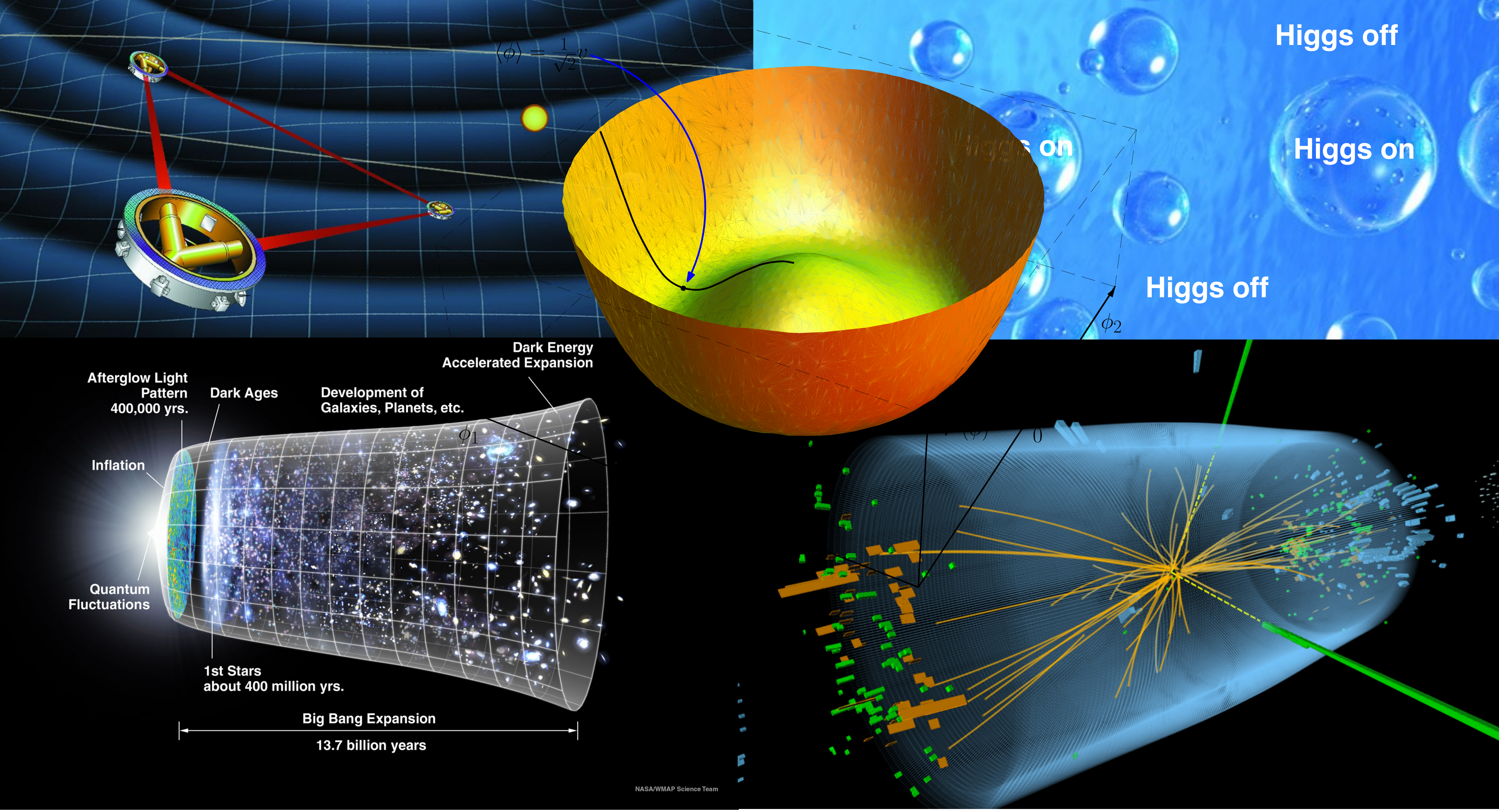

Impact of the trilinear Higgs self-coupling on resonant and non-resonant di-Higgs production

Georg Weiglein, DESY & UHH

Prague, 07 / 2024

Universität Hamburg
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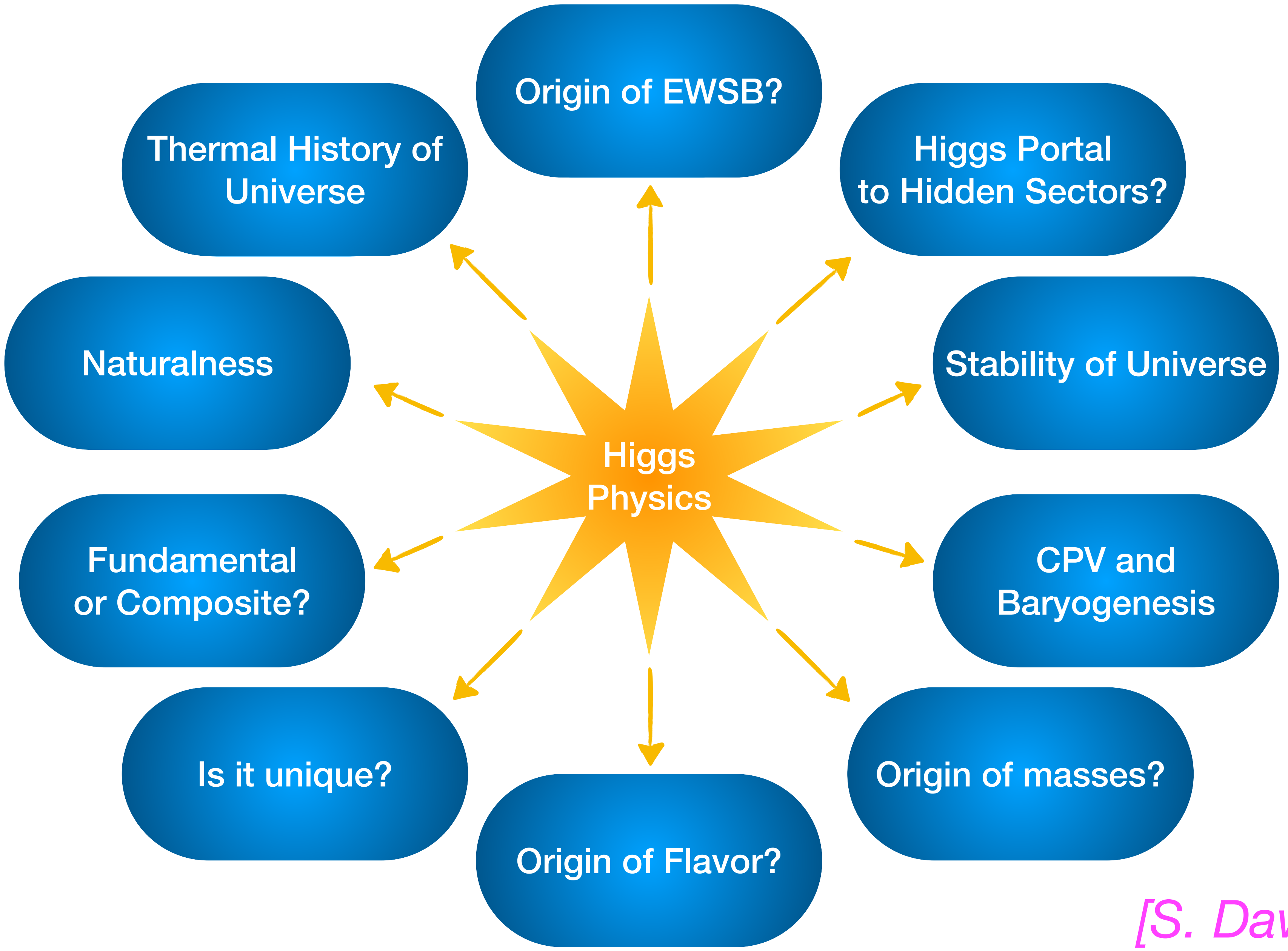
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Outline

- Introduction
- Resonant Higgs pair production
- Non-resonant di-Higgs production and the trilinear Higgs self-coupling
- Conclusions

Introduction

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



Higgs Physics

Origin of EWSB?

Higgs Portal to Hidden Sectors?

Stability of Universe

CPV and Baryogenesis

Origin of masses?

Origin of Flavor?

Is it unique?

Fundamental or Composite?

Naturalness

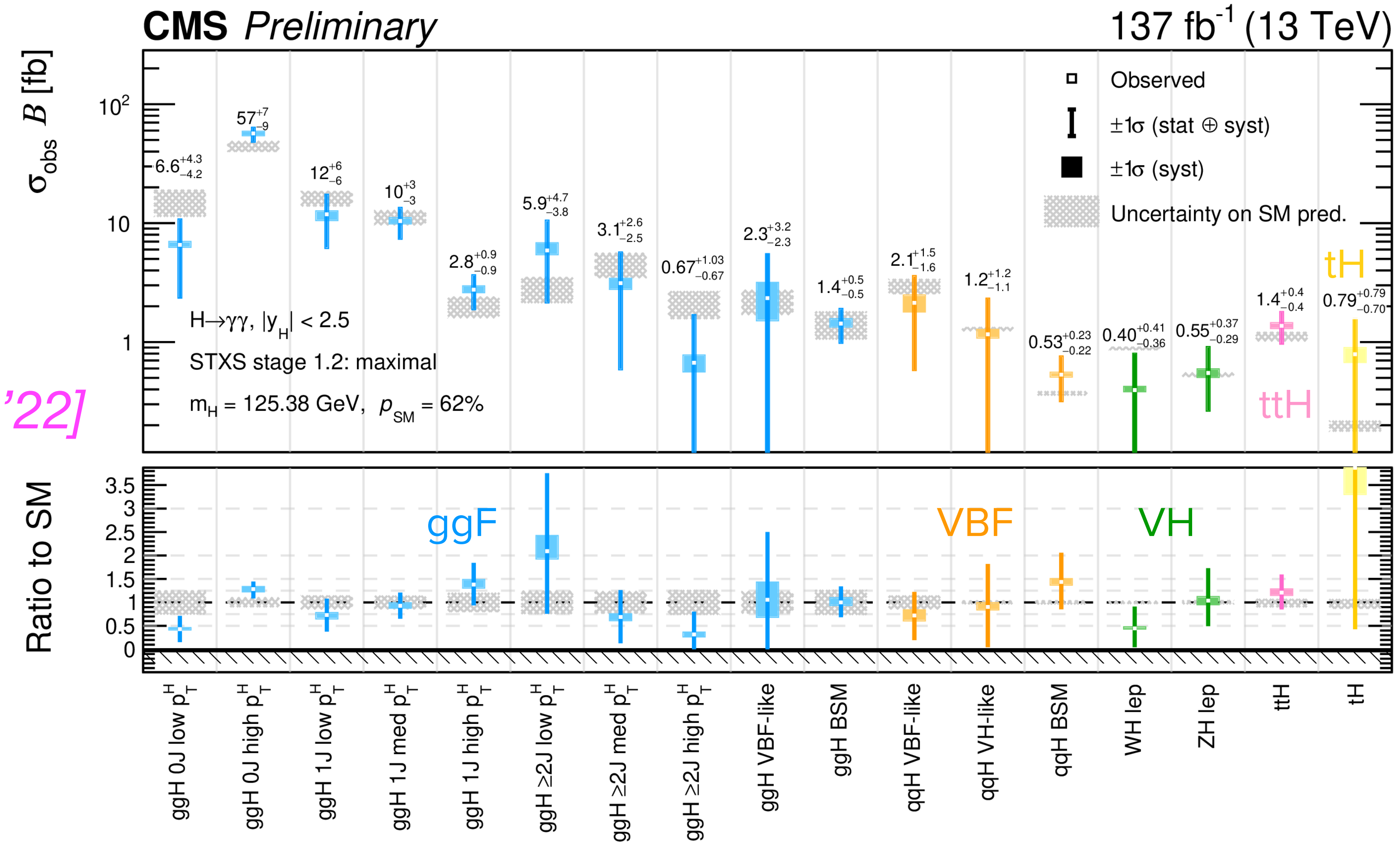
Thermal History of Universe

[S. Dawson et al. ’22]

Properties of the detected Higgs boson (h125)

The Standard Model of particle physics uses a ``minimal” form of the Higgs potential with a single Higgs boson that is an elementary particle

h125: inclusive and differential rates



[CMS Collaboration ’22]

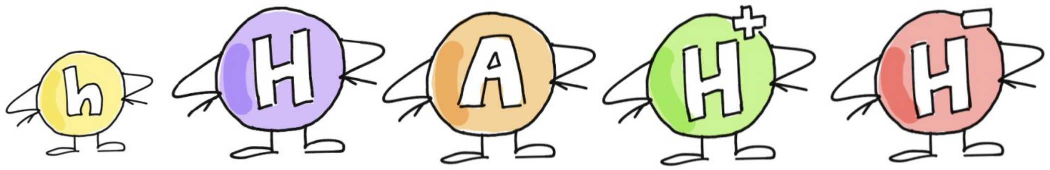
⇒SM-like properties

The LHC results on the discovered Higgs boson within the current uncertainties are compatible with the predictions of the Standard Model, but also with a wide variety of other possibilities, corresponding to very different underlying physics

Simple example of extended Higgs sector: 2HDM

Two Higgs doublet model (2HDM):

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$



[K. Radchenko '23]

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \rightarrow \Phi_1$; $\Phi_2 \rightarrow -\Phi_2$) entails 4 Yukawa types

- Potential:

$$\boxed{\begin{aligned} V_{\text{2HDM}} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \\ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2), \end{aligned}}$$

- Free parameters: $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ \tan\beta,\ \cos(\beta-\alpha),\ v$

$$\boxed{\begin{aligned} &\tan\beta = v_2/v_1 \\ &v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2 \end{aligned}}$$

In alignment limit, $\cos(\beta - \alpha) = 0$: h couplings are as in the SM at tree level

Masses of the BSM Higgs fields

$$m_A^2 = \left[m_{12}^2/(v_1 v_2) - 2\lambda_5\right](v_1^2 + v_2^2) \qquad m_+^2 = \left[m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5\right](v_1^2 + v_2^2)$$

In general: BSM Higgs fields receive contributions from two sources:

$$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2 \,, \qquad \Phi \in \{H, A, H^\pm\}$$

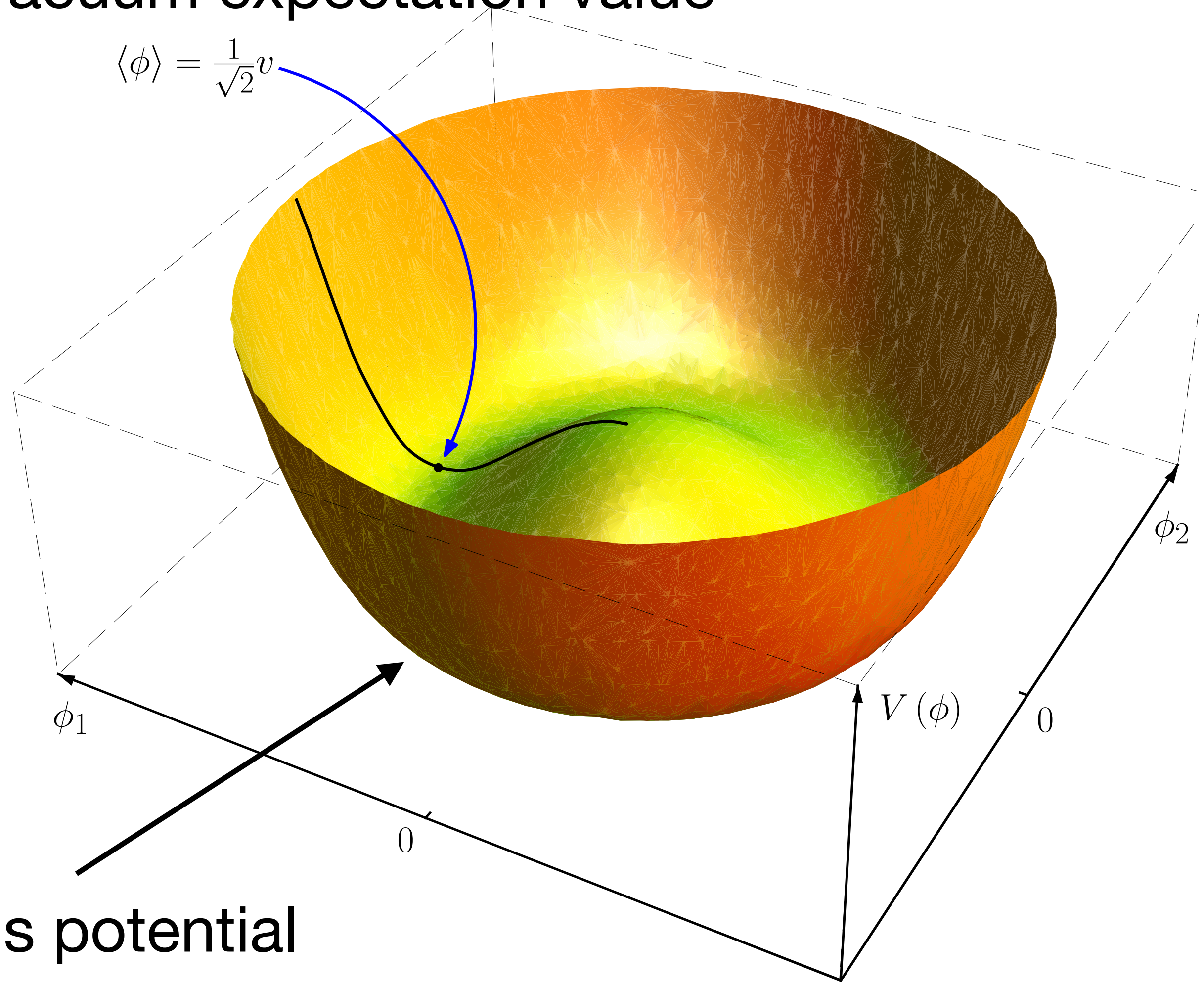
where $M^2 = 2\, m_{12}^2 / \sin(2\beta)$

Sizeable splitting between m_Φ and M induces large BSM contributions the the Higgs self-couplings (see below)

Higgs potential: the "holy grail" of particle physics

Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?

Vacuum expectation value



Higgs potential

Only known so far:

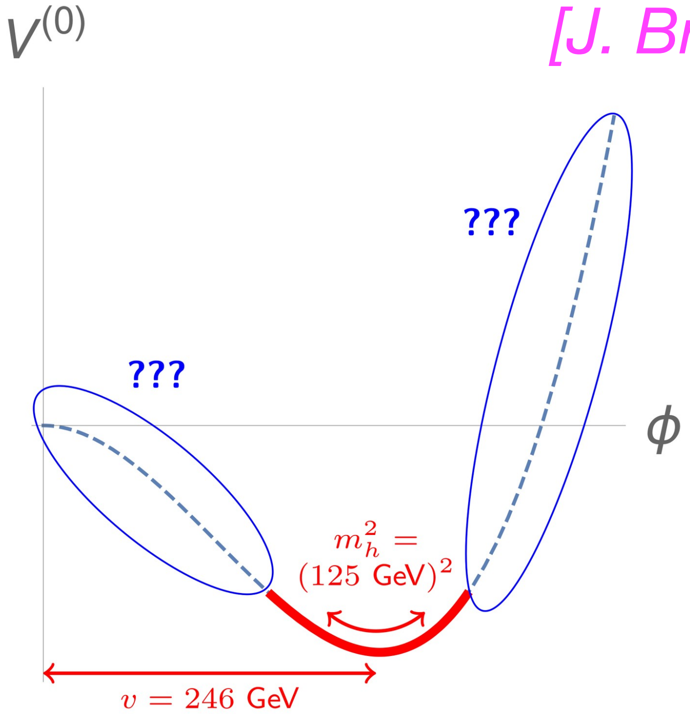
→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV

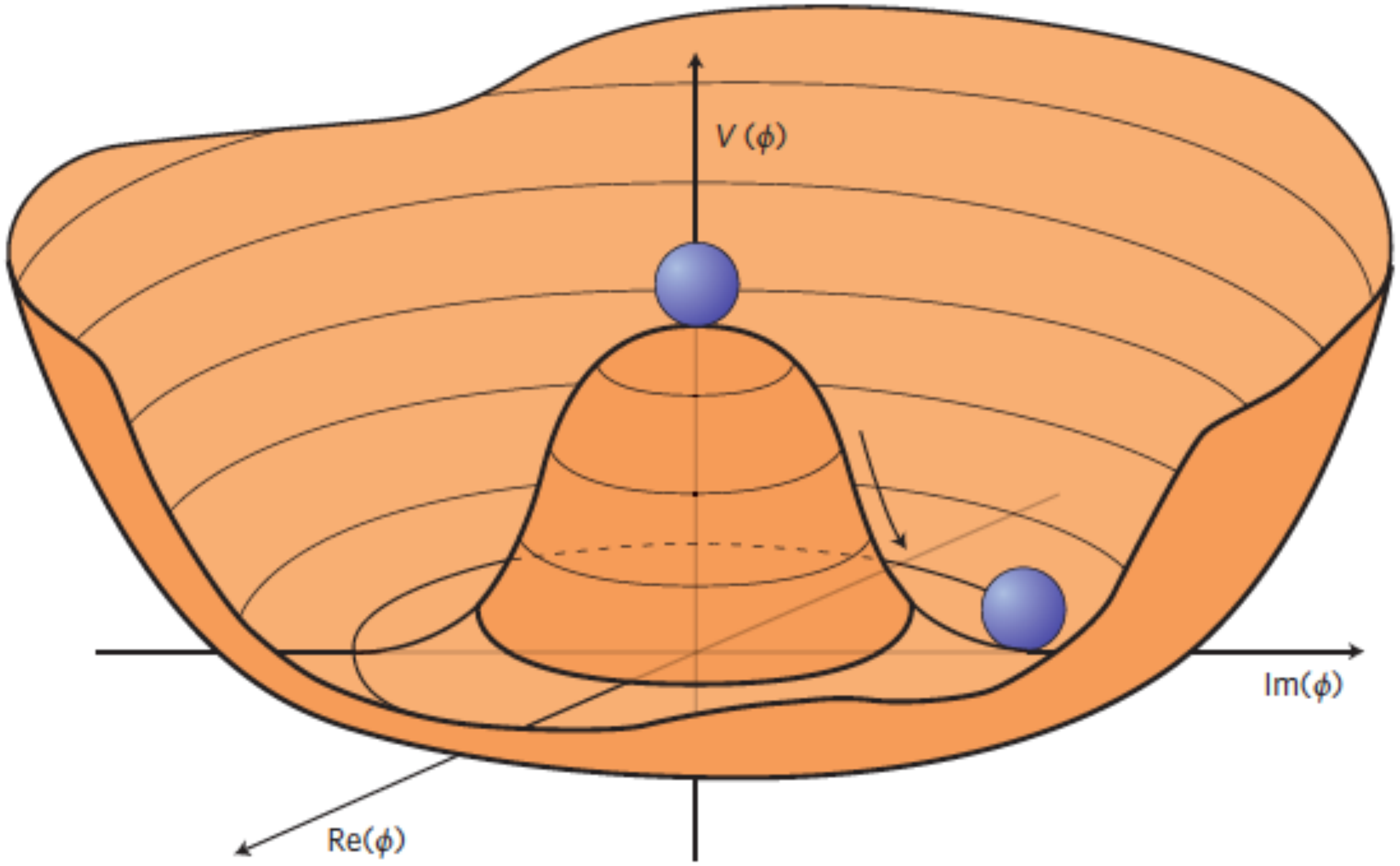
[J. Braathen '24]



Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

Higgs potential: the “holy grail” of particle physics

The simple picture



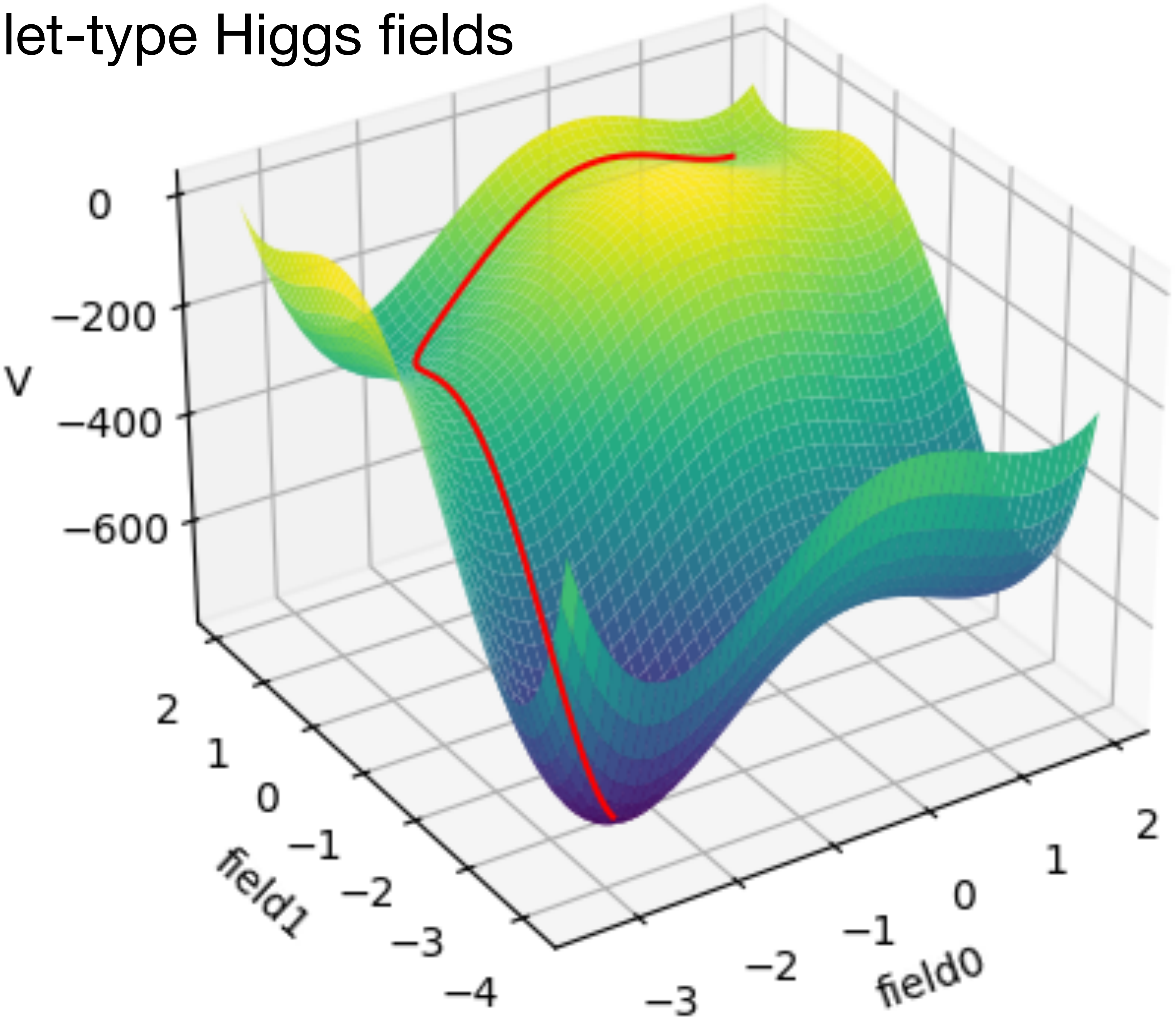
refers to the case of a single Higgs doublet field

If more than one scalar field is present, the Higgs potential is a multi-dimensional function of the components of the different scalar fields

The Higgs potential and vacuum stability

[T. Biekötter, F. Campello, G. W. '24]

Tunneling from a local minimum into the global minimum: toy example, two singlet-type Higgs fields

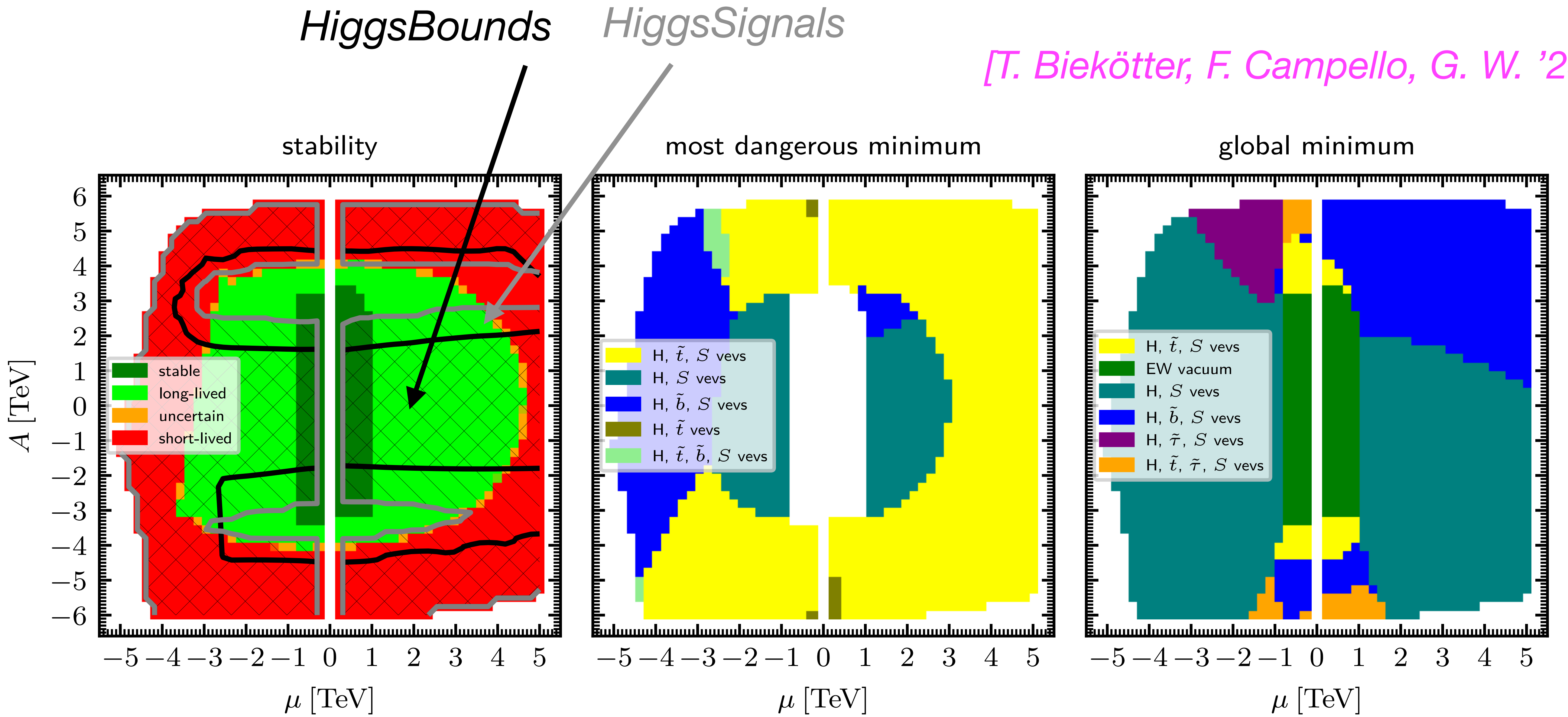


⇒ Proceeds via intermediate local minimum

Vacuum stability constraints in the NMSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt '18]*
Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*

[T. Biekötter, F. Campello, G. W. '24]



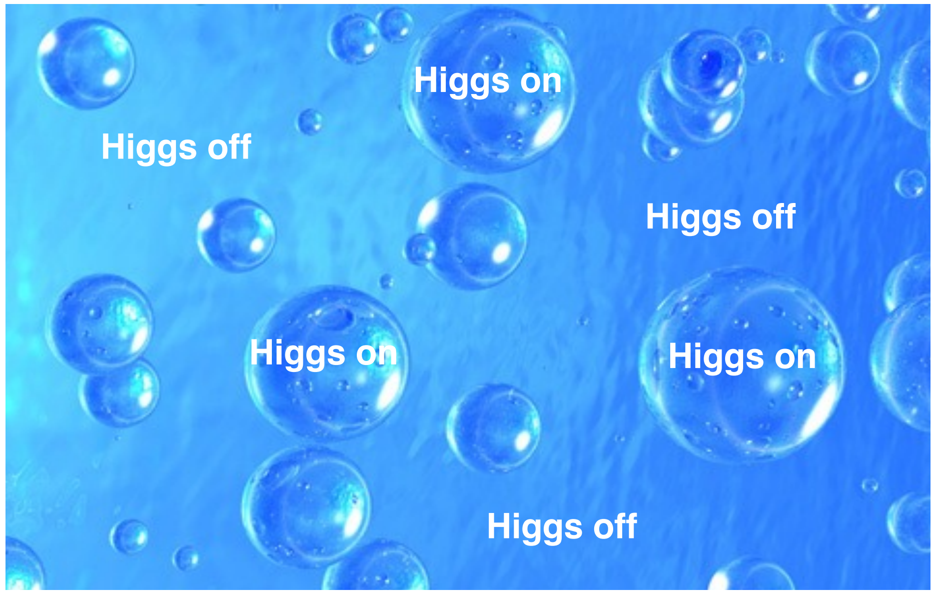
Character of most-dangerous minimum differs from global minimum

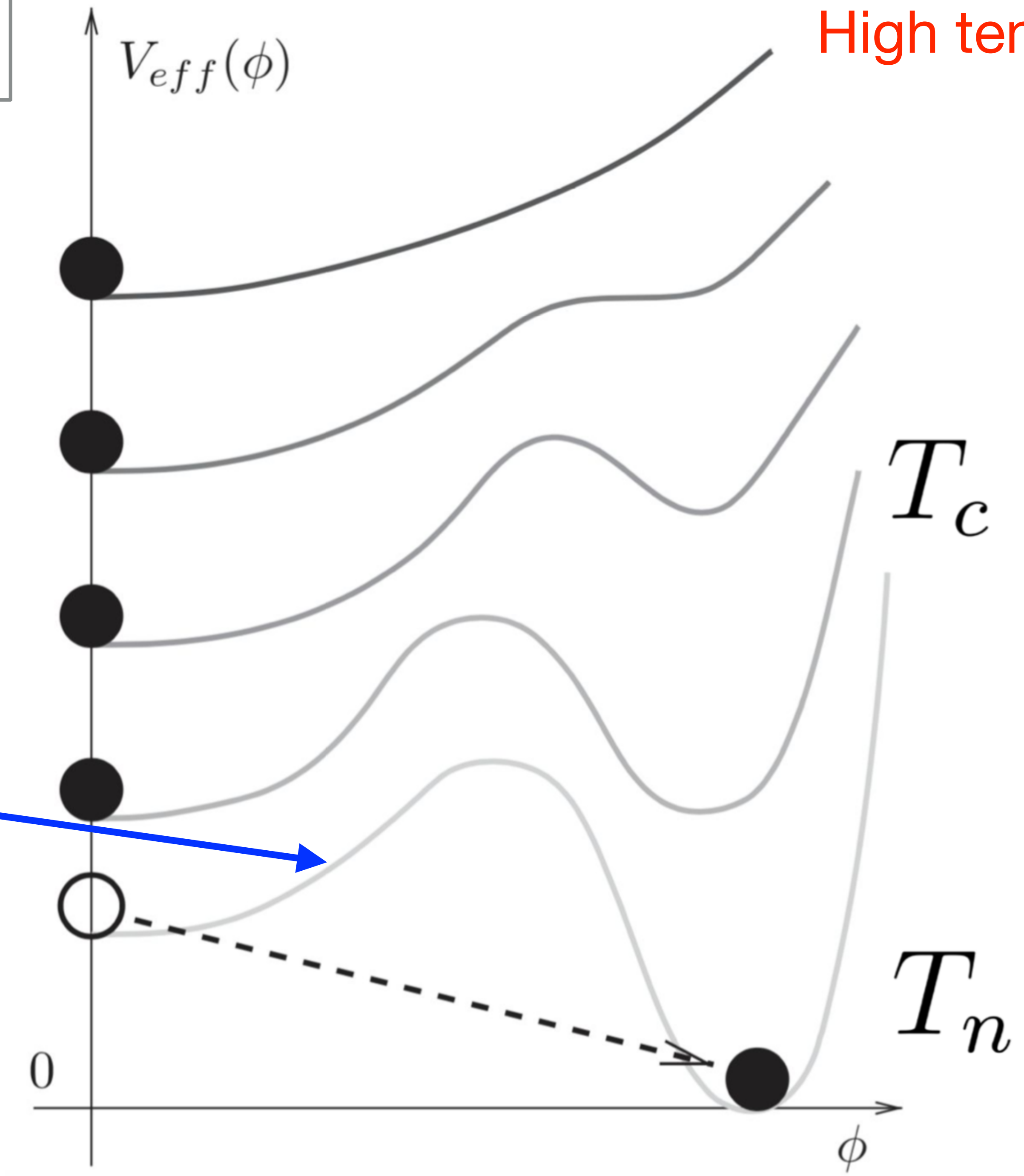
The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$





High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

Potential barrier depends on trilinear Higgs coupling(s)

Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

Pair production of the detected Higgs boson (h)

- Depends on trilinear Higgs self-coupling, $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$, and therefore provides experimental access to the Higgs potential

- SM-type contributions (see below): large interference effects between (non-resonant) vertex and box contributions

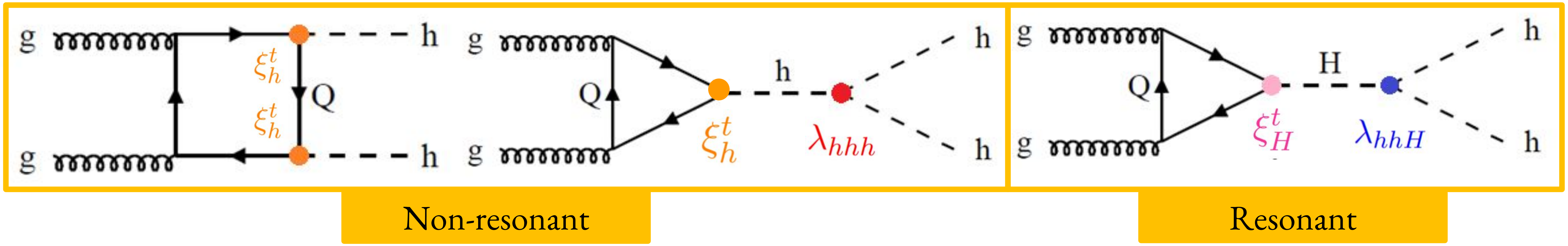
- In extended Higgs sectors: mass splitting between BSM Higgs bosons induces very large loop effects to $\varkappa_\lambda$, while the couplings of h to gauge bosons and fermions can be very close to the SM values

- Process is sensitive to resonant contributions of BSM states, e.g. additional Higgs boson H

Resonant Higgs pair production

ATLAS and CMS present their ``resonant” limits by ignoring the non-resonant contributions to the signal for Higgs pair production

In all realistic scenarios the resonant contribution, involving H, is accompanied by the non-resonant contribution, involving h, giving rise to potentially large interference contributions

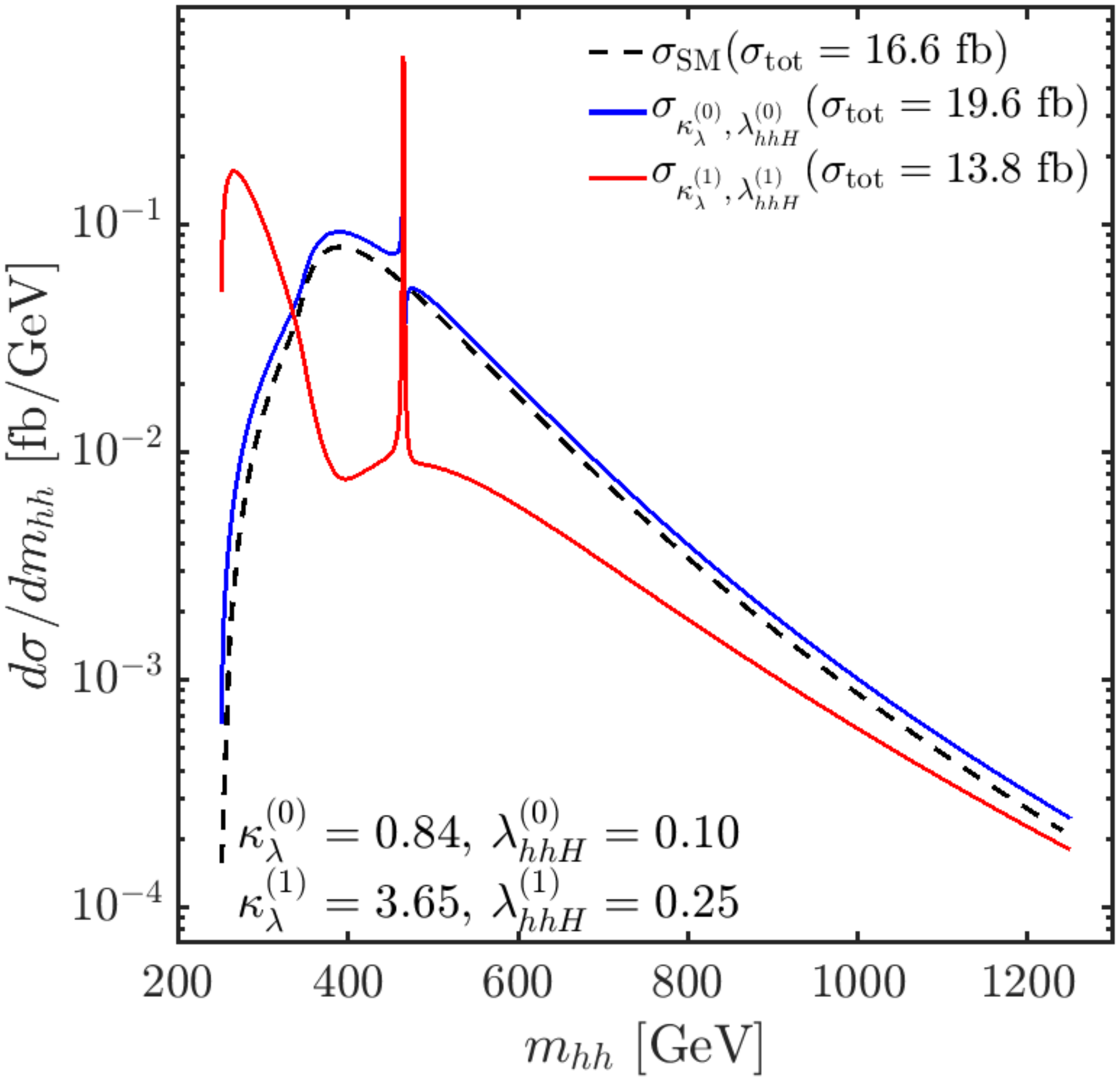


⇒The experimental results for Higgs pair production have to be such that they can be confronted with realistic theoretical models!

Interference effects in resonant Higgs pair production

2HDM example: [S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

theoretical prediction, experimental effects will be discussed below



$$t_\beta = 10,\ c_{\beta-\alpha} = 0.13\ (s_{\beta-\alpha} > 0)\ m_H = 465\ \mathrm{GeV},$$
$$m_A = m_{H^\pm} = 660\ \mathrm{GeV}\ m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$$

- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

- Drop in the m_{hh} ~ 400 GeV region due to a shift in the cancellation of form factors

- Change in the dip peak structure of the resonance

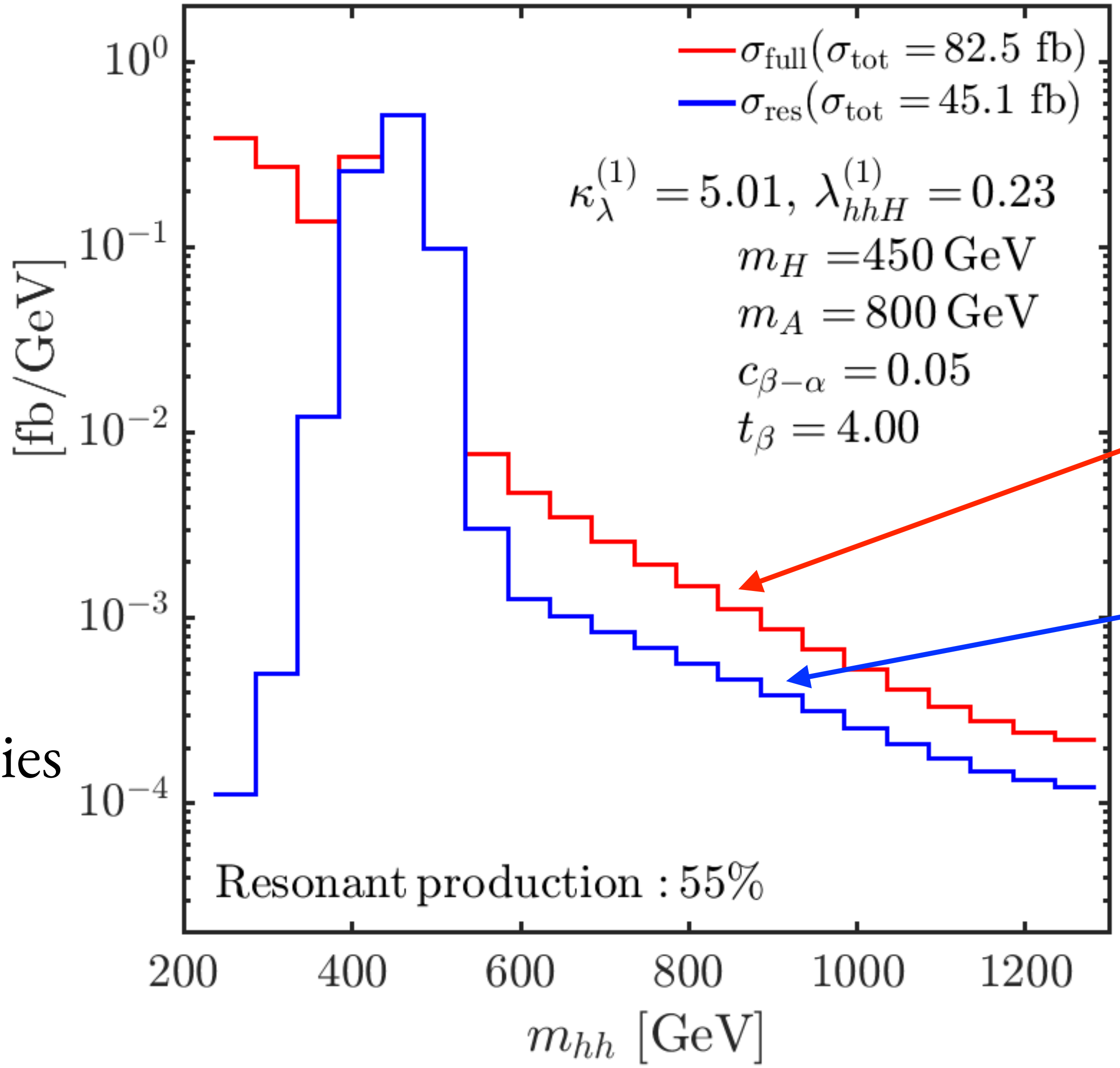
⇒ Inclusion of loop contributions (mainly from κ_λ) has drastic impact on invariant mass distribution, large interference effects

Interference effects in Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. ’24]

2HDM example, exp. smearing included, scenario that is claimed to be excluded by the resonant LHC searches, full result vs. resonant contrib.

15 % smearing
50 GeV binning
applied to account for
experimental uncertainties



full result

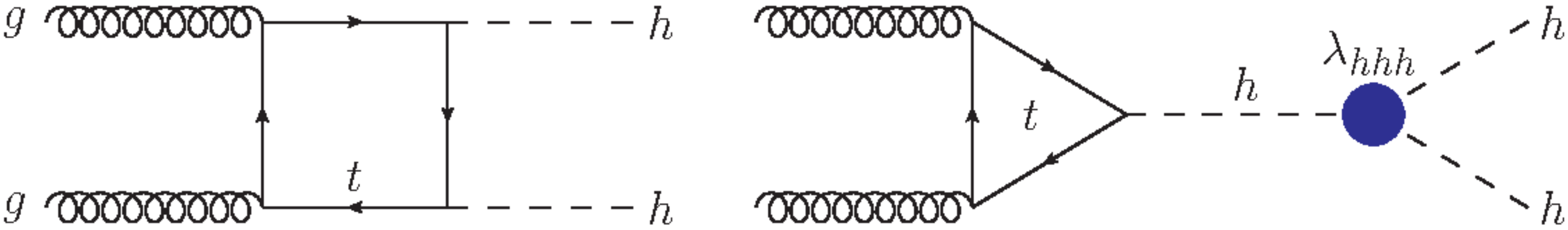
resonant contribution only

⇒ $m_{\rm HH}$ distribution depends very sensitively on $\varkappa_\lambda$, important interference effects, large deviation between resonant contribution and full result; limits using resonant contribution may be too optimistic

Non-resonant di-Higgs production and the trilinear Higgs self-coupling

Sensitivity to the trilinear Higgs self-coupling from Higgs pair production:

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

Note: the ``non-resonant" experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

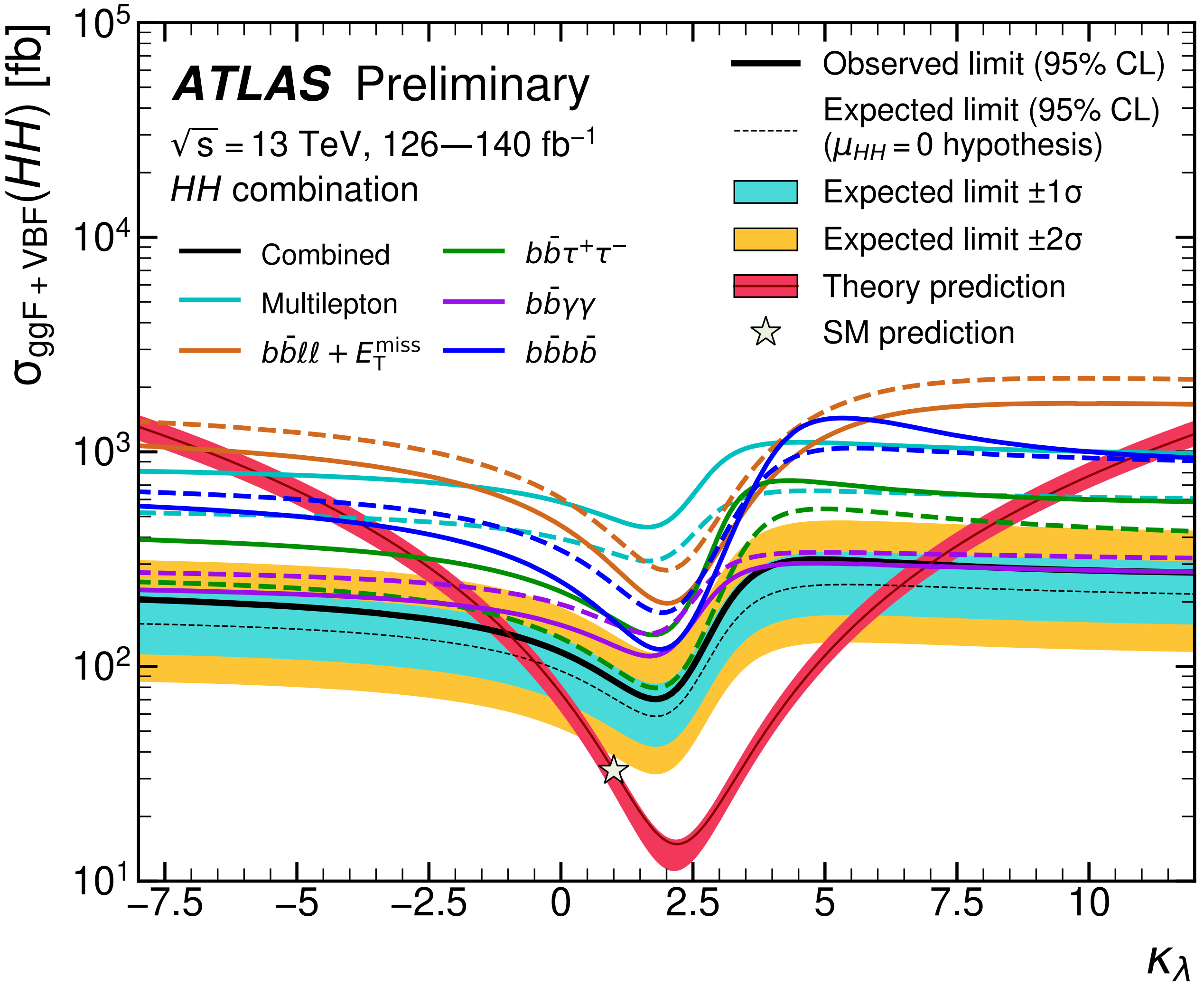
e^+e^- Higgs factory:

Indirect constraints from measurements of single Higgs production and electroweak precision observables at lower energies are not competitive

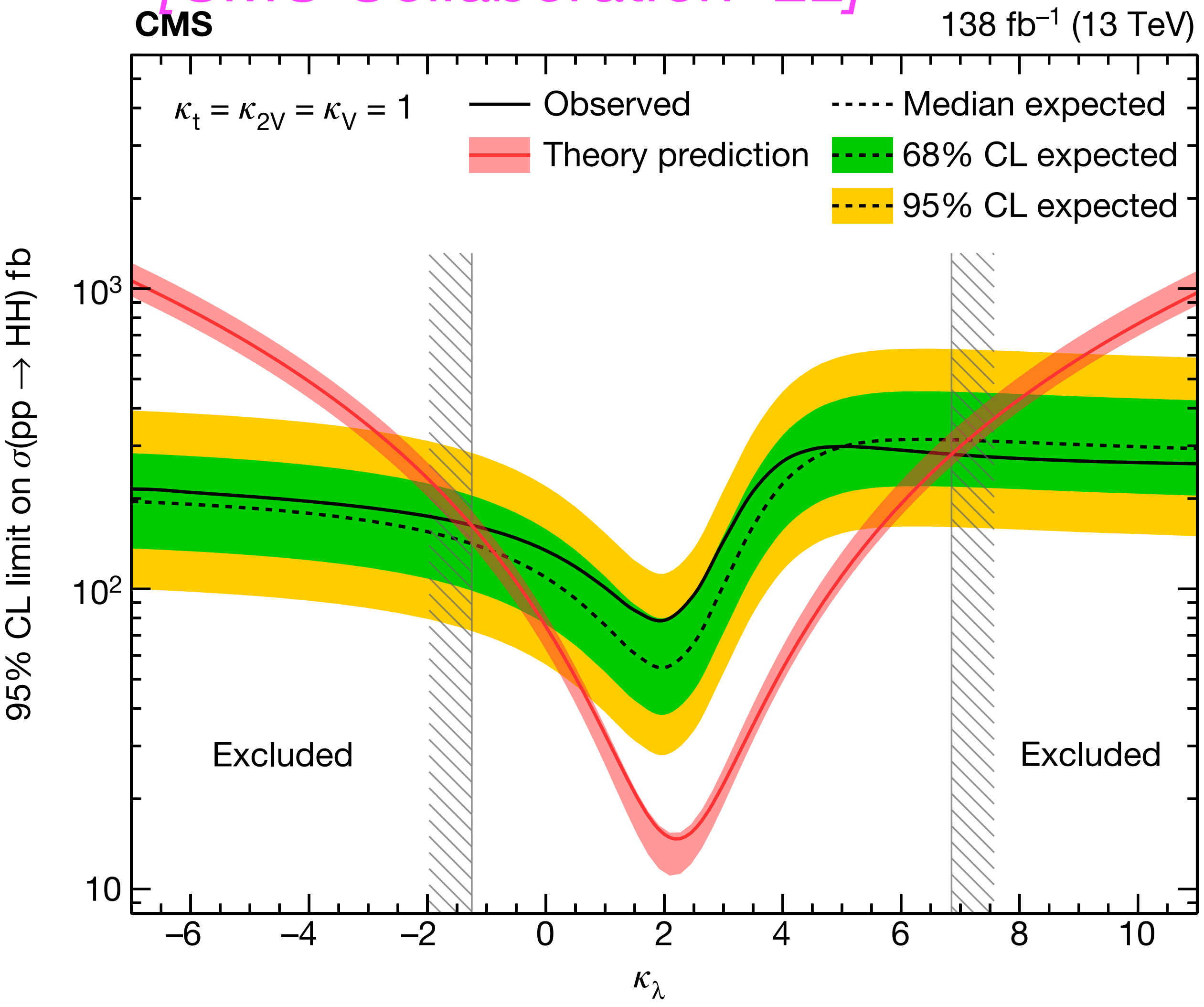
Direct measurement of trilinear Higgs self-coupling is possible at a lepton collider with at least 500 GeV c.m. energy

LHC, bound on the trilinear Higgs self-coupling: $\varkappa_\lambda$

[ATLAS Collaboration ’24]



[CMS Collaboration ’22]



Using only information from di-Higgs production and assuming that new physics only affects the trilinear Higgs self-coupling, this limit on the cross section translates to:

ATLAS: $-1.2 < \varkappa_\lambda < 7.2$ at 95% C.L. *[ATLAS Collaboration ’24]*

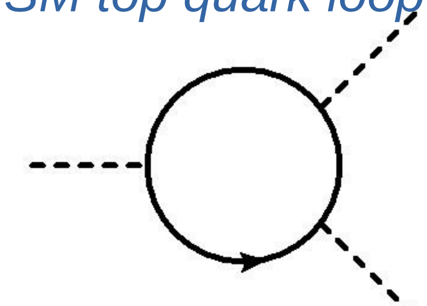
CMS: $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L. *[CMS Collaboration ’22]*

Effects of BSM particles on the trilinear Higgs coupling

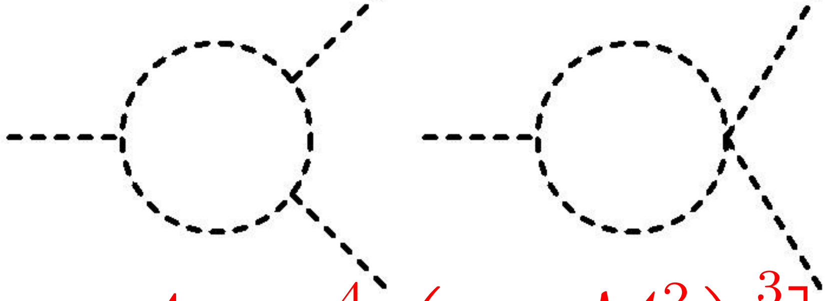
Trilinear Higgs coupling in extended Higgs sectors: potentially large loop contributions

- **Leading one-loop** corrections to λ_{hhh} in models with extended sectors (like 2HDM):

SM top quark loop



BSM scalar loops



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48 m_t^4}{v^3} + \sum_{\Phi} \frac{4 n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

First found in 2HDM:
[Kanemura, Kiyoura, Okada, Senaha, Yuan ‘02]

$\mathcal{M}$: **BSM mass scale**, e.g. soft breaking scale M of Z_2 symmetry in 2HDM
n_Φ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda} v^2$

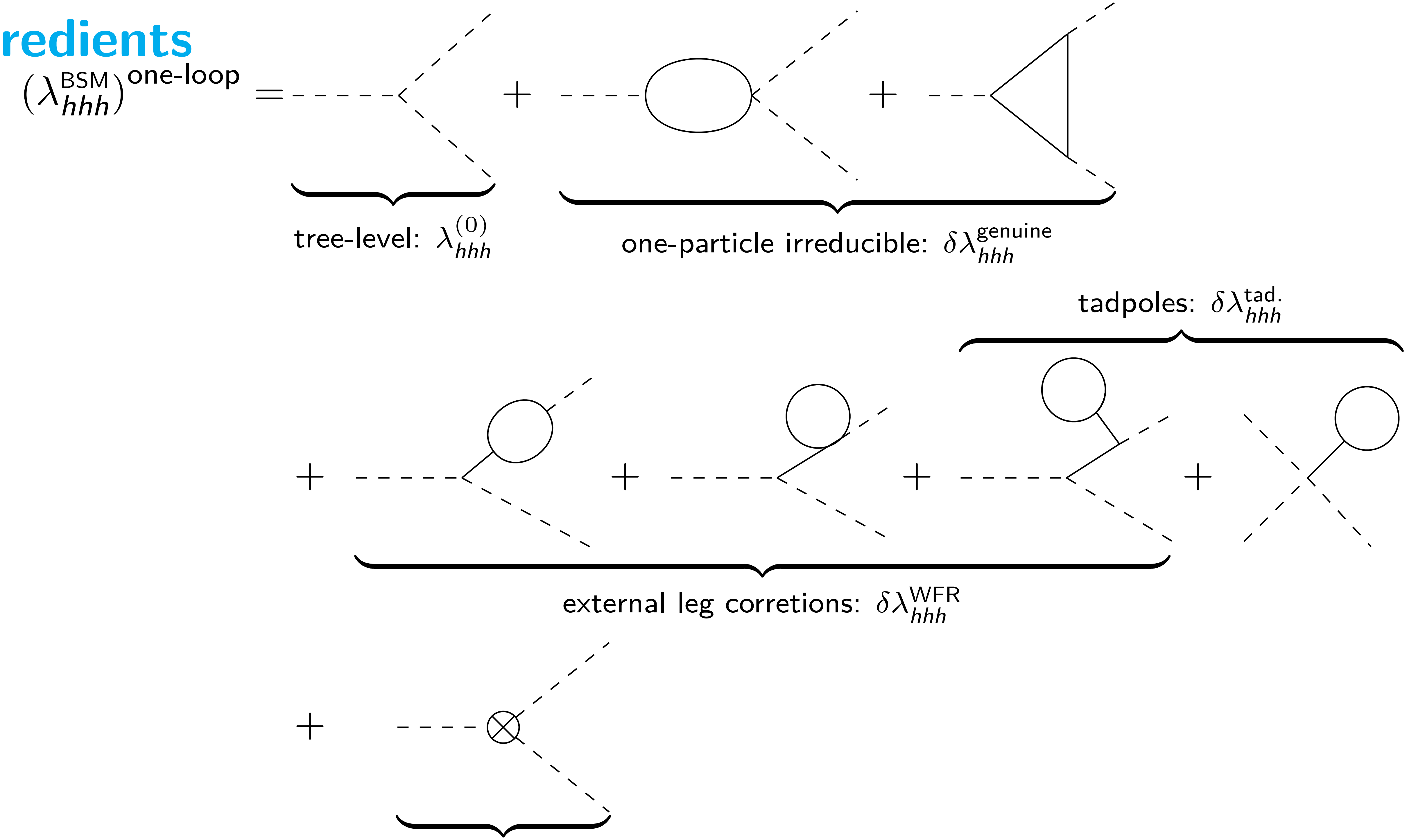
⇒ Large effects possible for sizeable splitting between m_Φ and $\mathcal{M}$

anyH3: automated one-loop predictions for λ_{hhh}

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '23]

Public tool, predictions for λ_{hhh} in arbitrary renormalisable models

Ingredients



$(\lambda^{\text{BSM}}_{hhh})^{\text{one-loop}} =$

tree-level: $\lambda^{(0)}_{hhh}$

one-particle irreducible: $\delta\lambda^{\text{genuine}}_{hhh}$

tadpoles: $\delta\lambda^{\text{tad.}}_{hhh}$

external leg corretions: $\delta\lambda^{\text{WFR}}_{hhh}$

renormalisation: $\delta\lambda_{hhh}^{\text{CT}}$, different choices for SM-type and BSM parameters

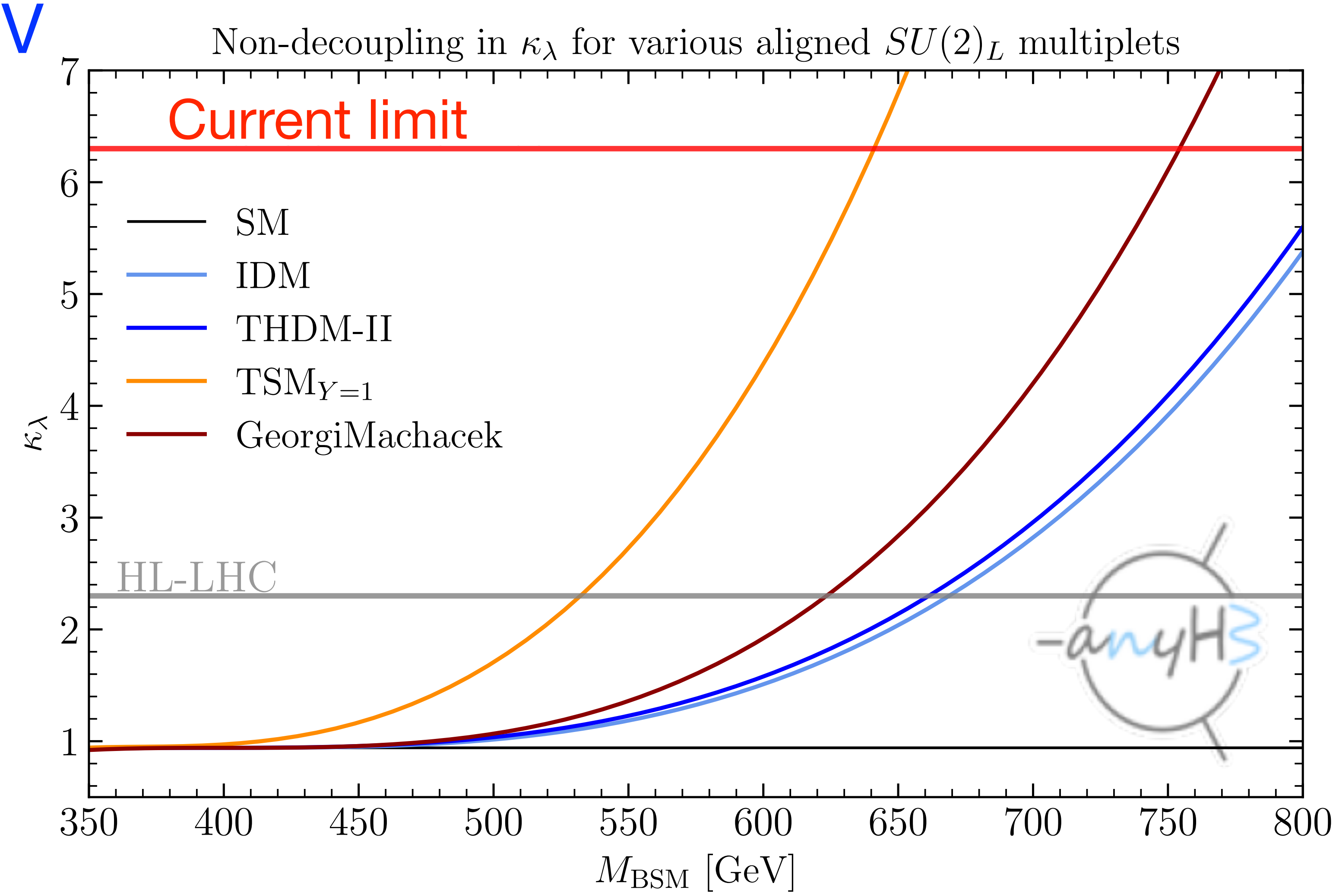
Higgs self-couplings in extended Higgs sectors

Effect of splitting between BSM Higgs bosons:

Very large corrections to the Higgs self-couplings, while all couplings of h_{125} to gauge bosons and fermions are SM-like (tree-level couplings agree with the SM in the alignment limit)

[H. Bahl, J. Braathen, M. Gabelmann, G. W. ’23]

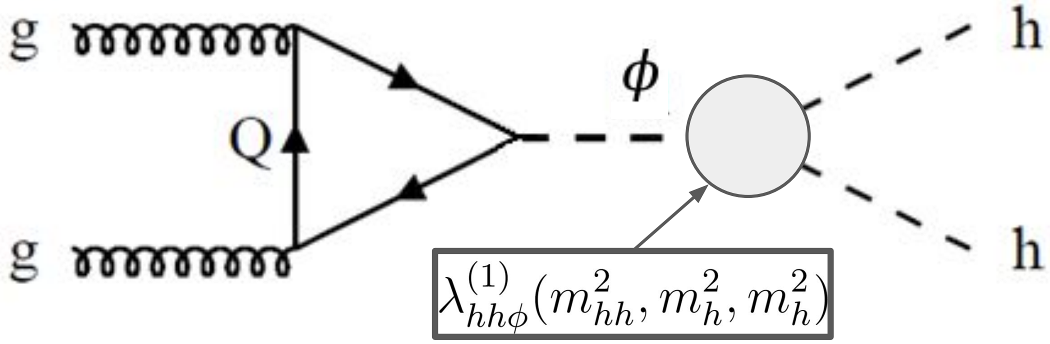
M_L = 400 GeV



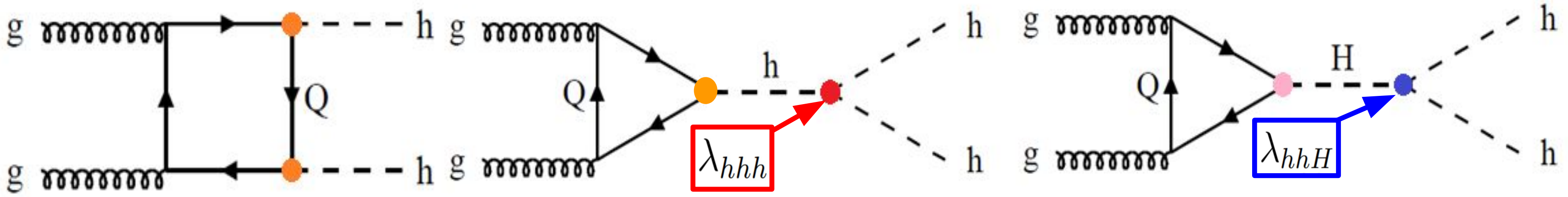
anyH3: ongoing developments

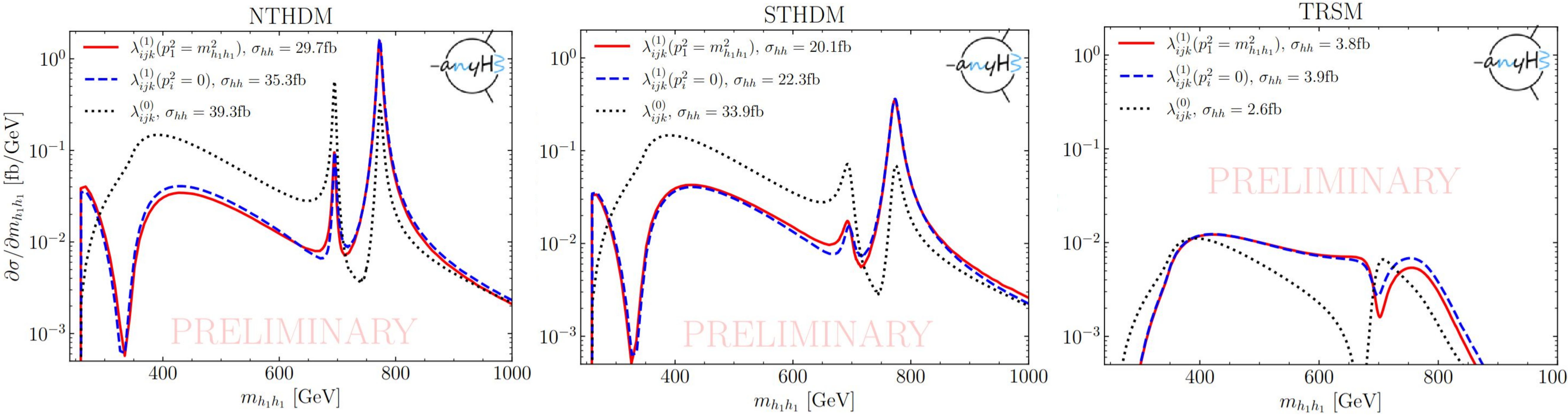
[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. ’23]

- Generalisation to trilinear couplings involving BSM Higgses: λ_{hhH}, …



- Prediction for di-Higgs production involving resonant and non-resonant contributions and loop-corrected trilinear couplings





Two-loop predictions for the trilinear Higgs coupling in the 2HDM vs. current experimental bounds

[H. Bahl, J. Braathen, G. W. '22]

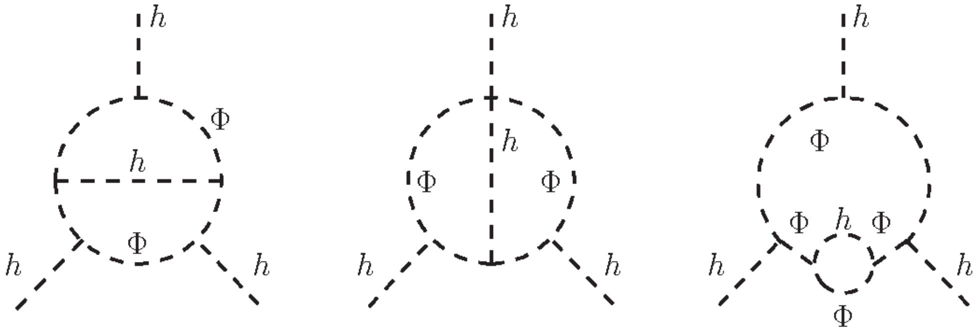
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2} \qquad \Phi \in \{H, A, H^\pm\}$$

Leading two-loop corrections involving heavy BSM Higgses and the top quark in the effective potential approximation

[J. Braathen, S. Kanemura '19, '20]

⇒Incorporation of the highest powers in $g_{hh\phi\phi}$



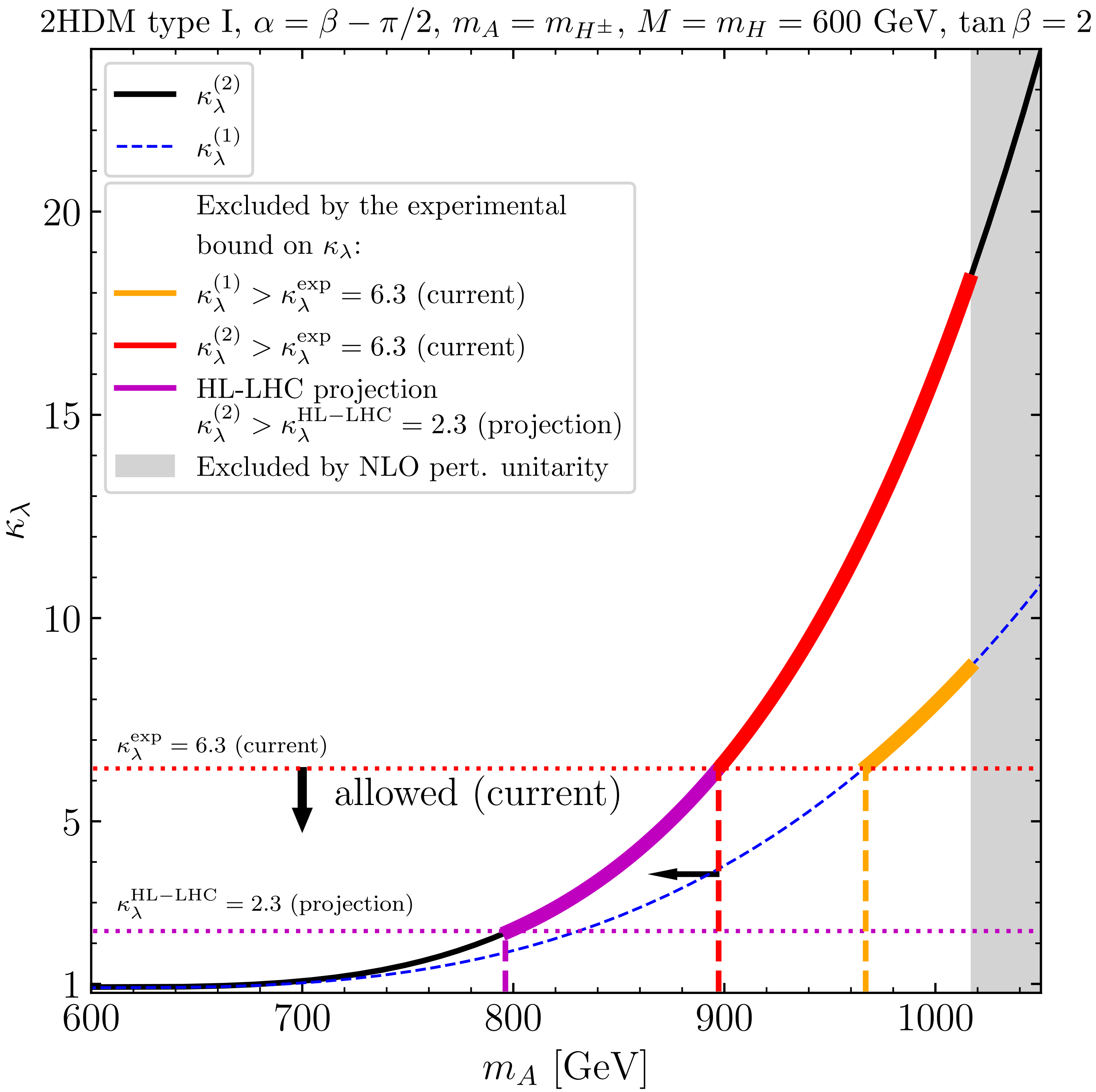
Analysis is carried out in the alignment limit of the 2HDM ($\alpha = \beta - \pi/2$)

⇒h has SM-like tree-level couplings

Trilinear Higgs coupling: current experimental limit vs. prediction from extended Higgs sector (2HDM)

Prediction for ϰλ up to the two-loop level:

[H. Bahl, J. Braathen, G. W. ’22, Phys. Rev. Lett. 129 (2022) 23, 231802]

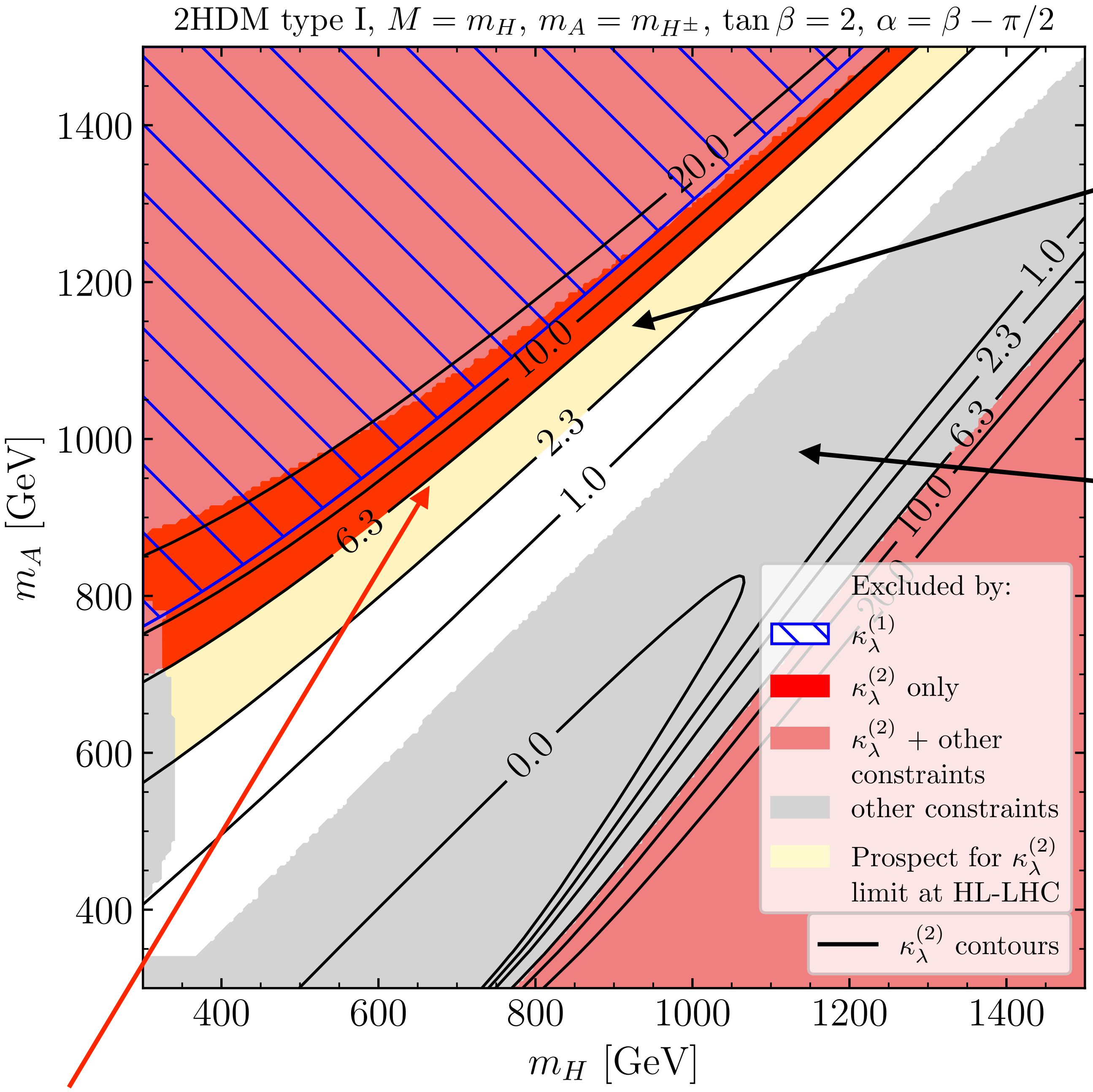


⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. W. ’22]



Sensitivity to κ_λ at the HL-LHC

Excluded by other constraints:
Higgs physics,
boundedness from below,
NLO perturbative unitarity, …

⇒ LHC limits exclude parameter regions that would be allowed by all other constraints; high sensitivity of future limits / measurements!

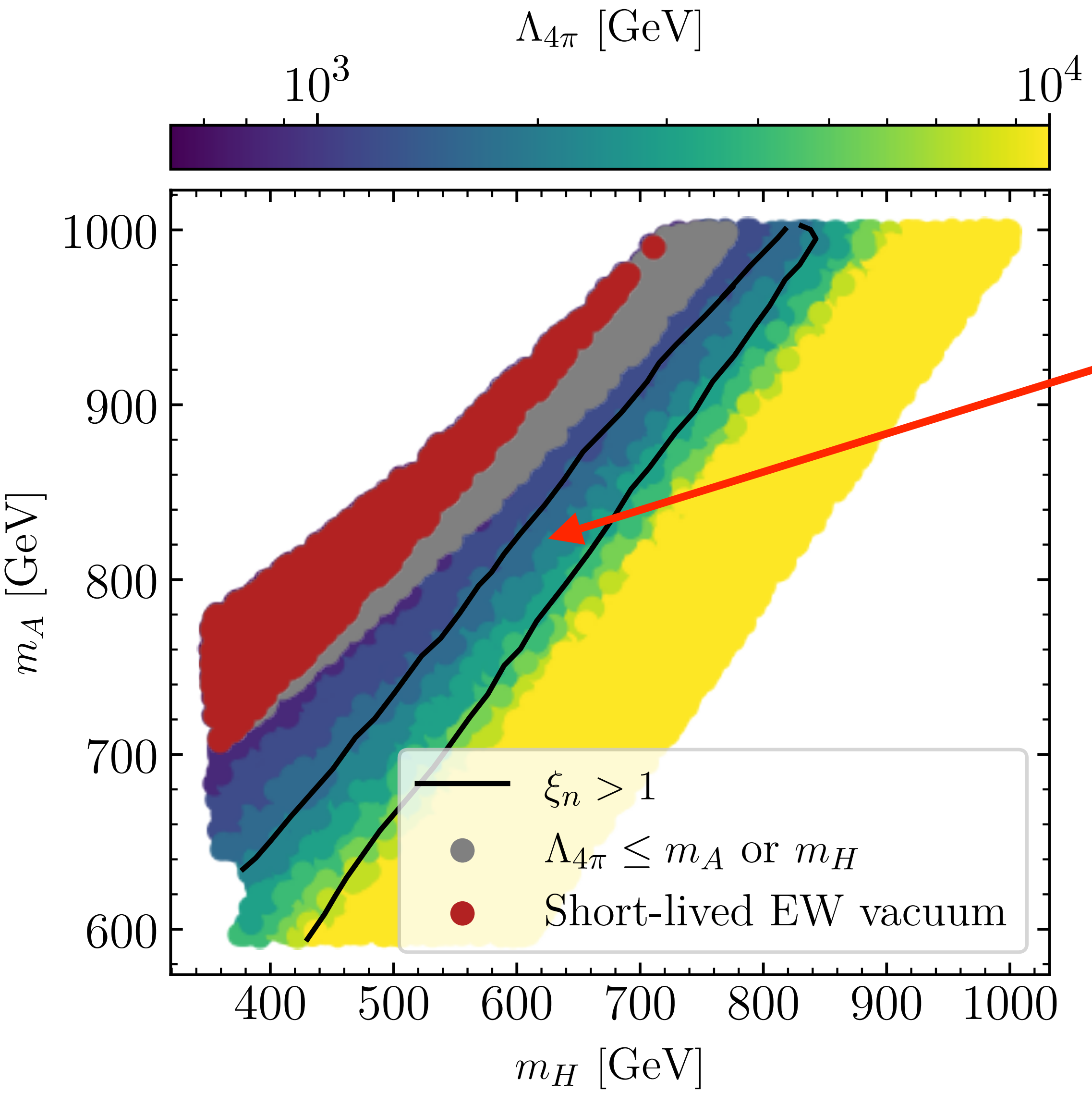
Connection between the trilinear Higgs coupling and the evolution of the early Universe

2HDM, N2HDM, … : the parameter region giving rise to a strong first-order EWPT, which may cause a detectable gravitational wave signal, is correlated with an enhancement of the trilinear Higgs self-coupling and with ``smoking gun” signatures at the LHC

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

2HDM of type II:

alignment limit,
tanβ = 3



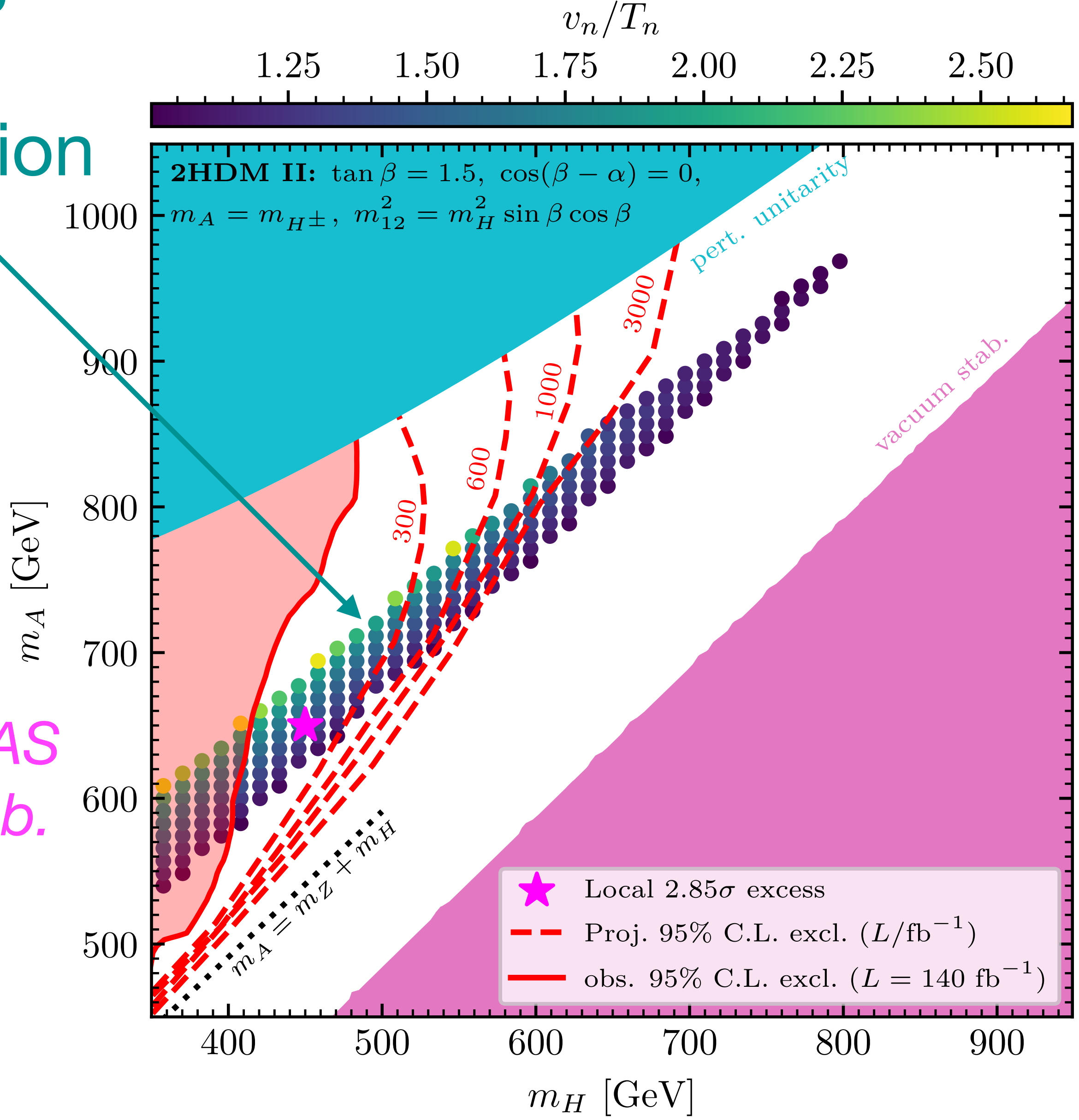
Parameter region giving rise to a strong first-order EWPT

Probing the electroweak phase transition with the "smoking gun" signature pp → A → ZH → Ztt

Projection for future sensitivity based on ATLAS result, 2HDM, tanβ =1.5:

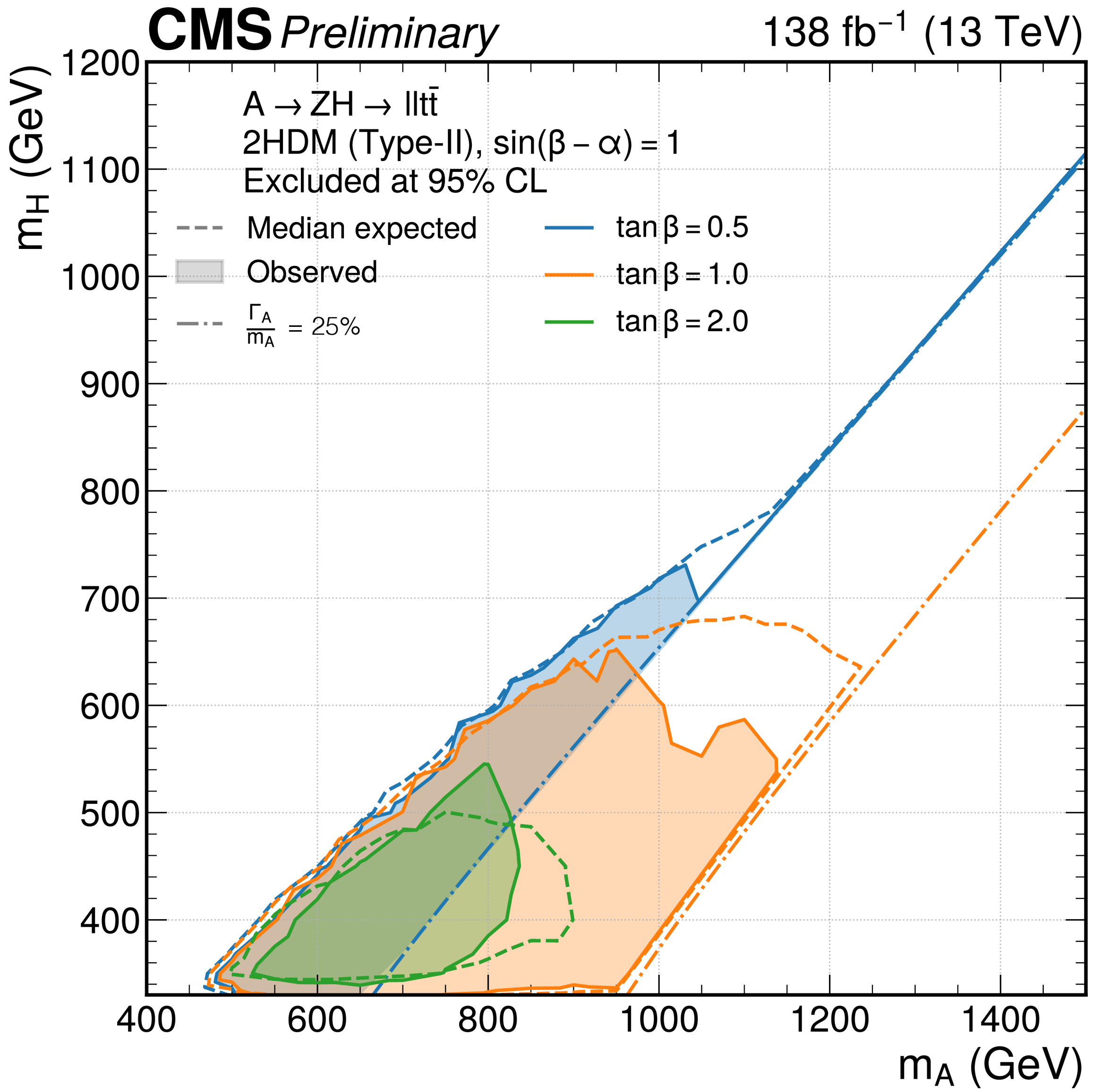
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

Strongest phase transition



[ATLAS Collab. '23]

[CMS Collaboration '24]

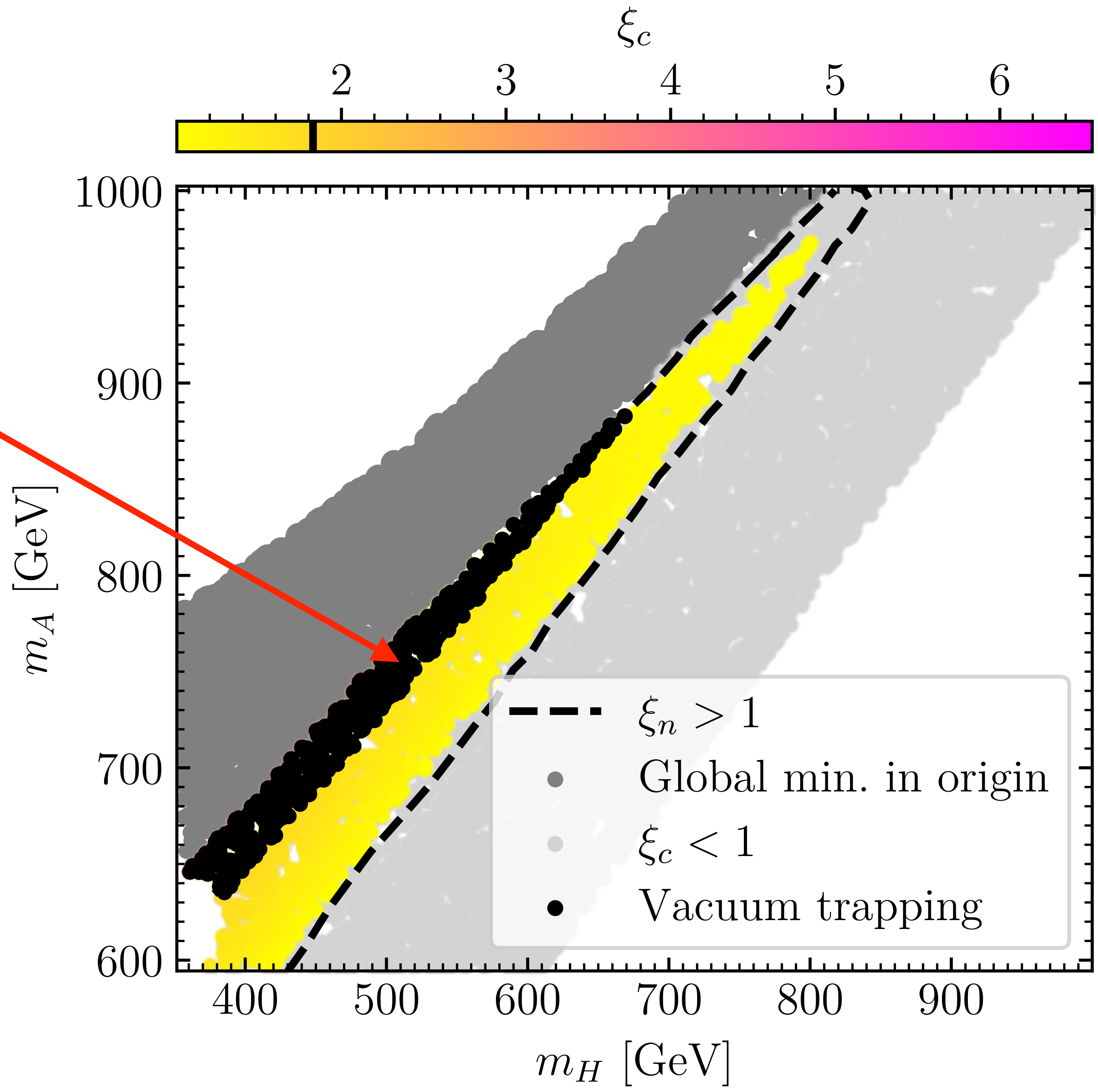


⇒LHC searches start probing the region giving rise to a strong FOEWPT

2HDM of type II: region of strong first-order EWPT

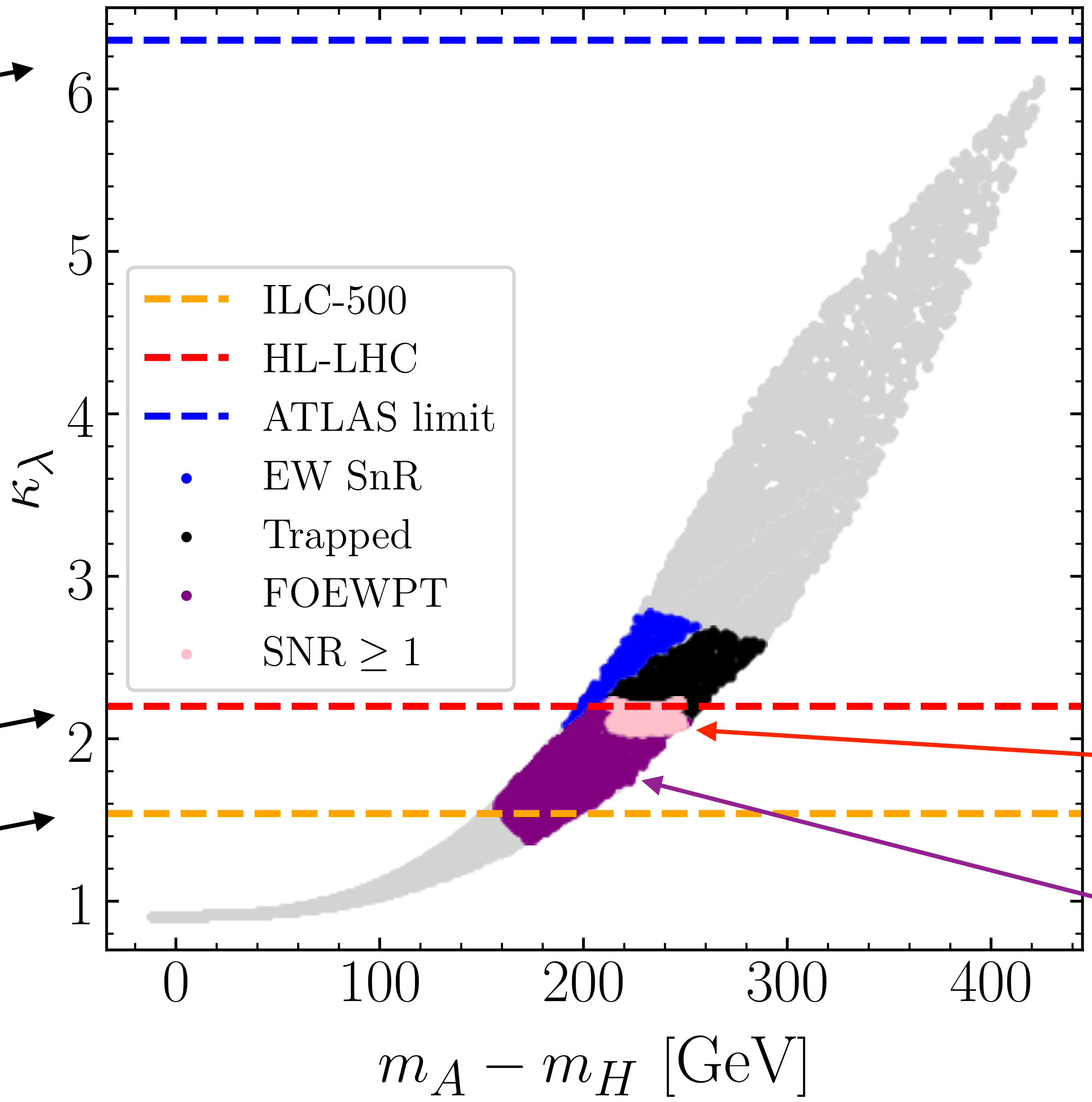
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

Constraints from ``vacuum trapping”: the universe may remain ``trapped” in a symmetry-conserving vacuum at the origin, because the conditions for a transition into the deeper EW-breaking minimum are not fulfilled



Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]



current bound

HL-LHC sensitivity

ILC sensitivity

alignment limit,
tanβ = 3,
1-loop prediction

region with potentially observable gravitational wave (GW) signal

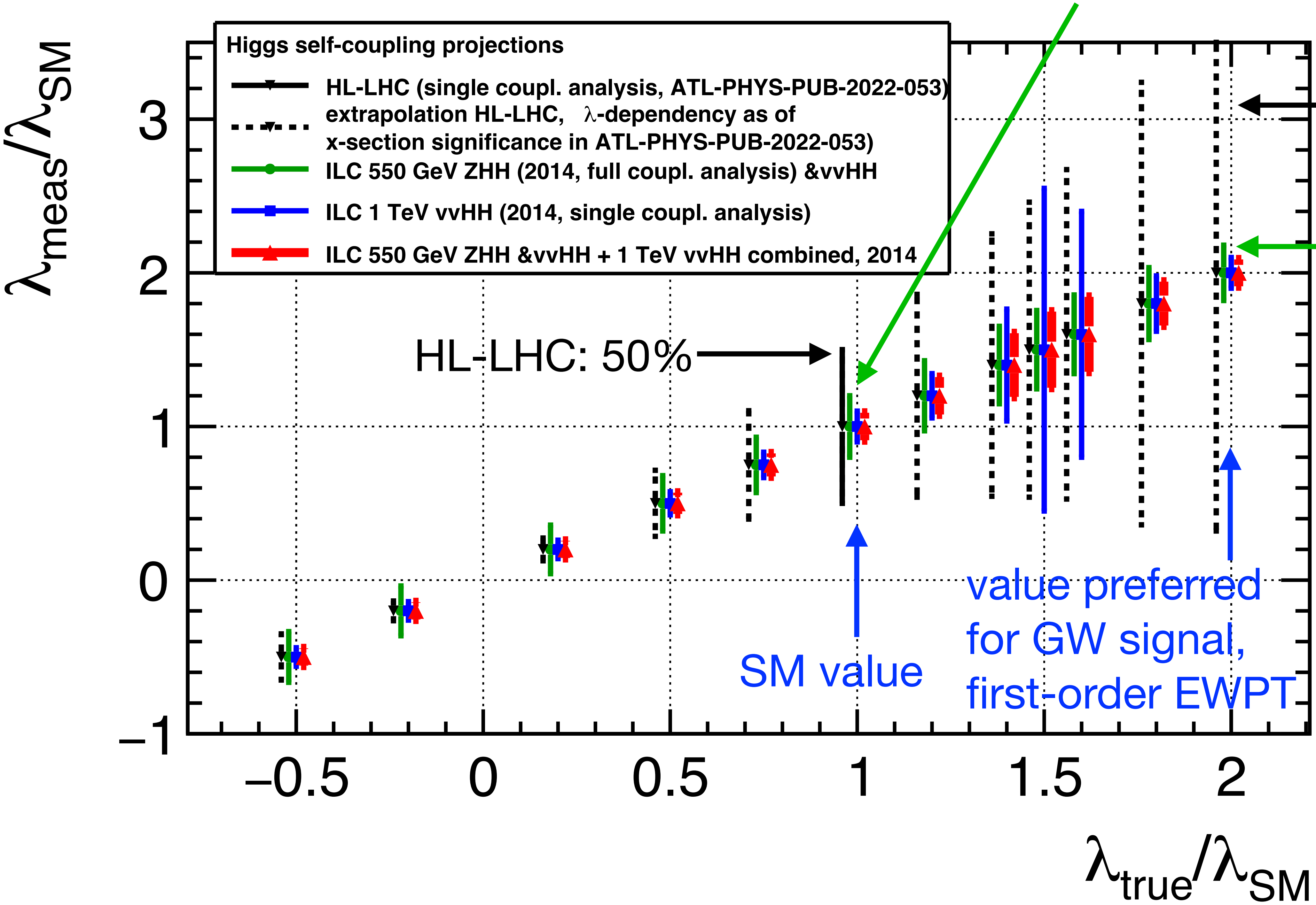
region with strong first-order EWPT

⇒ Region with strong first-order EWPT and potentially detectable GW signal is correlated with significant deviation of κ_λ from SM value

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (550 GeV, Higgs pair production)

ILC550: 20%

[J. List et al. '24]



HL-LHC: 84%

ILC550: 9%

HL-LHC: 50%

SM value

value preferred for GW signal, first-order EWPT

⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC550 than for HL-LHC

Reason: different interference contributions

Conclusions

Resonant di-Higgs production: the limits quoted by ATLAS and CMS so far may be too optimistic; a joint effort between experiment and theory would be useful in order to properly take into account the SM-like contributions and the interferences

Non-resonant di-Higgs production: current constraints on the trilinear Higgs self-coupling from LHC already probe physics of extended Higgs sectors that would otherwise be unconstrained; region with strong first-order EWPT (and potentially detectable GW signal) is typically correlated with significant deviation of $\varkappa_\lambda$ from the SM value and can be probed with LHC ``smoking gun" signatures

The possibility to measure the trilinear Higgs self-coupling in the Zhh production process at an e^+e^- collider with c.m. energy of at least 500 GeV is a qualitative game-changer compared to the capabilities of lower-energy Higgs factories

Backup

Electroweak phase transition and baryon asymmetry

Observed Baryon Asymmetry of the Universe (BAU)

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck '18]

n_b: baryon no. density
$n_{\bar{b}}$: antibaryon no. density
n_γ: photon no. density

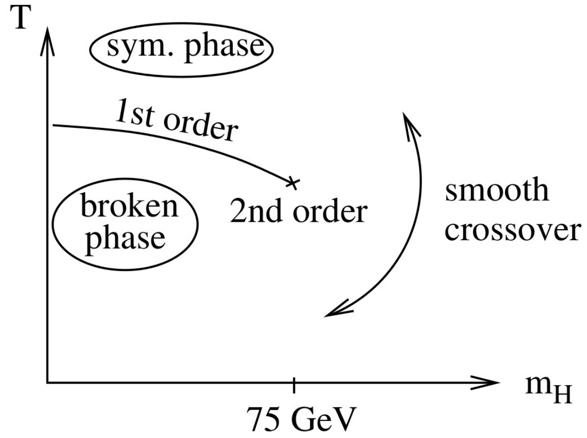
[J. M. No '23]

Sakharov Conditions

(*for dynamical generation of baryon asymmetry*)

- B Violation
- C/CP Violation ✘ not enough in SM
- Departure from Thermal Equilibrium

SM phase diagram



SM CP Violation insufficient by ~ 10 orders of magnitude

via 3-family fermion mixing
(CKM matrix)

Sakharov conditions:
- baryon (or lepton) number violation starting from symmetric state
- treat baryons and anti-baryons differently (to remove anti-matter)
- suppress inverse processes

Strongly first-order EWPT in the 2HDM

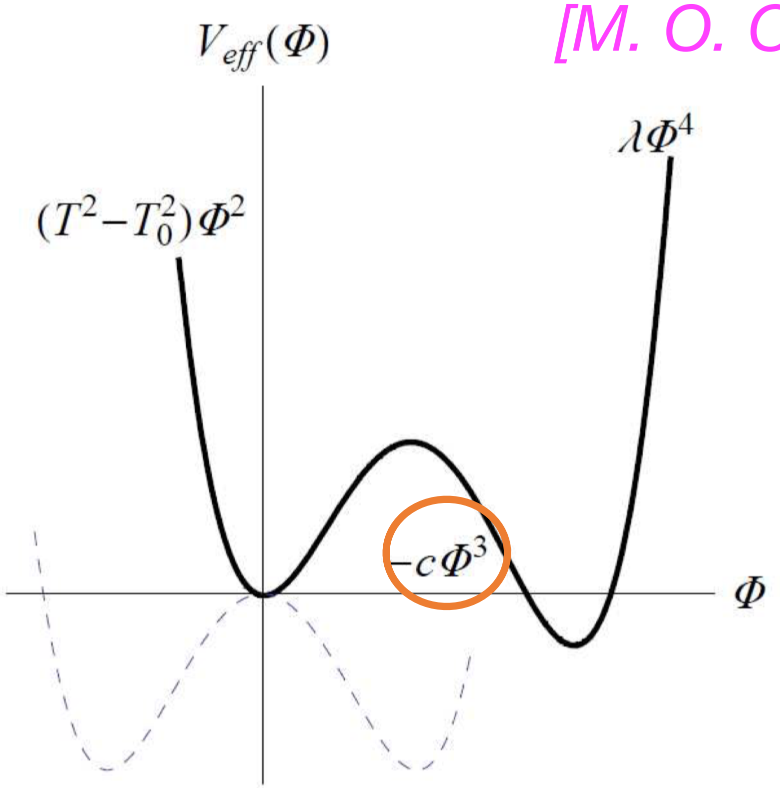
Barrier is related to a cubic term in the effective potential

Arises from higher-order contributions and thermal corrections to the potential, in particular:

$$-\frac{T}{12\pi}\left[\mu_S^2 + \boxed{\lambda_{HS}h^2} + \Pi_S\right]^{\boxed{3/2}}$$

⇒ For sizeable quartic couplings an effective cubic term in the Higgs potential is generated

[M. O. Olea '23]



⇒ Yields mass splitting between the BSM Higgs bosons and sizeable corrections to the trilinear Higgs coupling

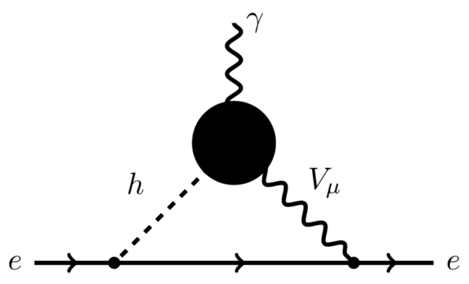
EWPT: are there additional sources for CP violation in the Higgs sector?

Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a strong first-order electroweak phase transition (EWPT)

First-order EWPT does not work in the SM
The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

First-order EWPT can be realised in extended Higgs sectors
could give rise to detectable gravitational wave signal

⇒ Search for additional sources of CP violation

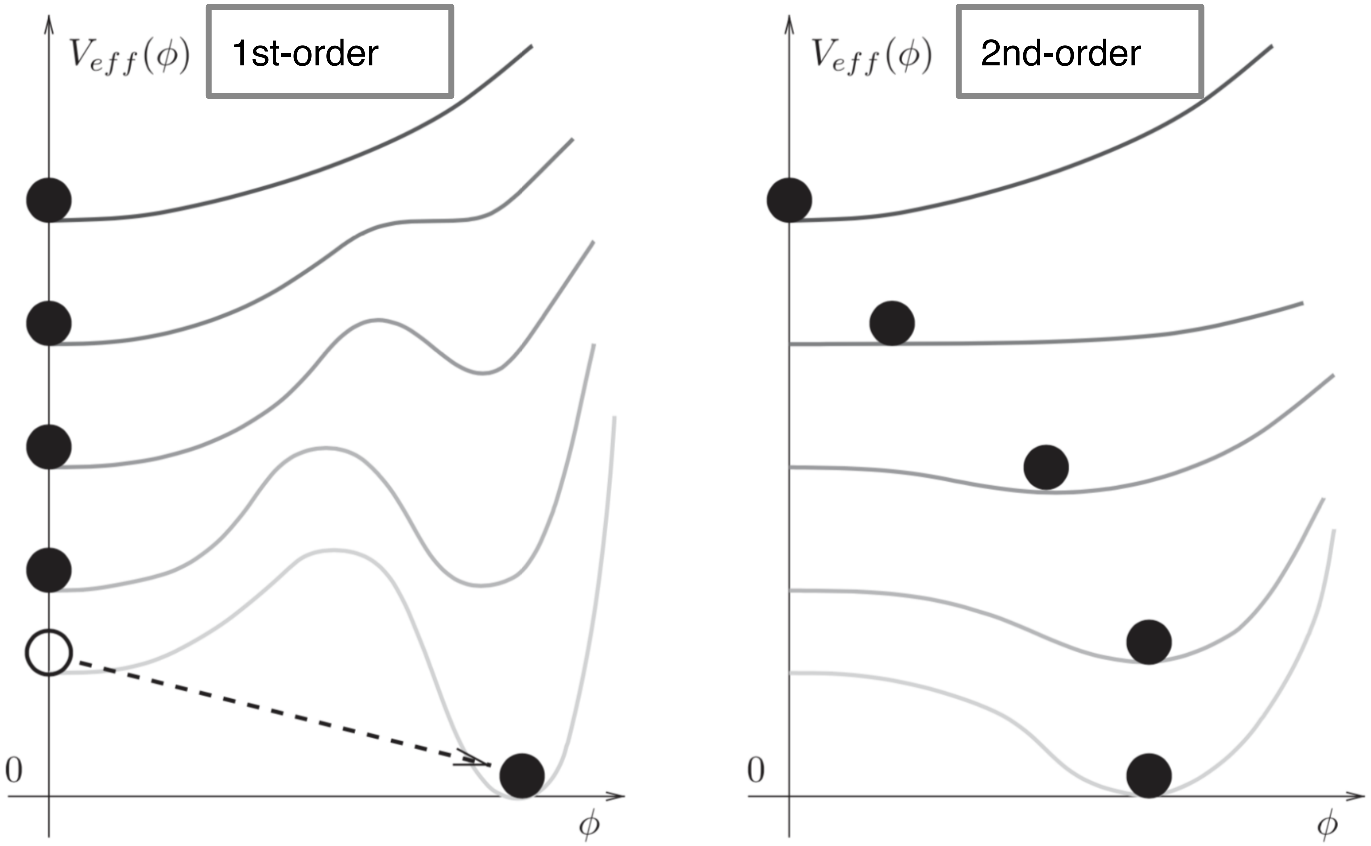


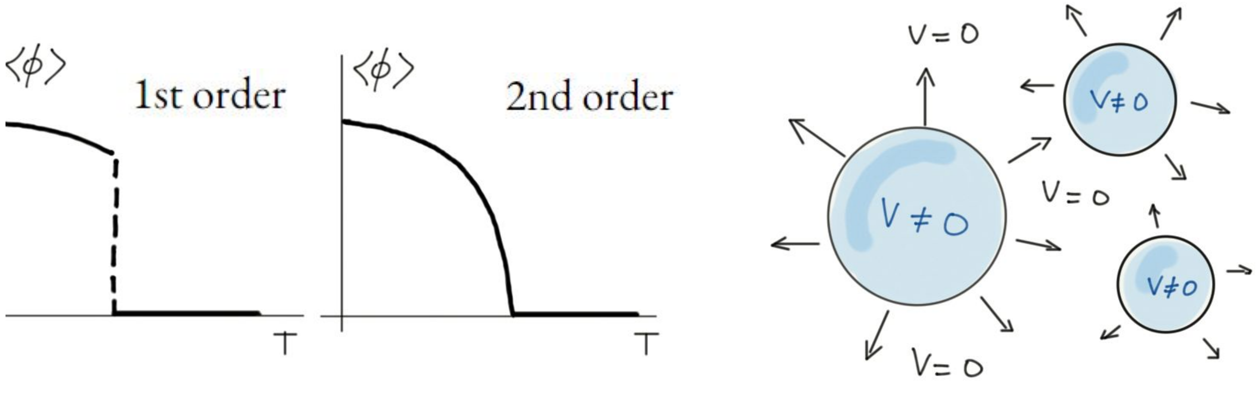
Two-loop "Barr-Zee"
electron EDM contribution

But: strong experimental constraints from limits on electric dipole moments (EDMs)

First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]





[K. Radchenko '23]

Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

Deviation of trilinear Higgs coupling from SM value is a typical feature of a strong first-order EWPT

Where should experiment and theory meet?

- Properties of h125:
  The comparison between experiment and theory is carried out at the level of signal strengths, STXS, fiducial cross sections, … , and to a lesser extent for $\varkappa$ parameters (signal strength modifiers; see example of $\varkappa_\lambda$ below) and coefficients of EFT operators

  Public tools for confronting the experimental results with model predictions: *HiggsSignals* (signal strengths, STXS), *Lilith* (signal strengths), *HEPfit* (signal strengths), …

New versions: *HiggsTools* *[H. Bahl et al. '22]*

- Limits from the searches for additional Higgs bosons:
  Public tools for reinterpretation / recasting of experimental results:
  HiggsBounds (limits on σ x BR, full likelihood information incorporated where provided by exp. collaborations)
  Recasting tools:
  MadAnalysis 5, *Rivet*, *ColliderBit*, *RECAST* (ATLAS-internal), …

``$\varkappa$ framework" and EFT approach for coupling analyses

Simplified framework for coupling analyses: deviations from SM parametrised by ``scale factors" $\varkappa_i$, where $\varkappa_i \equiv g_{Hii}/g^{\mathrm{SM},\,(0)}_{Hii}$

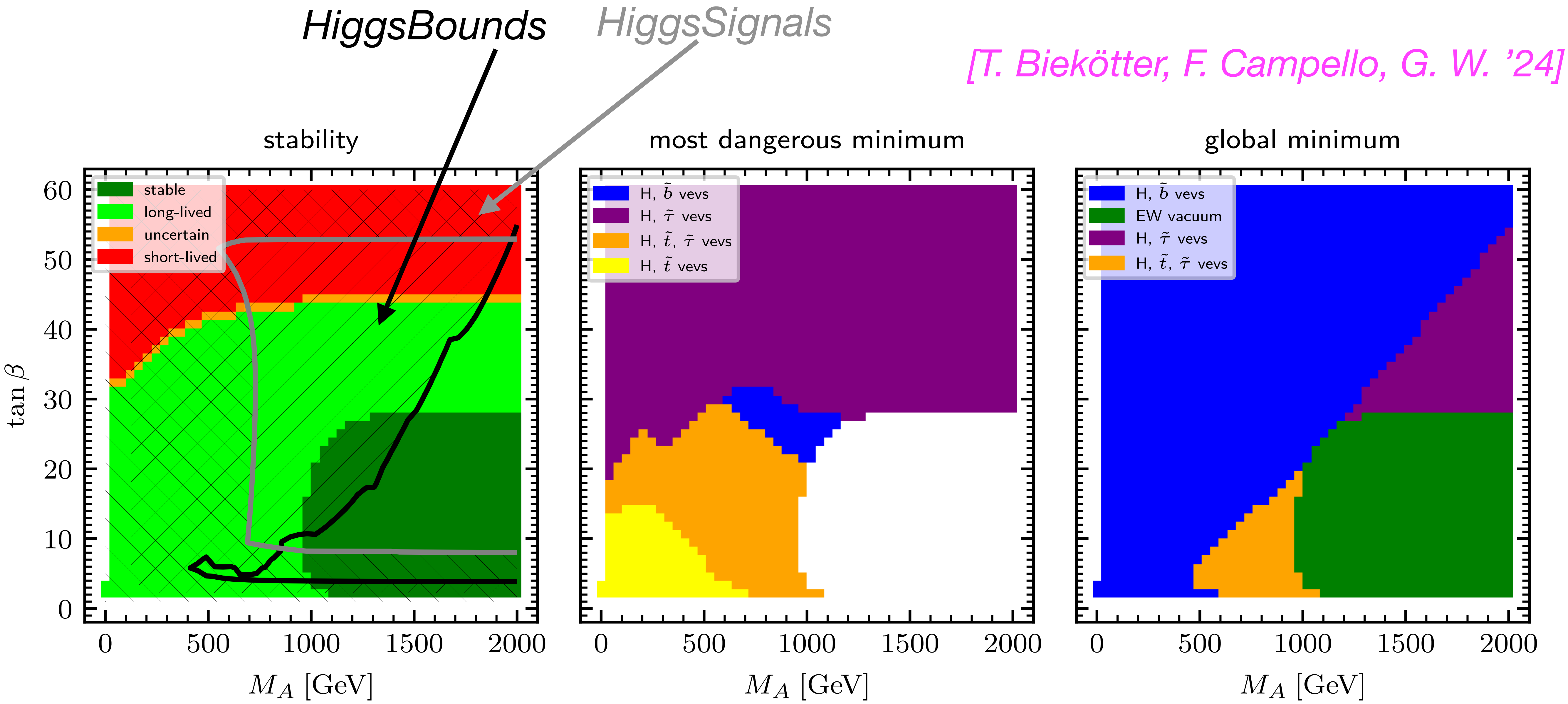
Assumptions inherent in the $\varkappa$ framework: signal corresponds to only one state, no overlapping resonances, etc., zero-width approximation, only modifications of coupling strengths (absolute values of the couplings) are considered
⇒ Assume that the observed state is a CP-even scalar

Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

EFT: fits for Wilson coefficients of higher-dimensional operators in SMEFT Lagrangian, …

Vacuum stability constraints in the MSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt '18]*
Example: constraints from vacuum stability in the MSSM on the region allowed by *HiggsBounds* and *HiggsSignals*



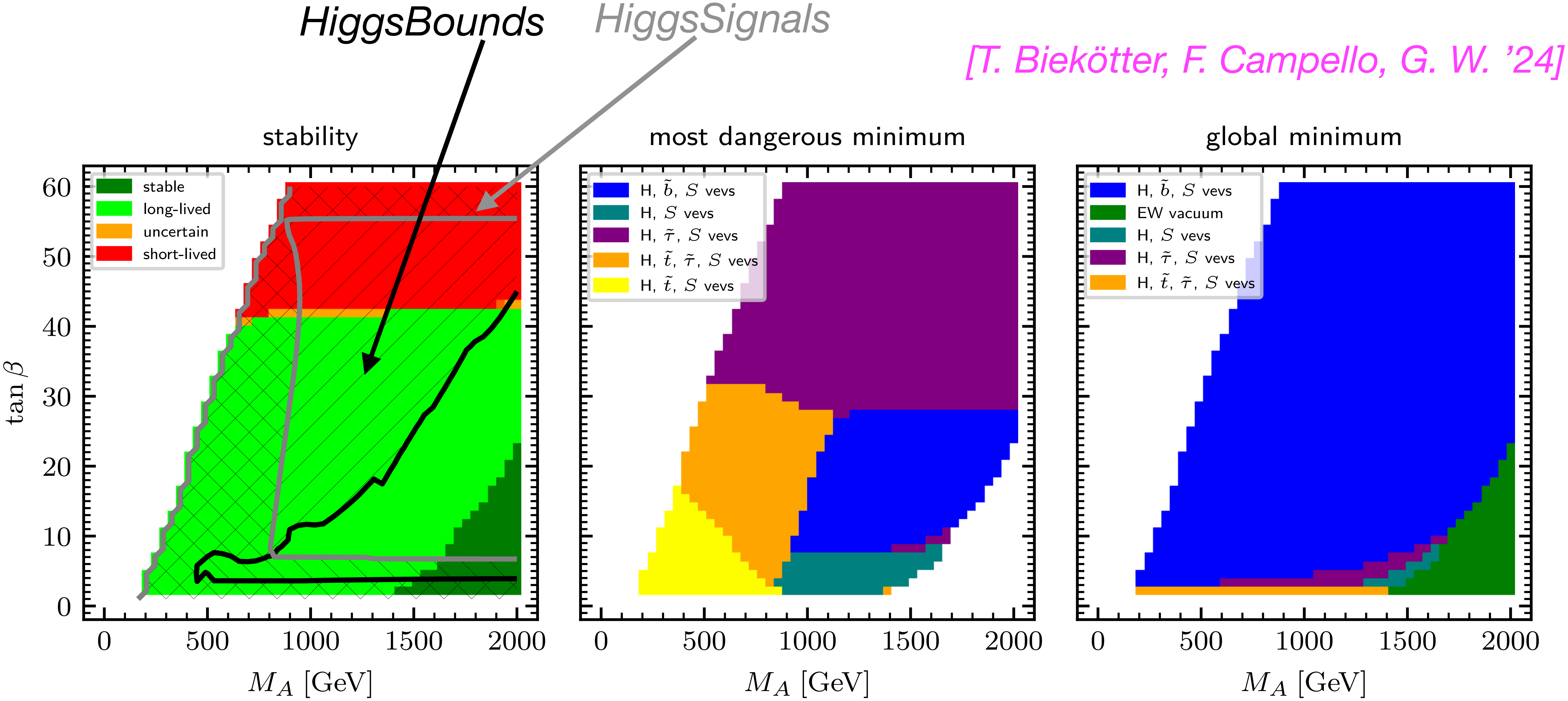
[T. Biekötter, F. Campello, G. W. '24]

Character of most-dangerous minimum differs from global minimum

Vacuum stability constraints in the NMSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt '18]*

Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*



[T. Biekötter, F. Campello, G. W. '24]

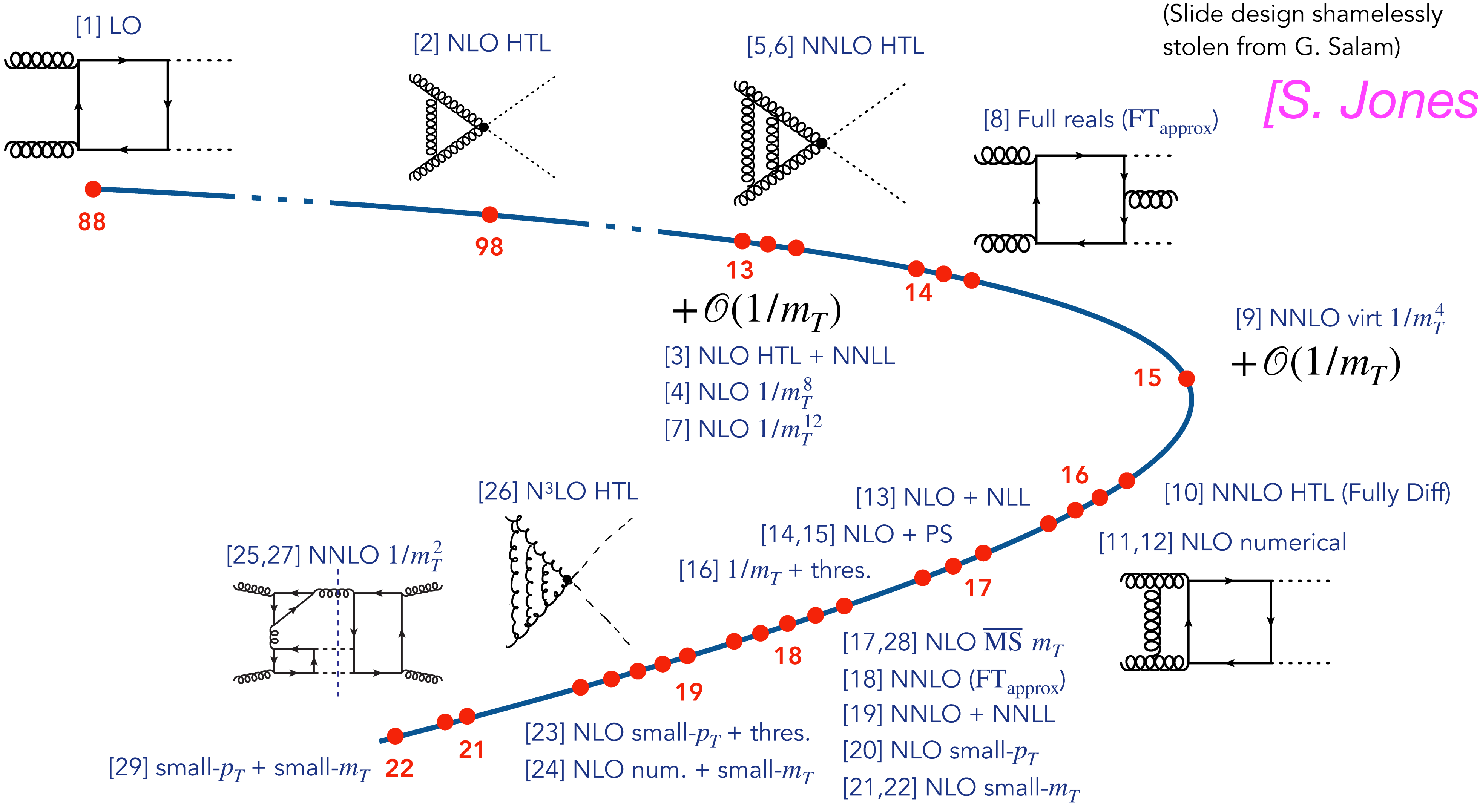
Character of most-dangerous minimum differs from global minimum

Higgs pair production: theory predictions

An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)

[S. Jones, G. Salam]



[1] LO

[2] NLO HTL

[5,6] NNLO HTL

[8] Full reals ($\mathrm{FT}_{\mathrm{approx}}$)

$+\mathcal{O}(1/m_T)$

[3] NLO HTL + NNLL

[4] NLO $1/m_T^8$

[7] NLO $1/m_T^{12}$

[9] NNLO virt $1/m_T^4$

$+\mathcal{O}(1/m_T)$

[10] NNLO HTL (Fully Diff)

[11,12] NLO numerical

[13] NLO + NLL

[14,15] NLO + PS

[16] $1/m_T$ + thres.

[26] N³LO HTL

[25,27] NNLO $1/m_T^2$

[17,28] NLO $\overline{\mathrm{MS}}$ m_T

[18] NNLO ($\mathrm{FT}_{\mathrm{approx}}$)

[19] NNLO + NNLL

[20] NLO small-p_T

[21,22] NLO small-m_T

[23] NLO small-p_T + thres.

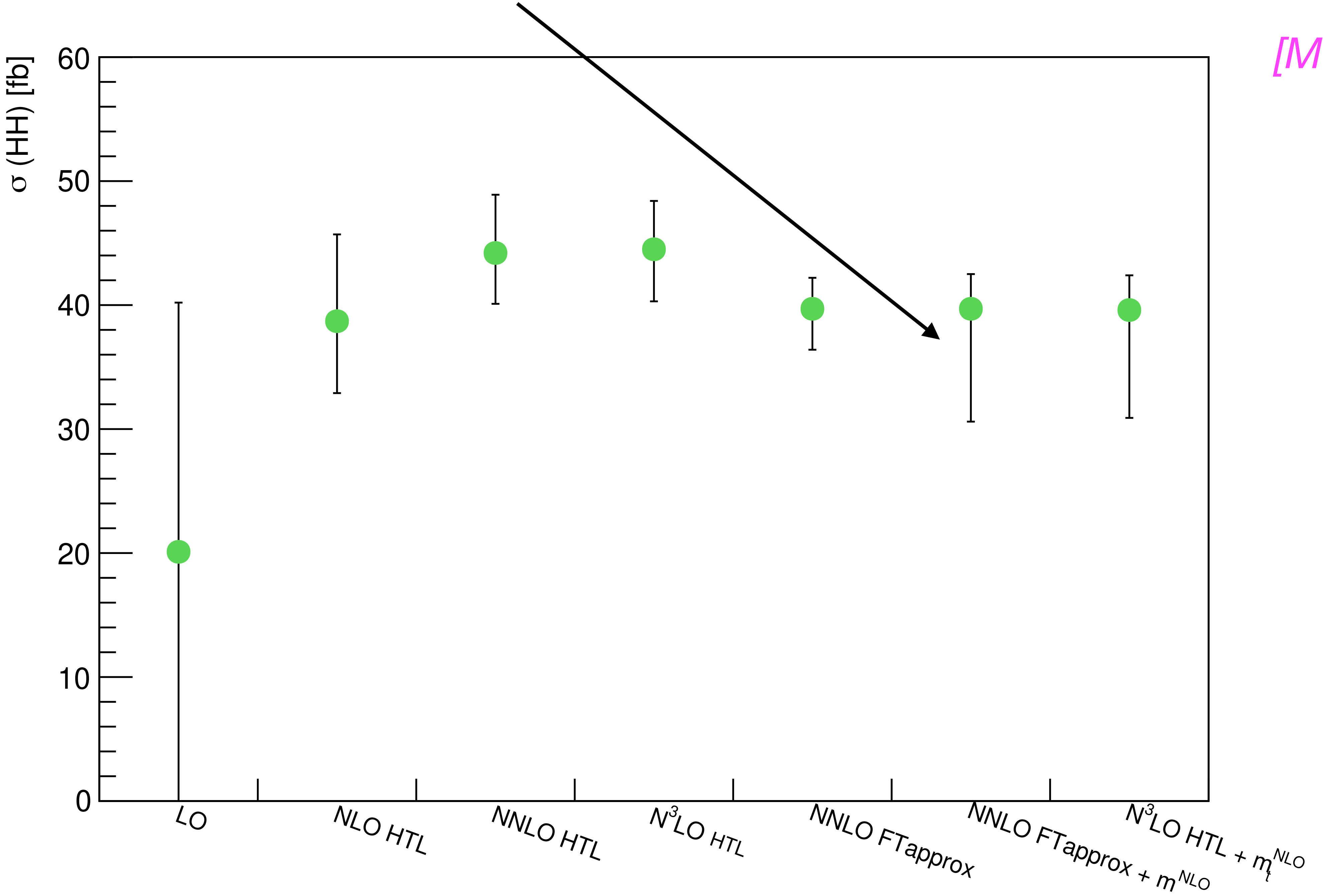
[24] NLO num. + small-m_T

[29] small-p_T + small-m_T

[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

Higgs pair production, prediction and uncertainties

Impact of the renormalisation-scheme dependence of the top mass:



[M. Spira ’22]

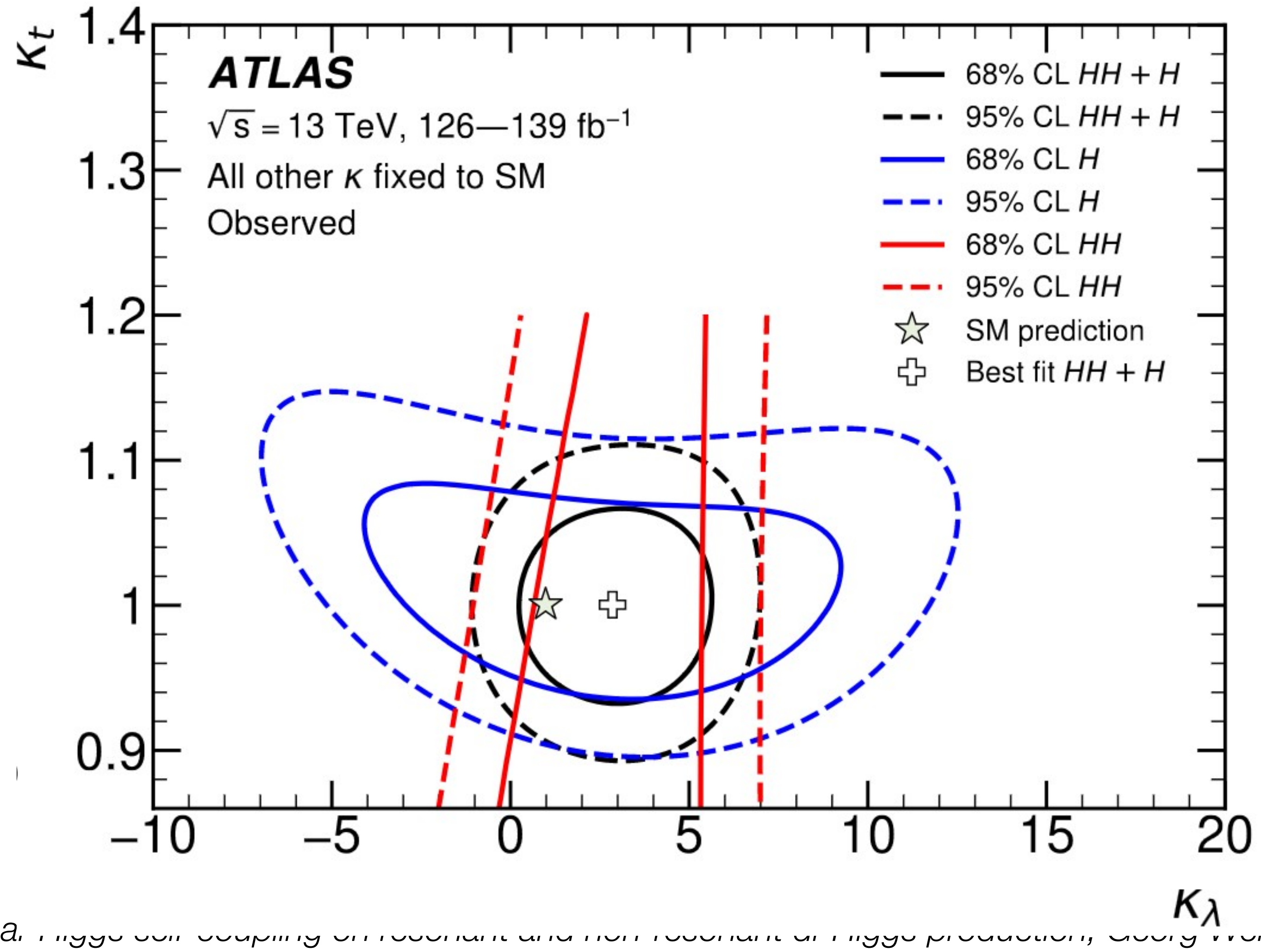
Electroweak corrections: top-Yukawa contributions

[M. Mühlleitner, J. Schlenk, M. Spira ’22] *[J. Davies et al. ’22]*

Experimental constraints on $\varkappa_\lambda$

[ATLAS Collaboration ’22]

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
$HH+H$ combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
$HH+H$ combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
$HH+H$ combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$



Check of applicability of the experimental limit on $\varkappa_\lambda$

The assumption that new physics only affects the trilinear Higgs self-coupling is expected to hold at most approximately in realistic models

BSM models can modify Higgs pair production via resonant and non-resonant contributions

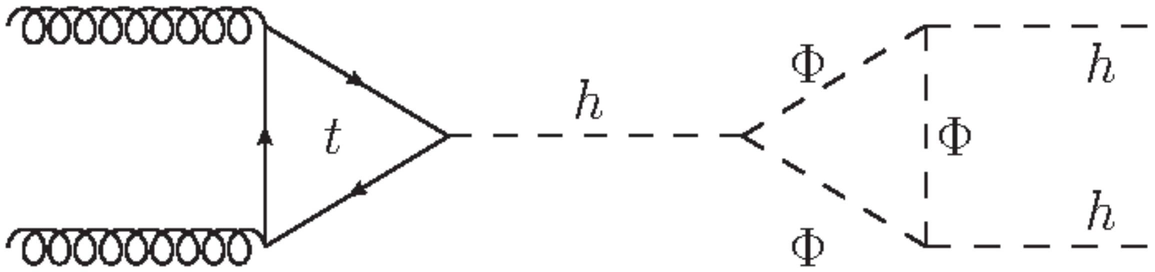
The current experimental limit can only probe scenarios with large deviations from the SM
⇒ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

Check of applicability of the experimental limit on $\varkappa_\lambda$

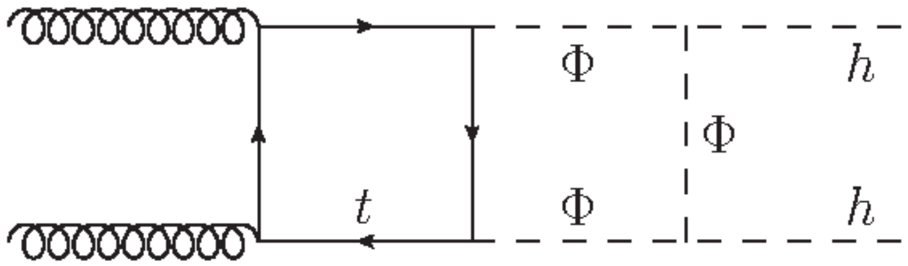
Alignment limit: h has SM-like tree-level couplings

Resonant contribution to Higgs pair production with H or A in the s channel is absent in the alignment limit

The dominant new-physics contributions enter via trilinear coupling



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

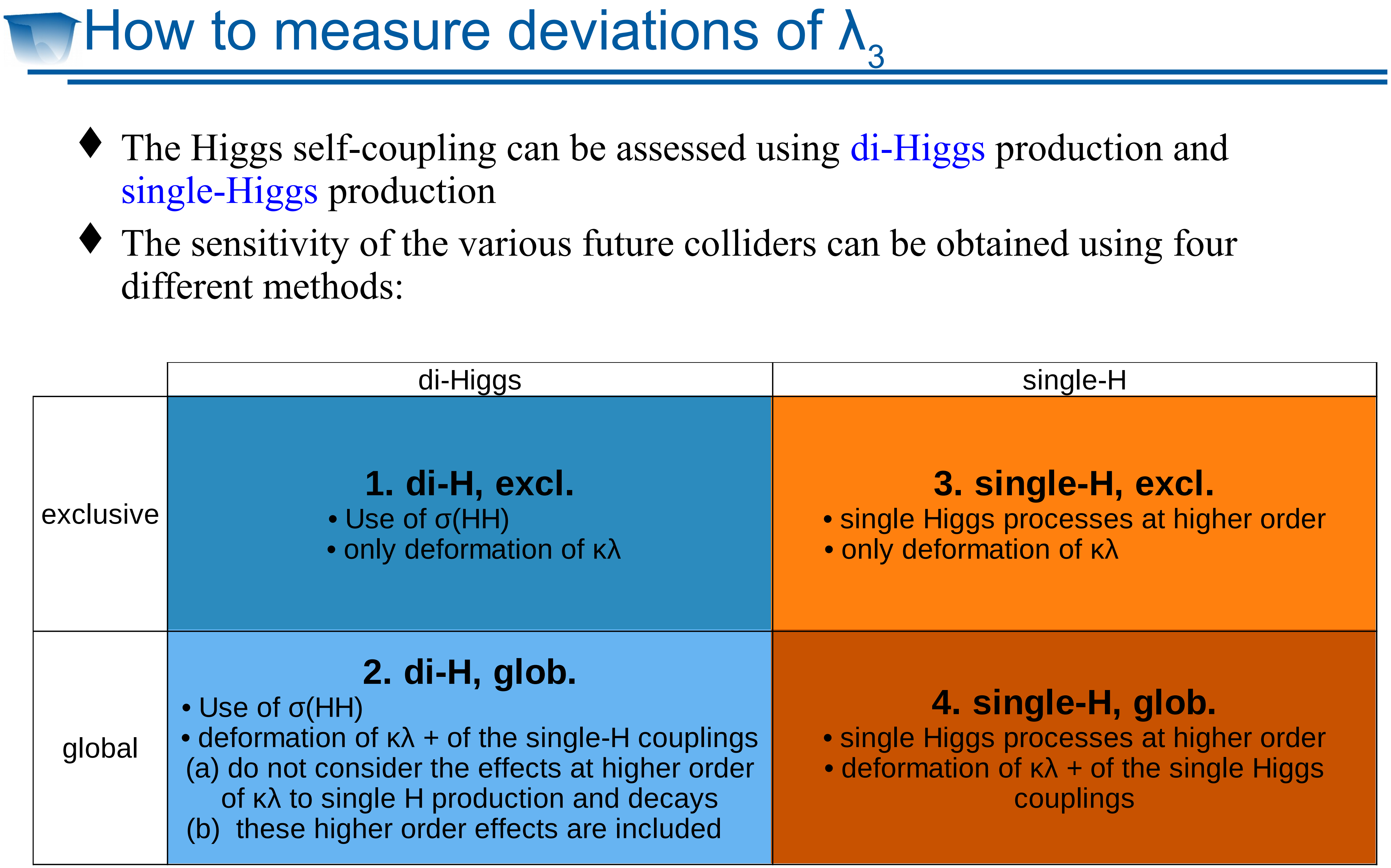


$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

⇒The leading effects in $g_{hh\Phi\Phi}$ to the Higgs pair production process are correctly incorporated at the 1- and 2-loop order via the corrections to the trilinear Higgs coupling!

Single-Higgs processes: λ enters at loop level

[E. Petit '19]



How to measure deviations of λ_3

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Note: this is based on the assumption that there is a large shift in λ, but no change anywhere else!

Single-Higgs processes: λ enters at loop level

[B. Heinemann ’19]

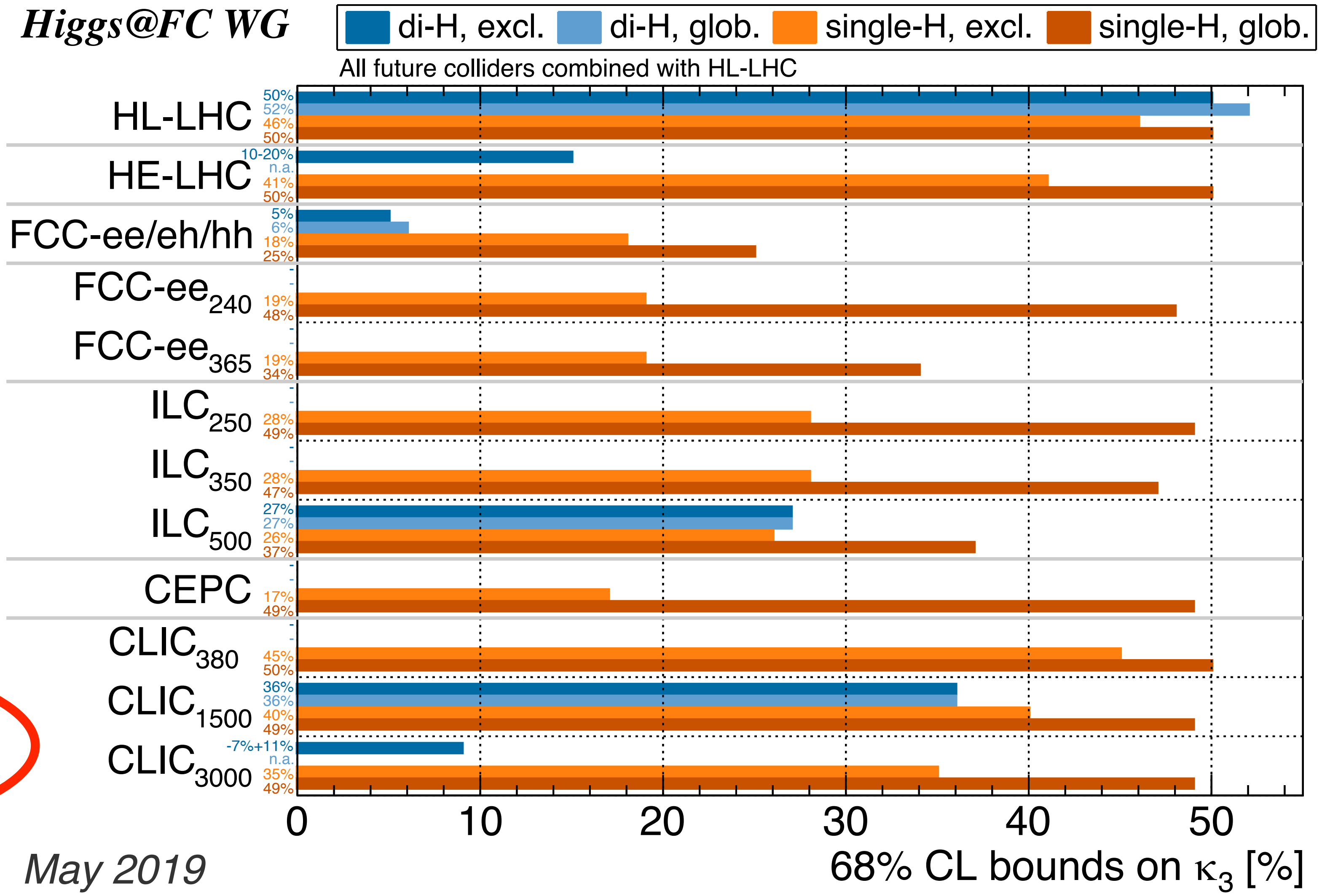
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC$_{500}$ (~27%), CLIC$_{1500}$ (~36%)
- Precisely by CLIC$_{3000}$ (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

Single-Higgs:

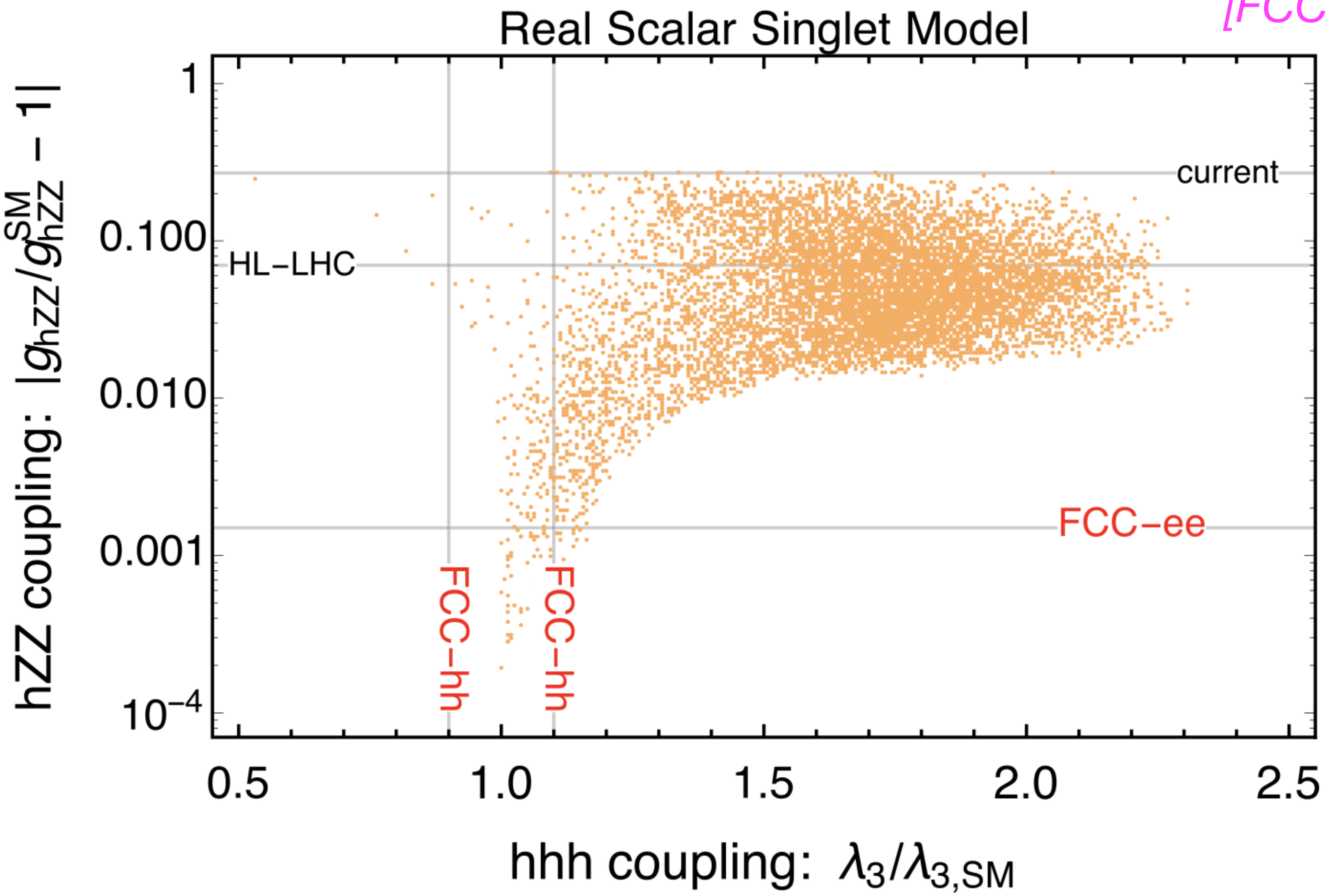
- **Global** analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- **Exclusive** analysis: too sensitive to other new physics to draw conclusion



Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Real scalar singlet model

This plot caused some discussions in the context of strategies for future colliders (displayed points feature a FOEWPT):

[FCC Midterm Report ’24]



[P. Huang, A. Long, L. Wang ’16]

In this plot: no higher-order contributions to $\varkappa_\lambda$ included, partial loop effects for hZZ coupling

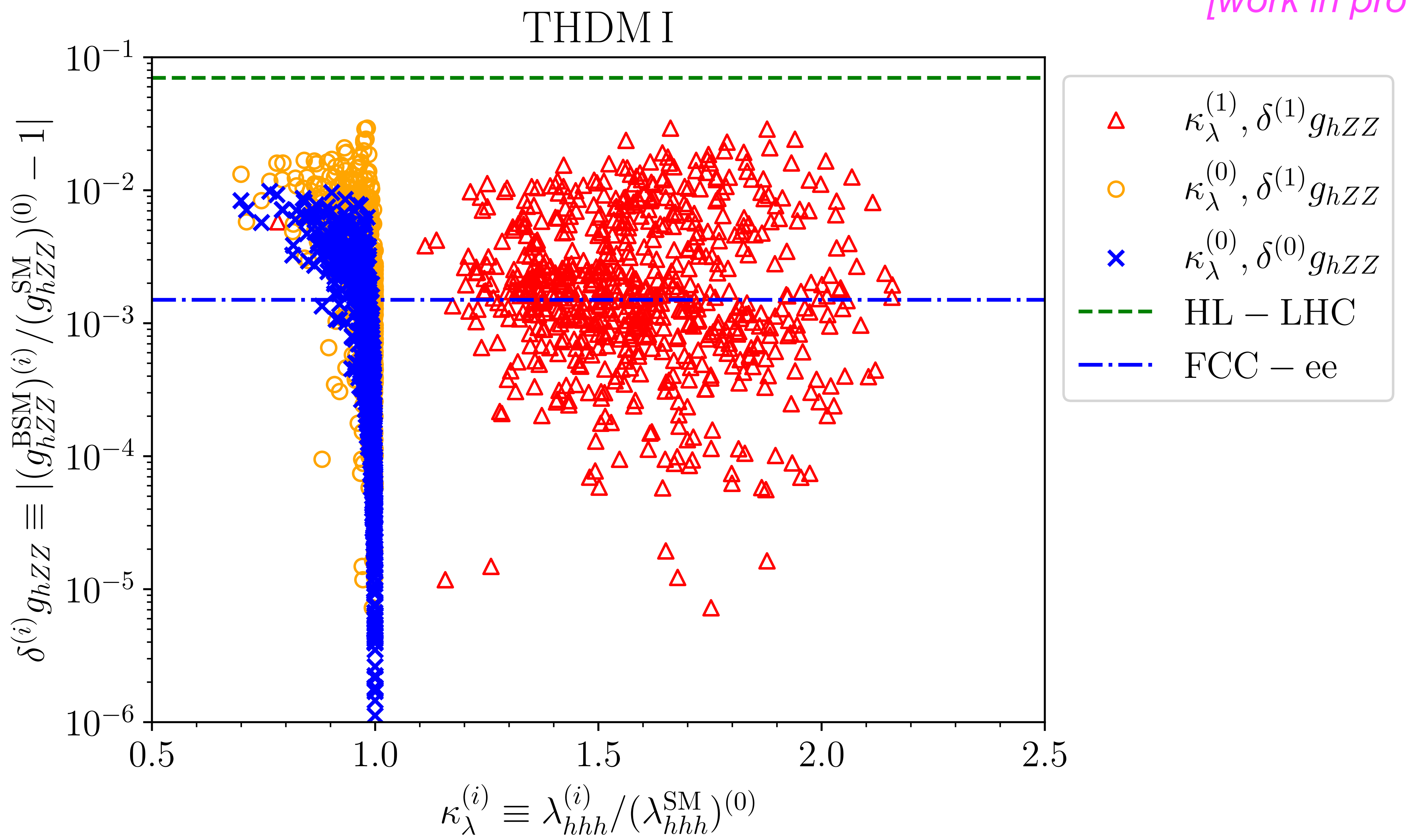
[investigation of the effects in progress]

⇒Do the deviations in $\varkappa_\lambda$ have to be small if the FCC-ee does not find a deviation in the h125 coupling to ZZ?

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Two Higgs Doublet model

Displayed points feature a FOEWPT

[H. Bahl et al. '24]
[work in progress]

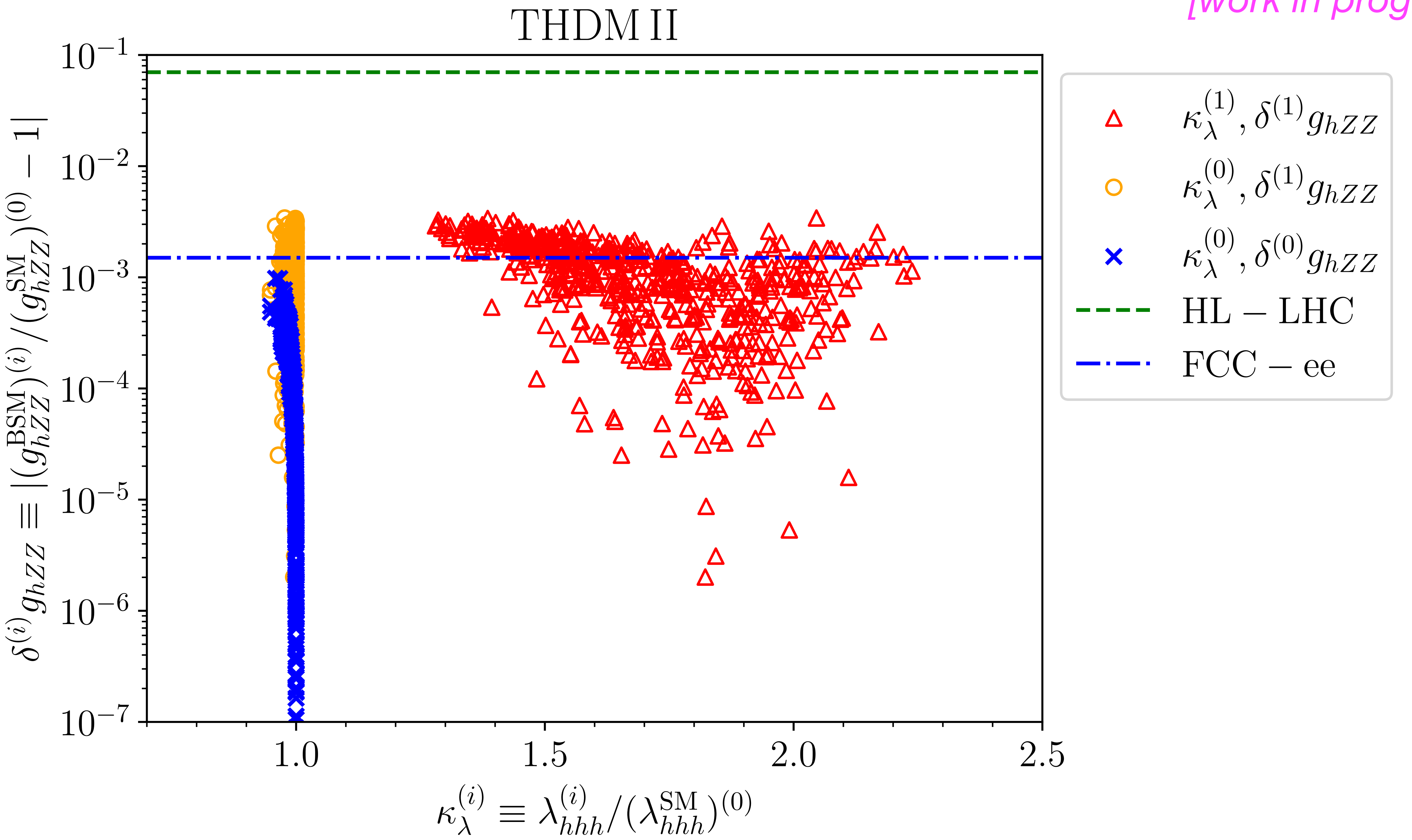


⇒Large deviations in $\varkappa_\lambda$ possible for effects in g_{hZZ} below the FCC sensitivity

Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Two Higgs Doublet model

Displayed points feature a FOEWPT

[H. Bahl et al. '24]
[work in progress]



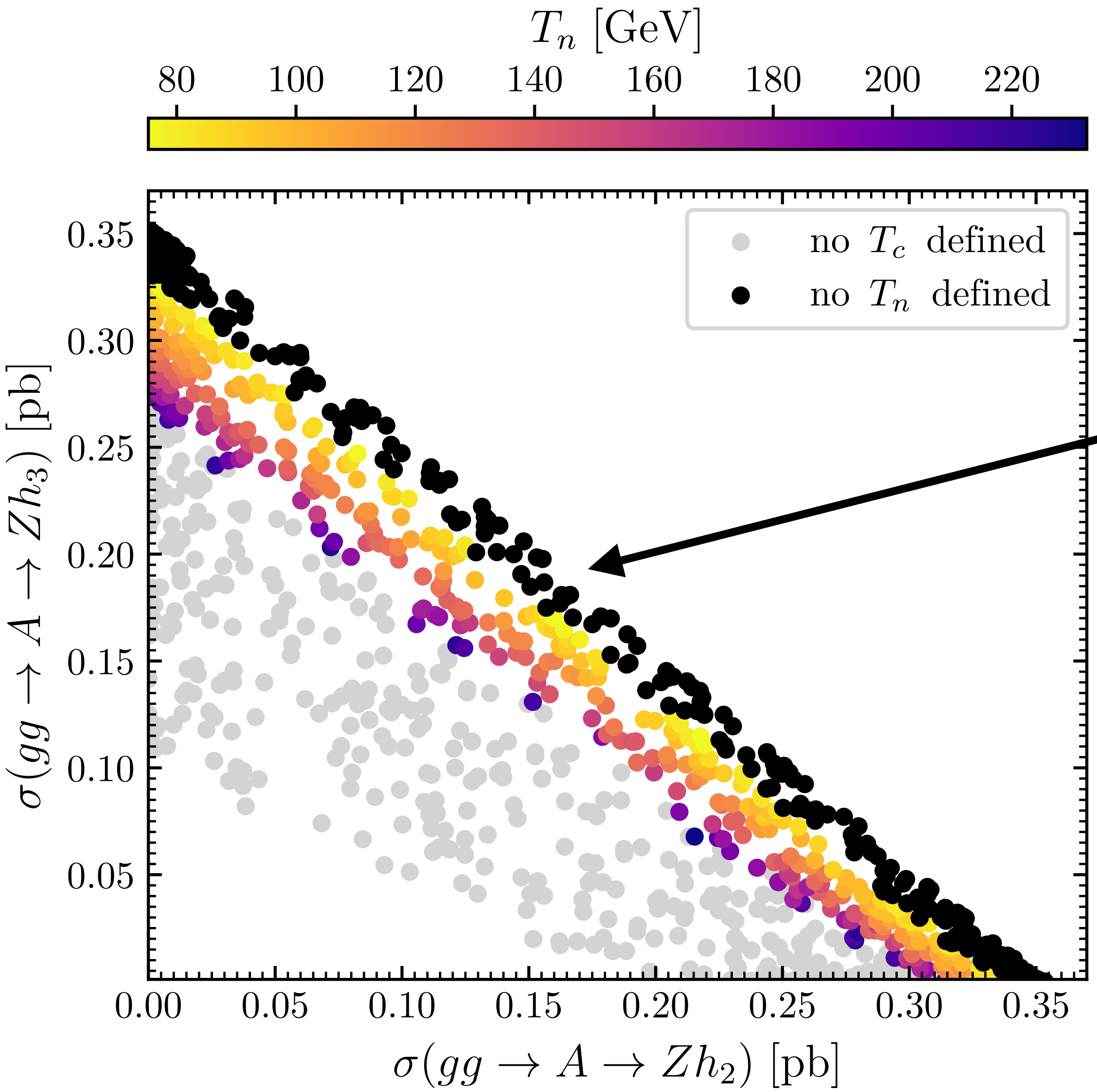
⇒Large deviations in $\varkappa_\lambda$ possible for effects in g_{hZZ} below the FCC sensitivity

N2HDM (two doublets + real singlet) example

``Smoking gun" collider signatures: A → Z h_2, A → Z h_3

Nucleation temperature for the first-order EWPT, N2HDM scan:

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '21]

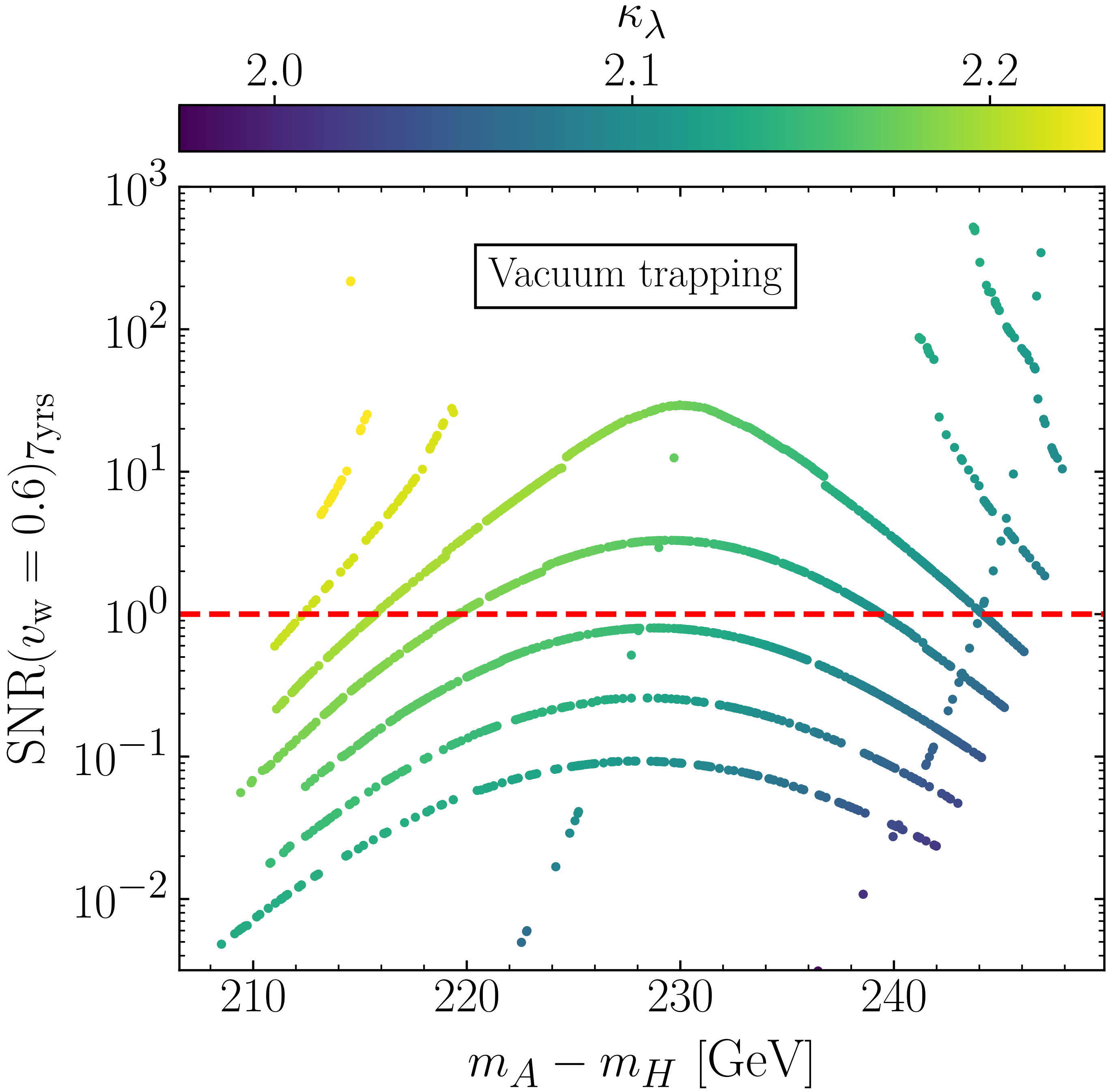


No first-order EWPT: universe is trapped in a ``false" vacuum

⇒ Lower nucleation temperatures, i.e. stronger first-order EWPTs, are correlated with larger signal rates at the LHC!

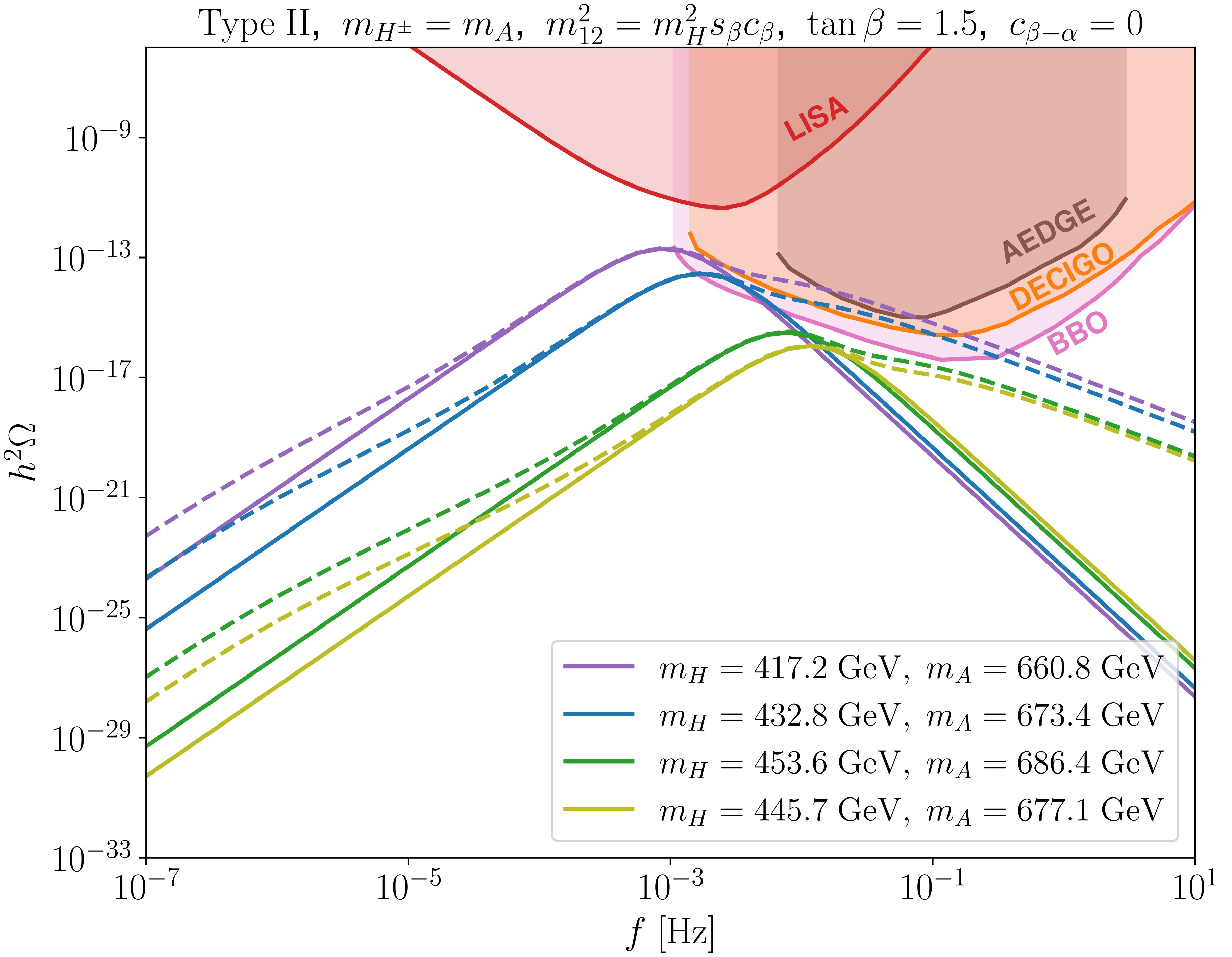
Correlation of $\varkappa_\lambda$ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]



⇒Region with potentially detectable gravitational wave signal: significant enhancement of $\varkappa_\lambda$ and non-vanishing mass splitting

GW spectra of scenarios fitting the excess



[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

⇒ Prospects for GW detection depend very sensitively on the precise details of the mass spectrum of the additional Higgs bosons

Higgs pair production at e⁺e⁻ colliders

[S. di Vita et al. '18]