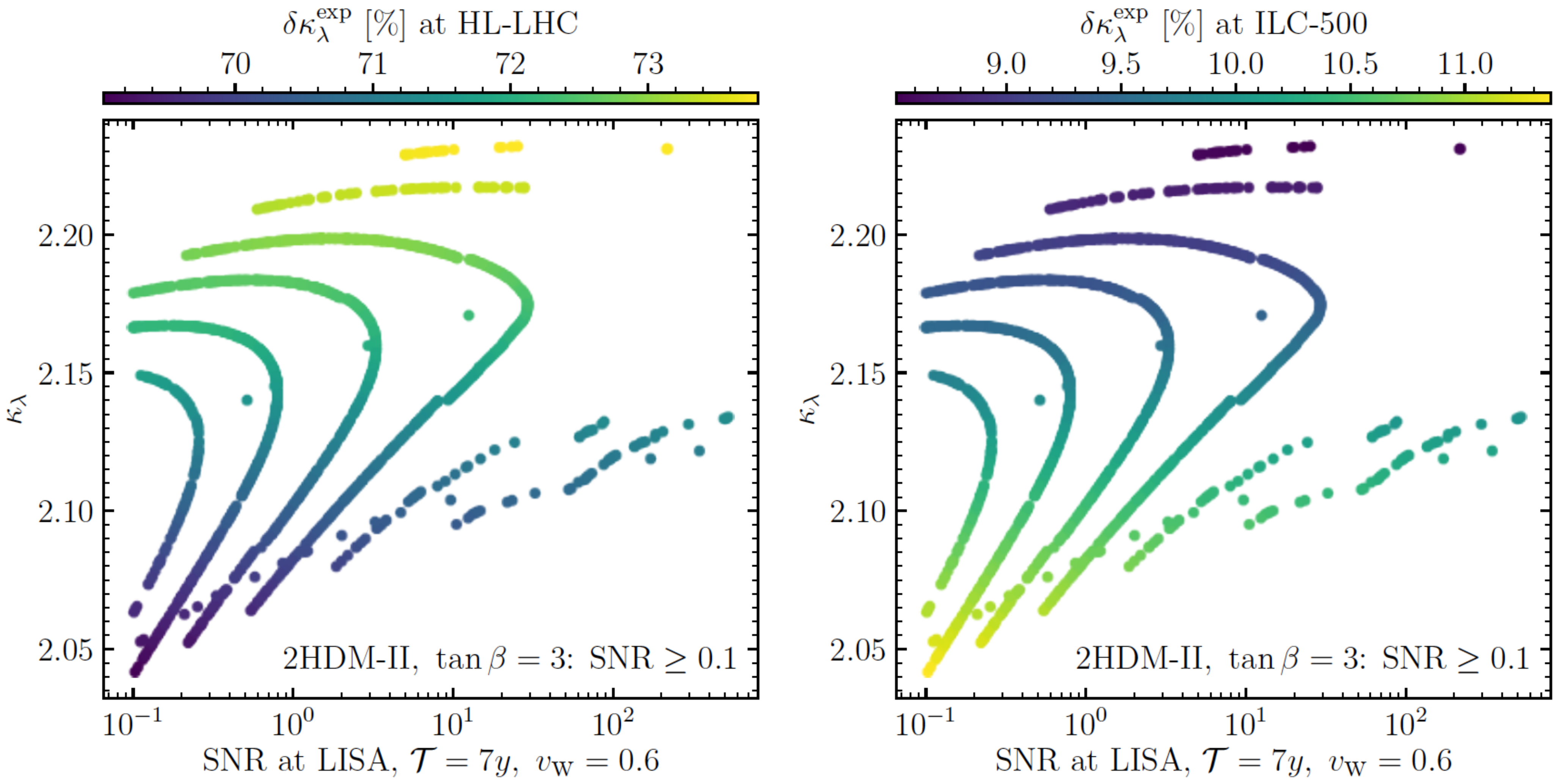
⇒ FOEWPT requires $\kappa_\lambda \lesssim 2$

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

Example: 2HDM ⇒ FOEWPT ⇒ GW's

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

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



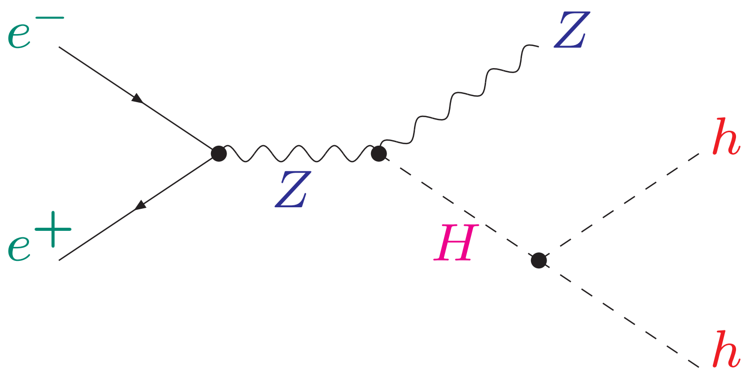
⇒ FOEWPT requires large λ_{hhh} ⇒ good for ILC, bad for HL-LHC

3. THCs in the 2HDM at the ILC/CLIC

Di-Higgs production with BSM Higgses at ILC/CLIC:

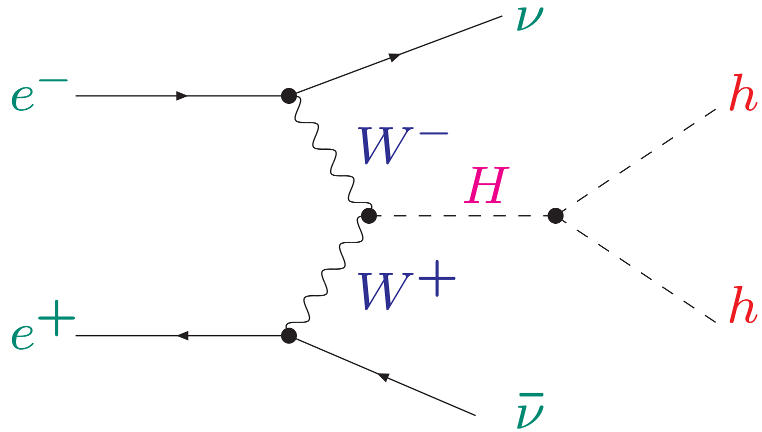
Higgs-strahlung:

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



weak boson fusion (WBF):

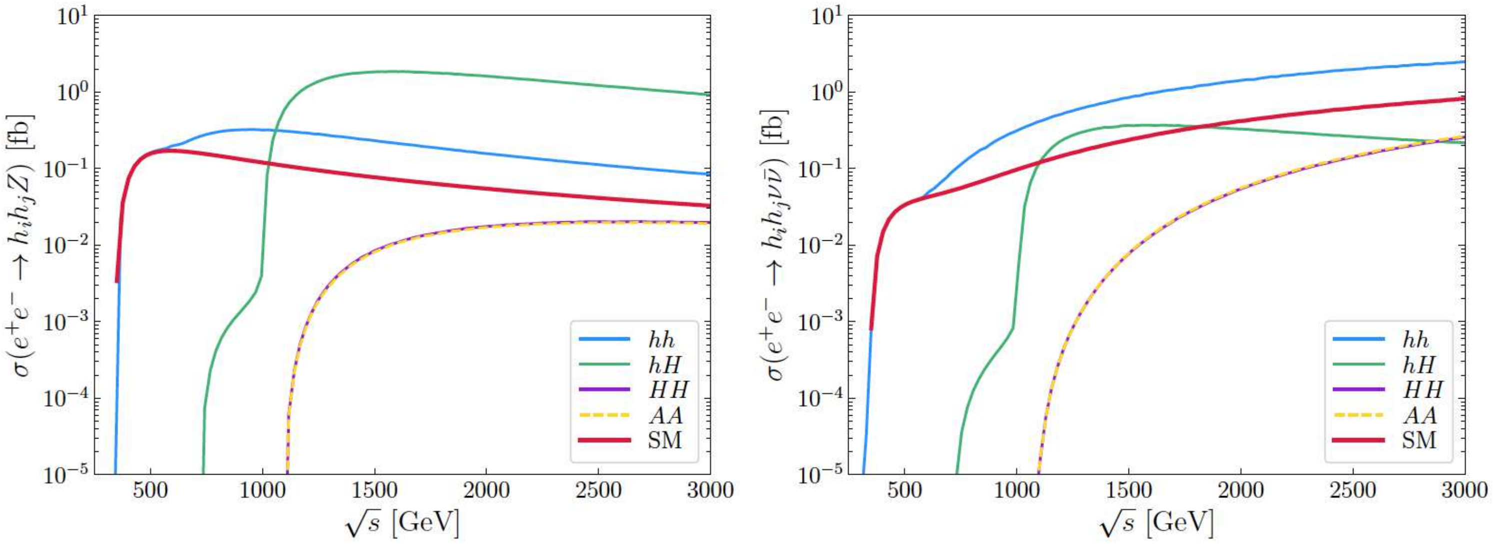
$e+e- \to \nu\bar{\nu}hh$



$\Rightarrow \lambda_{hhH}$ enters

$\Rightarrow$ resonant enhancement for $m_H > 2m_h$

Dependence with energy



Type I
$m = 500$ GeV
$\tan\beta = 10$
$c_{\beta-\alpha} = 0.2$
$m_{12}^2 = 24000$ GeV^2

↓

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{SM} \simeq 1$
$\lambda_{hhH} = -0.5$
$\lambda_{hHH} = \lambda_{hAA} = 6$
$\lambda_{hH^+H^-} = 12$

Z channel → decreases with the energy

$\nu\bar{\nu}$ channel → increases with the energy (VBF topologies!)

- hhZ and $hh\nu\bar{\nu}$: ~ 3 times the SM due to resonant diagrams mediated by H (contains λ_{hhH}) and A (without THC)
- hHZ and $hH\nu\bar{\nu}$: A mediated diagrams are the dominant contribution but we can still have THC sensitivity at large energies
- $HH\nu\bar{\nu}$ ~ $AA\nu\bar{\nu}$: dominated at large energies by λ_{hHH} (λ_{hAA}) if it is large enough (because $m_H = m_A$)

Fran Arco (UAM-IFT) Madgraph was used 5

$\kappa_\lambda \sim 1$ but σ_{hhZ} and $\sigma_{hh\nu\bar{\nu}}$ show a clear deviation from SM

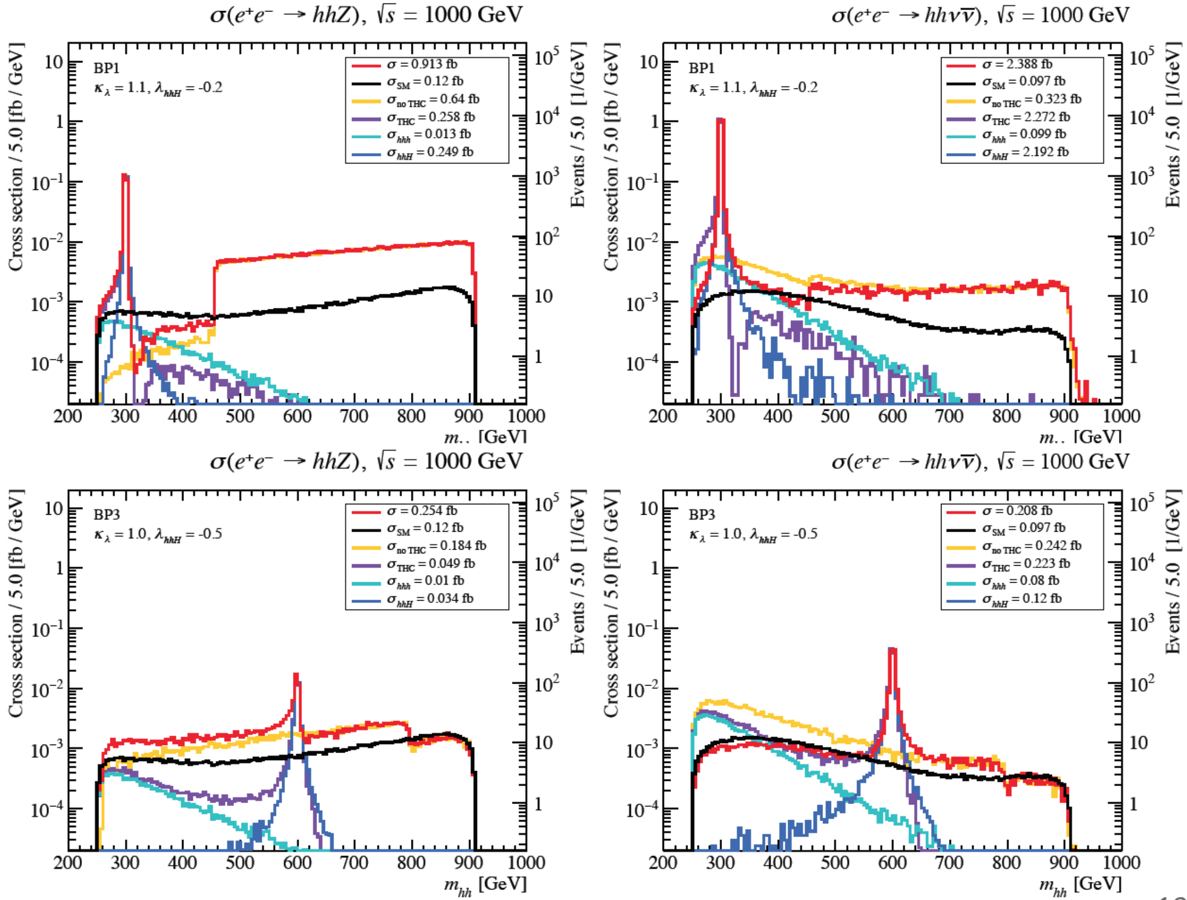
$\Rightarrow$ impact of BSM triple Higgs couplings $\Rightarrow$ can λ_{hhH} be extracted?

hh production, THC dependence, ILC 1TeV (type I)

Cross section distributions on m_{hh} for

Point	Type	m	$\tan\beta$	$c_{\beta-\alpha}$	m_{12}^2
BP1	I	300	10	0.25	Eq. (8)
BP2	I	500	7.5	0.1	32000
BP3	I	600	10	0.2	Eq. (8)
BP4	I	1000	8.5	0.08	Eq. (8)
BP5	II	650	1.5	0.02	10000

(Eq. (8) $\to m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta$)



- Effect from κ_λ: the region of low invariant mass
- Effect from λ_{hhH}: H resonant peak at $m_{hh} \sim m_H$

$\Longrightarrow$ which collider and channel are best suited to access to λ_{hhH}?

Fran Arco (UAM-IFT) 10

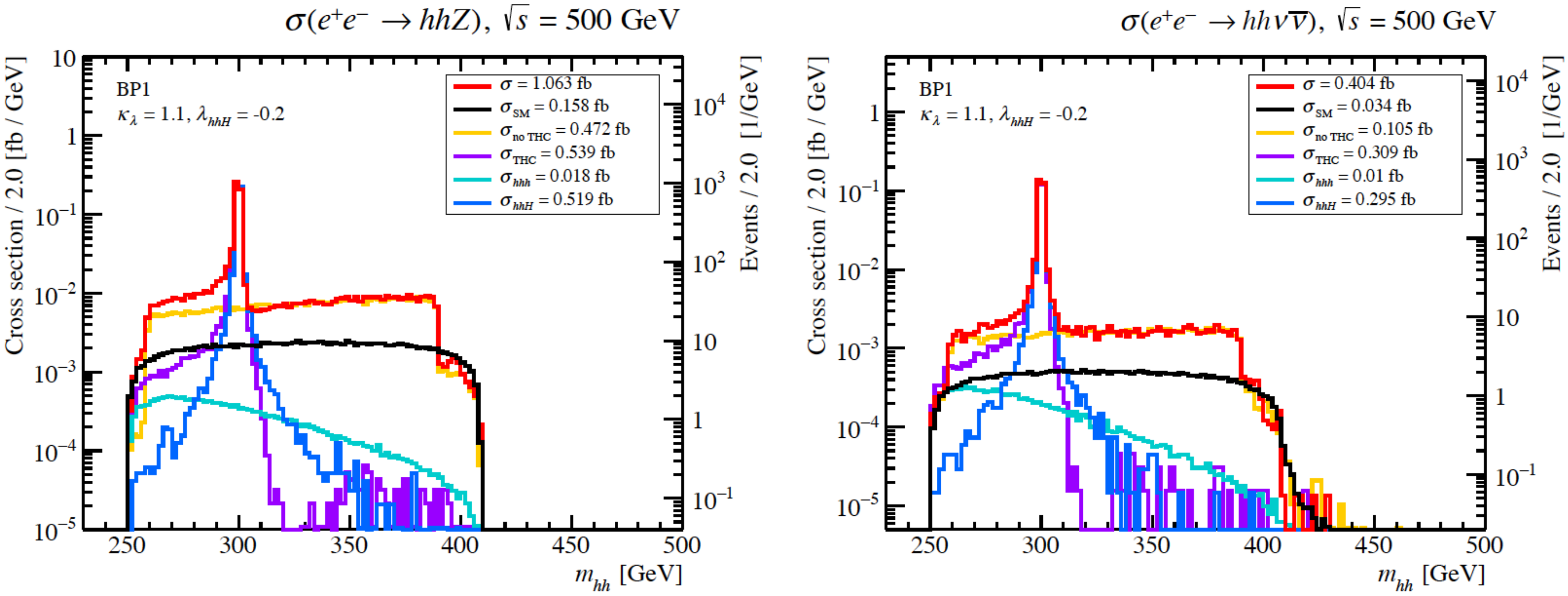
$\Rightarrow$ analysis of m_{hh} distribution

$\Rightarrow$ extraction of λ_{hhH} possibly possible $\Rightarrow$ exp. analysis needed!

Di-Higgs production at the ILC: [F. Arco, S.H., M. Herrero '21]

Example: 2HDM type I $e^+e^- \to Zhh/\nu\bar{\nu}hh$ with MadGraph

$m_{H,A,H^\pm} = 300$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.25, m_{12}^2 = m_H^2 c_\alpha^2/t_\beta \Rightarrow \kappa_\lambda = 1.1, \lambda_{hhH} = -0.2$



theory analysis: $R := (\bar{N}^R - \bar{N}^C)/\sqrt{\bar{N}^C}$

R = "resonance", C = "continuum", $\bar{N}$ incl. cuts and b-tagging efficiencies

$$\sqrt{s} = 500\ (1000)\ \text{GeV} \quad \Rightarrow \quad R = 58\ (205)$$

experimental analysis: crucially needed!

4. 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
  Bonus: FOEWPT can cause GWs, detectable with LISA

- Two BSM physics cases with THCs:
  - $\kappa_\lambda \neq 1$
  - genuine BSM THCs $\Rightarrow$ all must be measured!

- "Our" model: 2HDM
  Many triple Higgs couplings: λ_{hhh}, λ_{hhH}, λ_{hHH}, $\lambda_{hH^+H^-}$, λ_{HAA}, ...

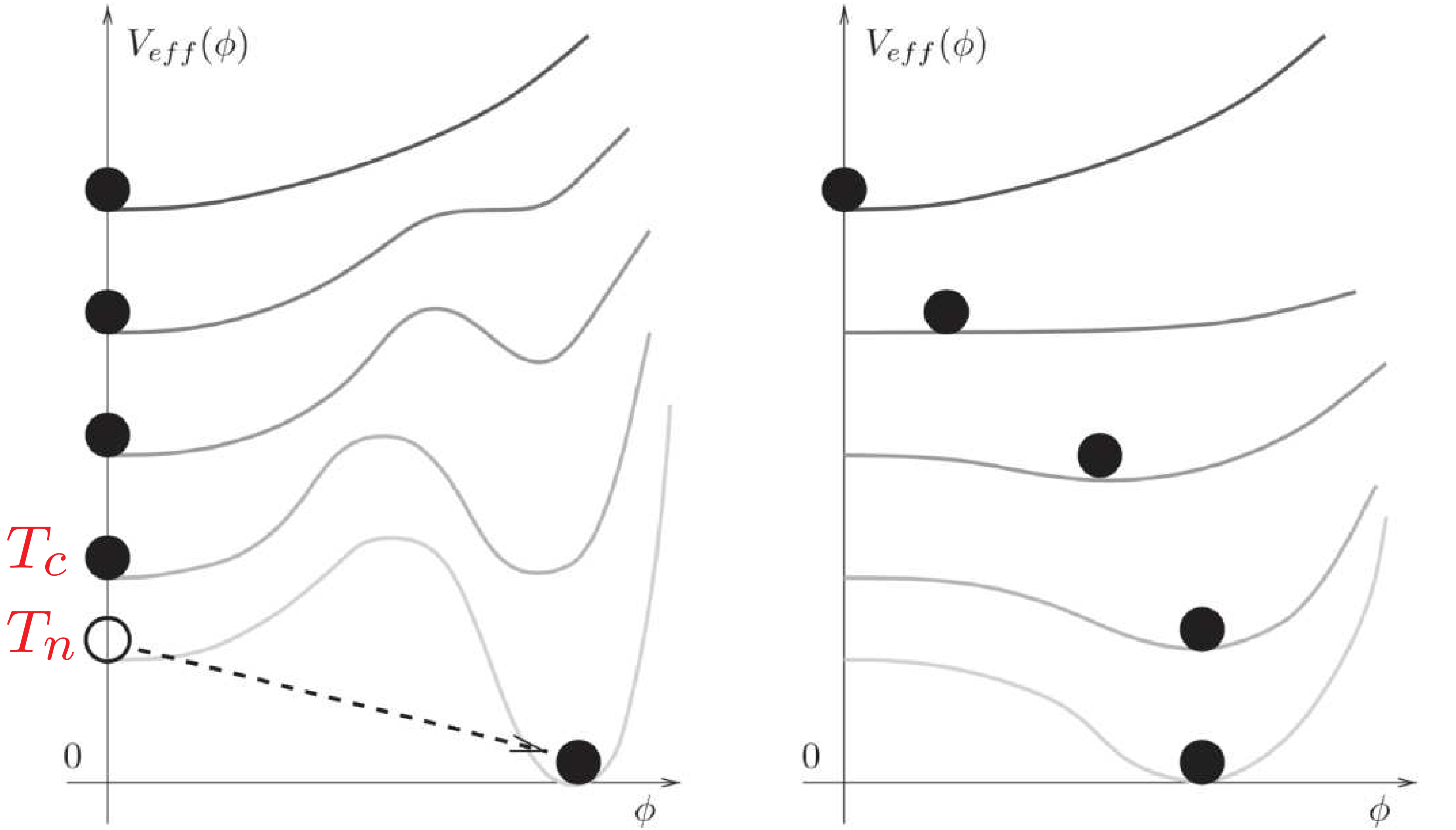
- 2HDM: $\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$ $\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$
  $\Rightarrow$ bad for HL-LHC ($\delta\lambda_{hhh} \sim 70\%$), good for ILC ($\delta\lambda_{hhh} \sim 10\%$)

- ILC/CLIC access to BSM THC's: λ_{hhH}
  $\Rightarrow$ resonant peak from $e^+e^- \to Z\,H \to Z\,hh$
  $\Rightarrow$ benchmark point in the 2HDM type I with $m_H = 300$ GeV
  theory analysis looks very good, experimental analysis: crucially needed


Further Questions?

Phase transition: BSM vs. SM

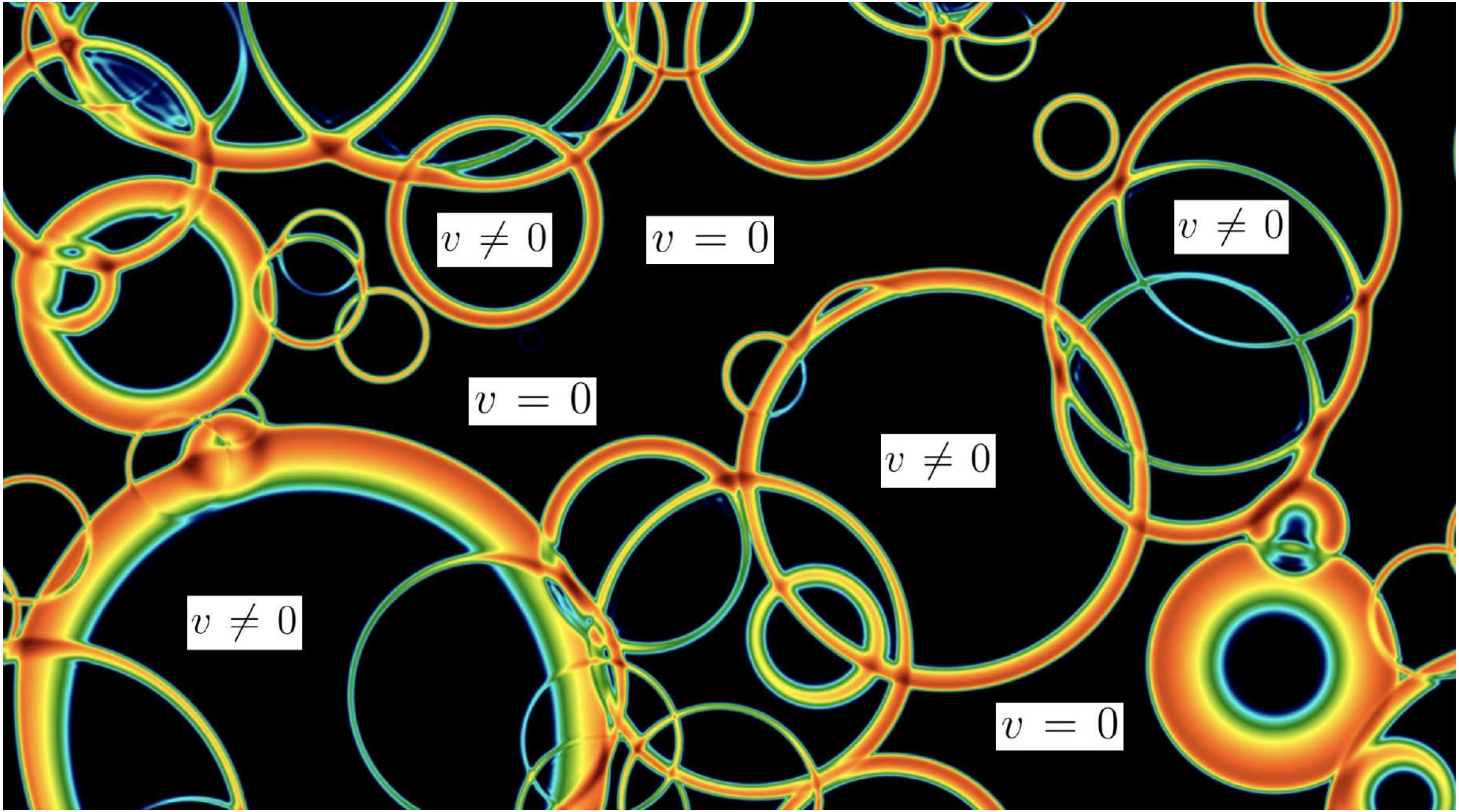
[*taken from V. A. Rubakov and D. S. Gorbunov*]



⇒ BSM Higgs sector required to realized FOEWPT

Bubble formation can lead to Gravitational Waves

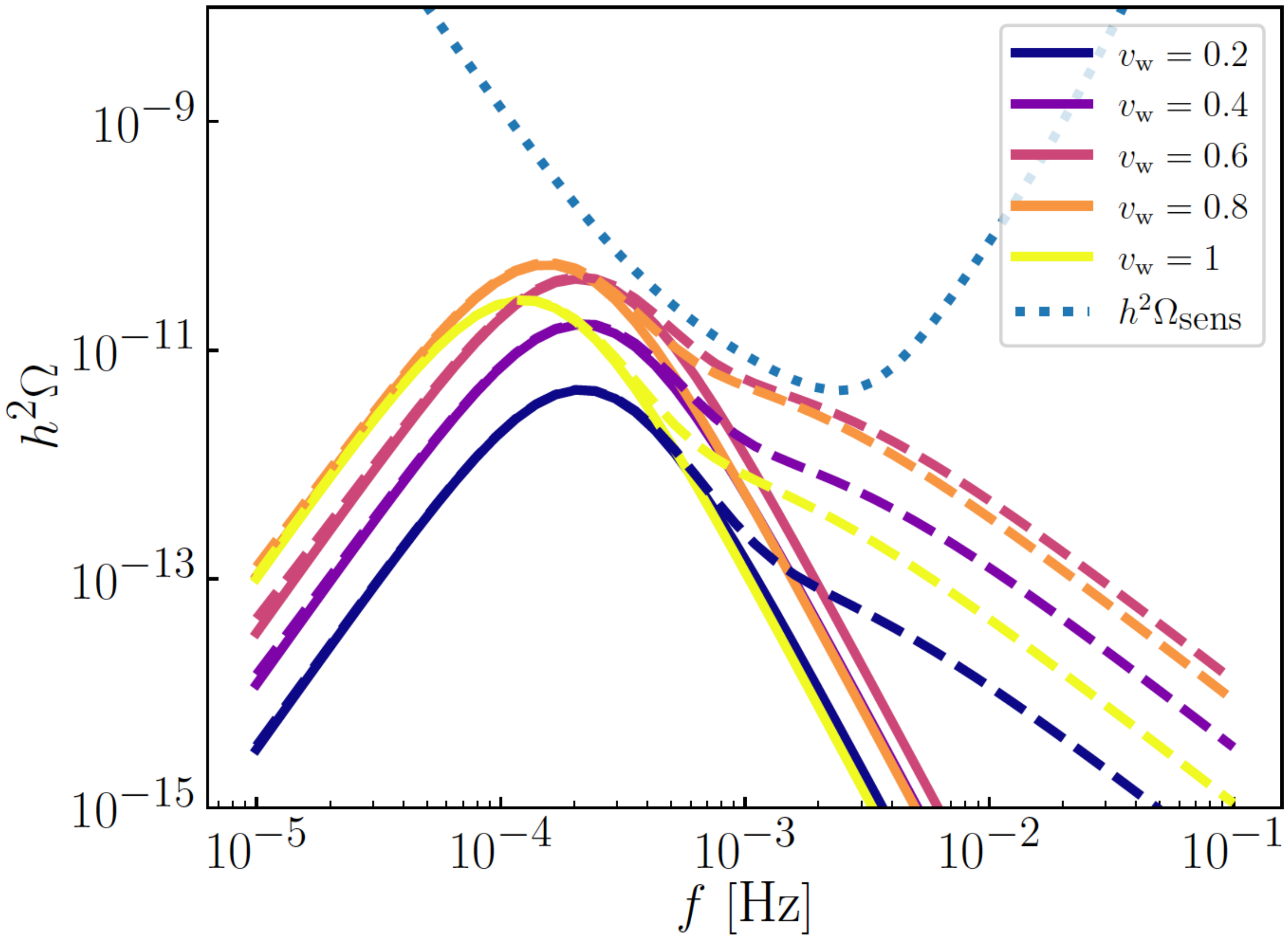
[*taken from D. Weir*]



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

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

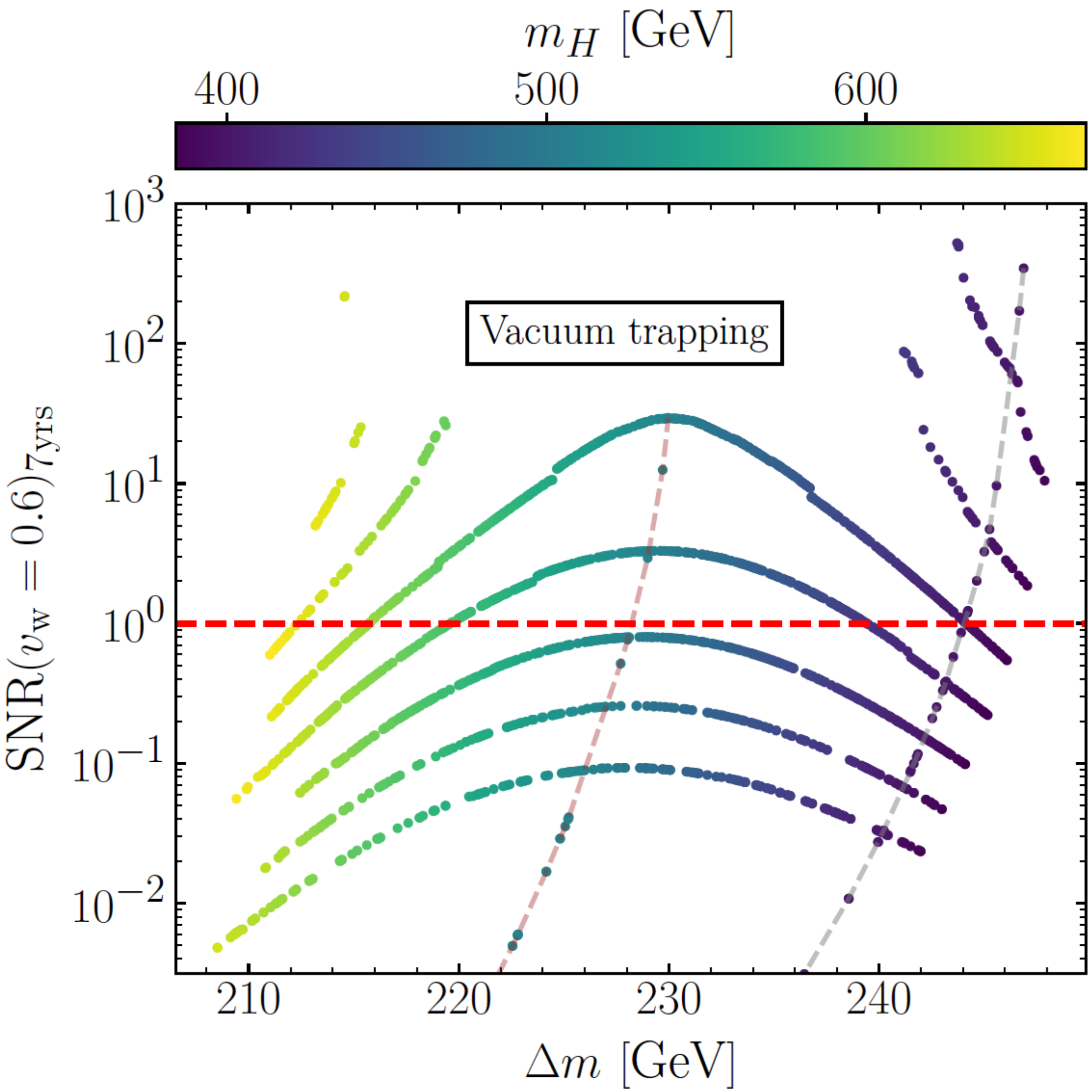
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



$\Rightarrow$ bubble wall velocity and turbulence important

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

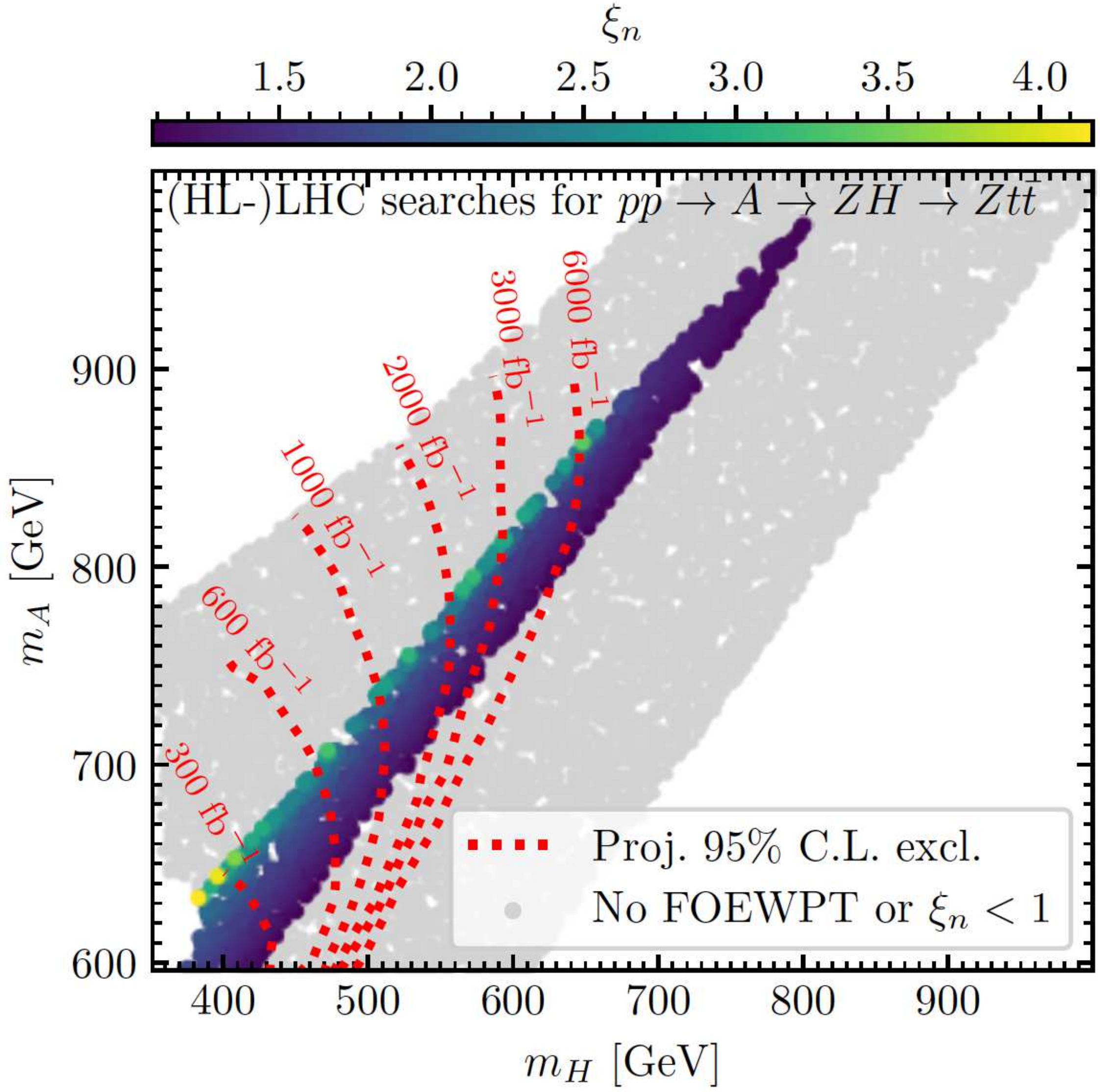
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



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

Smoking gun signature: gap between m_A and m_H

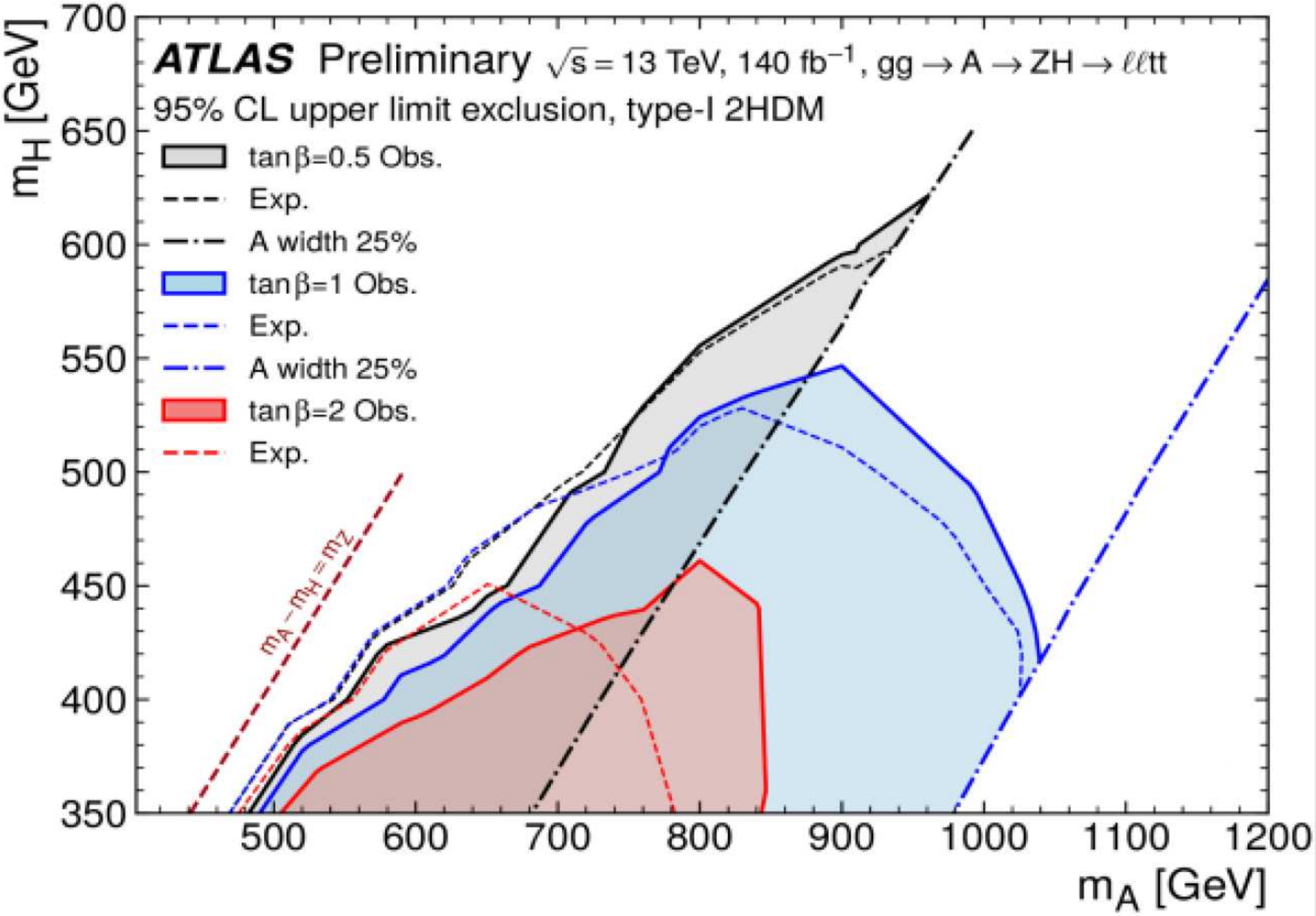
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



⇒ GW zone can be covered at the HL-LHC

Latest experimental results: ATLAS at LHCP23

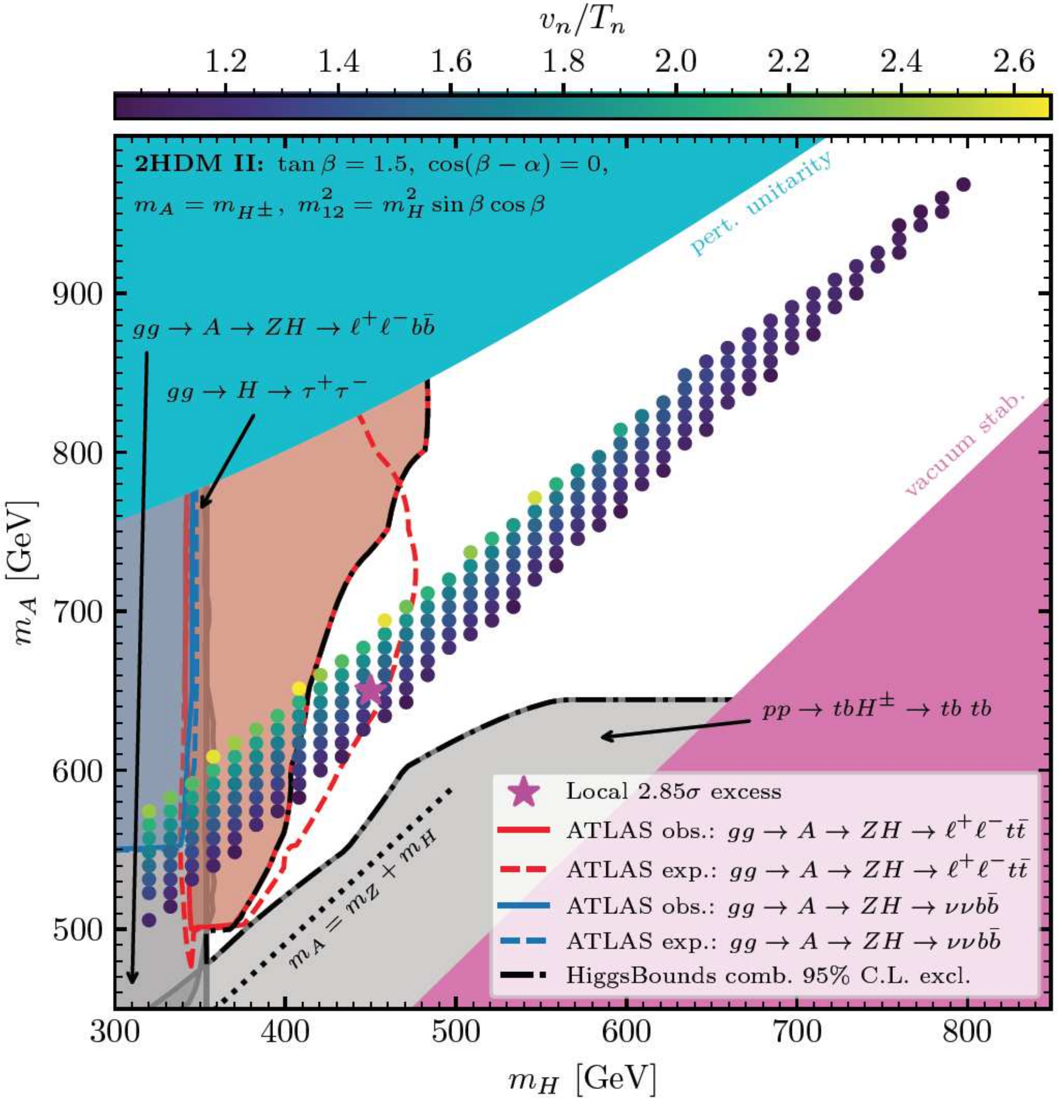
[ATLAS '23]



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

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

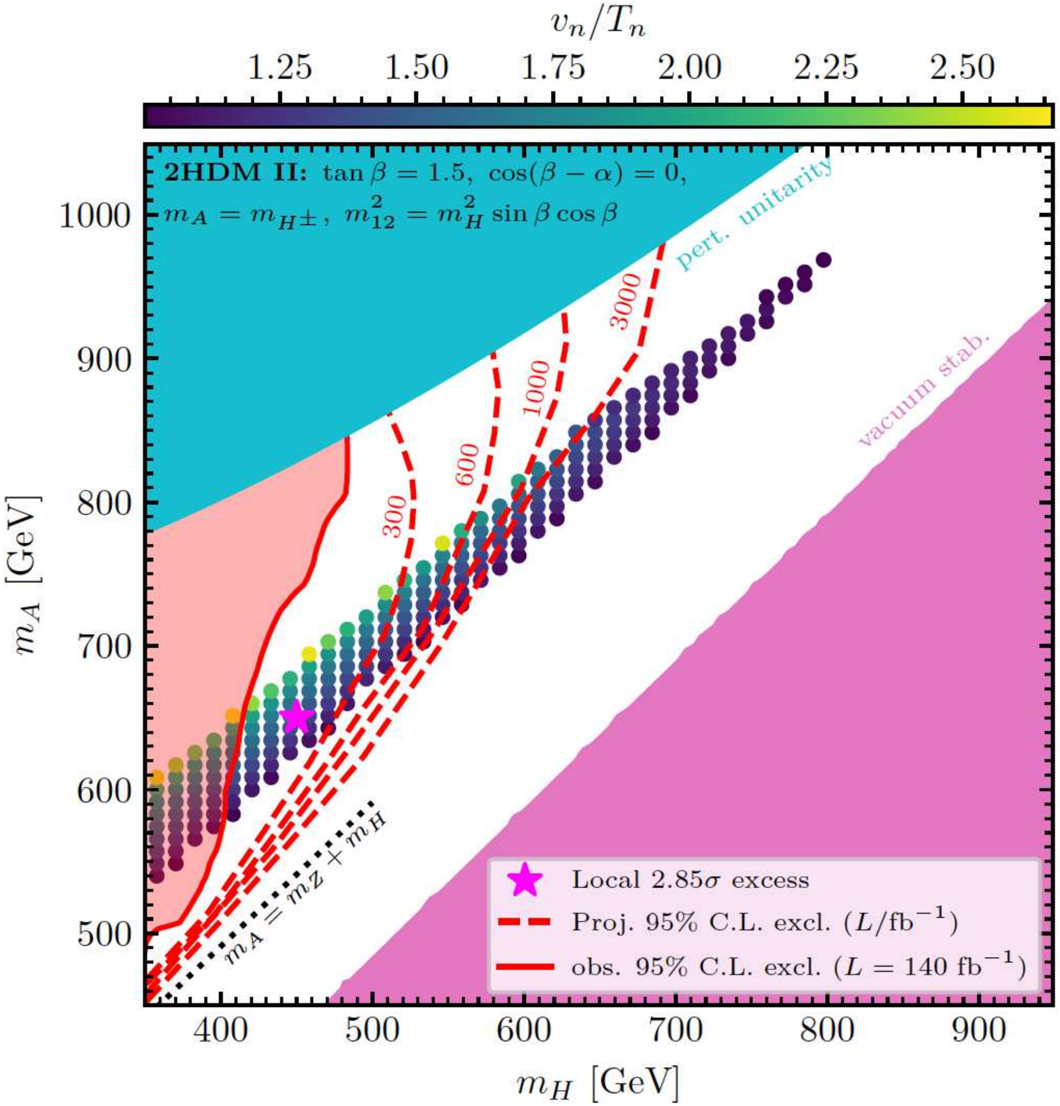
[T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein - PRELIMINARY]



⇒ excess in the sweet spot

Smoking gun signature: future projections

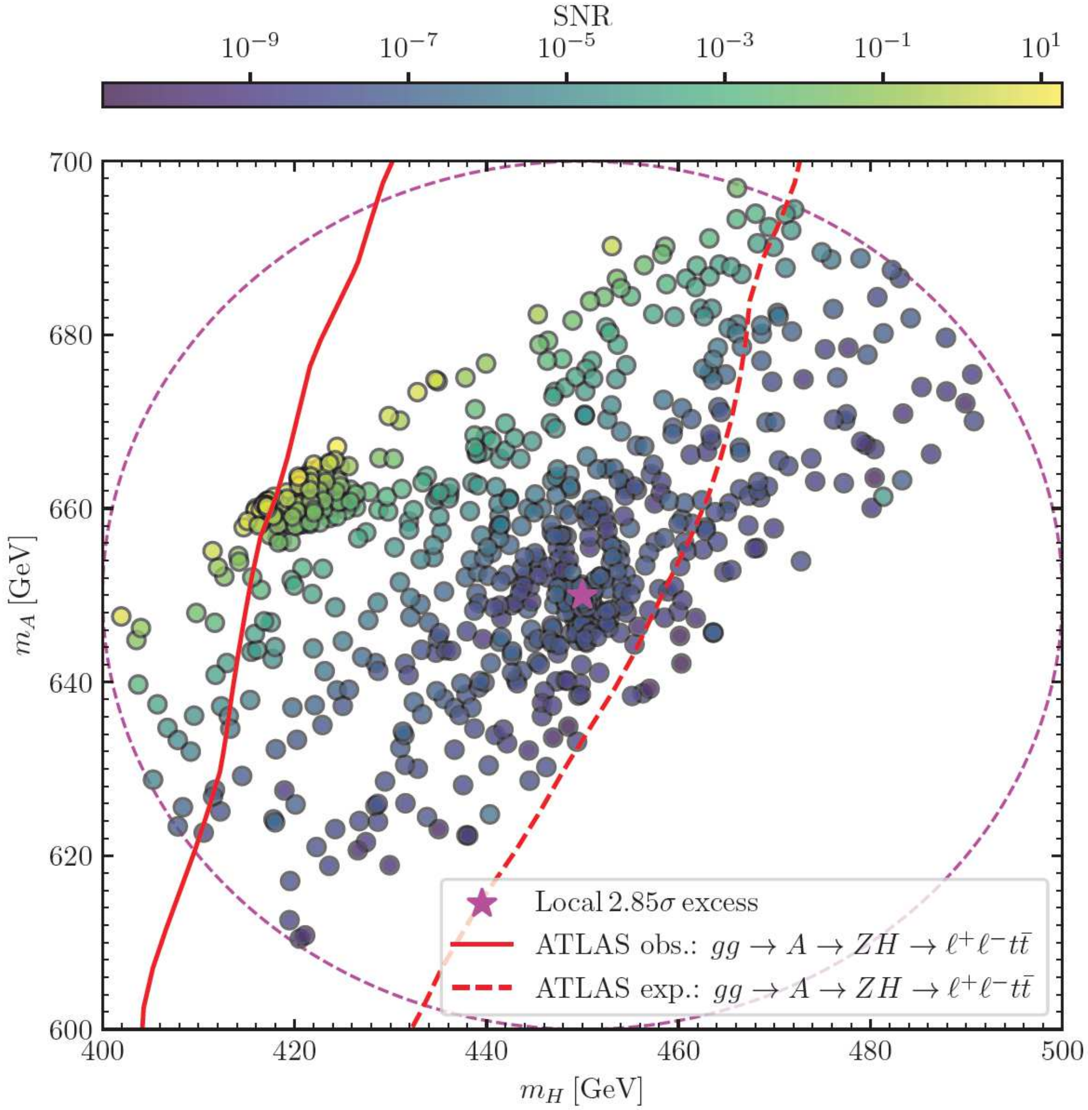
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein - PRELIMINARY*]



⇒ should be discoverable

Smoking gun signature: GW signal at LISA?

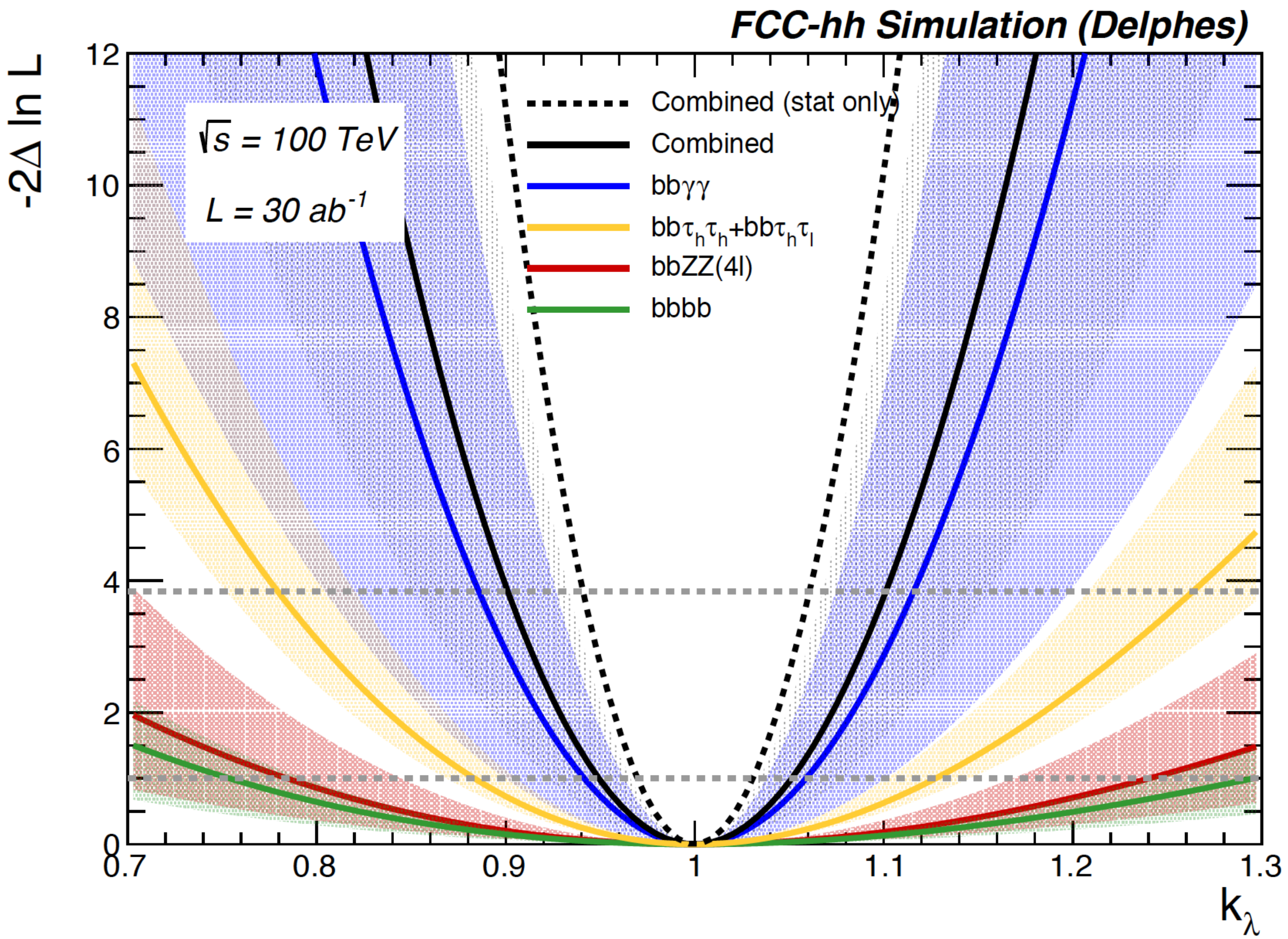
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein - PRELIMINARY*]



⇒ GW signal at LISA possible, but not guaranteed

Measurement of κ_λ at the FCC-hh:

[Mangano, Ortona, Selvaggi '20]

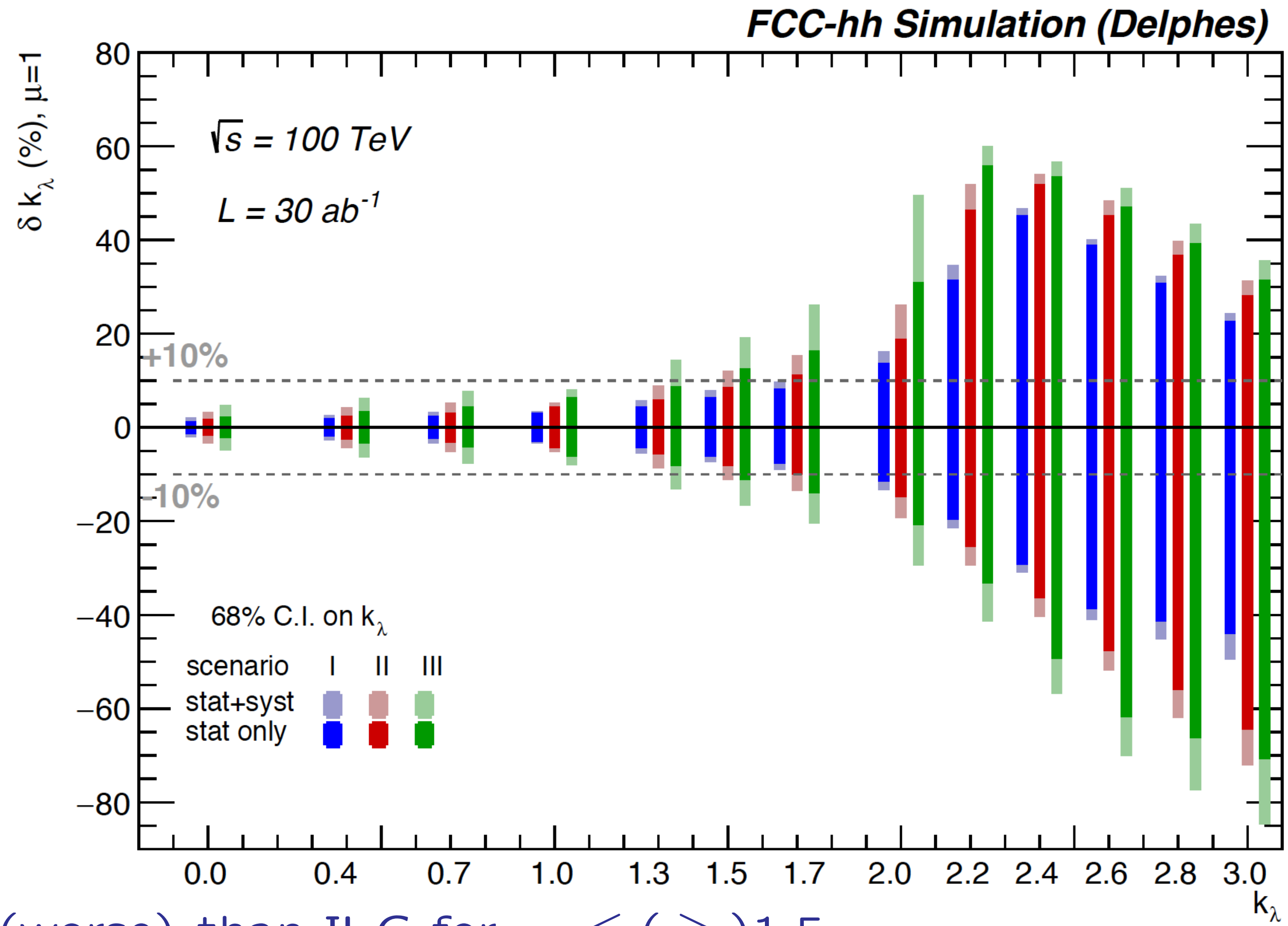


⇒ result only for $\kappa_\lambda = 1$

⇒ pile-up neglected . . .

Measurement of κ_λ at the FCC-hh:

[*Mangano, Ortona, Selvaggi '20*]



⇒ better (worse) than ILC for $\kappa_\lambda \lesssim (\gtrsim)1.5$

⇒ no results for $\kappa_\lambda \leq 0$

⇒ pile-up neglected . . .