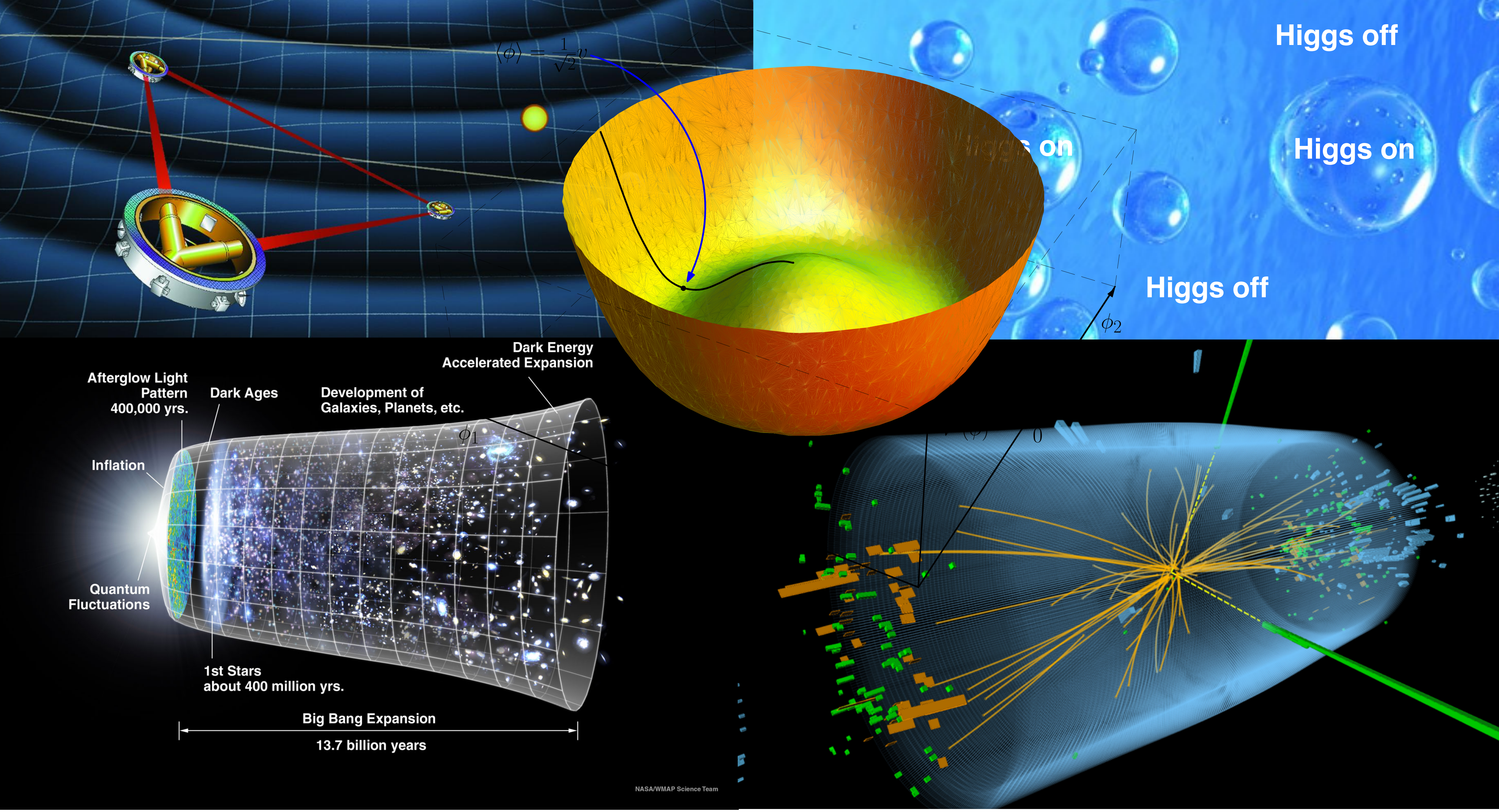

Exploring the scalar potential at the LHC and beyond

Gudrid Moortgat-Pick, UHH

Hamburg, 12 / 2023

Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

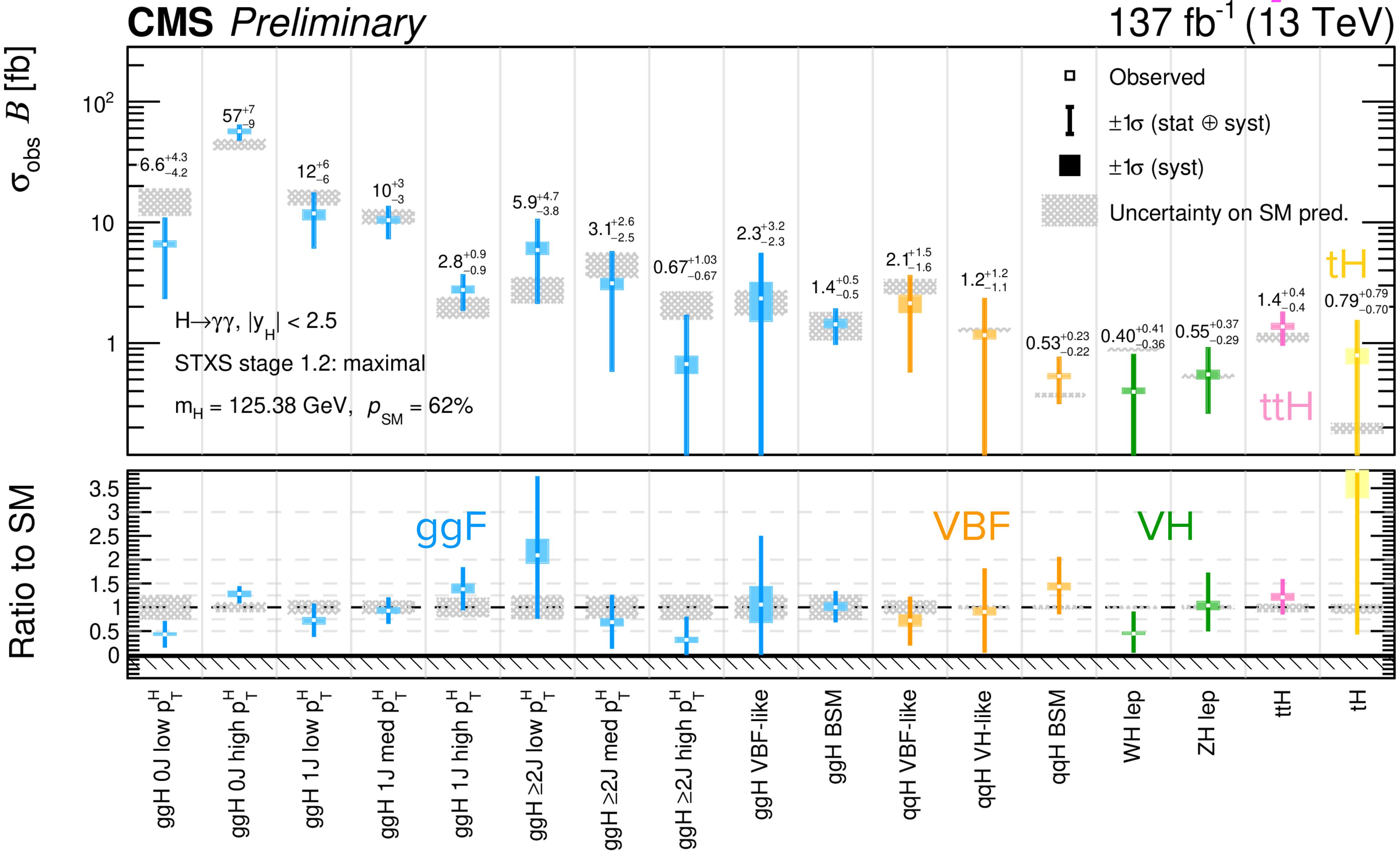
Outline

- Introduction
- Higgs self-couplings and probes of the electroweak phase transition with the ``smoking gun” signature
- Exploring HHH production w.r.t. Higgs self-couplings
- Conclusions

Introduction

A bit more than 11 years after the discovery of the Higgs boson at 125 GeV (h125): high-precision measurement of the mass, detailed investigations of inclusive and differential rates

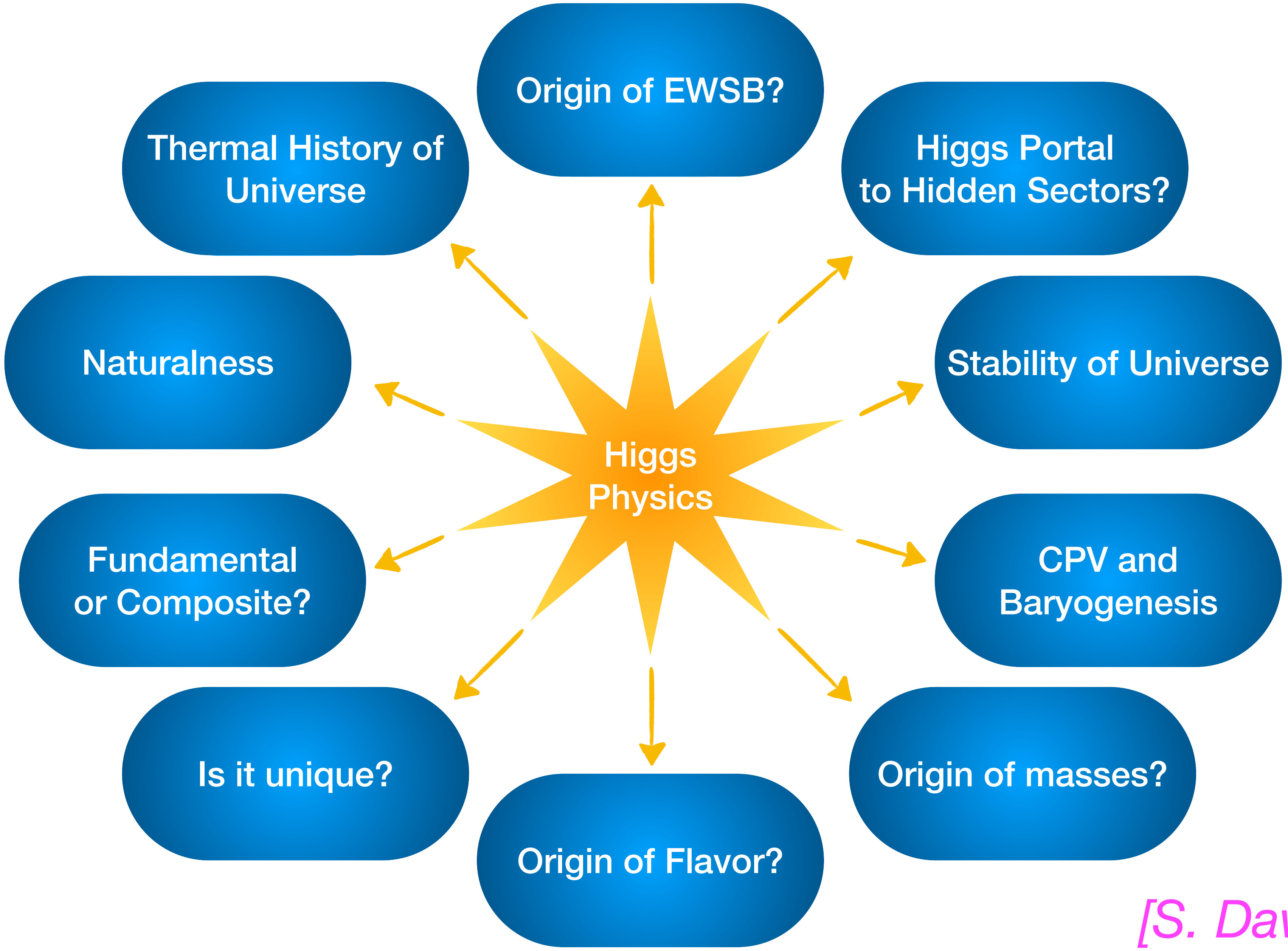
[CMS Collaboration '22]



⇒SM-like properties

Higgs potential: the “holy grail” of particle physics

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



Origin of EWSB?

Thermal History of Universe

Higgs Portal to Hidden Sectors?

Naturalness

Higgs Physics

Stability of Universe

Fundamental or Composite?

CPV and Baryogenesis

Is it unique?

Origin of masses?

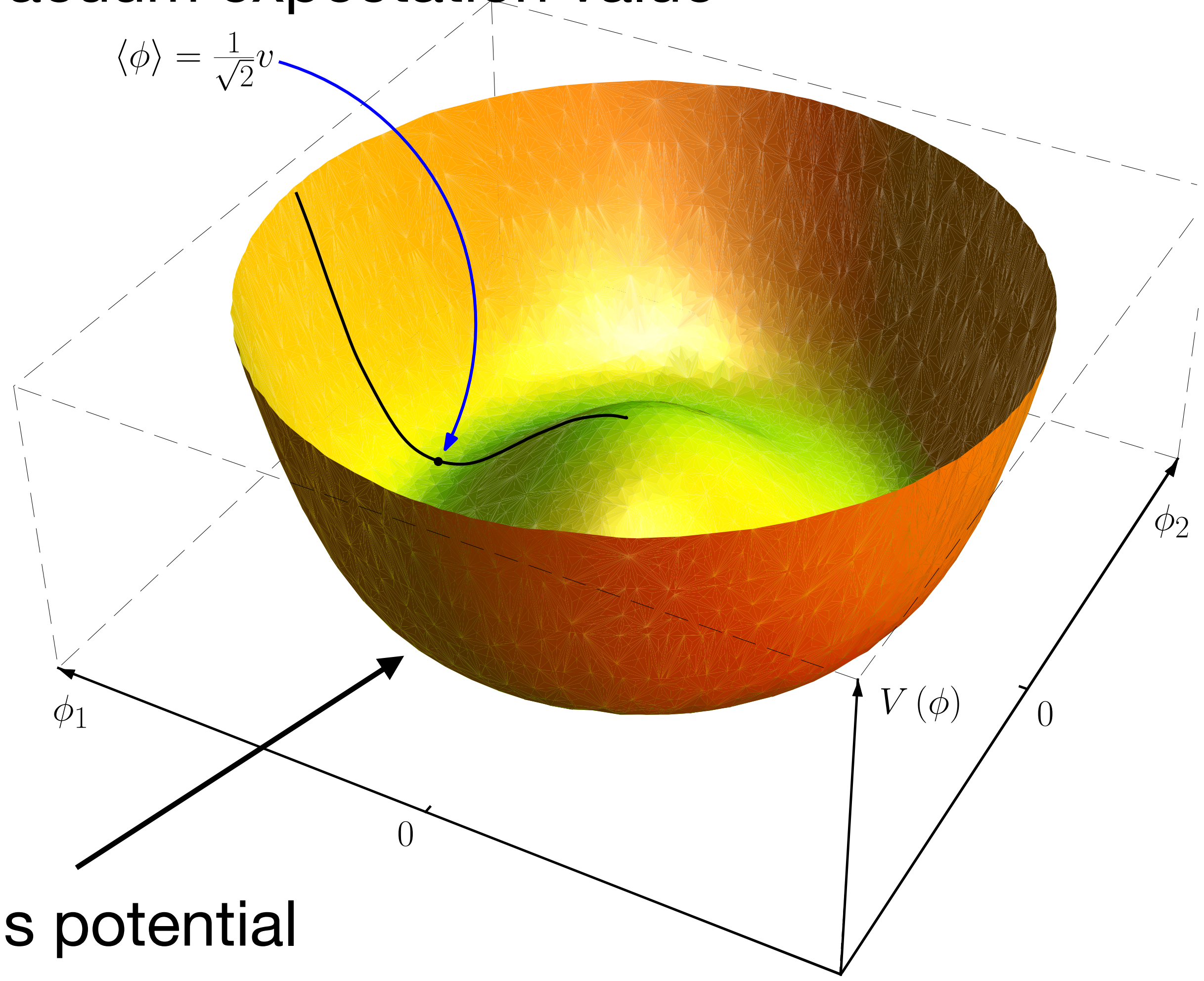
Origin of Flavor?

[S. Dawson et al. ’22]

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

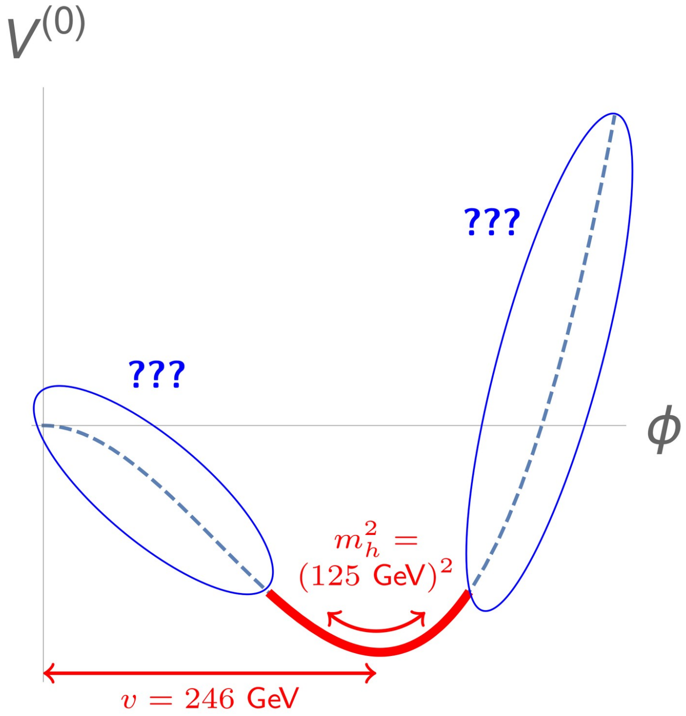
Only known so far:

→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV



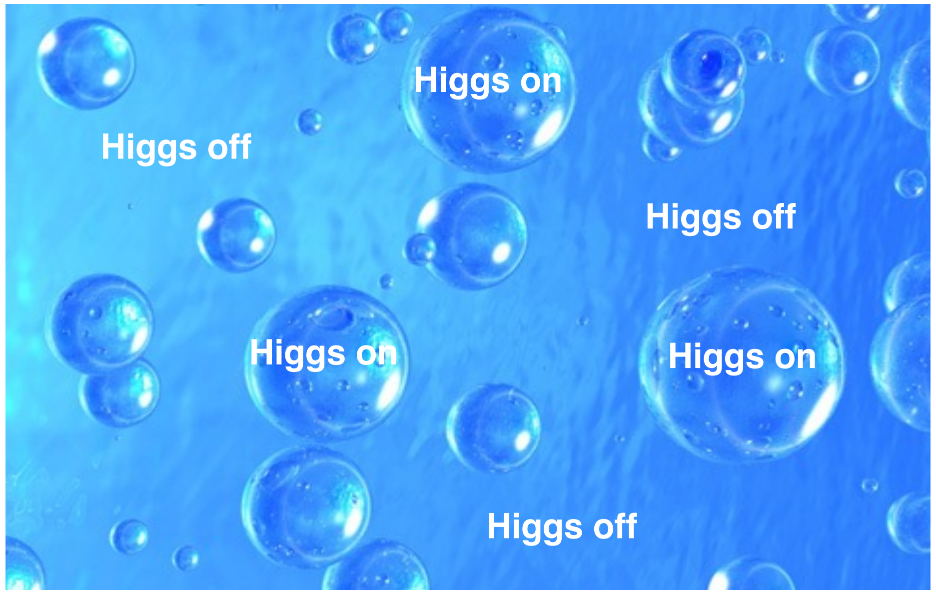
Information can be obtained from the trilinear and quartic Higgs self-couplings, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

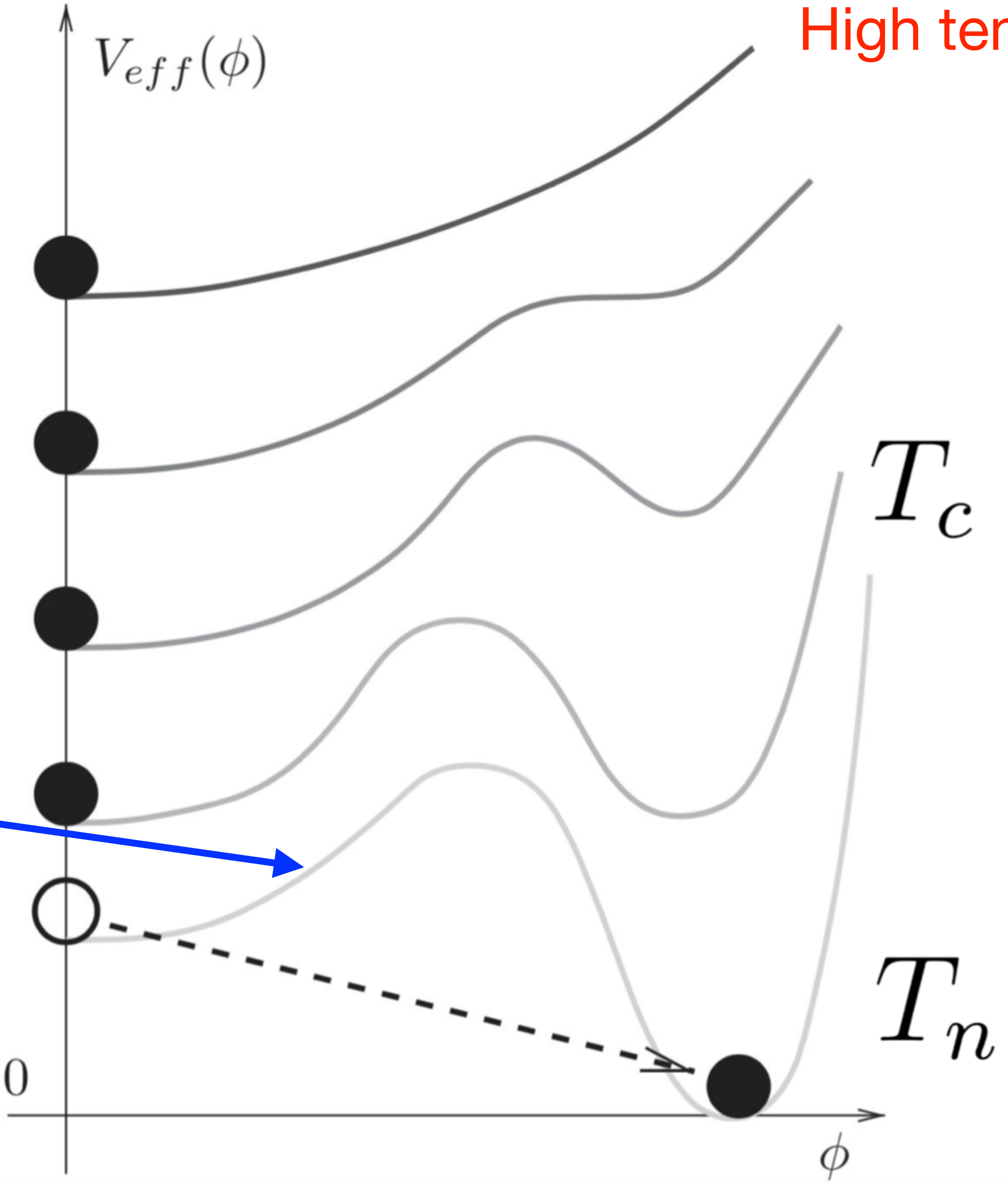
The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

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





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

The Higgs potential and vacuum stability

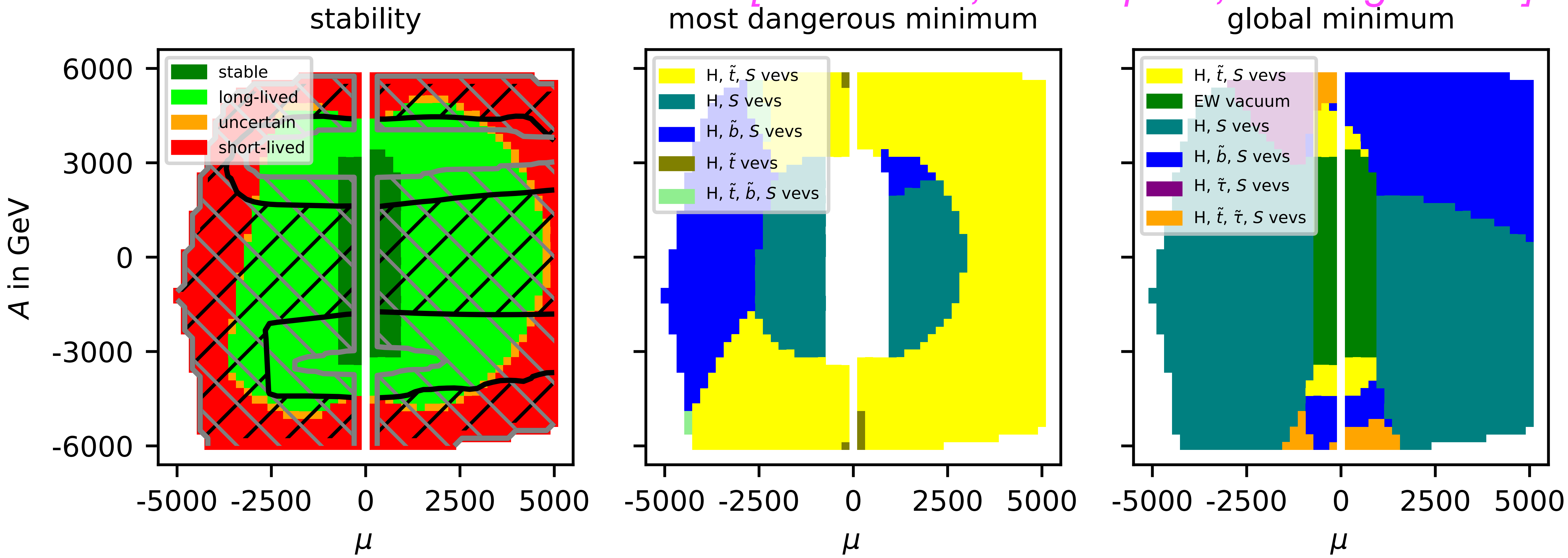
Extended Higgs sectors in general yield additional minima of the Higgs potential; the electroweak minimum may not be the global minimum

Need to check stability of the electroweak vacuum w.r.t. tunneling into deeper minima (analysis at $T = 0$) *[W.G. Hollik, G. Weiglein, J. Wittbrodt '18]*

Improved version of the public code *Evade*

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

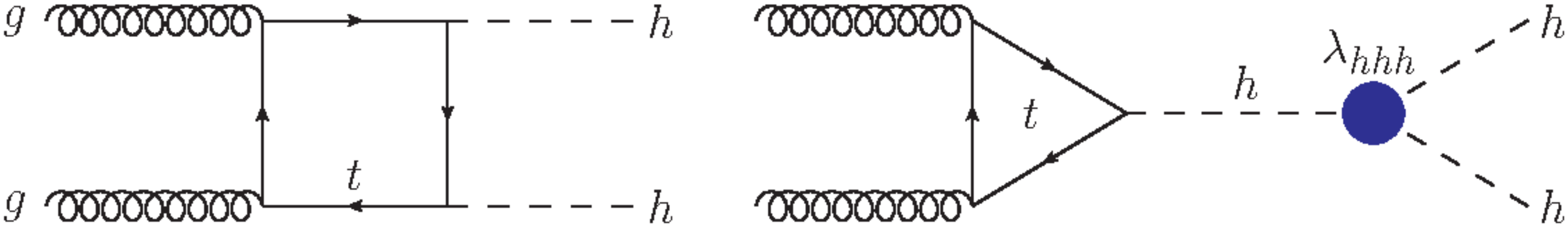
[T. Biekötter, F. Campello, G. Weiglein '23]



Higgs self-couplings and probes of the electroweak phase transition with the ``smoking gun” signature

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}**



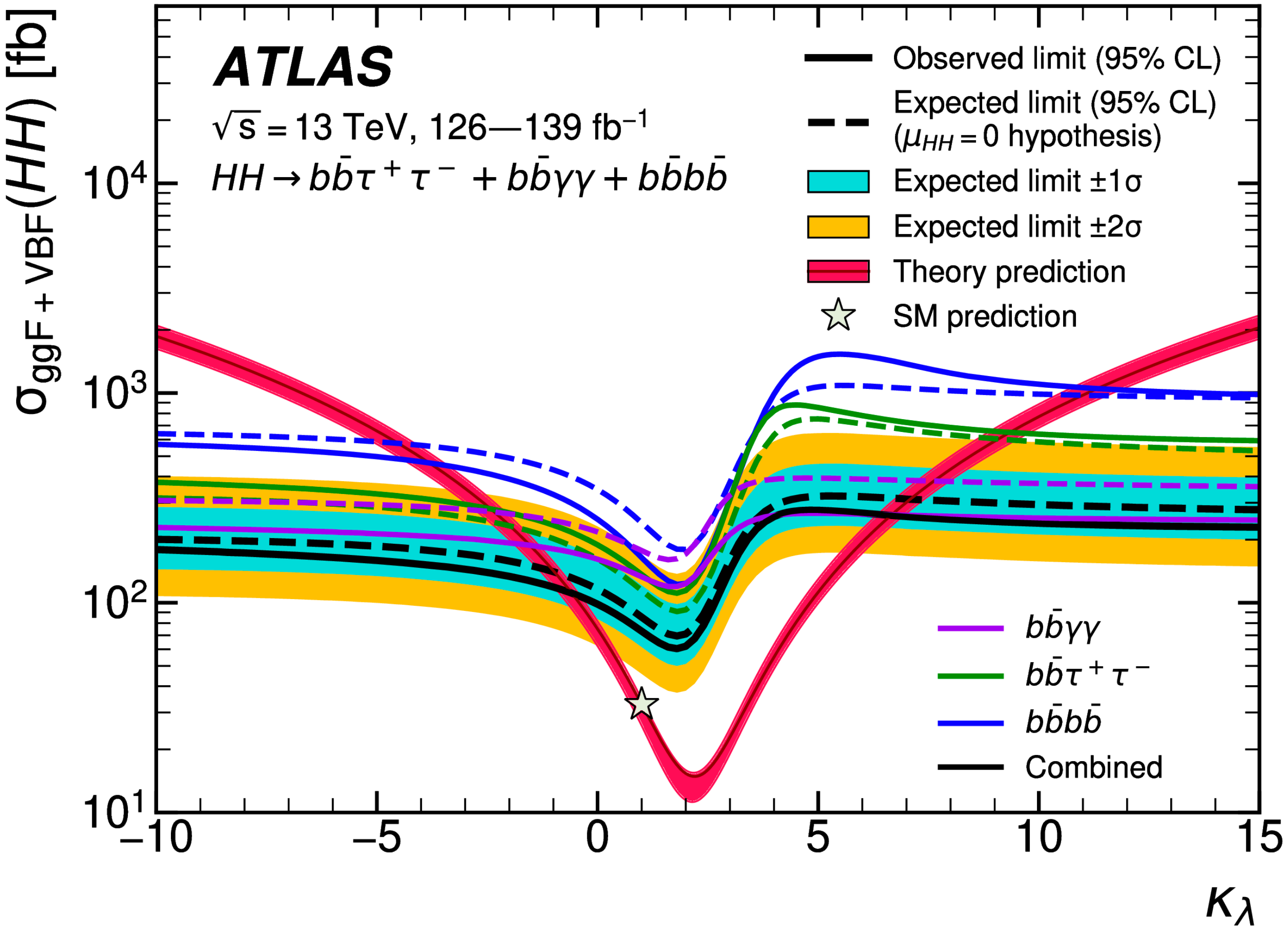
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

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

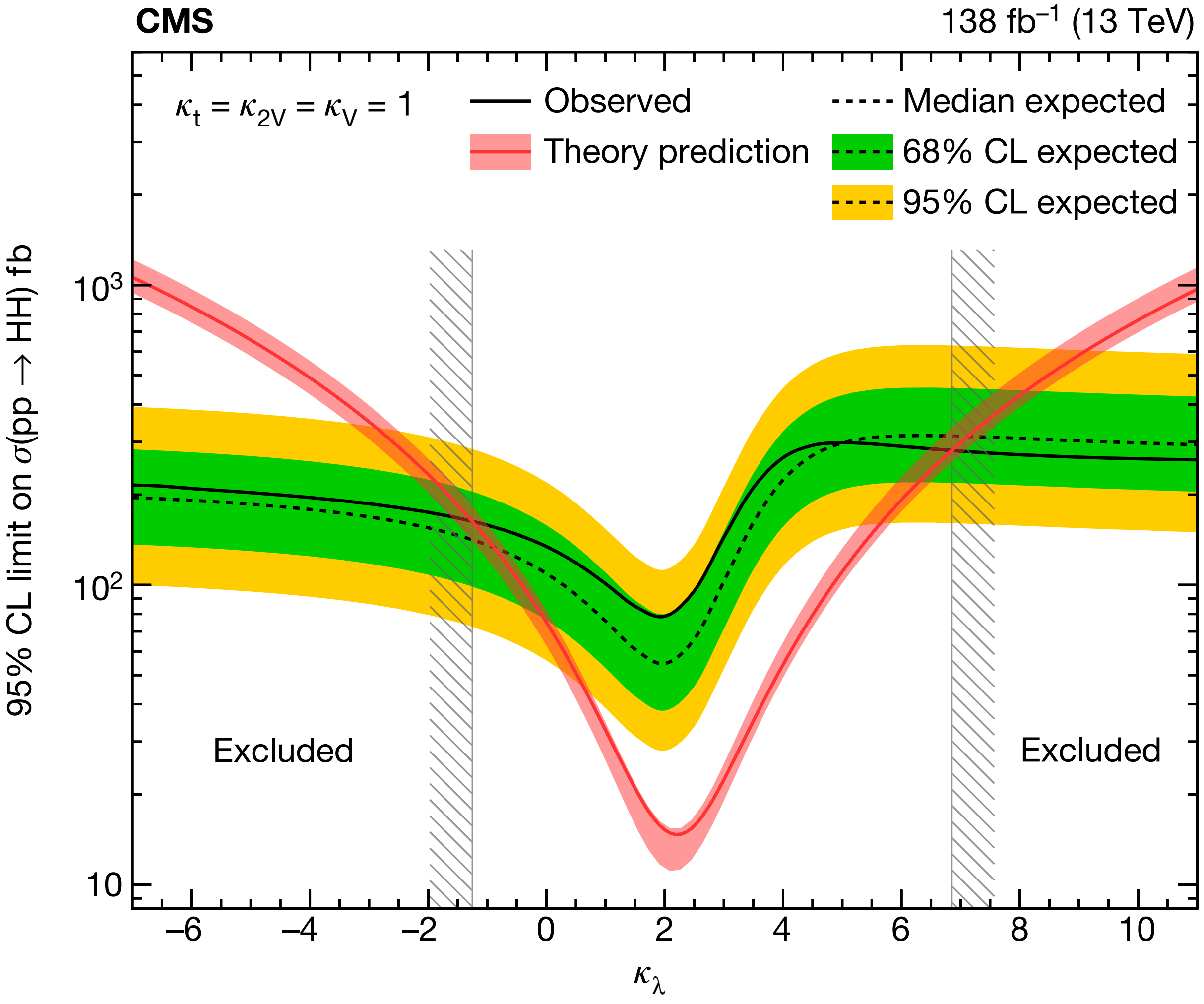
Using only information from di-Higgs production and assuming that new physics only affects the trilinear Higgs self-coupling, this limit on the cross section translates to:
ATLAS: $-0.6 < \varkappa_\lambda < 6.6$ at 95% C.L. *[ATLAS Collaboration ’22]*
CMS: $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L. *[CMS Collaboration ’22]*

Bound on the trilinear Higgs self-coupling: $\varkappa_\lambda$

[ATLAS Collaboration ’22]



[CMS Collaboration ’22]



Comparison between experiment and theory in terms of the limit on $\varkappa_\lambda$ or in terms of the limit on $\mu_{HH}(\varkappa_\lambda)$?

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
$\Rightarrow$ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

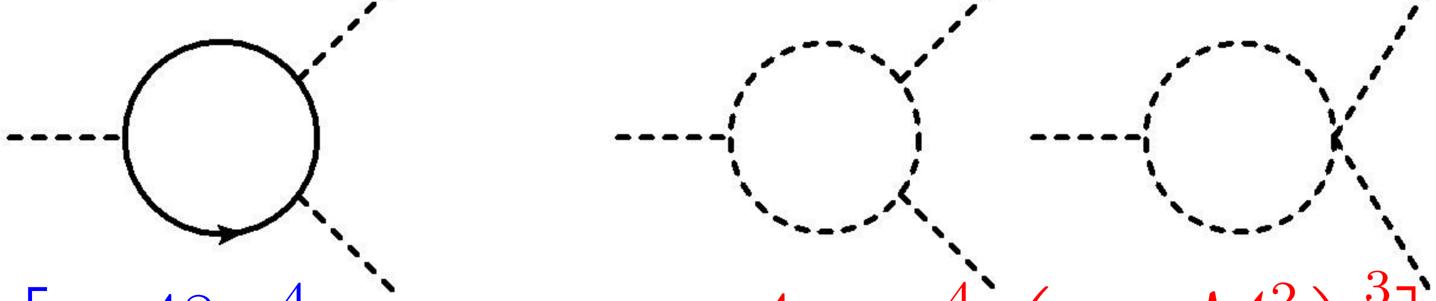
Effects of BSM particles on the trilinear Higgs coupling

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 $\mathcal{M}$

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

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

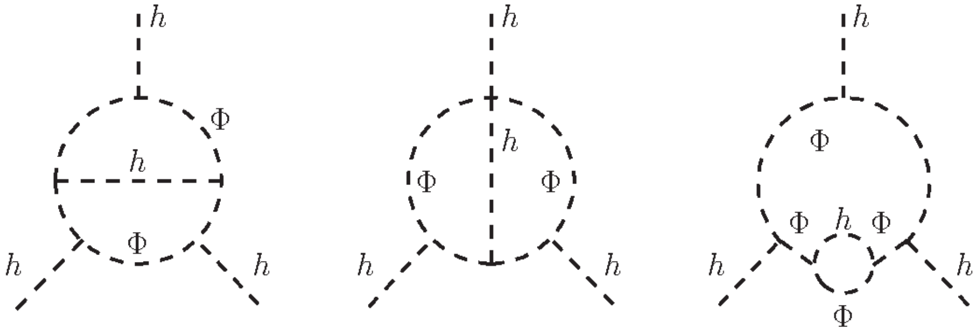
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

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

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 $g_{hh\phi\phi}$



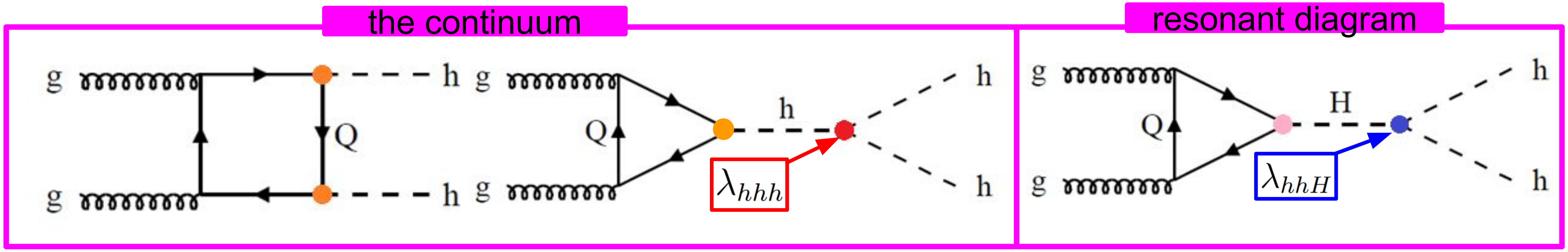
Analysis is carried out in the alignment limit of the 2HDM (α = β - π/2)

⇒h has SM-like tree-level couplings

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 is accompanied by the non-resonant contribution, involving h_{125}, giving rise to potentially sizeable interference contributions



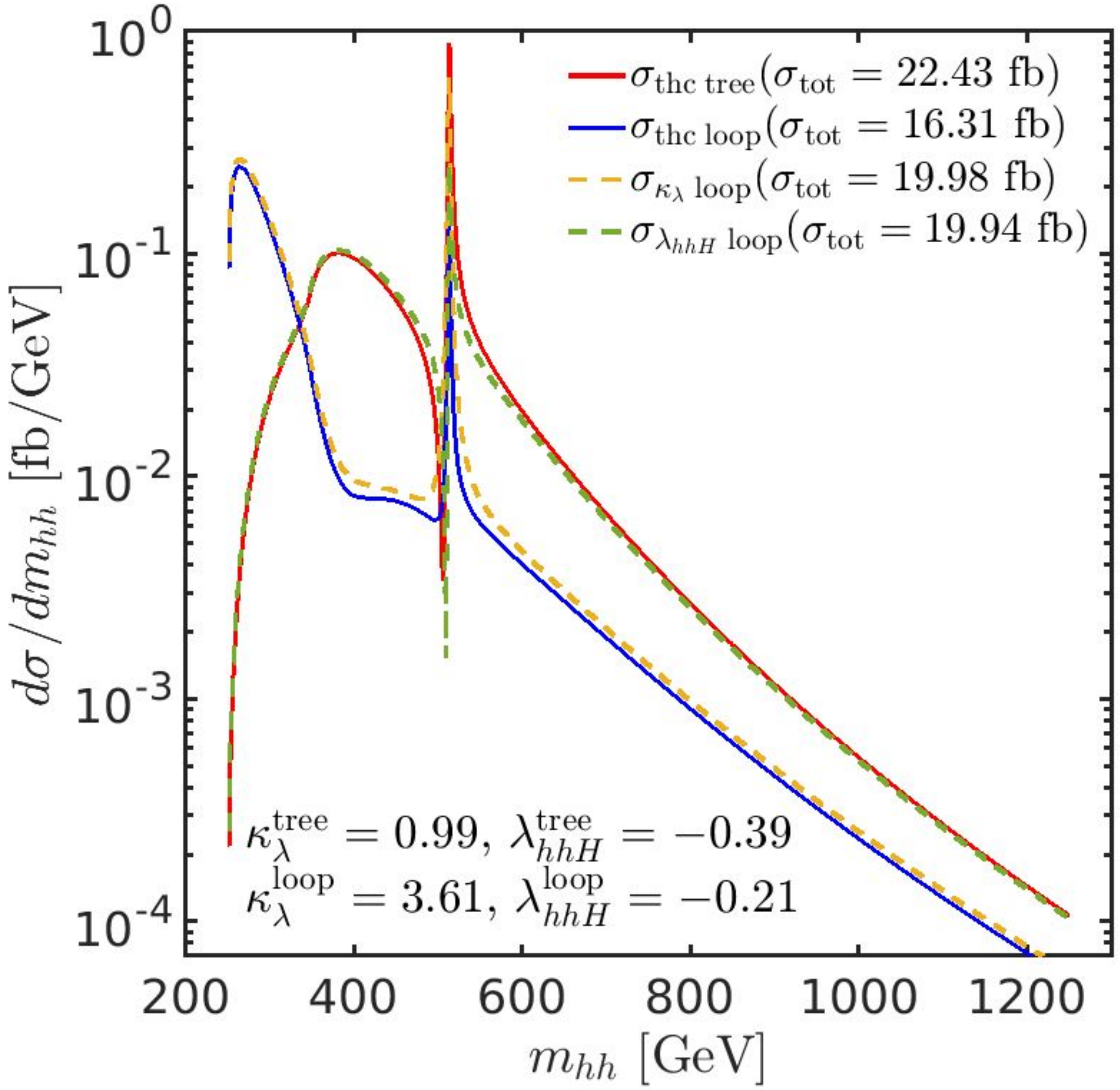
the continuum

resonant diagram

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

Interference effects in Higgs pair production

2HDM example: *[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. Weiglein'23]*



$$\boxed{\cos(\beta-\alpha) = 0.2,\ \tan\beta = 10,\ m_{12}^2 = m_H^2 \cos^2\alpha/\tan\beta}$$

- Resonance located at $m_{hh} \sim m_H$ not very affected by corrections to the trilinears

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

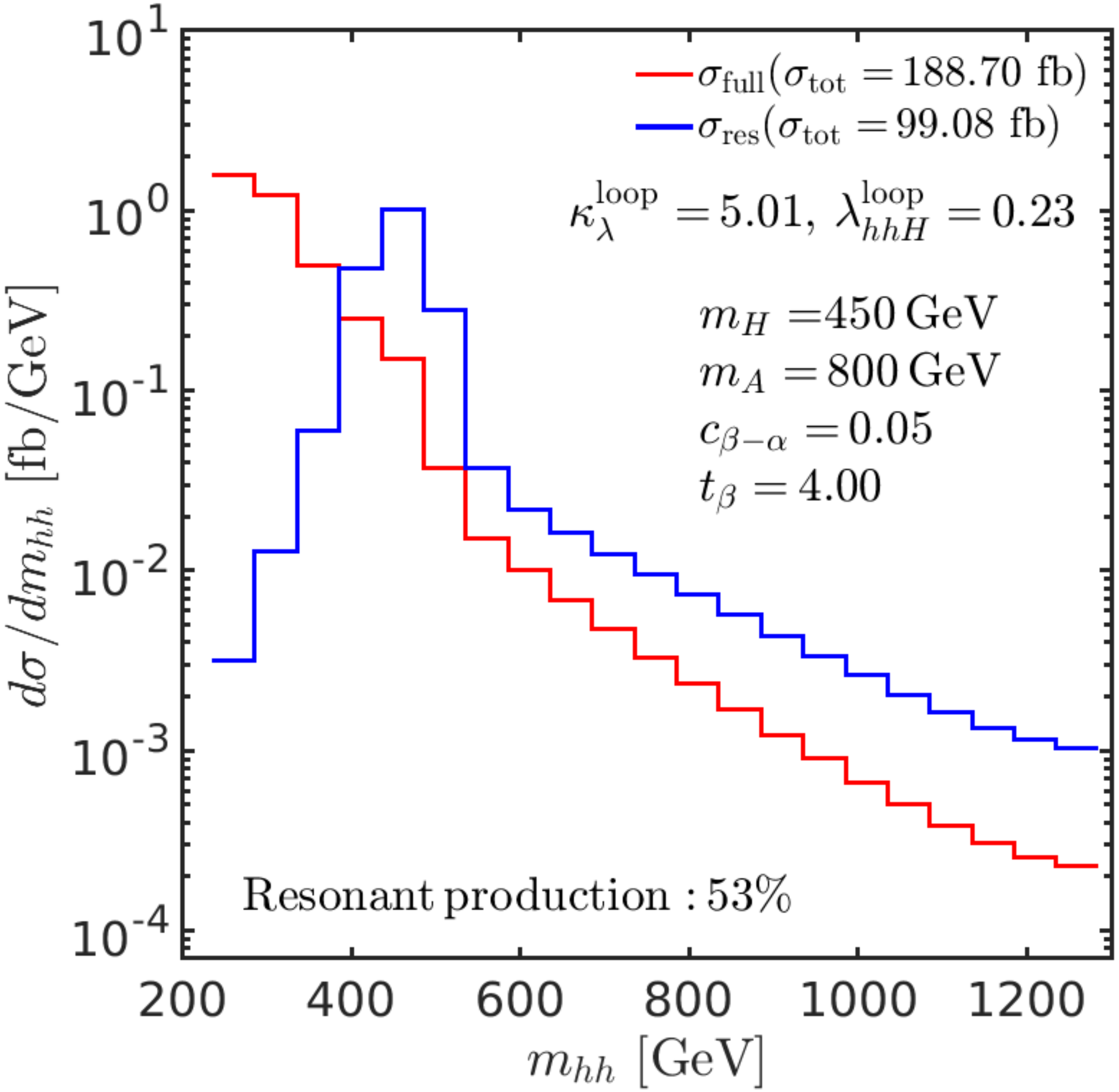
- m_{hh} are extremely sensitive to deviations in the trilinears and a precise theoretical prediction is necessary to interpret future results

⇒ m_{HH} distribution depends very sensitively on κ_λ
Important interference effects

Interference effects in Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. Weiglein'23]

2HDM example, experimental smearing included:



⇒ Large deviation in m_{HH} distribution between resonant contribution and full result; limits using resonant contribution may be too optimistic

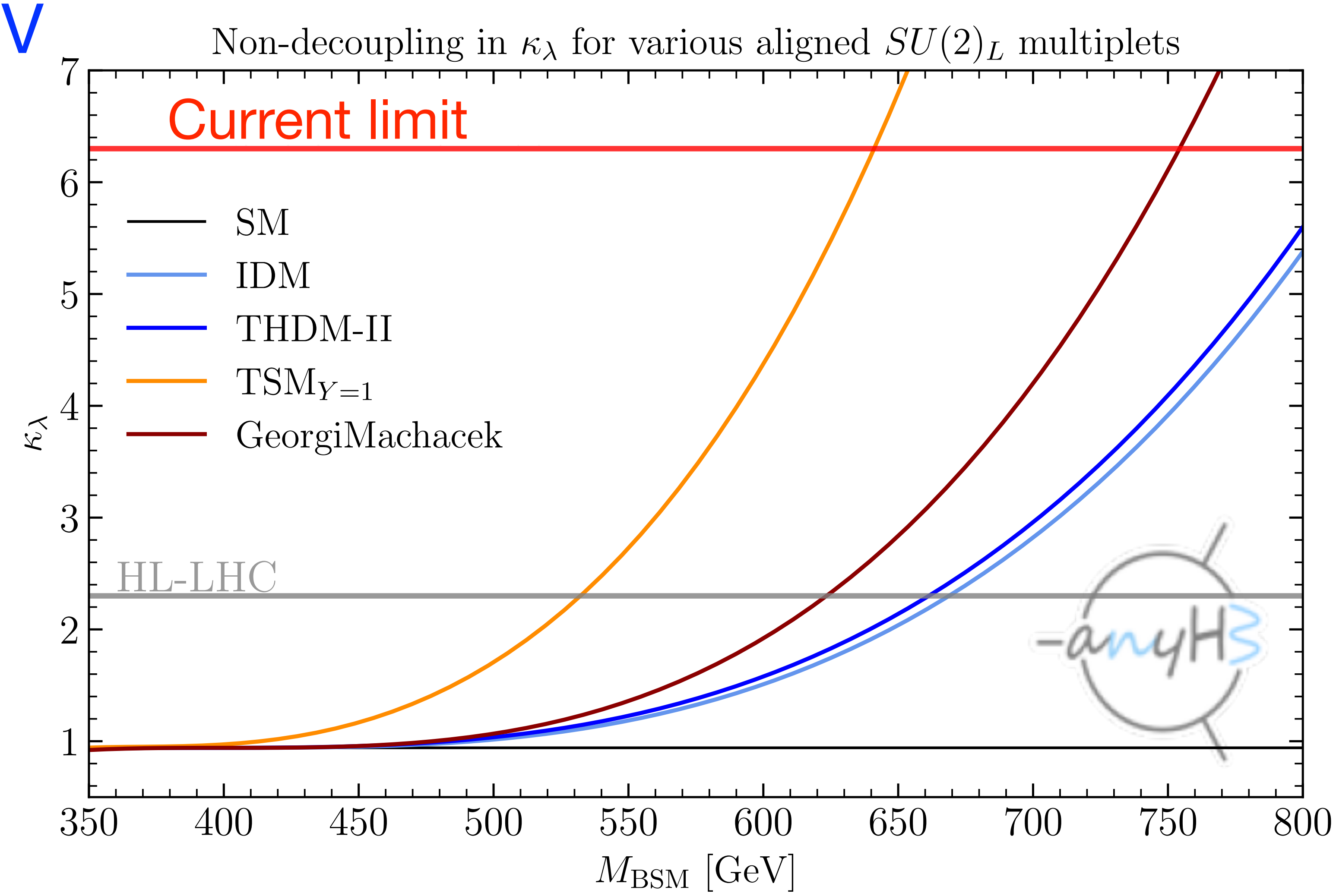
Higgs self-couplings in extended Higgs sectors

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)

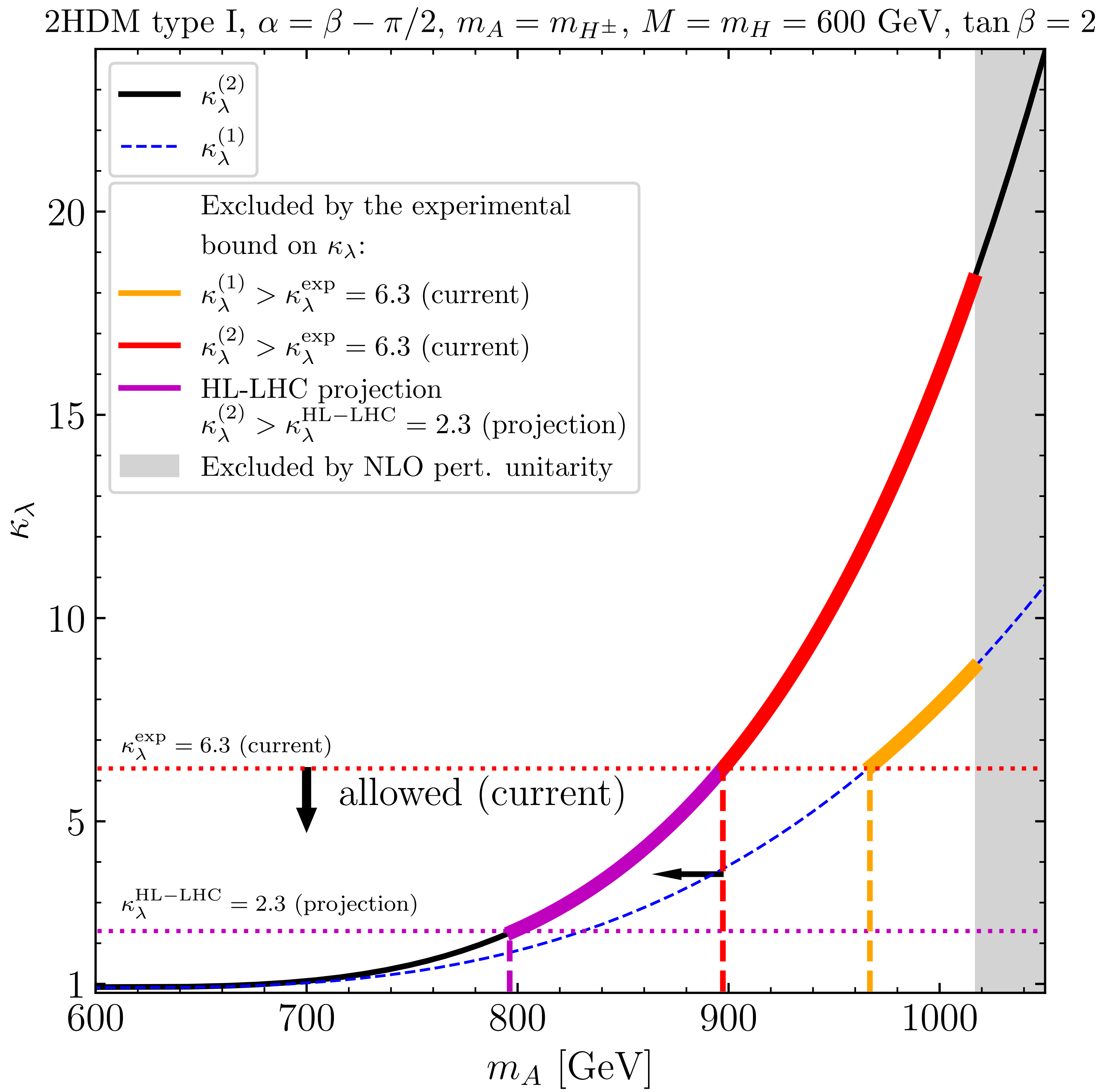
[H. Bahl, J. Braathen, M. Gabelmann, G. Weiglein ’23]

M_L = 400 GeV



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

Prediction for $\varkappa_\lambda$ up to the two-loop level: *[H. Bahl, J. Braathen, G. Weiglein '22, Phys. Rev. Lett. 129 (2022) 23, 231802]*

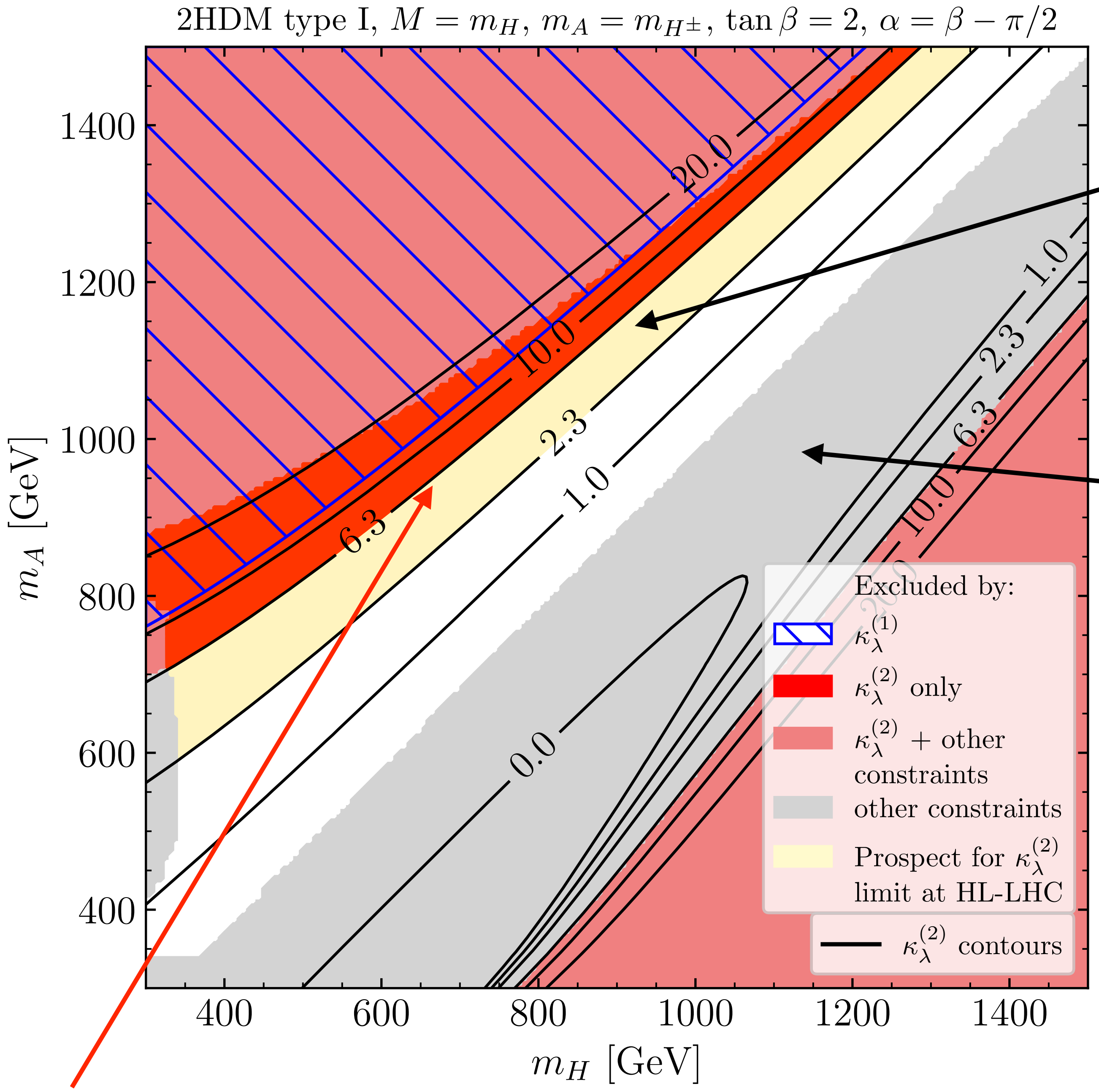


$\Rightarrow$ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

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

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. Weiglein '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!

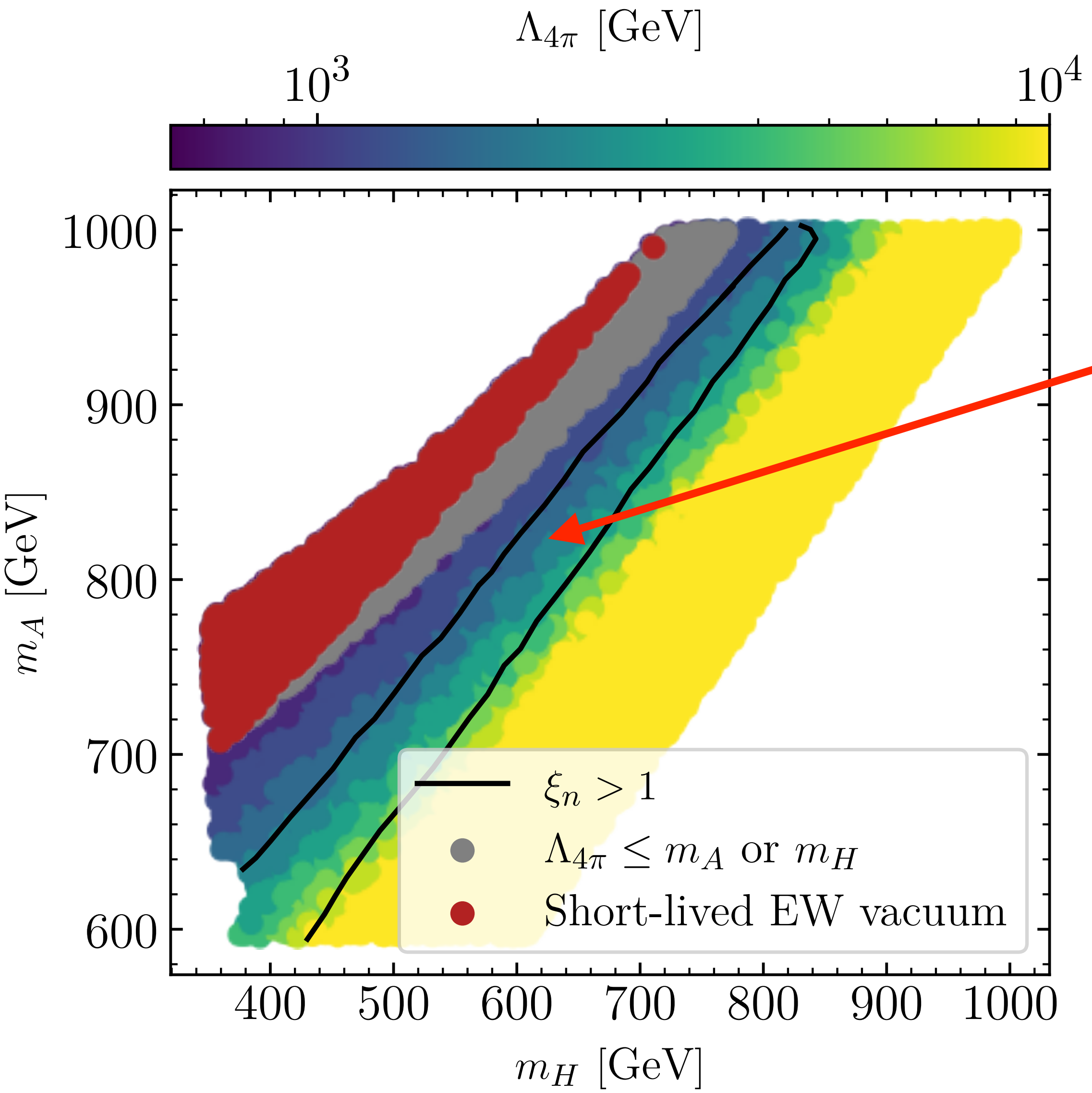
Connection between the trilinear Higgs coupling and the evolution of the early universe

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. Weiglein ’22]

2HDM of type II:

alignment limit,
tanβ = 3

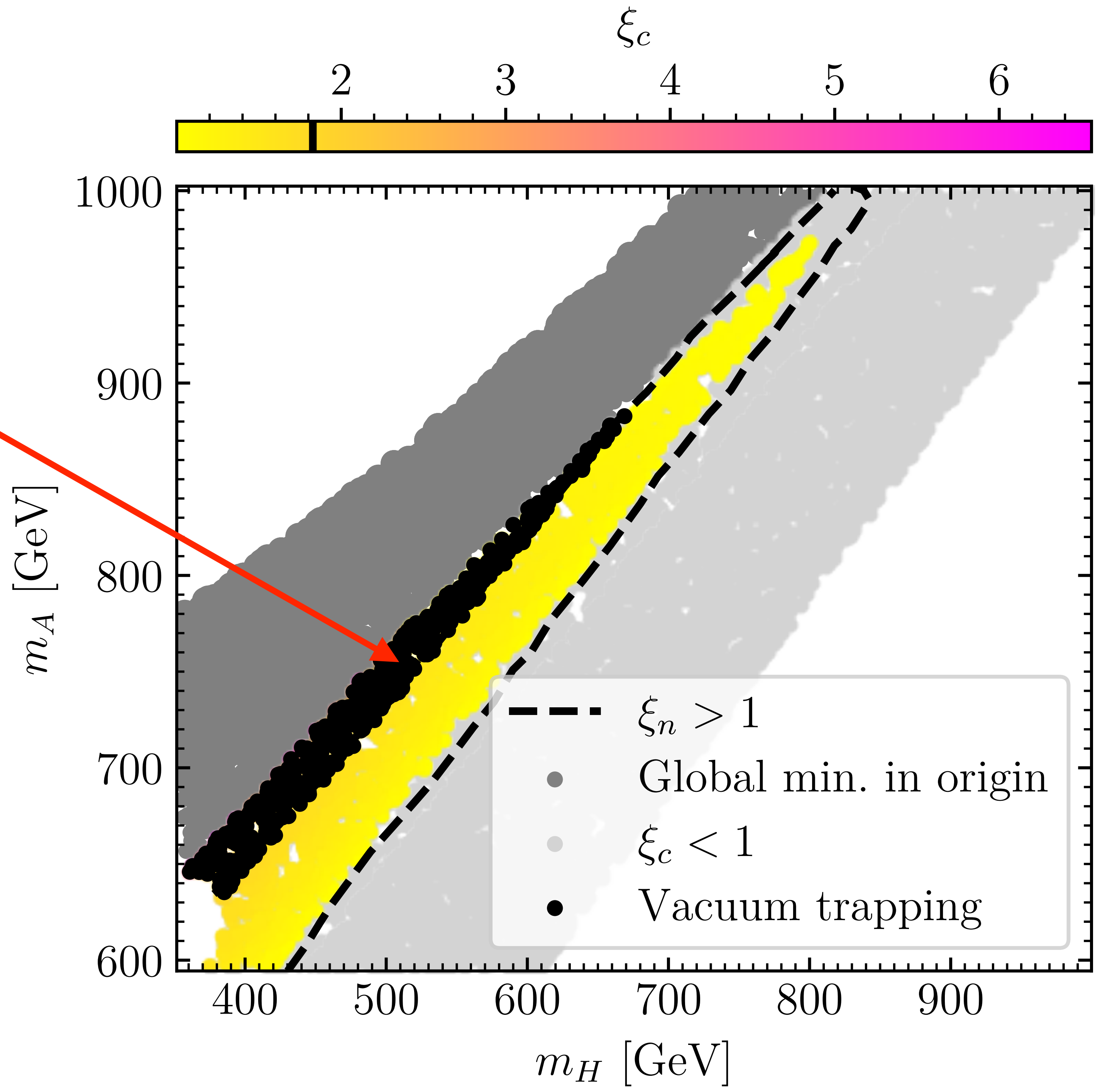


Parameter region giving rise to a strong first-order EWPT

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

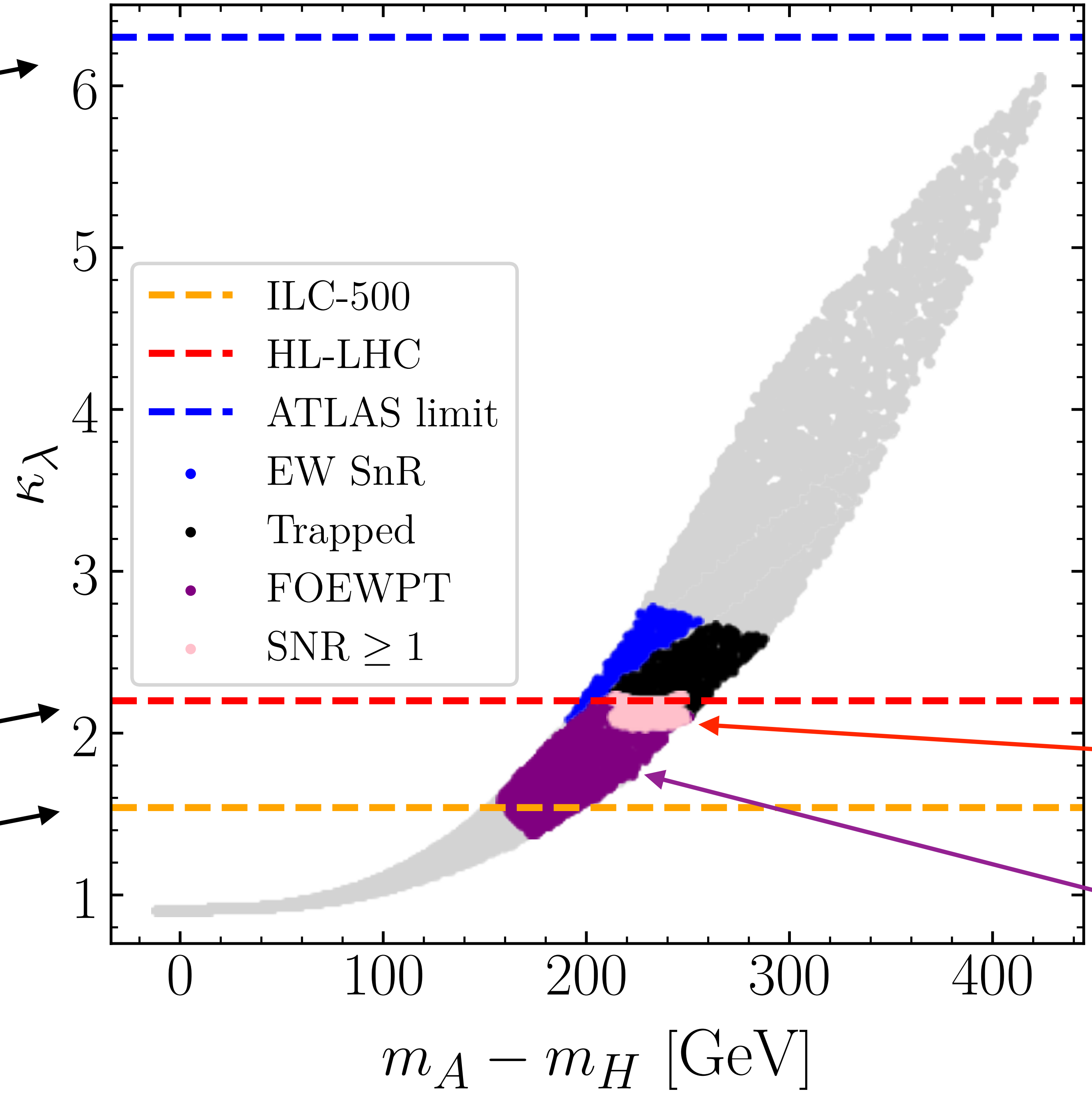
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. Weiglein ’22]

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. Weiglein ’22]



current bound

alignment limit,
tanβ = 3

HL-LHC sensitivity

ILC sensitivity

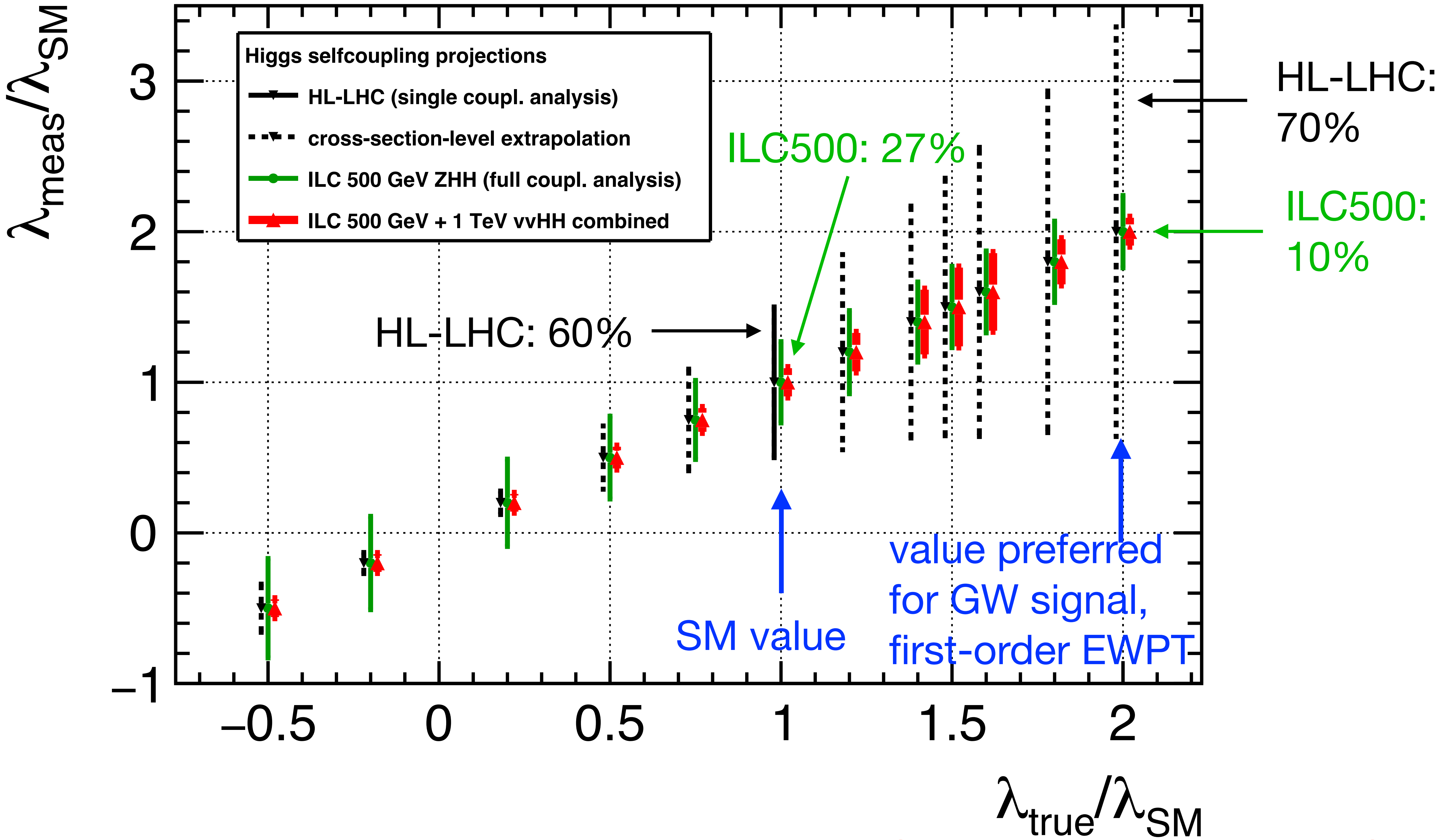
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

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

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC

[J. List et al. '21]



HL-LHC: 70%

ILC500: 27%

ILC500: 10%

HL-LHC: 60%

SM value

value preferred for GW signal, first-order EWPT

⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC500 than for HL-LHC

Reason: different interference contributions

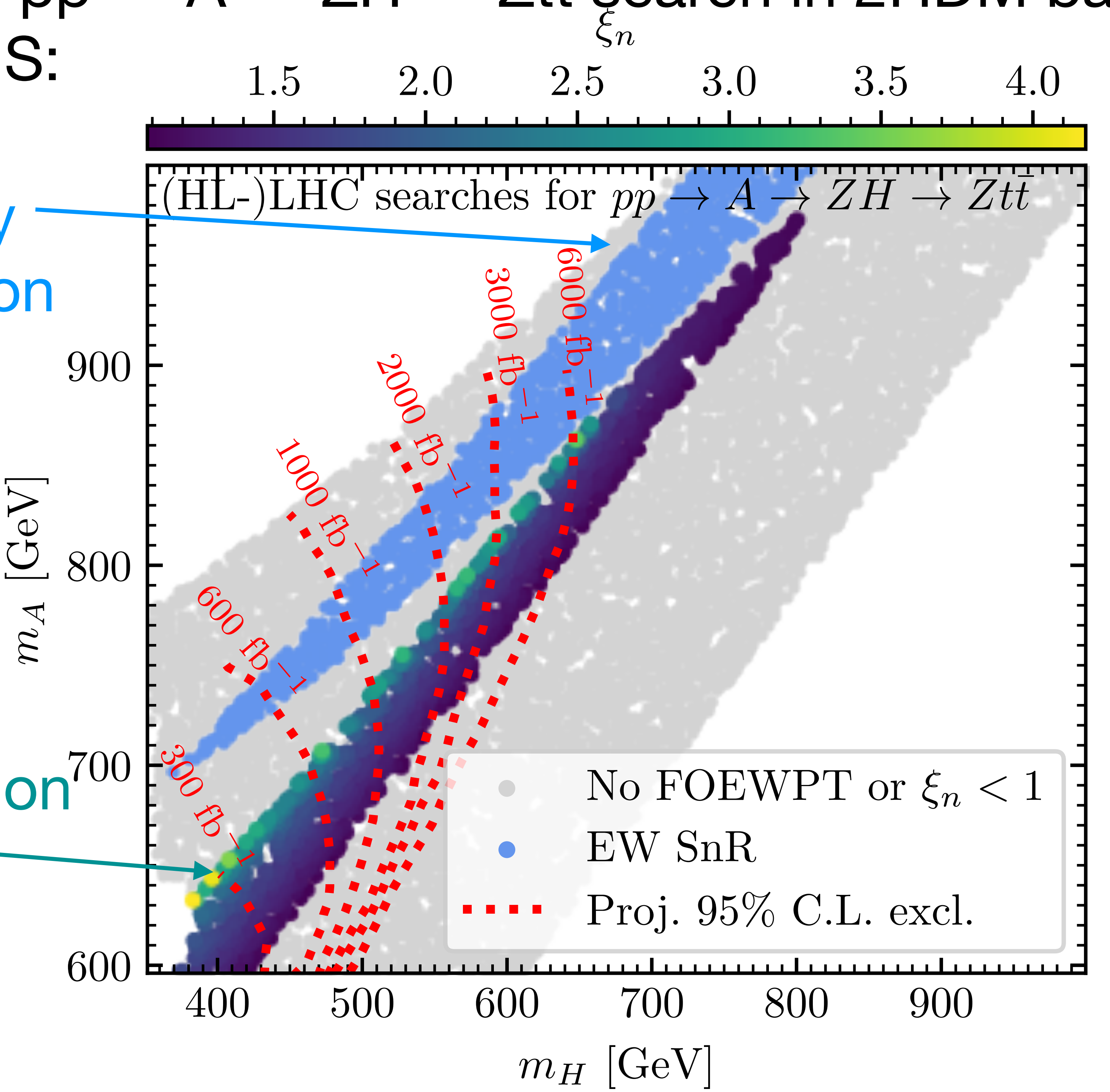
Probing the electroweak phase transition with the "smoking gun" signature

Projection for pp → A → ZH → Ztt search in 2HDM based on expected limit from CMS:

[Y. Fischer et al. '21]

EW symmetry non-restoration

Strongest phase transition



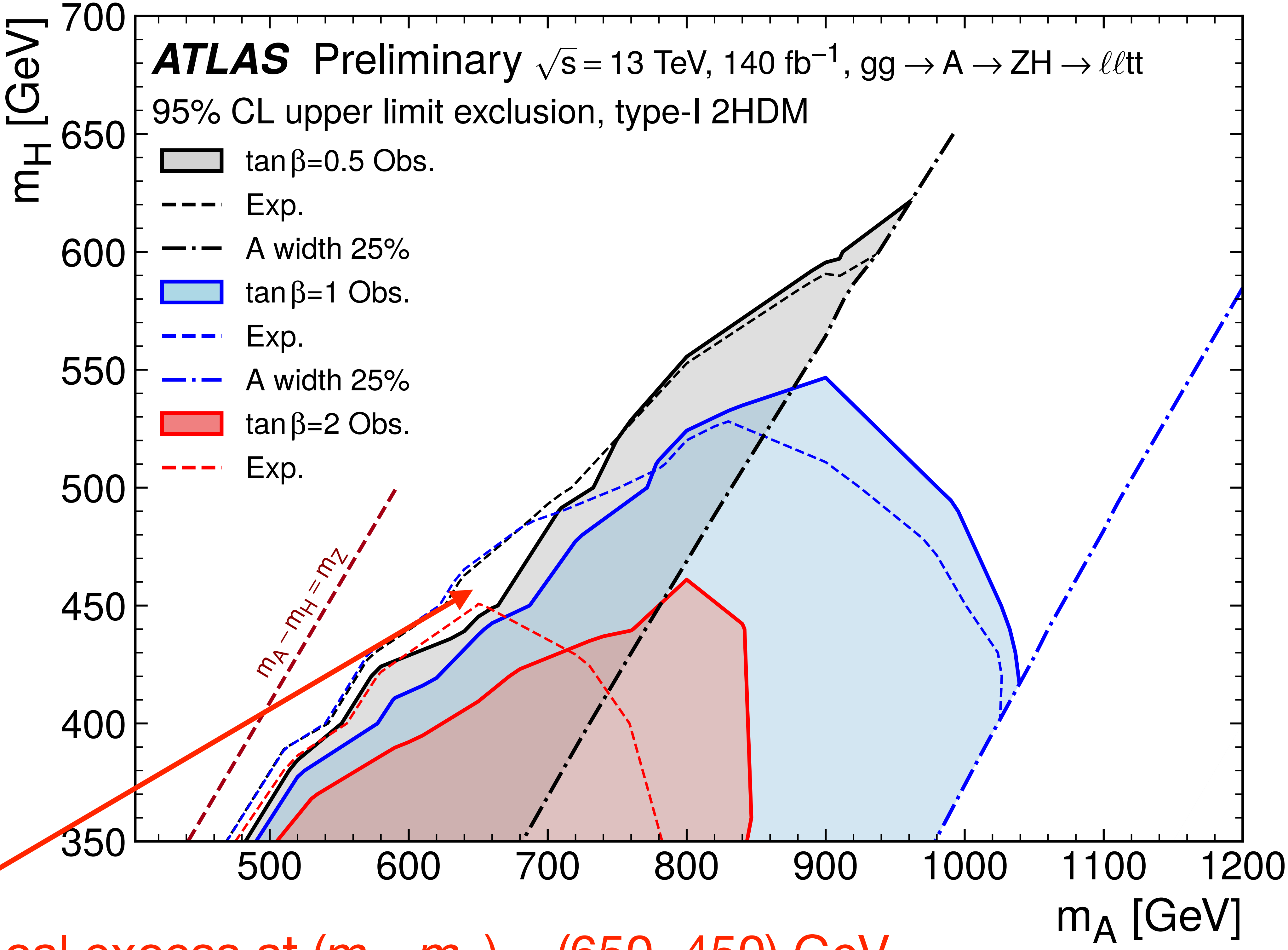
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. Weiglein '22]

alignment limit, tanβ = 3

⇒ Good prospects for probing the regions giving rise to strongest first-order EWPTs and to a potentially observable gravitational wave signal

New ATLAS result for the search for the “smoking gun” signature pp → A → ZH → Ztt in the 2HDM

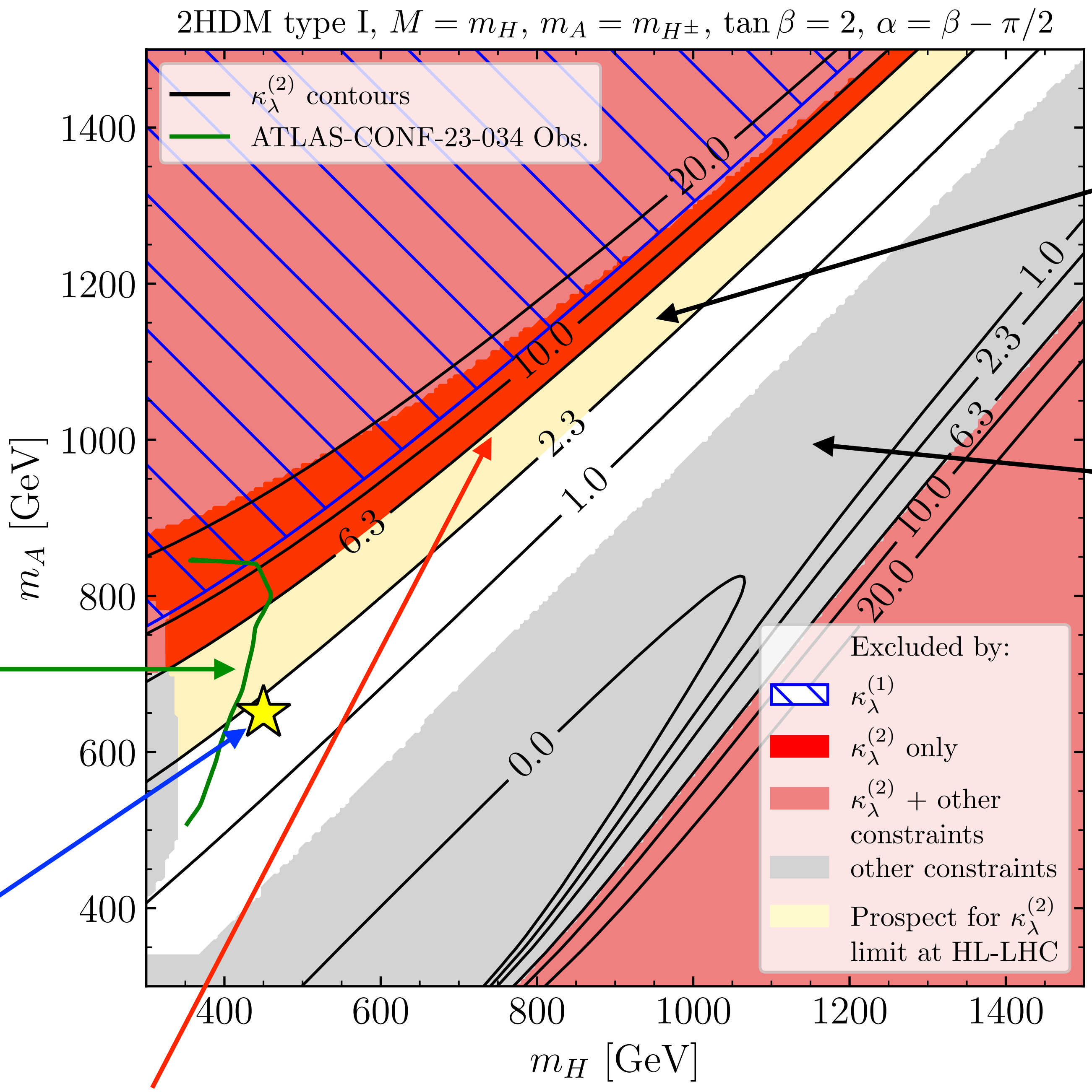
[ATLAS Collaboration ’23]



2.85 σ local excess at (m_A, m_H) = (650, 450) GeV

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. Weiglein ’23]



ATLAS limit

ATLAS excess

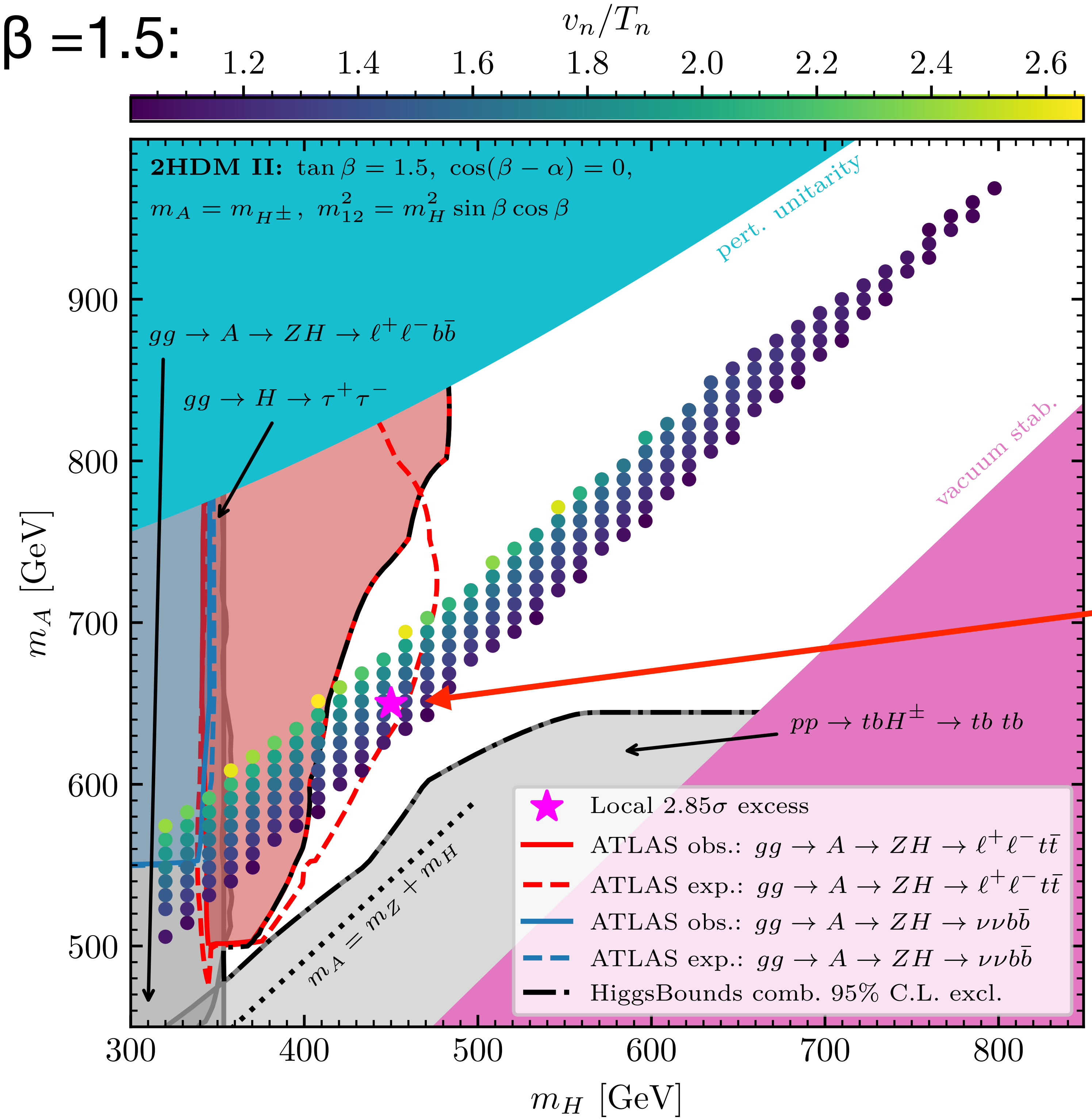
Sensitivity to ϰλ at the HL-LHC

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!

ATLAS result vs. preferred parameter region for strong first-order electroweak phase transition

2HDM, tanβ =1.5:



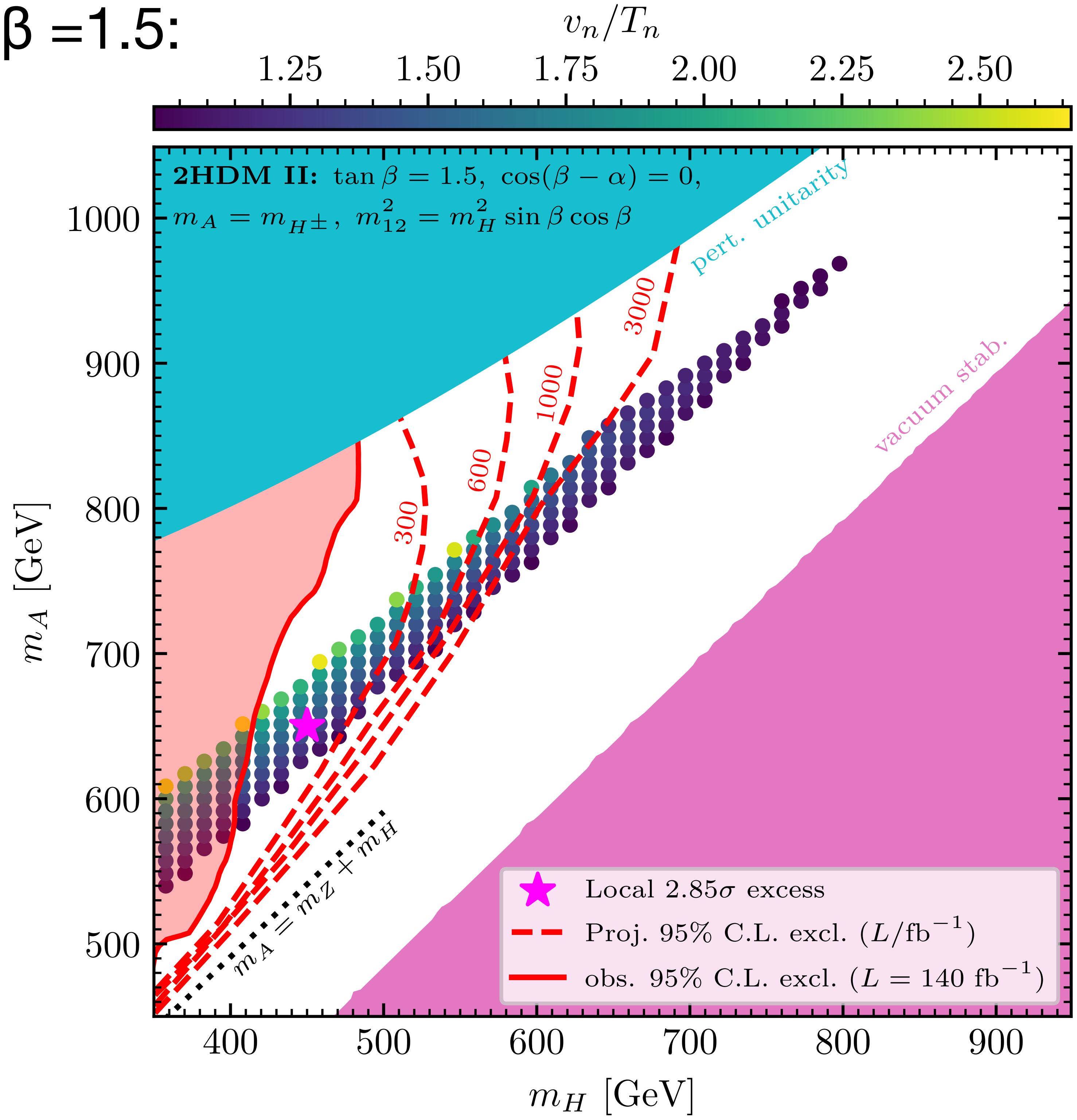
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. Weiglein '23]

2.85 σ local excess at (m_A, m_H) = (650, 450) GeV

⇒First hint for a strong first-order EWPT in the 2HDM?

Projection for future sensitivity based on ATLAS result

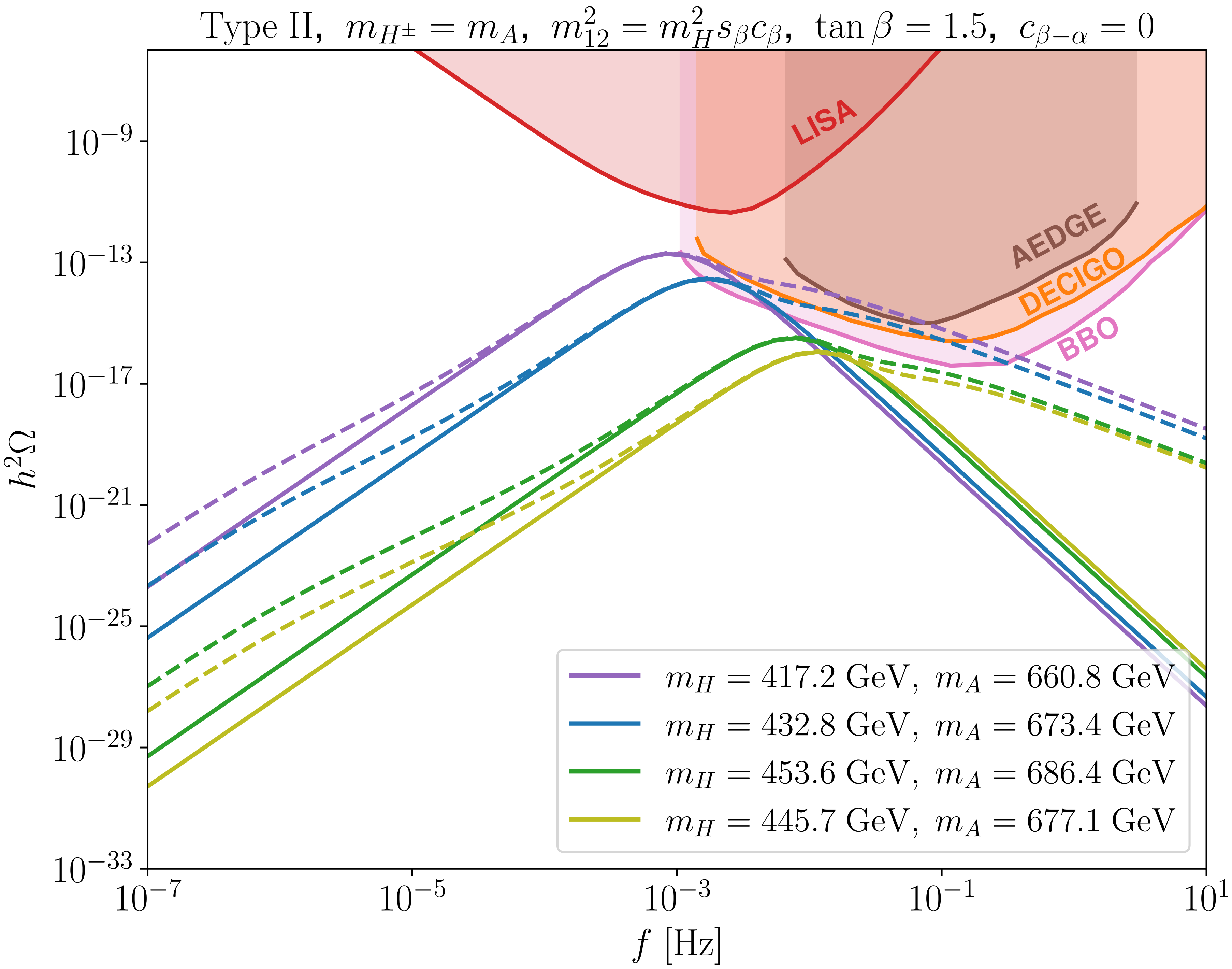
2HDM, tanβ =1.5:



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

⇒Good agreement with projection based on expected CMS limit

GW spectra of scenarios fitting the excess



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

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

Further “smoking gun” signature

The parameter region that potentially gives rise to a strong first-order EWPT can also be probed via the search

$$H^{\pm} \to W^{\pm} H \to \ell^{\pm} \nu t \bar{t}$$

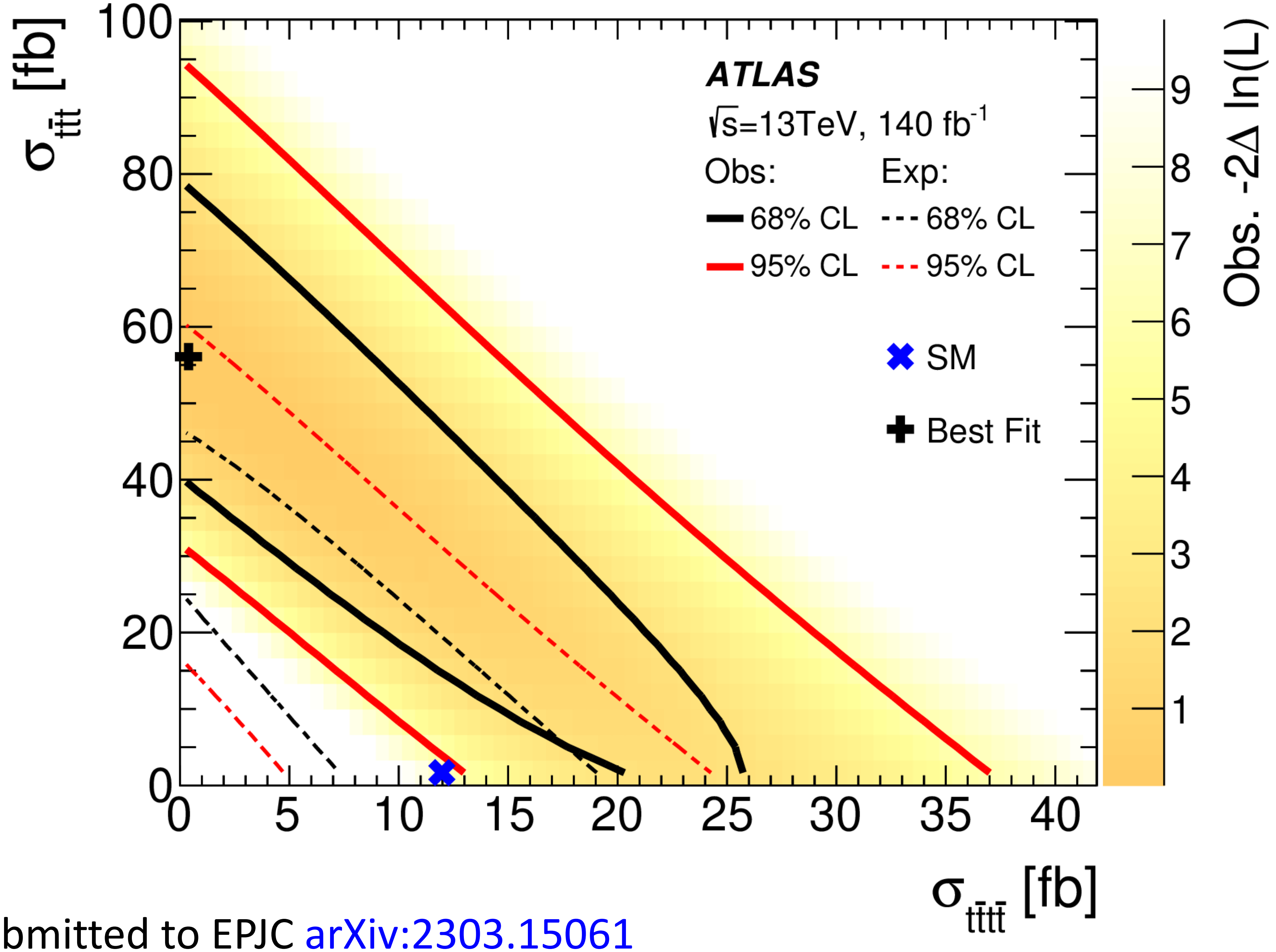
For the production of the charged Higgs together with *t b* this yields a 4-top like or 3-top like final state

Results for the 4-top final state exist from ATLAS and CMS (and for 3-top vs. 4-top from ATLAS), but so far no dedicated experimental analysis for the charged Higgs channel has been performed!

ATLAS: 3-top vs. 4-top final states

ATLAS: three tops?

[ATLAS Collaboration '23]

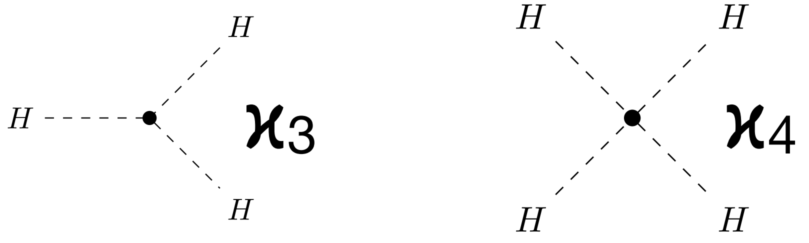


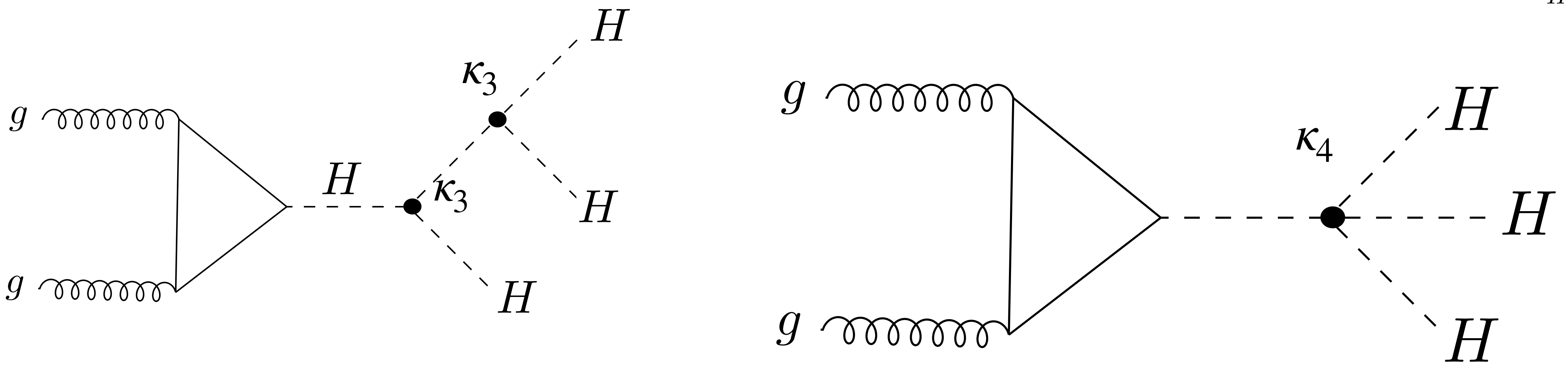
Submitted to EPJC arXiv:2303.15061

freyablekman FH physics discussion

Exploring HHH production w.r.t. 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

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

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:

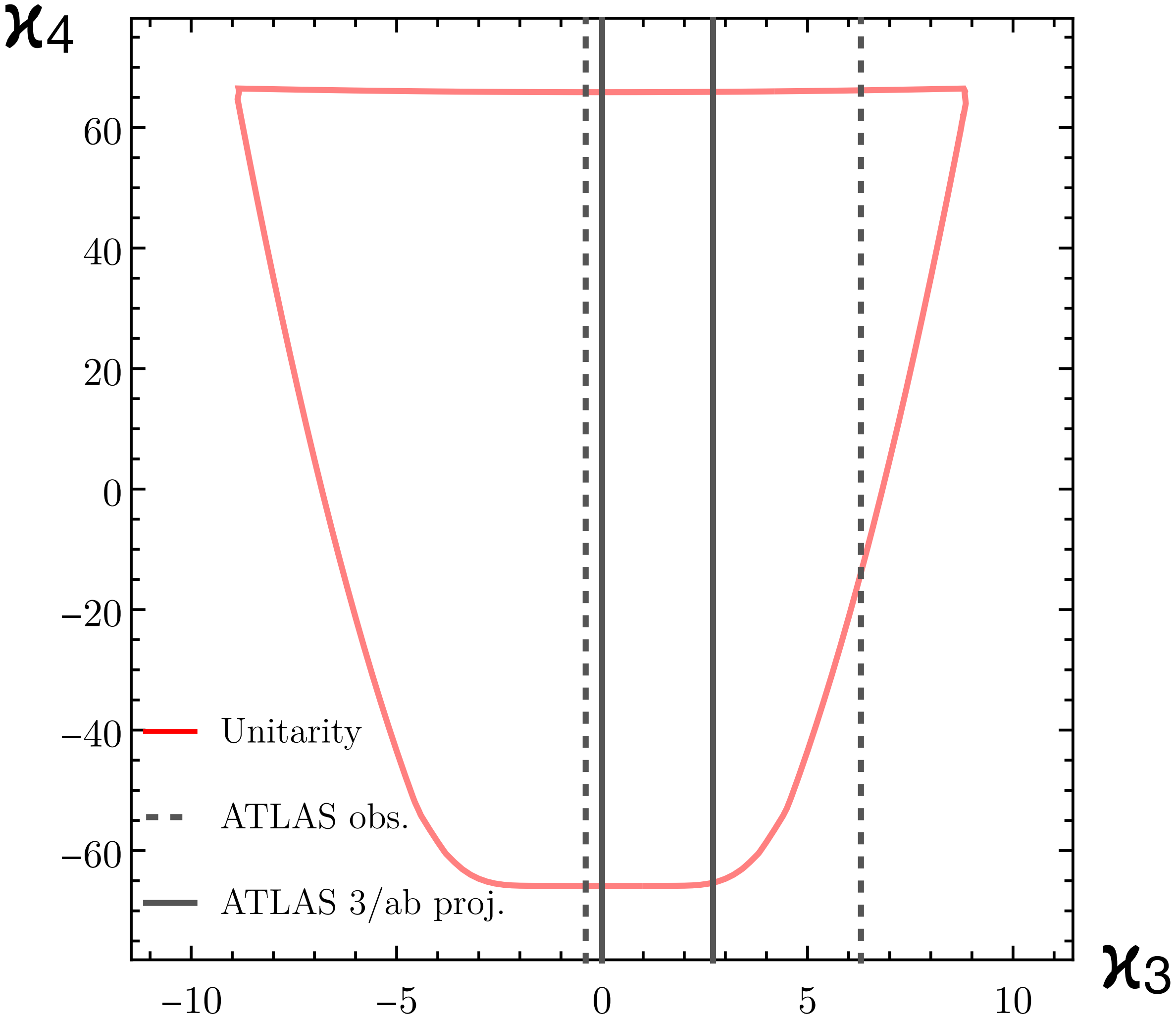
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

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]

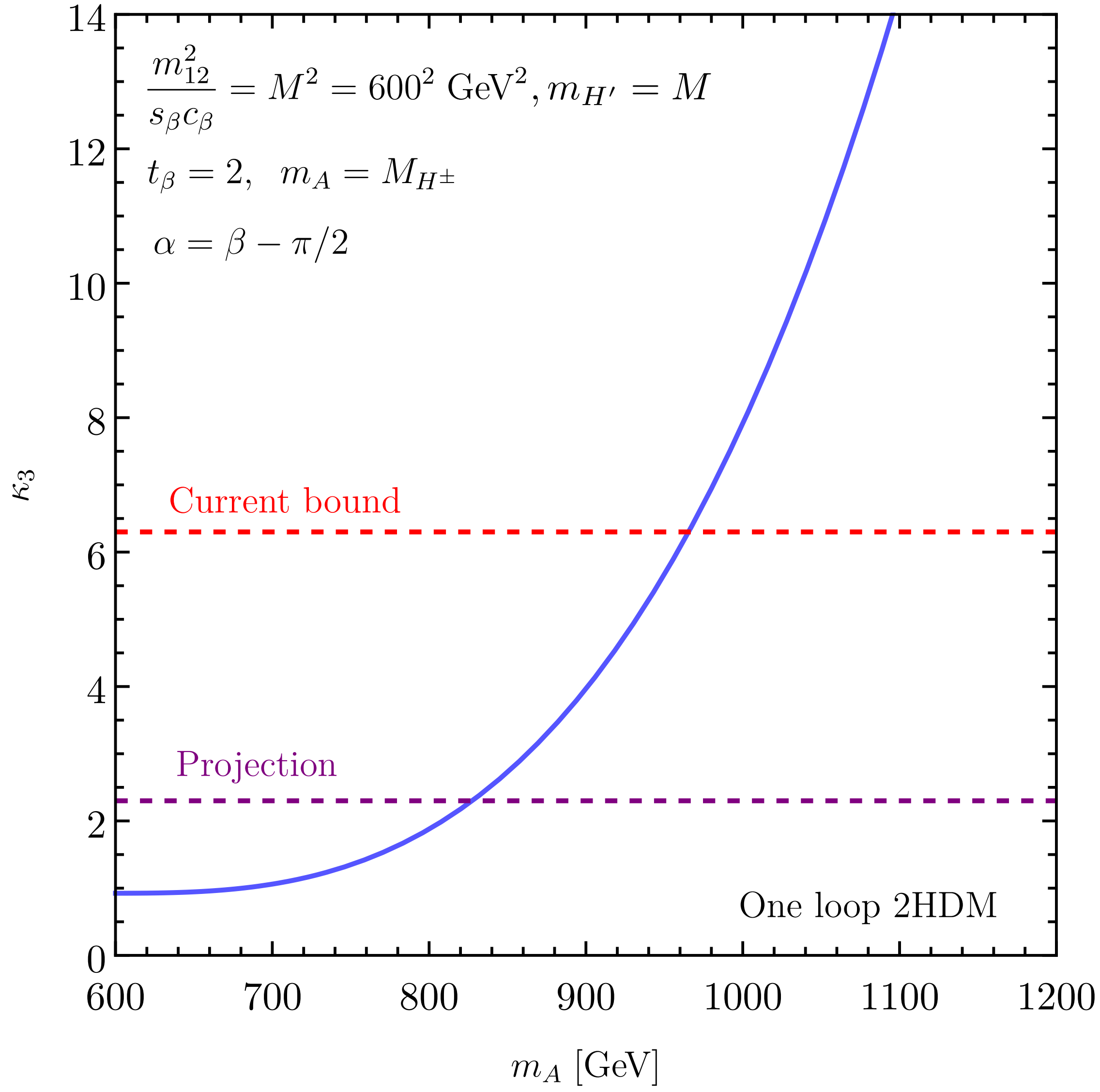


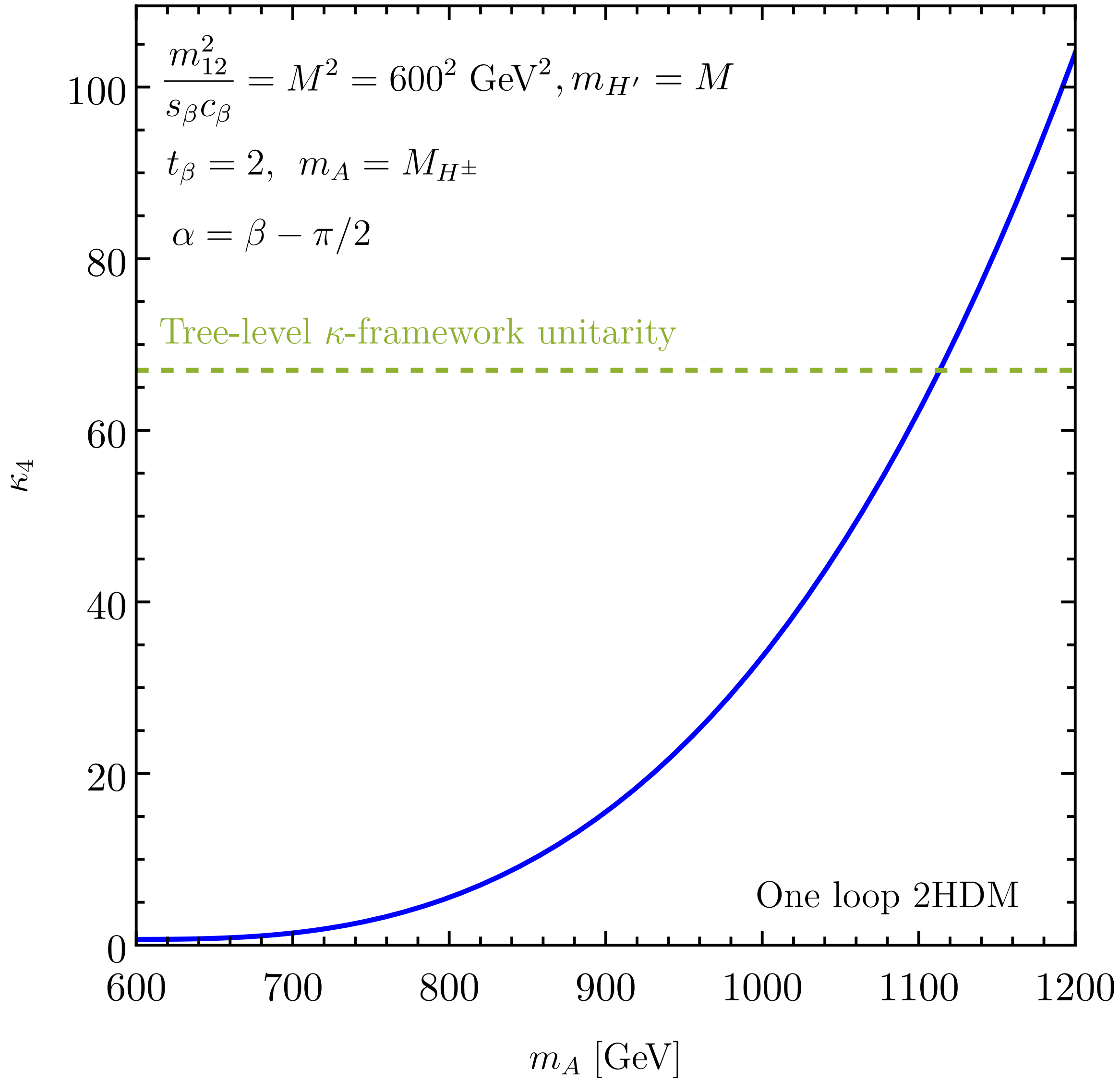
Model example: 2HDM, $\varkappa_3$ (see above) vs. $\varkappa_4$

- Benchmark Point of [Bahl, Braathen, Weiglein `22] → cross-check κ_3 result (also with anyH3)
- Expectedly deviations in κ_3 induce sizeable deviations in κ_4

$$\kappa_i = \frac{\Gamma_i^{(0)} + \hat{\Gamma}_i^{(1)}}{\Gamma_{\mathrm{SM},i}^{(0)}}$$

$$i \in \{3H, 4H\}$$





Prospects for the HL-LHC

- Use of Graph Neural Networks (GNN) for signal-background classification

- Focus on $6b$ and $4b2\tau$ final states with 5 and 3 tagged b-quarks, respectively

Backgrounds:

$6b$: dominant QCD contributions (see also [Papaefstathiou, Robens, Xolocotzi`21])

$4b2\tau$: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},$
$t\bar{t}(H \to \tau\tau),\ t\bar{t}(H \to b\bar{b}),$
$t\bar{t}(Z \to \tau\tau),\ t\bar{t}(Z \to b\bar{b}),\ t\bar{t}t\bar{t}$

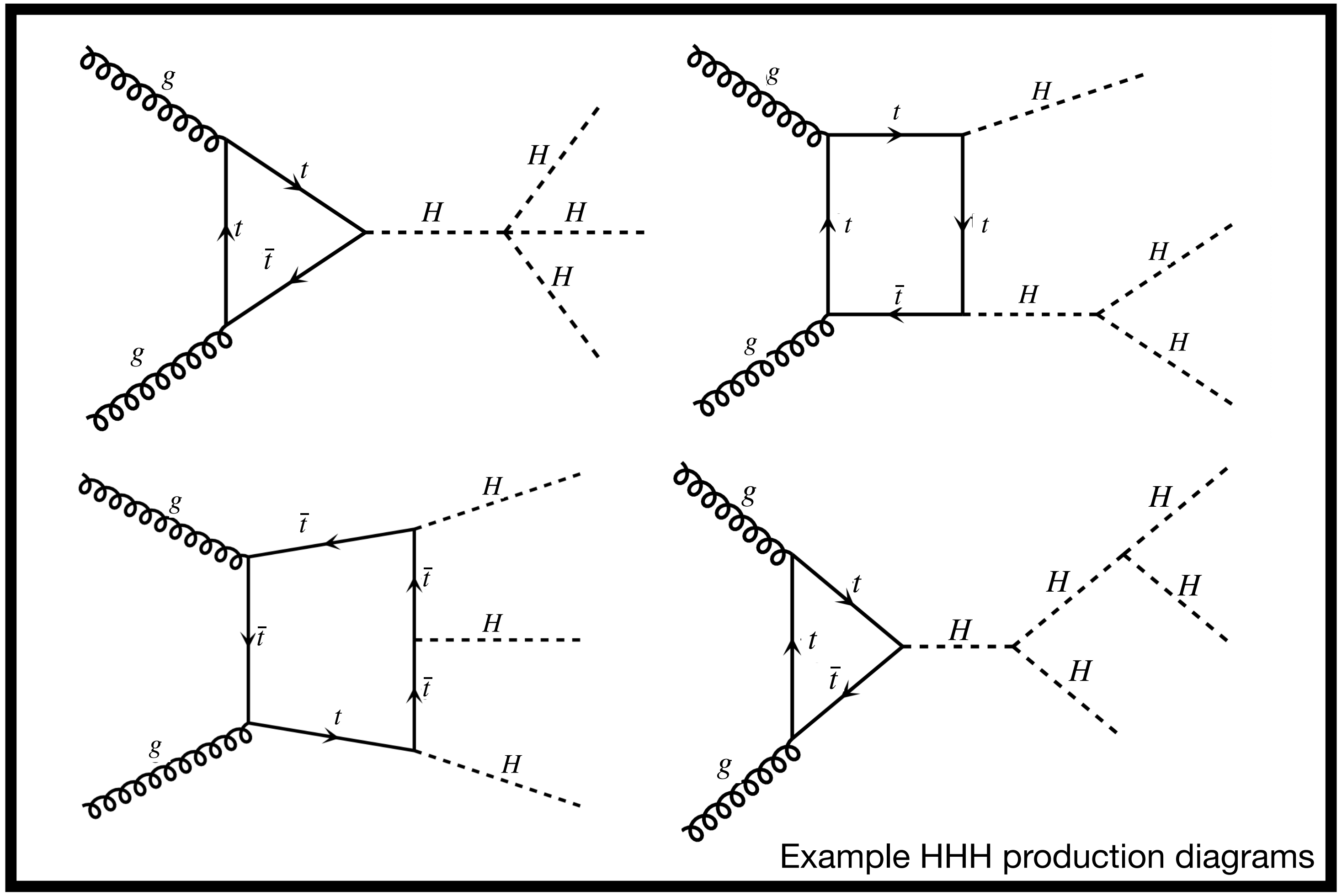
Event generation and pre-selection

- Events generated with MadGraph5_aMC@NLO
- Higgs states decayed with MadSpin

(conservative) background K-factor of 2

signal K-factor of 1.7

[Florian, Fabre, Mazzitelli` 20]



Example HHH production diagrams

Pre-selection cuts:

Invariant mass of final states: $\gtrsim 350$ GeV

At least one pair of tagged states with $m_{ij} \in [110,140]$

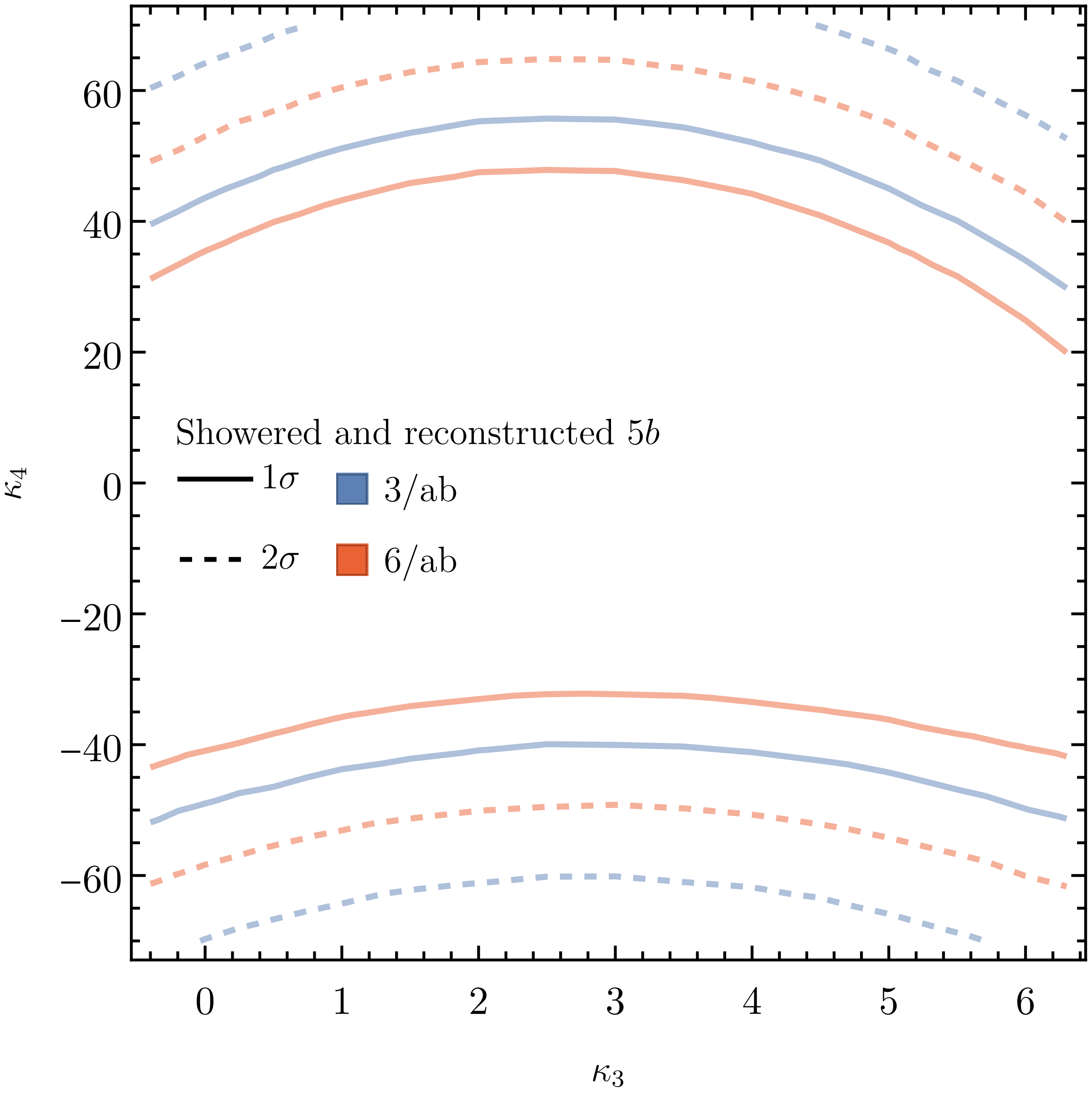
$p_T(b) > 30$ GeV $p_T(\tau) > 10$ GeV

$|\eta(\tau)| < 2.5$ $|\eta(b)| < 2.5$

Showered and reconstructed results: 5b

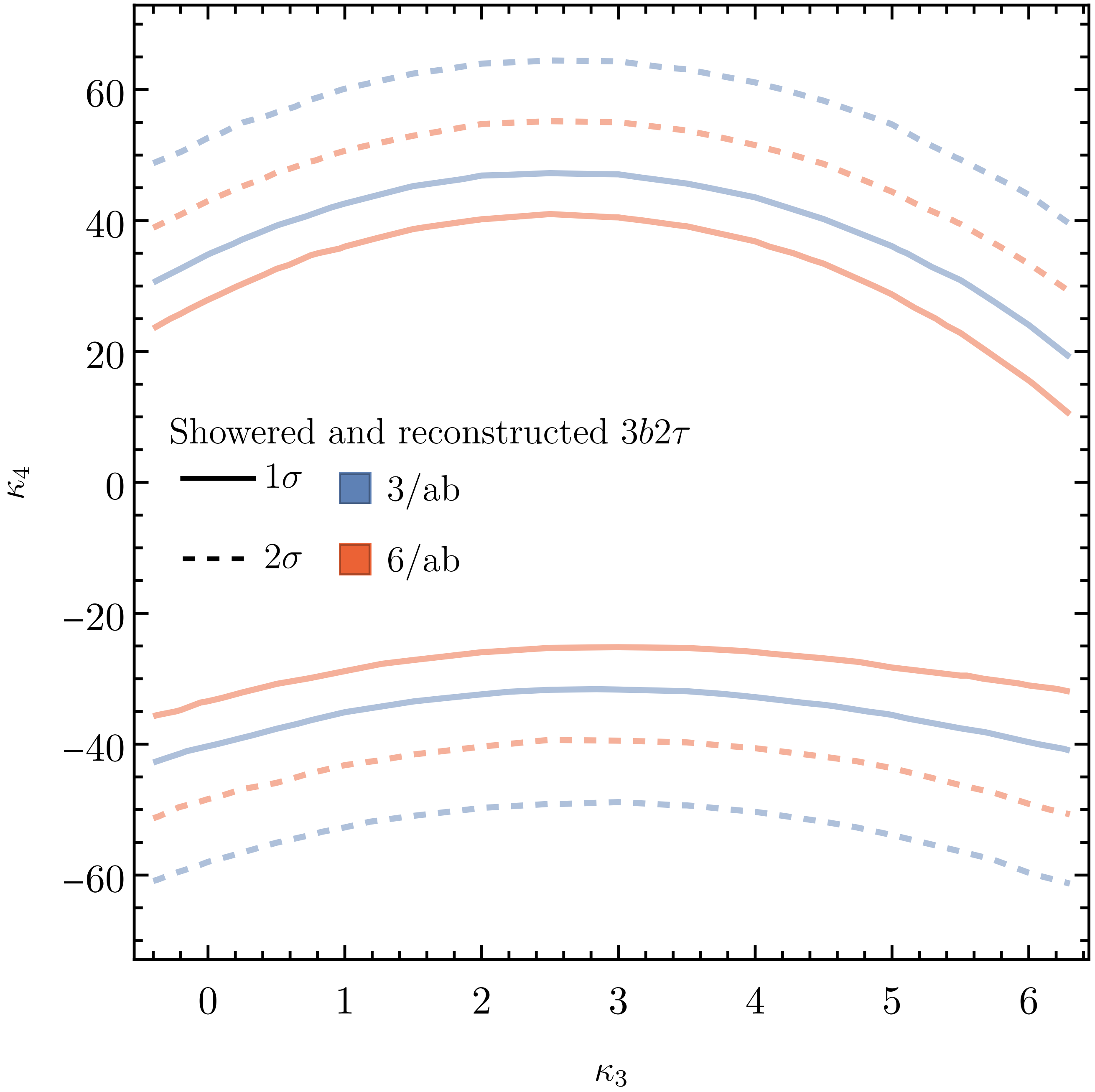
- Showering and reconstruction of events: Pythia, FastJet, Rivet
- HL-LHC luminosity of 3/ab and ATLAS-CMS combined luminosity of 6/ab

Signal region selected with cut on background score $P[QCD] \lesssim 0.5\,\%$



Showered and reconstructed results: 3b2$\boldsymbol{\tau}$

- $3b2\tau$ more complicated due to multiple backgrounds → multi-class classification
- Train on backgrounds: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},\ t\bar{t}(H \to \tau^+\tau^-)$

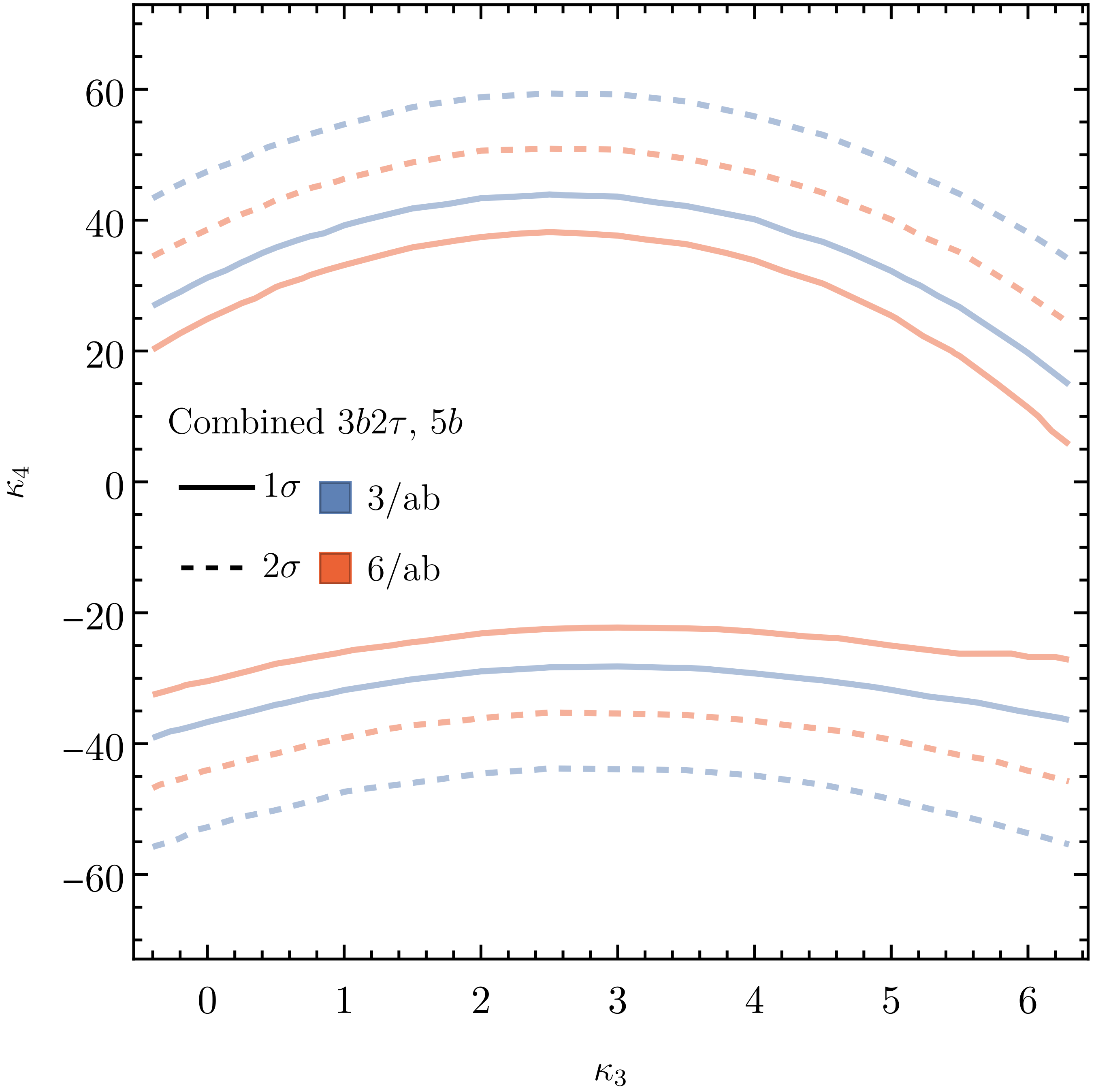


Combined results

- **Assumption:** No correlations
- Simplified combination of significances (Stouffer method)

$$Z_{\text{comb.}} = \frac{Z_{3b2\tau} + Z_{5b}}{\sqrt{2}}$$

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



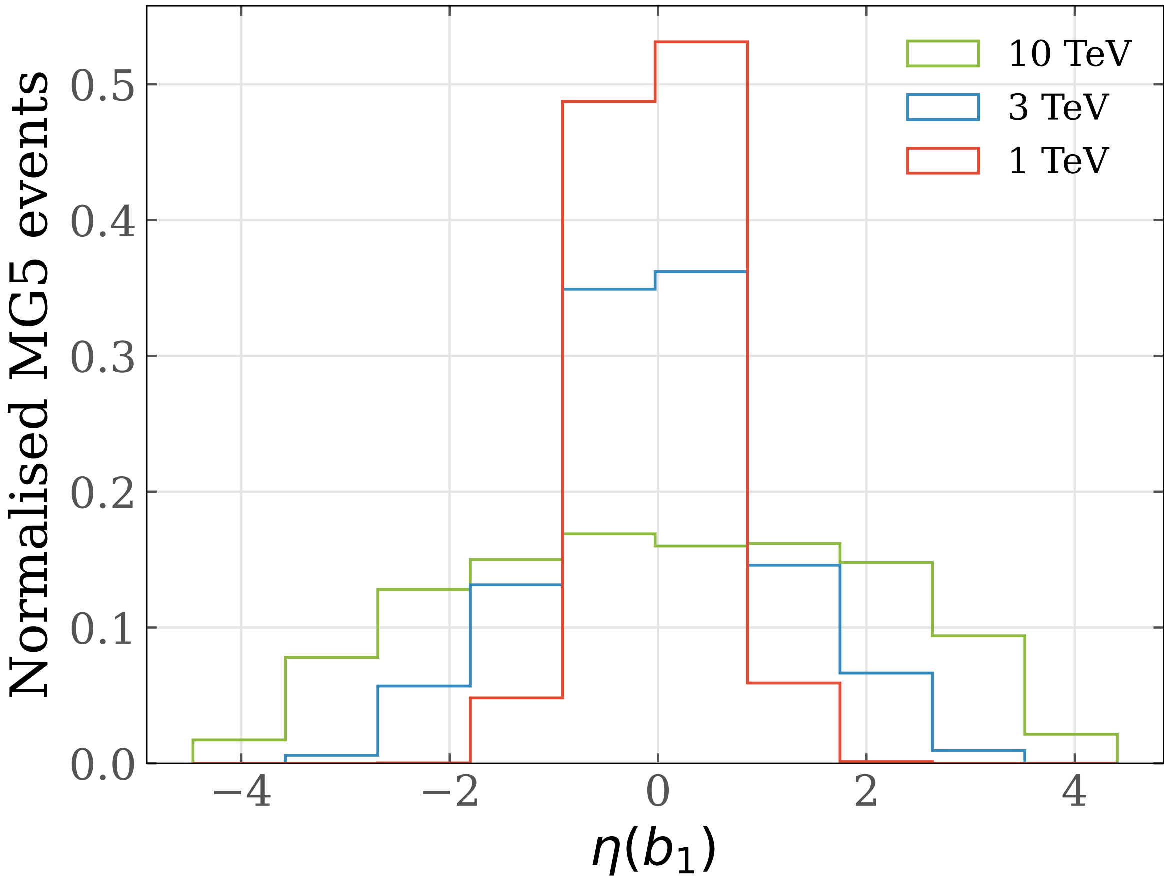
Prospects for future lepton colliders

- Inclusive $\ell\ell \to HHH + X$ analysis with $H \to b\bar{b}$

  - At least 5 tagged b-quarks with $p_T(b) > 30$ GeV
  - Tagging efficiency: $80\,\%$

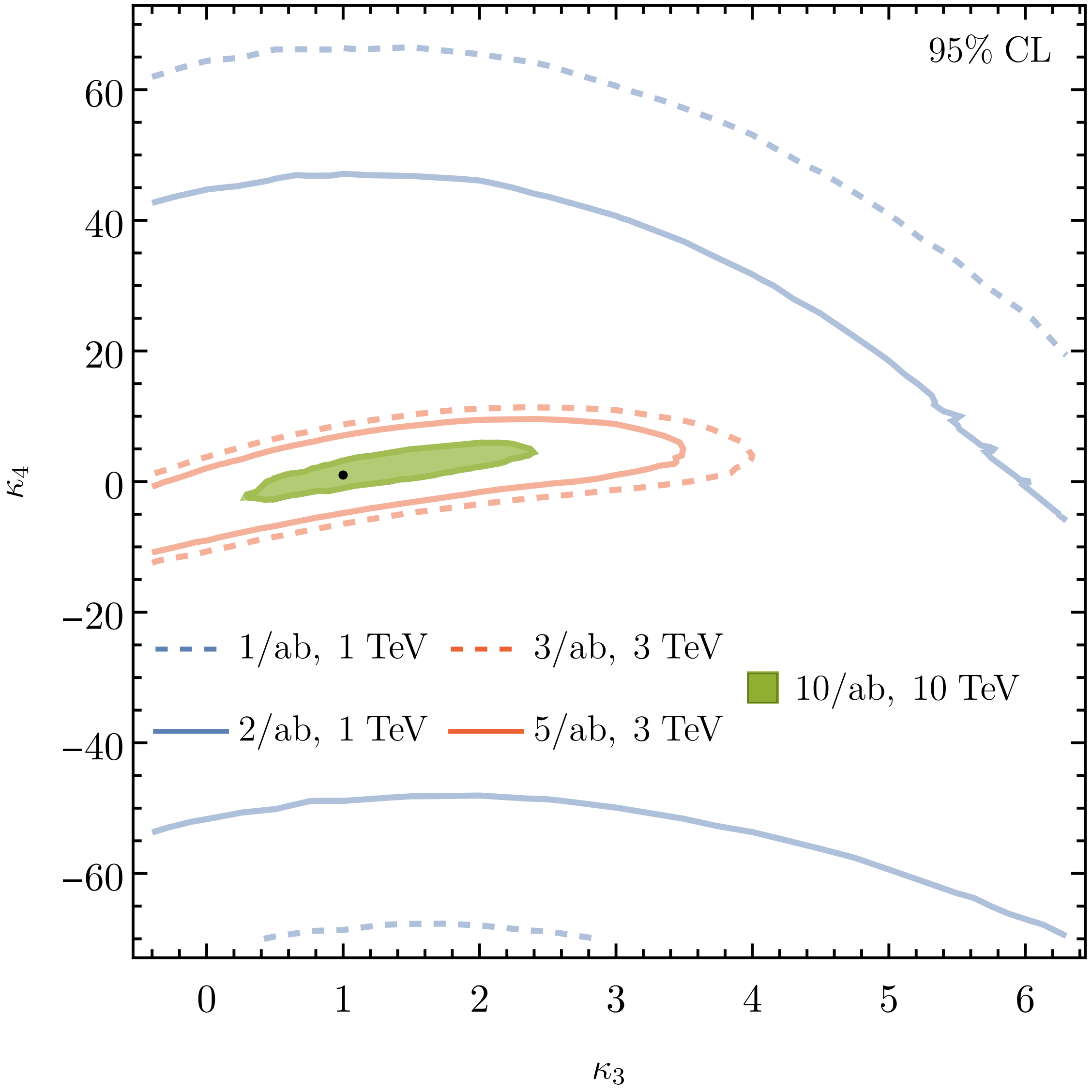
- **Important:** For high energies b-quarks are not only in the central part of detector → requires extended tagging capabilities

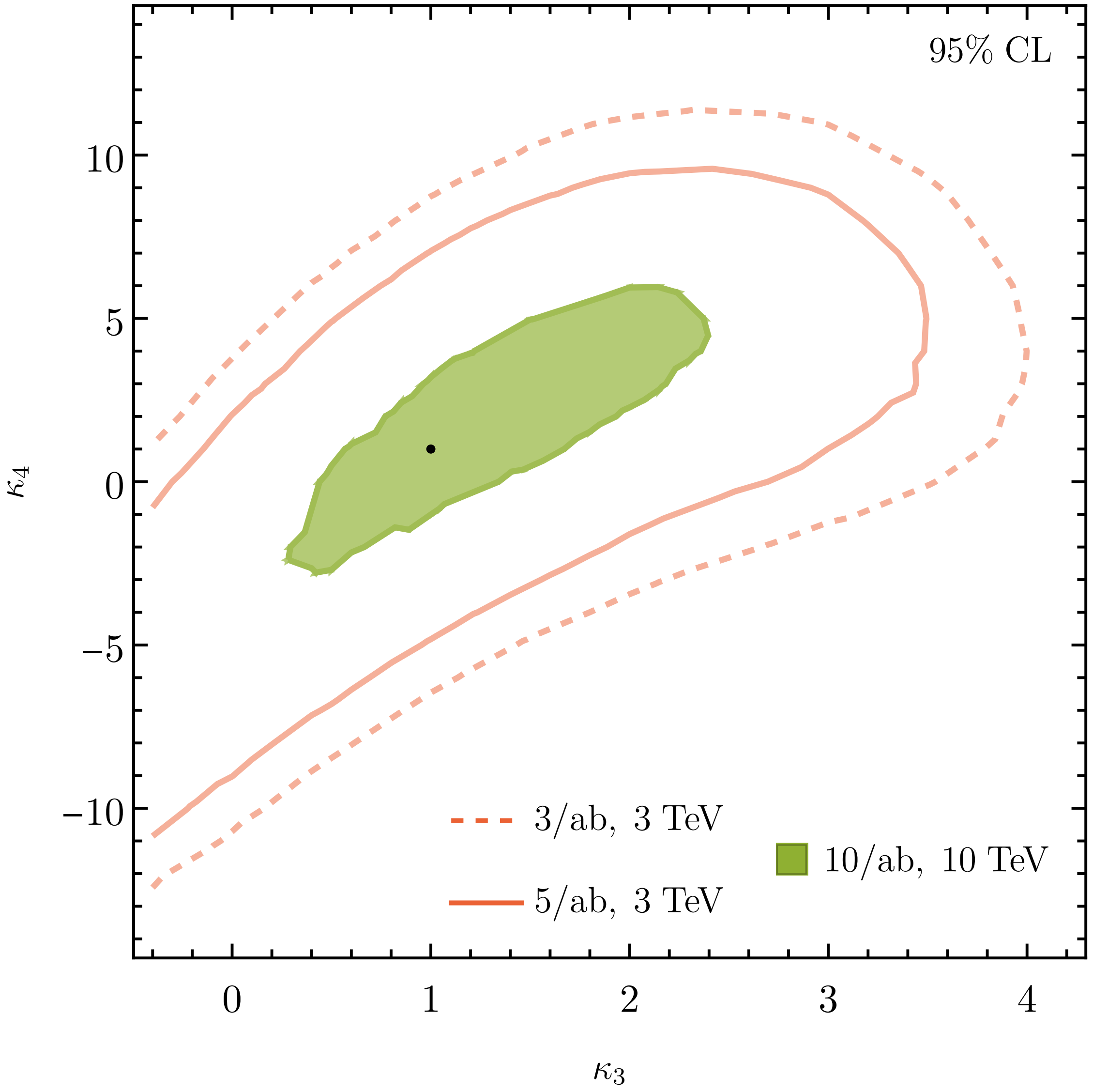
- Negligible background from other SM processes



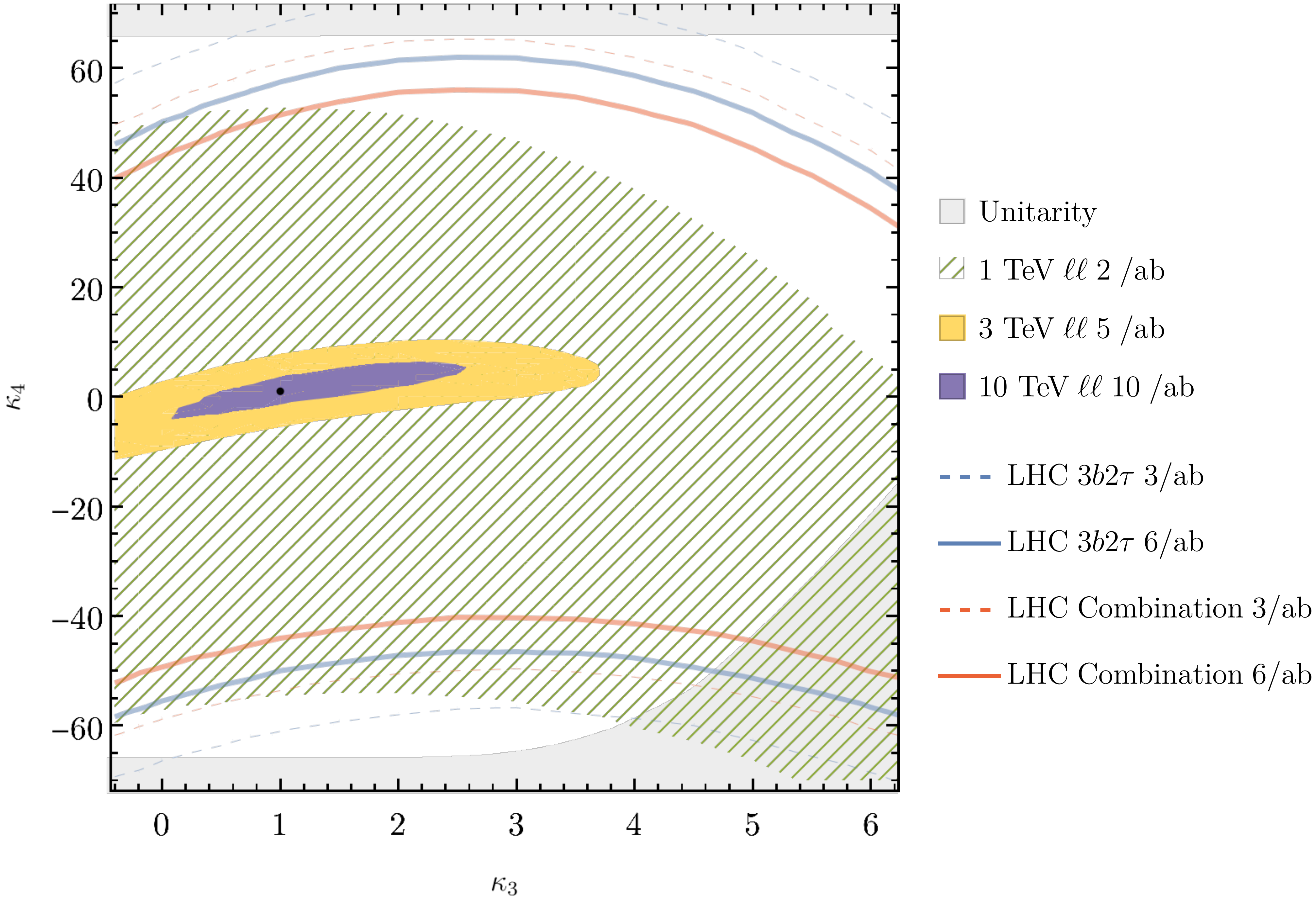
Higgs self-couplings at lepton colliders

- Poissonian analysis: $\mu_{\rm up} = \frac{1}{2} F^{-1}_{\chi^2}\left[2(n+1); {\rm CL}\right]$
- Results similar to other works with dedicated analyses for 1 and 3 TeV, e.g. [Maltoni, Pagani, Zhao ` 18]





Triple Higgs production: HL-LHC vs. lepton colliders



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

Conclusions

Trilinear Higgs self-coupling: close relation to electroweak phase transition and thermal evolution of the early universe

Current constraints on the trilinear Higgs coupling from the LHC have already sensitivity to the physics of extended Higgs sectors

2HDM, N2HDM: region with strong first-order EWPT (and potentially detectable GW signal) is correlated with significant deviation of $\varkappa_\lambda$ from the SM value and can be probed with LHC ``smoking gun” signature

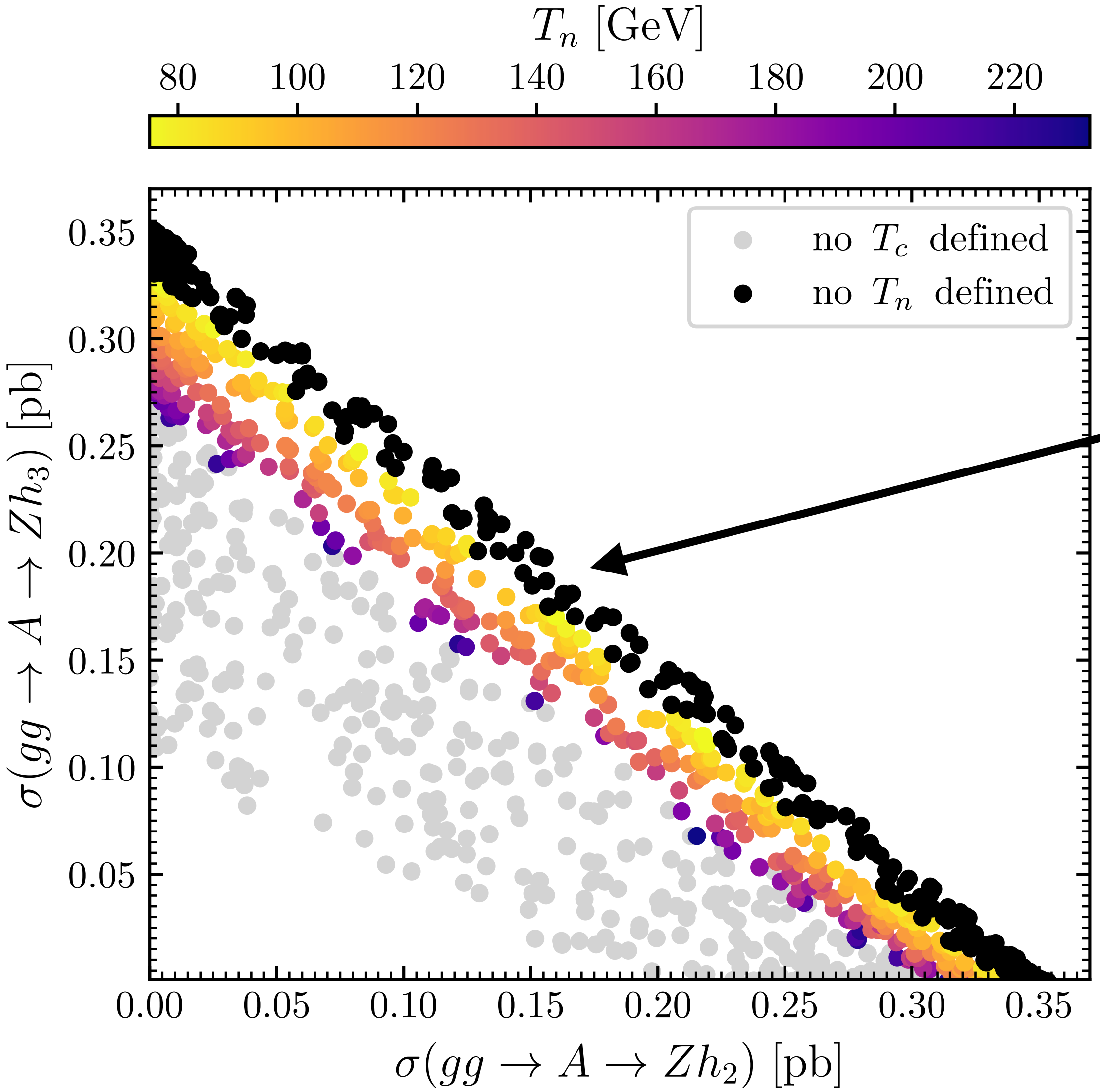
Triple Higgs production: HL-LHC has potential to probe $\varkappa_4$ beyond unitarity bounds and for complementary constraints on $\varkappa_3$

Backup

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. Weiglein '21]



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

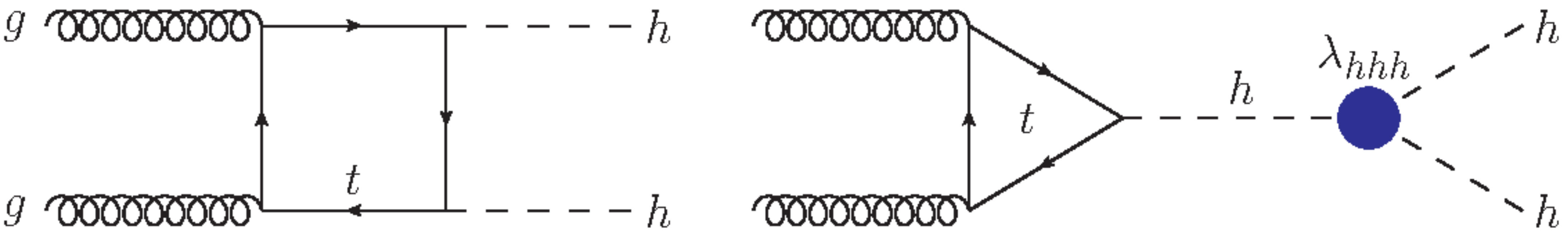
⇒ Lower nucleation temperatures, i.e. stronger first-order EWPTs, are correlated with larger signal rates at the LHC!

Trilinear Higgs self-coupling: experimental situation

The measurement of the trilinear Higgs self-coupling λ_{hhh} is a prime experimental goal, but a coupling by itself is not a physical observable

Experimental access via Higgs pair production (or indirectly via loop contributions involving λ_{hhh}):

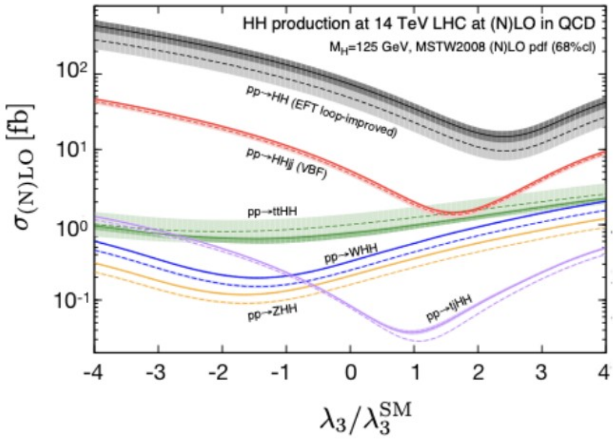
- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



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

Box and triangle diagrams interfere destructively

⇒ Small cross section in the SM, can be much enhanced if λ_{hhh} deviates from the SM value



[Frederix et al., '14]

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	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Simple example of extended Higgs sector: 2HDM

- 2 $SU(2)_L$ doublets $\Phi_{1,2}$ of hypercharge ½
- CP-conserving 2HDM, with softly-broken Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) to avoid tree-level FCNCs

$$V^{(0)}_{\rm 2HDM} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2)$$
$$+ \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \frac{\lambda_5}{2}\Big((\Phi_2^\dagger\Phi_1)^2 + \mathrm{h.c.}\Big)$$

- m_1,m_2 eliminated with tadpole equations, and $v_1^2 + v_2^2 = v^2 = (246\ \mathrm{GeV})^2$
- 7 free parameters in scalar sector: m_3, λ_i (i=1,..,5), $\tan\beta \equiv v_2/v_1$
- Mass eigenstates: h, H: CP-even Higgses, A: CP-odd Higgs, $H^\pm$: charged Higgs, α: CP-even Higgs mixing angle
- λ_i (i=1,..,5) traded for mass eigenvalues m_h, m_H, m_A, $m_{H\pm}$ and angle α
- m_3 replaced by a Z_2 soft-breaking mass scale

$$M^2 = \frac{2m_3^2}{s_{2\beta}}$$

- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde\lambda_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

In alignment limit, α = β - π/2 : h couplings are SM-like at tree level

Possible size of BSM contributions:
SMEFT: effects of higher-dimensional operators

[Boudjema, Chopin `96]
[Maltoni, Pagani, Zhao `18]

Linear power expansion for higher order terms in Λ^{-1} orders:

$$V_{\text{BSM}} = \frac{C_6}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 + \frac{C_8}{\Lambda^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4 + \ldots$$

Contributions to κ_3, κ_4:

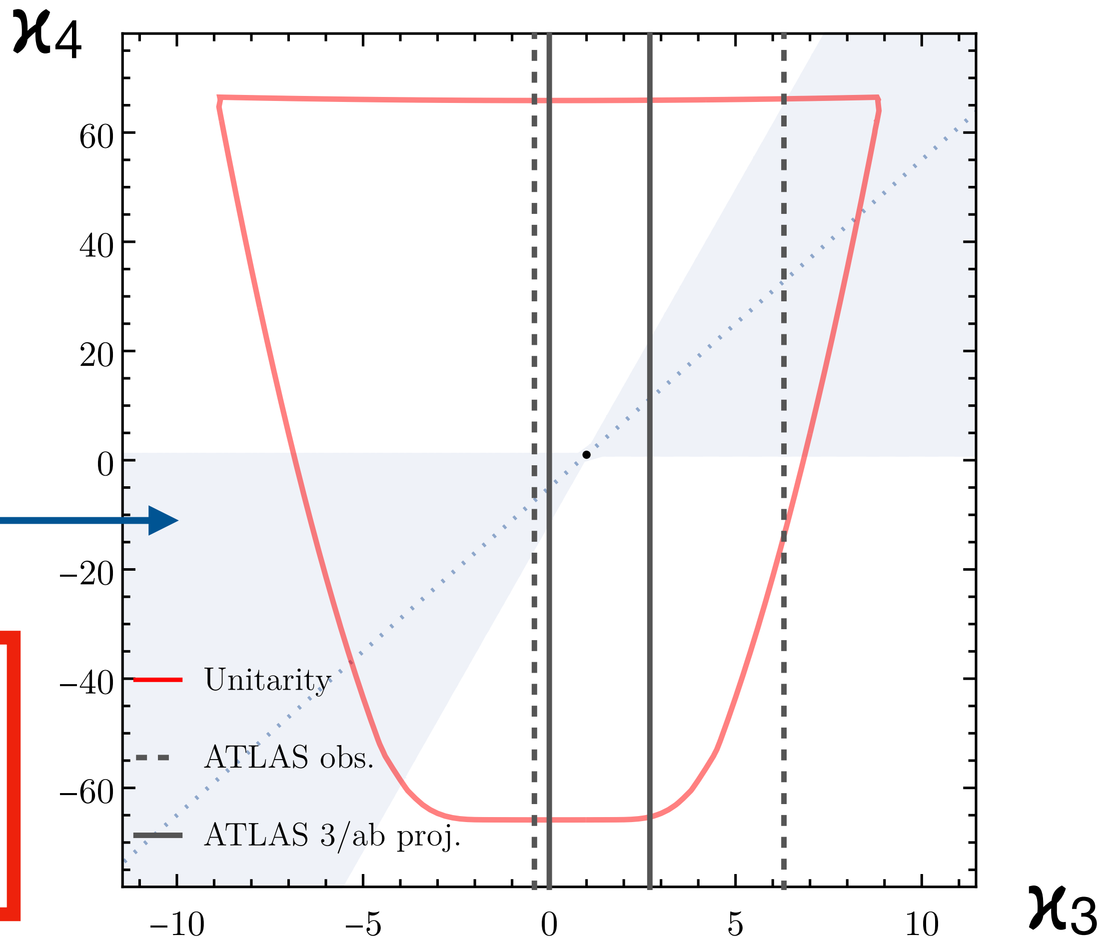
$$(\kappa_3 - 1) = \frac{C_6 v^2}{\lambda\Lambda^2}\,,$$

$$(\kappa_4 - 1) = \frac{6C_6 v^2}{\lambda\Lambda^2} + \frac{4C_8 v^4}{\lambda\Lambda^4}$$

vanishing dimension-8 →

$$\simeq 6(\kappa_3 - 1) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Shaded region: $\frac{4C_8 v^4}{\lambda\Lambda^4} < \frac{6C_6 v^2}{\lambda\Lambda^2}$ →



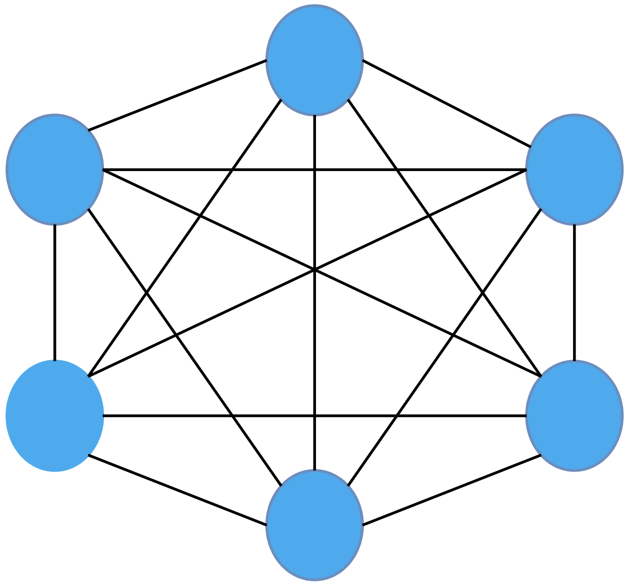
Electroweak Chiral Lagrangian (HEFT):
Higgs introduced as singlet and κ_3 and κ_4 are **free parameters** →probes **non-linearity**

⇒Deviation in κ_4 enhanced by factor 6!

Graph embedding

1.

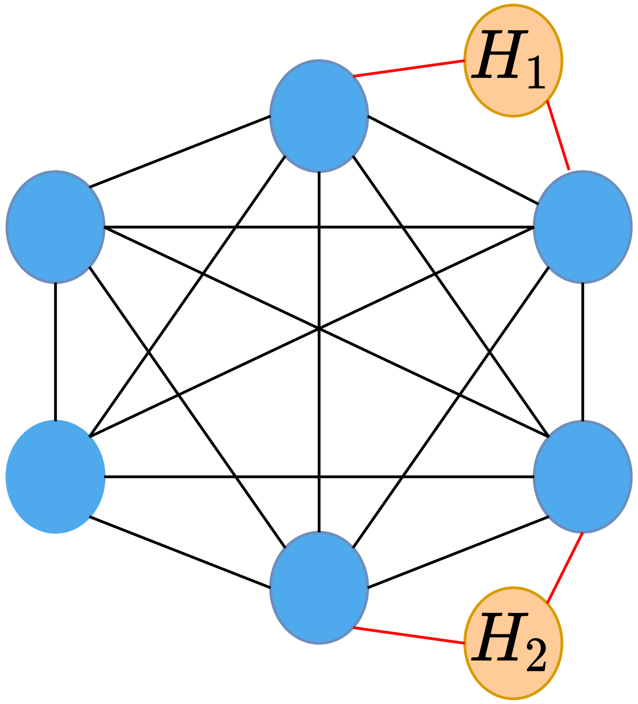
- Fully-connected nodes for b and τ final states
- **Input features**: $[p_T, \eta, \phi, E, m,$ PDGID$]$
- Additional node for Missing Transverse Momentum (MTM) in showered & reconstructed events



FC: Fully-Connected

2.

- Consider combinations of b-quarks and τ with reconstructed four-momentum $(p_i + p_j)$
- If $m_{ij} \in [100,150]$ (GeV) add extra node H_i



RN: Reconstructed Nodes

Edge convolution

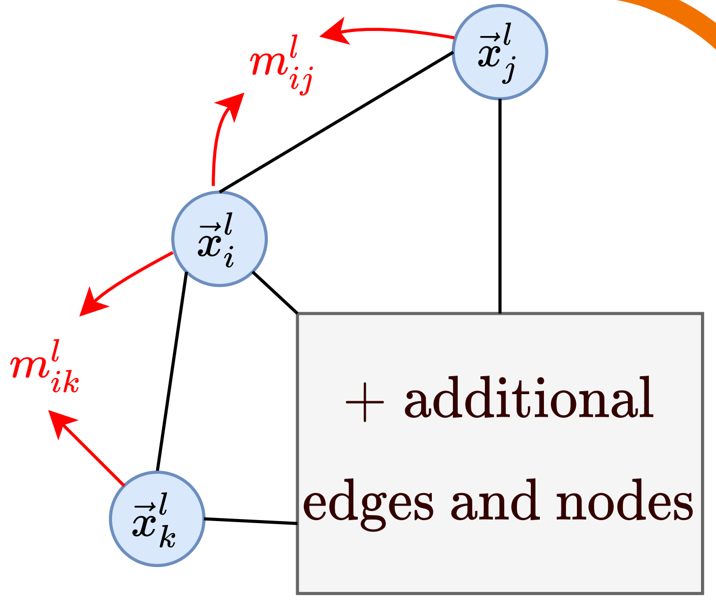
Input features: $\vec{x}_i^{(0)}$ → update iteratively with **Edge Convolution** operation:

Edge Convolution operation

‘Message’ calculation:

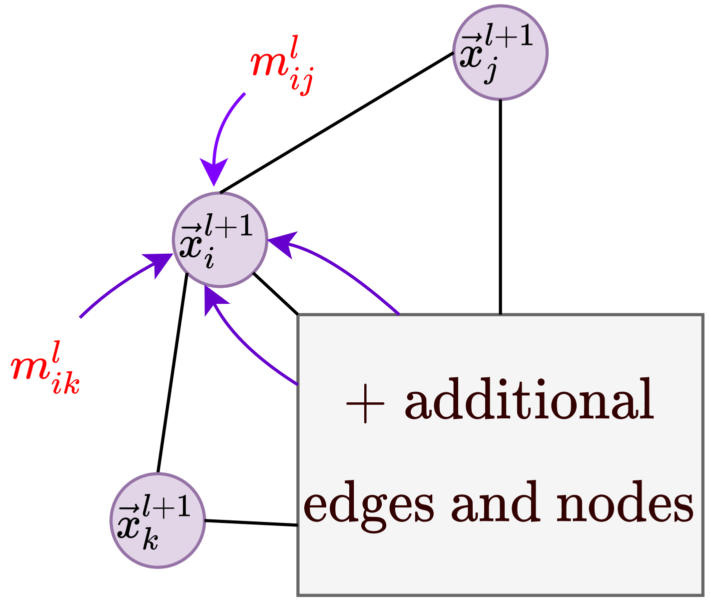
$$m_{ij}^{(l)} = \textsc{ReLU}\left(\Theta(\vec{x}_j^{(l)} - \vec{x}_i^{(l)}) + \Phi(\vec{x}_i^{(l)})\right)$$

linear layers



Aggregation: update node features

$$\vec{x}_i^{(l+1)} = \frac{1}{|\mathcal{N}(i)|} \sum_{j \in \mathcal{N}(i)} m_{ij}^{(l)}$$



GNN embedding efficiencies

Dataset with signal & background graphs → **GNN** 2 EdgeConv layers + linear → $\left\{ P(\mathbf{S}), P(\mathbf{B}_1), \ldots, P(\mathbf{B}_N) \right\}$

- GNN trained on $(\kappa_3, \kappa_4) = (1,1)$ sample

Complex final states

↓

- Compare embeddings at parton level with only parts of background
- Check signal efficiencies for 99% background rejection

	FC efficiency	RN efficiency
$5b$	0.21	0.47
$3b2\tau$	0.27	0.98

‘Reconstructed Nodes’ case outperforms Fully-Connected

↓

focus only on this embedding for full analysis

* for parton-level considerations H_i nodes have only $[p_T, E]$ as input features, with additional noise introduced

GNN embedding efficiencies

- **Assumption:** Same GNN efficiency for other values of (κ_3, κ_4)
- Flat optimistic $80\,\%$ b-tagging and τ-tagging efficiency
- **Significance:**

$$Z = \sqrt{2\left((S+B)\ln(1+\frac{S}{B}) - S\right)}$$

from [Cowan, Cranmer, Gross, Vitells ` 10]

Showered and reconstructed results: 3b2$\boldsymbol{\tau}$

- $3b2\tau$ more complicated due to multiple backgrounds → multi-class classification
- Train on backgrounds: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},\ t\bar{t}(H \to \tau^+\tau^-)$

- Impose cuts on NN scores to reduce backgrounds:

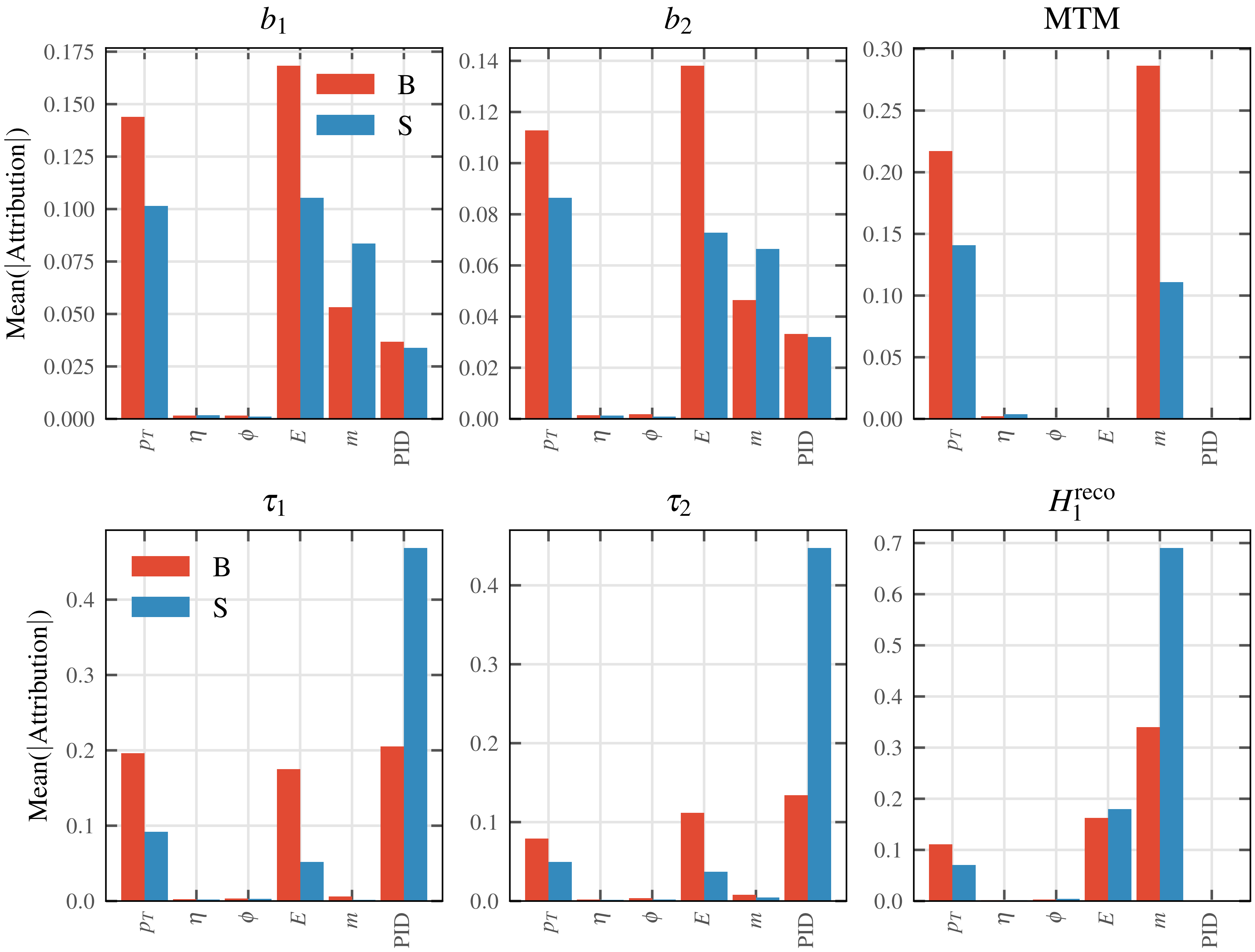
$$P[W^+W^-b\bar{b}b\bar{b}] < 0.03, \quad P[Zb\bar{b}b\bar{b}] < 0.1, \quad P[t\bar{t}(H \to b\bar{b})] < 0.3$$

	$\sigma(\text{gen.})(\text{fb})$	$\sigma(\text{sel.})(\text{fb})$	$\sigma(\text{NN})(\text{fb})$
$tt(H \to \tau\tau)$	3.8	0.17	0.010
$WWbbbb$	31	4.6	7.0×10^{-3}
$tt(H \to bb)$	3.5	0.89	3.6×10^{-3}
$Zbbbb$	4.3	0.45	3.3×10^{-4}
$tt(Z \to bb)$	0.77	0.15	2.9×10^{-4}
$tttt$	0.38	0.091	2.1×10^{-4}
$tt(Z \to \tau\tau)$	4.7	0.080	1.1×10^{-4}

Neural networks: understanding the physics behind the “black box”

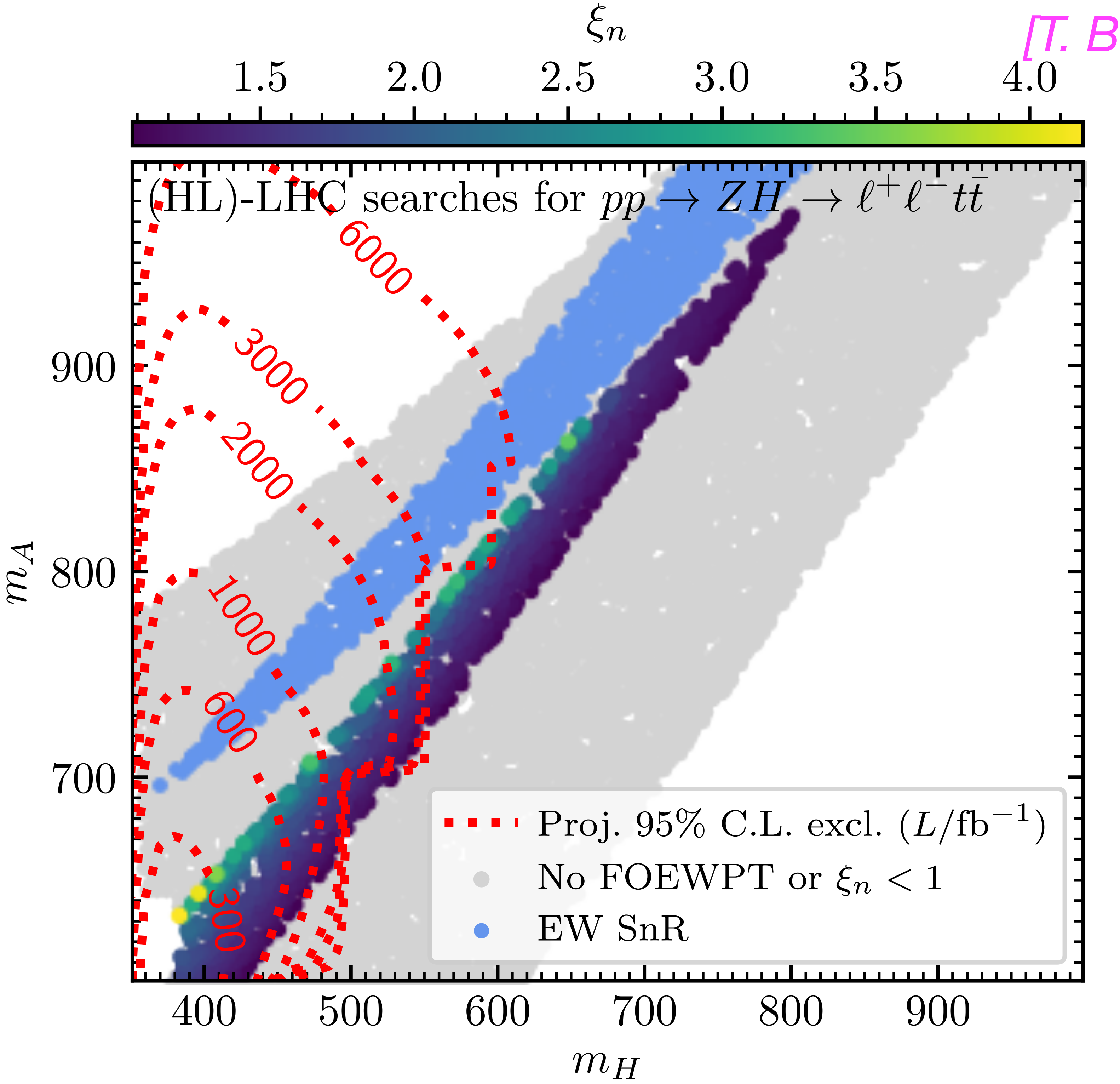
Neural network interpretations via “Integrated Gradients”: which features are actually used by the GNN to learn?

- Tagged b-jets and τ nodes ordered by p_T
- ‘Roughly’ reconstructed Higgs nodes ordered by ‘closeness’ to 125 GeV
- p_T , E and PID more important than angular observables
- Higgs masses most important



Updated projection based on new ATLAS result

[T. Biekötter et al. ’23]



⇒ Agrees well with previous projection