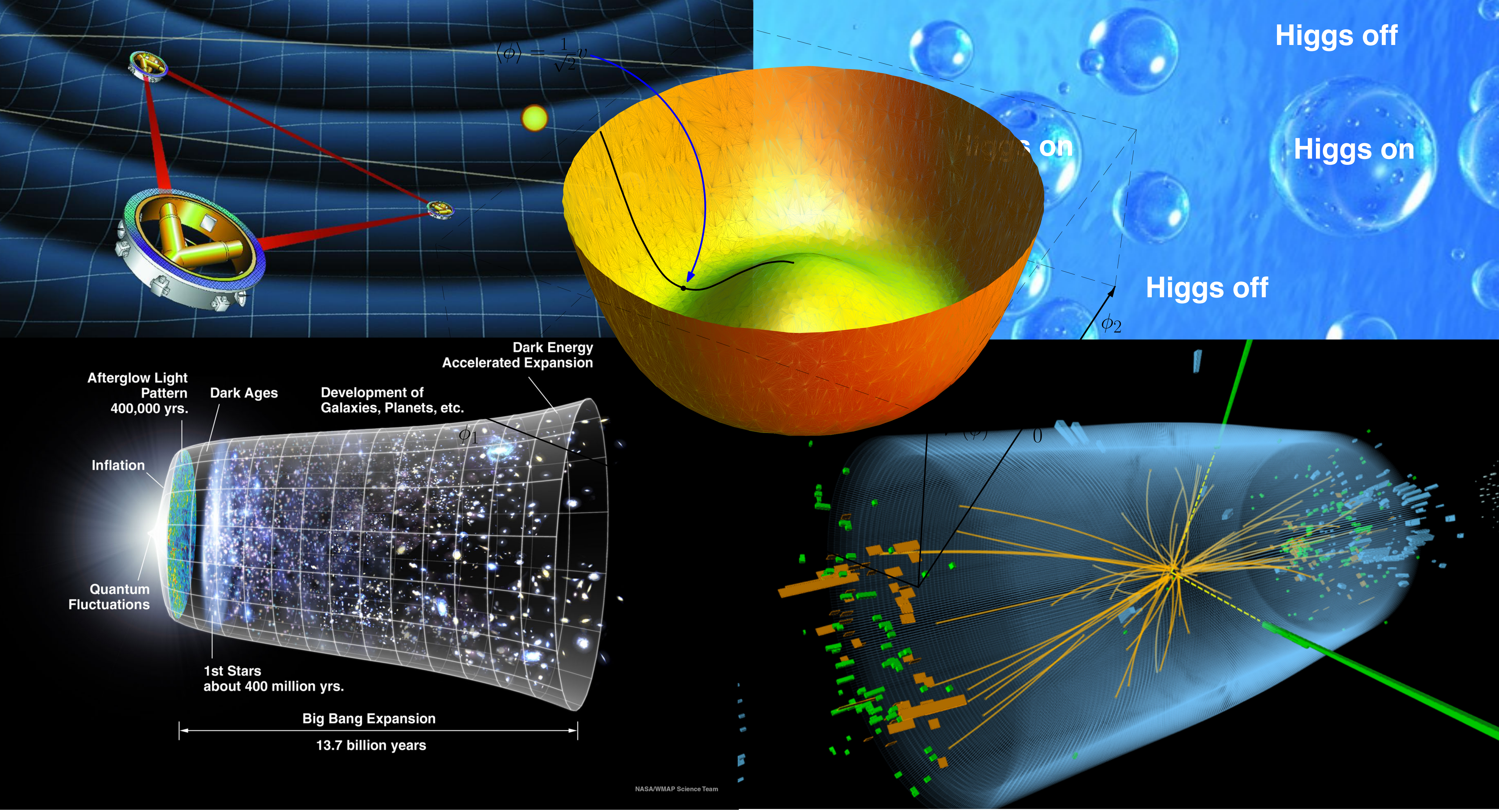


Exploring the Higgs potential and its impact on the evolution of the early Universe

Georg Weiglein, DESY & UHH

Frascati, 05 / 2024

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

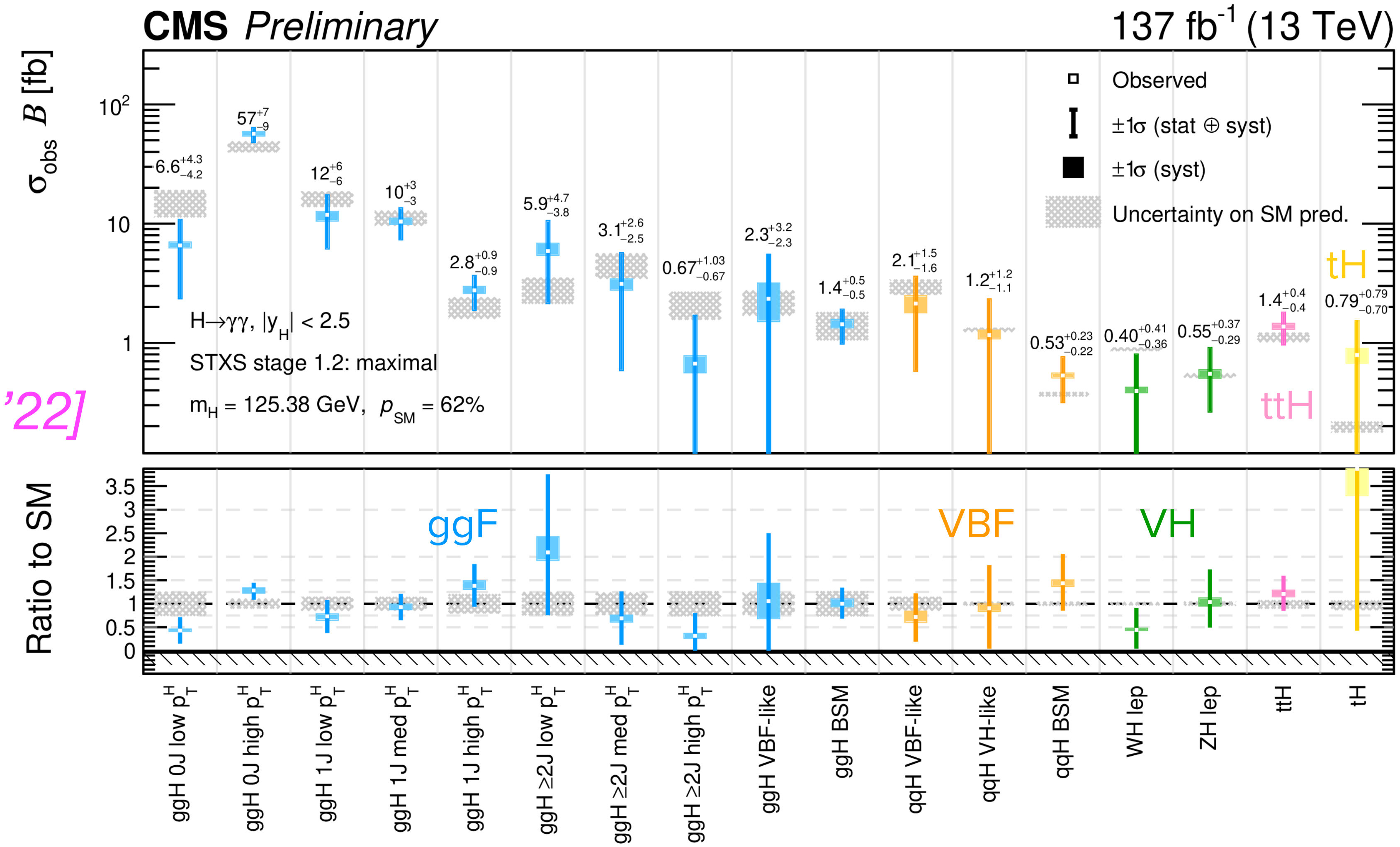
Outline

- Introduction
- Higgs self-couplings, the Higgs potential and probes of the electroweak phase transition
- Exploring HHH production w.r.t. Higgs self-couplings
- Conclusions

Introduction

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]

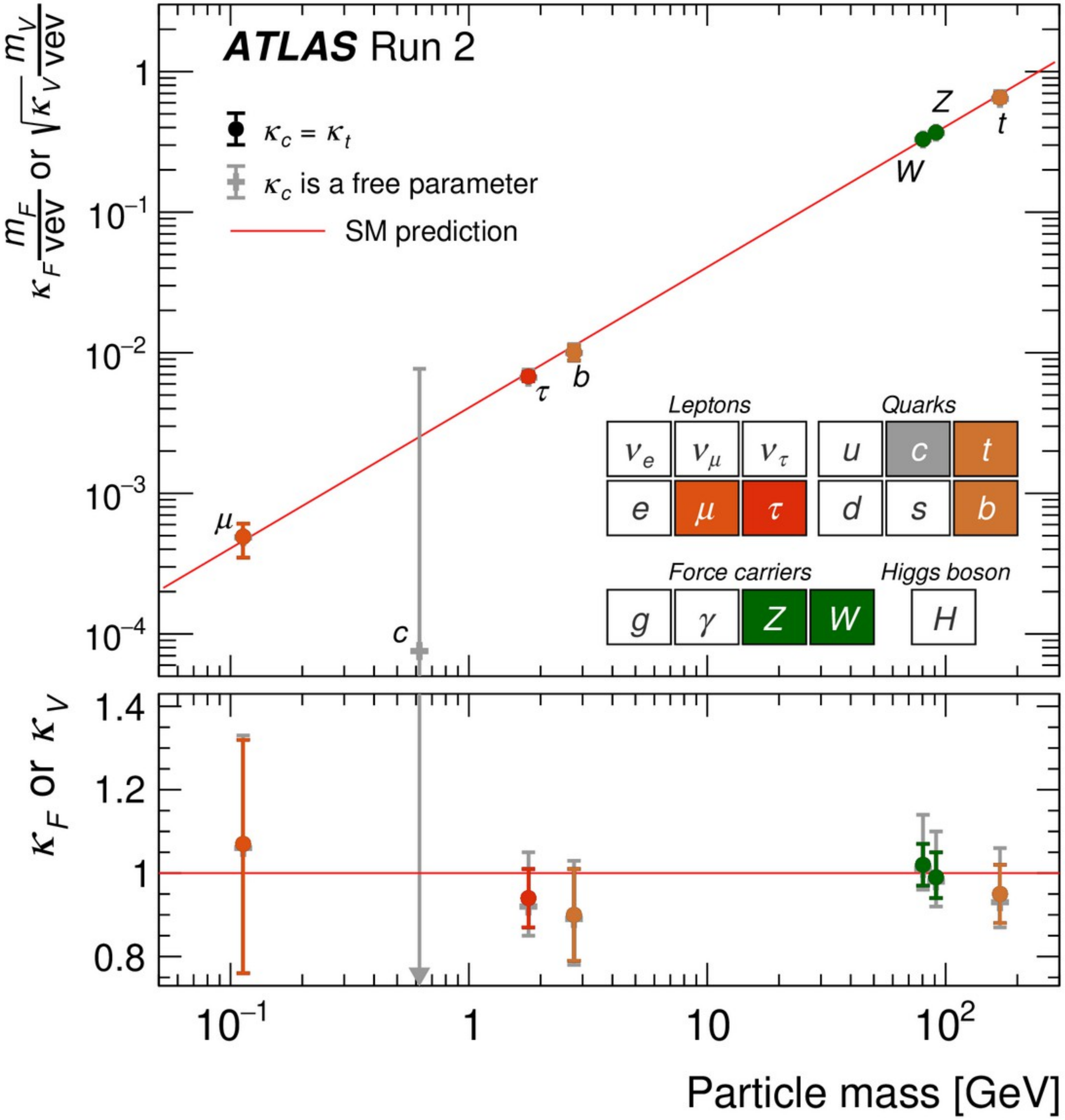
⇒SM-like properties

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]

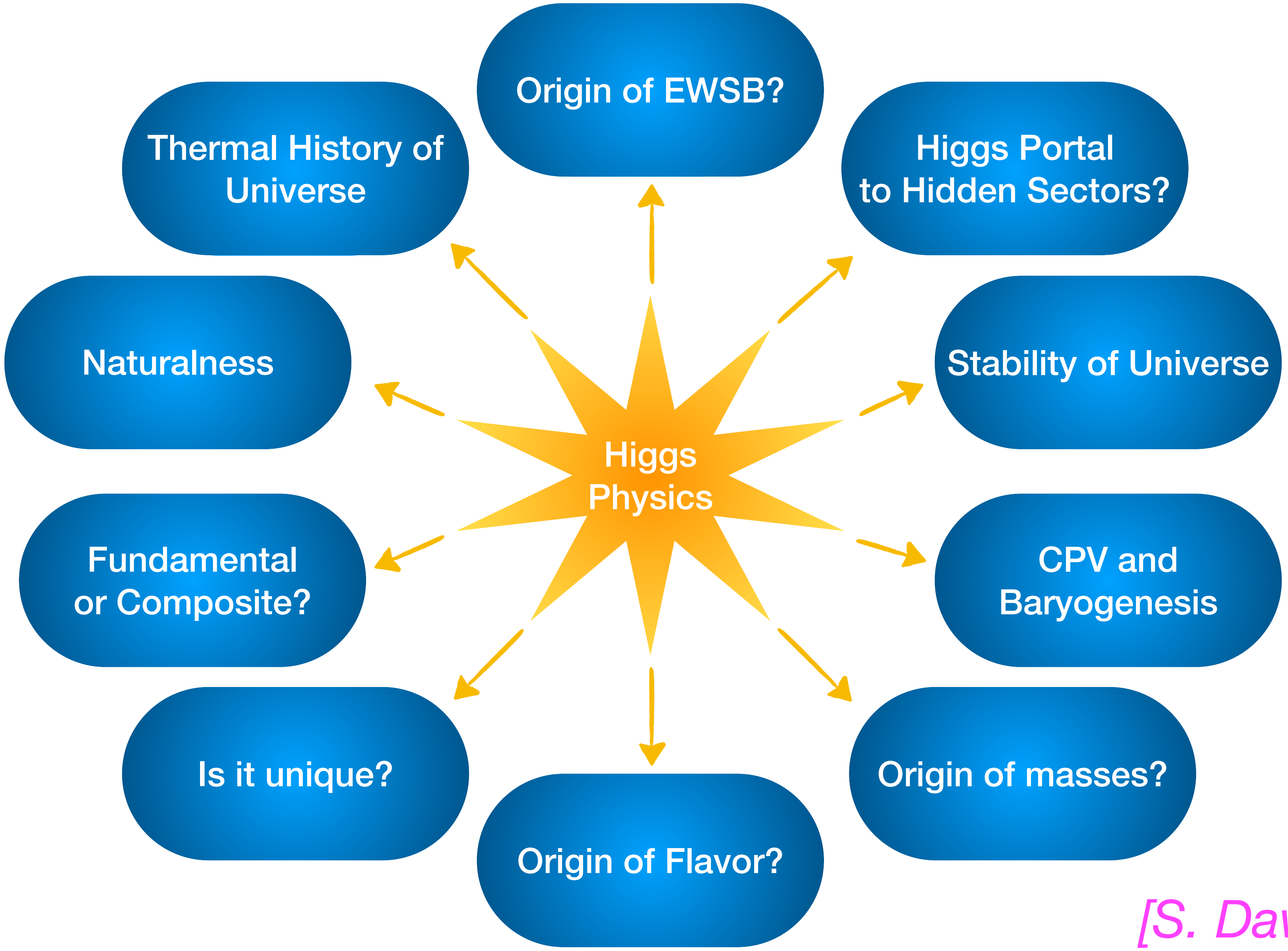


Nobel Prize 2013

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

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



[S. Dawson et al. '22]

Unsolved issues in the Higgs sector

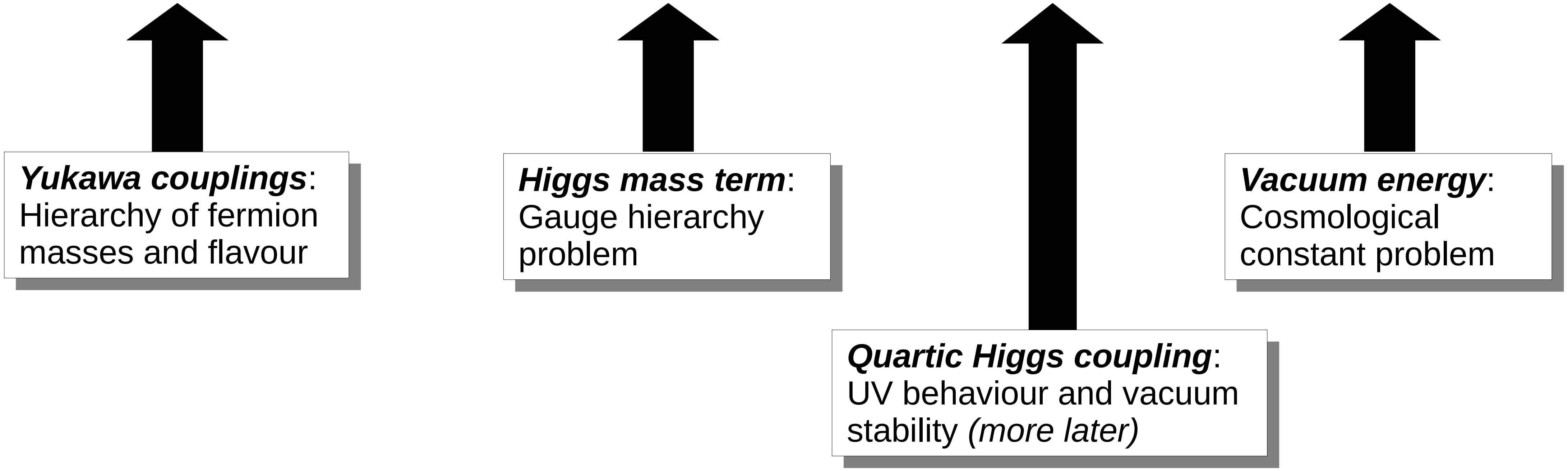
[J. Braathen '24]

Slide adapted from [Salam '23],
itself adapted from [Giudice]

$$\mathcal{L} \supset -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + \bar{\psi}_i \gamma_\mu D^\mu_{ij} \psi_j$$

→ entirely constrained by gauge symmetry, tested to high precision (e.g. LEP)

$$\mathcal{L} \supset -y_{ij} \bar{\psi}_i \Phi \psi_j + \mu^2 |\Phi|^2 + \lambda |\Phi|^4 - V_0$$



Yukawa couplings:
Hierarchy of fermion masses and flavour

Higgs mass term:
Gauge hierarchy problem

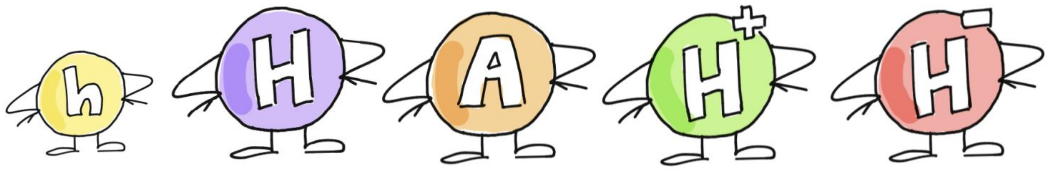
Quartic Higgs coupling:
UV behaviour and vacuum stability *(more later)*

Vacuum energy:
Cosmological constant problem

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:

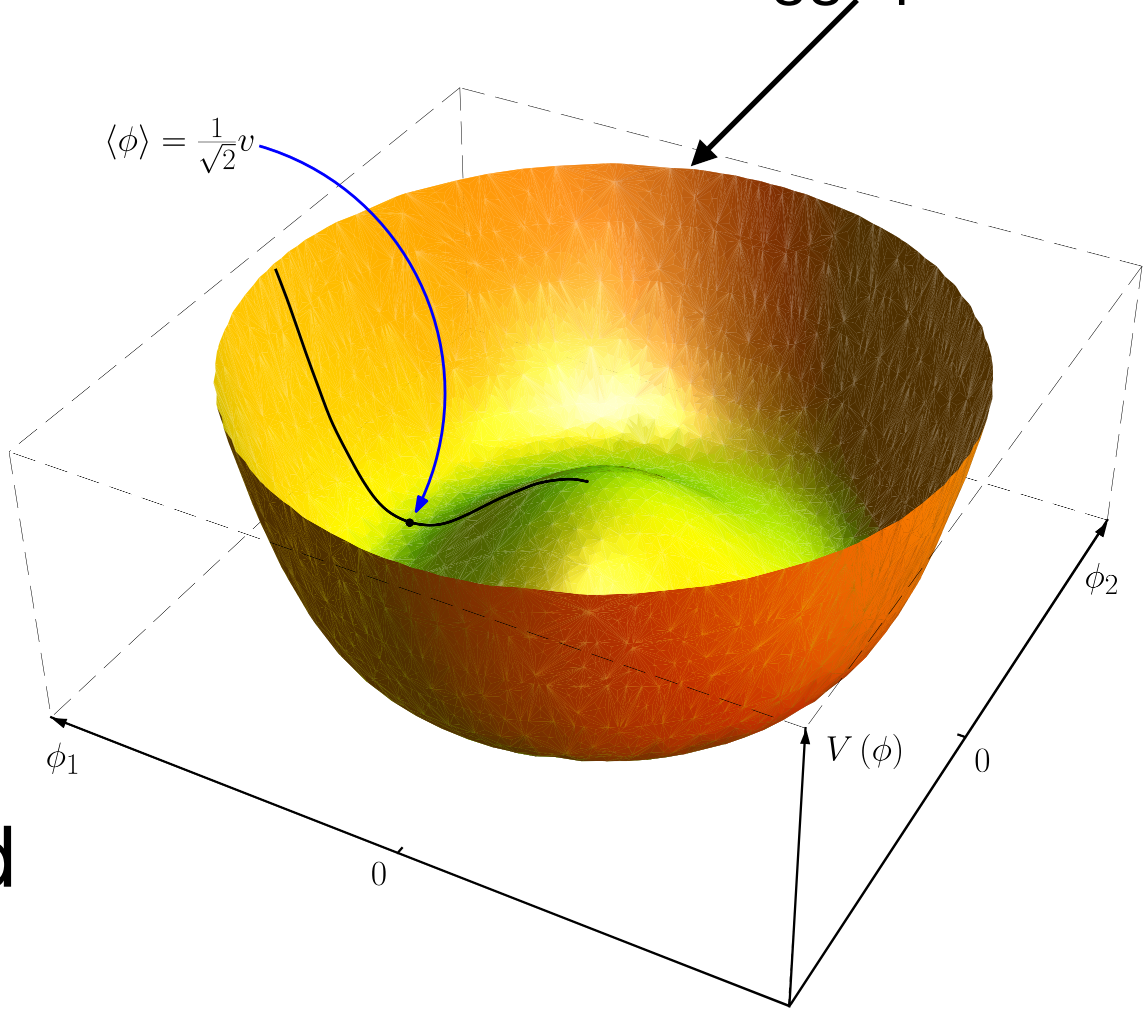
$$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2 \,, \qquad \Phi \in \{H, A, H^\pm\}$$

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)

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!


Higgs potential

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!

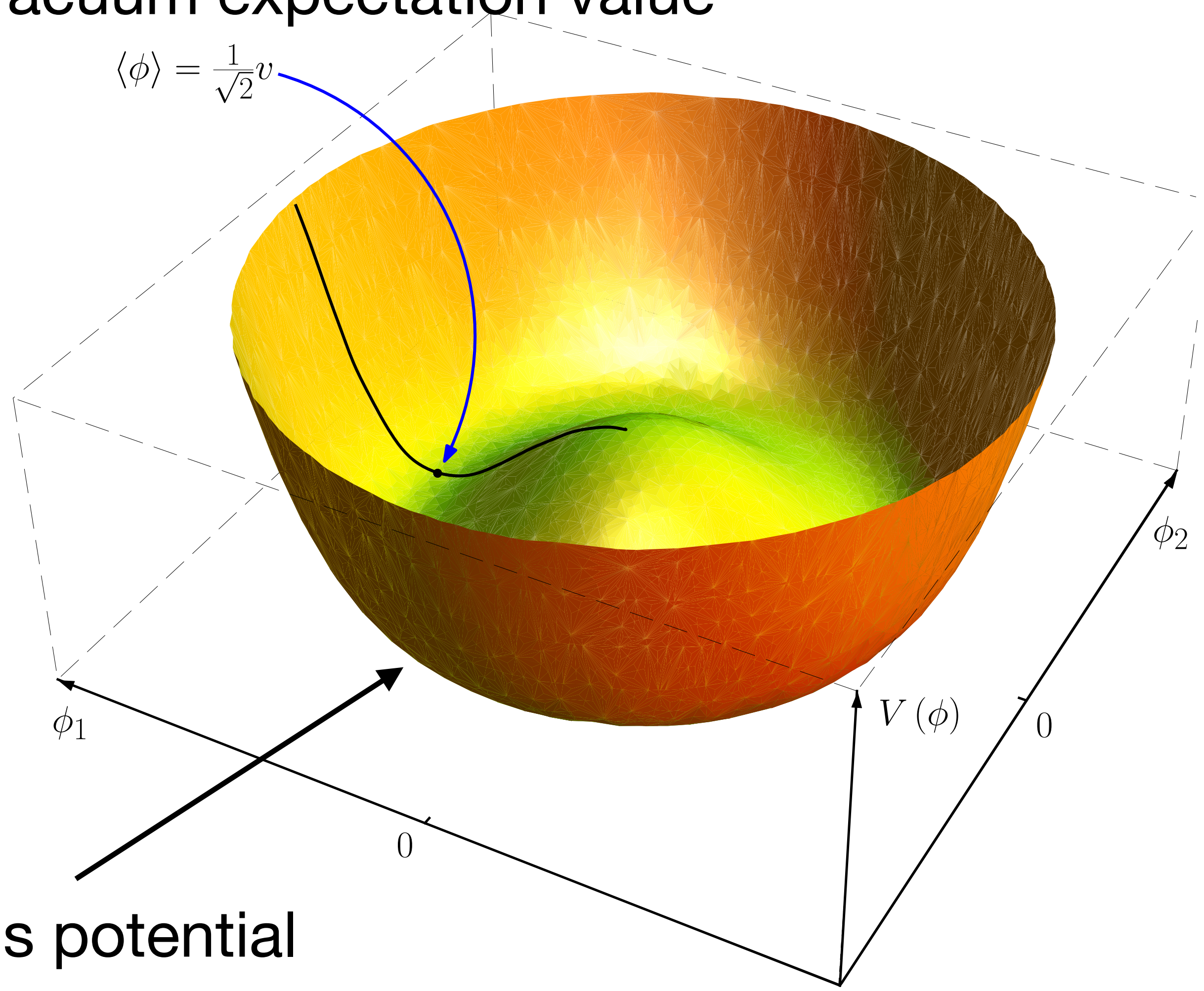
Single doublet or extended Higgs sector? (new symmetry?)

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

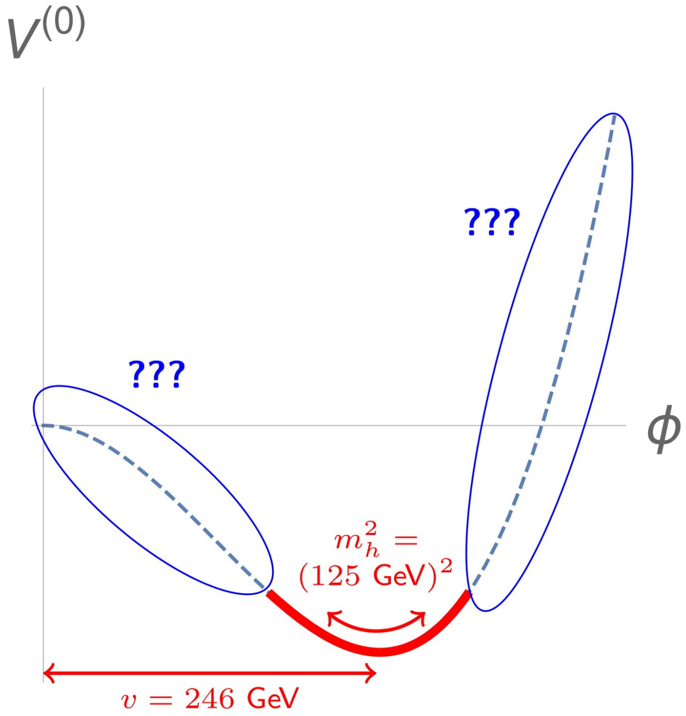
Only known so far:

→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

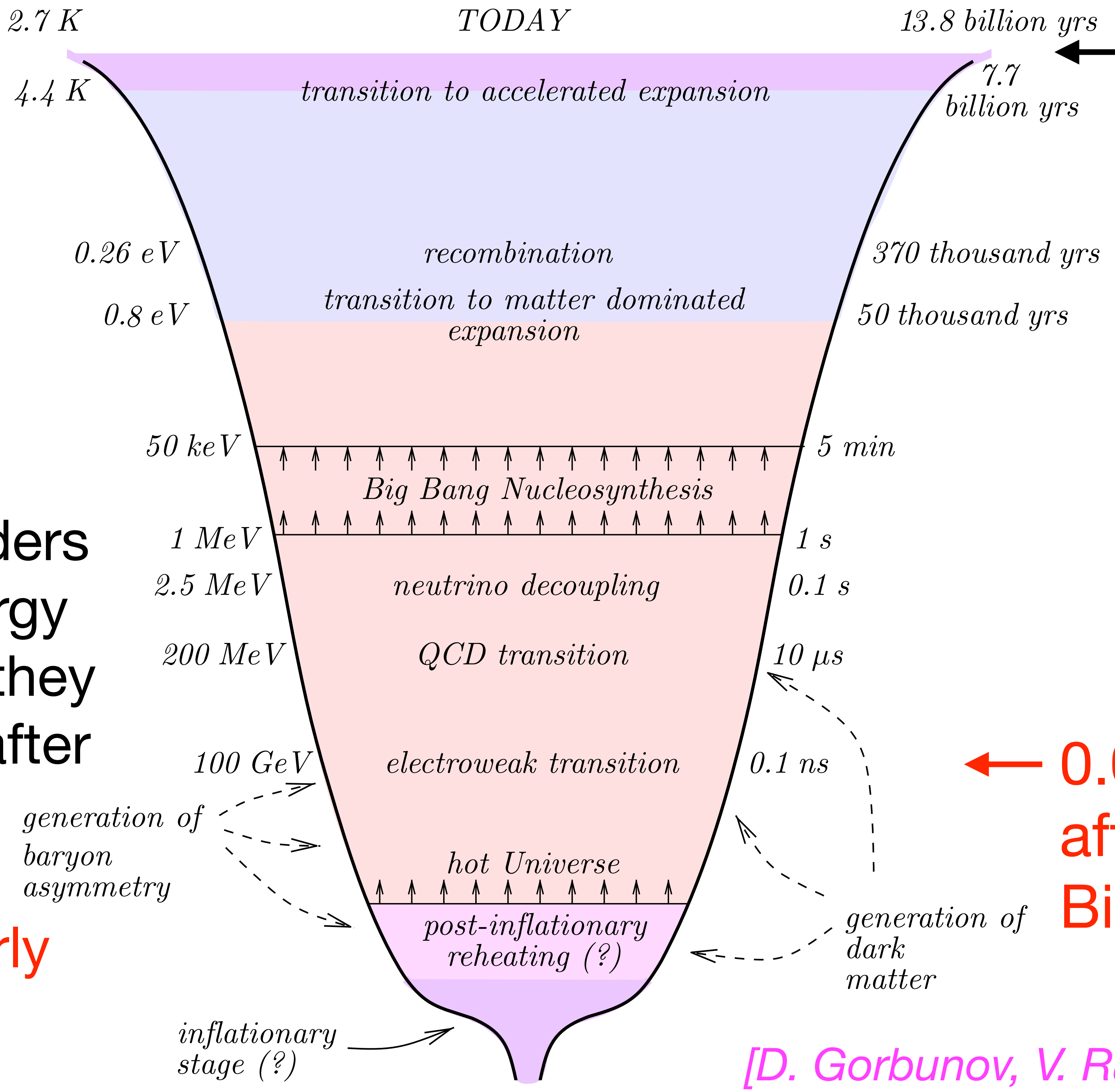
m_h = 125 GeV



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 electroweak phase transition (EWPT) and the evolution of the Universe

History of the Universe:



← Now: ~14 billion years after the Big Bang

Particle colliders produce energy densities as they existed just after the Big Bang

⇒Information about the early Universe

← 0.0000000001 s after the Big Bang

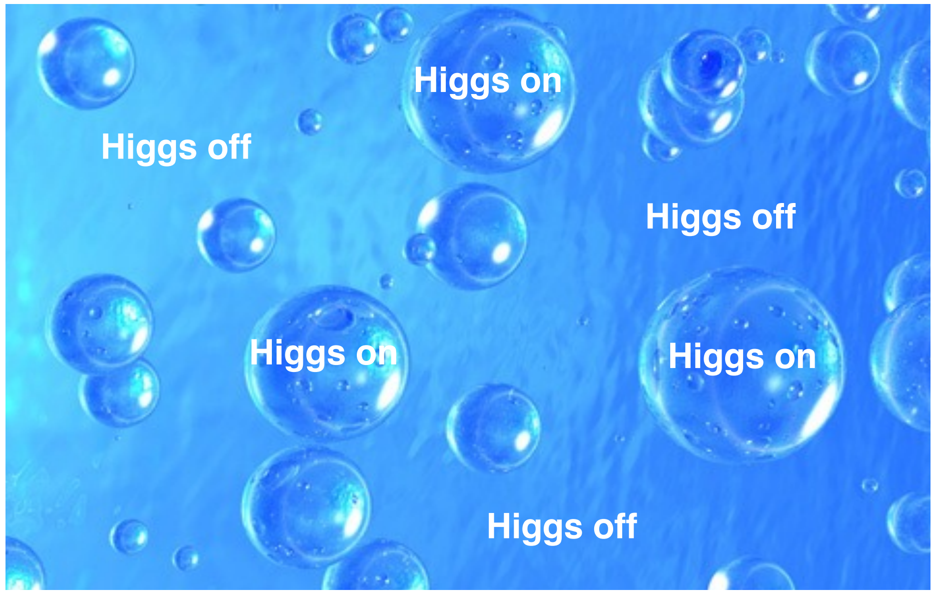
[D. Gorbunov, V. Rubakov]

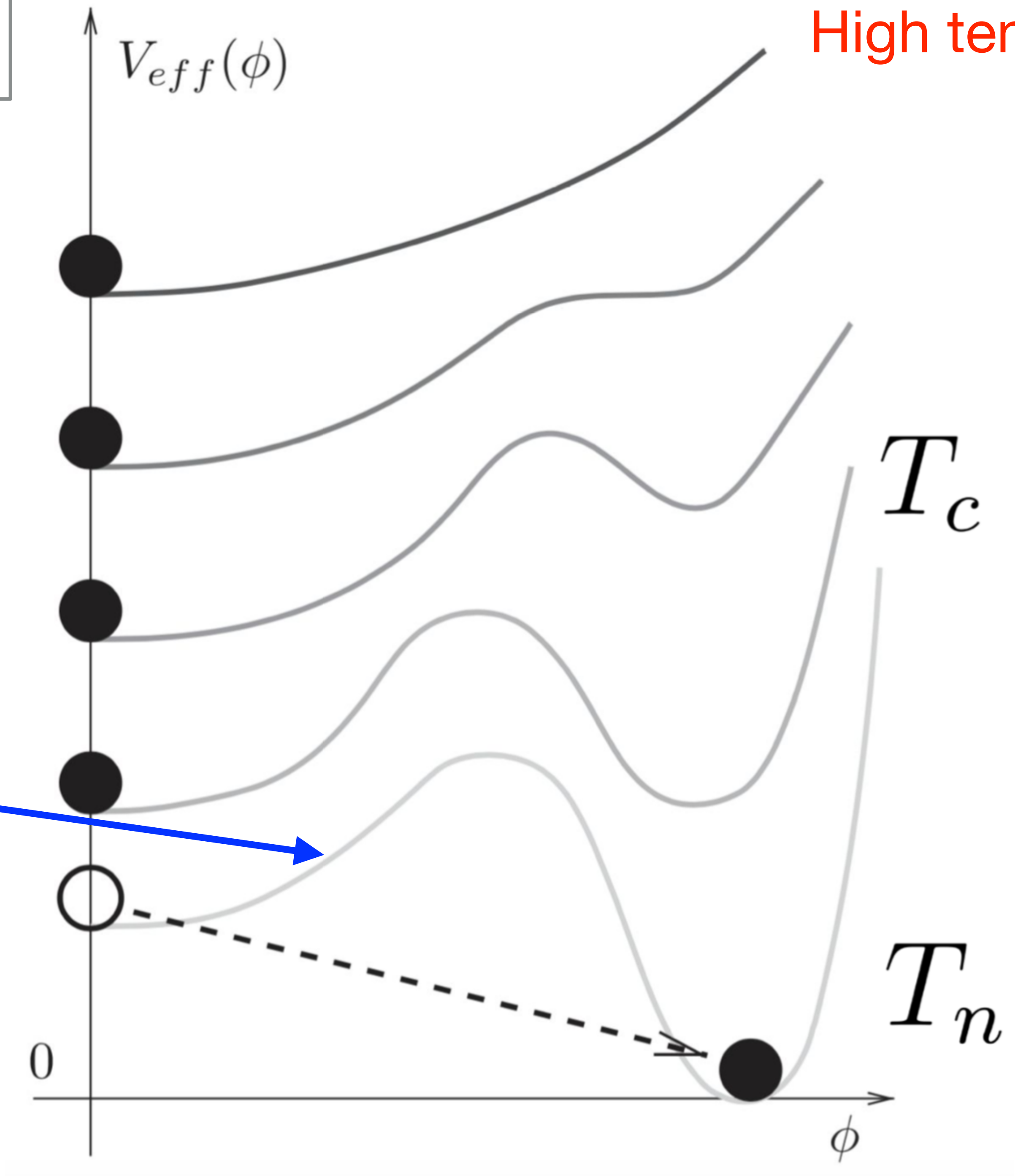
The Higgs potential and the electroweak phase transition (EWPT)

[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

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]

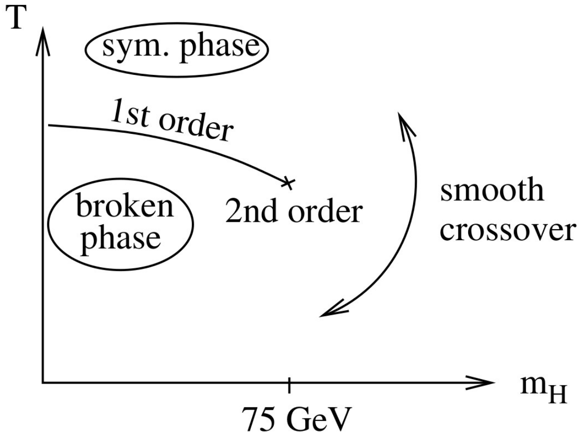
n_b: baryon no. density
$n_{\bar{b}}$: antibaryon no. density
n_γ: photon no. density

[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

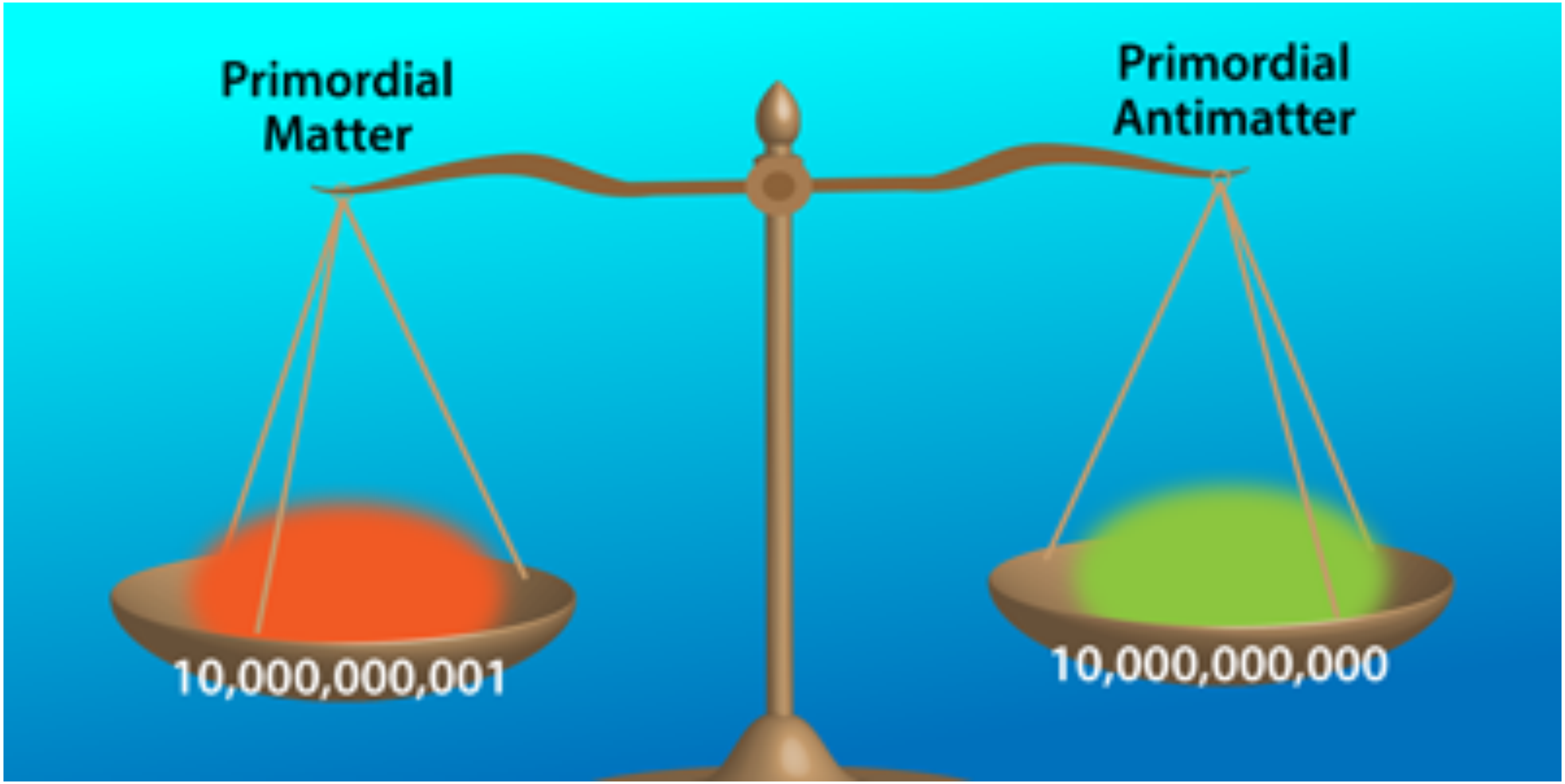


SM CP Violation insufficient by ~ 10 orders of magnitude

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

Asymmetry between matter and anti-matter



The created little excess of matter over anti-matter resulted in the matter dominance that is observed today

Electroweak phase transition and baryon asymmetry

Sakharov conditions are necessary but not sufficient to produce the observed baryon asymmetry

Does not work in the SM: BSM physics needed

Exciting option: generate the baryon asymmetry during the electroweak phase transition (electroweak baryogenesis)

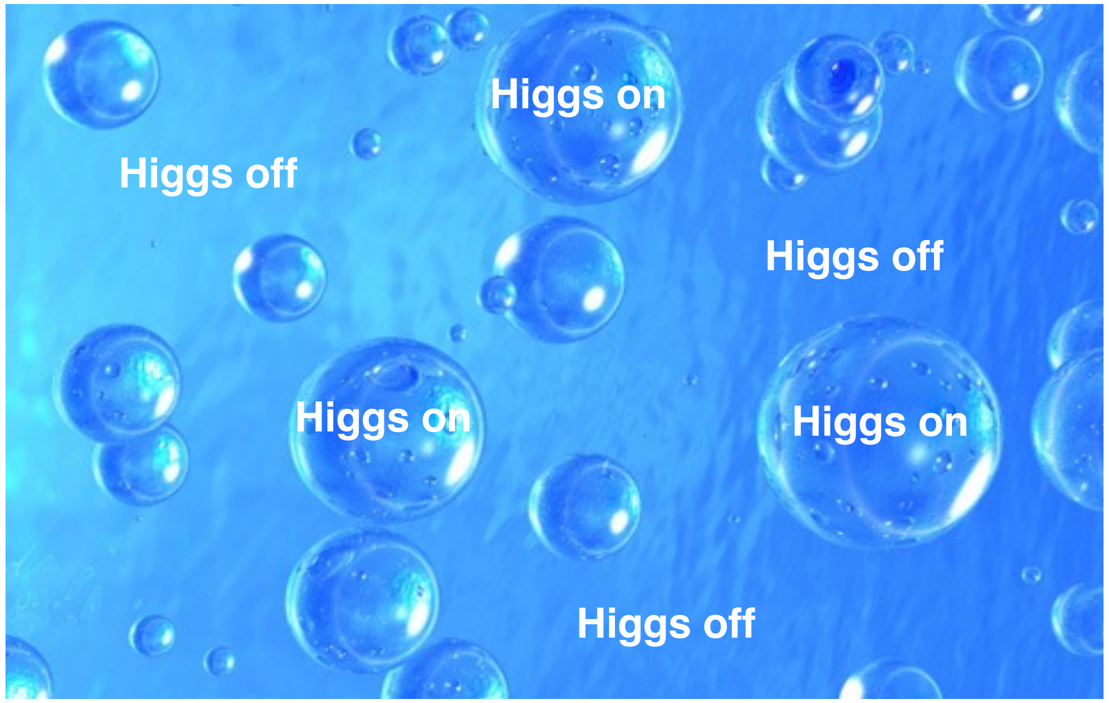
In the SM: baryon number conserved at classical level but violated at the quantum level (related to the axial anomaly)

Non-perturbative ``sphaleron” processes violate both baryon and lepton number (i.e., violate B+L), but preserve B–L

Baryon generation at the electroweak phase transition

Start from B=L at $T > T_C$

In a first-order EW phase transition the Universe tunnels from the phase with vanishing vacuum expectation value to the phase with non-vanishing vev via bubble nucleation



Bubbles expand near the speed of light; processes near the wall are highly out of thermal equilibrium

Baryon generation at the electroweak phase transition

Start from B=L at T > T_C

Particles flow into the expanding bubble wall, CP violation implies that the wall exerts different forces on particles and anti-particles

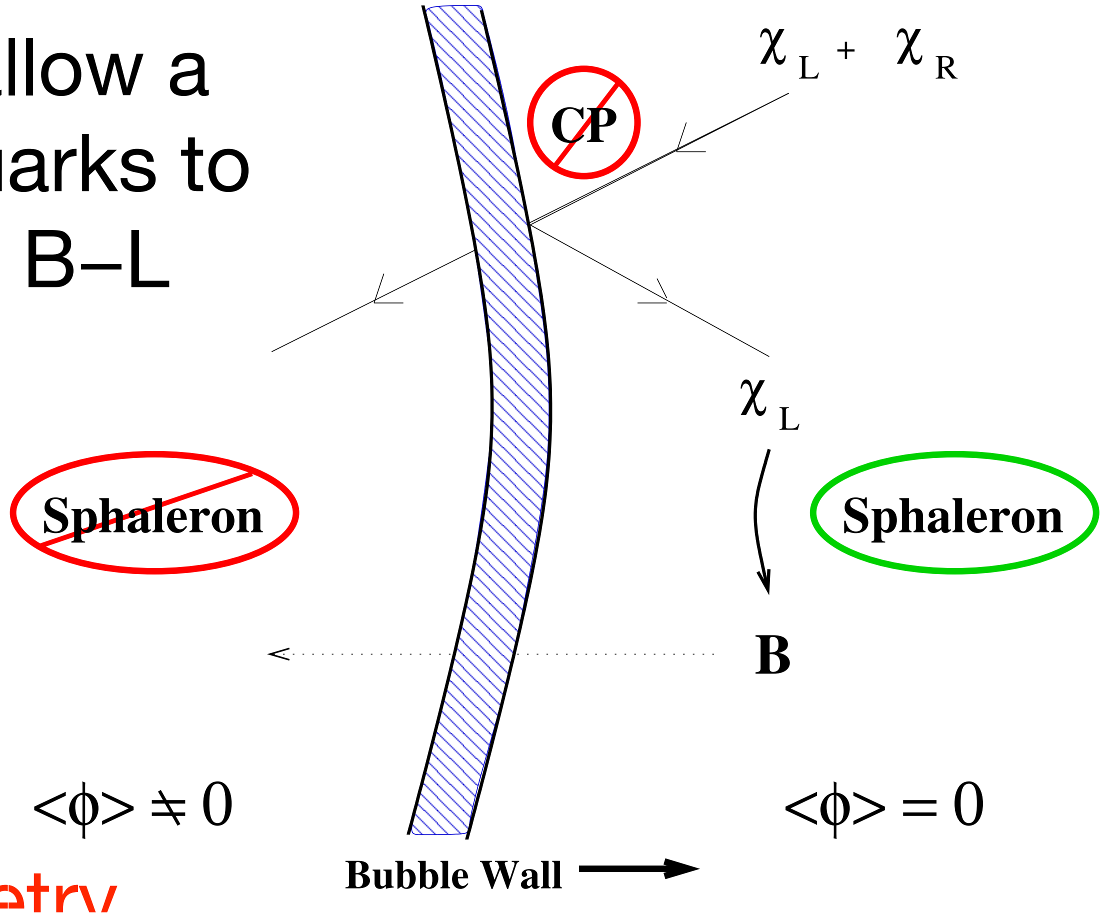
⇒ Creation of chiral asymmetry

[D.E. Morrissey, M.J. Ramsey-Musolf ’12]

Outside the bubble, EW sphalerons allow a fraction of the chiral asymmetry of quarks to be shared with leptons (B+L violated, B−L preserved)

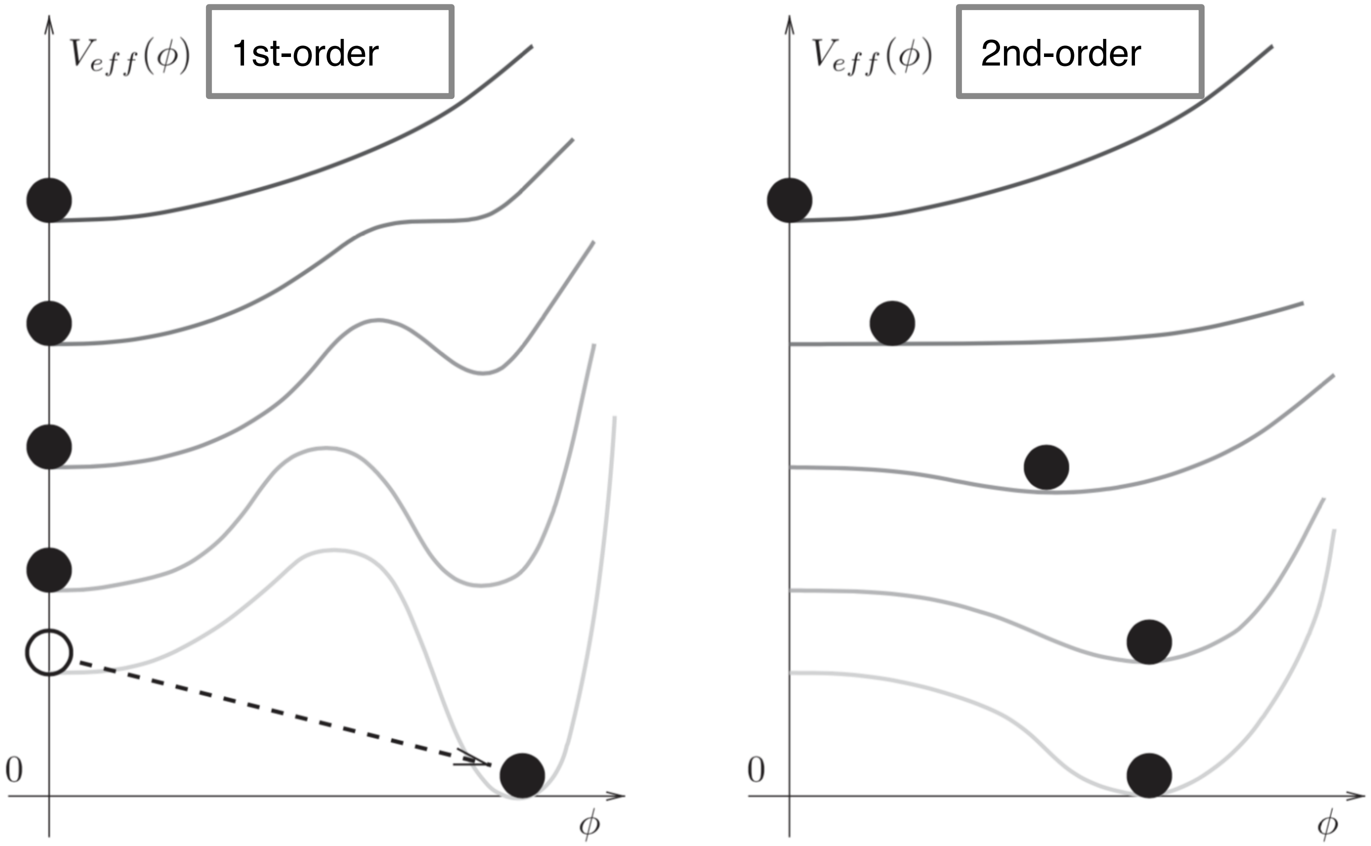
⇒ Creation of net baryon asymmetry

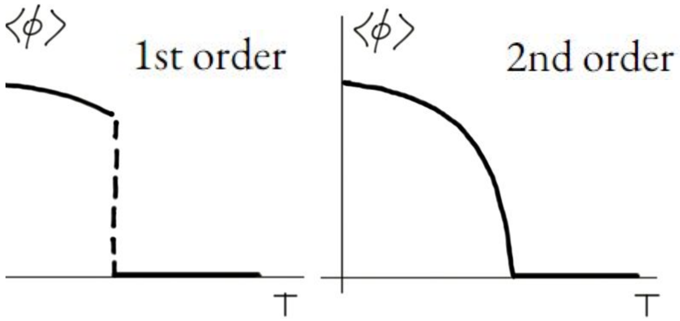
Strong first-order EWPT needed to prevent the `washout” of the asymmetry

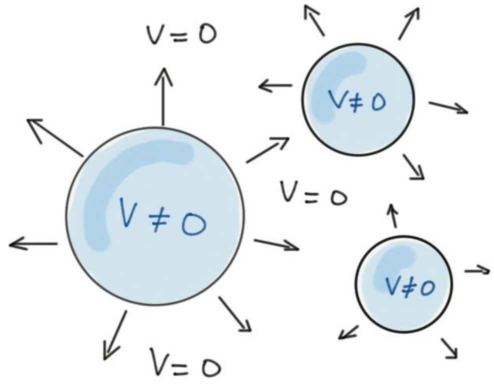


First-order vs. second order EWPT

[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

Strongly first-order EWPT in the 2HDM

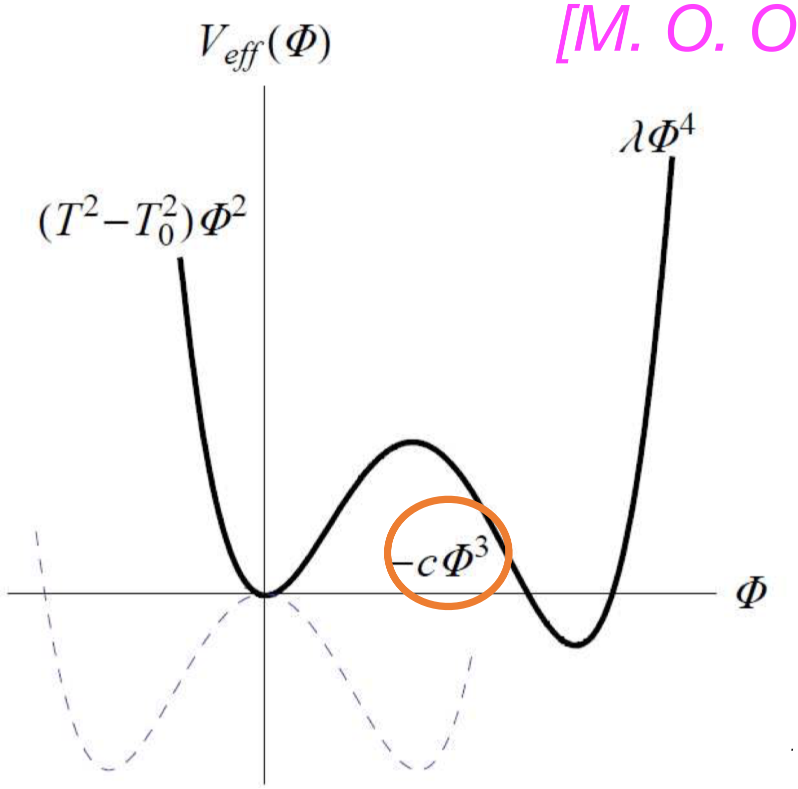
Barrier is related to a cubic term in the effective potential

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

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



[M. O. Olea '23]

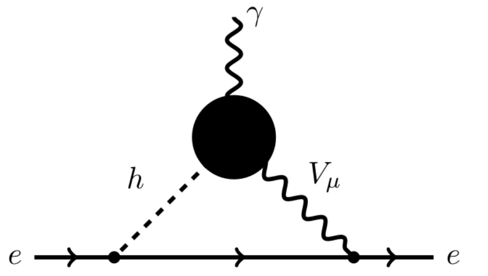
EWPT: are there additional sources for CP violation in the Higgs sector?

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



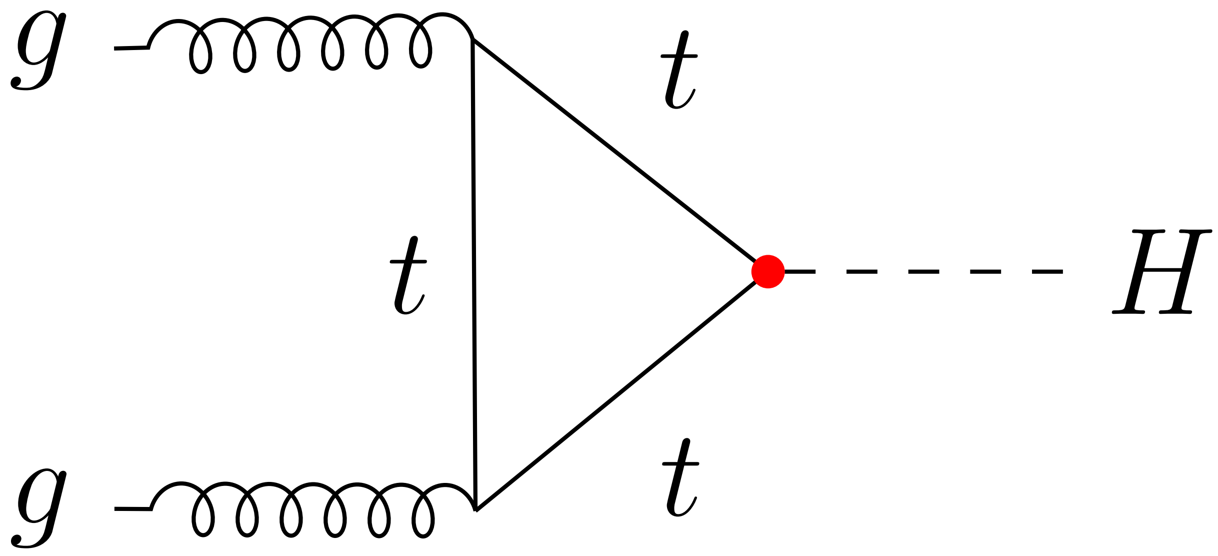
Two-loop “Barr-Zee”
electron EDM contribution

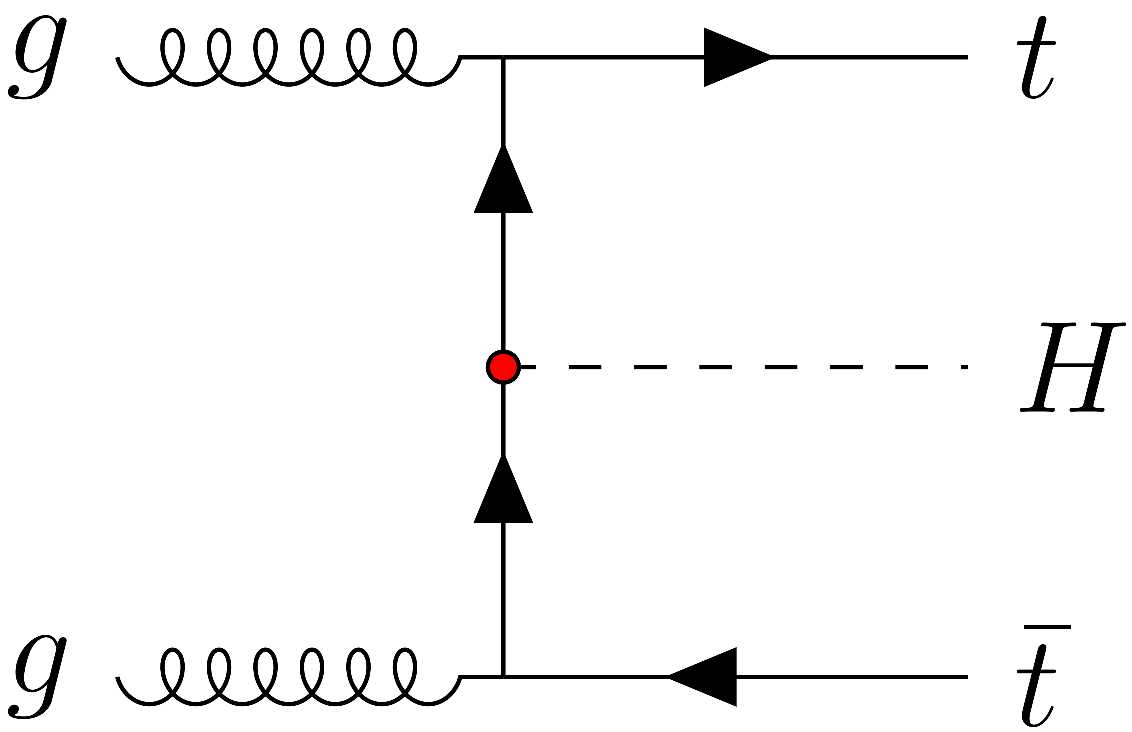
But: strong experimental constraints from limits on electric dipole moments (EDMs)

CP properties of h125

It has been experimentally verified that h125 is not a pure CP-odd state, but it is by no means clear that it is a pure CP-even state

Sensitive tests via processes involving only Higgs couplings to fermions



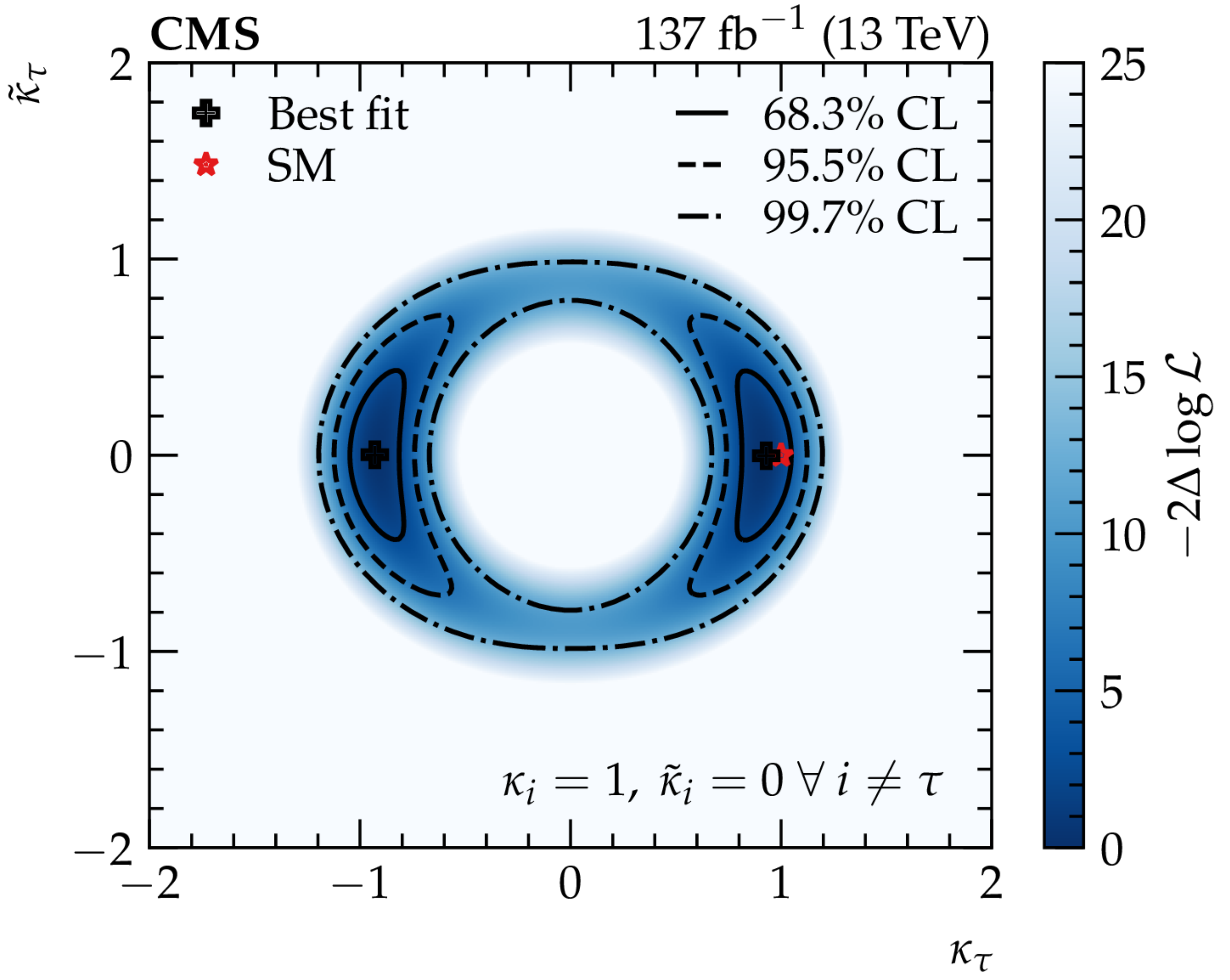


with H → $\boldsymbol{\tau\tau}$, bb, …

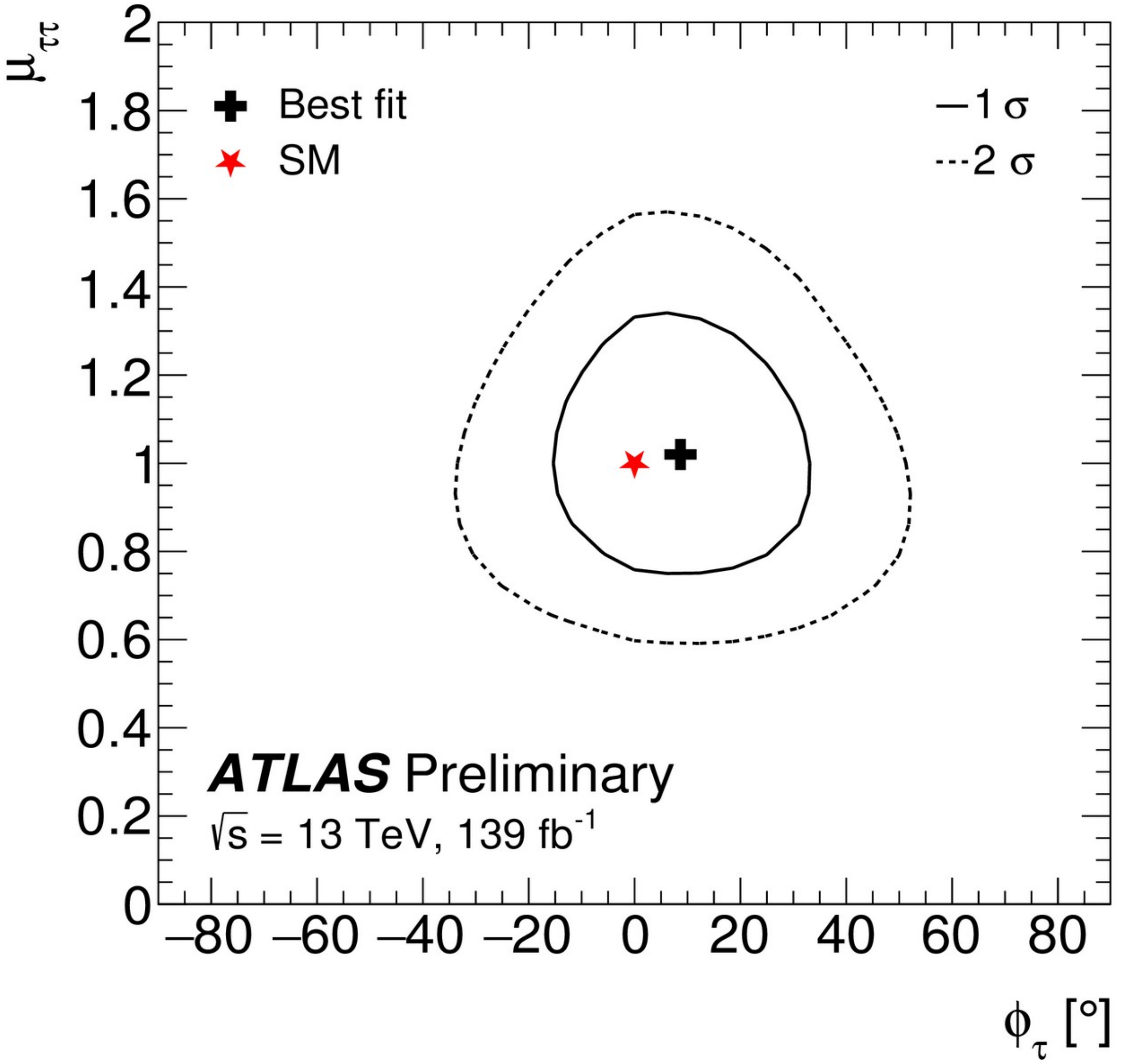
Test of CP violation in the tau Yukawa coupling

Constraints on the CP structure of the tau Yukawa coupling from h125 → **ττ** decays using angular correlation between decay products:

[CMS Collaboration ’21]



[ATLAS Collaboration ’22]



Effect on global CP analysis of Higgs-fermion couplings

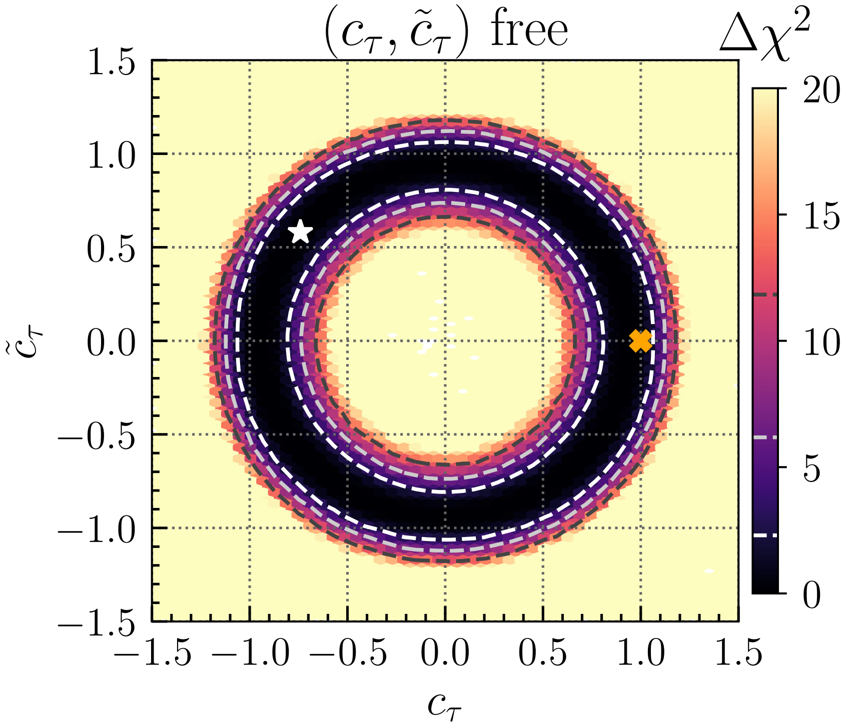
[H. Bahl et al. ’22]

Incorporation of recent CMS result on the CP structure of the tau Yukawa coupling from h125 → **ττ** decays using angular correlation between the decay products

$$\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f h,$$

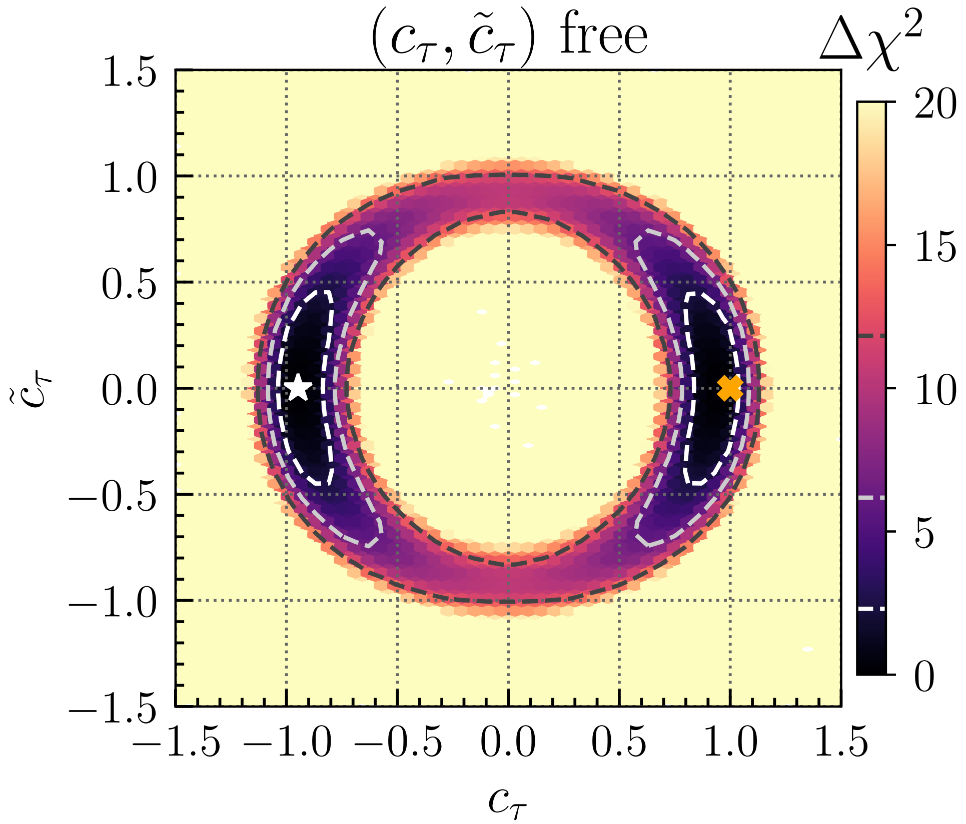
can also be analyzed in EFT

Global fit using **`HiggsSignals`** + recent analyses



CMS 2110.04836
h→ ττ CPV analysis

$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$



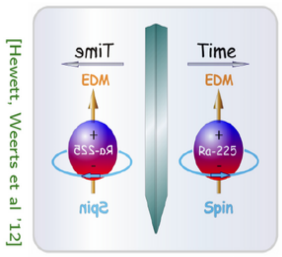
Ring-structure from upper/lower bound on BR

CMS analysis excludes large $\tilde{c}_\tau$

CP structure of the Higgs-fermion couplings

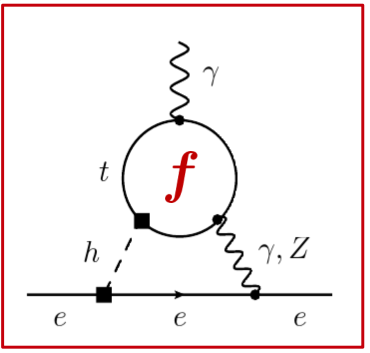
[H. Bahl et al. ’22]

Comparison with the existing EDM constraints



[Hewett, Weerts et al ’12]

EDM violates $\mathcal{T}$ and $\mathcal{P}$
$\Rightarrow \not{\mathcal{CP}}$



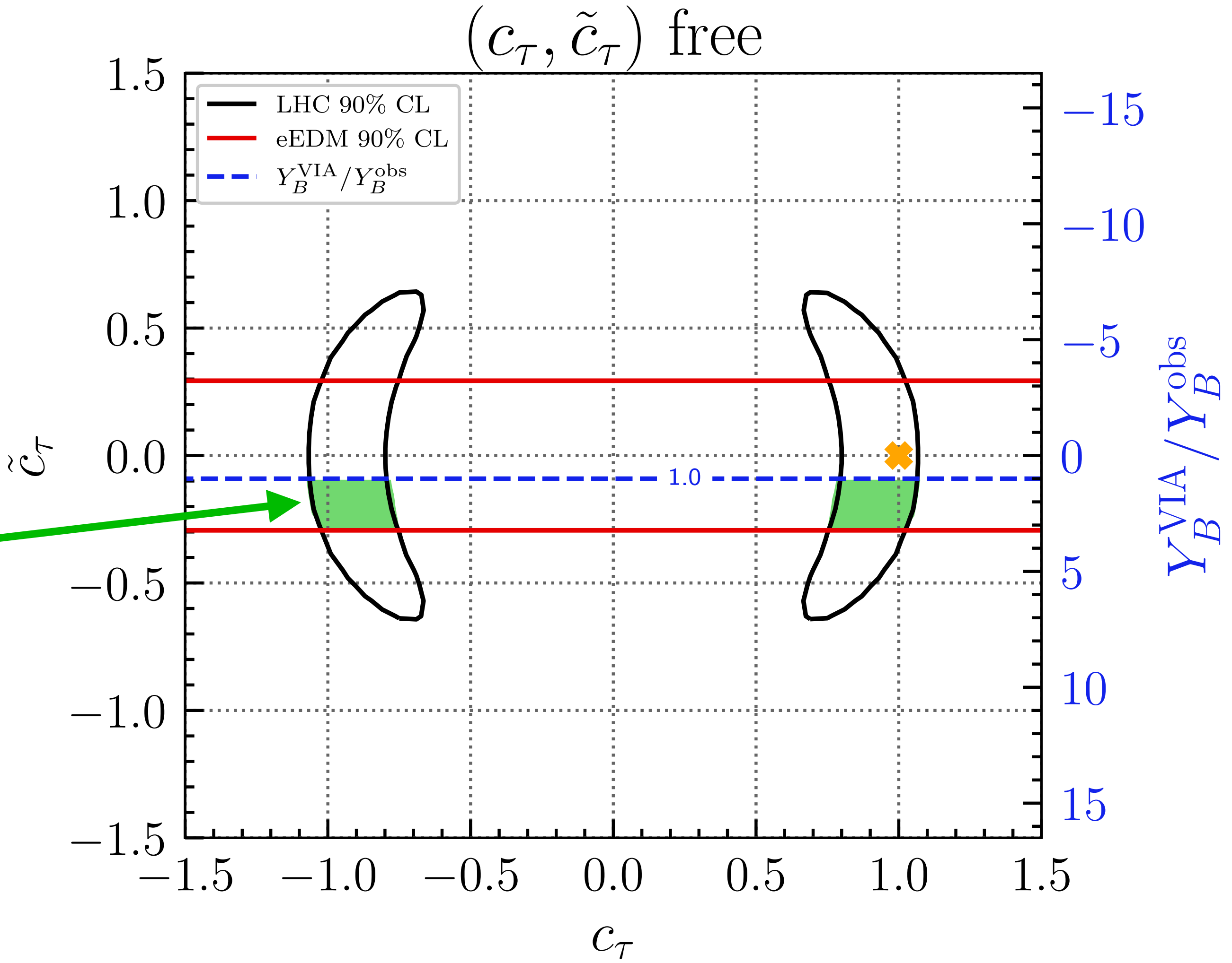
ACME [Nature ’18]:

$$d_e \leq 1.1 \times 10^{-29}\, e\,\text{cm at } 90\%\text{ CL}$$

Using [Panico, Pomarol, Riembau ’18], [Brod, Haisch, Zupan ’13], [Brod, Stamou ’18],...

Analysis of the resulting amount of baryon asymmetry in the Universe

Electron electric dipole moment $d_e \propto \tilde{c}_f$

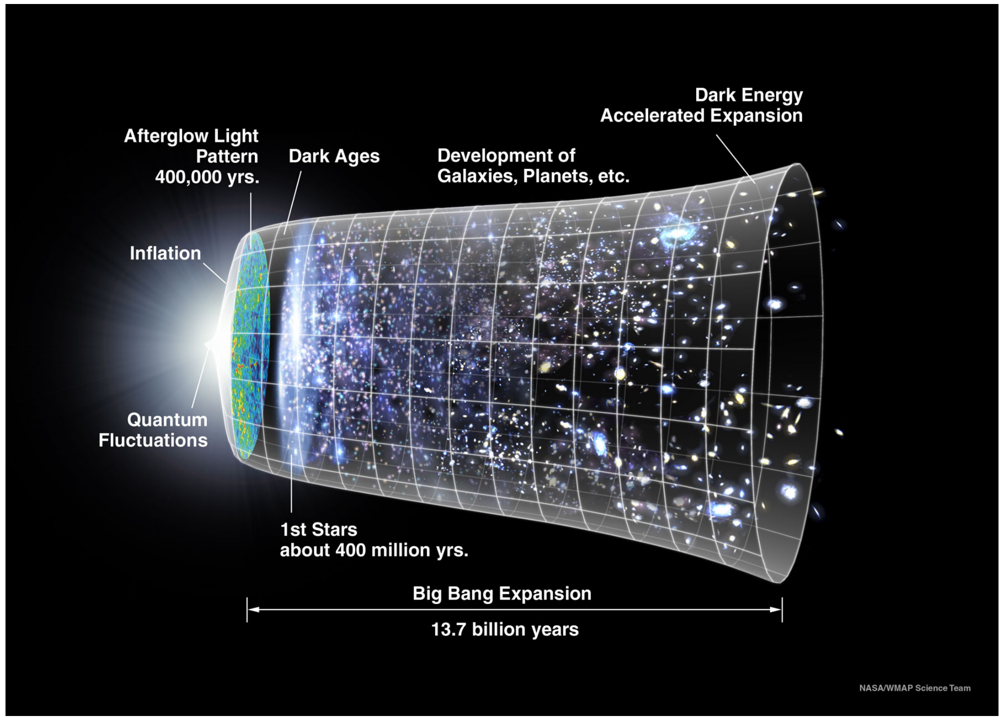


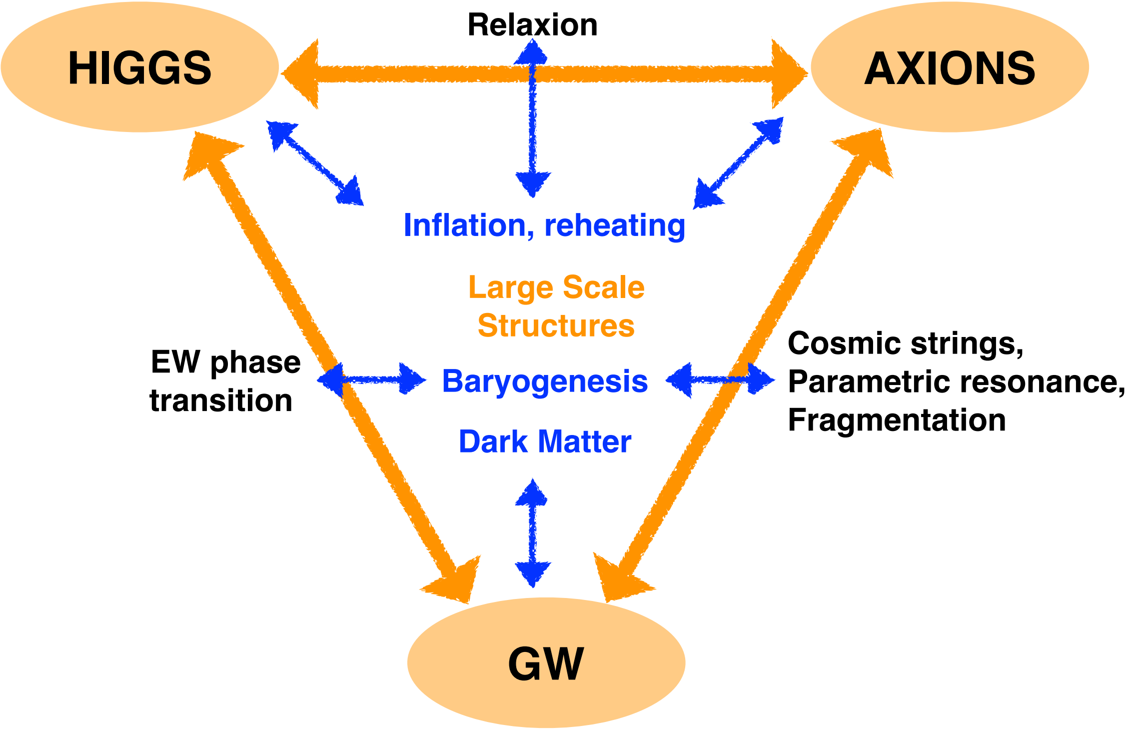
Allowed by LHC, EDM constraints and baryogenesis!

Could work even for the case where CP violation occurs just in the τ coupling (in optimistic scenario)!

$\Rightarrow$ CP violation in τ coupling could yield correct baryon asymmetry!

Gravitational waves as a probe of the early universe





HIGGS

Relaxion

AXIONS

Inflation, reheating

Large Scale Structures

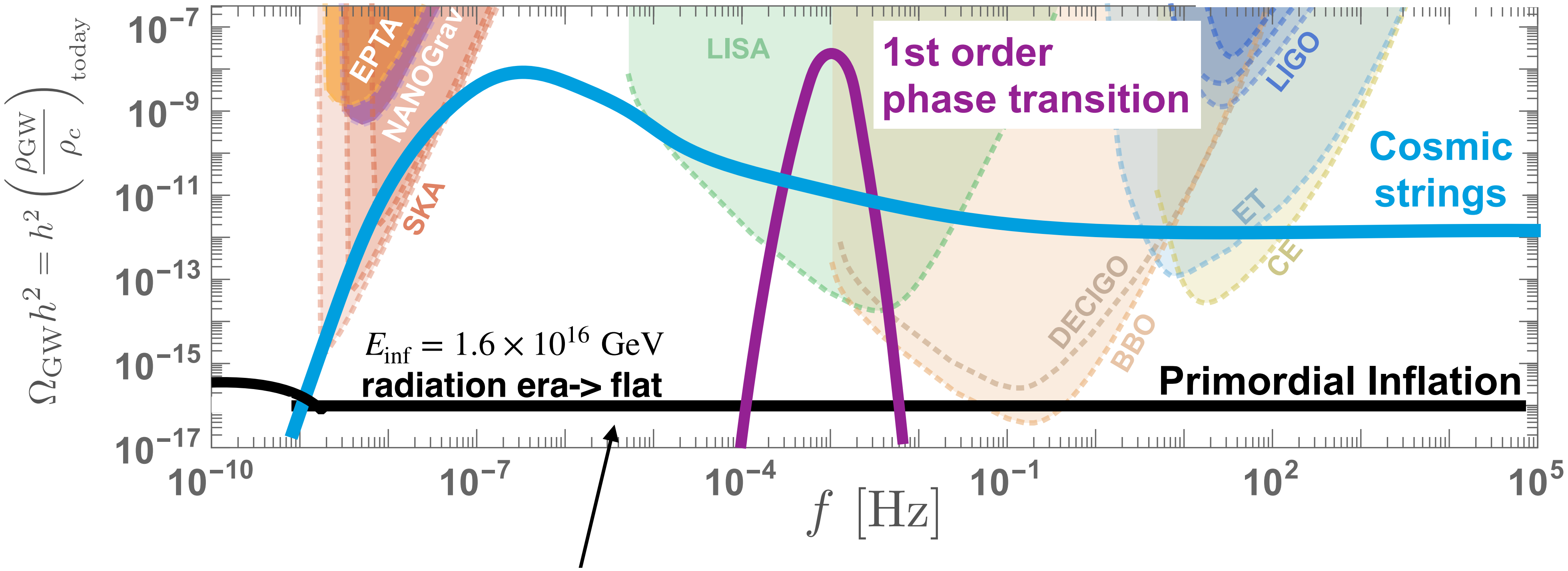
EW phase transition

Baryogenesis

Cosmic strings, Parametric resonance, Fragmentation

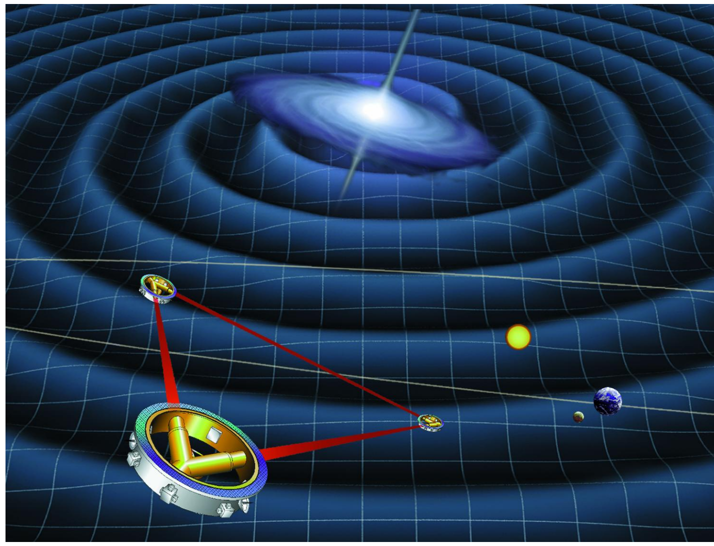
Dark Matter

GW



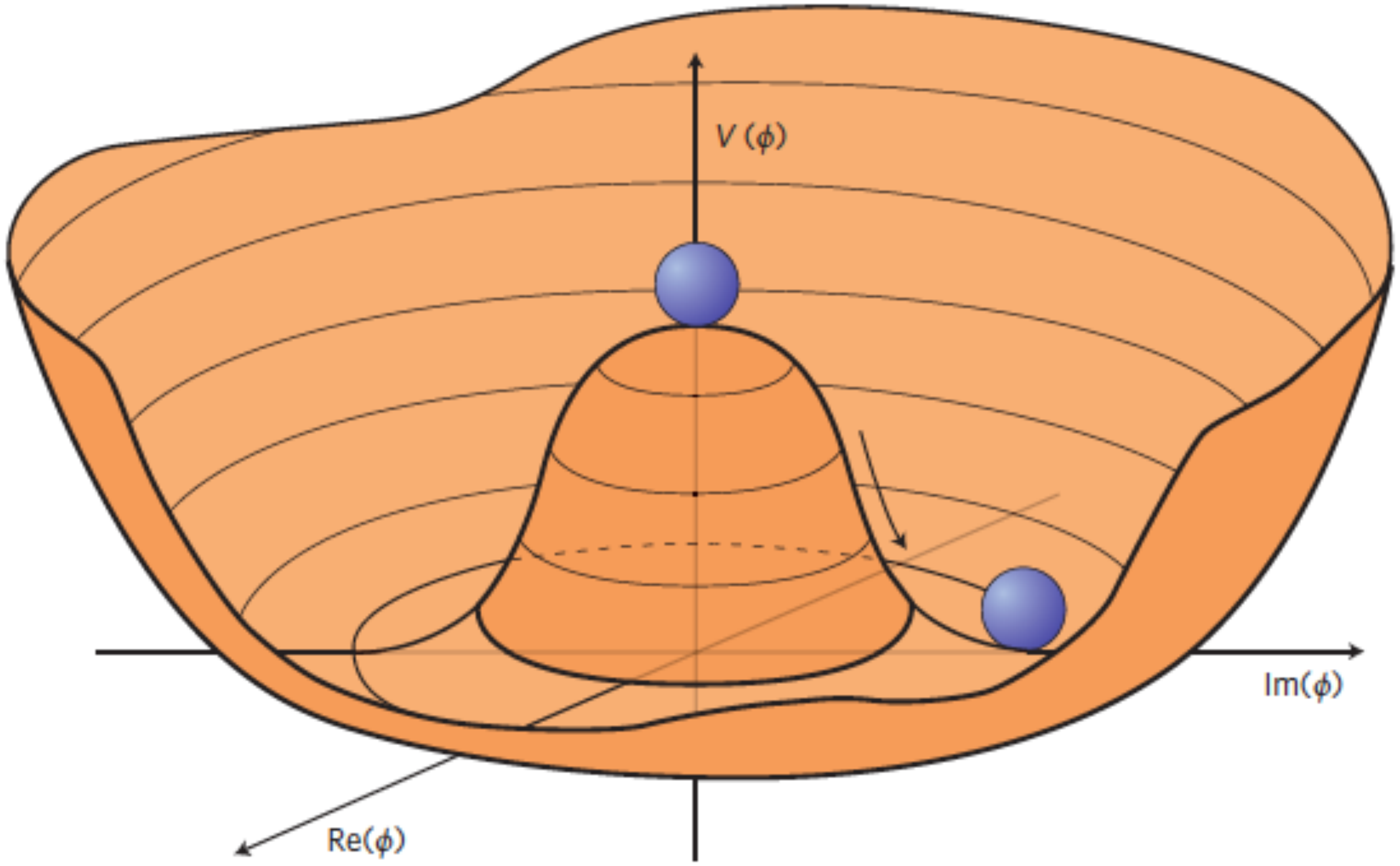
Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

LISA:



Higgs self-couplings, the Higgs potential and probes of the electroweak phase transition

The simple picture



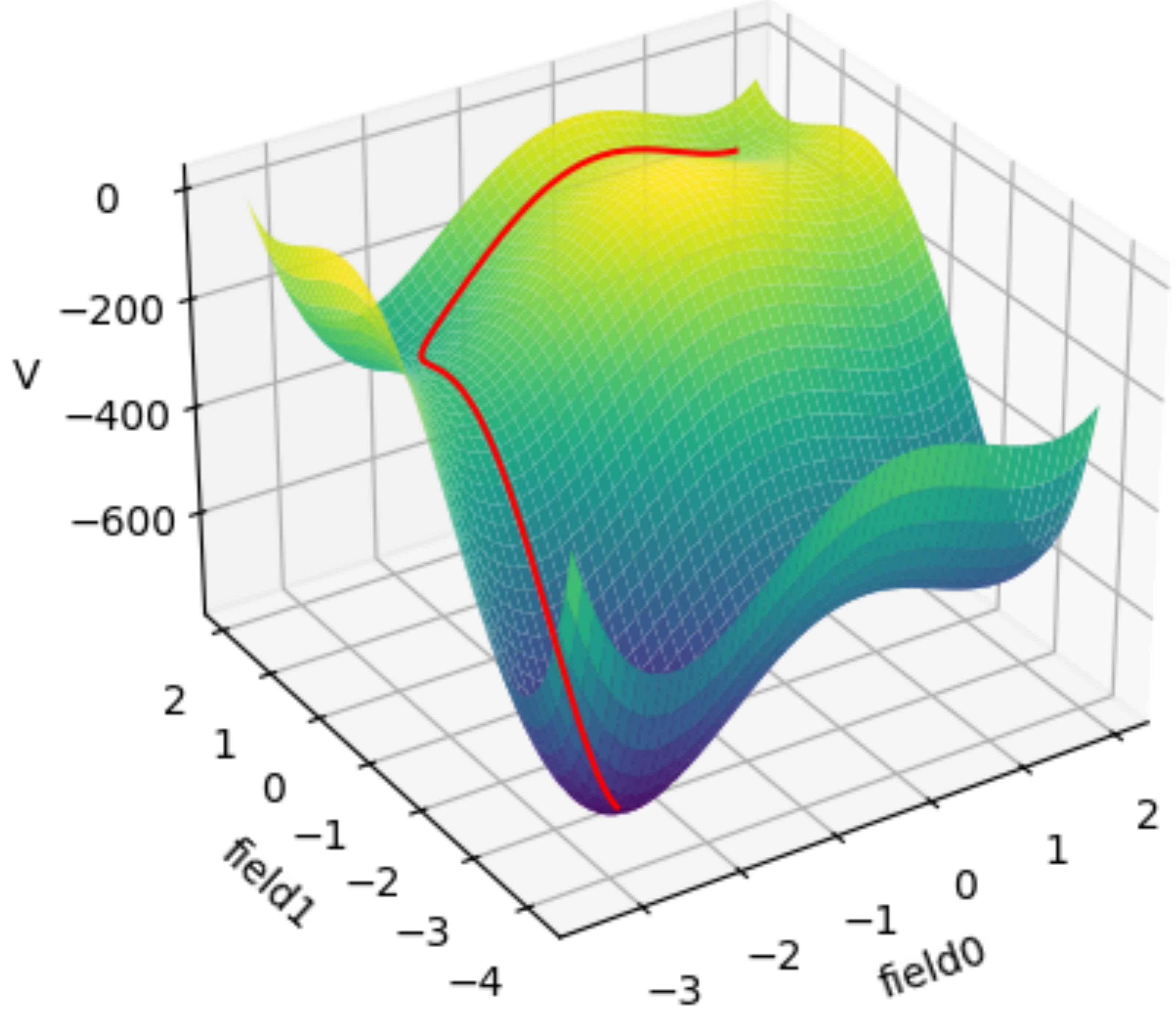
refers to the case of a single Higgs doublet field

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

Simple toy example: two singlet-type Higgs fields

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

Tunneling from a local minimum into the global minimum:



⇒ Proceeds via intermediate local minimum

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

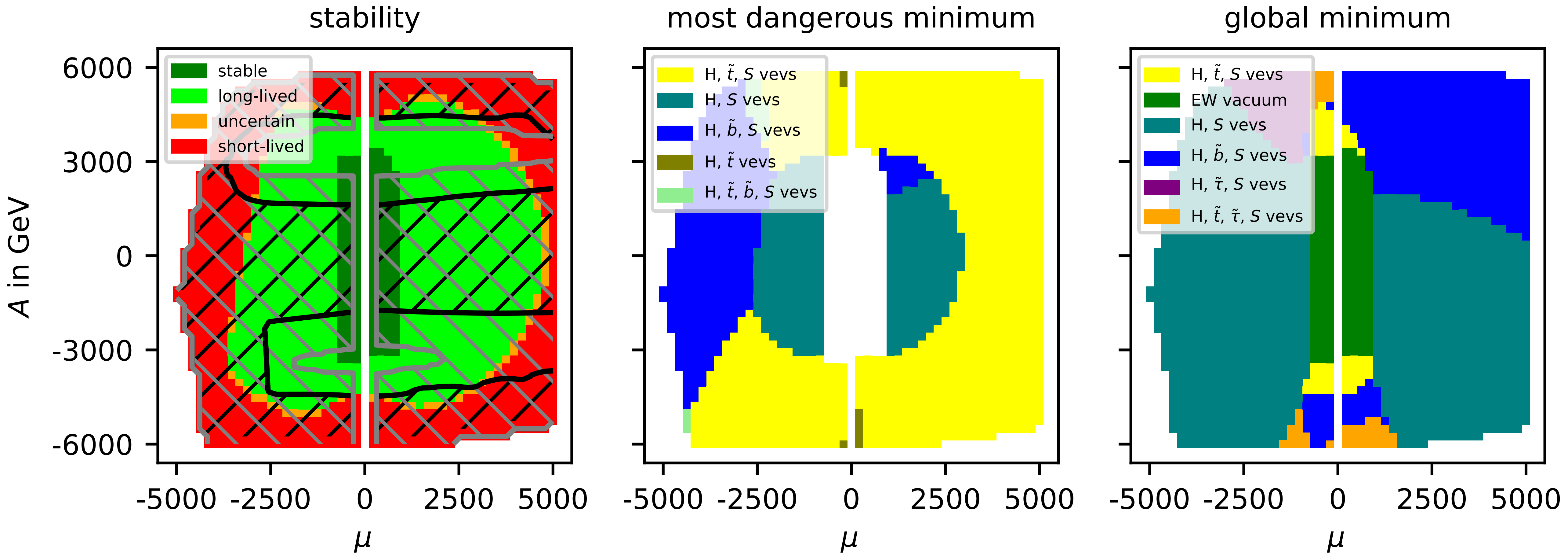
Need to check stability of the electroweak vacuum w.r.t. tunneling into deeper minima (analysis at T = 0)

[W.G. Hollik, G. W., 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. W. '23]

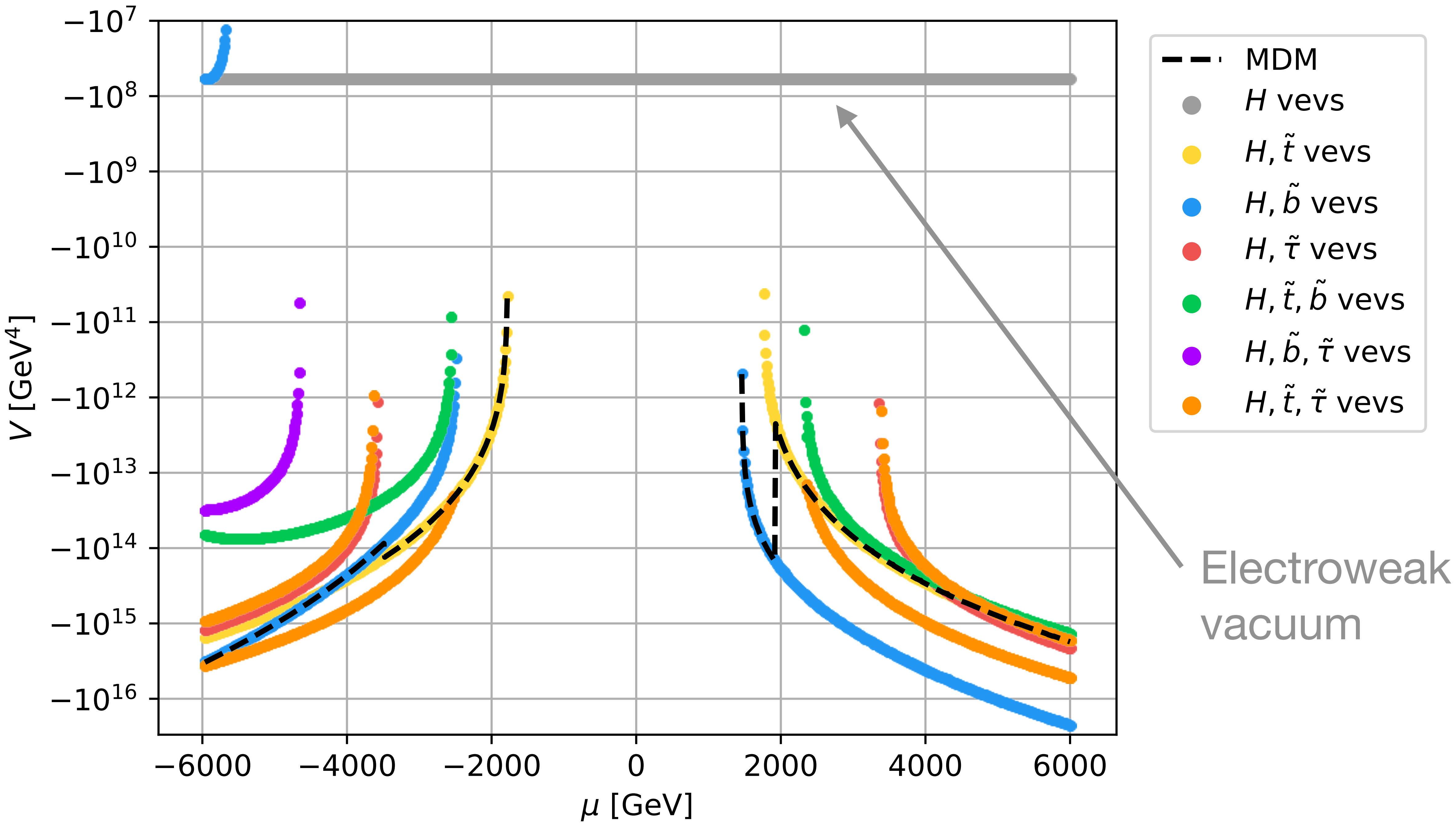


stability — most dangerous minimum — global minimum

Depth of stationary points of the Higgs potential

Along line with X_t = 2.8 TeV:

[W.G. Hollik, J. Wittbrodt, G. W. '18]

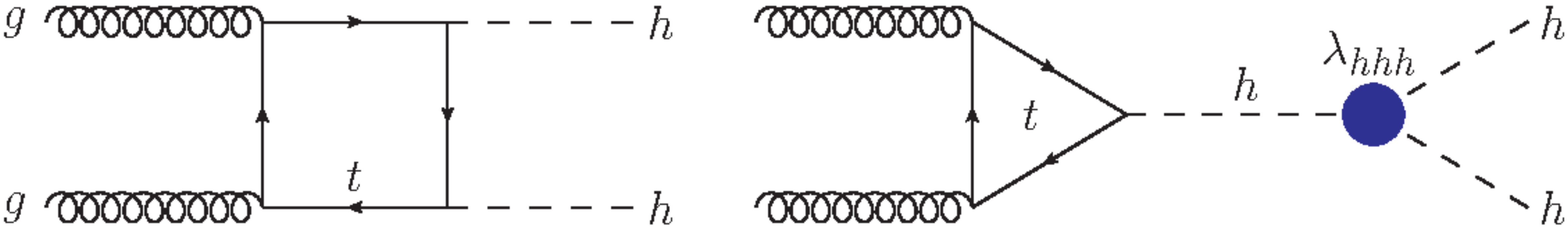


⇒ Most dangerous minimum (MDM) often differs from the global minimum and also from the one that is closest in field space

Trilinear Higgs self-coupling and the Higgs pair production process

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

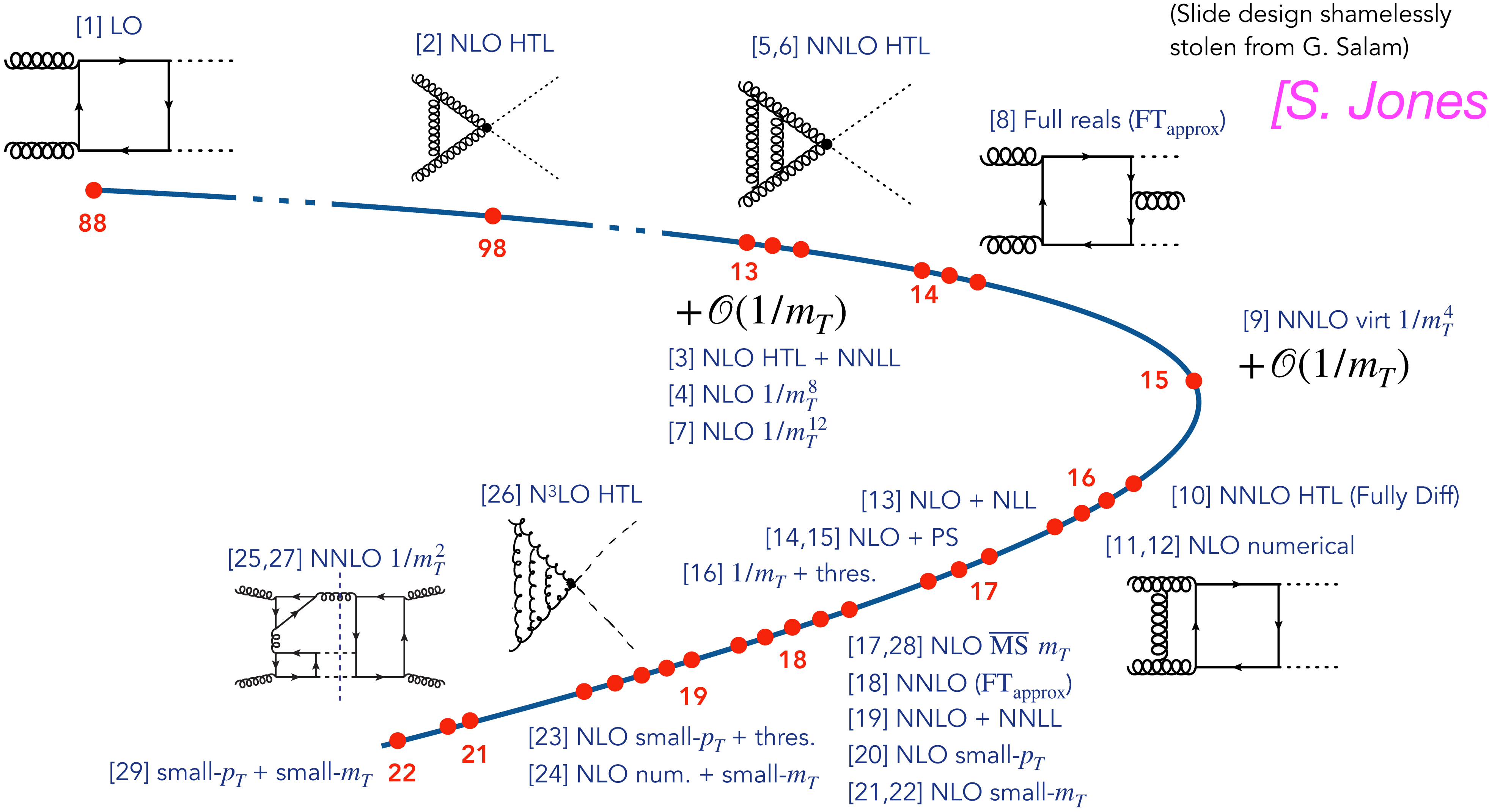
Direct measurement of trilinear Higgs self-coupling is possible a at lepton collider with at least 500 GeV c.m. energy

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.

[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

[26] N^3LO HTL

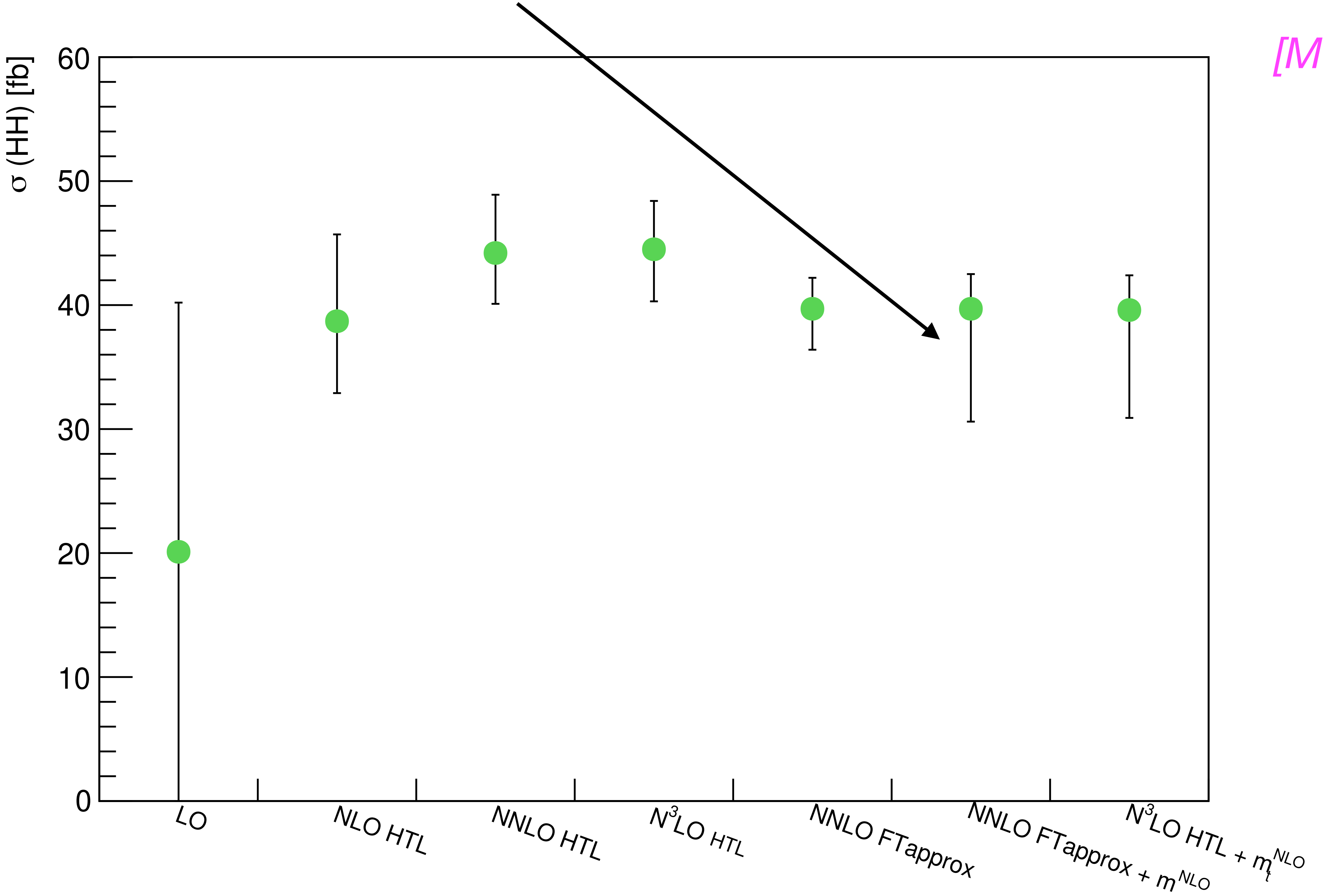
[25,27] NNLO $1/m_T^2$

[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:



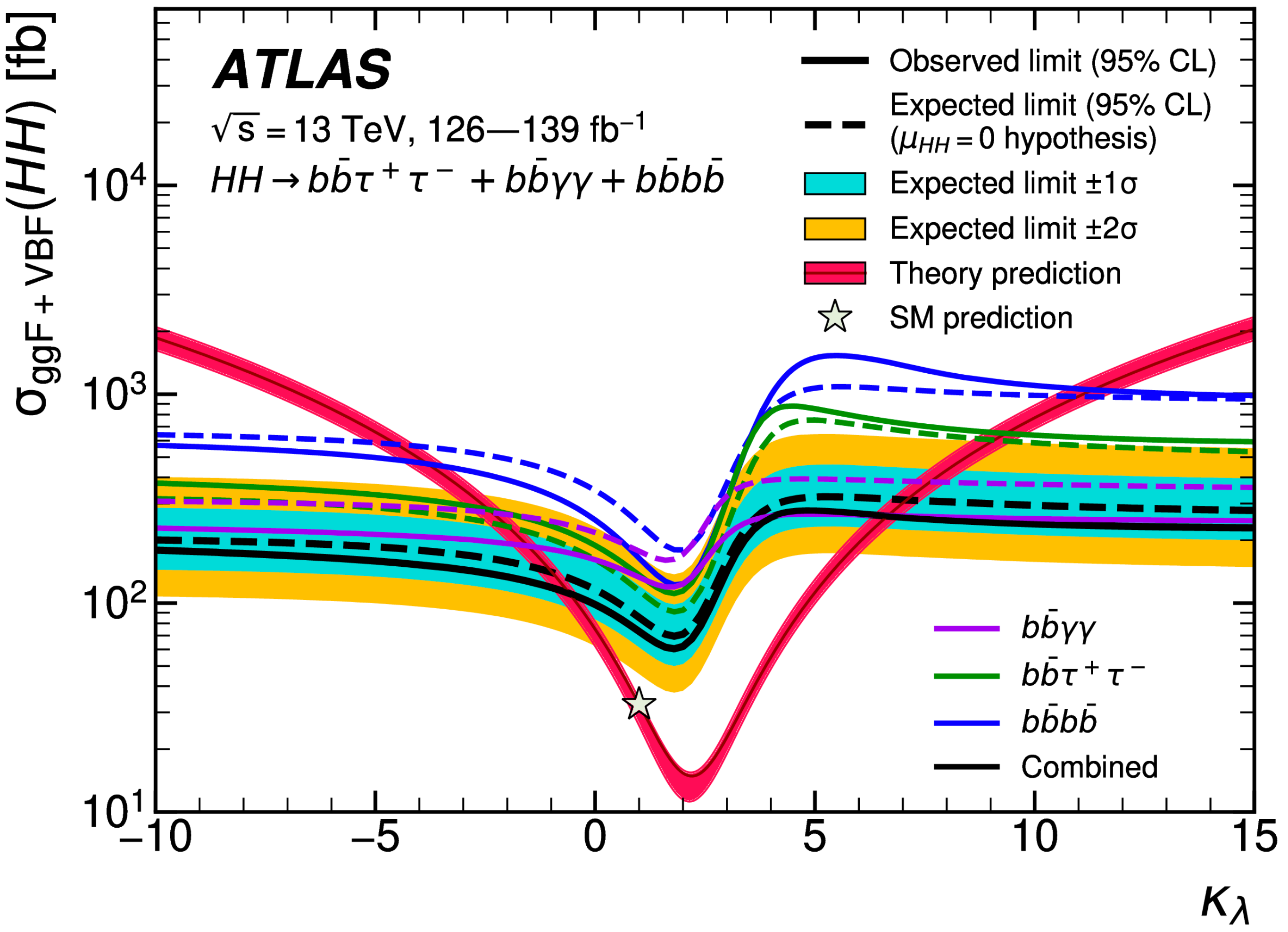
[M. Spira ’22]

Electroweak corrections: top-Yukawa contributions

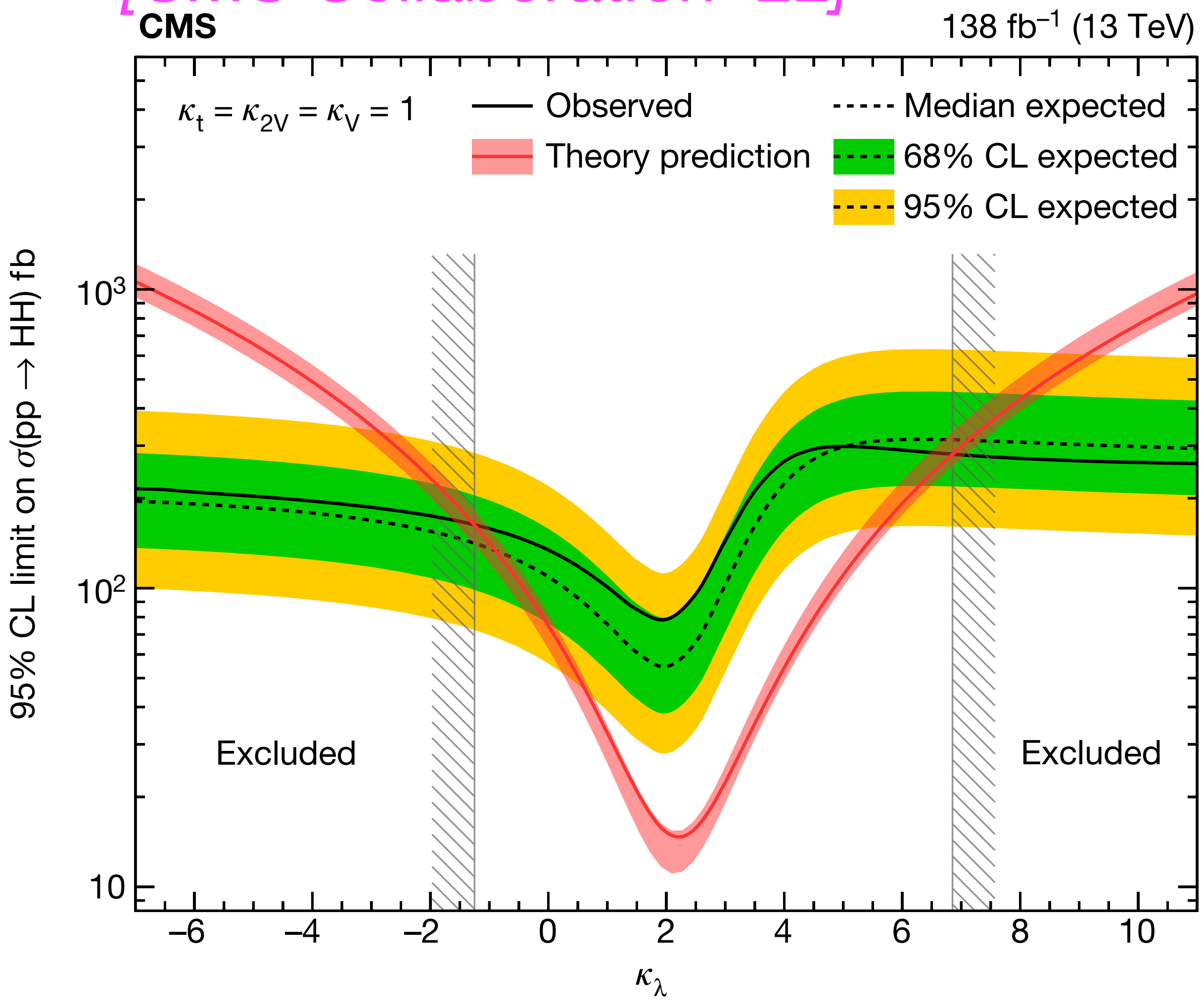
[M. Mühlleitner, J. Schlenk, M. Spira ’22]   [J. Davies et al. ’22]

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

[ATLAS Collaboration ’22]



[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: $-0.6 < \varkappa_\lambda < 6.6$ at 95% C.L. [ATLAS Collaboration ’22]

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

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

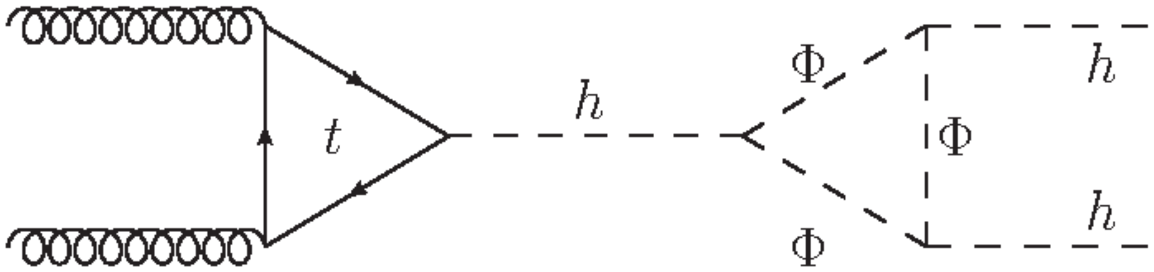
The current experimental limit can only probe scenarios with large deviations from the SM
⇒ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

Check of applicability of the experimental limit on κ_λ

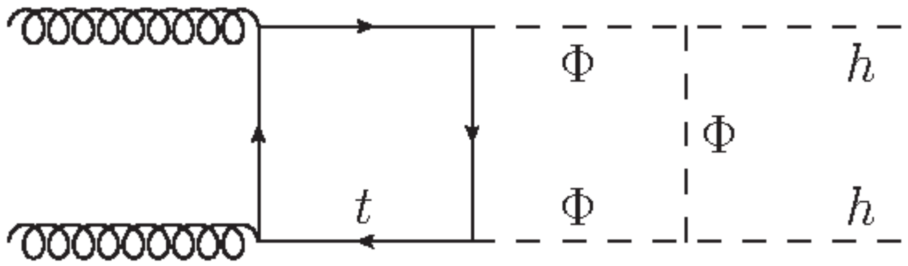
Alignment limit: h has SM-like tree-level couplings

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!

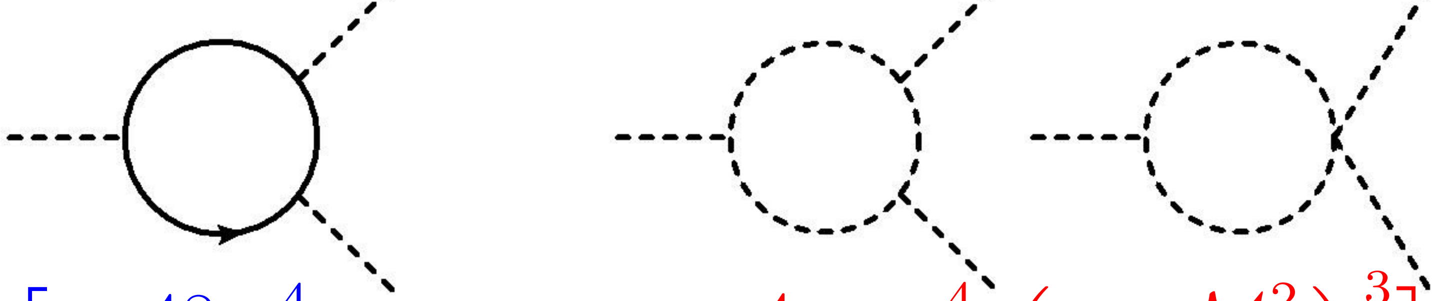
Effects of BSM particles on the trilinear Higgs coupling

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. W. ’22]

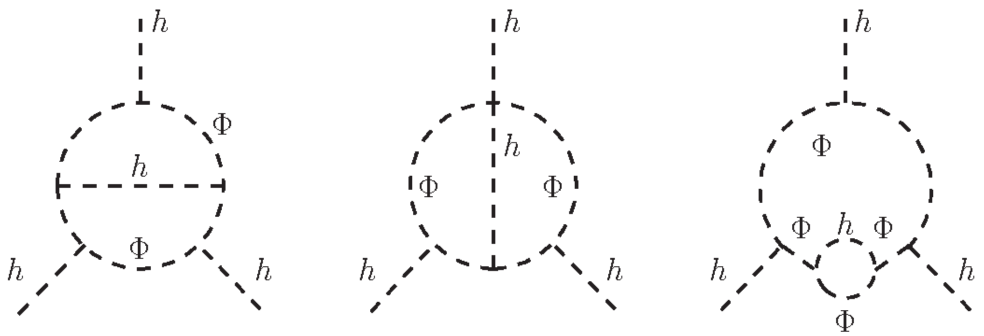
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

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

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 $g_{hh\phi\phi}$



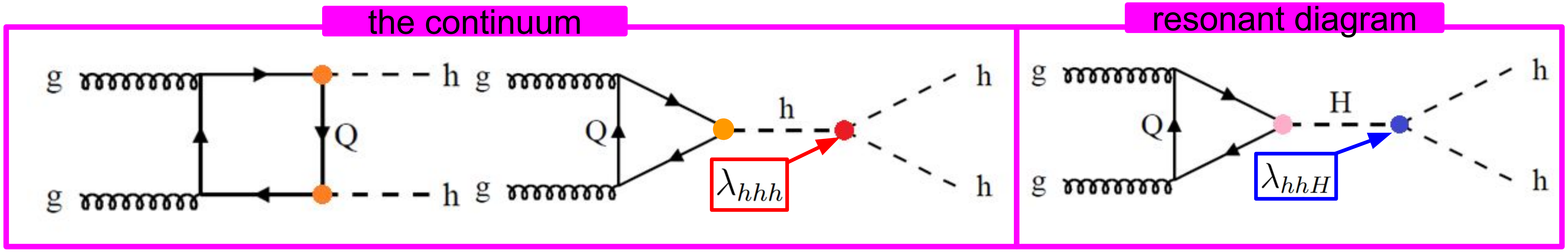
Analysis is carried out in the alignment limit of the 2HDM ($\alpha = \beta - \pi/2$)

⇒h has SM-like tree-level couplings

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

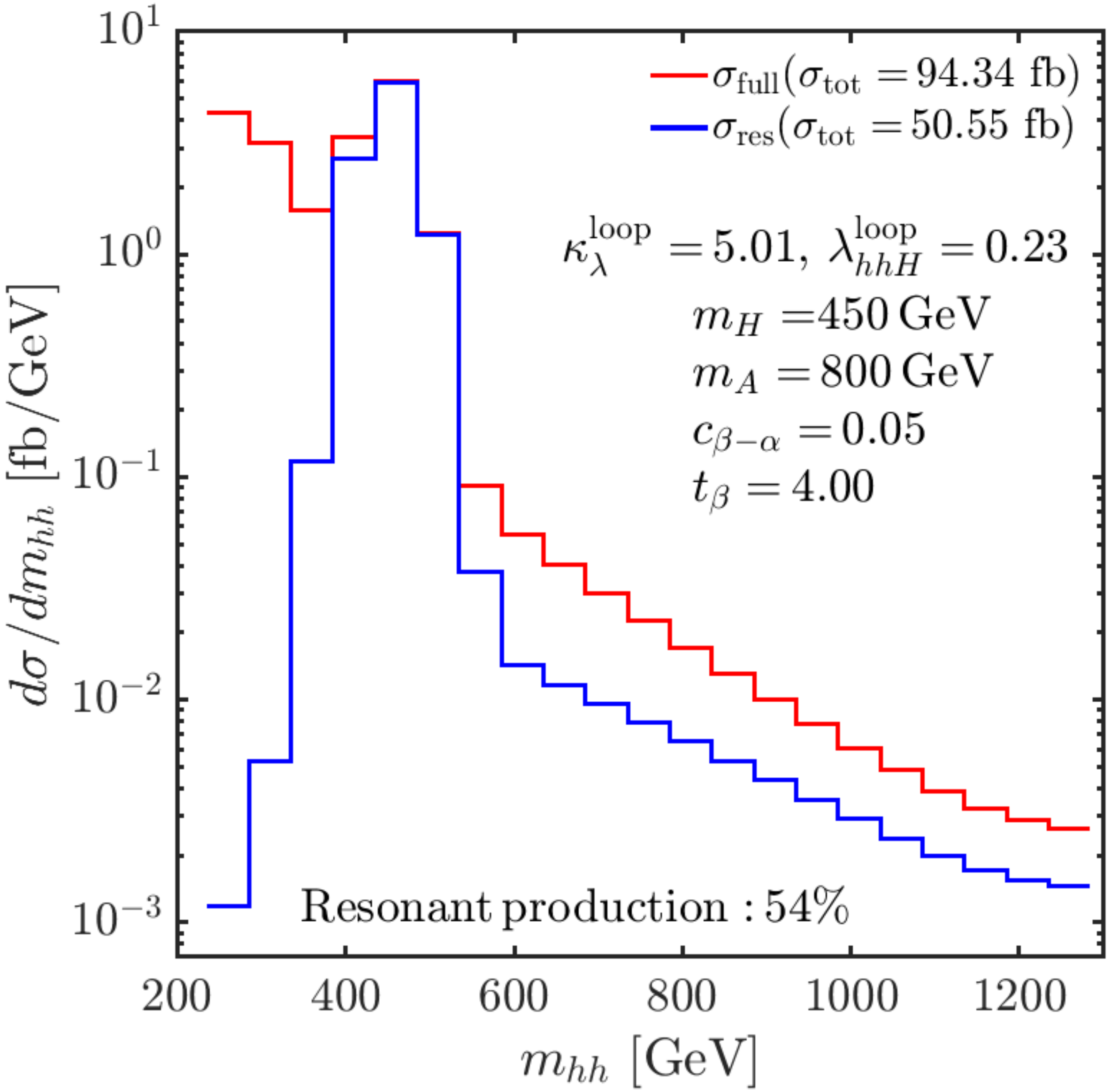
resonant diagram

⇒ 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

[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.



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

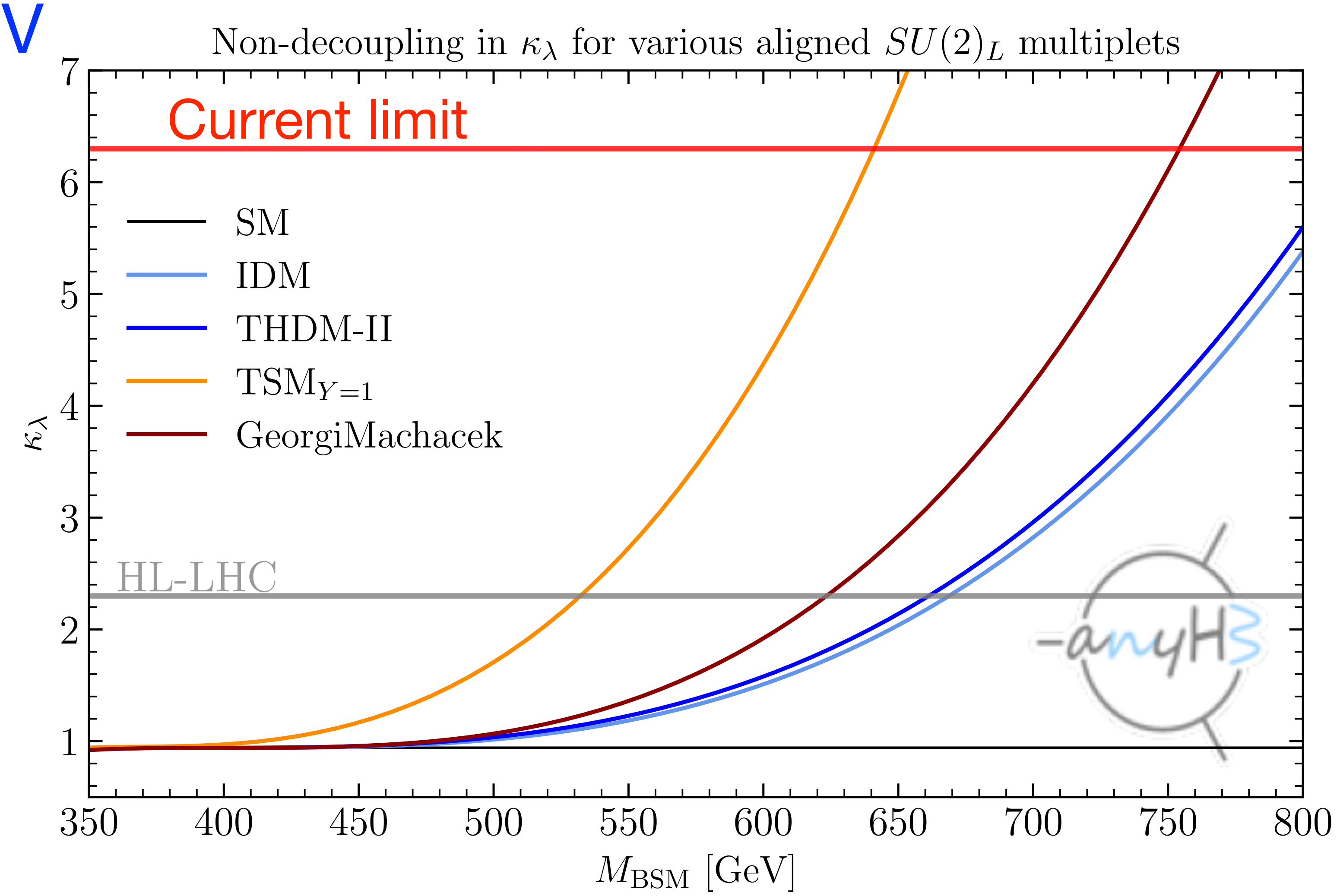
Higgs self-couplings in extended Higgs sectors

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. W. '23]

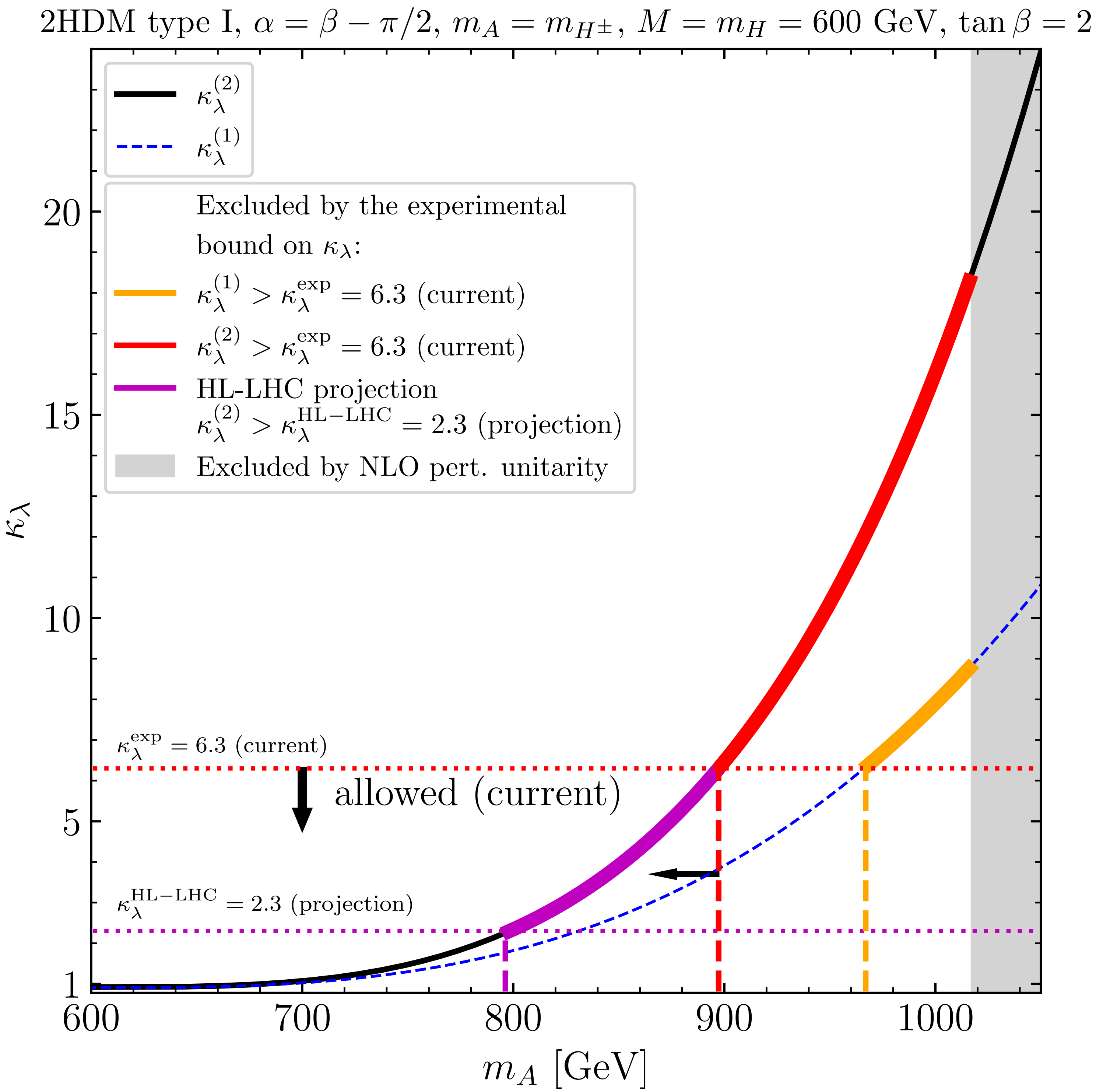
M_L = 400 GeV



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. W. '22, Phys. Rev. Lett. 129 (2022) 23, 231802]

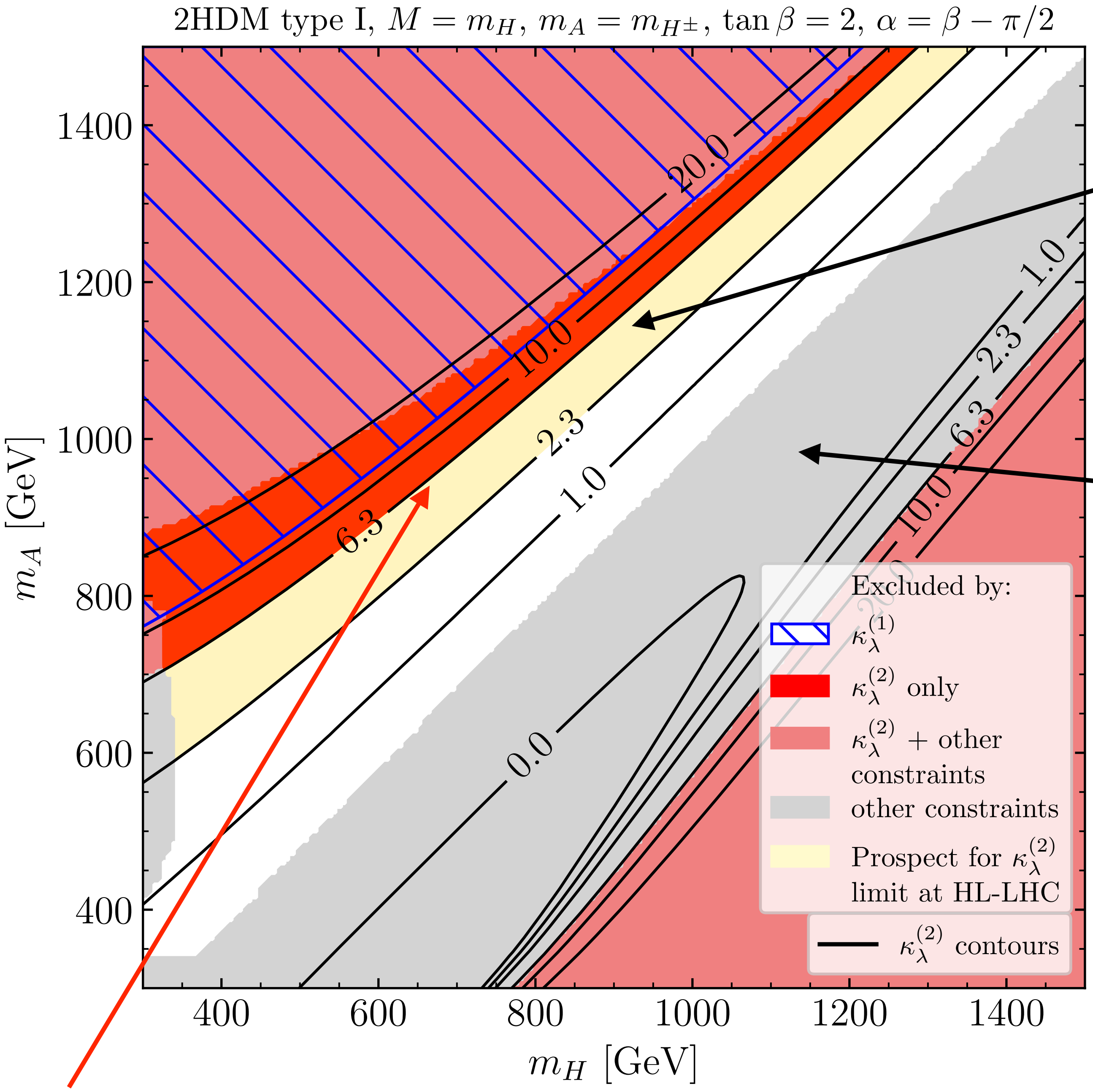


⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

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!

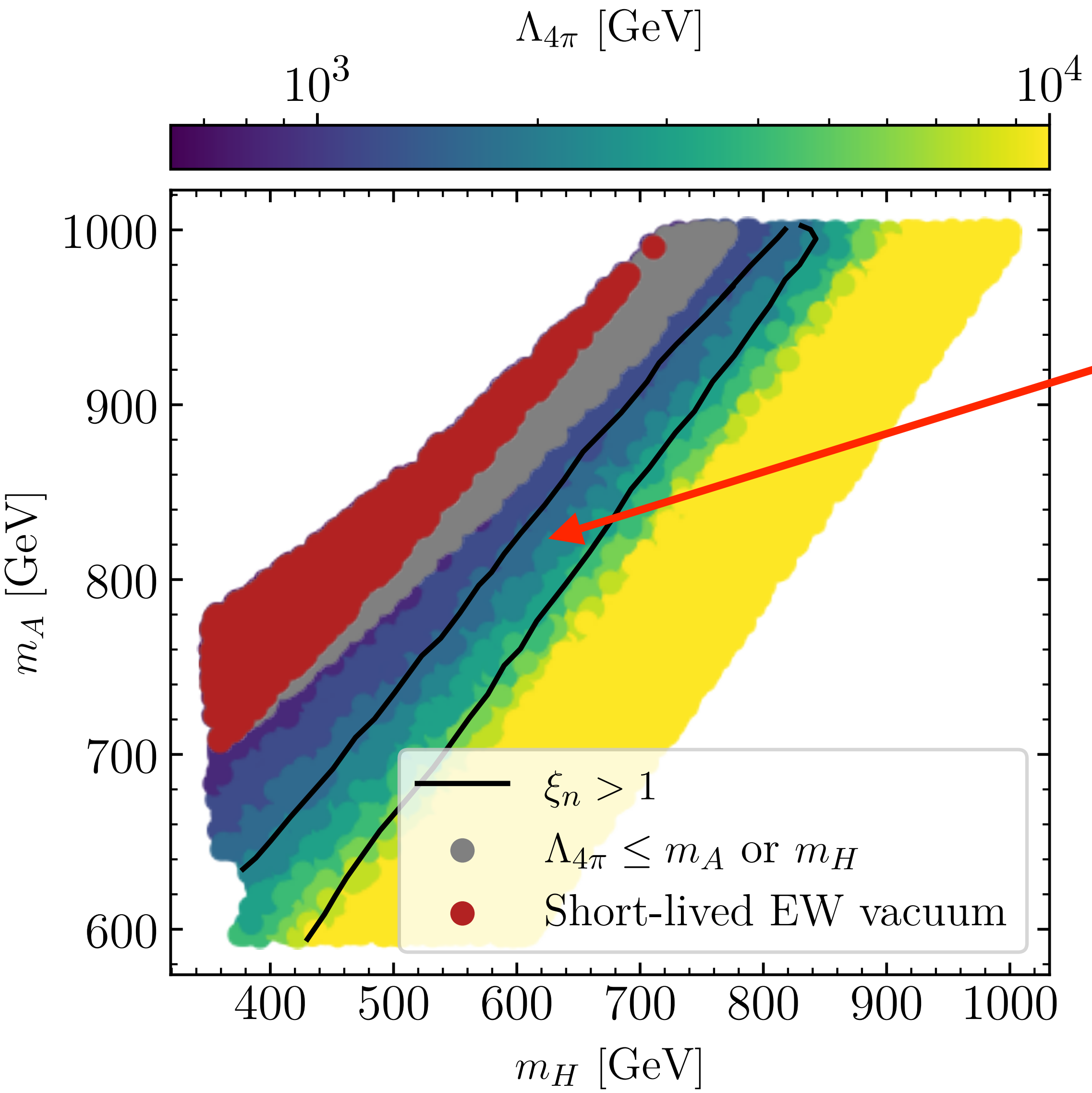
Connection between the trilinear Higgs coupling and the evolution of the early Universe

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

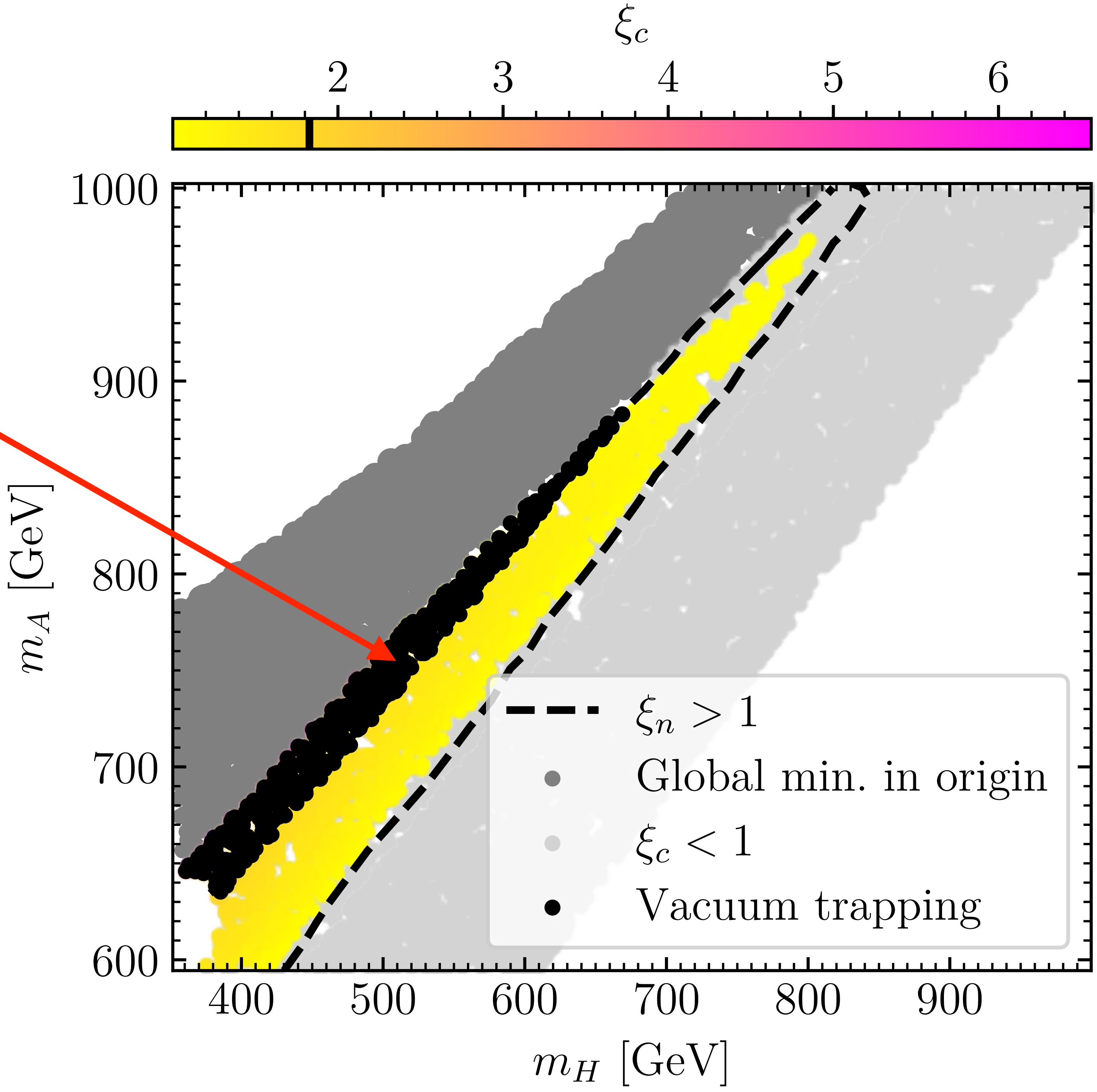


Parameter region giving rise to a strong first-order EWPT

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

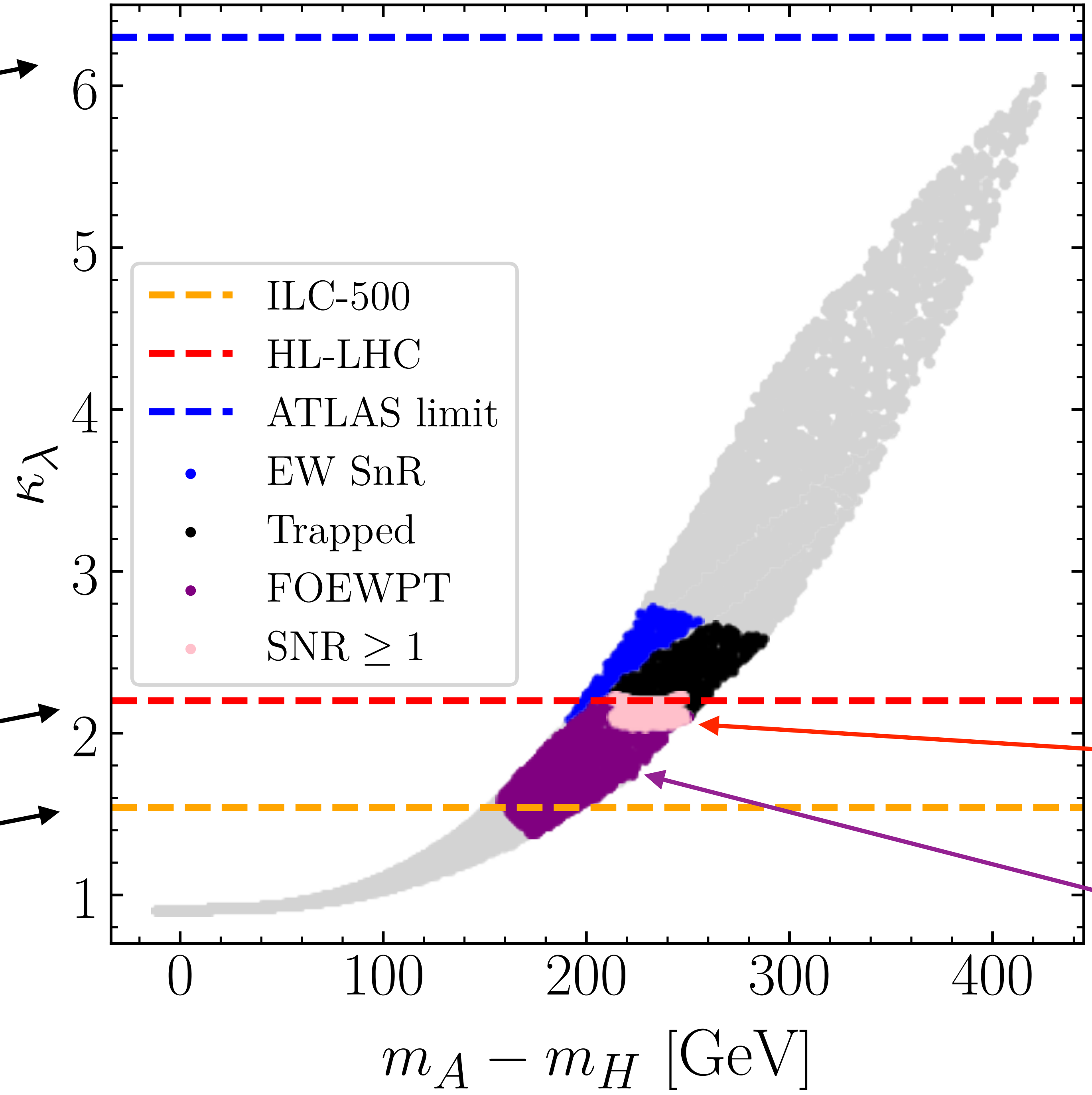
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

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]



alignment limit,
tanβ = 3

current bound

HL-LHC
sensitivity

ILC sensitivity

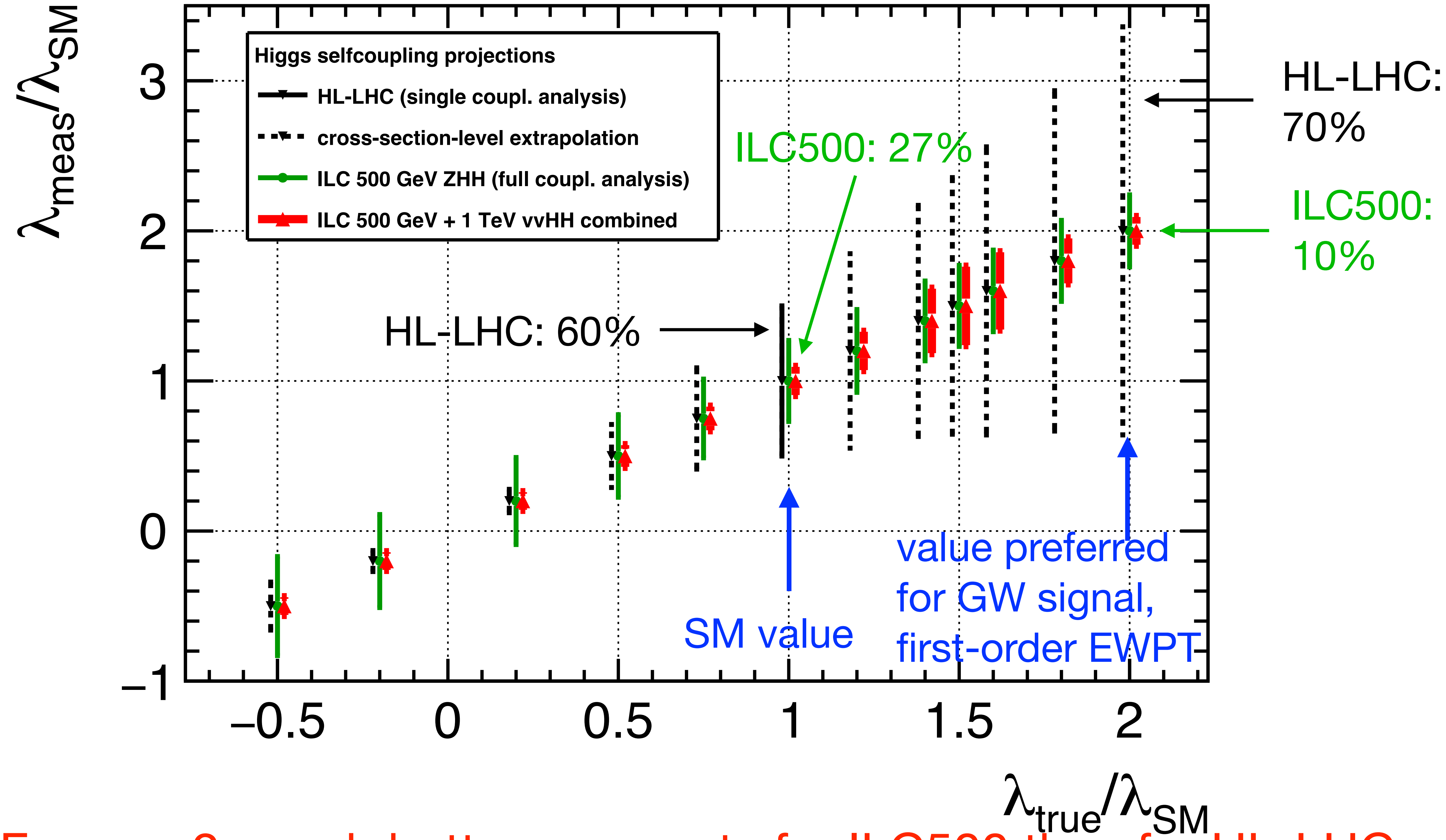
region with potentially observable gravitational wave (GW) signal

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 (500 GeV, Higgs pair production)

[J. List et al. '21]



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

Reason: different interference contributions

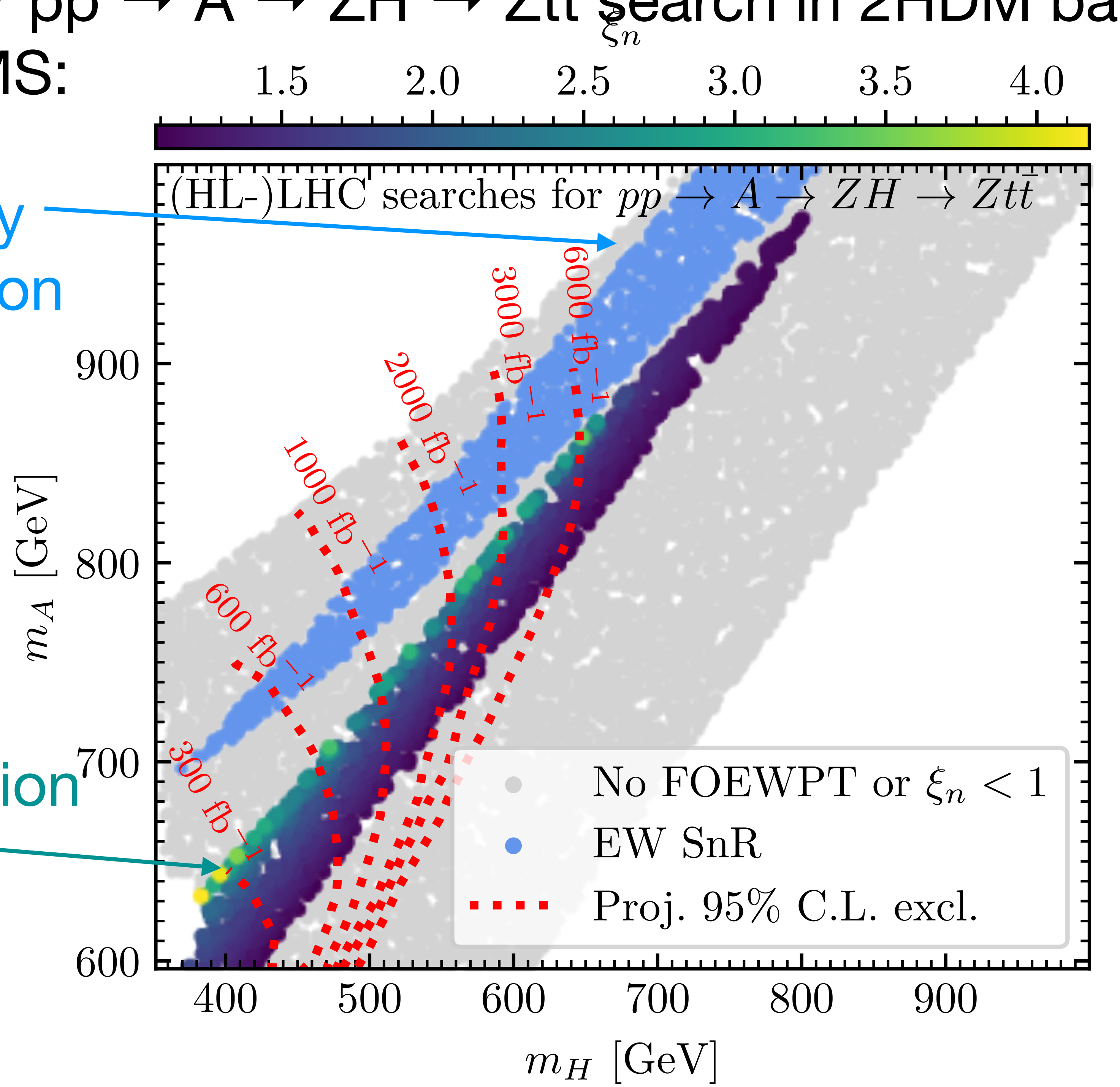
Probing the electroweak phase transition with the "smoking gun" signature

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



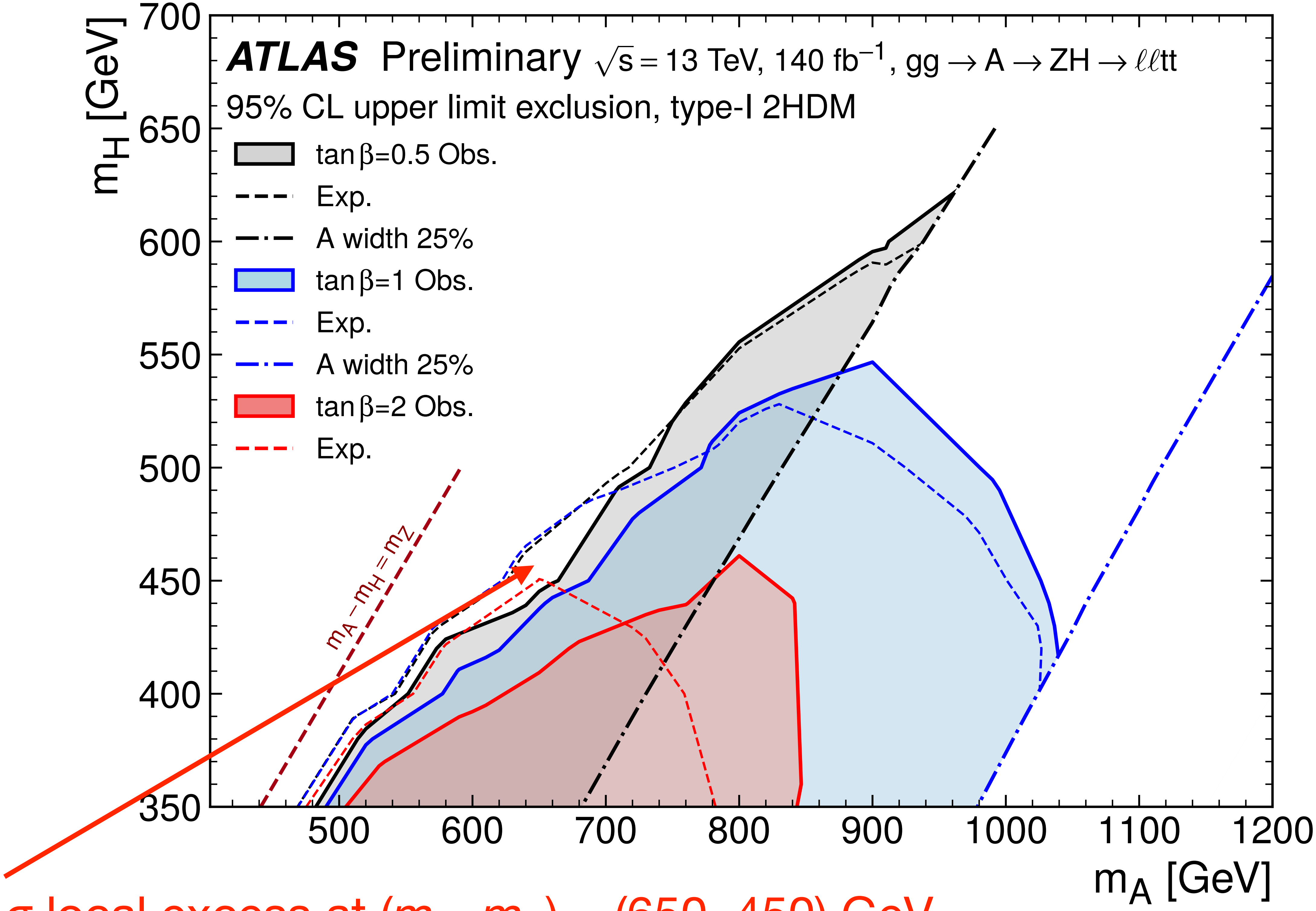
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

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

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

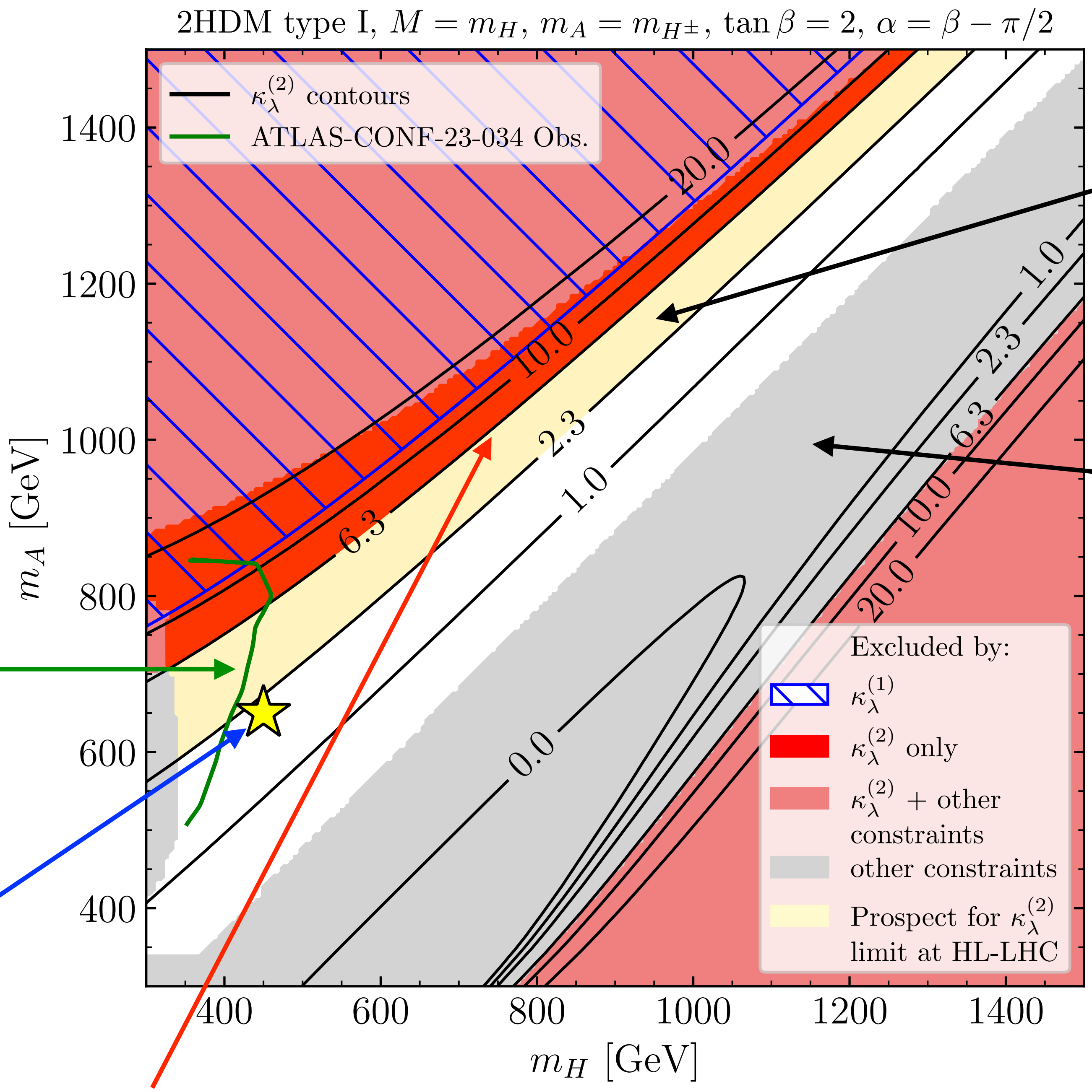
[ATLAS Collaboration ’23]



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. W. ’23]



Sensitivity to $\varkappa_\lambda$ at the HL-LHC

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

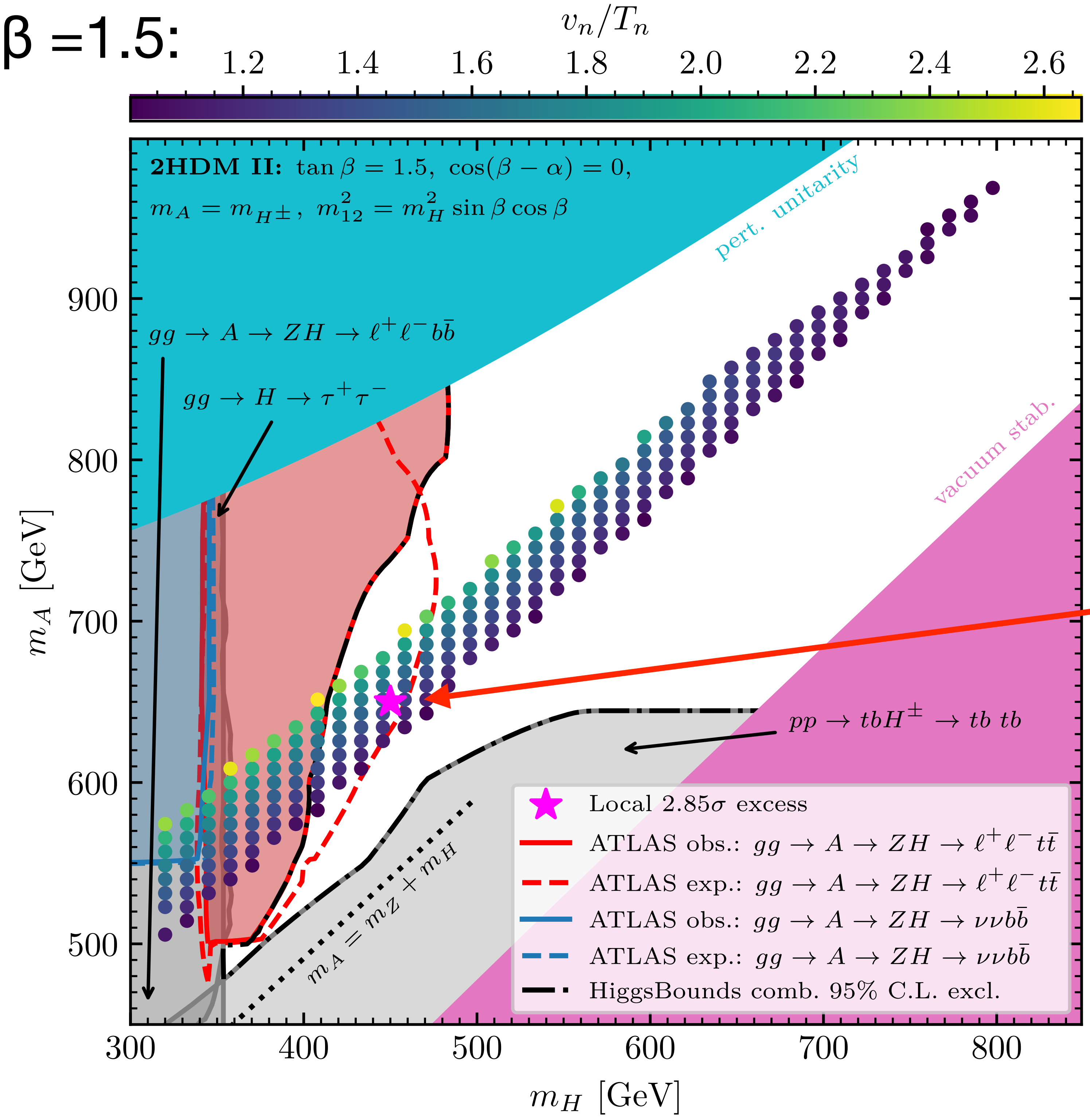
ATLAS limit

ATLAS excess

⇒ 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:



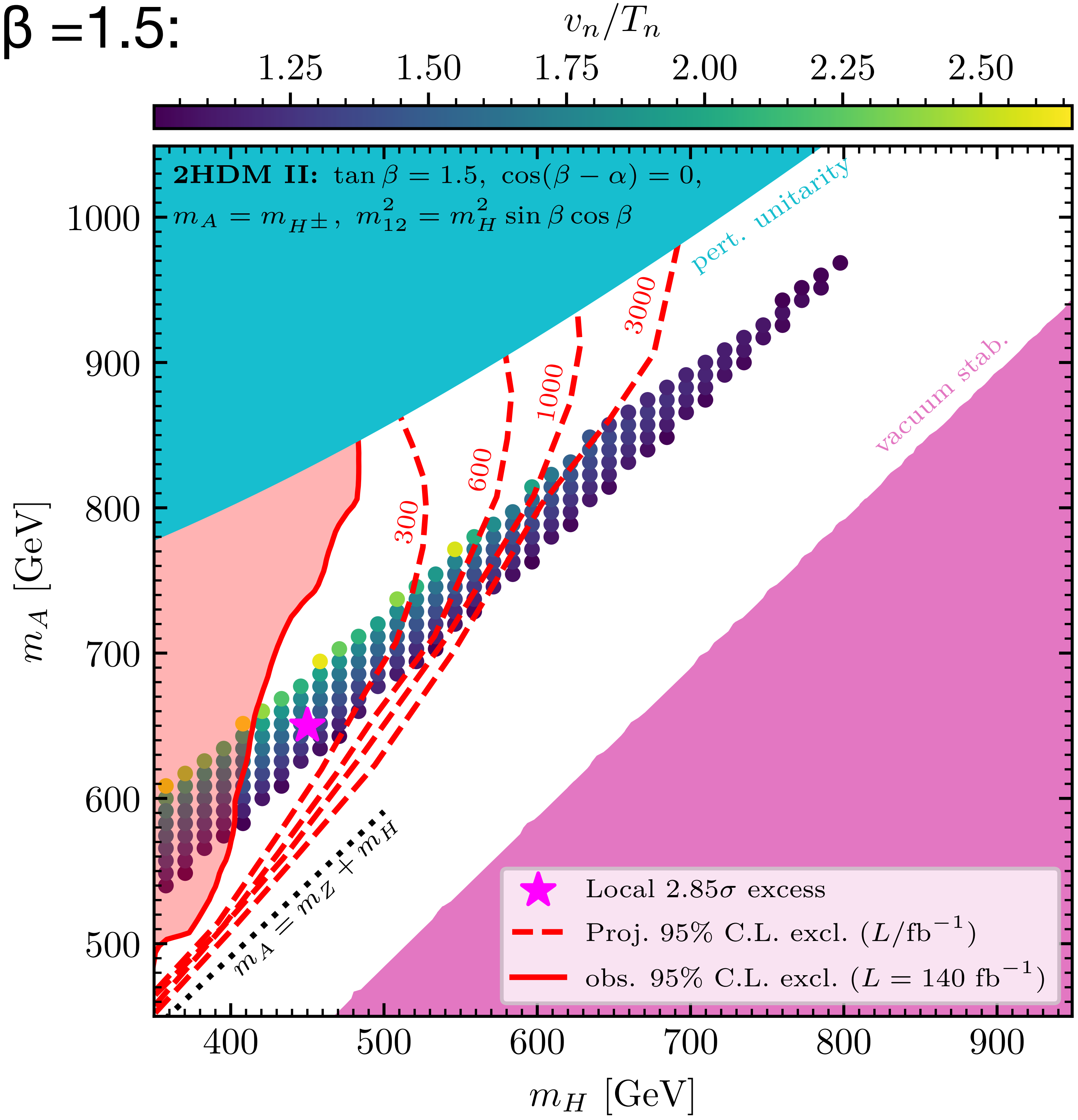
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

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

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

Projection for future sensitivity based on ATLAS result

2HDM, tanβ =1.5:

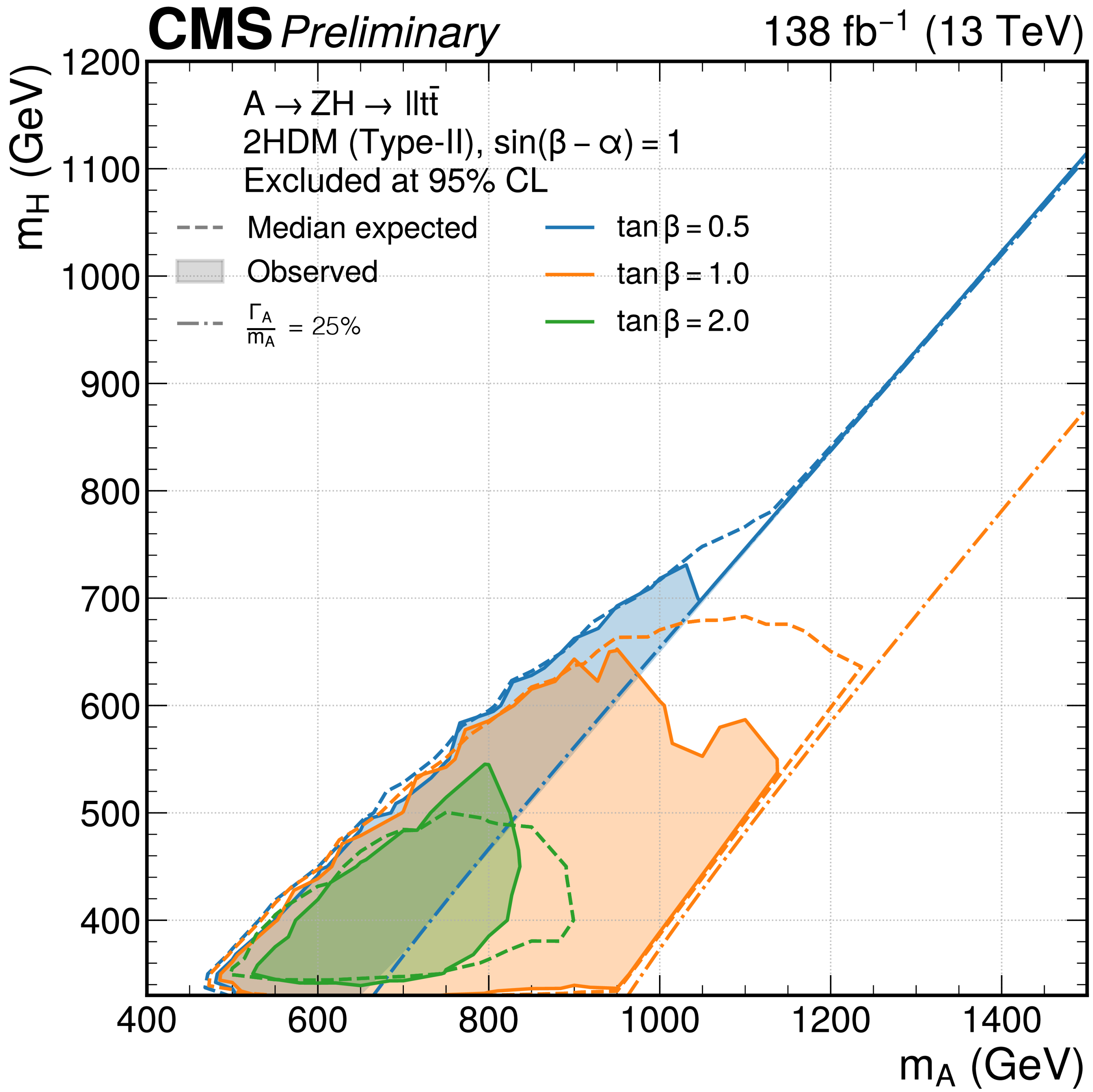


[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

⇒Good agreement with projection based on expected CMS limit

New CMS result for pp ➞ A ➞ ZH ➞ Ztt in the 2HDM

[CMS Collaboration '24]



⇒ ATLAS excess not confirmed by CMS

Further “smoking gun” signature

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

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

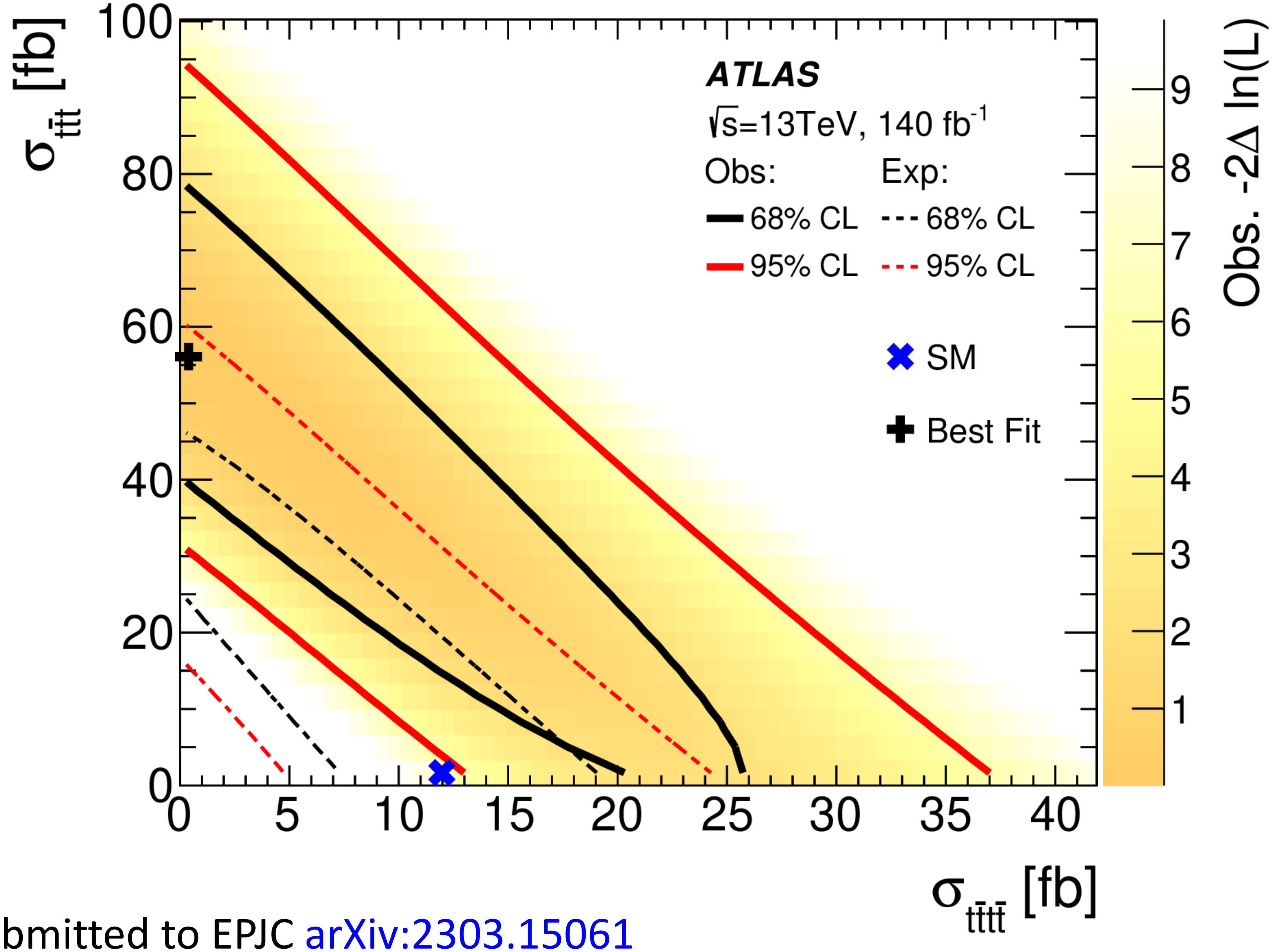
For the production of the charged Higgs together with *t b* this yields a 4-top like or 3-top like final state

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 Collaboration '23]

ATLAS: three tops?

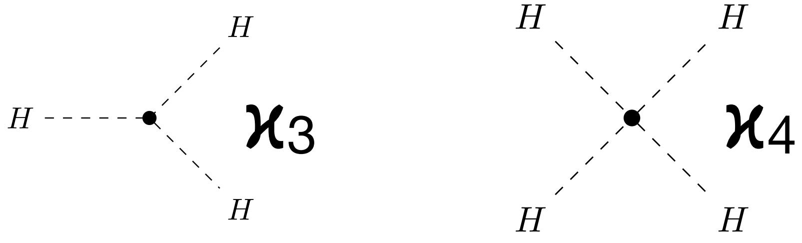


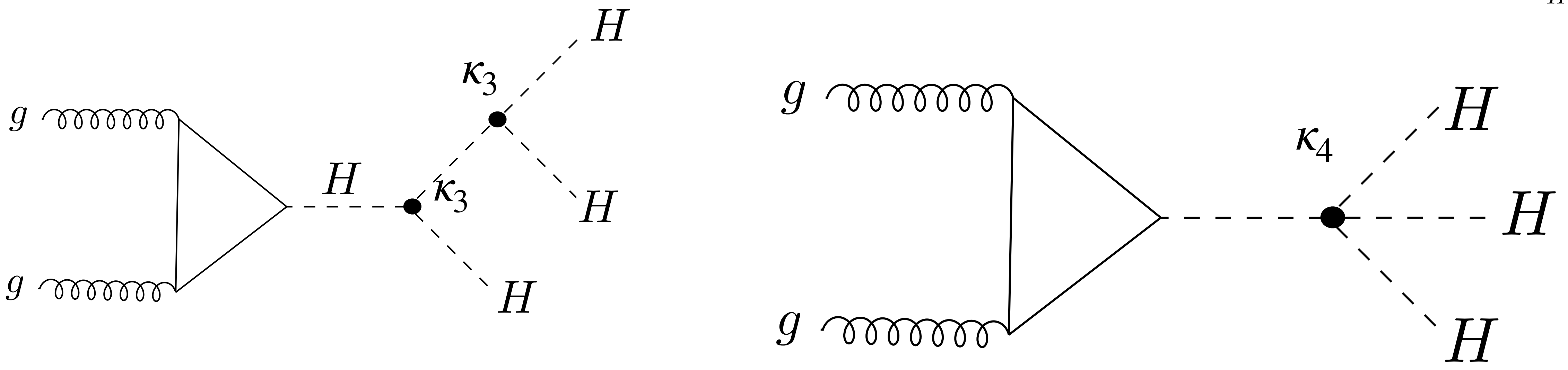
Submitted to EPJC arXiv:2303.15061

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

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

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

Wigner functions

- Tree level unitarity:

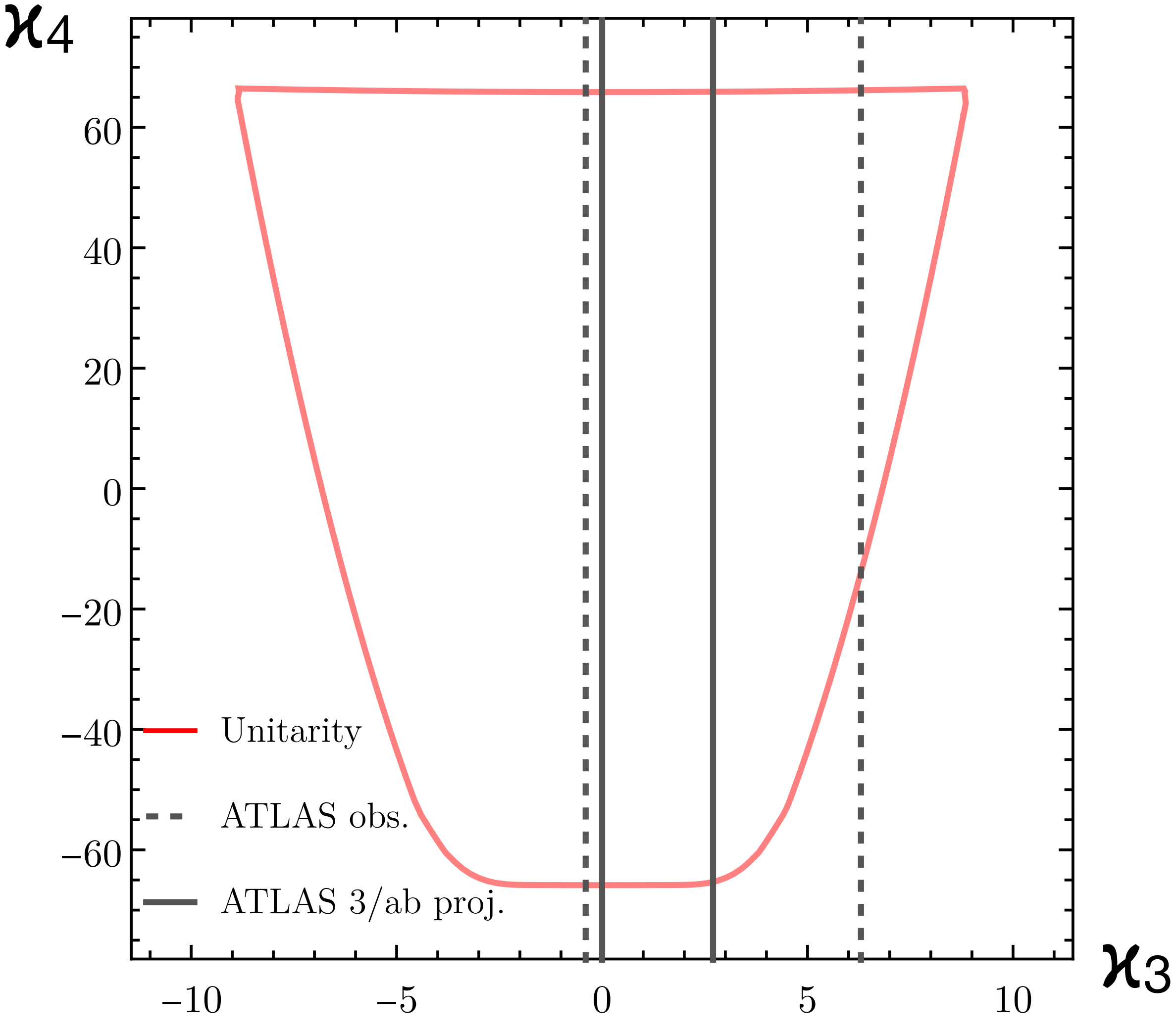
$$\mathrm{Im}a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re}a^0_{ii}| \leq \frac{1}{2}$$

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]



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

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

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

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

Contributions to κ_3, κ_4:

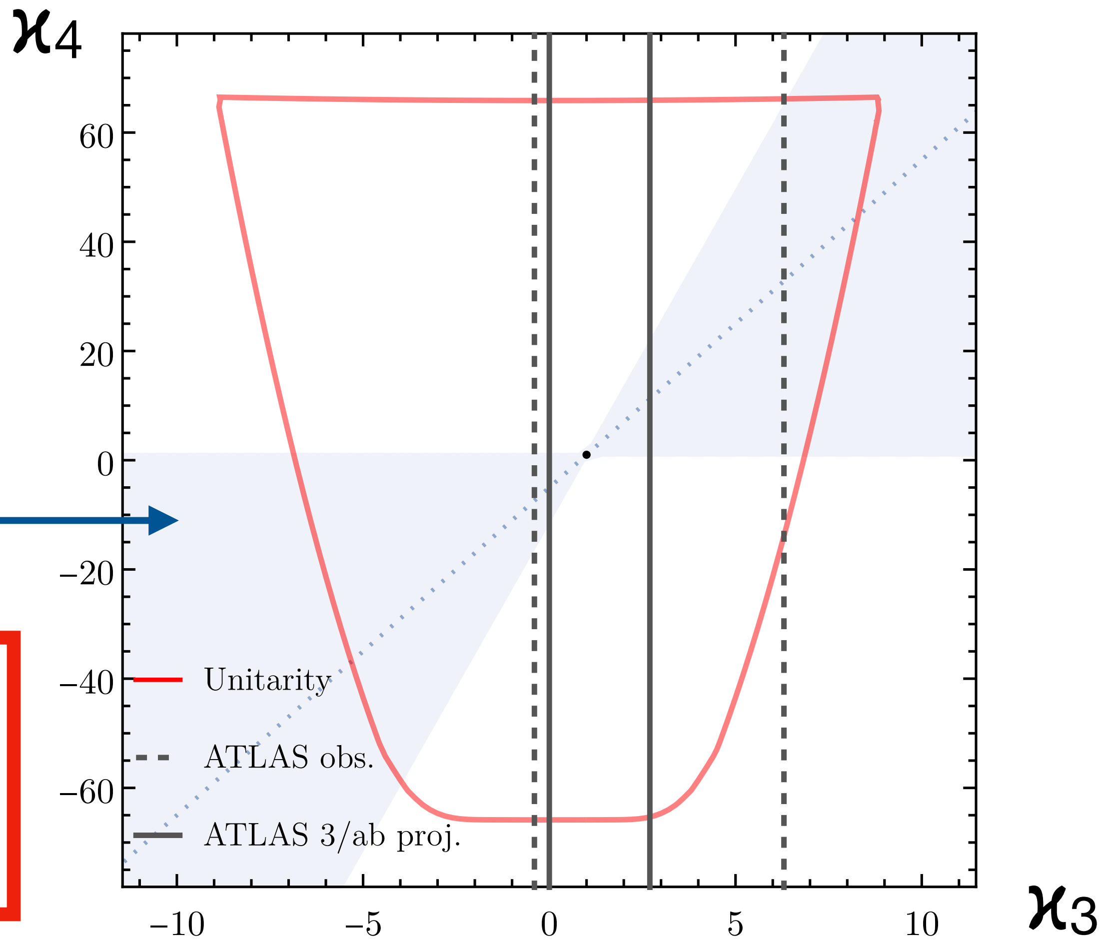
$$(\kappa_3 - 1) = \frac{C_6 v^2}{\lambda\Lambda^2}\,,$$

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

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 ϰ4 enhanced by factor 6!

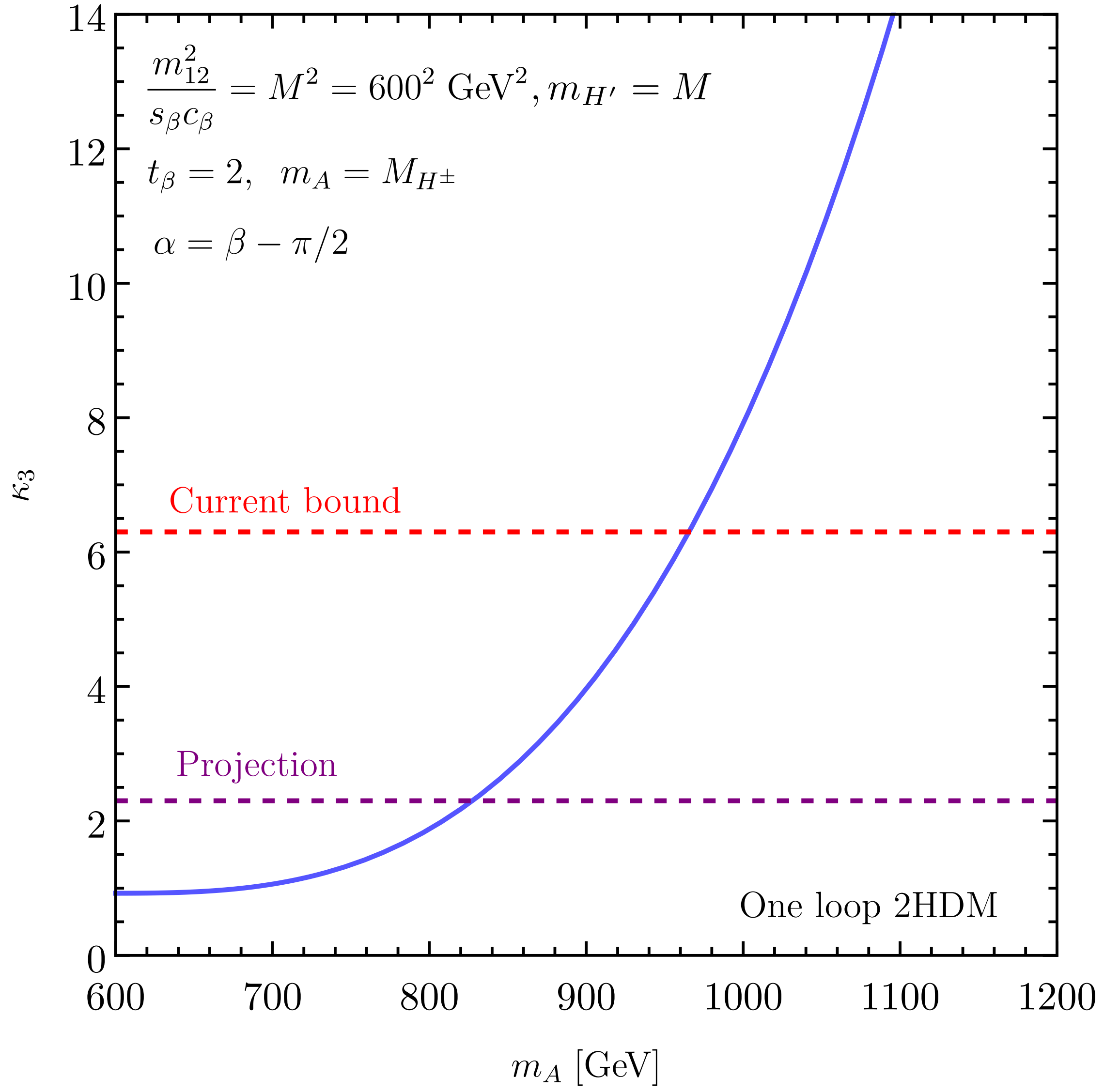
Model example: 2HDM, $\varkappa_3$ (see above) vs. $\varkappa_4$

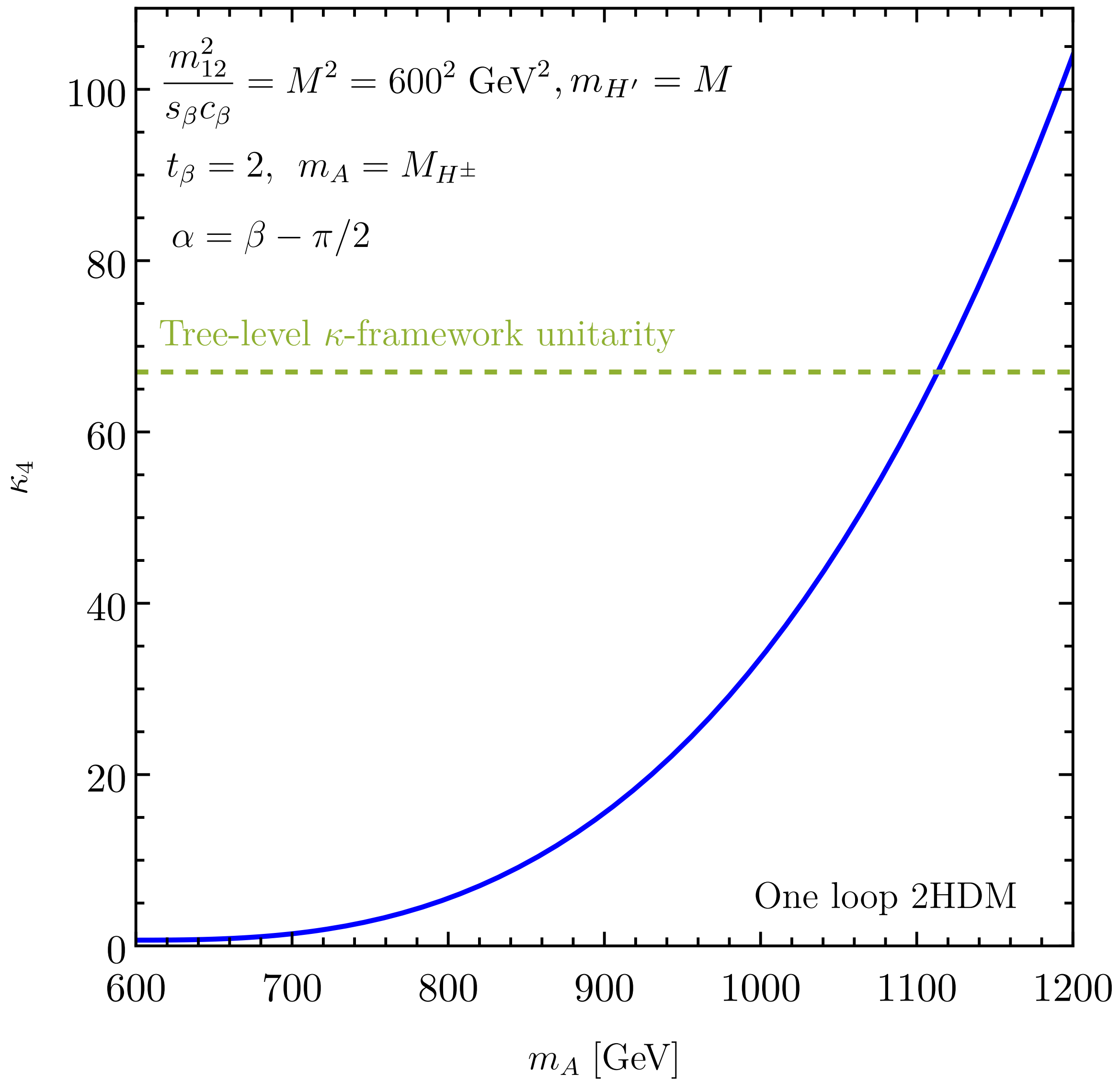
- Benchmark Point of [Bahl, Braathen, Weiglein ` 22] → cross-check κ_3 result (also with anyH3)

- 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

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

- 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

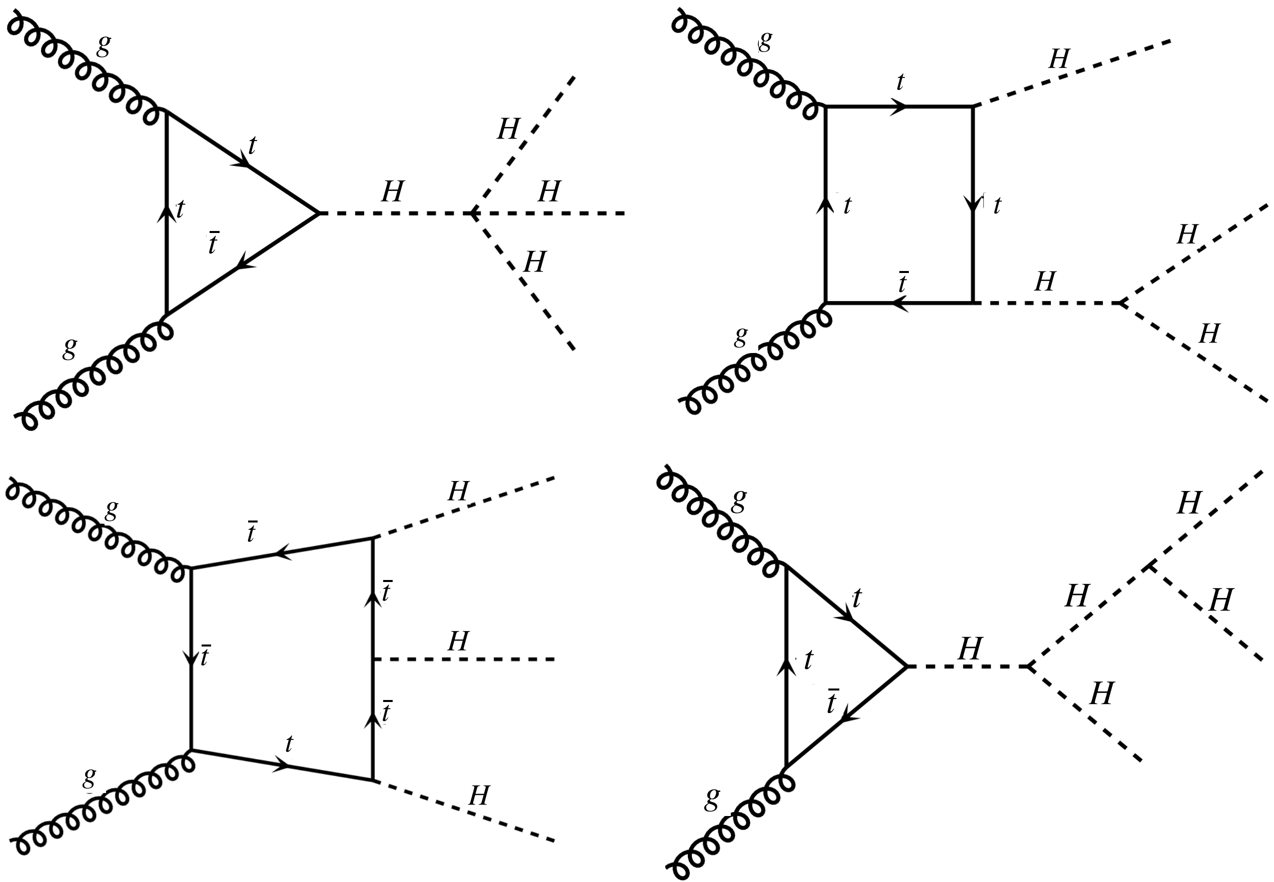
[P. Stylianou, G. W. '24]

- 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 $\quad p_T(\tau) > 10$ GeV

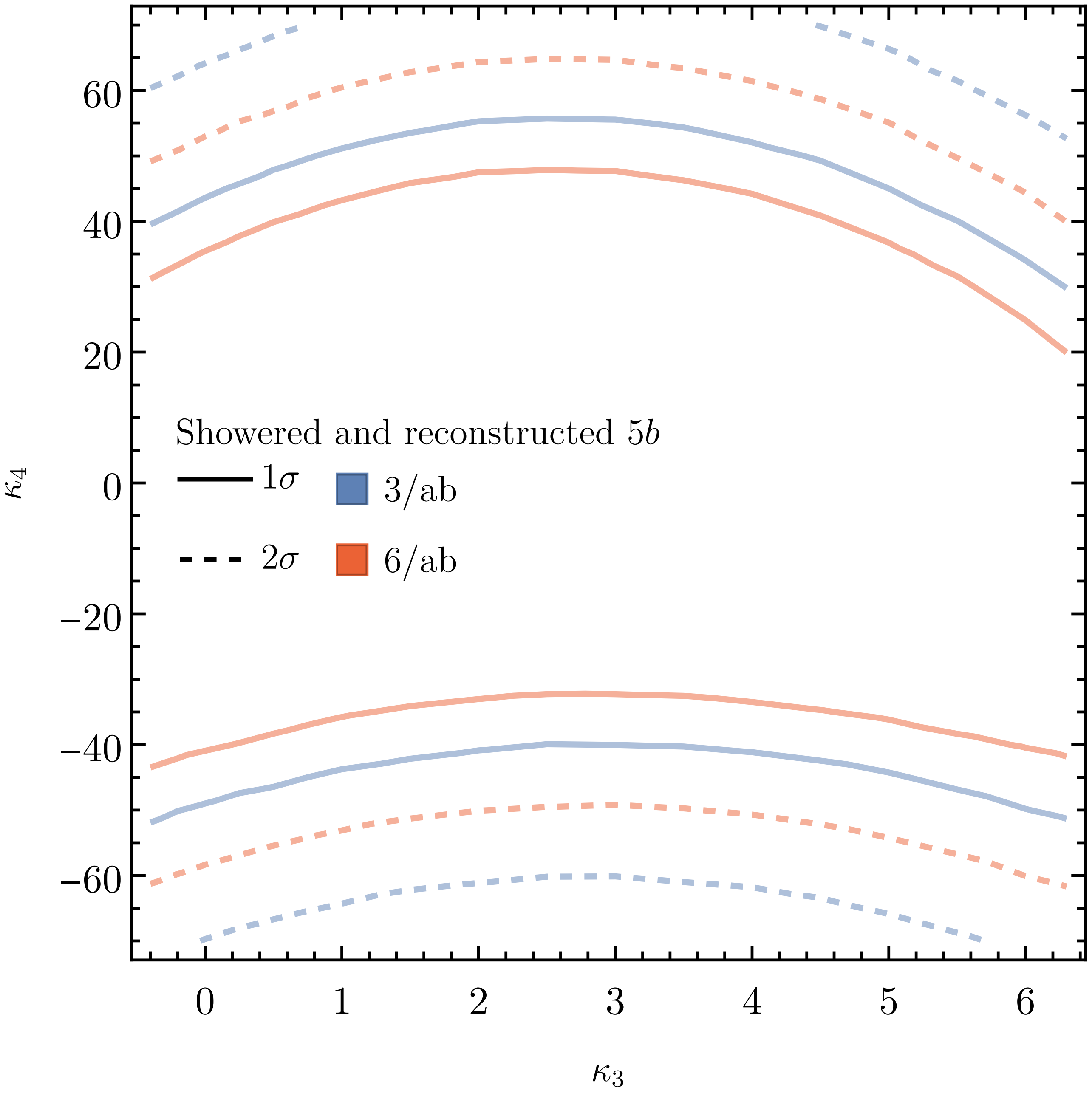
$|\eta(\tau)| < 2.5 \quad |\eta(b)| < 2.5$

Showered and reconstructed results: 5b

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

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

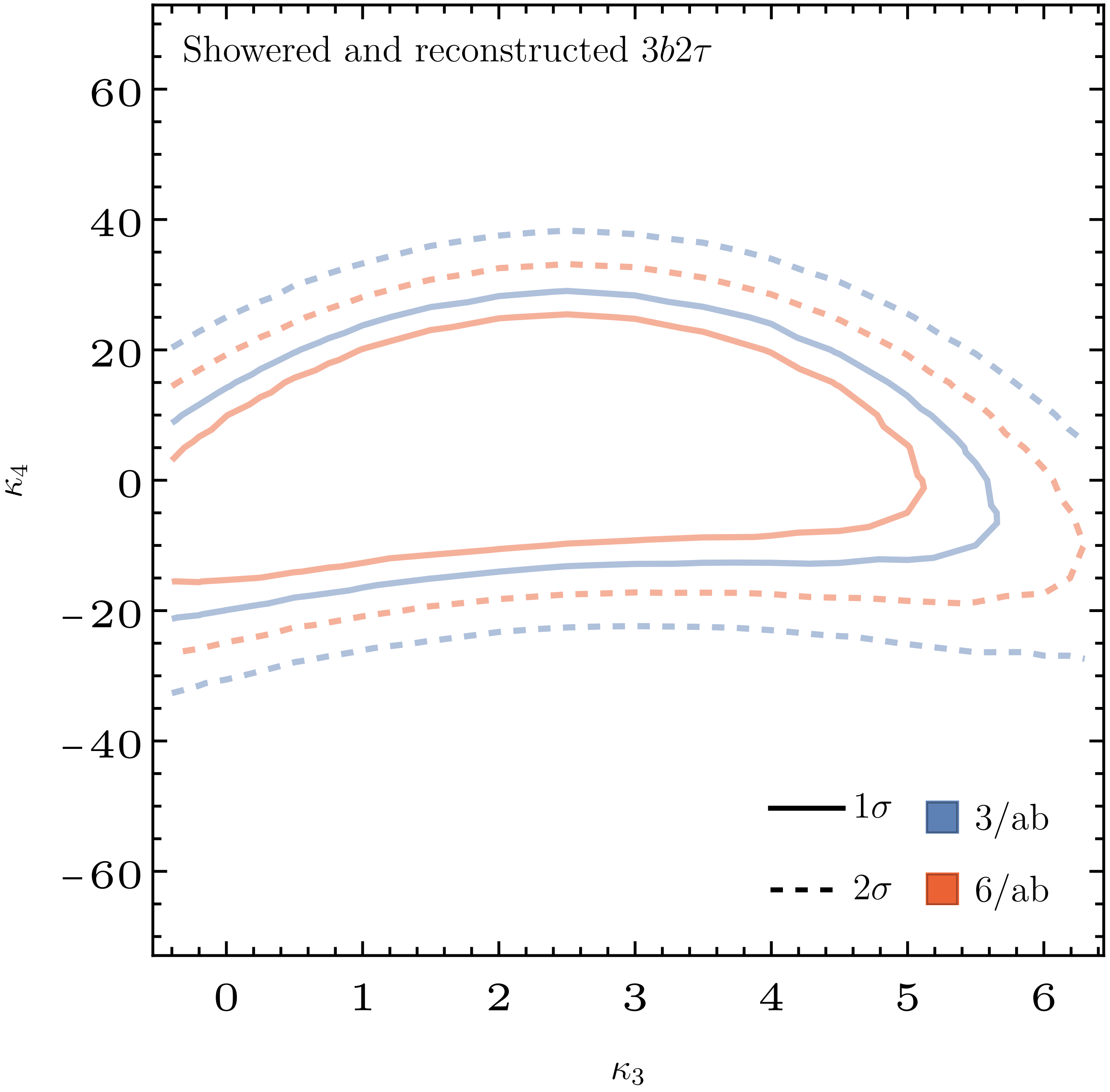
Signal region selected with cut on background score
$P[QCD] \lesssim 0.5\,\%$



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

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

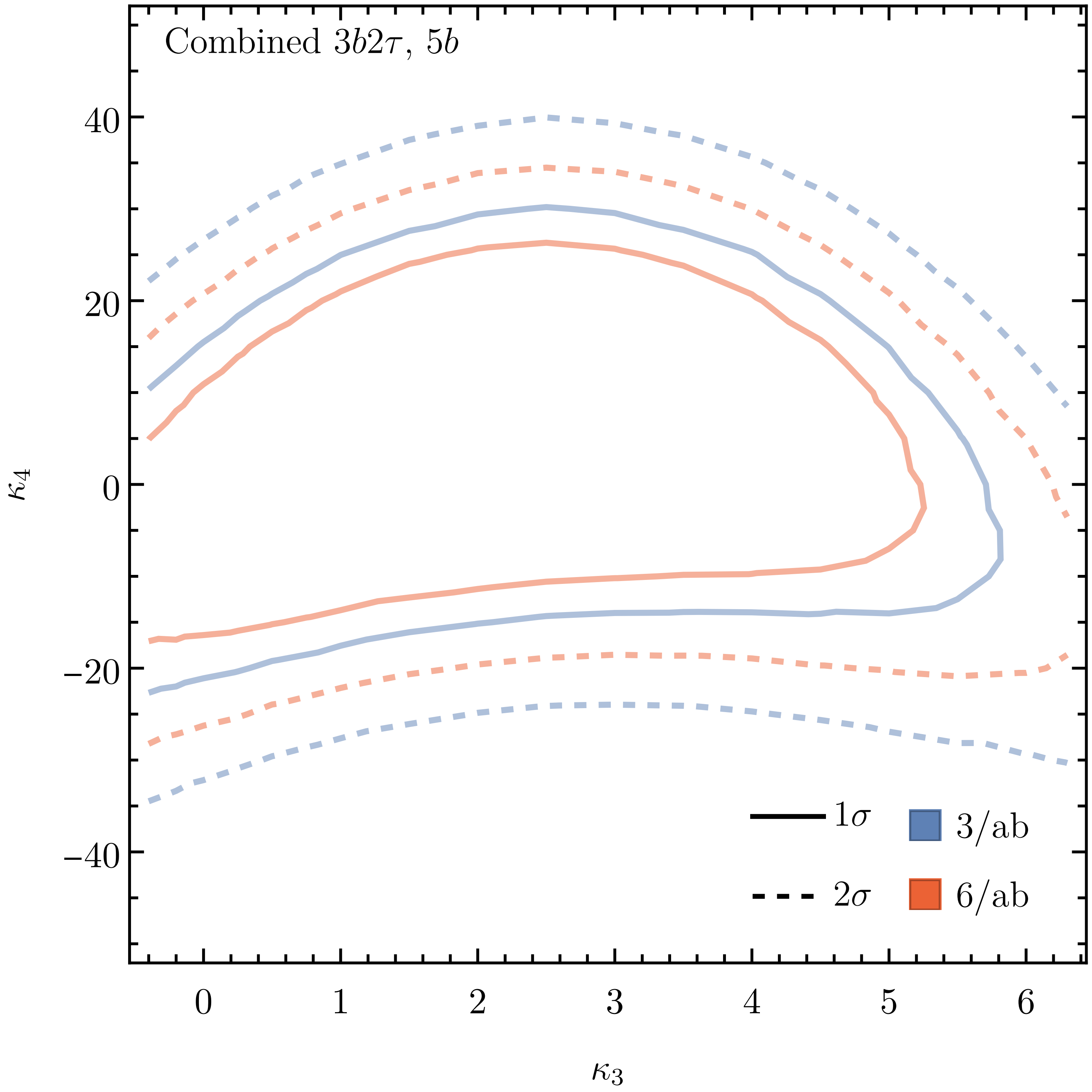
- $3b2\tau$ more complicated due to multiple backgrounds → multi-class classification
- Train on backgrounds: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},\ t\bar{t}(H \to \tau^+\tau^-)$



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

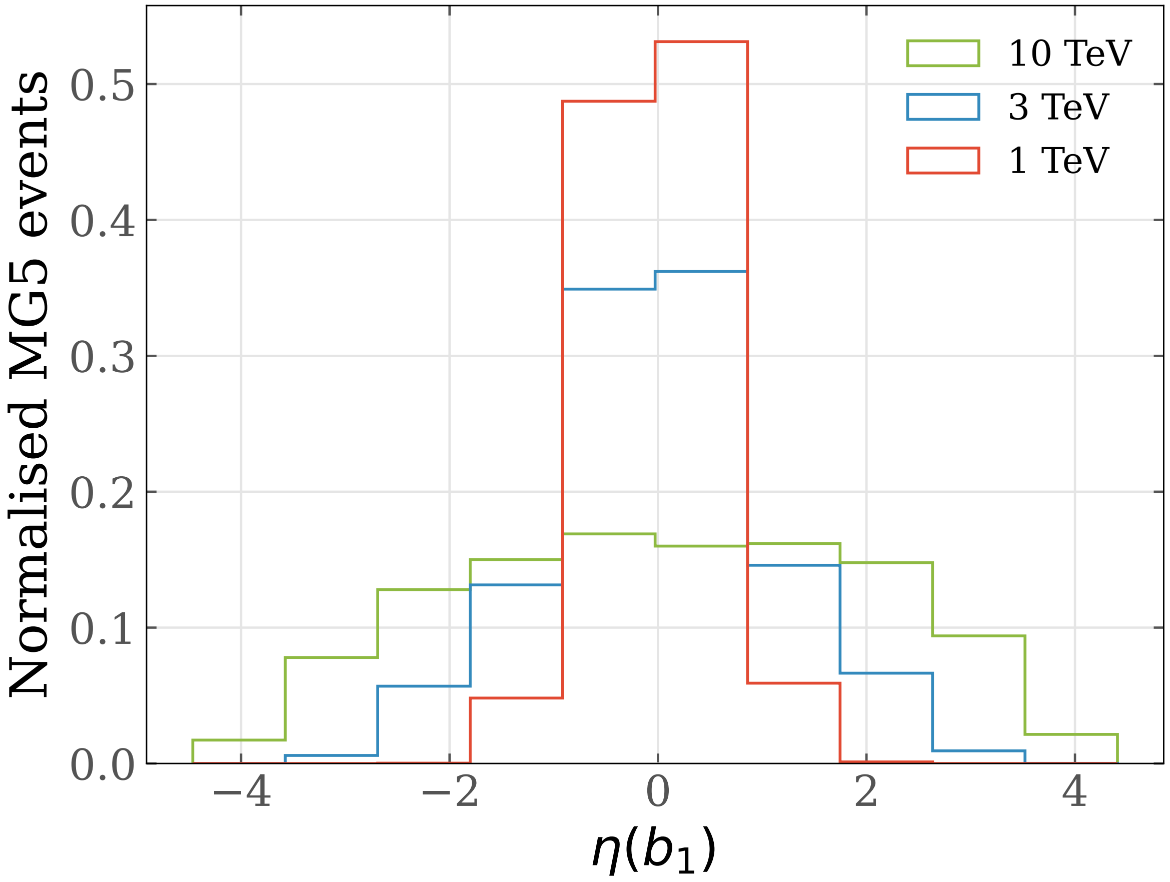
Prospects for future lepton colliders

- 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

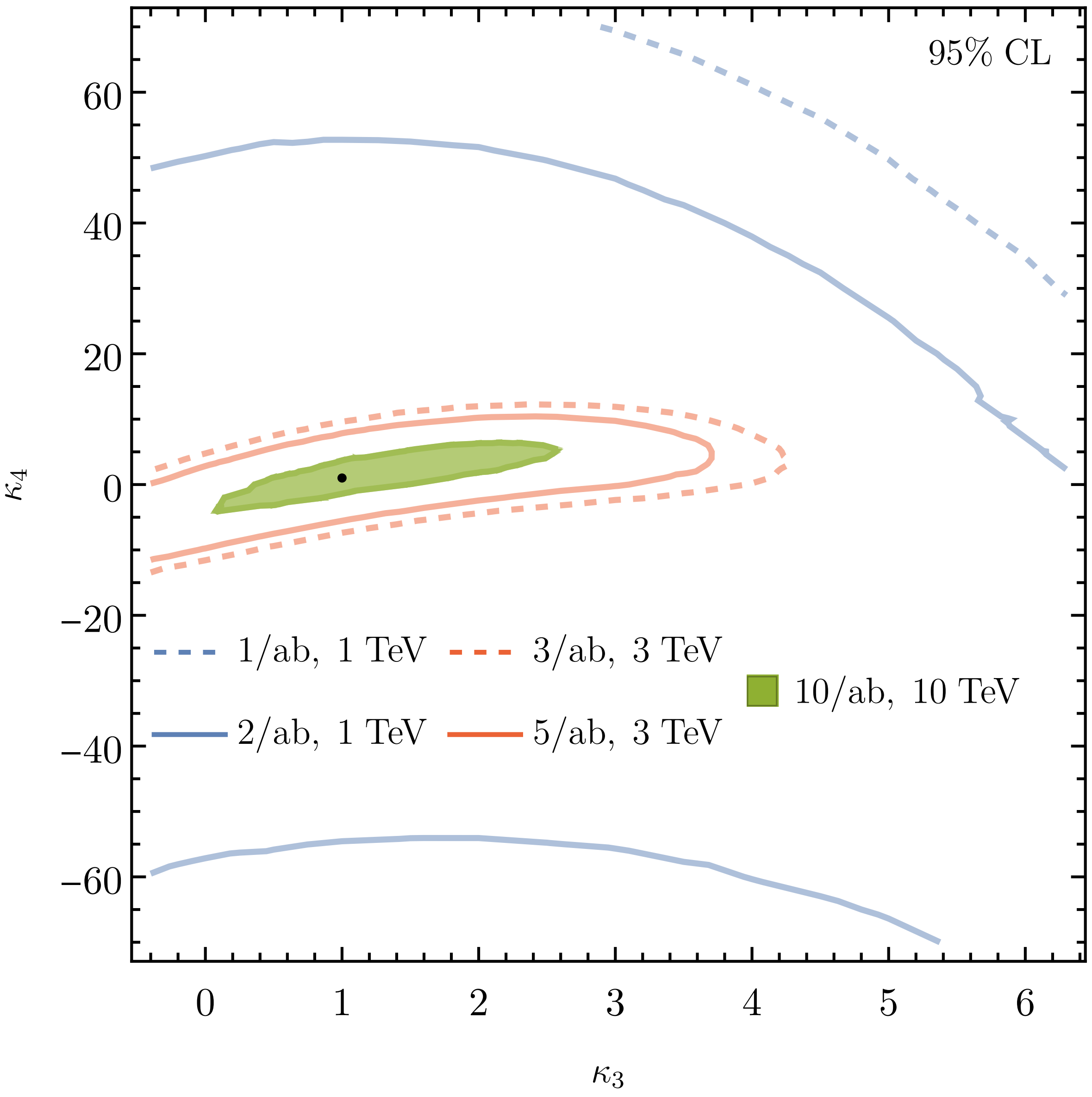
- Negligible background from other SM processes

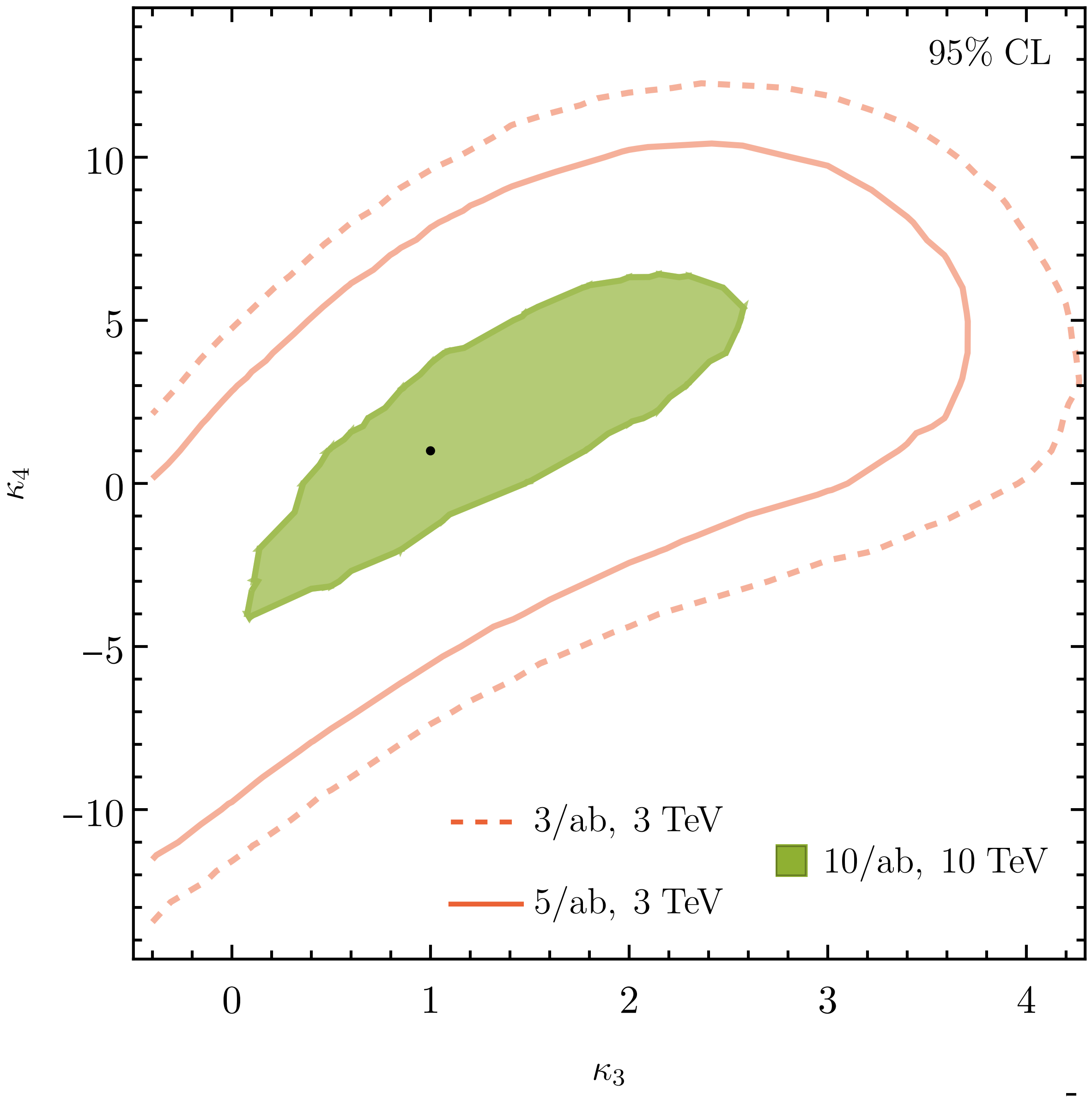


Higgs self-couplings at lepton colliders

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

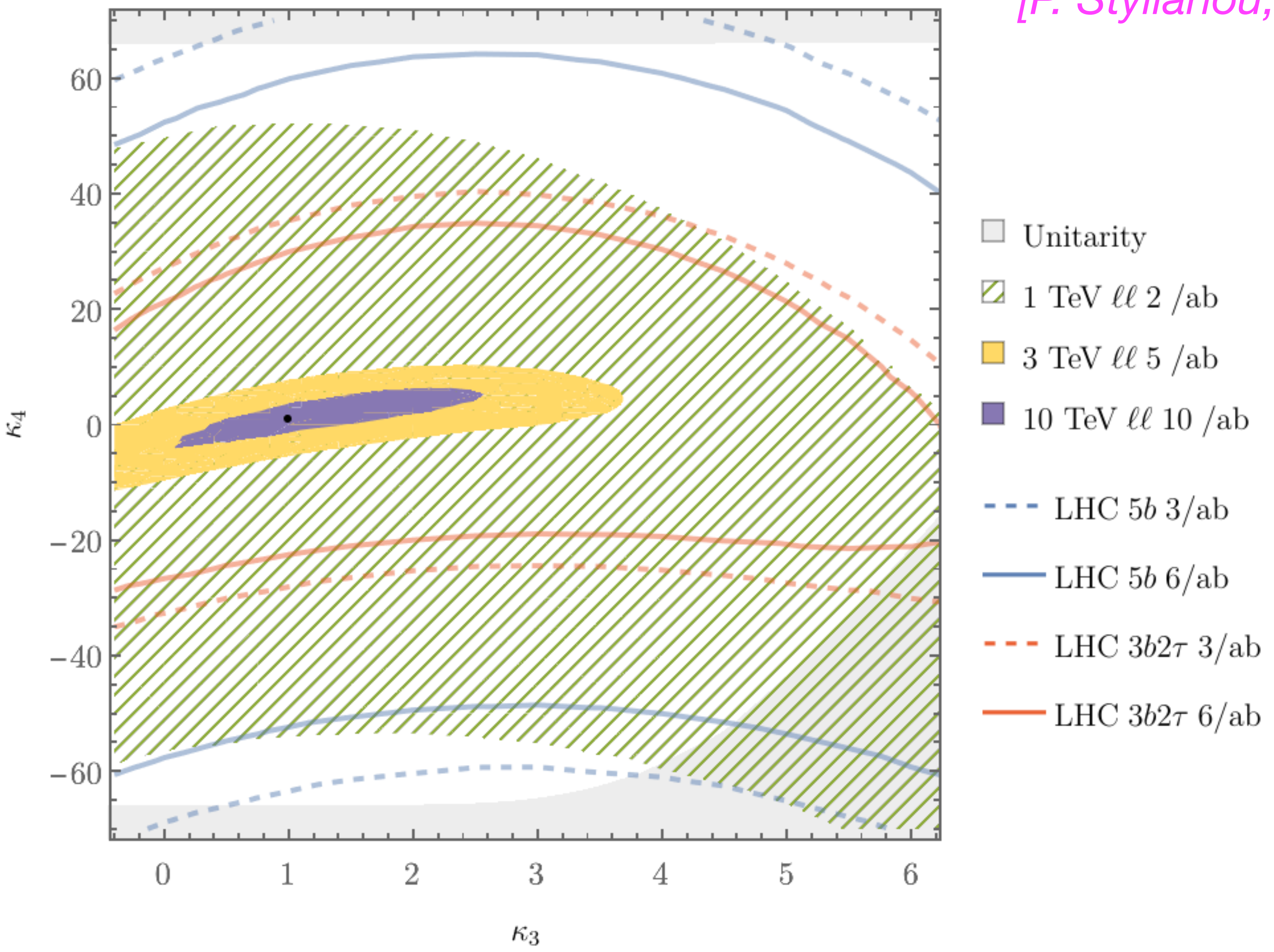
- Poissonian analysis: $\mu_{\text{up}} = \frac{1}{2} F^{-1}_{\chi^2}\left[2(n+1); \text{CL}\right]$
- Results similar to other works with dedicated analyses for 1 and 3 TeV, e.g. [Maltoni, Pagani, Zhao ` 18]





Triple Higgs production: HL-LHC vs. lepton colliders

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



HL-LHC is competitive 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

Extended Higgs sectors (e.g. 2HDM): 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

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

Backup

What is the underlying dynamics of electroweak symmetry breaking?

SM: phenomenological description of the known particles and their interactions, but we do not know the underlying dynamics (Higgs potential is just postulated in the SM)

Similar to the development of the understanding of superconductivity?
Phenomenological description: Ginzburg-Landau theory
Actual understanding: microscopic BCS theory

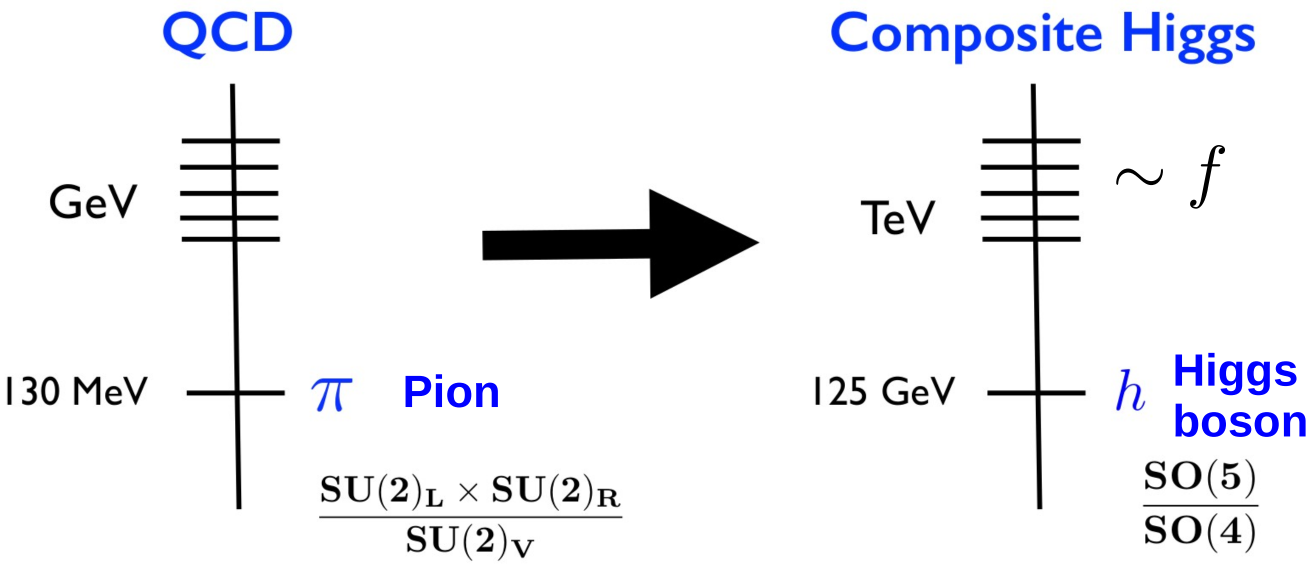
How is the scale of electroweak symmetry breaking protected from physics at high scales (new space-time symmetry, new interaction of nature, extra dimensions of space, parallel universes, …)?

⇒ Further information from the exploration of the detected Higgs signal

Composite PGB, identified with the Higgs boson

Composite Higgs models can be viewed as an interpolation between a weakly coupled Higgs model and a strongly coupled technicolour model

Composite Higgs is a bound state, similar to the pion in QCD



$$\frac{\mathbf{SU(2)_L \times SU(2)_R}}{\mathbf{SU(2)_V}}$$

Spontaneous breaking of chiral symmetry in QCD

$$\frac{\mathbf{SO(5)}}{\mathbf{SO(4)}}$$

Minimal Composite Higgs Model

Figure adapted from [Grojean '23]

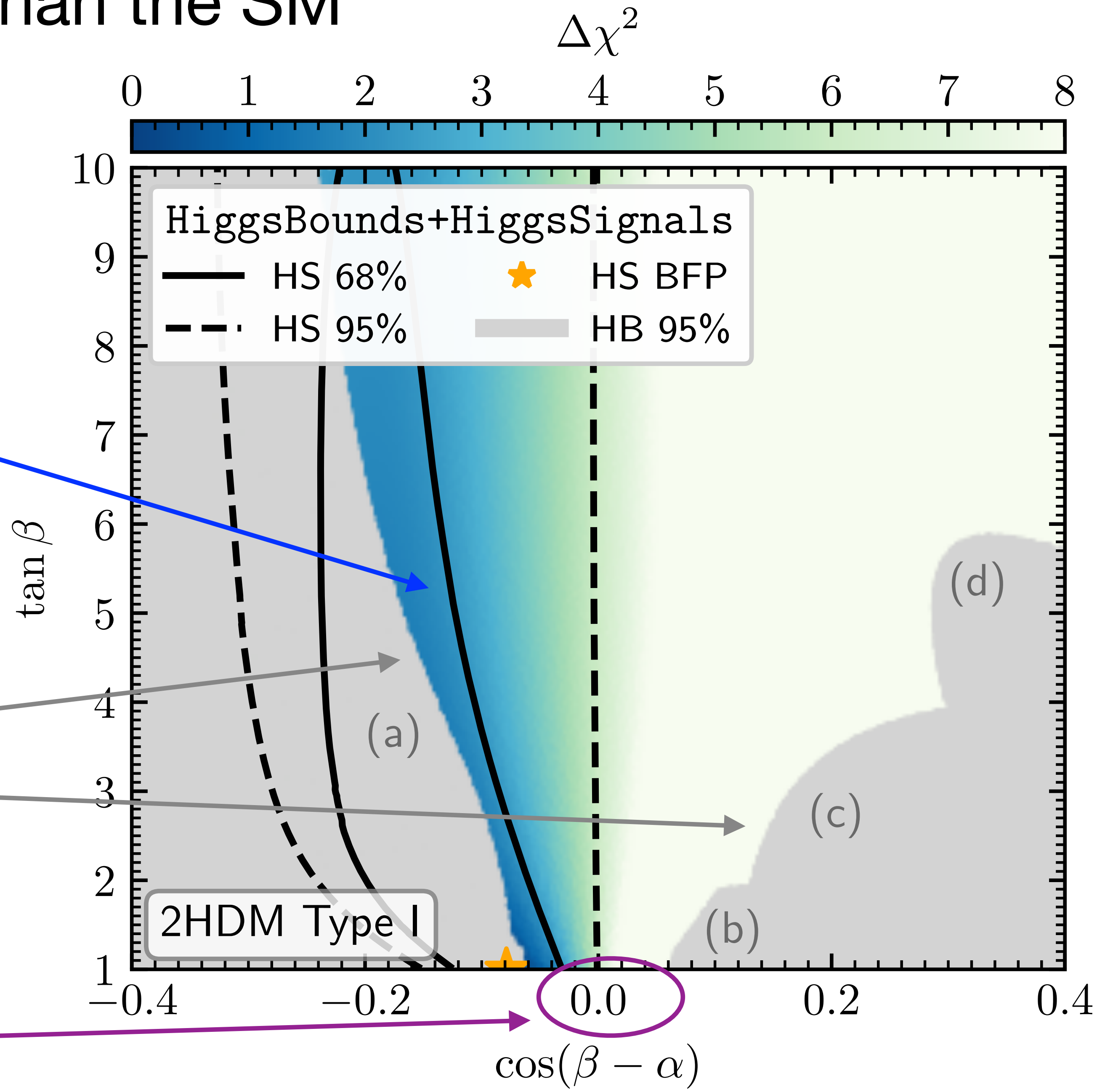
Mass of the bound state is not sensitive to virtual effects above the compositeness scale

Probing the SM and extended Higgs sectors

The experimental results indicate that the observed state h125 has SM-like properties, but extensions of the SM may have a higher compatibility with the data than the SM

Example: 2HDM of type I

[H. Bahl et al. '22]



Preferred region from Higgs measurements

Limits from Higgs searches

SM limit (alignment)

⇒Alignment limit disfavoured, slight preference for non-zero BSM contrib.

SMEFT: parametrising possible deviations from the SM

Effective Lagrangian approach, obtained from integrating out heavy particles

Assumption: new physics only appears at scale $\Lambda \gg M_h \approx 125$ GeV

Systematic approach: expansion in inverse powers of Λ; parametrises deviations of coupling strenghts and tensor structure

$$\Delta\mathcal{L} = \sum_i \frac{a_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{a_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

How about light BSM particles?

Difficult to incorporate in a generic way, need full structure of particular models

Higgs couplings: towards high precision

- A coupling is not a physical observable: if one talks about measuring Higgs couplings at the % level or better, one needs to precisely define what is actually meant by those couplings!

- For the determination of an appropriate coupling parameter at this level of accuracy the incorporation of strong and electroweak loop corrections is inevitable. This is in general not possible in a strictly model-independent way!

- For comparisons of present and future facilities it is crucial to clearly spell out under which assumptions these comparisons are done

Vacuum stability of extended Higgs sectors (T = 0)

Extended Higgs sectors with additional minima of the scalar potential at the weak scale that may be deeper than the EW vacuum

⇒ Tunneling from EW vacuum to deeper vacua possible depending on the ``bounce action” B (stationary point of the euclidian action) for the tunnelling process

⇒ EW vacuum can be short-lived, metastable or stable

Decay rate per spatial volume: $$\frac{\Gamma}{V_S} = K e^{-B}$$

``Most dangerous minimum”: highest tunnelling rate from EW vacuum

Constraints from vacuum stability at T = 0 can be combined with the ones from the thermal evolution of the Universe (see below)

``ϰ framework" and EFT approach for coupling analyses

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

Assumptions inherent in the ϰ 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

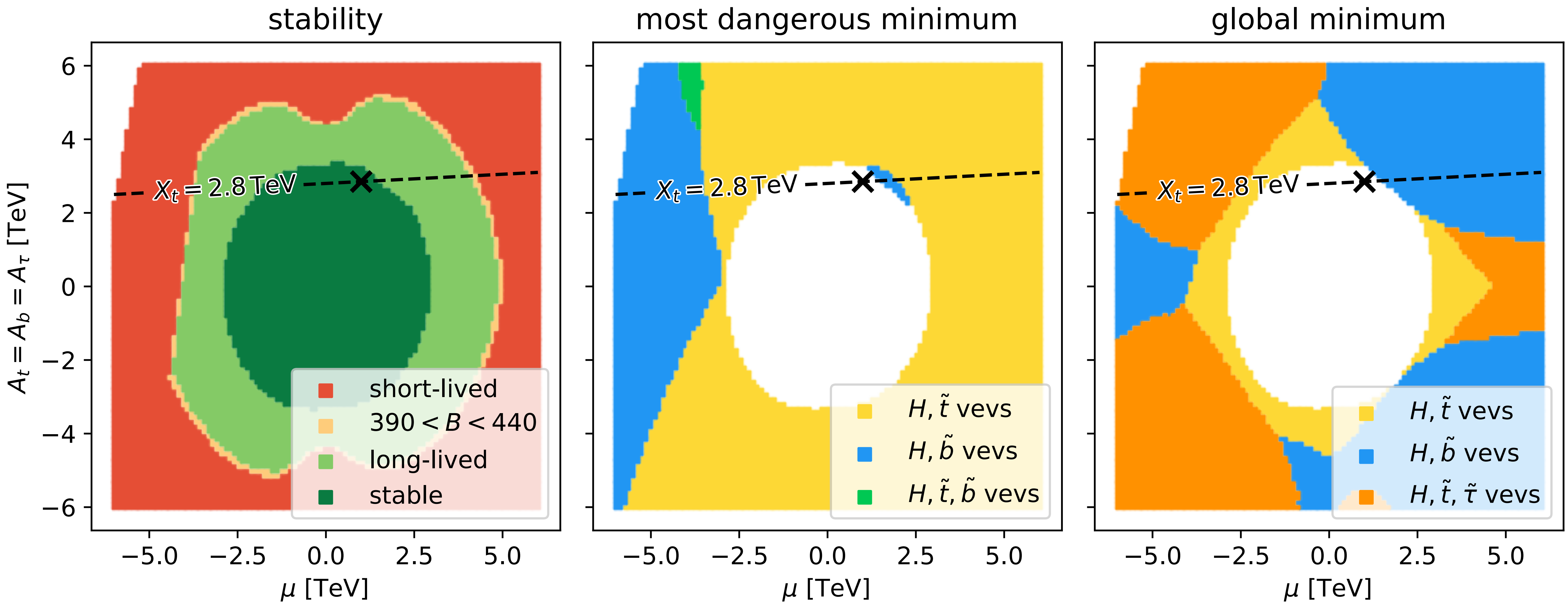
Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

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

Vacuum stability constraints in the MSSM

[W.G. Hollik, J. Wittbrodt, G. W. ’18]

Parameter plane around example point of M_h^{125} benchmark scenario



⇒ Particularly important: instabilities in directions with sfermion vevs (charge or colour-breaking minima, CCB)

Character of most-dangerous minimum differs from global minimum

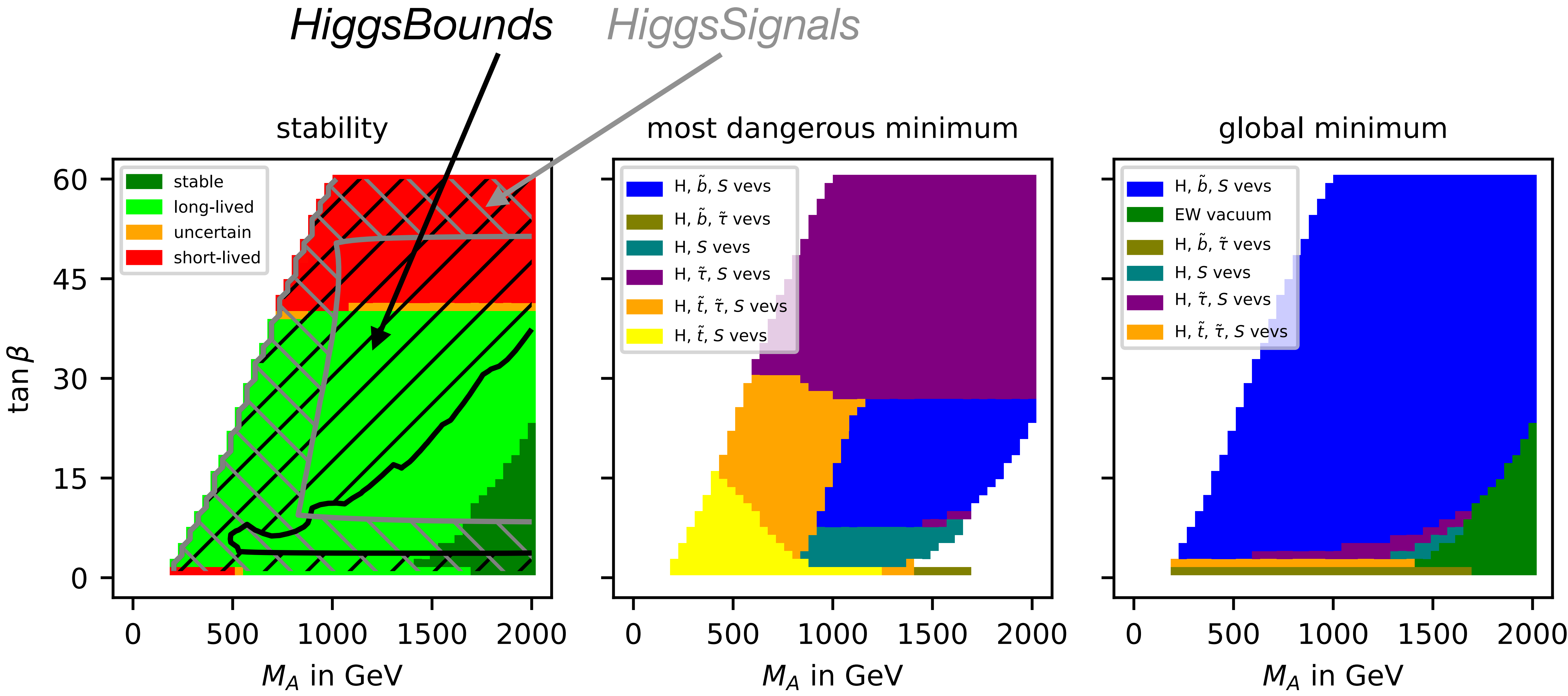
Region of absolute stability and global minimum sensitively depend on fields with small couplings to the Higgs

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]



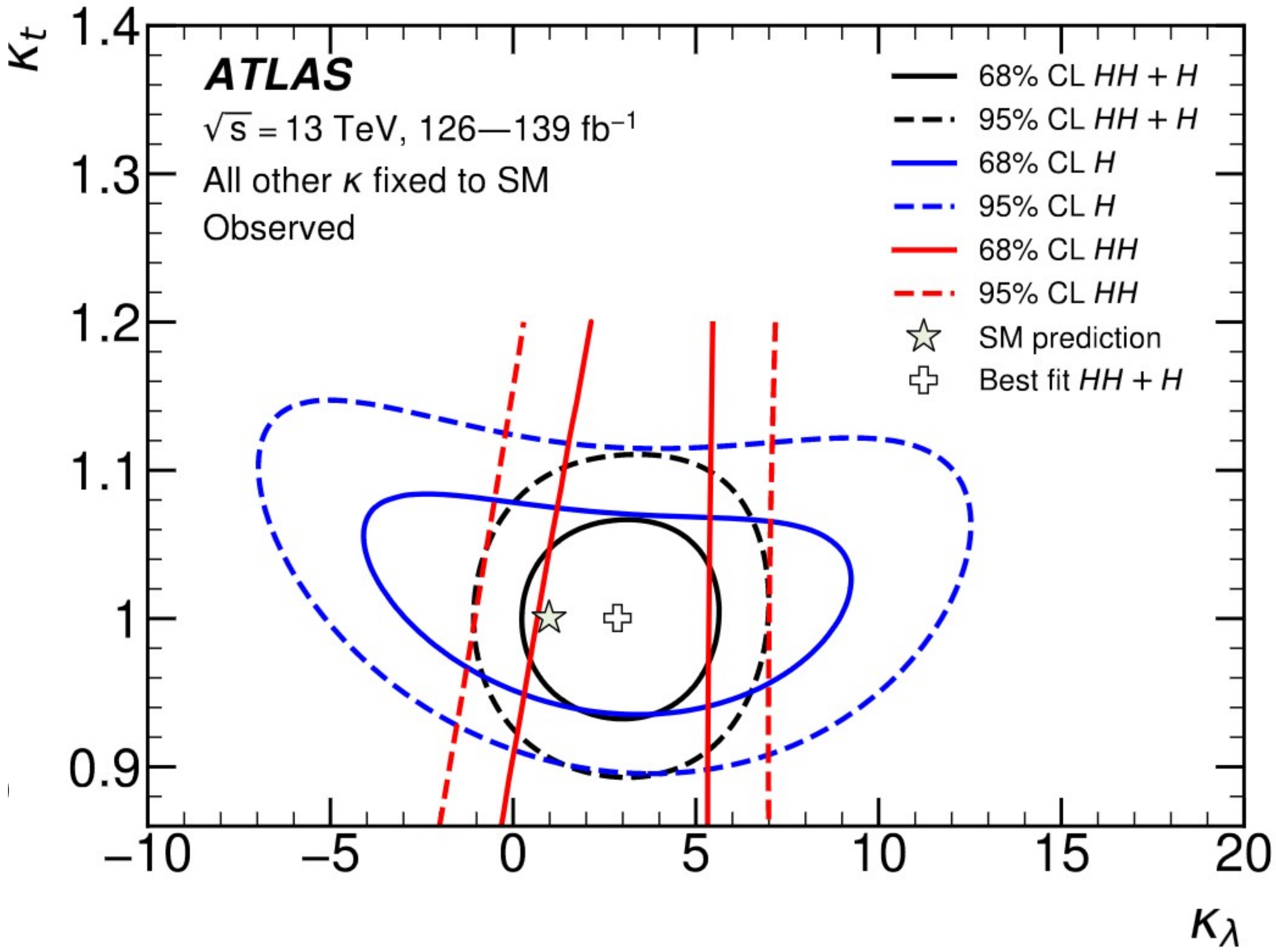
HiggsBounds *HiggsSignals*

stability most dangerous minimum global minimum

Experimental constraints on $\varkappa_\lambda$

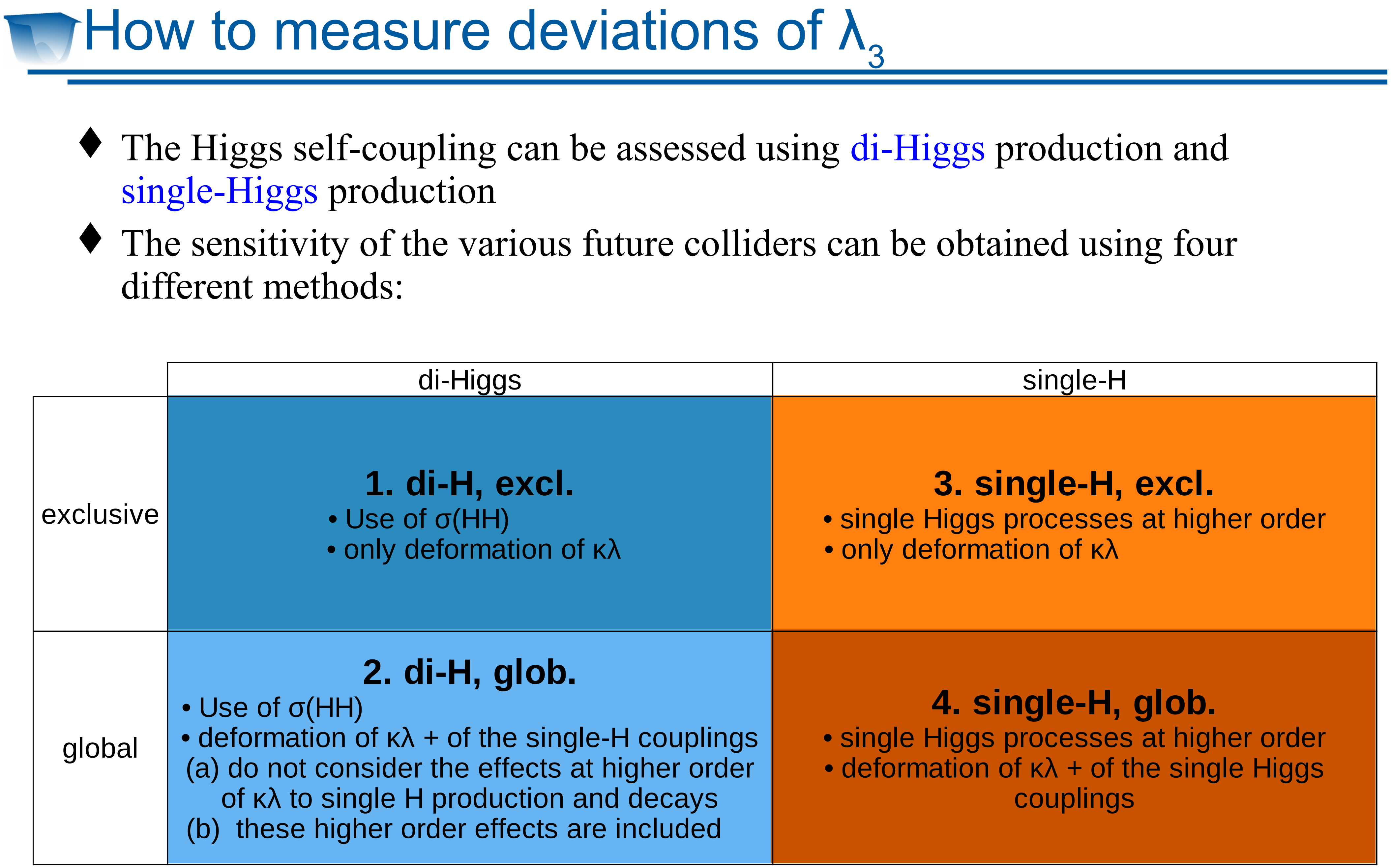
[ATLAS Collaboration ’22]

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



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]

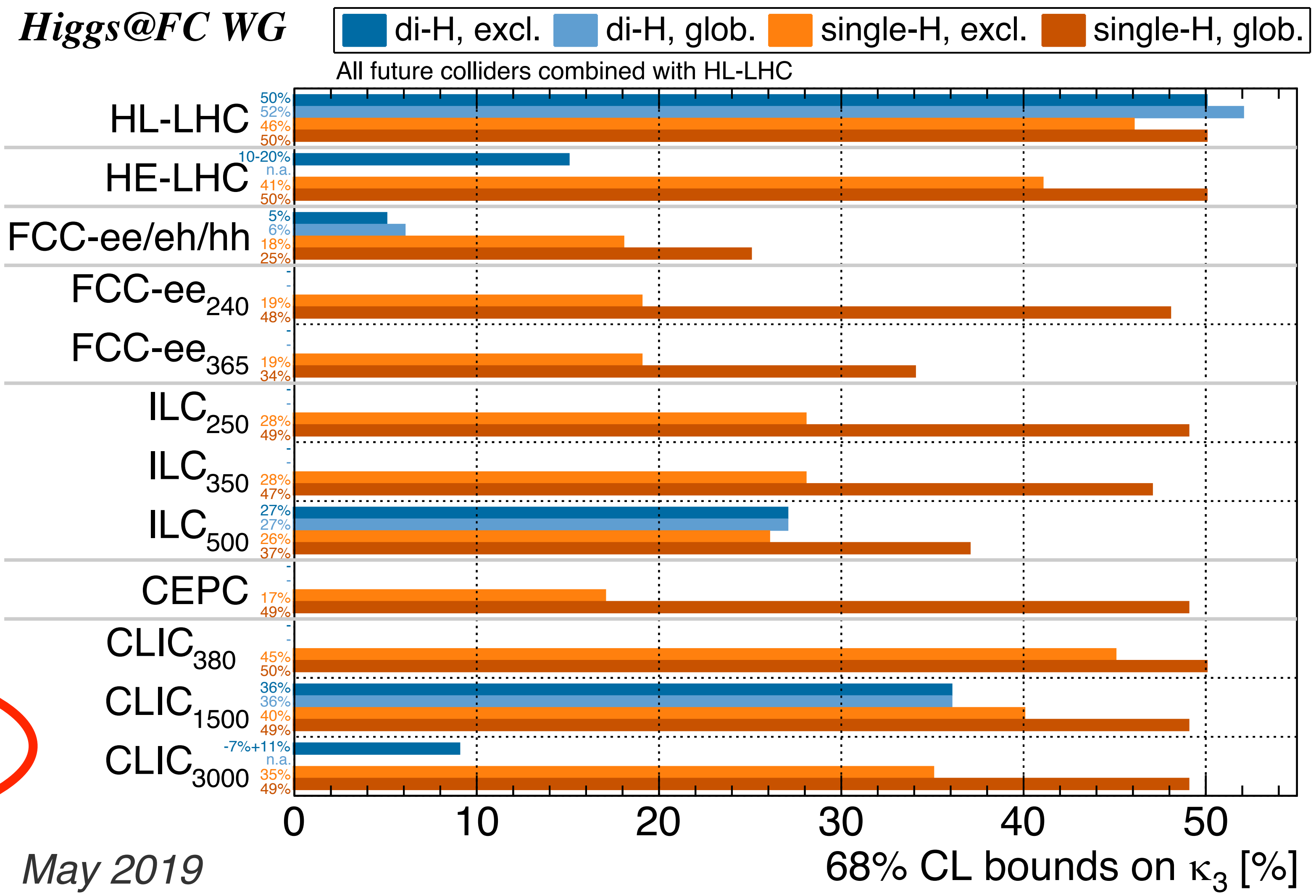
Sensitivity to λ: via single-H and di-H production

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:

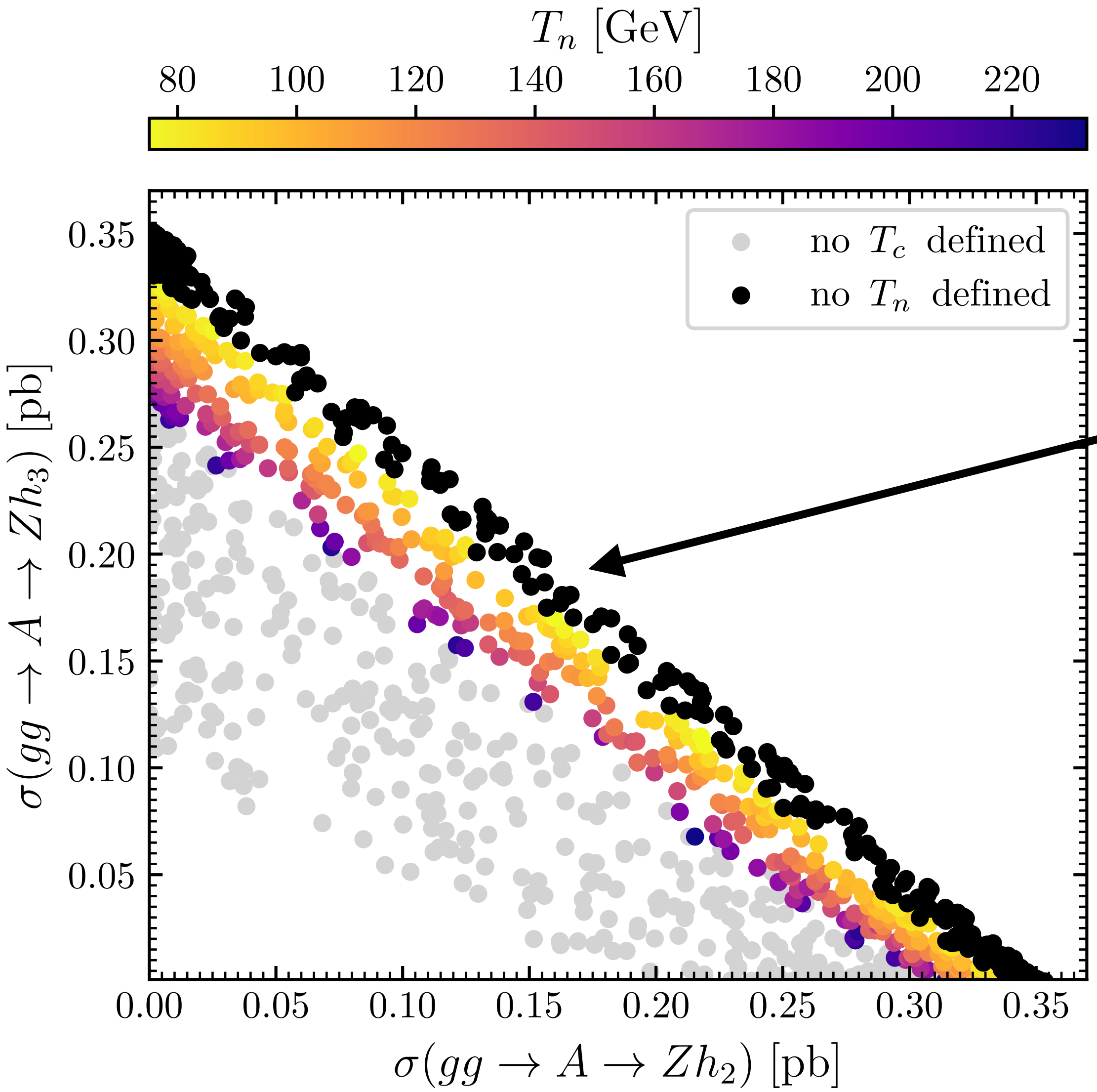
- **Global** analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- **Exclusive** analysis: too sensitive to other new physics to draw conclusion



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]

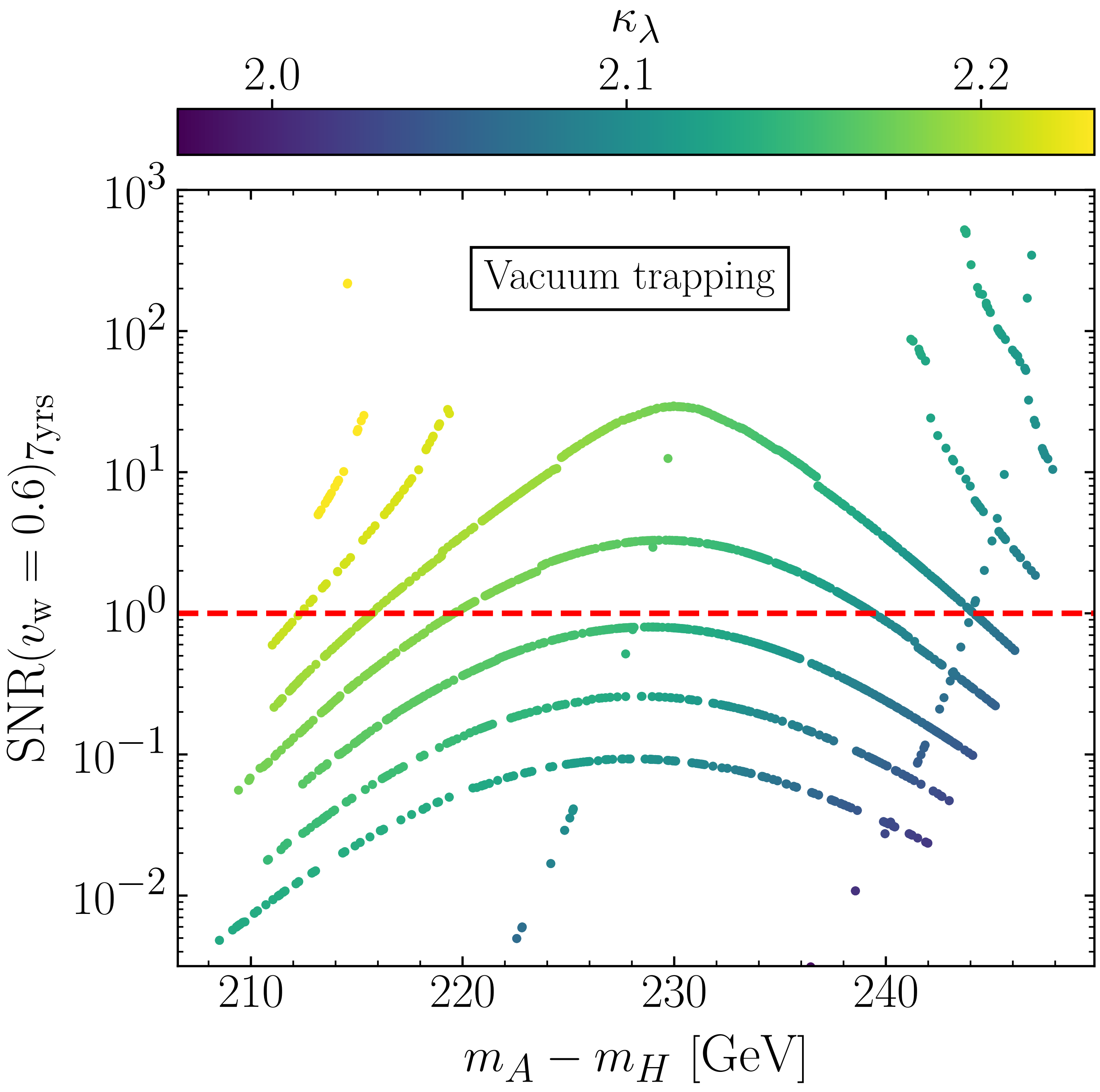


No first-order EWPT: universe is trapped in a ``false” vacuum

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

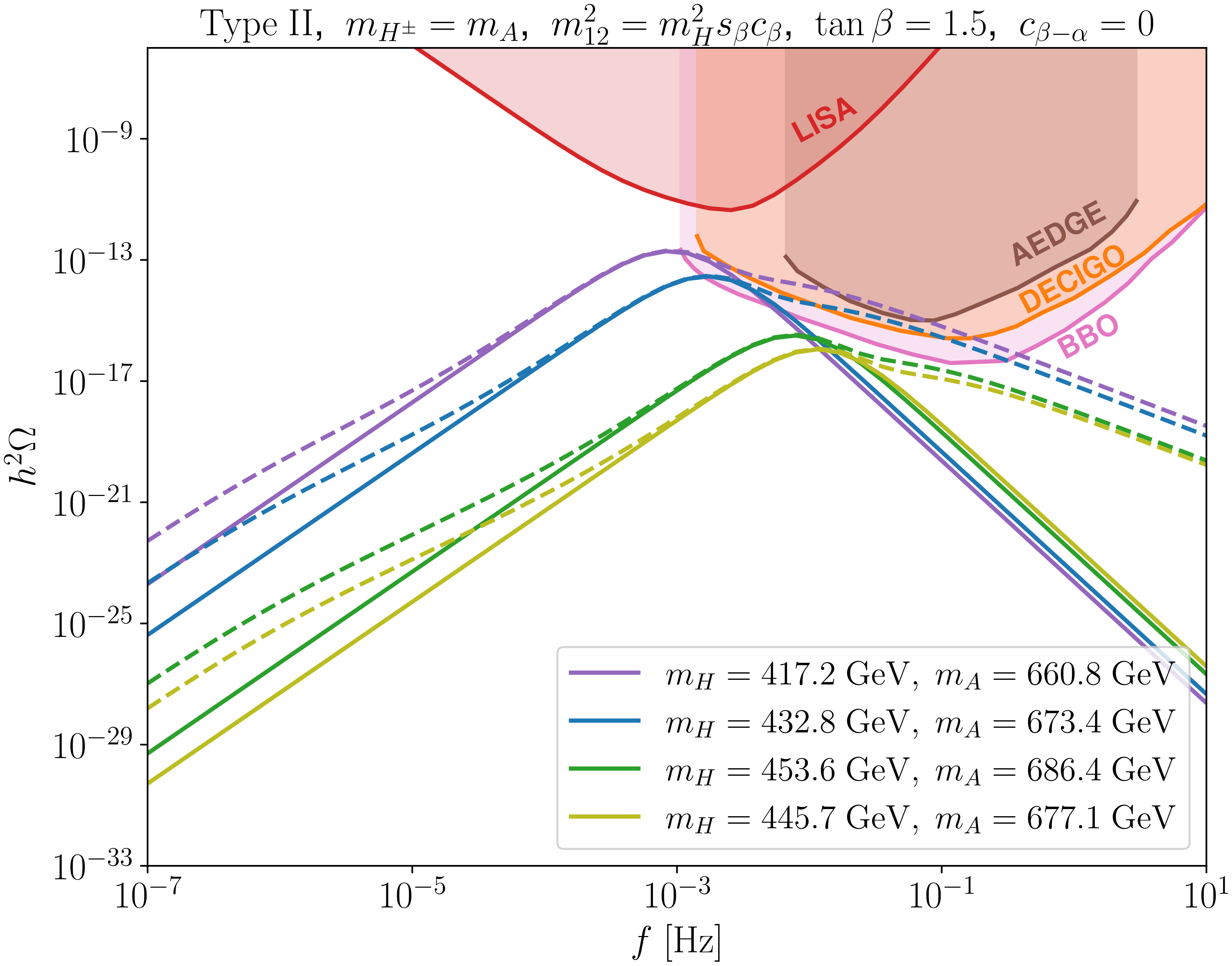
Correlation of $\varkappa_\lambda$ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

[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