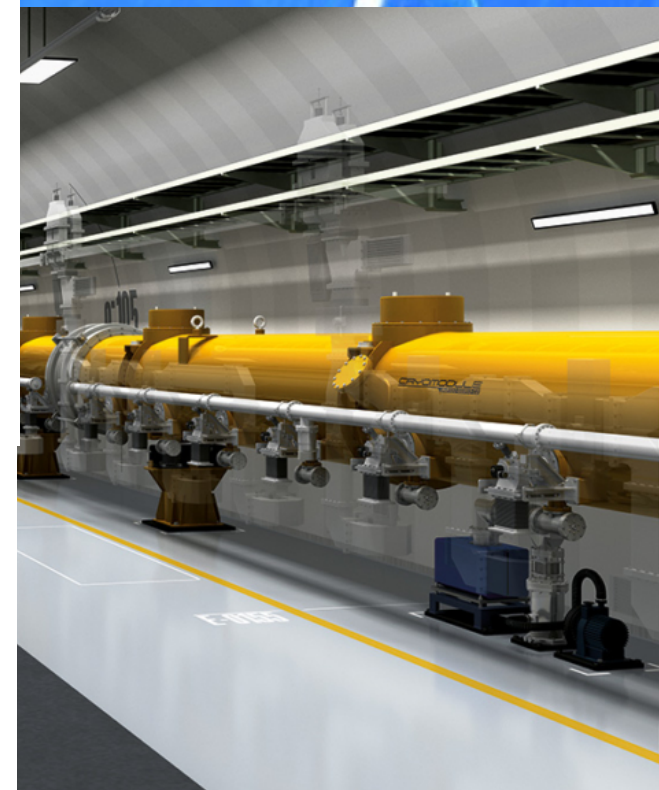
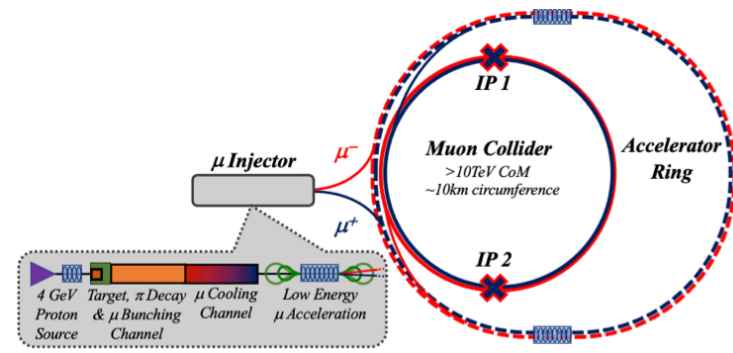
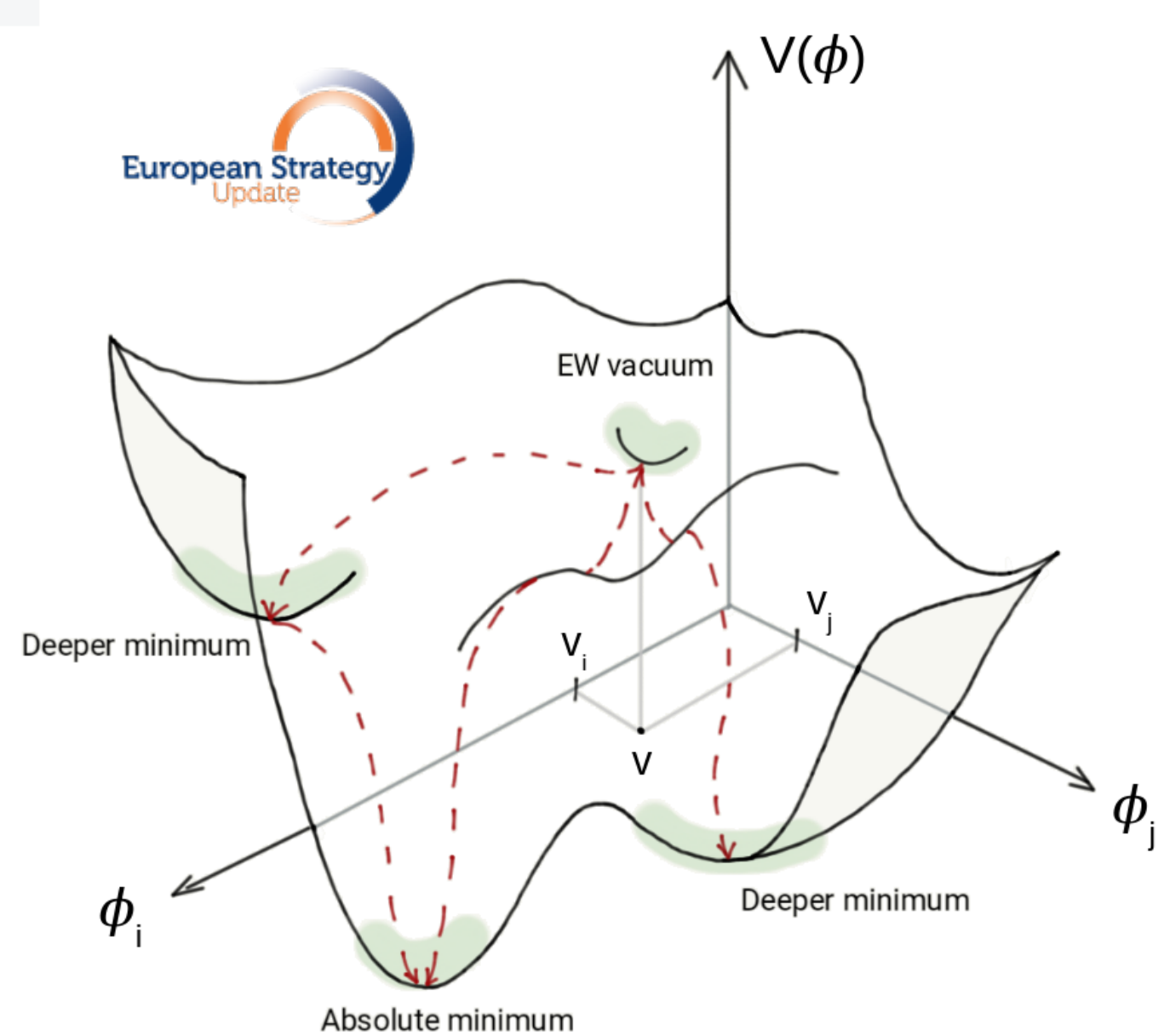
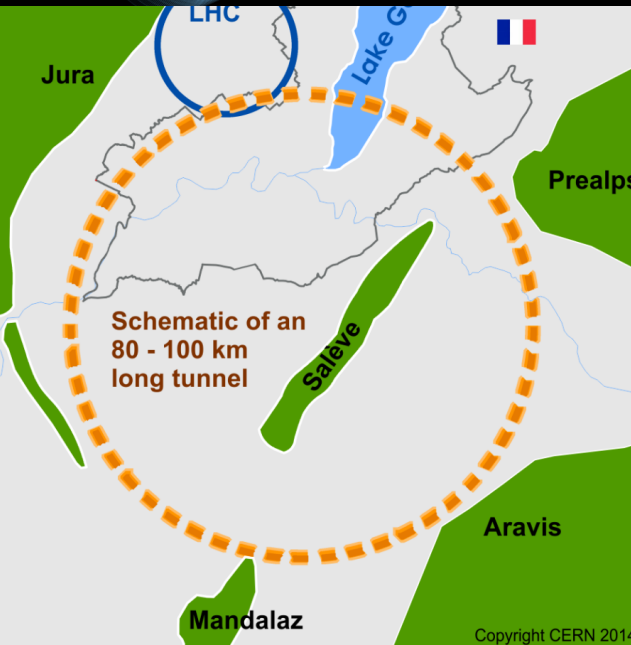
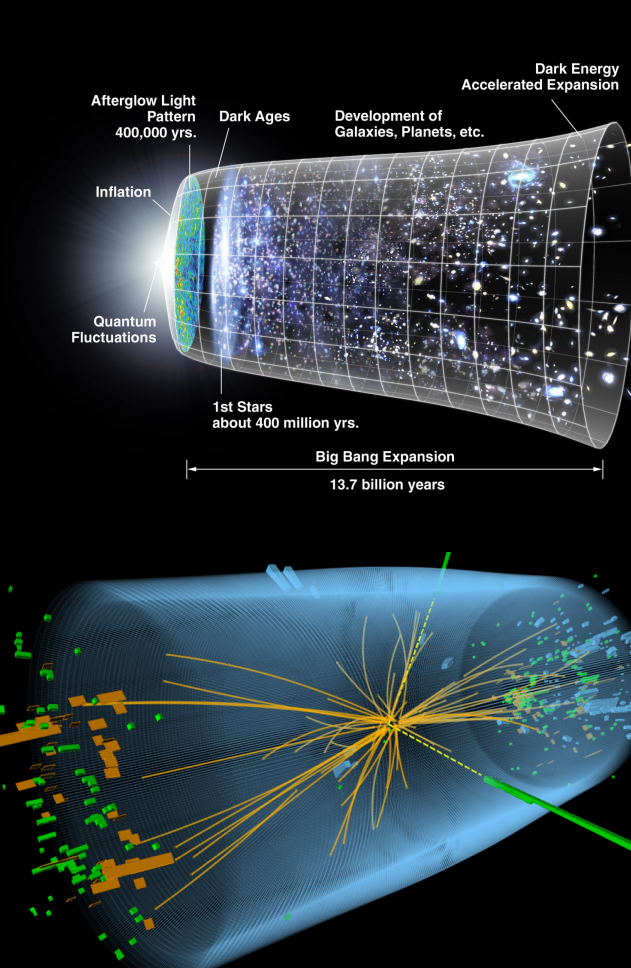




Future Perspectives for Higgs Physics

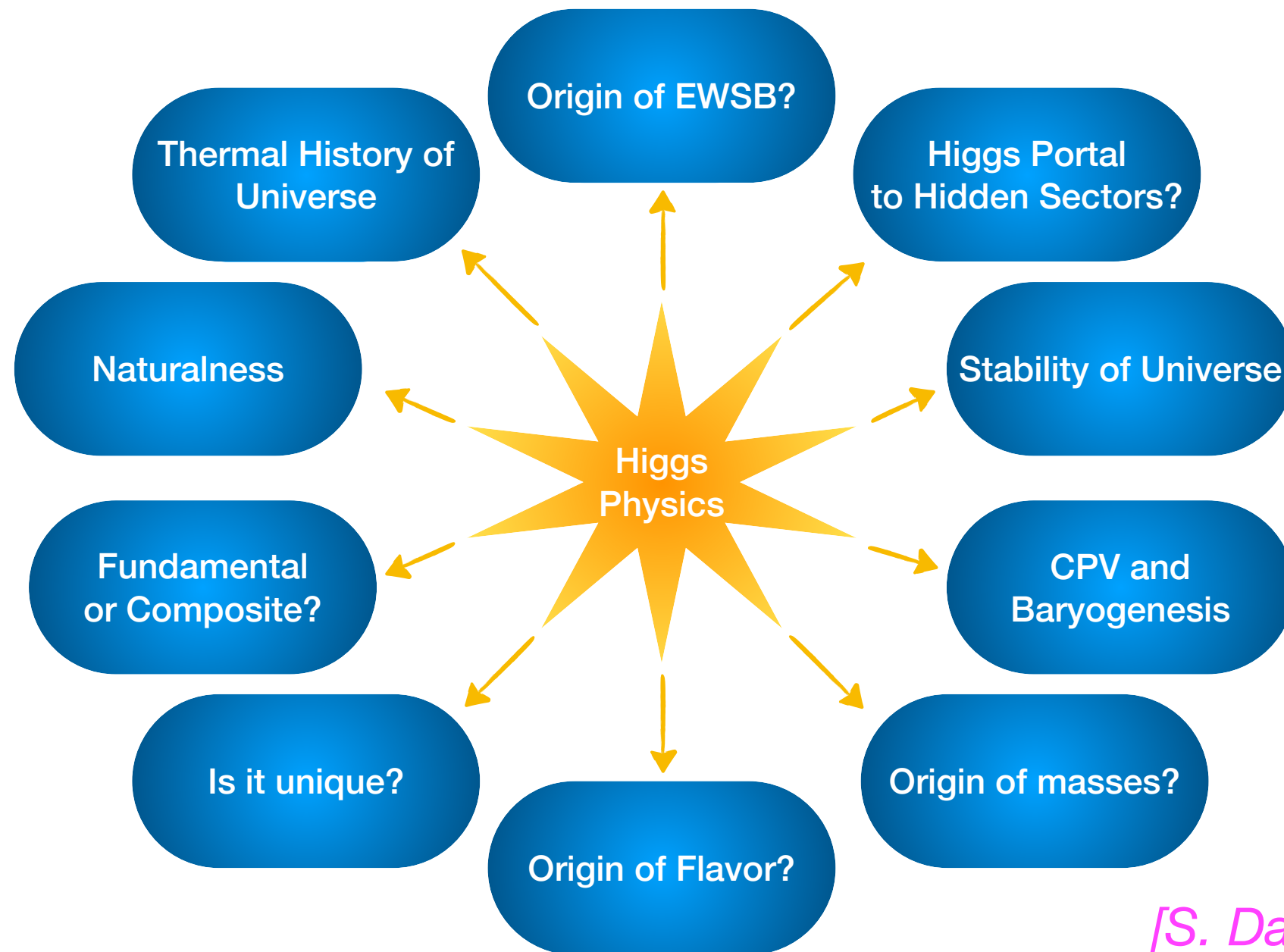
Georg Weiglein, DESY & UHH
Hamburg, 09 / 2025

Outline

- Introduction
- Properties of the detected Higgs boson (h125)
- Higgs self-couplings, the Higgs potential and probes of the electroweak phase transition
- Comparison of future options (personal view)
- 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]

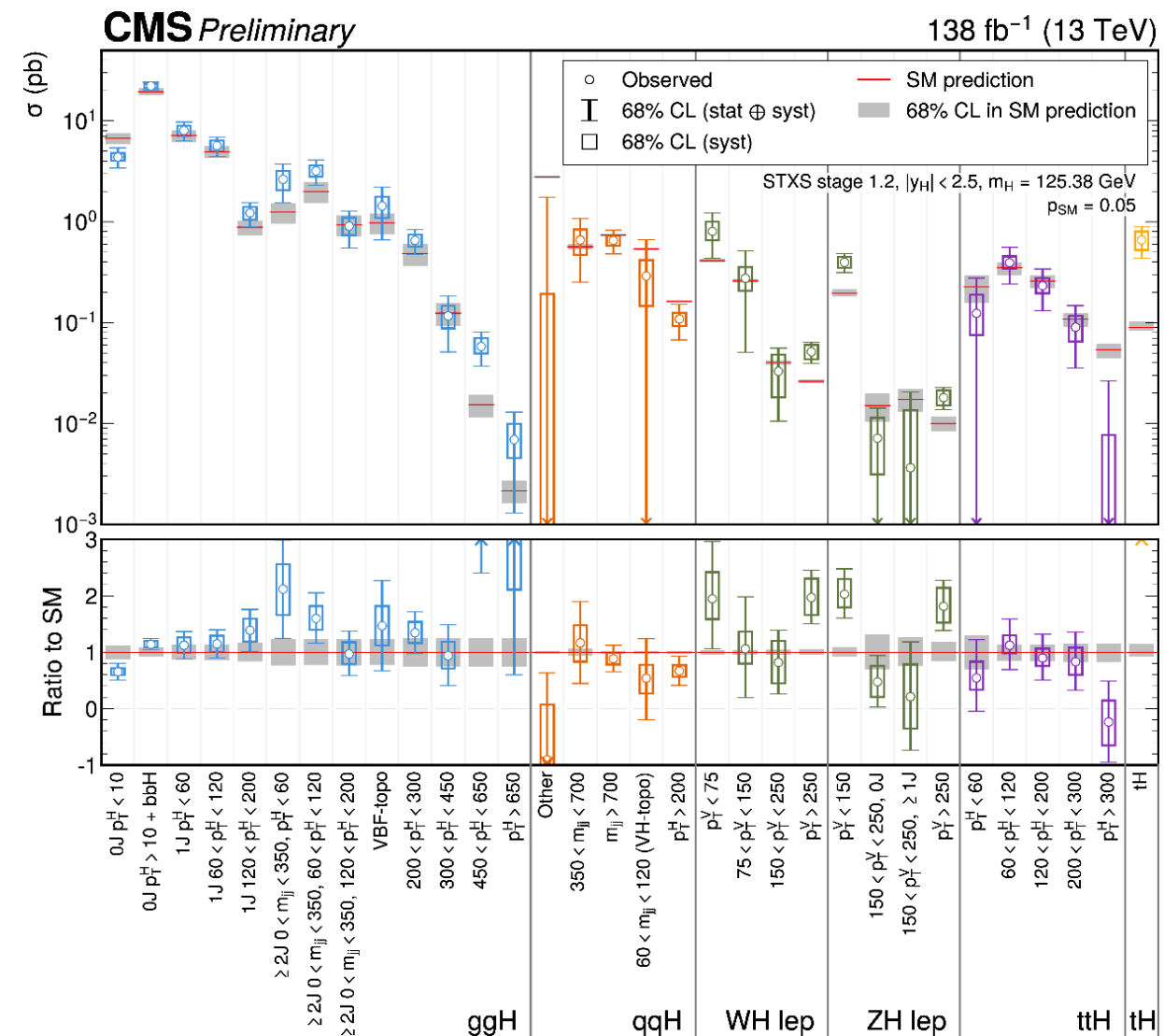
Properties of the detected Higgs boson (h125)

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

h125: inclusive and differential rates

[CMS Collaboration '25]

⇒ SM-like properties



The LHC results on h125 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



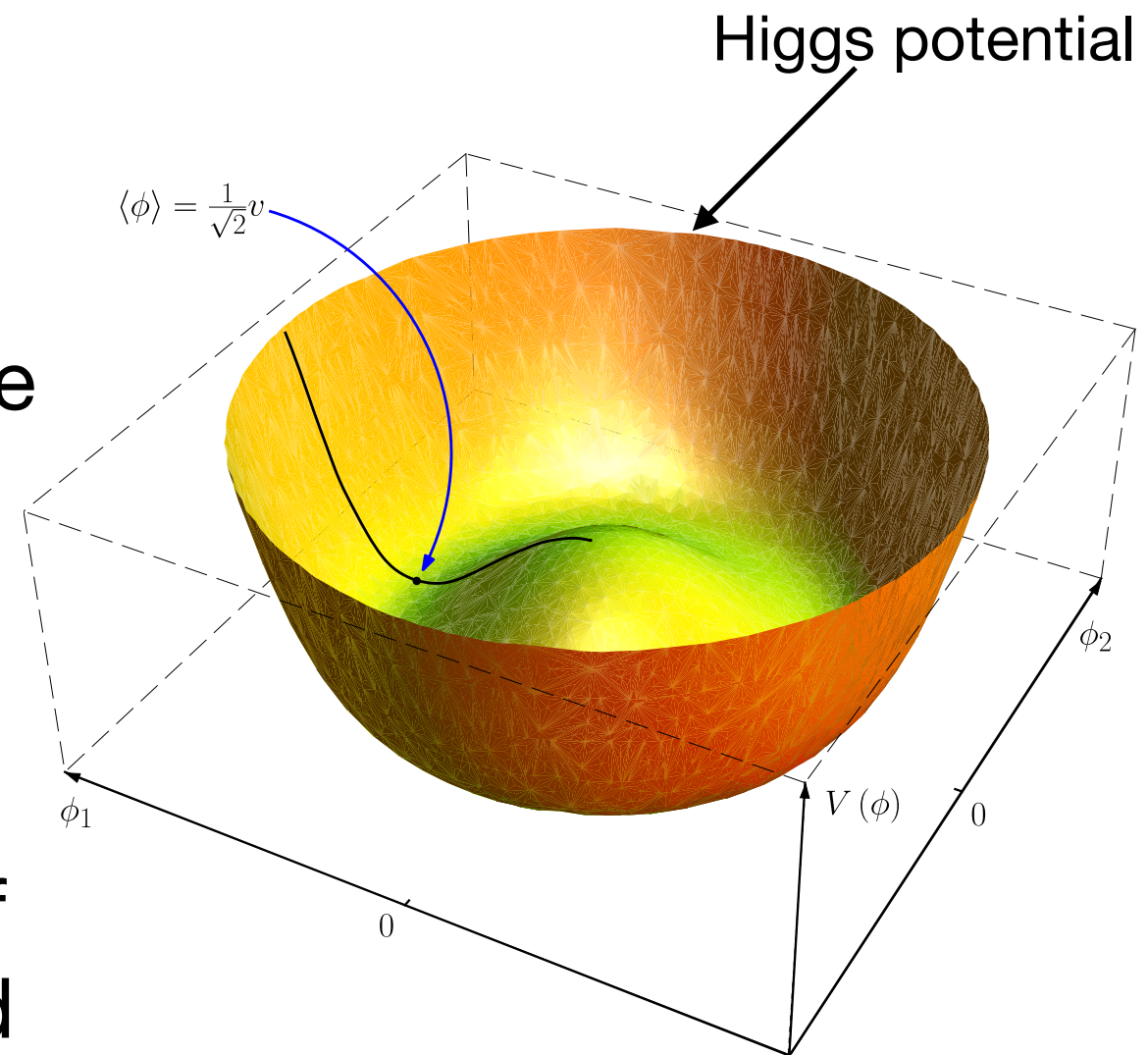
What is the underlying **dynamics of electroweak symmetry breaking**?

The vacuum structure with $v \neq 0$ 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?

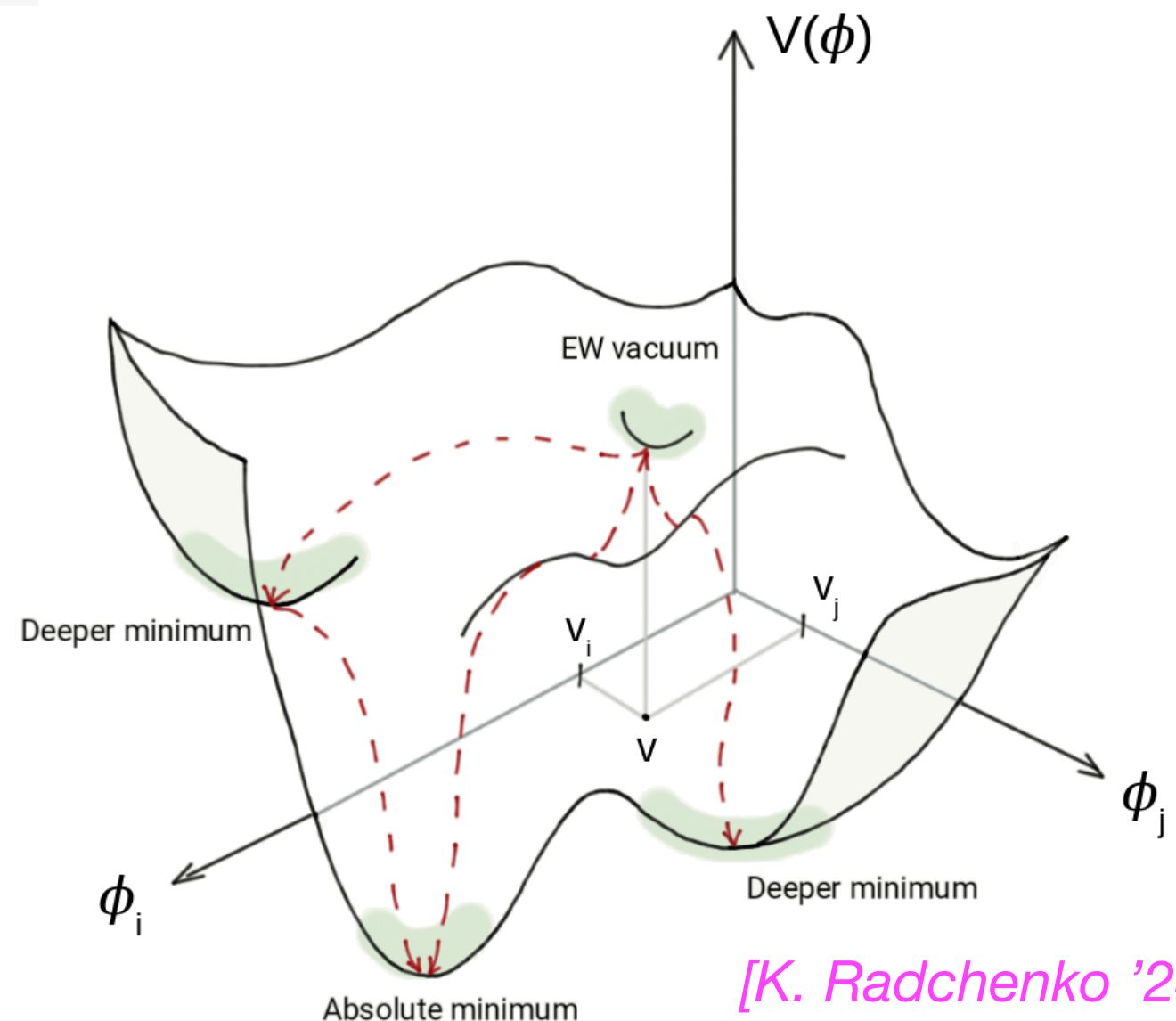
Trilinear coupling Quartic coupling Possible couplings involving additional scalars

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

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

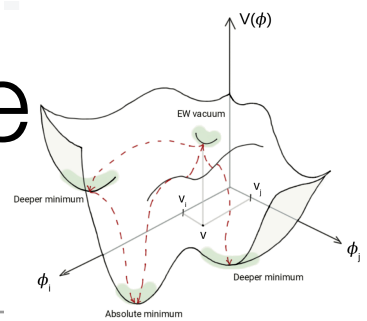
Distance of EW minimum
from origin of field space: v

Curvature of the potential
around the EW minimum: m_h



[K. Radchenko '24]

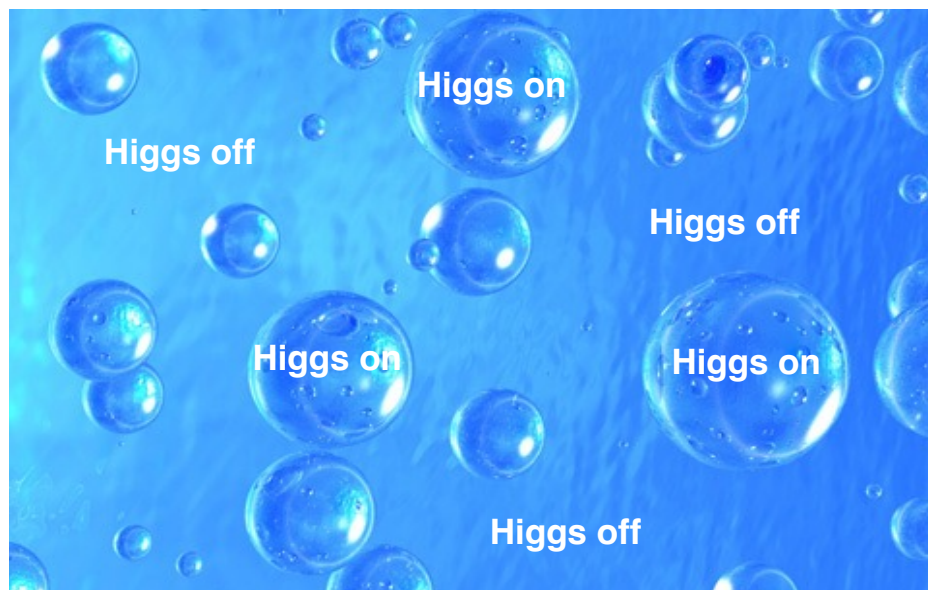
The Higgs potential and the electroweak phase transition (EWPT)



[D. Gorbunov, V. Rubakov]

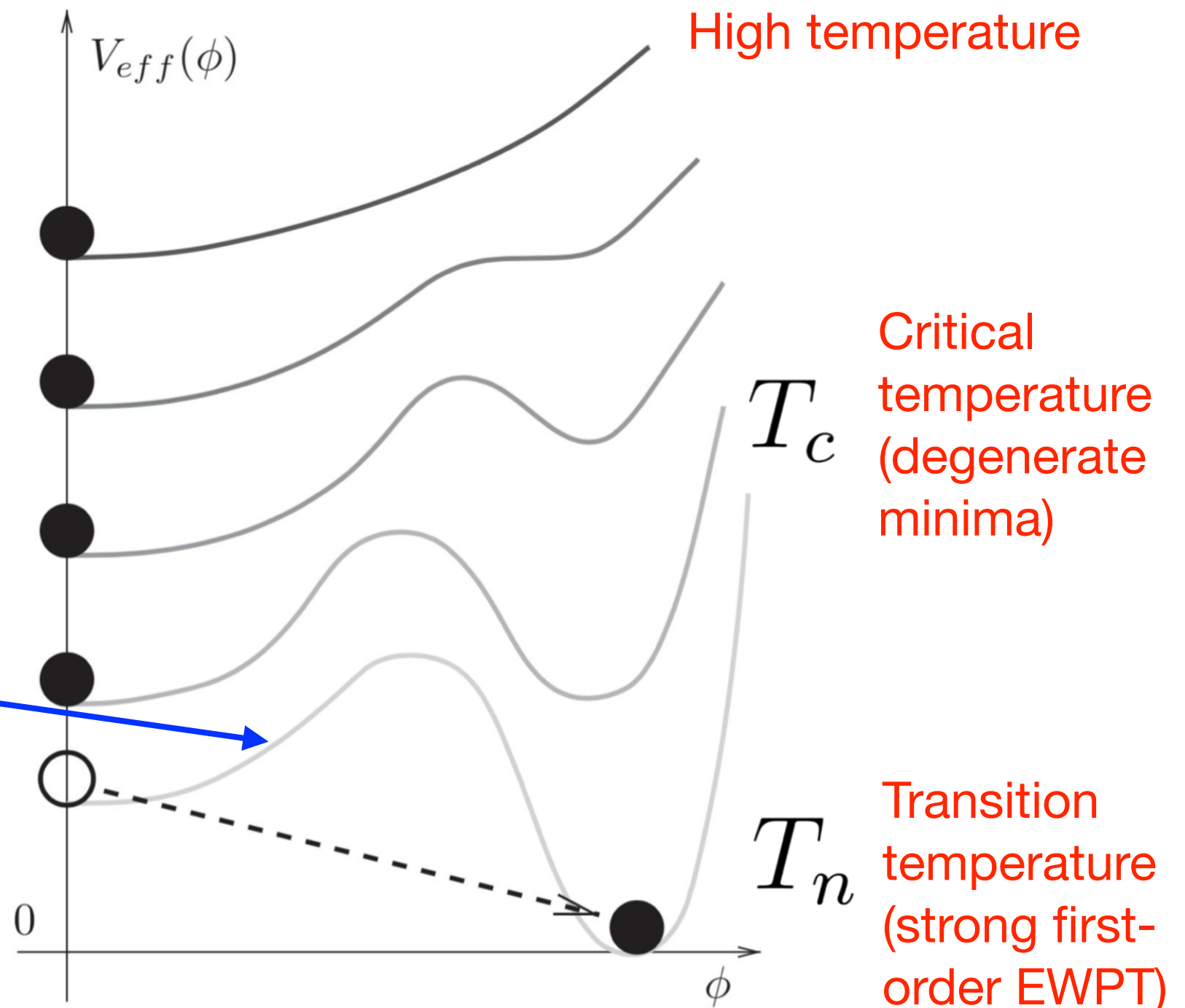
Temperature evolution of the Higgs potential in the early universe:

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

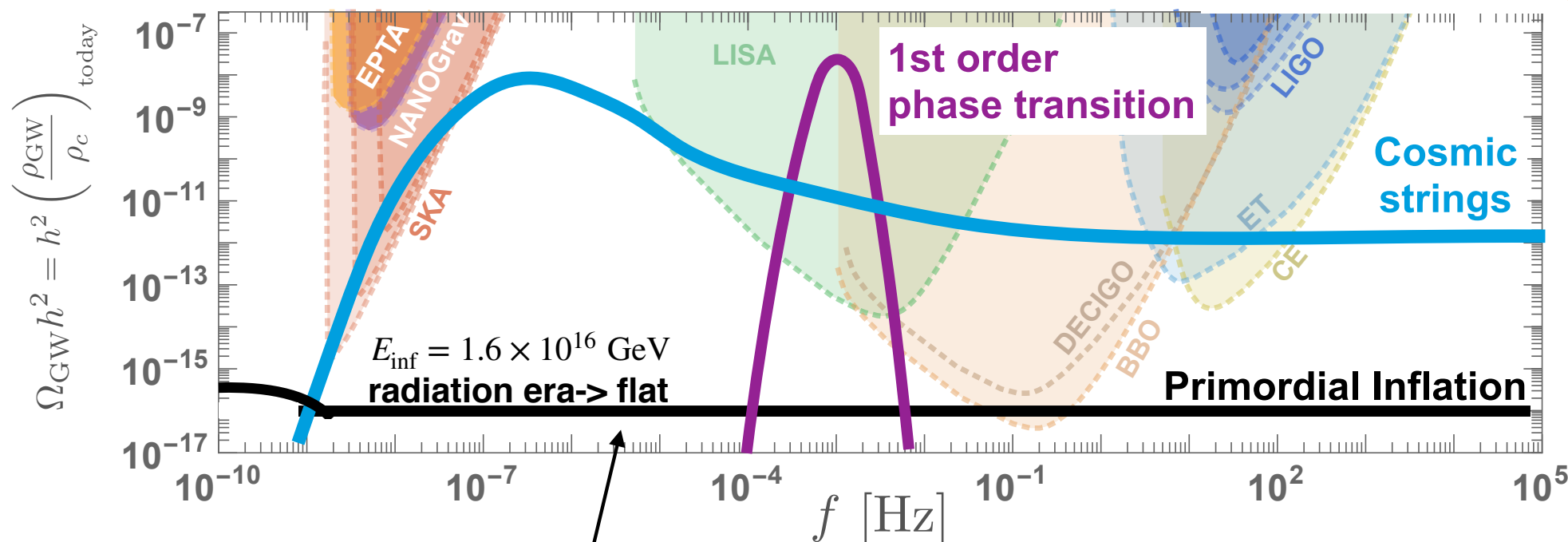
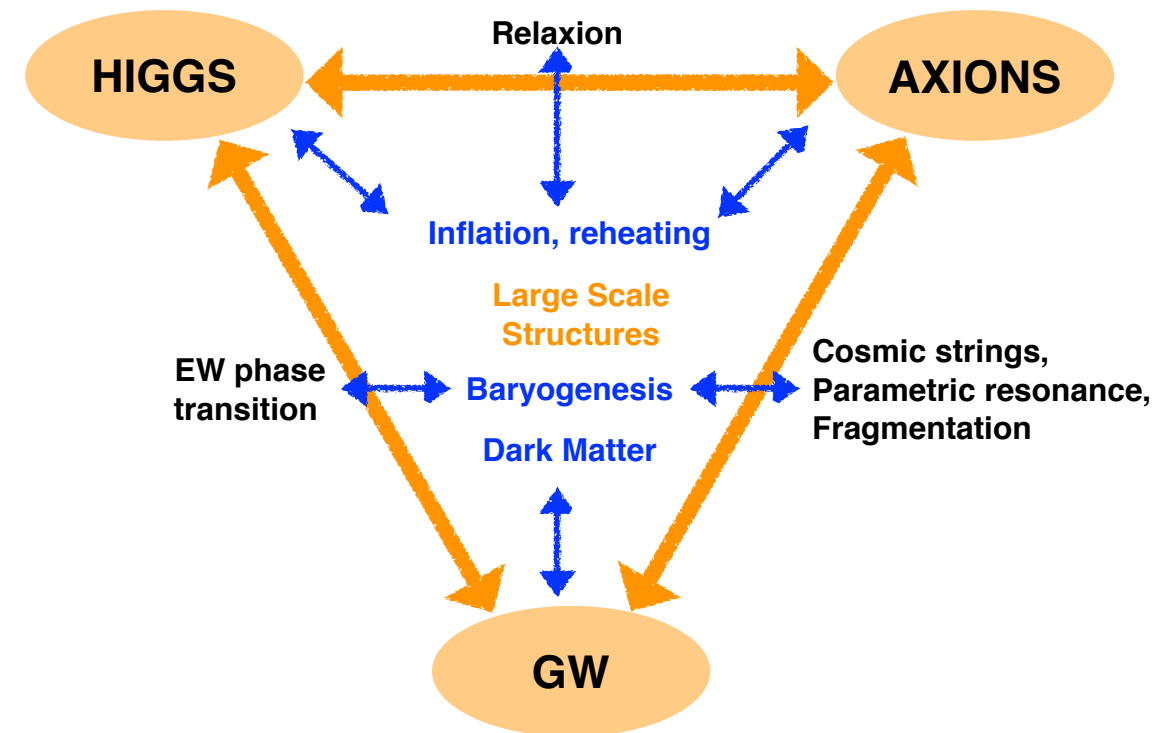
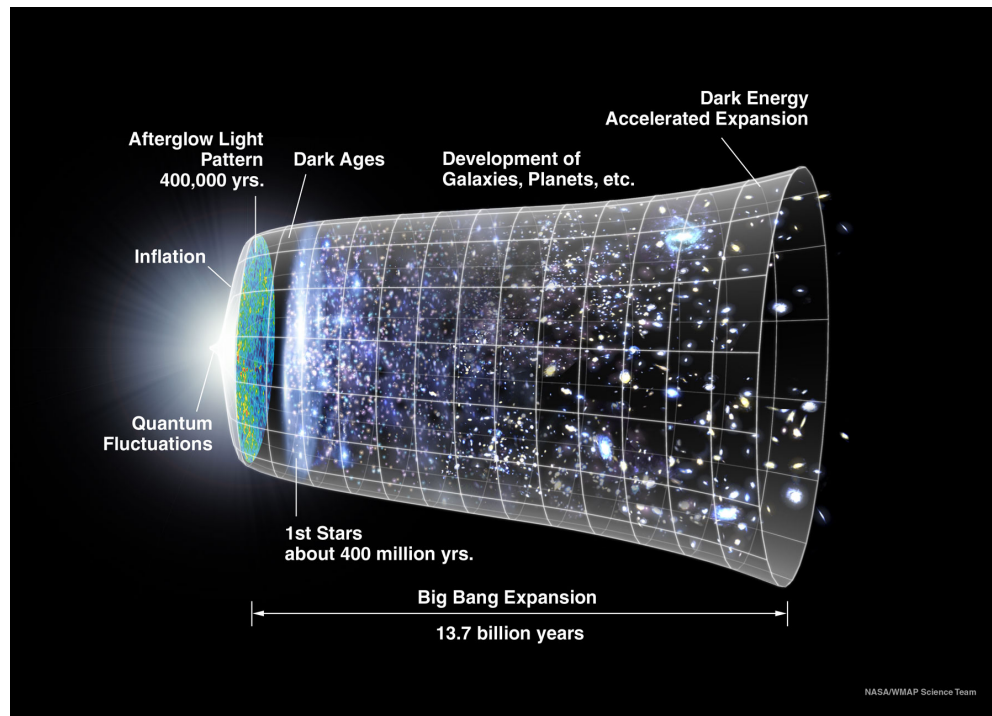


Potential barrier depends on trilinear Higgs coupling(s)

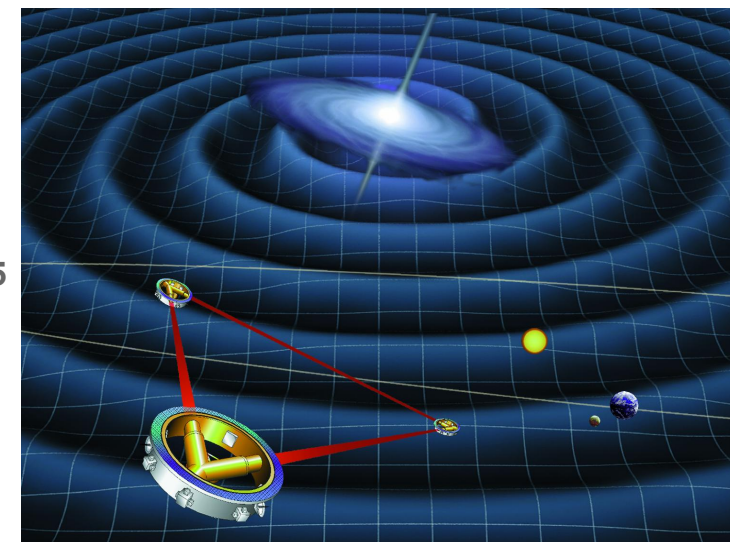
EW baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT



Gravitational waves as a probe of the early universe



LISA:



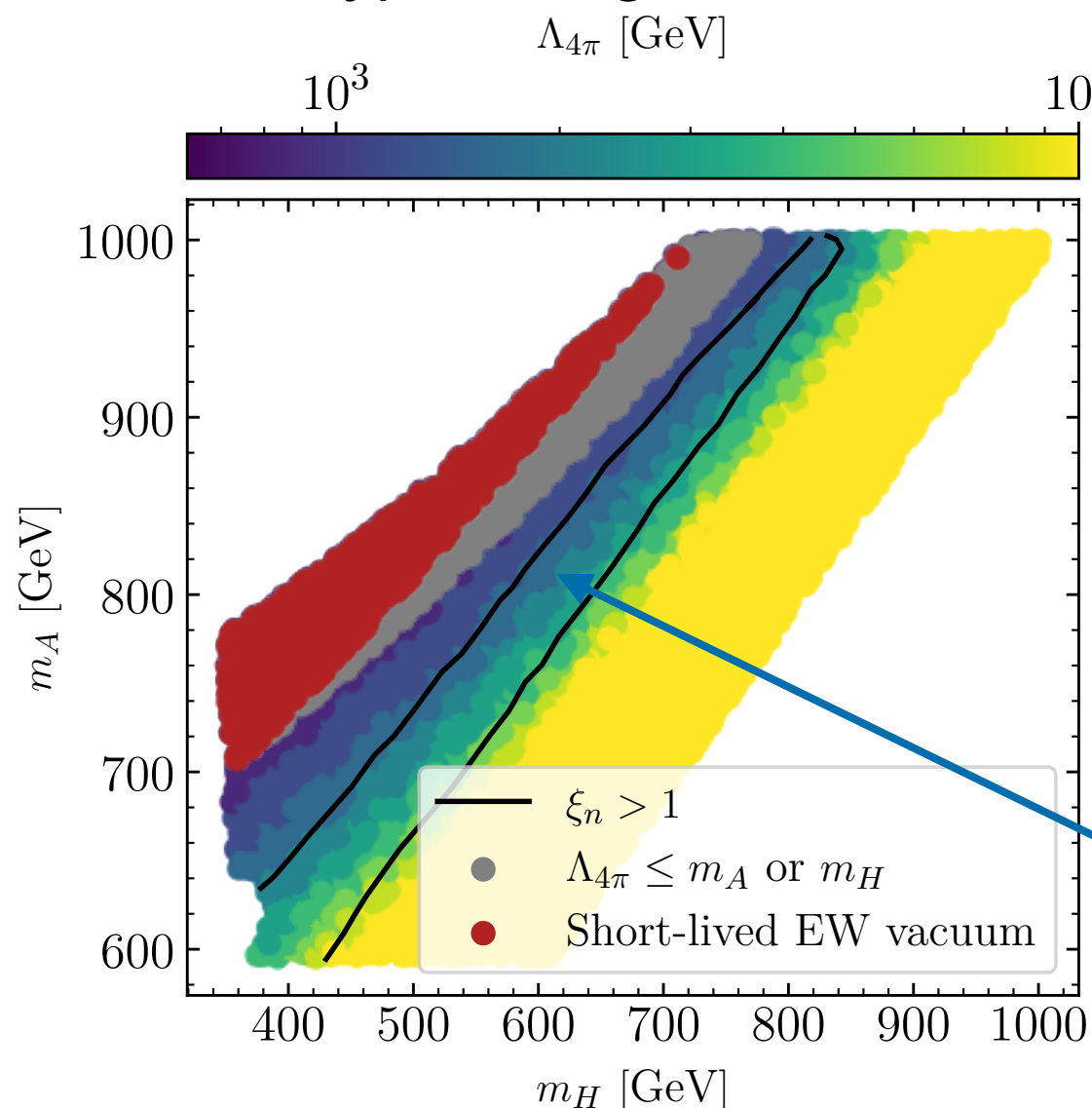
Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

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, $\tan\beta = 3$:

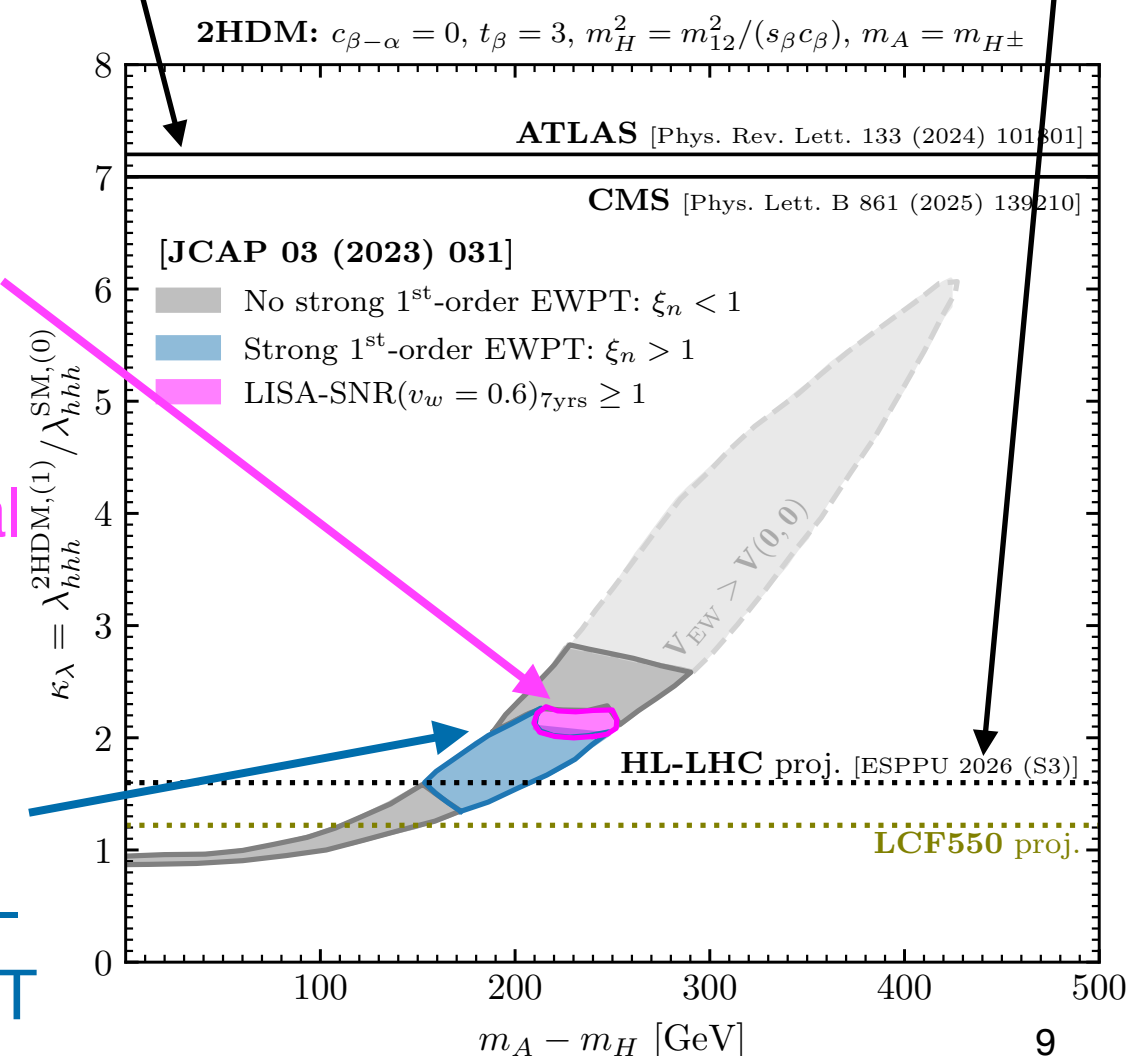


region with potentially observable gravitational wave (GW) signal

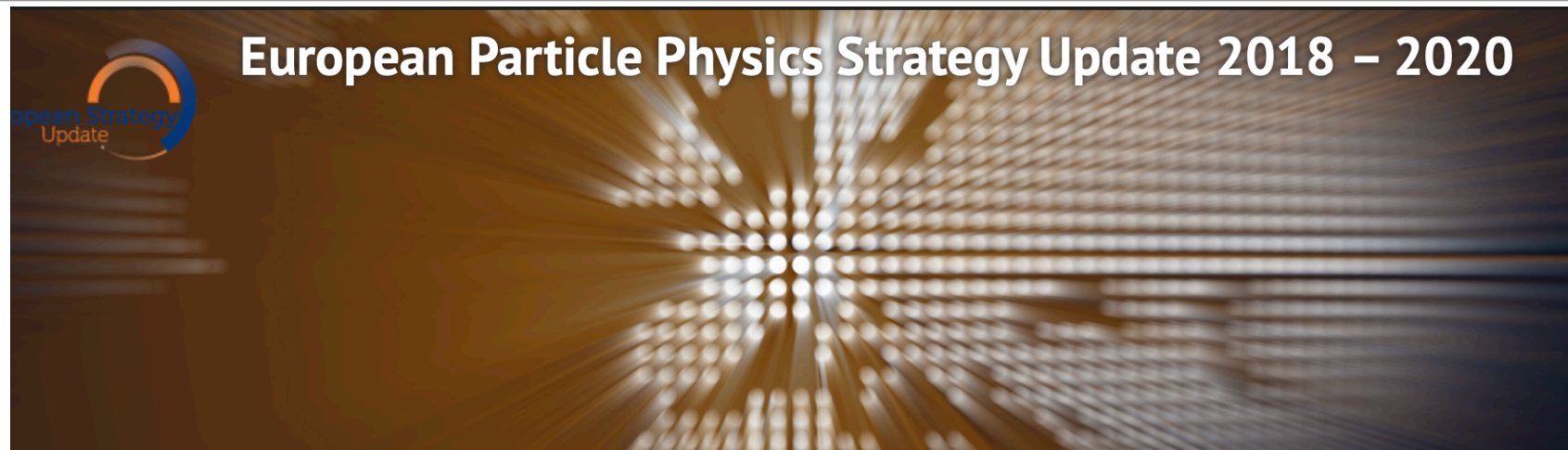
region with strong first-order EWPT

current bound

HL-LHC sensitivity



Previous update of European Strategy for Particle Physics



Future Projects:

3. High-priority future initiatives

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- *the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;*
- *Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.*

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

e^+e^- Higgs factories

Linear

International Linear Collider

Circular

Future Circular Collider

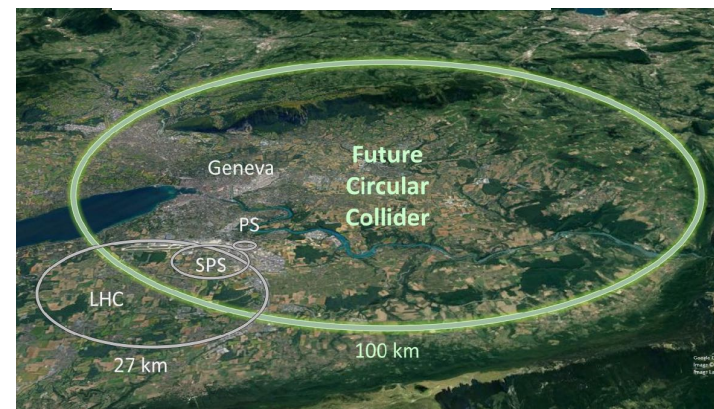
High-level differences:

- Energy reach
- Luminosity

ILC
Japan



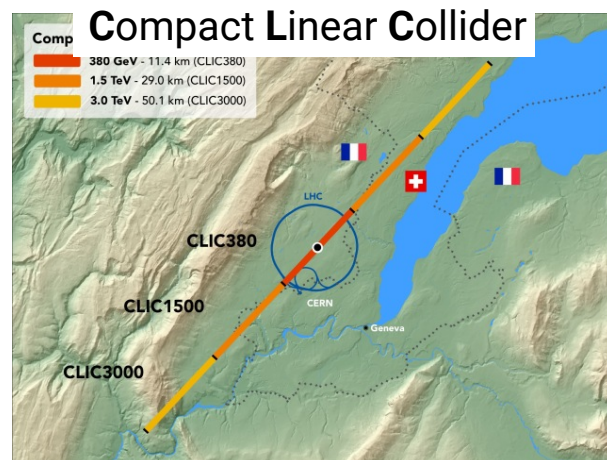
FCC-ee
CERN



LEP3 (e^+e^- , circular, 91 – 230 GeV)



CLIC
CERN



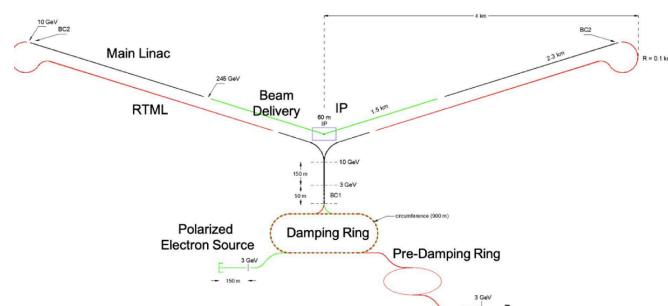
CEPC
China

Circular Electron Positron Collider



CCC

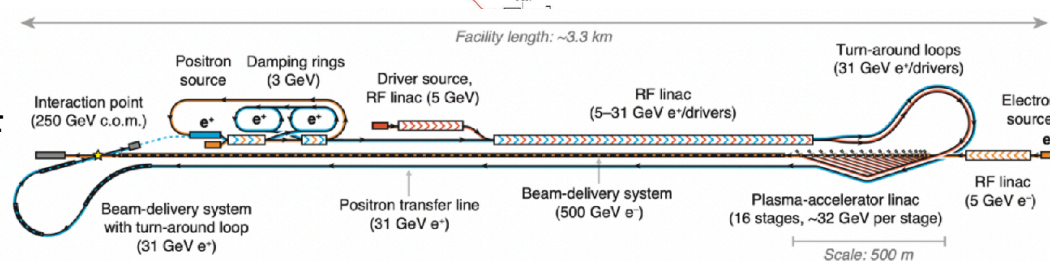
C³ - 8 km Footprint for 250/550 GeV



- 250 GeV — ZH threshold
- 350 GeV — tt threshold
- 550 GeV — HHH coupling
- ca. 1.5 TeV technology limit

- Based on superconducting RF (liquid nitrogen)
- Proposed at SLAC; very compact machine

HALHF



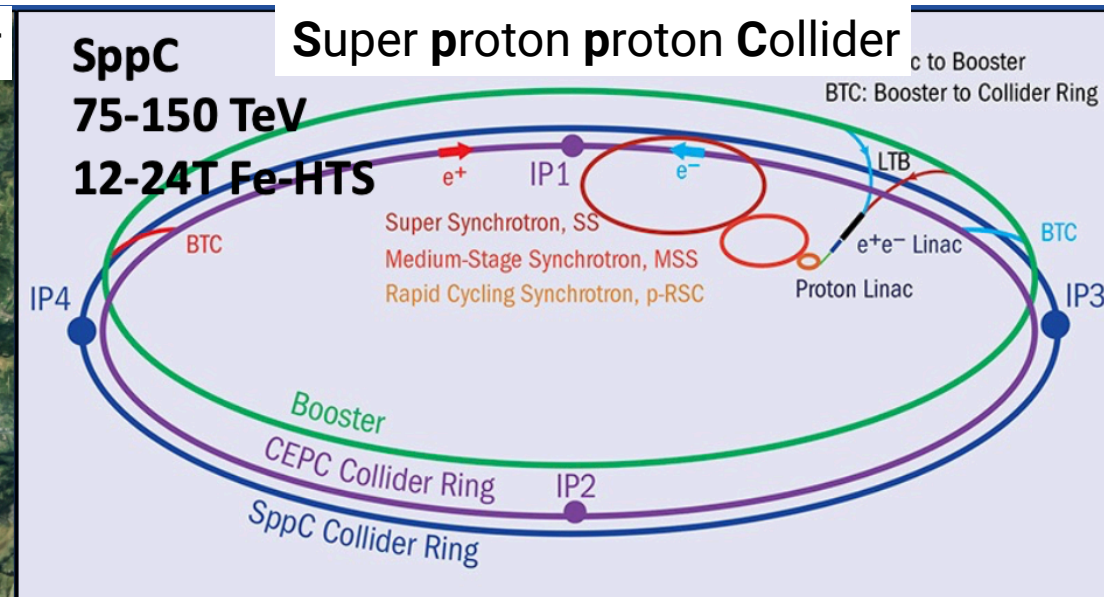
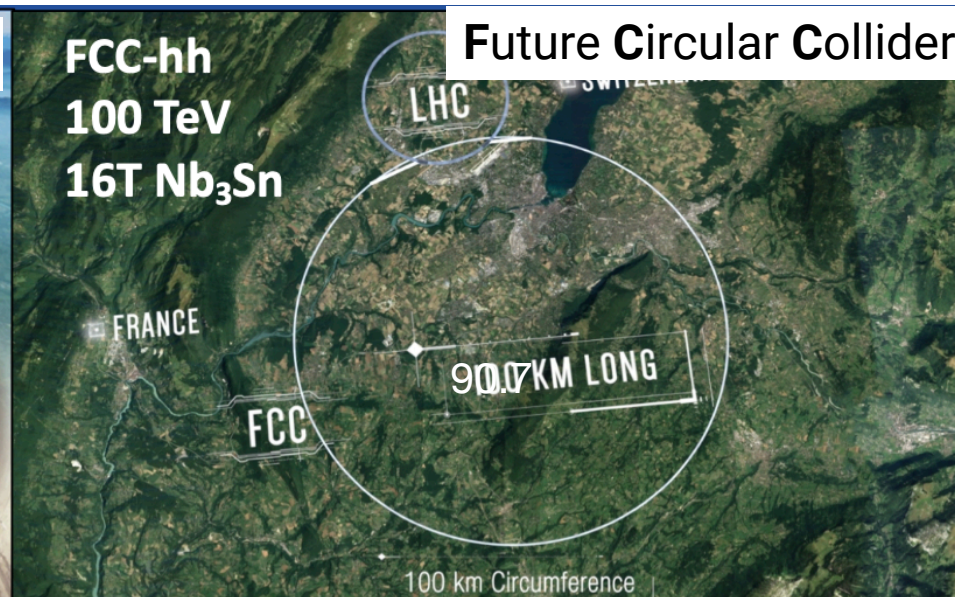
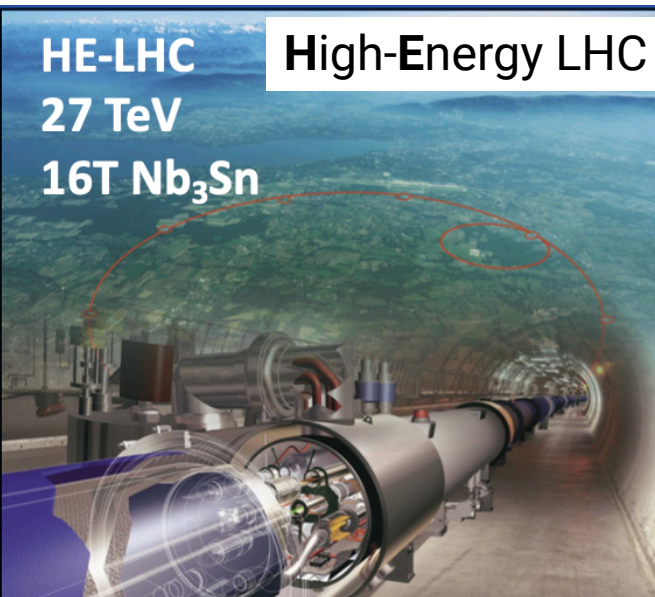
Source: Foster, D'Arcy & Lindström, preprint at arXiv:2303.10150 (2023)

- 250 GeV — ZH threshold
- 365 GeV — tt threshold
- 10-30 TeV ?? technology limit

- New idea: e^- plasma acceleration, e^+ conventional LinAc
- ca. 10 years R&D needed to demonstrate feasibility
- Extremely compact: 3-4 km size, suitable for national lab

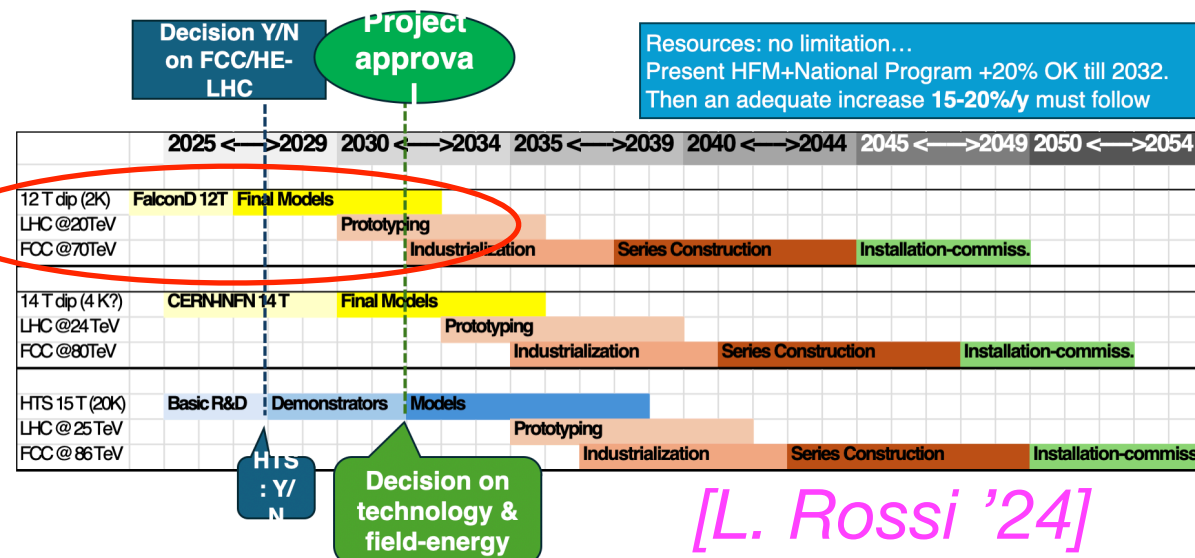
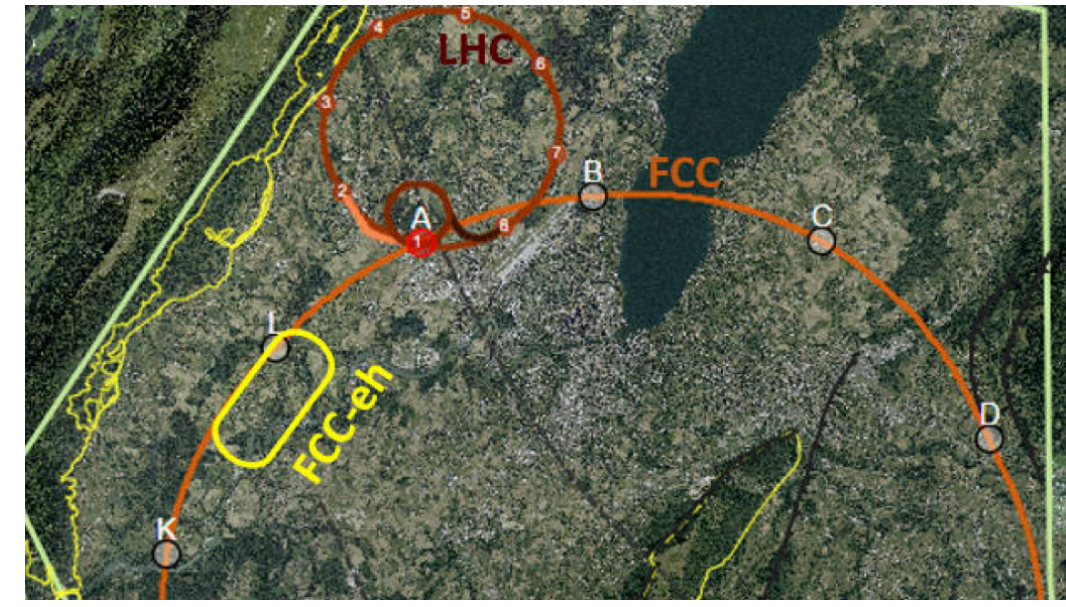
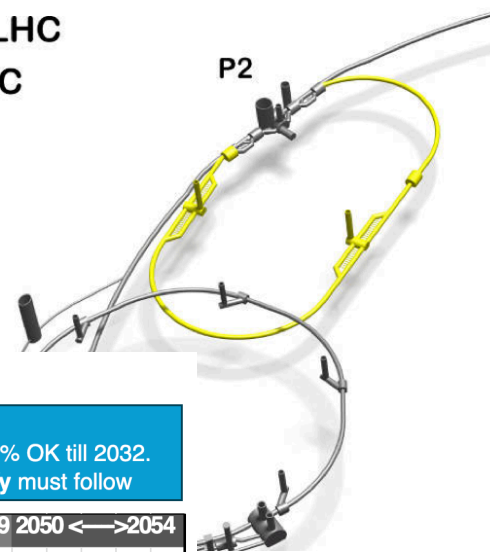
s for Higgs Physics, Georg Weiglein, Future Colliders@DESY, Hamburg, 09 / 2025

Future hadron colliders, muon collider, LHeC

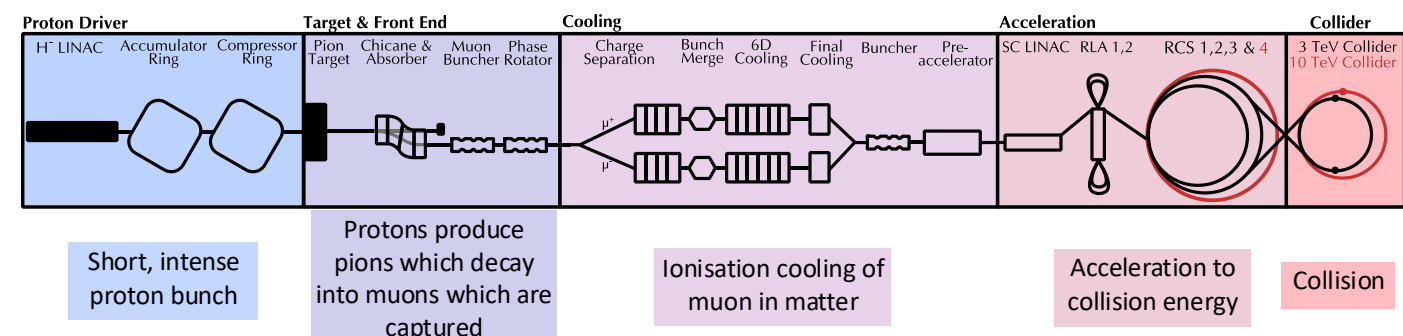


- The main challenge:
high-field magnets: ~ 16+ T
- Electron-hadron collisions when
combined with ERLs: LHeC, FCC-eh
at CERN

● EXISTING INFRASTRUCTURES
● HL-LHC
● LHeC



[L. Rossi '24]



Properties of the detected Higgs boson (h125)

- Mass
- Spin and CP properties
- Couplings, partial widths, total width, branching ratios, production cross sections (total and differential), information from off-shell contributions, interference effects, ...

~13 years after the discovery of the Higgs boson at 125 GeV (h125):
high-precision measurement of the mass, detailed investigations of
inclusive and differential rates

Mass at e^+e^- Higgs factory: $O(10 \text{ MeV})$ accuracy possible

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \rightarrow ZH$, $Z \rightarrow e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields **combinations** of Higgs couplings ($\Gamma_{\text{prod, decay}} \sim g_{\text{prod, decay}}^2$):

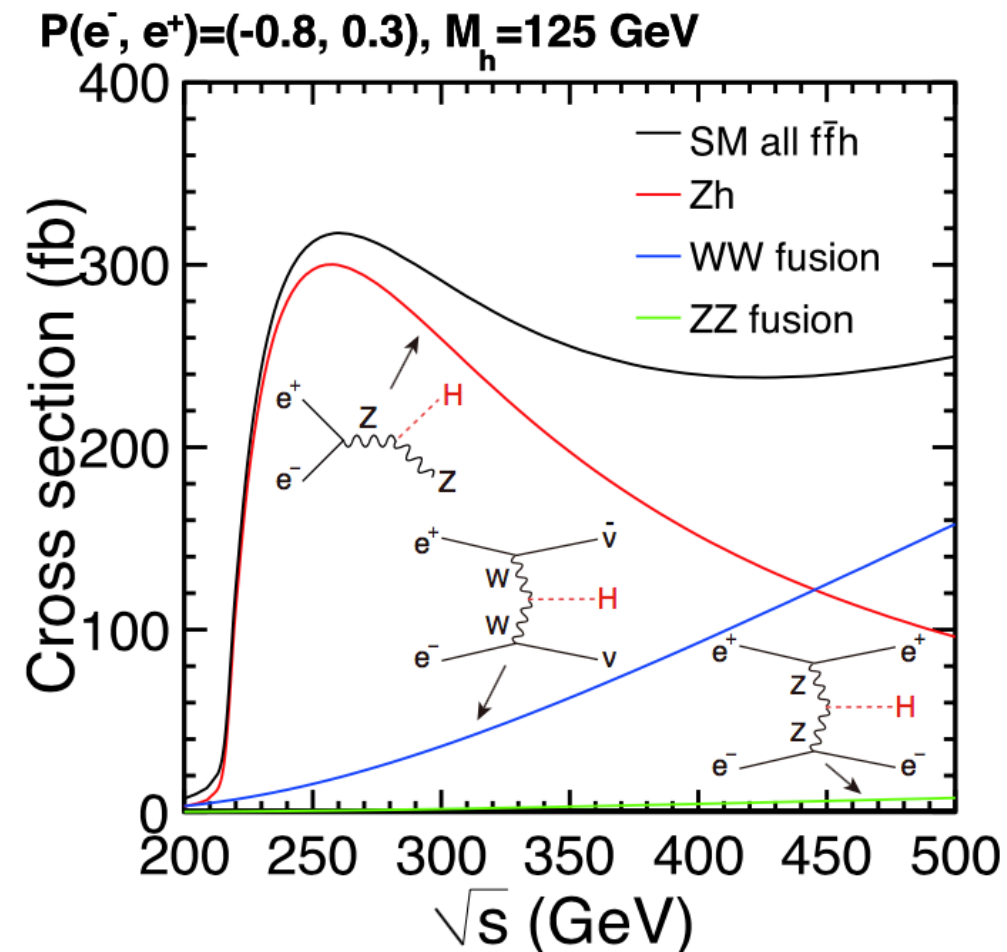
$$\sigma(H) \times \text{BR}(H \rightarrow a + b) \sim \frac{\Gamma_{\text{prod}} \Gamma_{\text{decay}}}{\Gamma_{\text{tot}}},$$

Total Higgs width cannot be determined without further assumptions

$\Rightarrow$ LHC can directly determine only **ratios** of couplings,
e.g. $g_{H\tau\tau}^2 / g_{HWW}^2$

Qualitative new feature at an e^+e^- Higgs factory

“Golden channel”, $e^+e^- \rightarrow ZH$, can best be exploited at 250 GeV



With this channel it is possible to detect the Higgs boson independently from the way it decays: “recoil method”

This leads to **absolute and model-independent measurements** of the Higgs production process and of the Higgs decay branching ratios

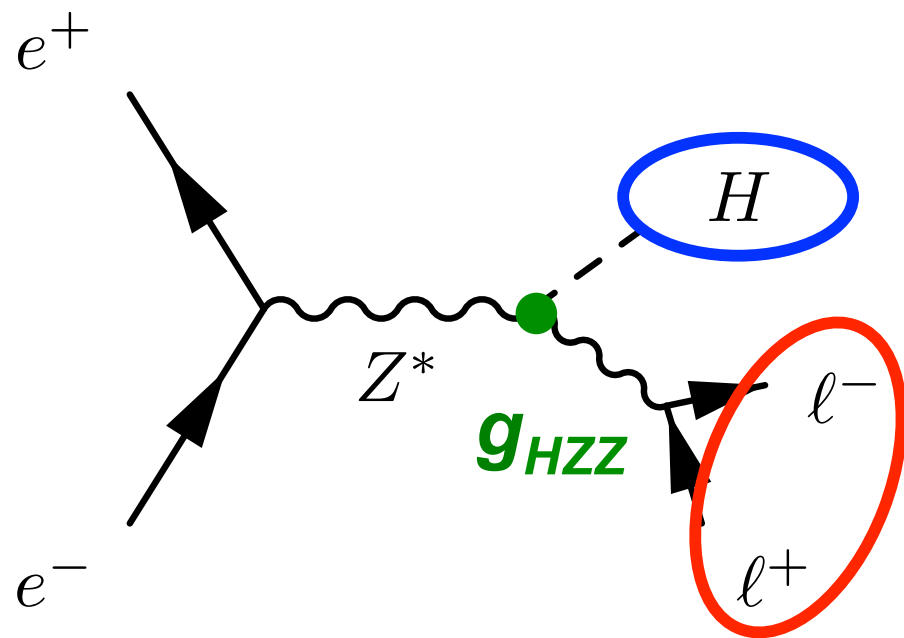
“Golden channel”: $e^+e^- \rightarrow ZH, Z \rightarrow e^+e^-, \mu^+\mu^-$

Recoil method: detecting the Higgs boson without using its decay!

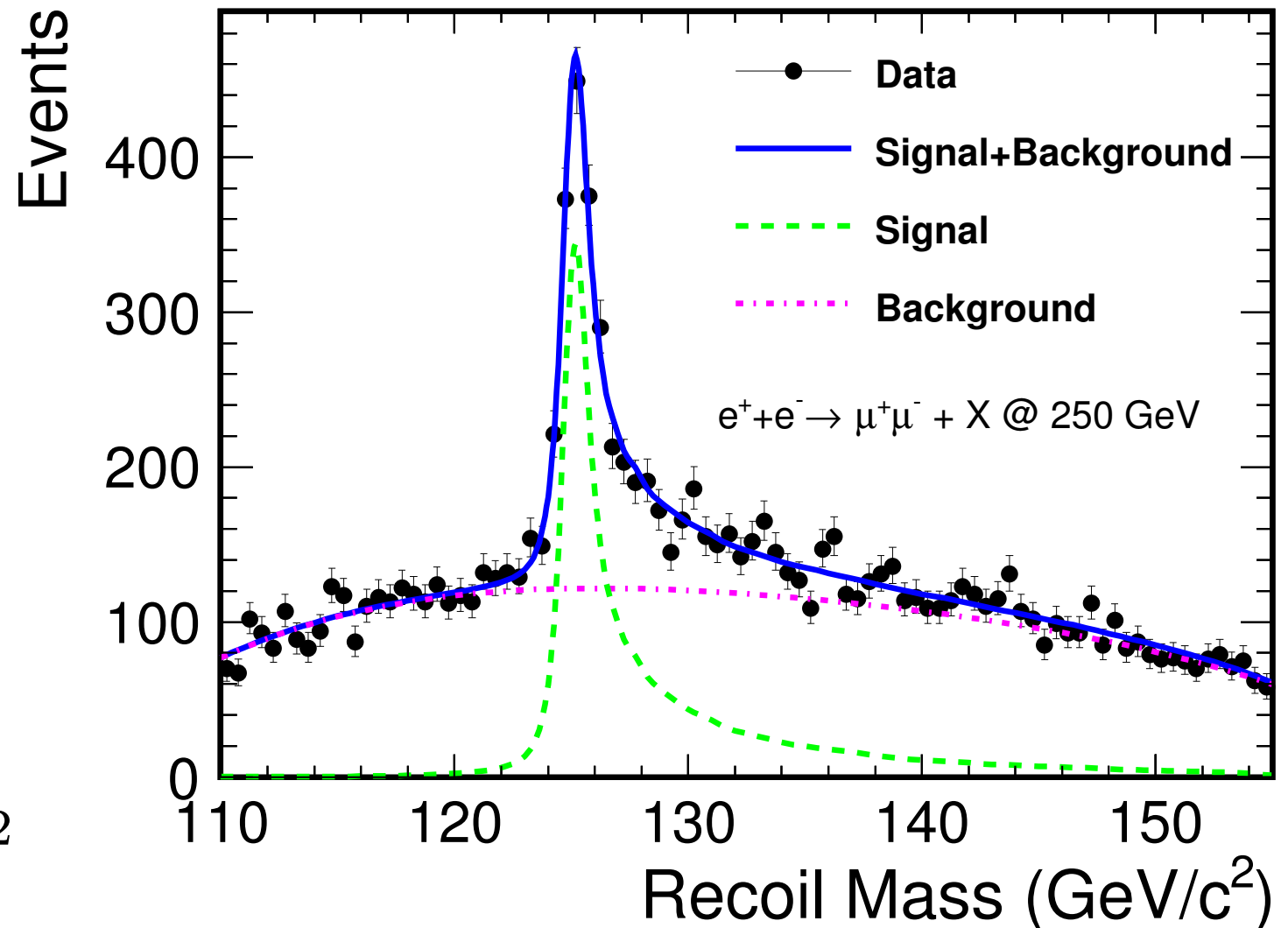
Reconstruct $Z \rightarrow \ell^+\ell^-$

independent of Higgs decay

sensitive to invisible Higgs decays



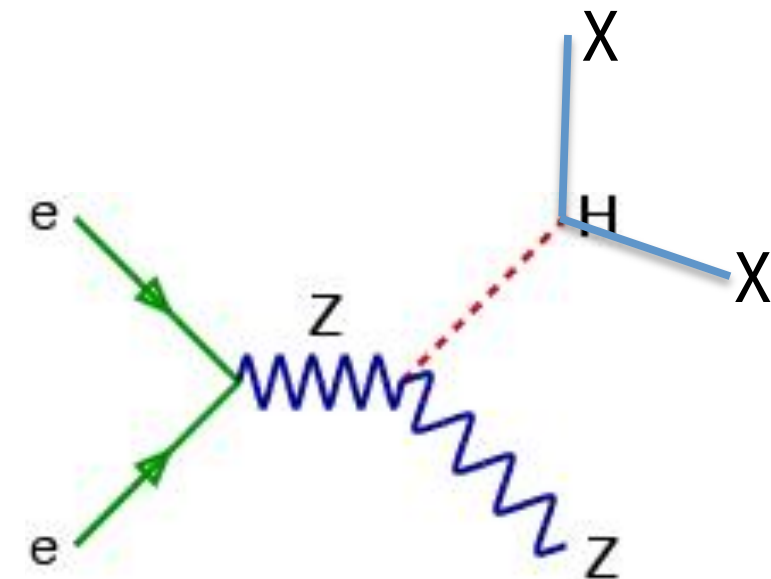
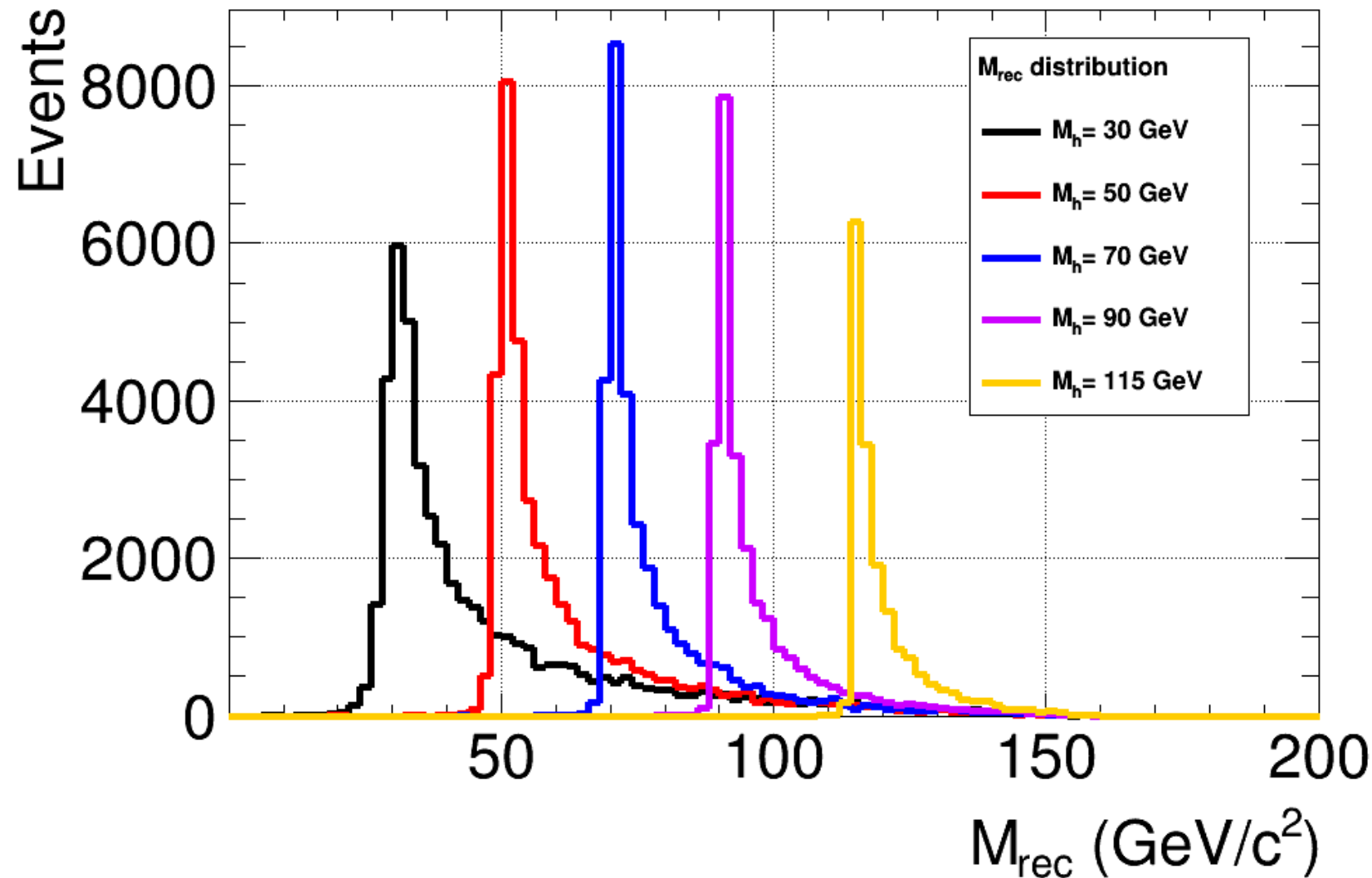
$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Since the $Z \rightarrow \ell^+\ell^-$ decay branching fraction is known from the e^+e^- collider LEP, this method yields an **absolute measurement** of the **ZH cross section**, the **Higgs branching ratios** and the **Higgs width**!

⇒ Large quantitative + qualitative improvements over HL-LHC

Invisible decays



⇒ Unique sensitivity at an e^+e^- Higgs factory!

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

h125 couplings to gauge bosons and fermions:

In many BSM models one expects only % level deviations or less from the SM couplings for BSM particles in the TeV range.
Example of 2HDM-type model in decoupling limit:

$$\begin{aligned}\frac{g_{hVV}}{g_{h_{\text{SM}}VV}} &\simeq 1 - 0.3\% \left(\frac{200 \text{ GeV}}{m_A} \right)^4 \\ \frac{g_{htt}}{g_{h_{\text{SM}}tt}} = \frac{g_{hcc}}{g_{h_{\text{SM}}cc}} &\simeq 1 - 1.7\% \left(\frac{200 \text{ GeV}}{m_A} \right)^2 \\ \frac{g_{hbb}}{g_{h_{\text{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\text{SM}}\tau\tau}} &\simeq 1 + 40\% \left(\frac{200 \text{ GeV}}{m_A} \right)^2.\end{aligned}$$

⇒ Need very high precision for the couplings

Higgs couplings: towards high precision

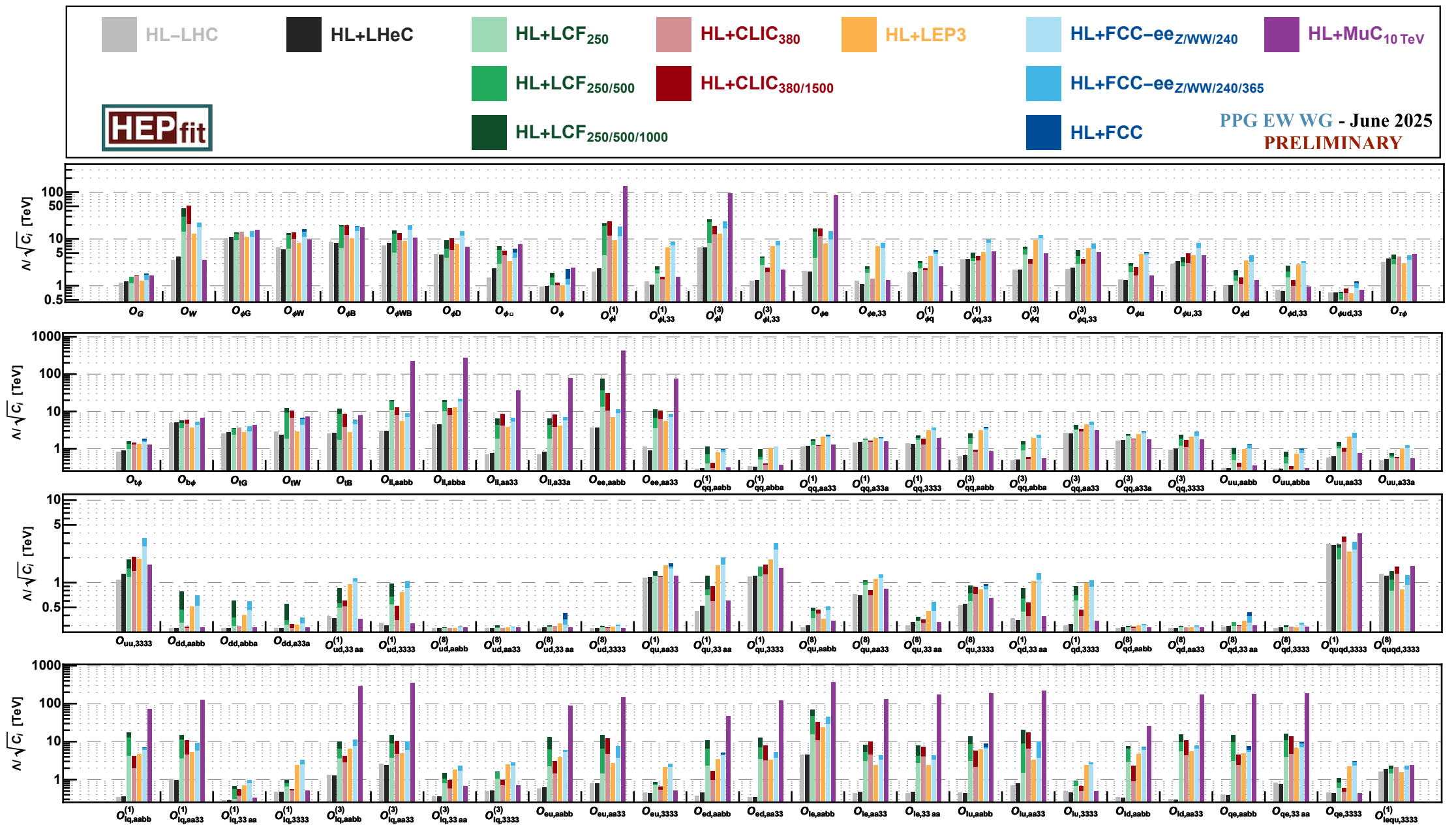
- A coupling is **not a physical observable**: if one talks about measuring Higgs couplings at the % level or better, one needs to **precisely define** what is actually meant by those couplings!
- For the determination of an appropriate coupling parameter at this level of accuracy the **incorporation 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

Global EFT fits: projections for future colliders

Effective Field Theories for BSM physics

A simple fit to 100 of these operators

[J. de Blas et al. '25]

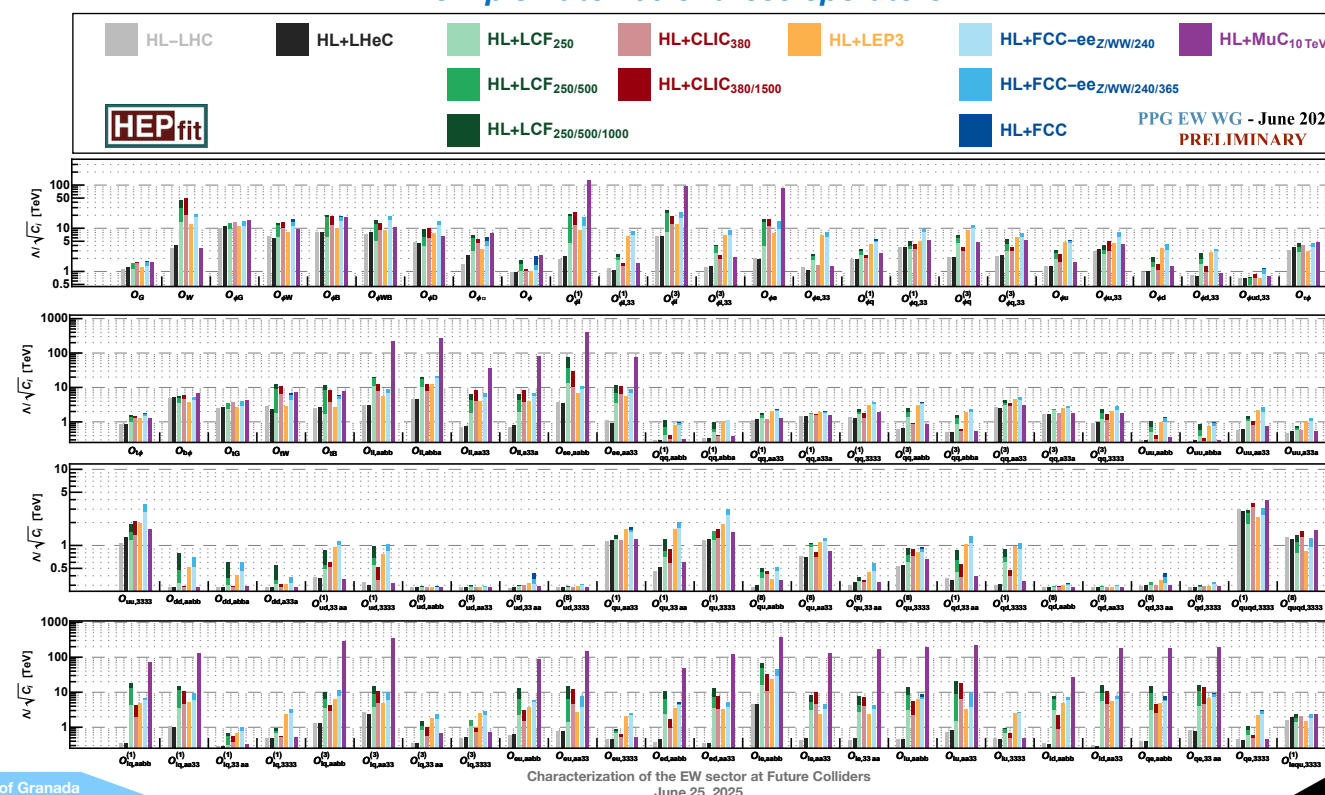


[J. Reuter '24]

- ✓ All Higgs factories perform similar: luminosity vs. polarization
- ✓ Couplings will be pushed to single percent-few per mille
- ✓ Gain at least one order of magnitude precision over HL-LHC
- ✓ If exotic Higgs decays exist: no absolute couplings from LHC

Effective Field Theories for BSM physics

A simple fit to 100 of these operators

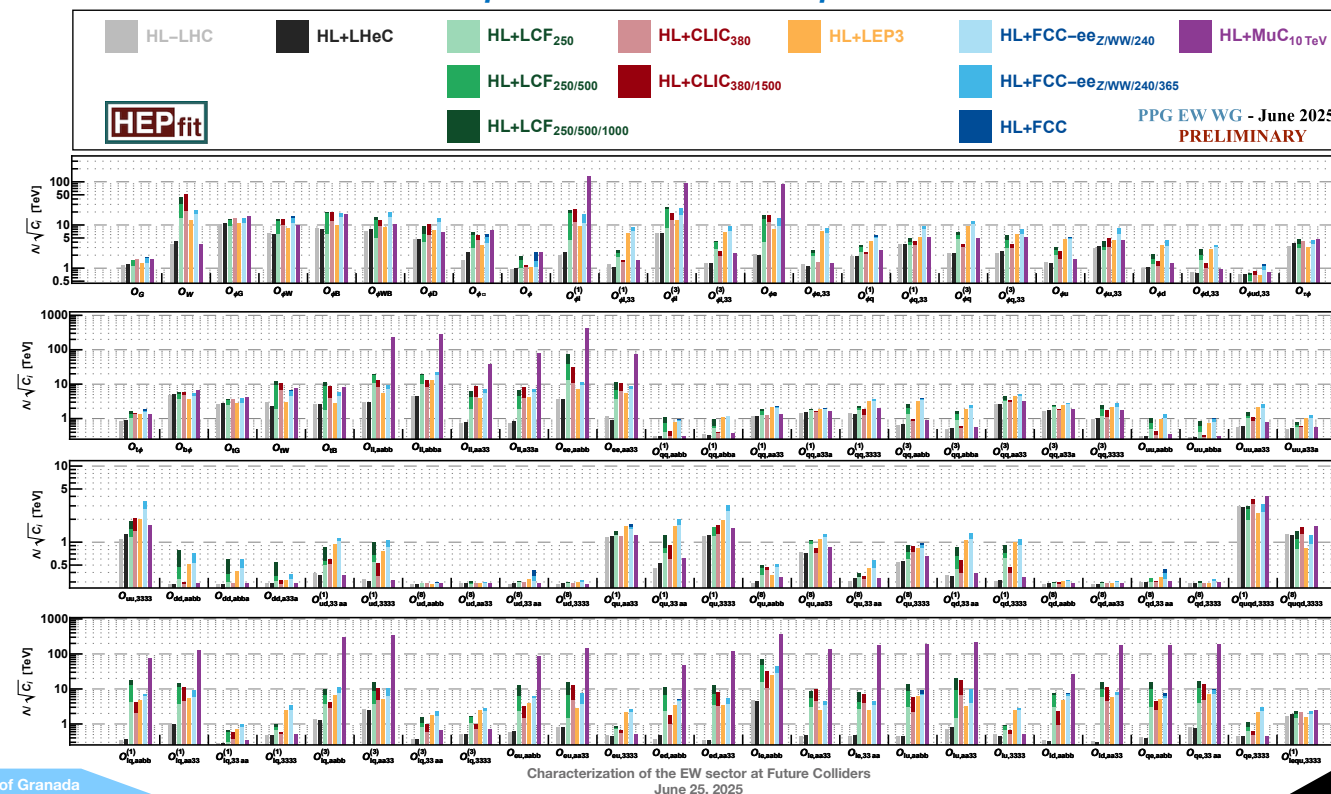


Global EFT fits: projections for future colliders

[J. de Blas et al. '25]

Effective Field Theories for BSM physics

A simple fit to 100 of these operators



Jorge de Blas - U. of Granada

Let's be frank: **hardly anybody** outside of our field is going to be impressed by plots like that!

We do not just need to demonstrate that a future collider will yield a significantly improved precision for the Higgs couplings, but we have to show **what we will do with this improved precision**, i.e. how it will help to solve our big open questions!

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

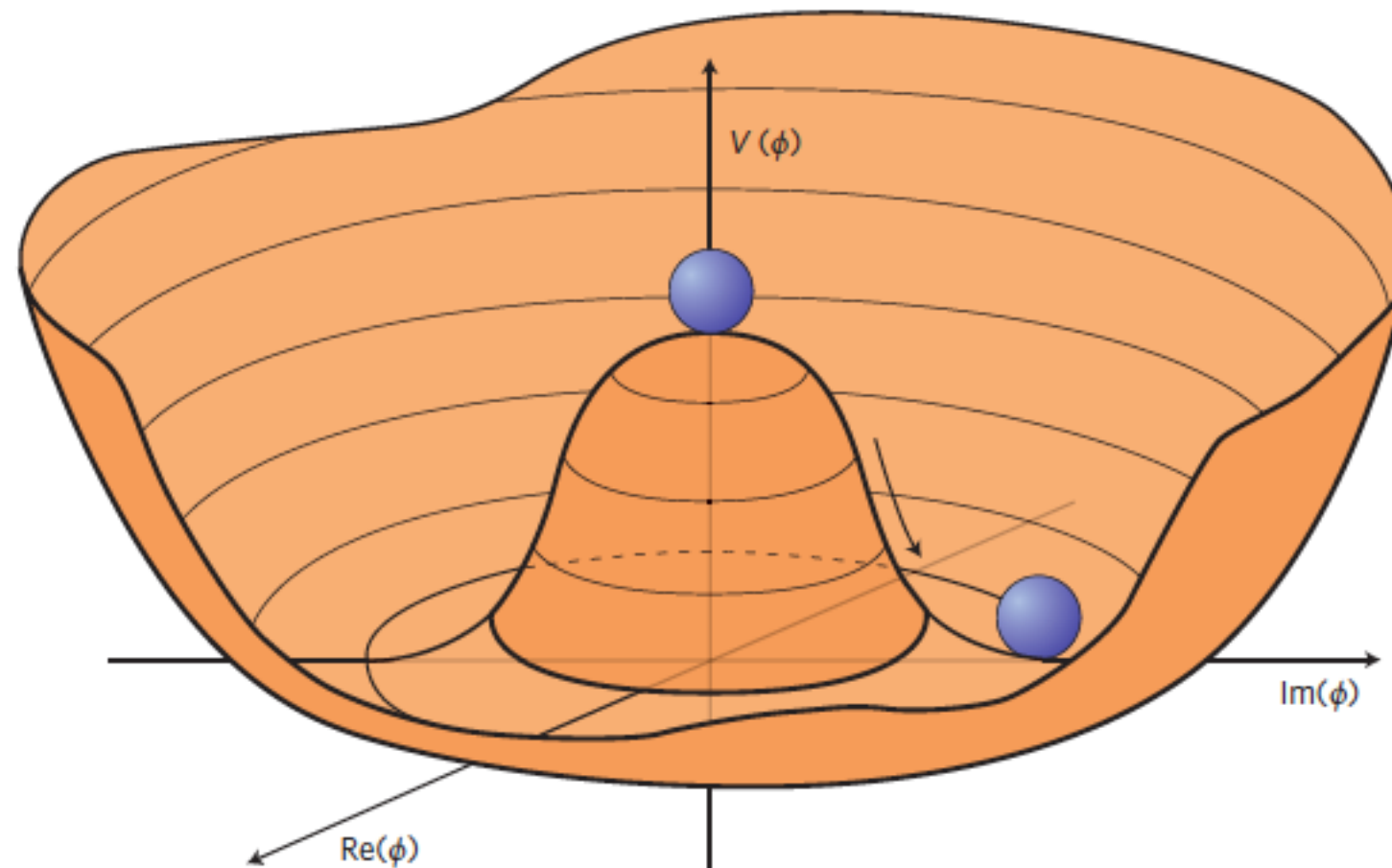
- Future Higgs factories: what can we learn from the enhanced precision ($\sim$ factor 10 better than HL-LHC) in comparison to the direct searches at the HL-LHC (existing limits and future prospects)?
- How significant will possible patterns of deviations be? How stringent are indirect hints for additional particles (typically scale like coupling/mass²)?
- How well can one distinguish between different realisations of possible BSM physics?

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

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



The simple picture of the Higgs potential



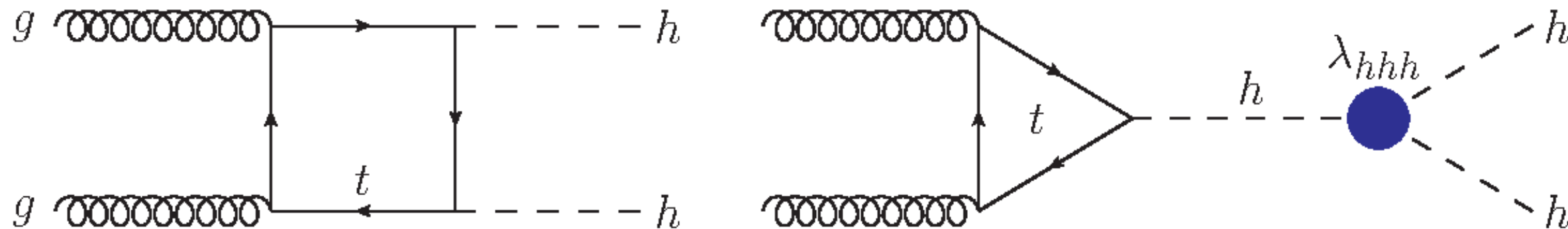
refers to the case of a single Higgs doublet field

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 λ_{hhh} from Higgs pair production:

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



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

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

Experimental limits on the di-Higgs cross sections yield **constraints on κ_λ**

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

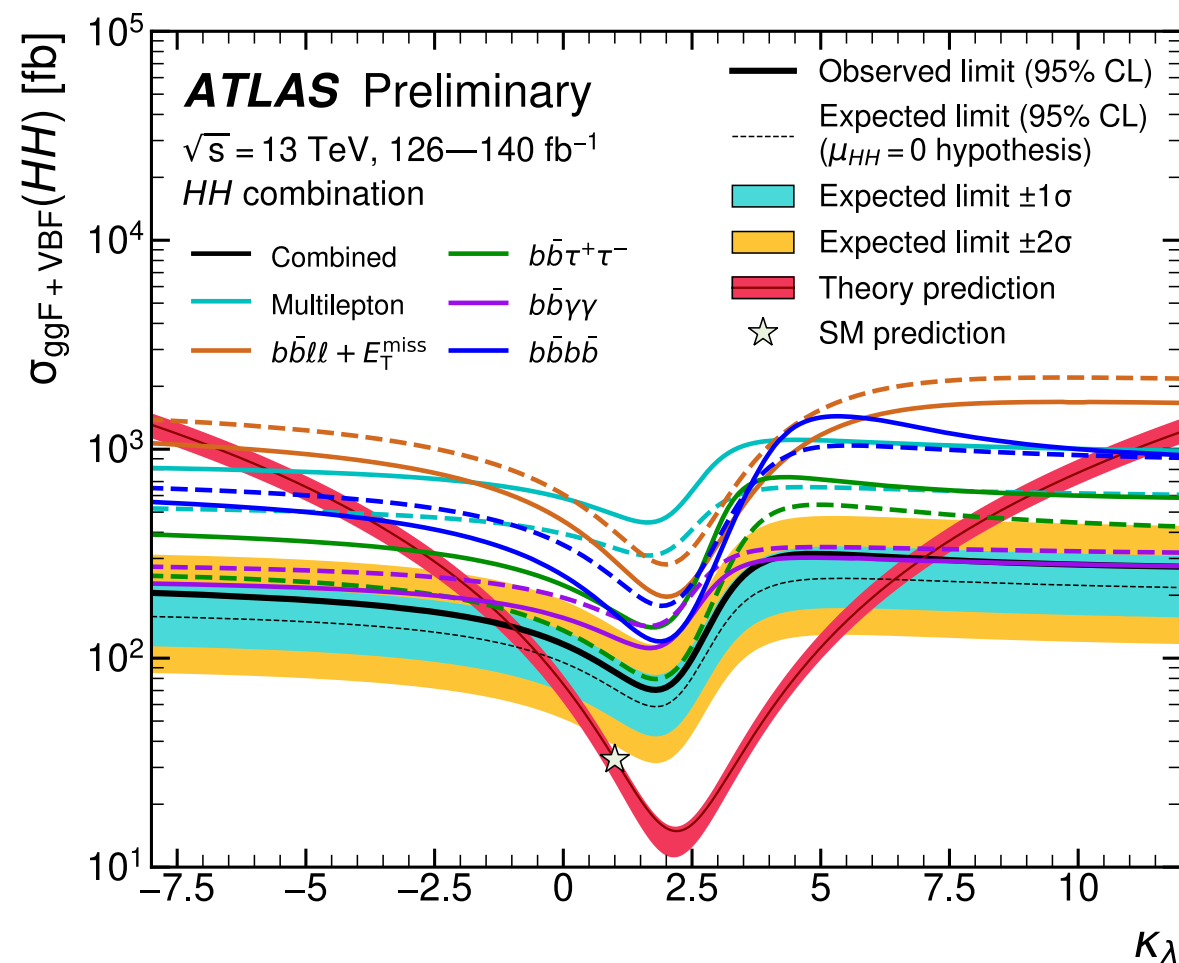
Limits from non-resonant di-Higgs production

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

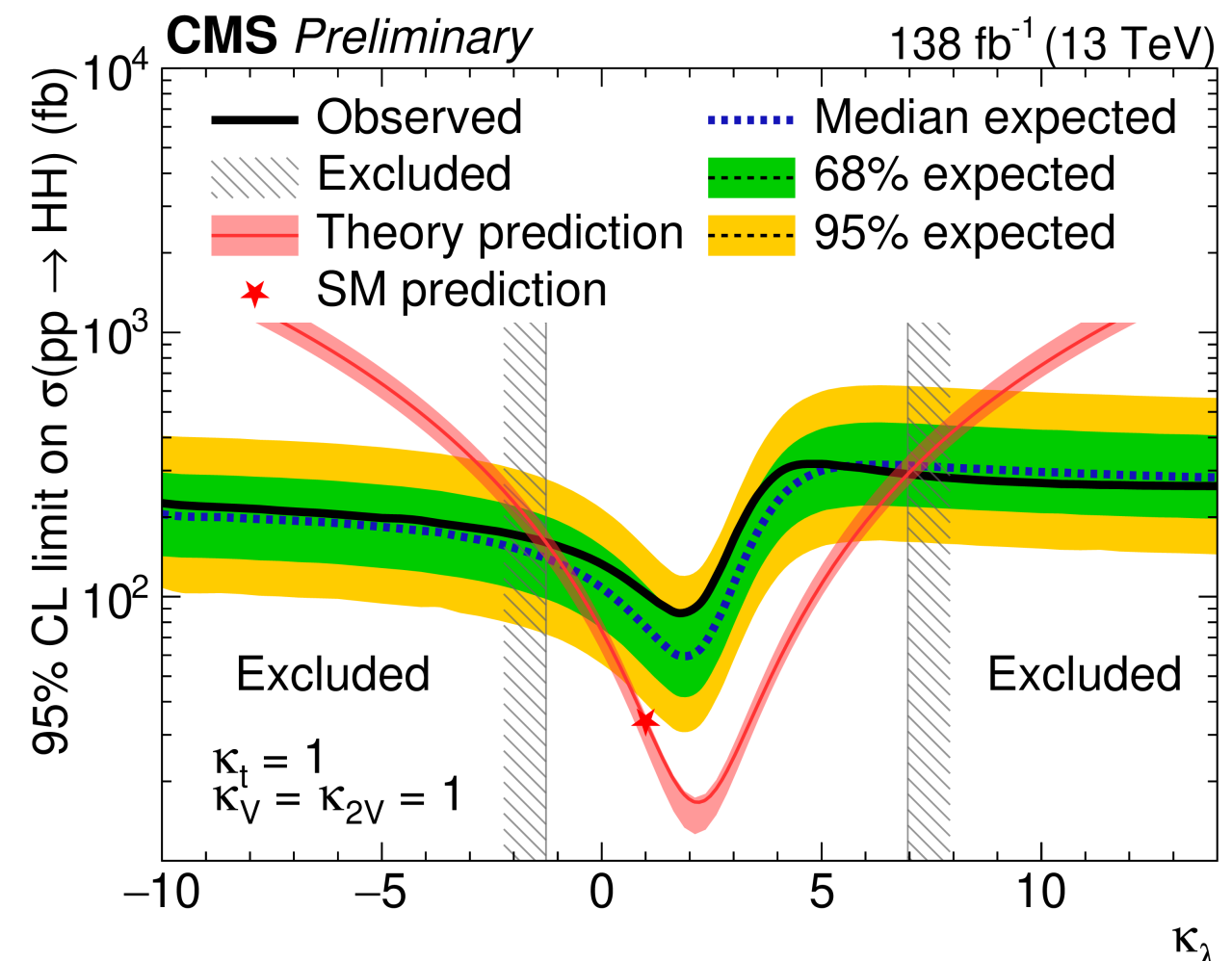
$$\kappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{\text{SM}, 0}$$

[ATLAS Collaboration '24]

[CMS Collaboration '24]



$$-1.2 < \kappa_\lambda < 7.2 \text{ at } 95\% \text{ C.L.}$$

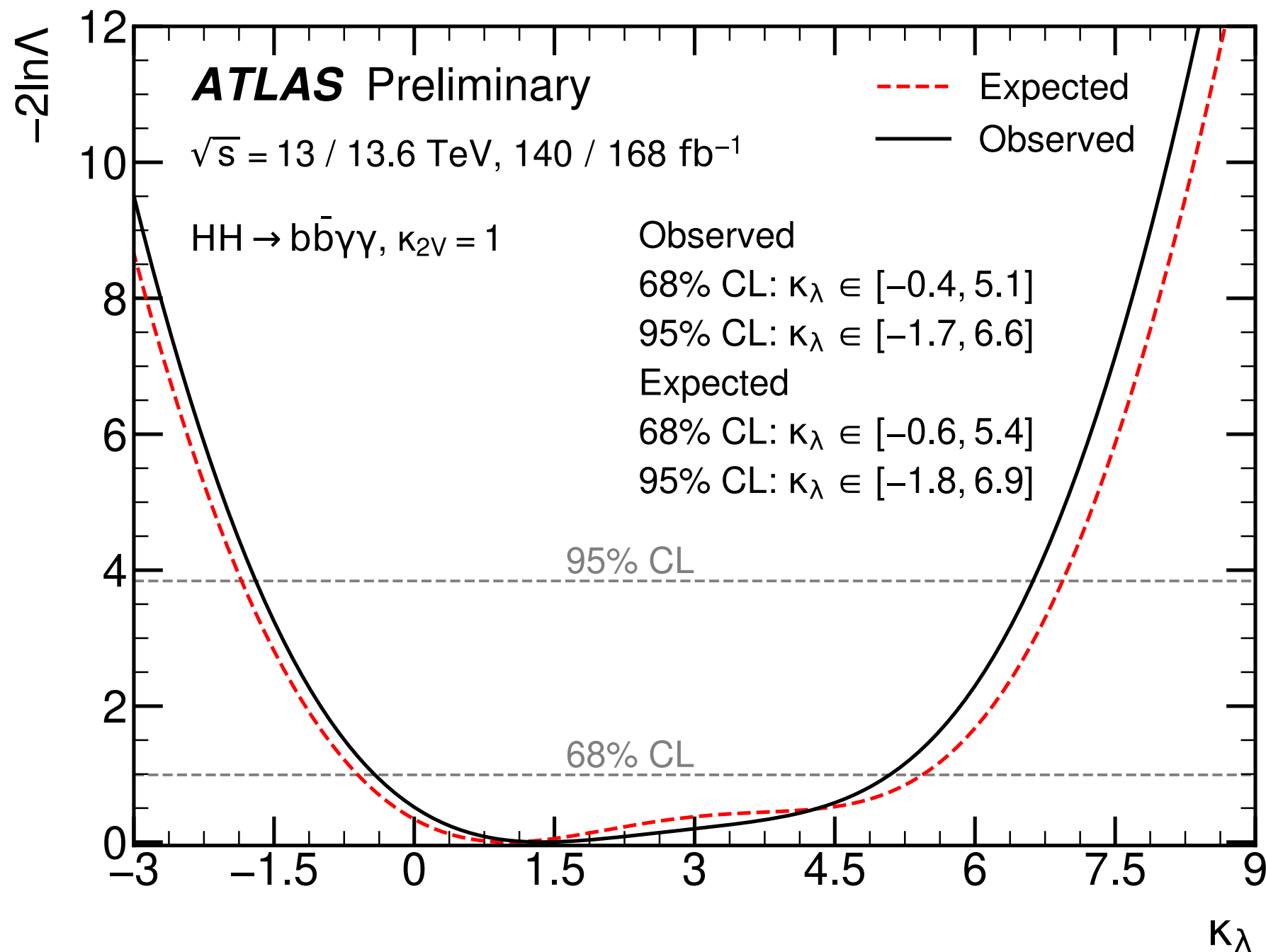


$$-1.4 < \kappa_\lambda < 7.0 \text{ at } 95\% \text{ C.L.}$$

⇒ Upper bound on λ_{hhh} of currently about 7 x (SM value)

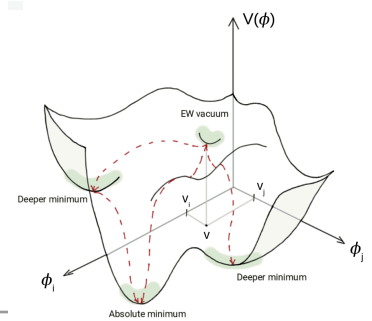
Latest update from ATLAS

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



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

How big can modifications of λ_{hhh} be?



Limits from non-resonant di-Higgs production:

Upper bound on λ_{hhh} of currently about 7 x (SM value), i.e. deviation of up to 700% from the SM is allowed

- **SM:** relatively small higher-order contributions to λ_{hhh} at the level of about **-7%, mostly from top loop**; note: $\kappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{\text{SM}, 0}$
- **BSM models (UV-complete):**
Generic feature of extended Higgs sectors: **mass splitting** between BSM Higgs states yields **large enhancement of λ_{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 λ_{hhh} possible, effects of several 100%**

λ_{hhhh} : 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!

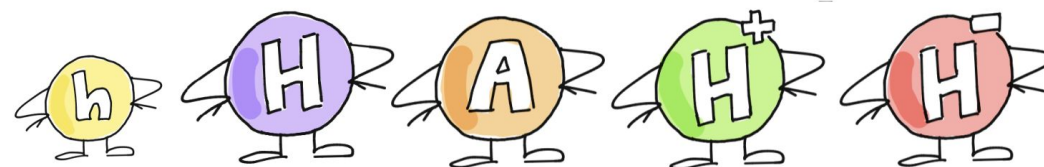
“Higgs self-coupling, ... arguably the most important of them all!”

Durieux, MM,
Salvioni. 2022

Simple example of extended Higgs sector: 2HDM

Two Higgs doublet model (2HDM):

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



[K. Radchenko '23]

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

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

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

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

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

Masses of the BSM Higgs fields

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

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

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

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

Sizeable splitting between m_Φ and M induces large BSM contributions to the Higgs self-couplings

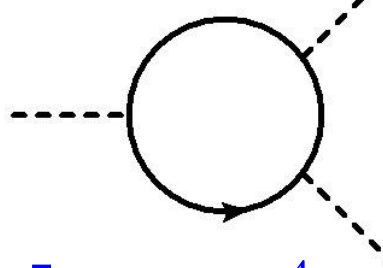
Effects of BSM particles on the trilinear Higgs coupling

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

[see Martin's talk]

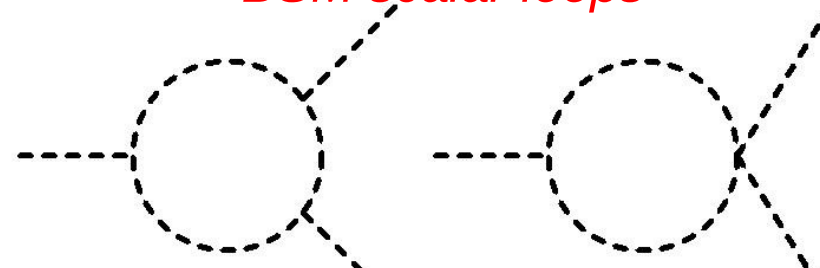
- **Leading one-loop** corrections to λ_{hhh} in models with extended sectors (like 2HDM):

SM top quark loop



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2} \left[-\frac{48m_t^4}{v^3} \right]$$

BSM scalar loops



$$+ \sum_{\Phi} \frac{4n_{\Phi}m_{\Phi}^4}{v^3} \left(1 - \frac{\mathcal{M}^2}{m_{\Phi}^2} \right)^3$$

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]

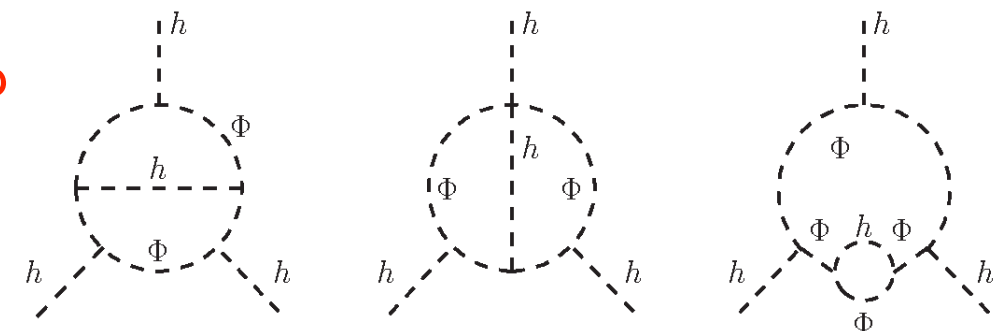
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons Φ of the form

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

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

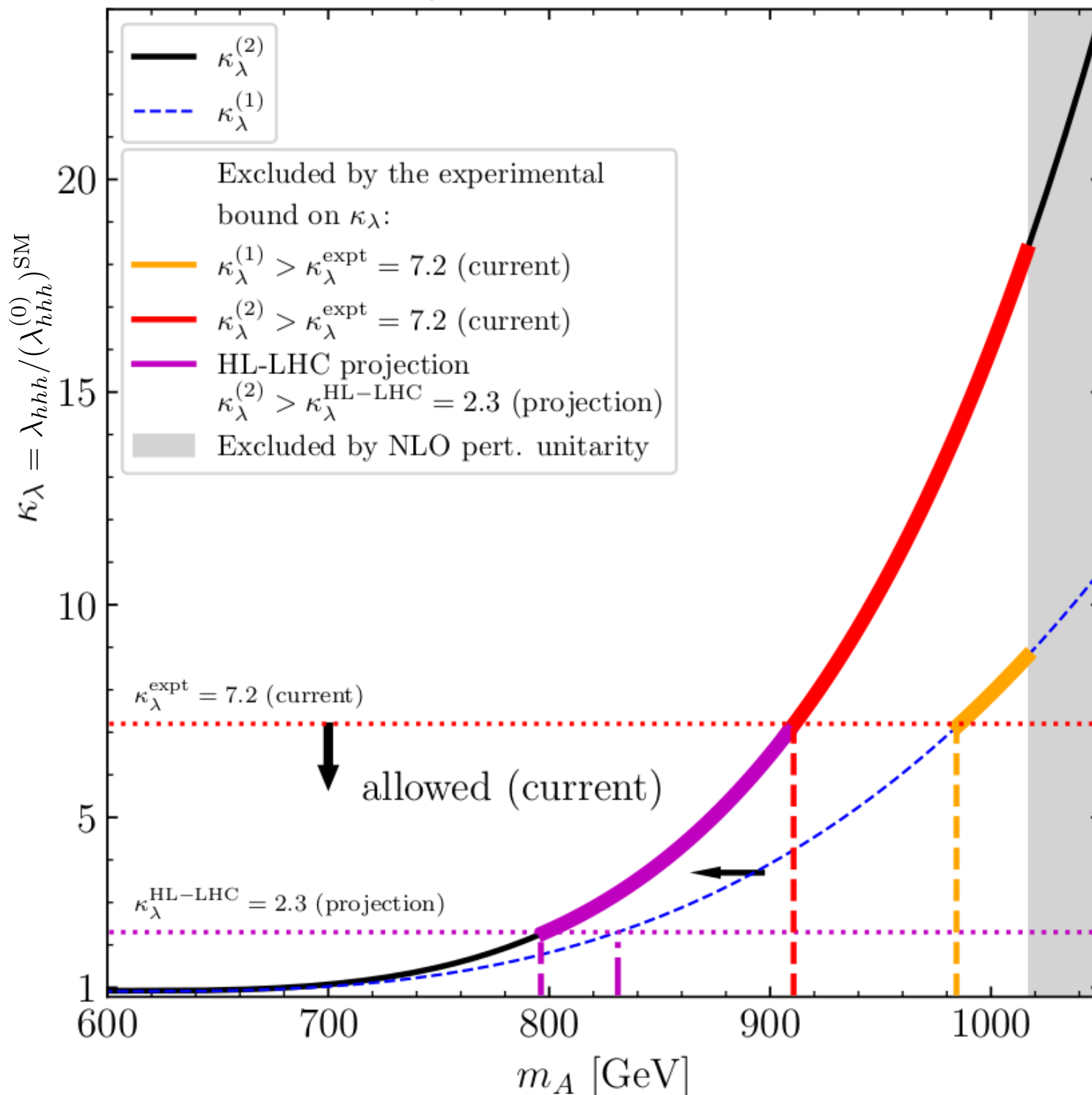
⇒ Tree-level couplings of h exactly agree with the SM

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

Prediction for κ_λ 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!

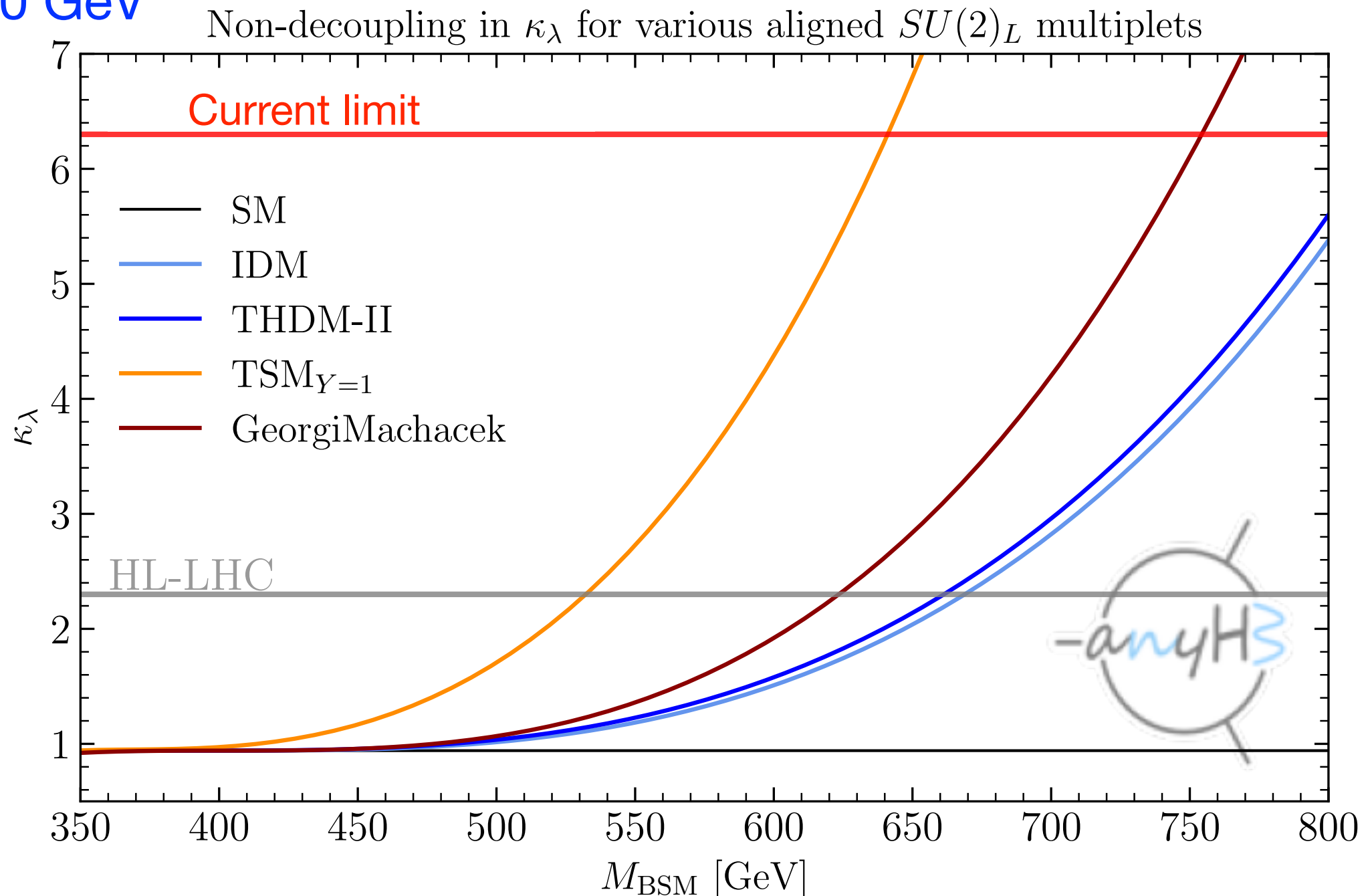
Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

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]

$M_L = 400 \text{ GeV}$



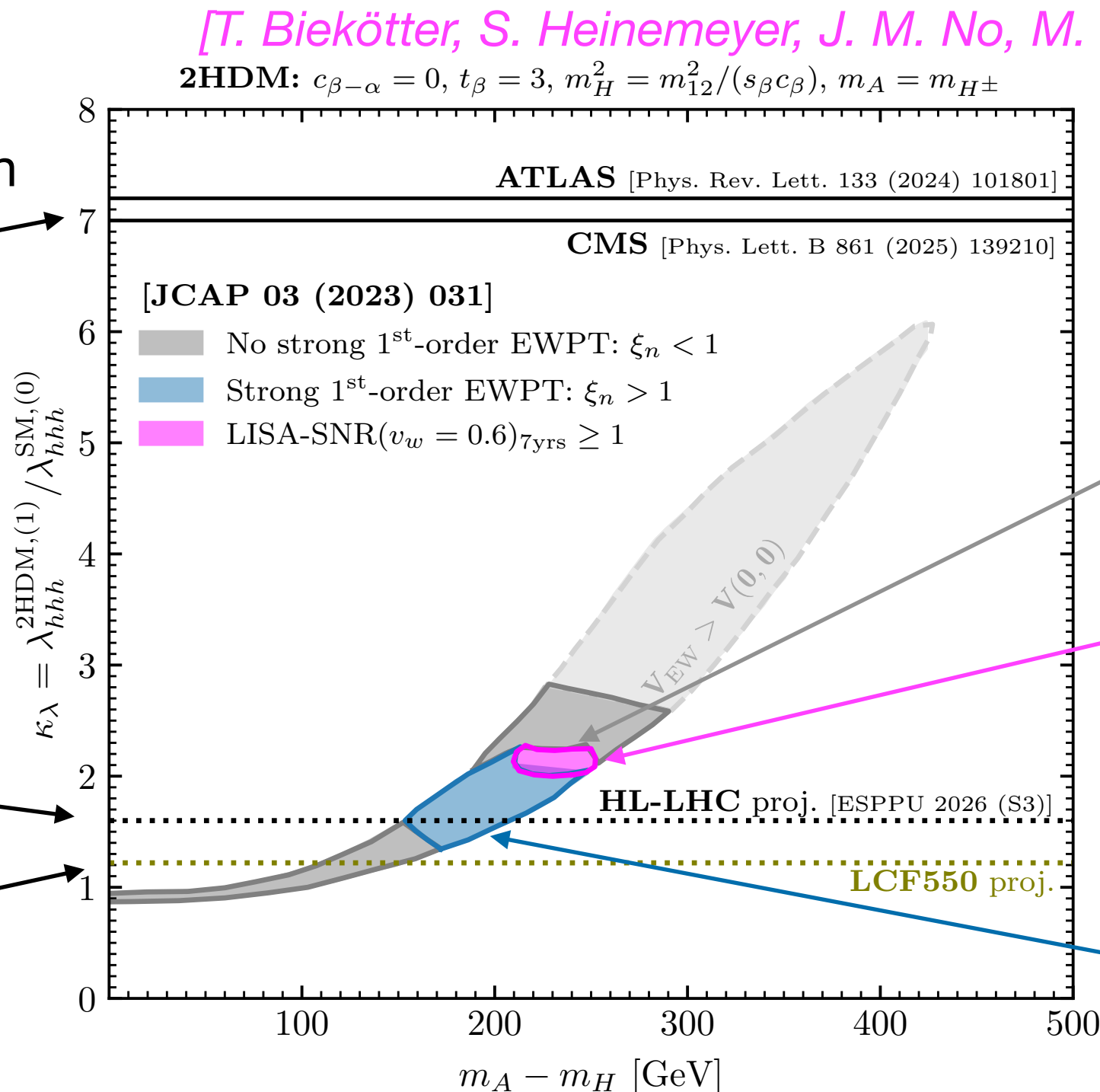
Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

alignment limit,
 $\tan\beta = 3$,
 1-loop prediction

current bound

HL-LHC
 sensitivity

LC550
 sensitivity



excluded
 because of
 "vacuum
 trapping"

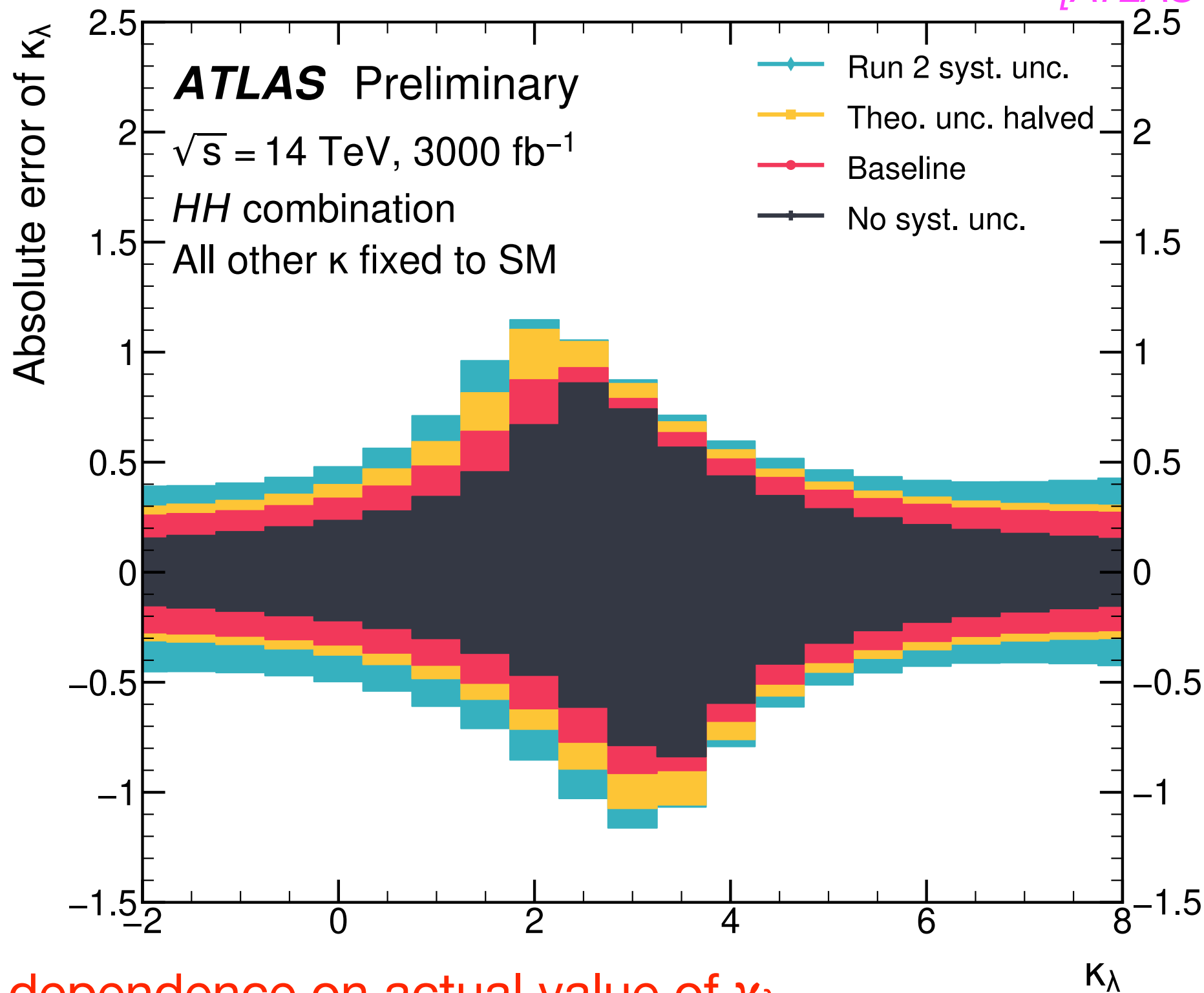
region with
 potentially
 observable
 gravitational
 wave (GW)
 signal

region with
 strong first-
 order EWPT

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

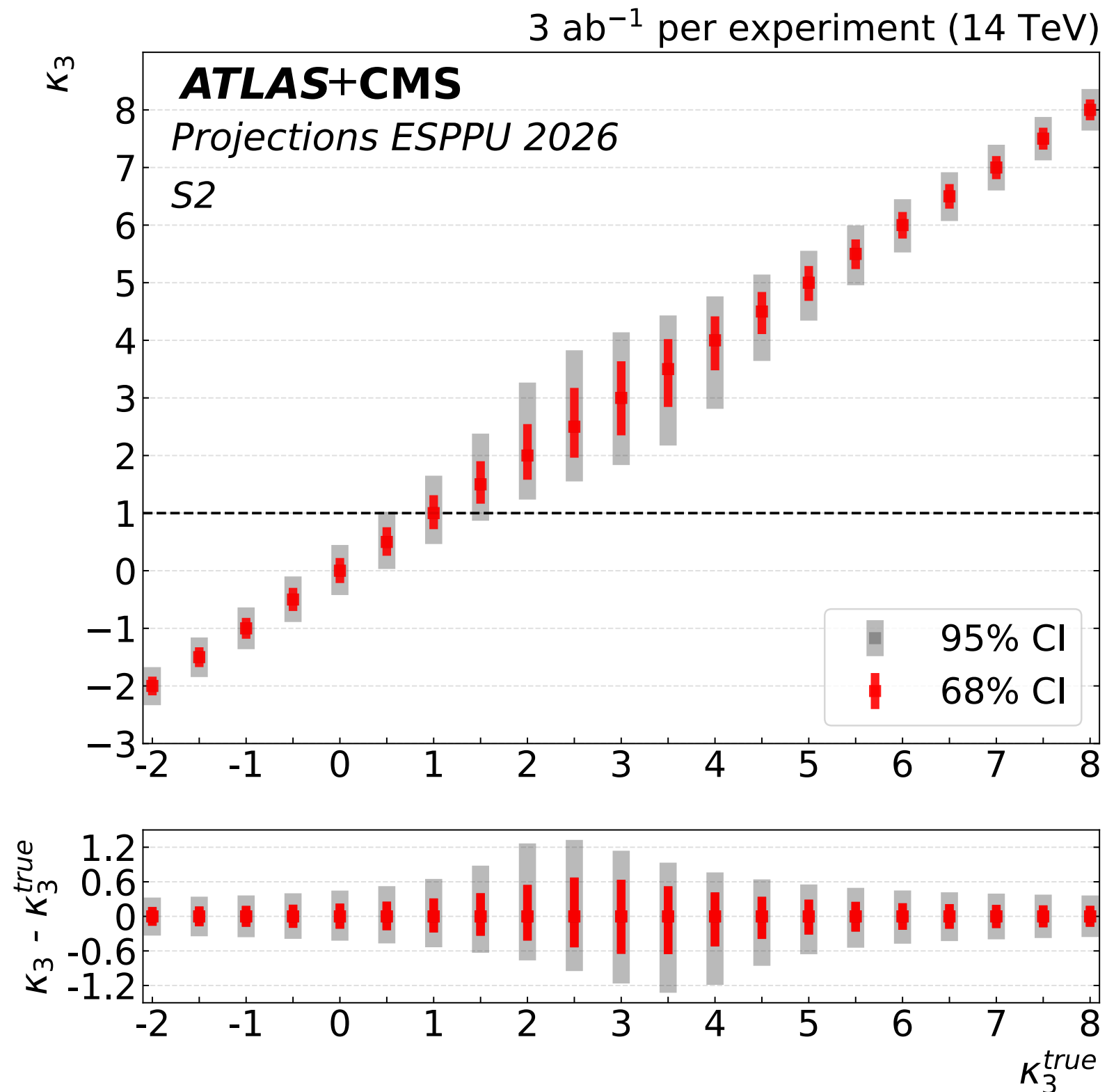
Recent ATLAS projection going beyond the assumption of $\kappa_\lambda = 1$

[ATLAS Collaboration '25]



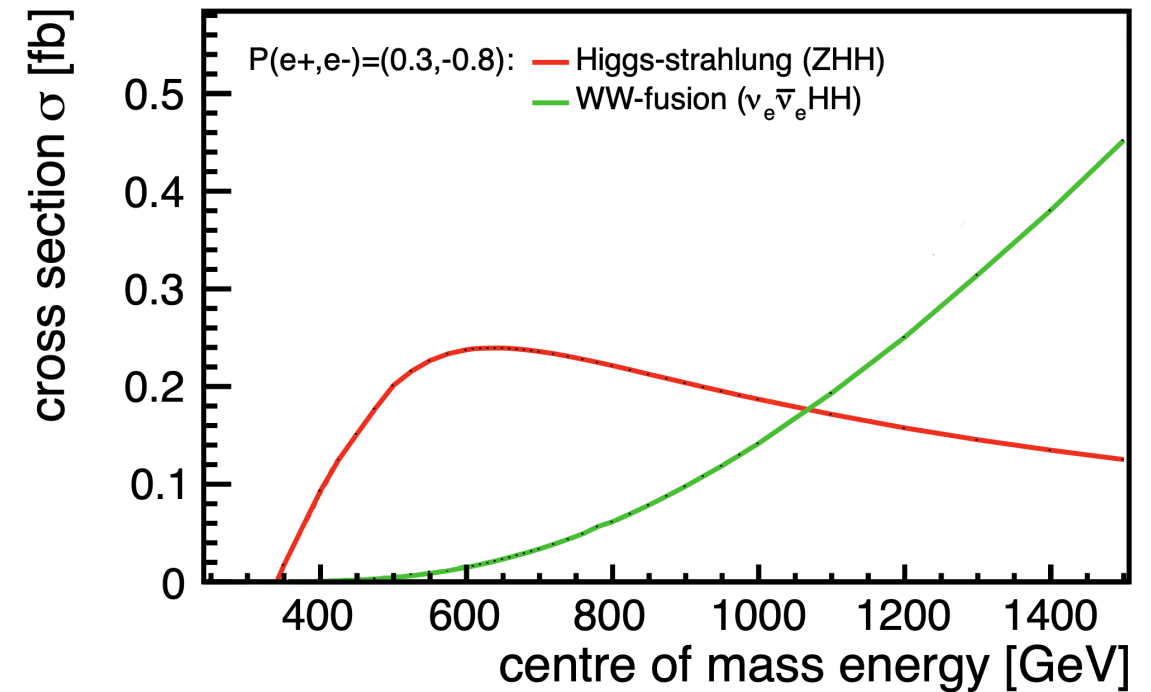
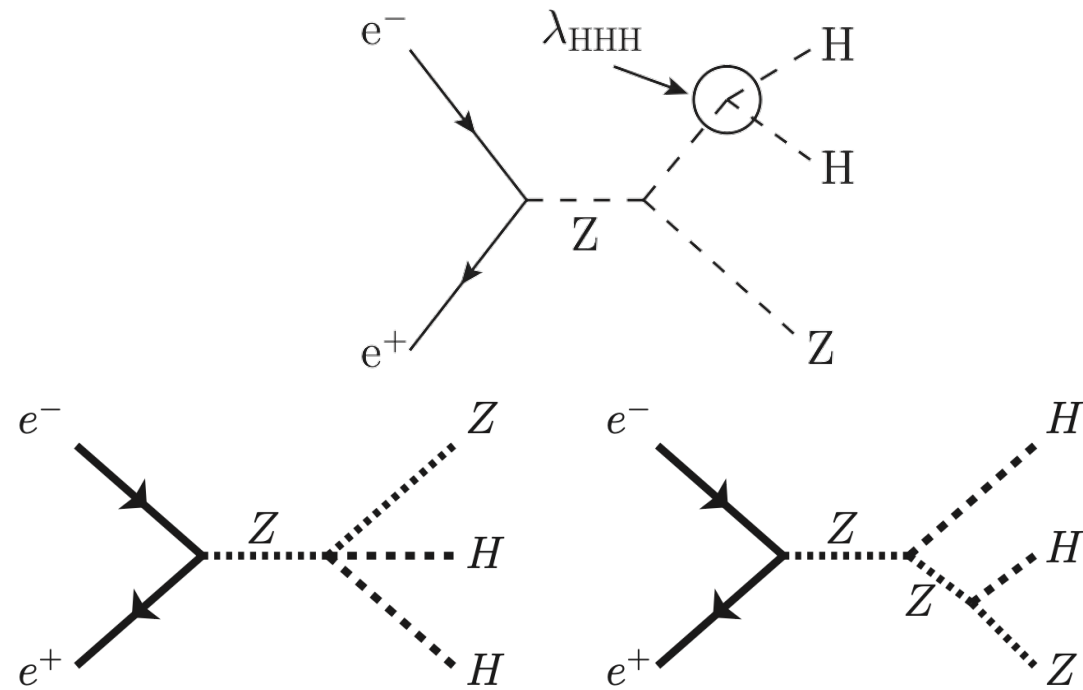
⇒ Large dependence on actual value of κ_λ

HL-LHC projection

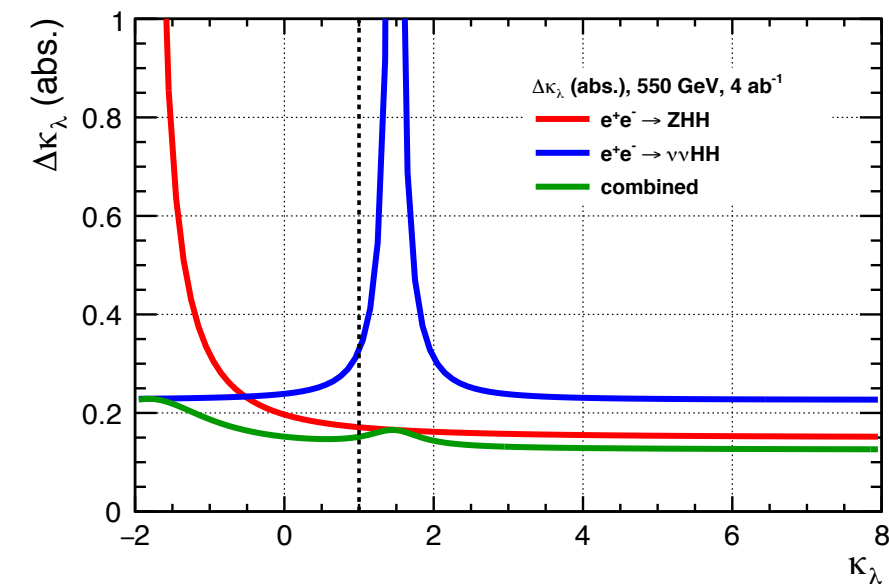
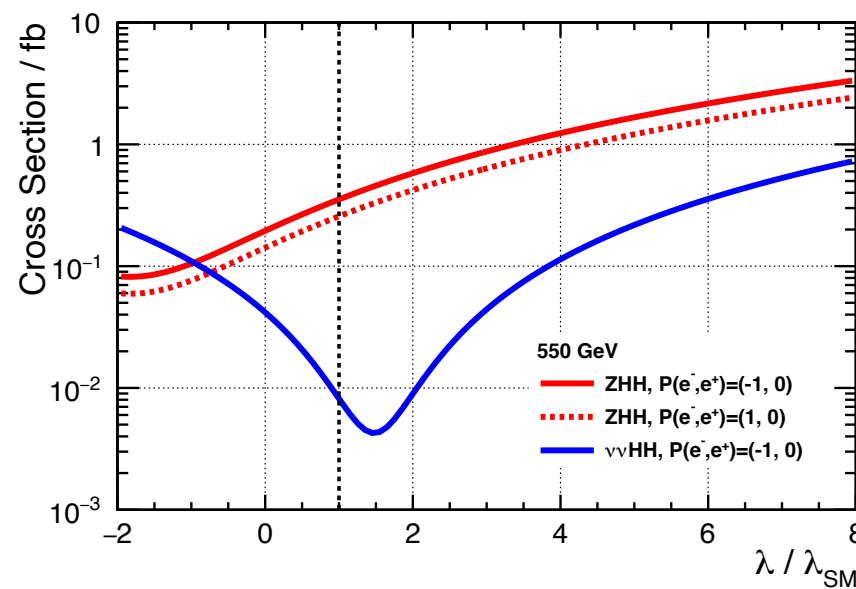
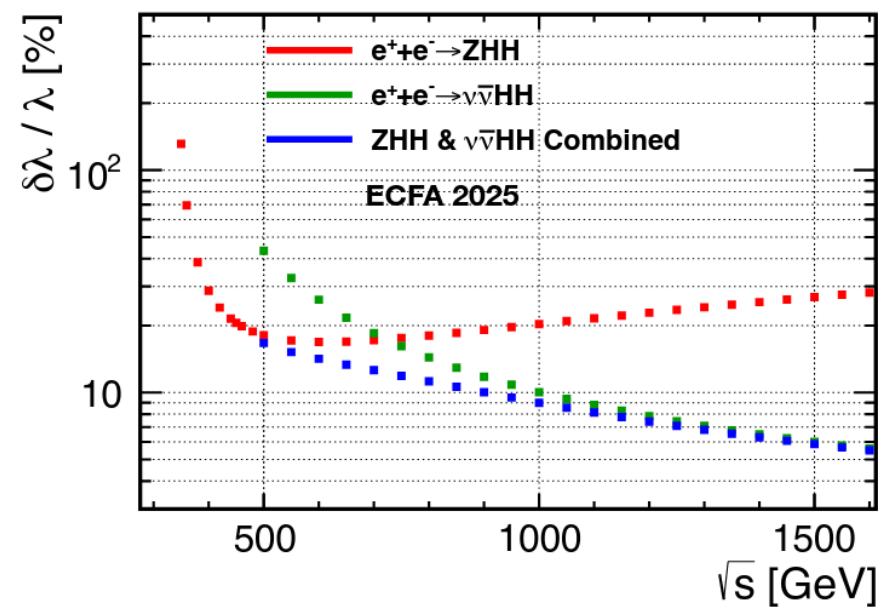


[ATLAS and CMS
Collaborations '25]

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



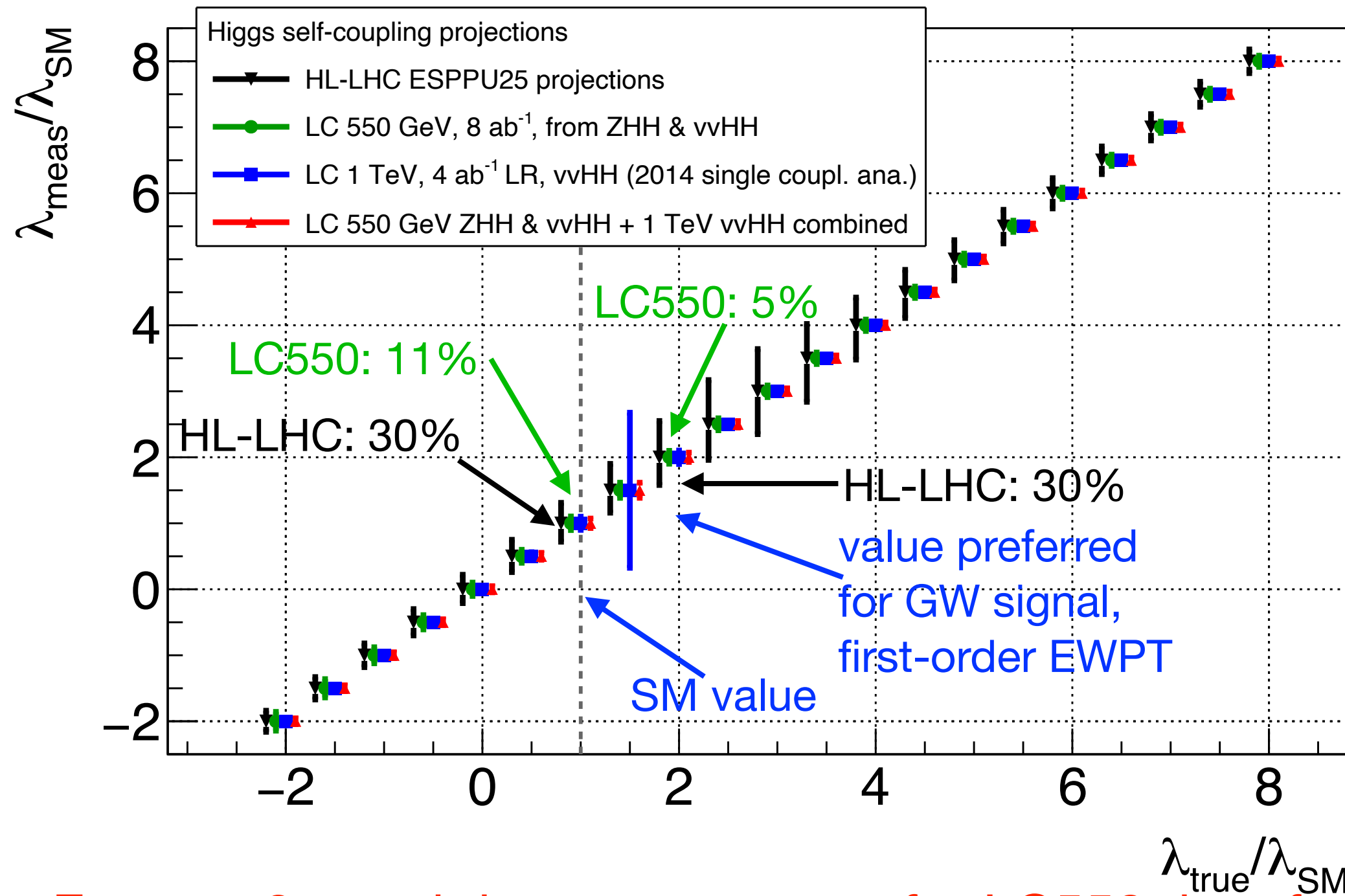
[J. List, J. Tian et al. '25]



$\Rightarrow$ 11% accuracy on κ_λ for SM case, constructive interference for $\lambda > \lambda_{\text{SM}}$

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

[J. List et al. '25]



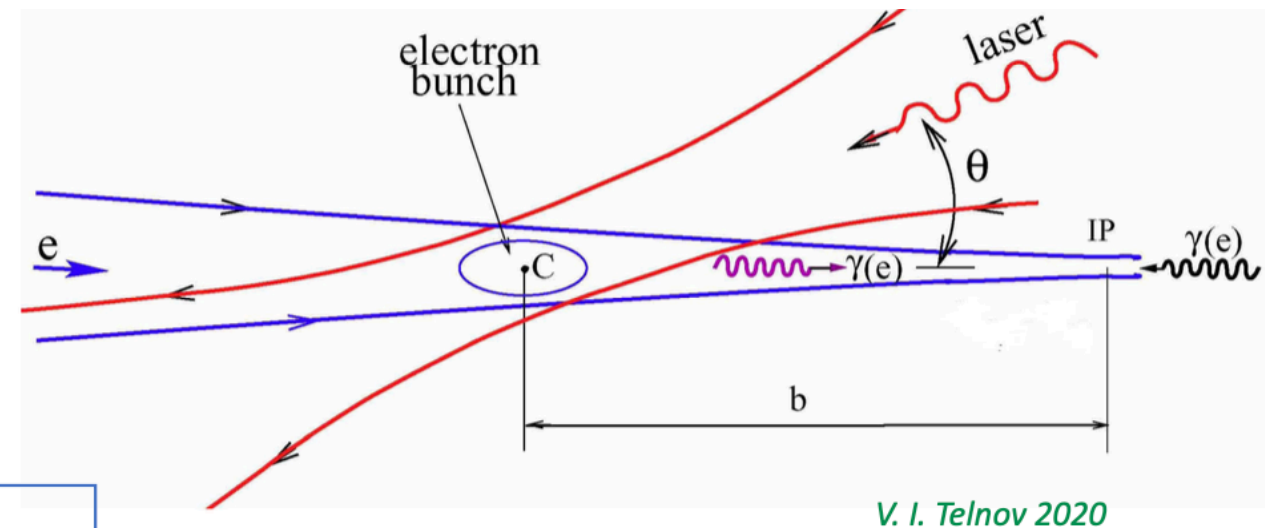
⇒ For $\kappa_\lambda \approx 2$: much better prospects for LC550 than for HL-LHC

Reason: different interference contributions

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

[G. Moortgat-Pick '25]

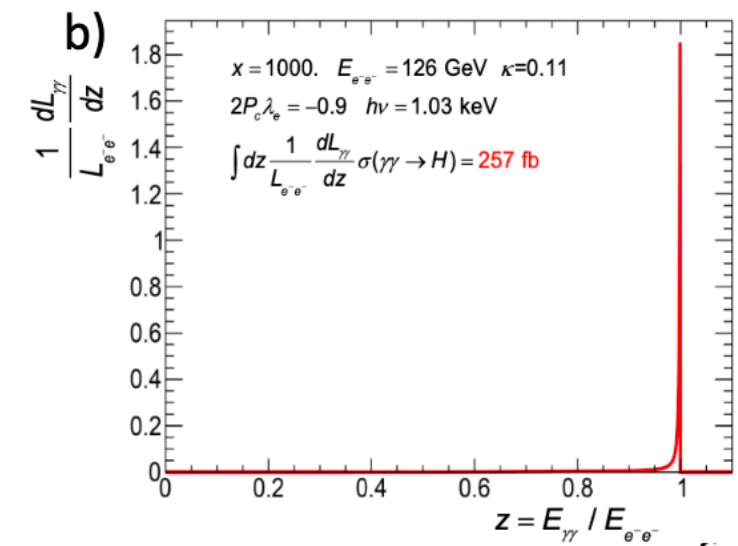
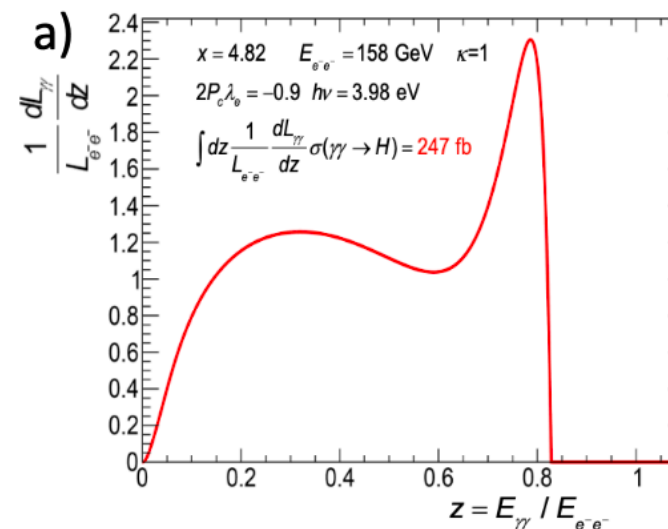
- Compton backscattering
- Getting access to $\gamma\gamma$ and γe processes



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

Laser is decisive:

- a) optical
- b) XFEL-like

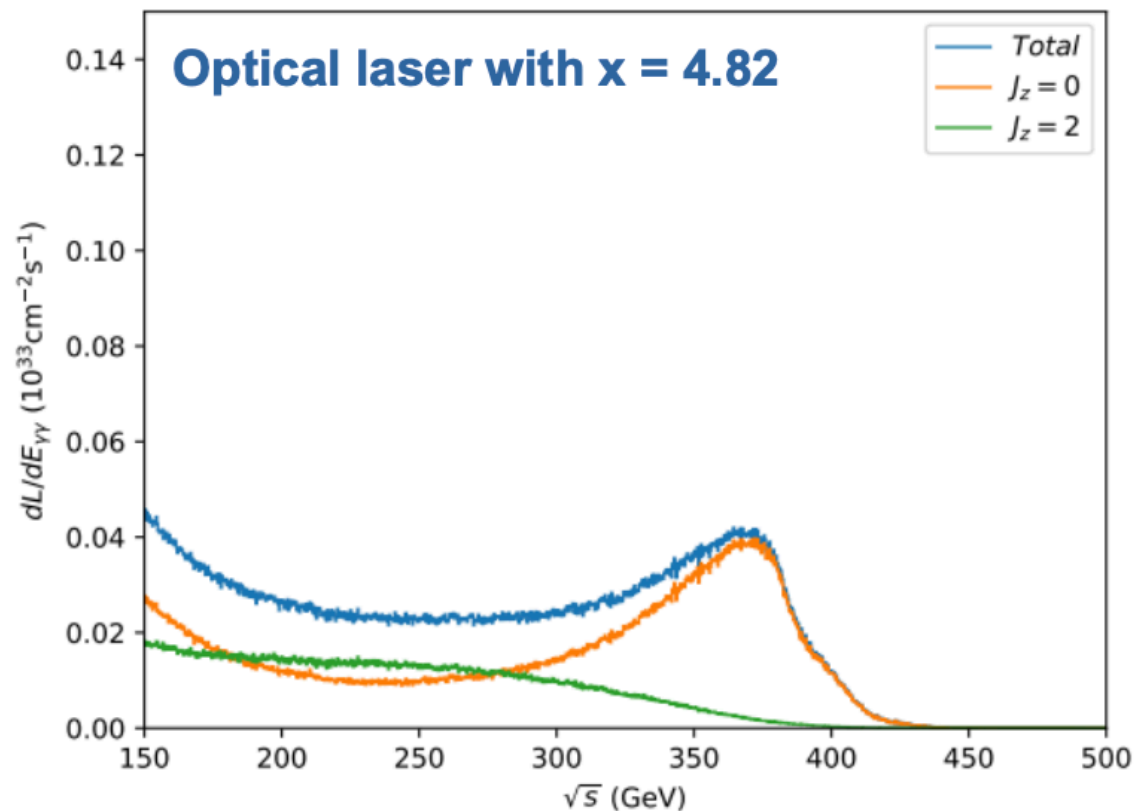


Laser options: optical and XCC

[G. Moortgat-Pick '25]

Optical

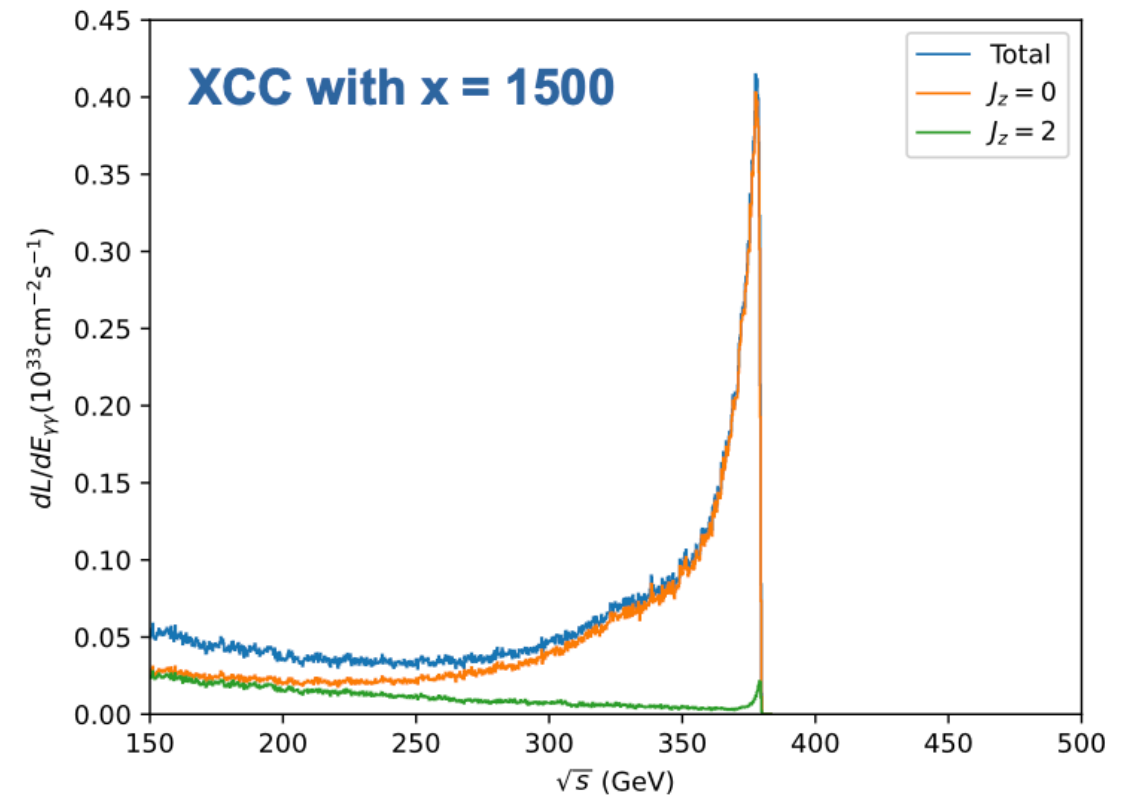
- Laser for $x = 4.82$
- Energy of colliding photon up to $\sim 80\%$ E_e
- Broad spectrum
- most electrons converted
- h-production at $E_e = 108$ GeV
- di-Higgs at $E_e = 250$ GeV
- $\lambda_e P_c = -0.9$



XCC

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

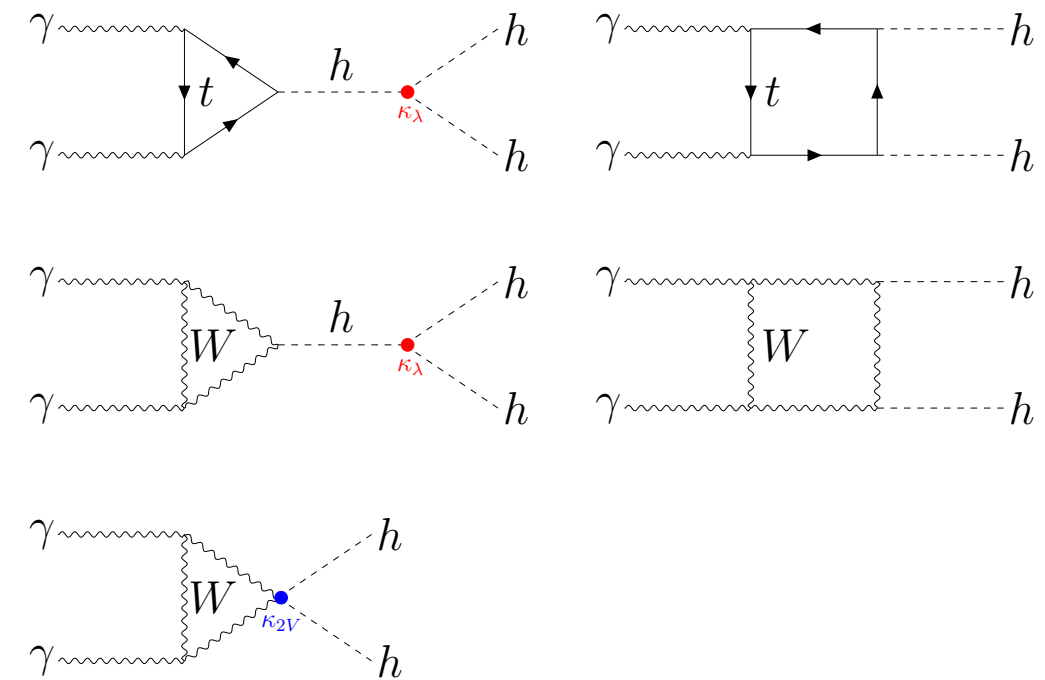
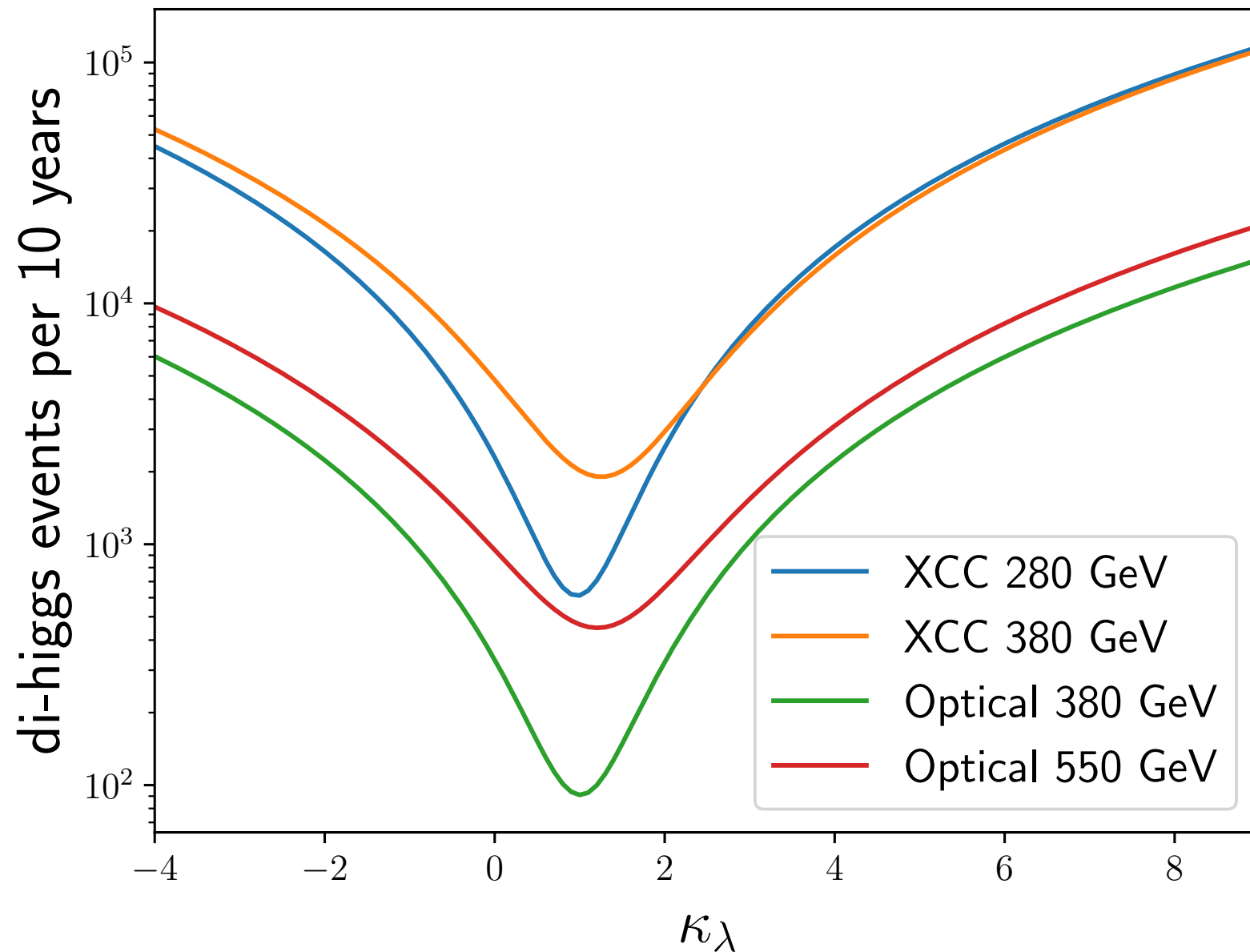
T. Barklow et al 23



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

$\sigma(\gamma\gamma \rightarrow hh) \mathcal{L}_{\text{int}}$

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

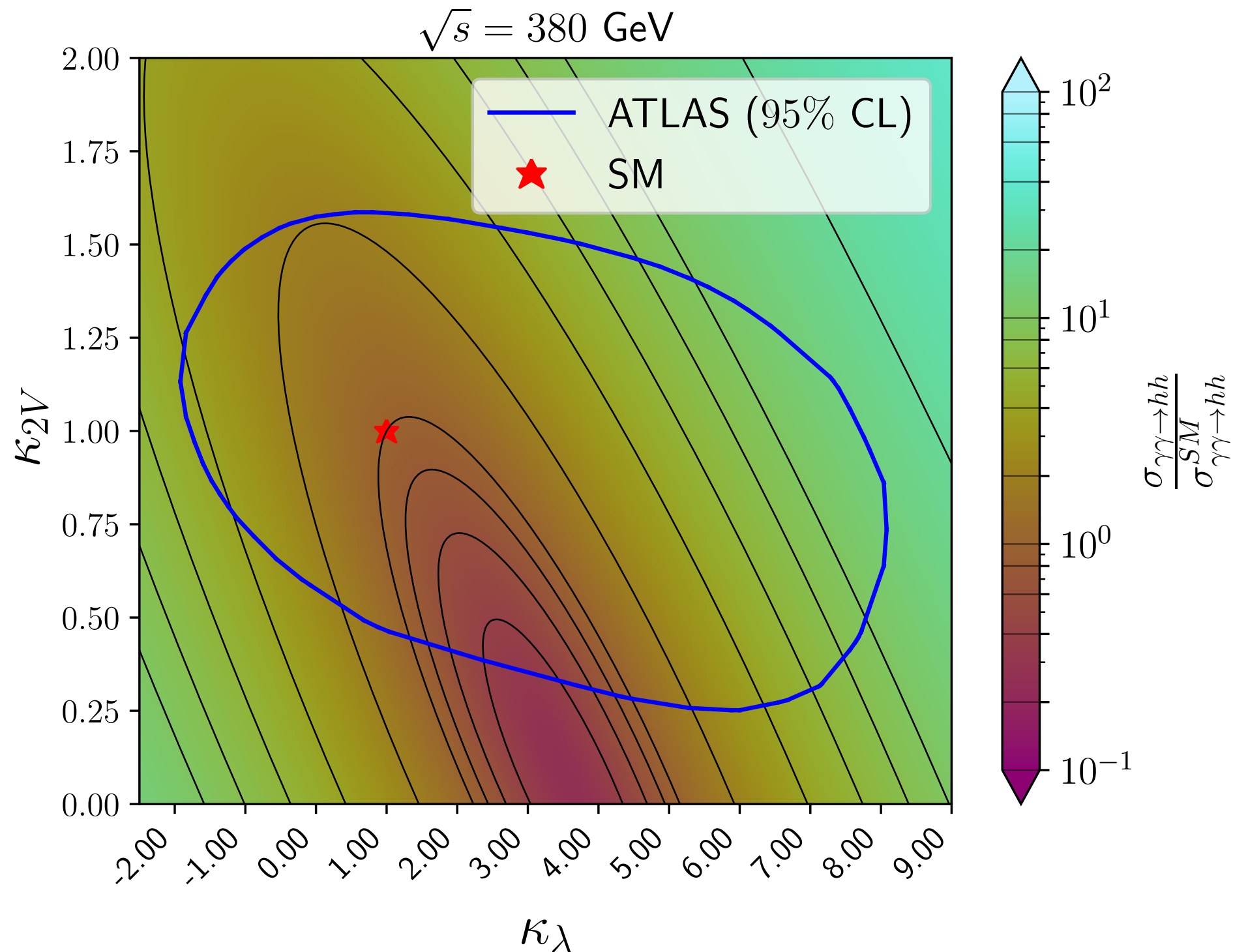


[T. Barklow '24]

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

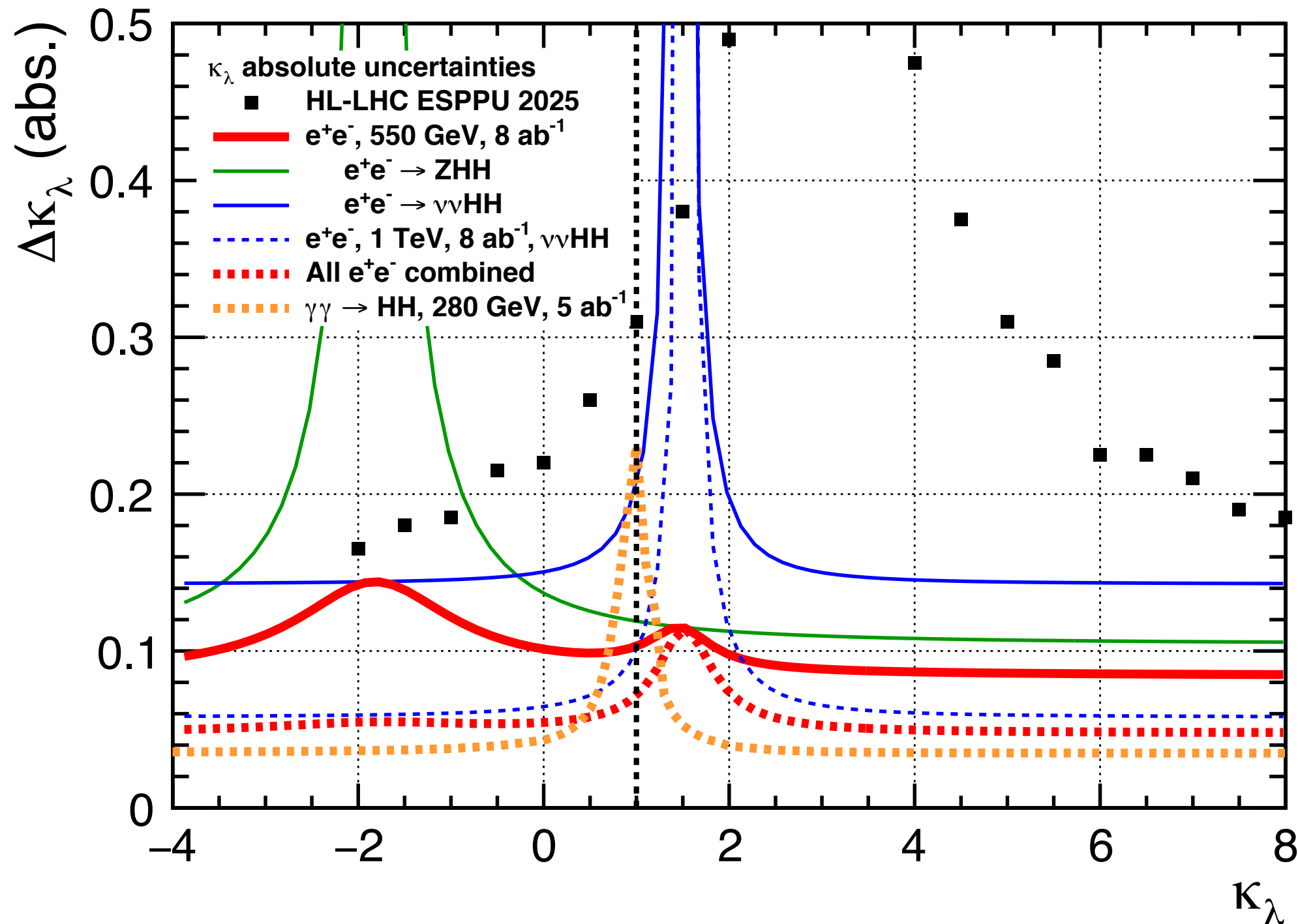
$\gamma\gamma \rightarrow hh$ cross section compared to the SM case in the allowed region for κ_λ and κ_{2V}

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



⇒ Sensitive dependence on κ_λ , moderate dependence on κ_{2V}

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



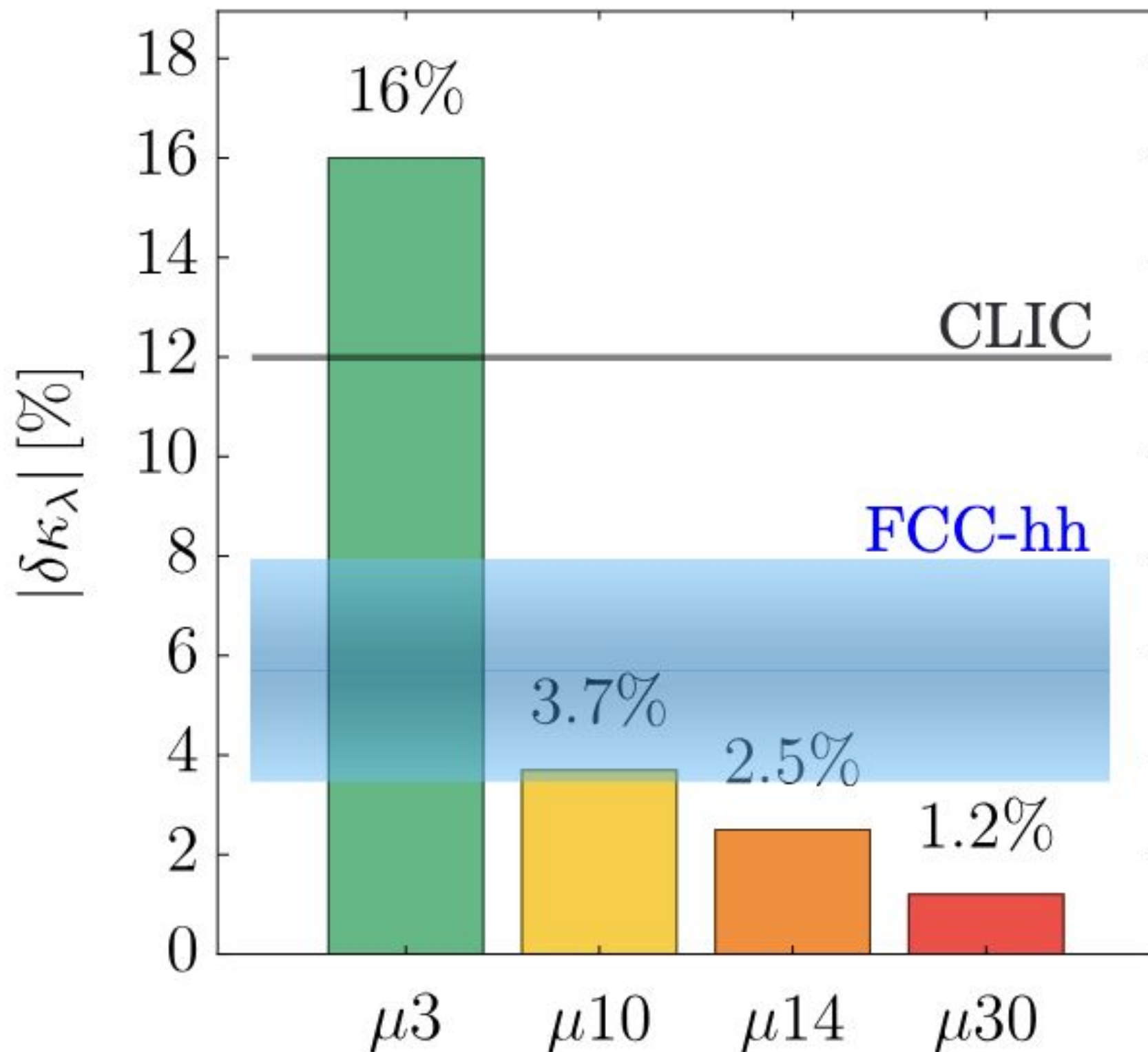
[J. List, J. Tian
et al. '25]

[T. Barklow et
al. '25]
[preliminary]

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

CLIC, Muon collider (3, 10, 14, 30 TeV), FCC-hh

[IMCC, C. Accettura et al. '24]



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

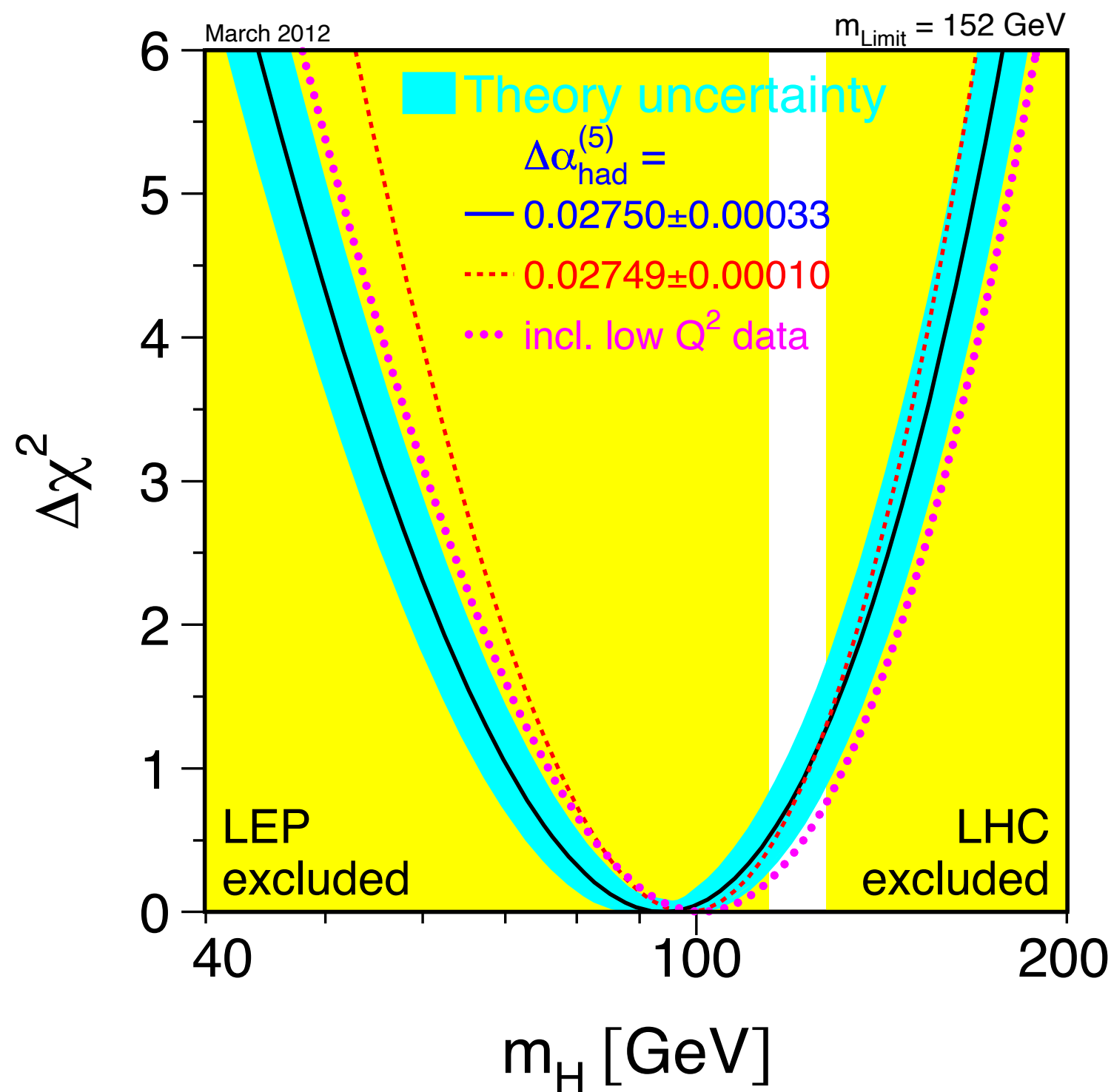
Indirect access to λ_{hhh} via

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

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

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

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



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

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

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

- M_h is a free parameter of the SM, but λ_{hhh} is **not**!
 - ⇒ Cannot vary λ_{hhh} “within” the SM, need consistent theoretical framework for possible deviations in λ_{hhh} from SM value, e.g. EFT
 - EFT: need complete basis of operators, involves model-dependence: consistent sub-set of operators? dim-6 vs. dim-8 operators? possible effects of light new particles? range of validity of the EFT description? ...
 - ⇒ Need much more than avoiding just some “blind directions” among certain operators
- Recent SMEFT analysis emphasising importance of complete operator basis and EW SMEFT corrections
[K. Asteriadis, S. Dawson, P. P. Giardino, R. Szafron '24]

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

λ_{hhh} and the Higgs pair production process

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

The **actual physical observable** in this context is the cross section for the **Higgs pair production process**, i.e. $gg \rightarrow hh$ at the LHC and $e^+e^- \rightarrow Zhh$, $e^+e^- \rightarrow \nu\nu hh$ at an e^+e^- collider with a c.m. energy of at least 500 GeV (or $\gamma\gamma \rightarrow hh$ 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 λ_{hhh} from its impact on loop corrections?

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

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 λ_{hhh} (within the LHC uncertainties): how well can such a deviation be associated with λ_{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 $\kappa_\lambda \neq 1$

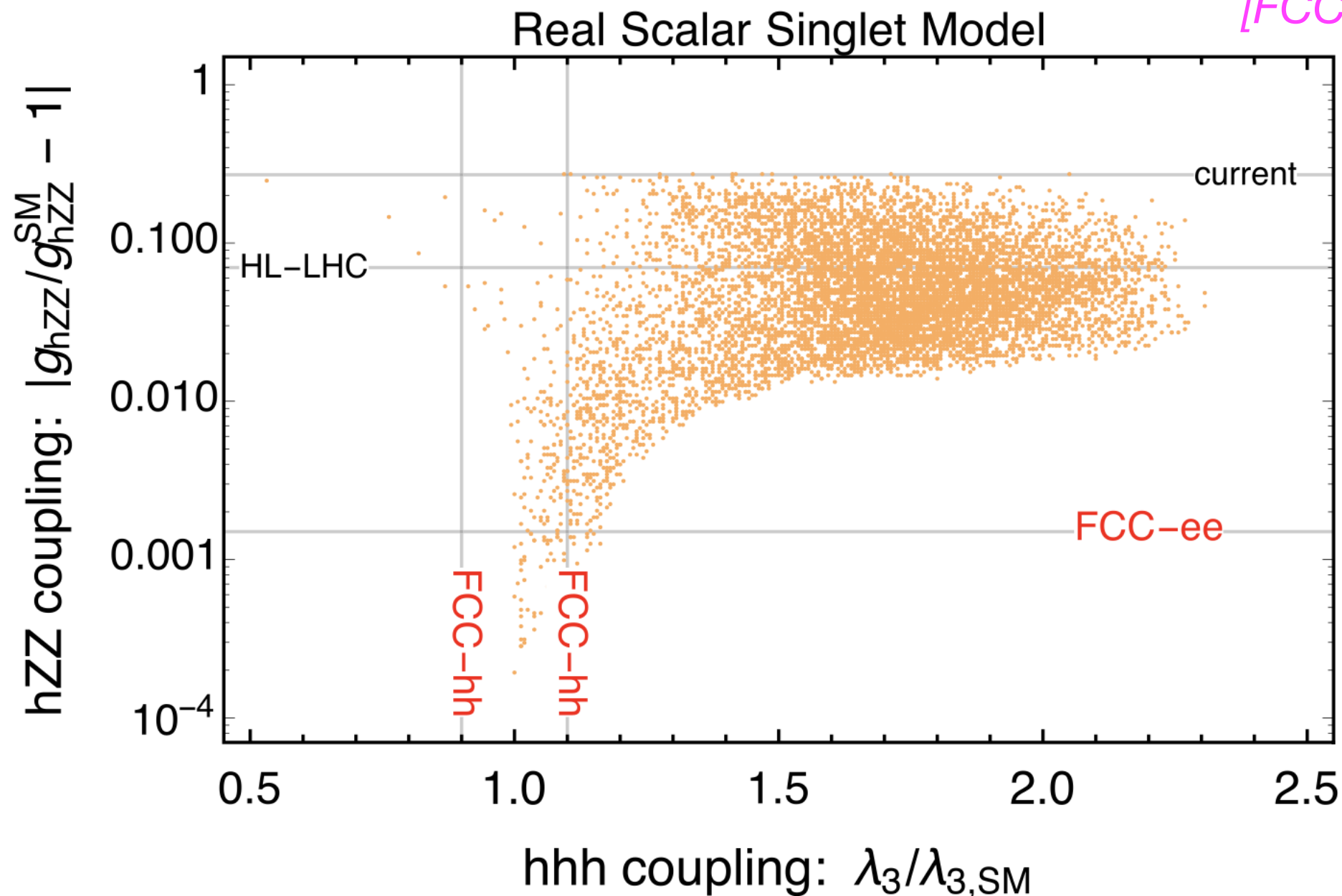
[H. Bahl, P. Bechtle, J. Braathen, S. Heinemeyer, J. List, M. Vellasco, G. W. '25]

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 κ_λ with effects in other couplings? Real scalar singlet model

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



[FCC Midterm Report '24]

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

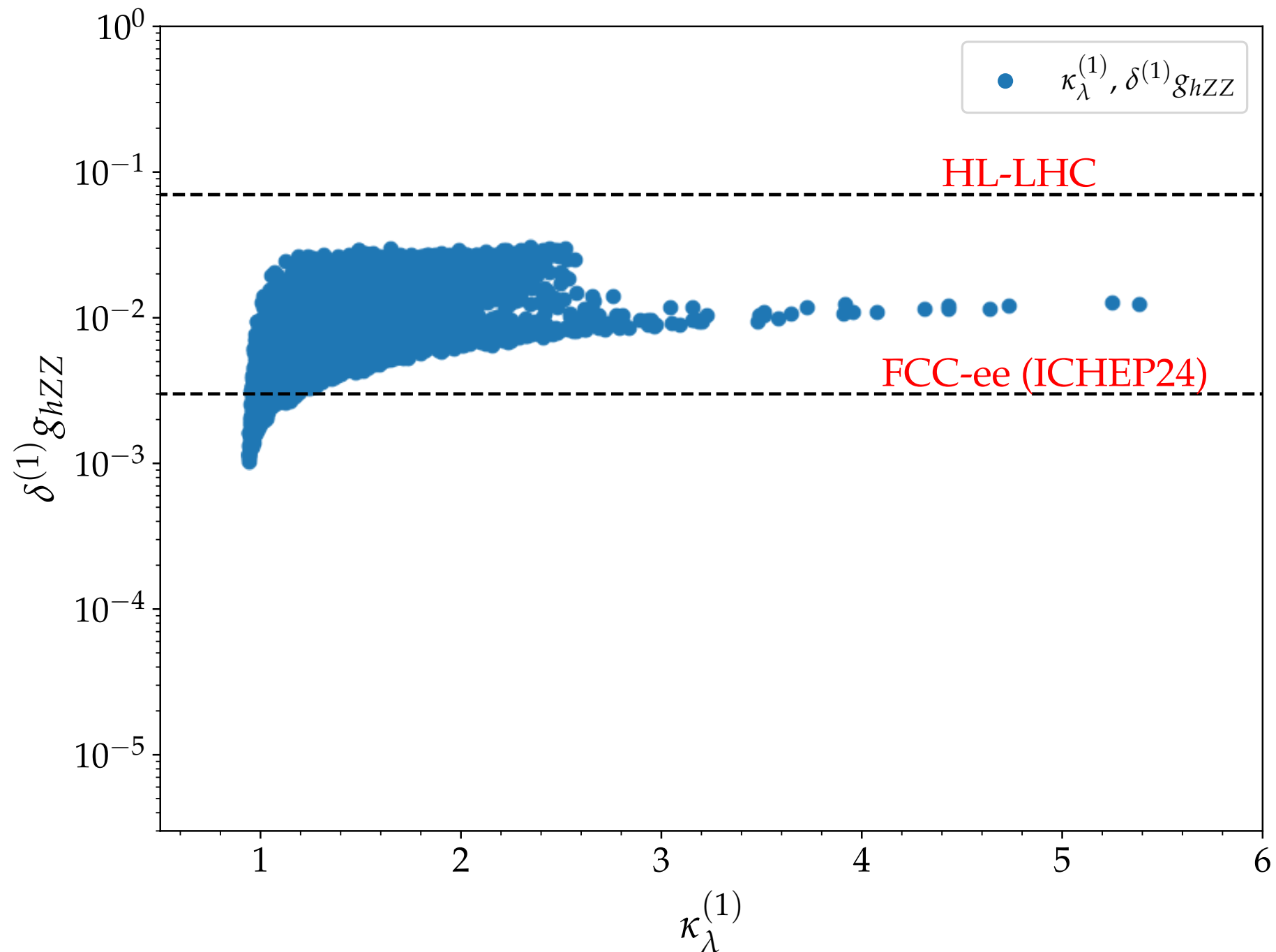
In this plot: no higher-order contributions to κ_λ included, partial loop effects for hZZ coupling

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

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hW} , 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:

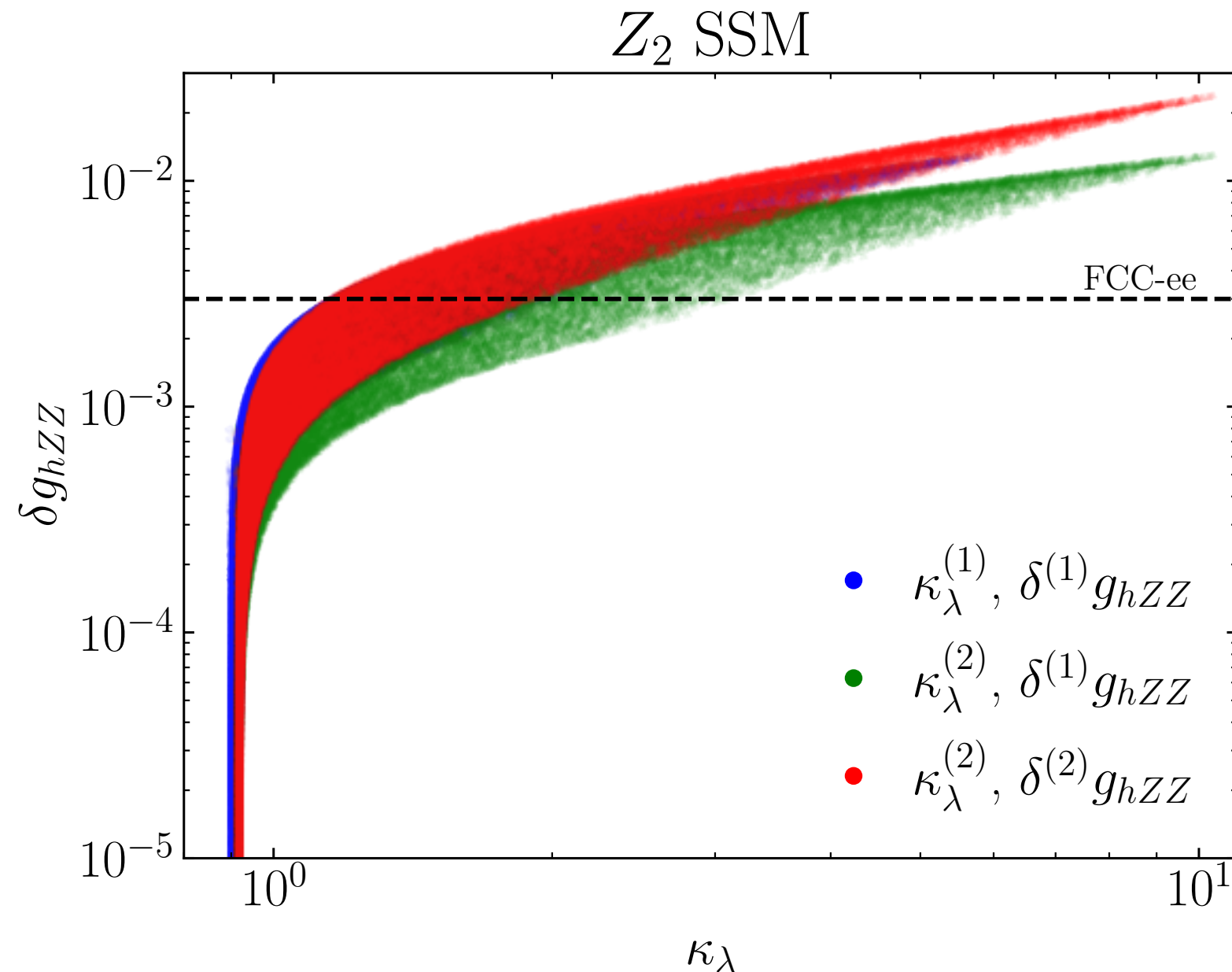


⇒ Large effects possible in λ_{hhh} while modification of the couplings of h to gauge bosons is beyond the HL-LHC sensitivity

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hW} , 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 κ_λ and δg_{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 1σ accuracy of FCC-ee on the hZZ coupling.

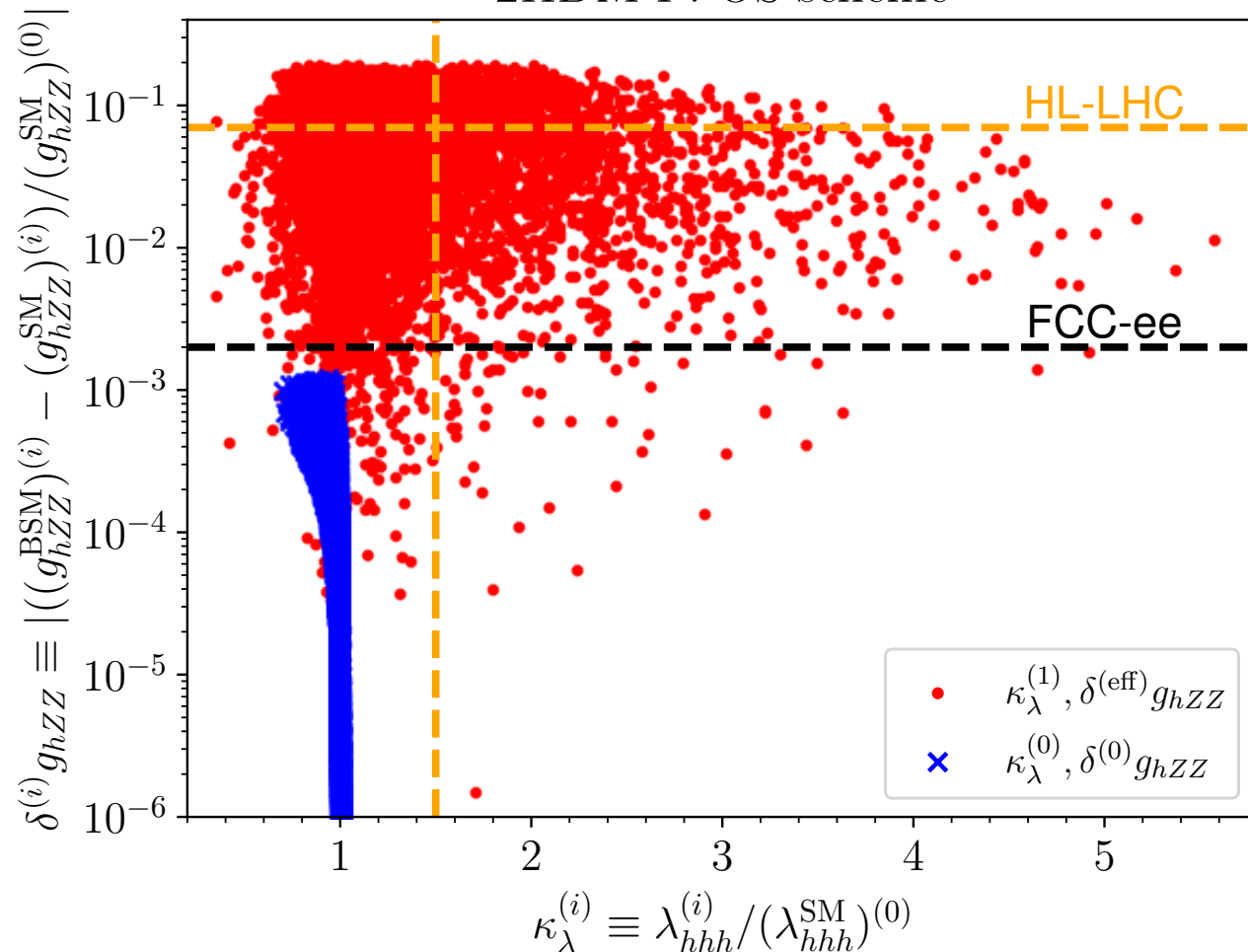
⇒ Large effects possible in λ_{hhh} while the couplings of h to gauge bosons and fermions are very close to the SM value!

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hW} , g_{hff} couplings)

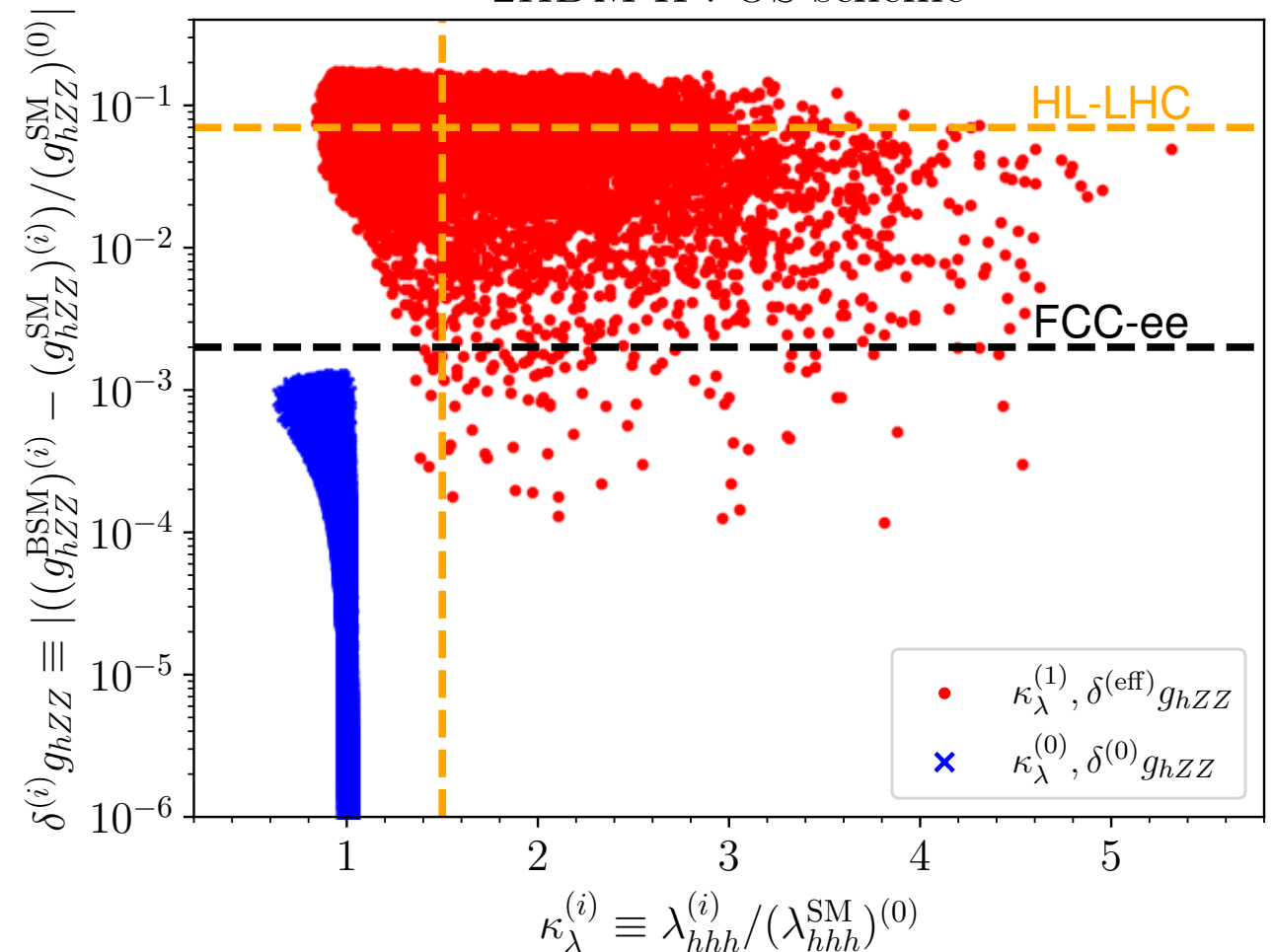
[H. Bahl, J. Braathen, M. Gabelmann, S. Heinemeyer, K. Radchenko, A. Verduras, G. W. '25]

2HDM of type I and type II:

2HDM I : OS scheme



2HDM II : OS scheme

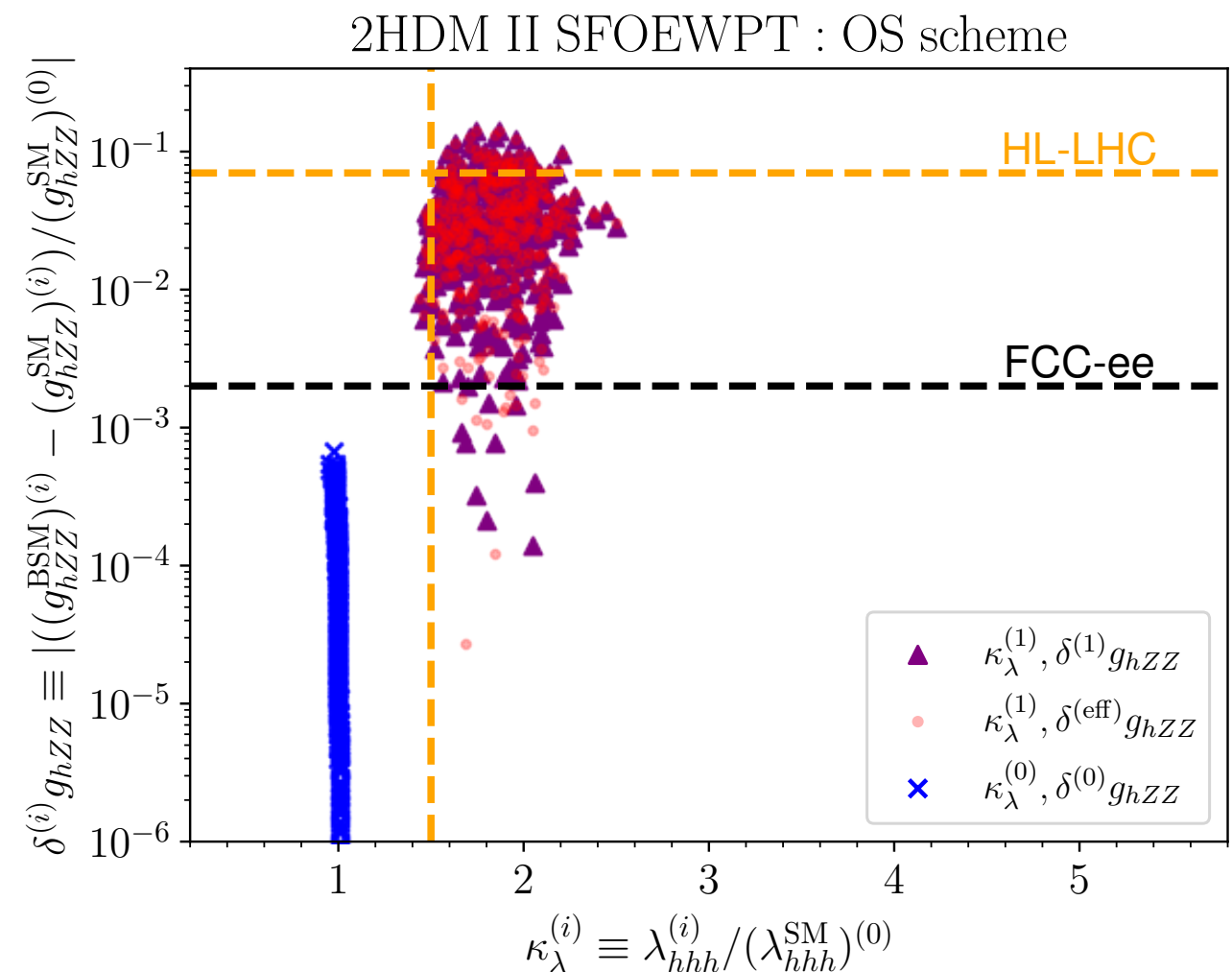
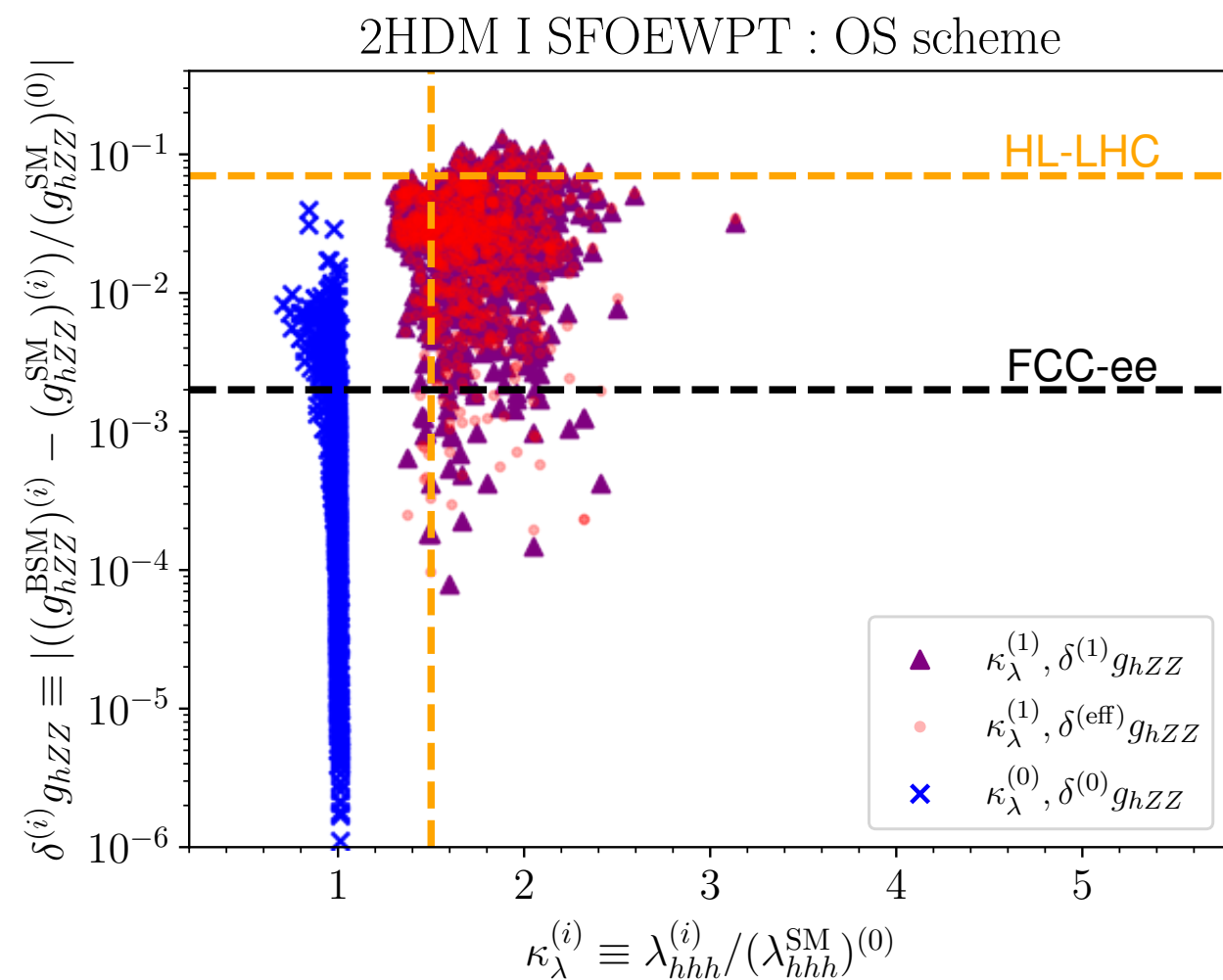


⇒ Large effects possible in λ_{hhh} while the couplings of h to gauge bosons and fermions are very close to the SM value!

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hW} , g_{hff} couplings)

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

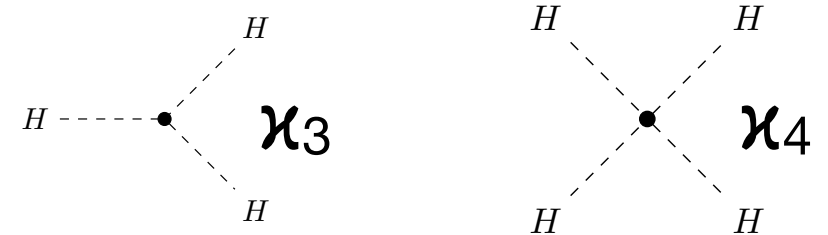
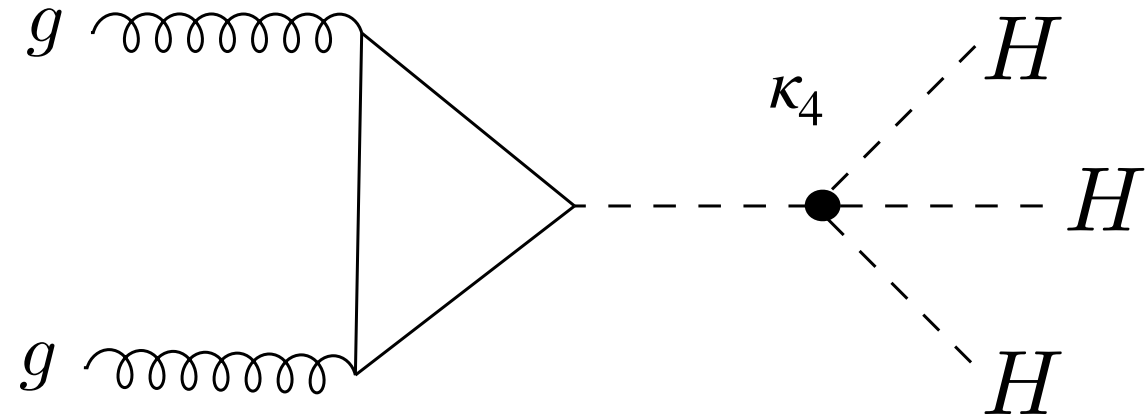
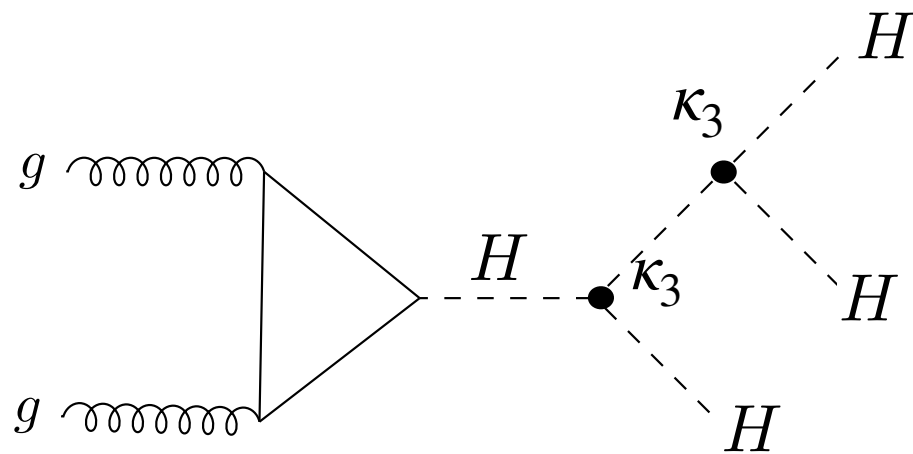
2HDM of type I and type II (FOEWPT condition imposed):



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

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

Triple-Higgs production depends on κ_3 and κ_4 !



Is it possible to obtain bounds from triple-Higgs production on $\kappa_\lambda \equiv \kappa_3$ and κ_4 that go beyond the existing theoretical bounds from perturbative unitarity? Potential for κ_3 constraints beyond the ones from di-Higgs production?

How big could the deviations in κ_4 from the SM value ($= 1$) be in BSM scenarios?

Bounds from perturbative unitarity

- Process relevant for κ_3, κ_4 is $HH \rightarrow HH$ scattering (see also [Liu et al `18])
- Jacob-Wick expansion allows to extract partial waves

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

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

Wigner functions

- Tree level unitarity:

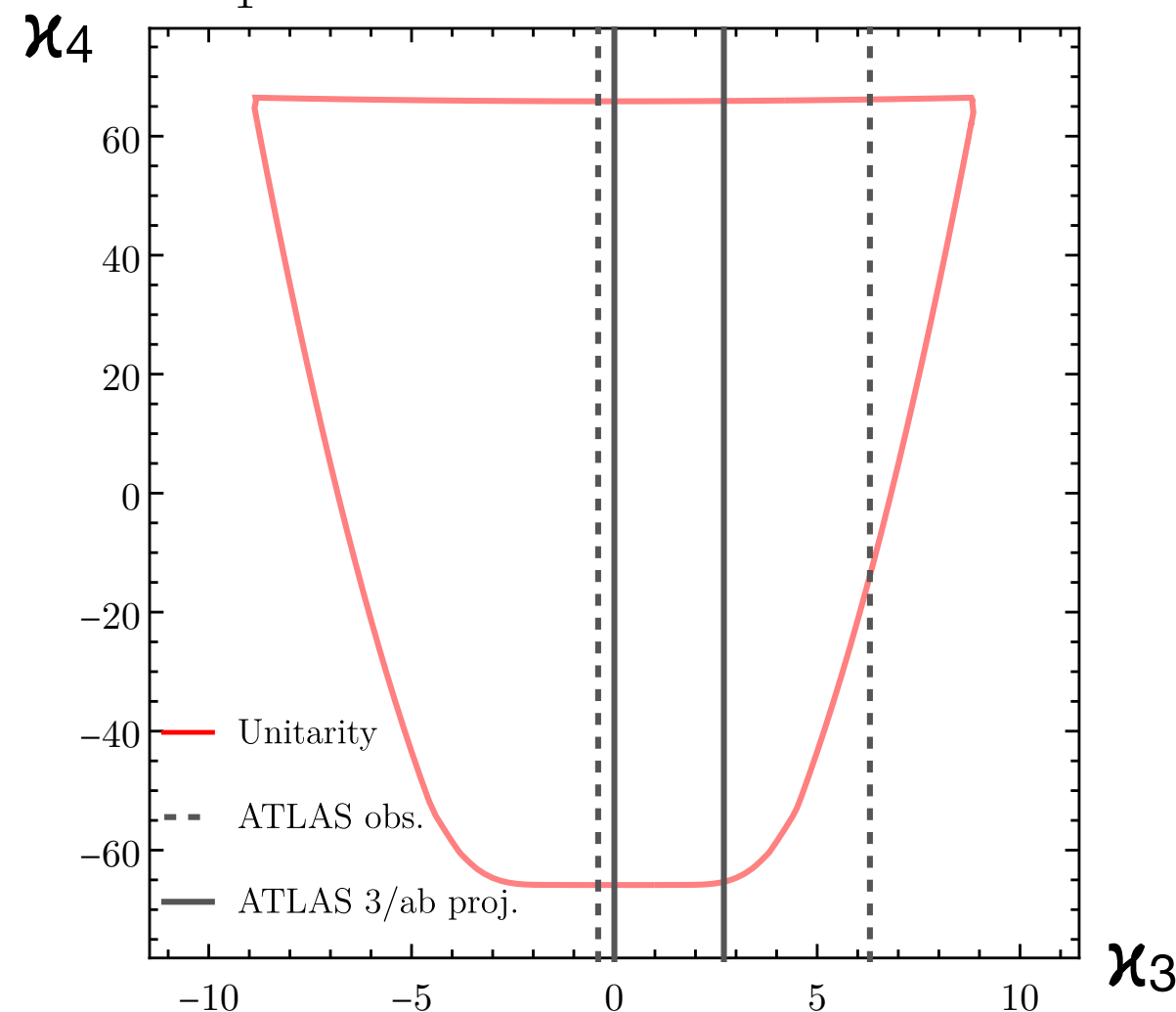
$$\text{Im} a_{ii}^0 \geq |a_{ii}^0|^2 \implies |\text{Re} a_{ii}^0| \leq \frac{1}{2}$$

ATLAS current bounds: $[-0.4, 6.3]$ 95 % CL

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]

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

Contributions to κ_3 , κ_4 :

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

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

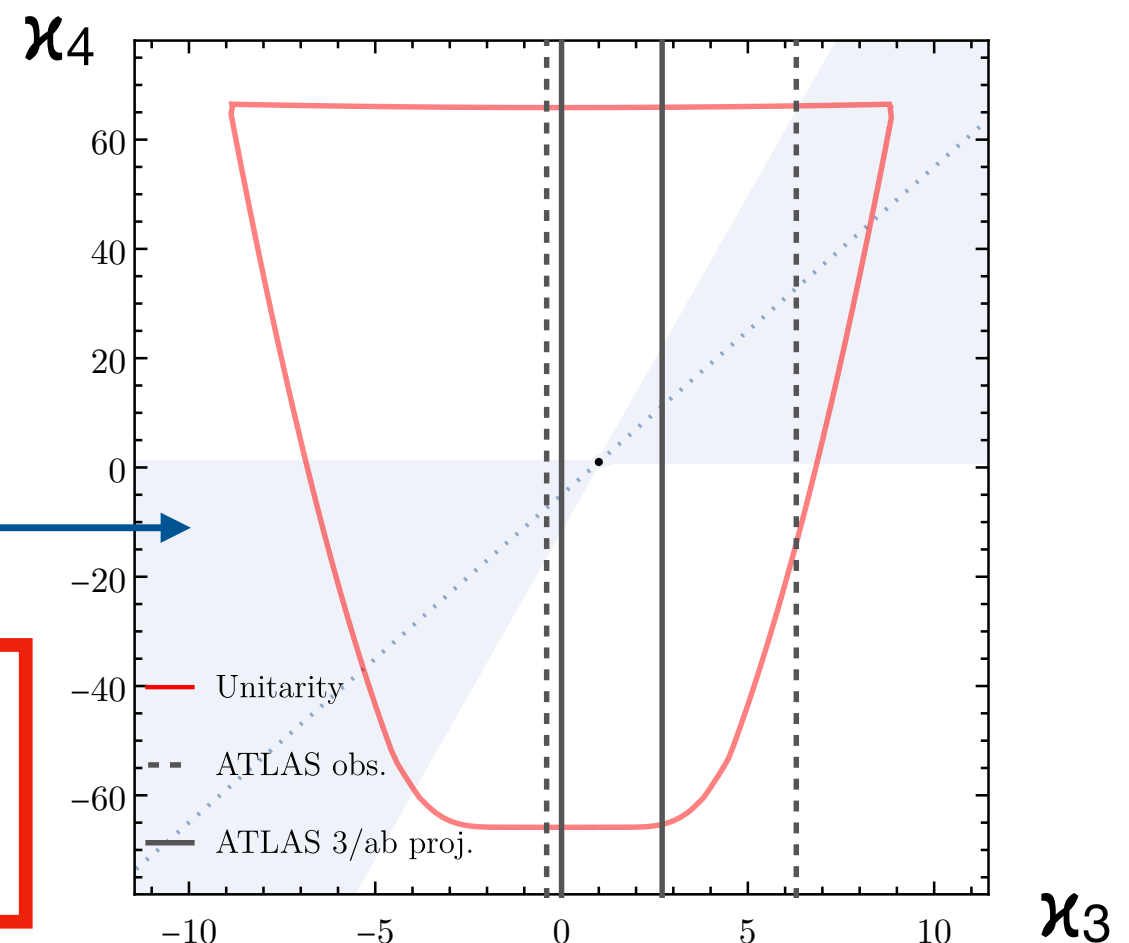
vanishing
dimension-8

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

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 $\rightarrow$ probes **non-linearity**



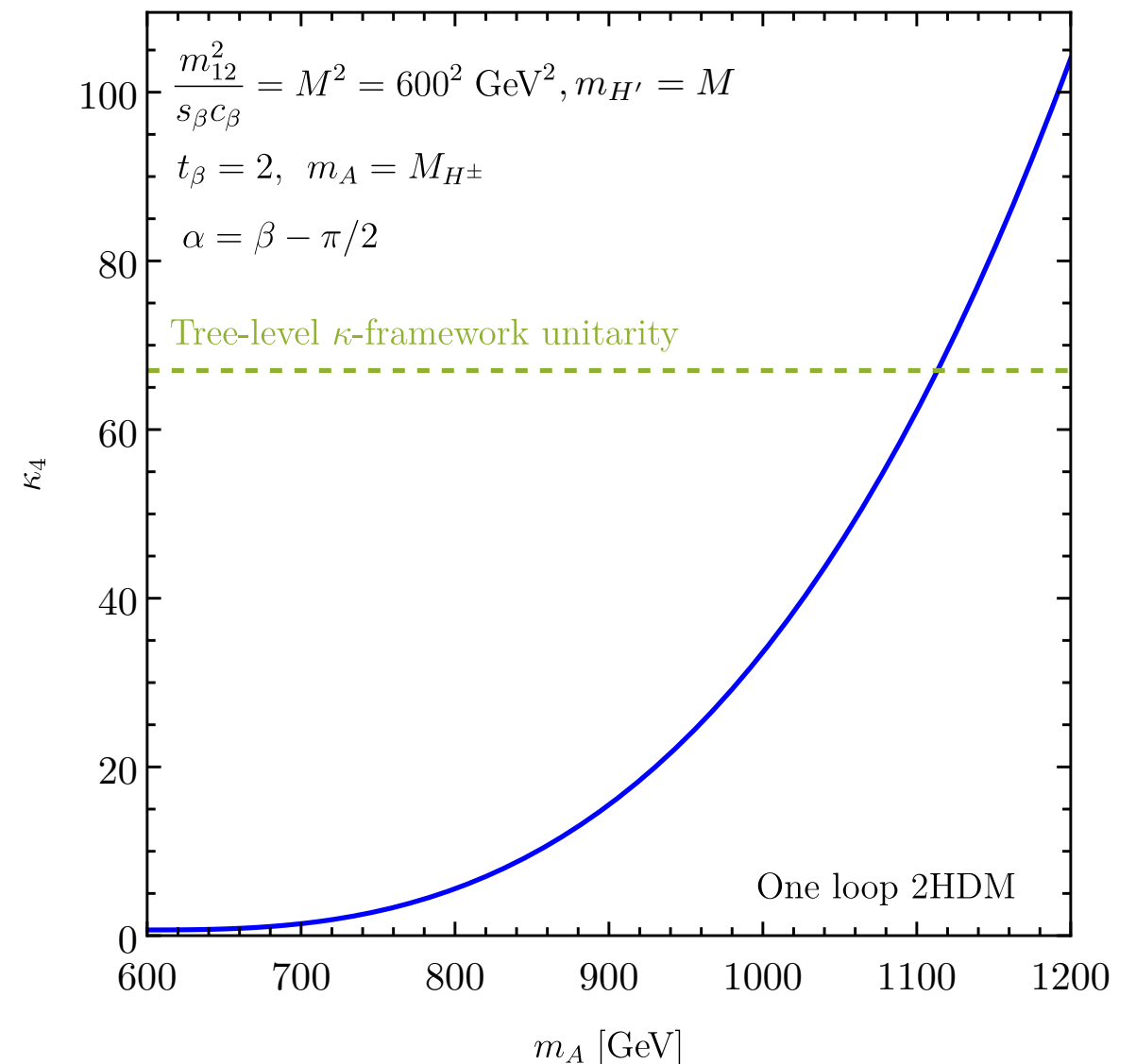
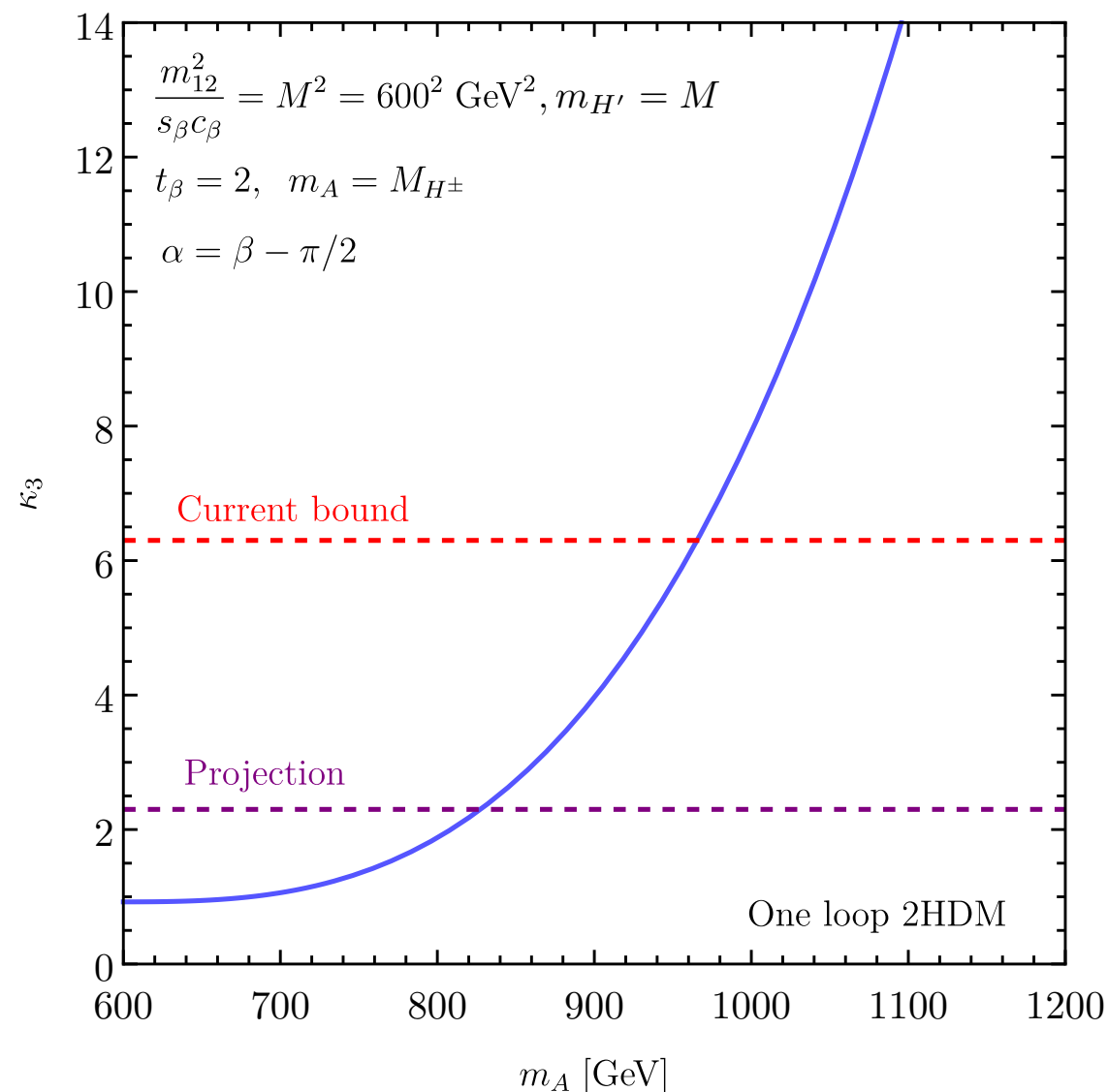
$\Rightarrow$ Deviation in κ_4 enhanced by factor 6!

Model example: 2HDM, κ_3 (see above) vs. κ_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

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

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



Prospects for the HL-LHC

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

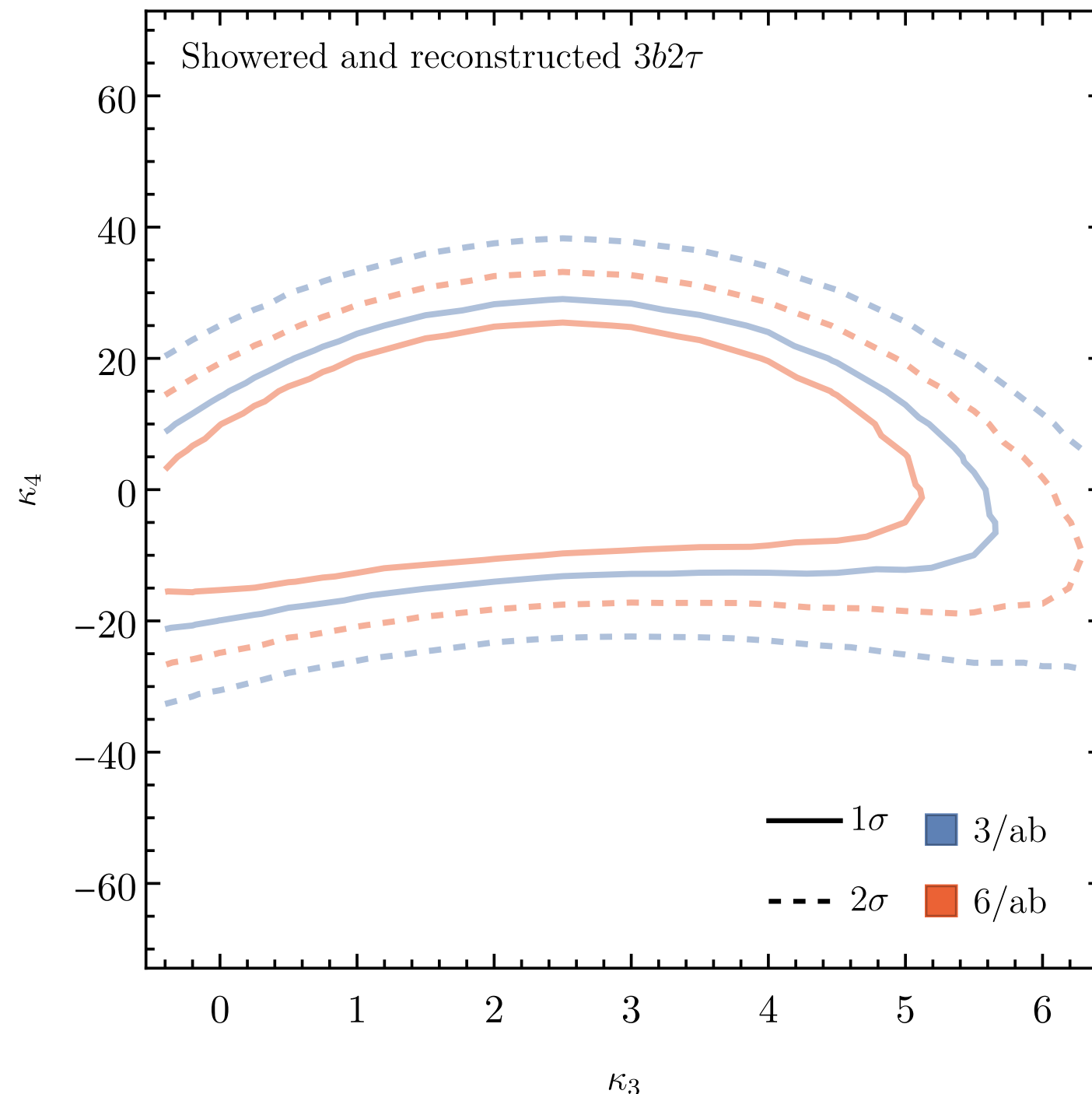
- Use of Graph Neural Networks (GNN) for signal-background classification
- Focus on $6b$ and $4b2\tau$ final states with 5 and 3 tagged b -quarks, respectively

Backgrounds:

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

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

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



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

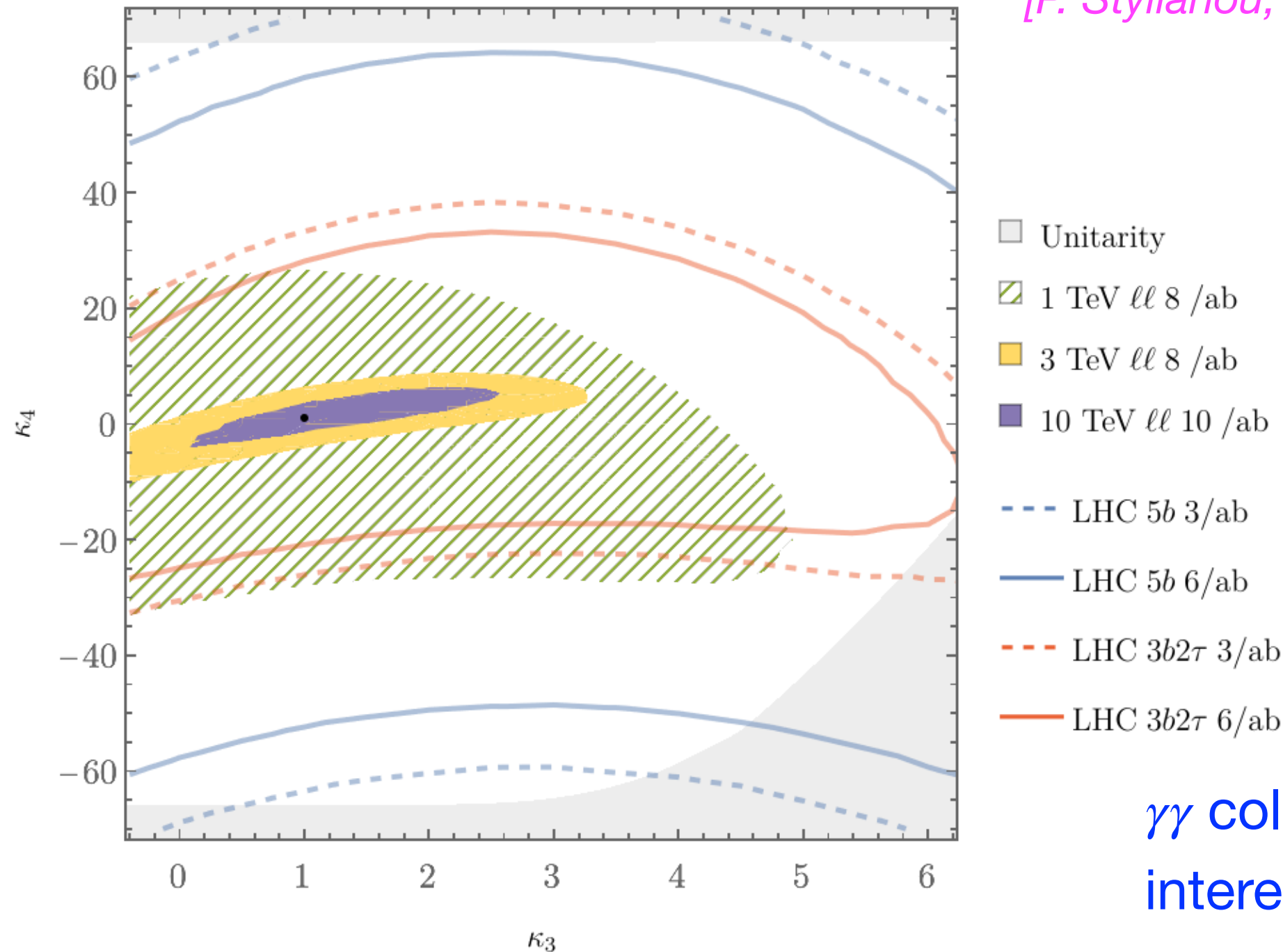
Recent HL-LHC
projection for the
 $6b$ channel:
[ATLAS and CMS
Collaborations '25]

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

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

Comparison of future options (personal view)

In view of the outcome of the previous update of the European strategy I focus here on options involving an e^+e^- Higgs factory

Remark on the muon collider: exciting physics programme, but the open issues regarding its technical realisability from my point of view essentially preclude it as an option for a possible next step

FCC-ee + FCC-hh integrated programme

For CERN this is the biggest (in size and time span) and most expensive option

FCC-ee: precision measurements of h_{125} couplings to gauge bosons and fermions

But: will not be able to tell us much about the Higgs potential

FCC-hh: will start, if everything is on time, at best in **50 years from now!**

Suppose in 1975 a collider would have been designed that would be about to go into operation now ...

From my point of view, this is **not** an exciting perspective for Higgs physics

CEPC + SppC

Similar physics potential as FCC-ee + FCC-hh, but realisation could come **much faster**

The SppC may turn out to be the most realistic way to get to the big hadron machine that many people dream about

Linear Collider Facility at CERN

Affordable initial investment; leaves flexibility for future programme

Clear path (much earlier and much cheaper than FCC-hh) to the exploration of the Higgs potential via the Higgs pair production process

Additional exciting option: $\gamma\gamma$ collider, either in addition to e^+e^- or stand-alone

$\gamma\gamma$ collider: s-channel production of h125 with 125 GeV c.m. energy
A 280 GeV XCC may be the most cost-efficient way to Higgs pair production and the trilinear Higgs self-coupling

LEP3

Less attractive physics programme than FCC-ee, CEPC

Future perspective after the end of operation?

Maybe HE-LHC, i.e. reusing the same tunnel once more, if the high-field magnets are sufficiently far developed by then?

Intermediate projects

[K. Jakobs, Open Symposium summary talk '25]

(Leave room (time, budget, resources) for further development of THE machine that can probe directly the energy frontier at the 10 TeV parton scale)

I don't share Karl's optimism regarding LEP3 as an "intermediate project": We cannot afford FCC-hh right now. It seems not very likely to me that after pursuing the LEP3 programme and spending very significant resources on it, FCC-hh will then be affordable for us. For me it seems much more likely that going for LEP3 as our next project essentially means to **give up** on a new tunnel in the Geneva area

Conclusions

Properties of h_{125} : high-precision measurements at e^+e^- Higgs factory at low energy; we need to demonstrate the physics gain from the improved accuracy of the couplings to gauge bosons and fermions!

Higgs potential: close relation to electroweak phase transition and thermal evolution of early universe; trilinear and quartic Higgs self-couplings + possible couplings involving BSM Higgs bosons

Trilinear Higgs self-coupling: large deviations from SM value possible even if couplings to gauge bosons and fermions are SM-like;

LC500 and beyond, $\gamma\gamma$ collider: access via Higgs pair production;

FCC-ee, CEPC: indirect constraints via loop effects on lower-energy observables

Quartic Higgs self-coupling: HL-LHC has potential for constraints beyond unitarity bounds; big improvements possible at **highest-energetic lepton colliders** and **FCC-hh**

Backup

Possible EU support?

[S. Gascon-Shotkin '25]

**NUCLÉAIRE
& PARTICULES**

**IP2i**
LES 2 INFINIS
LYON

Status of EU Support

**European
Commission**

**Lyon1**

**UNIVERSITÉ
DE LYON**

Moonshots

Objective: ambitious technology driven projects that boost the EU's strategic autonomy through research, development and deployment.

- ▶ the future circular collider ▶ clean aviation ▶ quantum computing ▶ next-generation AI ▶ data sovereignty ▶ automated transport and mobility ▶ regenerative therapies ▶ fusion energy ▶ space economy ▶ zero water pollution ▶ ocean observation

EUROPE'S BUDGET

HORIZON EUROPE (2028-2034)

JULY 2025

Possible 'moonshots':

- Investing in the European Organization for Nuclear Research's (CERN) Future Circular Collider, alongside other CERN's participating countries. The objective is to maintain Europe's leadership in particle physics research. The funding (up to 20% of the overall cost) could come from Horizon Europe.

Horizon Europe (2028-2034) will build on the achievements of its predecessors, scaling what works, simplifying what is possible, and focusing investment where Europe needs it most. It will be tightly connected to the European Competitiveness Fund.

Possible hints from searches for additional Higgs bosons?

Compatibility of extended Higgs sectors with exp. results:

- A SM-like Higgs at ~ 125 GeV
- Properties of the other Higgs bosons (masses, couplings, ...) have to be such that they are in agreement with the present bounds

⇒ Additional Higgs bosons may well be lighter than the SM-like Higgs boson (h125)

If h125 is the lightest state of an extended Higgs sector, a typical feature is that the other states are nearly mass-degenerate and show “decoupling” behaviour

At lepton colliders heavy BSM Higgses are typically pair-produced

⇒ Best prospects at highest c.m. energy!

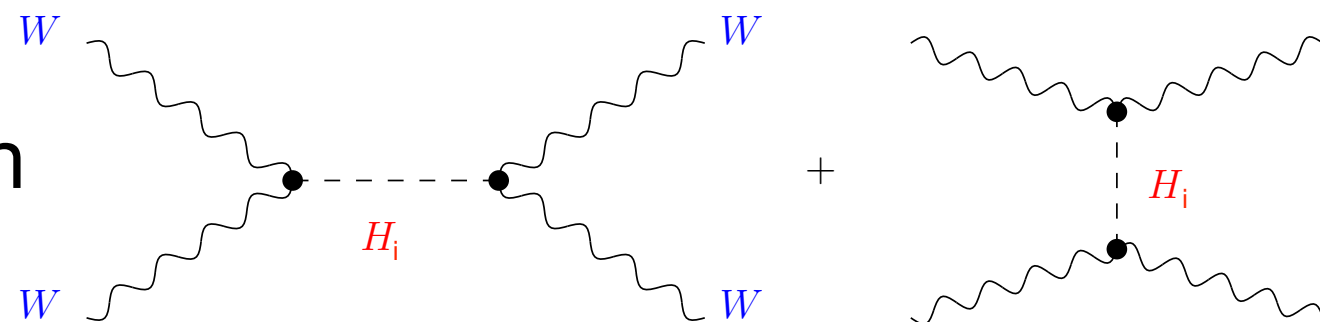
Search for additional Higgs bosons

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a “sum rule”:

$$\sum_i g_{H_i V V}^2 = \left(g_{H V V}^{\text{SM}}\right)^2$$

The SM coupling strength is “shared” between the Higgses of an extended Higgs sector, $\kappa_V \leq 1$

⇒ Unitarisation of the vector boson scattering amplitudes



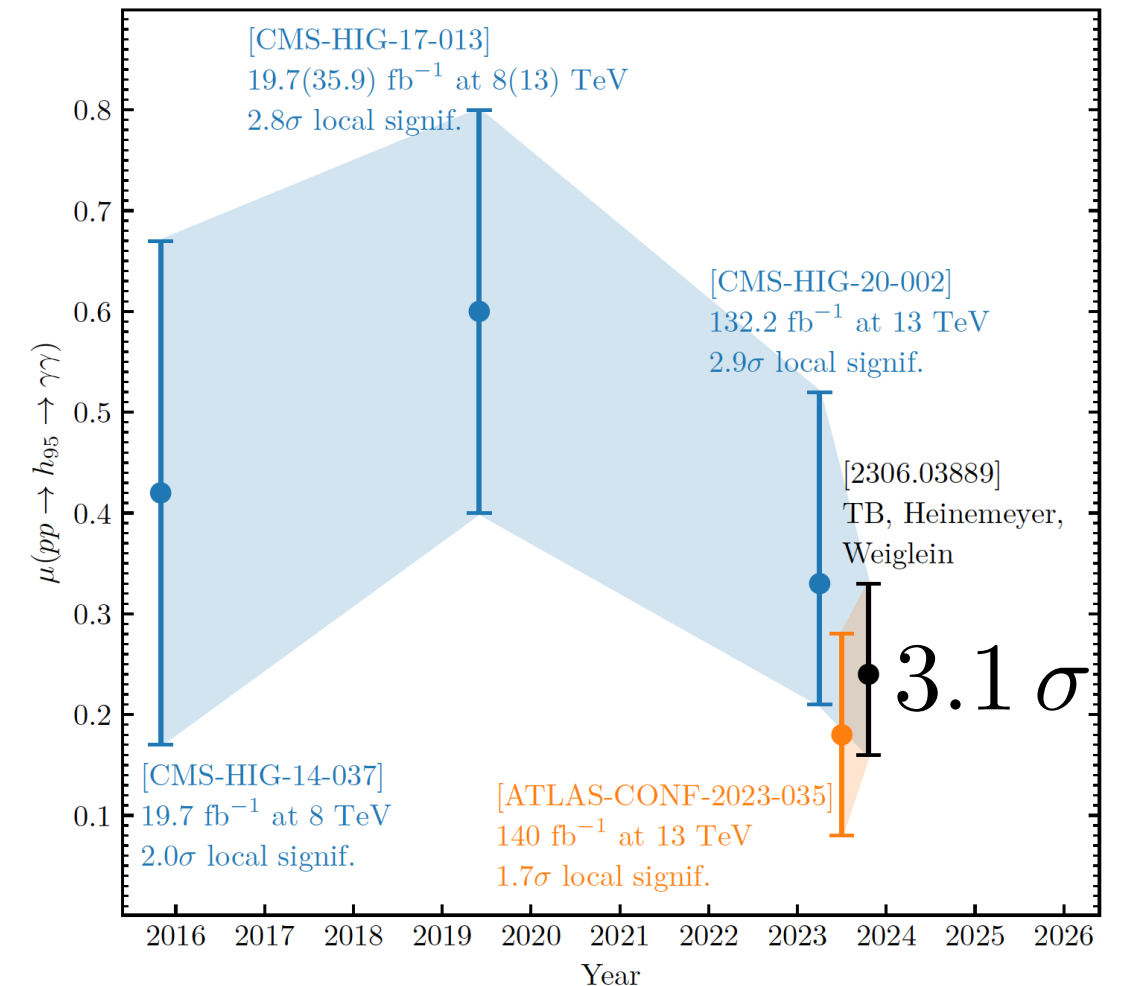
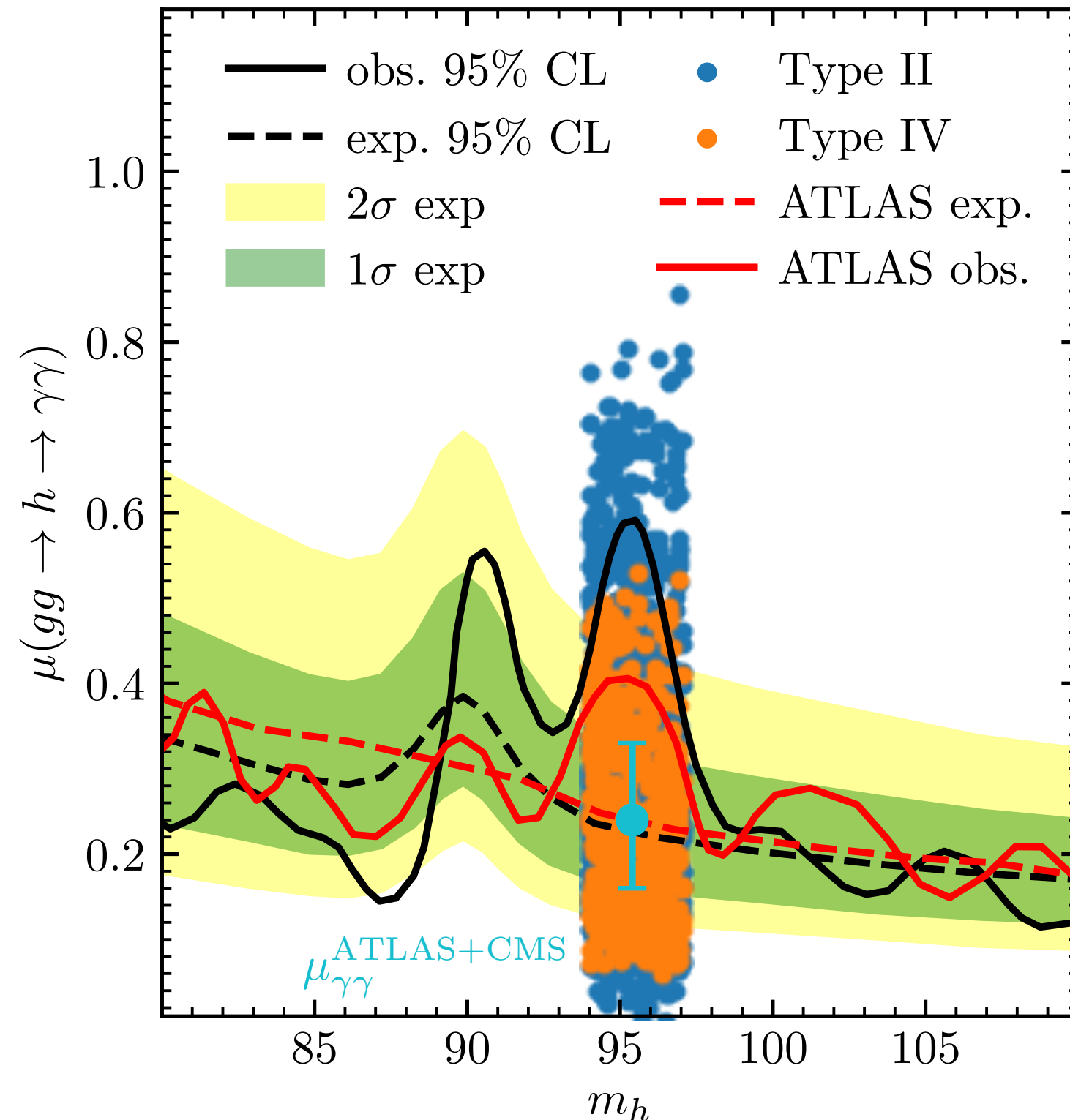
⇒ The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons

⇒ Heavy Higgs bosons usually have a much smaller total width than a SM-like Higgs of the same mass

A possible light Higgs at 95 GeV?

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

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



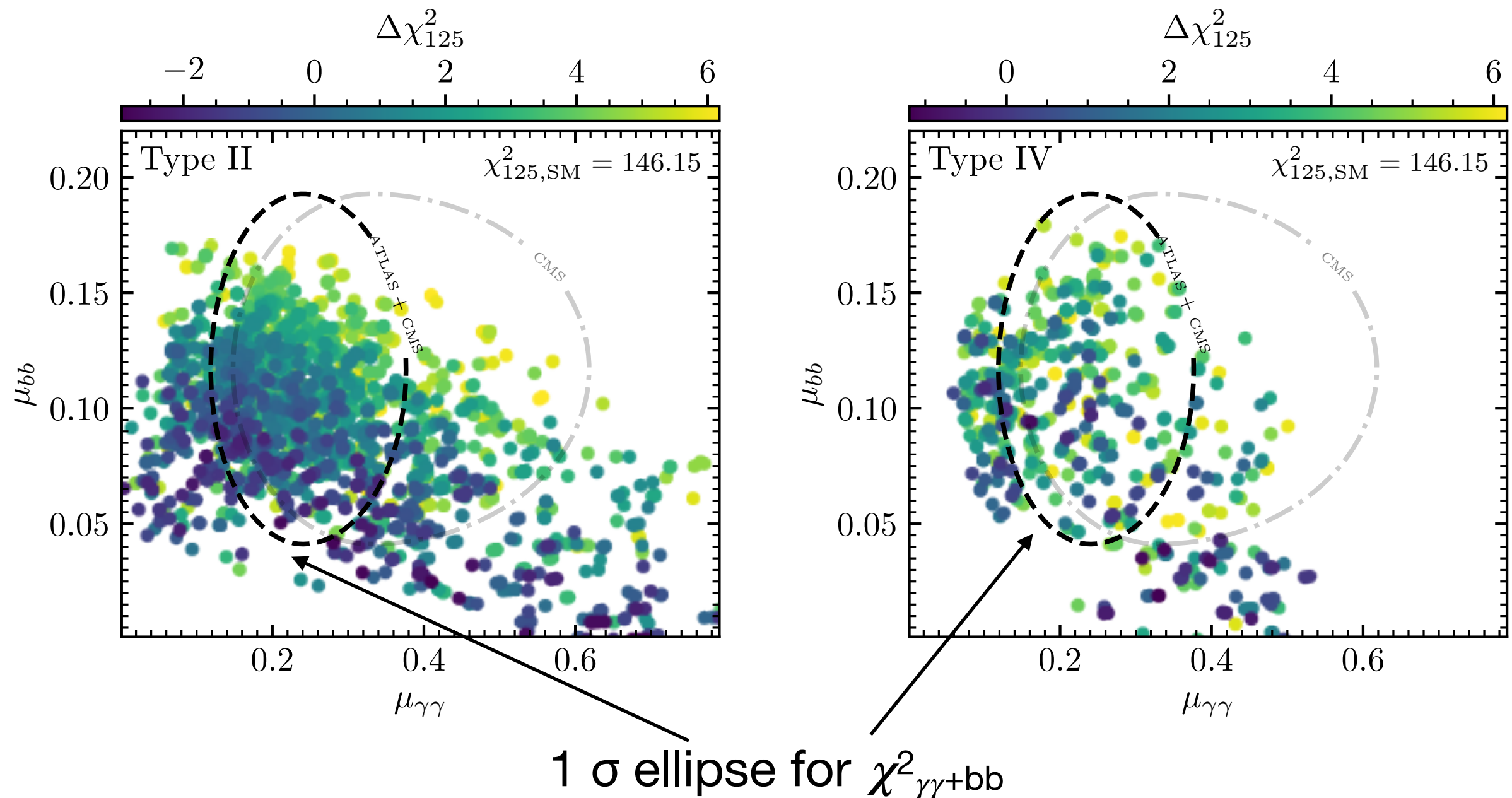
Example interpretation:
S2HDM, type II and IV

⇒ 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!

A possible light Higgs at 95 GeV?

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

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

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

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

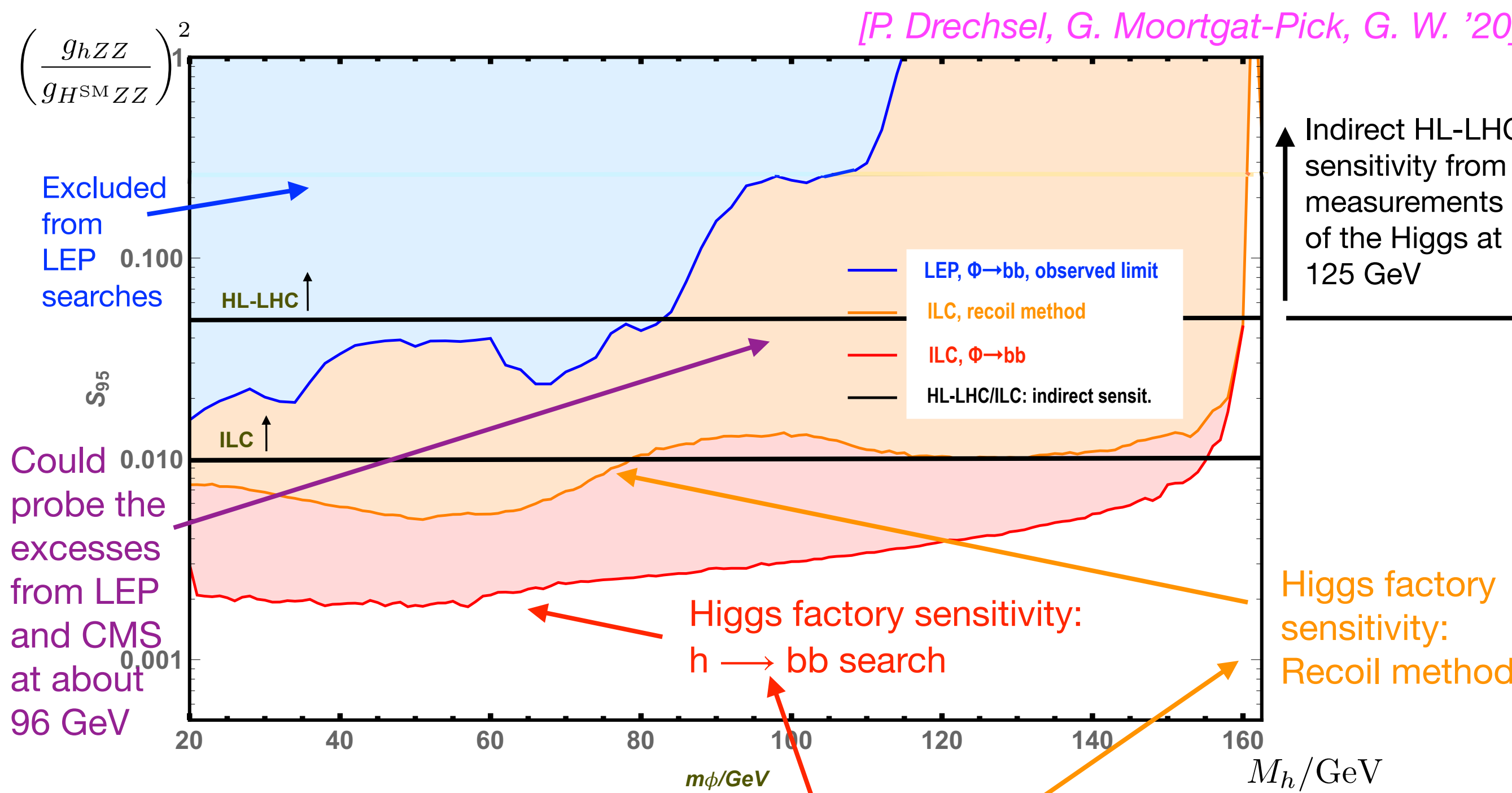
⇒ Expect sizeable coupling of h95 to top quarks

Prospects at e^+e^- colliders?

$e^+e^- \rightarrow t\bar{t} h95$, $e^+e^- \rightarrow Z h95 h95$ (via intermediate h125), ...

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

Higgs factory: discovery potential for a low-mass Higgs; Sensitivity at 250 GeV with 500 fb⁻¹

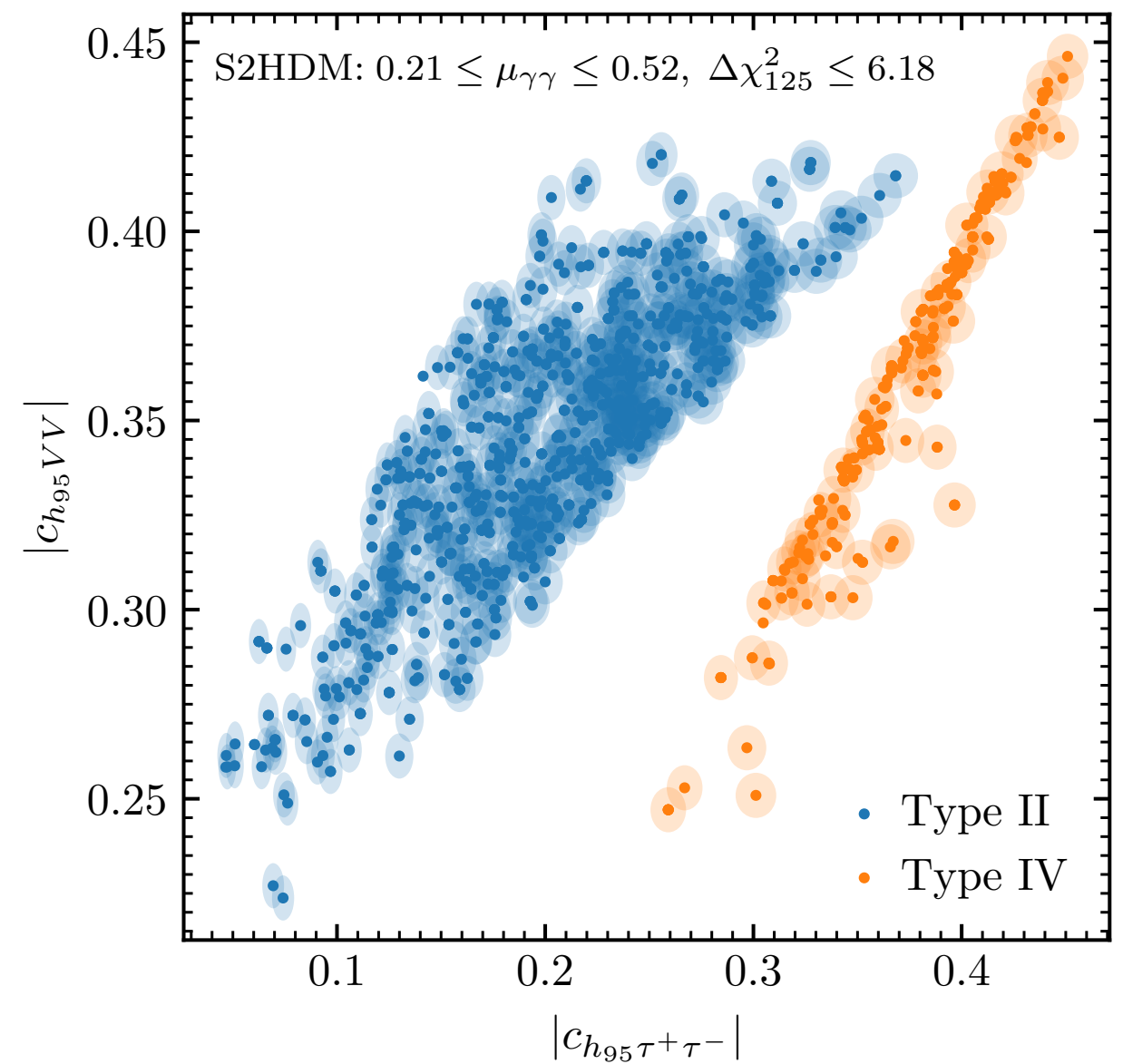
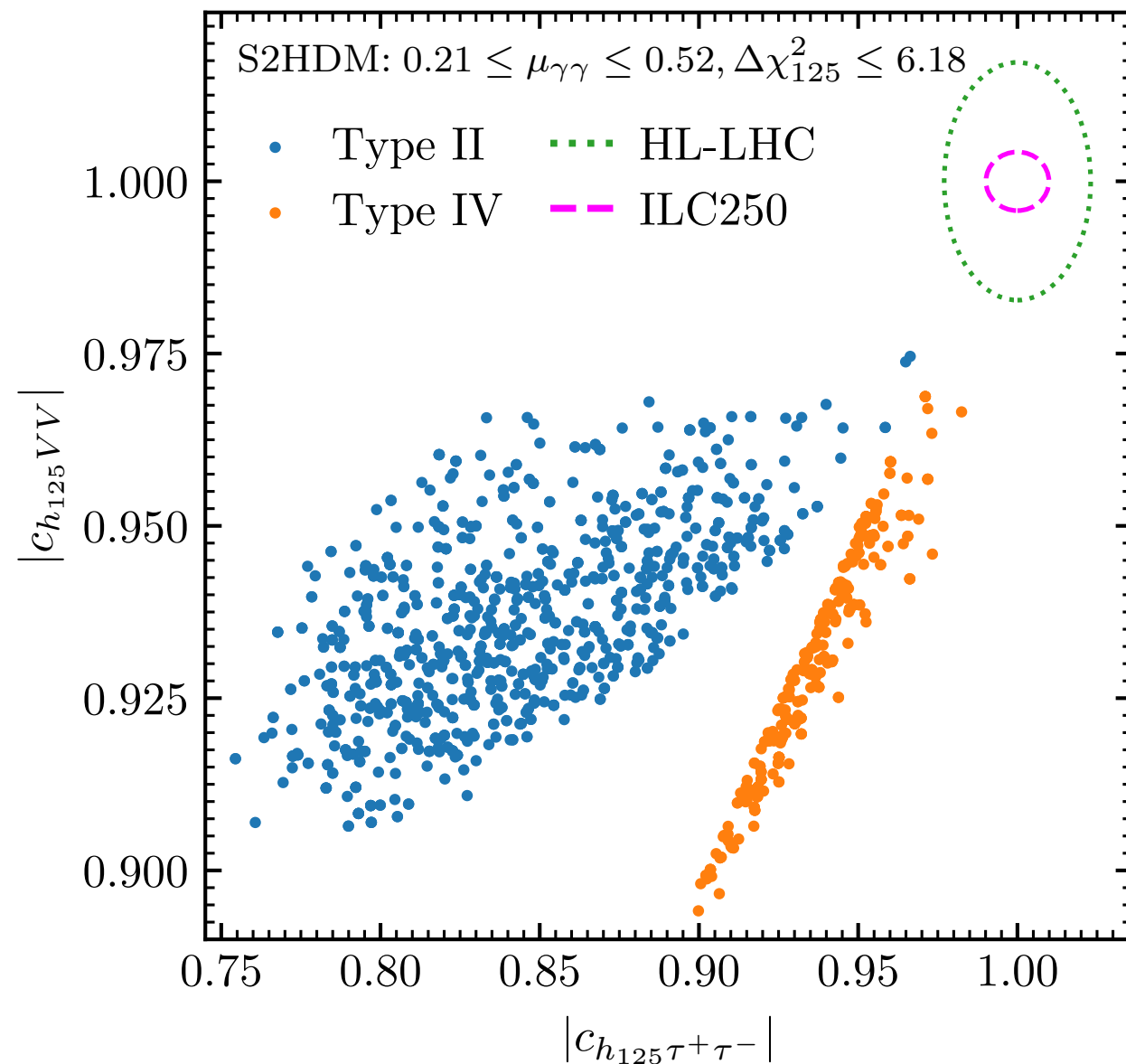


⇒ Higgs factory at 250 GeV will explore a large untested region!

Prospects for coupling measurements of h125 and h95 at an e⁺e⁻ Higgs factory

S2HDM, type II and IV:

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



⇒ Precision measurements of the couplings of both h125 and h95
High sensitivity to the realised physics scenario (Yukawa type, ...)

Unsolved issues in the Higgs sector

[J. Braathen '24]

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

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

→ 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

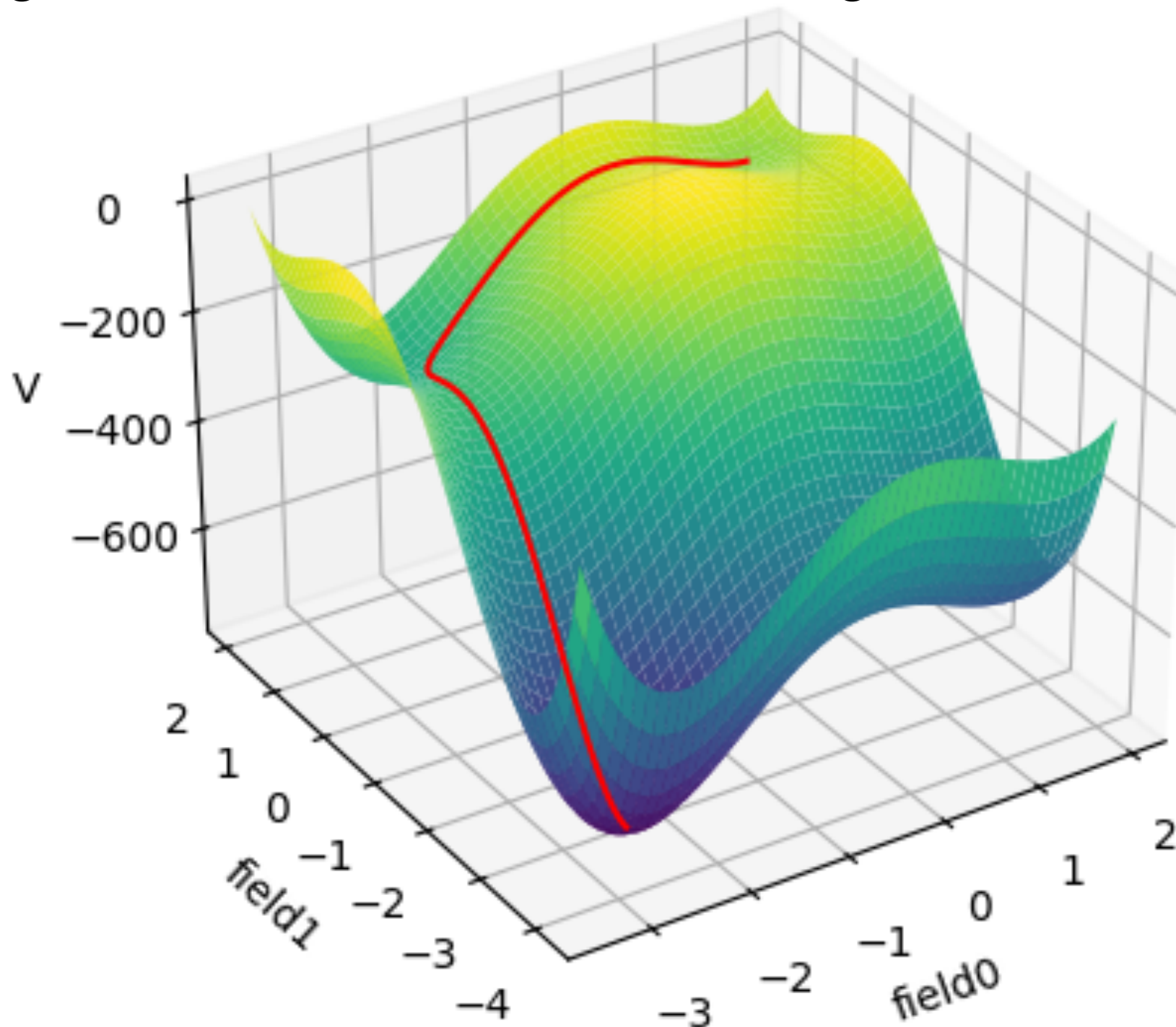
How is the scale of electroweak symmetry breaking **protected from physics at high scales** (new space-time symmetry, new interaction of nature, extra dimensions of space, parallel universes, ...)?

⇒ **Further information from the exploration of the detected Higgs signal**

Simple toy example: two singlet-type Higgs fields

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

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

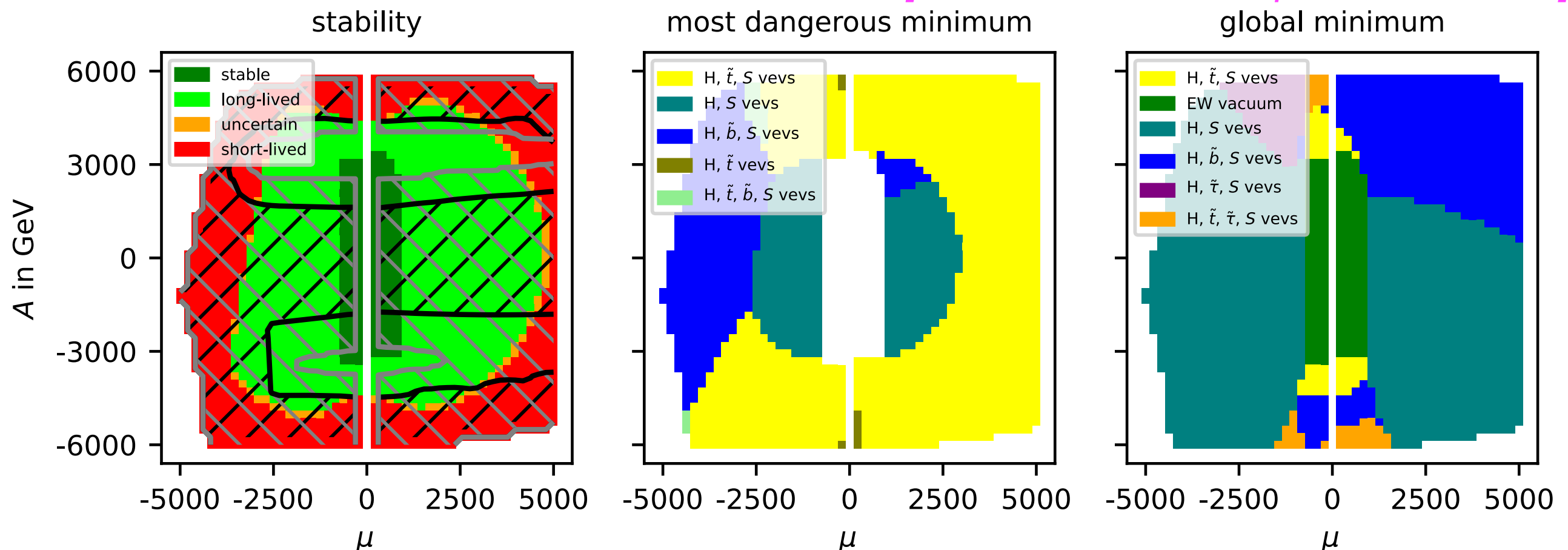
Need to **check stability of the electroweak vacuum** w.r.t. tunneling into all deeper minima (analysis at $T = 0$)

[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*

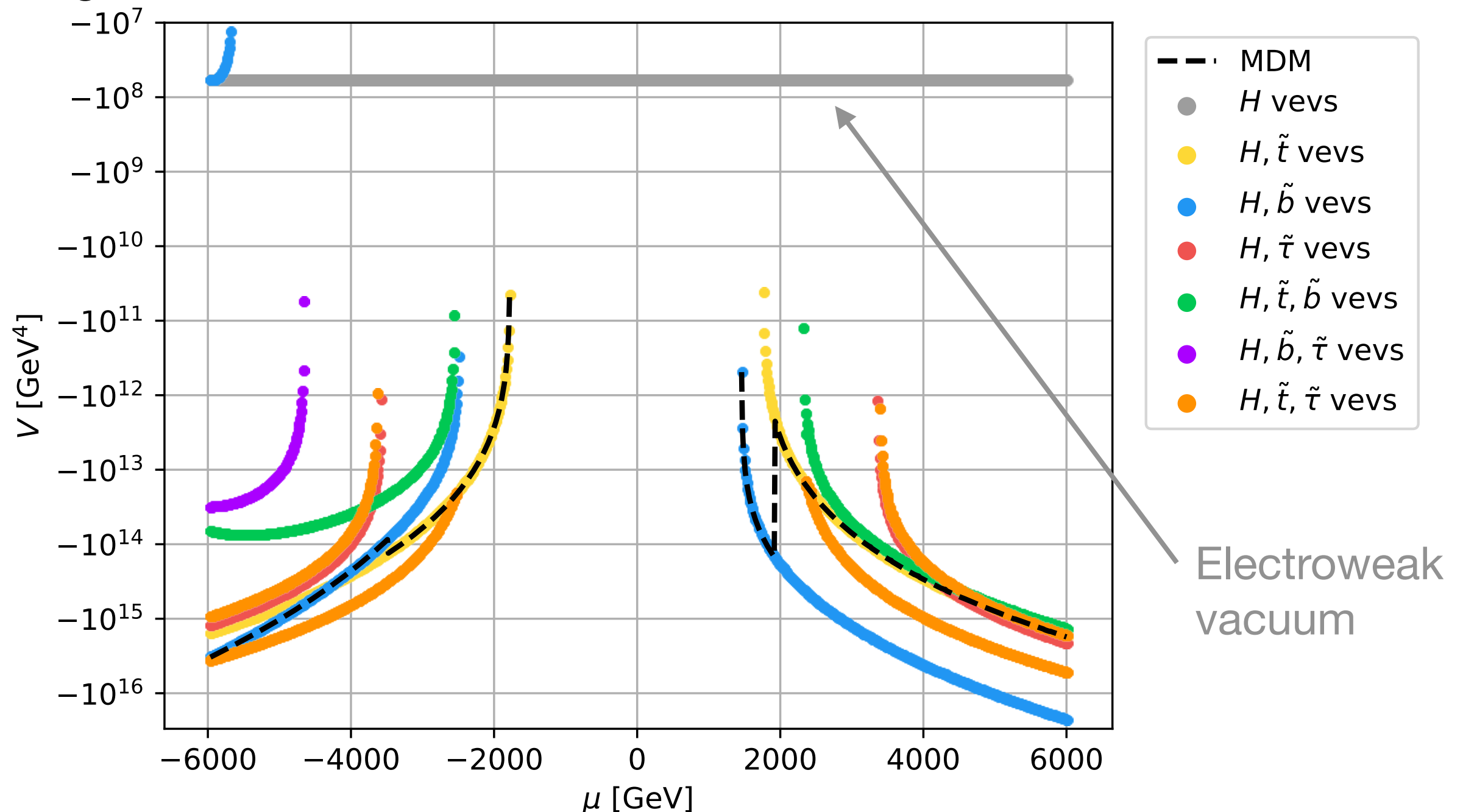
[T. Biekötter, F. Campello, G. W. '23]



Depth of stationary points of the Higgs potential

Along line with $X_t = 2.8$ TeV:

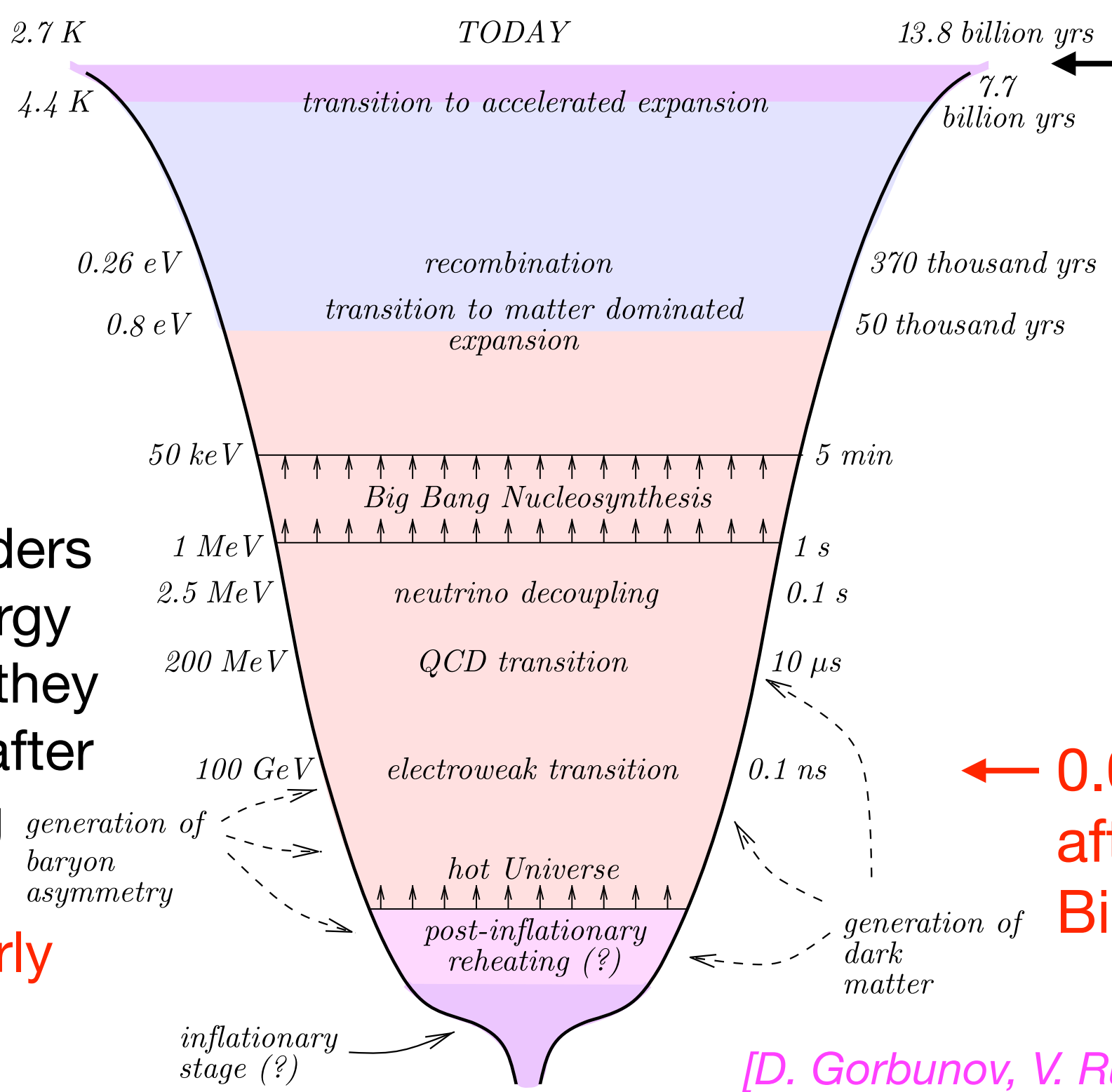
[W.G. Hollik, J. Wittbrodt, G. W. '18]



⇒ 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

← 0.0000000000001 s
after the
Big Bang

[D. Gorbunov, V. Rubakov]

Electroweak phase transition and baryon asymmetry

Observed Baryon Asymmetry of the Universe (BAU)

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

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

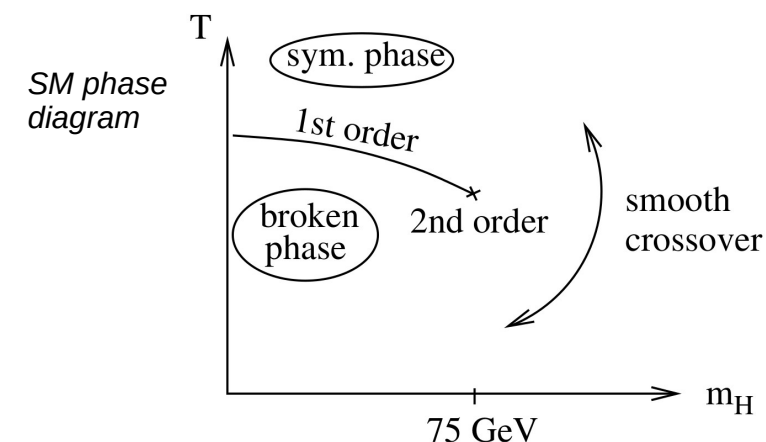


Sakharov Conditions

(for dynamical generation of baryon asymmetry)

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

[J. M. No '23]



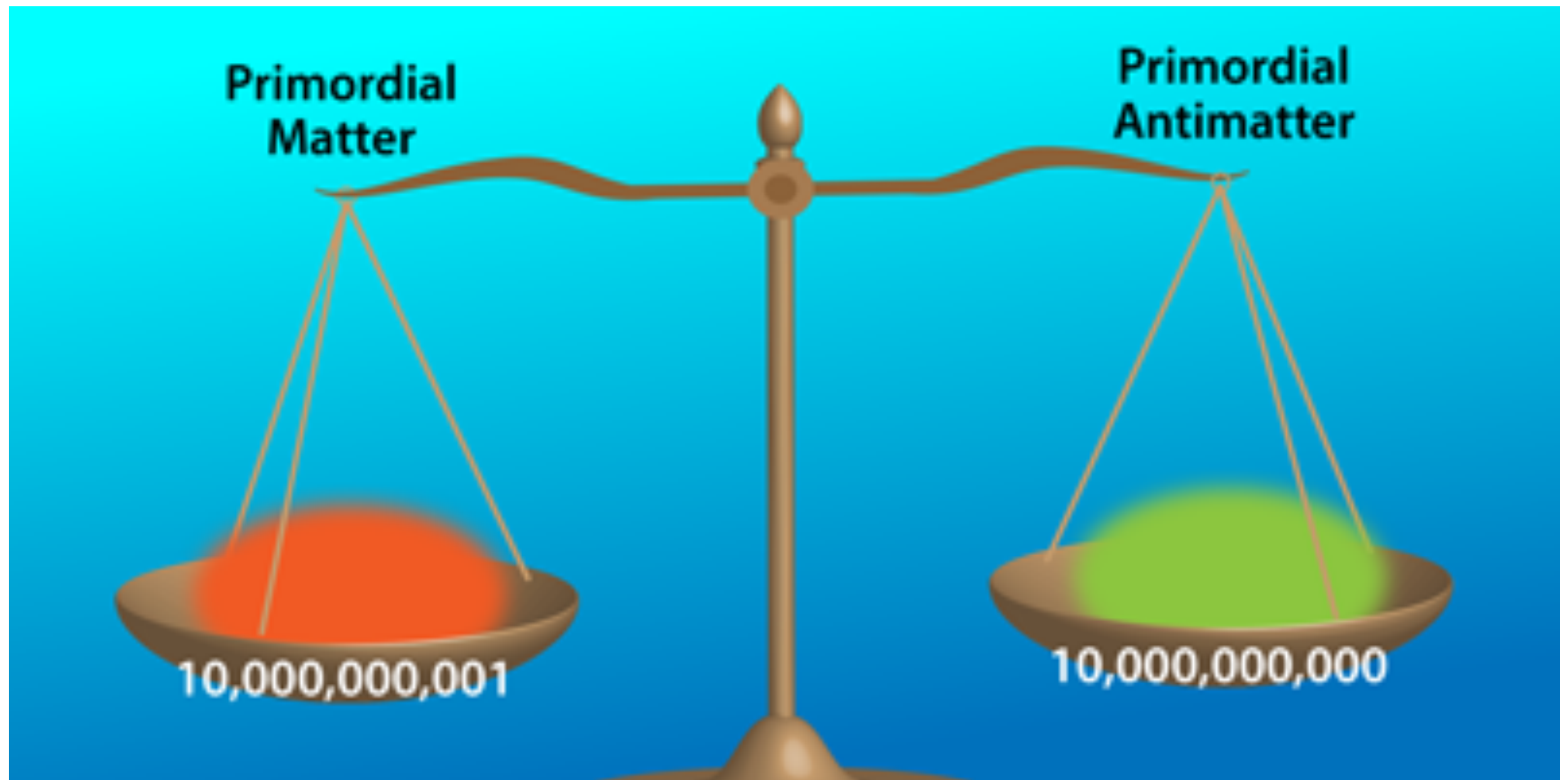
SM CP Violation insufficient by ~ 10 orders of magnitude

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

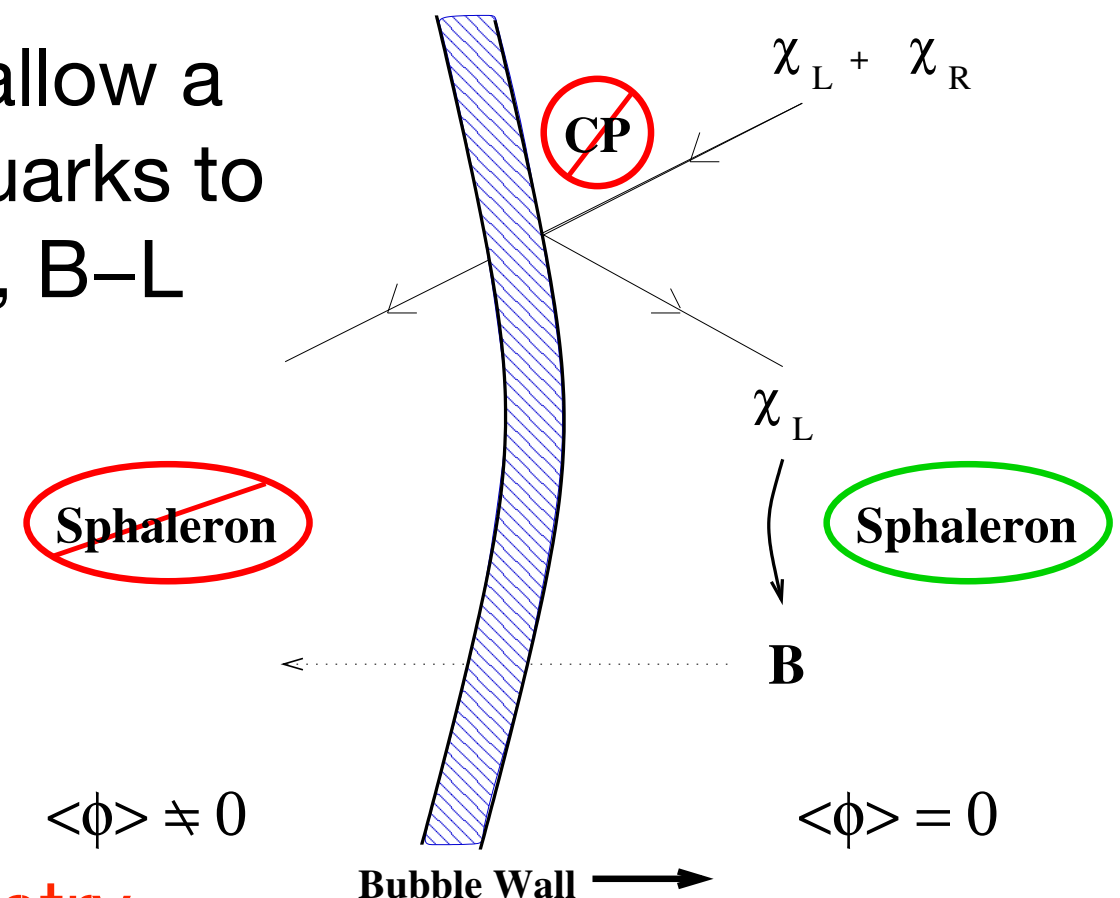
⇒ Creation of chiral asymmetry

[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)

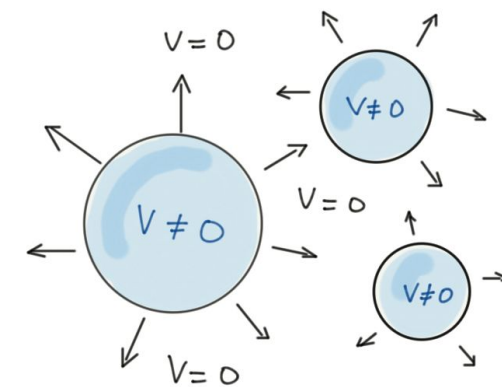
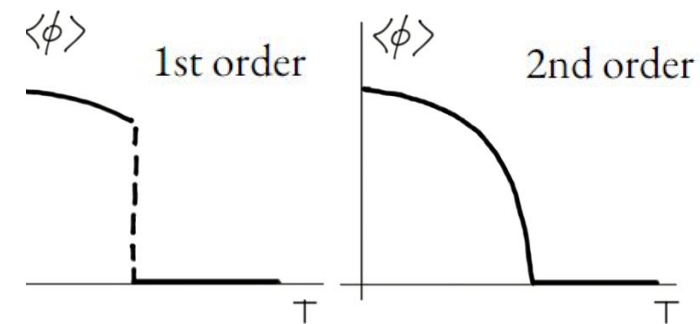
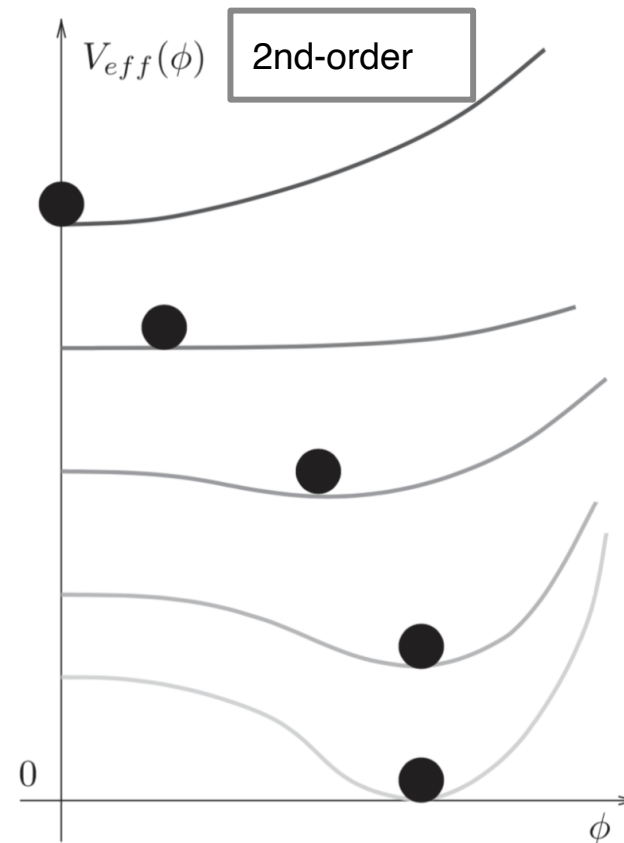
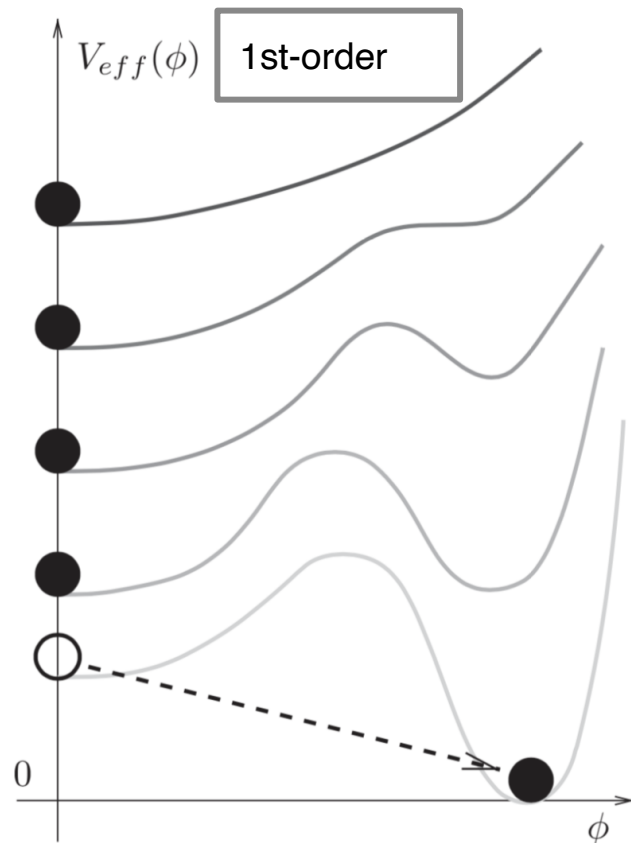
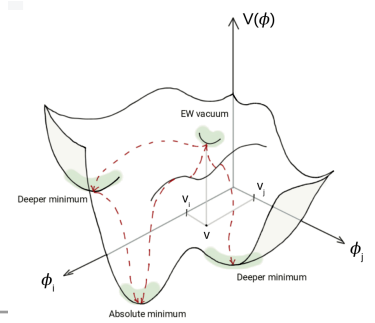
⇒ Creation of net baryon asymmetry

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 (counterexamples exist)

Strongly first-order EWPT in the 2HDM

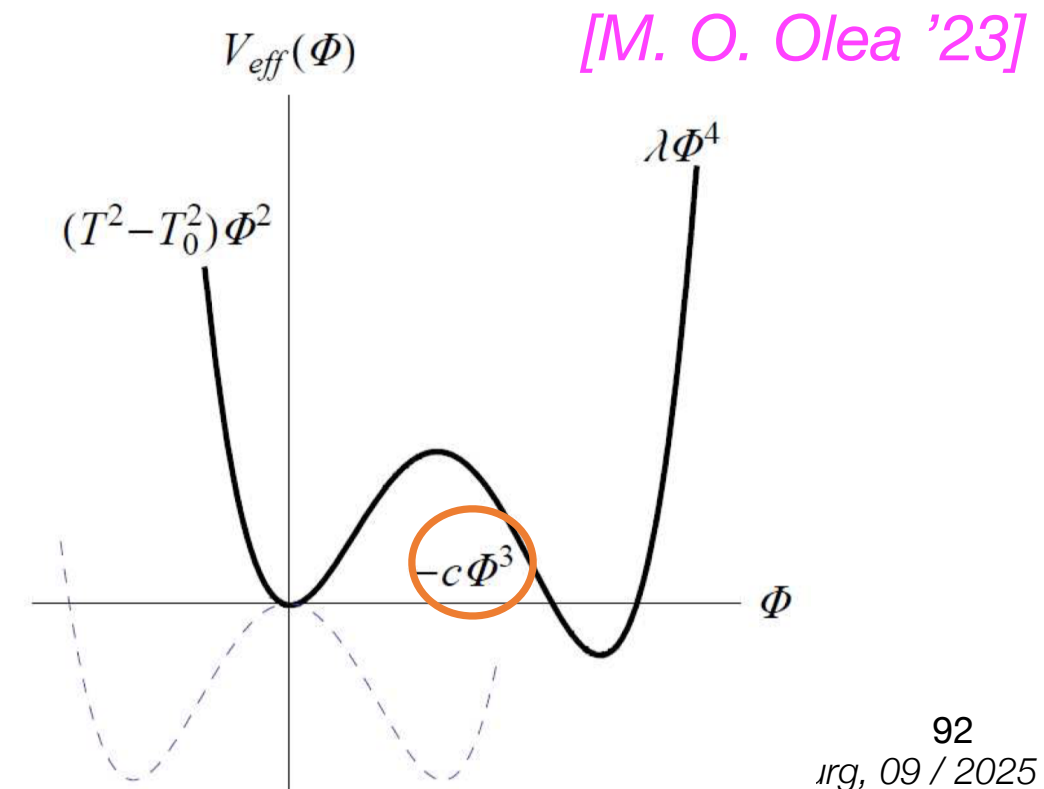
Barrier is related to a cubic term in the effective potential

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

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

⇒ 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



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

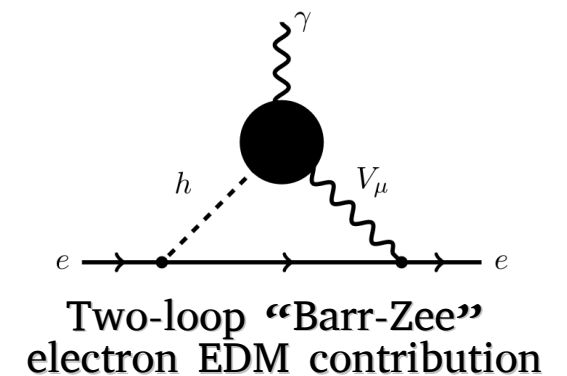
Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a strong **first-order electroweak phase transition (EWPT)**

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**

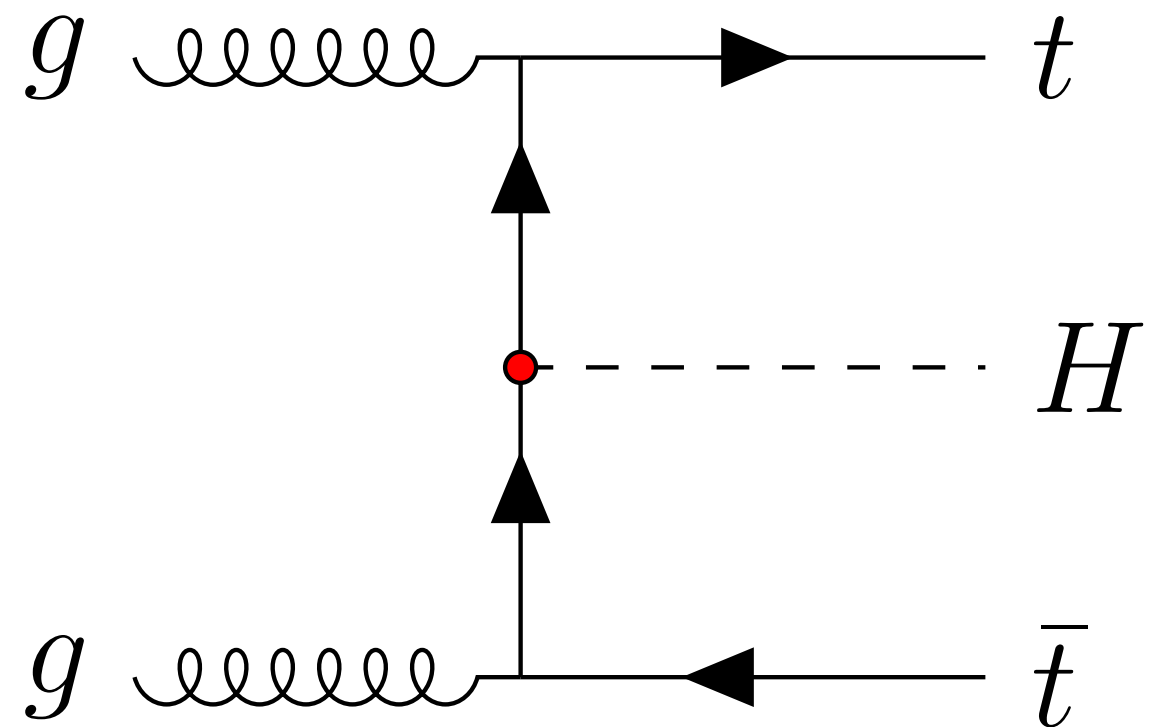
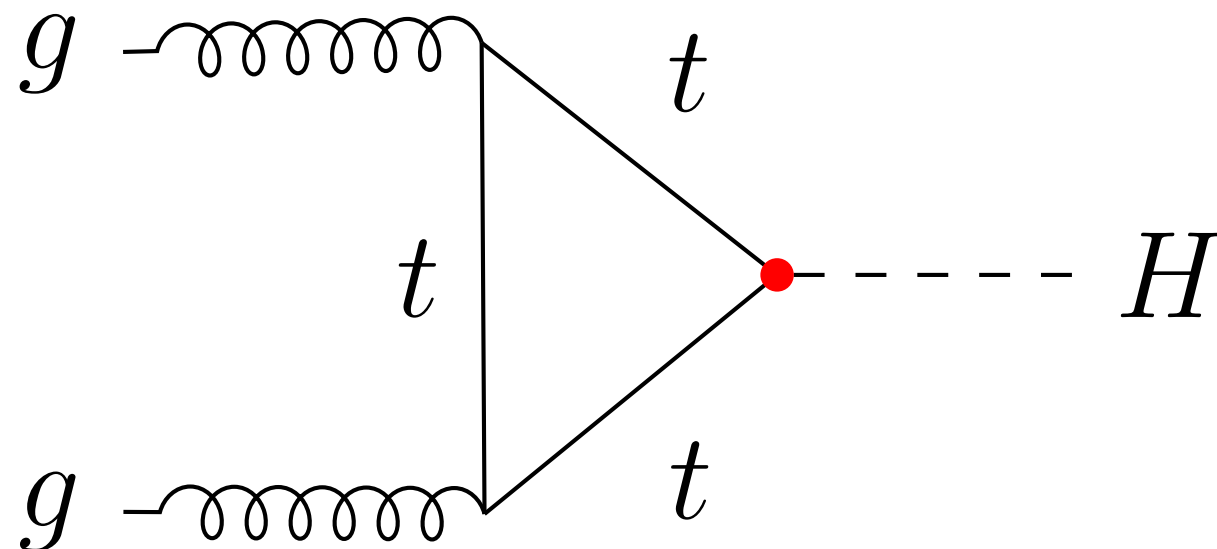


But: strong experimental constraints from **limits on electric dipole moments (EDMs)**

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**

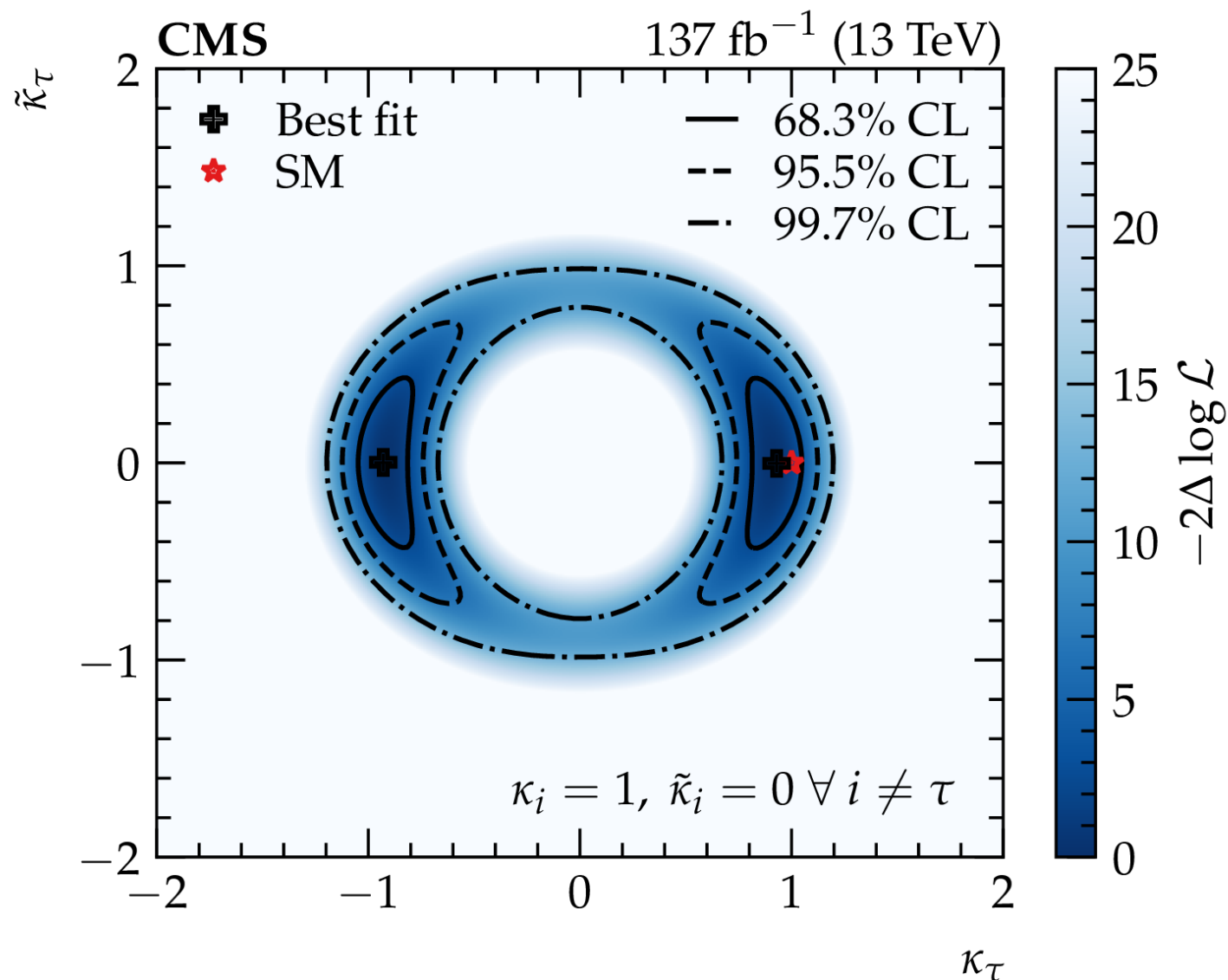


with $H \rightarrow \tau\tau, b\bar{b}, \dots$

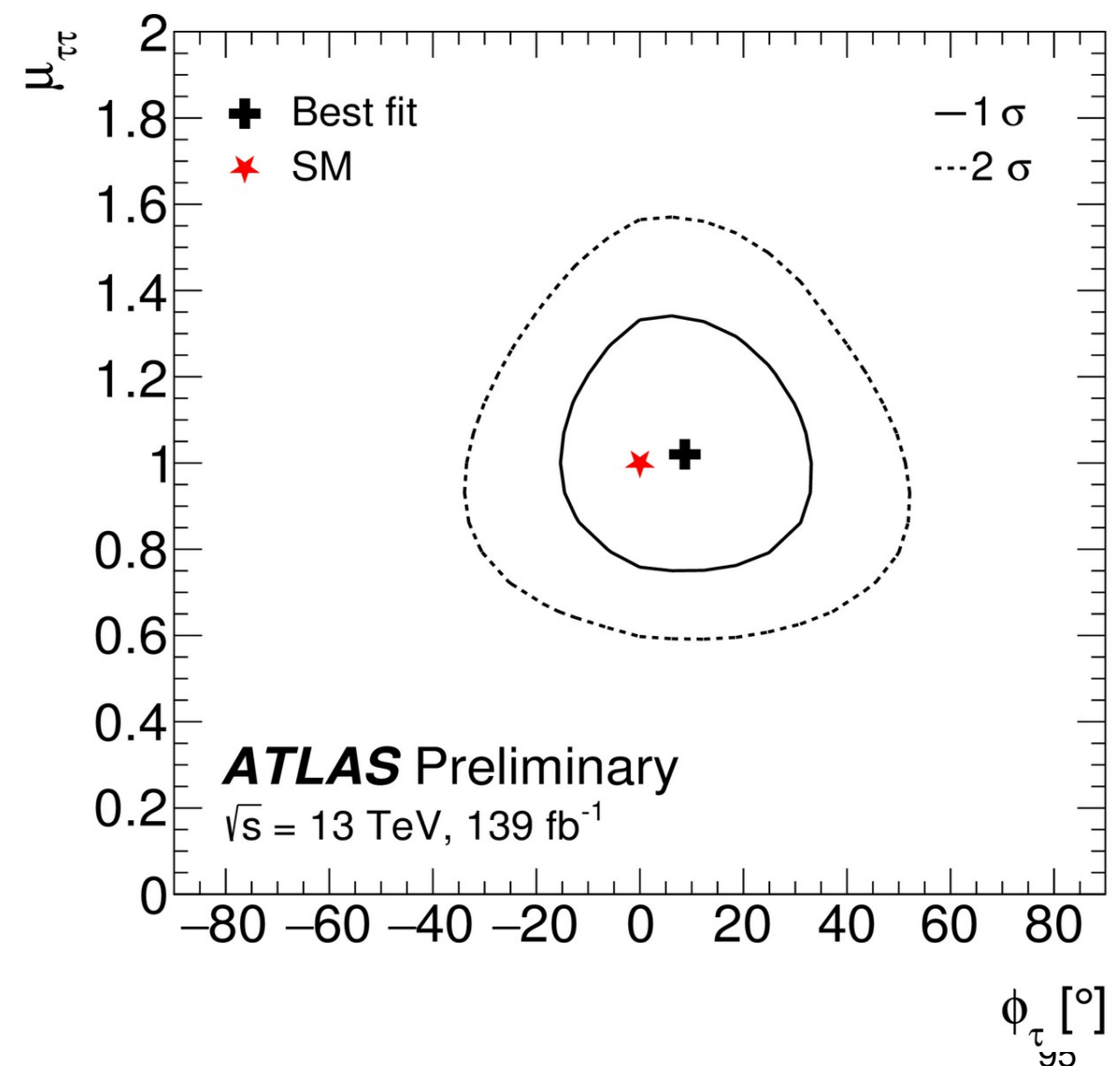
Test of CP violation in the tau Yukawa coupling

Constraints on the CP structure of the tau Yukawa coupling from $h125 \rightarrow \tau\tau$ decays using angular correlation between decay products:

[CMS Collaboration '21]



[ATLAS Collaboration '22]



Effect on global CP analysis of Higgs-fermion couplings

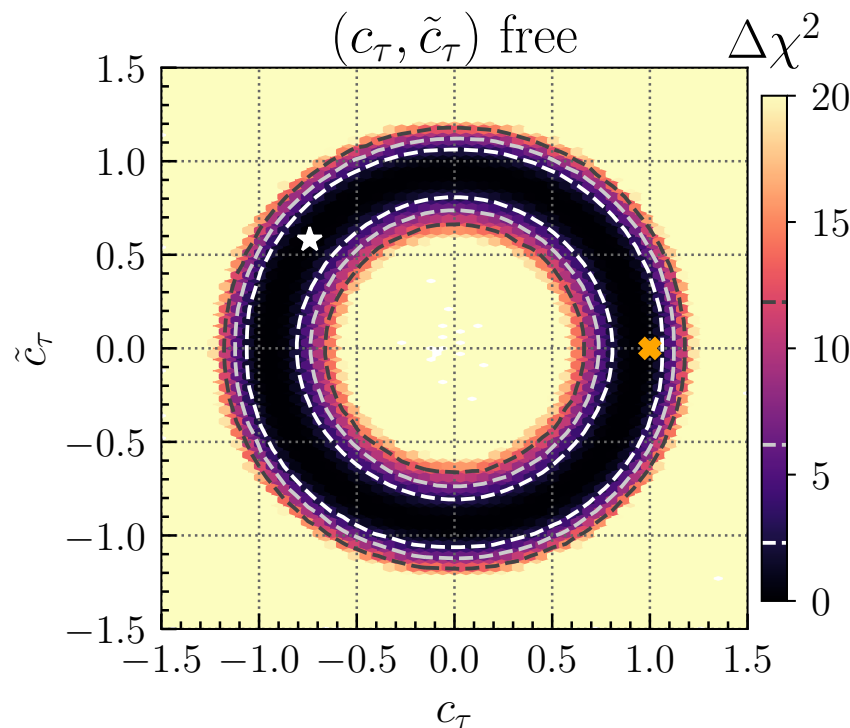
[H. Bahl et al. '22]

Incorporation of recent CMS result on the CP structure of the tau Yukawa coupling from $h125 \rightarrow \tau\tau$ decays using angular correlation between the decay products

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

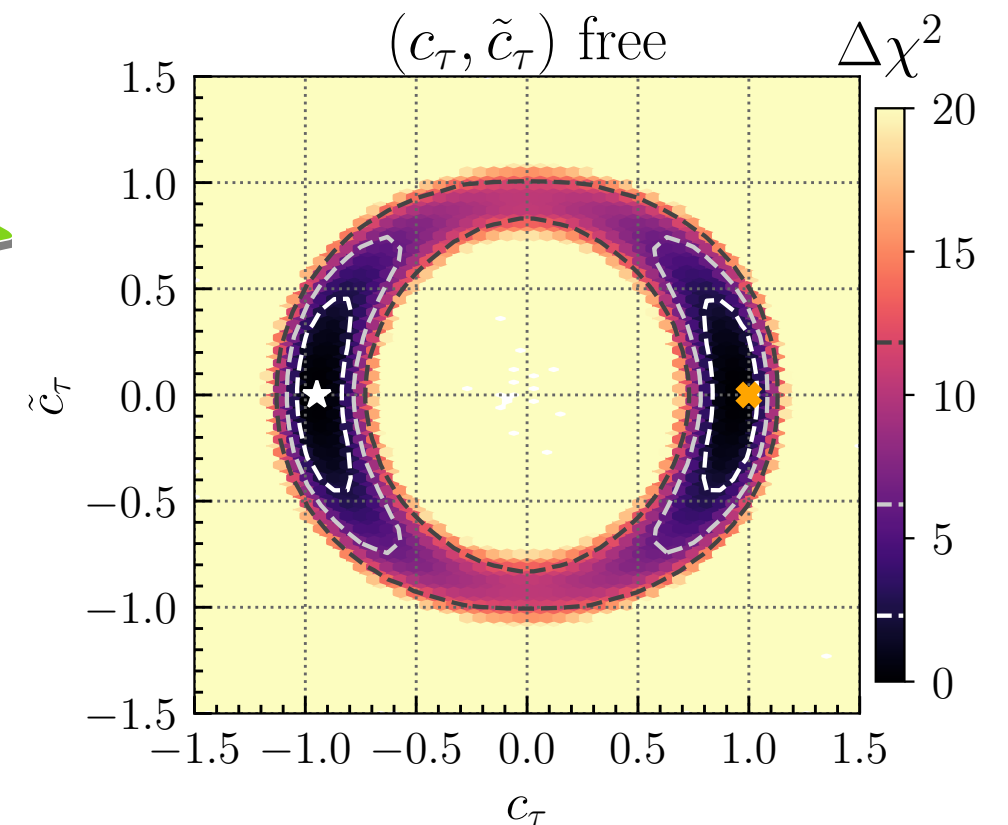
Global fit using **HiggsSignals** + recent analyses

can also be analyzed in EFT



CMS 2110.04836
 $h \rightarrow \tau\tau$ CPV analysis

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



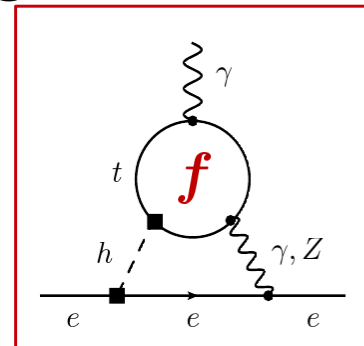
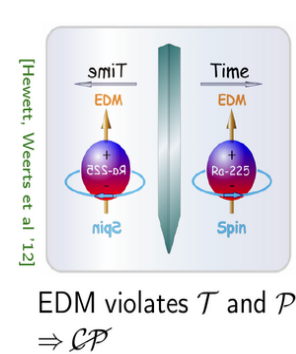
Ring-structure from upper/lower bound on BR

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

CP structure of the Higgs-fermion couplings

[H. Bahl et al. '22]

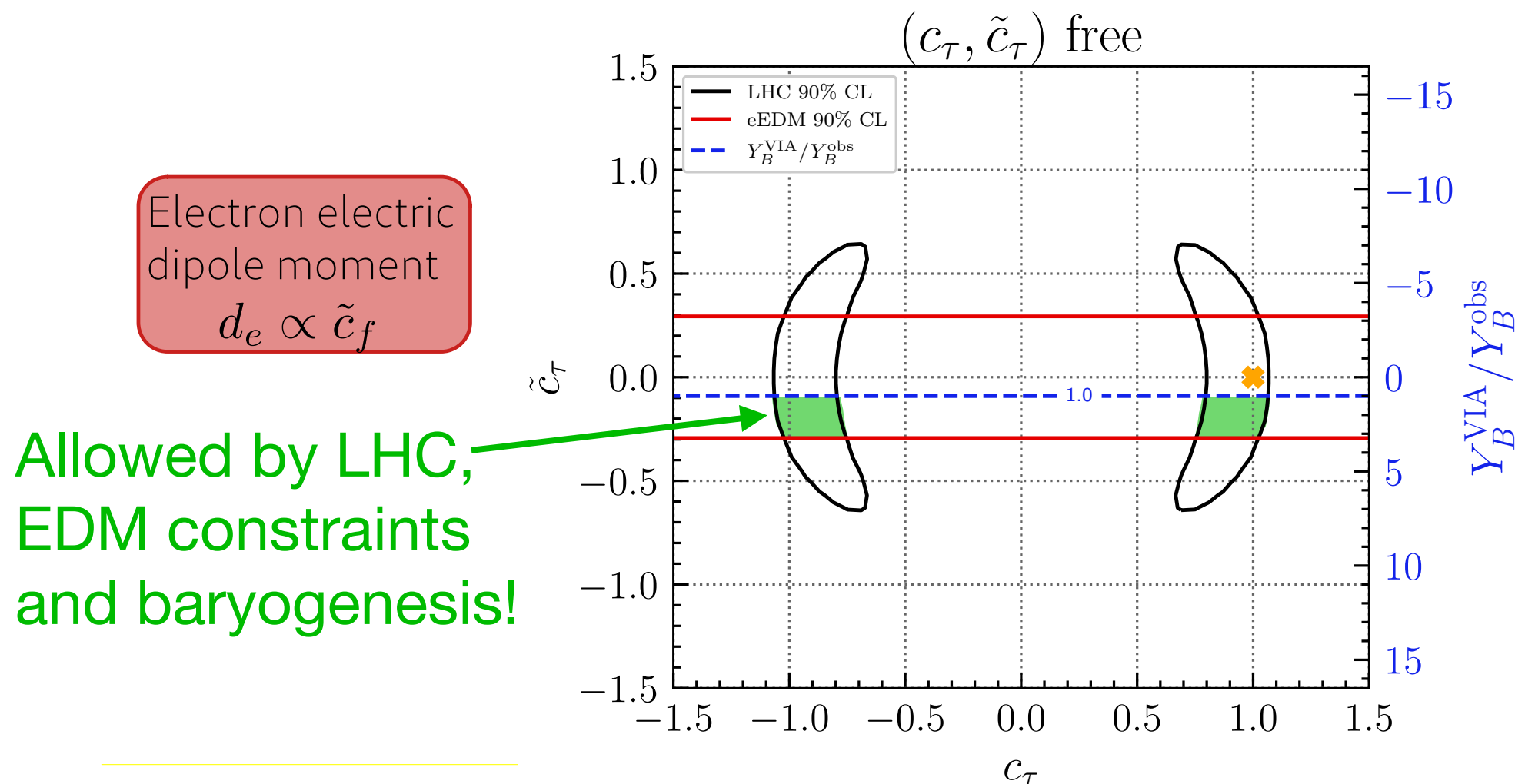
Comparison with the existing EDM constraints



ACME [Nature '18]:
 $d_e \leq 1.1 \times 10^{-29} \text{ e cm}$ at 90% CL

Using [Panico, Pomarol, Rimbau '18], [Brod, Haisch, Zupan '13], [Brod, Stamou '18],...

Analysis of the resulting amount of baryon asymmetry in the Universe



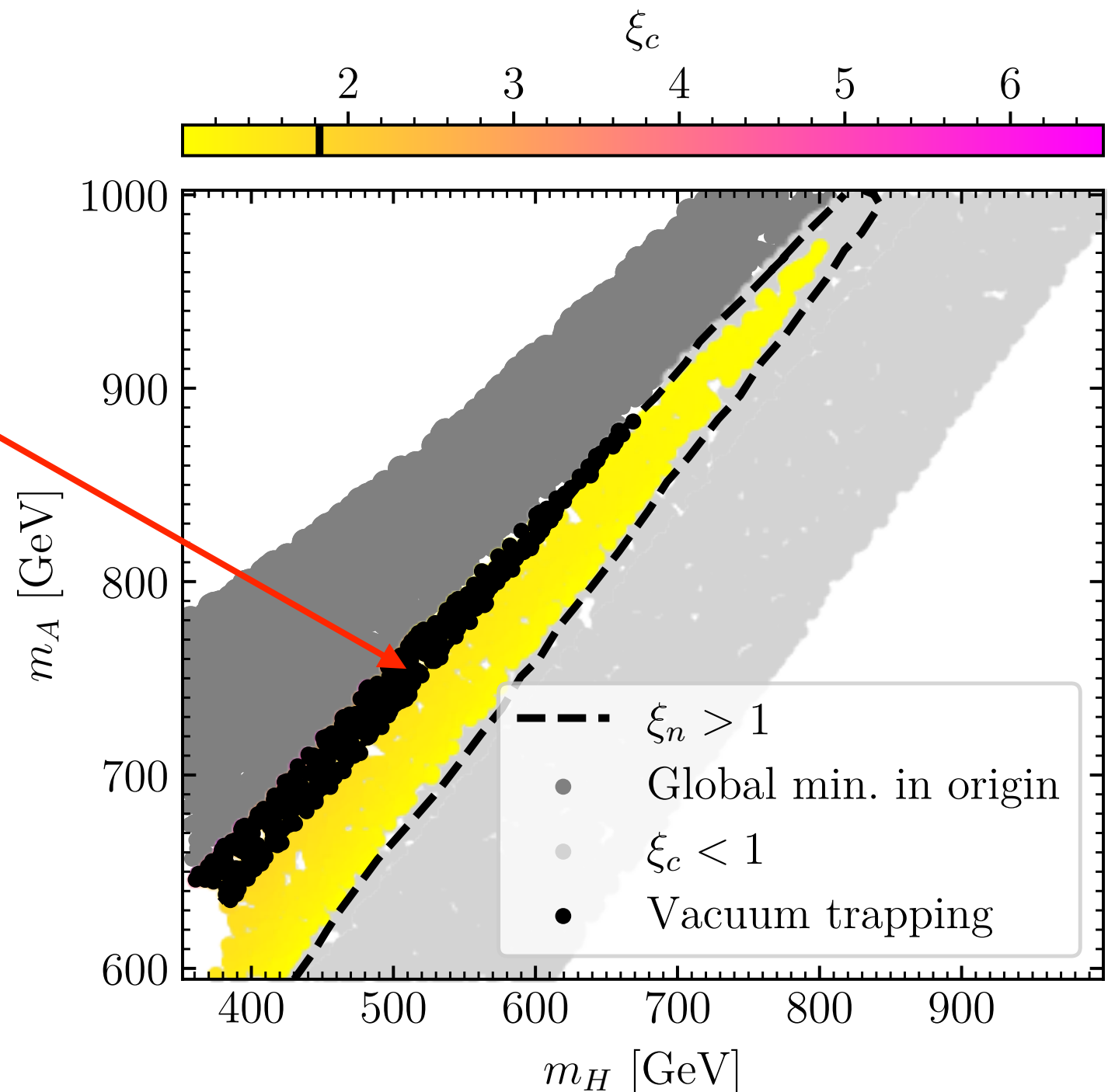
Could work even for the case where CP violation occurs just in the τ coupling (in optimistic scenario)!

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

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

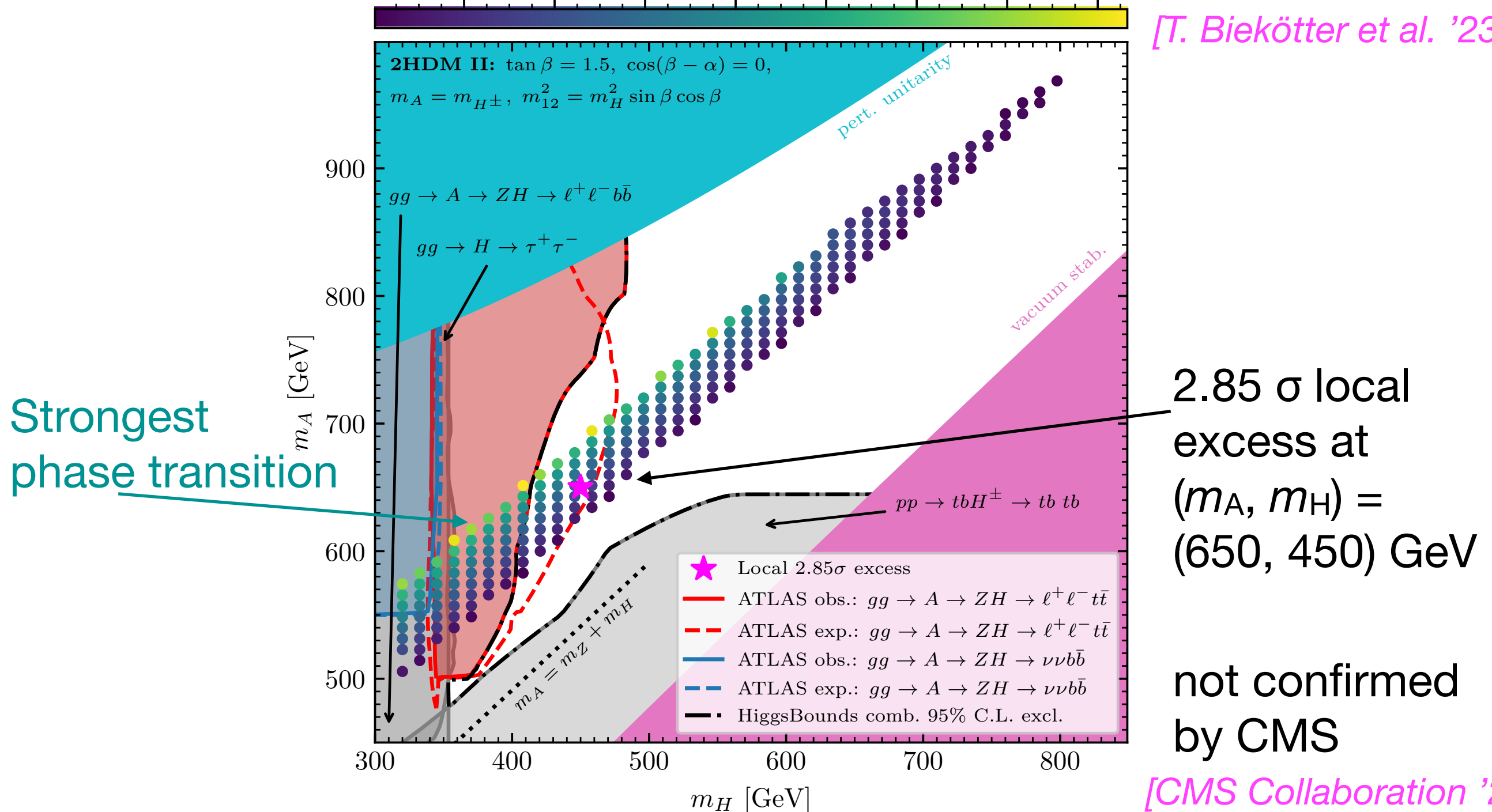


ATLAS “smoking gun” search $pp \rightarrow A \rightarrow ZH \rightarrow Zt\bar{t}$ vs. preferred region for strong first-order EWPT

2HDM, $\tan\beta = 1.5$:

[ATLAS Collaboration '23]

[T. Biekötter et al. '23]

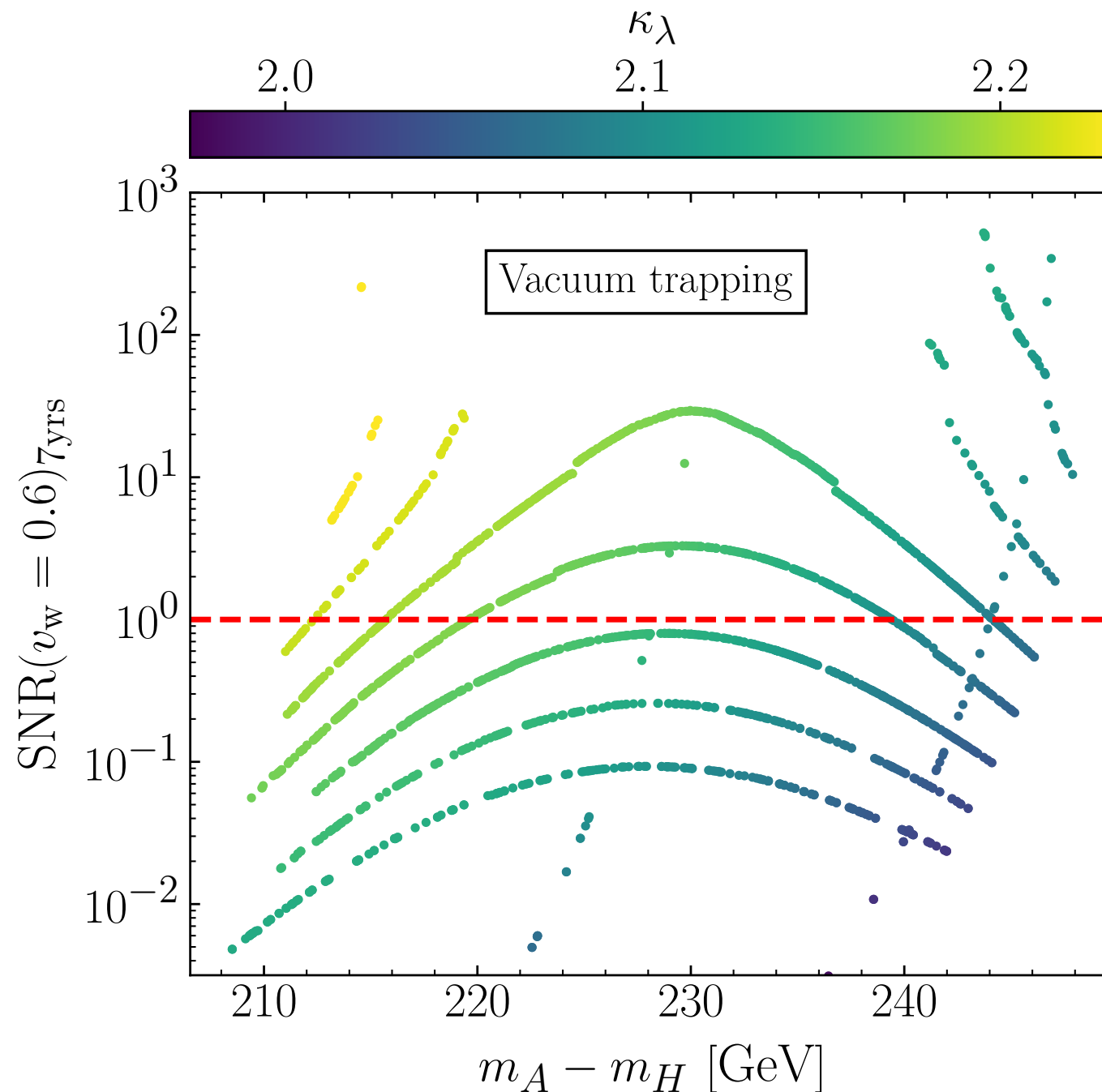


[CMS Collaboration '24]

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

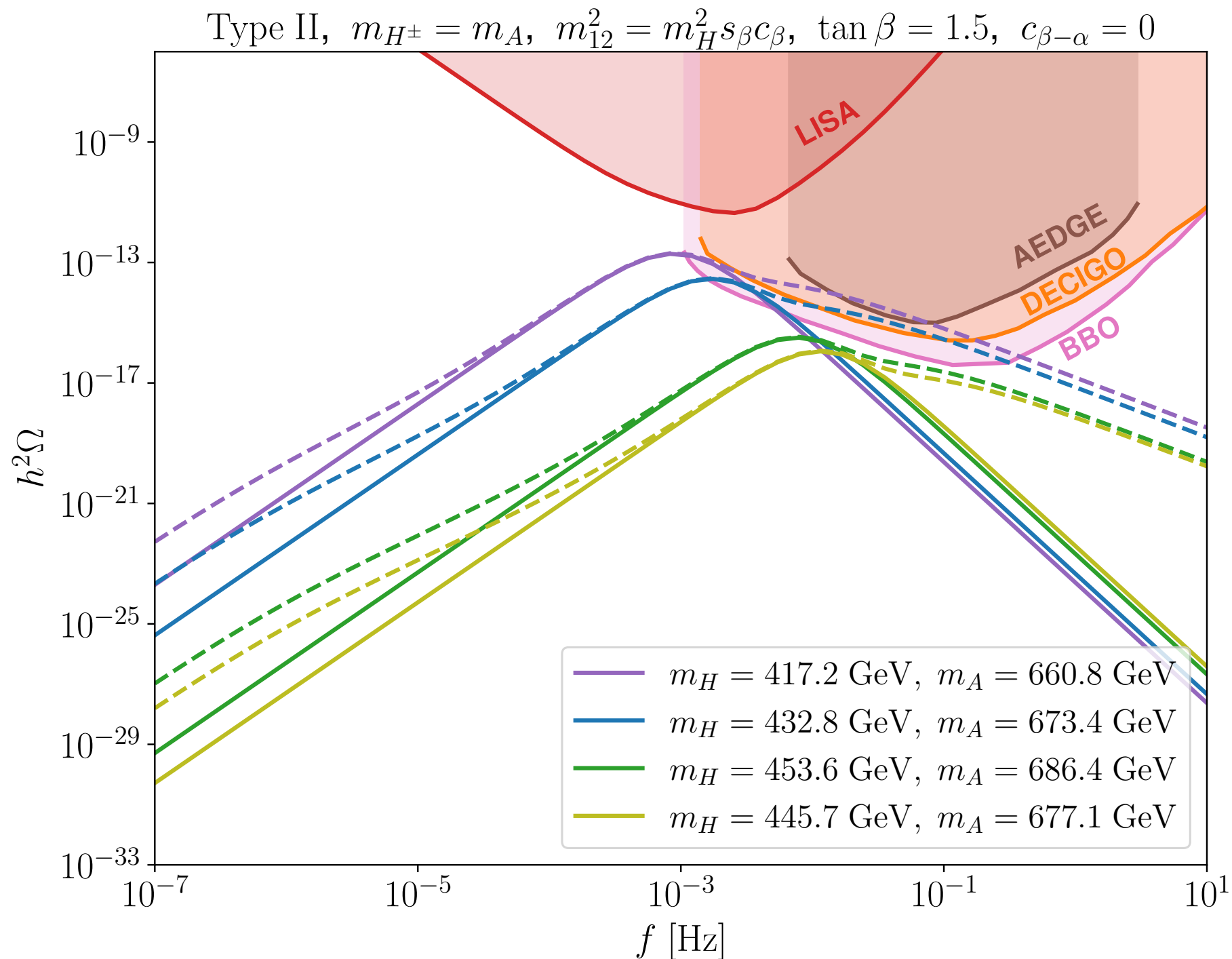
Correlation of κ_λ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

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



⇒ Region with potentially detectable gravitational wave signal:
significant enhancement of κ_λ 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]

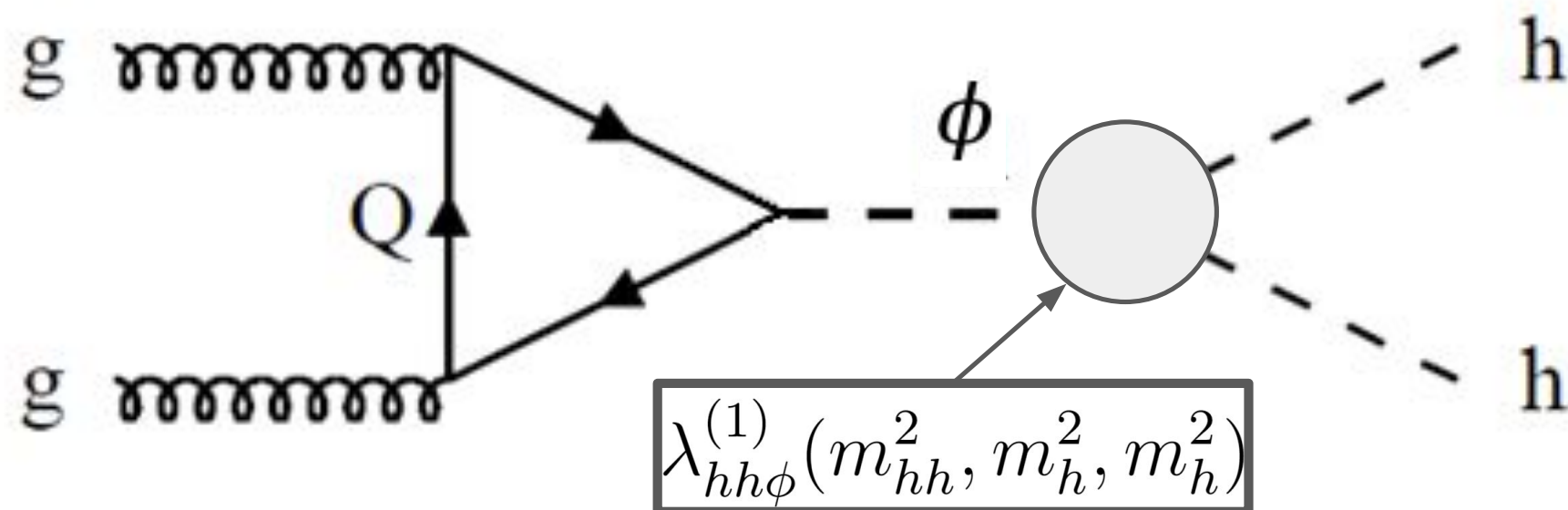
⇒ Prospects for GW detection depend very sensitively on the precise details of the mass spectrum of the additional Higgs bosons

Examples of BSM model predictions

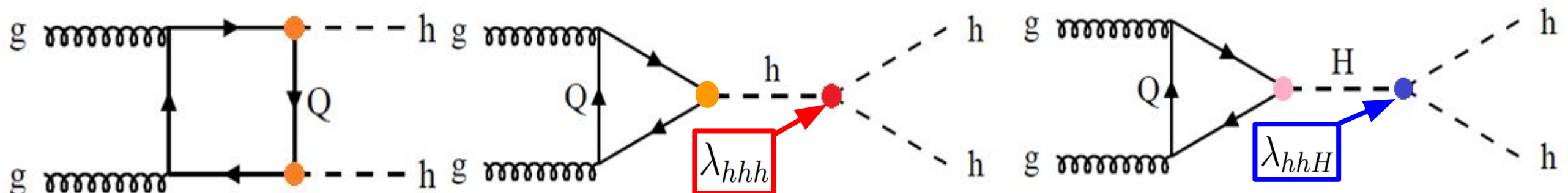
Di-Higgs production for arbitrary renormalisable models (*anyHH*)

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

- Loop-corrected trilinear couplings involving BSM Higgses: λ_{hhH} , ...



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

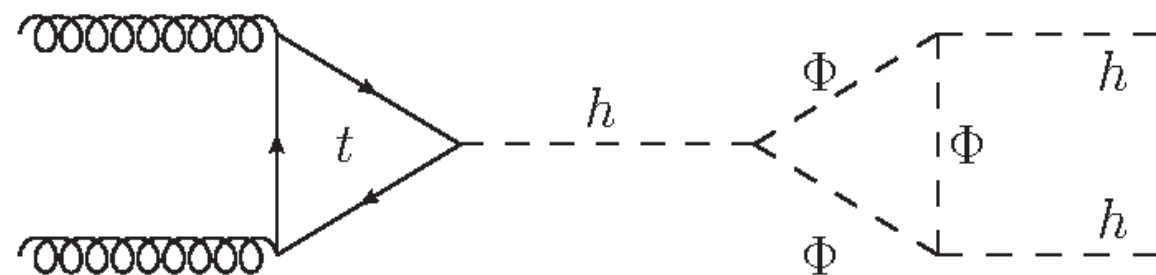


Check of applicability of the experimental limit on κ_λ

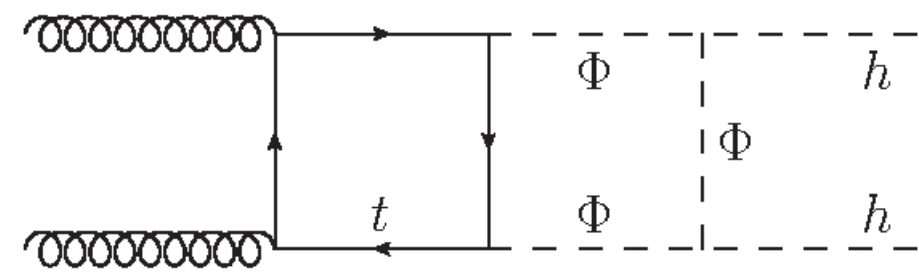
Alignment limit: h has SM-like tree-level couplings

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



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



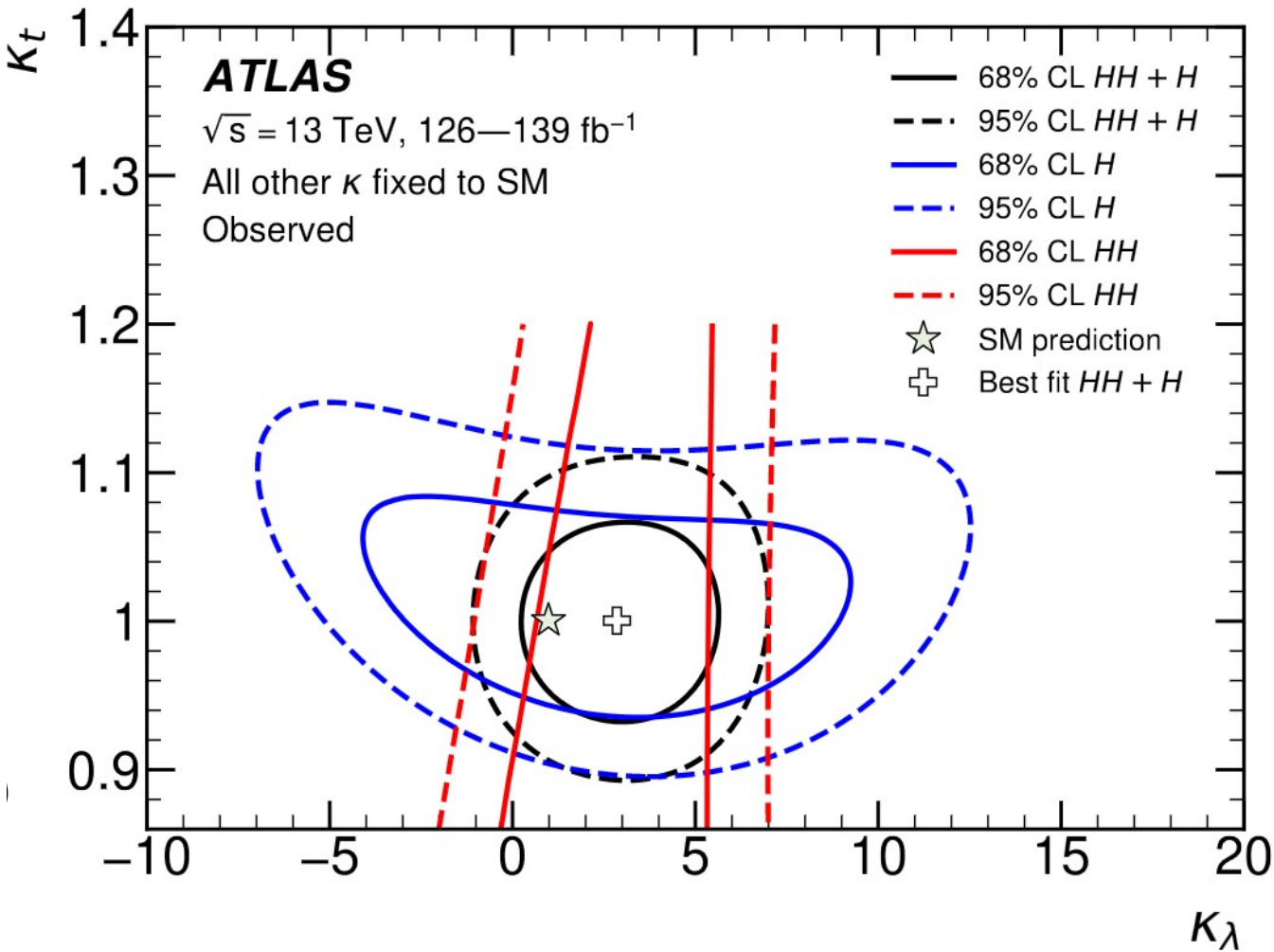
$\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ **not included**

⇒ 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 κ_λ

[ATLAS Collaboration '22]

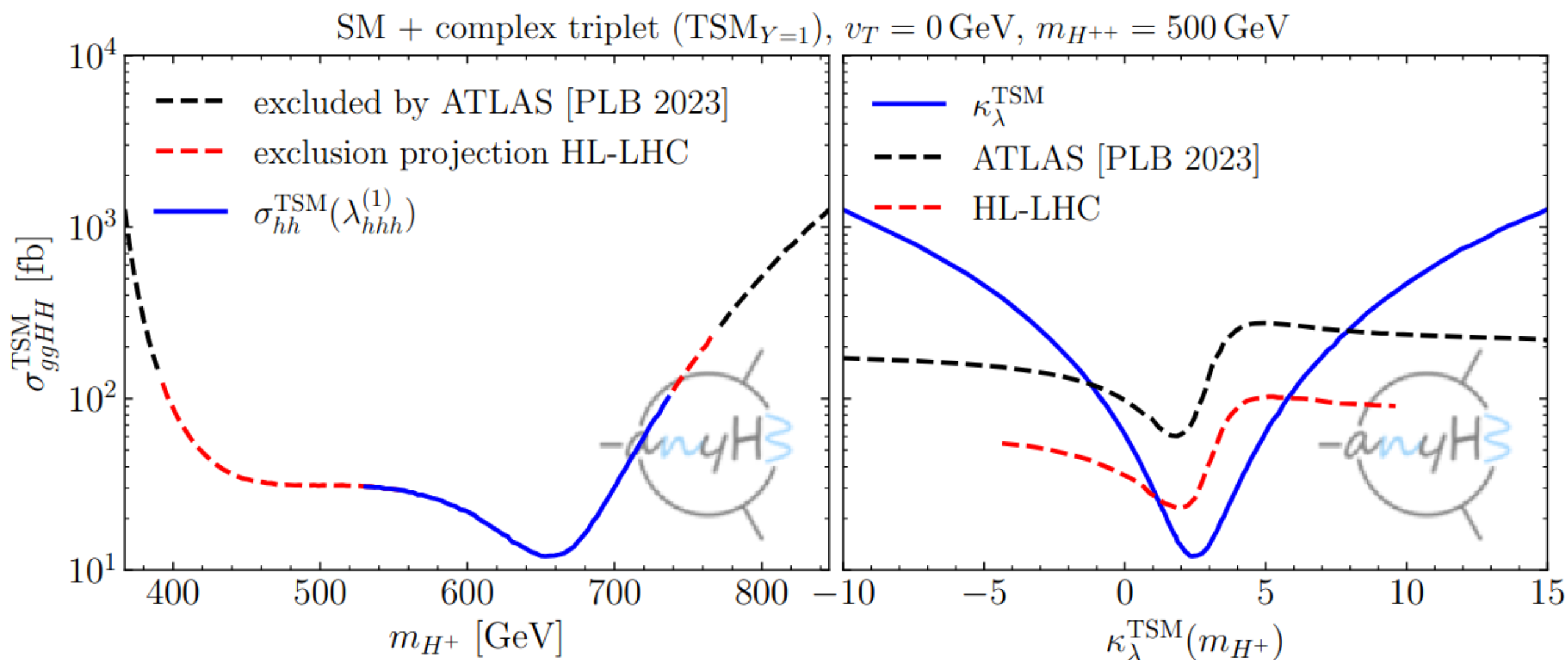
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value $^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single- H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
$HH+H$ 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, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$



Di-Higgs production ($anyHH$)

Example: SM + complex triplet (TSM)

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



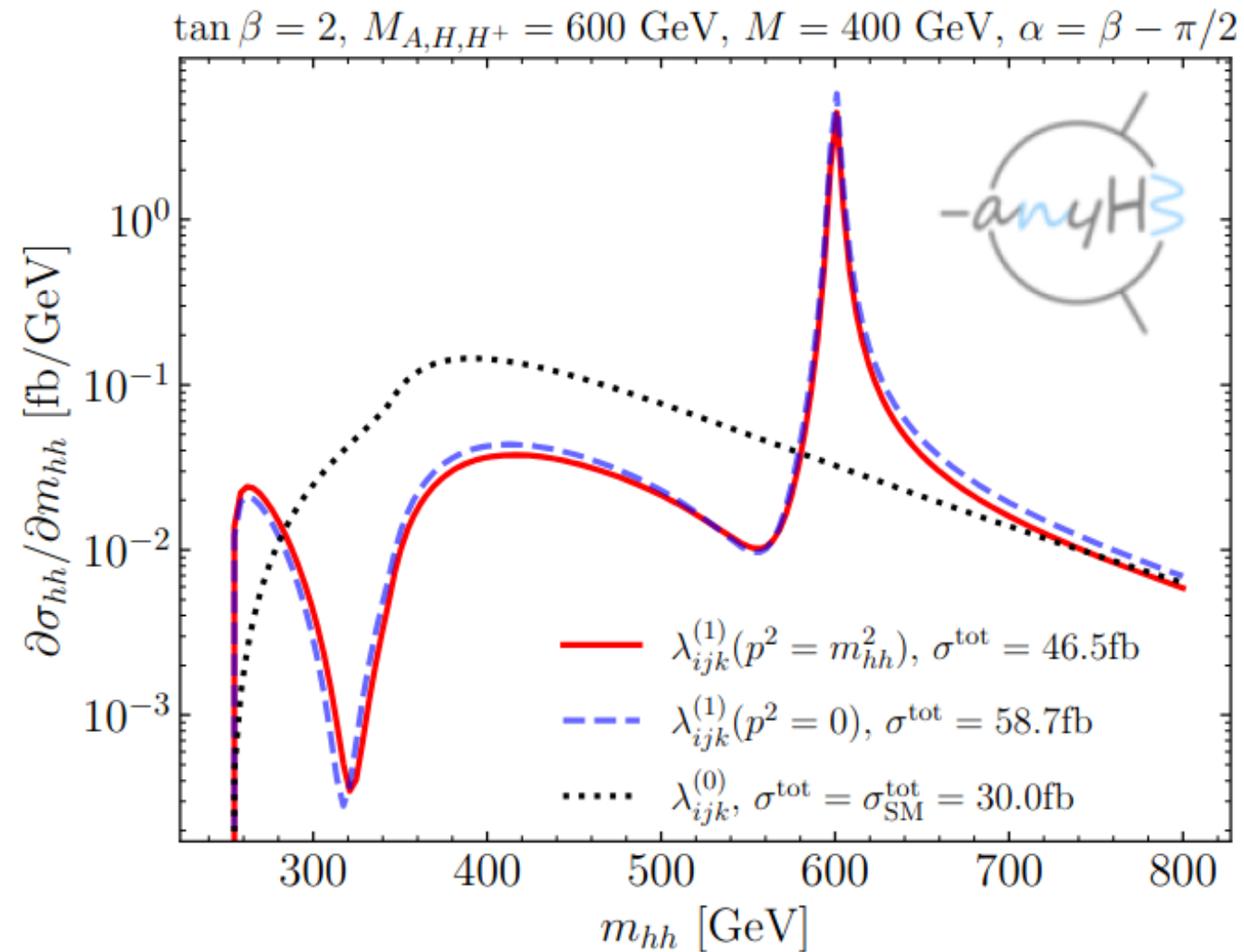
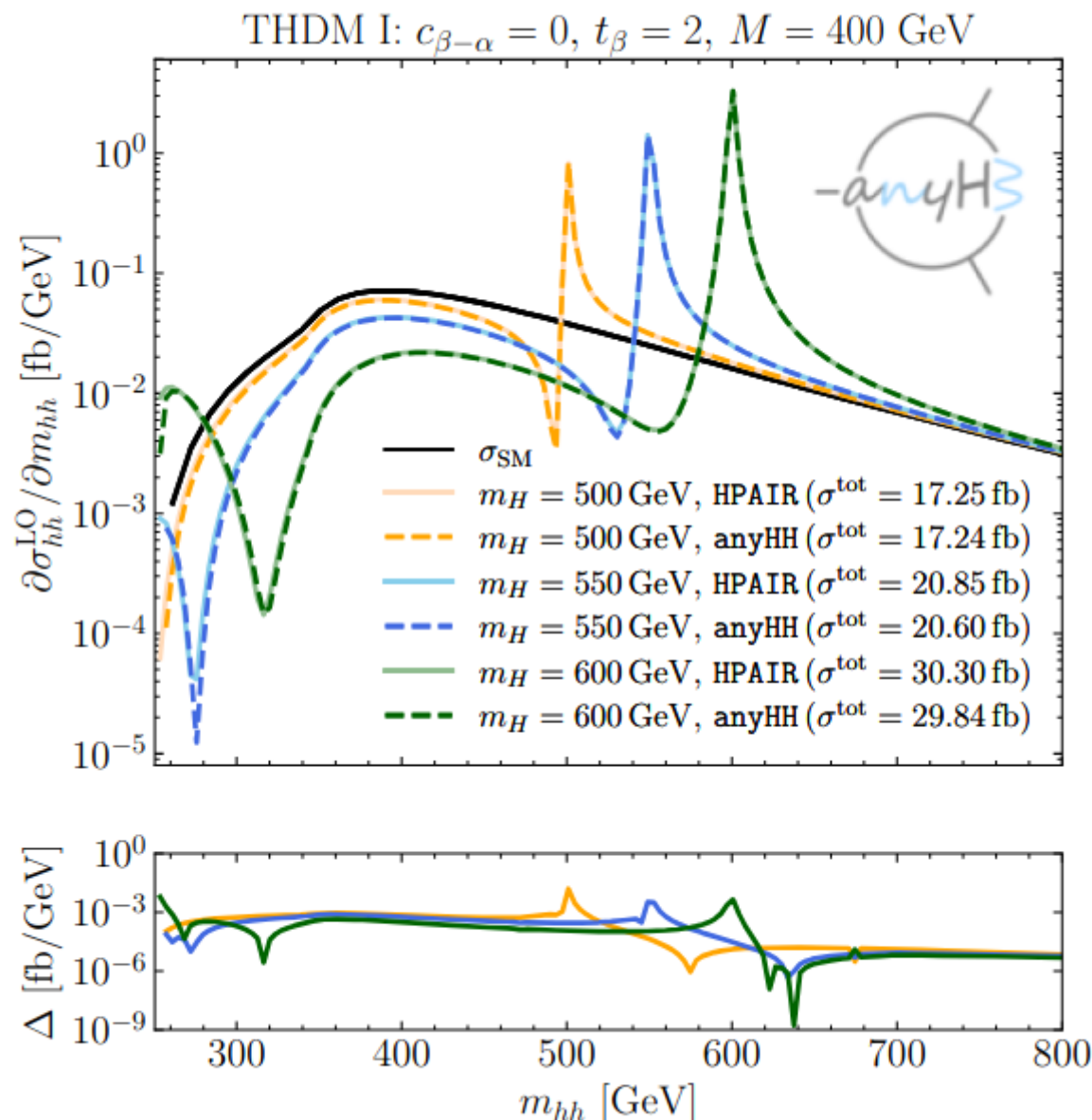
⇒ Present bounds from non-resonant searches already put important constraints

anyHH: 2HDM results

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

Comparison with HPAIR:

[M. Mühlleitner, M. Spira, et al.]



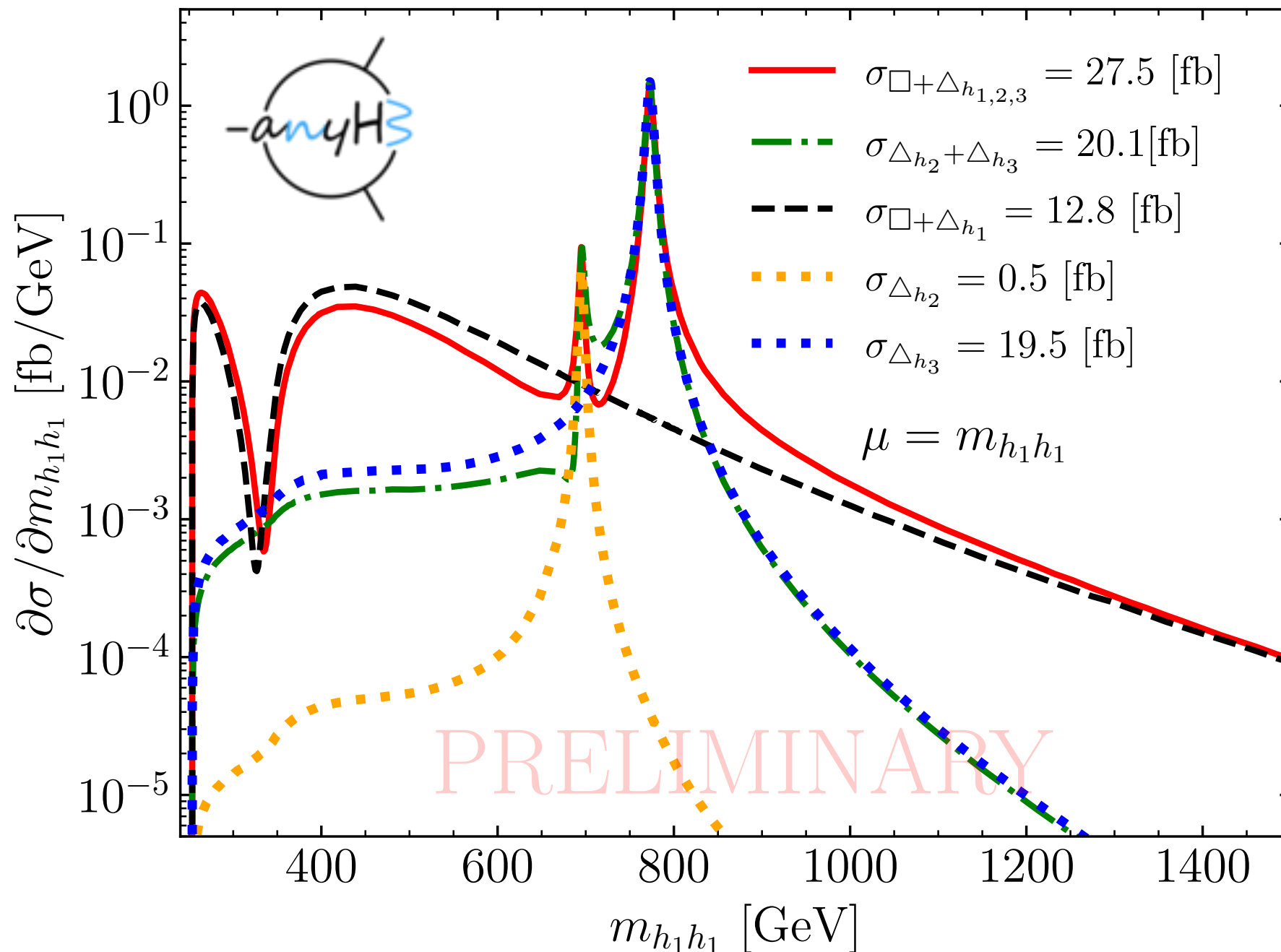
Very good agreement with *HPAIR*, using one-loop trilinear scalar couplings computed by *anyH3* for 2HDM benchmarks (here: alignment limit)

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]

$gg \rightarrow h_1 h_1$ in the NTHDM at 14 TeV: loop-corrected trilinears

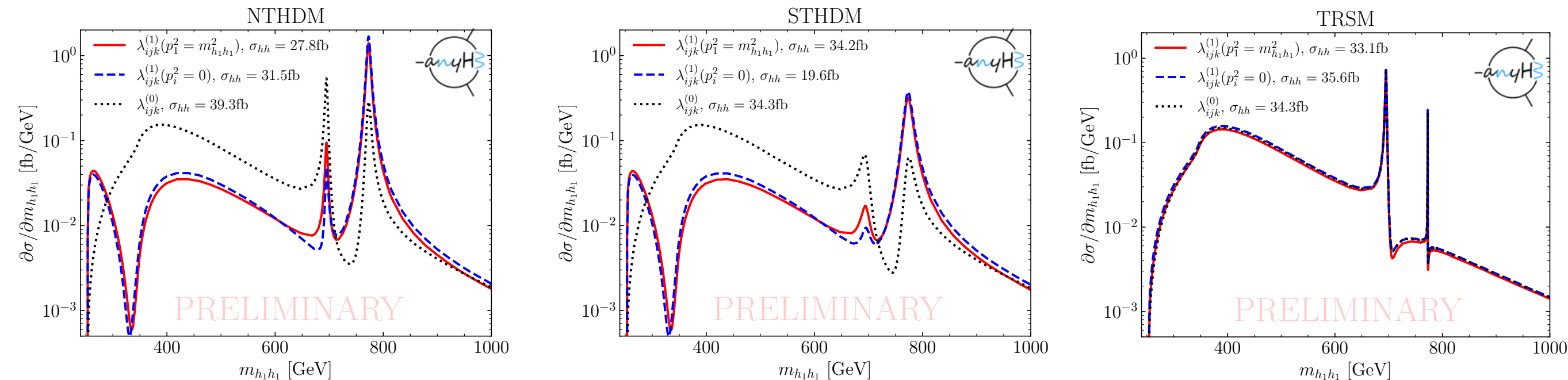


⇒ Shape of distribution determined by resonances, interference effects and loop contributions

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 λ_{ijk} (with momentum dependence) from *anyHH* to UFO format, so that loop-corrected trilinear couplings can be used directly in *MadGraph* simulations

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 κ parameters (signal strength modifiers; see example of κ_λ 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 $\sigma \times \text{BR}$, full likelihood information incorporated where provided by exp. collaborations)

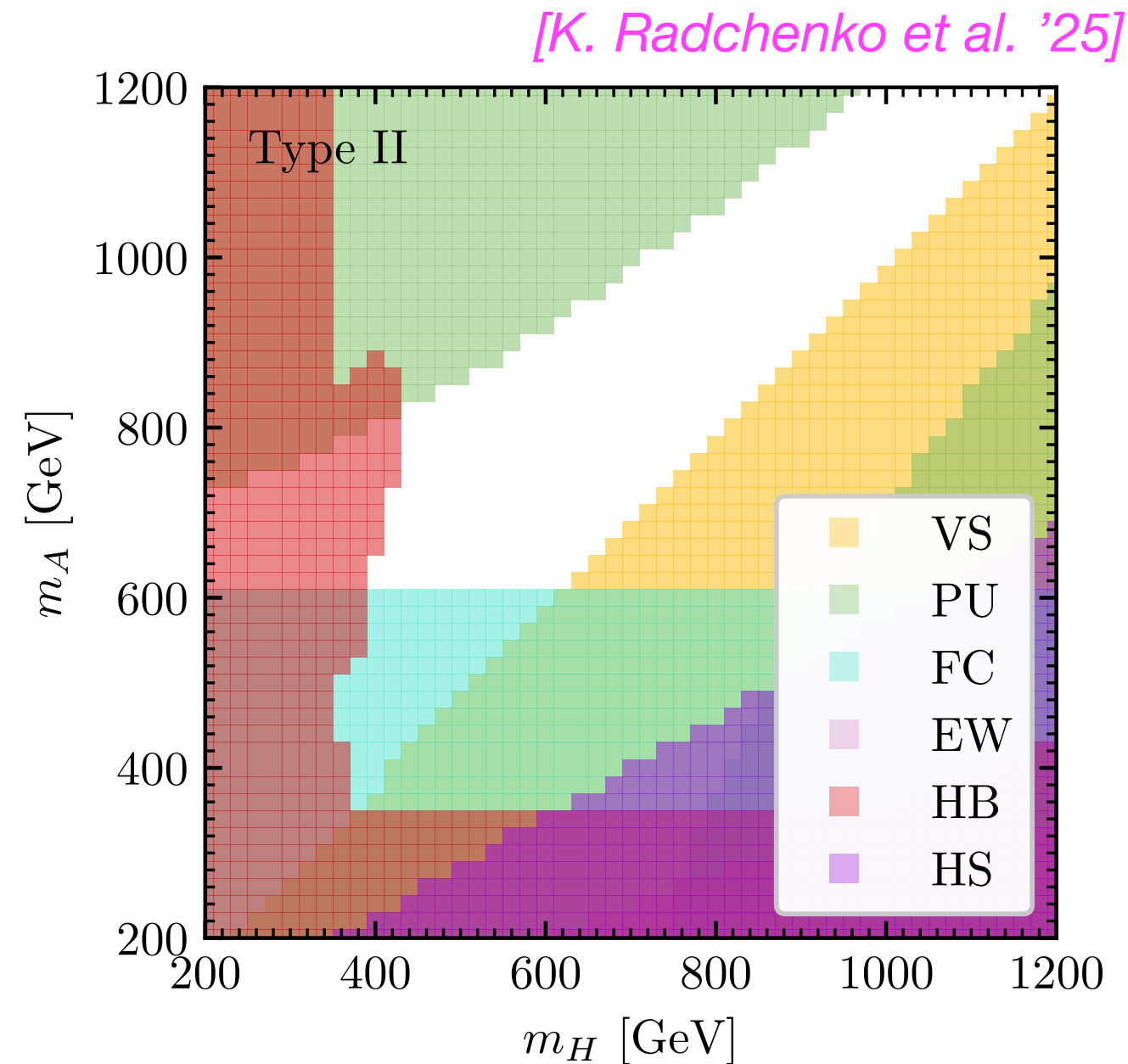
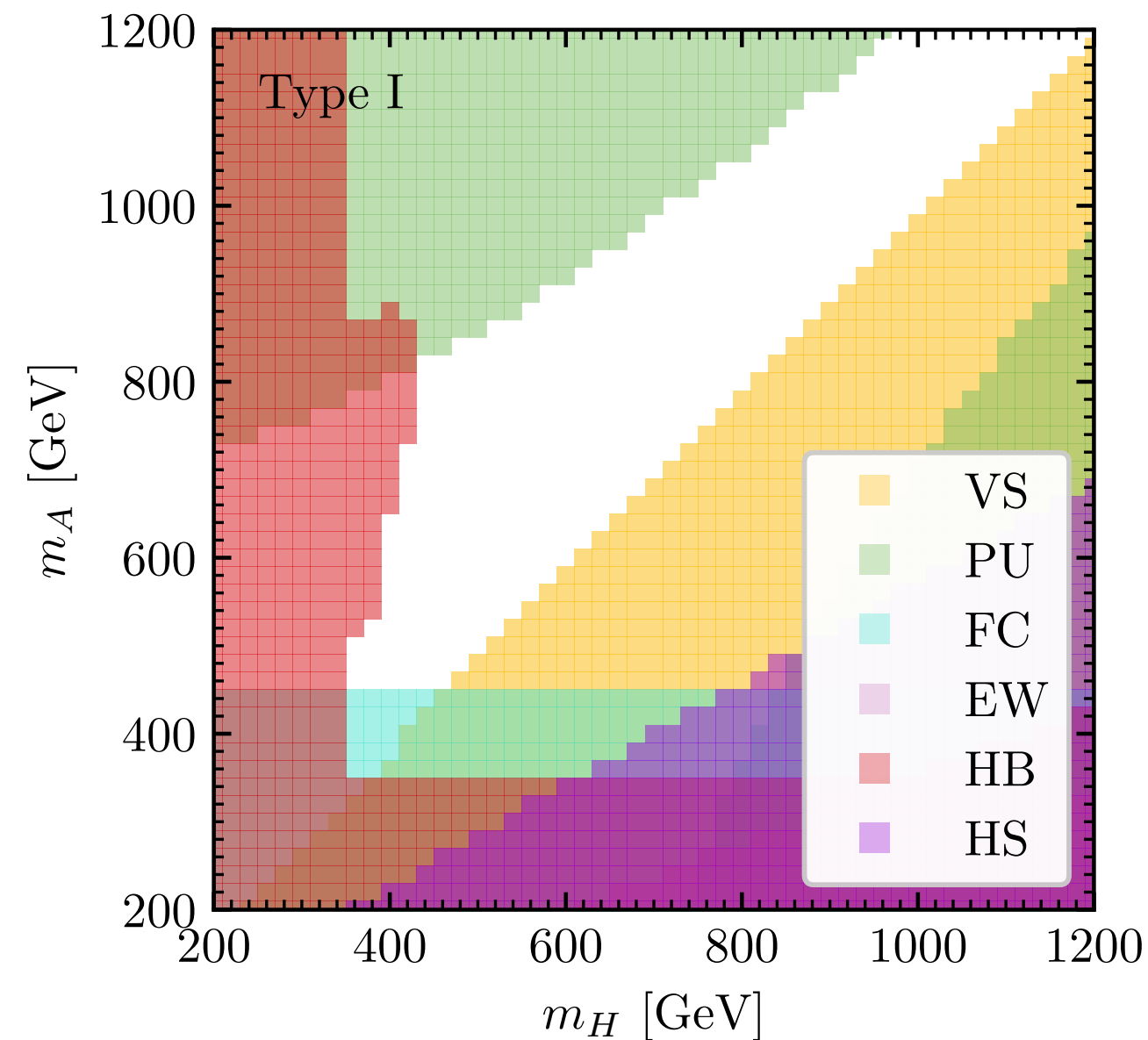
Recasting tools:

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:



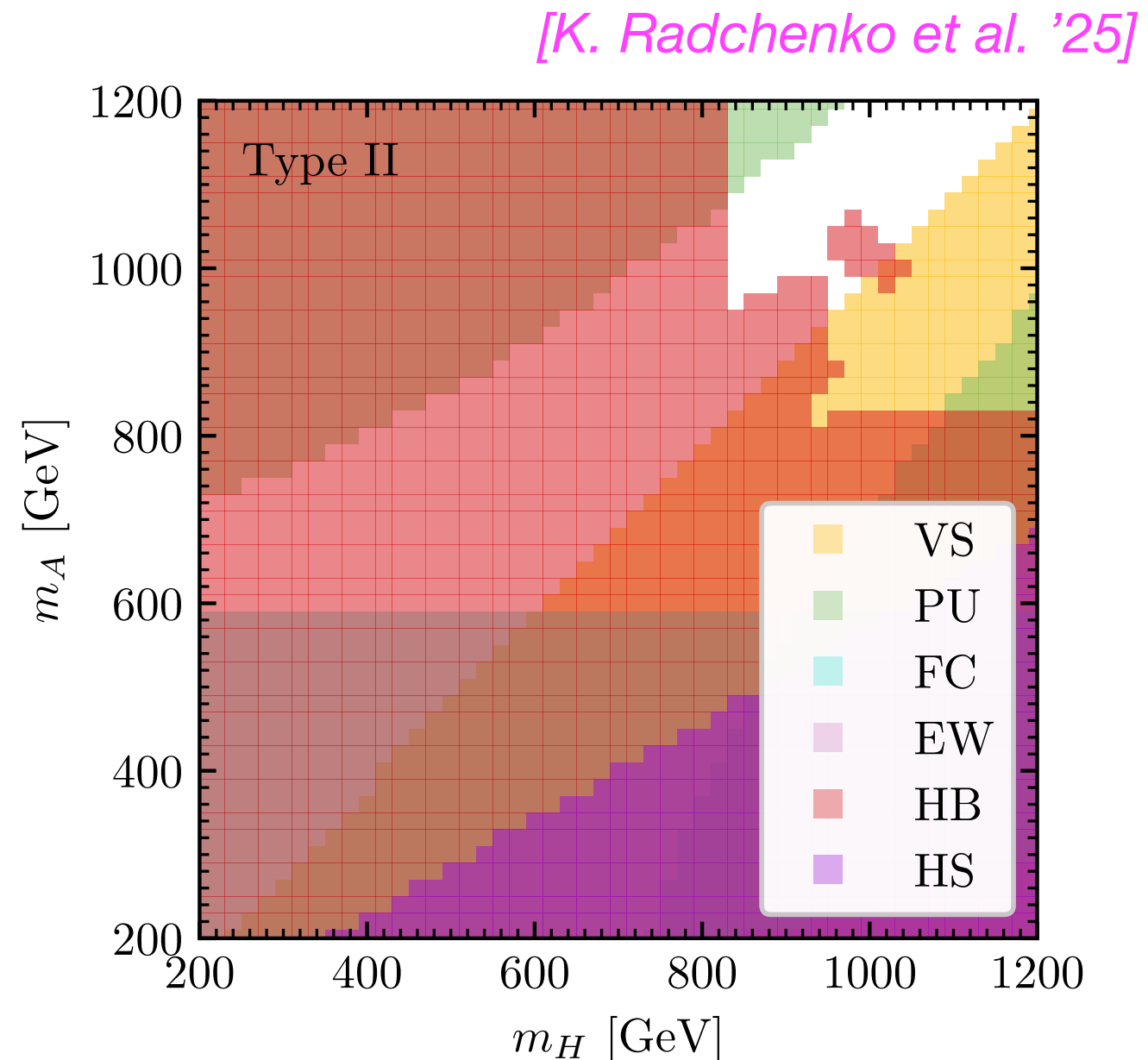
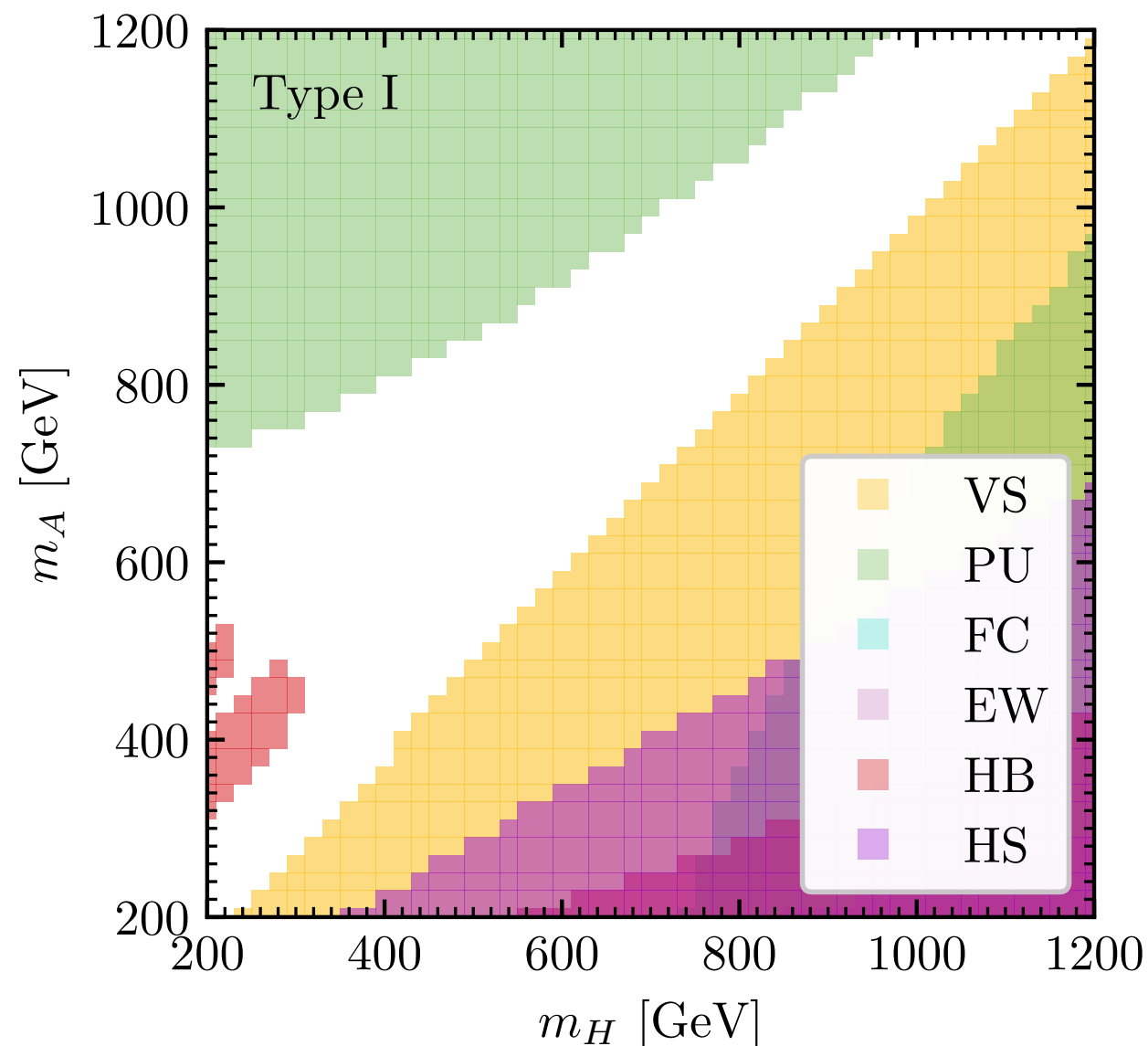
[K. Radchenko et al. '25]

⇒ 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)

$\tan\beta = 10$, alignment limit:



[K. Radchenko et al. '25]

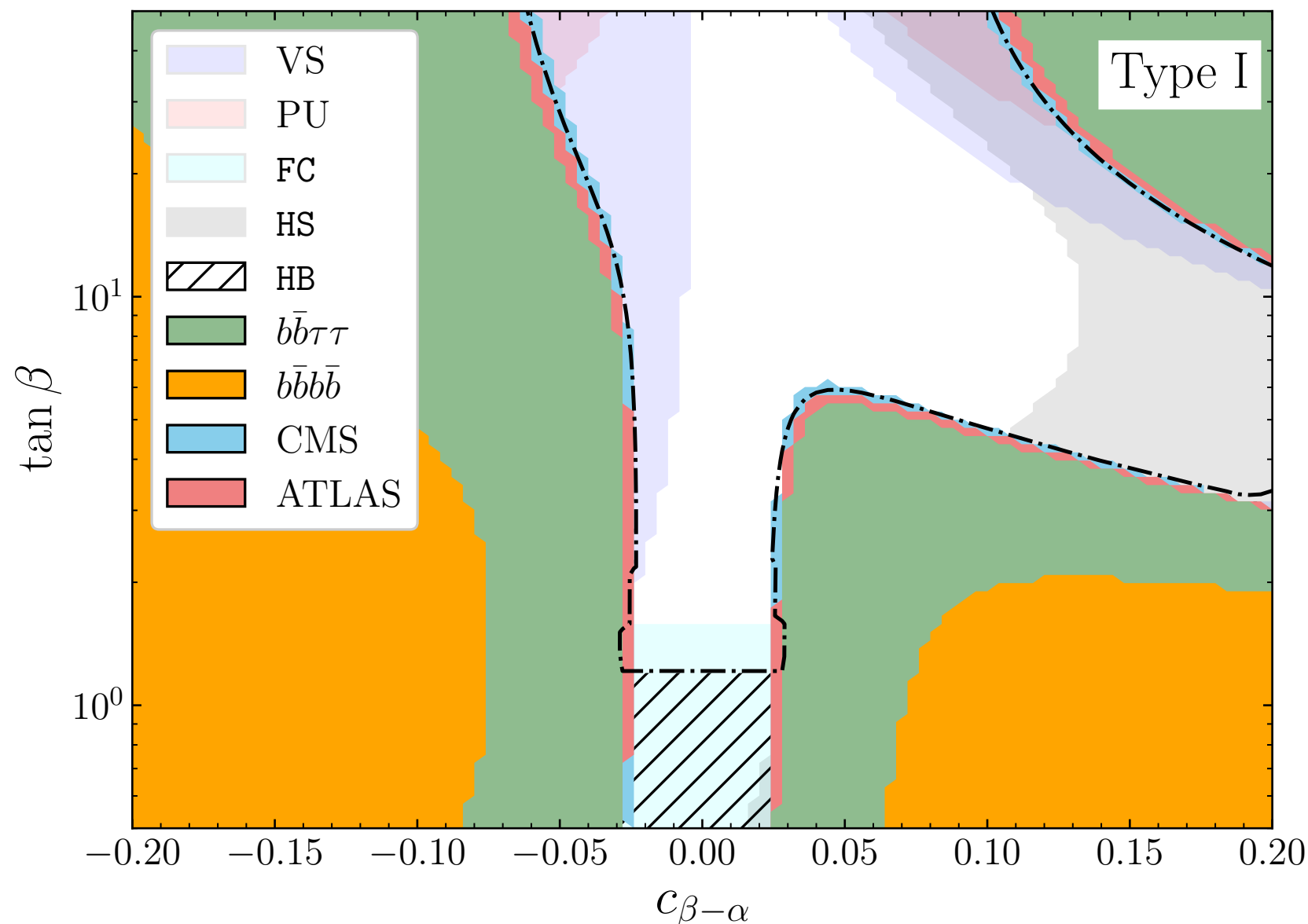
⇒ For larger values of $\tan\beta$: much reduced allowed region in type II because of limits from BSM Higgs searches ($H, A \rightarrow \tau\tau, \dots$)

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 $\tan \beta$

Triple Higgs production at e^+e^- colliders

[F. Maltoni et al. '18]

