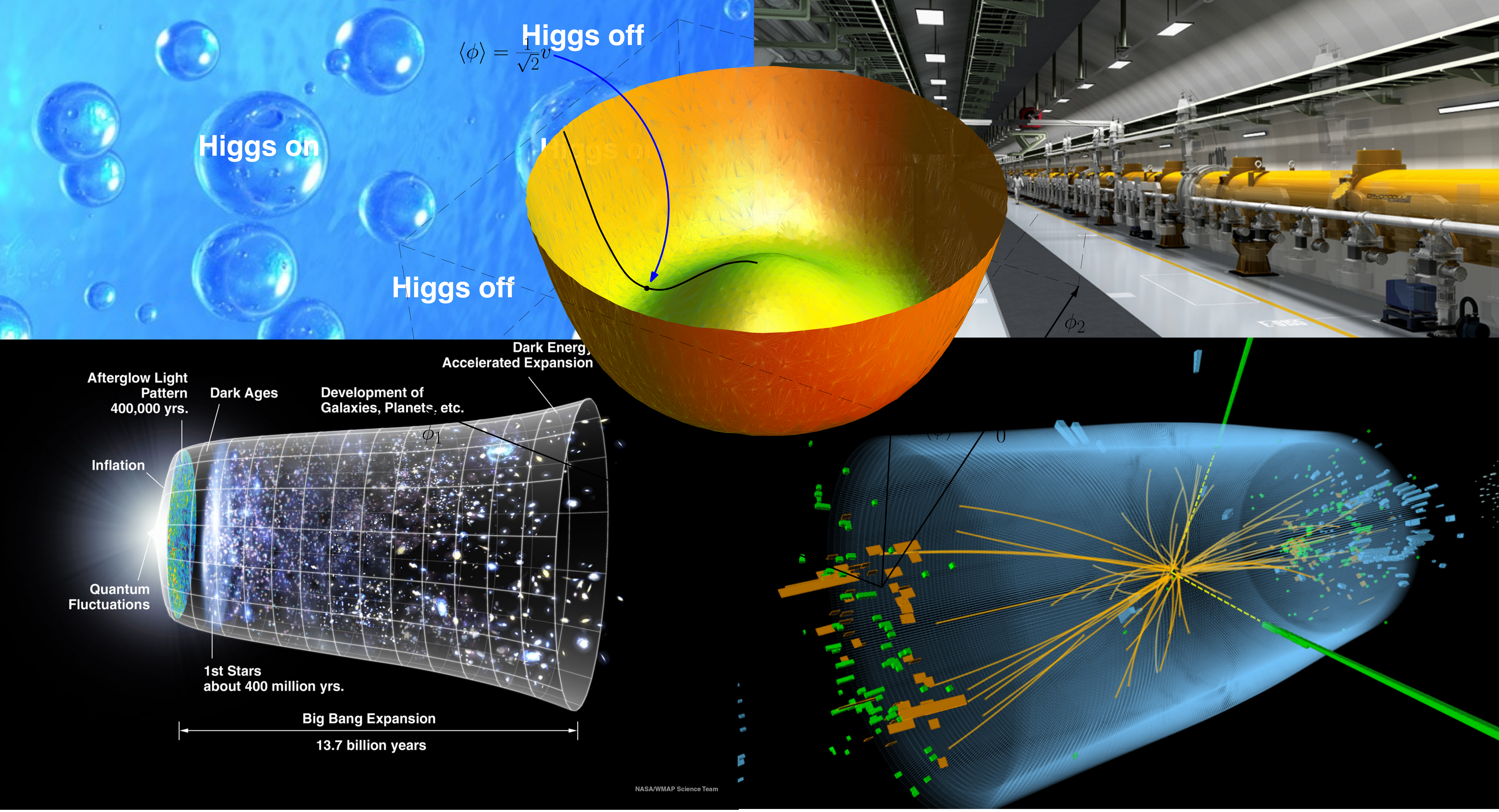


Physics case for an e^+e^- collider at 500 GeV and above

Georg Weiglein, DESY & UHH

Paris, 10 / 2024

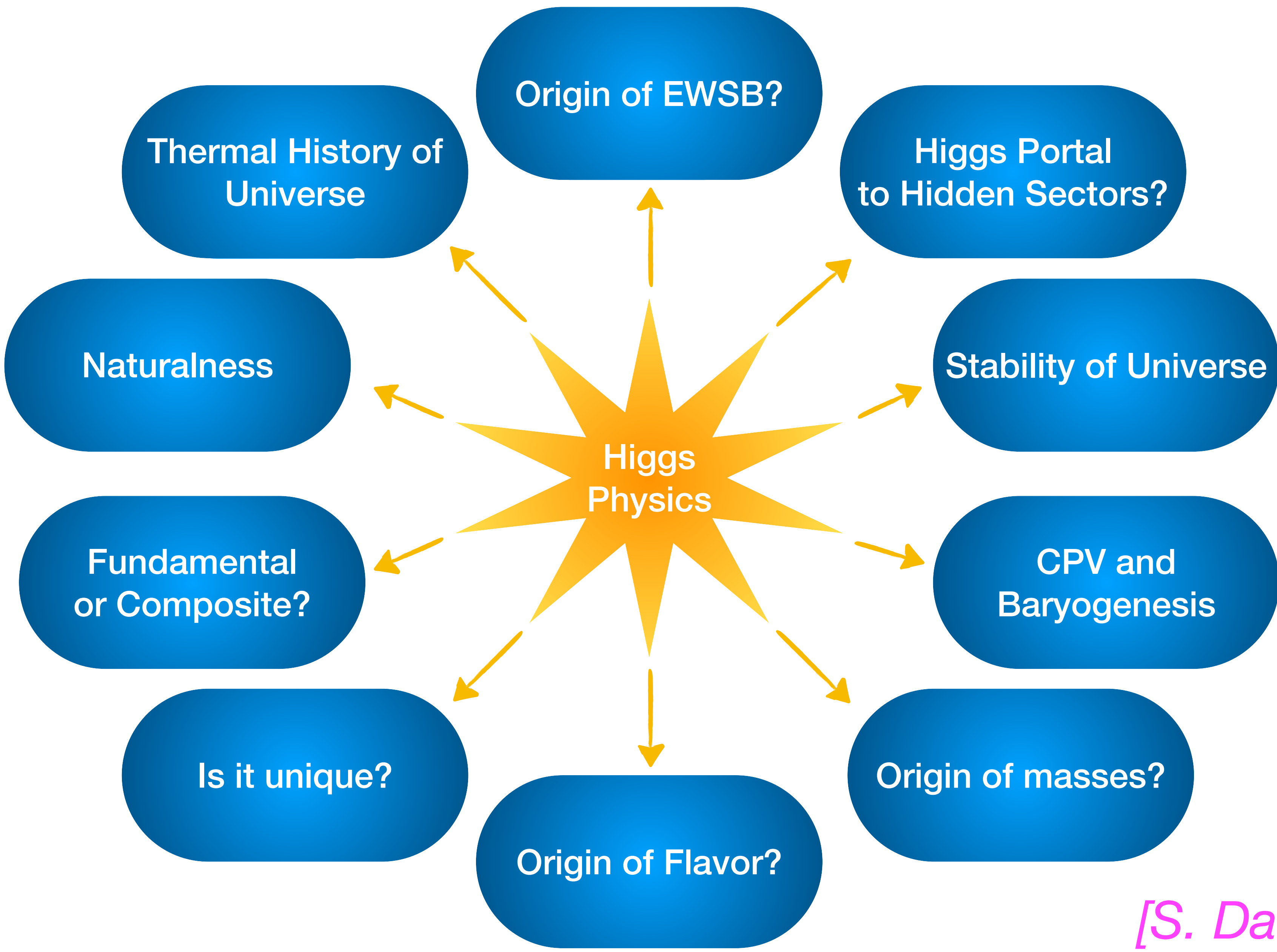
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
DESY.

Outline

- Introduction
- LC at 500 or 550 GeV: guaranteed measurements
- Beyond 500 GeV: guaranteed ``measurements”
- Sensitivity to new particles at 500 GeV and beyond
- Conclusions

Introduction

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



[S. Dawson et al. '22]

Higgs potential: the "holy grail" of particle physics

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

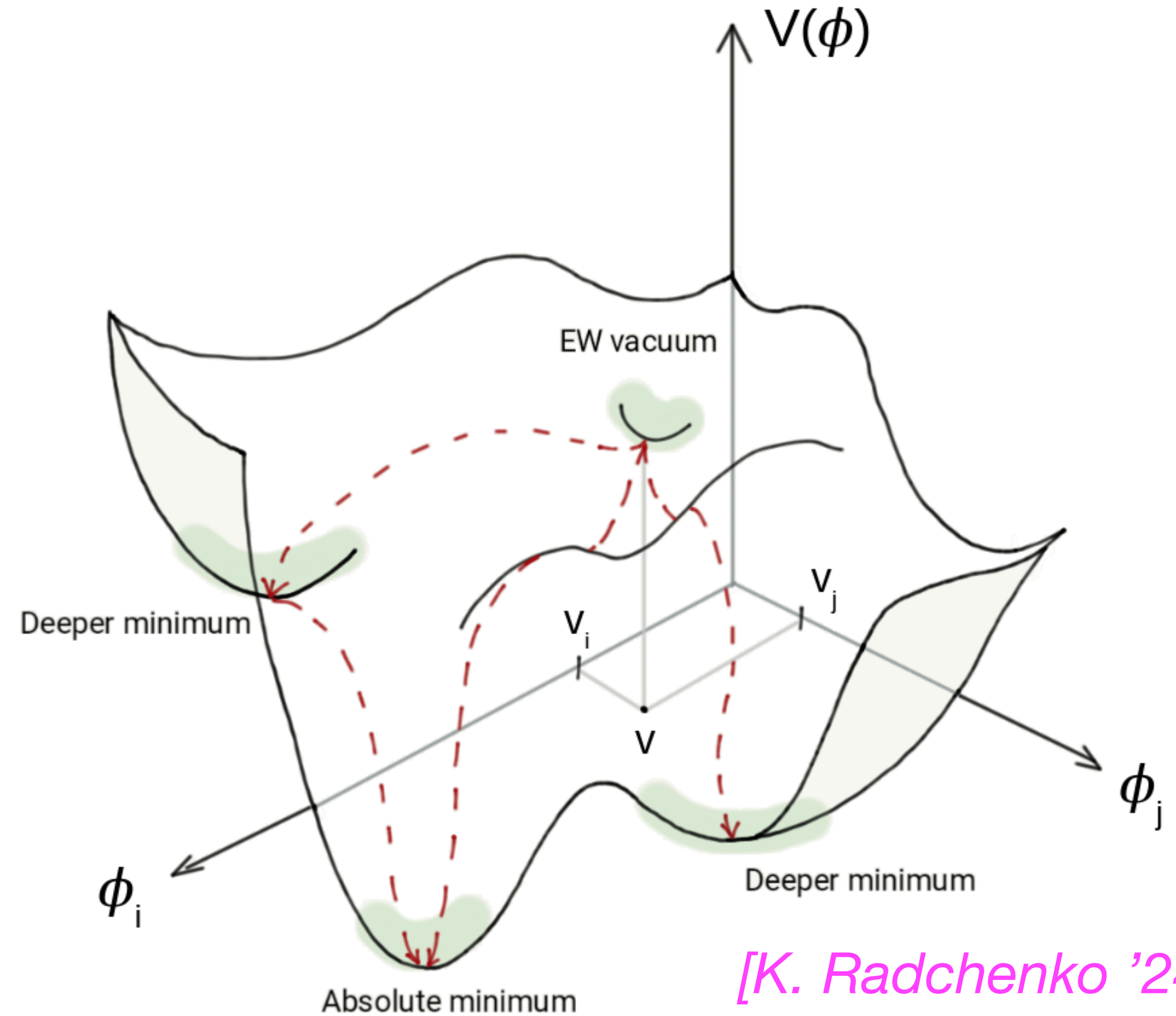
Trilinear coupling Quartic coupling Possible couplings involving additional scalars

$V = 1/2\, m_h^2\, h^2 + v\, \lambda_{hhh}\, h^3 + \lambda_{hhhh}\, h^4 + \ldots + v\, \lambda_{hhH}\, h^2 H + v\, \lambda_{HHH}\, H^3 + \ldots$

Known so far:
(h: detected Higgs at 125 GeV)

Distance of EW minimum from origin of field space: v

Curvature of the potential around the EW minimum: m_h

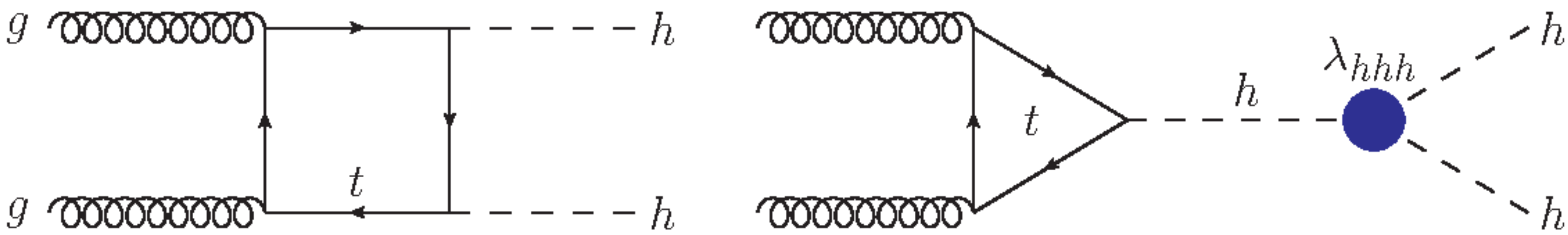


[K. Radchenko '24]

Trilinear Higgs self-coupling, λ_{hhh}: LHC

Sensitivity to λ_{hhh} from Higgs pair production:

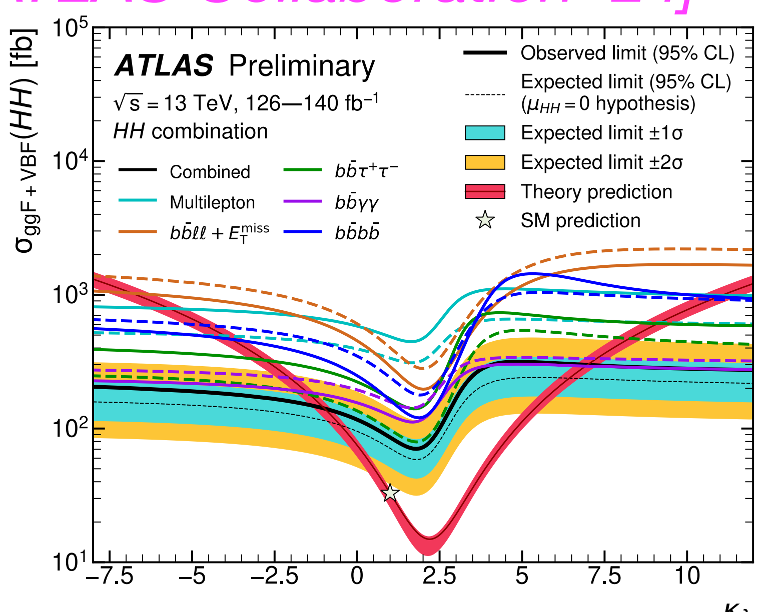
- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



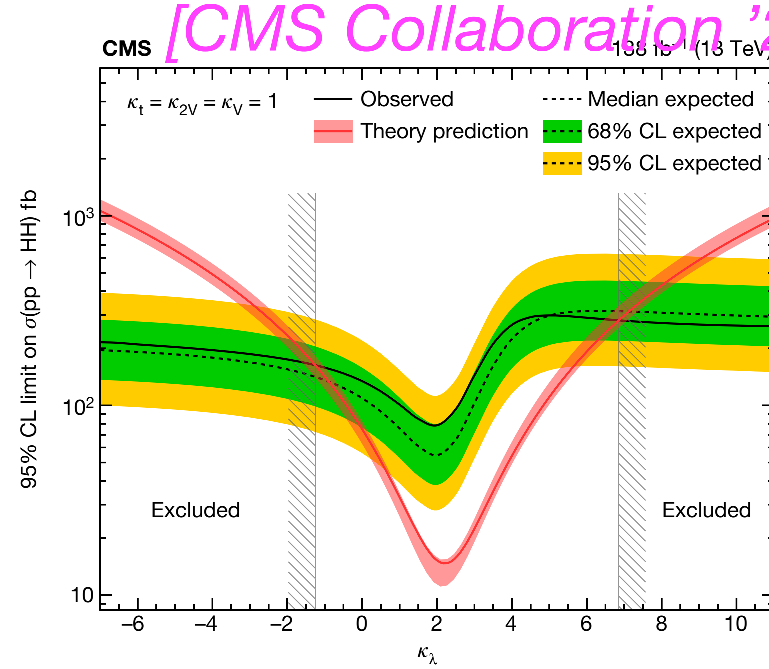
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

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

[ATLAS Collaboration ’24]



[CMS Collaboration ’22]



Using only information from di-Higgs production and assuming that new physics only affects λ_{hhh}

$-1.2 < \varkappa_\lambda < 7.2$ at 95% C.L. $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L.

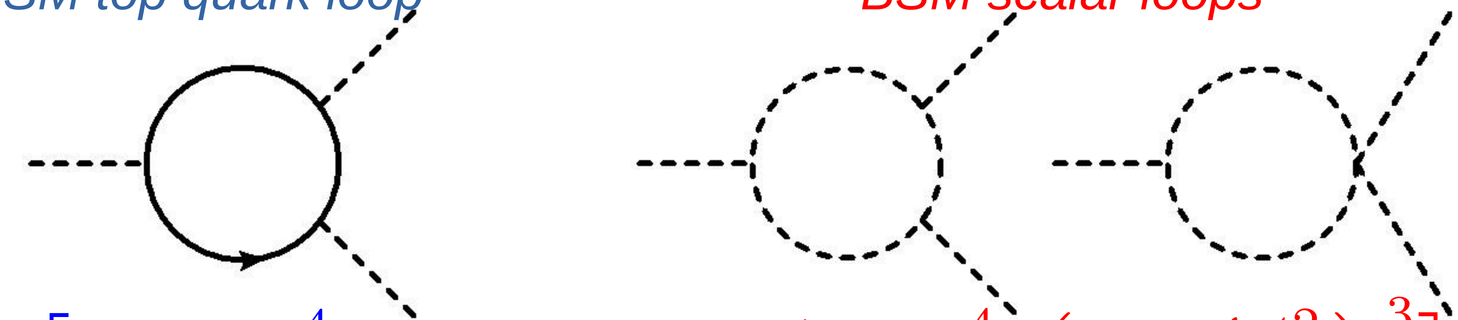
λ_{hhh}: very large deviations from the SM value possible!

[see J. Braathen's talk]

λ_{hhh} 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*



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

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: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda}v^2$

BSM Higgs masses in general receive contributions from two sources: BSM mass scale $\mathcal{M}$ and (quartic couplings) vev^2, $\tilde{\lambda}v^2$

Mass splitting can yield loop effects of several 100%, in contrast to h couplings to gauge bosons and fermions (only up to % level)

λ_{hhh}: very large deviations from the SM value possible!

EFT perspective: *[M. McCullough, ICHEP 2024]*

Self-Coupling Dominance

No obstruction to having Higgs self-coupling modifications a "loop factor" greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

Durieux, MM, Salvioni. 2022

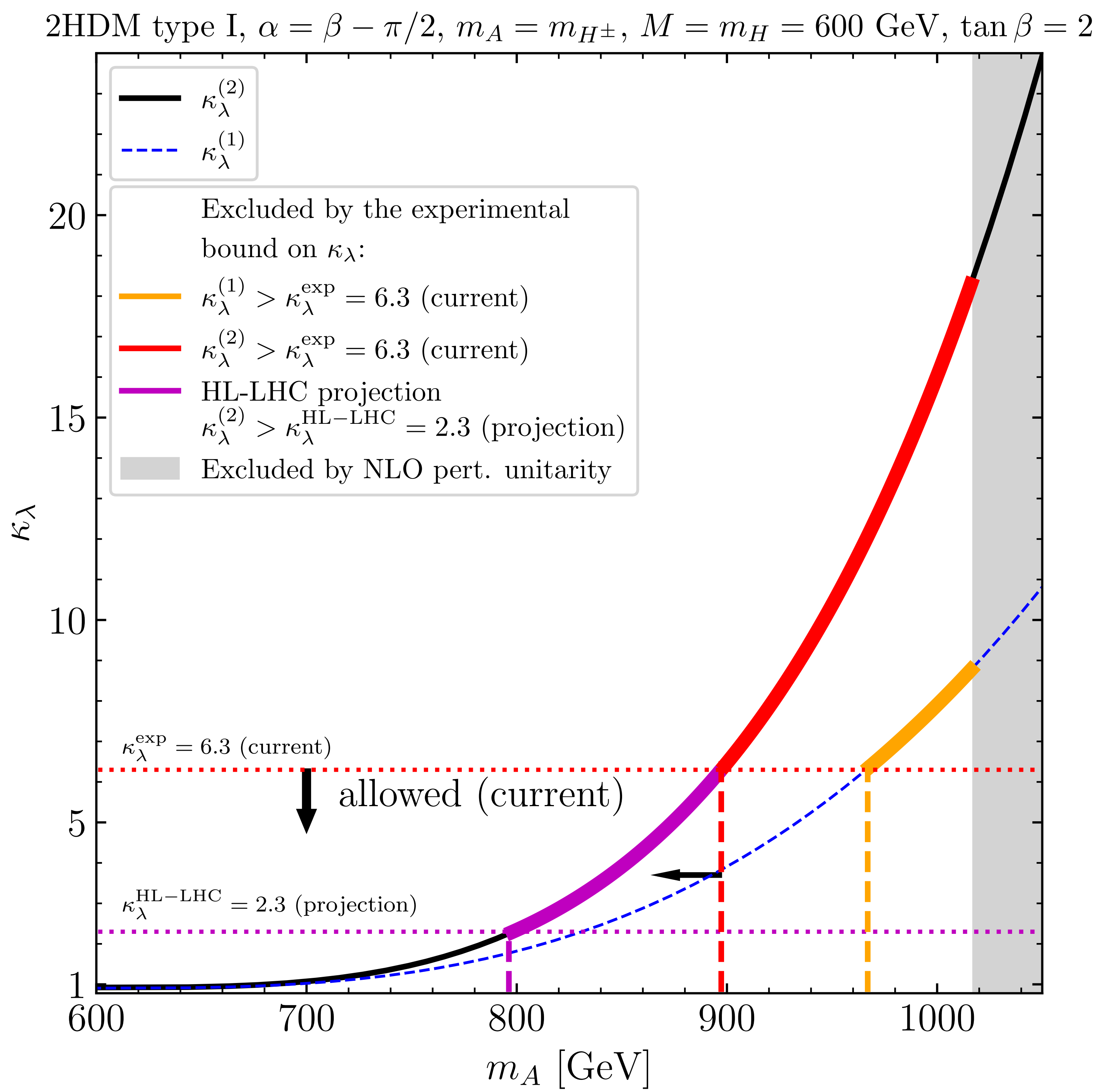
"Higgs self-coupling, … arguably the most important of them all!"

λ_{hhh}: very large deviations from the SM value possible!

[see J. Braathen's talk]

Prediction for κ_λ up to the two-loop level in the 2HDM:

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

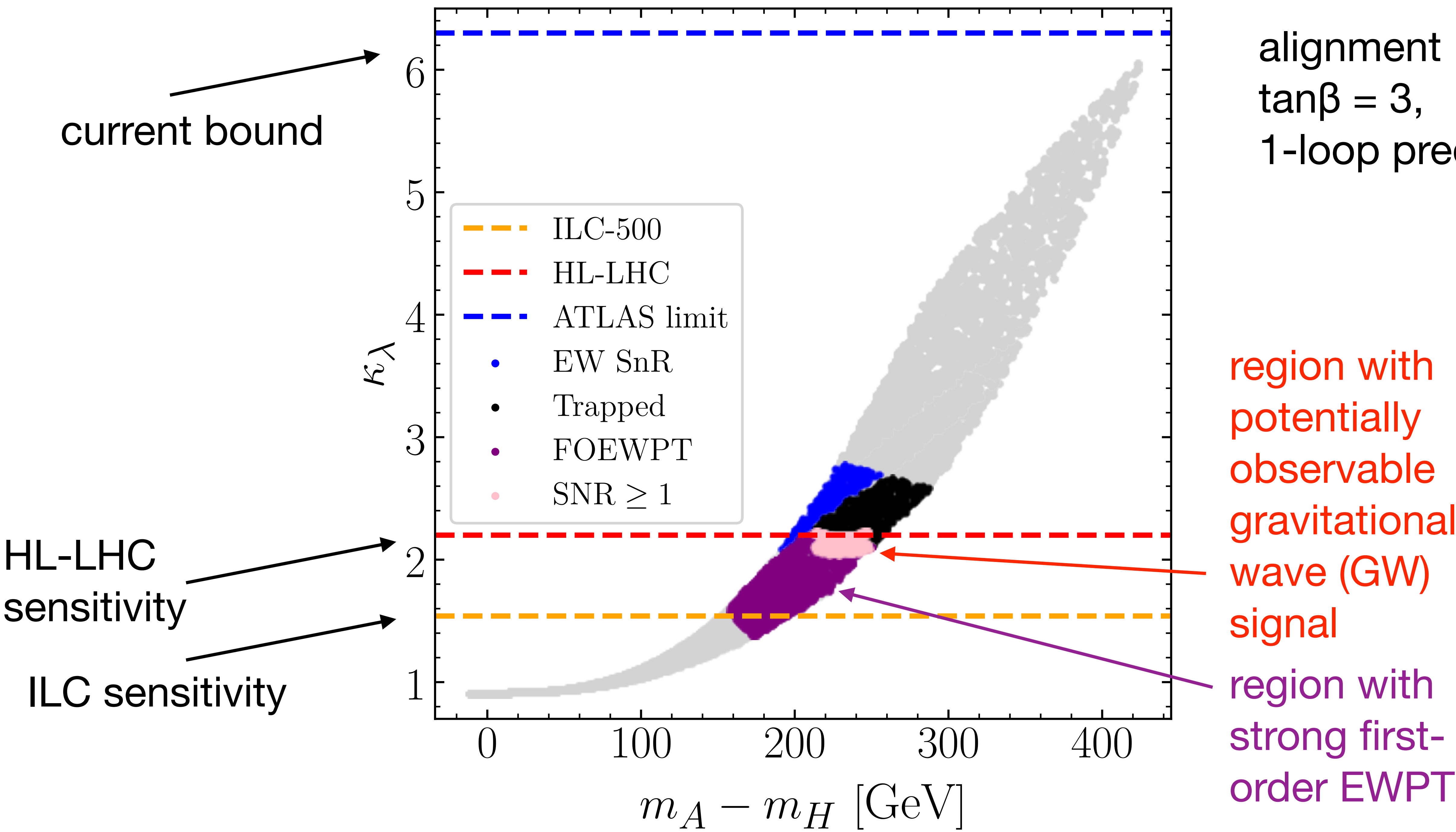


$\Rightarrow$ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

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

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]



alignment limit,
tanβ = 3,
1-loop prediction

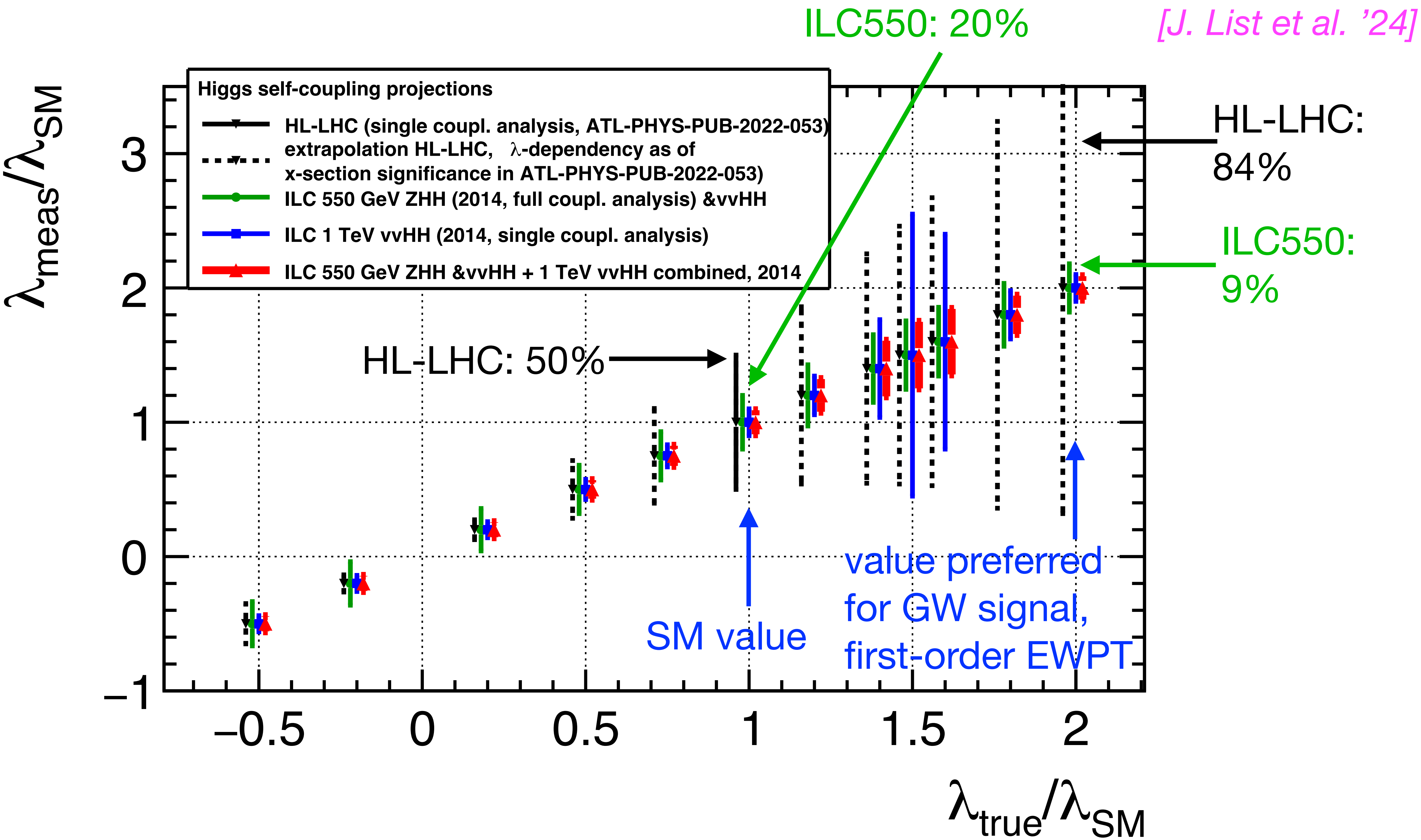
⇒ Region with strong first-order EWPT and potentially detectable GW signal is correlated with significant deviation of κ_λ from SM value

LC at 500 or 550 GeV: guaranteed measurements

- Higgs couplings to fermions and bosons: Zh + $\nu\nu$h
- tth (c.m. energy slightly above 500 GeV beneficial)
- Higgs pair production process: Zhh, trilinear Higgs self-coupling λ_{hhh}
- …

Main focus here:
Direct measurement of trilinear Higgs self-coupling is possible a at lepton collider with at least 500 GeV c.m. energy via Zhh production

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



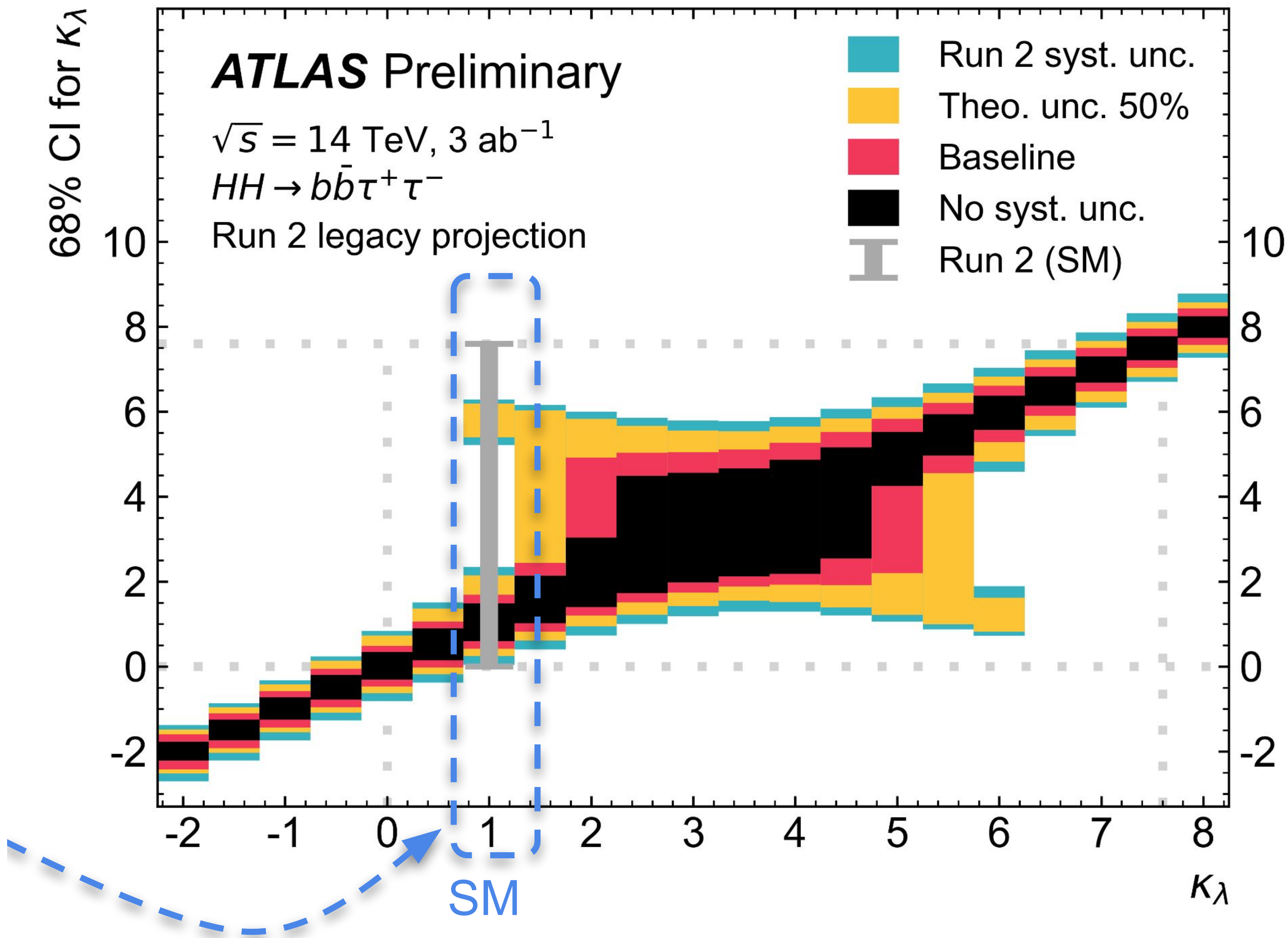
⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC550 than for HL-LHC

Reason: different interference contributions

Recent ATLAS projection going beyond the assumption of $\varkappa_\lambda = 1$

[ATLAS Collaboration '24]

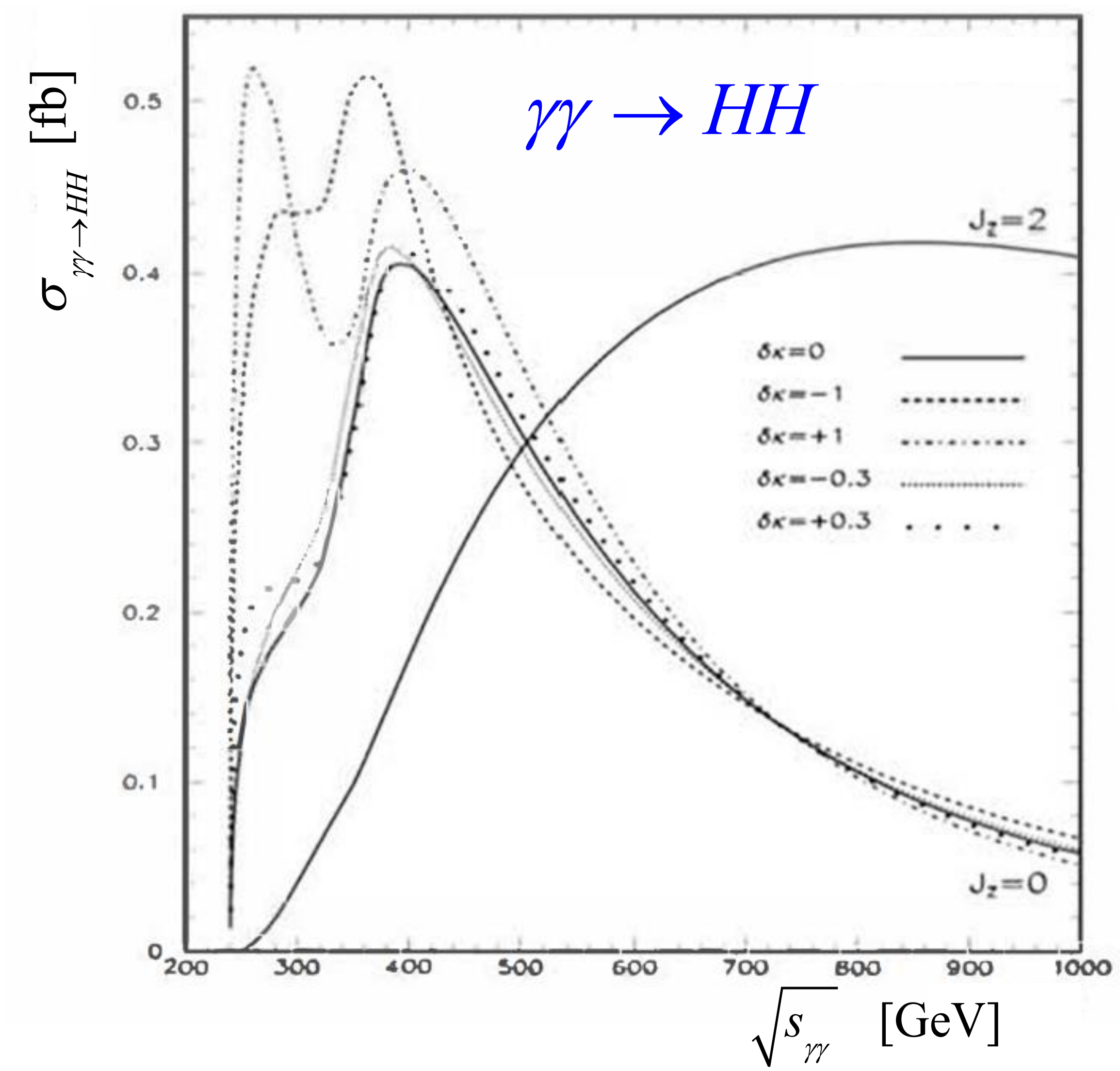
68% CI for κ_λ at **3000 fb^{-1}** varying κ_λ



⇒ Large dependence on actual value of $\varkappa_\lambda$

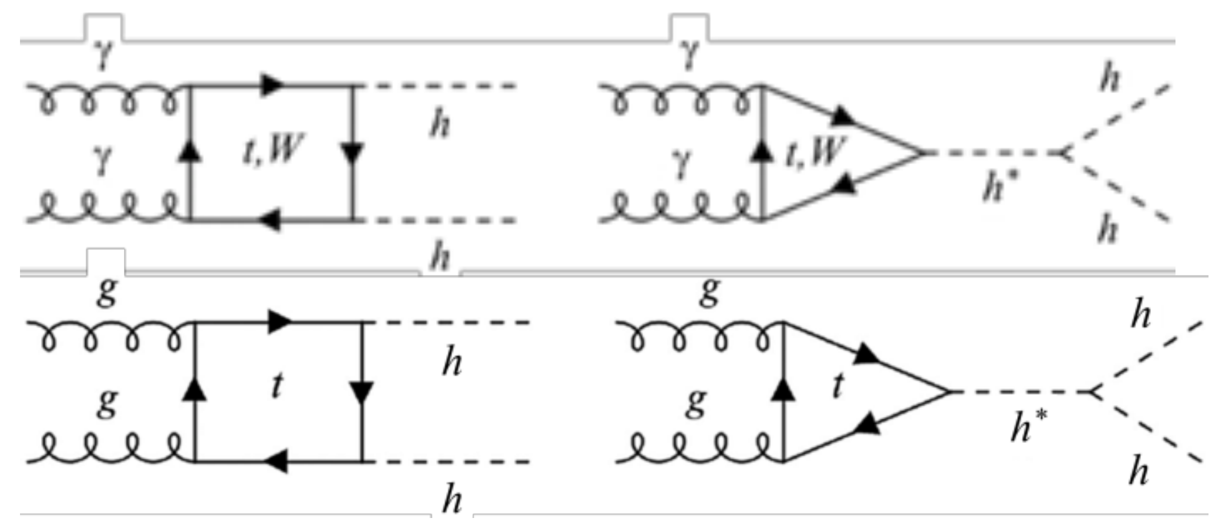
XFEL Compton Collider (XCC): $\gamma\gamma \to$ hh at 380 GeV

[T. Barklow '24]



XCC

LHC



	$\sqrt{s}$ (GeV)	polarization	σ (fb)
$\gamma\gamma \to HH$	380	$+100\%\ \gamma$ $+100\%\ \gamma$	0.40
$e^+e^- \to ZHH$	500 / 550	$-80\%\ e^-$ $+30\%\ e^+$	0.20 / 0.22

How about indirect constraints on λ_{hhh} from Higgs factories at lower c.m. energies (CEPC, FCC-ee, …)?

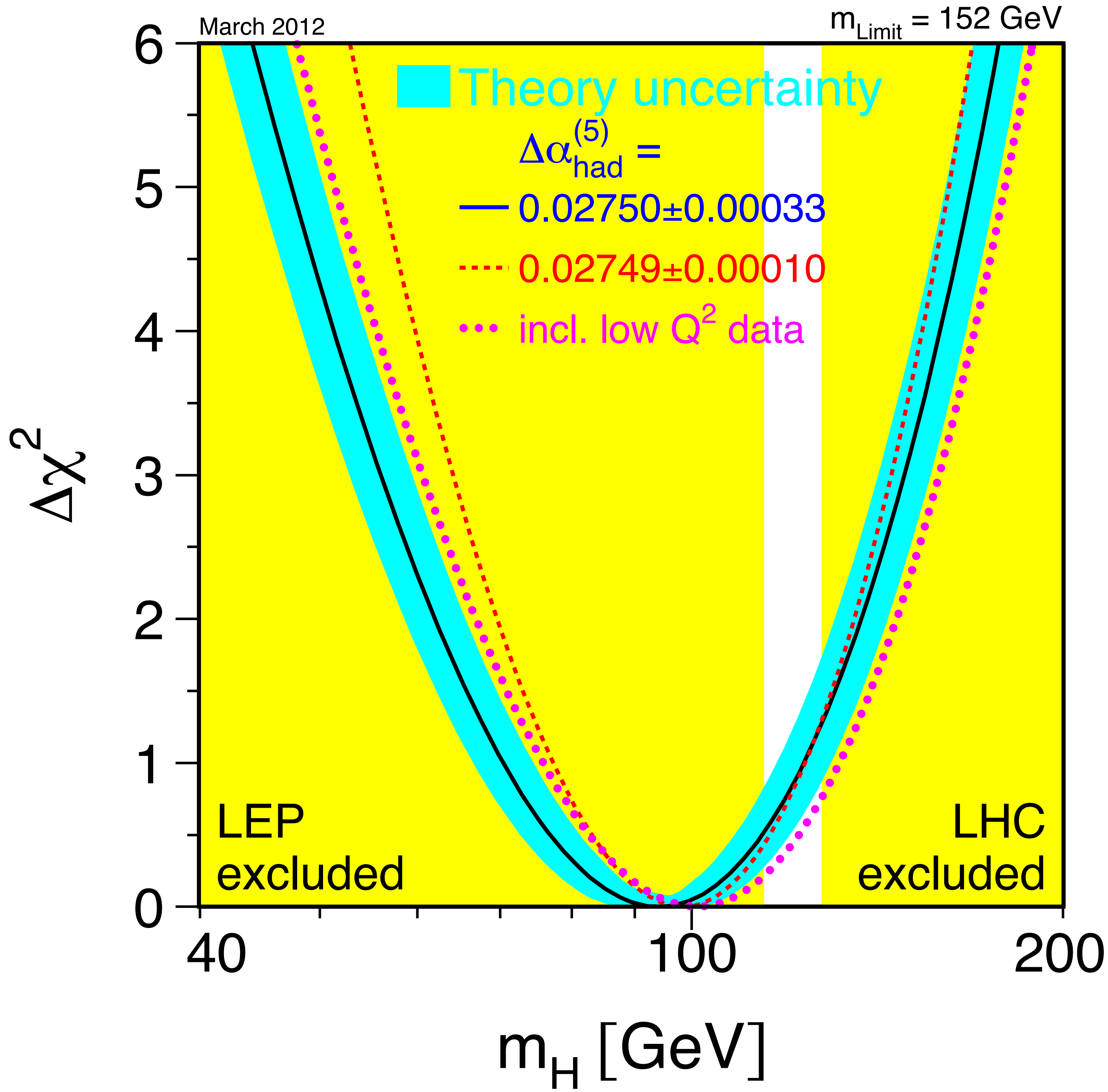
Indirect access to λ_{hhh} via

- single Higgs processes: λ_{hhh} enters at 1-loop order
- electroweak precision observables: λ_{hhh} enters at 2-loop order

Loop contribution of λ_{hhh} competes with much larger lowest-order contributions, other loop contributions (e.g. top loop) that are numerically dominant and potentially with BSM loop contributions

Indirect sensitivity via loop effects is limited by the experimental errors of the considered observables and by the theoretical uncertainties that are induced by unknown higher-order contributions and via the experimental errors of the input parameters (α_{em}, α_s, m_t, m_b, …)

A lesson from the past: the ``blue band plot”, global fit for the Higgs-boson mass in the SM



[LEPEWWG ’12]

We did not claim a measurement of the Higgs-boson mass at 95 GeV from this analysis!

⇒ This is not a ``measurement” of m_h, but an indirect constraint from loop contributions within a specific model (in this case the SM)

Indirect constraints on λ_{hhh} are much more difficult to obtain than the indirect constraints on M_h in the SM

- M_h is a free parameter of the SM, but λ_{hhh} is not!

⇒ Cannot vary λ_{hhh} ``within” the SM, need consistent theoretical framework for possible deviations in λ_{hhh} from SM value, e.g. EFT

- EFT: need complete basis of operators, involves model-dependence: consistent sub-set of operators? dim-6 vs. dim-8 operators? possible effects of light new particles? range of validity of the EFT description? …

⇒ Need much more than avoiding just some ``blind directions” among certain operators
Recent SMEFT analysis emphasising importance of complete operator basis and EW SMEFT corrections
[K. Asteriadis, S. Dawson, P. P. Giardino, R. Szafron ’24 — see Pier Paolo’s talk]

Example of EW precision observables: possible deviations of M_W, g_μ–2, $\sin^2\theta_{eff}$, … have given rise to many possible model interpretations

How much can we learn about λ_{hhh} from its impact on loop corrections?

We want to determine λ_{hhh}, accounting for the fact that it may differ substantially from the SM value

If the observables used for a global fit based on data from the LHC and CEPC or FCC-ee, i.e. no input from the e^+e^- machines on the Higgs pair production process, show a deviation from the SM prediction that is compatible with a non-SM value for λ_{hhh} (within the LHC uncertainties) it will be very difficult to show that this deviation is indeed associated with λ_{hhh} rather than with other higher-order contributions

This issue has not at all been demonstrated for the FCC-ee fits so far; the future experimental results have always been assumed to perfectly agree with the SM; up to now not even statistical fluctuations of the assumed central values around the SM predictions have been taken into account

λ_{hhh} and the Higgs pair production process

As a fact of life, λ_{hhh} (as well as all other Higgs couplings) as such is not a physical observable

The actual physical observable in this context is the cross section for the Higgs pair production process, i.e. $gg \to hh$ at the LHC and $e^+e^- \to Zhh$, $e^+e^- \to \nu\nu hh$ at an e^+e^- collider with a c.m. energy of at least 500 GeV (or $\gamma\gamma \to hh$ at a 380 GeV $\gamma\gamma$ collider)

We want to make a precise and model-independent measurement of this crucial observable at an e^+e^- collider rather than just making an indirect and necessarily model-dependent prediction!

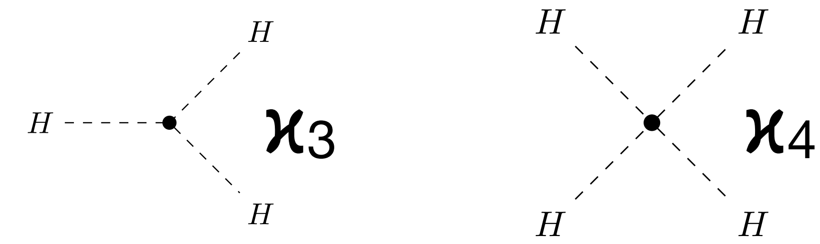
Beyond 500 GeV: guaranteed ``measurements”

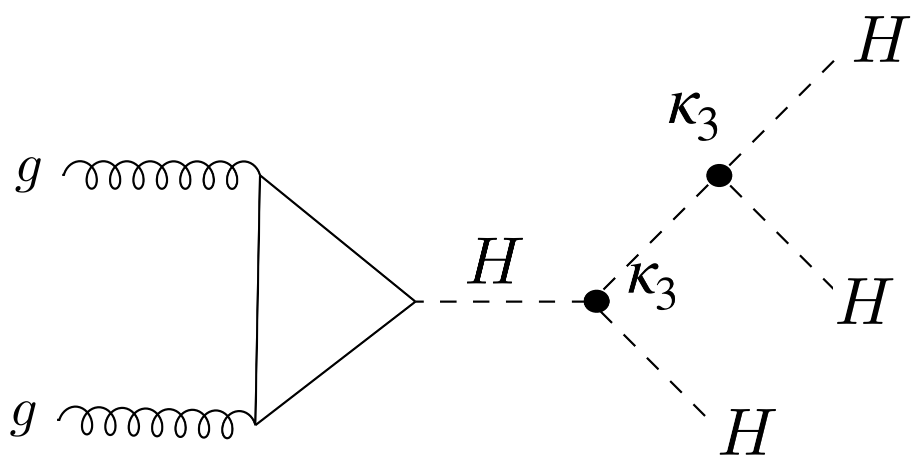
- Higgs couplings to fermions and bosons, $\nu\nu$h: high statistics
- Zhh, $\nu\nu$hh
- Zhhh, $\nu\nu$hhh, quartic Higgs self-coupling
- …

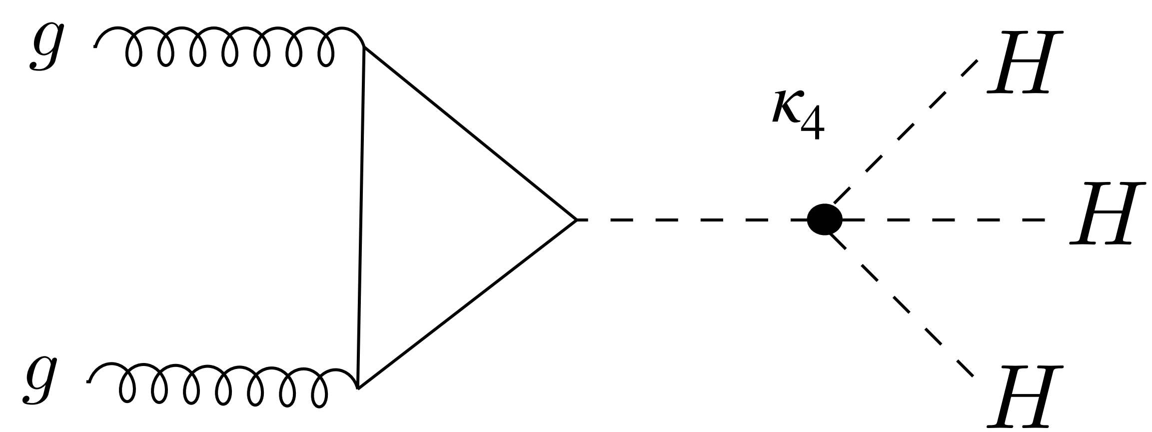
Main focus here:
access to the quartic Higgs self-coupling via triple Higgs-boson production: Zhhh, $\nu\nu$hhh

LHC: HHH production and Higgs self-couplings

Triple Higgs production depends on $\varkappa_3$ and $\varkappa_4$!







Is it possible to obtain bounds from triple Higgs production on $\varkappa_3$ and $\varkappa_4$ that go beyond the existing theoretical bounds from perturbative unitarity? Potential for $\varkappa_3$ constraints beyond the ones from di-Higgs production?

How big could the deviations in $\varkappa_4$ from the SM value (= 1) be in BSM scenarios?

Bounds from perturbative unitarity

- Process relevant for κ_3, κ_4 is $HH \to HH$ scattering (see also [Liu et al ` 18])

- Jacob-Wick expansion allows to extract partial waves

$$\beta(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$$

Wigner functions

$$a^J_{fi} = \frac{\beta^{1/4}(s, m^2_{f_1}, m^2_{f_1})\beta^{1/4}(s, m^2_{i_1}, m^2_{i_1})}{32\pi s} \int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{D}^J_{\mu_i \mu_f}\, \mathcal{M}(s, \cos\theta)$$

- Tree level unitarity:

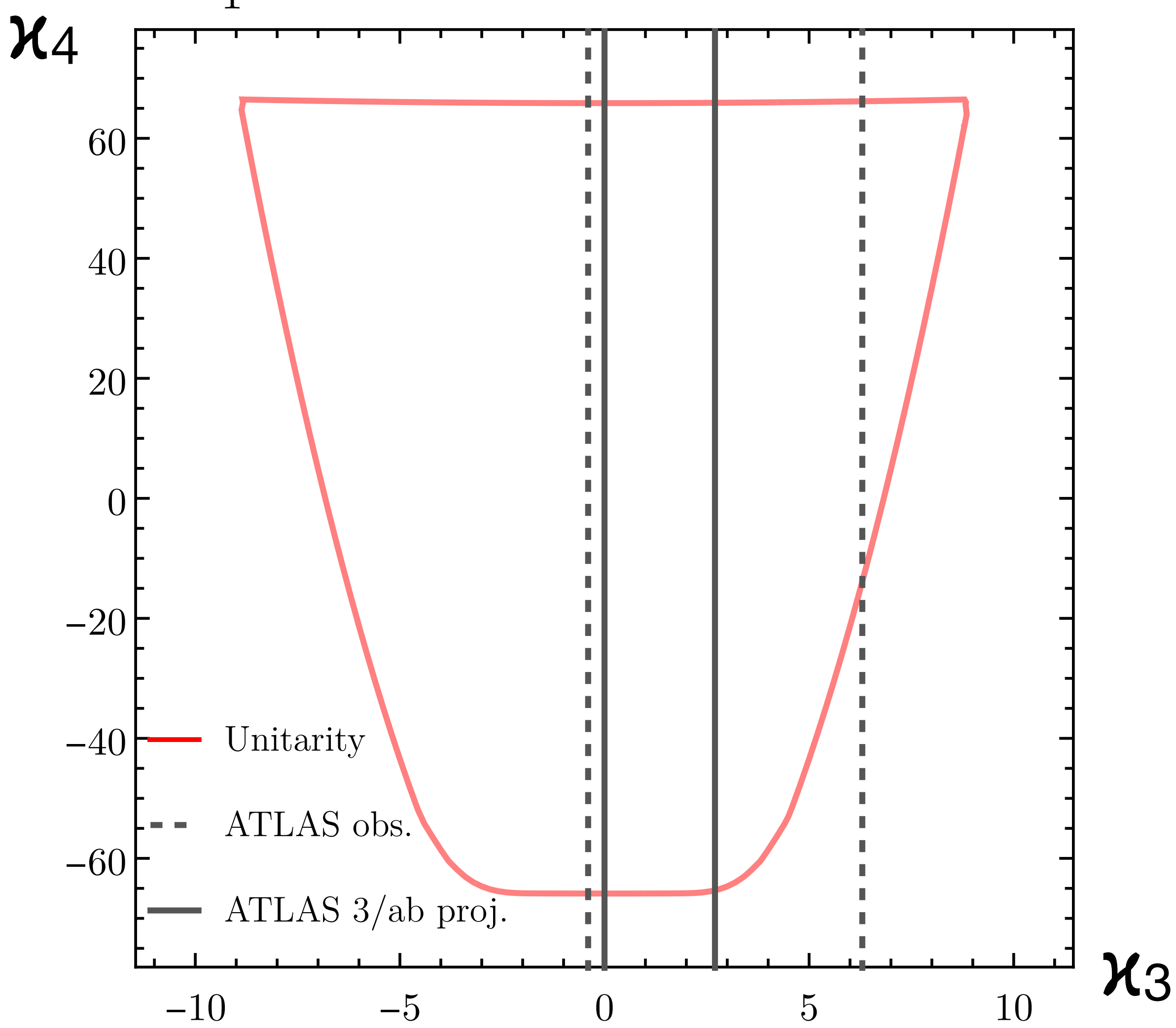
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

95 % CL

ATLAS current bounds: $[-0.4, 6.3]$

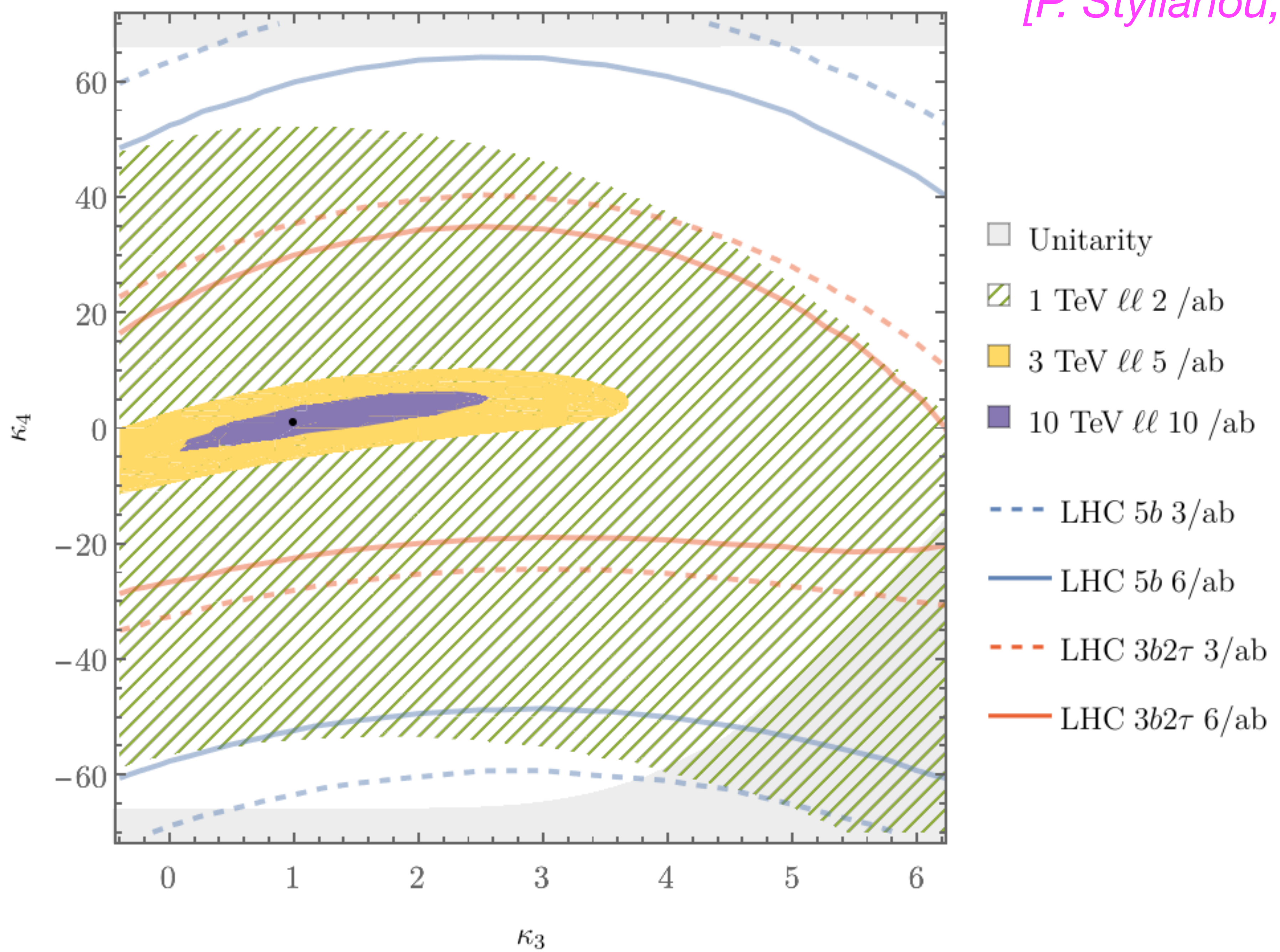
CMS & ATLAS HH projections: $[0.1, 2.3]$

[ATLAS 2211.01216]
[CERN Yellow Rep. 1902.00134]



Triple Higgs production: HL-LHC vs. lepton colliders

[P. Stylianou, G. W. '24]



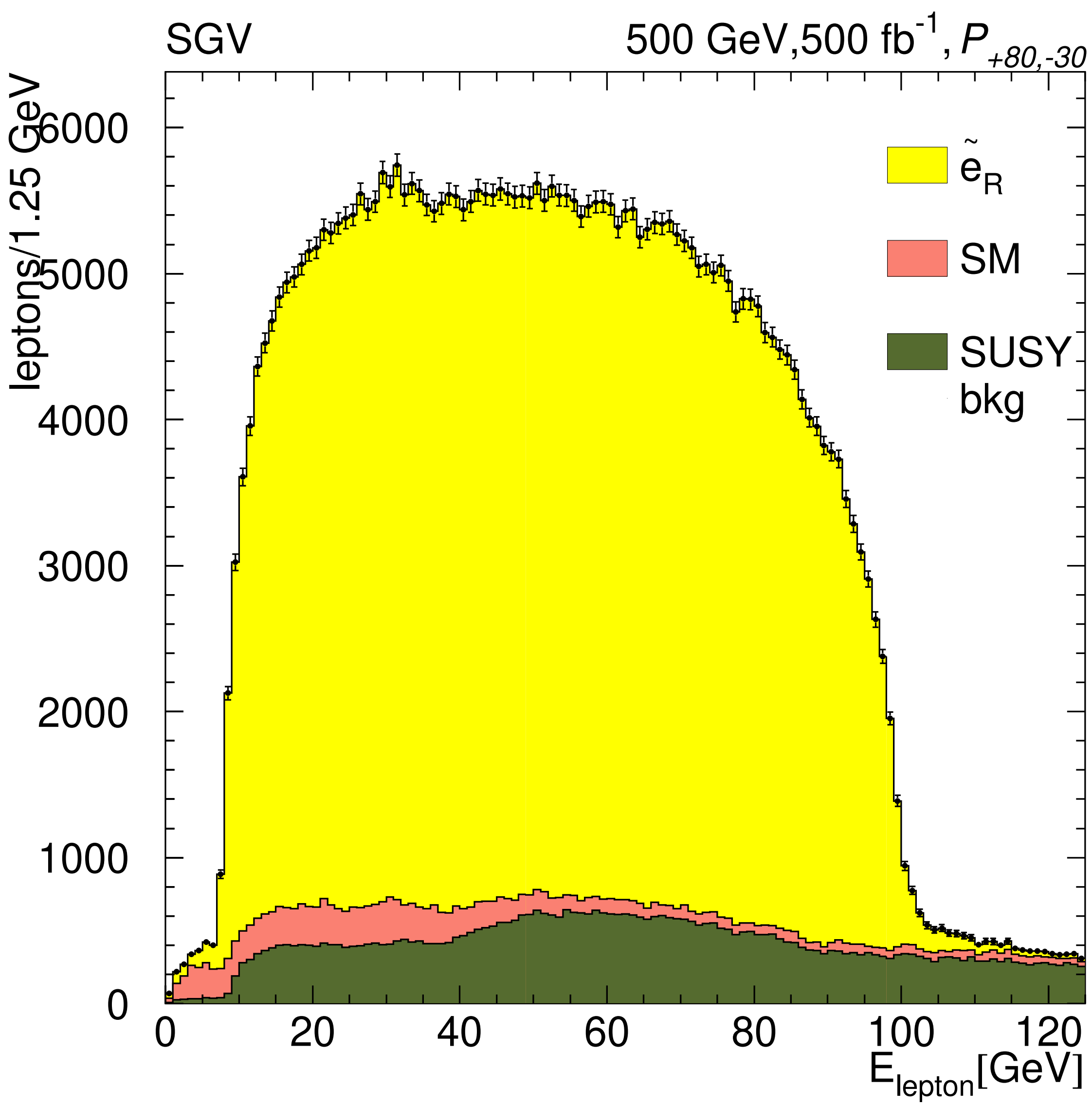
HL-LHC is competitive to 1 TeV lepton collider; higher-energetic lepton colliders have better sensitivity

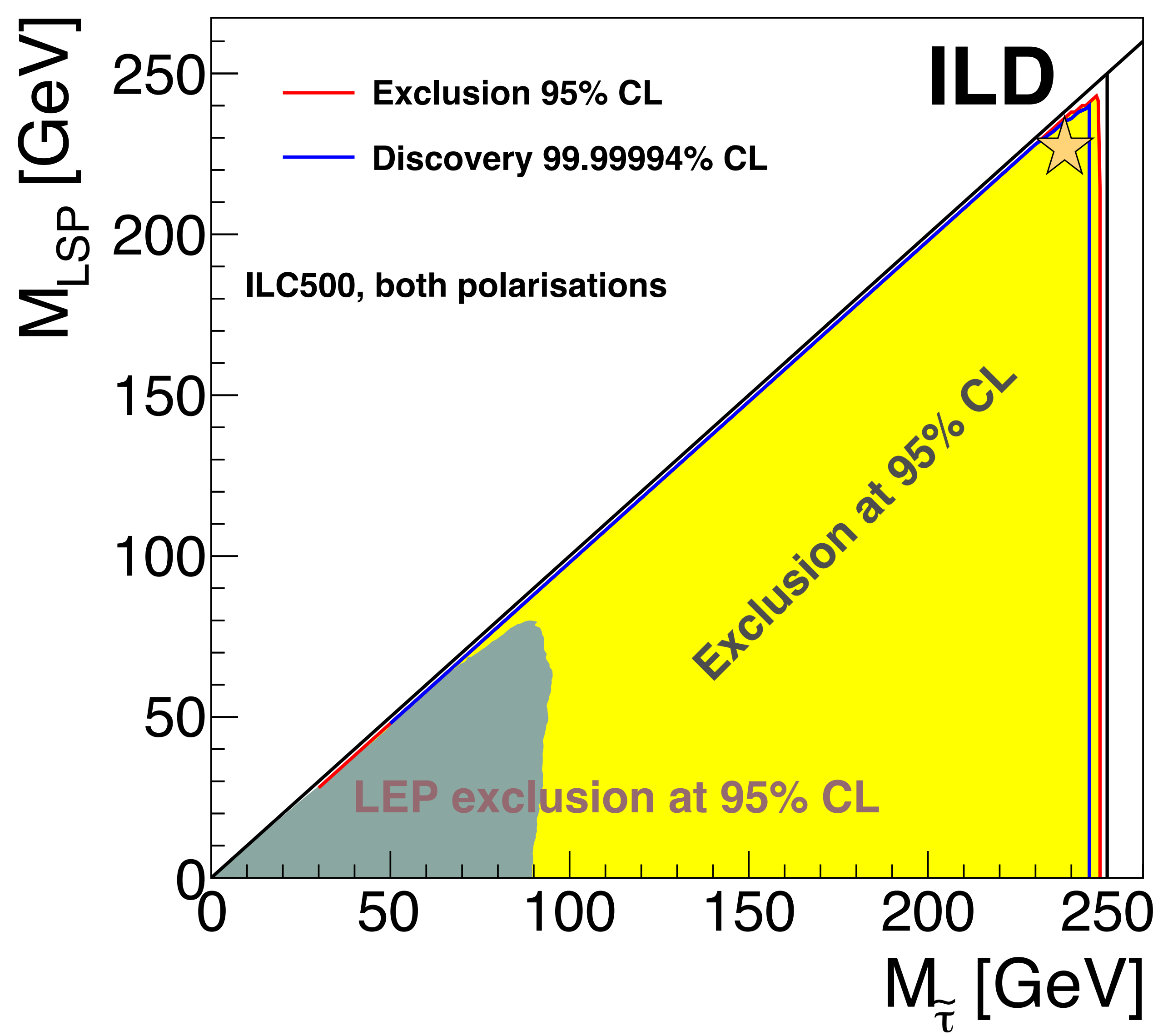
Sensitivity to new particles at 500 GeV and beyond

Pair production of BSM particles

⇒ best prospects at highest c.m. energy!

In particular: very robust exclusion and discovery reach for charged particles (charged Higgs bosons, charginos, …) via photon exchange (remember the LEP limits!) *[M. Berggren et al. '16]*





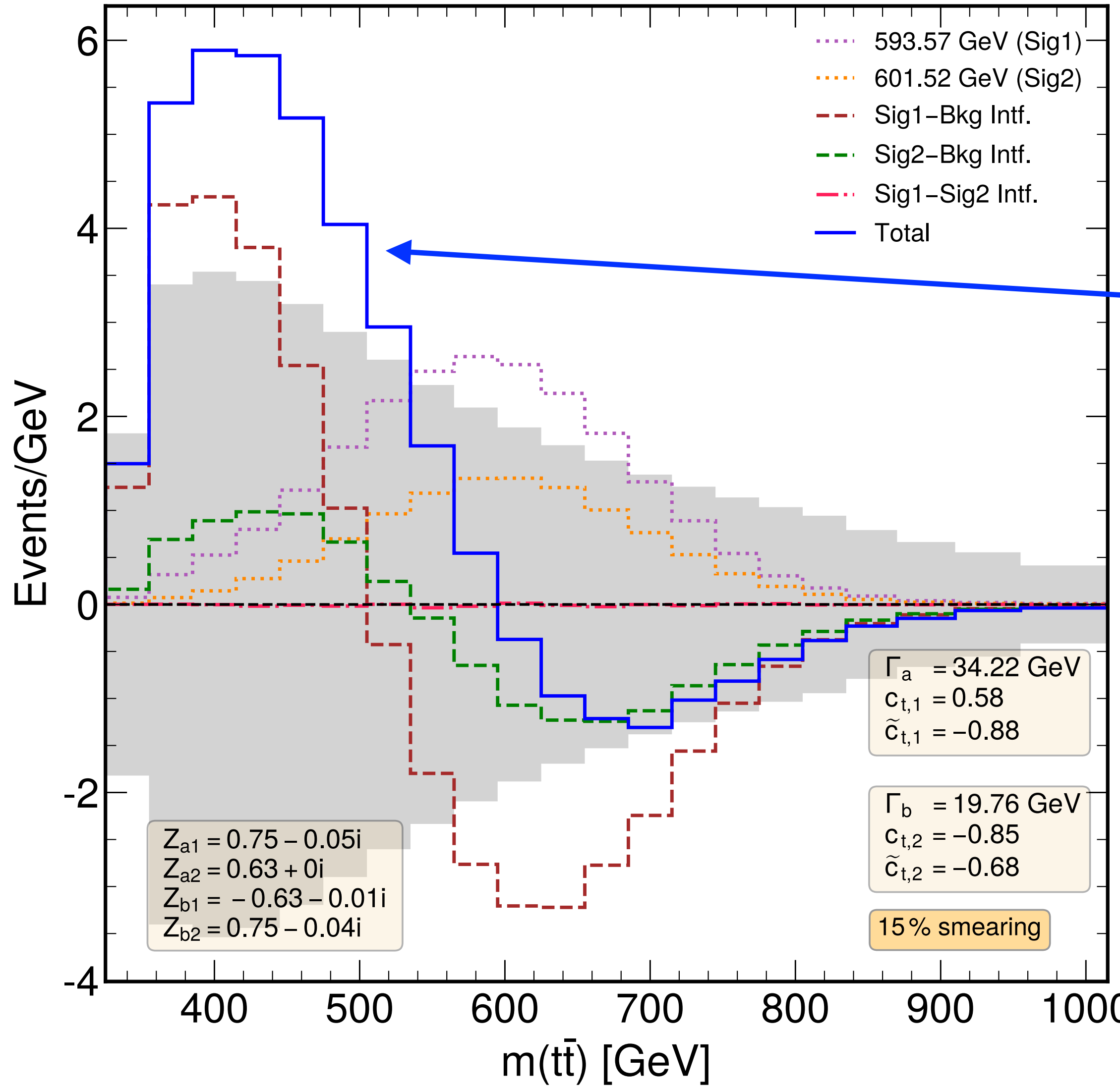
Recent CMS result: 9 σ excess near tt threshold

[CMS Collaboration '24]

tt bound state? Which rate? tt + …? CP-odd Higgs? ALP?
Overlap of two heavier CP-mixed states (here: ≈600 GeV)? …

C2HDM, result for BP 3 of [P. Basler, S. Dawson, C. Englert, M. Mühlleitner '20]

[H. Bahl, R. Kumar, G. W. '24]



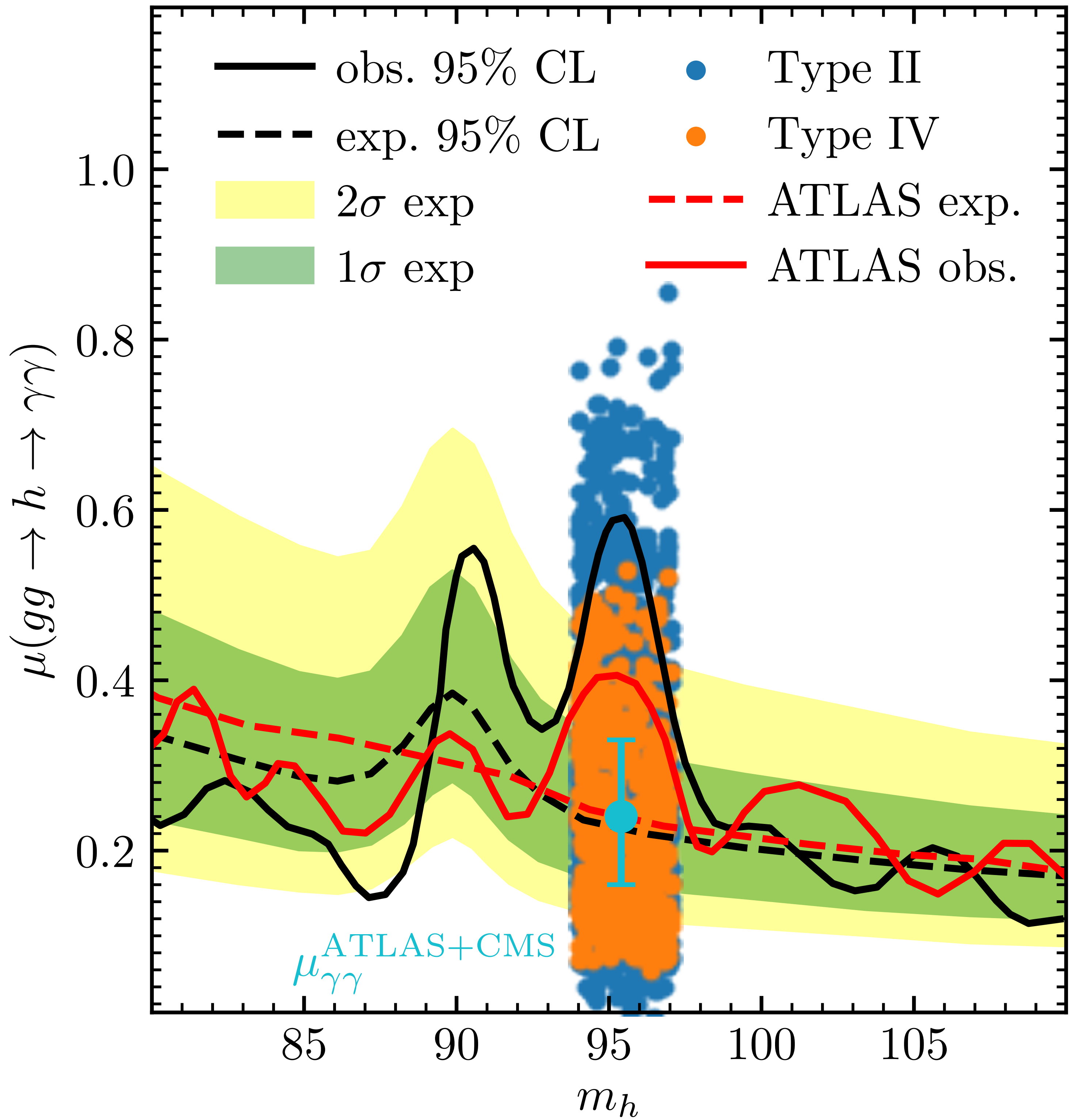
Total result

Resembles shape for a single particle at lower mass; highest sensitivity in the region just above the tt threshold!

⇒ Strong motivation for BSM Higgs searches at TeV scale e^+e^- collider!

Different case: how about a light BSM Higgs boson?

CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV:



[T. Biekötter, S. Heinemeyer, G. W. '23]

Example interpretation: S2HDM, type II and IV

⇒Good description in extended Higgs sectors with an additional doublet and a singlet

Different case: how about a light BSM Higgs boson?

- Possible signal (h95) with significant ZZ h95 coupling (possibly explaining also the ``LEP excess” near 95 GeV)

⇒ h95 can be studied in detail at 250 GeV e^+e^- Higgs factory

- Possible signal (h95) explaining only the LHC excess in the $\gamma\gamma$ channel

  E.g.: CP-odd Higgs boson at 95 GeV

⇒ Expect sizeable coupling of h95 to top quarks

  Prospects at e^+e^- colliders?

  $e^+e^- \to t\, t$ h95, $e^+e^- \to$ Z h95 h95 (via intermediate h125), …

⇒ Need higher c.m. energy (about 500 GeV for t t h95 final state) and high luminosity

Conclusions

The Higgs self-couplings are crucial for gaining experimental access to the Higgs potential!

Direct measurements with the best possible precision are needed!
CEPC and FCC-ee will not be able to tell us much about the Higgs potential beyond what we will know from the LHC

An e^+e^- Linear Collider with c.m. energy of at least 500 GeV can directly measure λ_{hhh} in the Zhh production processs: qualitative game-changer compared to capabilities of lower-energy Higgs factories

This, in combination with the significantly extended reach for BSM searches, is a strong motivation for designing a future e^+e^- Higgs factory such that an upgrade to at least 500 GeV is possible

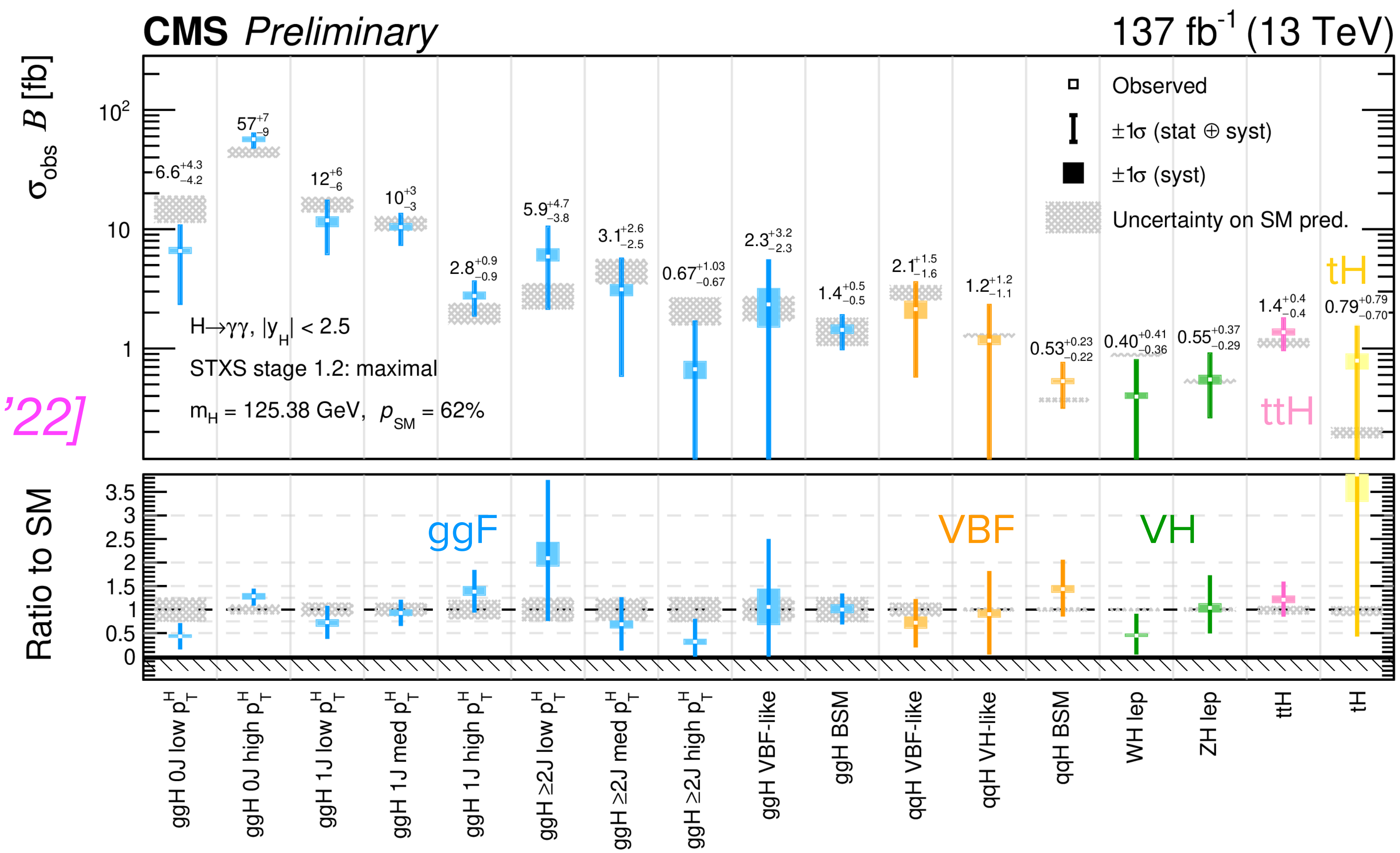
The highest-energetic lepton colliders provide sensitivity for constraining the quartic Higgs self-coupling

Backup

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]

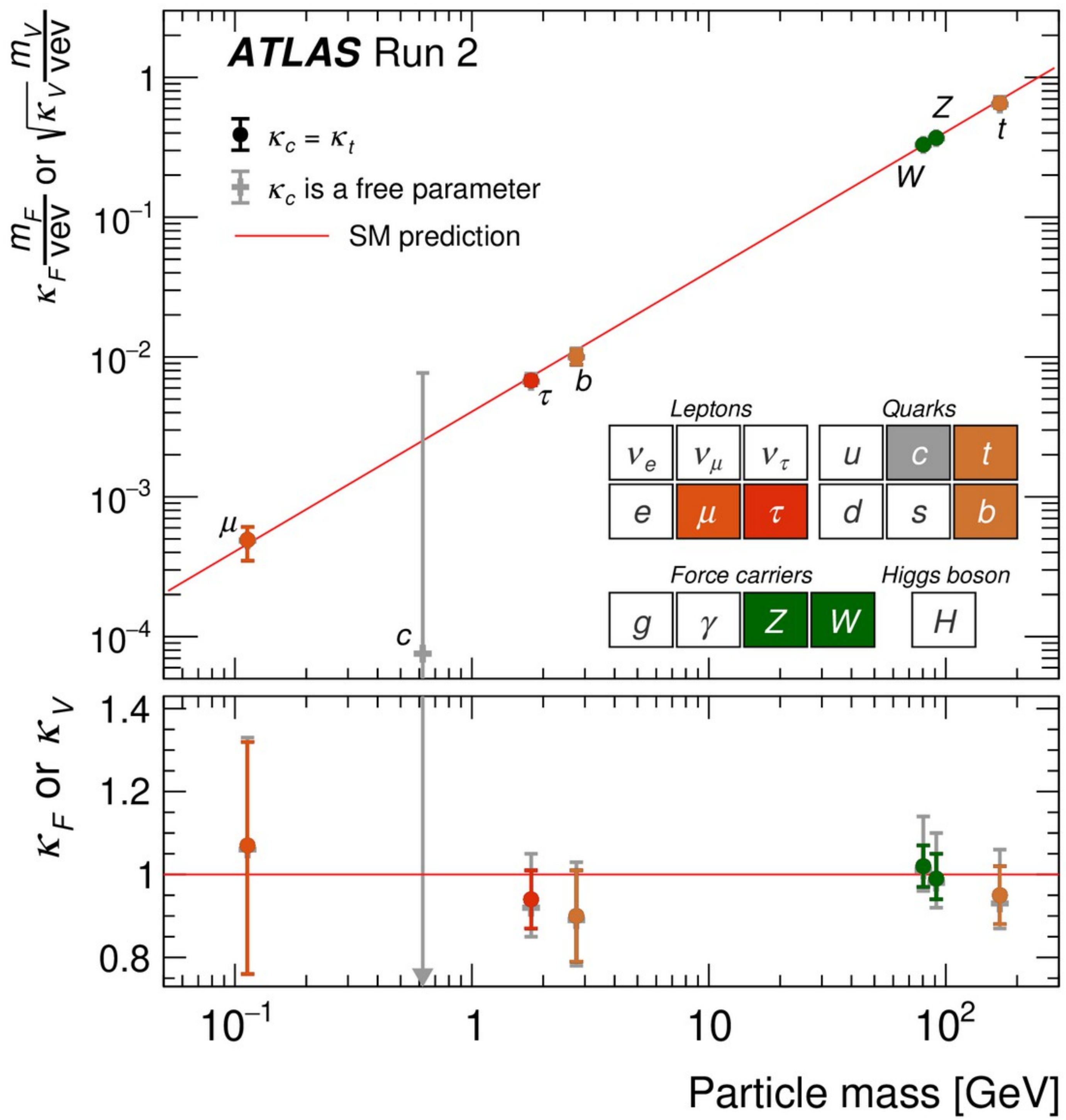
⇒SM-like properties

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

Properties of the detected Higgs boson (h125)

Couplings of the detected Higgs boson to other particles:

[ATLAS Collaboration '22]



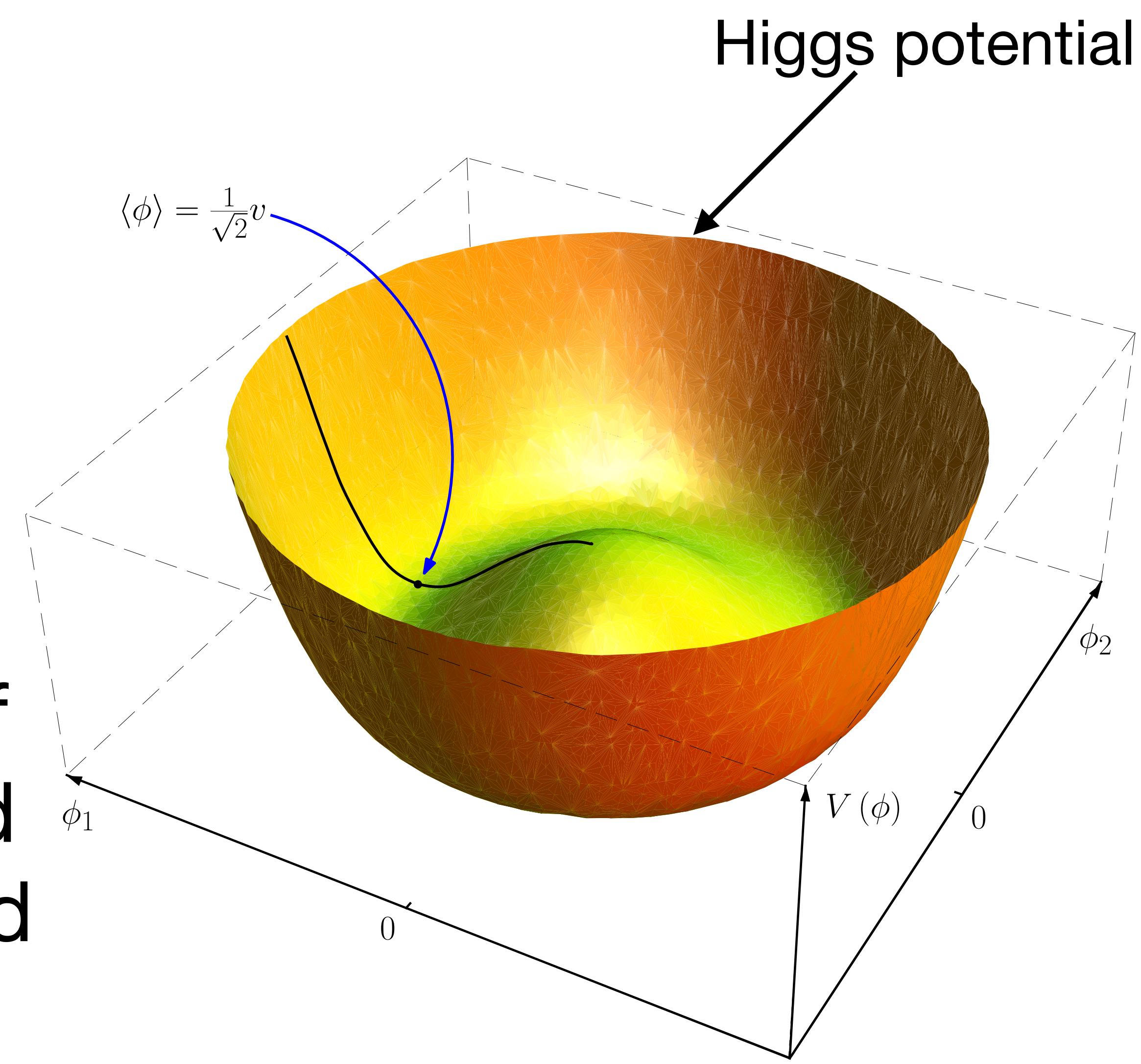
Nobel Prize 2013

⇒ Agrees with predictions of the Brout-Englert-Higgs (BEH) mechanism

What is the underlying dynamics of electroweak symmetry breaking?

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!

We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!



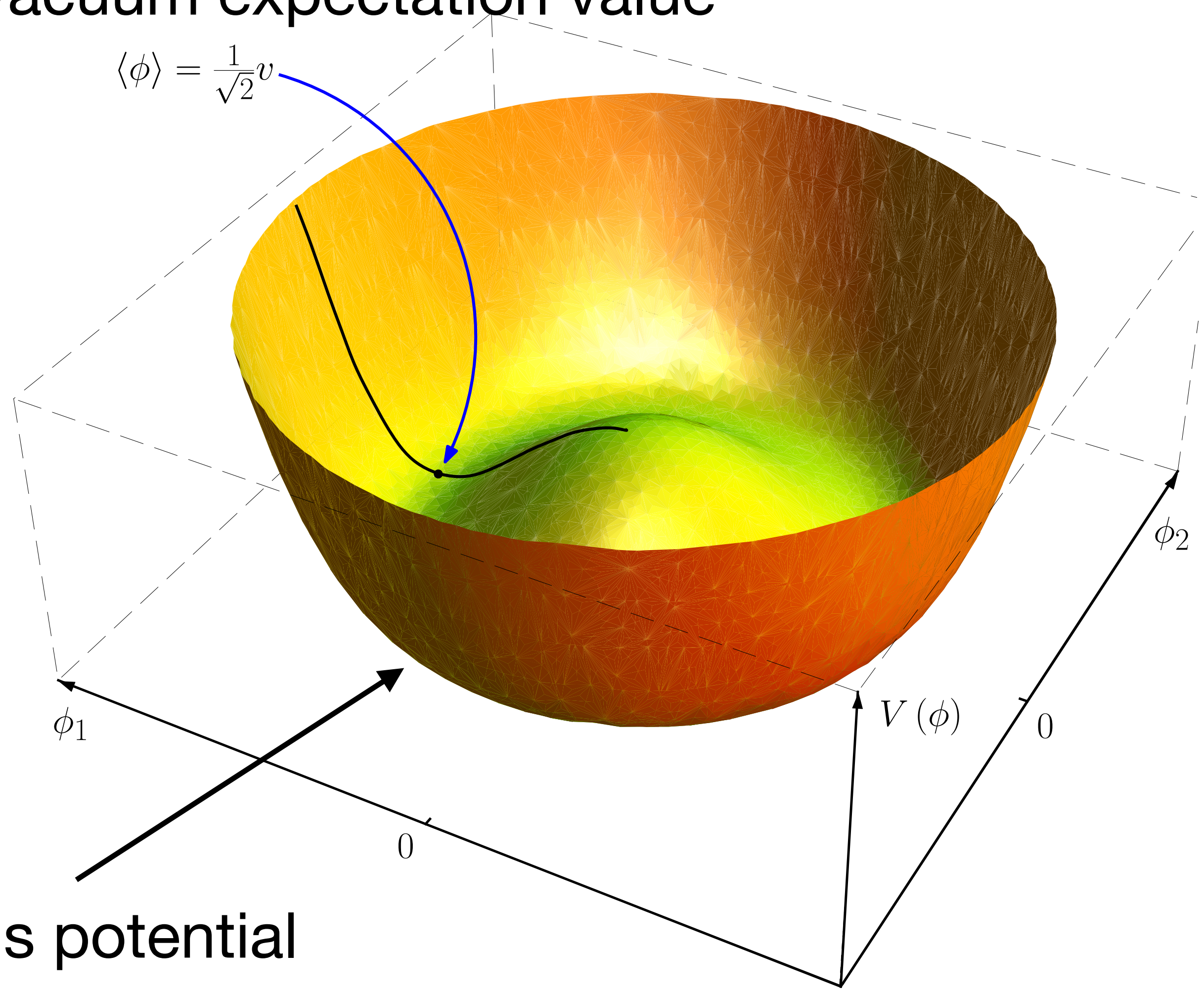
Single doublet or extended Higgs sector? (new symmetry?)

Fundamental scalar or compositeness? (new interaction?)

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:

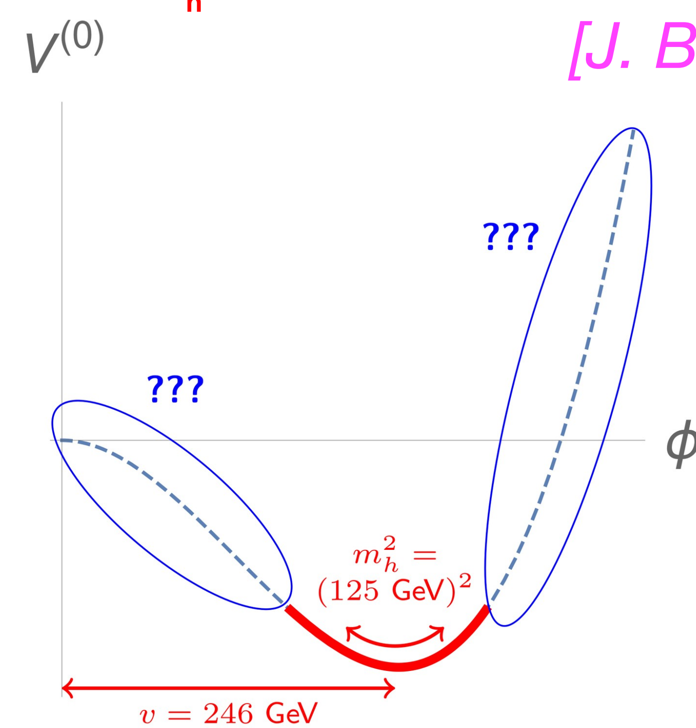
→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV

[J. Braathen '24]



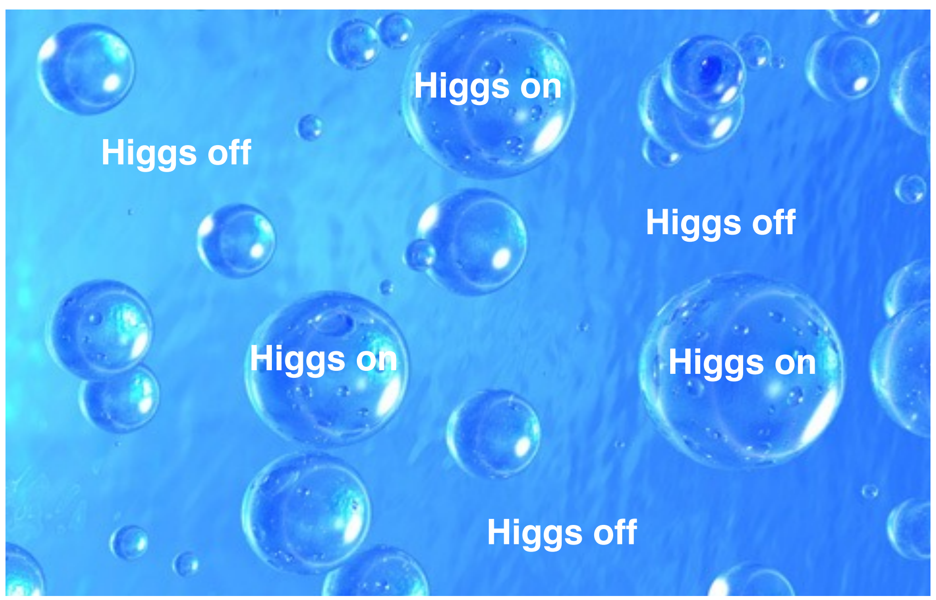
Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

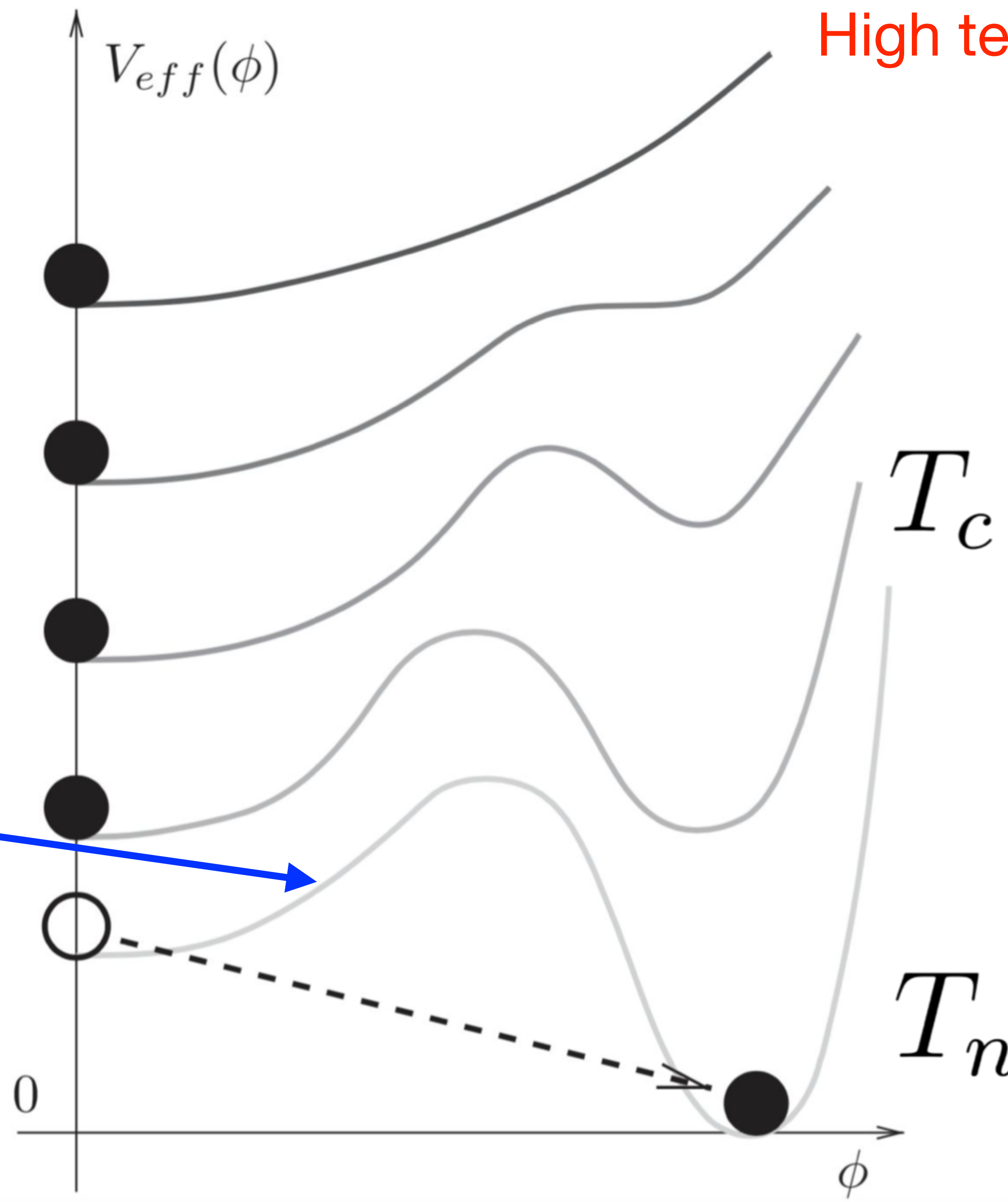
The Higgs potential and the electroweak phase transition (EWPT)

[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

Strongly first-order EWPT in the 2HDM

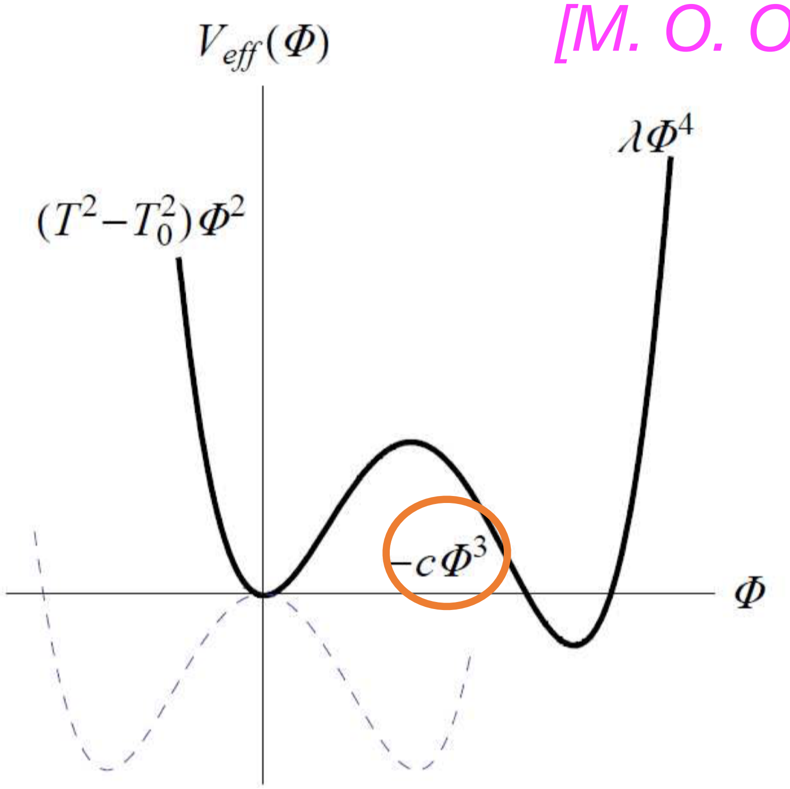
Barrier is related to a cubic term in the effective potential

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

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

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

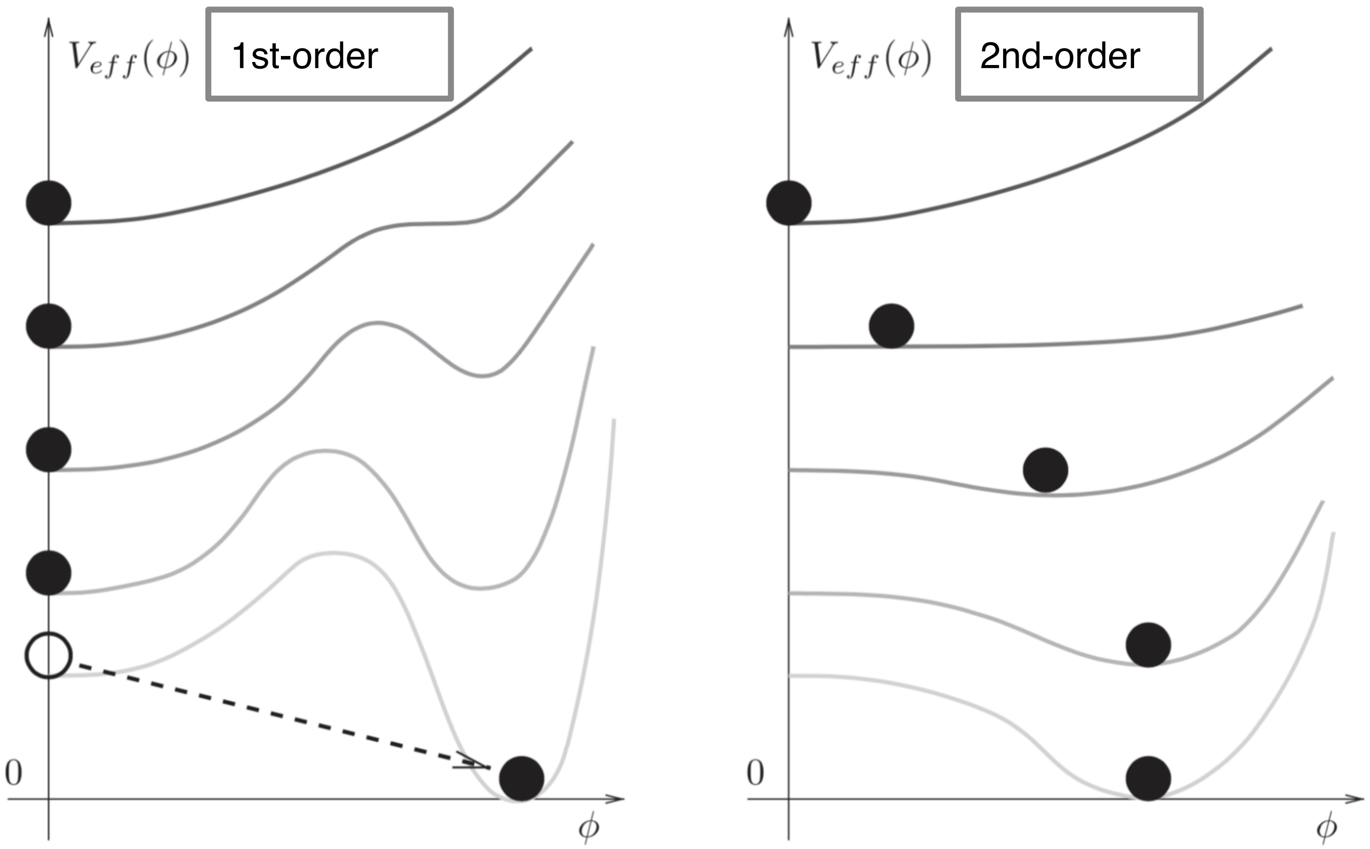
[M. O. Olea '23]

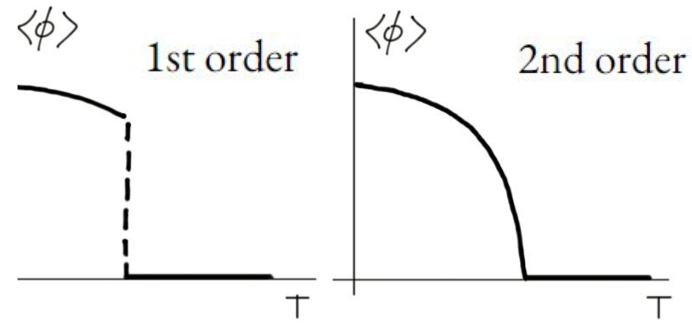


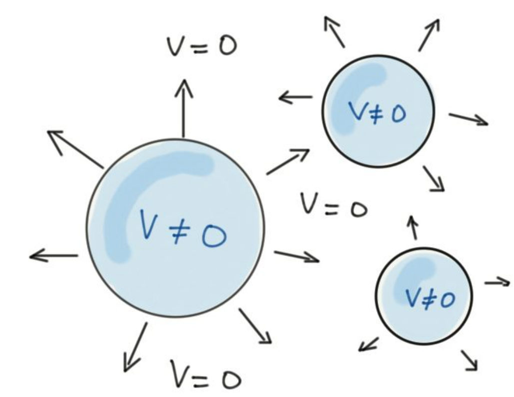
⇒ Yields mass splitting between the BSM Higgs bosons and sizeable corrections to the trilinear Higgs coupling

First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]







[K. Radchenko '23]

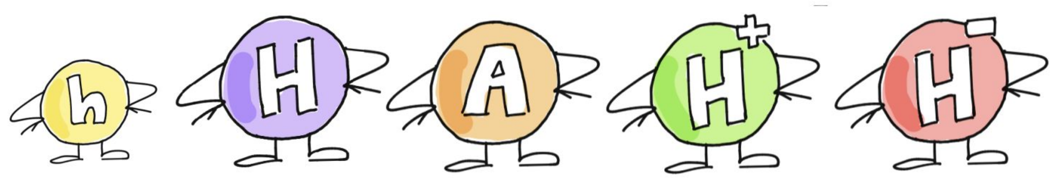
Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

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

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:

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

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

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

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

Masses of the BSM Higgs fields

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

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

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

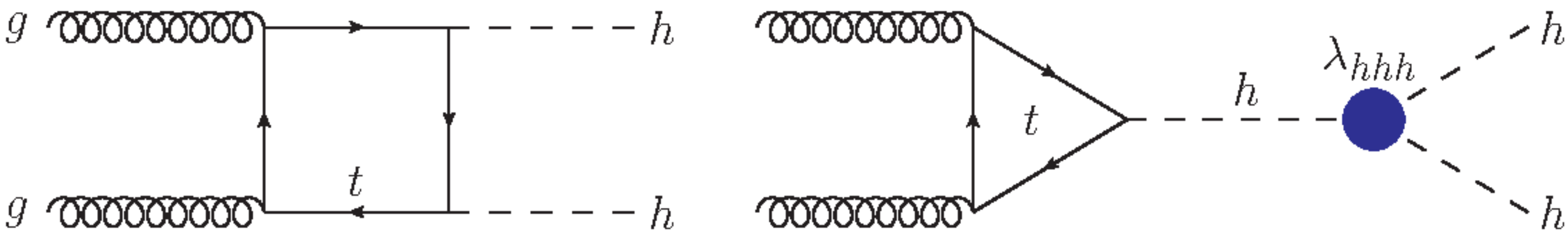
where $M^2 = 2\, m_{12}^2 / \sin(2\beta)$

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

Trilinear Higgs self-coupling and the Higgs pair production process: LHC and e^+e^- collider

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 a at lepton collider with at least 500 GeV c.m. energy

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

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

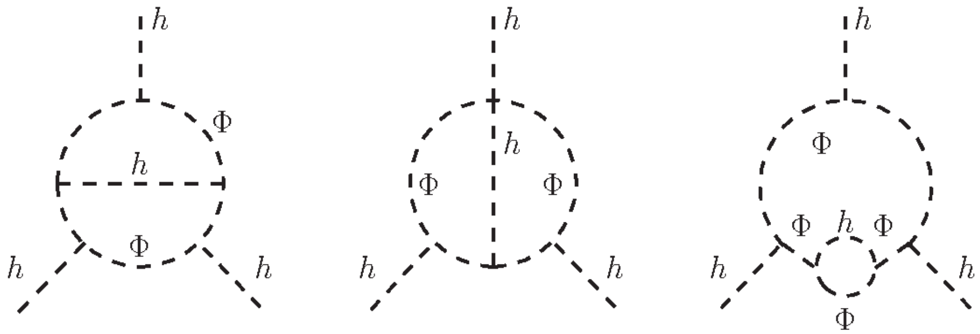
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

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

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 $g_{hh\phi\phi}$

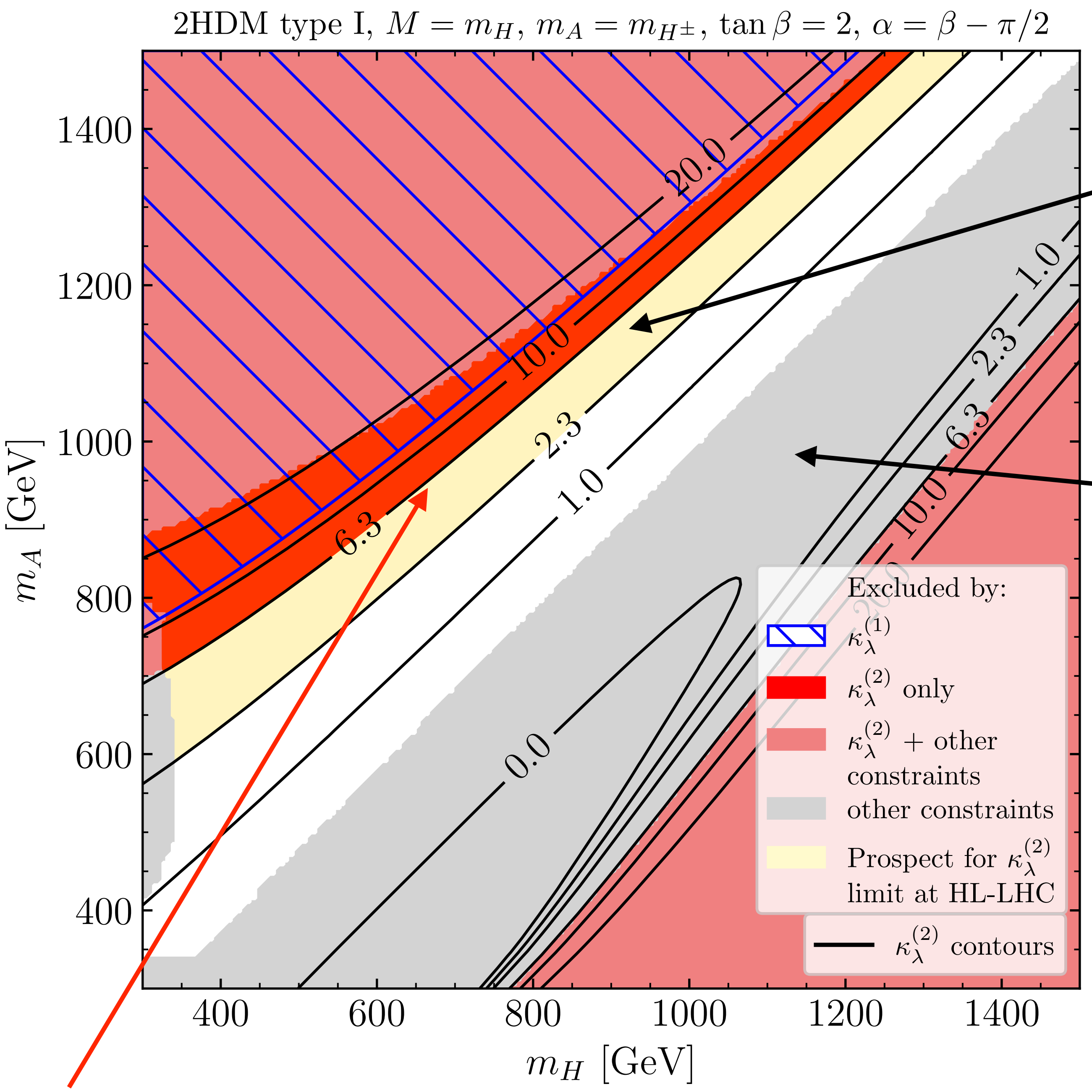


Analysis is carried out in the alignment limit of the 2HDM (α = β - π/2)

⇒h has SM-like tree-level couplings

Constraints in the mass plane of H and A

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



Sensitivity to $\varkappa_\lambda$ 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!

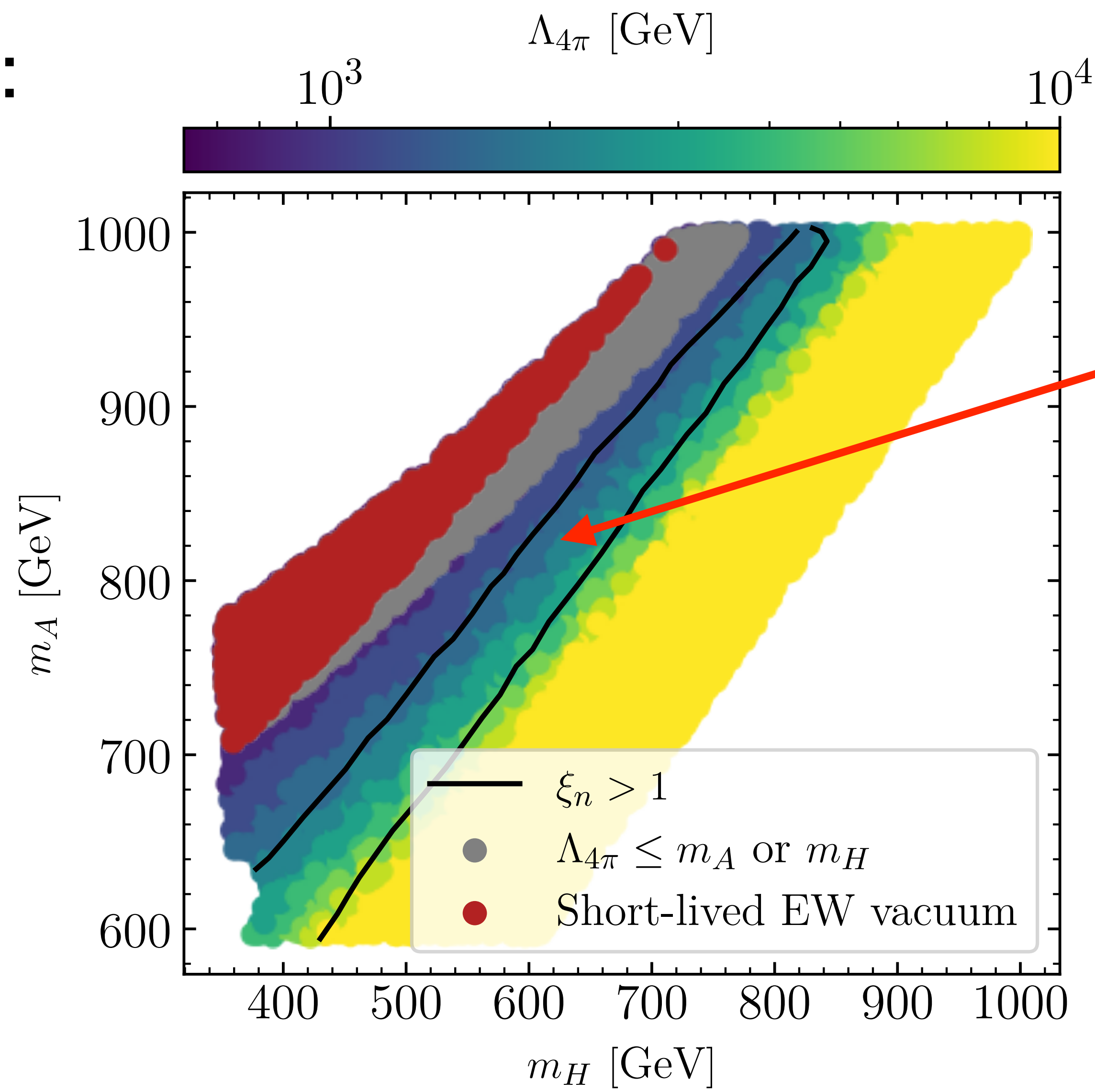
Connection between the trilinear Higgs coupling and the evolution of the early Universe

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

Higgs couplings to fermions and gauge bosons: the quest for identifying the underlying physics

- Future Higgs factories: what can we learn from the enhanced precision (~factor 10 better than HL-LHC) in comparison to the direct searches at the HL-LHC (existing limits and future prospects)?

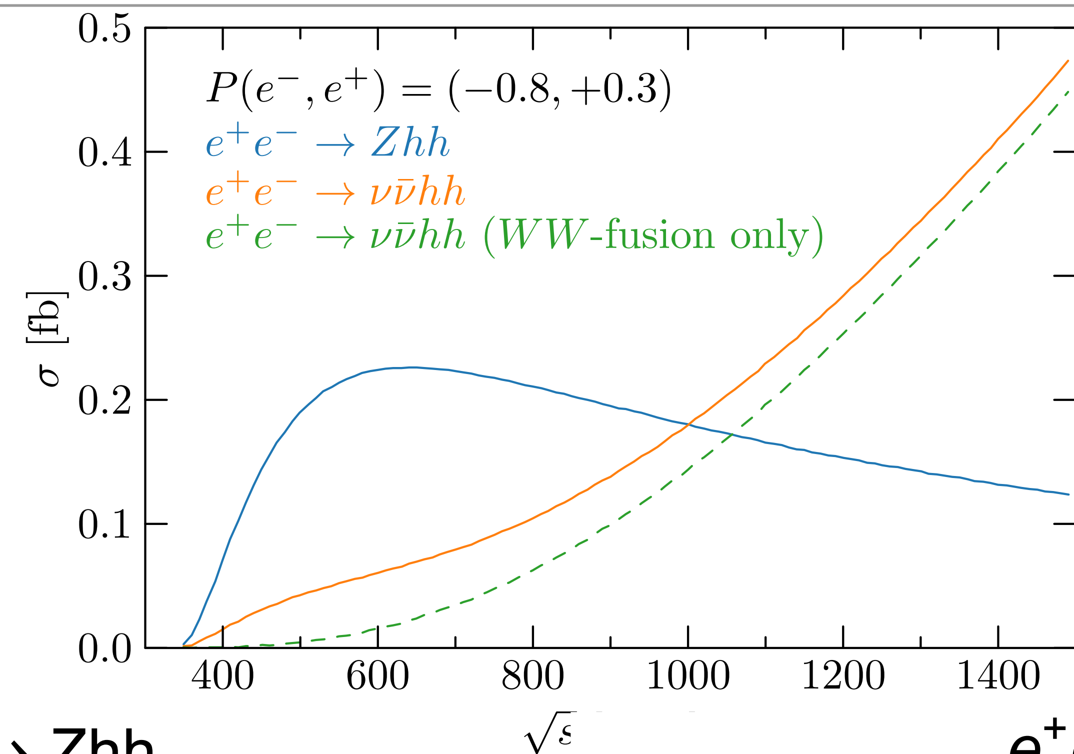
- How significant will possible patterns of deviations be? How stringent are indirect hints for additional particles (typically scale like coupling/mass^2)?

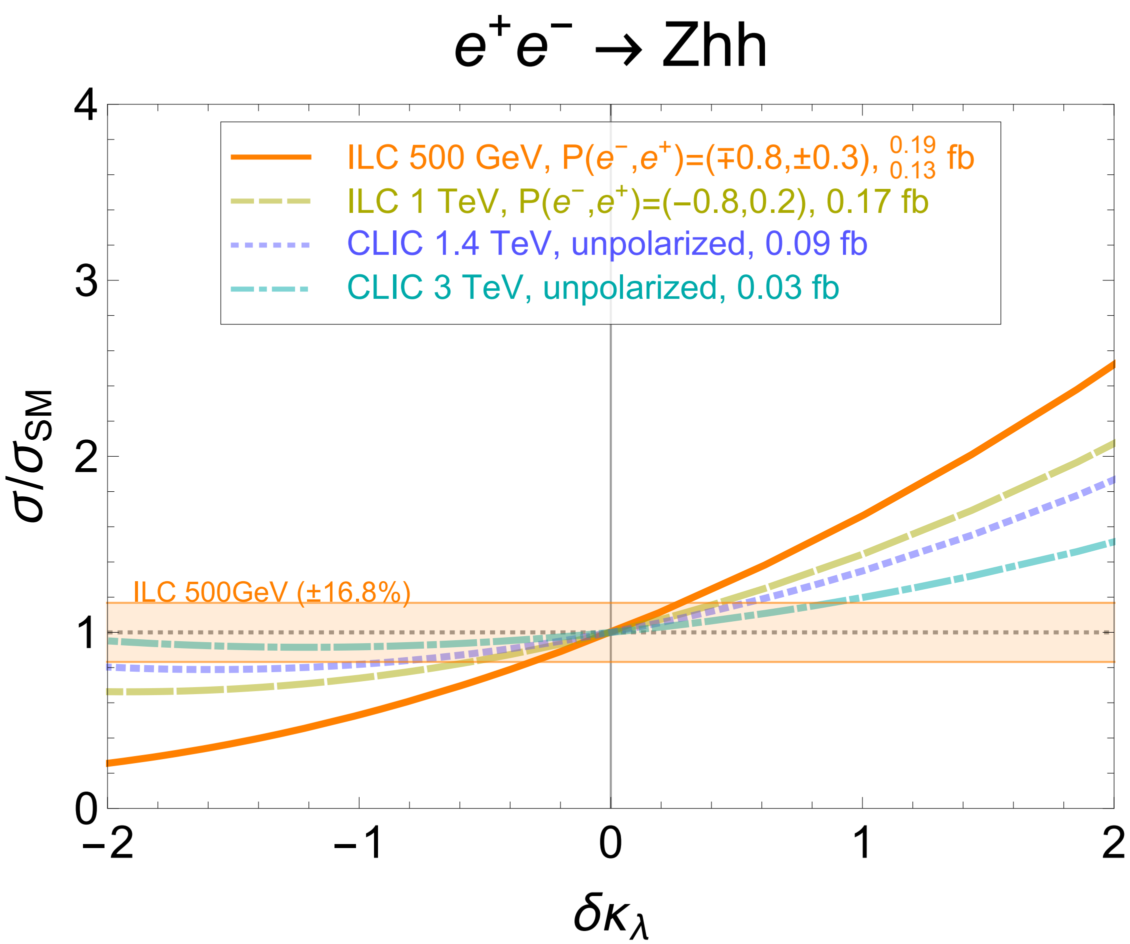
- How well can one distinguish between different realisations of possible BSM physics?

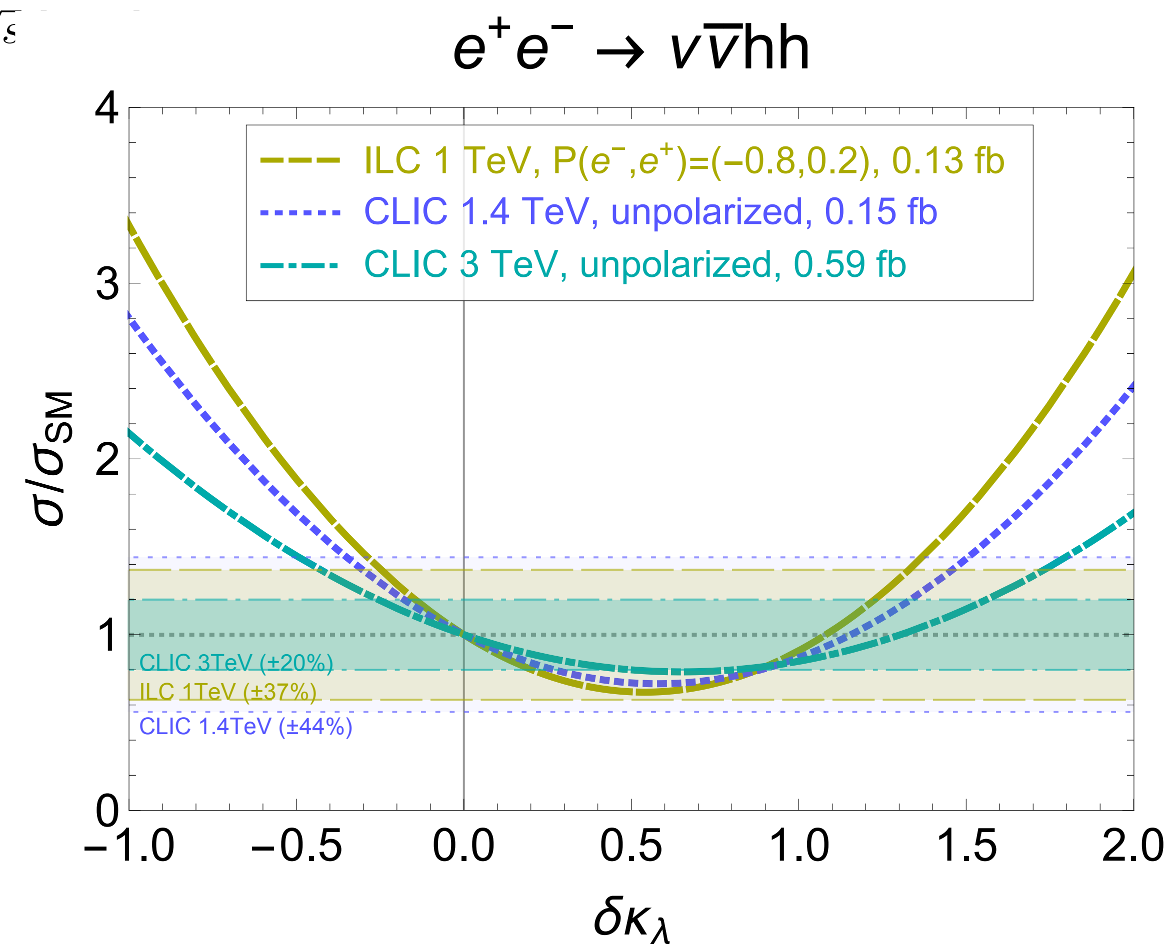
Questions of this kind have hardly been touched upon, for instance, at the previous update of the European Strategy for Particle Physics, but they are crucial for making the case for a (low-energy) e^+e^- Higgs factory in the wider scientific community!

Higgs pair production at e⁺e⁻ colliders

[S. di Vita et al. ’18]



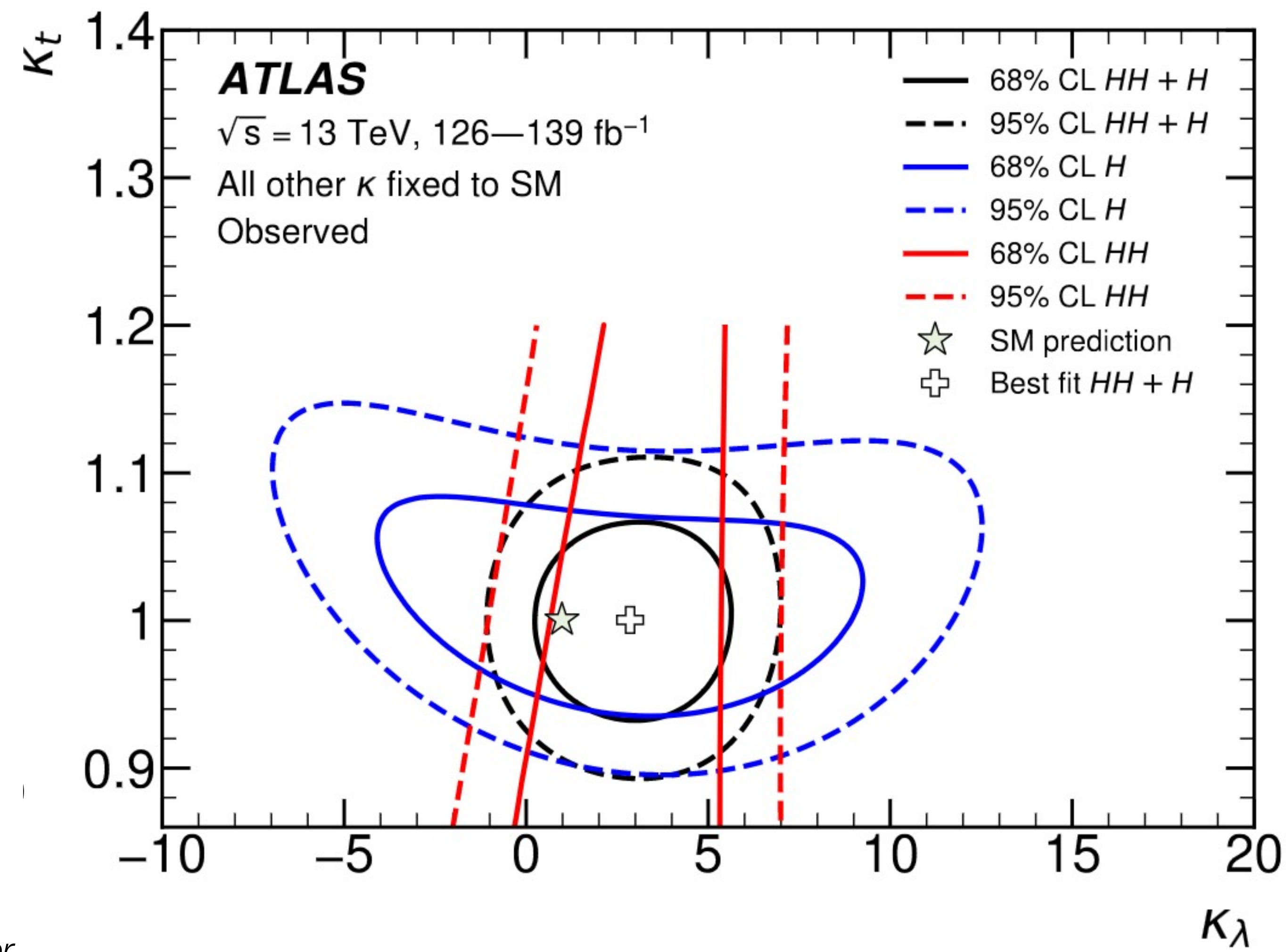




Experimental constraints on $\varkappa_\lambda$

[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

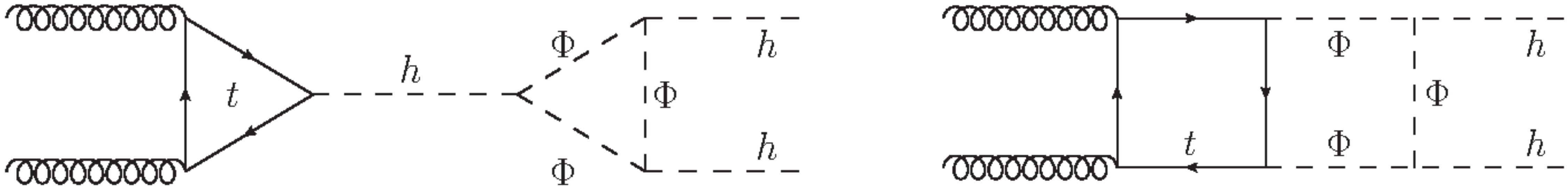
The current experimental limit can only probe scenarios with large deviations from the SM
⇒ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

Check of applicability of the experimental limit on ϰ$_\lambda$

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!

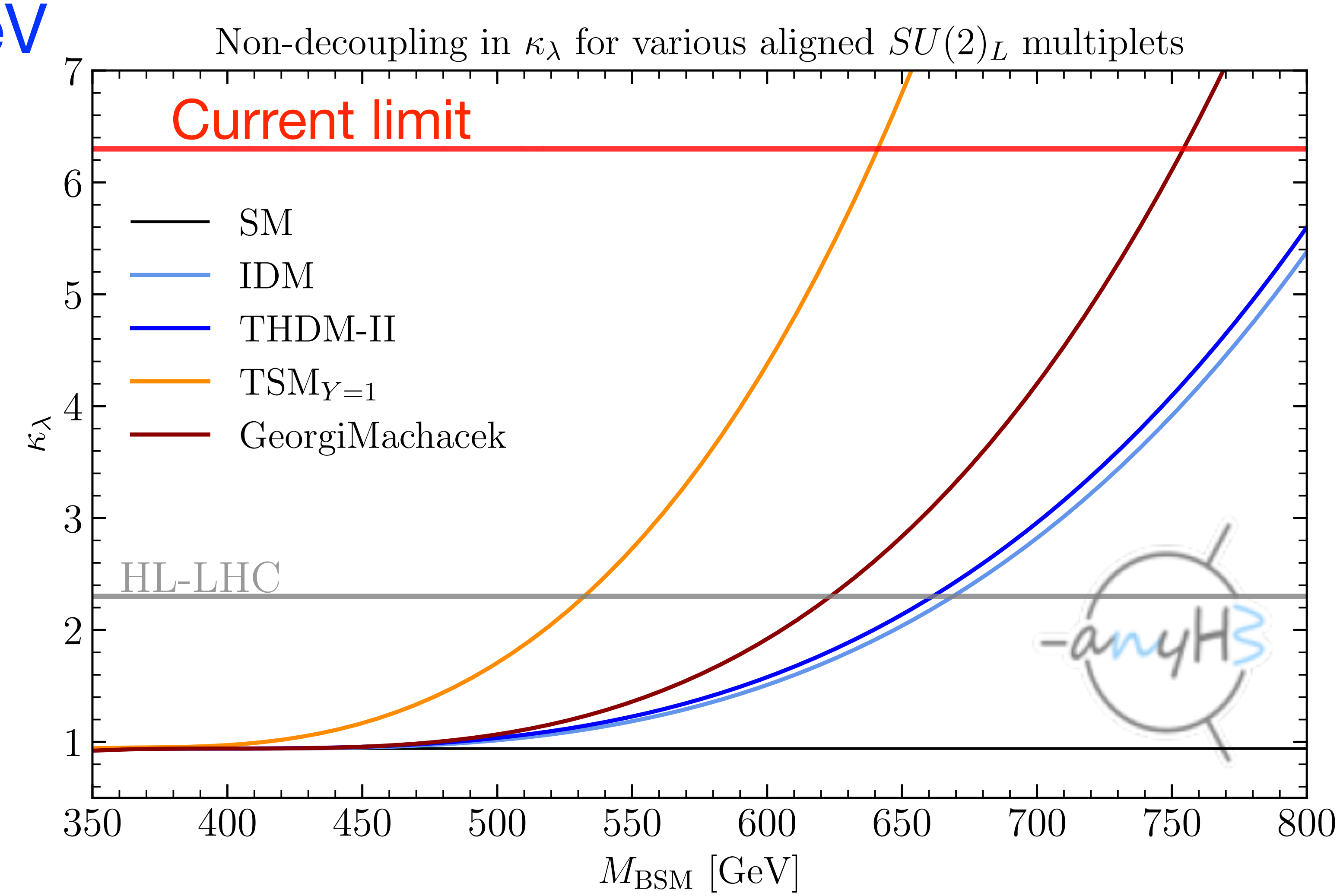
Higgs self-couplings in extended Higgs sectors

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



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]

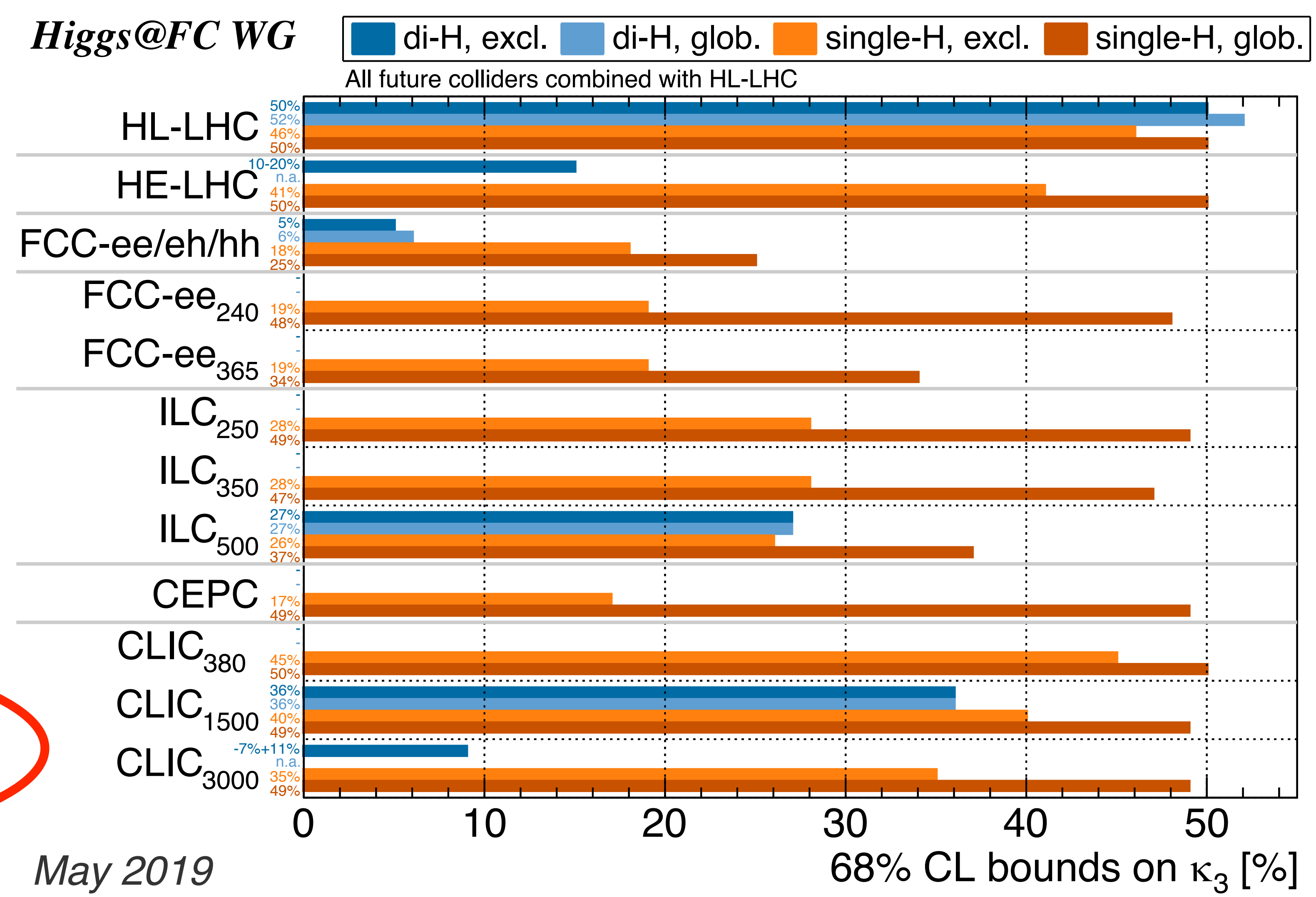
Sensitivity to λ: via single-H and di-H production

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:

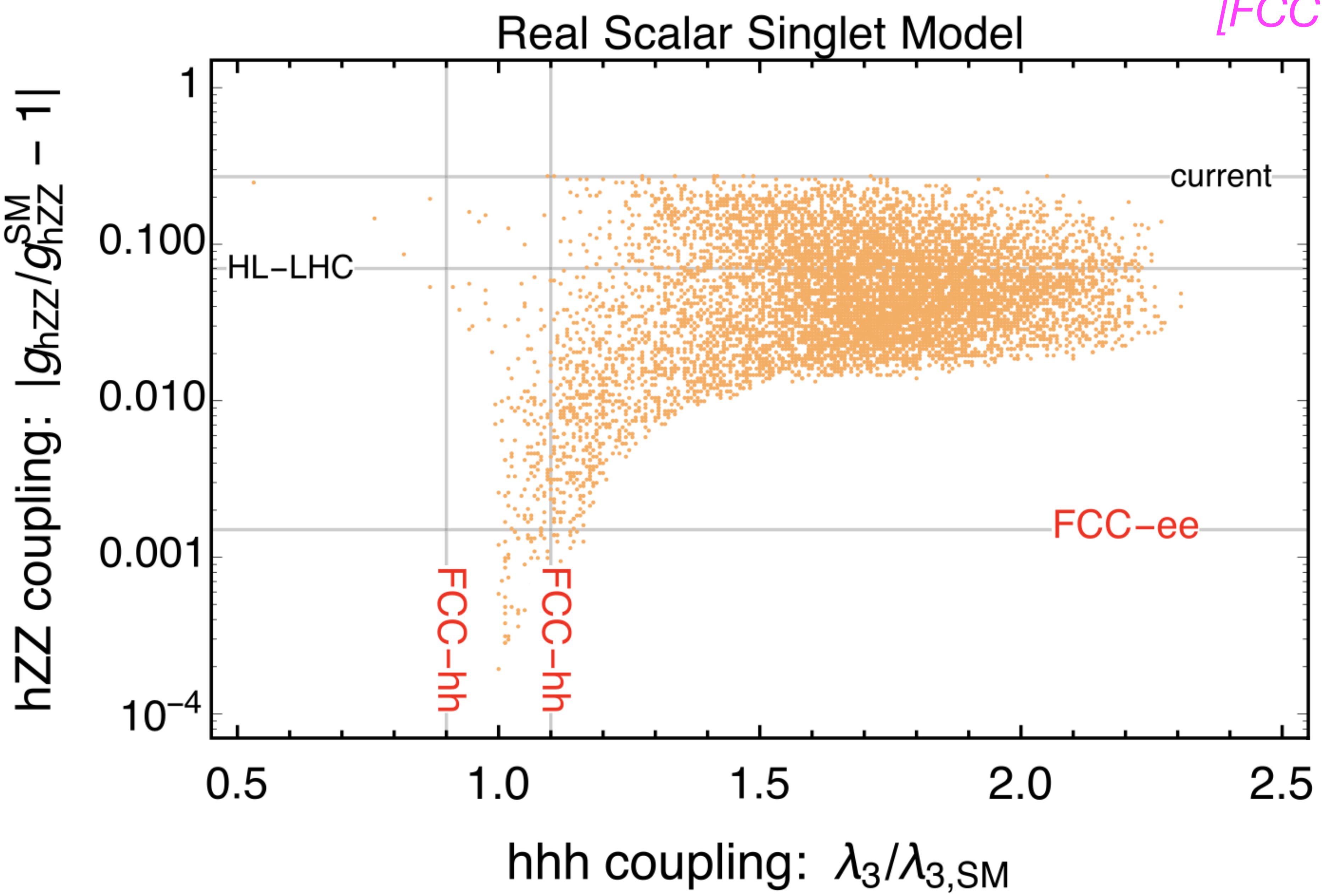
- **Global analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC**
  - **~21% if FCC-ee has 4 detectors**
- **Exclusive analysis: too sensitive to other new physics to draw conclusion**



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

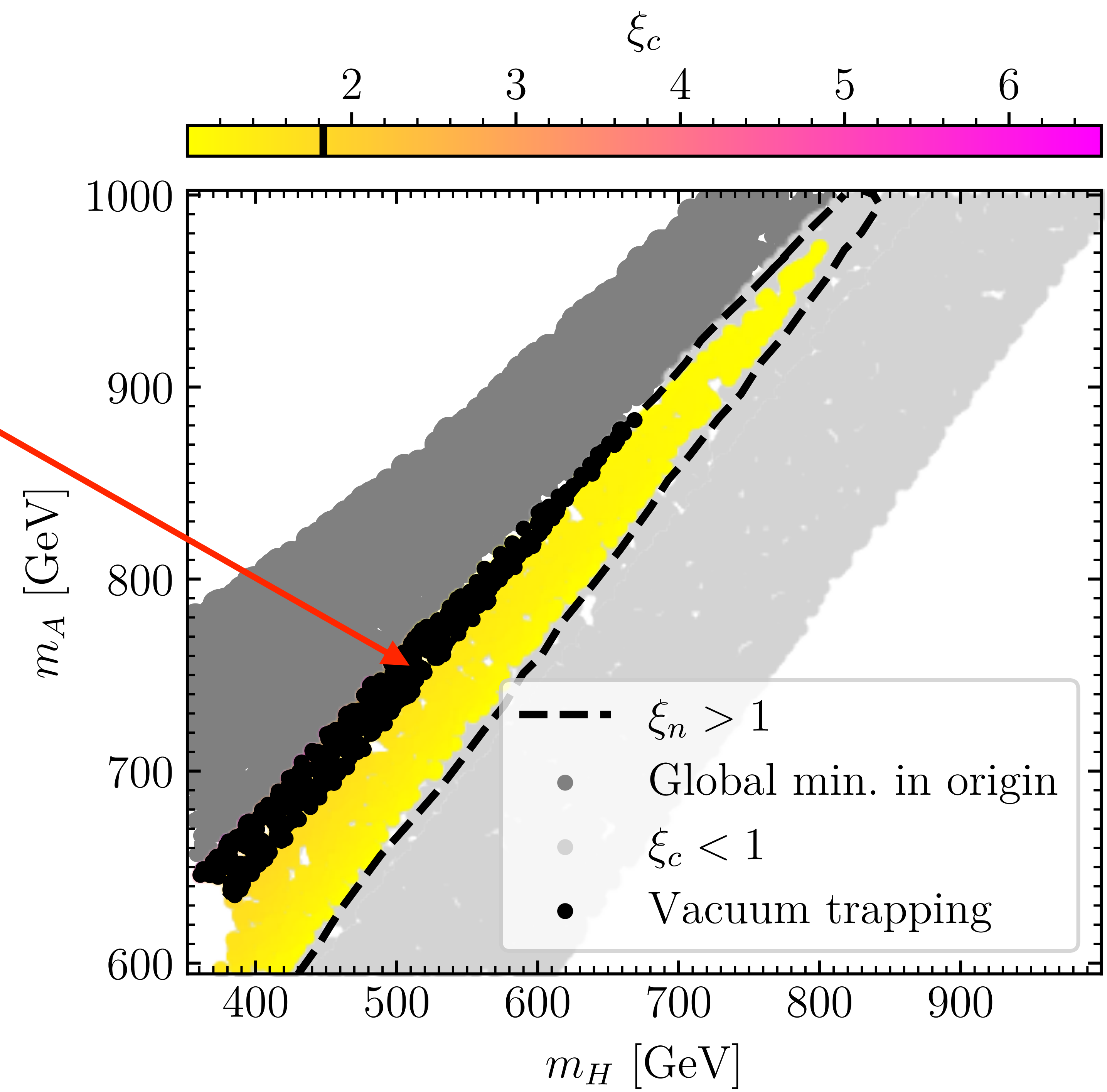
[investigation of the effects in progress]

⇒ 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?

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

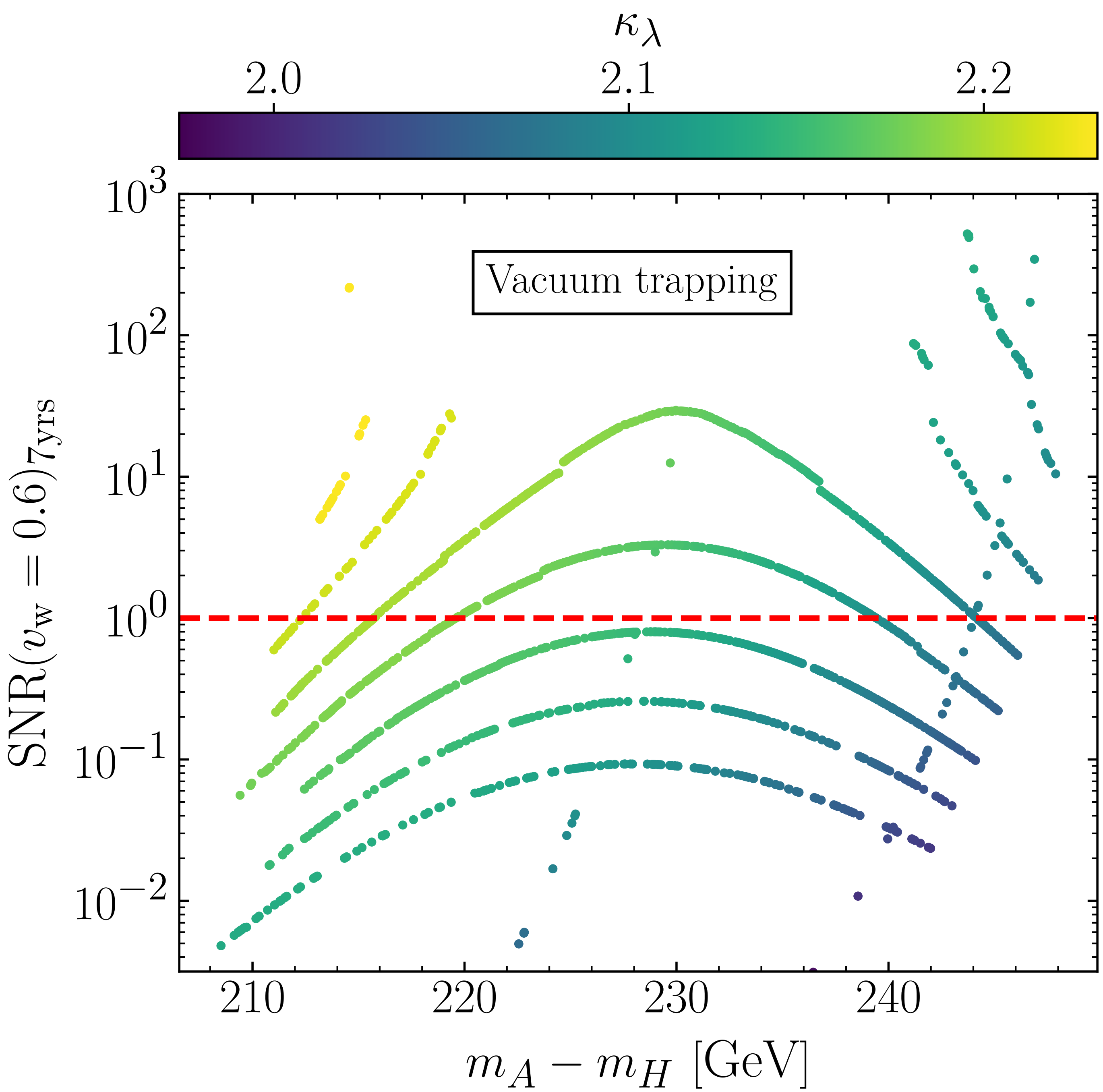
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

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



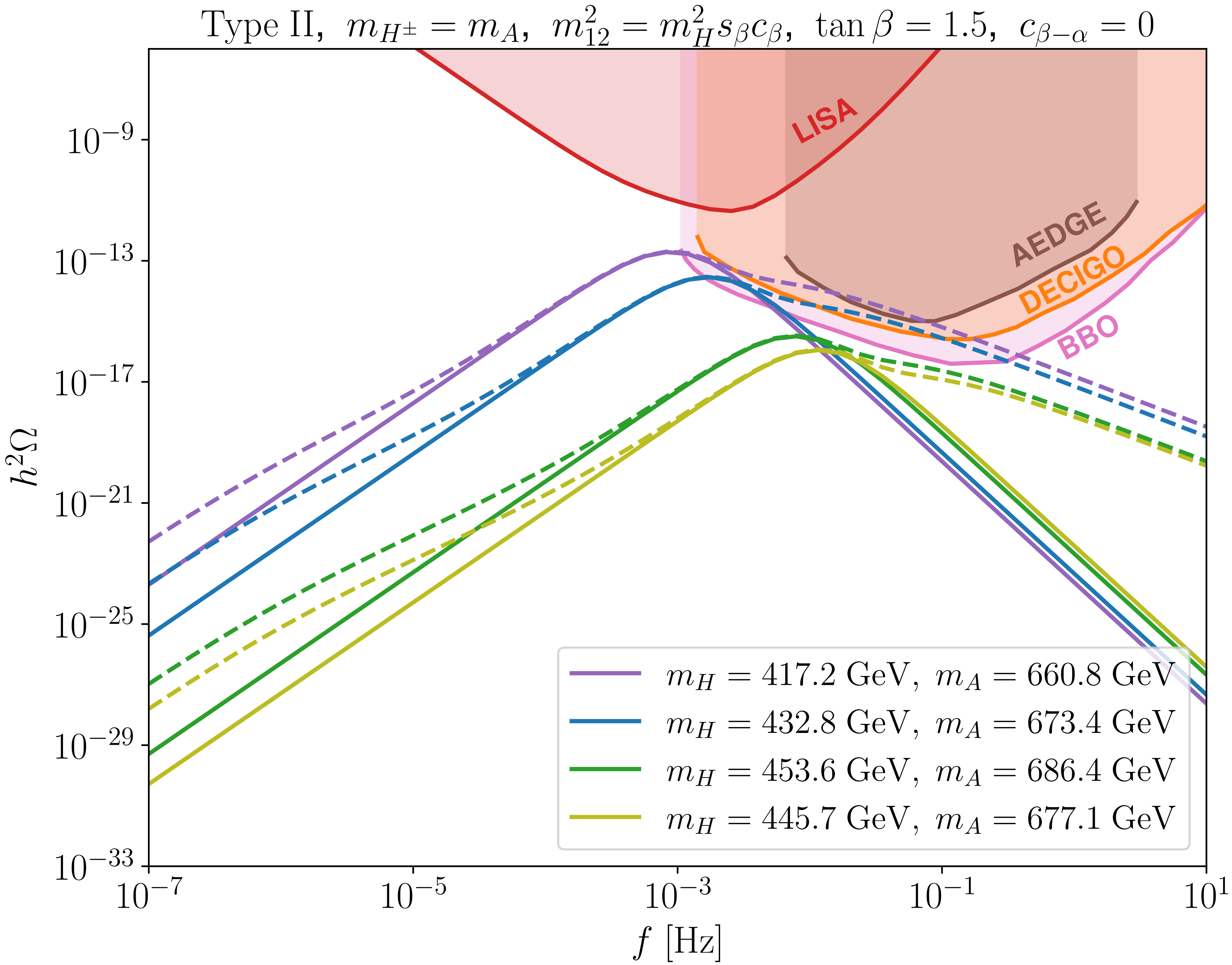
Correlation of $\varkappa_\lambda$ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

[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

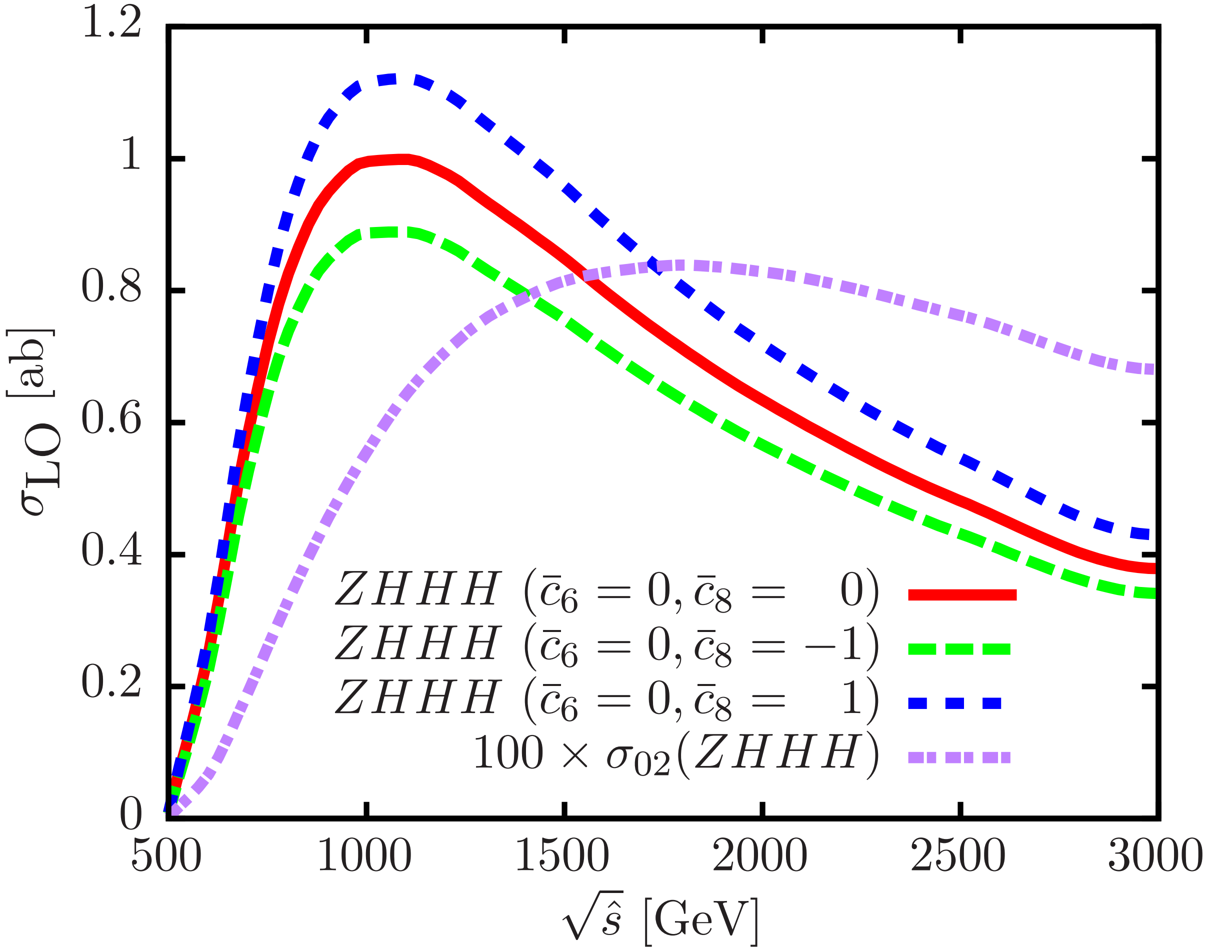


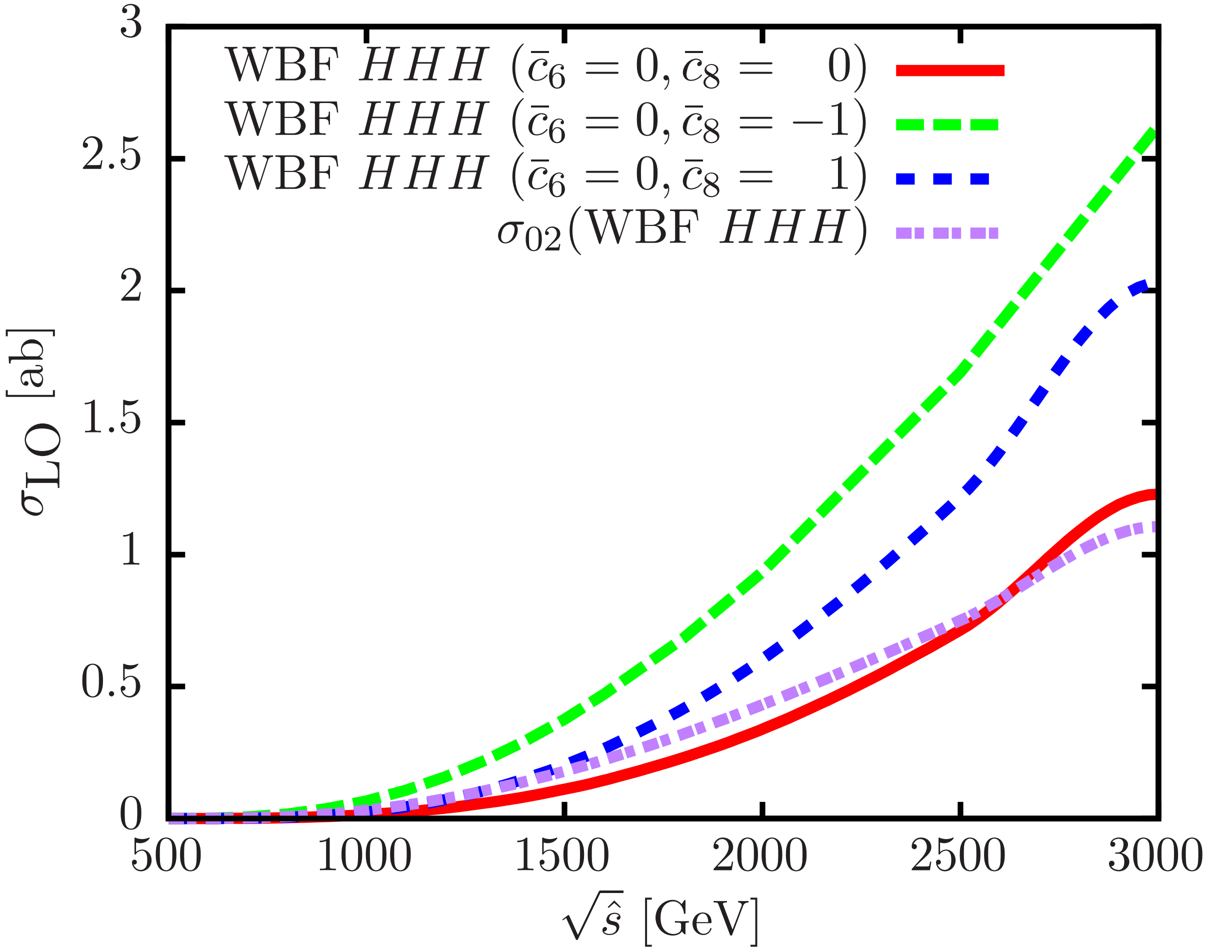
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

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

Triple Higgs production at e+e− colliders

[F. Maltoni et al. ’18]

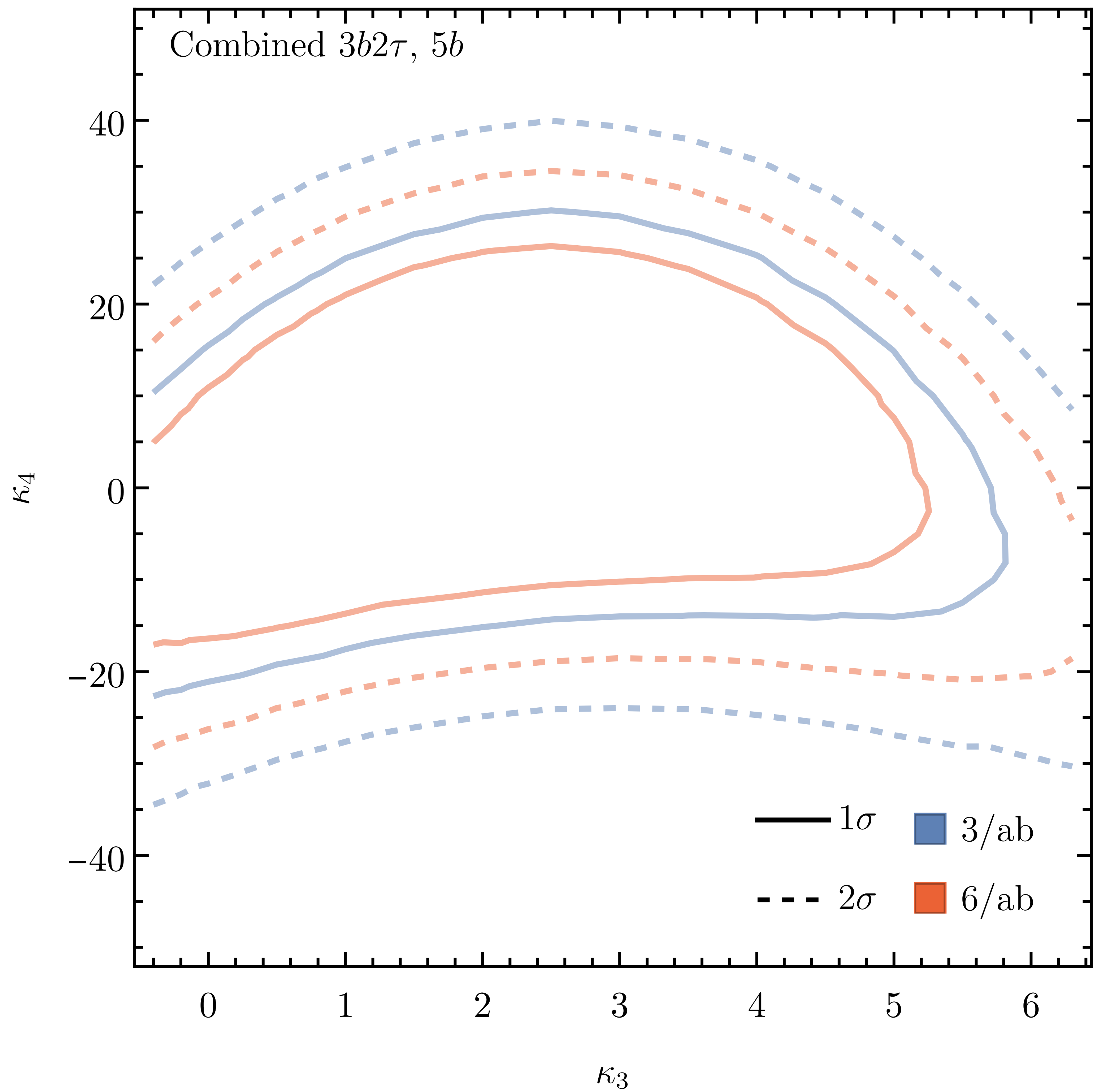




Prospects for the HL-LHC: 6b and 4b2τ channels comb.

[P. Stylianou, G. W. '24]

- **Assumption:** No correlations



Combination of further channels and improvements of **tagging/reconstruction** methods could enhance results further