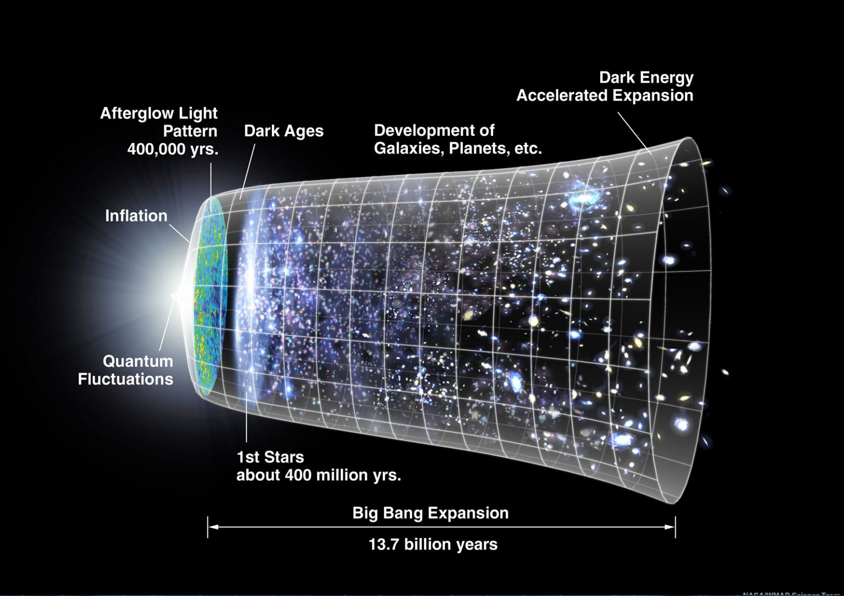
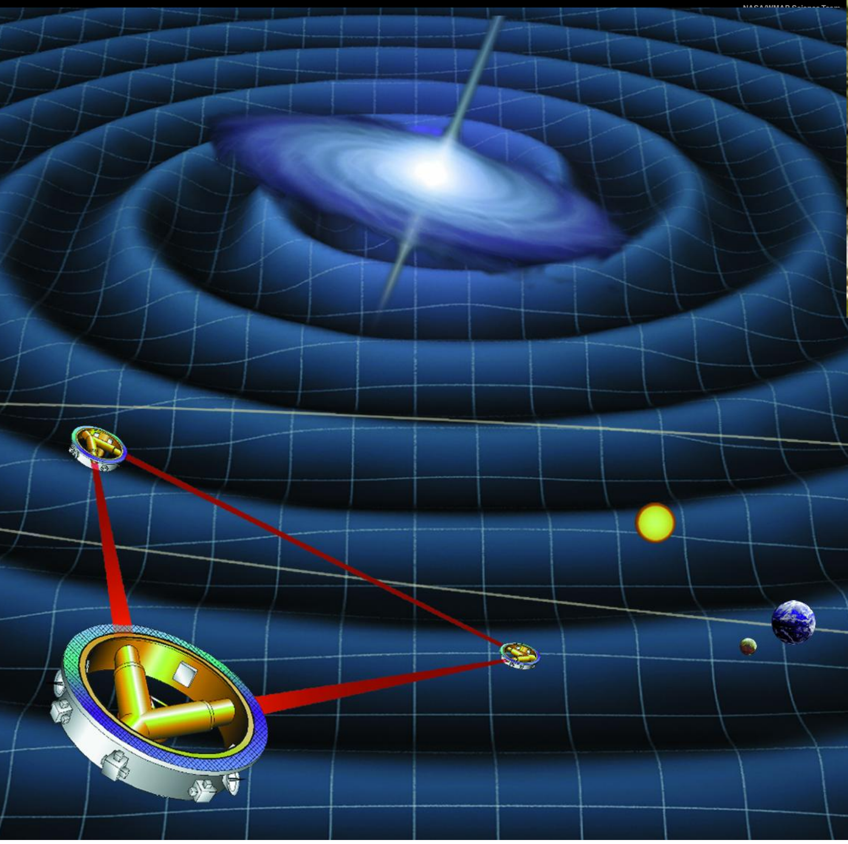
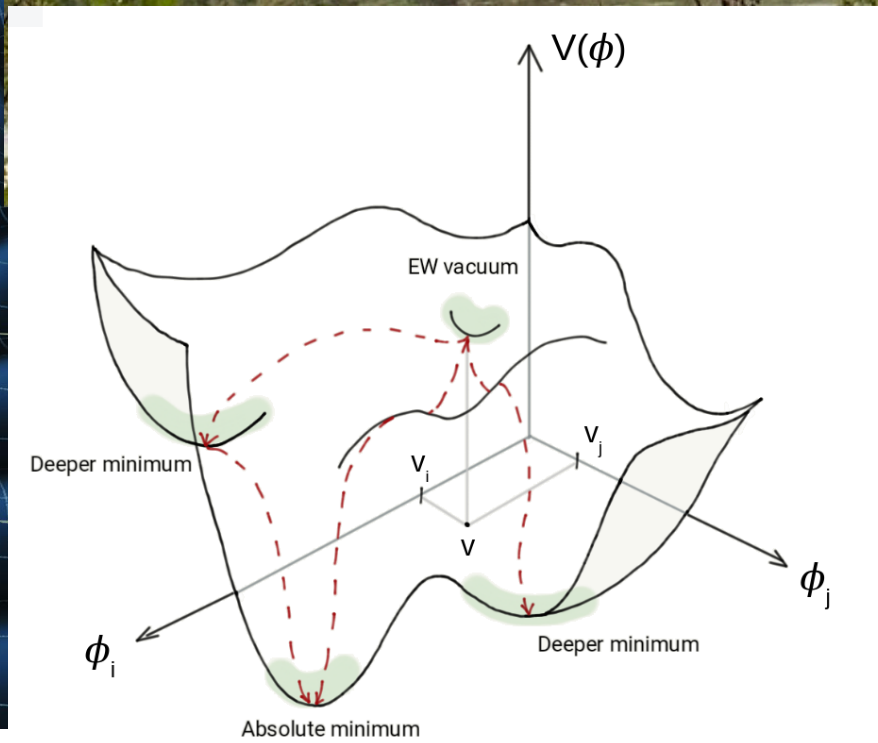
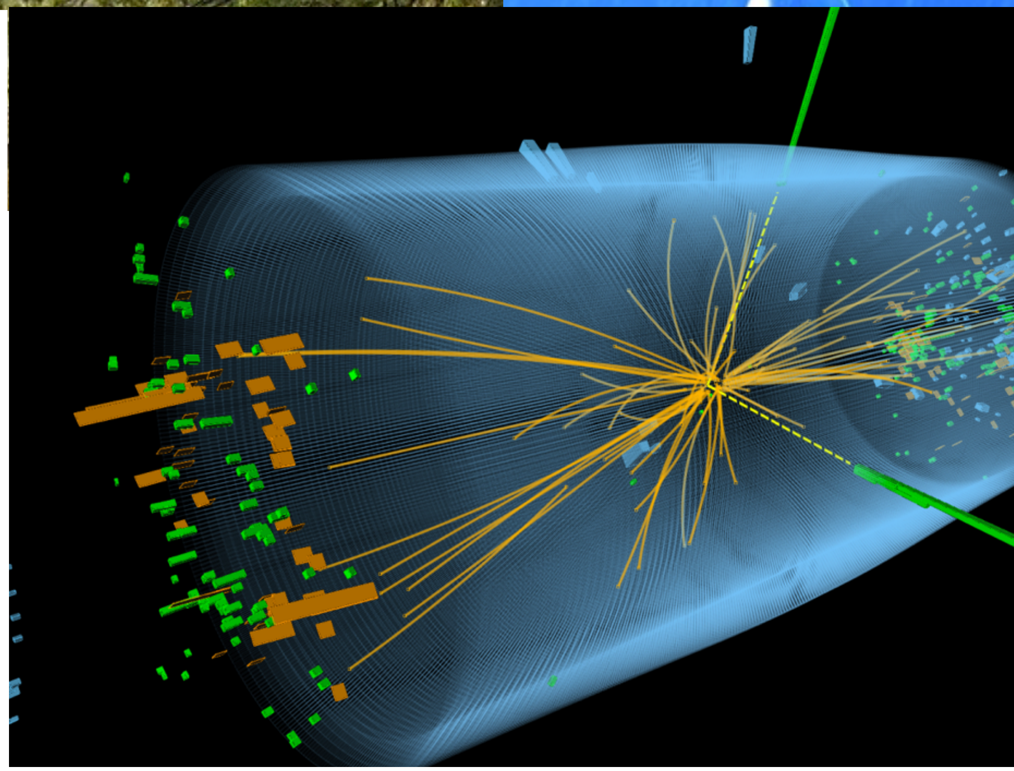




# Higgs Boson Phenomenology connected to Early Universe Physics

Georg Weiglein, DESY & UHH

Durham, 12 / 2025

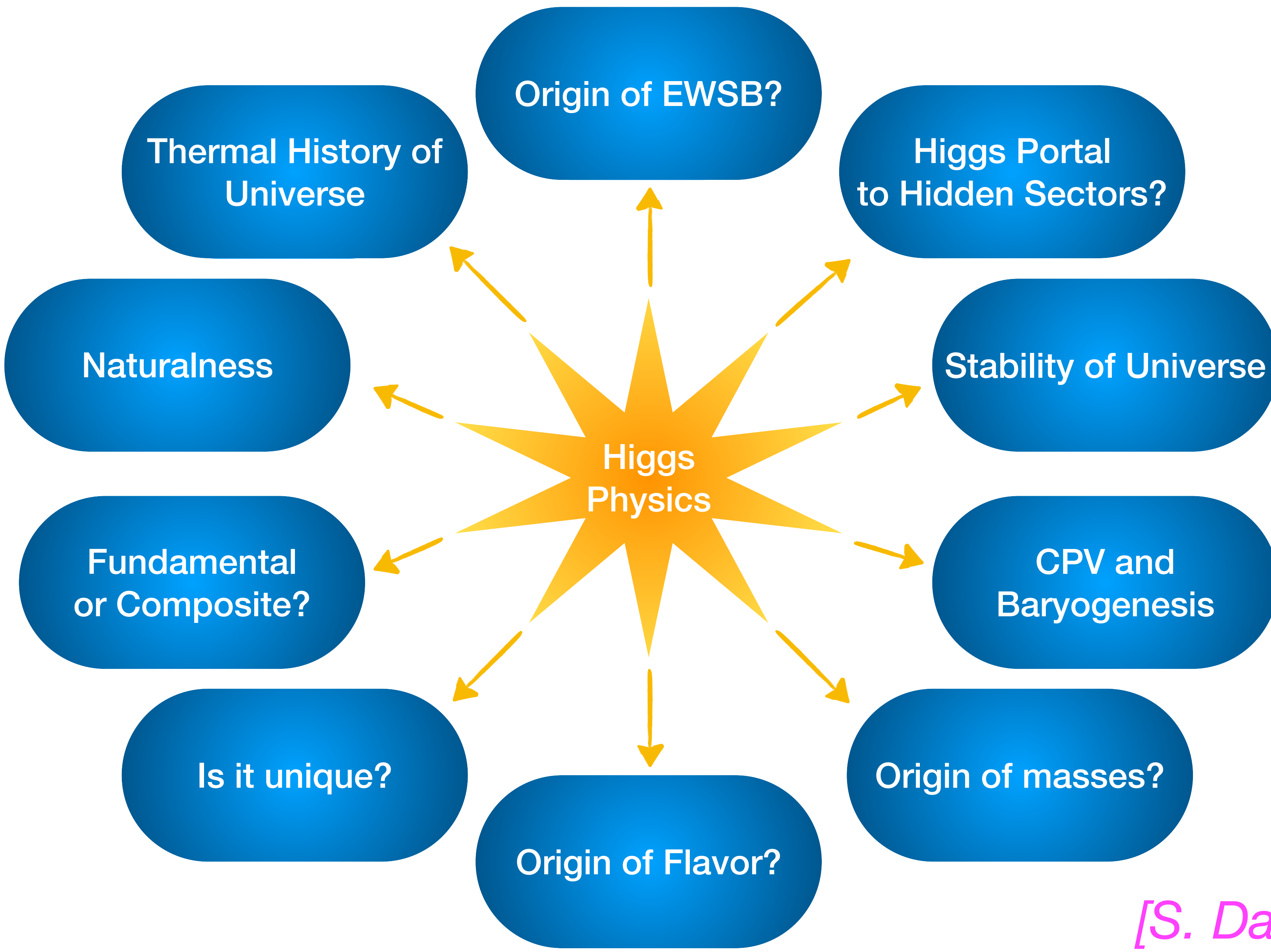
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
DESY.

# Outline

- Introduction
- Higgs pair production, the trilinear Higgs self-coupling and the electroweak phase transition
- Exploring triple Higgs production w.r.t. Higgs self-couplings
- Recent results regarding BSM Higgs searches
- Conclusions

# Introduction

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



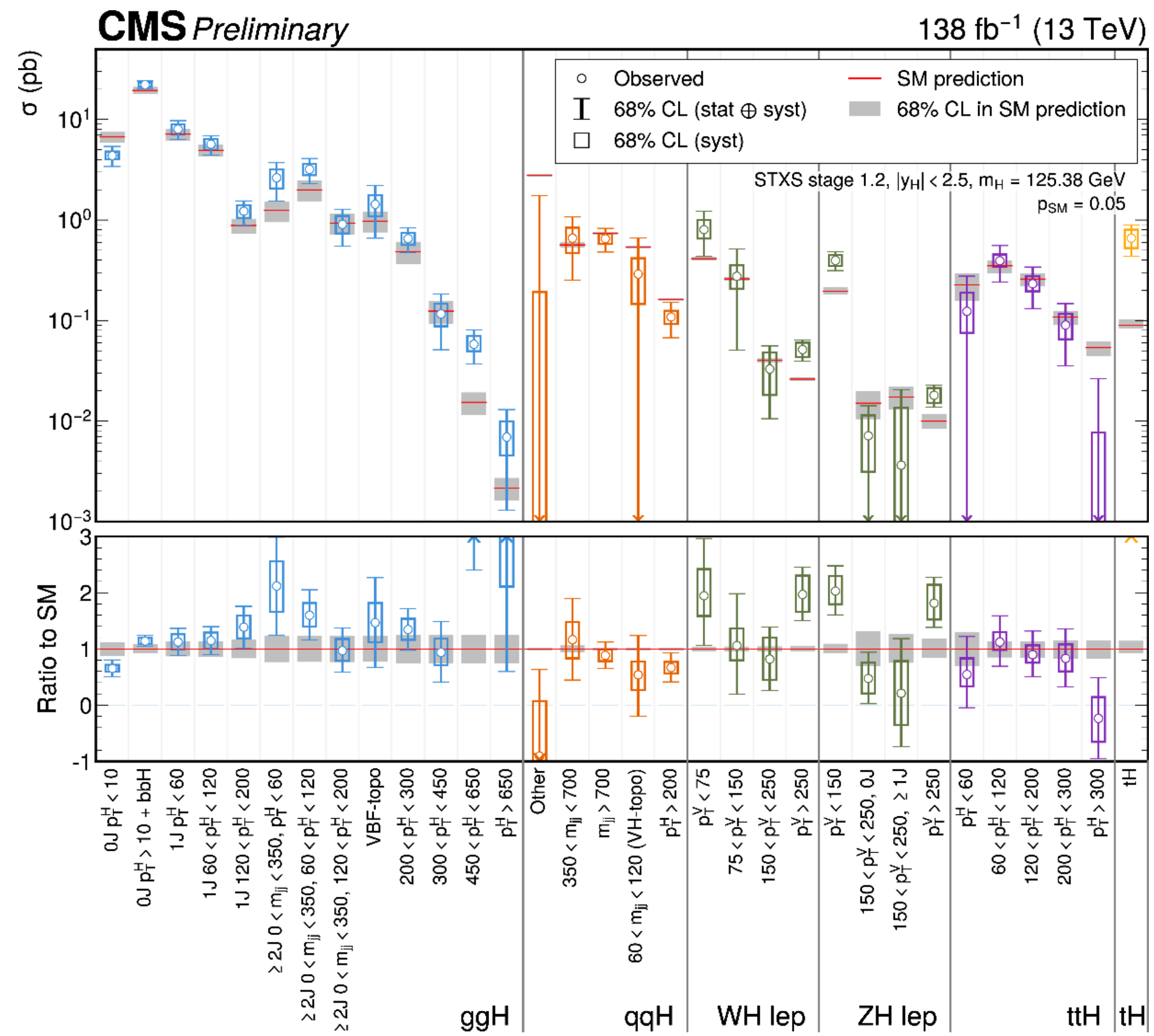

[S. Dawson et al. '22]

# Properties of the detected Higgs boson (h)

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

h: inclusive
and differential
rates

*[CMS Collaboration '25]*

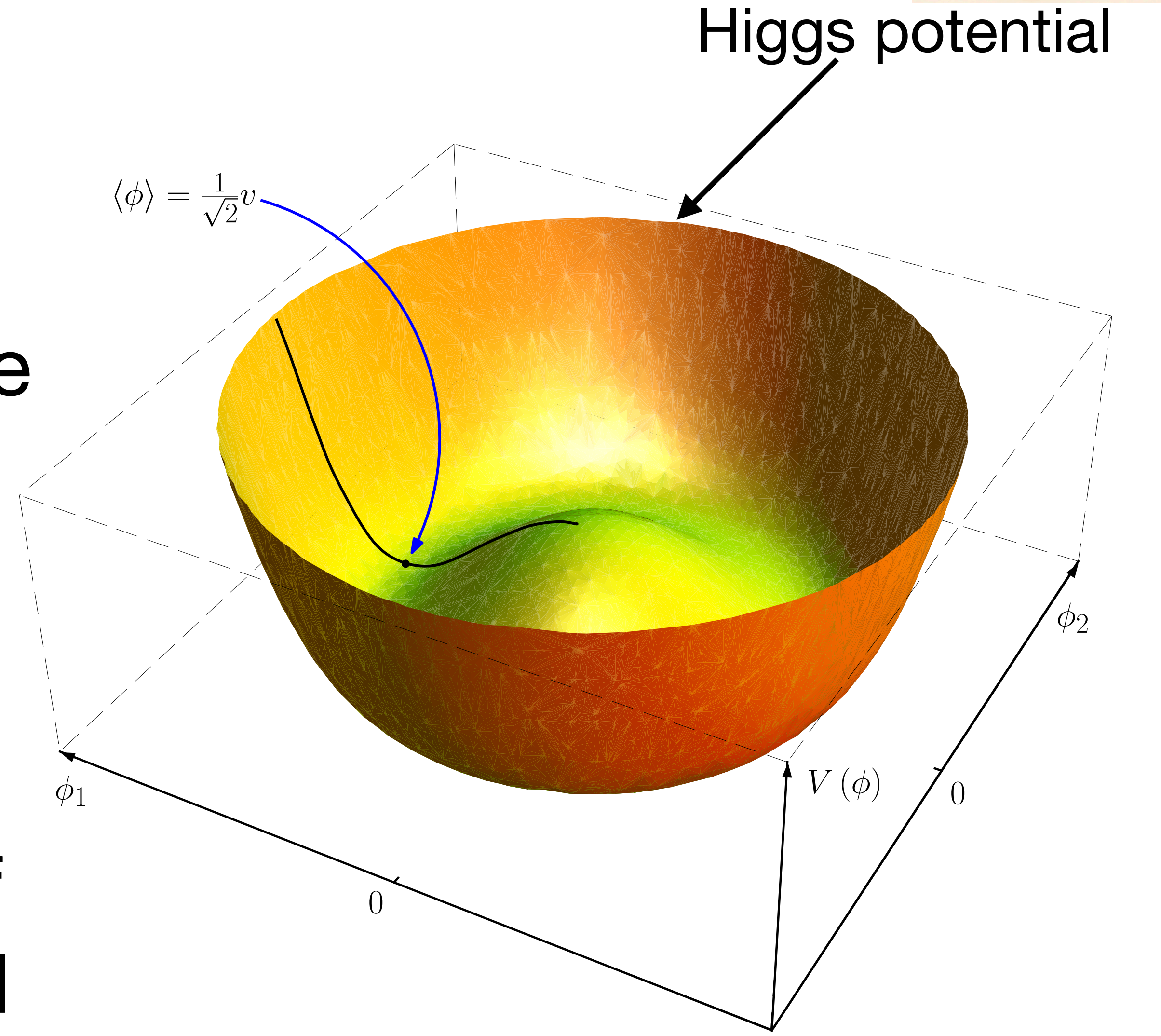



⇒ SM-like properties

The LHC results on h 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

# Higgs potential: the "holy grail" of particle physics

What is the underlying dynamics of electroweak symmetry breaking? The vacuum structure with v ≠ 0 is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!




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

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

Fundamental scalar or compositeness? (new interaction?)

# Higgs potential: the "holy grail" of particle physics

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

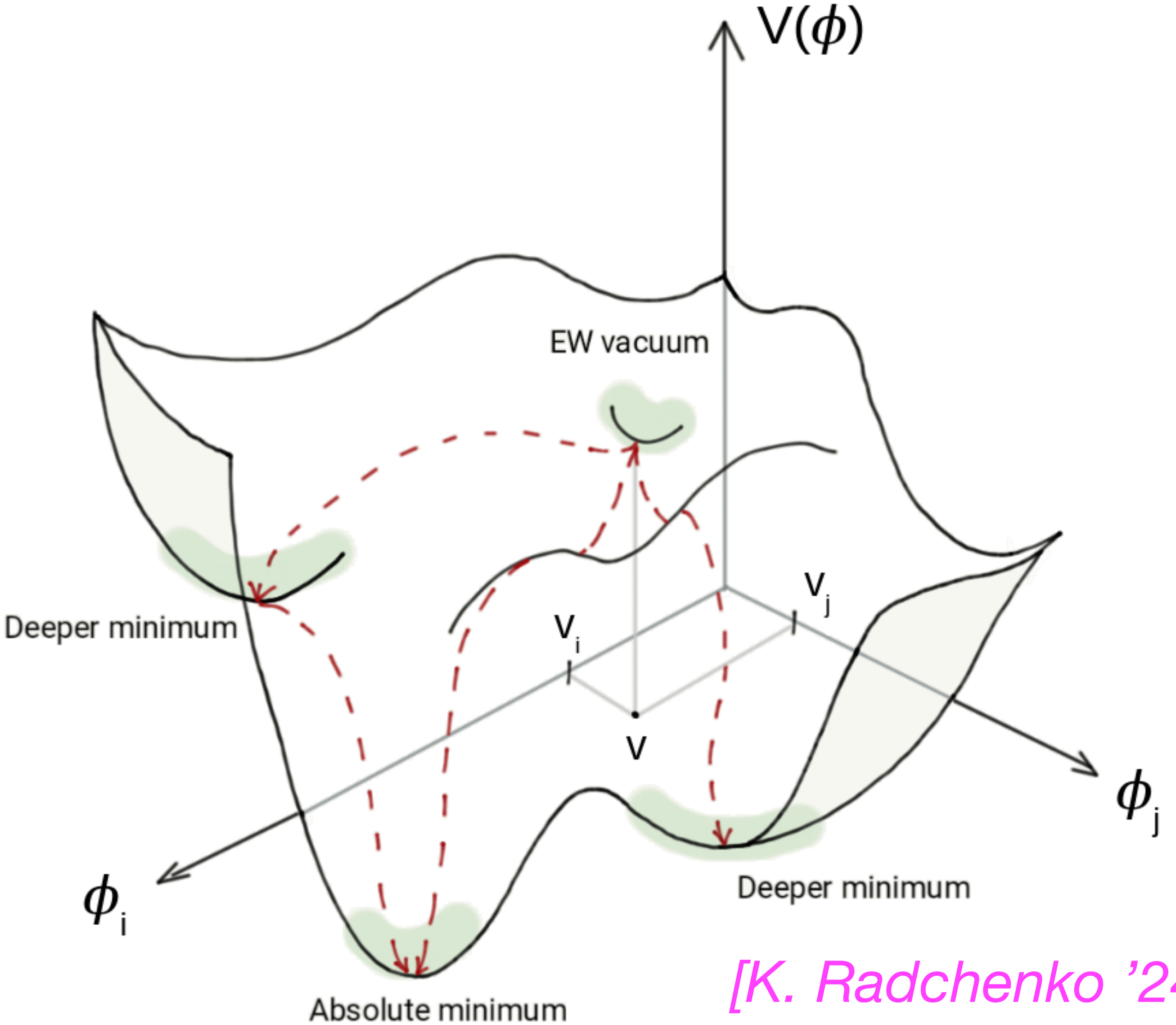
Trilinear coupling  Quartic coupling  Possible couplings involving additional scalars

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

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

Distance of EW minimum from origin of field space: v

Curvature of the potential around the EW minimum: $m_h$



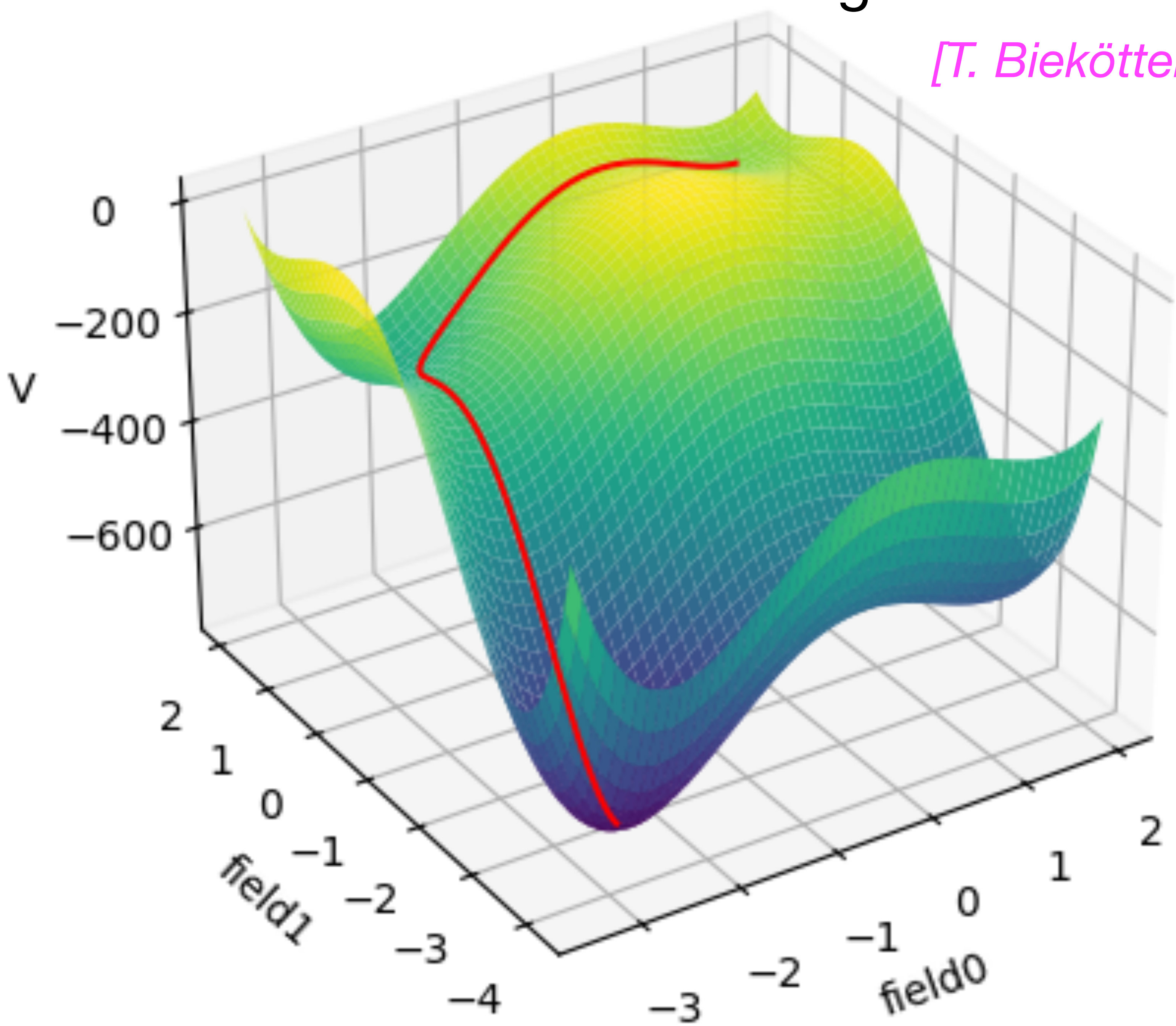

*[K. Radchenko '24]*

# The Higgs potential and vacuum stability

Simple toy example: two singlet-type Higgs fields

Tunneling from a local minimum into the global minimum:

*[T. Biekötter, F. Campello, G. W. '25]*




⇒ Proceeds via intermediate local minimum

# The Higgs potential and vacuum stability

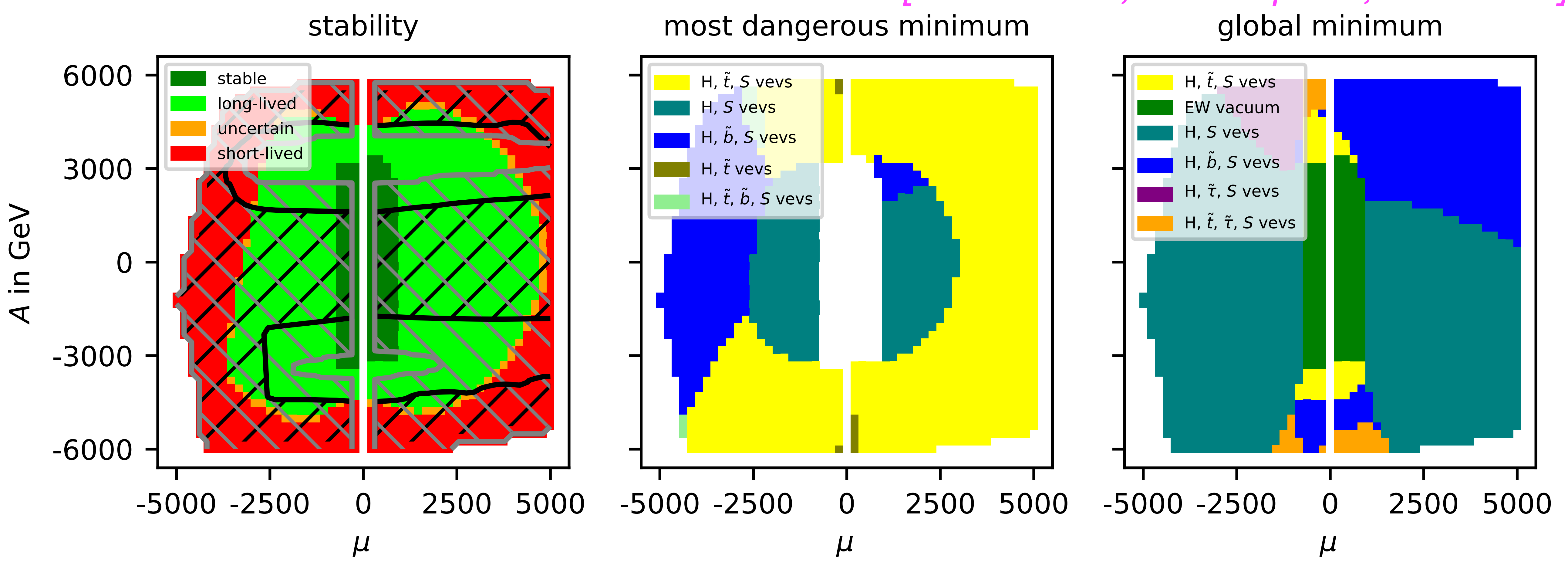
Extended Higgs sectors in general yield additional minima of the Higgs potential; the electroweak minimum may not be the global minimum

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

Improved version of the public code *Evade*

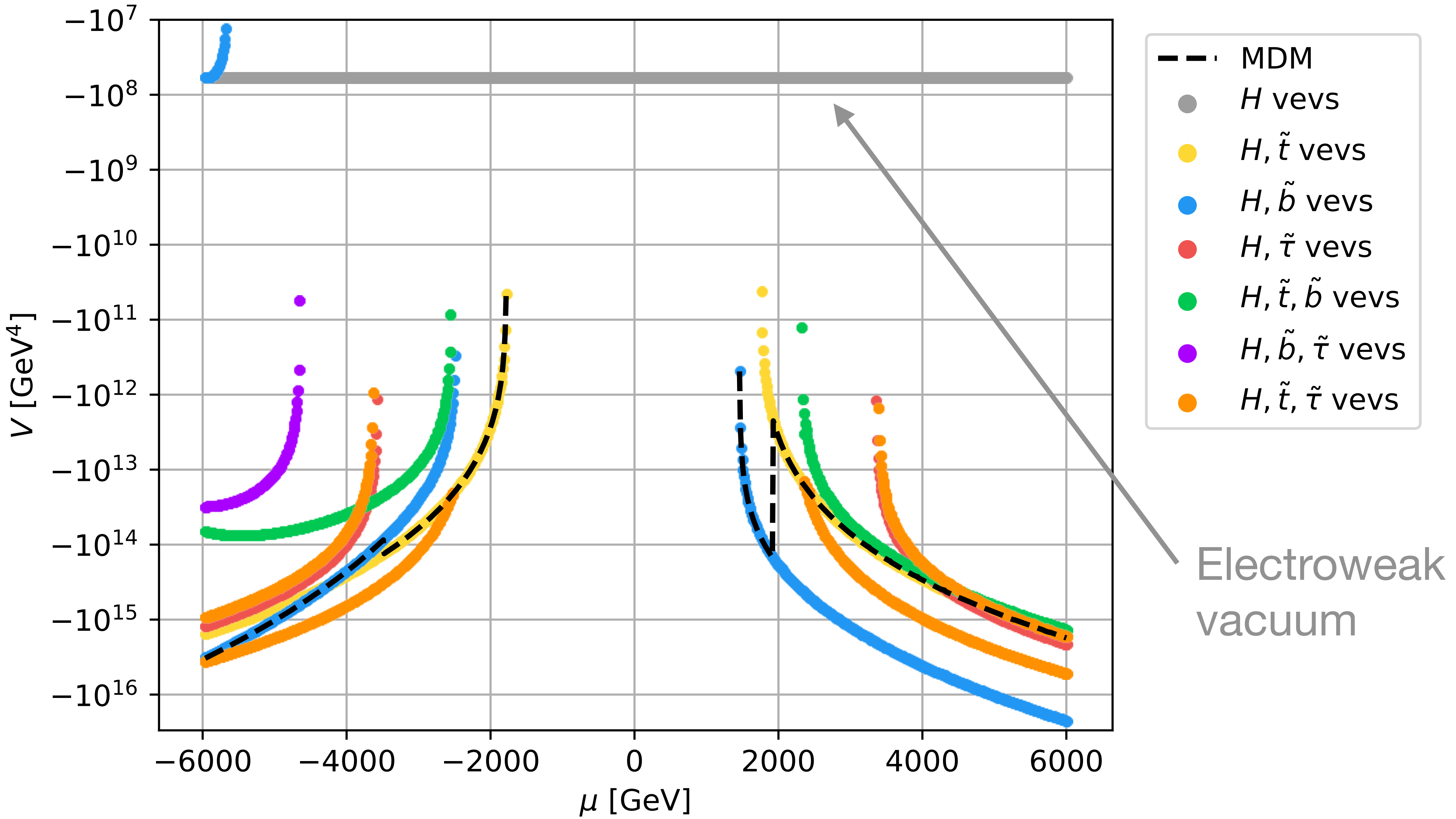
Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*

*[T. Biekötter, F. Campello, G. W. '25]*



# Depth of stationary points of the Higgs potential

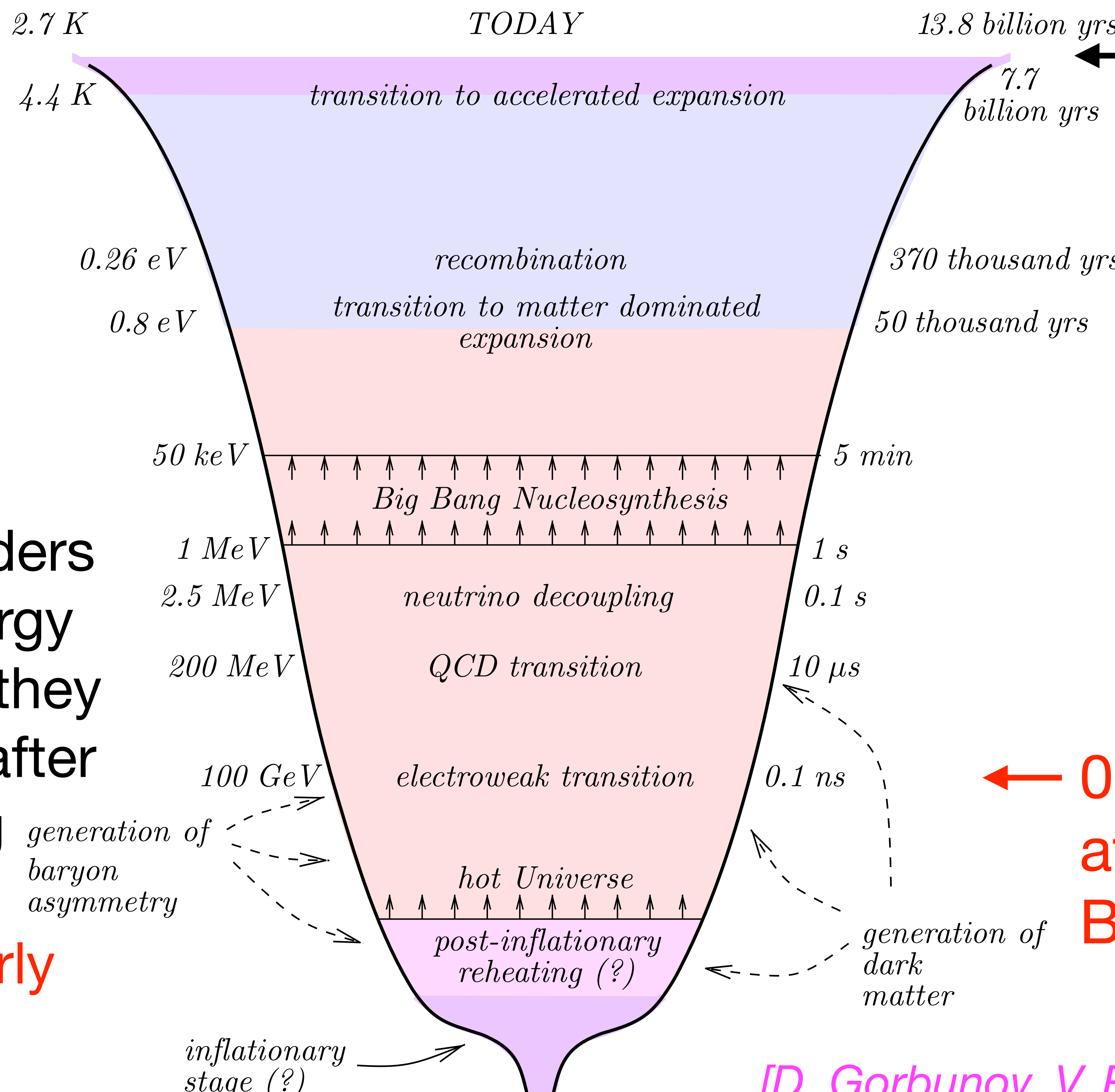
Along line with $X_t$ = 2.8 TeV: [W.G. Hollik, J. Wittbrodt, G. W. ’18]




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

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

History of the Universe:




Now: ~14 billion years after the Big Bang

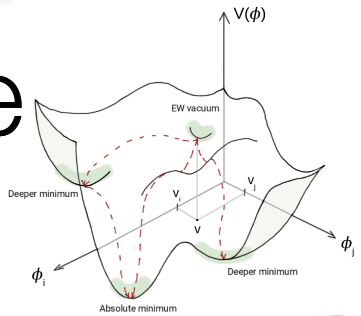
Particle colliders produce energy densities as they existed just after the Big Bang

⇒ Information about the early Universe

0.0000000001 s after the Big Bang

[D. Gorbunov, V. Rubakov]

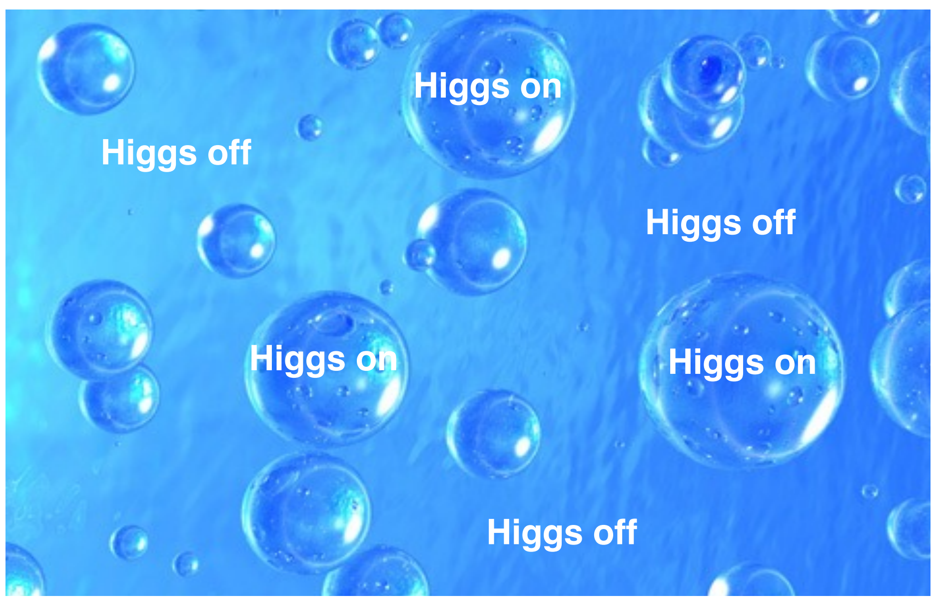
# The Higgs potential and the electroweak phase transition (EWPT)

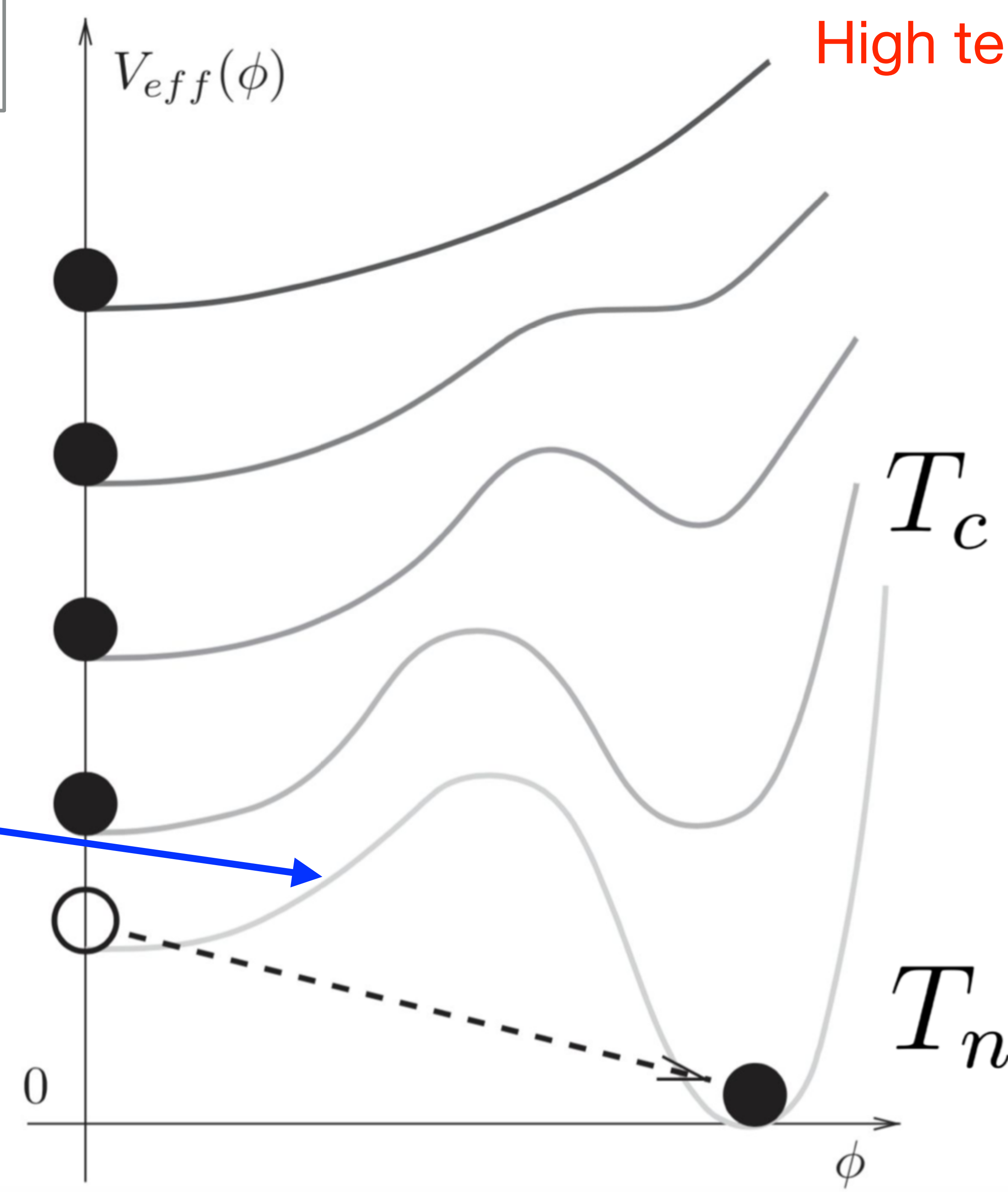



[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

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




High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

Potential barrier depends on trilinear Higgs coupling(s)

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

# Electroweak phase transition and baryon asymmetry

*[see Julia's talk yesterday]*

**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]

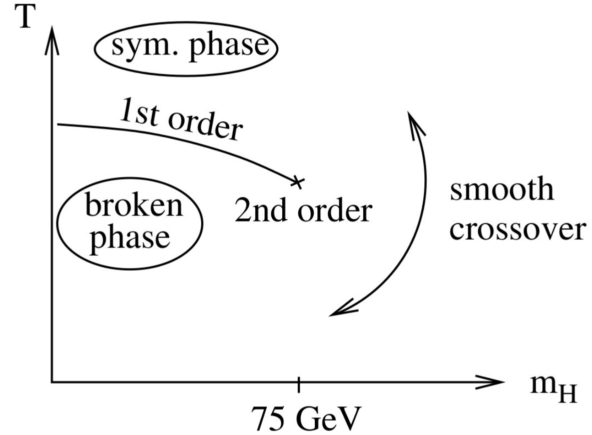
*$n_b$: baryon no. density*
*$n_{\bar{b}}$: antibaryon no. density*
*$n_\gamma$: photon no. density*

*[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*

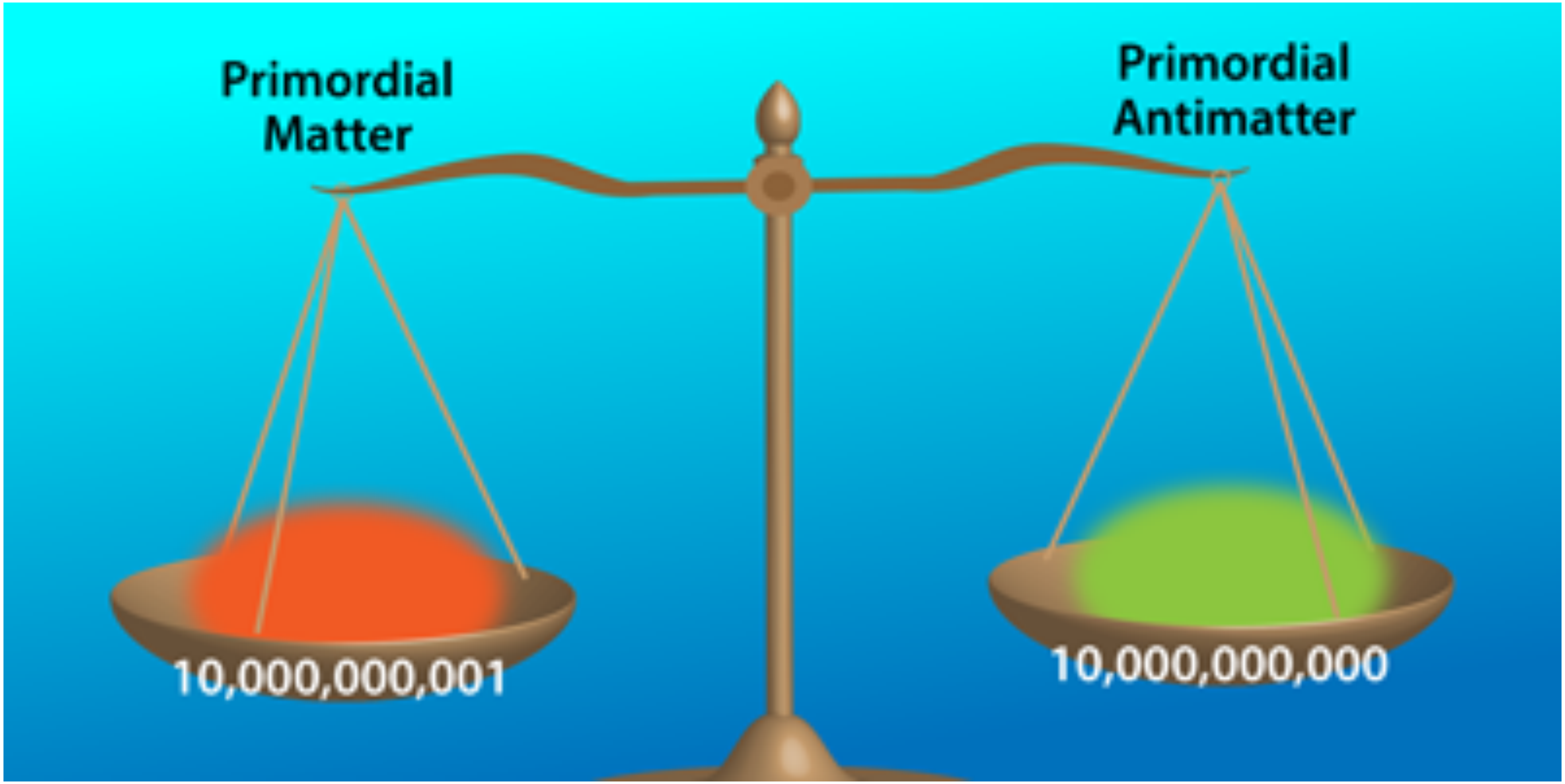



SM CP Violation insufficient by ~ 10 orders of magnitude

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

*[see Julia's talk yesterday]*

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)

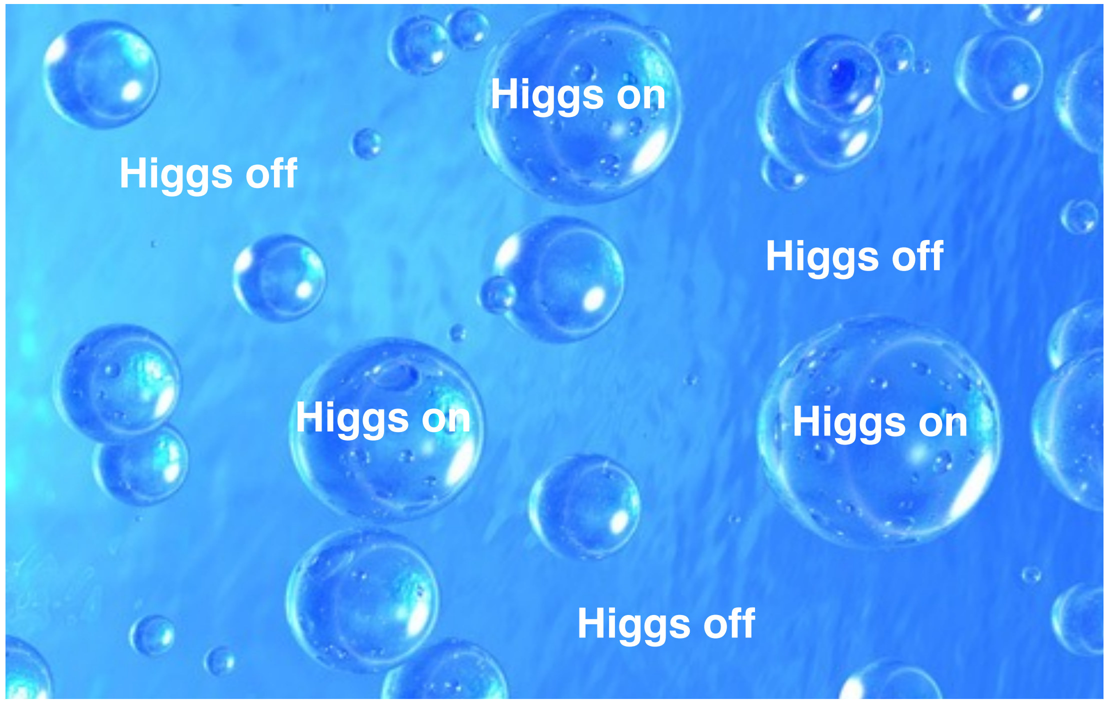
Non-perturbative ``sphaleron" processes violate both baryon and lepton number (i.e., violate B+L), but preserve B−L

# Baryon generation at the electroweak phase transition

*[see Julia's talk yesterday]*

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

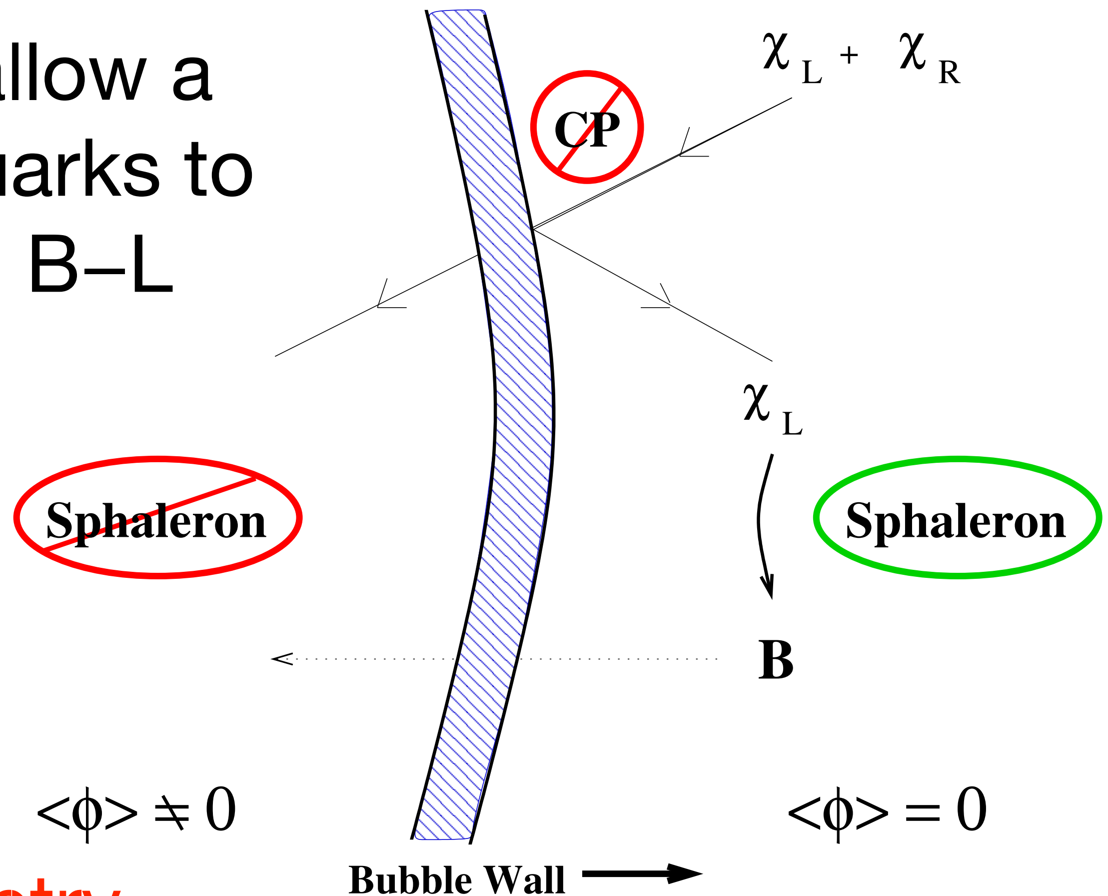
*[see Julia's talk yesterday]*

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]*

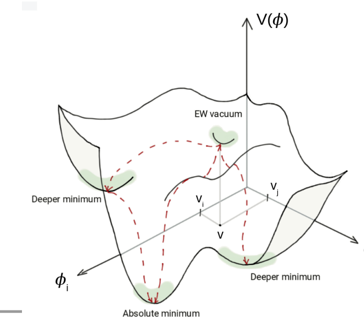
Outside the bubble, EW sphalerons allow a fraction of the chiral asymmetry of quarks to be shared with leptons (B+L violated, B−L preserved)



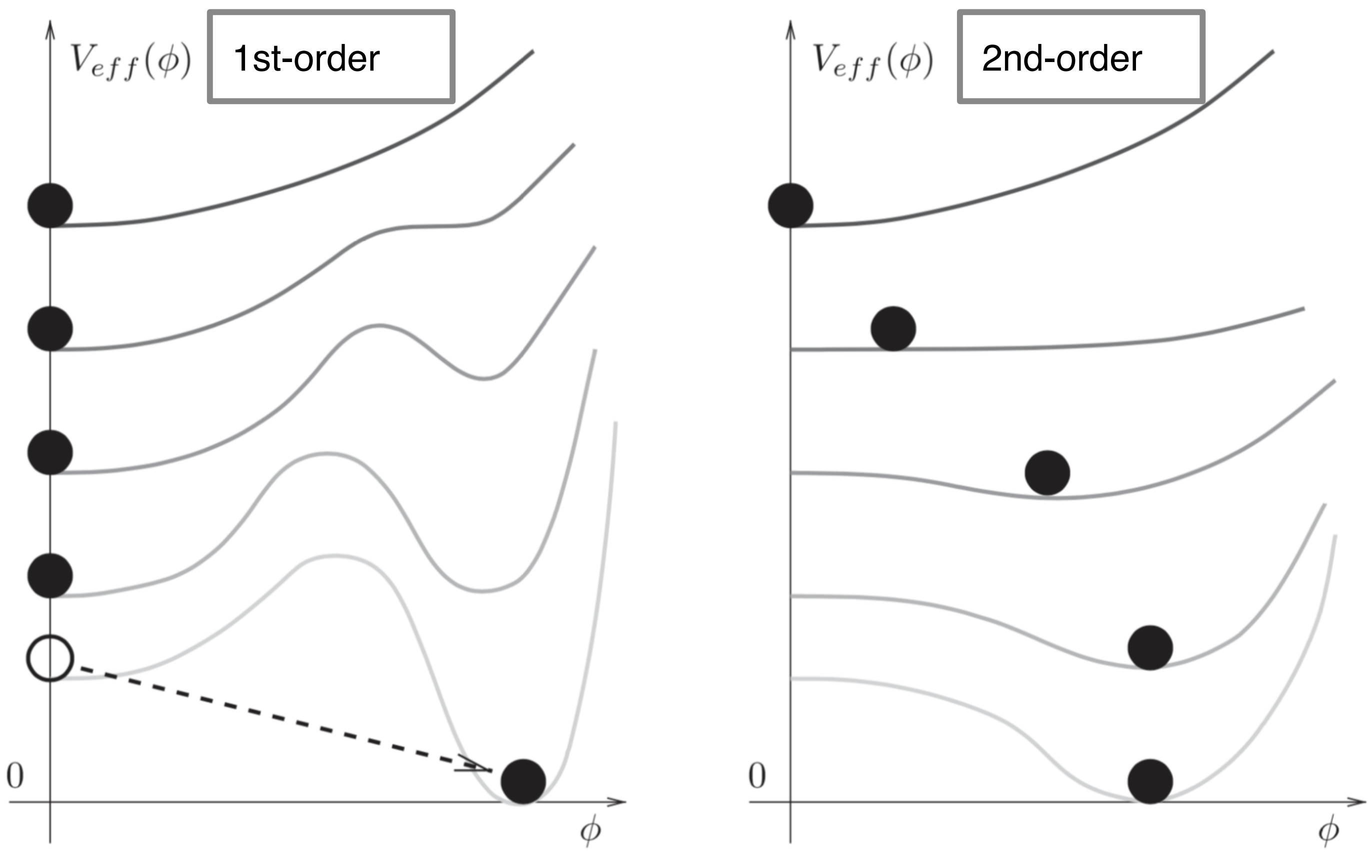

⇒ Creation of net baryon asymmetry

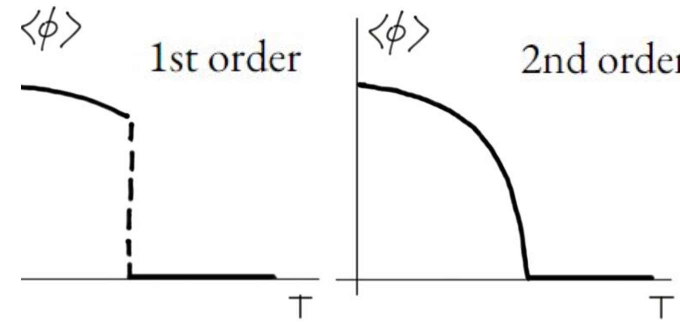
Strong first-order EWPT needed to prevent the "washout" of the asymmetry

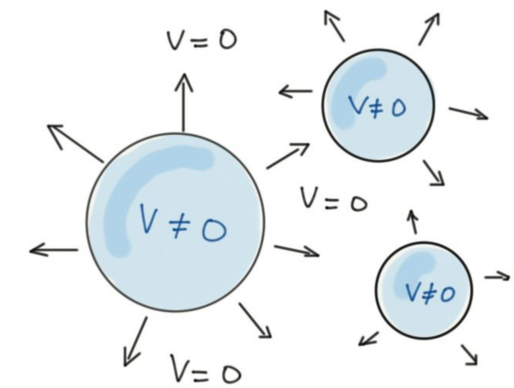
# First-order vs. second order EWPT




[D. Gorbunov, V. Rubakov]



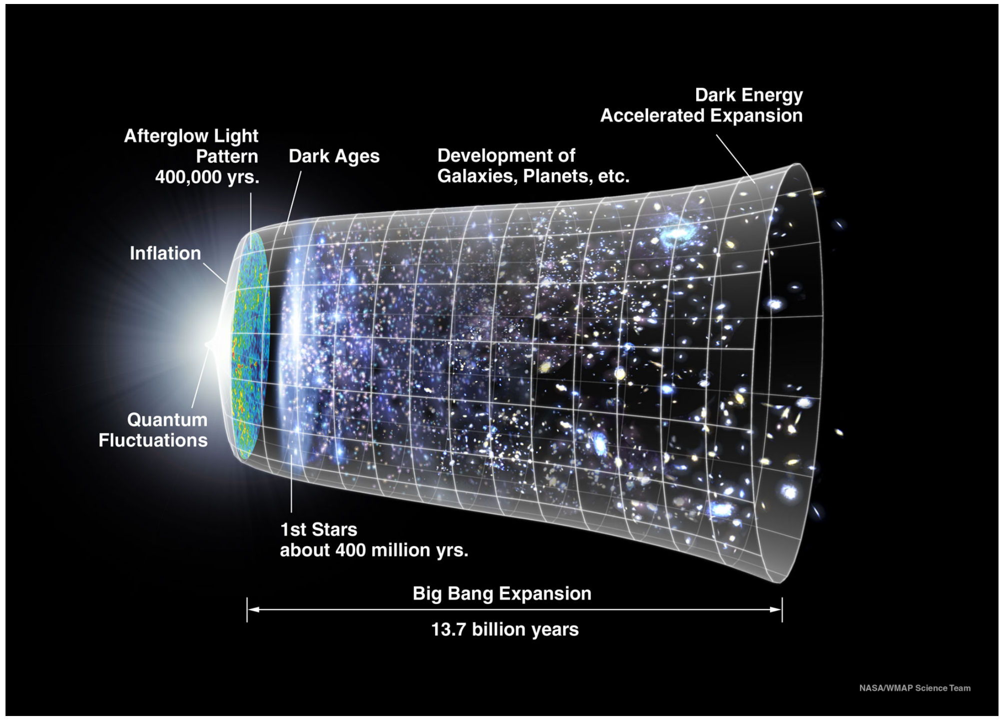



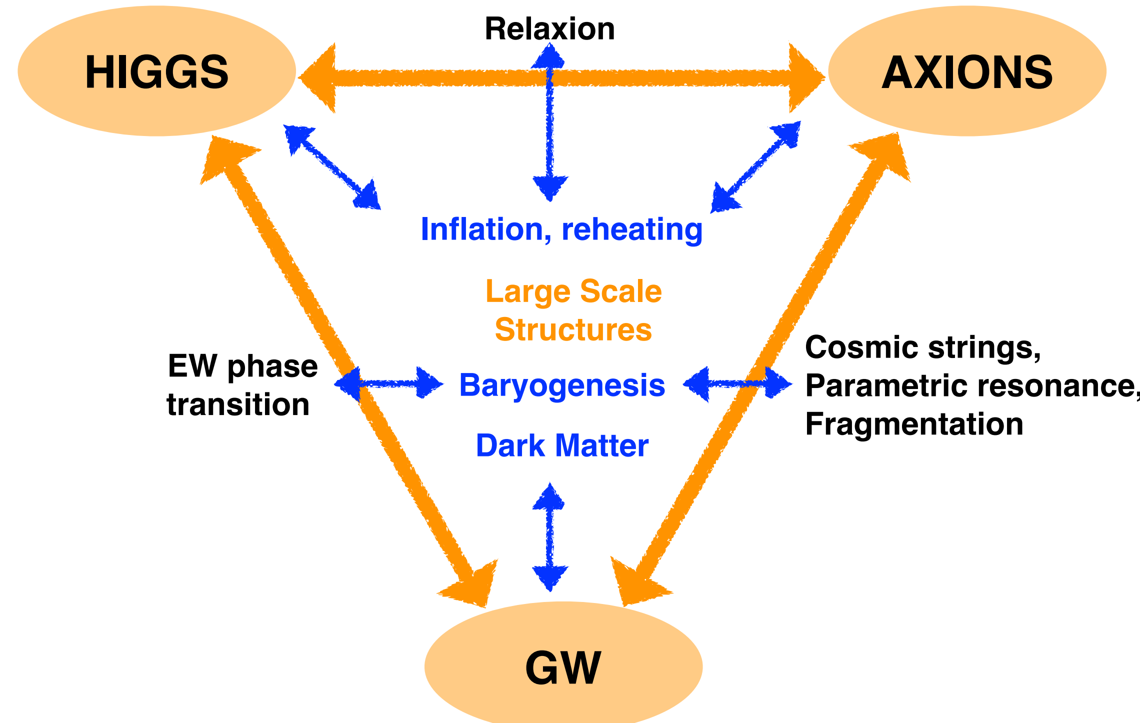

[K. Radchenko ’23]

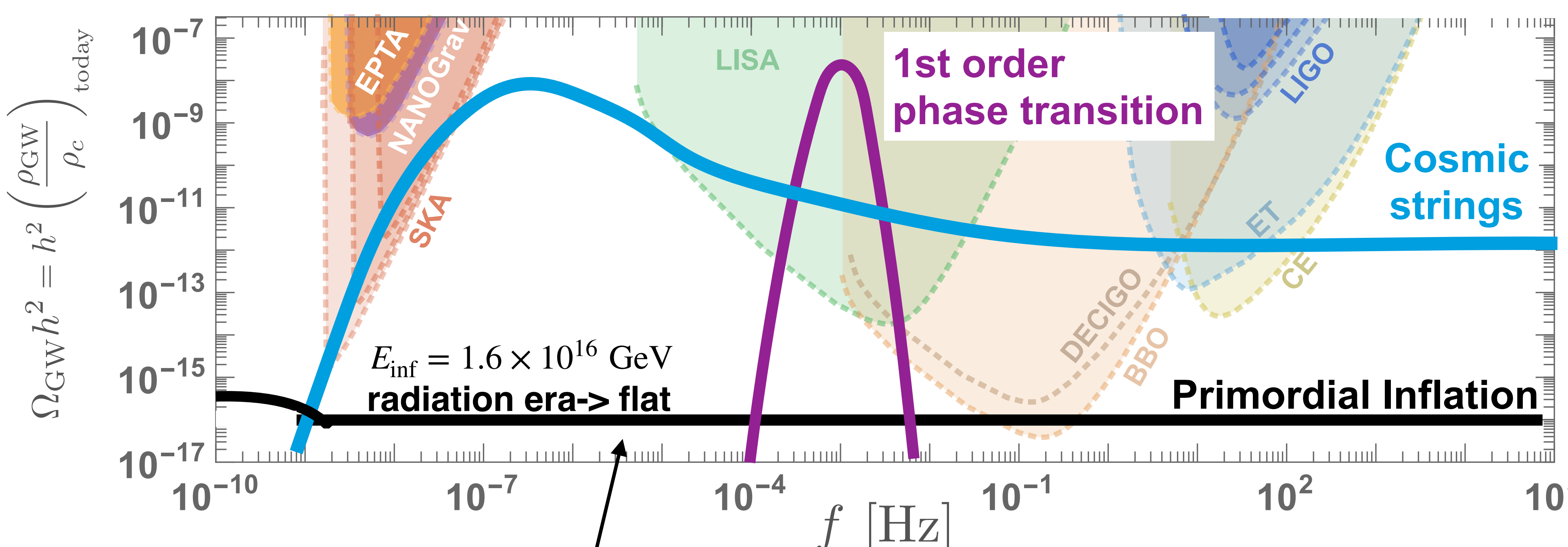
Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

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

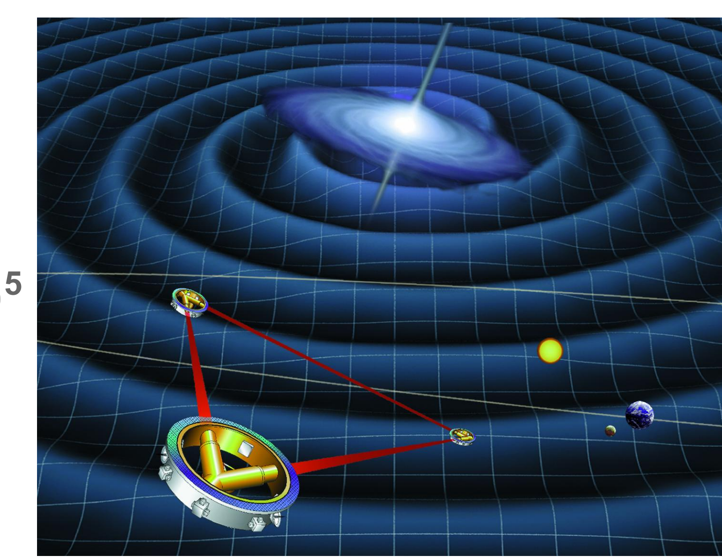
# Gravitational waves as a probe of the early universe




LISA:



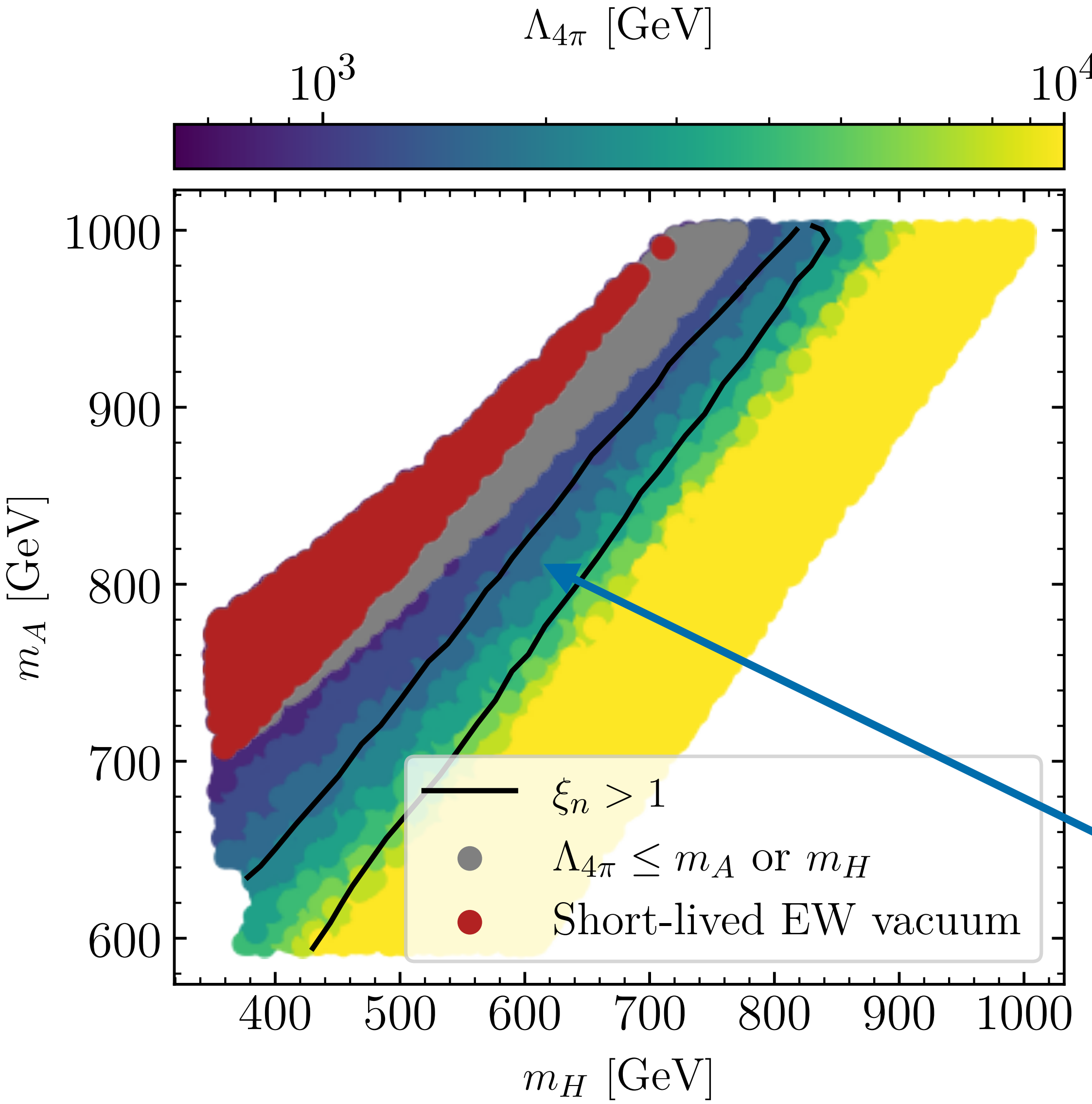
**Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation**

# Correlation of strong first-order EWPT with splitting between BSM Higgs masses of extended Higgs sector

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

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

2HDM of type II, alignment limit, tanβ = 3:

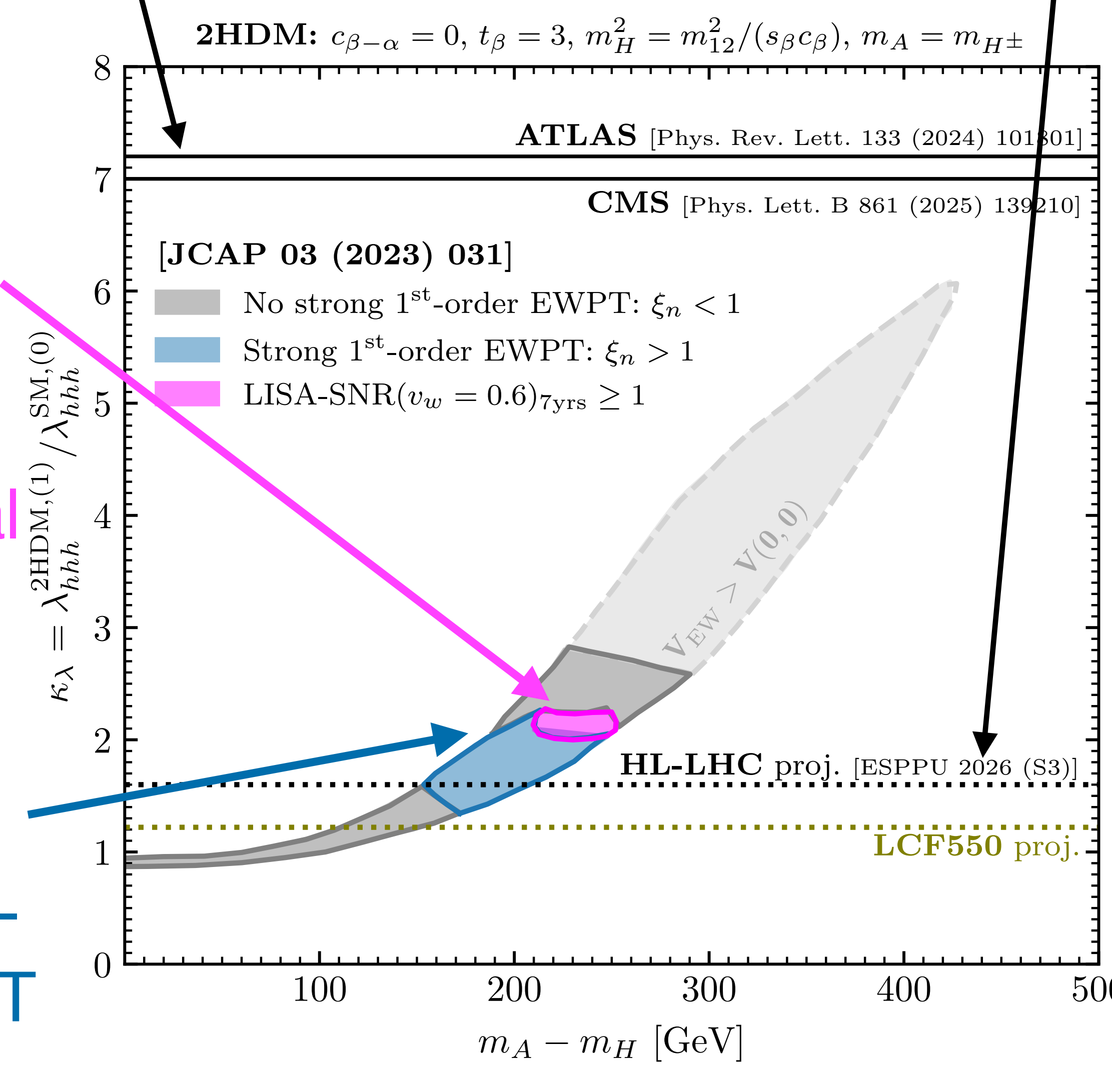



current bound

HL-LHC sensitivity

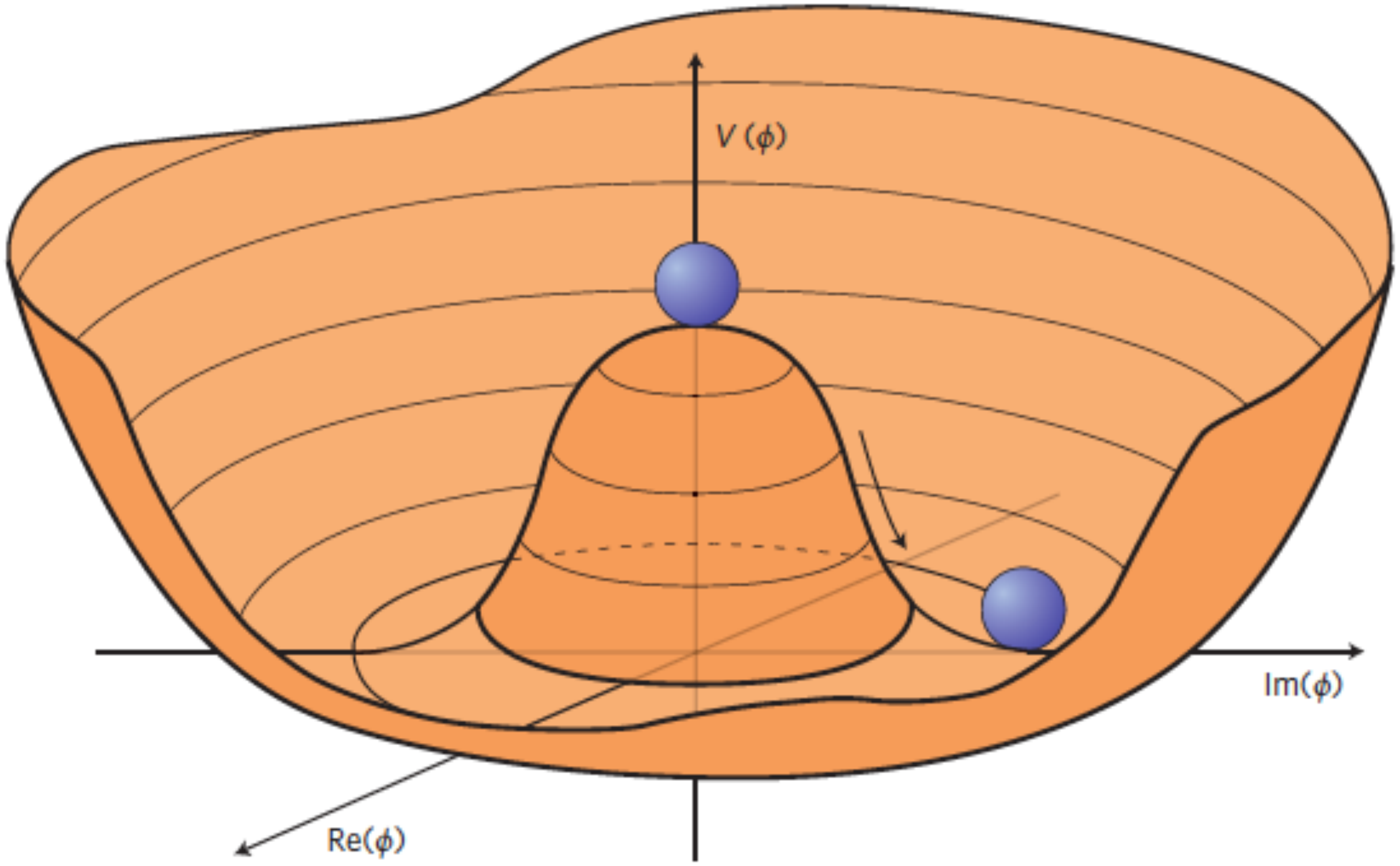
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT



# Higgs pair production, the trilinear Higgs self-coupling and the electroweak phase transition

The simple picture of the Higgs potential



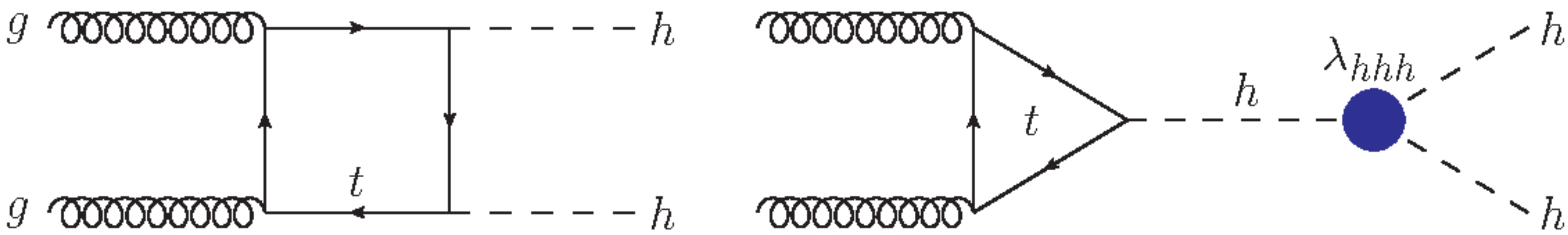

refers to the case of a single Higgs doublet field

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

# Trilinear Higgs self-coupling and the Higgs pair production process (h: detected Higgs boson at 125 GeV)

Sensitivity to trilinear self-coupling $\lambda_{hhh}$ from Higgs pair production:

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



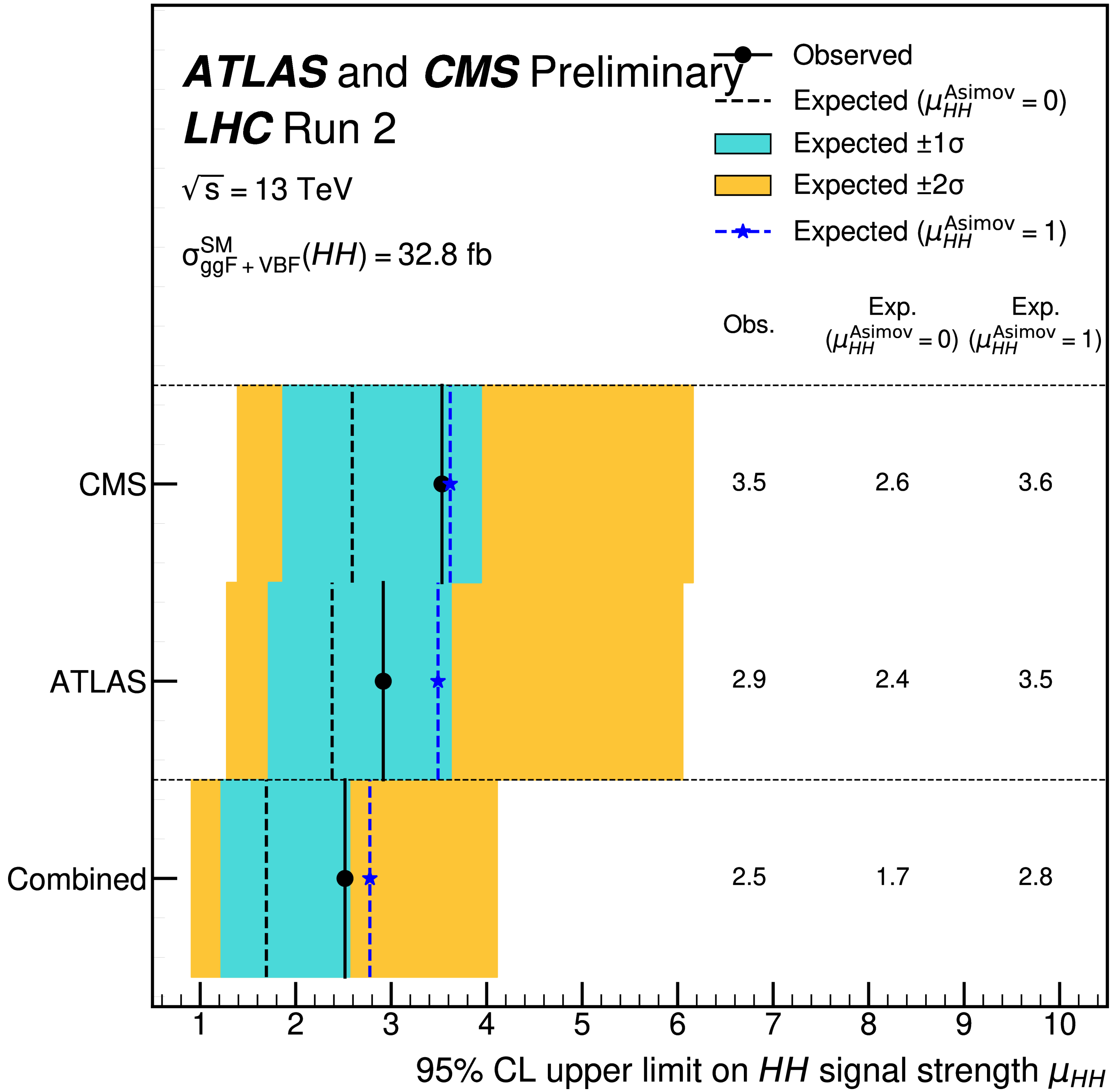

*[ Note: Single-Higgs production (EW precision observables) → $\lambda_{hhh}$ enters at NLO (NNLO) ]*

⇒ Large destructive interference contribution (signal-signal interference), depends sensitively on $\kappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

Experimental limits on the di-Higgs cross sections yield constraints on $\kappa_\lambda$

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

# Limits on the non-resonant di-Higgs cross section




*[ATLAS and CMS Collaborations '25]*

Run 2 combination

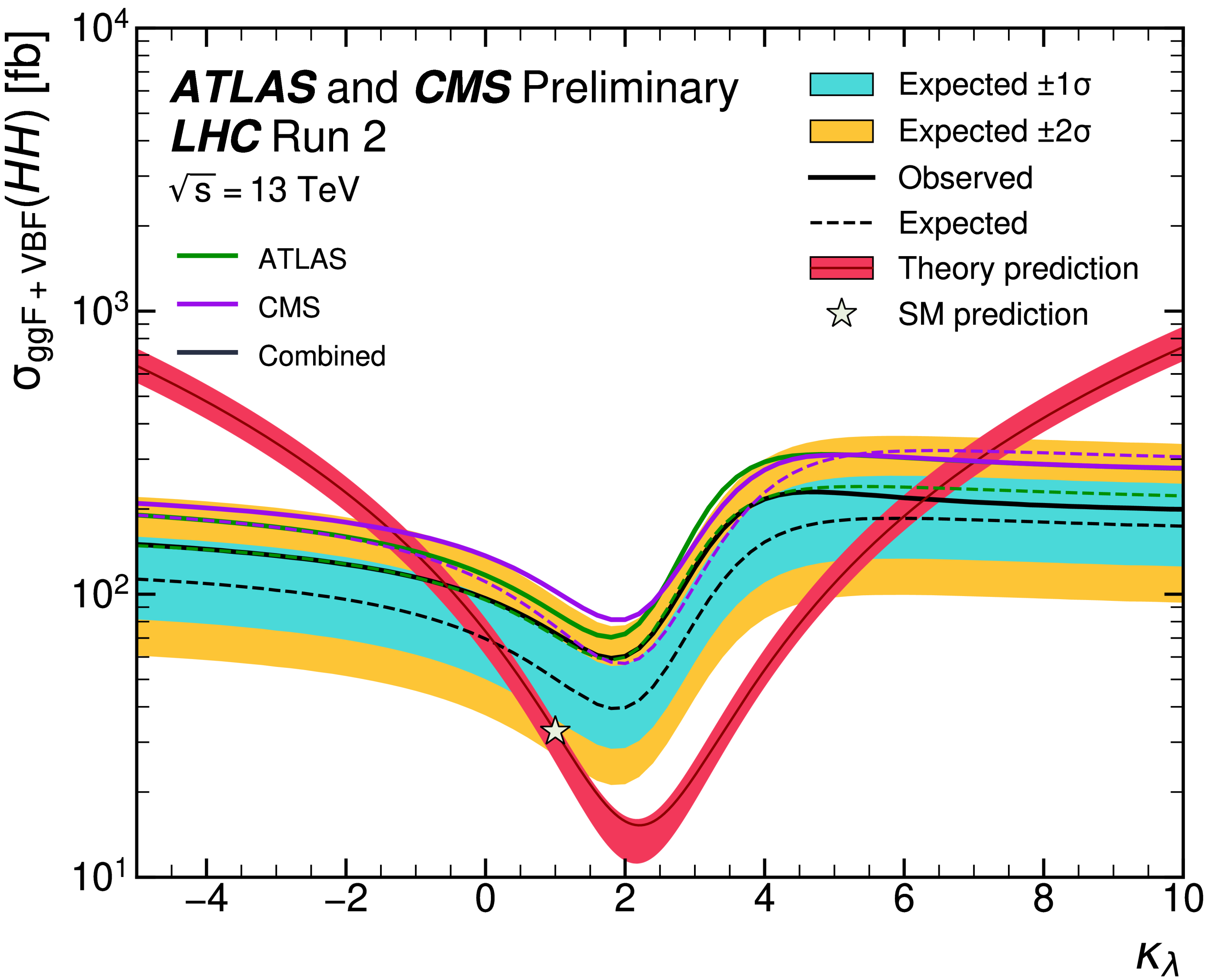
⇒ Upper bound of 2.5 $\sigma^{SM}$ for $\varkappa_\lambda = 1$

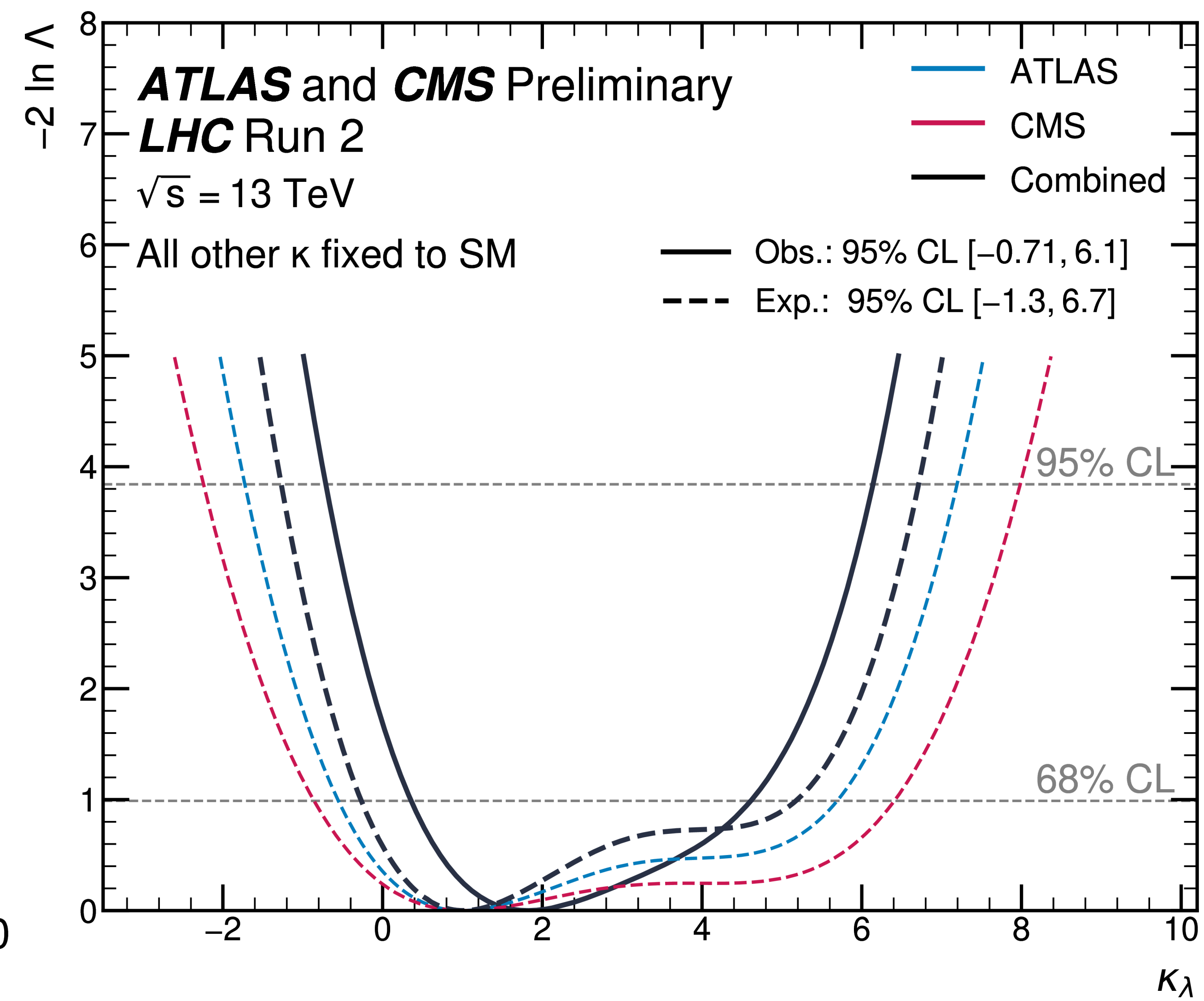
# Limits from non-resonant di-Higgs production

*[ATLAS and CMS Collaborations '25]*

Using only information from di-Higgs production and assuming that new physics only affects $\lambda_{hhh}$ :

$\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$



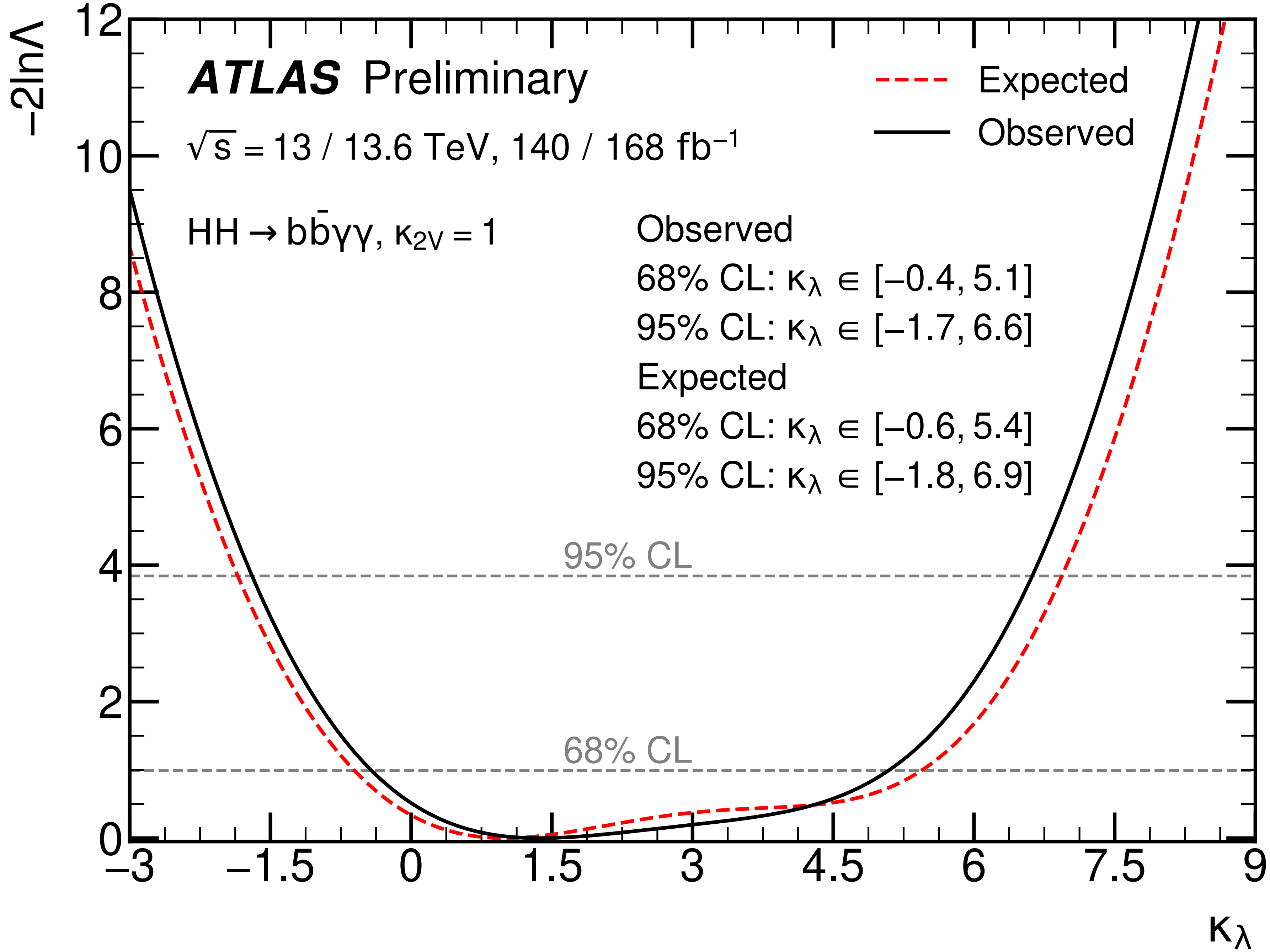




obs: $-0.7 < \varkappa_\lambda < 6.1$ at 95% C.L., exp.: $-1.3 < \varkappa_\lambda < 6.7$ at 95% C.L.

⇒ Upper bound on $\lambda_{hhh}$ of currently about 6 x (SM value)

# Latest updates from ATLAS and CMS

$bb\gamma\gamma$ channel, Run 2 + Run 3 (up to 2024) data: *[ATLAS Collaboration '25]*




$bb\gamma\gamma$ channel, partial Run 3 data (2022 + 2023)

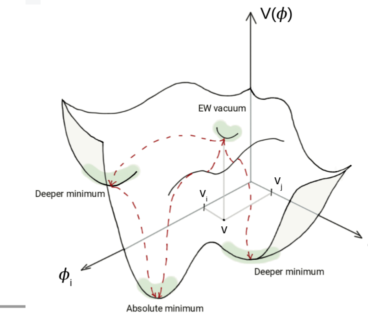
*[CMS Collaboration '25]*

4b channel, partial Run 3 data (2022 + 2023)

*[CMS Collaboration '25]*

$\Rightarrow -1.7 < \kappa_\lambda < 6.6$ at 95% C.L.

# How big can modifications of $\lambda_{hhh}$ be?




Limits from non-resonant di-Higgs production:
Upper bound on $\lambda_{hhh}$ of currently about 6 x (SM value), i.e. deviation of up to 600% from the SM is allowed

- SM: relatively small higher-order contributions to $\lambda_{hhh}$ at the level of about –7%, mostly from top loop; note: $\varkappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{SM, 0}$

- BSM models (UV-complete):
  Generic feature of extended Higgs sectors: mass splitting between BSM Higgs states yields large enhancement of $\lambda_{hhh}$, effects of several 100% possible within existing theoretical and experimental constraints

- Effective field theories:
  BSM effects parameterised as higher-dimensional operators, large enhancement of $\lambda_{hhh}$ possible, effects of several 100%

# $\lambda_{hhh}$: very large deviations from the SM value possible!

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

## Self-Coupling Dominance

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

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

without fine-tuning any parameters, as big as,

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

which is significant!

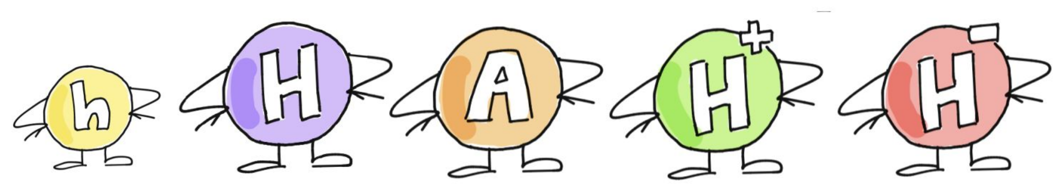
Durieux, MM, Salvioni. 2022

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

# 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** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types

- Potential:

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

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

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

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

# Masses of the BSM Higgs fields

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

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

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

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

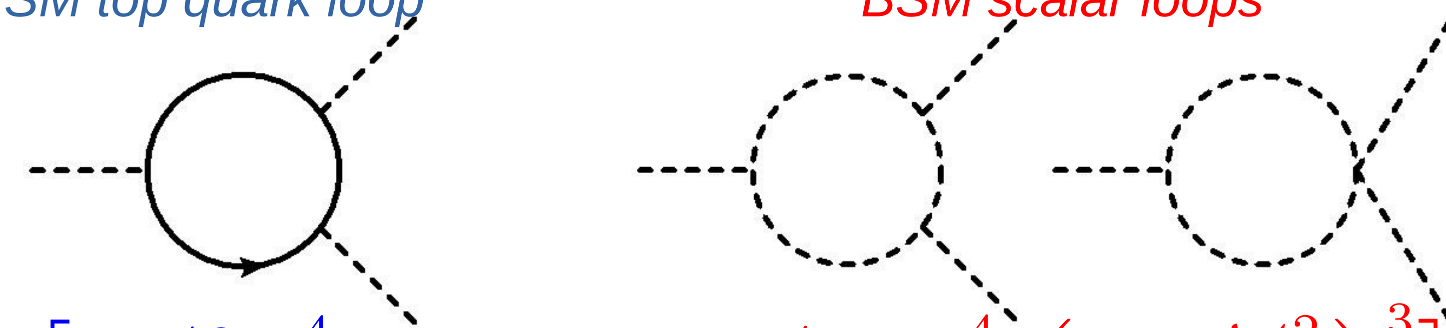
Sizeable splitting between $m_\Phi$ and $M$ induces large BSM contributions to the Higgs self-couplings

# 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 $\lambda_{hhh}$ 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
$n_\Phi$ : # 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 $m_\Phi$ 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]

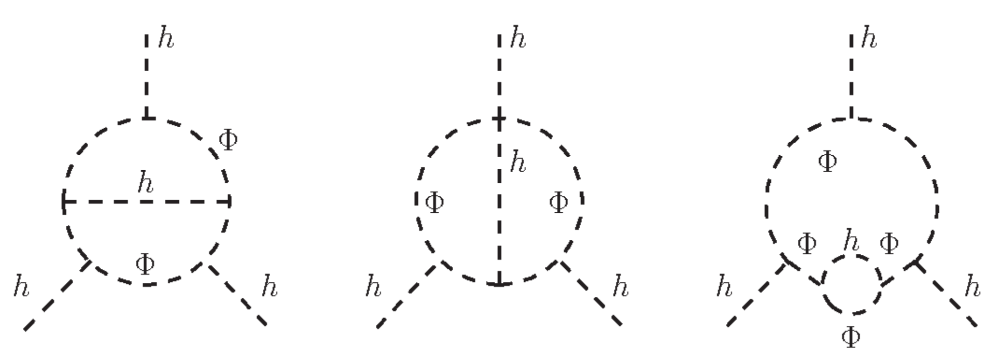
The largest loop corrections to $\lambda_{hhh}$ in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons $\phi$ of the form

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

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 ($\alpha = \beta - \pi/2$)

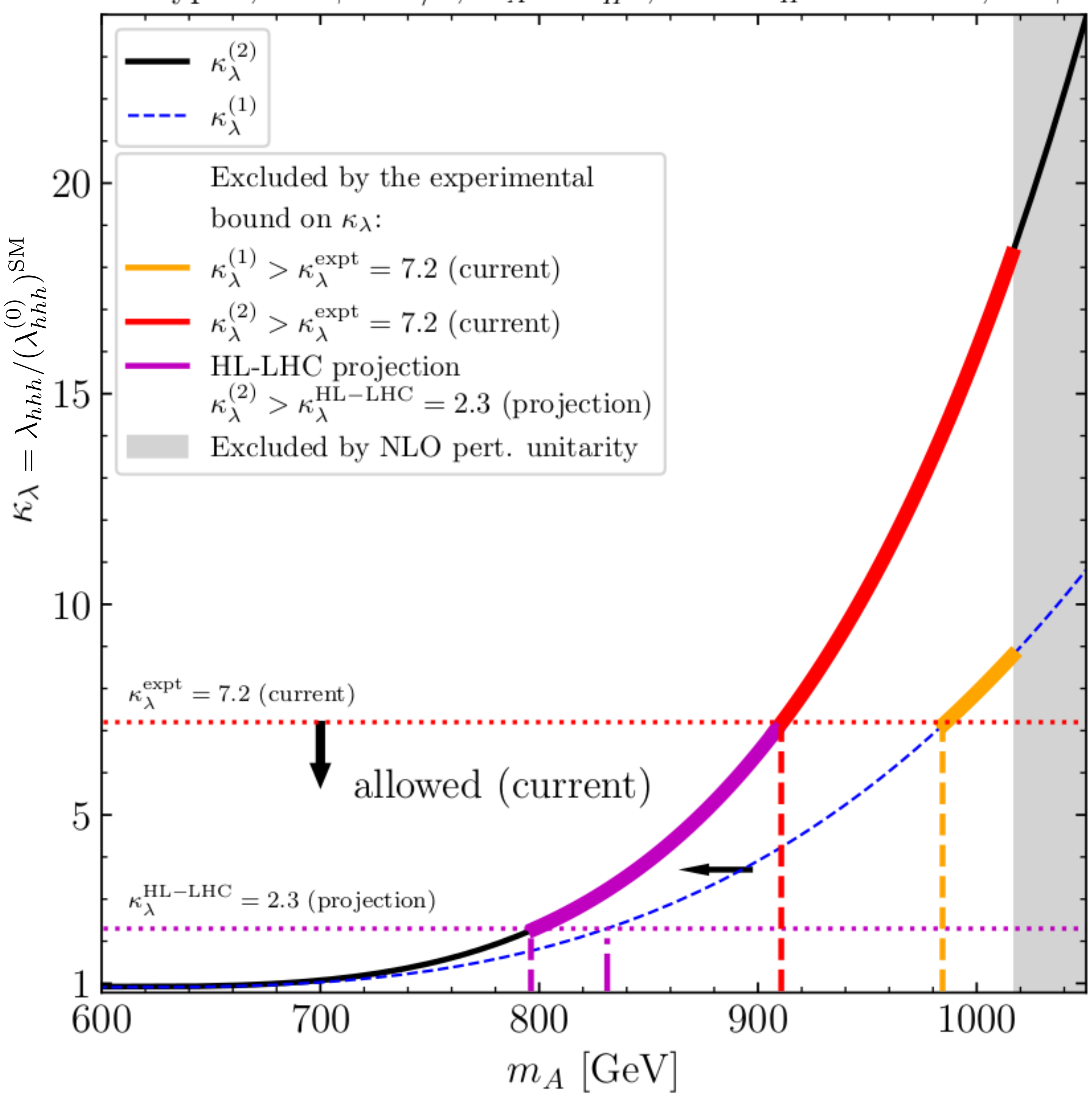
⇒Tree-level couplings of h exactly agree with the SM

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

Prediction for ϰ$_\lambda$ up to the two-loop level:

*[H. Bahl, J. Braathen, G. W. '22, '24 Phys. Rev. Lett. 129 (2022) 23, 231802]*

2HDM type I, $\alpha = \beta - \pi/2$, $m_A = m_{H^\pm}$, $M = m_H = 600$ GeV, $\tan\beta = 2$




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

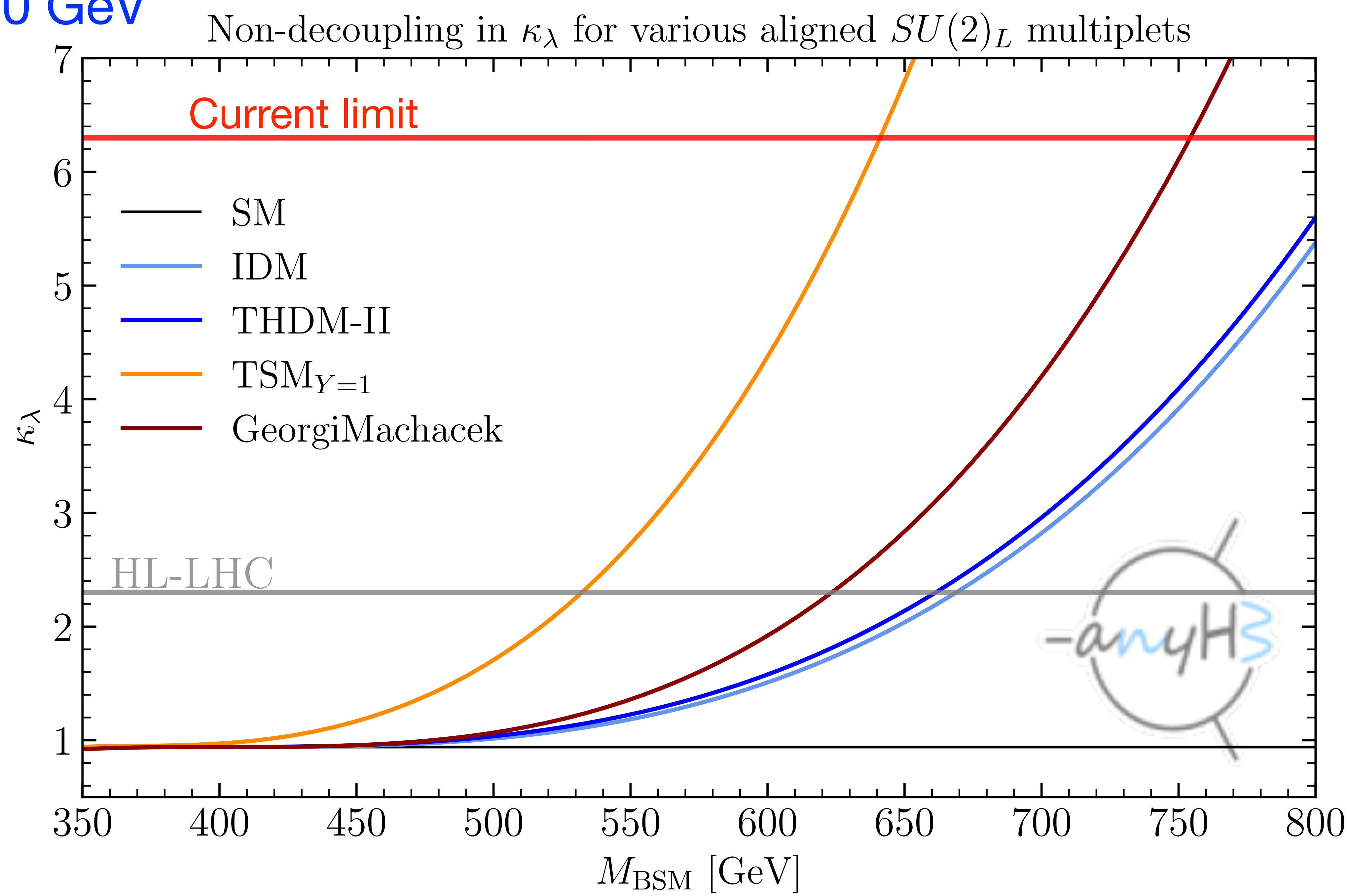
Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

# Trilinear Higgs self-coupling in extended Higgs sectors

Effect of splitting between BSM Higgs bosons: generic feature in extended Higgs sectors (here: one-loop results)

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

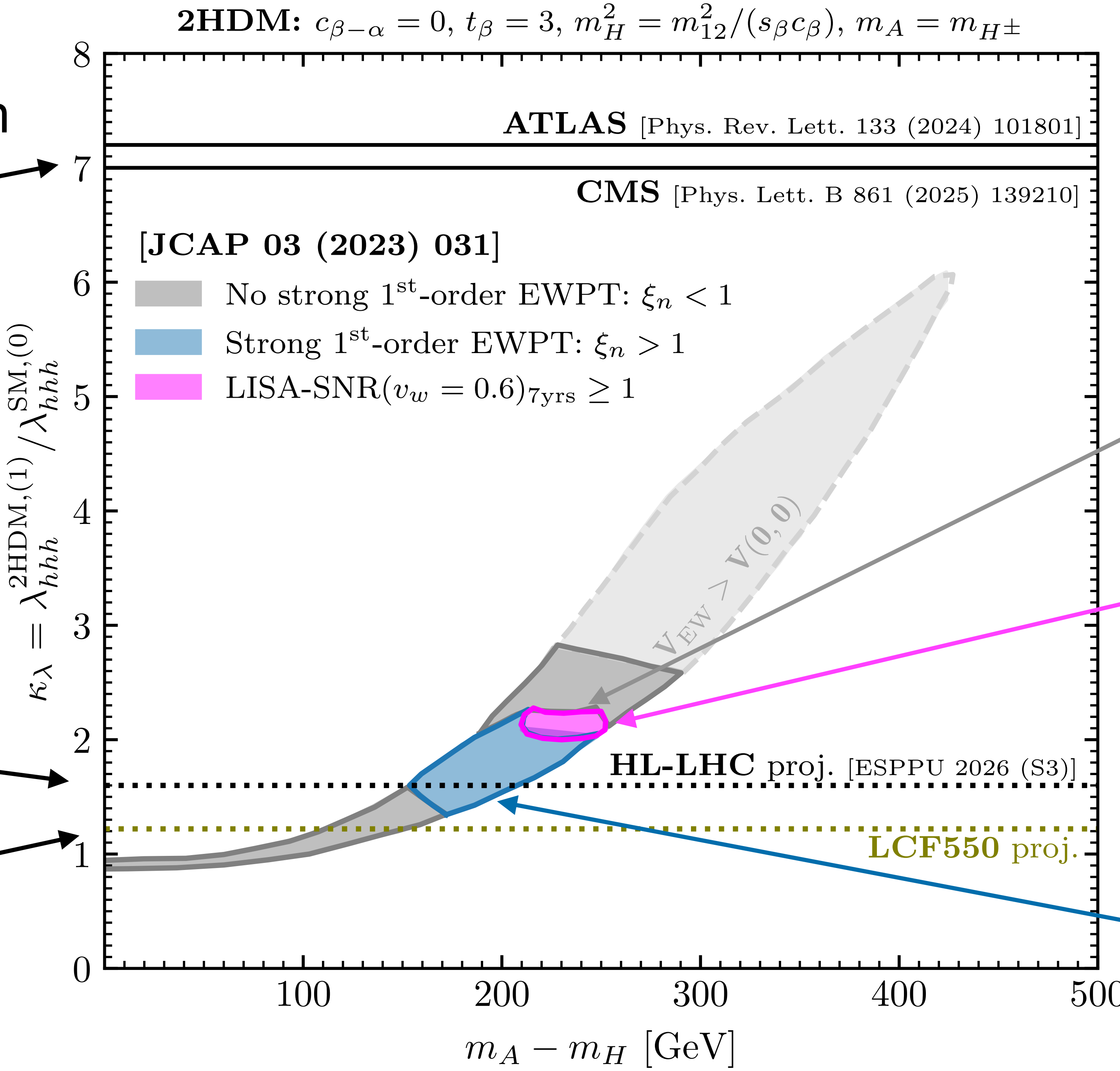
$M_L$ = 400 GeV



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

alignment limit,
tanβ = 3,
1-loop prediction

*[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22, ’25]*

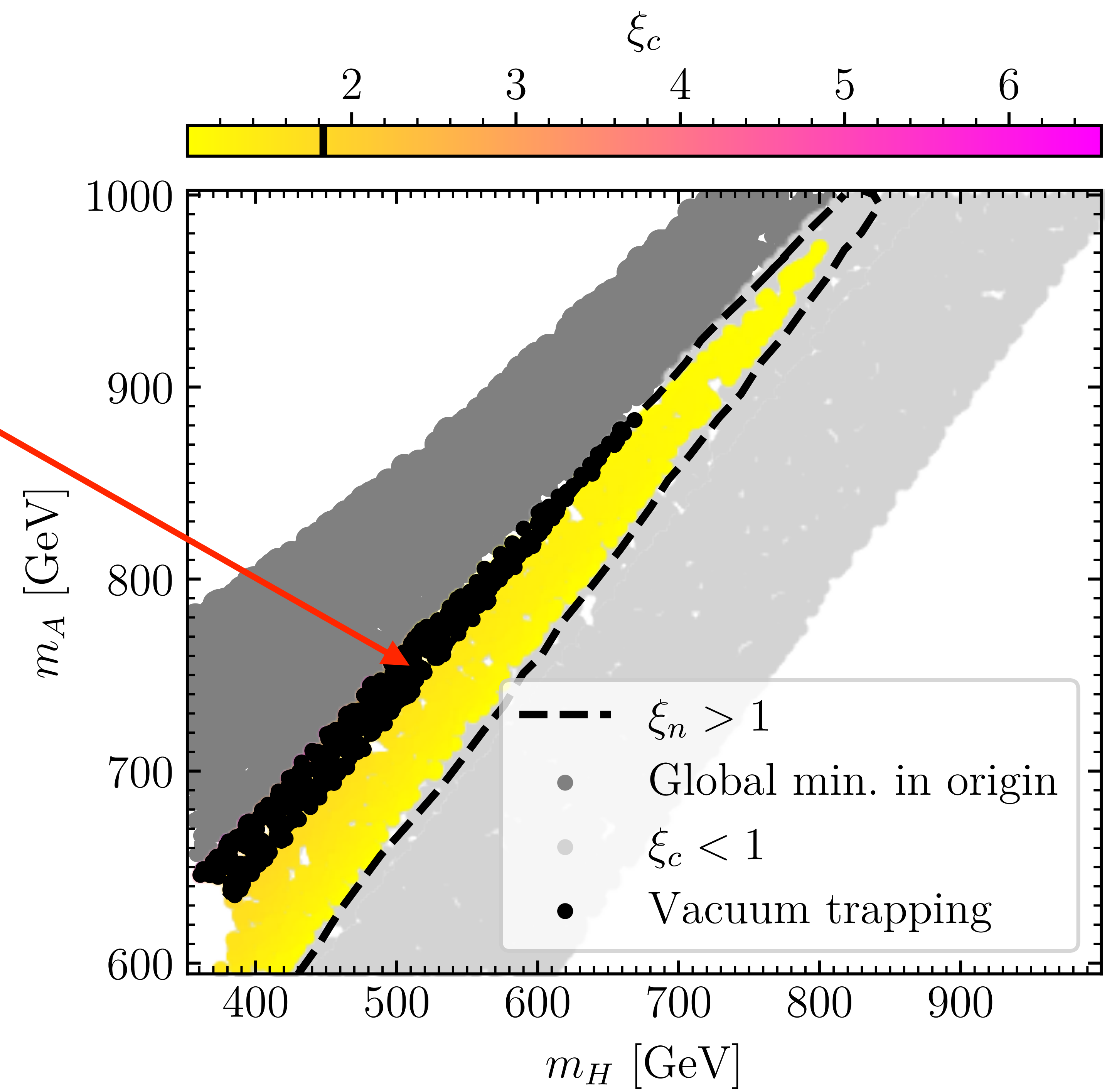



⇒ Region with strong first-order EWPT and potentially detectable GW signal is correlated with significant deviation of $\kappa_\lambda$ from SM value

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

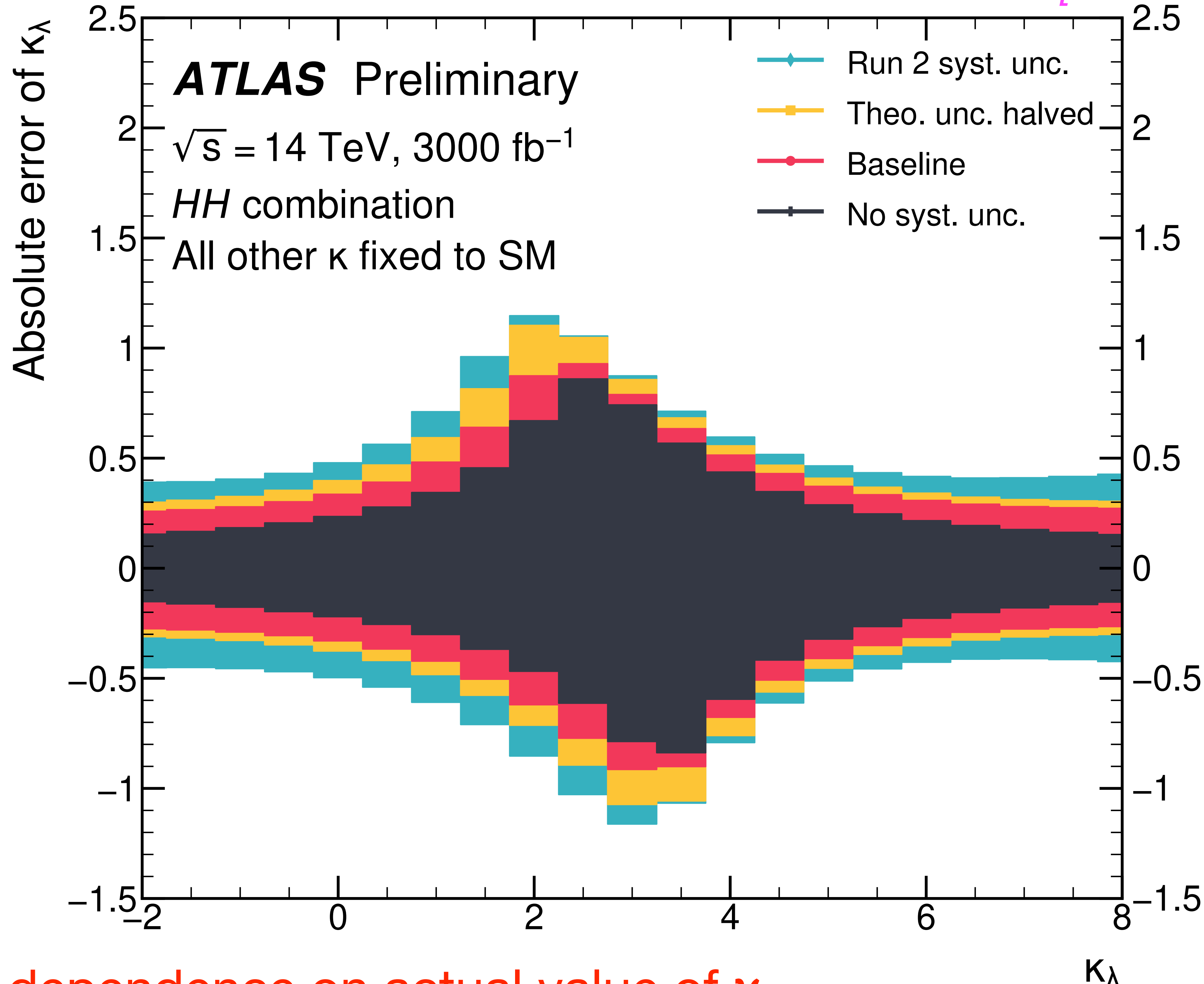
*[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]*

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



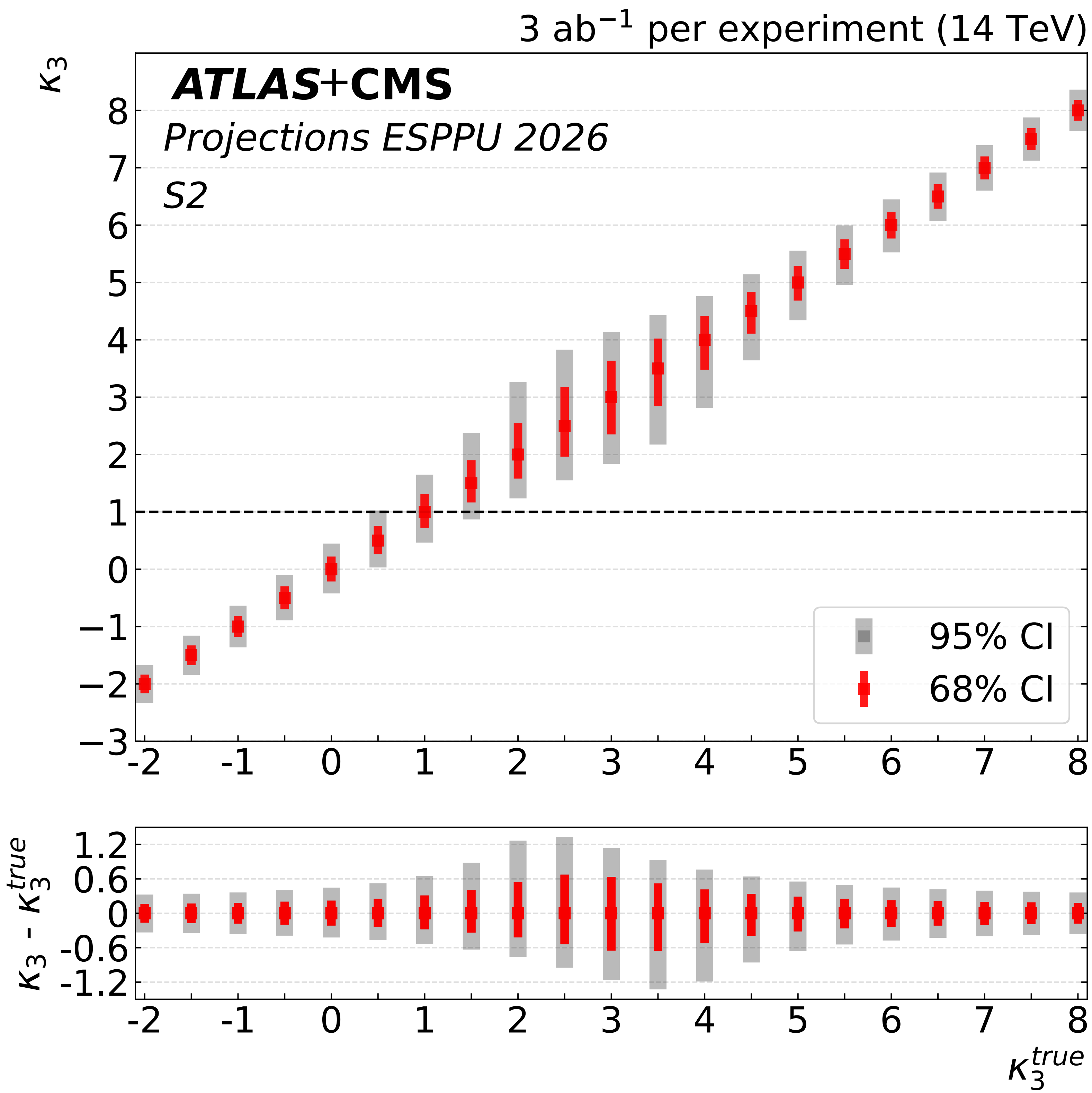
# Recent ATLAS projection going beyond the assumption of $\kappa_\lambda = 1$

[ATLAS Collaboration '25]



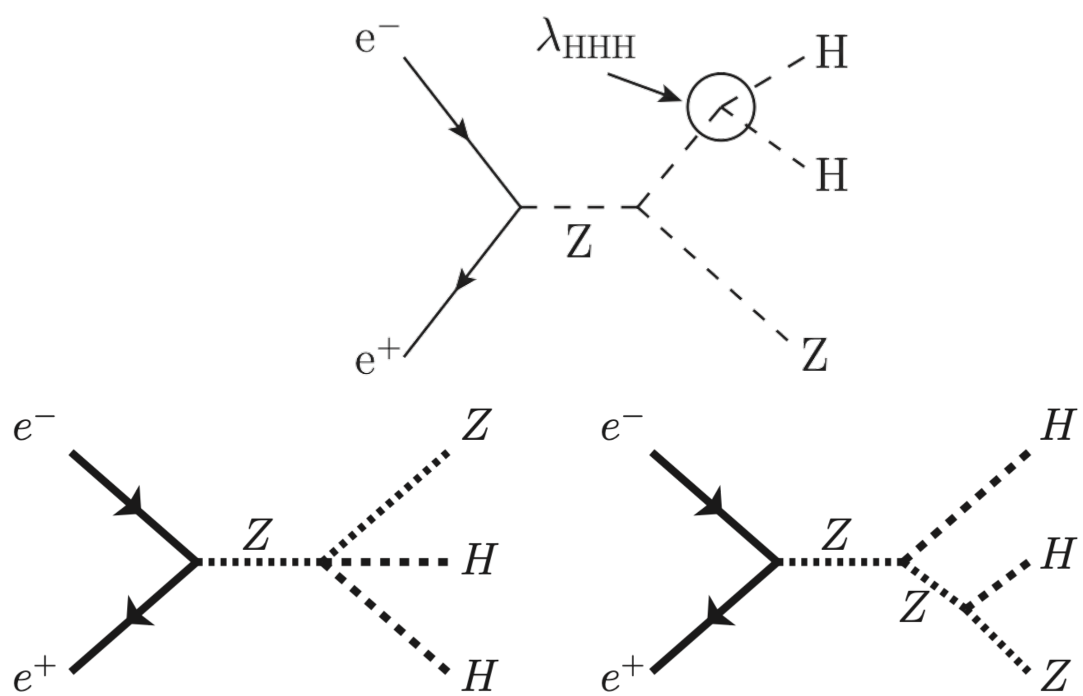

⇒ Large dependence on actual value of $\kappa_\lambda$

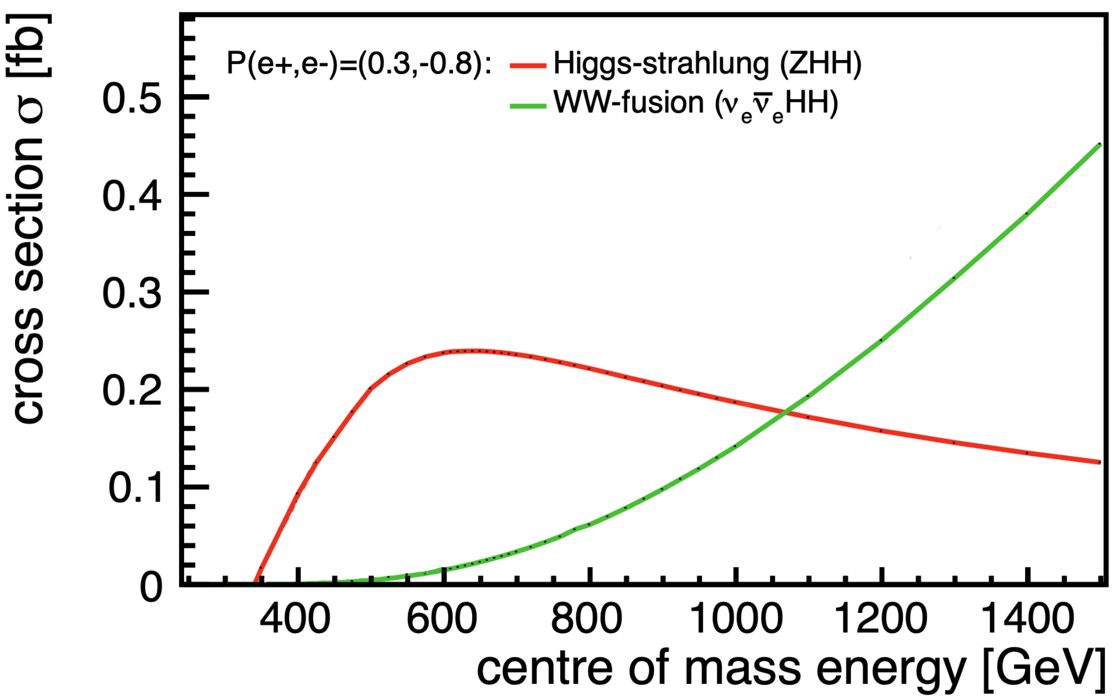
# HL-LHC projection



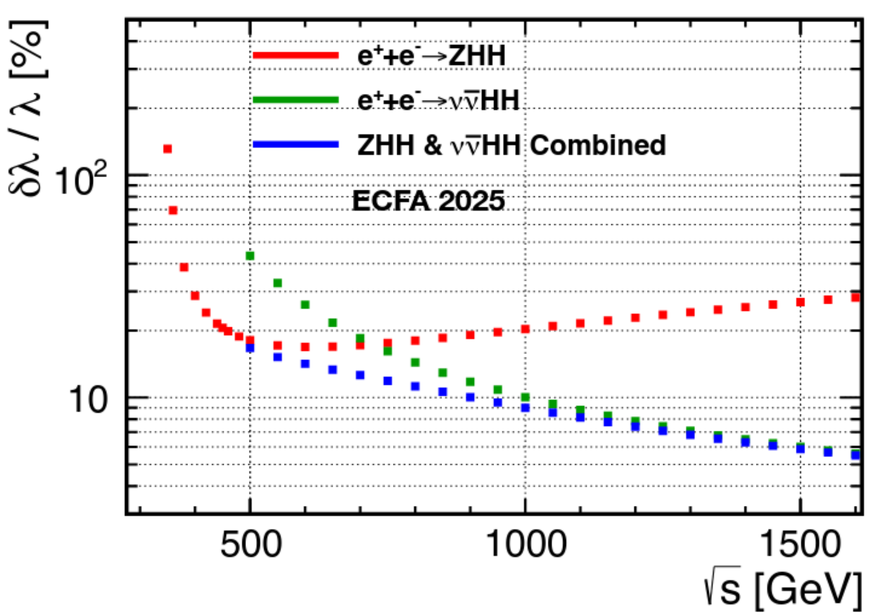

[ATLAS and CMS Collaborations '25]

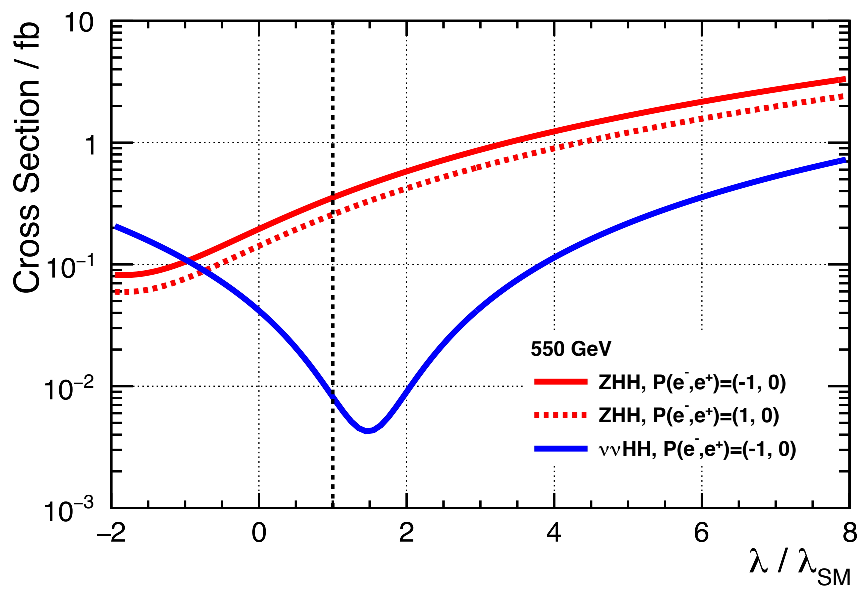
# Higgs pair prod. at $e^+e^-$ linear colliders ($E_{CM} \gtrsim 500$ GeV)

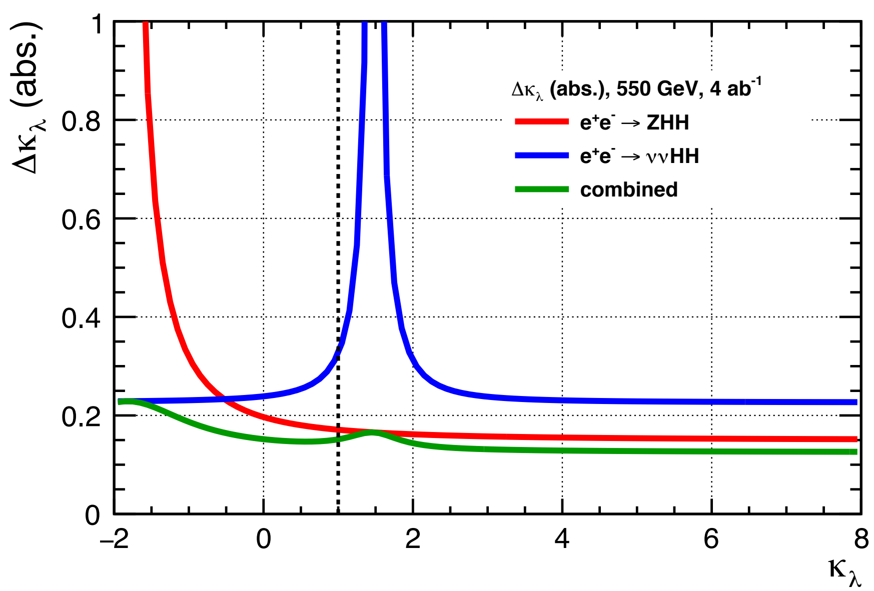



*[LC Vision document '25]*



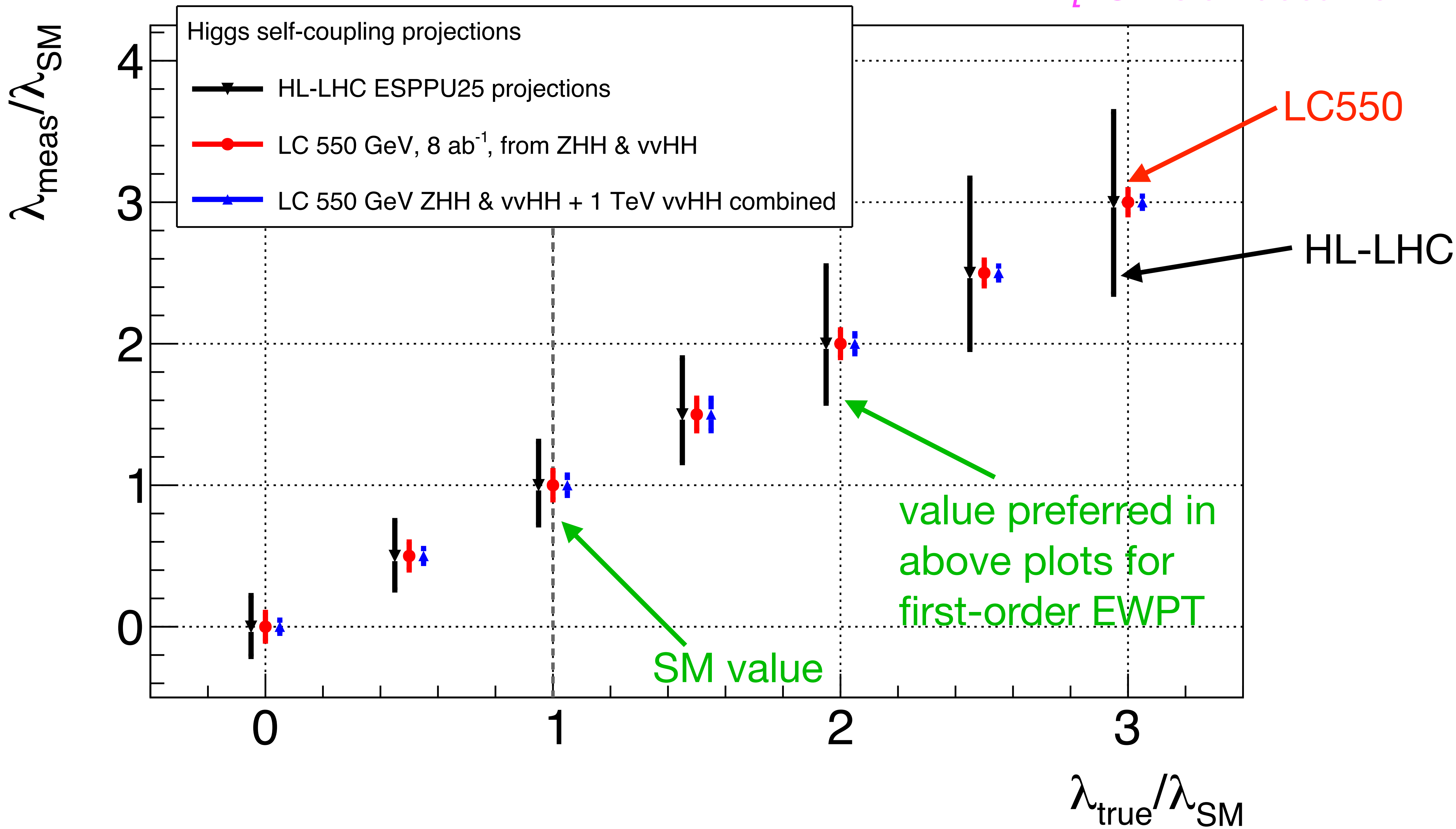




⇒ 11% accuracy on $\varkappa_\lambda$ for SM case, constructive interference for $\lambda > \lambda_{SM}$

# Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. LC with 550 GeV, Higgs pair production

*[LC Vision document '25]*



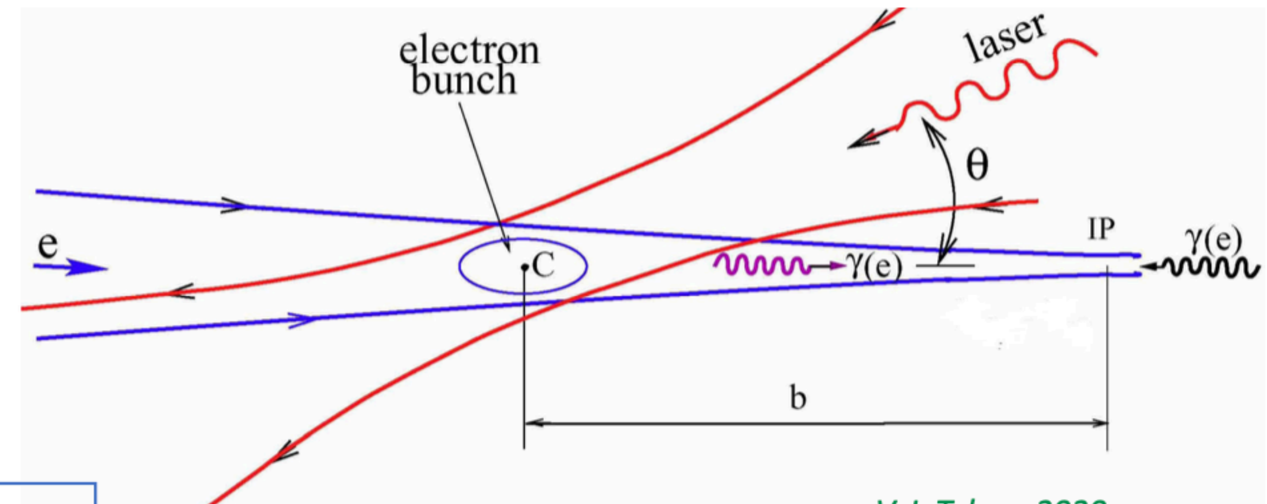

⇒ For $\varkappa_\lambda \approx 2$: much better prospects for LC550 than for HL-LHC

Reason: different interference contributions

# Another possibility: $\gamma\gamma$ collider (combined with $e^+e^-$ or stand-alone)

*[G. Moortgat-Pick '25]*

- **Compton backscattering**
- **Getting access to $\gamma\gamma$ and $\gamma e$ processes**



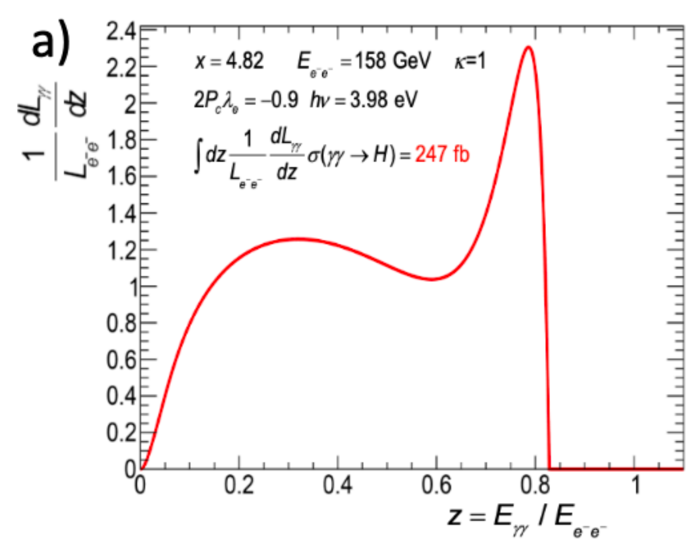

*V. I. Telnov 2020*

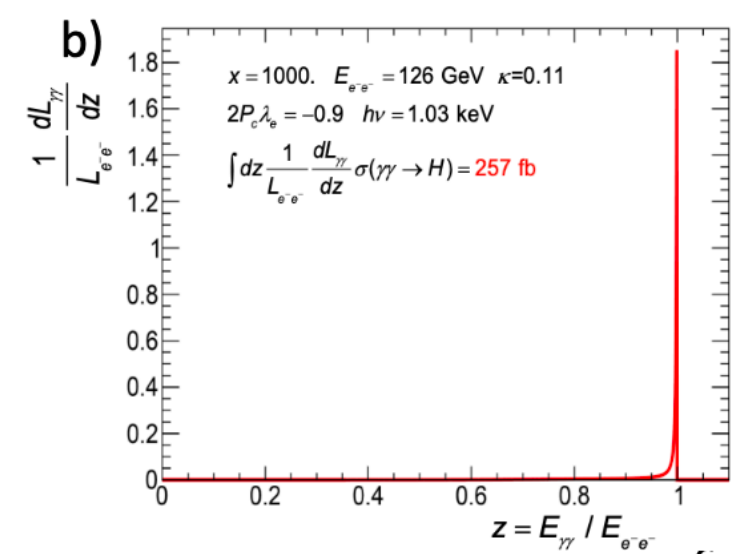
$$\omega_m \approx \frac{x}{x+1} E_0 \qquad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right] = 19 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\mu\text{m}}{\lambda}\right]$$

**Laser is decisive:**

a) optical

b) XFEL-like



# Laser options: optical and XCC

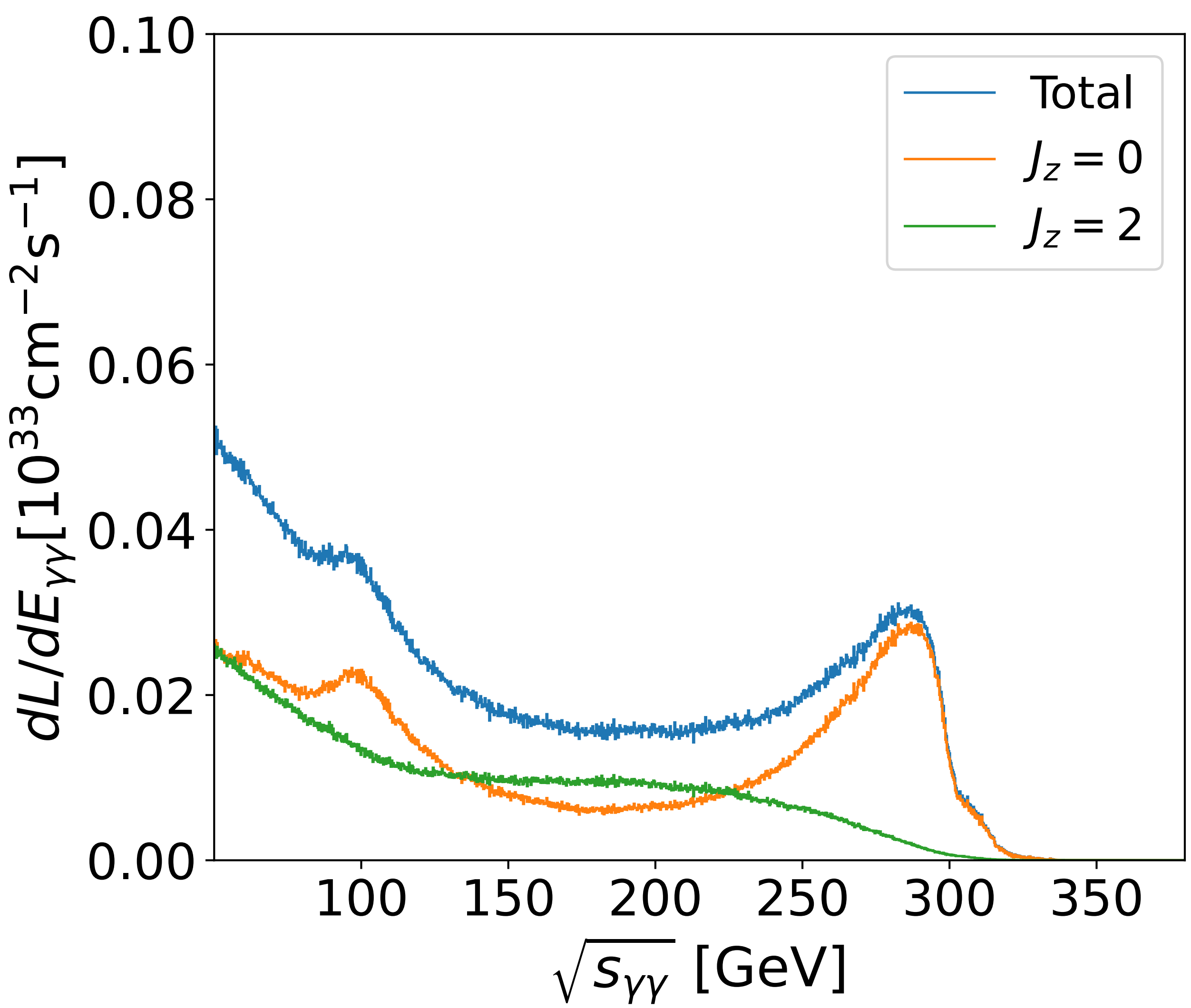
[M. Berger, J. Braathen, G. Moortgat-Pick, G. W. '25]

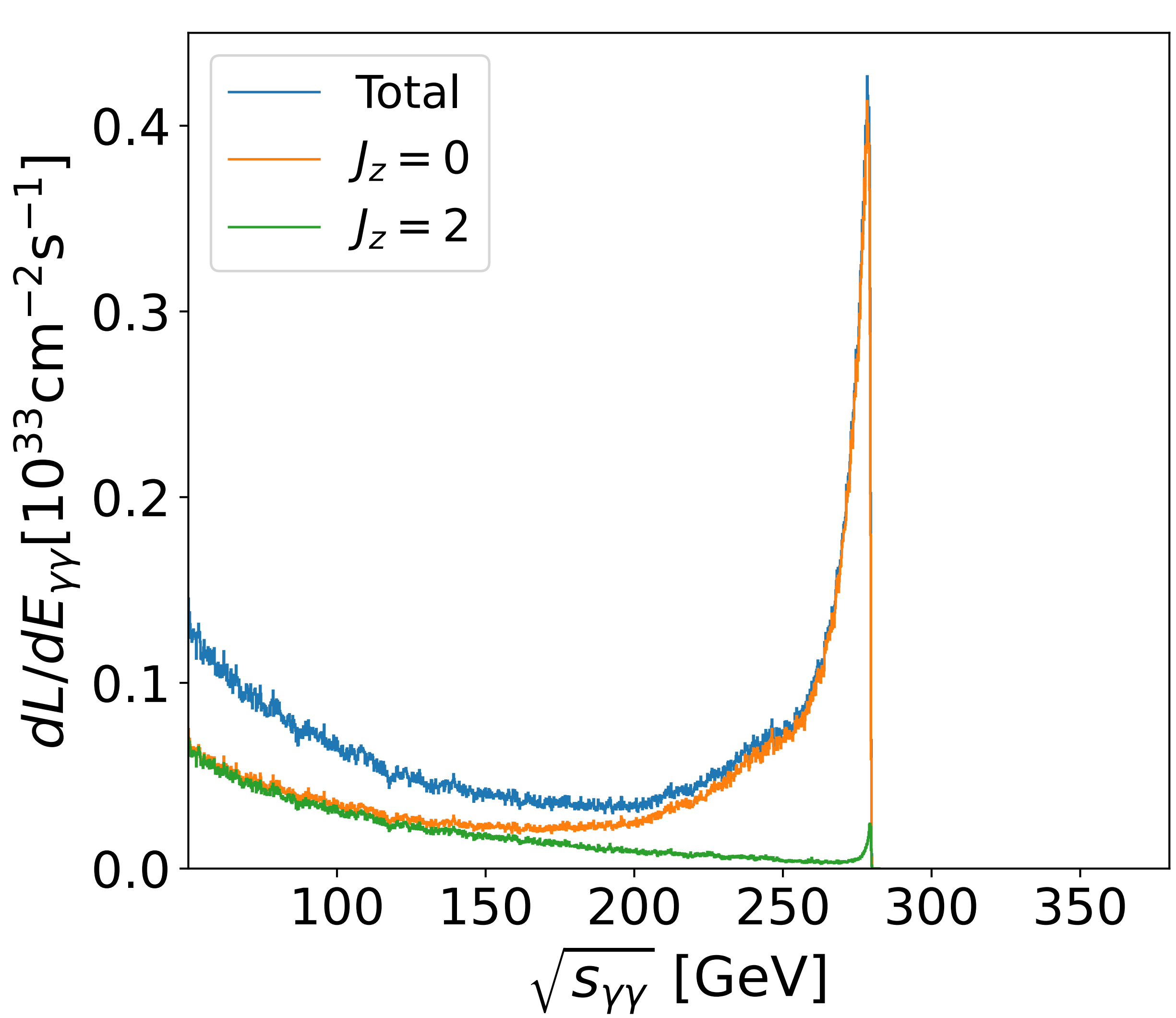
**Optical**

- Laser for x = 4.82
- Energy of colliding photon up to ~80% $E_e$
- Broad spectrum
- most electrons converted
- h-production at $E_e$ = 108 GeV
- di-Higgs at $E_e$ = 250 GeV
- $\lambda_e P_c$ = -0.9

**XCC**

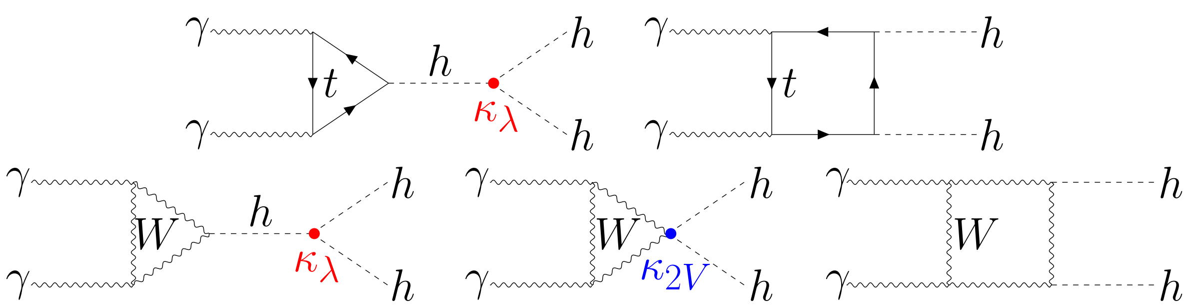
- XFEL for x >1000
- Energy of colliding photon close to 100% $E_e$
- Peaked spectrum
- ~20% of electrons converted
- h-production at $E_e$ = 62.8 GeV
- di-Higgs at $E_e$ = 190 (140) GeV
- $\lambda_e P_c$ = 0.9



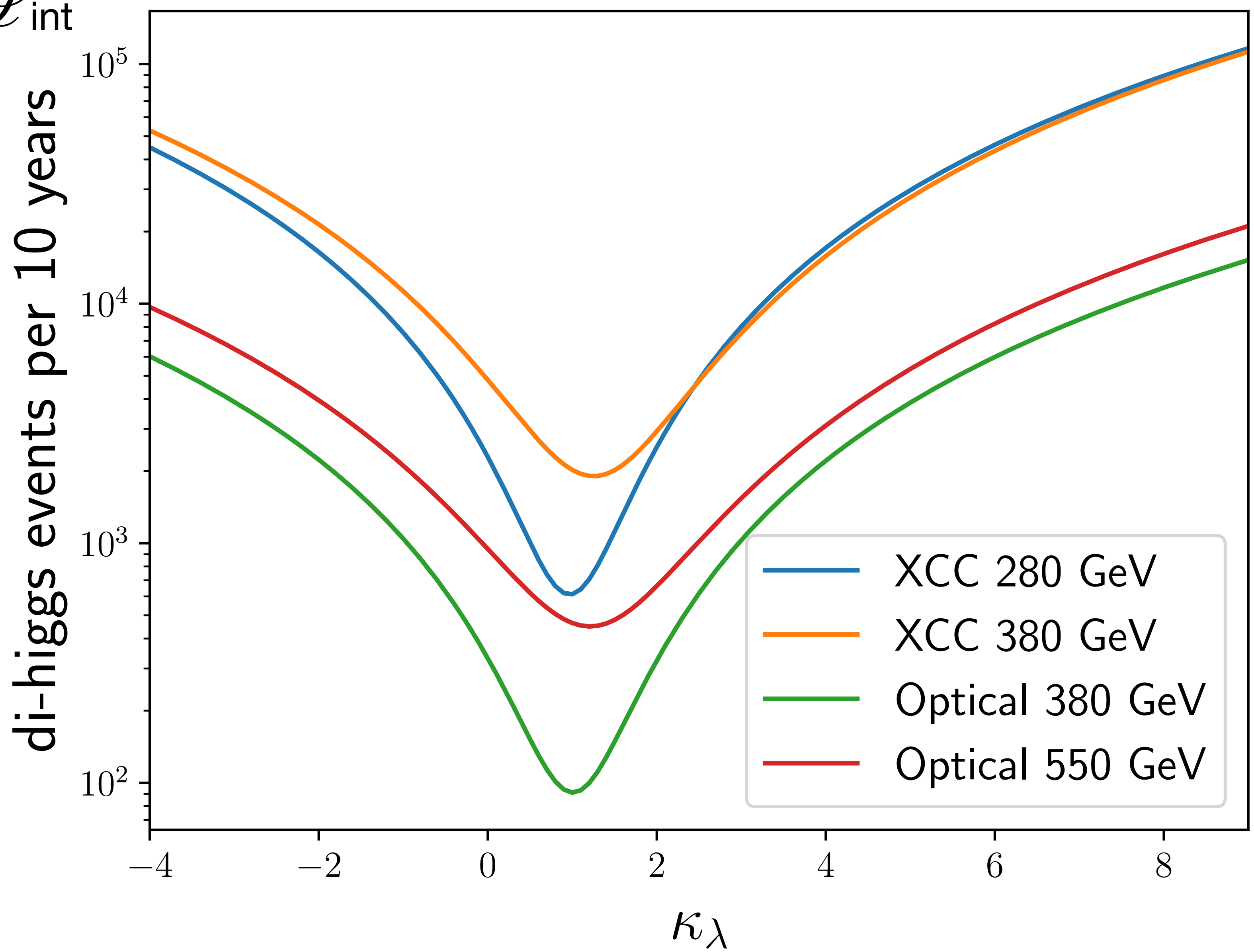
# $\gamma\gamma \to$ hh at 280 GeV and 380 GeV: optical laser and XFEL (XCC)

[M. Berger, J. Braathen, G. Moortgat-Pick, G. W. '25]




$$\sigma = \int_{4m_h^2/s}^{y_{max}^2} \mathrm{d}\tau \frac{1}{2}\left[\frac{1}{L_{\gamma\gamma}^{++}}\frac{\mathrm{d}L_{\gamma\gamma}^{++}}{\mathrm{d}\tau}\hat{\sigma}_{++}(s_{\gamma\gamma}) + \frac{1}{L_{\gamma\gamma}^{+-}}\frac{\mathrm{d}L_{\gamma\gamma}^{+-}}{\mathrm{d}\tau}\hat{\sigma}_{+-}(s_{\gamma\gamma})\right]$$

$\sigma(\gamma\gamma \to hh)\,\mathscr{L}_{int}$

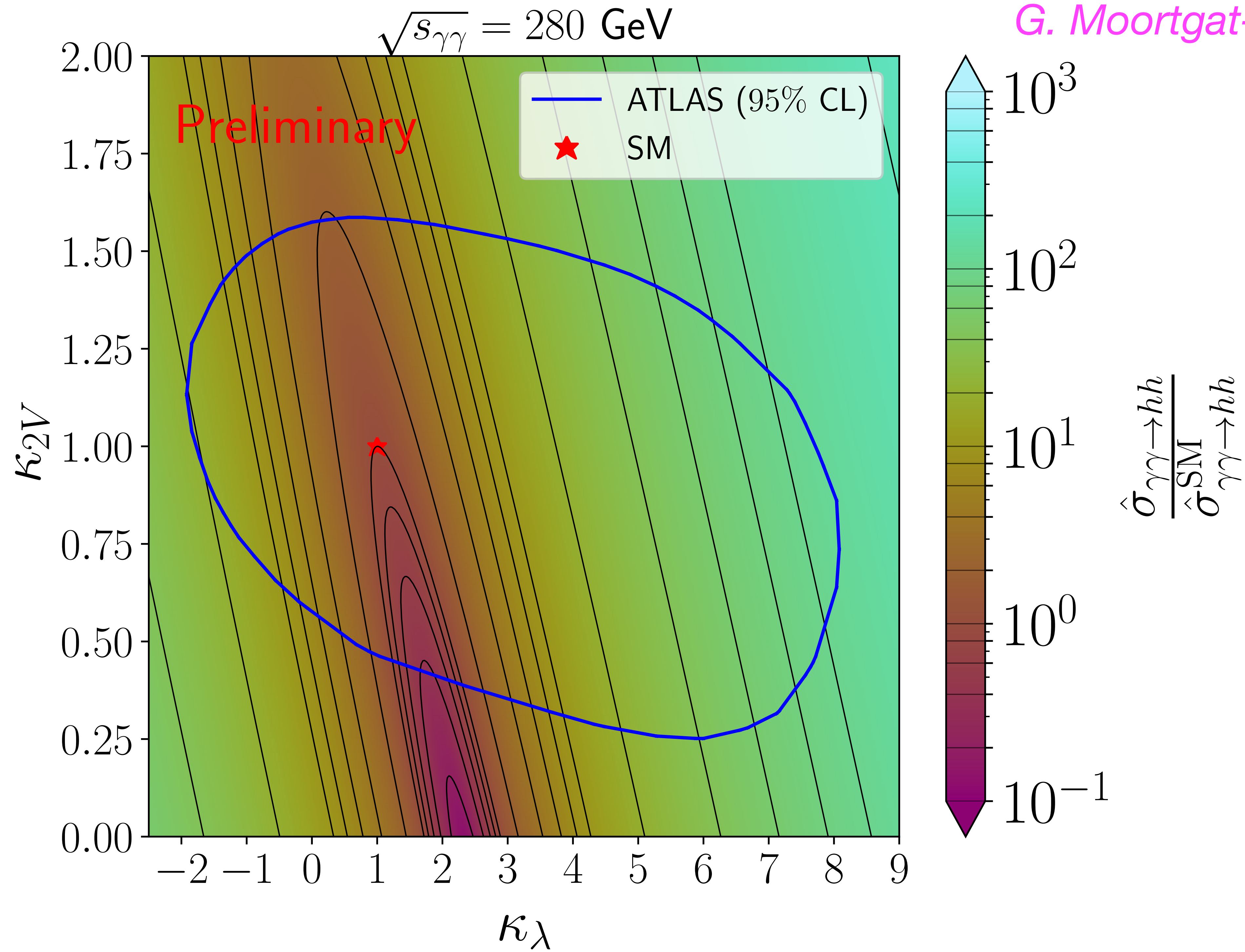



$\varkappa_{2V} = 1$

⇒ $\gamma\gamma$ collider at 280 GeV has high sensitivity to $\varkappa_\lambda$

# $\gamma\gamma \to$ hh cross section compared to the SM case in the allowed region for $\varkappa_\lambda$ and $\varkappa_{2V}$

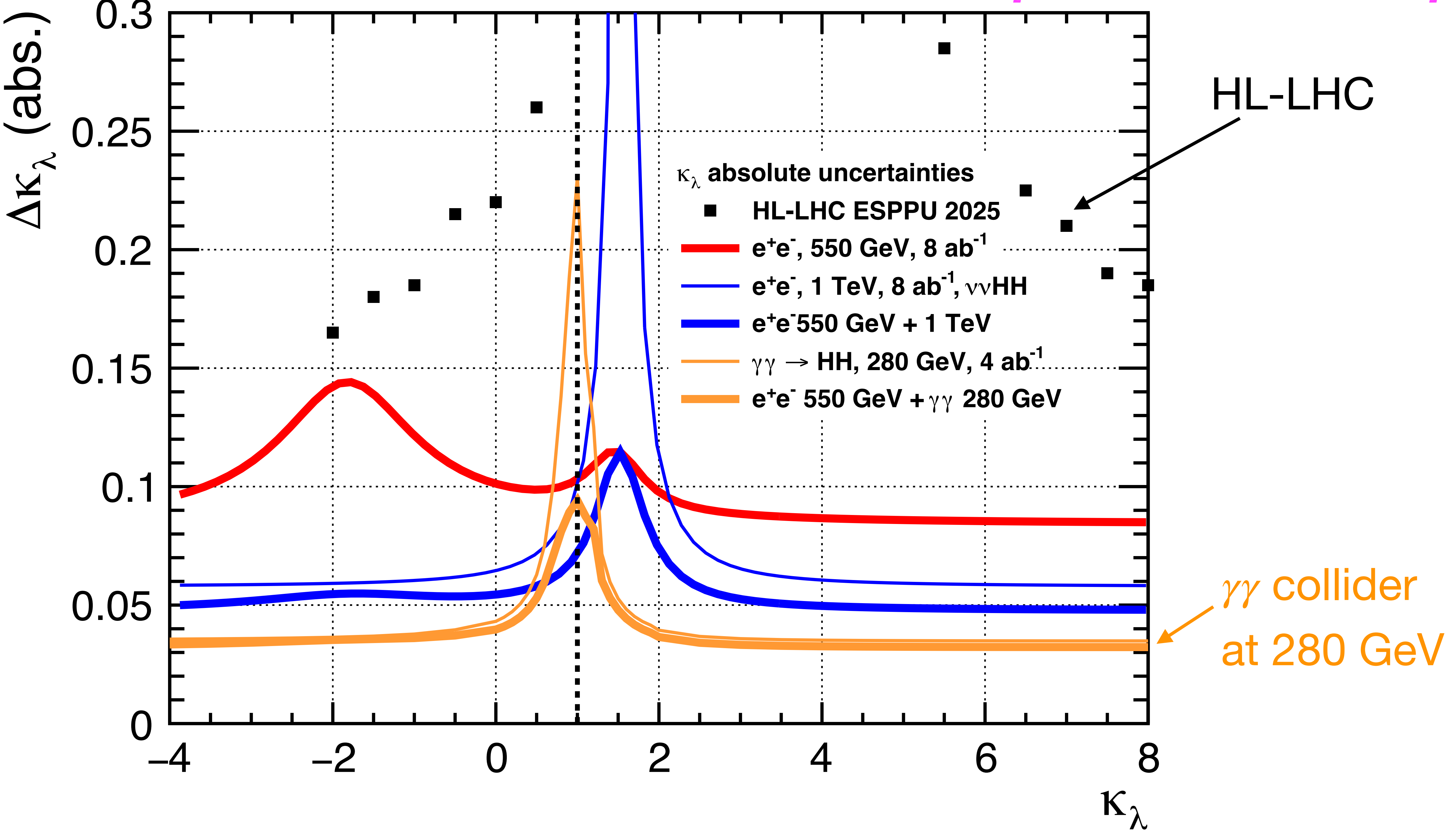
*[M. Berger, J. Braathen, G. Moortgat-Pick, G. W. '25]*




⇒ Sensitive dependence on $\varkappa_\lambda$, small correlation with $\varkappa_{2V}$

# Prospects at HL-LHC, $e^+e^-$ linear and $\gamma\gamma$ collider

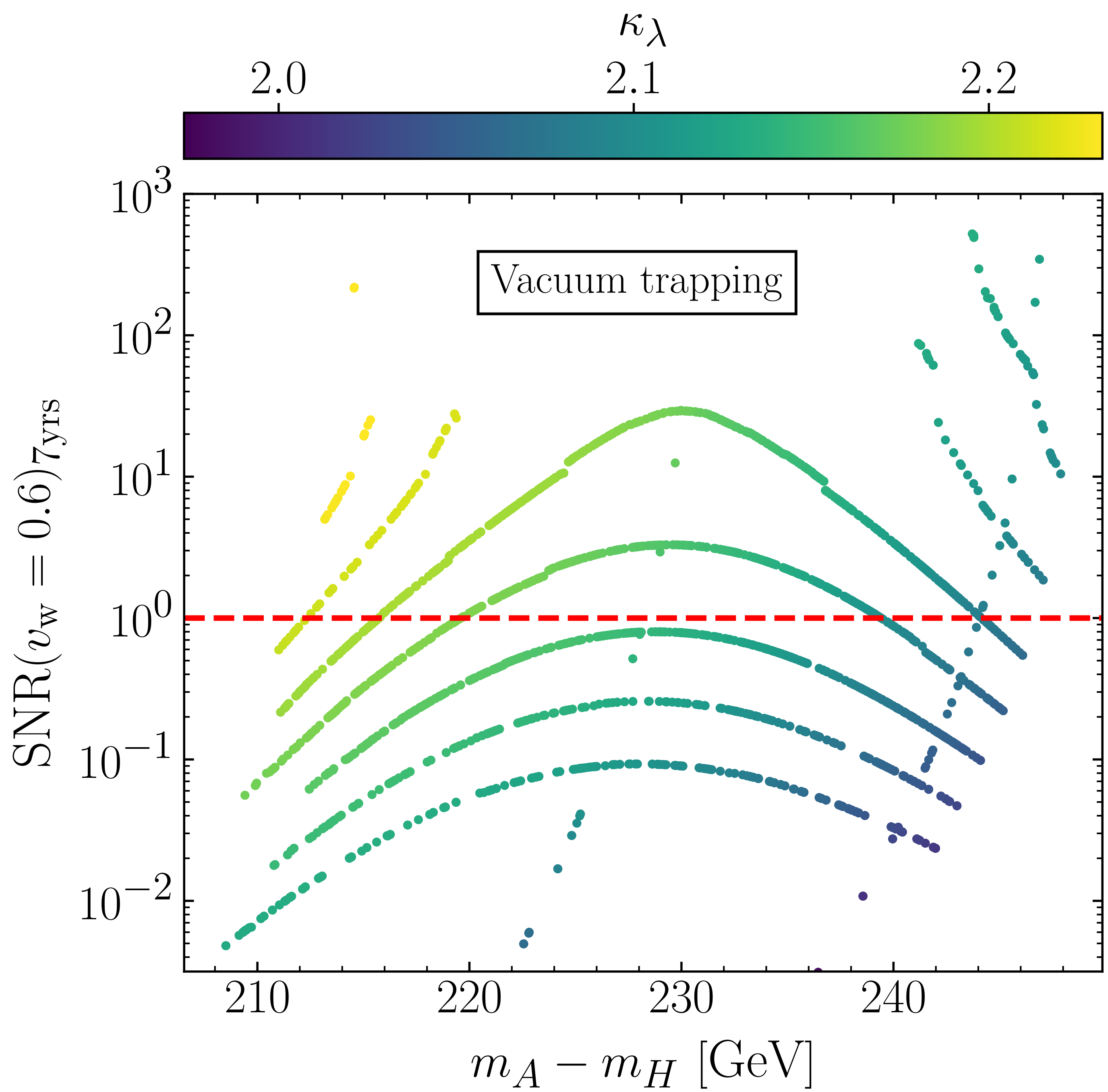
*[LC Vision document '25]*




⇒ $\gamma\gamma$ collider at 280 GeV could yield big improvement of the measurement of the trilinear Higgs coupling

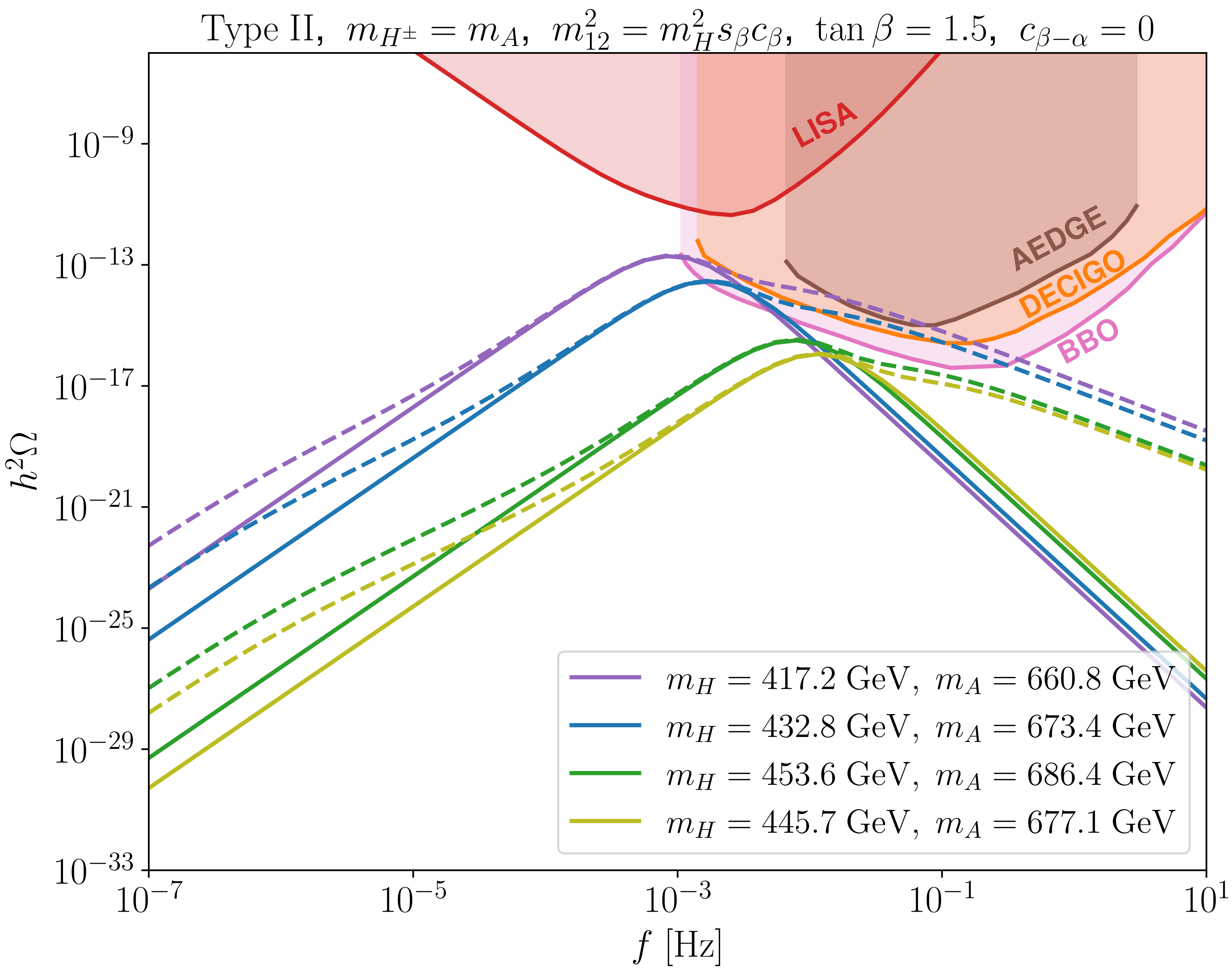
# Correlation of $\varkappa_\lambda$ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

*[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



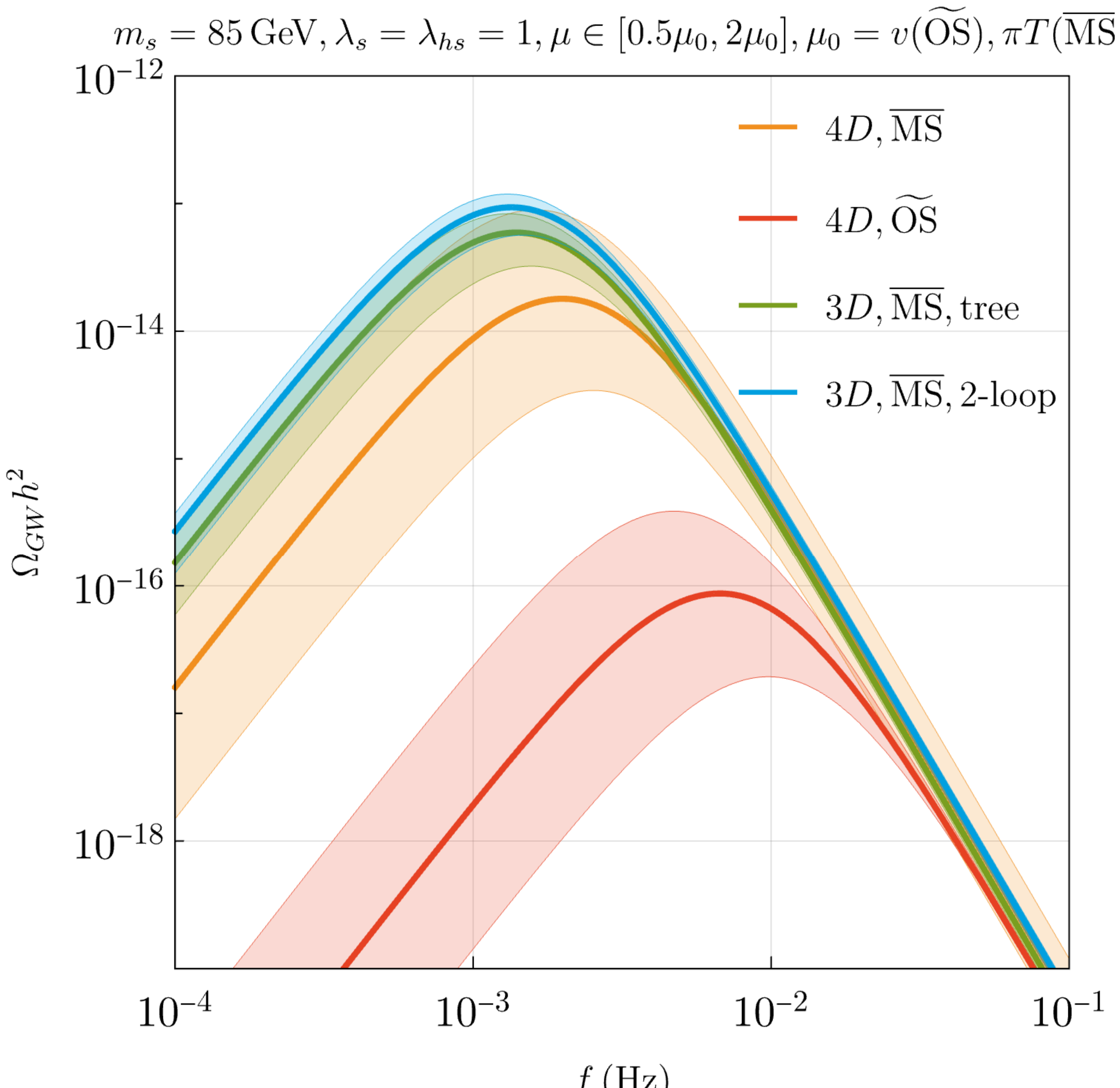

*[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]*

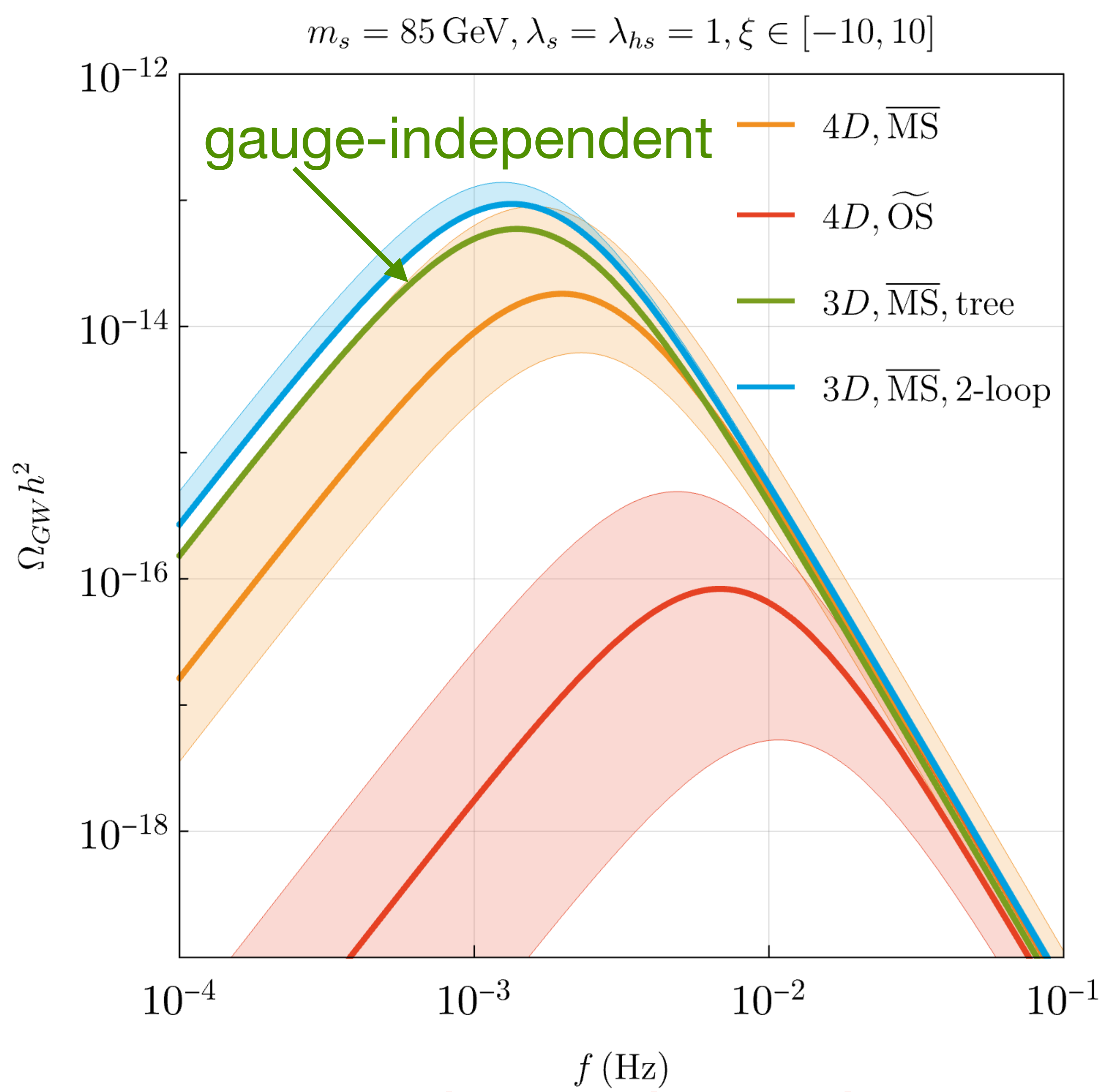
⇒ Prospects for GW detection depend very sensitively on the precise details of the mass spectrum of the additional Higgs bosons

# Theoretical uncertainties of GW predictions

[T. Biekötter, A. Dashko, M. Löschner, G. W. ’25]

Extension of the SM by a complex singlet: effects of renormalisation scale (left) and gauge parameter variation (right) for 4-dimensional treatment with resummation and for 3-dimensional EFT



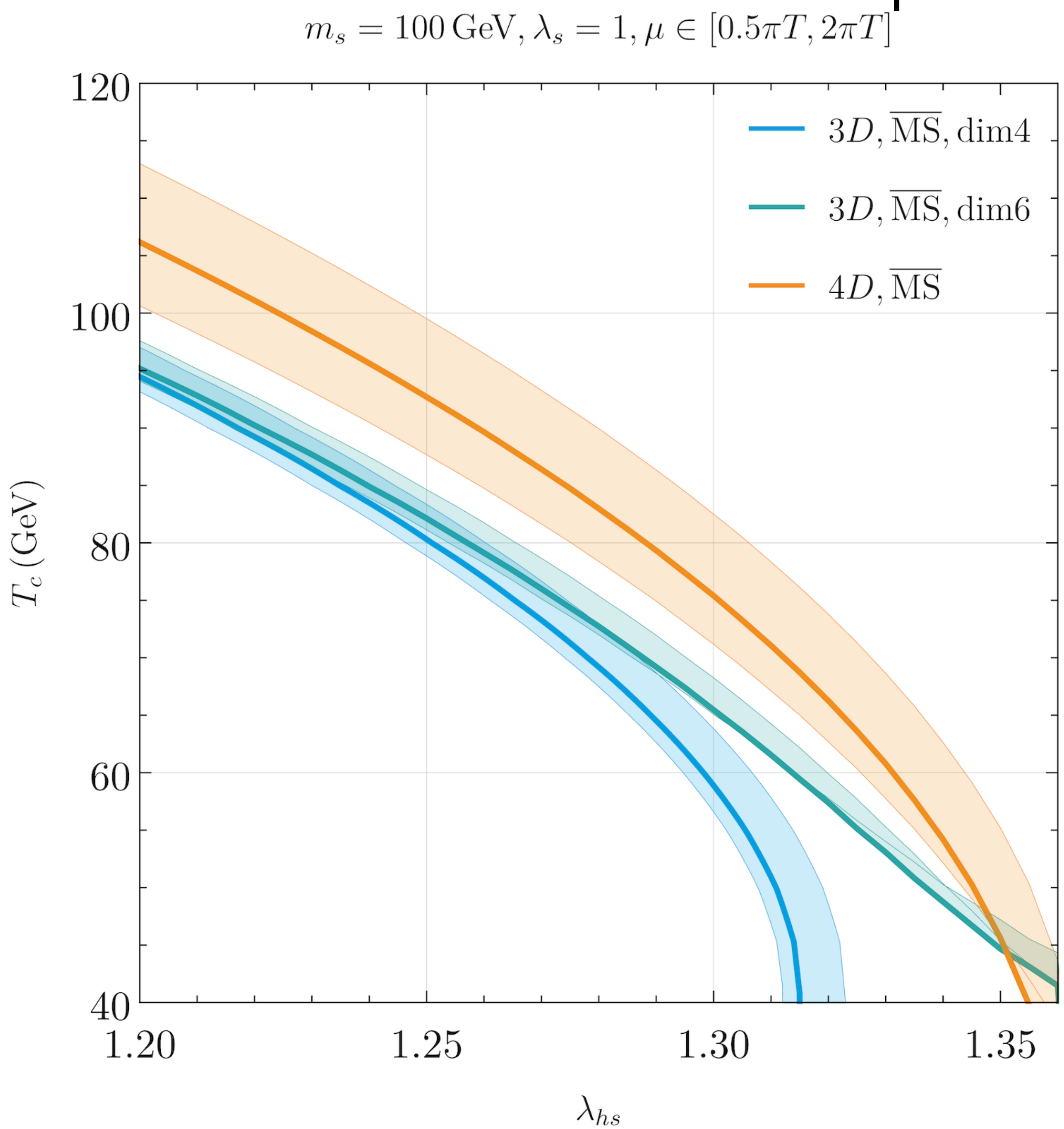



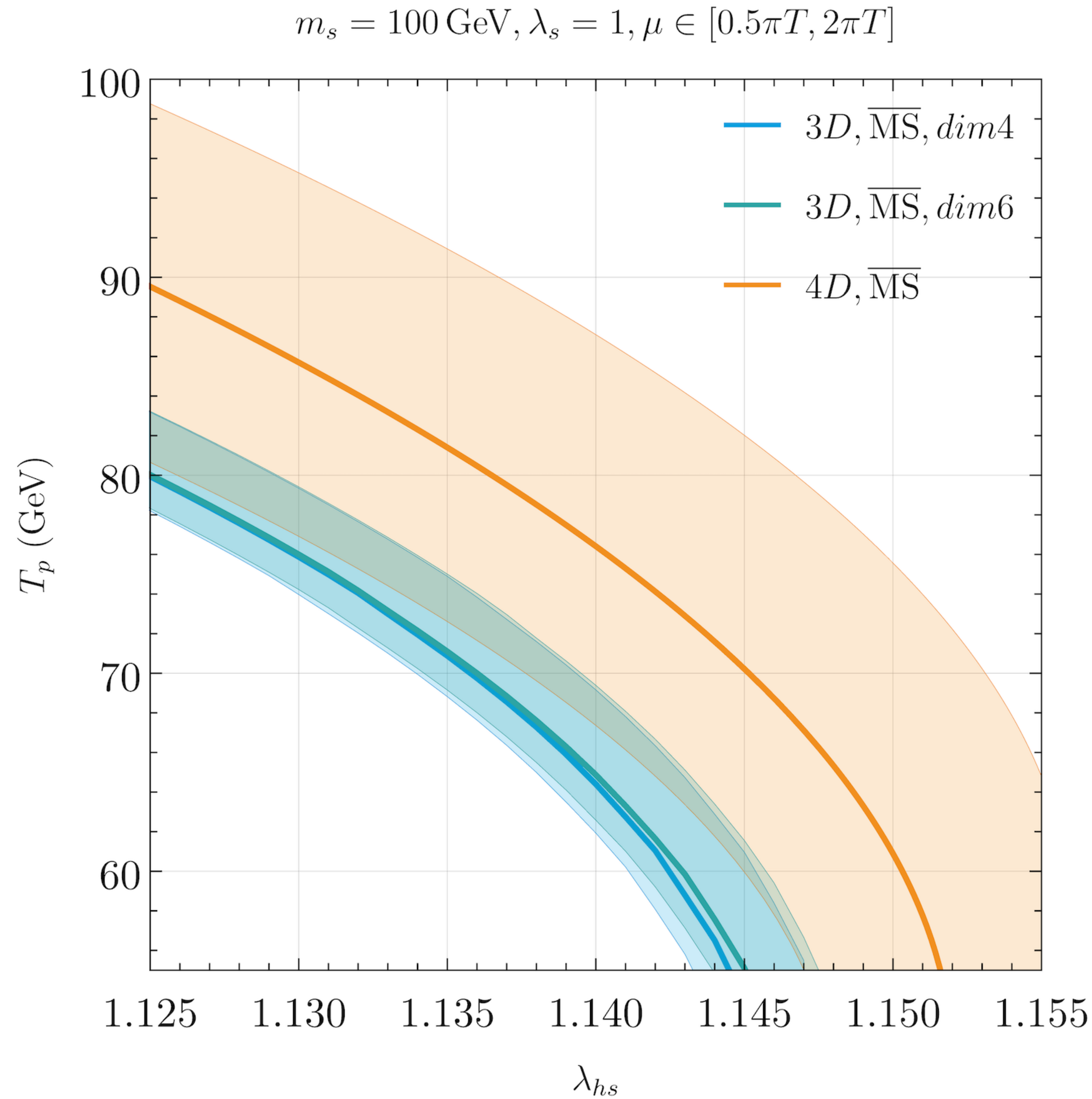

$\Rightarrow$ Significantly smaller scale and gauge-parameter dependence in 3-dimensional EFT approach

# Impact of higher-dimensional operators in the 3-dimensional EFT approach on $T_c$ and $T_p$

[T. Biekötter, A. Dashko, M. Löschner, G. W. '25]

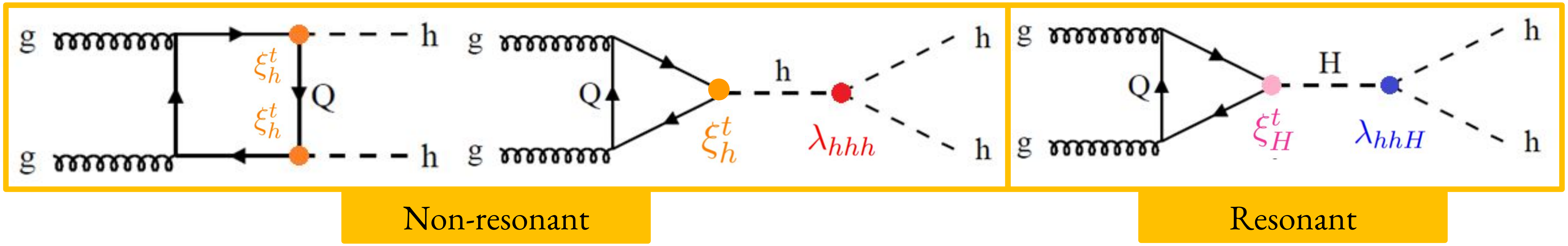
Bands: renormalisation scale dependence




⇒ Higher-dimensional operators in the EFT approach have significant impact for the lowest values of the critical temperature $T_c$

# Constraints from resonant di-Higgs production




Non-resonant contributions (SM-type contributions) + resonant contribution of additional Higgs boson H

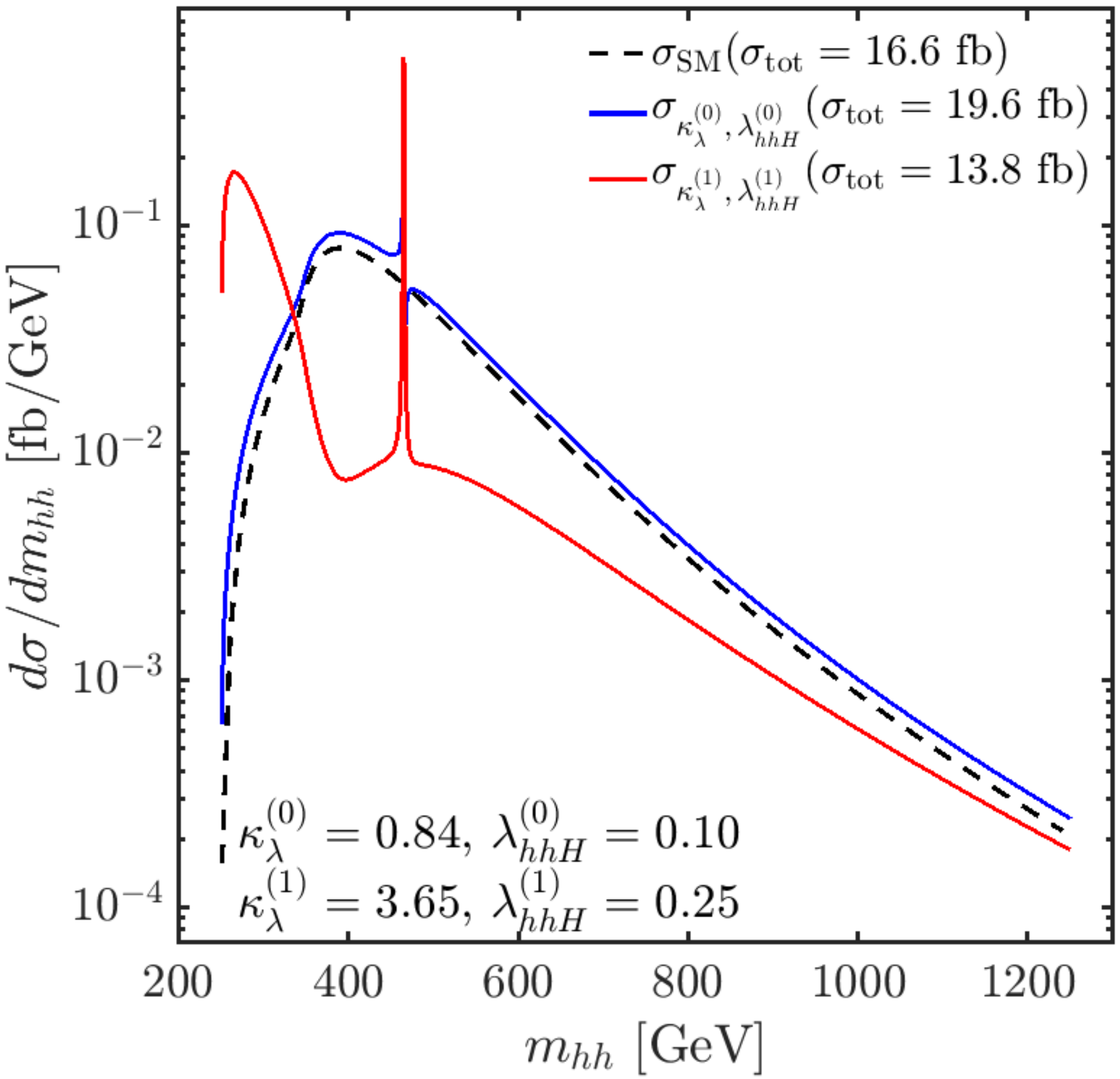
$m_{hh}$ invariant mass distribution: size and location of the interference contribution depends sensitively on $\lambda_{hhh}$ ($\kappa_\lambda$) and in general also on $\lambda_{hhH}$

Large impact on the shape of the distribution

In contrast to what ATLAS and CMS have done up to now for their resonant di-Higgs searches the non-resonant contributions and the associated interference effects in general must not be neglected

# Interference effects in resonant Higgs pair production

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




2HDM example:

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

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

- Drop in the $m_{hh}$ ~ 400 GeV region due to a shift in the cancellation of form factors (see next slide)

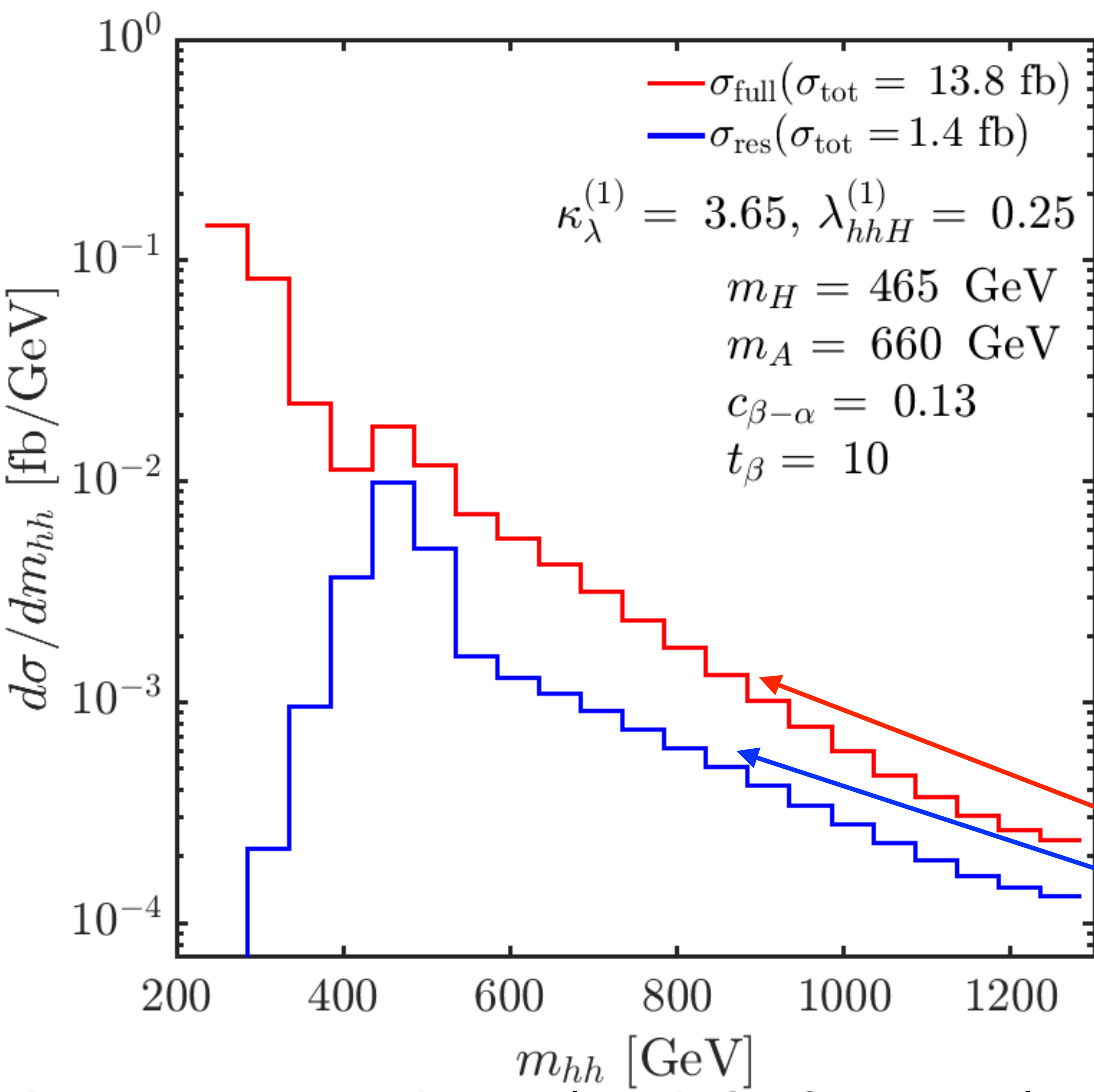
- Change in the dip peak structure of the resonance

⇒ Tree-level result: suppression at threshold (cancellation of vertex and box contrib.), close to SM result + resonance (peak-dip structure)
Inclusion of loop contributions to $\lambda_{hhh}$ ($\kappa_\lambda$) and $\lambda_{hhH}$: cancellation at higher $m_{hh}$ values, resonance peak, large interference effects, drastic impact on invariant mass distribution

# Interference effects in resonant Higgs pair production

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

2HDM example, $m_{hh}$ invariant mass distrib.: effects of smearing (15%) and binning (50 GeV) incorporated to account for finite exp. resolution




Same scenario as above:

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

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

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

- Change in the dip peak structure of the resonance

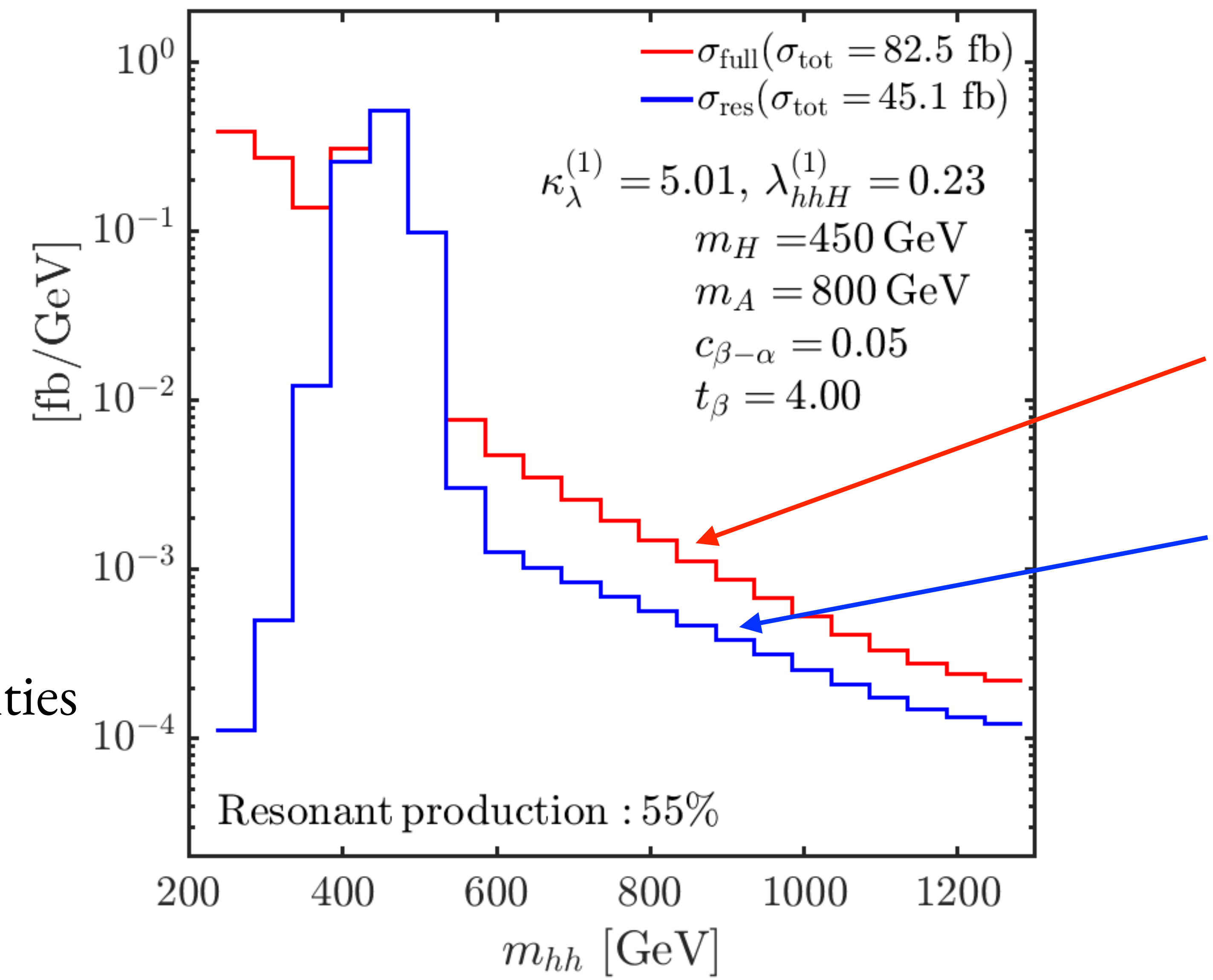
⇒ Loop corrections (mainly from $\kappa_\lambda$) and interference with non-resonant contributions has drastic impact on the shape of the $m_{hh}$ distribution

# Interference effects in resonant Higgs pair production

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

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

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



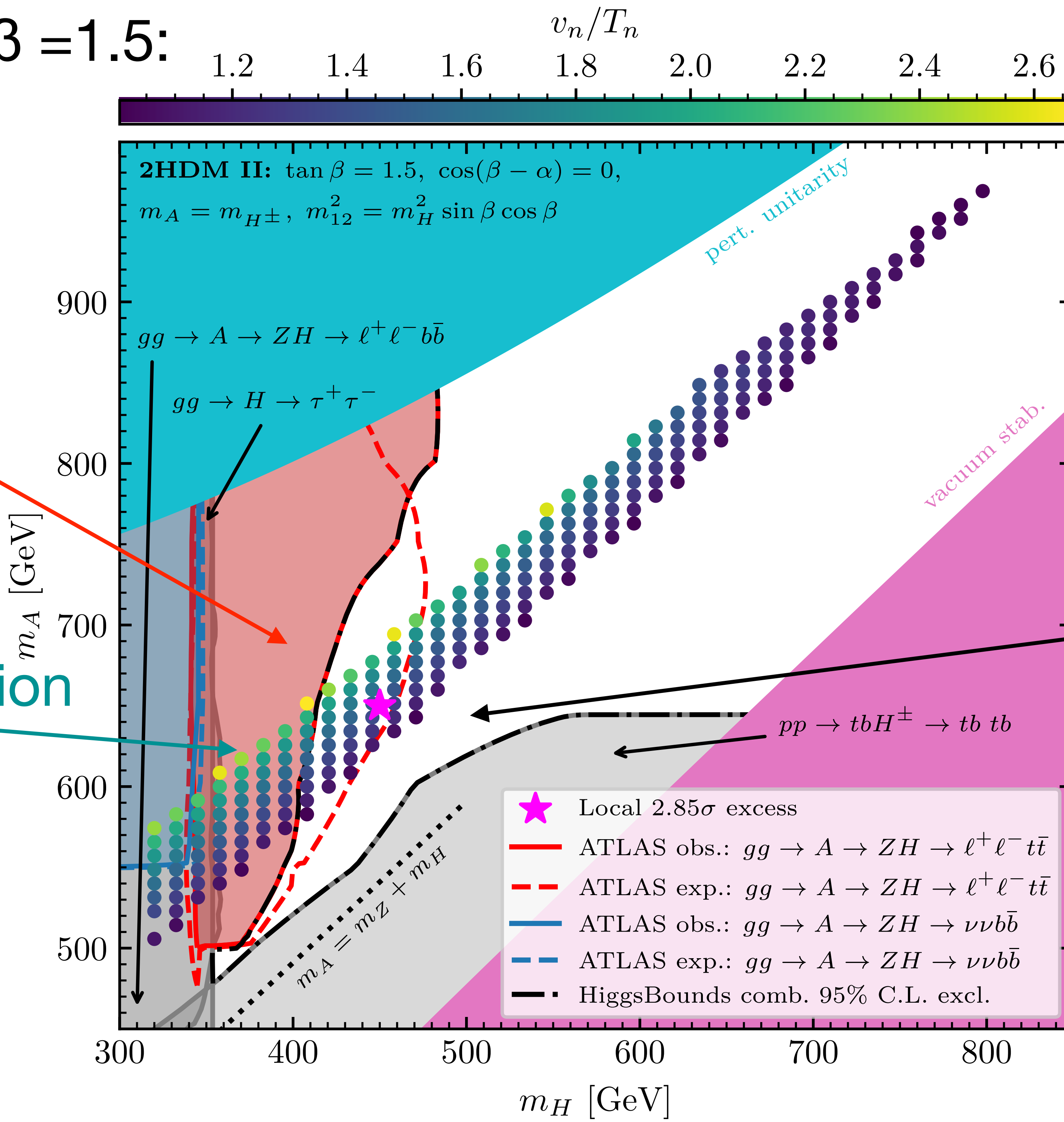

⇒ $m_{hh}$ distribution depends very sensitively on $\kappa_\lambda$, important interference effects, large deviation between resonant contribution and full result; limits using resonant contribution may be too optimistic

# ATLAS “smoking gun” search pp → A → ZH → Ztt vs. preferred region for strong first-order EWPT

2HDM, tanβ =1.5:

[ATLAS Collaboration ’23]

Strongest phase transition




[T. Biekötter et al. ’23]

[F. Arco et al. ’25]

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

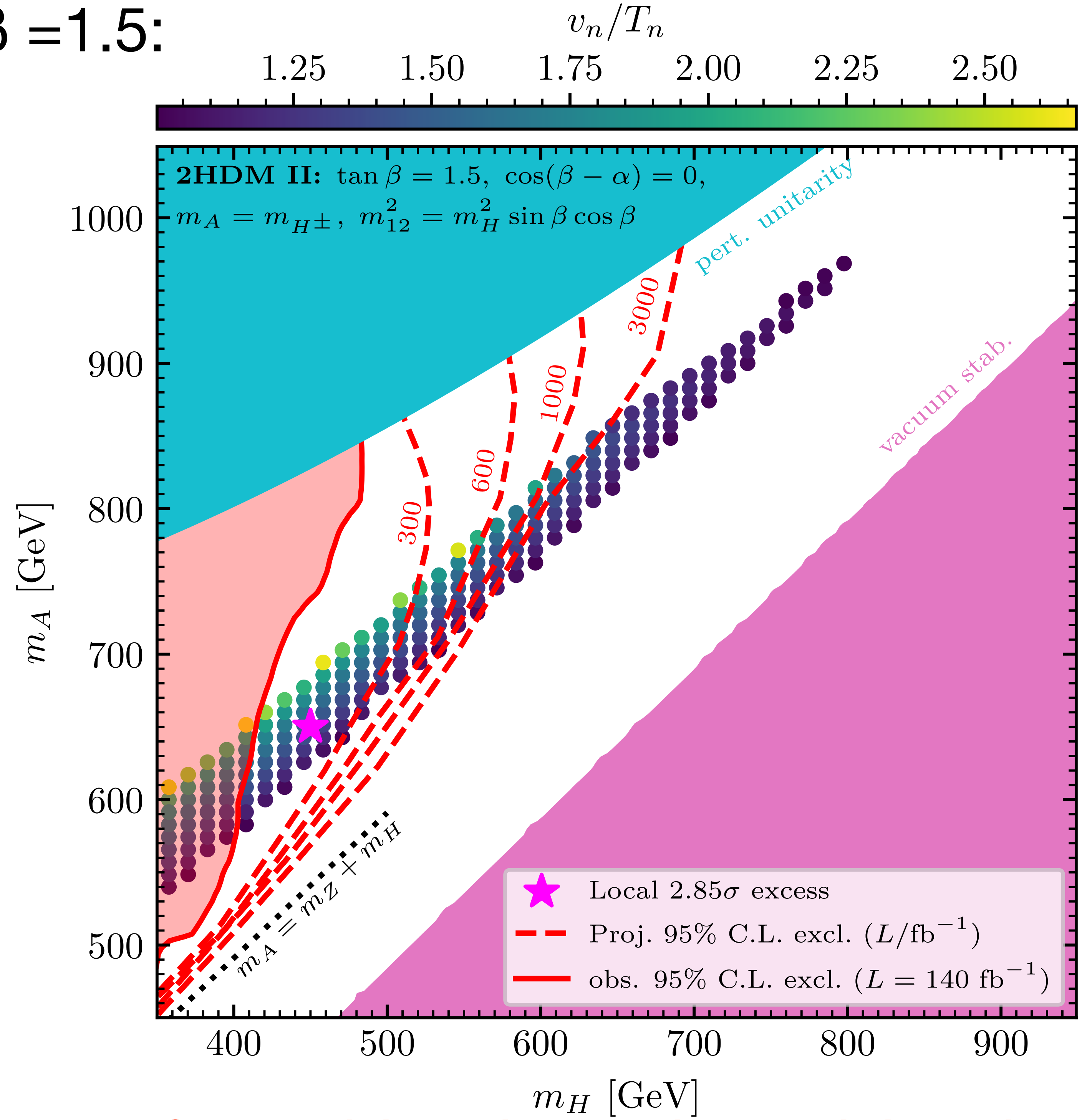
not confirmed by CMS

[CMS Collaboration ’24]

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

# Projection for future sensitivity based on ATLAS result

2HDM, tanβ =1.5:

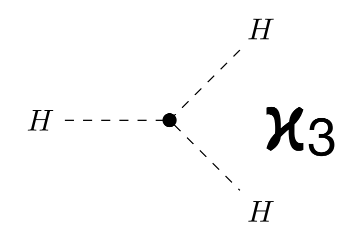


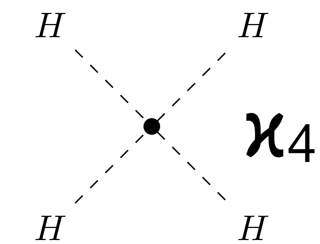

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. '23]

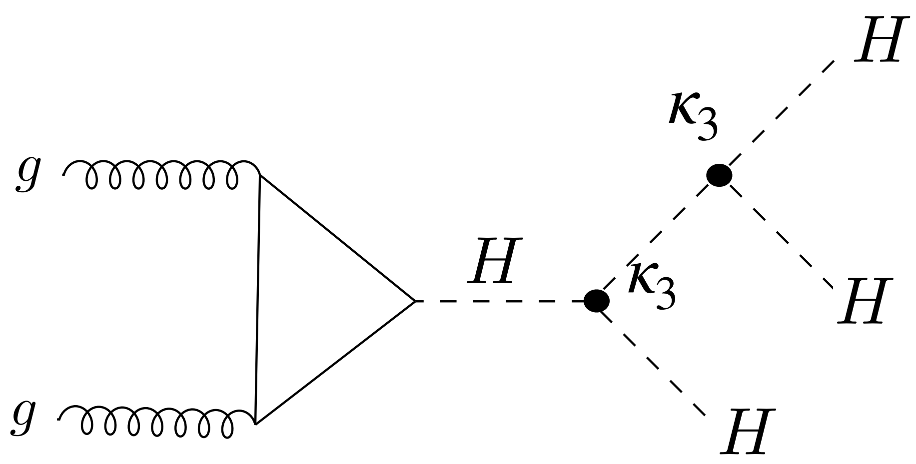
⇒ Good prospects for probing the regions giving rise to strongest first-order EWPTs and to potentially observable gravitational wave signal

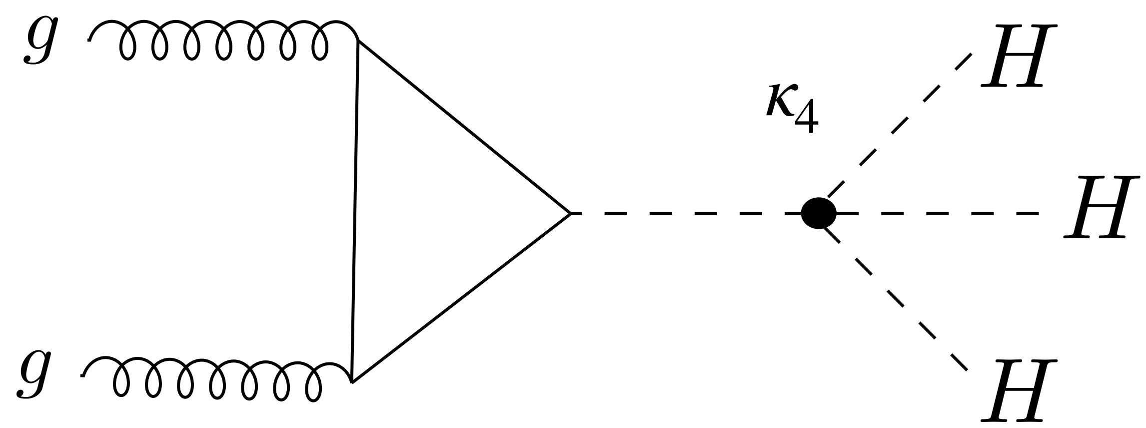
# Exploring triple Higgs production w.r.t. Higgs self-couplings

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




Is it possible to obtain bounds from triple Higgs production on $\varkappa_\lambda \equiv \varkappa_3$ 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 $\kappa_3$, $\kappa_4$ is $HH \to HH$ scattering (see also [Liu et al ` 18] )
- Jacob-Wick expansion allows to extract partial waves

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

Wigner functions

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

- Tree level unitarity:

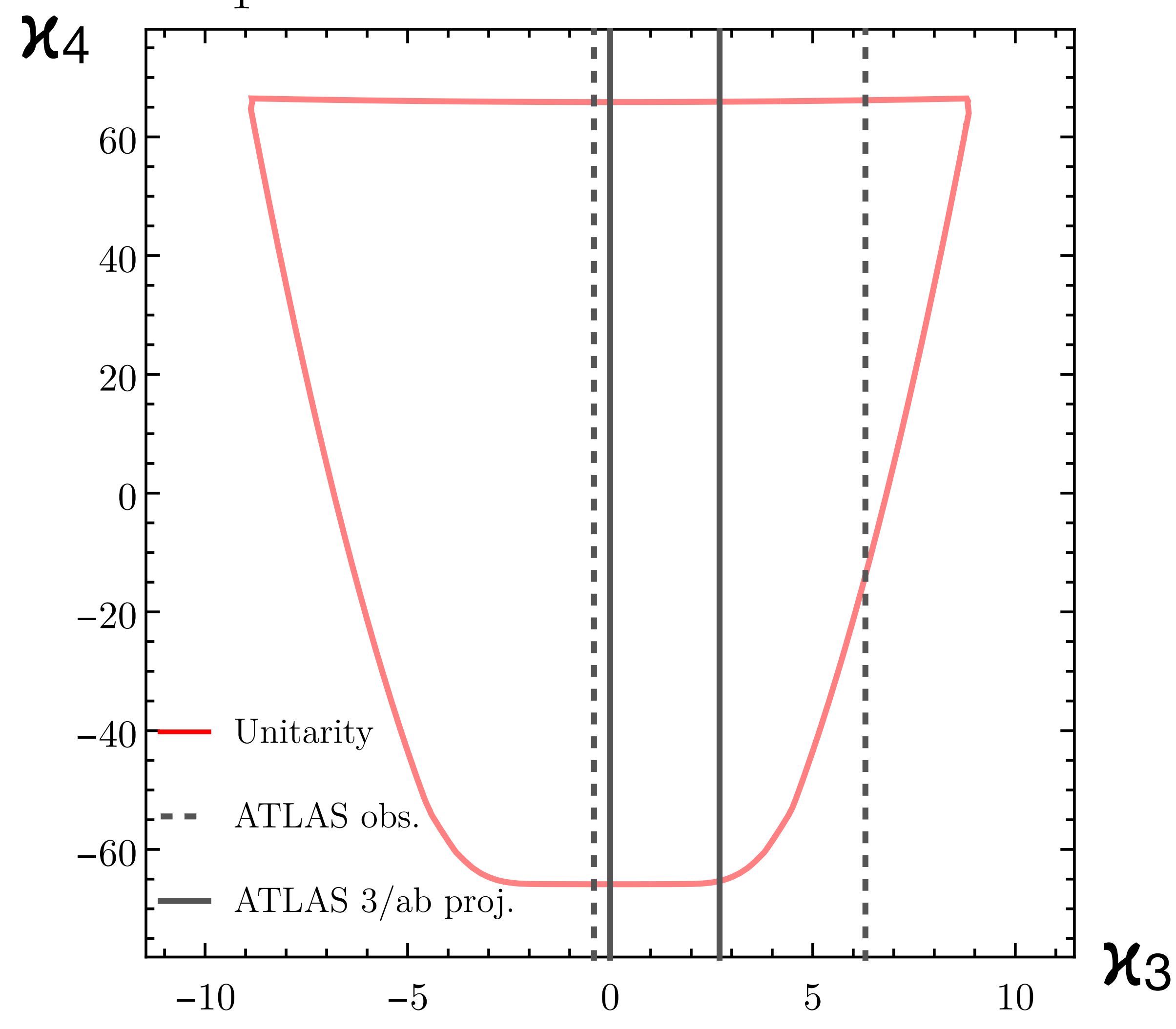
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

95 % CL

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

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

[ATLAS 2211.01216]
[CERN Yellow Rep. 1902.00134 ]



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

Linear power expansion for higher order terms in $\Lambda^{-1}$ orders:

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

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

Contributions to $\kappa_3$, $\kappa_4$:

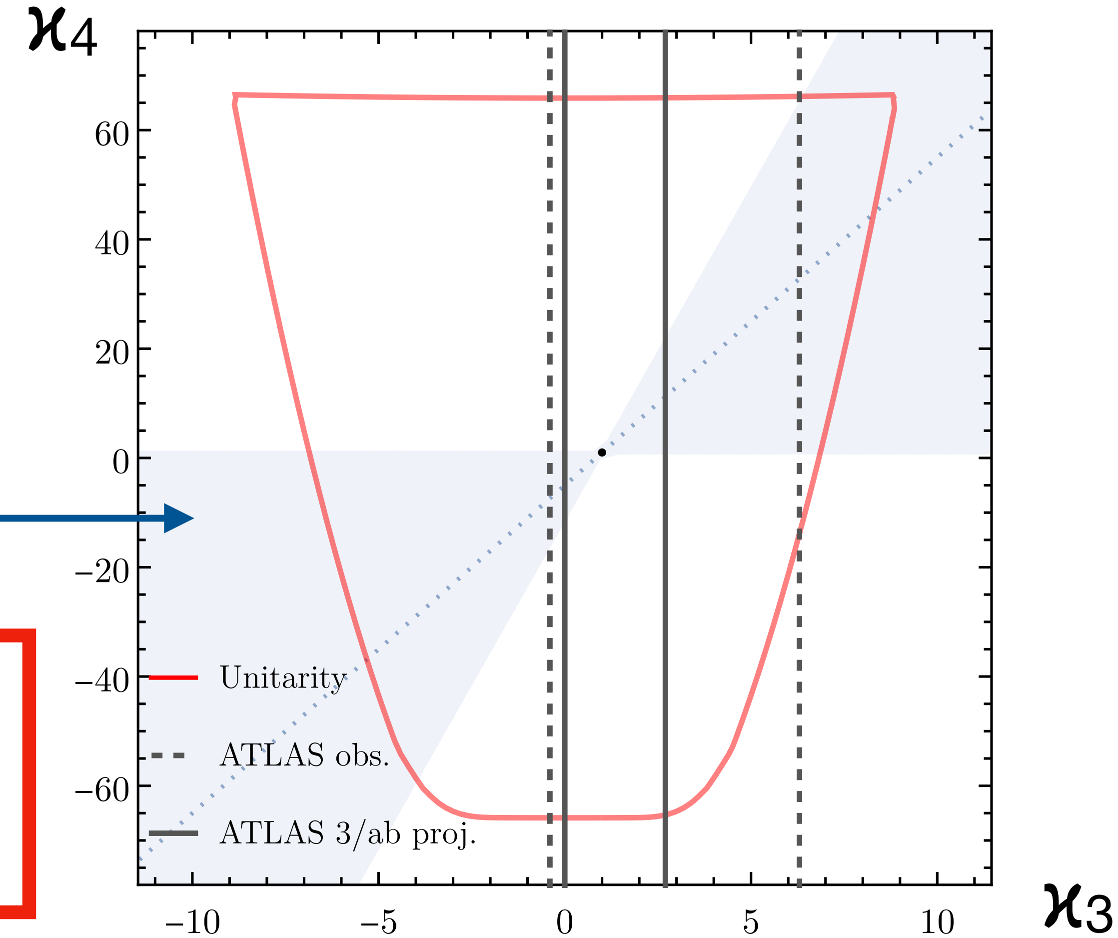
$$(\kappa_3 - 1) = \frac{C_6 v^2}{\lambda\Lambda^2}\,,$$

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

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 $\kappa_3$ and $\kappa_4$ are **free parameters** →probes **non-linearity**

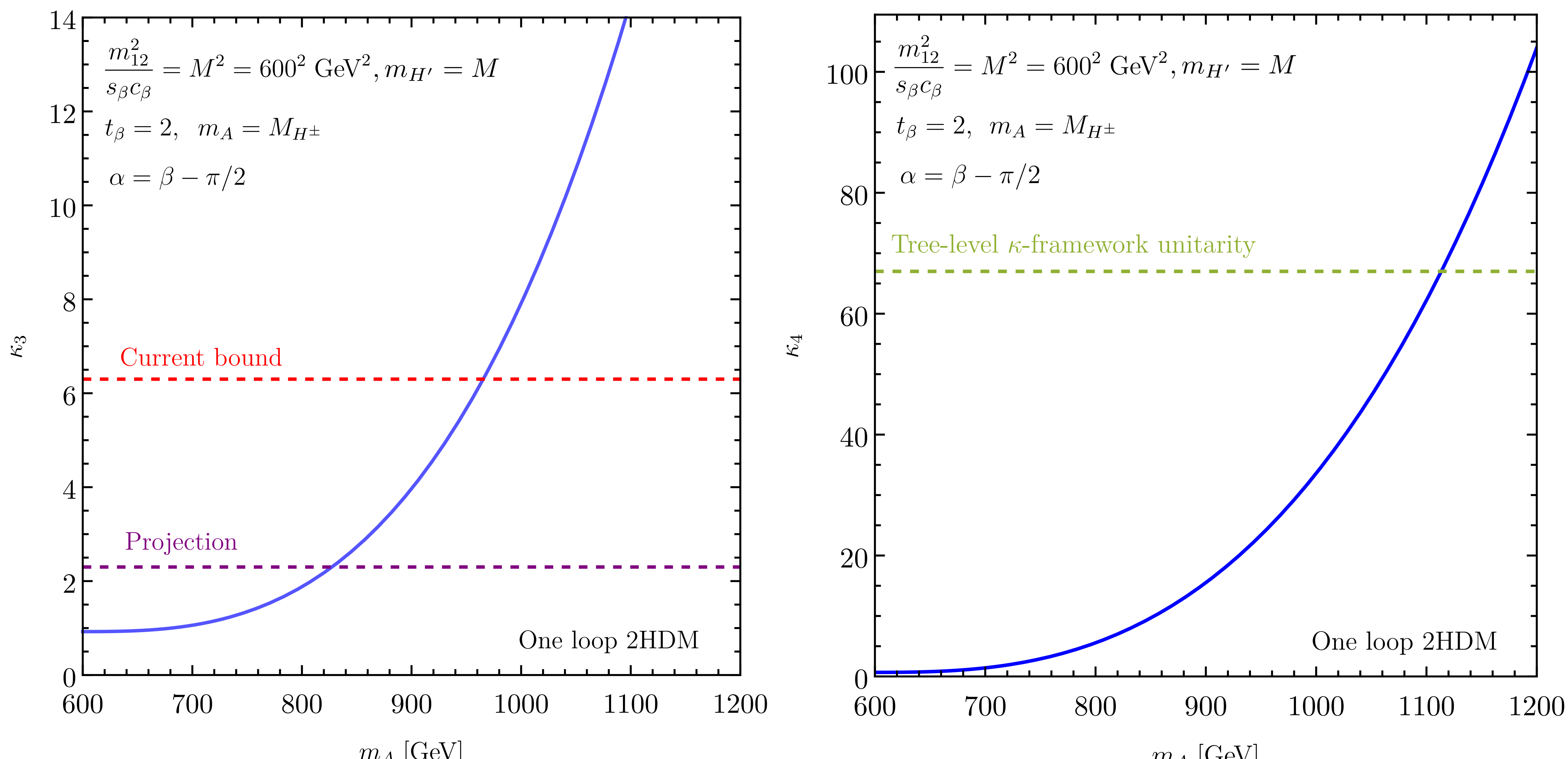
⇒Deviation in $\kappa_4$ enhanced by factor 6!

# Model example: 2HDM, $\kappa_3$ (see above) vs. $\kappa_4$

- Benchmark Point of [Bahl, Braathen, Weiglein `22] → cross-check $\kappa_3$ result (also with anyH3)
- Expectedly deviations in $\kappa_3$ induce sizeable deviations in $\kappa_4$

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

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



# 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:**

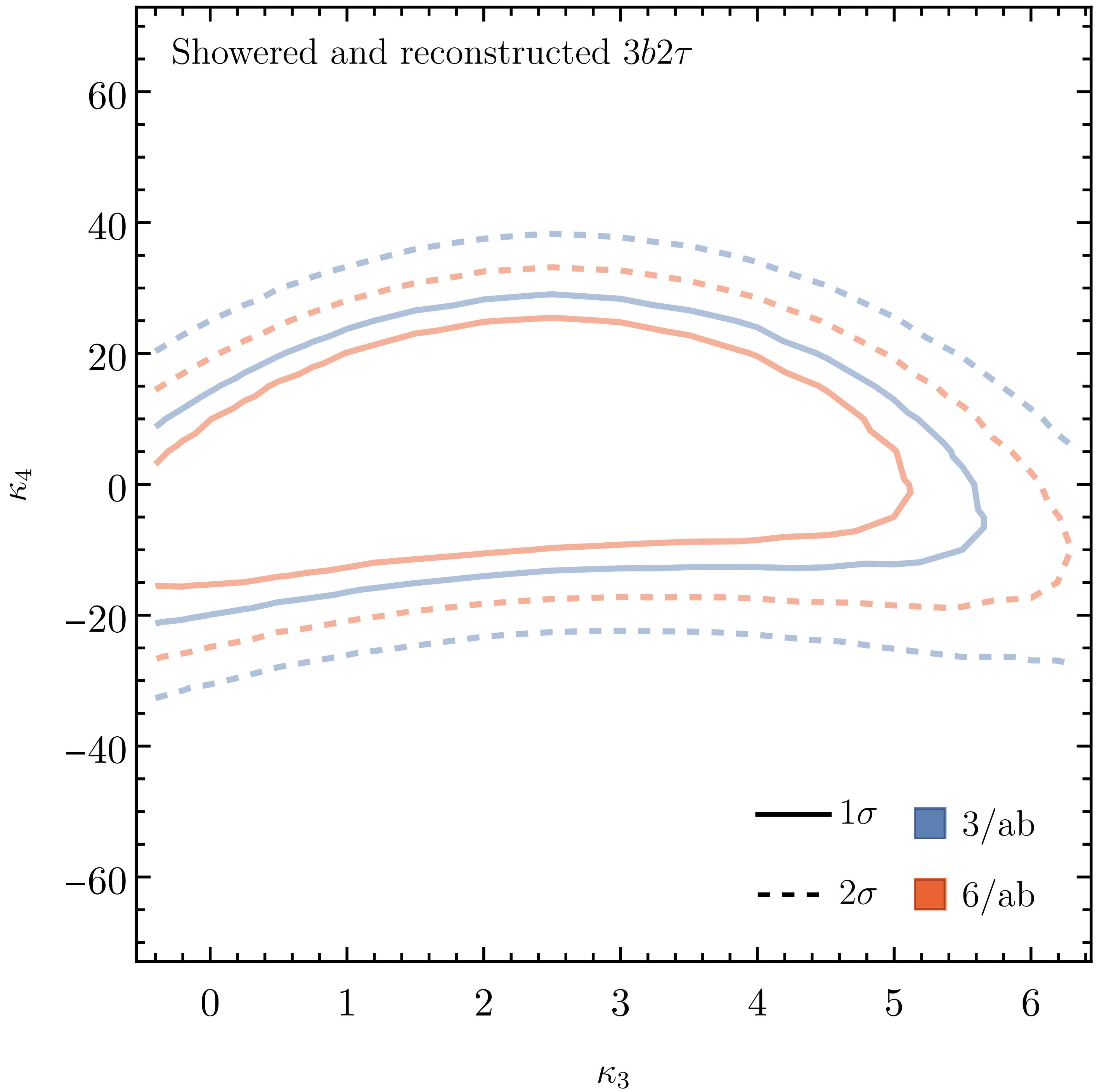
$6b$: dominant QCD contributions (see also [Papaefstathiou, Robens, Xolocotzi `21])

$4b2\tau$: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},$

$t\bar{t}(H \to \tau\tau),\ t\bar{t}(H \to b\bar{b}),$

$t\bar{t}(Z \to \tau\tau),\ t\bar{t}(Z \to b\bar{b}),\ t\bar{t}t\bar{t}$

# Result: HL-LHC projection, $3b2\tau$ channel




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

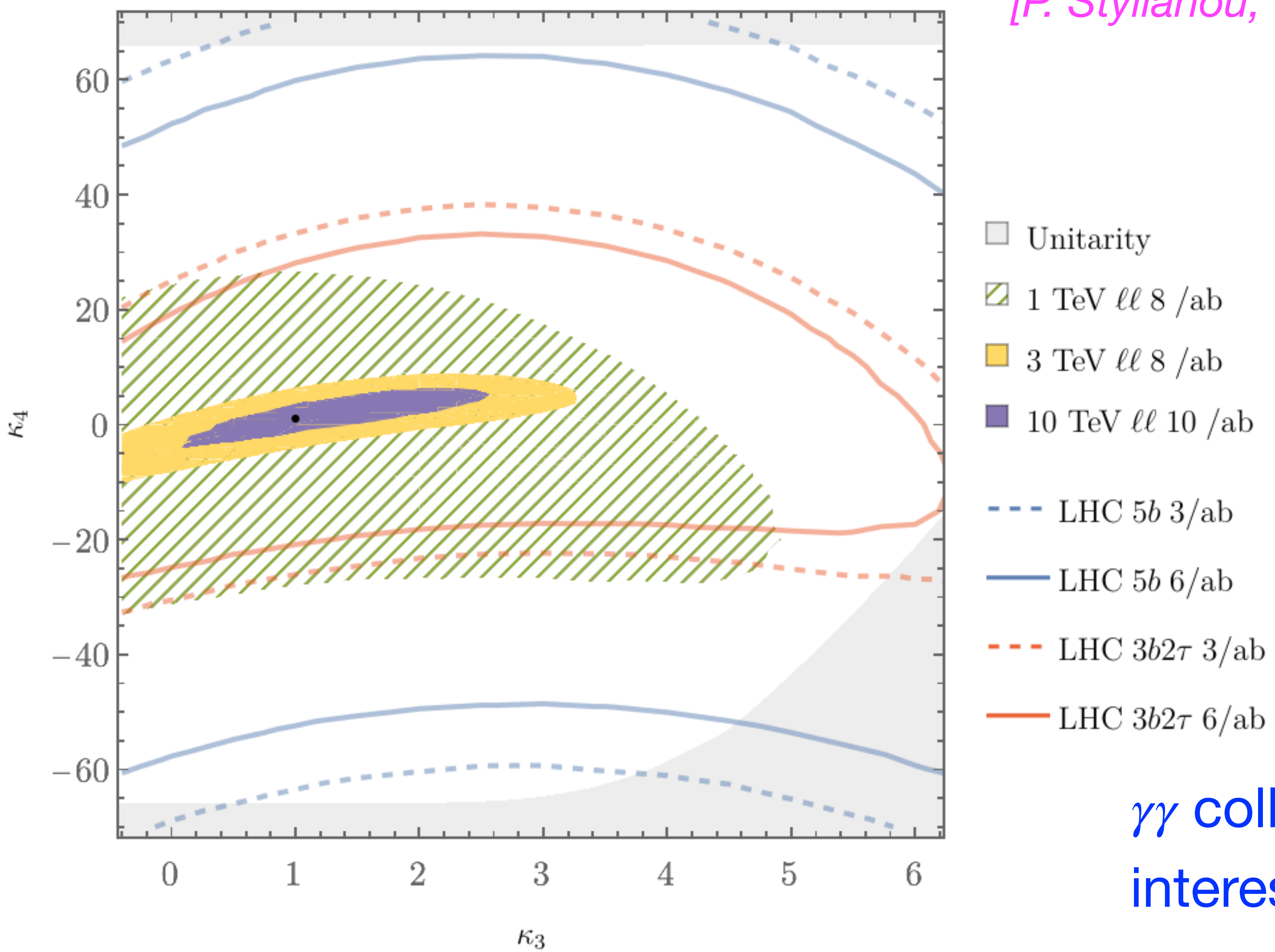
Recent HL-LHC projection for the $6b$ channel: [ATLAS and CMS Collaborations '25]

Current results by ATLAS and CMS [ATLAS and CMS Collaborations '25]

⇒Good prospects for constraints at the LHC that go far beyond the unitarity bounds!

# Triple Higgs production: HL-LHC vs. lepton colliders

[P. Stylianou, G. W. ’24, ’25]



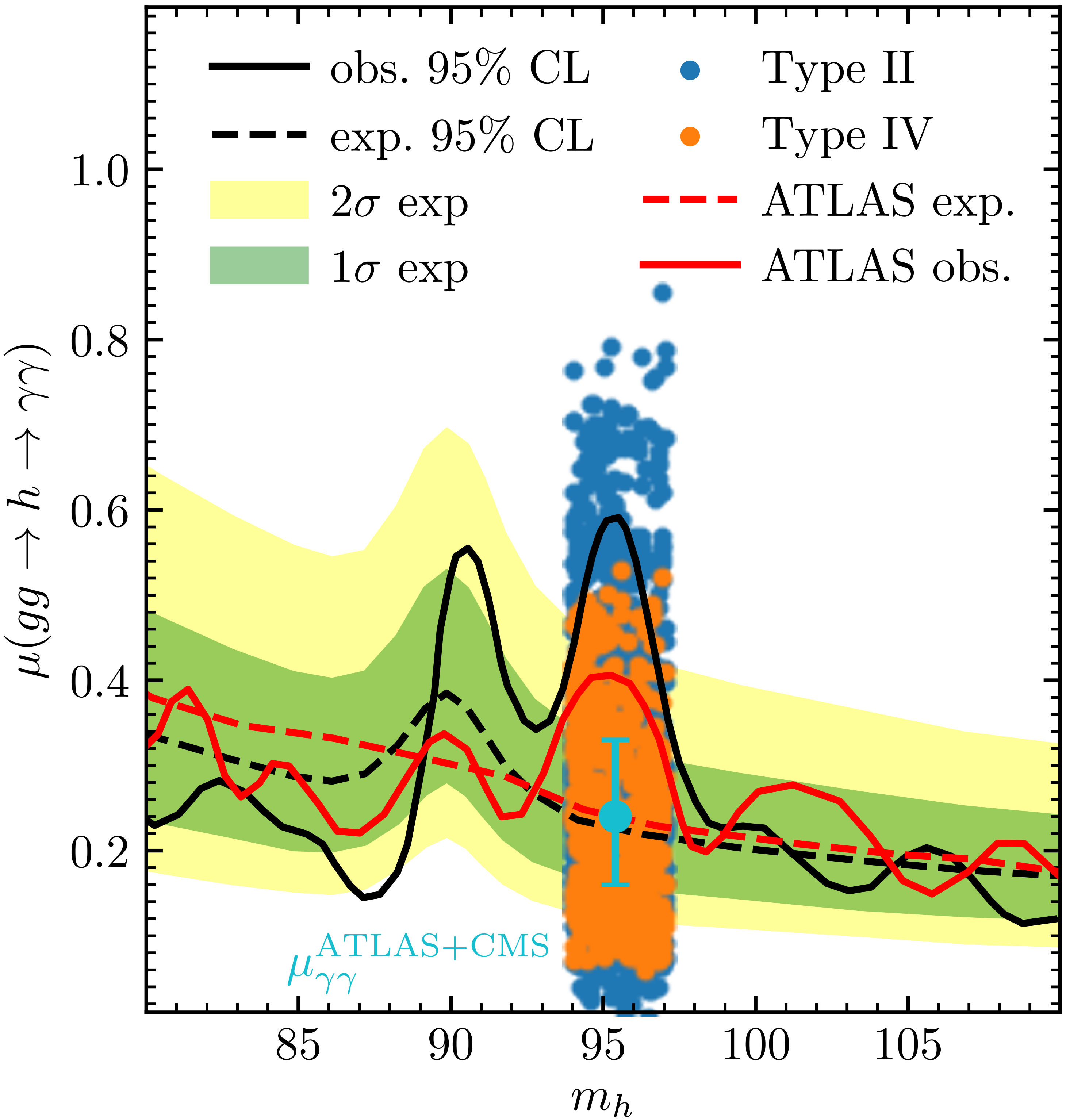

$\gamma\gamma$ collider could have interesting potential

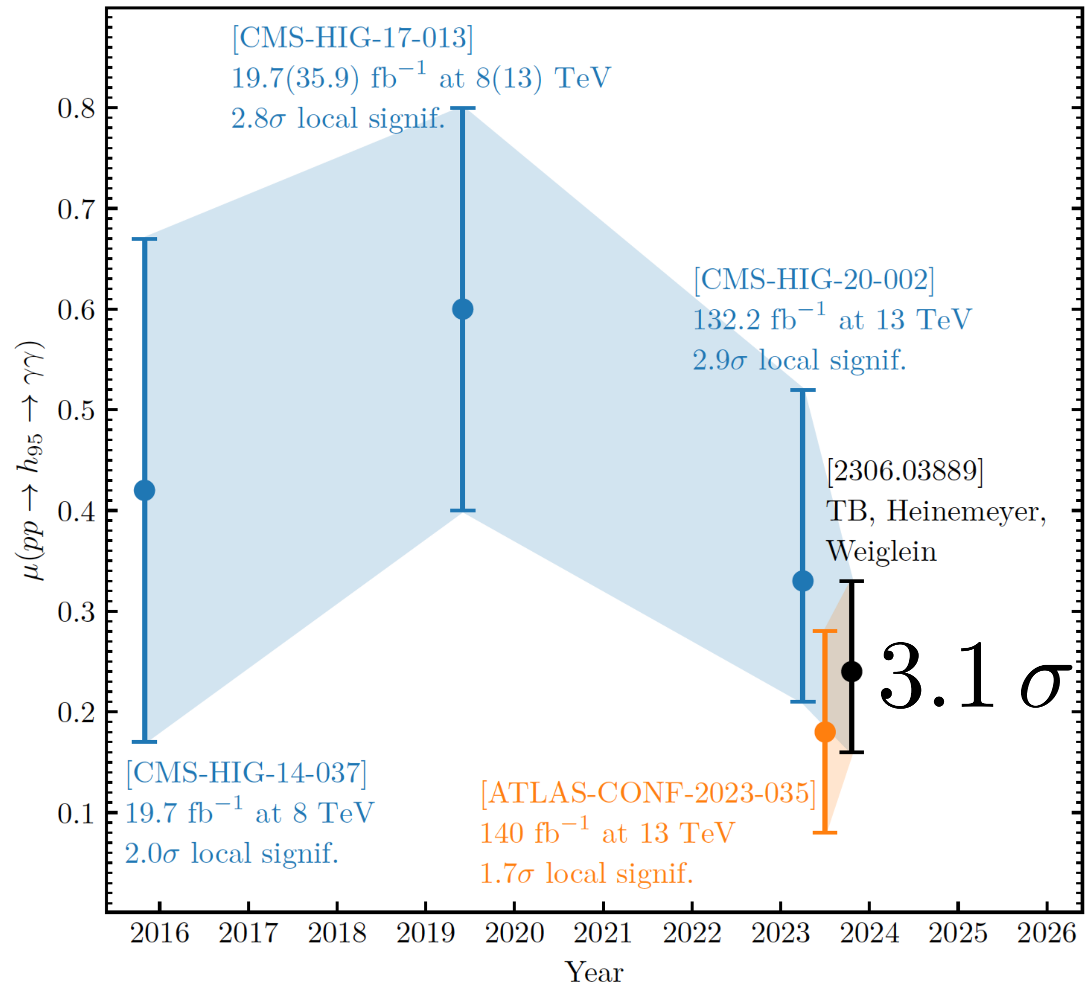
⇒ HL-LHC is comparable to 1 TeV lepton collider for $\varkappa_\lambda \approx 1$
Higher-energetic lepton colliders have better sensitivity

# Recent results regarding BSM Higgs searches

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

CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV: $\mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08}$



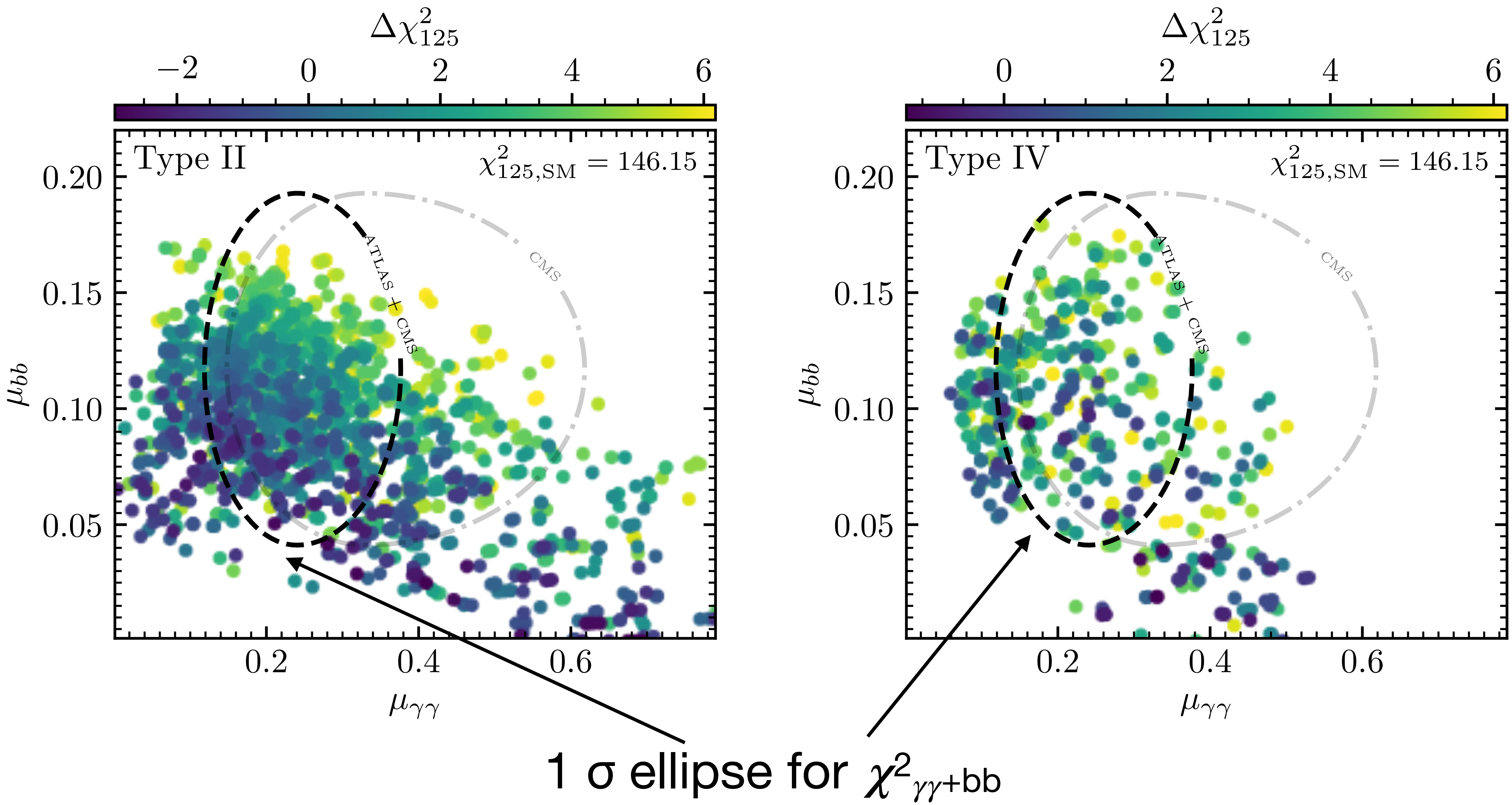

Example interpretation:
S2HDM, type II and IV

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

# Excesses near 95 GeV at the LHC and at LEP

S2HDM, type II and IV:

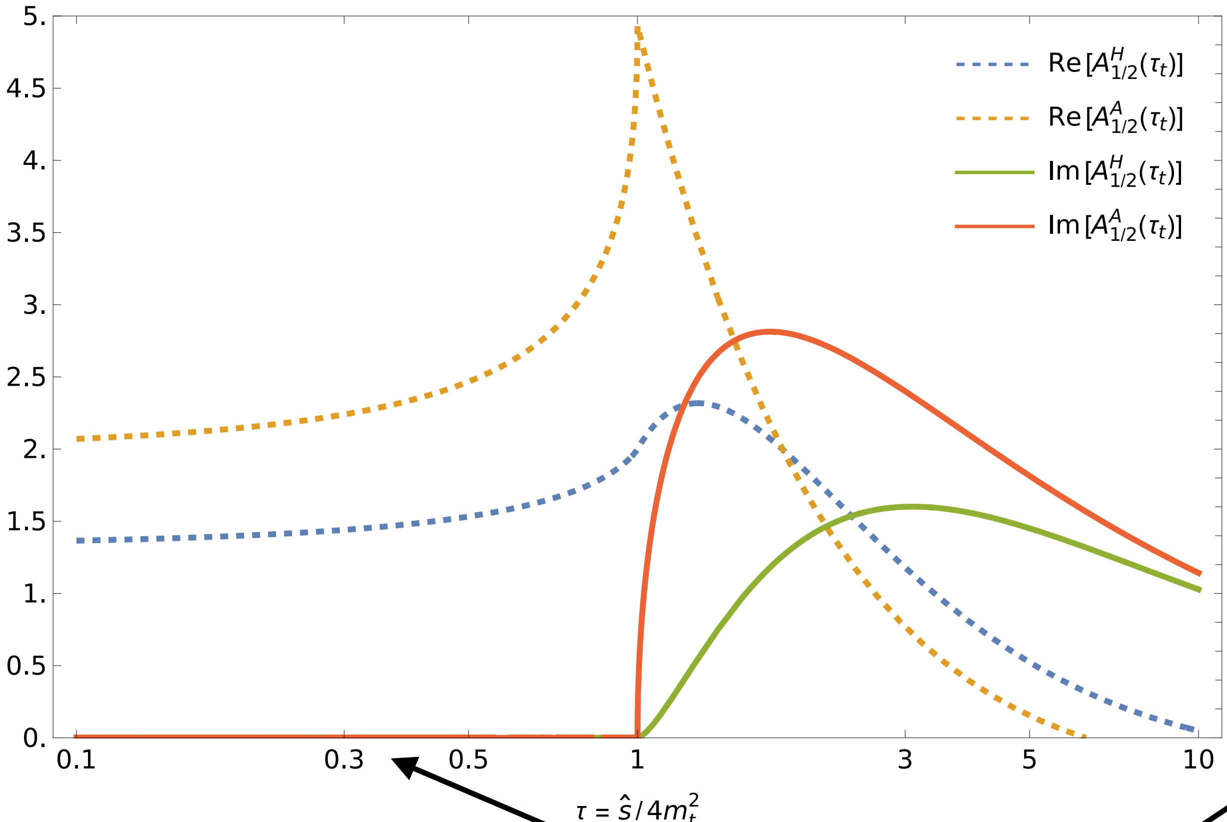
[T. Biekötter, S. Heinemeyer, G. W. '23]

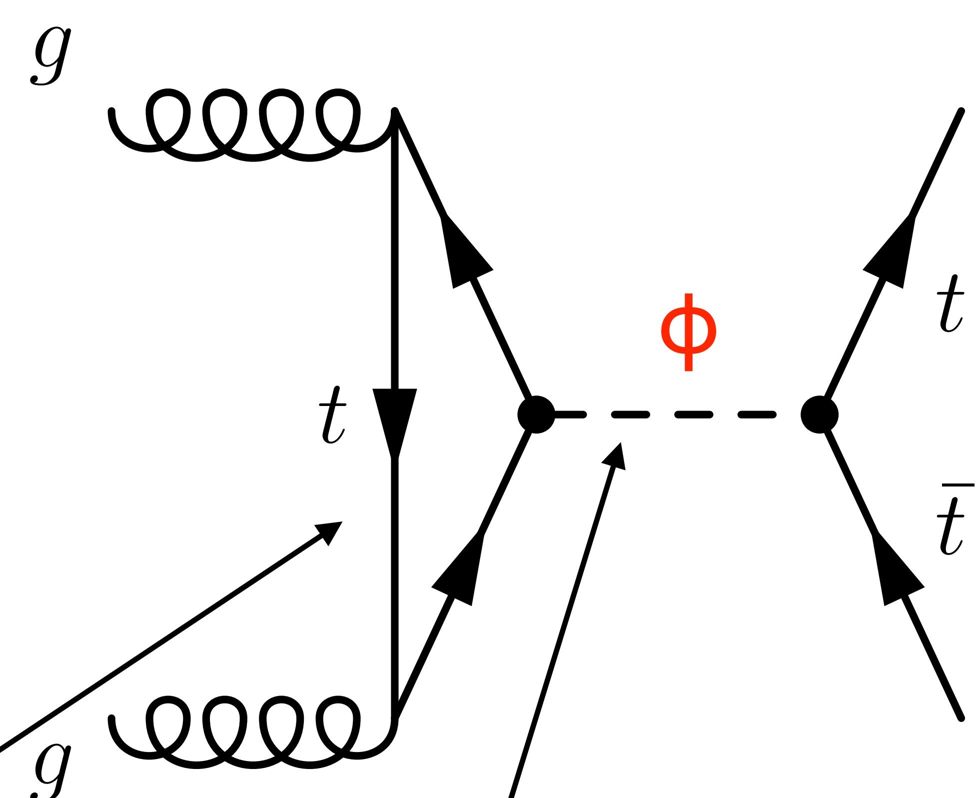



⇒ The LHC excess in the $\gamma\gamma$ channel and the LEP excess in the bb channel can be described very well simultaneously!

# BSM Higgs searches in the tt final state

S-channel resonance in gluon fusion: signal-background interference can receive large contribution above the di-top threshold,
e.g.: gg → ϕ → tt



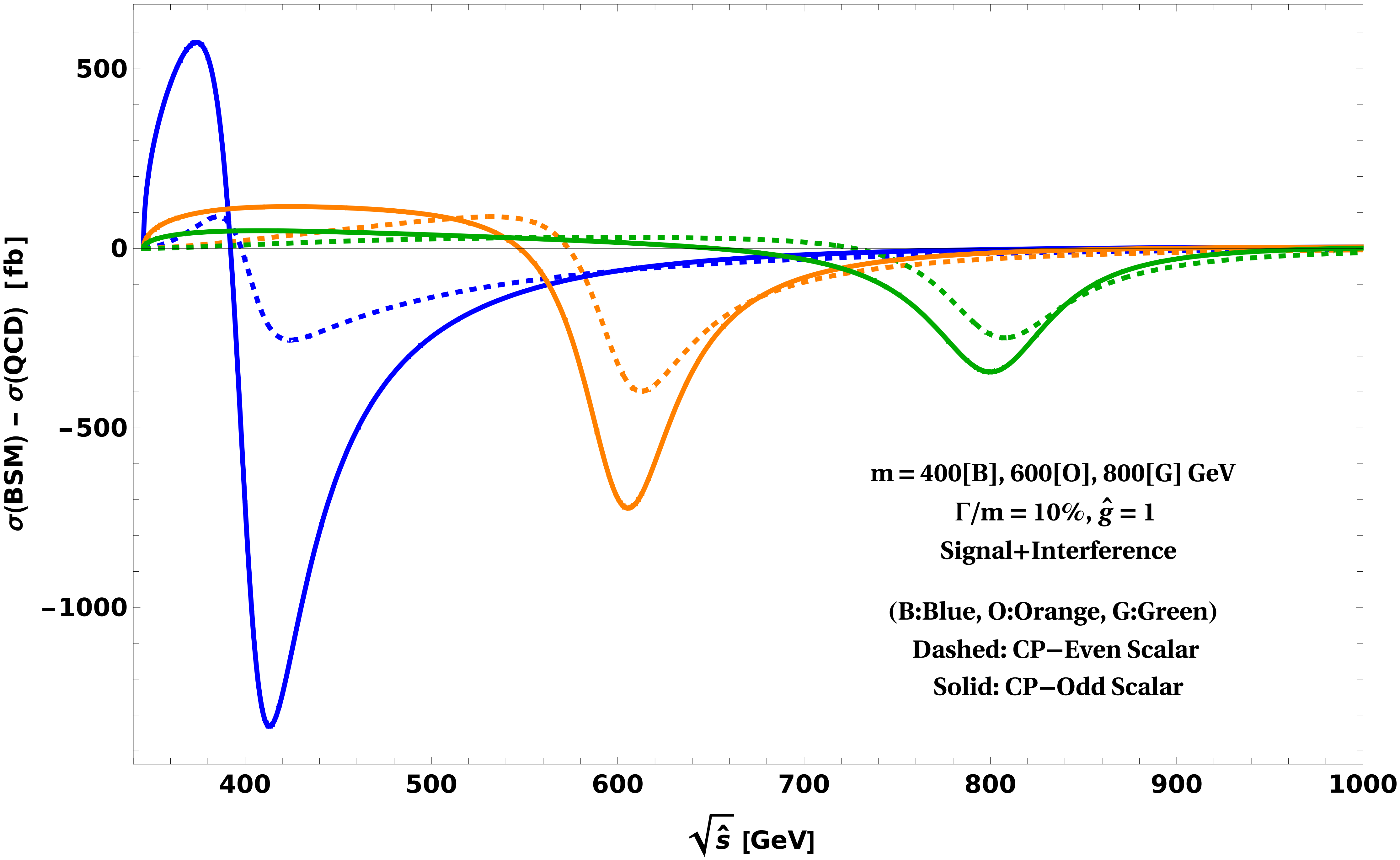

Loop function Aᶲ(τ) develops imaginary part above the threshold $\tau \equiv \frac{\hat{s}}{4m_t^2} \geq 1$

propagator $\sim \frac{1}{\hat{s} - m_\Phi^2 + i m_\Phi \Gamma_\Phi}$

⇒ Interference contribution ~ Im[ Aᶲ(τ) ] $m_\phi$ $\Gamma_\phi$

# Interference patterns for background-subtracted gg → ϕ → tt cross section, parton level

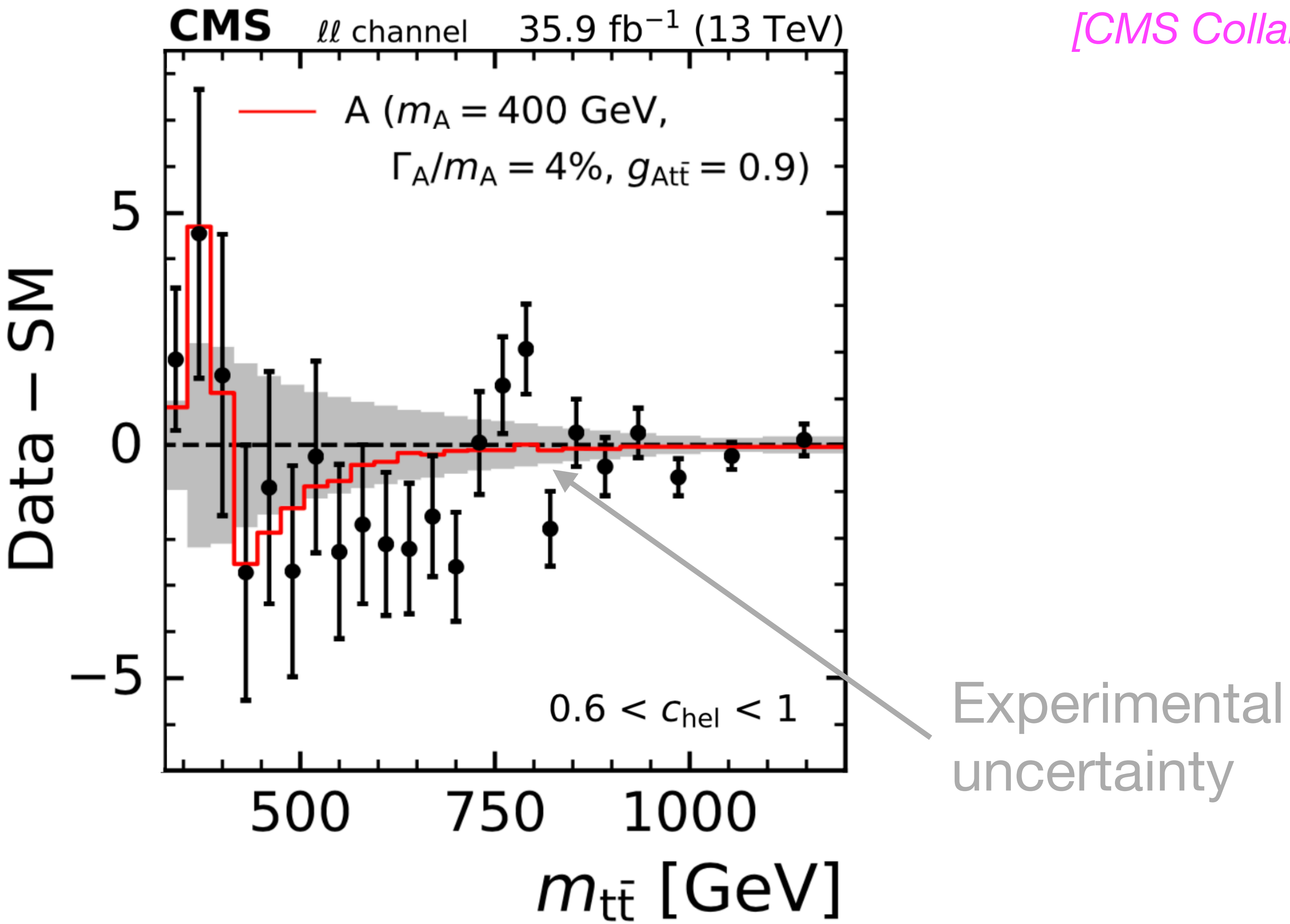
*[H. Bahl, R. Kumar, G. W. ’22]*




⇒ Signal-background interference yields peak-dip structure

# H, A → tt search in CMS (first year of Run 2)

*[CMS Collaboration '19]*



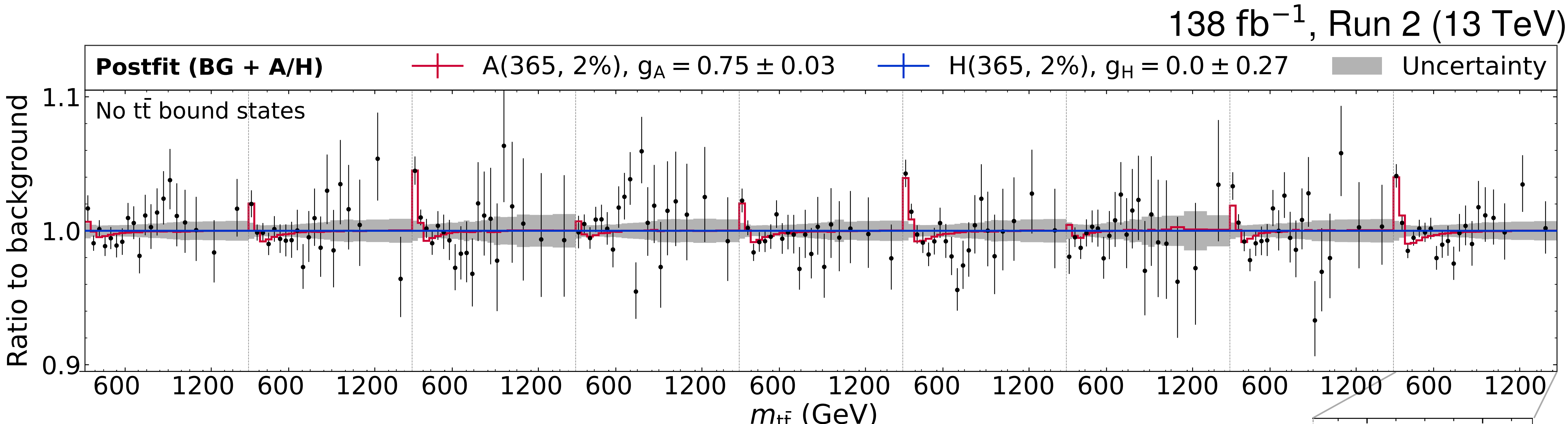

⇒ CMS analysis exploiting top spin correlation information: sensitivity to the peak-dip structure caused by a signal-background interference

Observed excess (3.5 σ): compatible with CP-odd Higgs at ≈400 GeV

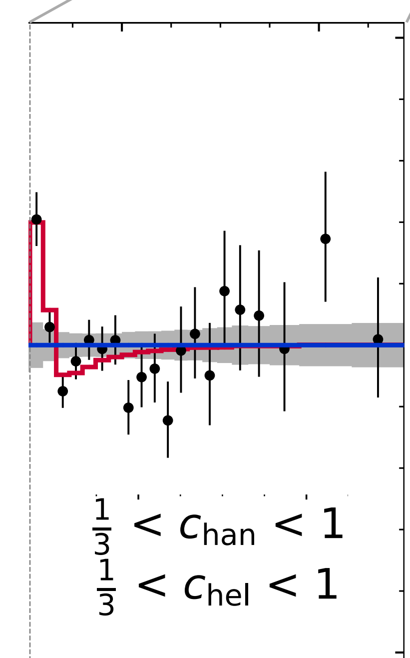
# CMS full Run 2 result: > 5 σ excess near tt threshold

[CMS Collaboration '24]

CMS result for search in the tt final state:
ϕ = H, A, $\eta_t$ (tt bound state), using spin correlations (variables $c_{hel}$ and $c_{han}$), di-lepton channel, different bins of the two variables:




Excess of more than 5 σ compared to SM background from perturbative QCD



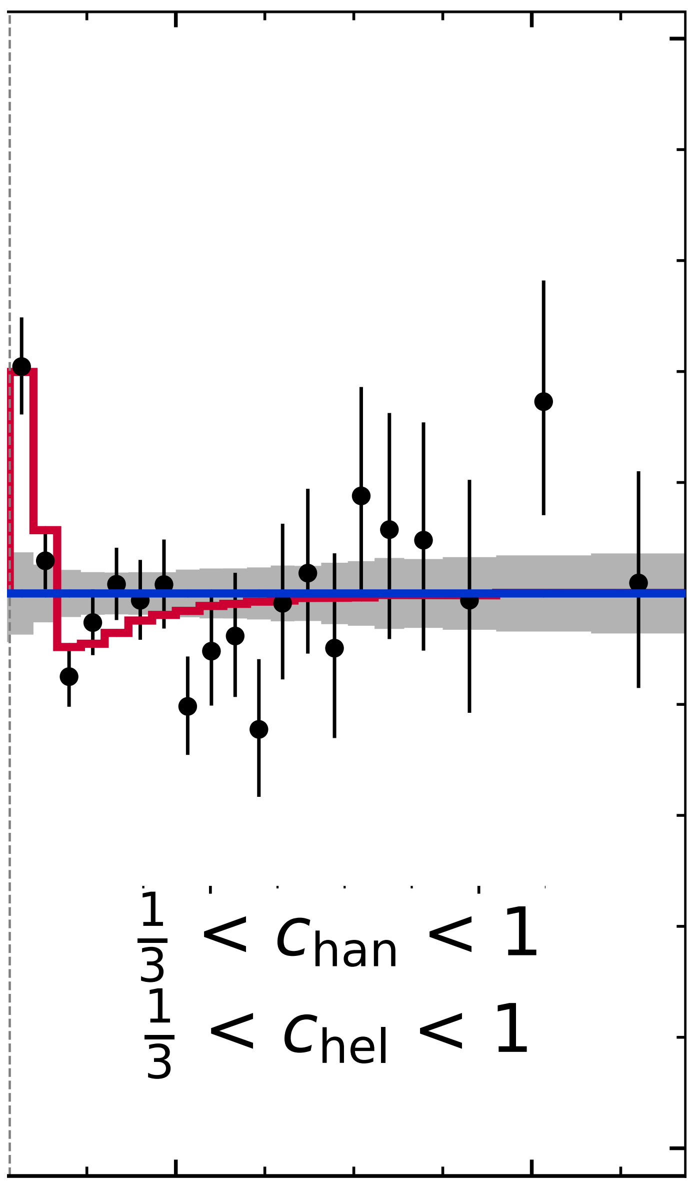

SM physics? SM + BSM physics??

Results are well compatible with tt bound state at 343 GeV or CP-odd Higgs boson A at 365 GeV

# CMS results (same data!): interpretation in terms of BSM Higgs or bound state type effect

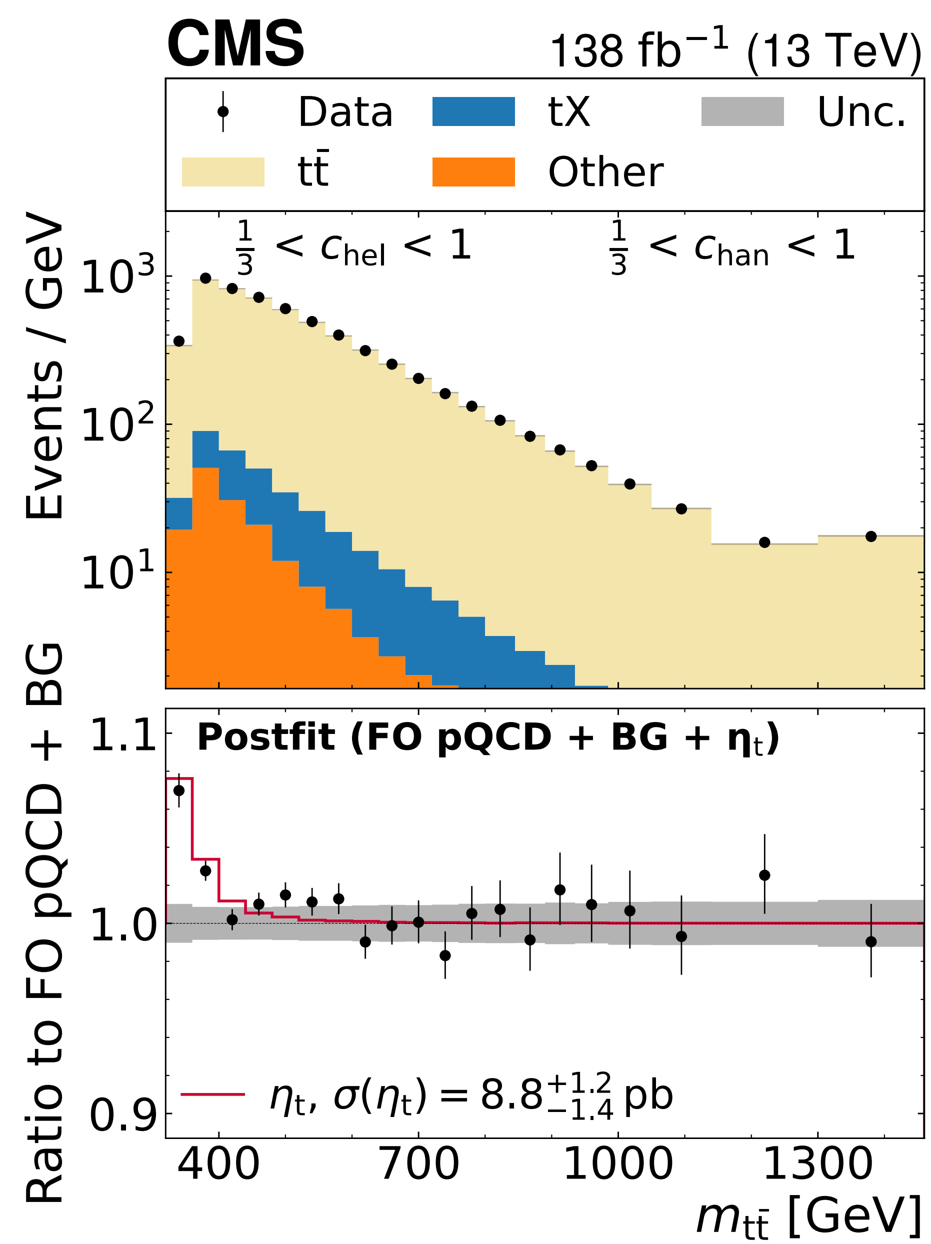
## Postfit (BG + A/H):

[CMS Collaboration ’24]




## Postfit (BG + $\eta_t$):

[CMS Collaboration ’25]




⇒ Peak-dip or just a peak? Distinction between SM and BSM effects?

# Recent ATLAS result (full Run 2)

Similar analysis as CMS, also observe very significant excess over the perturbative QCD background (7.7 σ for their default signal model)

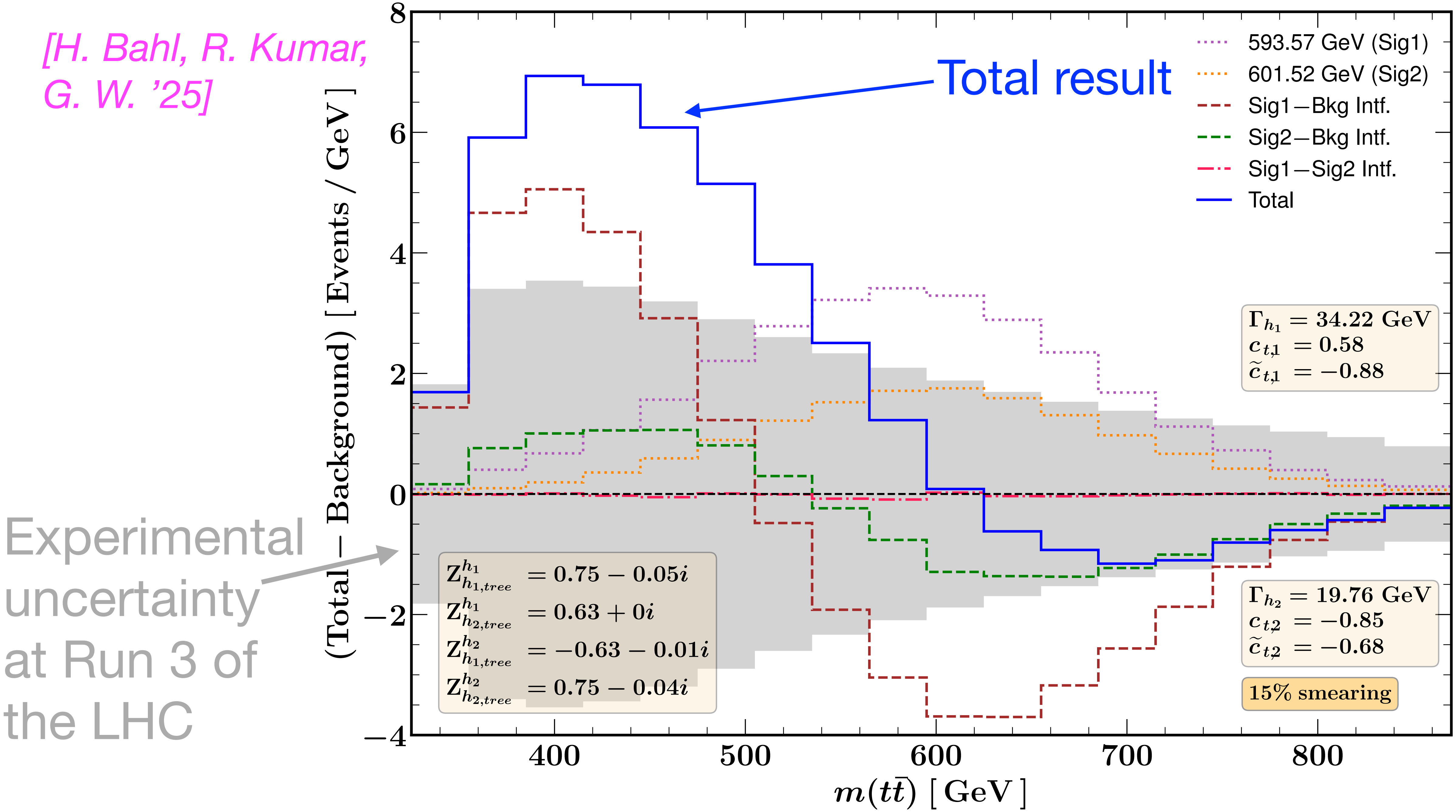
However, if ATLAS uses the same signal model for tt bound state as CMS they find a much larger cross section than with their default model (13.4 ± 1.9 pb vs. 9.0 ± 1.3 pb; predicted: 6.4 pb) and than CMS ($8.8^{+1.2}_{-1.4}$ pb)

Compatibility with ATLAS BSM Higgs search result (no excess over perturbative QCD, spin correlation information not fully exploited, strong limits, tension with the CMS result)?

# However: heavier states also affect tt threshold
# Example: two CP-mixed states at about 600 GeV

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

*[H. Bahl, R. Kumar, G. W. '25]*

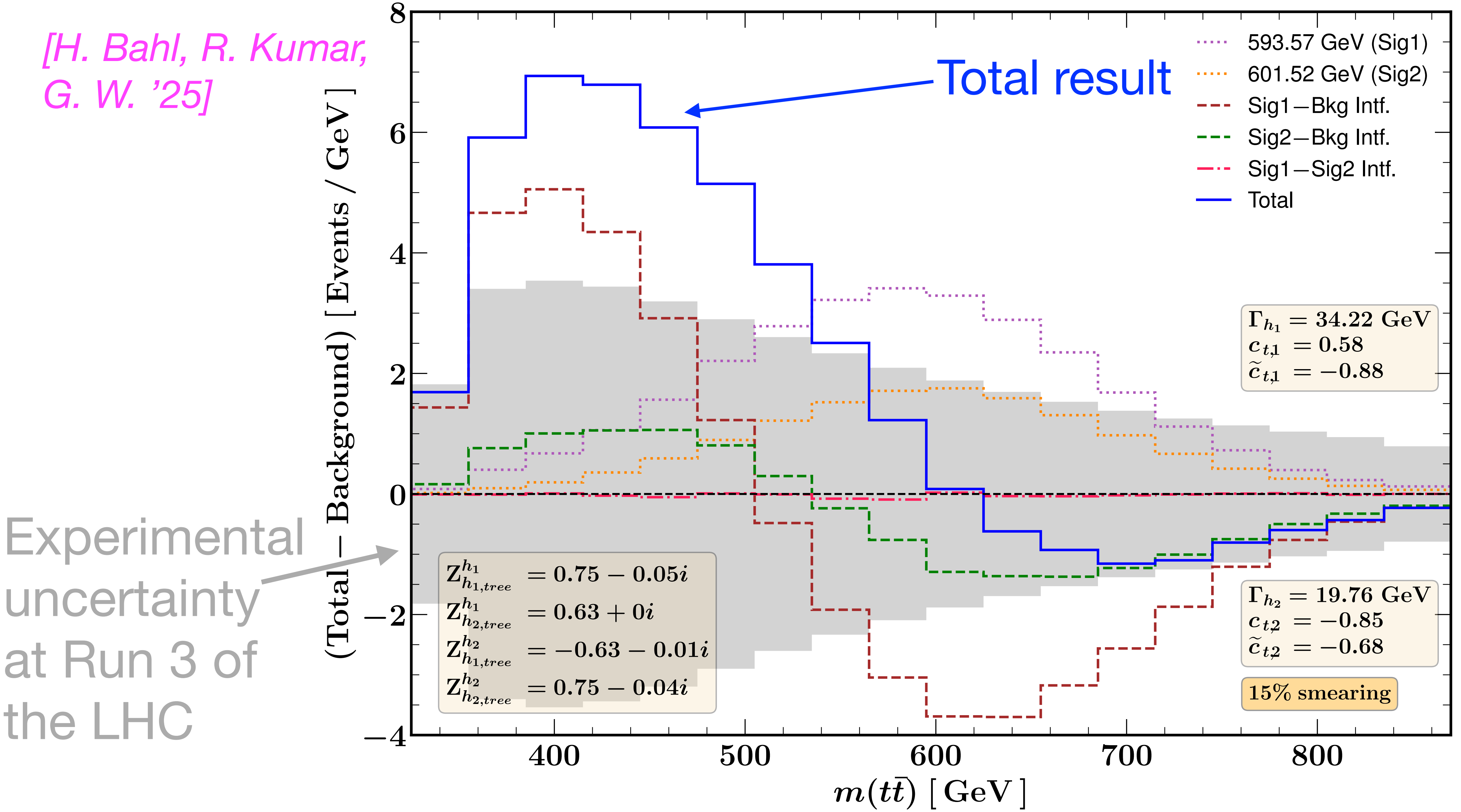



⇒ Resembles shape for a single particle at lower mass; highest sensitivity in the region just above the tt threshold!

# However: heavier states also affect tt threshold
# Example: two CP-mixed states at about 600 GeV

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

*[H. Bahl, R. Kumar, G. W. ’25]*




⇒ BSM effects tend to manifest themselves at the tt threshold, even for much higher BSM masses! Can yield peak or peak-dip structure!

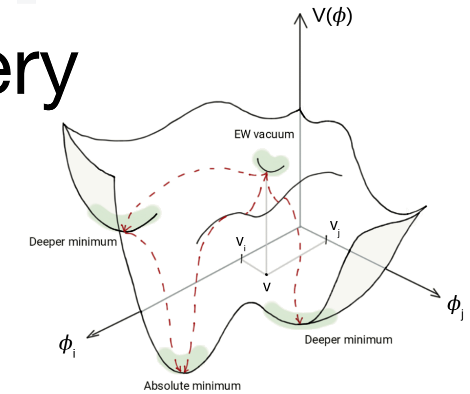
# Conclusions

Trilinear Higgs self-coupling: shape of Higgs potential, close relation to EW 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

The preferred region with strong first-order EWPT and potentially detectable gravitational wave signal in extended Higgs sectors (e.g. 2HDM) is typically correlated with significantly enhanced trilinear Higgs self-coupling that is allowed by all existing constraints, can be probed with LHC ``smoking gun” signatures

Higgs pair production at present and future colliders is a very powerful way for probing the shape of the Higgs potential and the evolution of the early universe




Triple Higgs production: $\varkappa_4$ can be probed at HL-LHC and beyond

# Backup

# 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

# 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, …)?

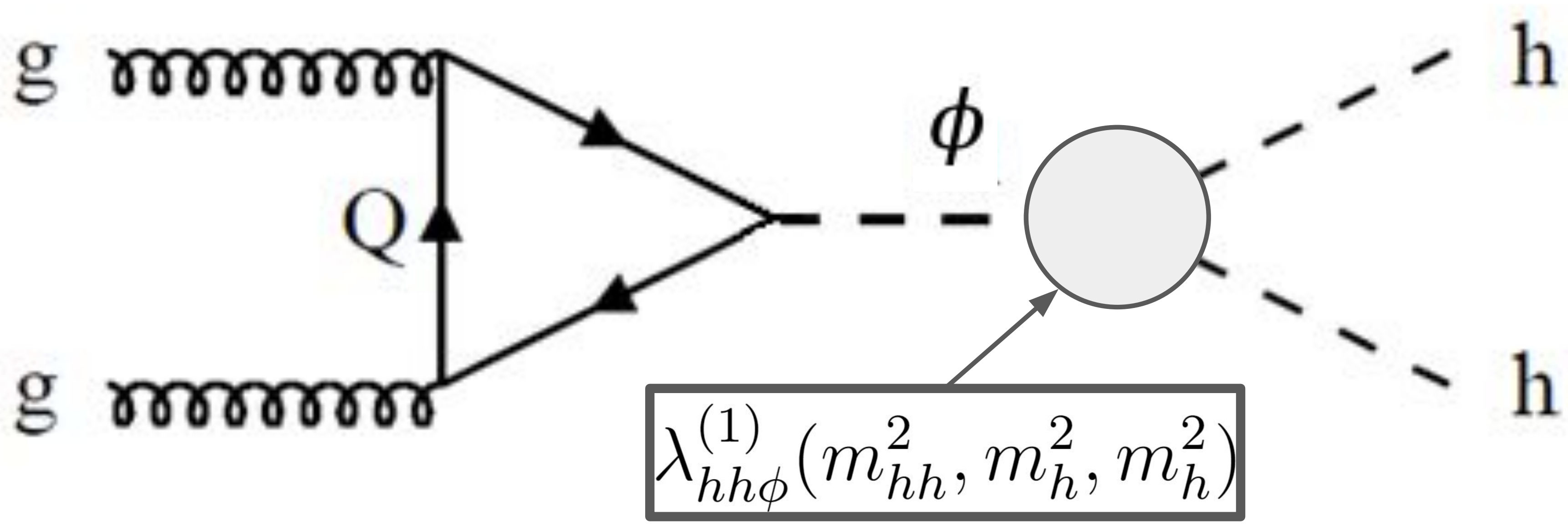
⇒ Further information from the exploration of the detected Higgs signal

# Examples of BSM model predictions

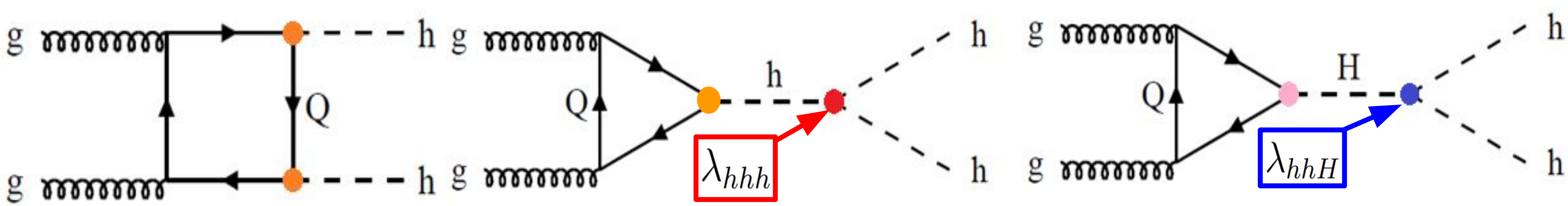
Di-Higgs production for arbitrary renormalisable models (*anyHH*)

*[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '25]*

- Loop-corrected trilinear couplings involving BSM Higgses: $\lambda_{hhH}$, …




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

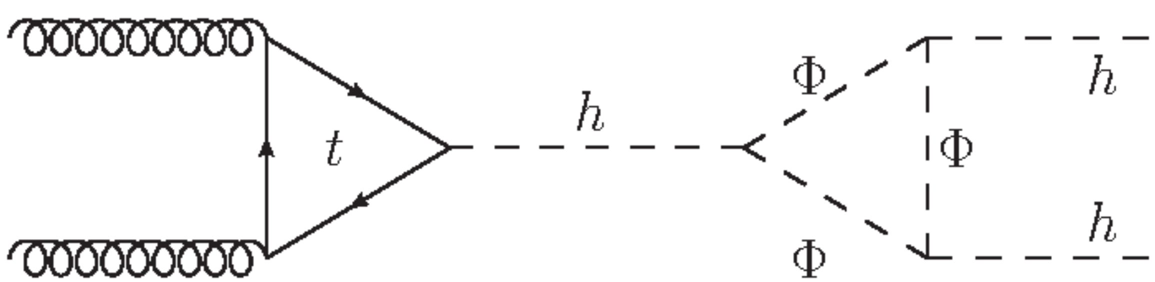


# Check of applicability of the experimental limit on $\varkappa_\lambda$

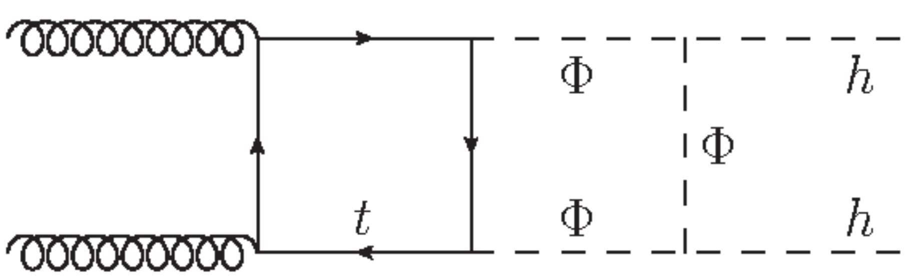
Alignment limit: h has SM-like tree-level couplings

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

The dominant new-physics contributions enter via trilinear coupling




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



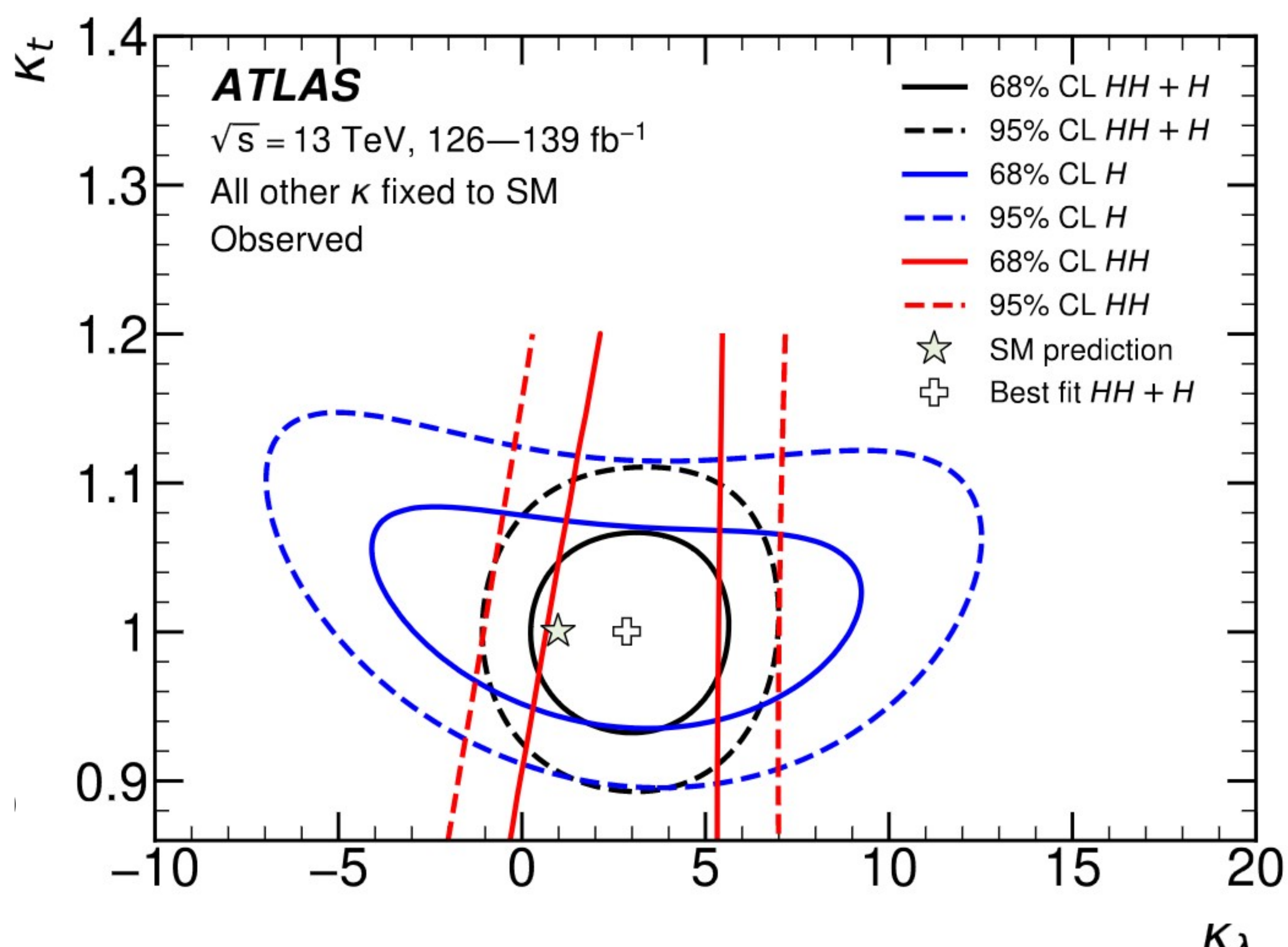

$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

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

# 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, $\kappa_t$ floating | $-0.4 < \kappa_\lambda < 6.3$ | $-1.9 < \kappa_\lambda < 7.6$ | $\kappa_\lambda = 3.0^{+1.8}_{-1.9}$ |
| $HH$+$H$ combination, $\kappa_t$, $\kappa_V$, $\kappa_b$, $\kappa_\tau$ floating | $-1.3 < \kappa_\lambda < 6.1$ | $-2.1 < \kappa_\lambda < 7.6$ | $\kappa_\lambda = 2.3^{+2.1}_{-2.0}$ |



# Strongly first-order EWPT in the 2HDM

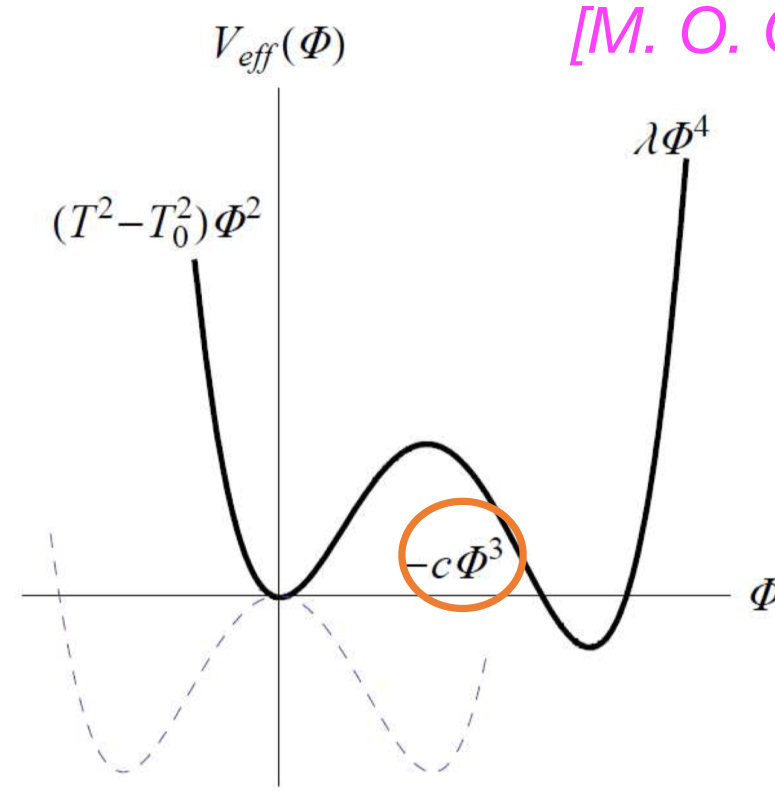
Barrier is related to a cubic term in the effective potential

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

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

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

[M. O. Olea '23]




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

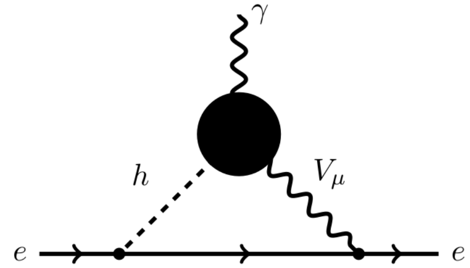
# EWPT: are there additional sources for CP violation in the Higgs sector?

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



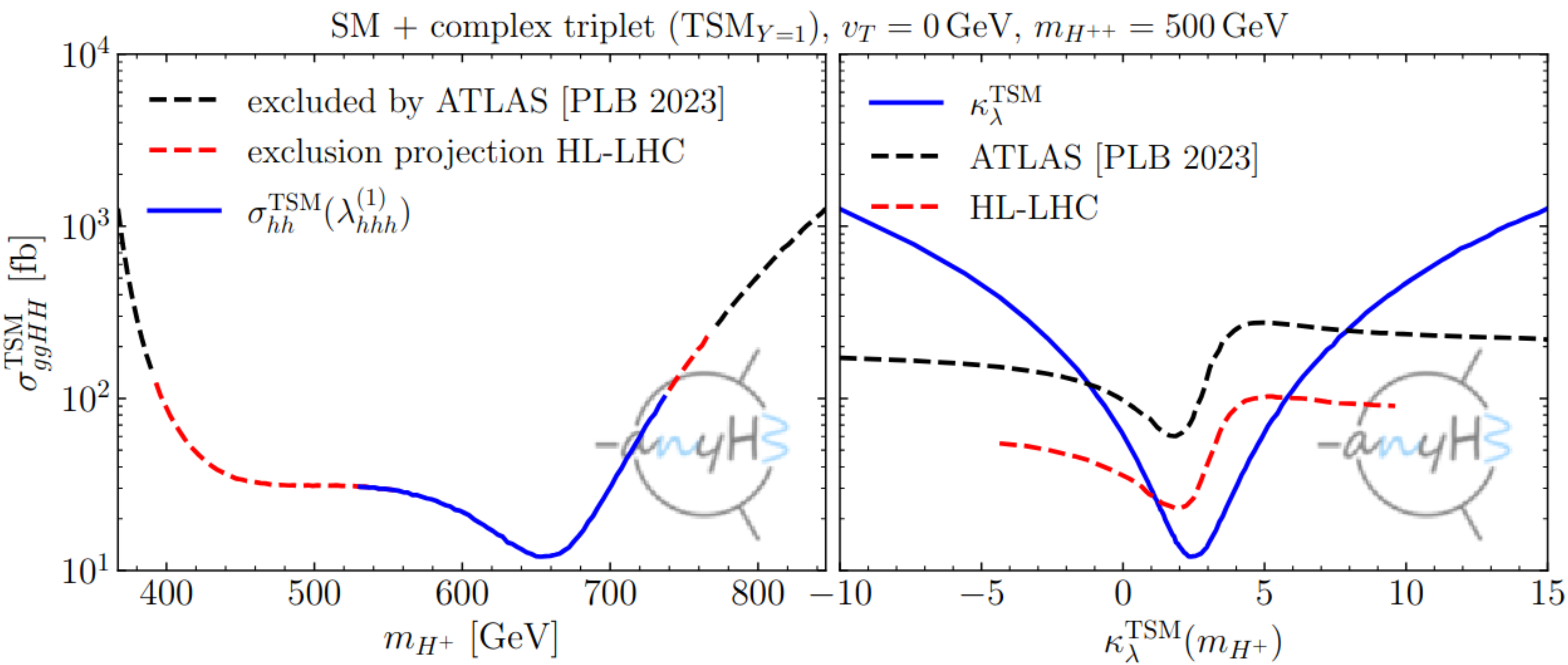
Two-loop "Barr-Zee" electron EDM contribution

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

# Di-Higgs production (*anyHH*)

## Example: SM + complex triplet (TSM)

*[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '25]*



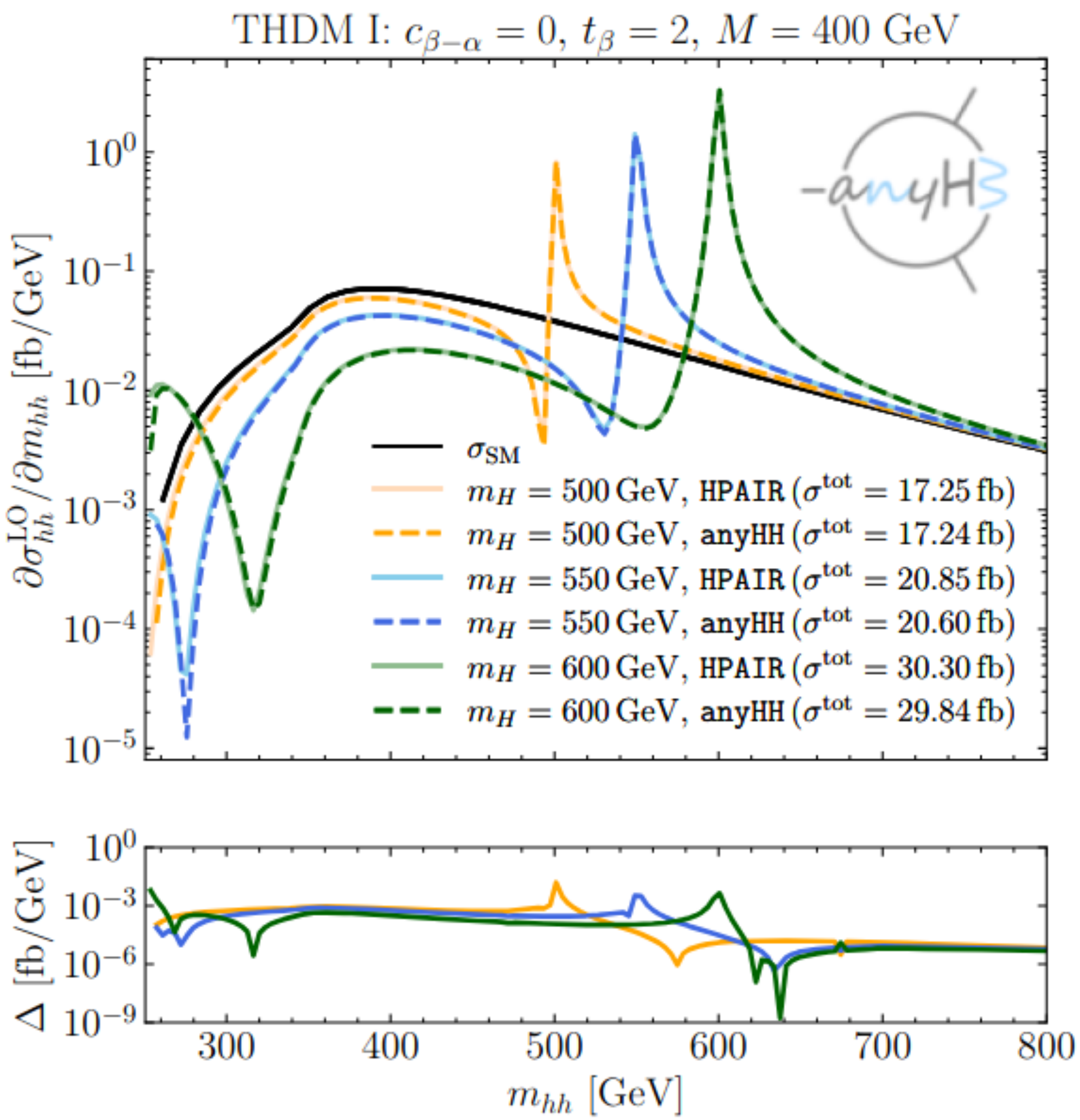

⇒ Present bounds from non-resonant searches already put important constraints

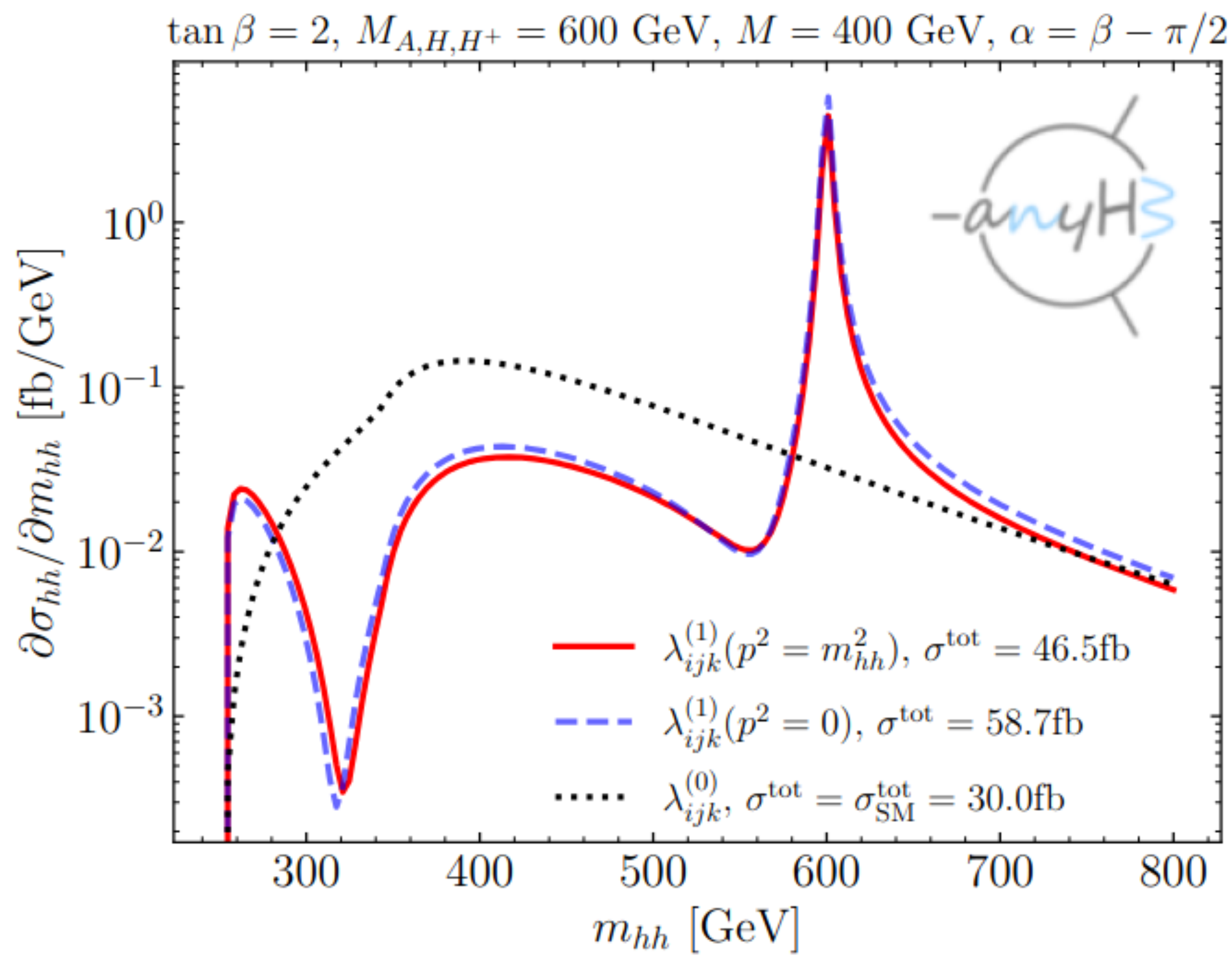
# *anyHH*: 2HDM results

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '25]

## Comparison with *HPAIR*:

[M. Mühlleitner, M. Spira, et al.]



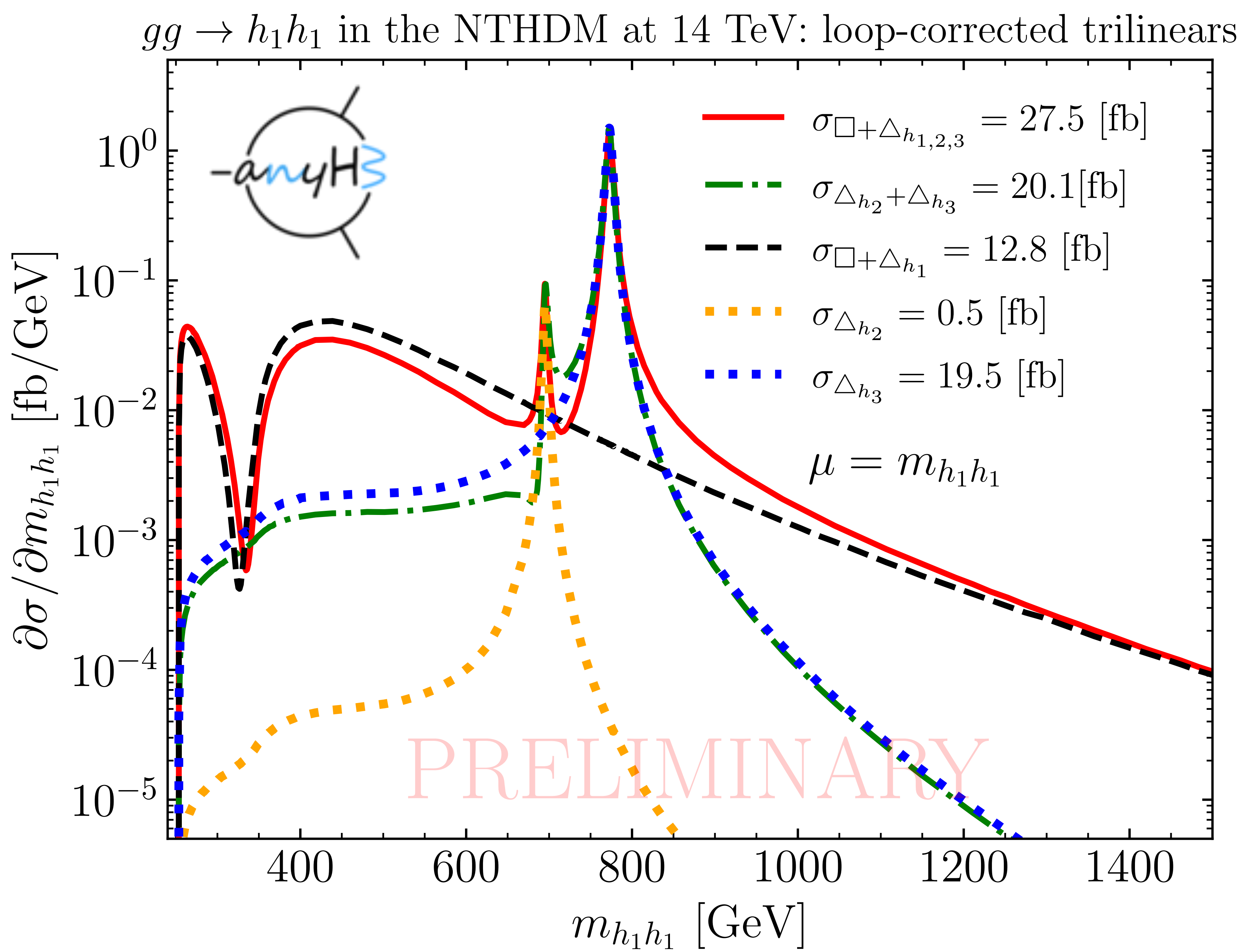




Very good agreement with *HPAIR*, using one-loop trilinear scalar couplings computed by *anyH3* for 2HDM benchmarks (here: alignment limit)

One-loop corrections to trilinear Higgs couplings have large impact on differential distribution
Moderate effect of momentum dependence of trilinear couplings (up to 20% on total cross-section)

# *anyHH*: N2HDM (2HDM + real singlet) example

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '25]

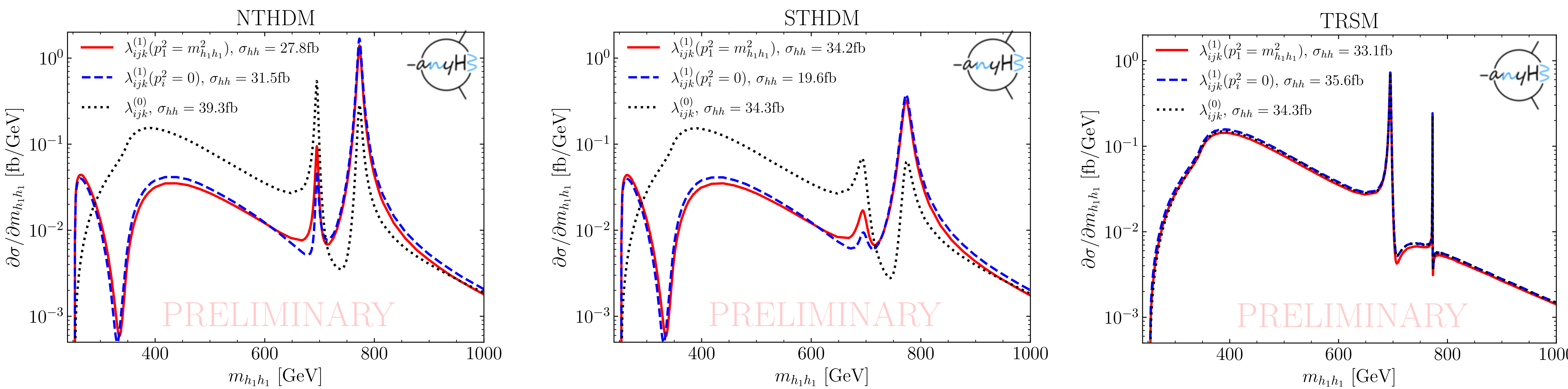



⇒ Shape of distribution determined by resonances, interference effects and loop contributions

# *anyHH* results for different models, link to *MadGraph*

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '25]

Examples: NTHDM = 2HDM + real singlet; STHDM = 2HDM + complex singlet DM; TRSM: two-real singlet model




Under development: link to the *MadGraph* event generator

Export analytical expressions for loop-corrected trilinear couplings $\lambda_{ijk}$ (with momentum dependence) from *anyHH* to UFO format, so that loop-corrected trilinear couplings can be used directly in *MadGraph* simulations

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

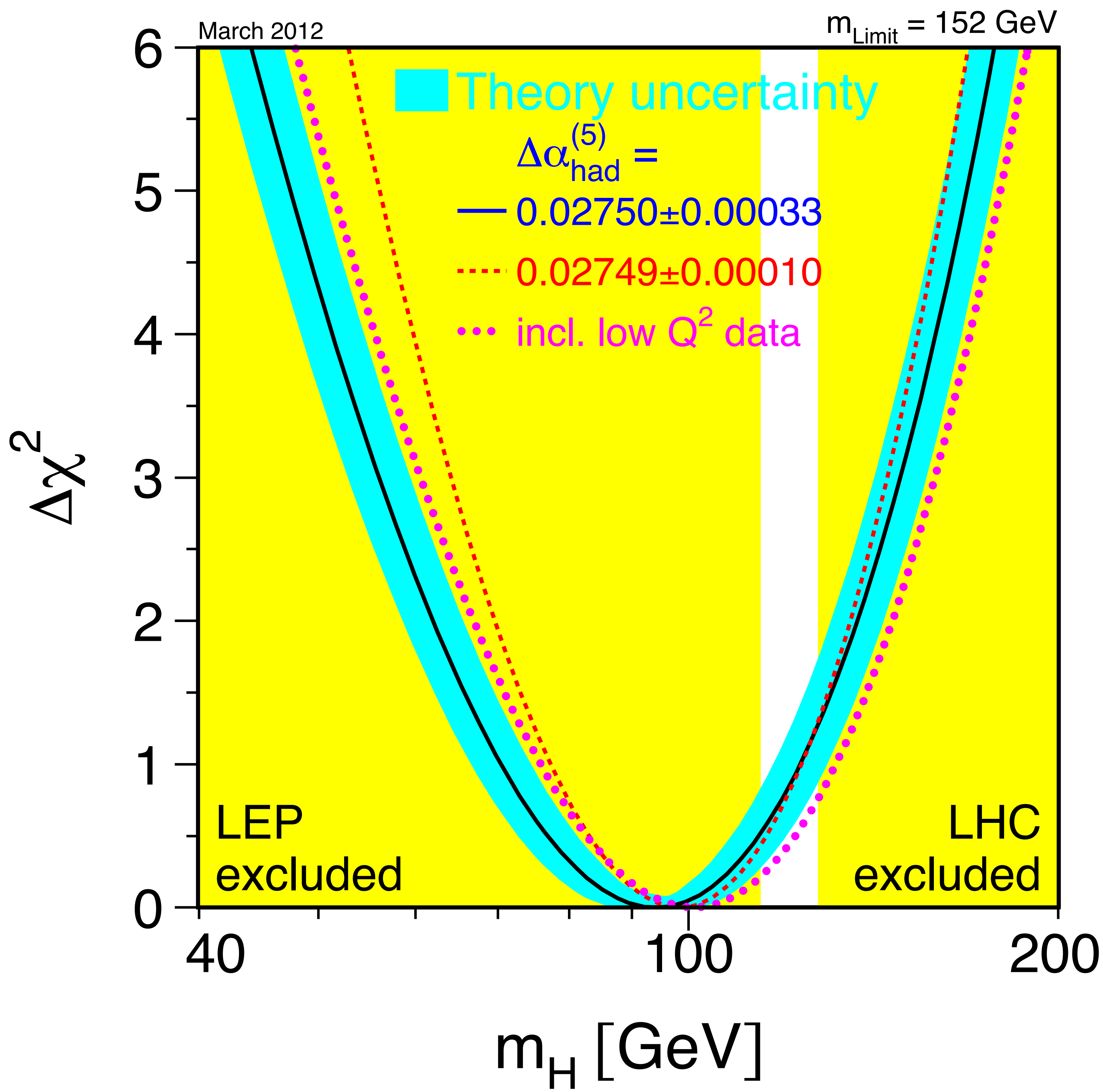
Indirect access to $\lambda_{hhh}$ via

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

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

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

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




*[LEPEWWG '12]*

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

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

# Indirect constraints on $\lambda_{hhh}$ are much more difficult to obtain than the indirect constraints on $M_h$ in the SM

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

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

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

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

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

# $\lambda_{hhh}$ and the Higgs pair production process

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

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

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

# How much can we learn about $\lambda_{hhh}$ from its impact on loop corrections?

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

Case where the observables used for a global fit based on data from the LHC and CEPC or FCC-ee, i.e. no input from the $e^+e^-$ machines on the Higgs pair production process, show a deviation from the SM prediction that is compatible with a non-SM value for $\lambda_{hhh}$ (within the LHC uncertainties): how well can such a deviation be associated with $\lambda_{hhh}$ rather than with other higher-order contributions?

This issue had not been addressed for the FCC-ee fits so far; the future experimental results had always been assumed to perfectly agree with the SM (even without accounting for statistical fluctuations of the assumed central values around the SM predictions)

# EFT fit for the case where $\varkappa_\lambda \neq 1$

[H. Bahl, P. Bechtle, J. Braathen, S. Heinemeyer, J. List, M. Vellasco, G. W. ’25]

Considered: case where a certain BSM scenario is realised in nature; example: IDM, used to generate ``pseudo-data” as input for the SMEFT fit

⇒ Result of the SMEFT fit sensitively depends on the treatment of higher-dimensional operators (dim. 6 vs. dim. 8, …) and of theoretical uncertainties

⇒ The determination of SMEFT coefficients in a global fit is very different from experimental measurements of physical observables; the resulting pattern of SMEFT coefficients may be very difficult to relate to the physics scenario that is actually realised in nature

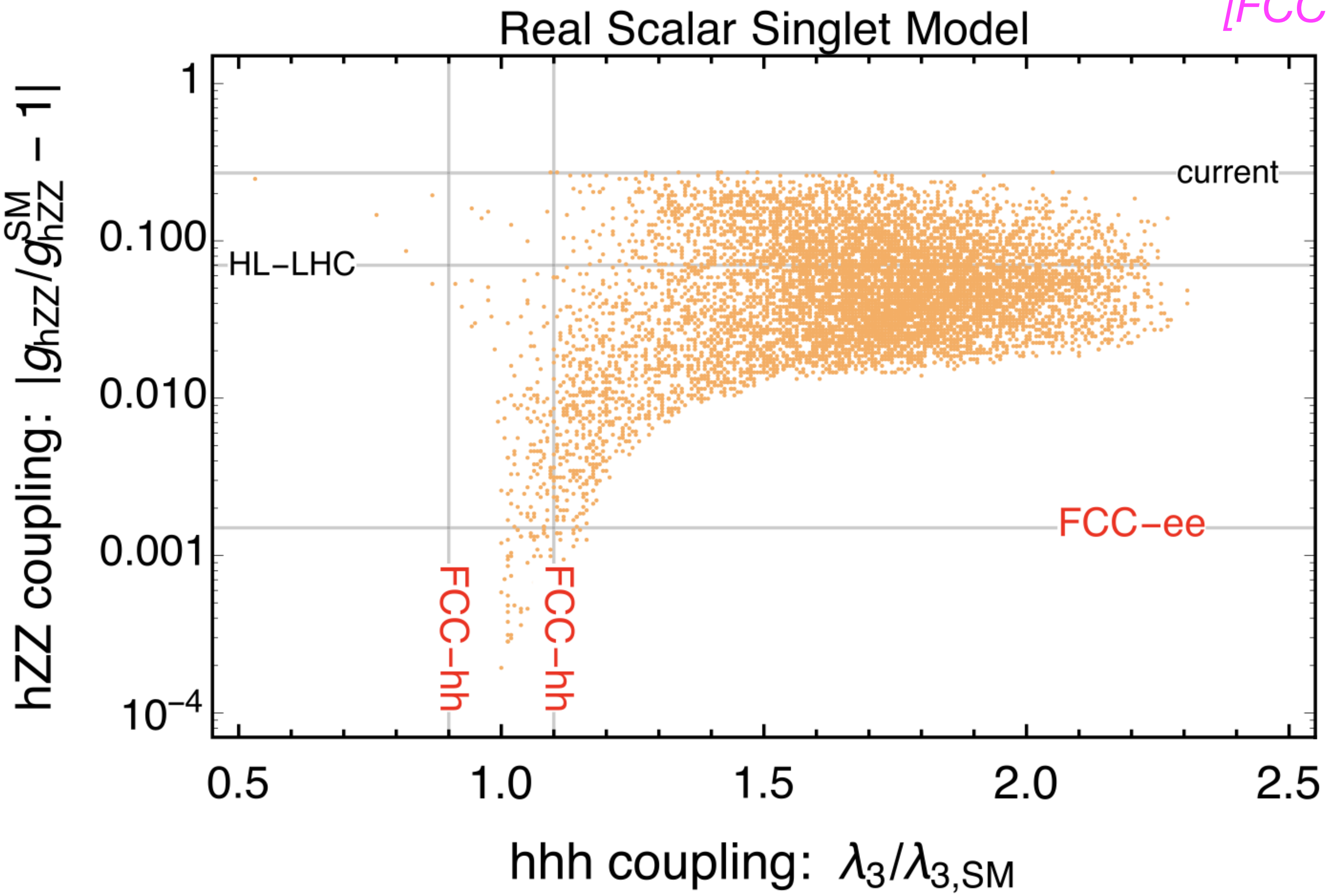
# Correlation of deviations in $\varkappa_\lambda$ with effects in other couplings? Real scalar singlet model

*[see talk by K. Radchenko]*

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

*[FCC Midterm Report '24]*

*[P. Huang, A. Long, L. Wang '16]*



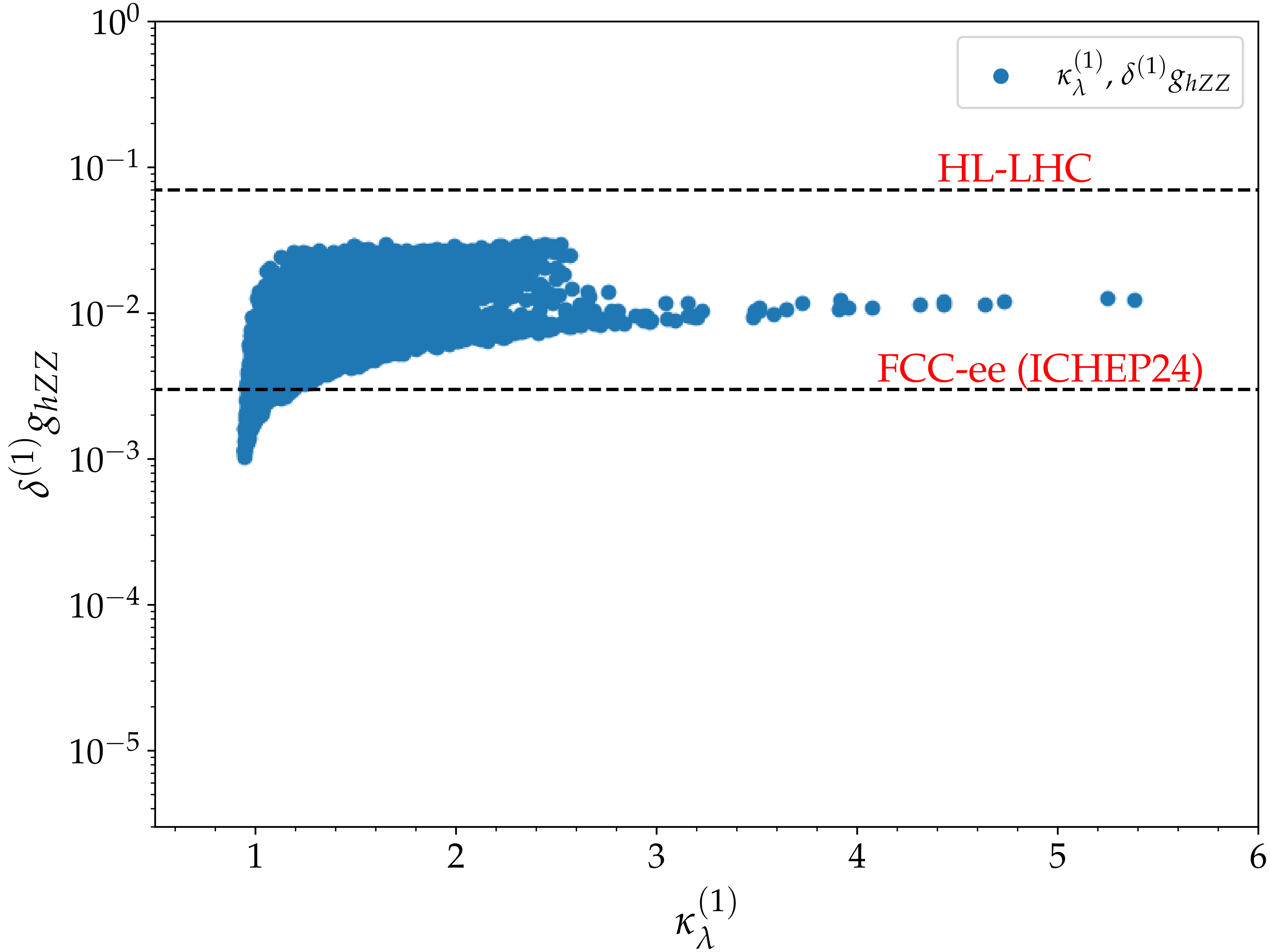

In this plot: no higher-order contributions to $\varkappa_\lambda$ included, partial loop effects for hZZ coupling

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

# Effects in $\lambda_{hhh}$ vs. $g_{hZZ}$ (and other $g_{hVV}$, $g_{hff}$ couplings)

[H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. Radchenko, A. Verduras, G. W. '25]

Real singlet extension, full 1-loop, OS, FOEWPT condition not imposed:

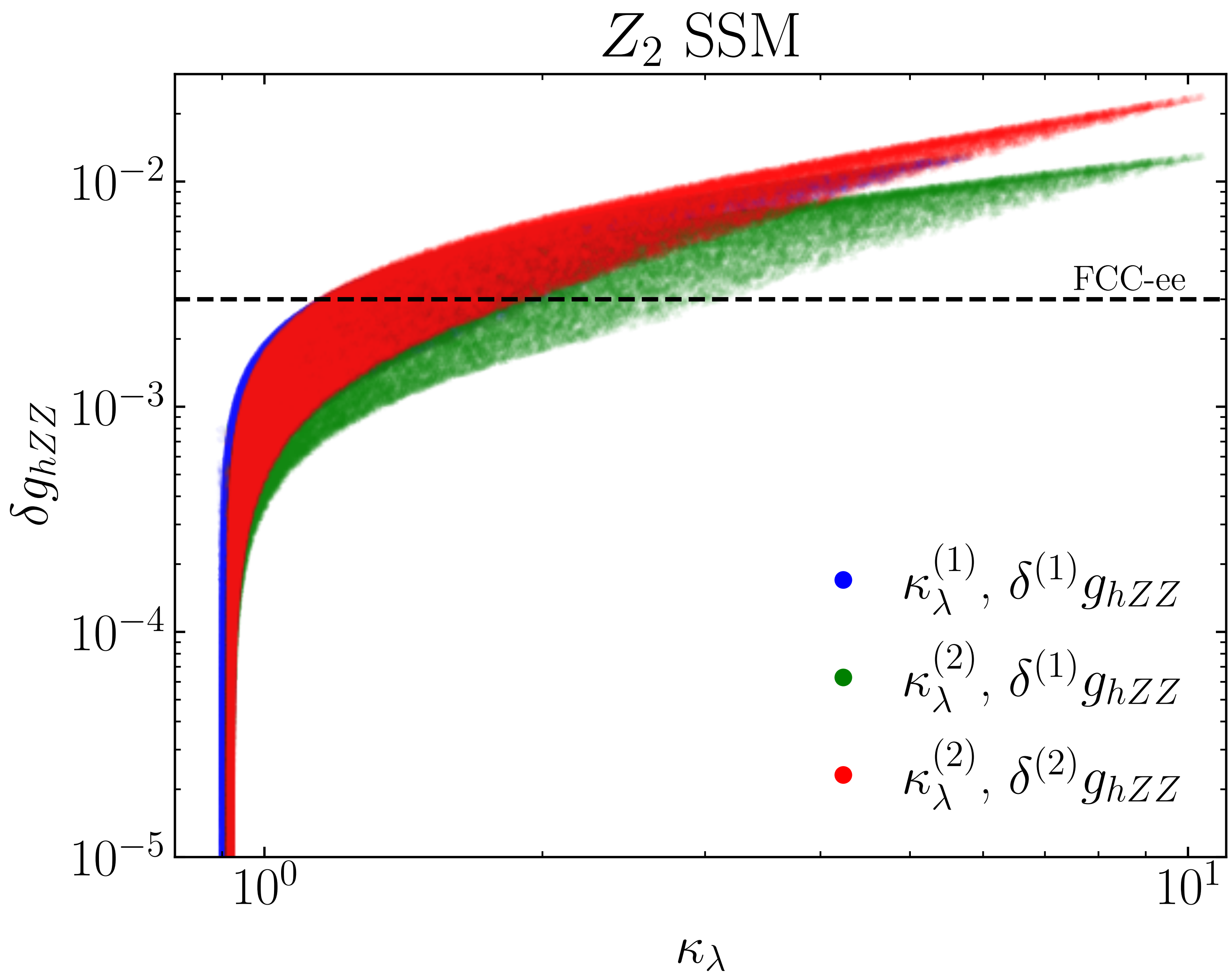



⇒ Large effects possible in $\lambda_{hhh}$ while modification of the couplings of h to gauge bosons is beyond the HL-LHC sensitivity

# Effects in $\lambda_{hhh}$ vs. $g_{hZZ}$ (and other $g_{hVV}$, $g_{hff}$ couplings)

*[H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. Radchenko, A. Verduras, G. W. '25]*

## $Z_2$-symmetric singlet extension of the SM up to 2-loop level:



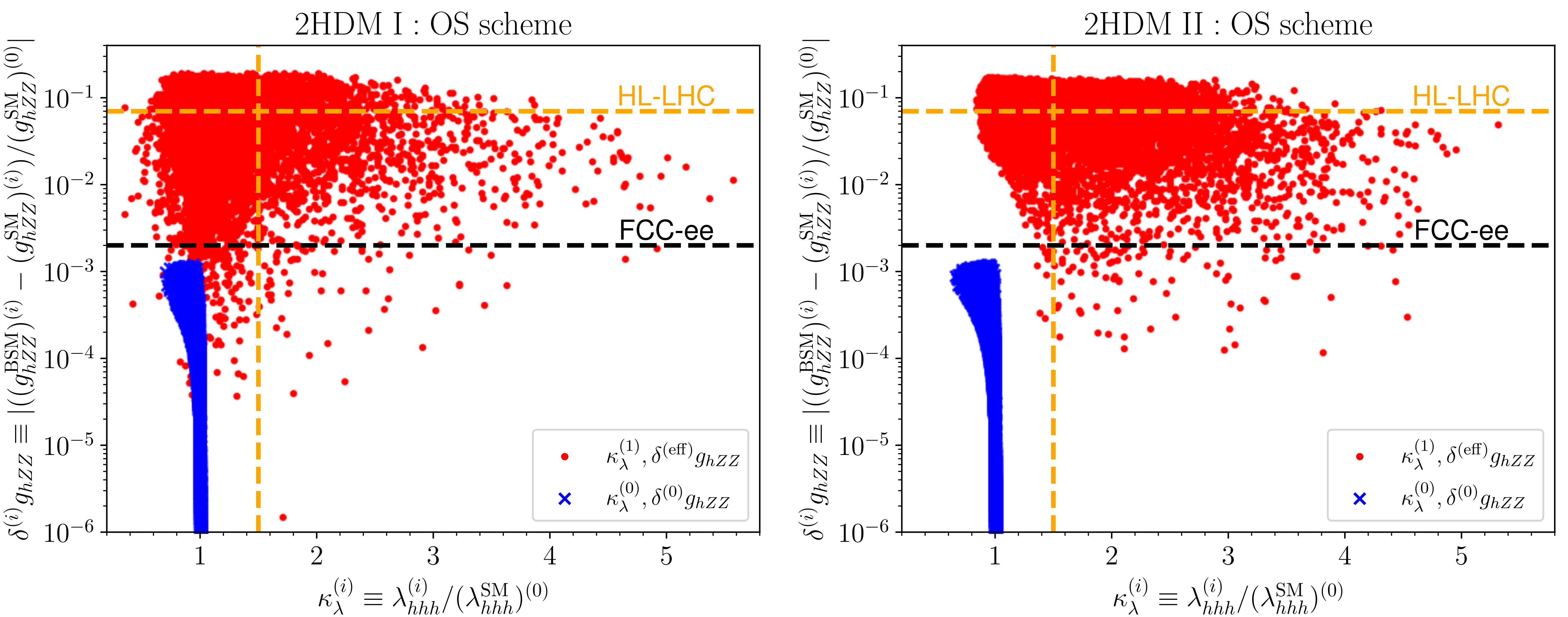

Scan results for the $Z_2$-SSM, shown in the plane of $\kappa_\lambda$ and $\delta g_{hZZ}$. The colour of the points indicates the order (one or two loops) at which these two quantities are computed, and is explained in the legend of the plot. The black dashed line corresponds to the expected $1\sigma$ accuracy of FCC-ee on the hZZ coupling.

$\Rightarrow$ Large effects possible in $\lambda_{hhh}$ while the couplings of h to gauge bosons and fermions are very close to the SM value!

# Effects in $\lambda_{hhh}$ vs. $g_{hZZ}$ (and other $g_{hVV}$, $g_{hff}$ couplings)

[H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. Radchenko, A. Verduras, G. W. '25]

## 2HDM of type I and type II:

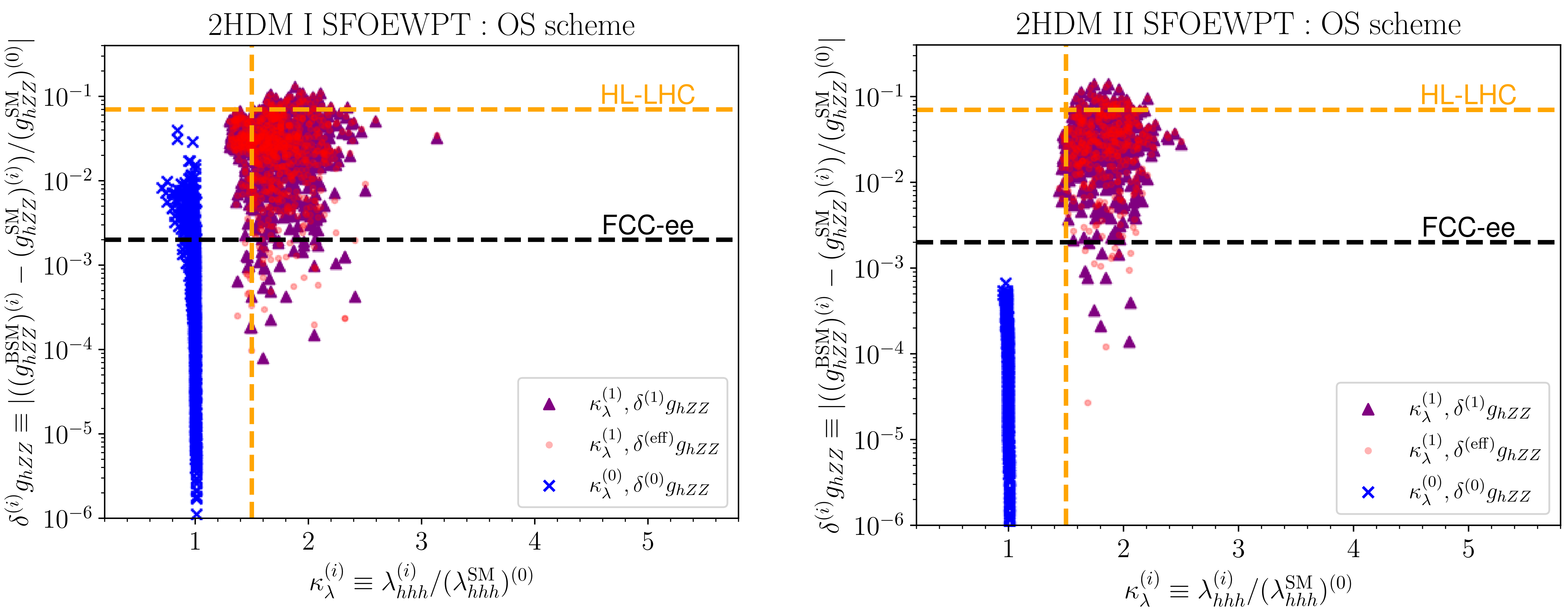



⇒ Large effects possible in $\lambda_{hhh}$ while the couplings of h to gauge bosons and fermions are very close to the SM value!

# Effects in $\lambda_{hhh}$ vs. $g_{hZZ}$ (and other $g_{hVV}$, $g_{hff}$ couplings)

*[H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. Radchenko, A. Verduras, G. W. '25]*

2HDM of type I and type II (FOEWPT condition imposed):




⇒ Large effects possible in $\lambda_{hhh}$ while the couplings of h to gauge bosons and fermions are very close to the SM value!

# Further "smoking gun" signature

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

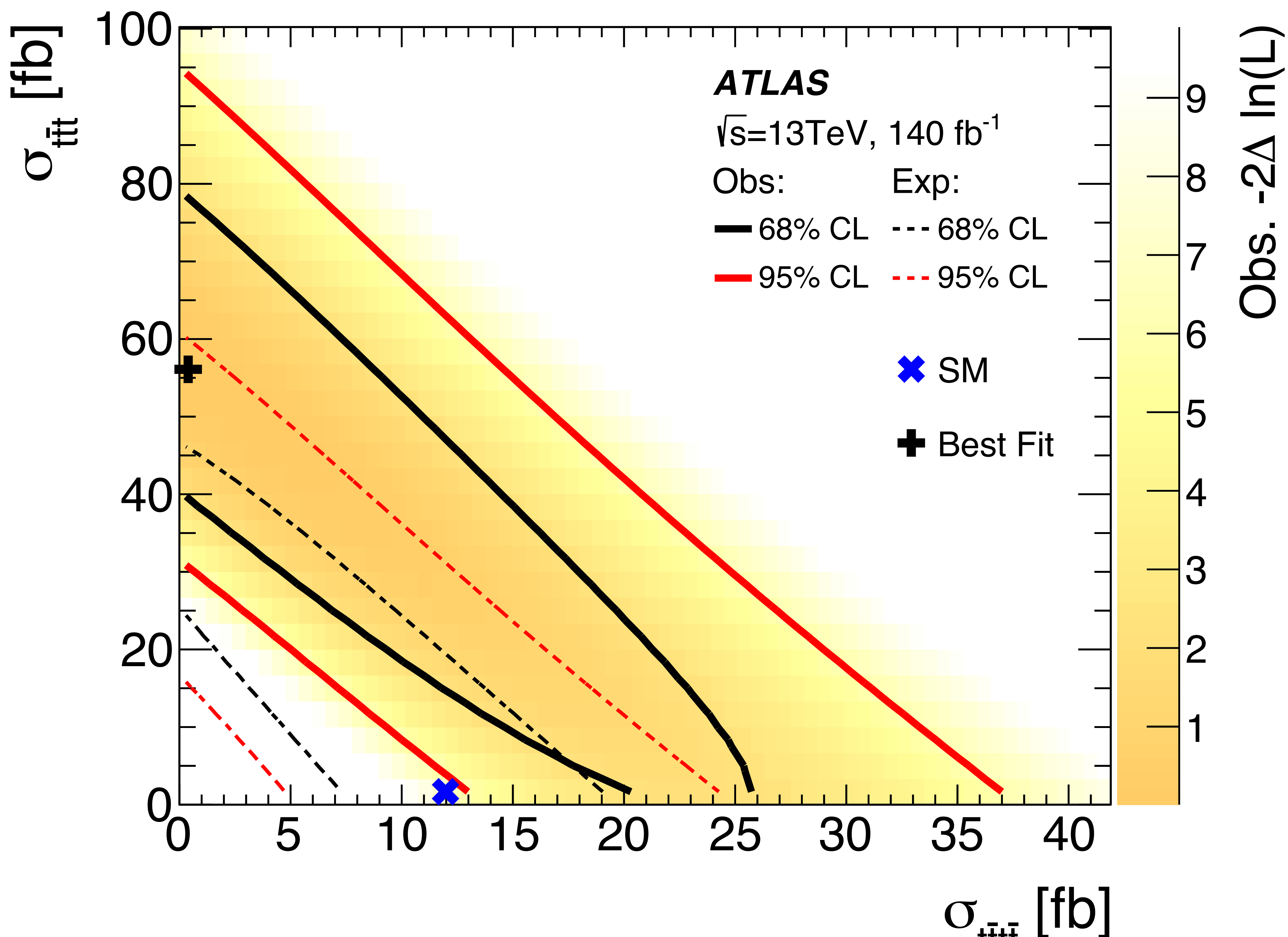
$$H^\pm \to W^\pm H \to \ell^\pm \nu t\bar{t}$$

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 cross section measurement: 4-top vs. 3-top final states

*[ATLAS Collaboration '23]*



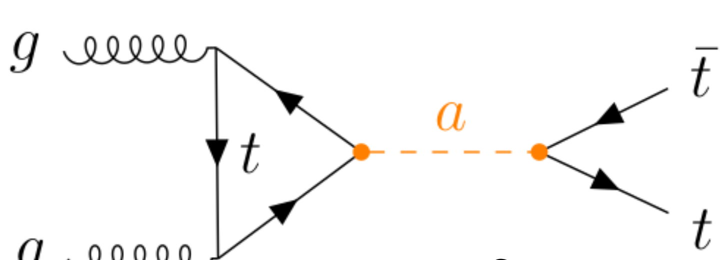
# Interference contributions as powerful tool for determining the nature of a possible signal

CP-odd Higgs boson vs. ALP (axion-like particle: coupling to top quarks like for CP-odd Higgs, but additional effective coupling to gluons)

[L. Jeppe '23]

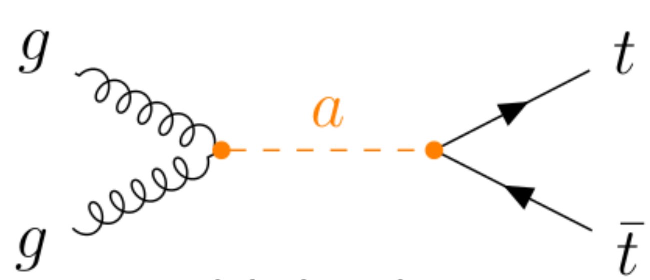
- ALP couplings: photons, EW bosons, gluons, massive fermions
  - massive fermions: usual models: Yukawa-like ~ $m_f$
- Produce at the LHC via gluon fusion
- If $m_a > 2m_t$: decay to top quarks $\rightarrow$ interferes with SM final state:

ALP




$\propto c_t^2$

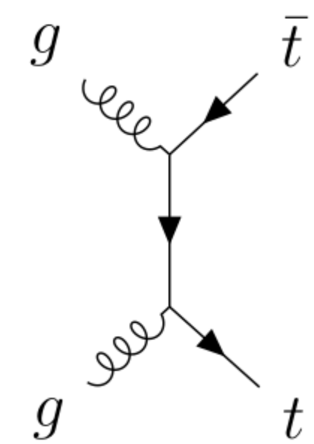
\+




$\propto c_G \, c_t$

\+

SM




\+ ...

$O(m_a) \approx m_t$
$\rightarrow$ top quark loop explicitly considered

Explicit gluon coupling - physics at high scales integrated out

Effective ALP Lagrangian:

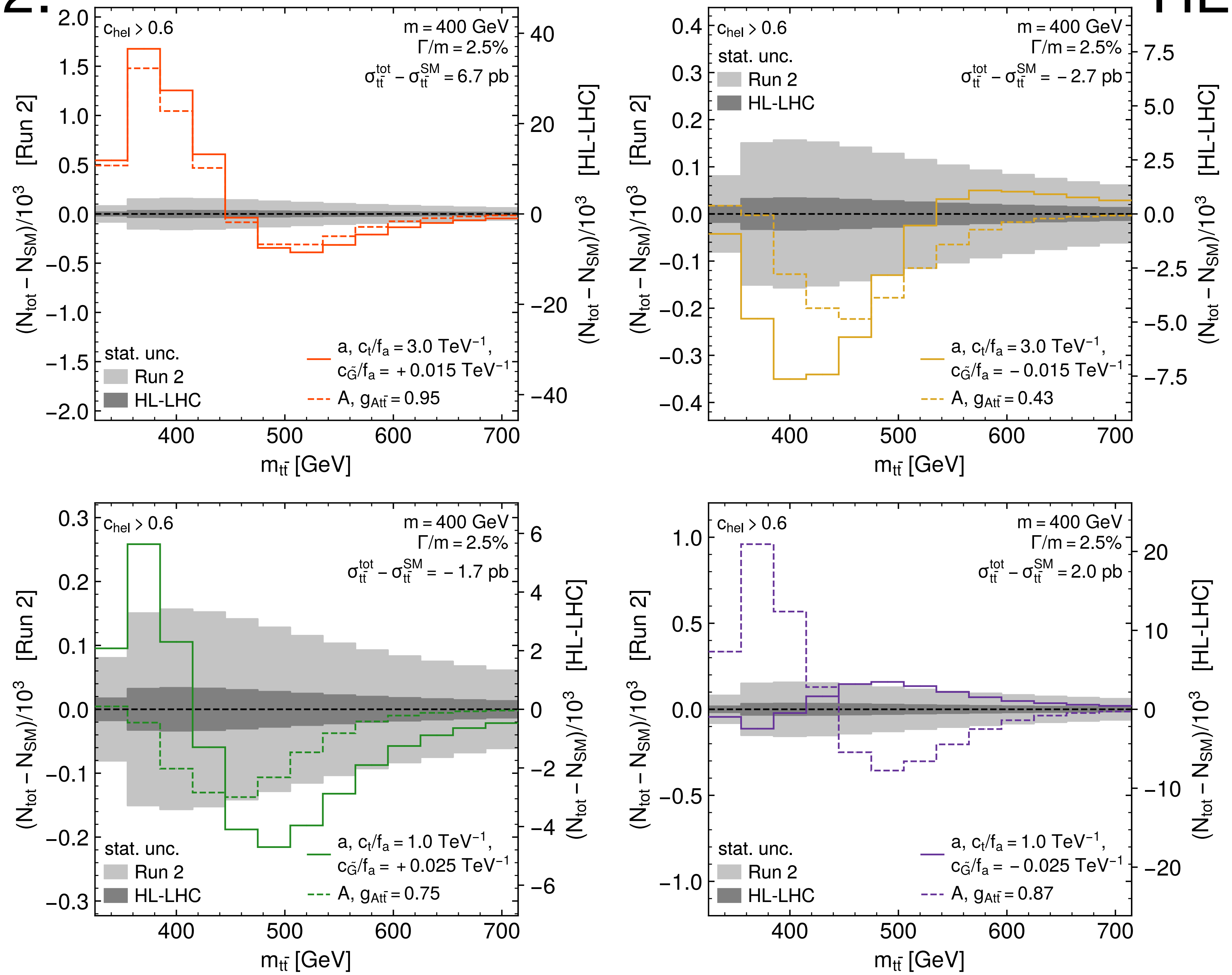
ALP couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \frac{m_a^2}{2}a^2 - \frac{a}{f_a} c_{\tilde{G}}\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + i c_t \, \frac{a}{f_a}\left(\bar{q}\, Y_t\, \tilde{H}\, t_R + \text{h.c.}\right)$$

# Expected sensitivity for an ALP ($c_{\tilde{G}} \neq 0$) and a CP-odd Higgs boson with same total cross section

*[A. Anuar et al. '24]*

LHC Run 2: HL-LHC:




⇒ High sensitivity for detecting a signal, good prospects for distinguishing ALP from CP-odd Higgs

# Where should experiment and theory meet?

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

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

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

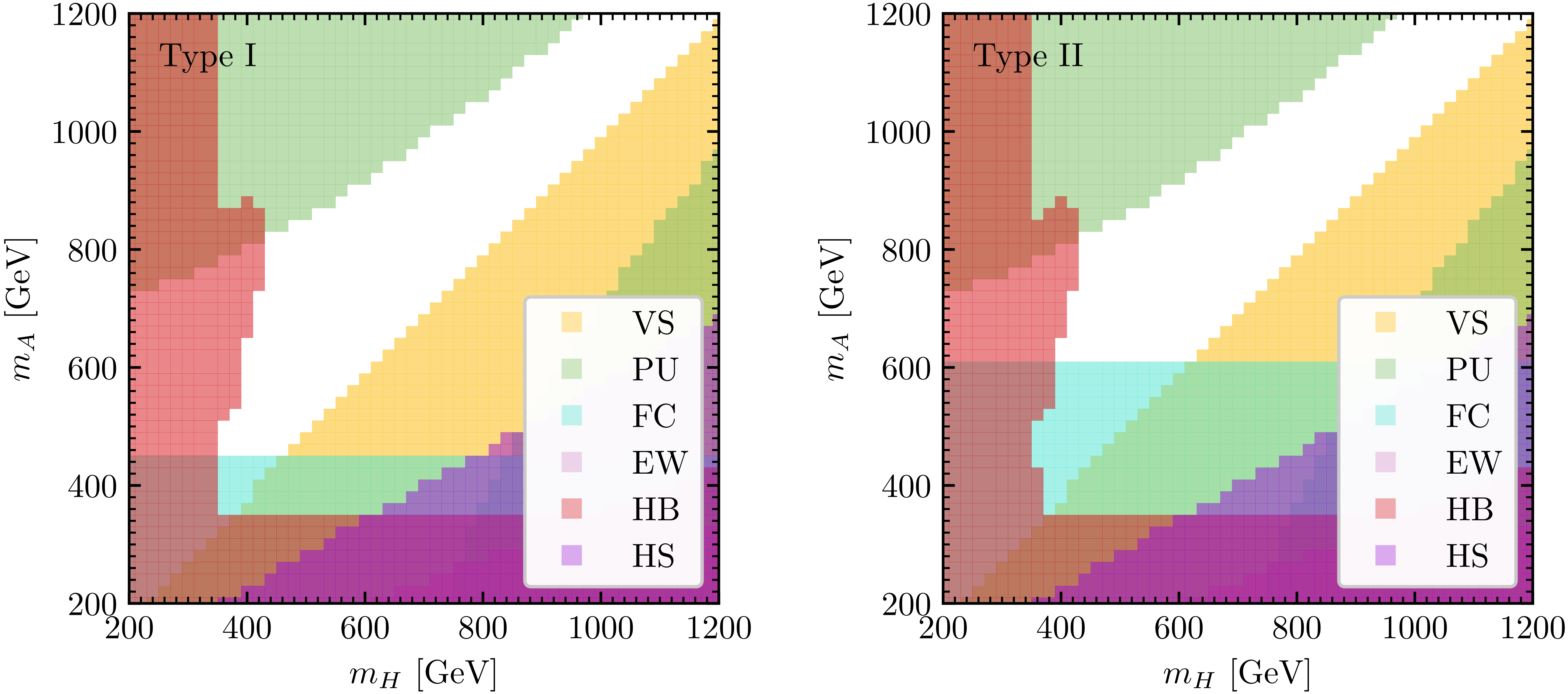
- Limits from the searches for additional Higgs bosons:
  Public tools for reinterpretation / recasting of experimental results:
  *HiggsBounds* (limits on σ x BR, full likelihood information incorporated where provided by exp. collaborations)
  Recasting tools:
  *MadAnalysis 5*, *Rivet*, *ColliderBit*,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

# Example: constraints on 2HDM type I and II

Impact of theo. and exp. constraints: vacuum stability, perturbative unitarity, flavour constraints, EWPOs, Higgs search limits (HB), Higgs measurements (HS)

$\tan\beta = 2$, alignment limit:

*[K. Radchenko et al. '25]*



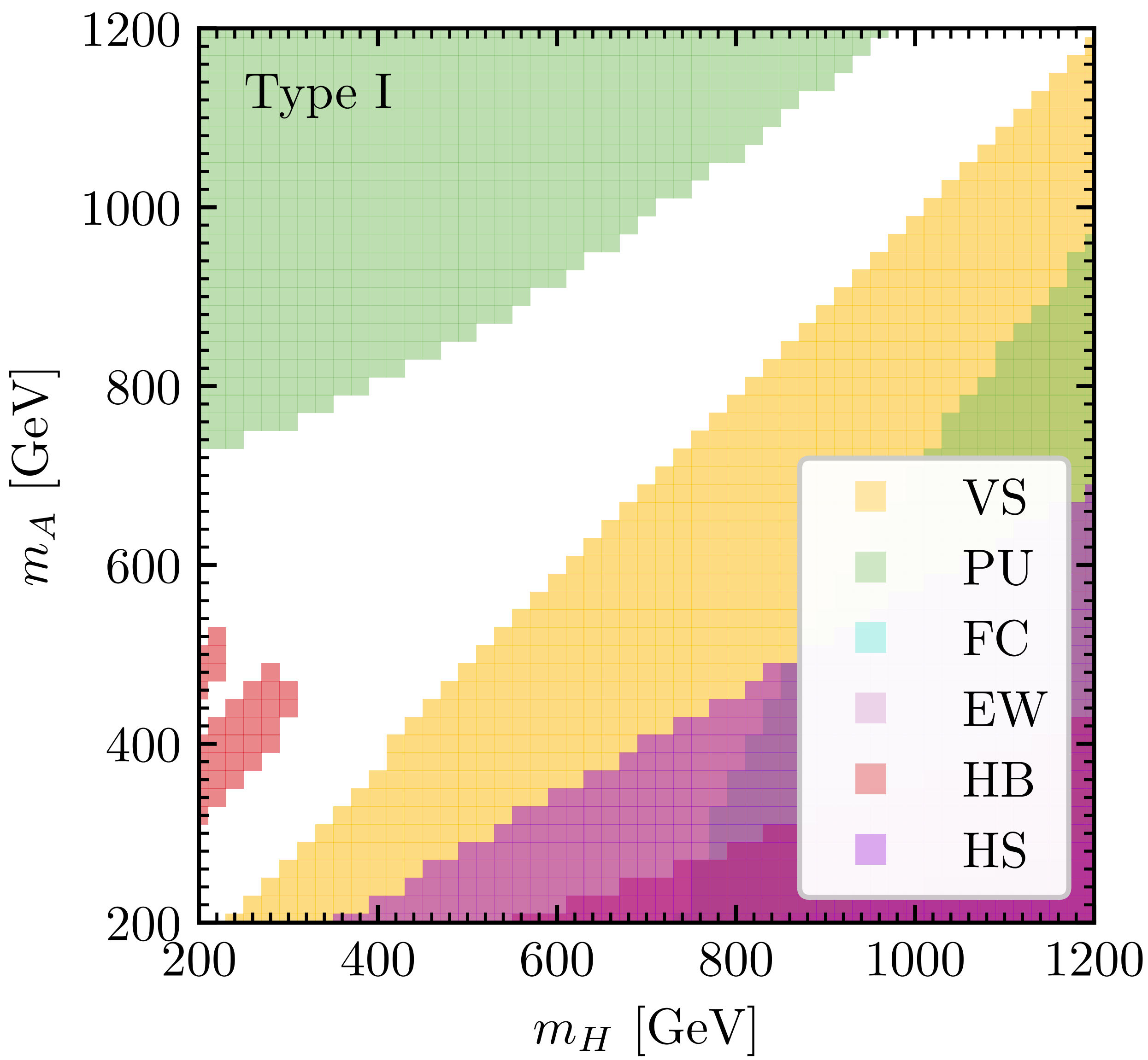

⇒ Shape of allowed region is determined by several constraints

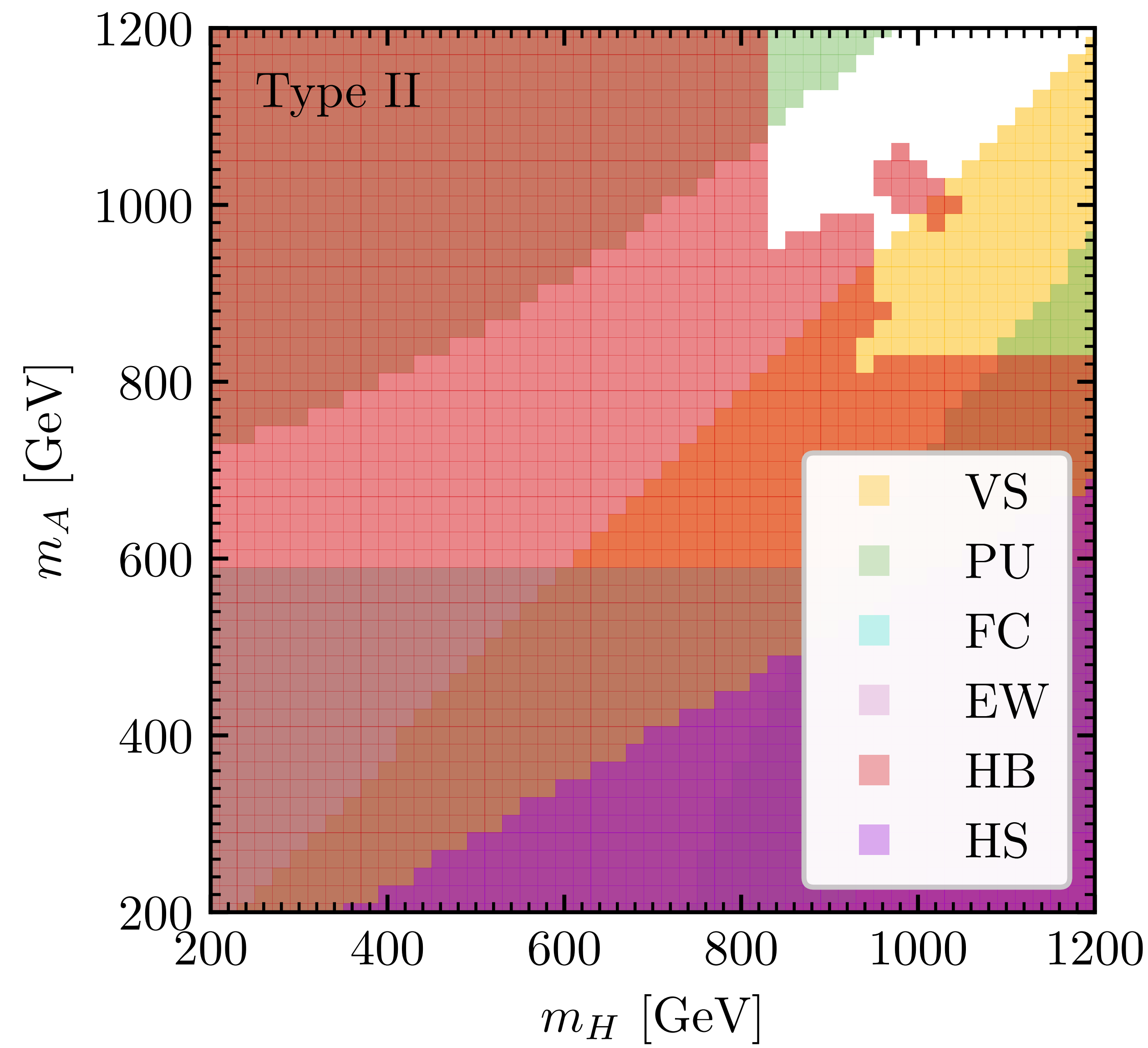
# Example: constraints on 2HDM type I and II

Impact of theo. and exp. constraints: vacuum stability, perturbative unitarity, flavour constraints, EWPOs, Higgs search limits (HB), Higgs measurements (HS)

tanβ = 10, alignment limit:

*[K. Radchenko et al. '25]*



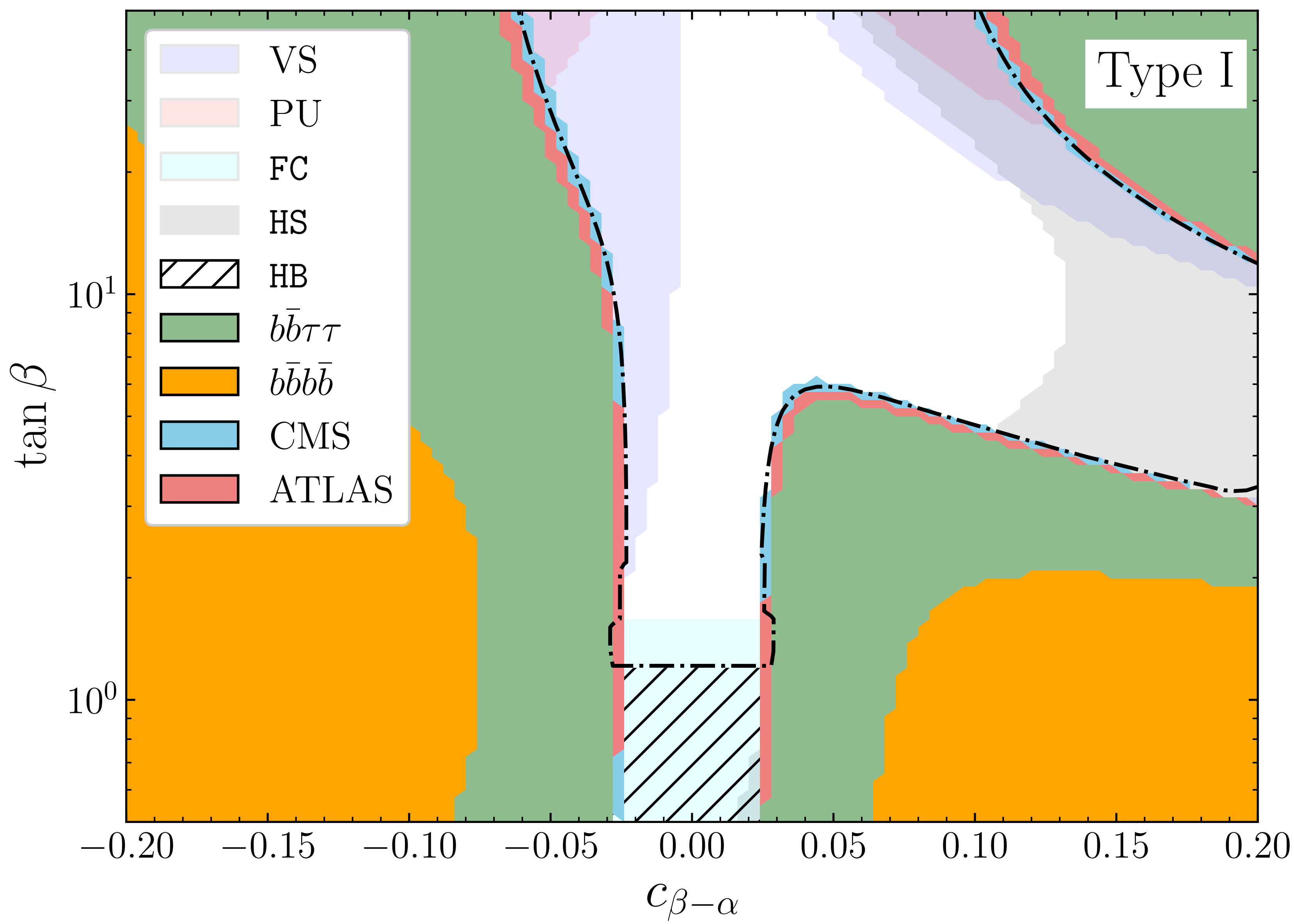

⇒ For larger values of tanβ: much reduced allowed region in type II because of limits from BSM Higgs searches (H, A → ττ, …)

# Example: constraints on 2HDM type I

Impact of theo. and exp. constraints: vacuum stability, perturbative unitarity, flavour constraints, EWPOs, Higgs search limits (HB), Higgs measurements (HS)

$m_H$ = 450 GeV, $m_A$ = $m_{H\pm}$ = 650 GeV:

*[K. Radchenko et al. '25]*




⇒ Allowed deviations from the alignment limit depend on tanβ