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BSM Higgs Sectors, triple Higgs couplings and Gravitational Waves

Sven Heinemeyer, IFT (CSIC, Madrid)

Daejeon, 06/2023

1. Introduction


HIGGS 2013
Gravitational
Waves 2017

1. Introduction

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

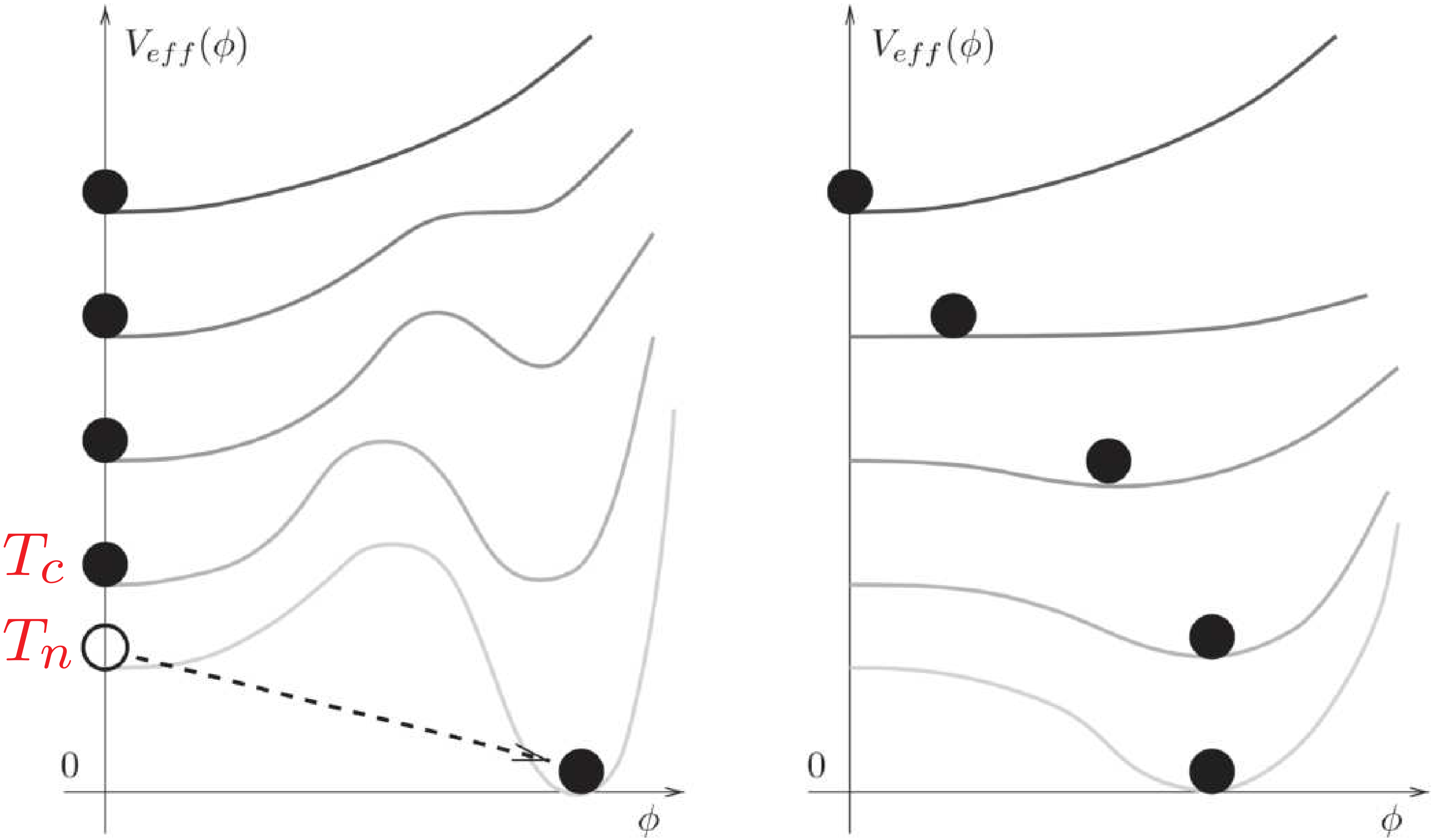
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM THC's required

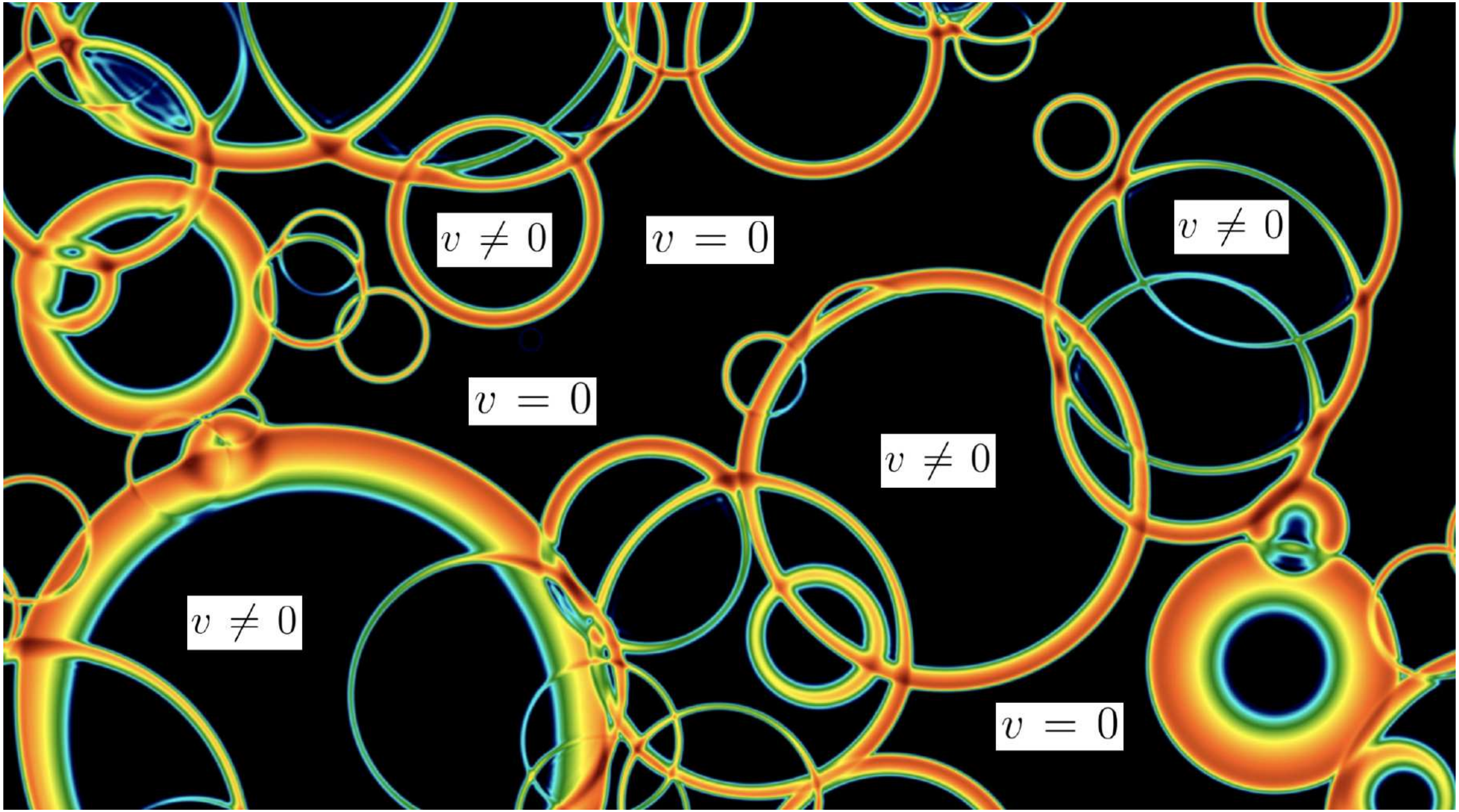
FOEWPT can cause Gravitational Waves (GW), detectable with LISA, . . .

Phase transition: BSM vs. SM

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



$\Rightarrow$ BSM Higgs sector required to realized FOEWPT



$\Rightarrow$ 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

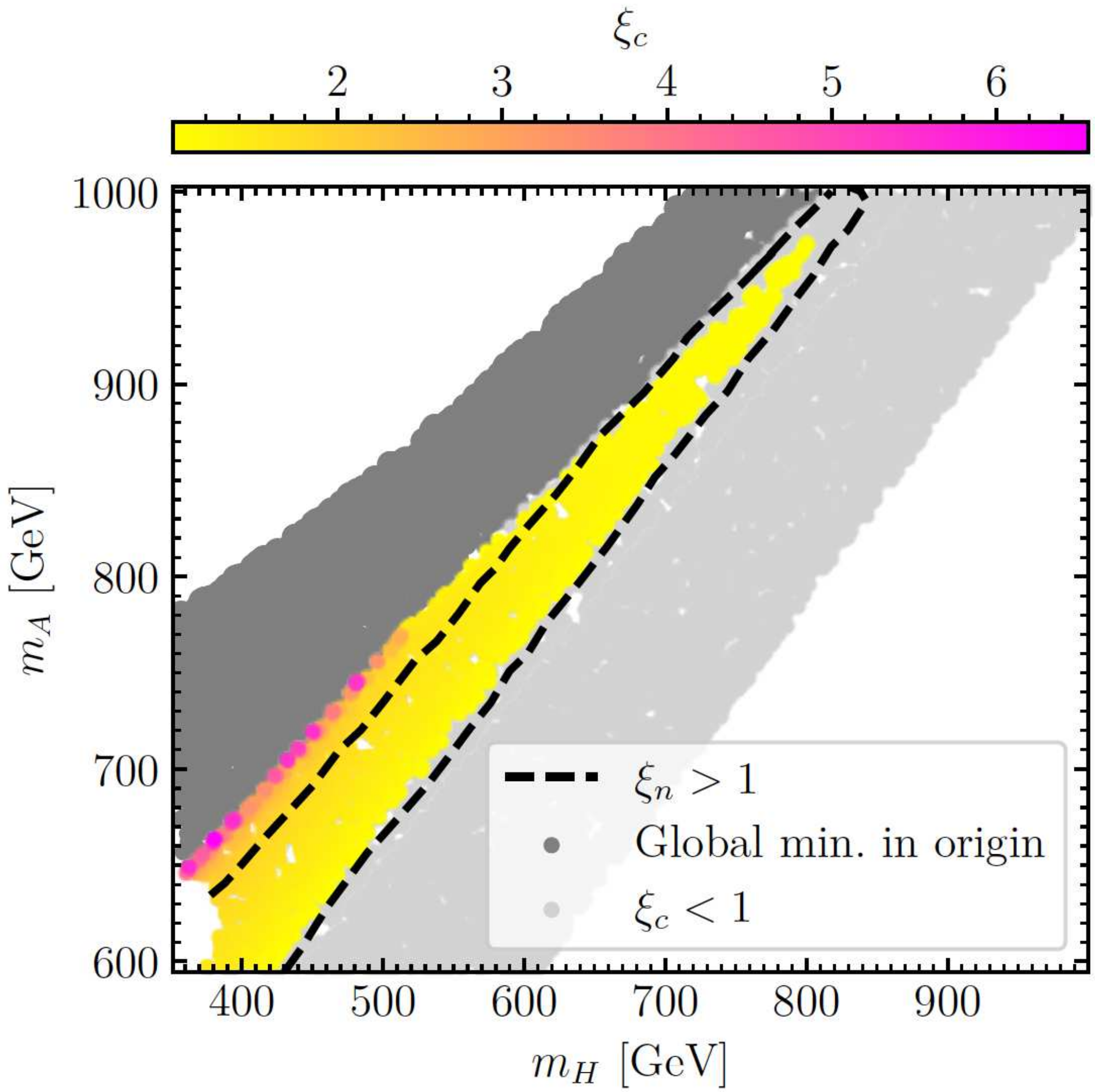
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\le m_H \le$ 1 TeV, 0.6 TeV $\le m_A = m_{H^\pm} \le$ 1.2 TeV

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: $\xi_n := v_n/T_n \gtrsim 1$

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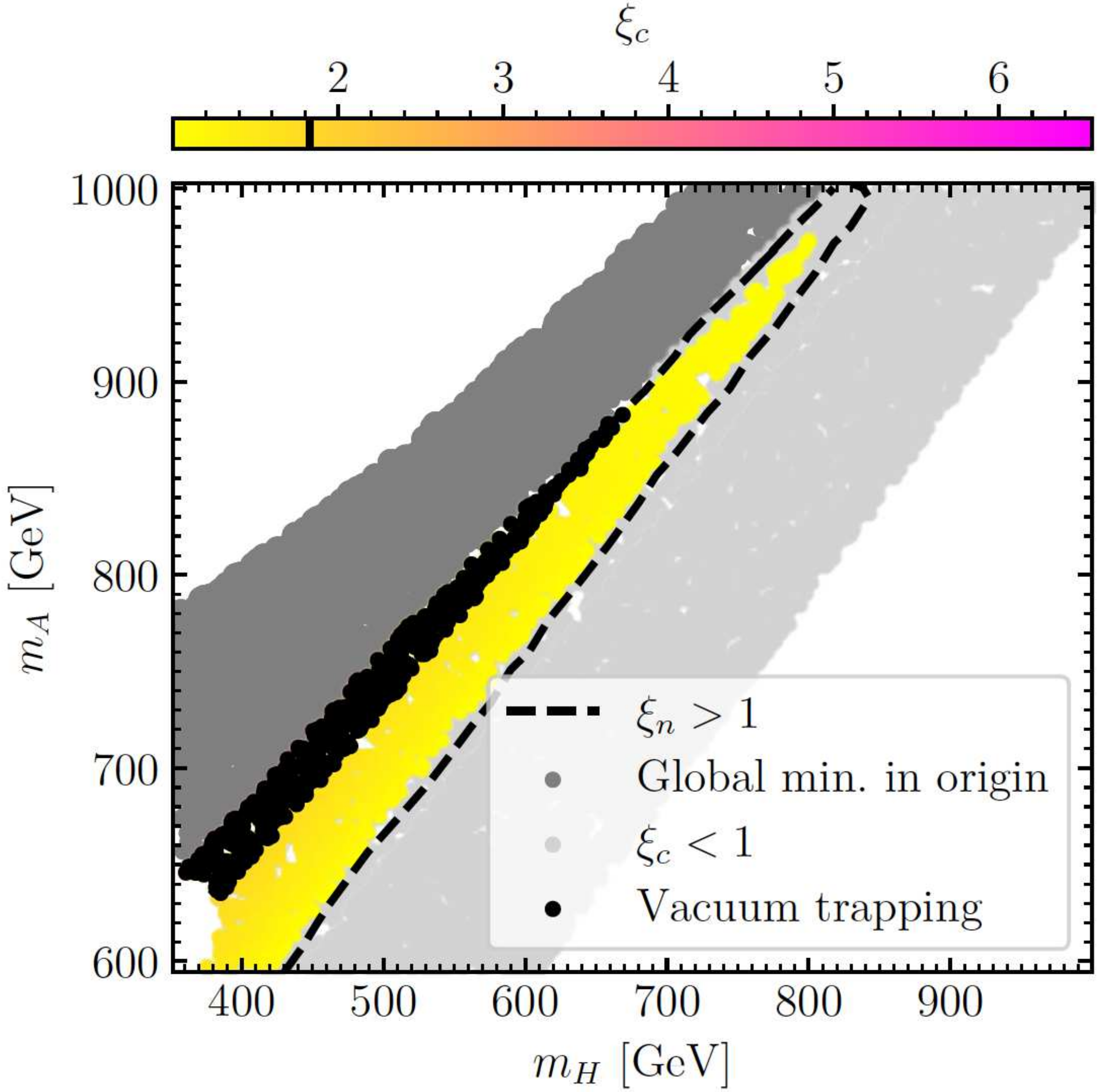
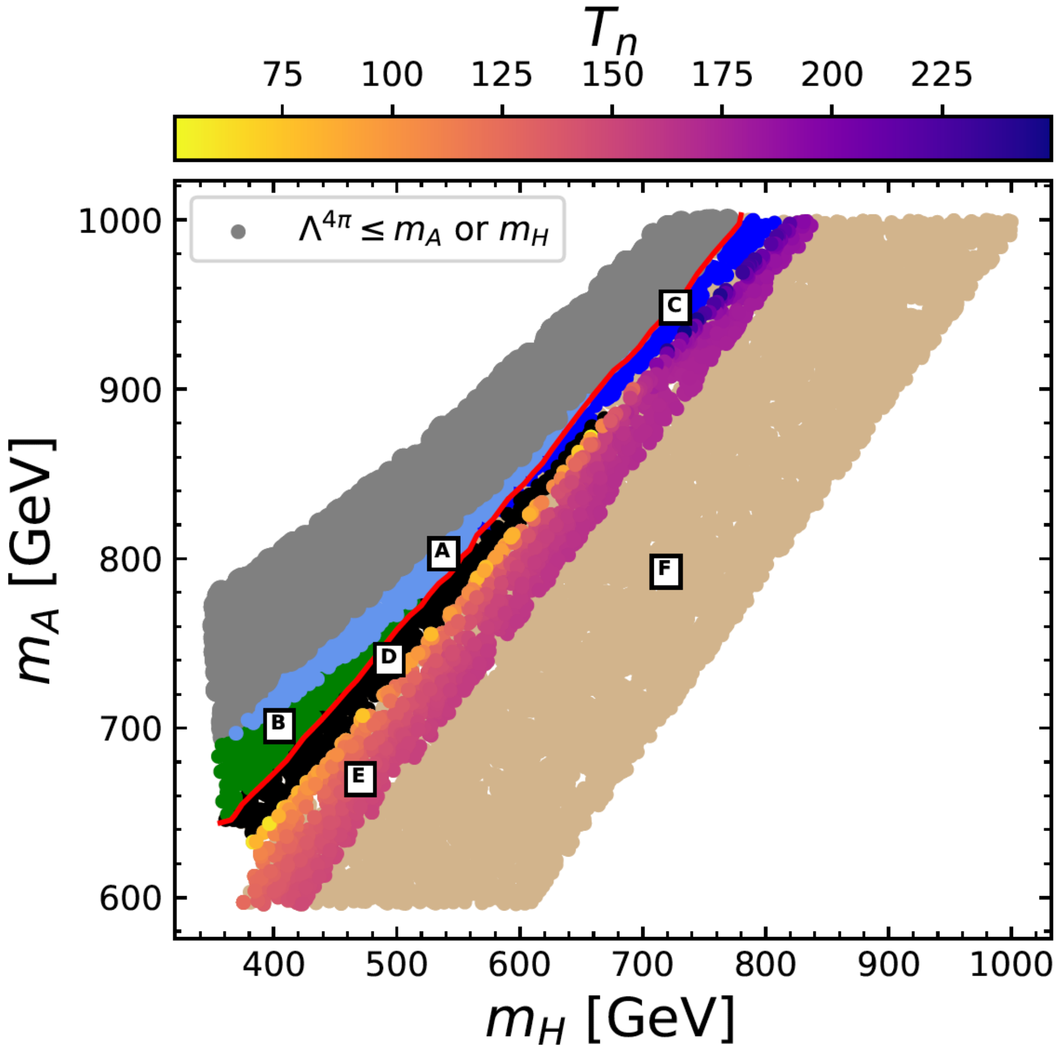


$\Rightarrow$ potentially strongest GW signal: forbidden by vacuum trapping

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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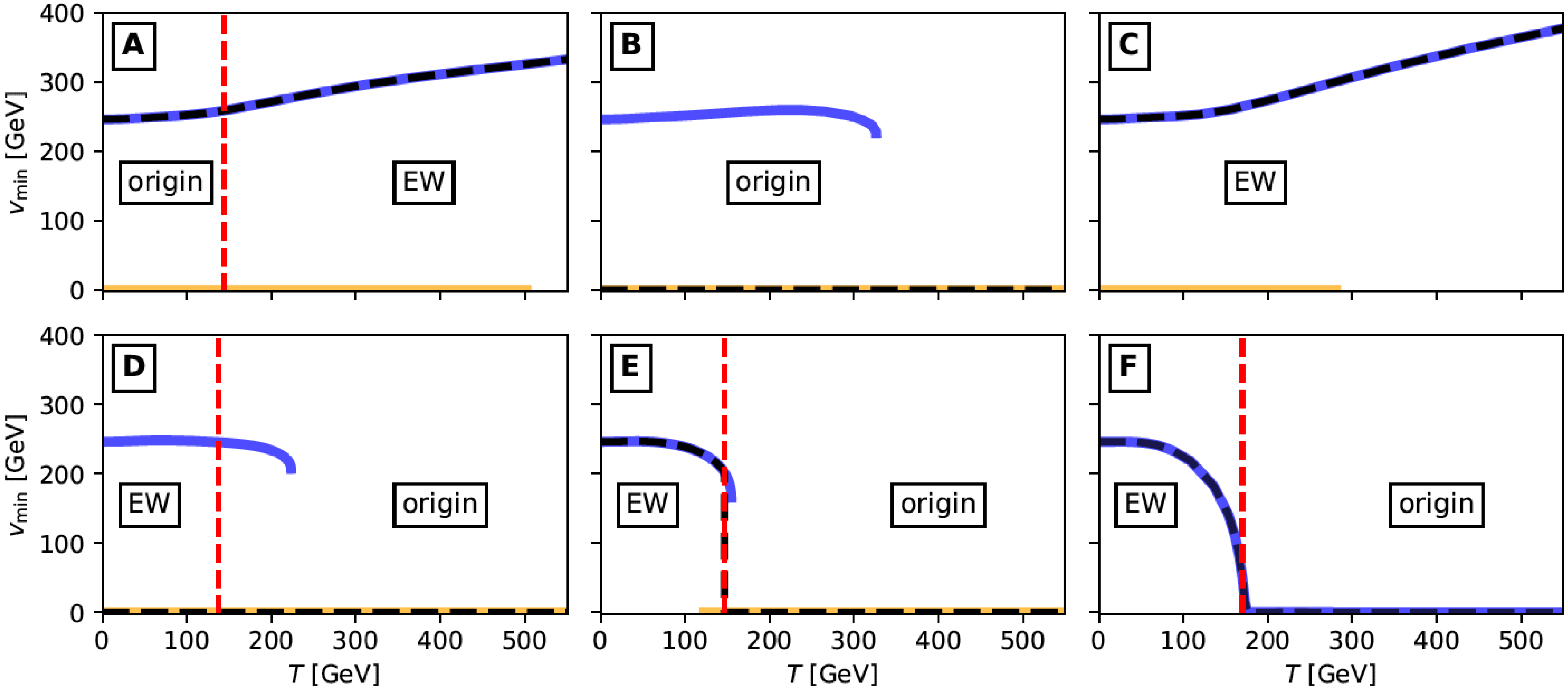
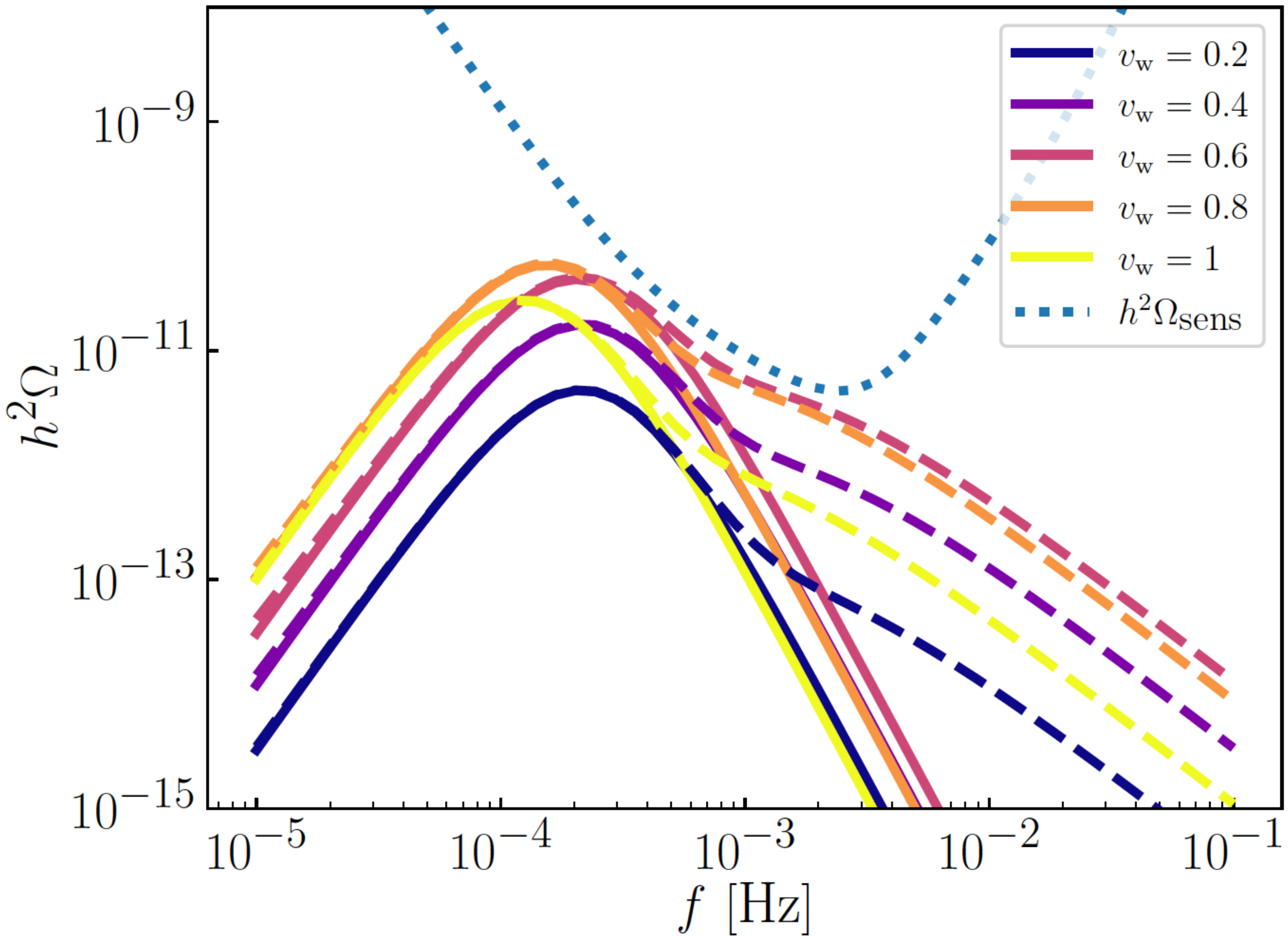


⇒ Zone E preferred by phenomenology/FOEWPT

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

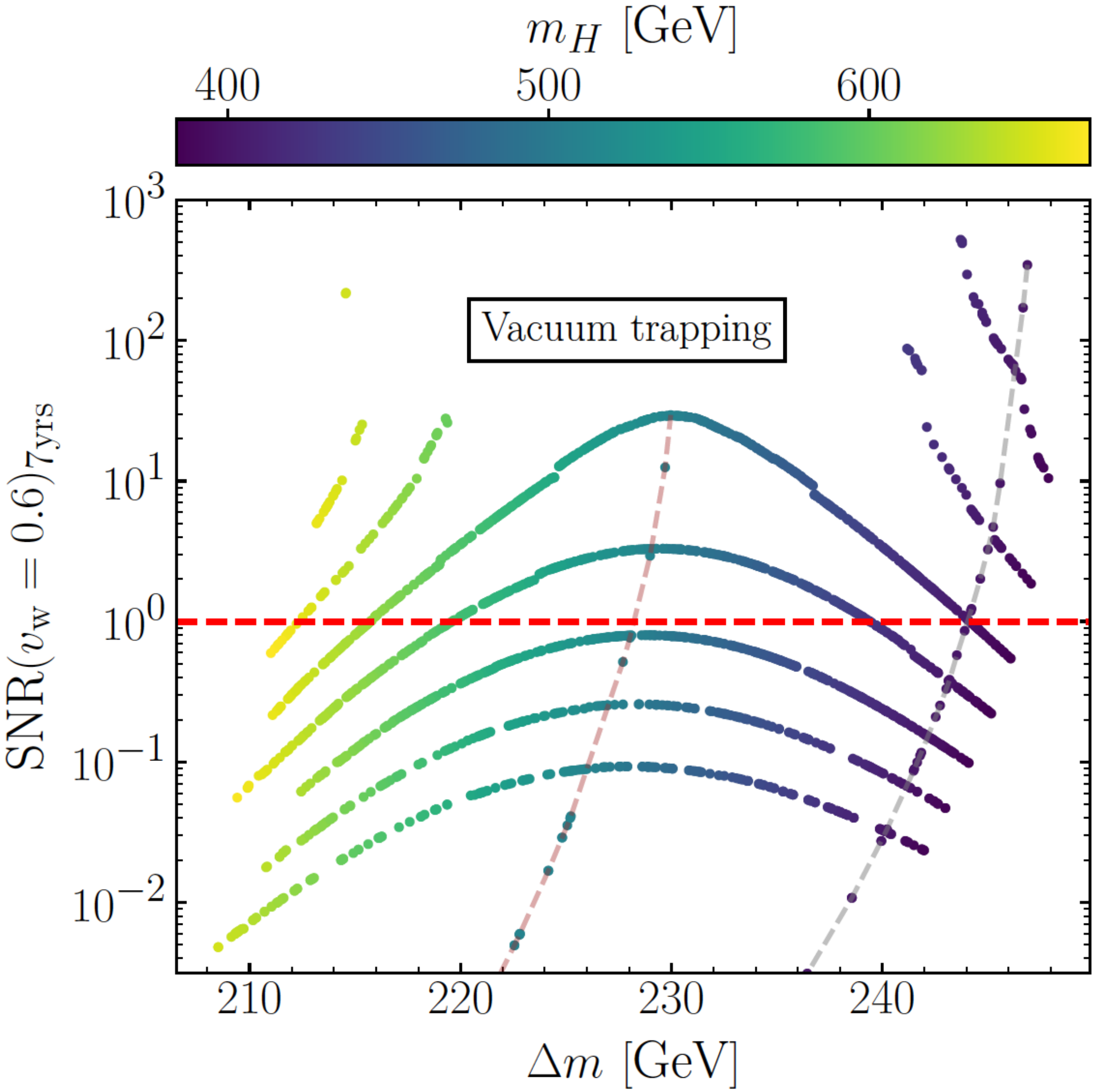
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



$\Rightarrow$ bubble wall velocity and turbulence important

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

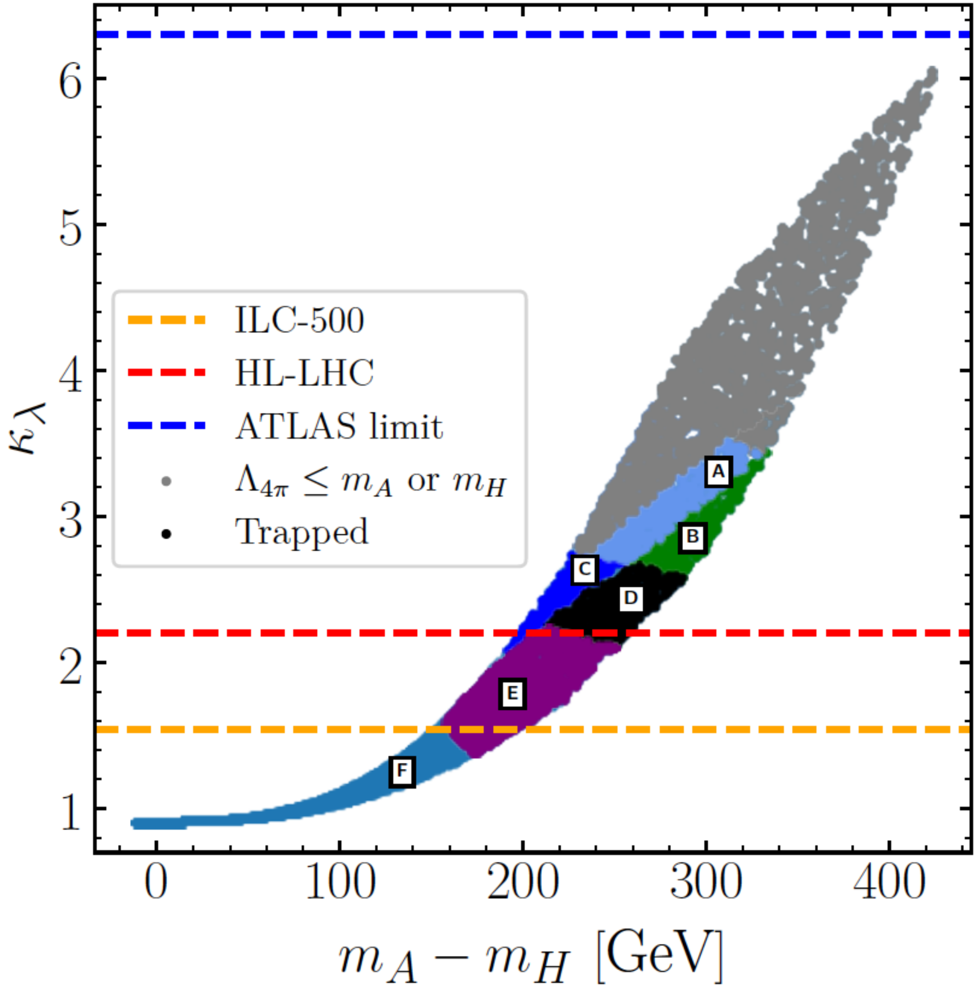
[T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22]

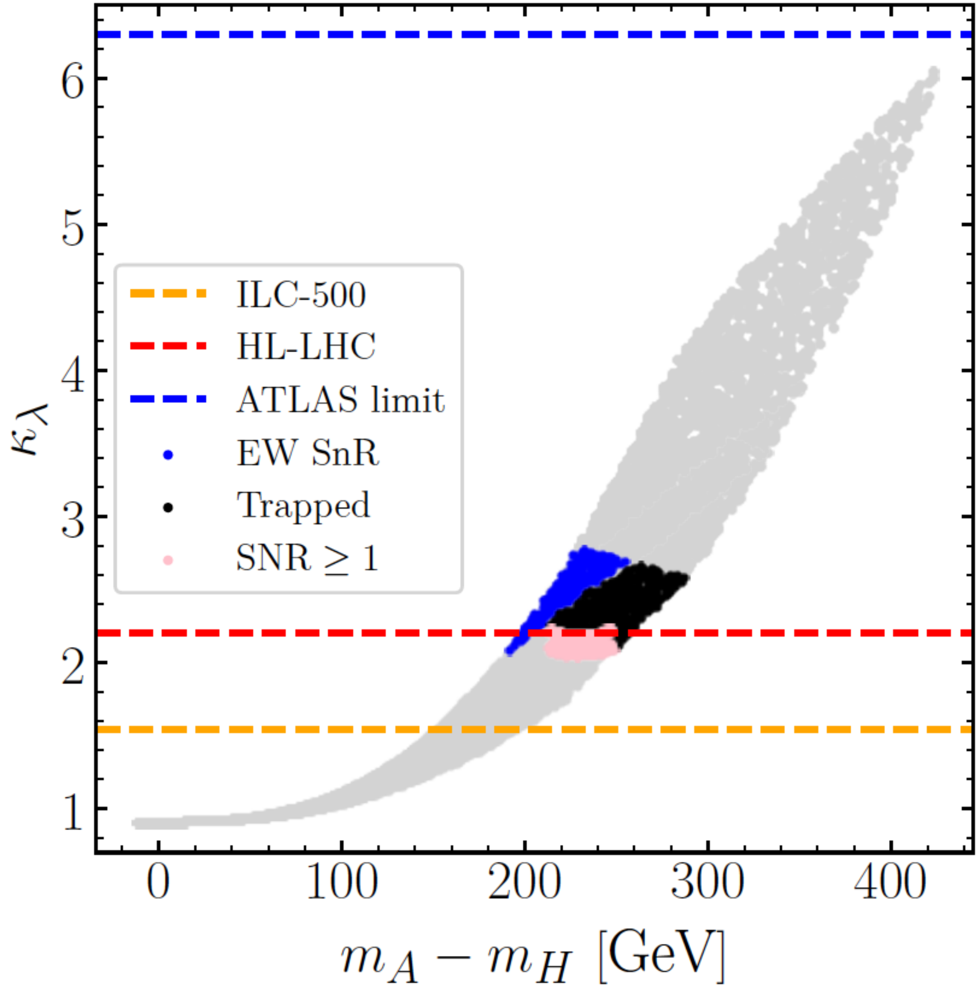


$\Rightarrow$ detectable GWs only in a very small zone close to VT

2HDM parameter scan to yield FOEWPT:

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



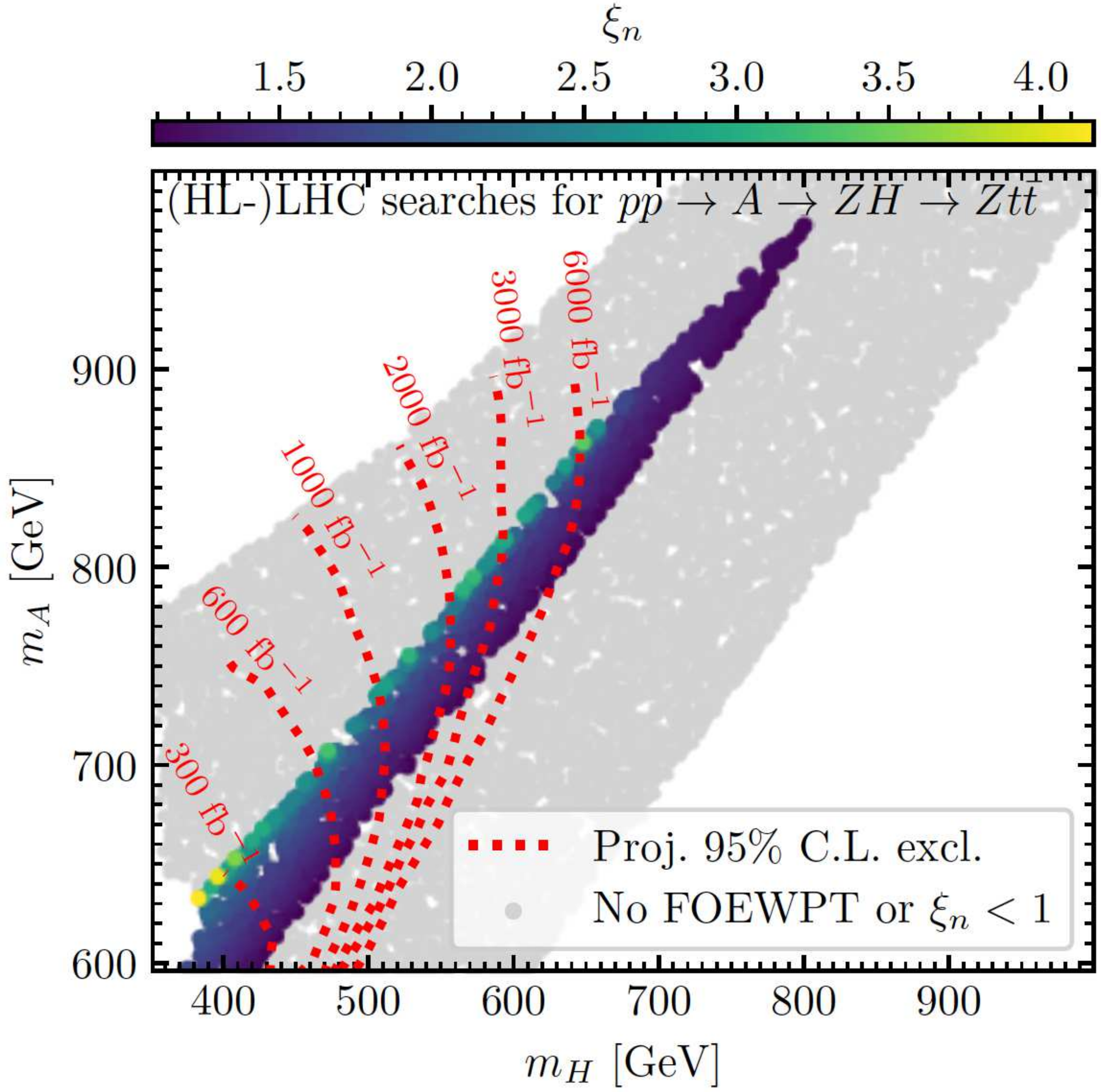


$\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$

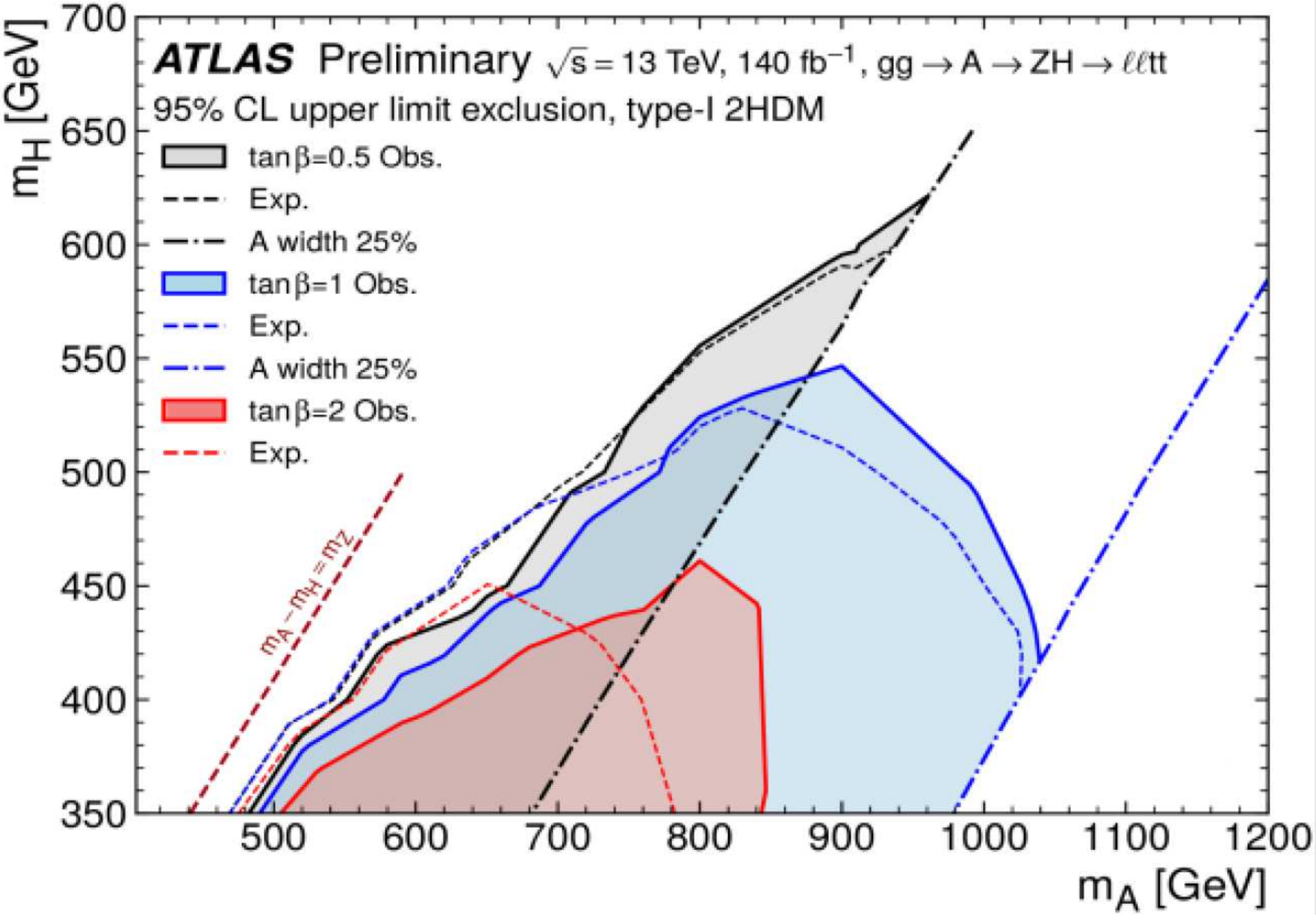
$\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$

Smoking gun signature: gap between m_A and m_H

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



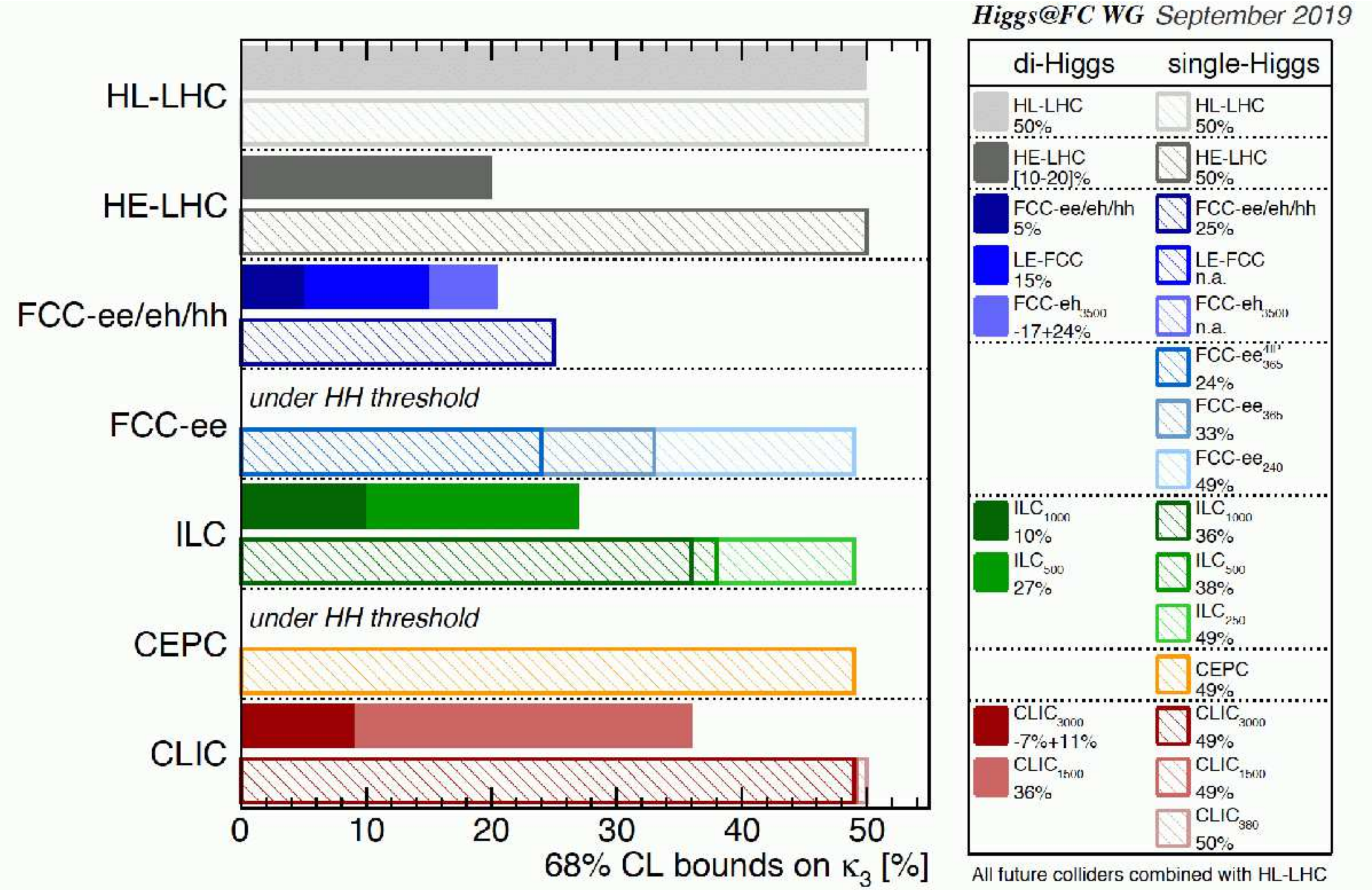
⇒ GW zone can be covered at the HL-LHC



⇒ interesting excess in the "right spot" :-) ($m_H = 420$ GeV, $m_A = 650$ GeV)

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

SM triple Higgs coupling: comparison of all colliders:

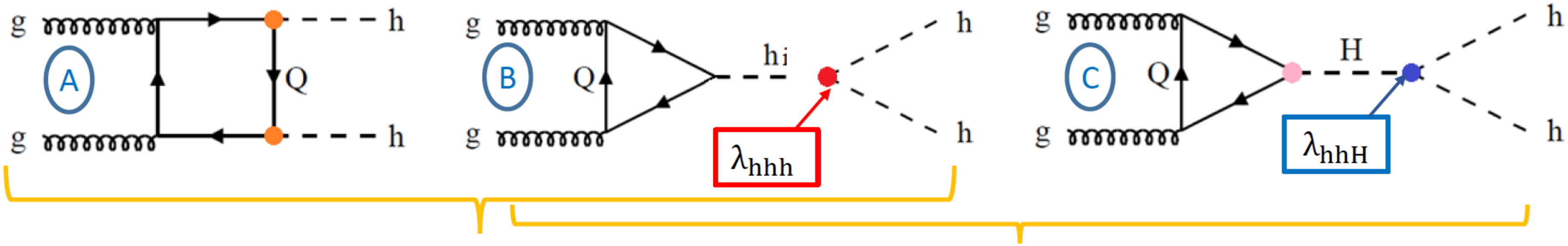


$\Rightarrow$ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$

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

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

Di-Higgs production at the LHC:

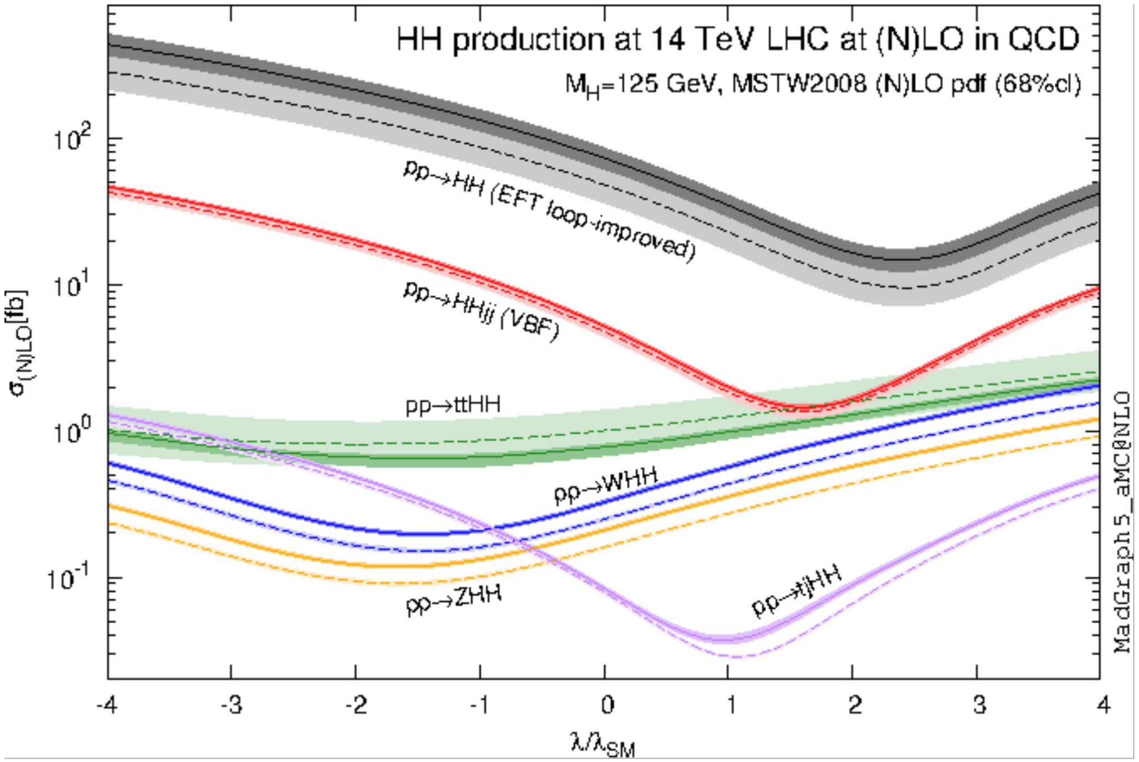


$\sigma_{SM} \sim$ 38 fb at NLO

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

Diagrams that are sensitive
to triple Higgs couplings

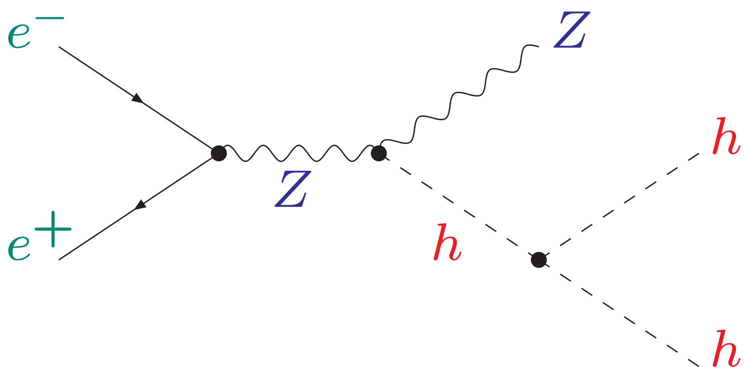
$\Rightarrow$ strong interference of "box" and "SM-like Higgs"



Di-Higgs production at ILC/CLIC:

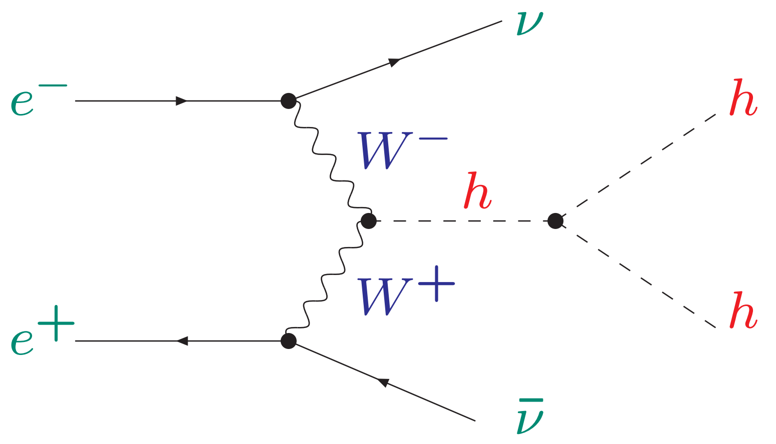
Higgs-strahlung:

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

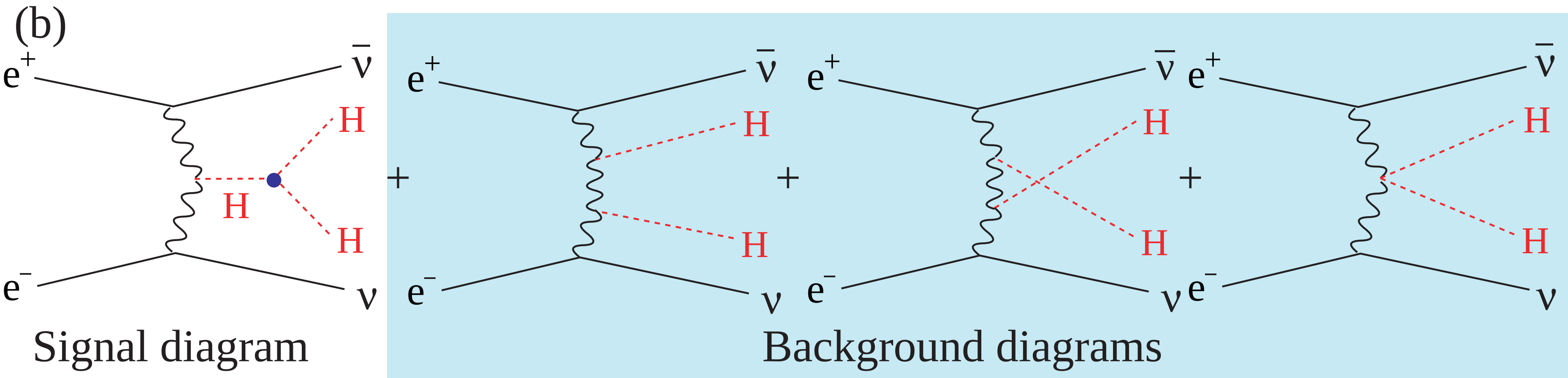


weak boson fusion (WBF):

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



Signal and background interference:



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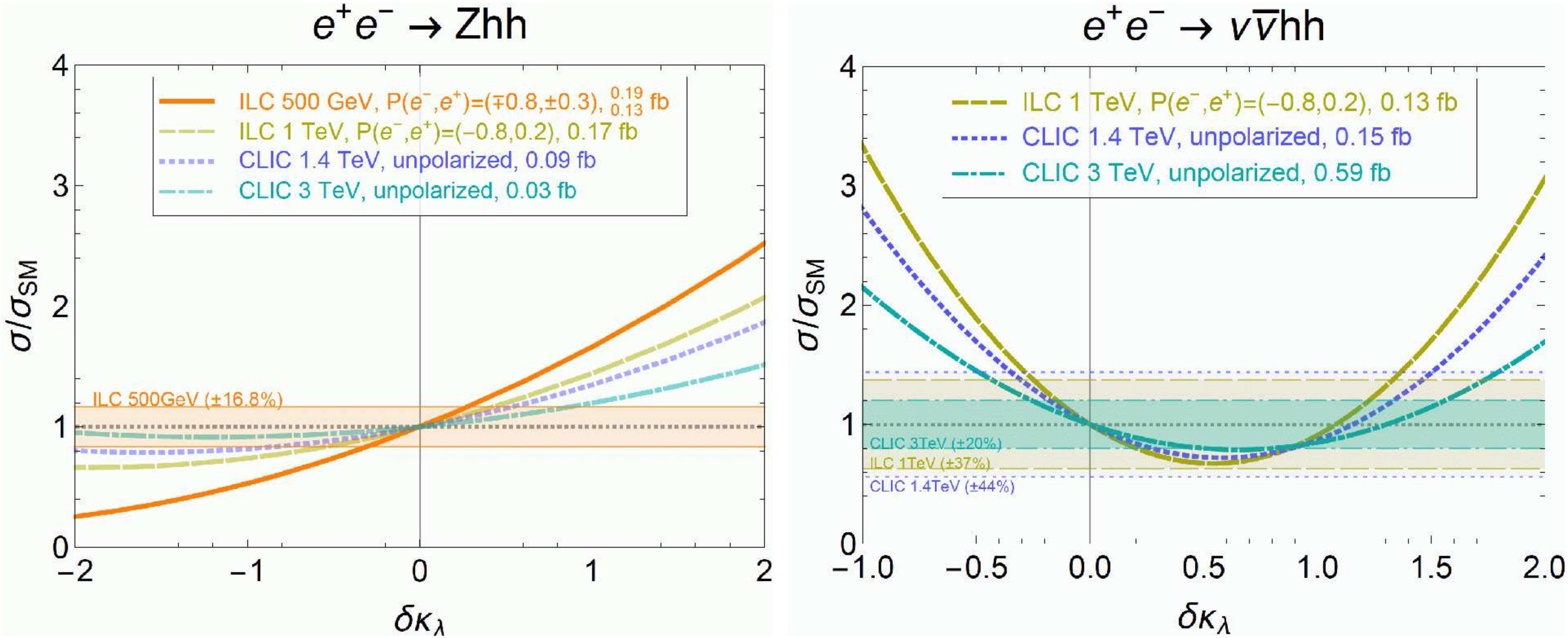
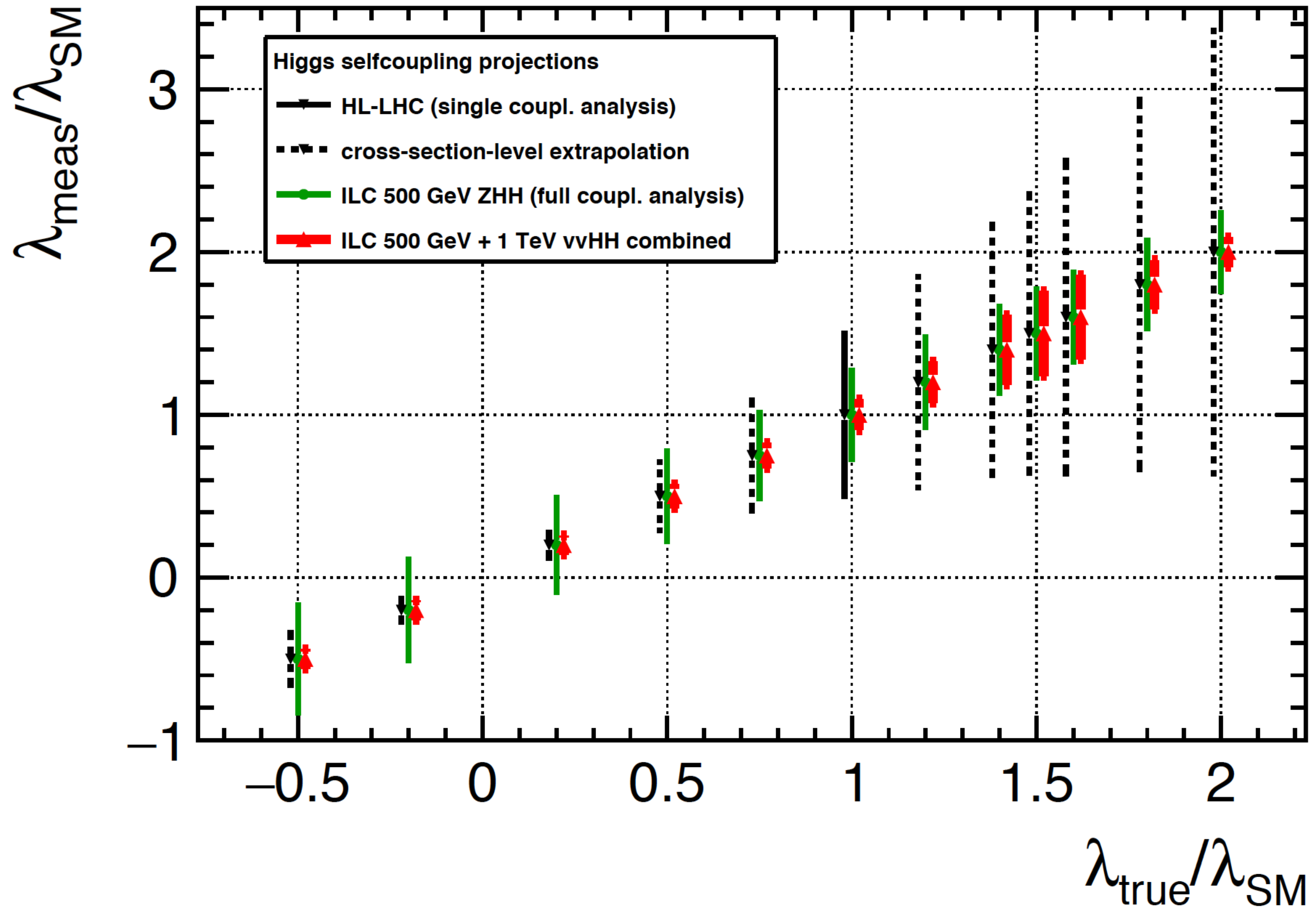


$\kappa_\lambda := 1 + \delta\kappa_\lambda$

$\Rightarrow$ strong and different dependence on κ_λ

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

[*J. List et al. – PRELIMINARY*]



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

Measurement of κ_λ selfcoupling at HL-LHC/ILC:

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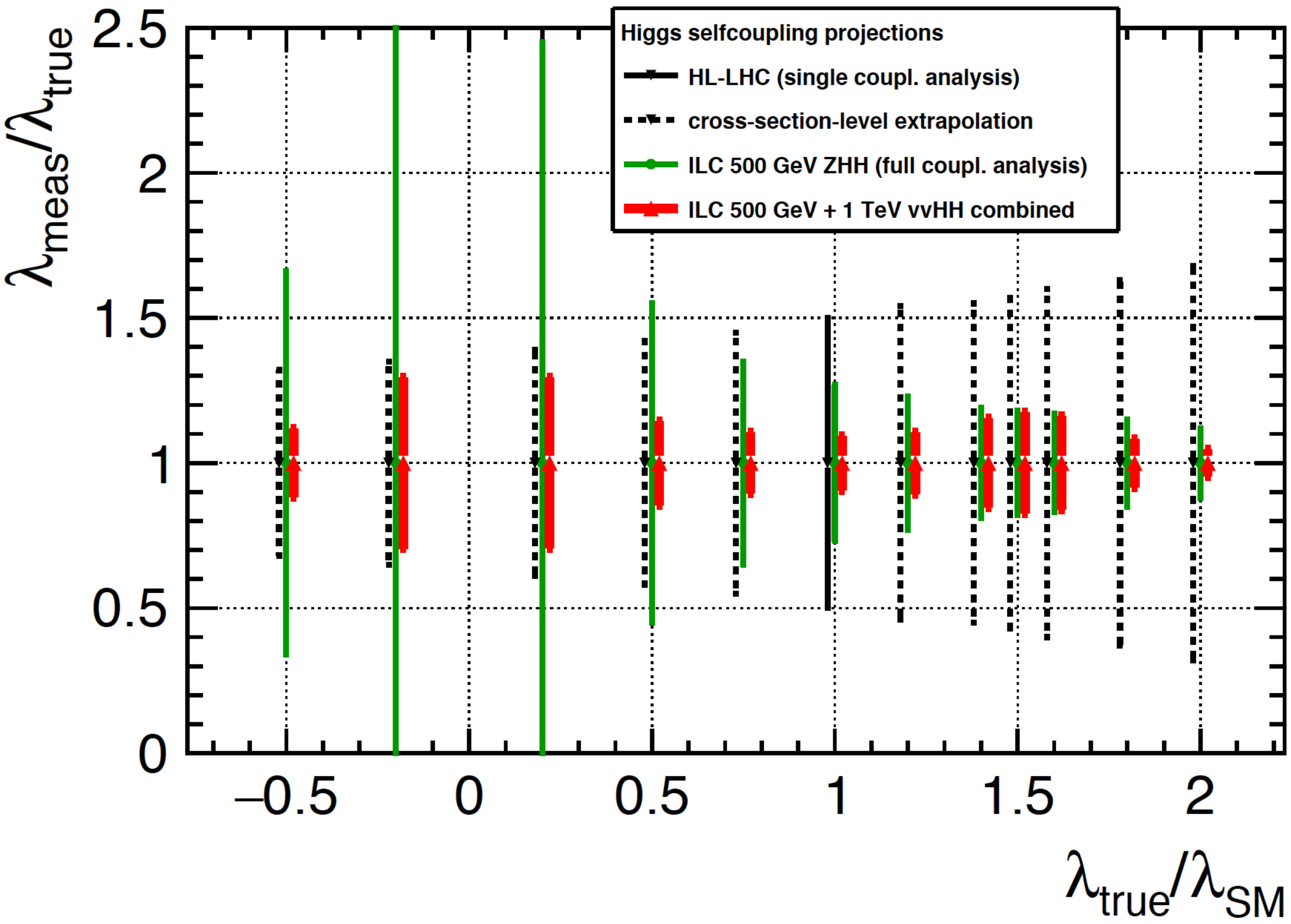
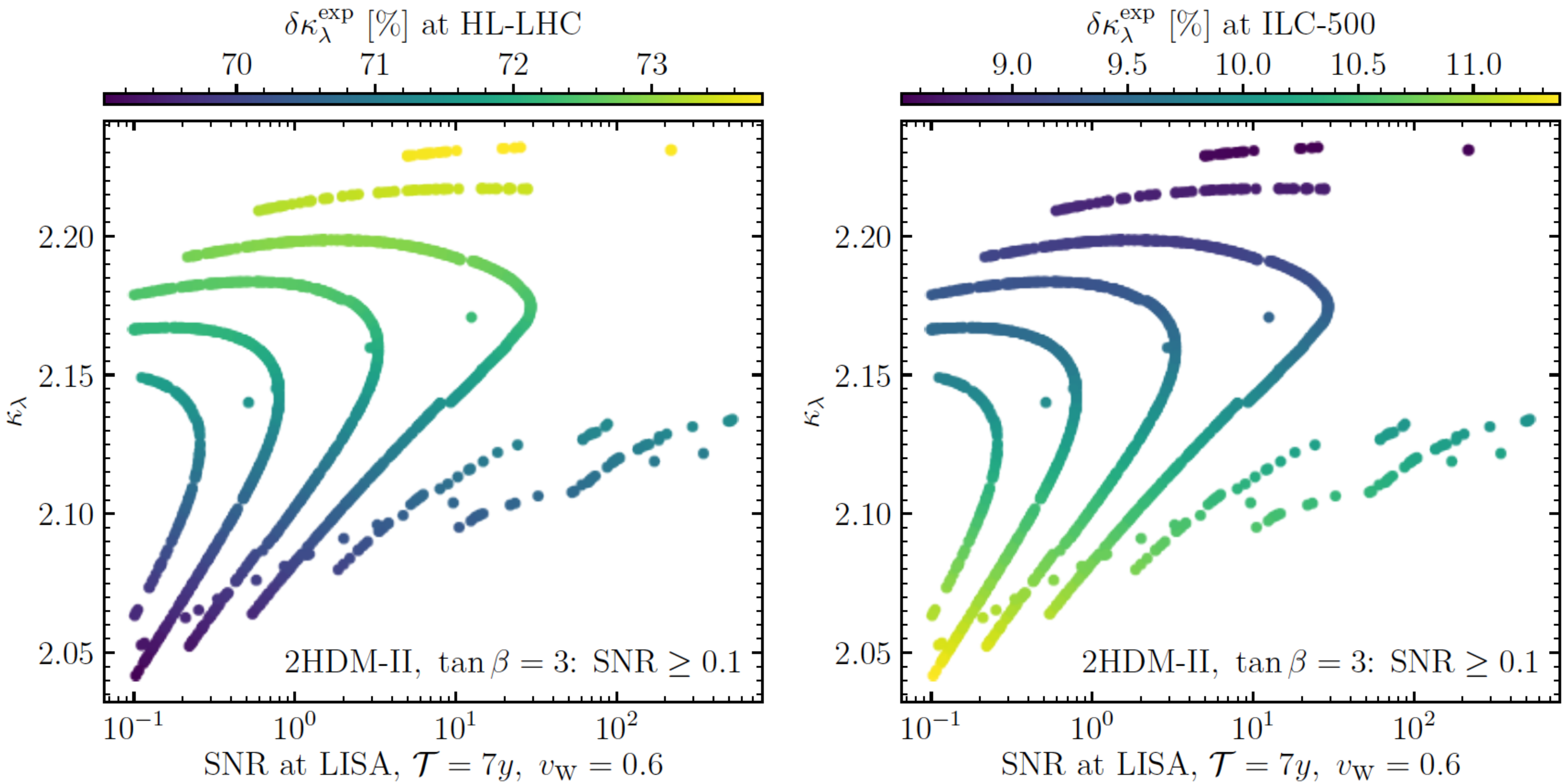


$\Rightarrow$ over most of the parameter space ILC is clearly superior to HL-LHC

Example: 2HDM $\Rightarrow$ FOEWPT $\Rightarrow$ GW's

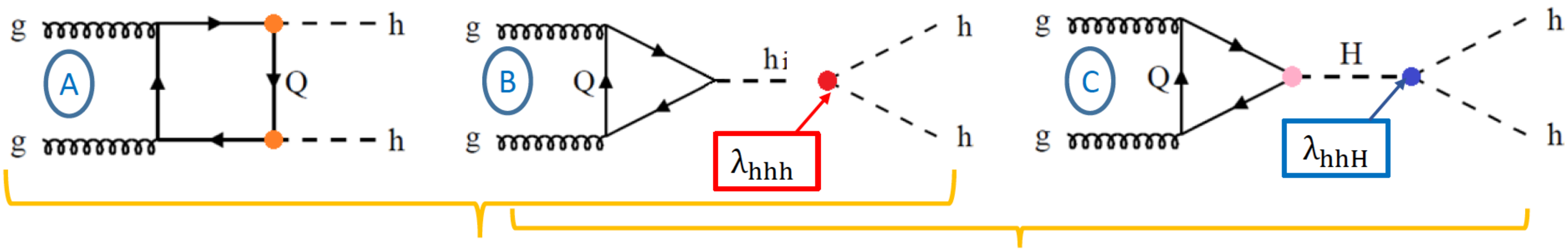
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]

$\Rightarrow$ Synergies: collider: λ_{hhh} $\Leftrightarrow$ LISA: GW signals



$\Rightarrow$ FOEWPT requires large λ_{hhh} and can induce GW signals

BSM THCs at the HL-LHC and ILC



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

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

Diagrams that are sensitive
to triple Higgs couplings

$\Rightarrow$ possible strong resonance with BSM Higgs

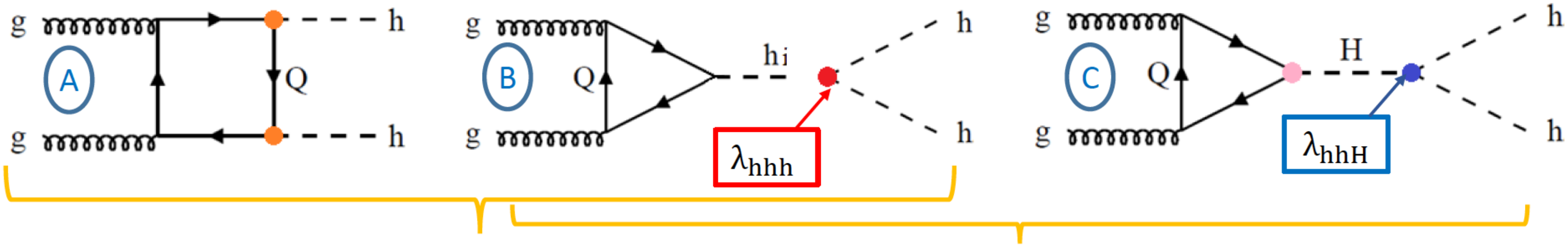
Sideremark: experimental limtis are obtained for

– non-resonant production

– purely resonant production

$\Rightarrow$ no limits available for mixed scenarios :-(

BSM THCs at the HL-LHC and ILC



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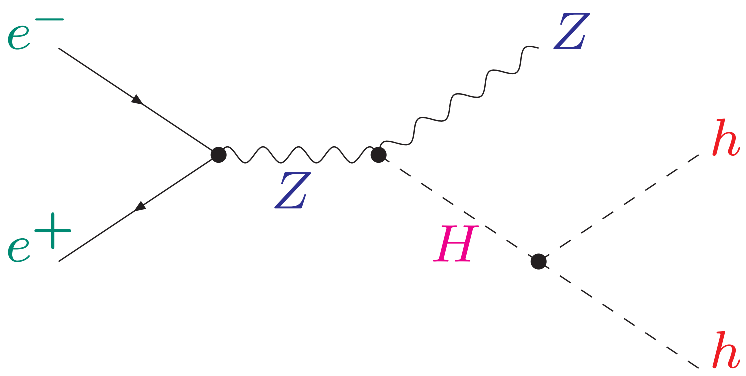
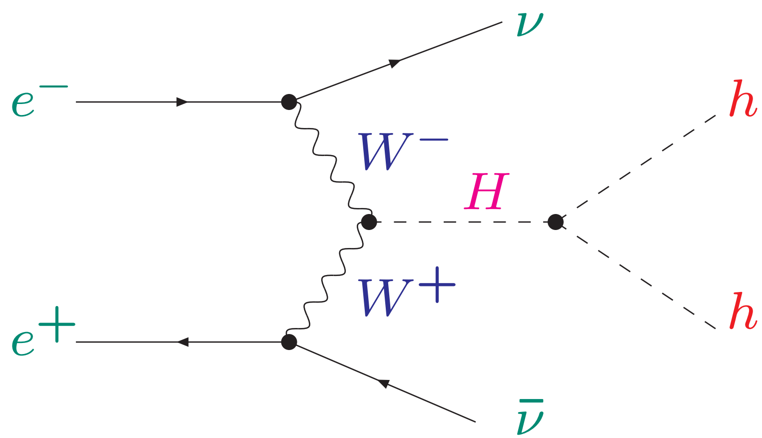


weak boson fusion (WBF):

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

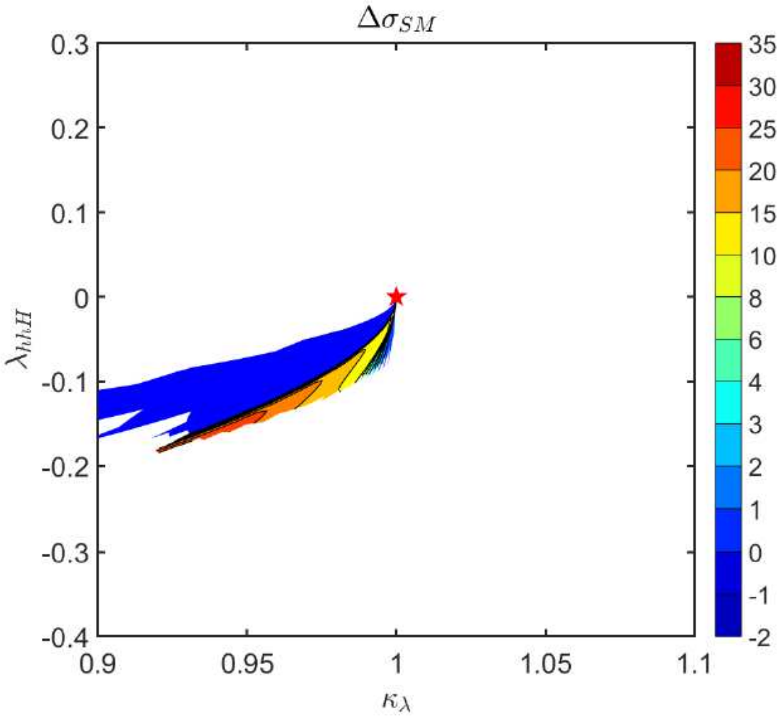


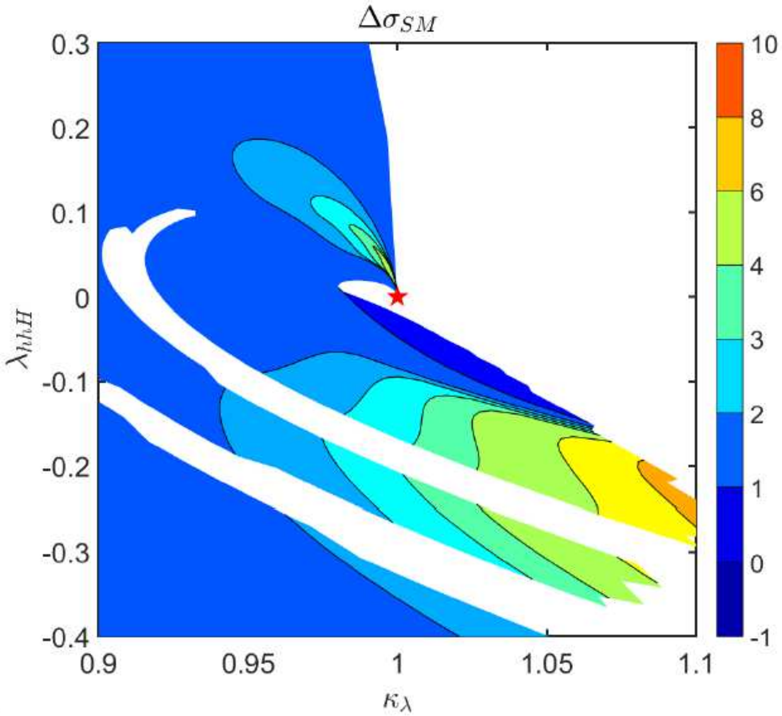
Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

$gg \to hh$ in the 2HDM with HPAIR

Benchmark plane: 2HDM type I, $m_{12}^2 = (m_H^2 \cos^2\alpha)/\tan\beta$, $\tan\beta = 10$

$\Delta\sigma_{\rm SM}$: precision in σ (based on $\kappa_\lambda = 1$)





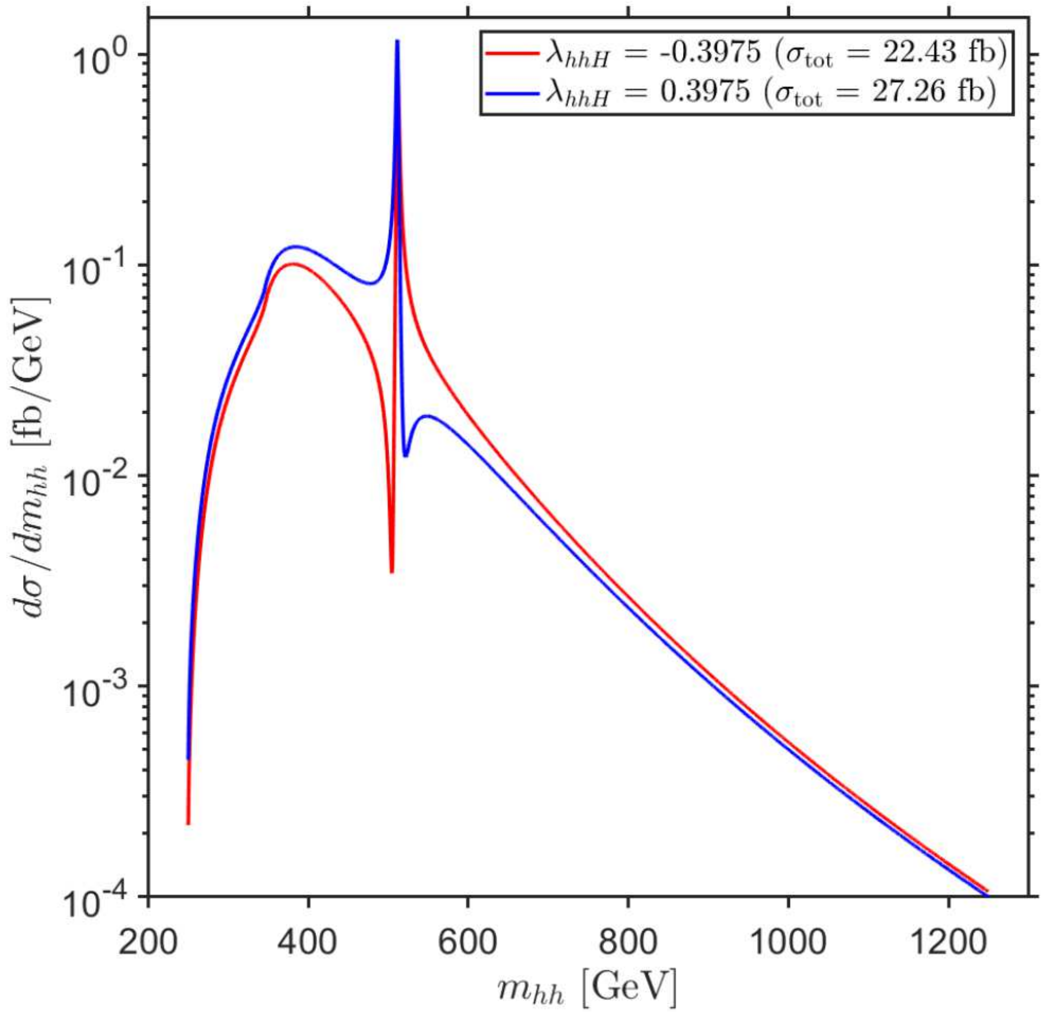
$\Rightarrow$ $\kappa_\lambda \sim 1$, no effect on di-Higgs cross section

$\Rightarrow$ strong variation with λ_{hhH} from resonant H-exchange

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, $t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$



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

Di-Higgs production at the HL-LHC:

[F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

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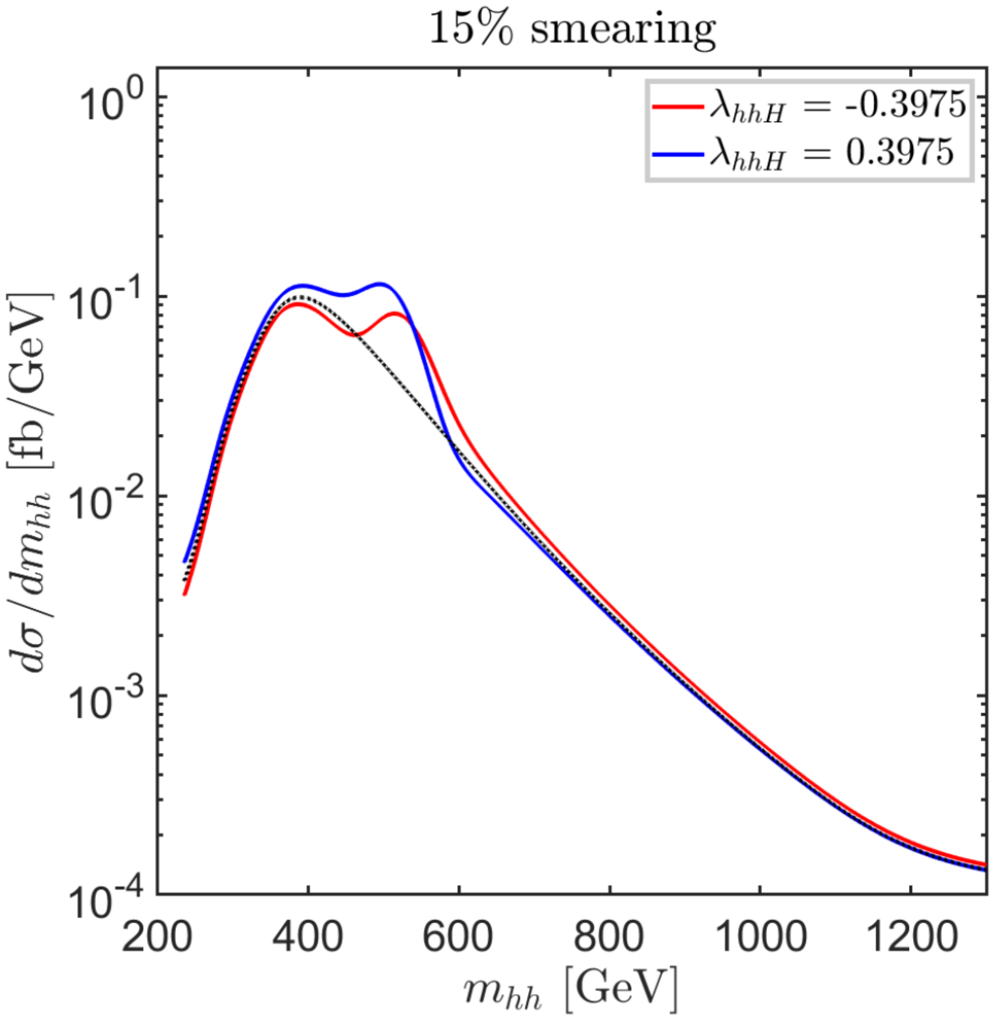
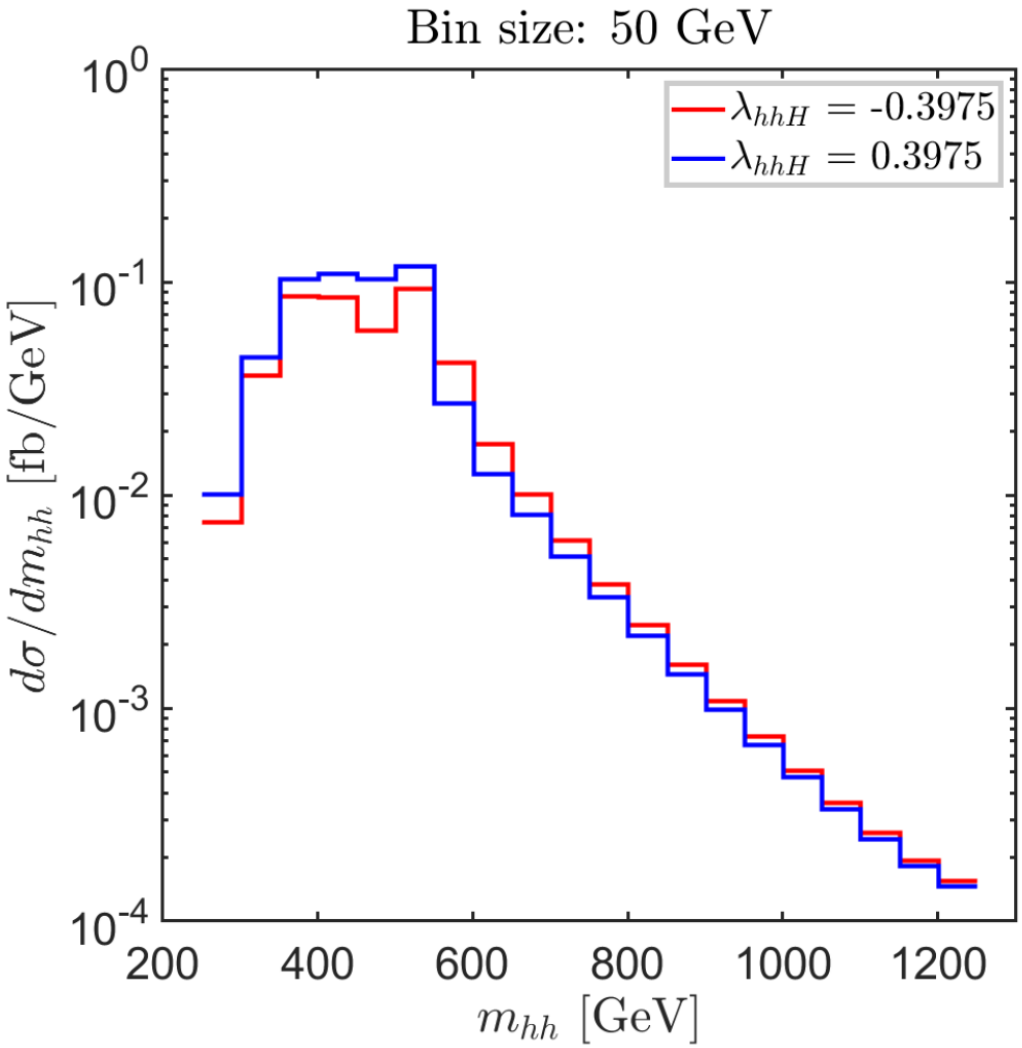


$\Rightarrow$ smearing of 15% applied (optimistic?) $\Rightarrow$ access to λ_{hhH}?

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, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

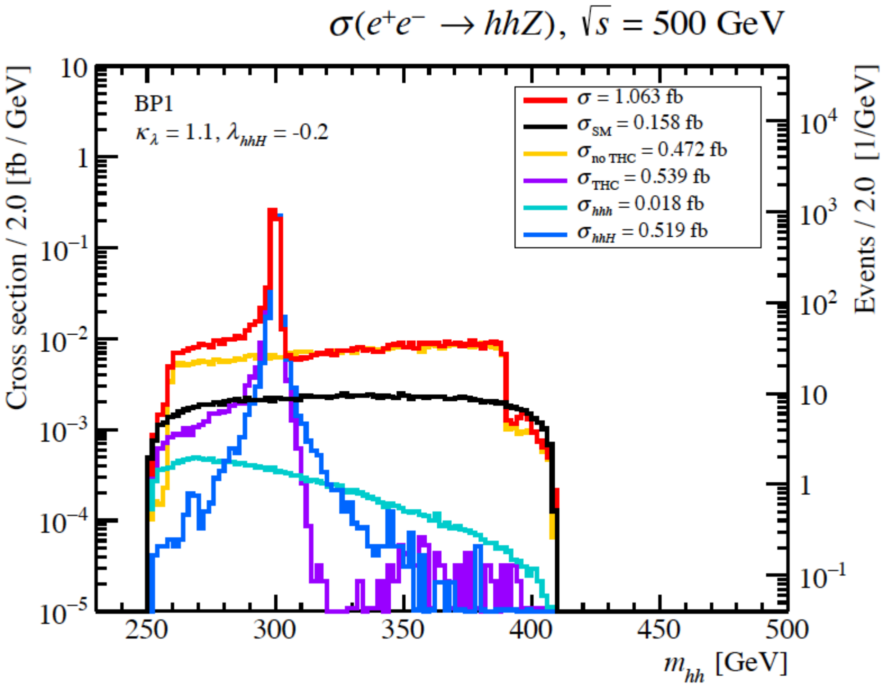


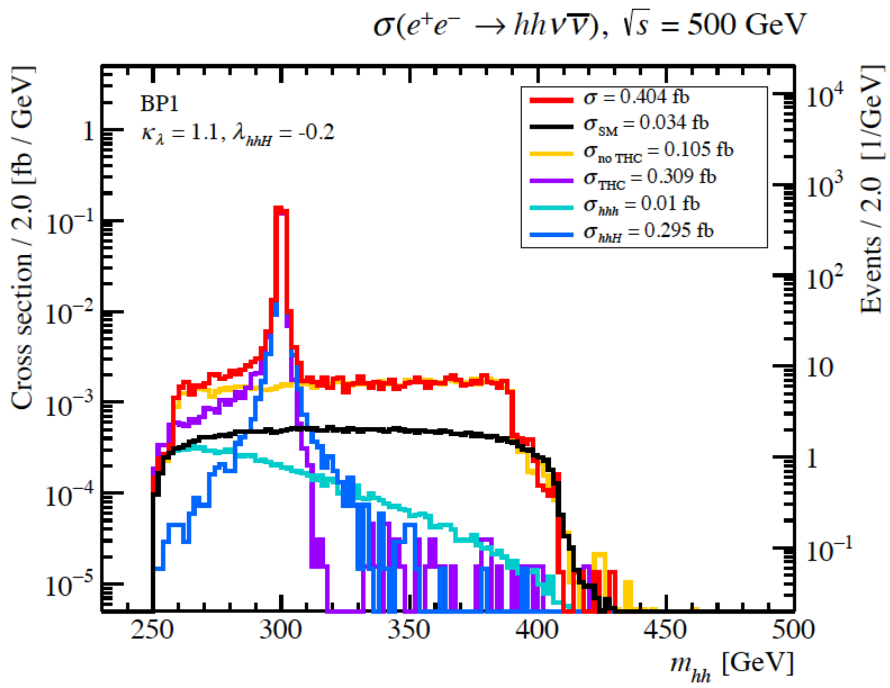
⇒ binning of 50 GeV applied (realistic?) ⇒ access to λ_{hhH}?

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

Example: 2HDM type I $\qquad e^+e^- \to Zhh/\nu\bar{\nu}hh$ 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. Bonus track: Discovery of the second Higgs boson

LHC Seminar

Measurement of Higgs boson production and search for new resonances in final states with photons and Z bosons

by Chiara Arcangeletti (INFN e Laboratori Nazionali di Frascati (IT))

Tuesday 6 Jun 2023, 11:00 → 12:00 Europe/Zurich

500/1-001 - Main Auditorium (CERN)

New ATLAS result on the low-mass Higgs search in $pp \to \phi \to \gamma\gamma$

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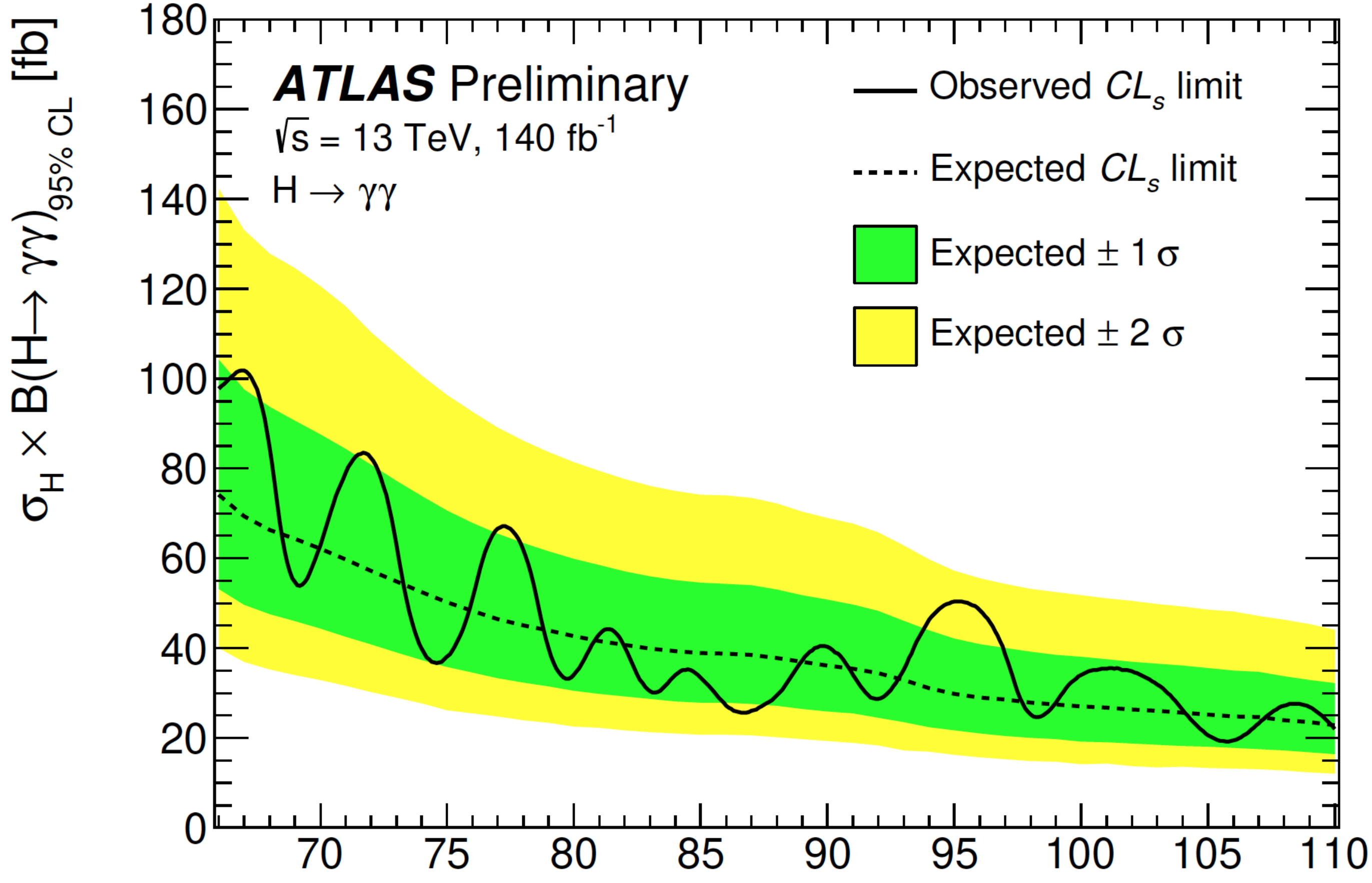
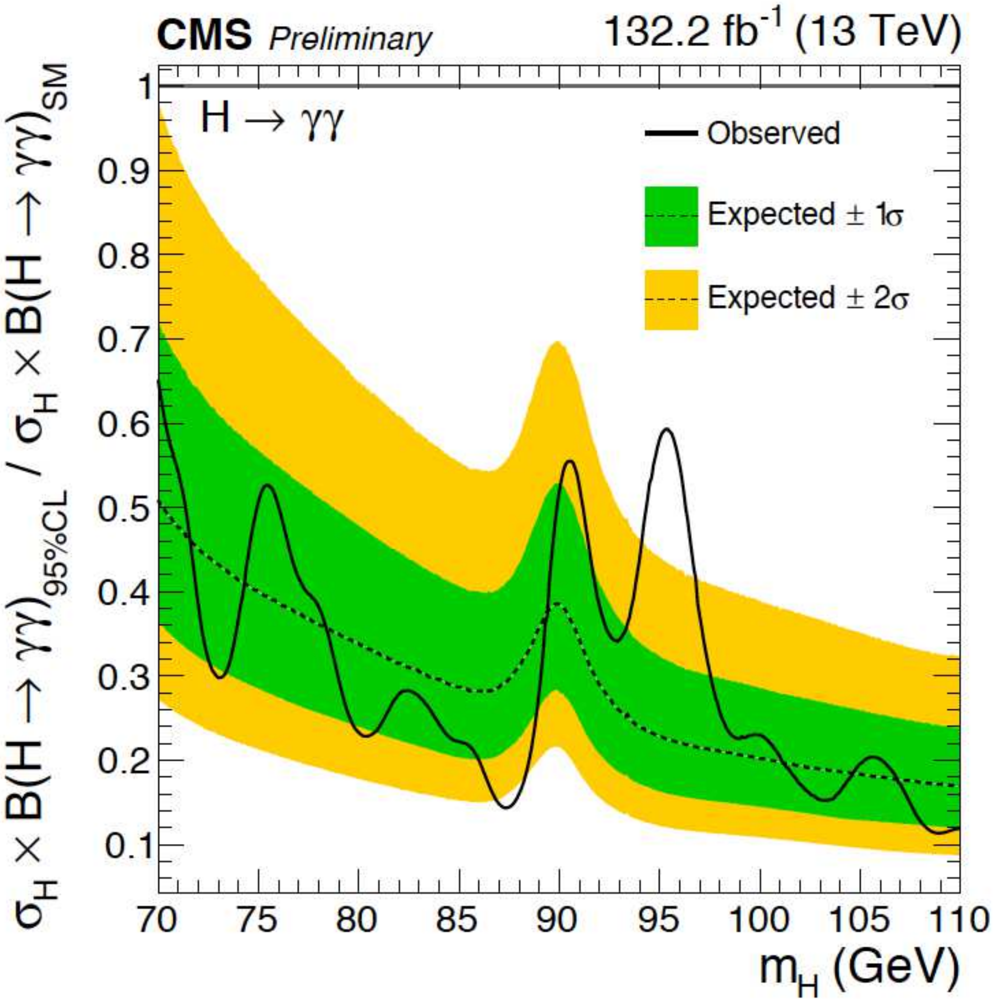
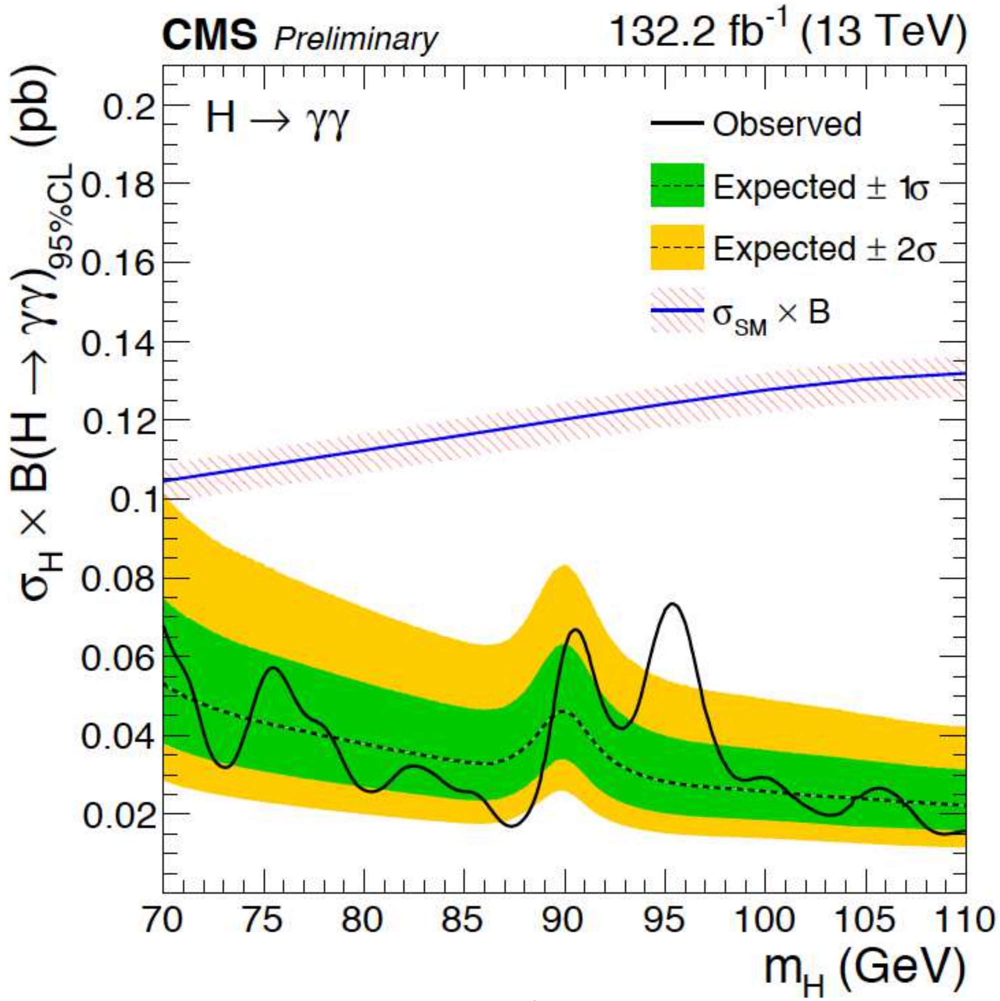


⇒ higest "excess" at 95.4 GeV

Full Run 2 results from CMS: excess at 95.4 GeV [CMS '23]



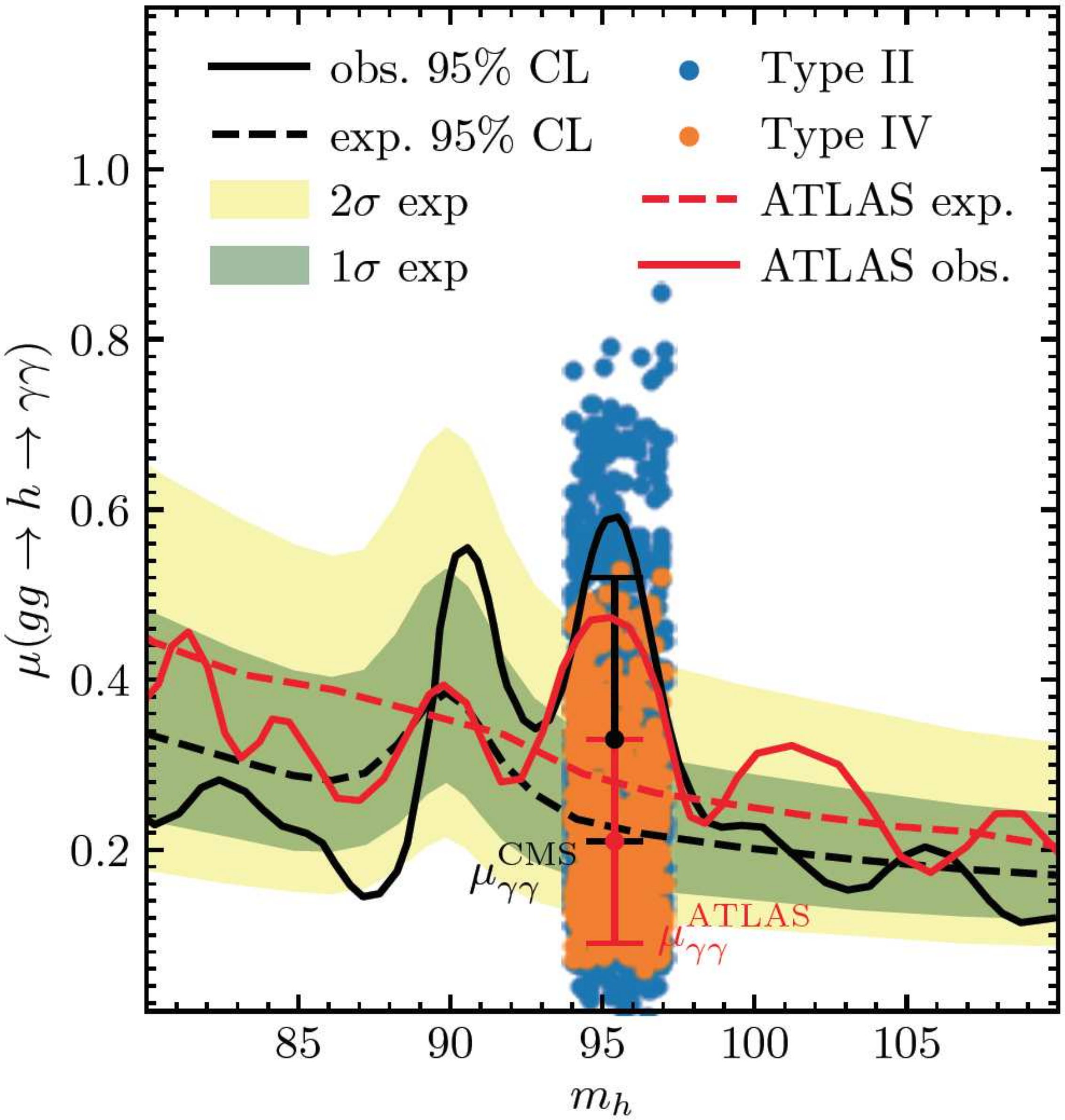


$$\mu_{\gamma\gamma}^{\text{CMS}} = [\sigma(gg \to h_{95}) \times \text{BR}(h_{95} \to \gamma\gamma)]_{\text{exp/SM}} = 0.33^{+0.19}_{-0.12}\ (2.9\,\sigma)$$

$$\mu_{\gamma\gamma}^{\text{ATLAS}} = 0.21 \pm 0.12\ (1.7\,\sigma)$$

New CMS/ATLAS comparison:

[T. Biekötter, S.H., G. Weiglein '23]



$\Rightarrow$ agreement between ATLAS and CMS!

New CMS/ATLAS comparison:

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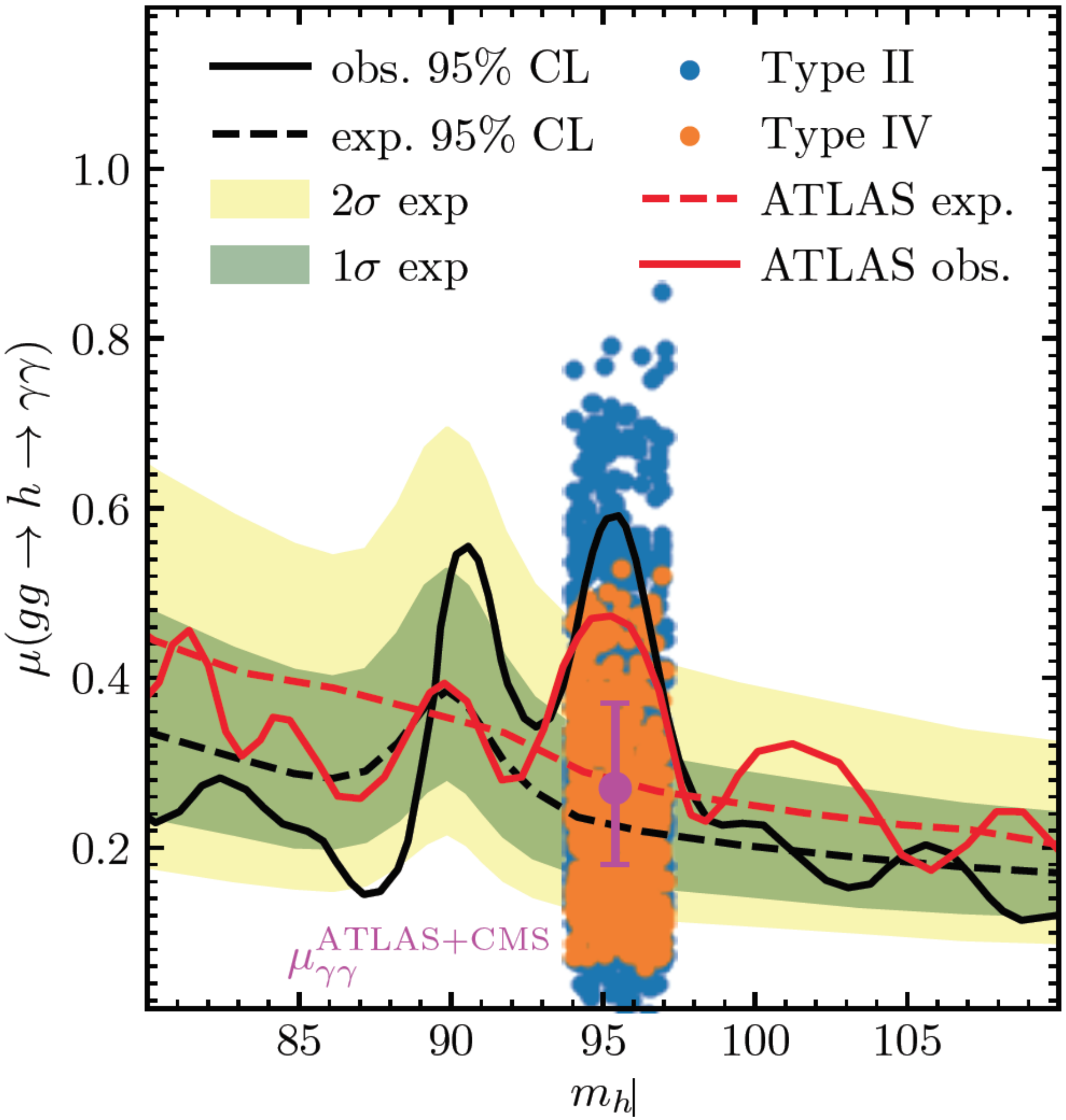
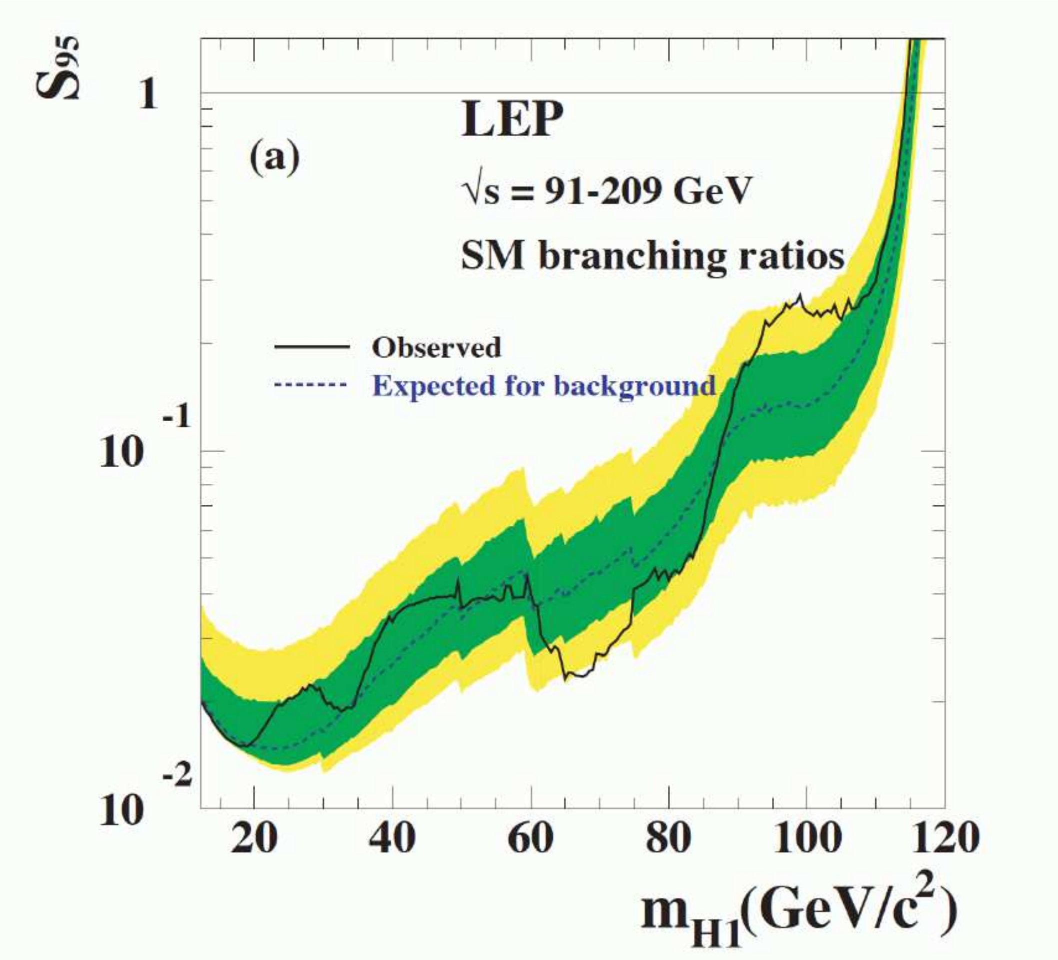
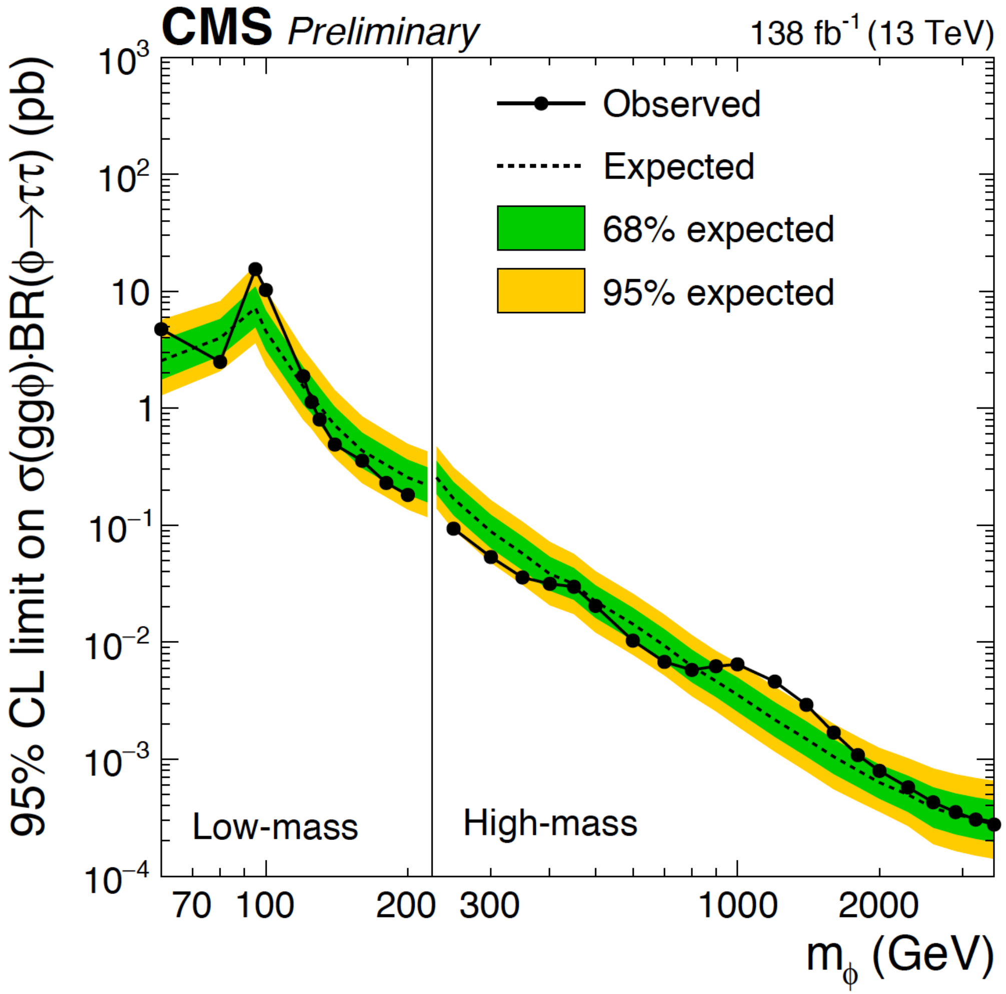


$\Rightarrow$ agreement between ATLAS and CMS! $\mu_{\gamma\gamma} = 0.27^{+0.10}_{-0.09}$ ($3.2\,\sigma$)

LEP: $e^+e^- \to Z\phi \to Zb\bar{b}$ $(2\,\sigma)$

CMS: $pp \to \phi \to \tau^+\tau^-$ $(2.4\,\sigma)$





$\Rightarrow$ no LEE (as theorist I am allowed to add naively)

$\boxed{\Rightarrow \sim 4.6\,\sigma}$

S2HDM: 2 Higgs doublets (complex) + 1 Higgs singlet (complex)

Three neutral $\mathcal{CP}$-even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} , \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Coupling to fermions: (same pattern as in 2HDM)

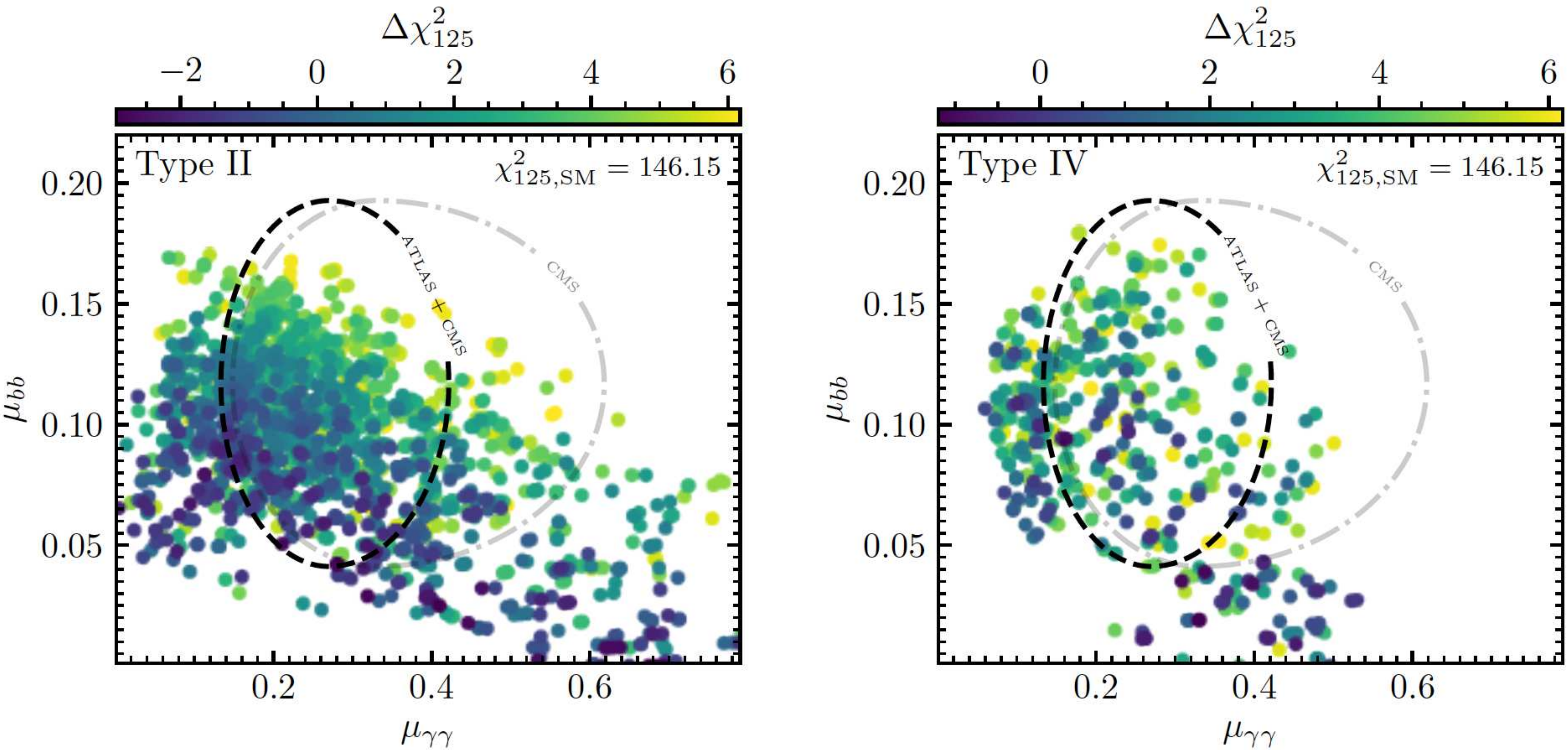
	u-type ($c_{h_i tt}$)	d-type ($c_{h_i bb}$)	leptons ($c_{h_i \tau\tau}$)
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

"Physical" input parameters:

$$\alpha_{1,2,3}\,, \quad \tan\beta\,, \quad v\,, \quad v_S\,, \quad m_{h_{1,2,3}}\,, \quad m_A\,, \quad M_{H^\pm}\,, \quad m_\chi\,, \quad m_{12}^2$$

S2HDM type II vs. type IV

[*T. Biekötter, S.H., G. Weiglein '23*]

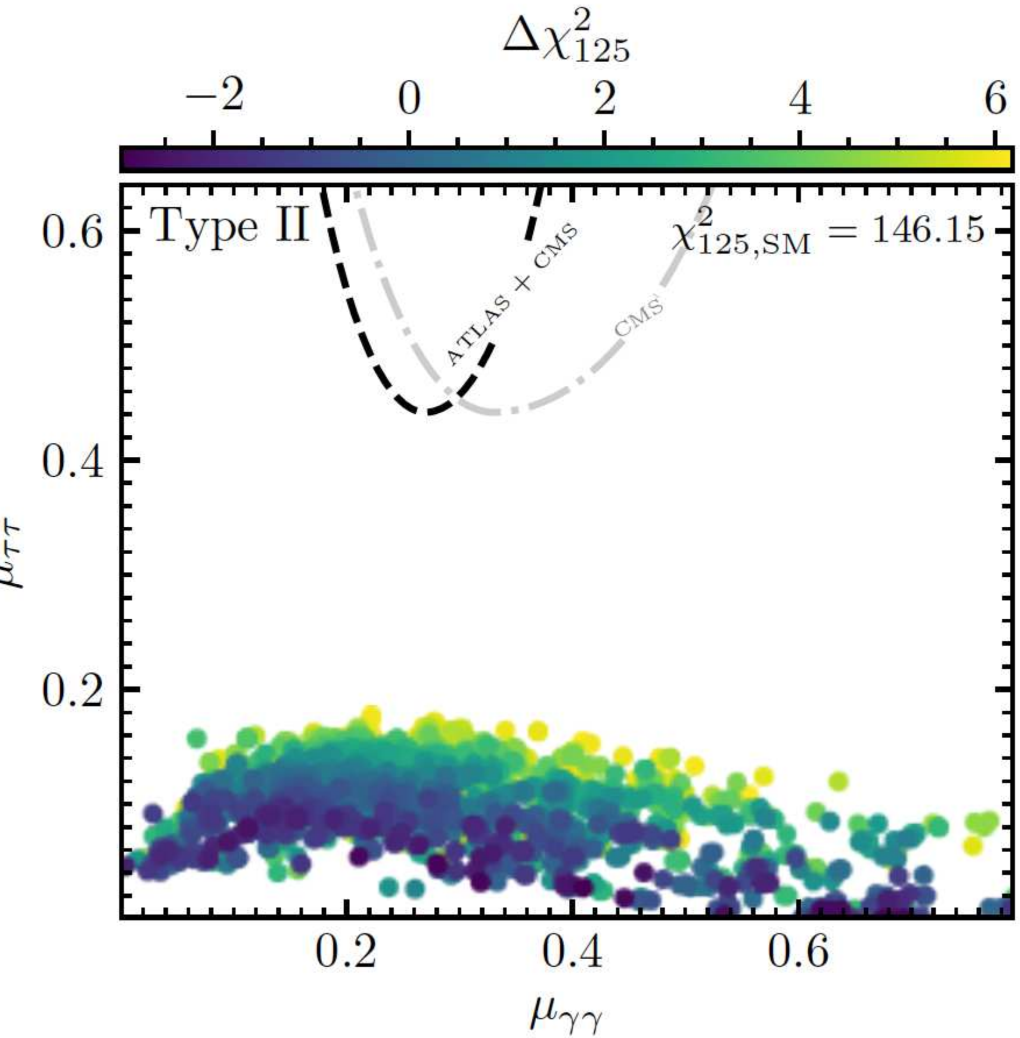


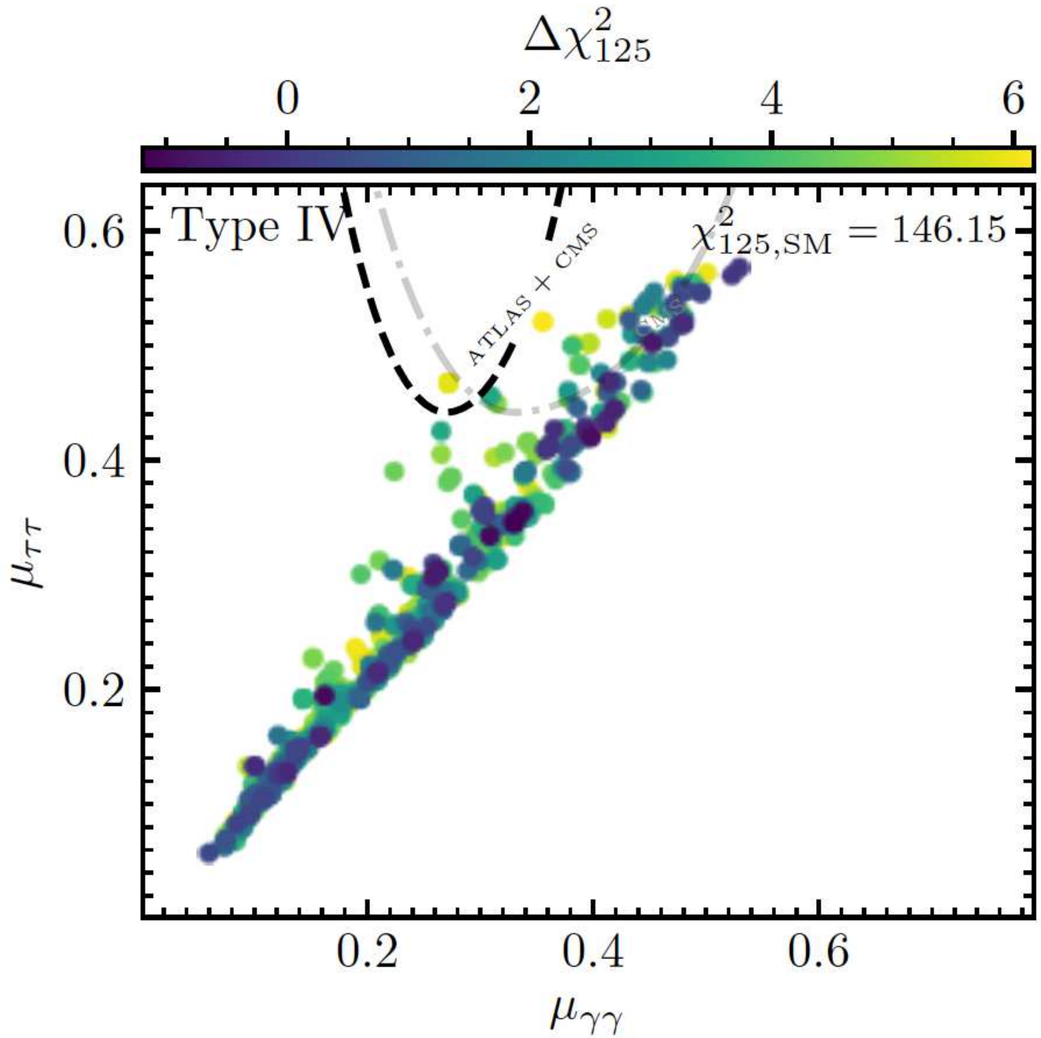
Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ both type II and IV can fit the $\gamma\gamma$ and bb excesses

S2HDM type II vs. type IV

[*T. Biekötter, S.H., G. Weiglein '23*]





Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ only type IV can fit marginally the $\gamma\gamma$ and $\tau\tau$ excesses

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 THC's required
  FOEWPT can cause Gravitational Waves (GW), detectable with LISA
  Q: Can this happen in the 2HDM? Implications for THCs?

- 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 signature: $A \to ZH \to Zt\bar{t}$

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

- Access to BSM THC's: λ_{hhH}
  $\Rightarrow$ benchmark point in the 2HDM type I with $m_H = 300$ GeV
  HL-LHC: $\Rightarrow$ dip-peak / peak-dip from resonant H-exchange
  smearing/binning crucial $\Rightarrow$ full exp. study needed!
  ILC: theory analysis looks very good, exp. analysis: crucially needed


Higgs Days at Santander 2023
Theory meets Experiment
4 - 8 September
Contact: Sven.Heinemeyer@cern.ch
Local: Alicia.Calderon@cern.ch
Gervasio.Gomez@cern.ch
http://hdays.csic.es


Further Questions?

Needed to fit the two excesses: $m_{h_1} \sim 95$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1VV}$ strongly reduced for μ_{LEP}
- c_{h_1bb} reduced to enhance BR($h_1 \to \gamma\gamma$)
- c_{h_1tt} not reduced for μ_{CMS}
- $c_{h_1\tau\tau}$ possibly reduced to enhance BR($h_1 \to \gamma\gamma$)

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	No enhancement $c_{h_1\tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$
type II	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$

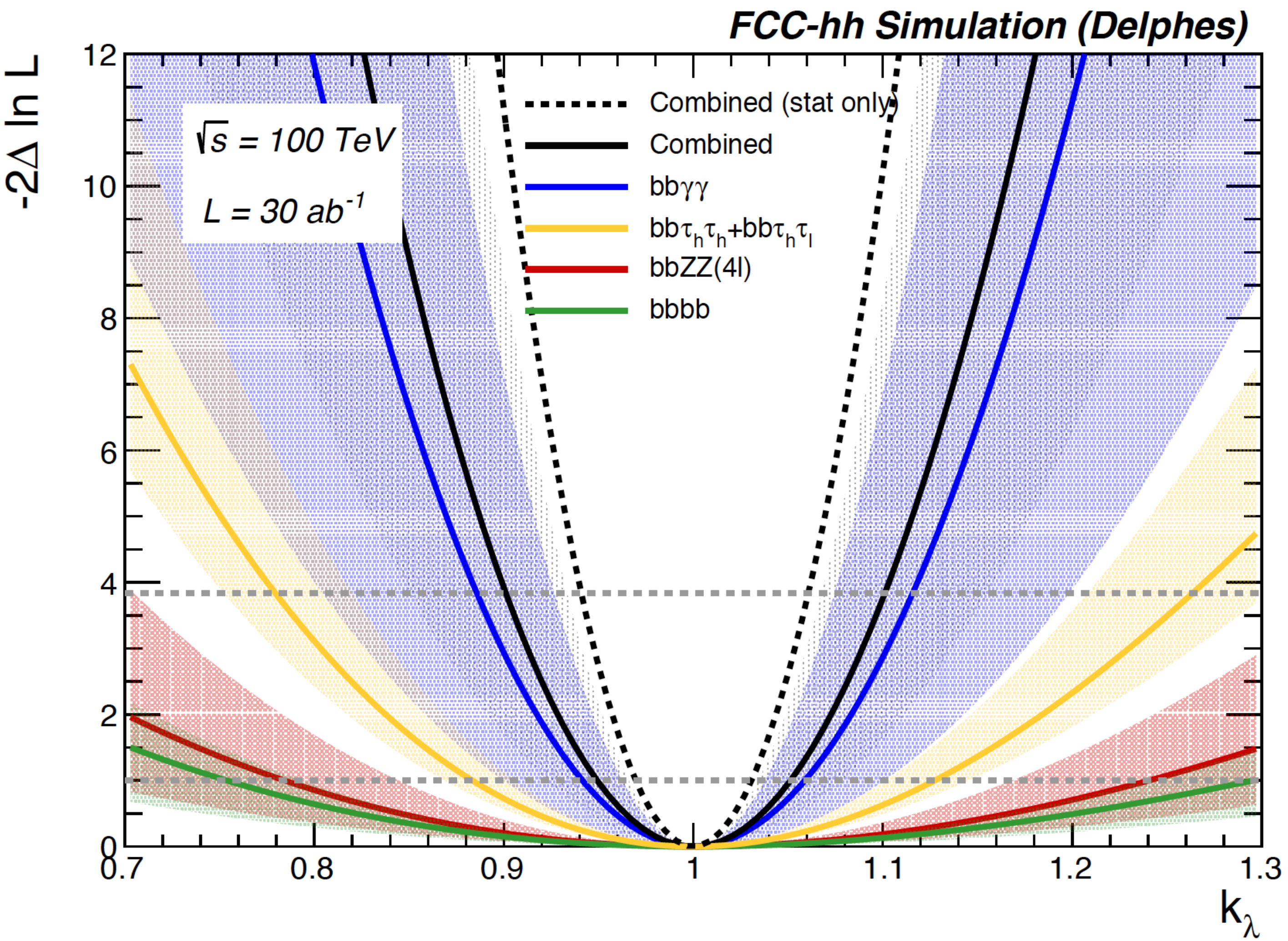
Type II and IV: c_{h_1bb} and c_{h_1tt} independent

Type II vs. IV: $c_{h_1\tau\tau}$ can be suppressed or enhanced

$\Rightarrow$ only type II and IV can fit CMS and LEP excesses

Measurement of κ_λ at the FCC-hh:

[*Mangano, Ortona, Selvaggi '20*]

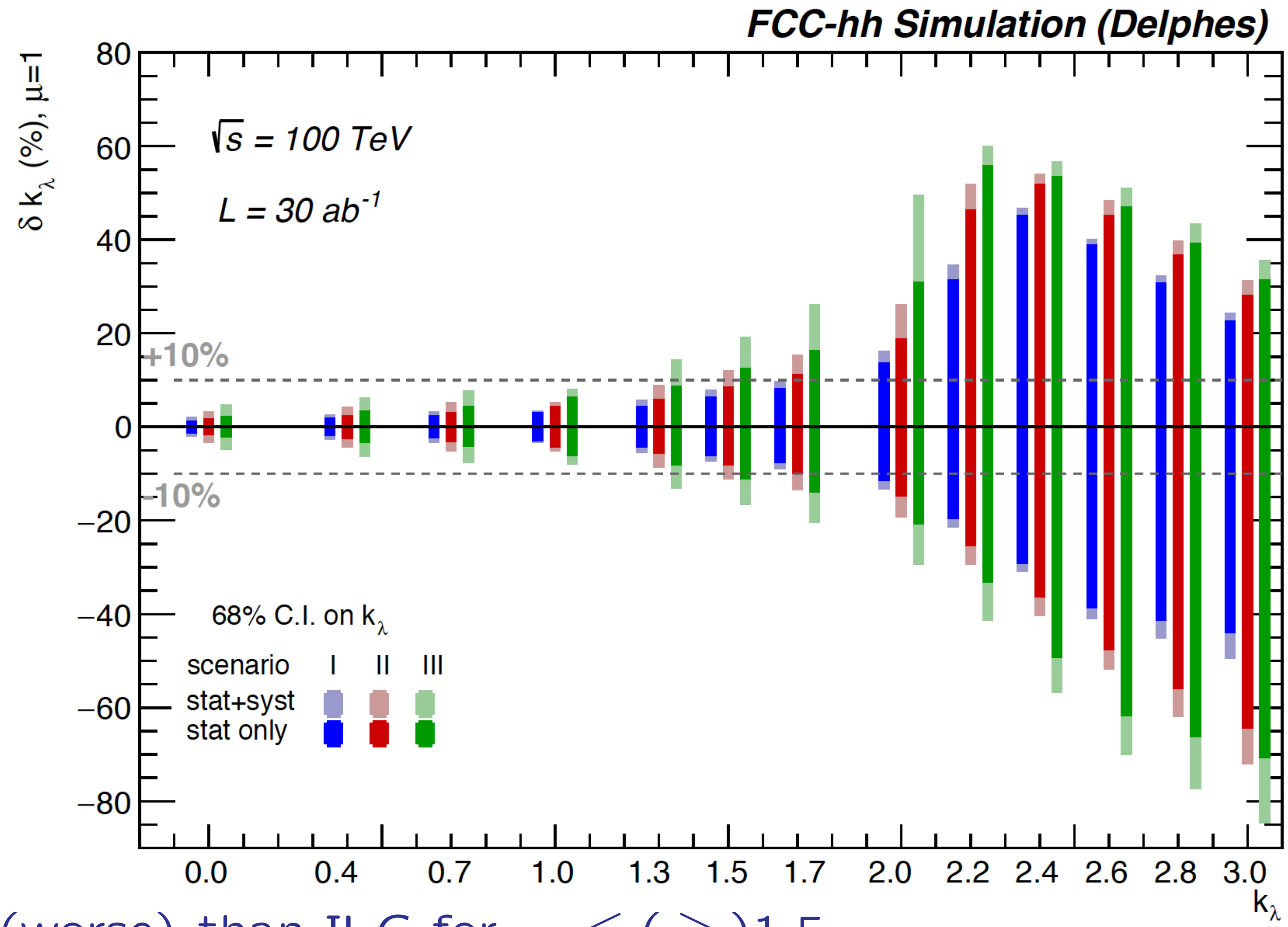


⇒ result only for $\kappa_\lambda = 1$

⇒ 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 . . .