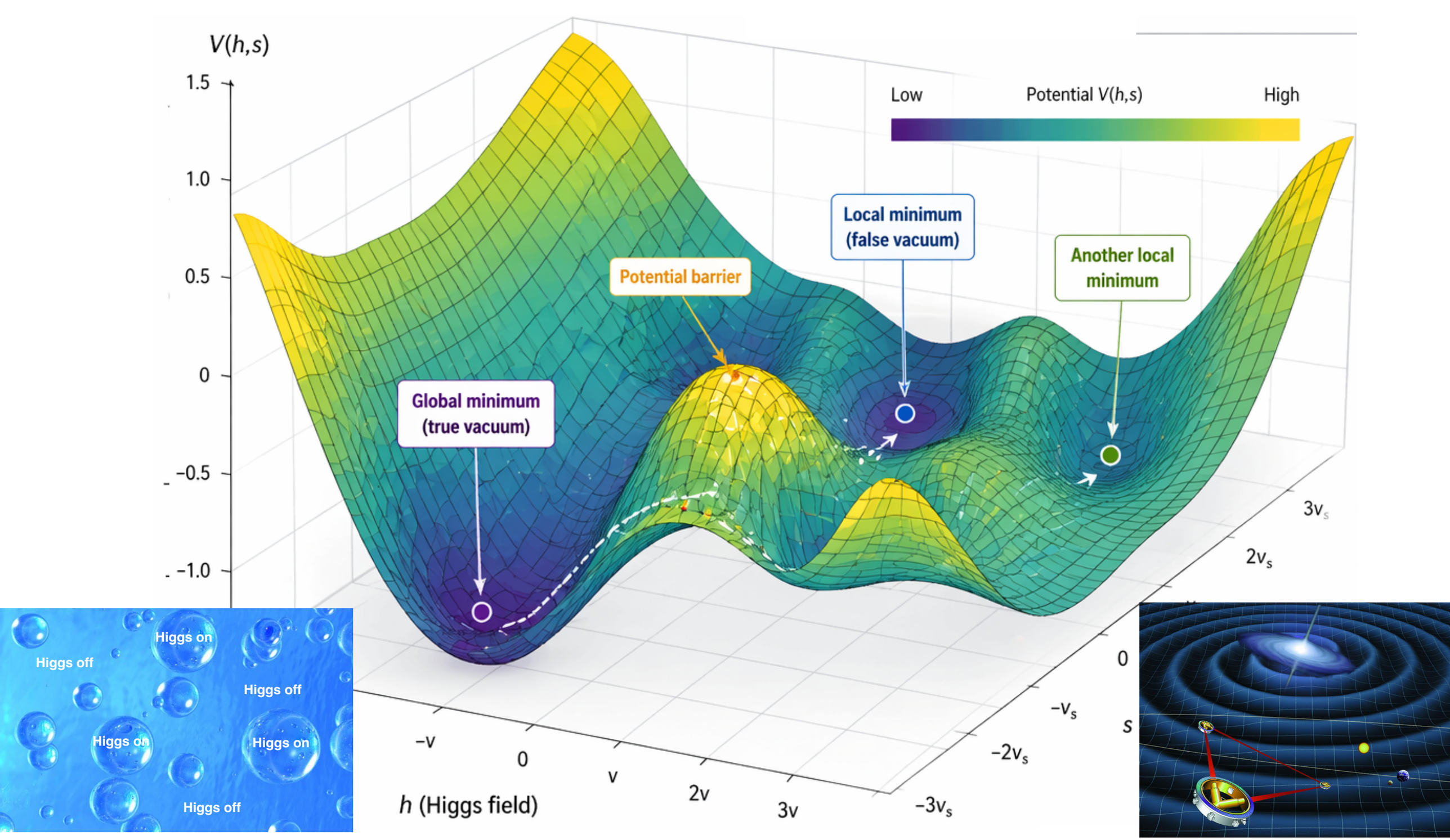


Exploring the Higgs potential at e^+e^- and $\gamma\gamma$ colliders

Johannes Braathen, Georg Weiglein

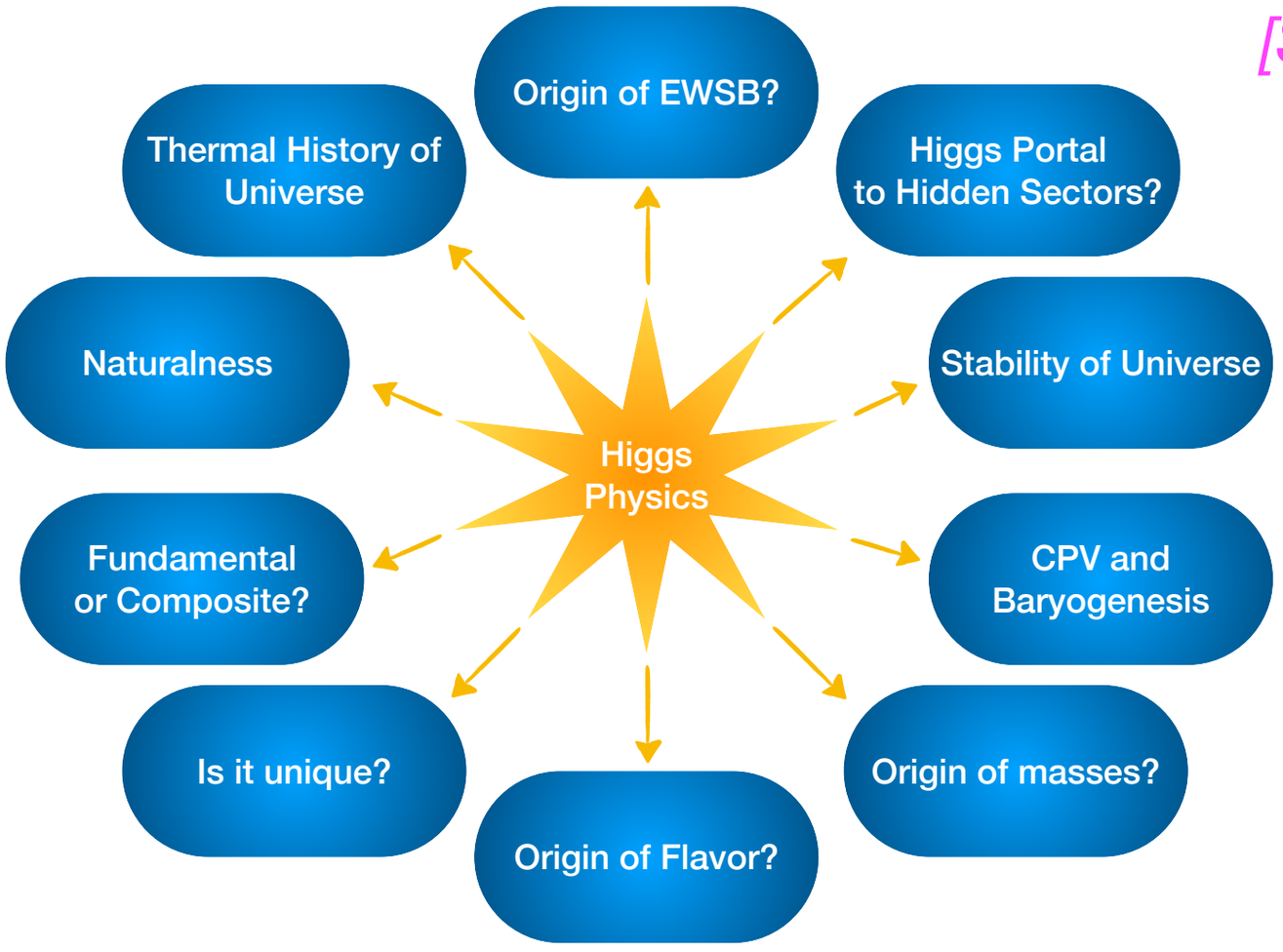
Tsukuba, 11 / 2026

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Introduction

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

[S. Dawson et al. '22]



Higgs discovery ⇔ non-vanishing vev v, caused by Higgs potential

The actual form of the Higgs potential that is realised in nature and the underlying physics giving rise to the Higgs potential are unknown so far

Higgs potential: the `holy grail" of particle physics



Simple picture of Higgs potential refers to case of single Higgs doublet field

[J. Reuter '26]

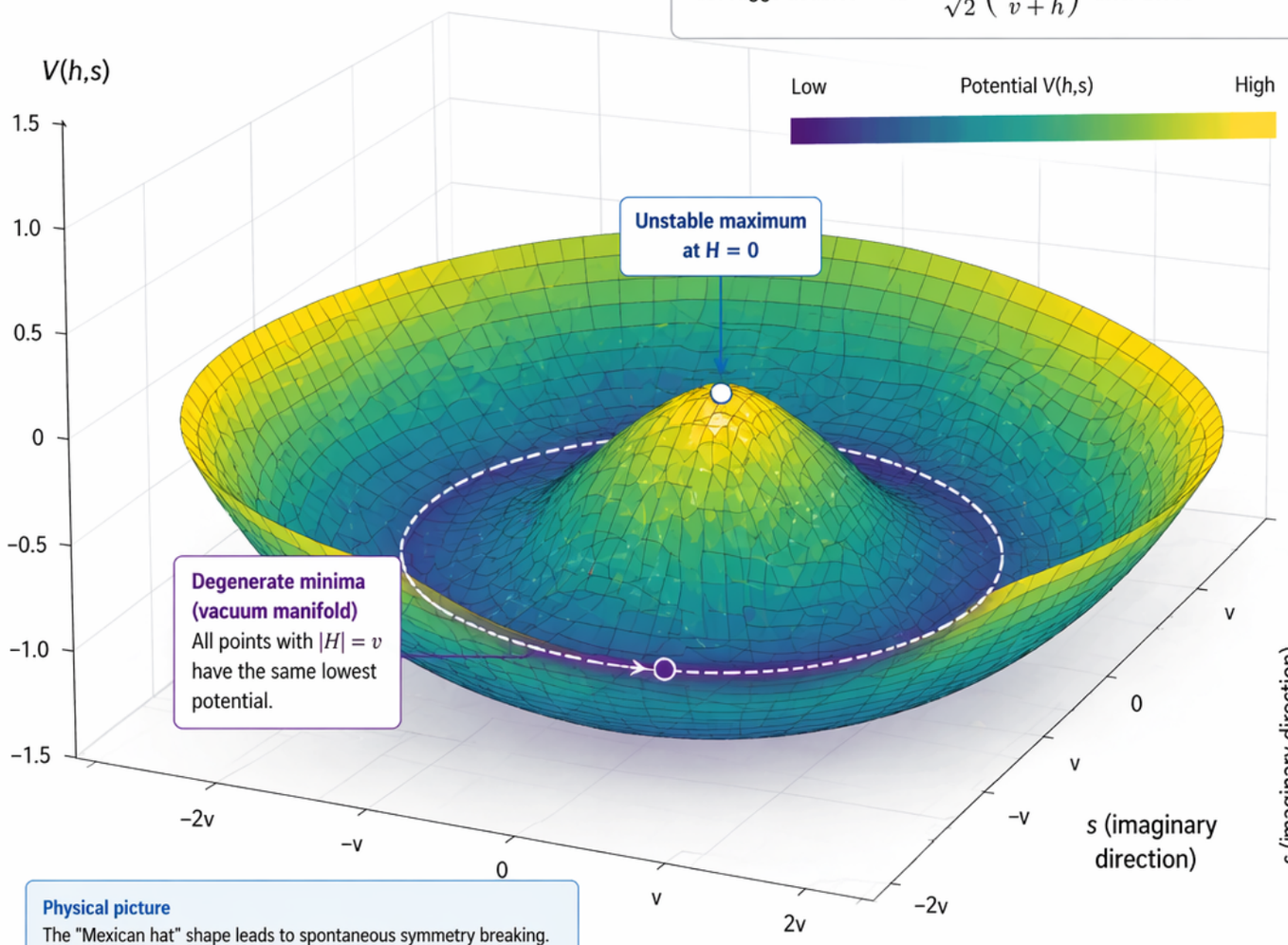
The Standard Model Higgs Potential

A Single Minimum (Mexican Hat Potential)

Standard Model potential:

$V(H) = -\mu^2 |H^\dagger| H + \lambda (H^\dagger |H)^2 \qquad (\mu^2 > 0, \lambda > 0)$

H: Higgs doublet $\quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ after EWSB

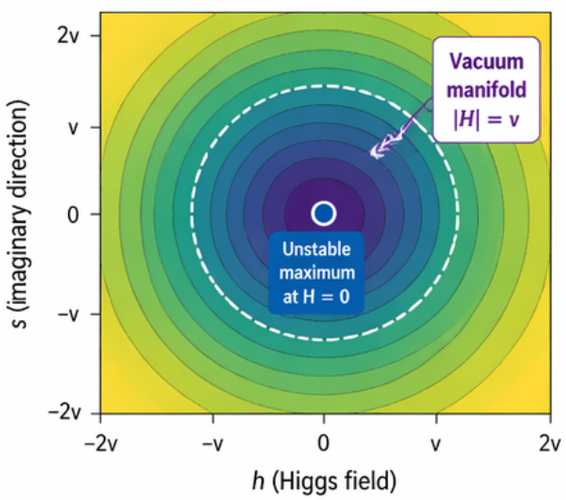


Physical picture

The "Mexican hat" shape leads to spontaneous symmetry breaking. The Higgs field chooses a vacuum on the circle $|H| = v$, giving particles their masses while preserving electromagnetic gauge symmetry $(U(1)_{em})$.

- **Single minimum (degenerate circle):** The true vacuum lies at $|H| = v$. All directions in field space with the same magnitude v are equivalent.
- **Unstable maximum at the origin:** $H = 0$ is a maximum (symmetric phase) and is not the vacuum.
- **No potential barriers:** The field rolls smoothly from the origin to the vacuum manifold.
- **Electroweak symmetry breaking (EWSB):** The Higgs field acquires a non-zero vacuum expectation value $v \approx 246$ GeV, giving masses to W, Z and fermions.

Top-down view (contours of V)



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

Higgs potential: the `holy grail" of particle physics



Example of extended Higgs sector (artist's (AI) view):

[J. Reuter '26]

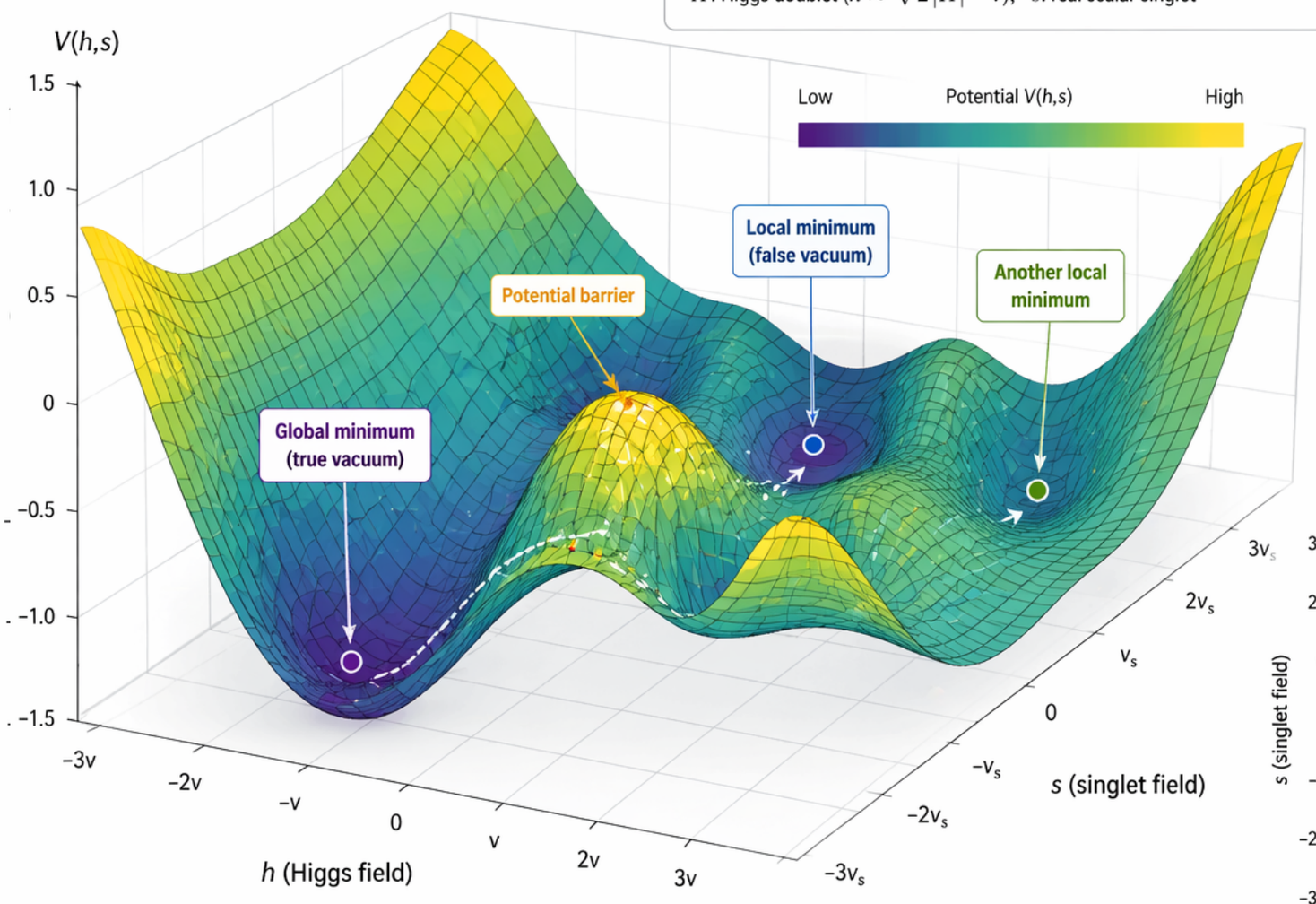
A More Complicated Higgs Potential

Potential with Several Minima

Example potential:

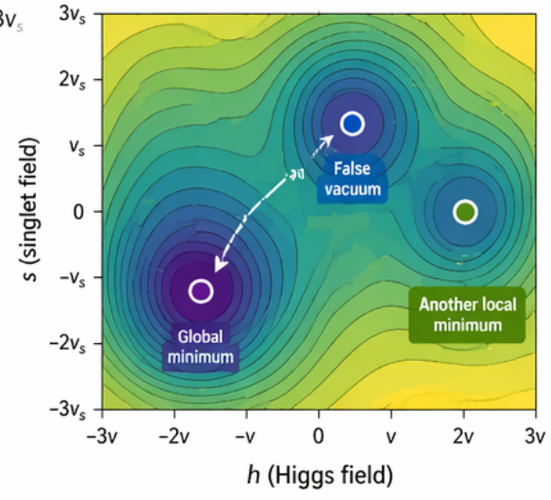
$$V(h,s) = -\mu_h^2|H|^2 + \lambda_h|H|^4 + \frac{1}{2}m_s^2 s^2 + \frac{\kappa}{2}|H|^2 s^2 + \frac{\lambda_s}{4}s^4 + \mu_3 s^3,$$

H: Higgs doublet ($h \approx \sqrt{2}|H| - v$), s: real scalar singlet



- **Global minimum (true vacuum):** Our Universe is (presumably) in this lowest-energy state.
- **Local minima (false vacua):** Metastable states where the Universe could get trapped.
- **Potential barriers:** Separate minima; quantum tunneling can allow transitions.
- Different minima correspond to different possible vacuum states with different physical properties.

Top-down view (contours of V)



Shape can drastically differ from single field case, rich structure of minima, requirement of vacuum stability yields important constraints

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?

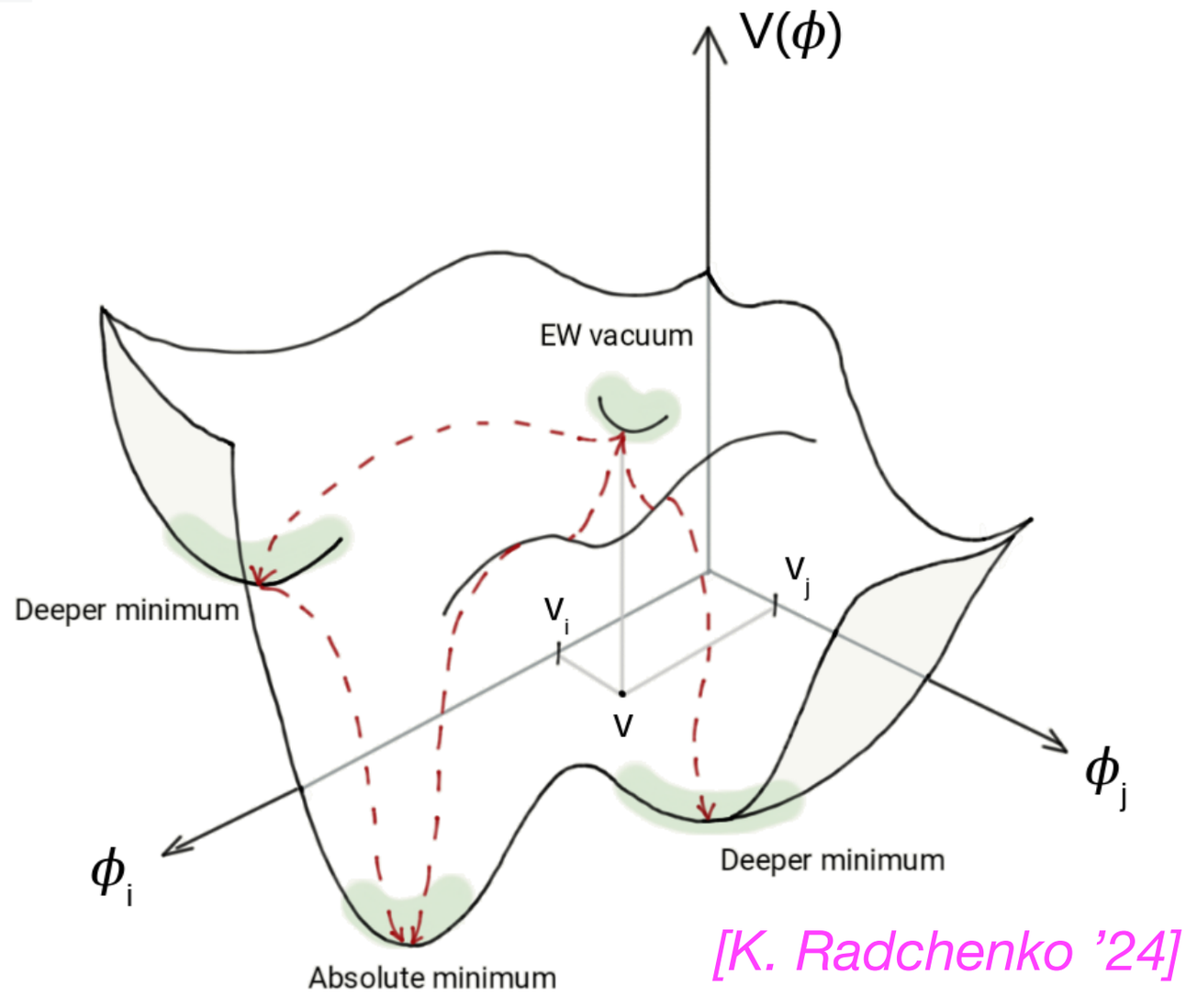
Trilinear coupling Quartic coupling Possible couplings involving additional scalars

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

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

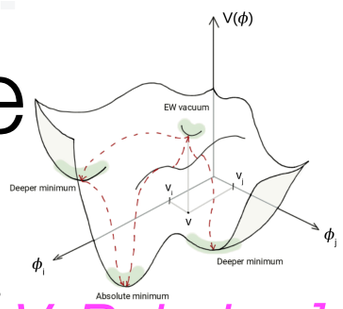
Distance of EW minimum from origin of field space: v

Curvature of the potential around the EW minimum: m_h



[K. Radchenko '24]

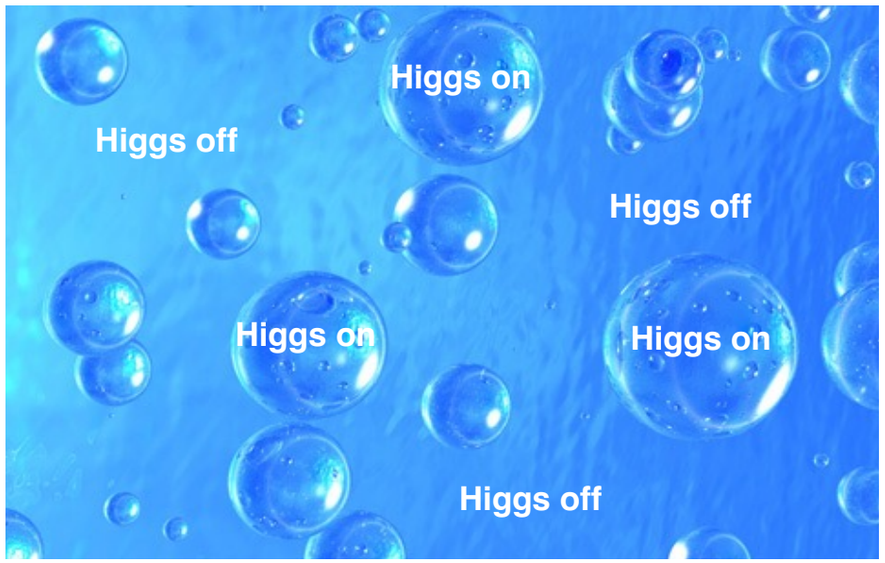
The Higgs potential and the electroweak phase transition (EWPT)

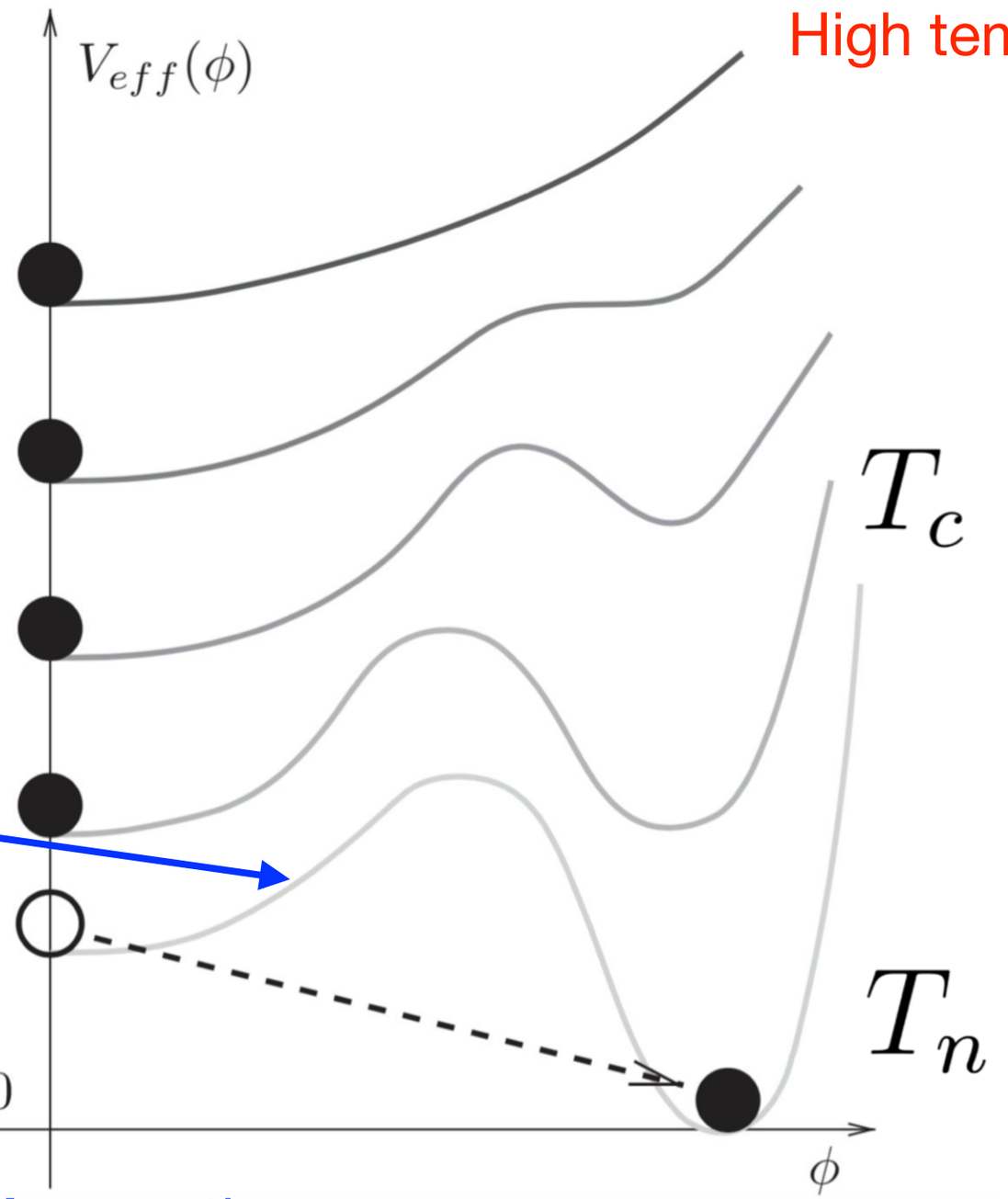


[D. Gorbunov, V. Rubakov]

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

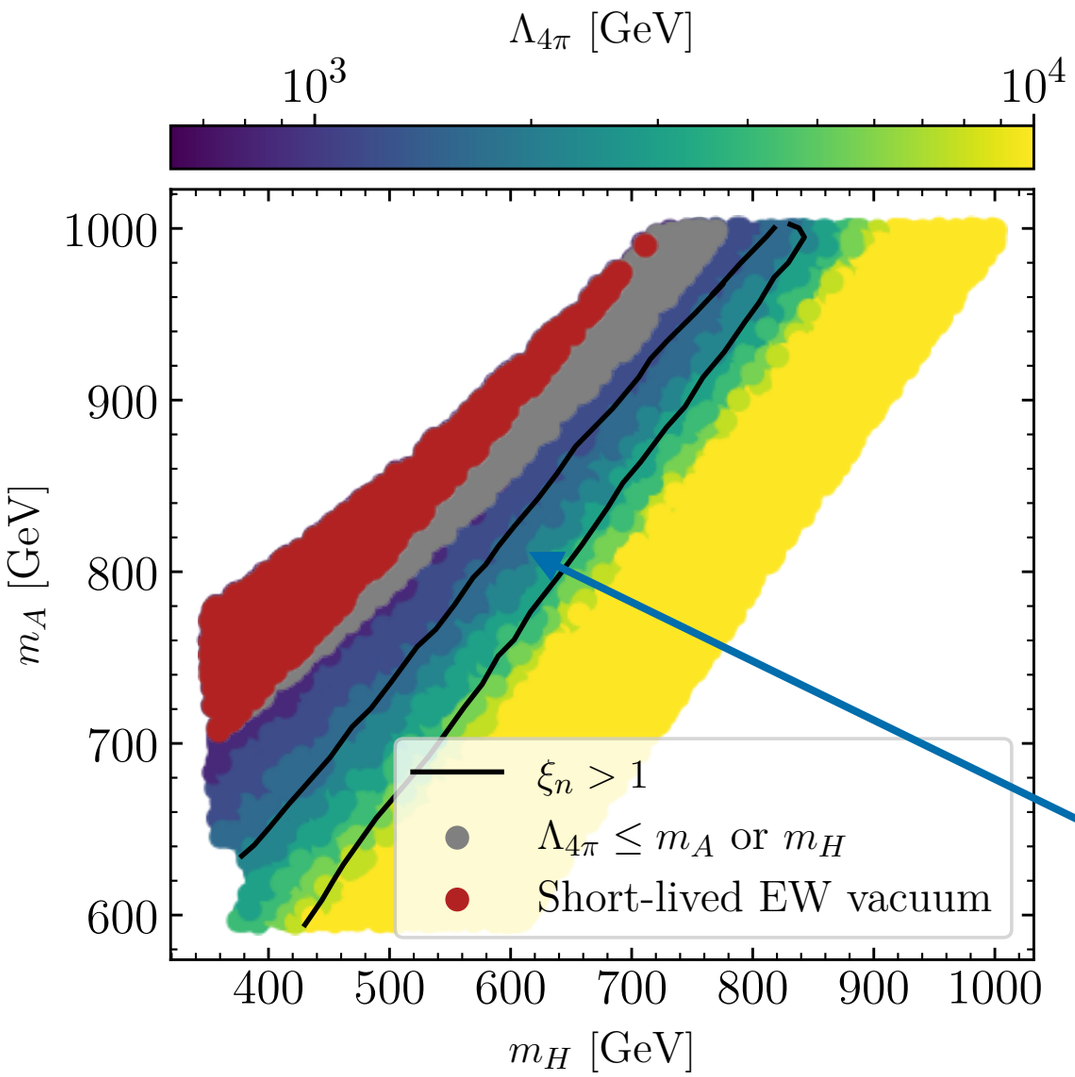
SM: smooth cross-over

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]

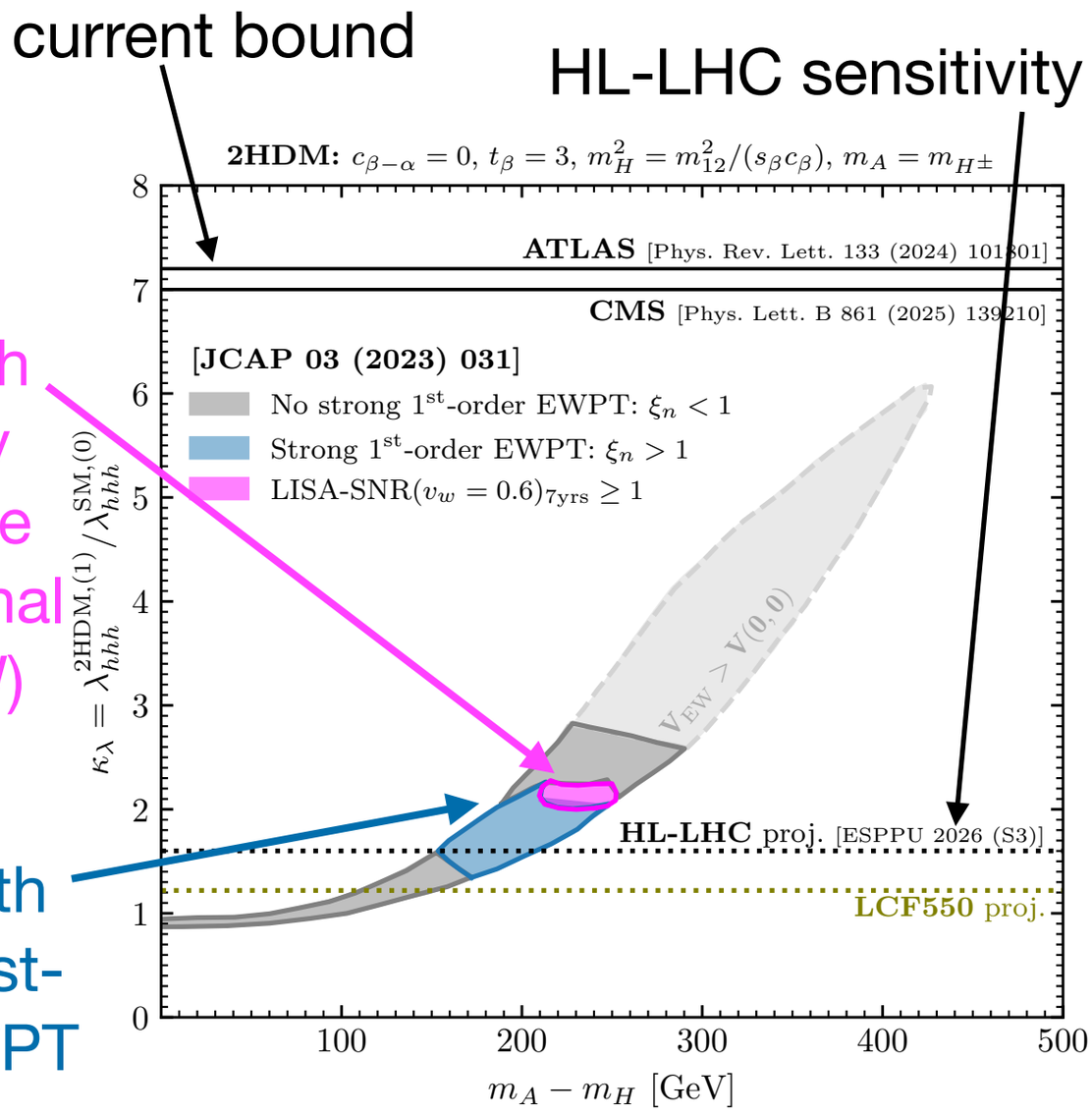
2HDM, N2HDM, … : the parameter region giving rise to a strong first-order EWPT (if along Higgs field direction), which may cause a detectable gravitational wave signal, yields an enhancement of the trilinear Higgs self-coupling and ``smoking gun" signatures at the LHC

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



region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT



Determination of the trilinear Higgs self-coupling: LHC, e^+e^- LC and $\gamma\gamma$ collider

Most direct access to trilinear Higgs self-coupling $\kappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$:
Higgs pair production process, requires for e^+e^- a Linear Collider,
not accessible at FCC-ee!

In most analyses at the LHC and future collider studies so far:
only κ_λ allowed to vary, all other coupling modifiers fixed to their Standard Model (SM) values

However: EWSB mechanism realised in nature may yield deviations from the SM in κ_λ and further κ's

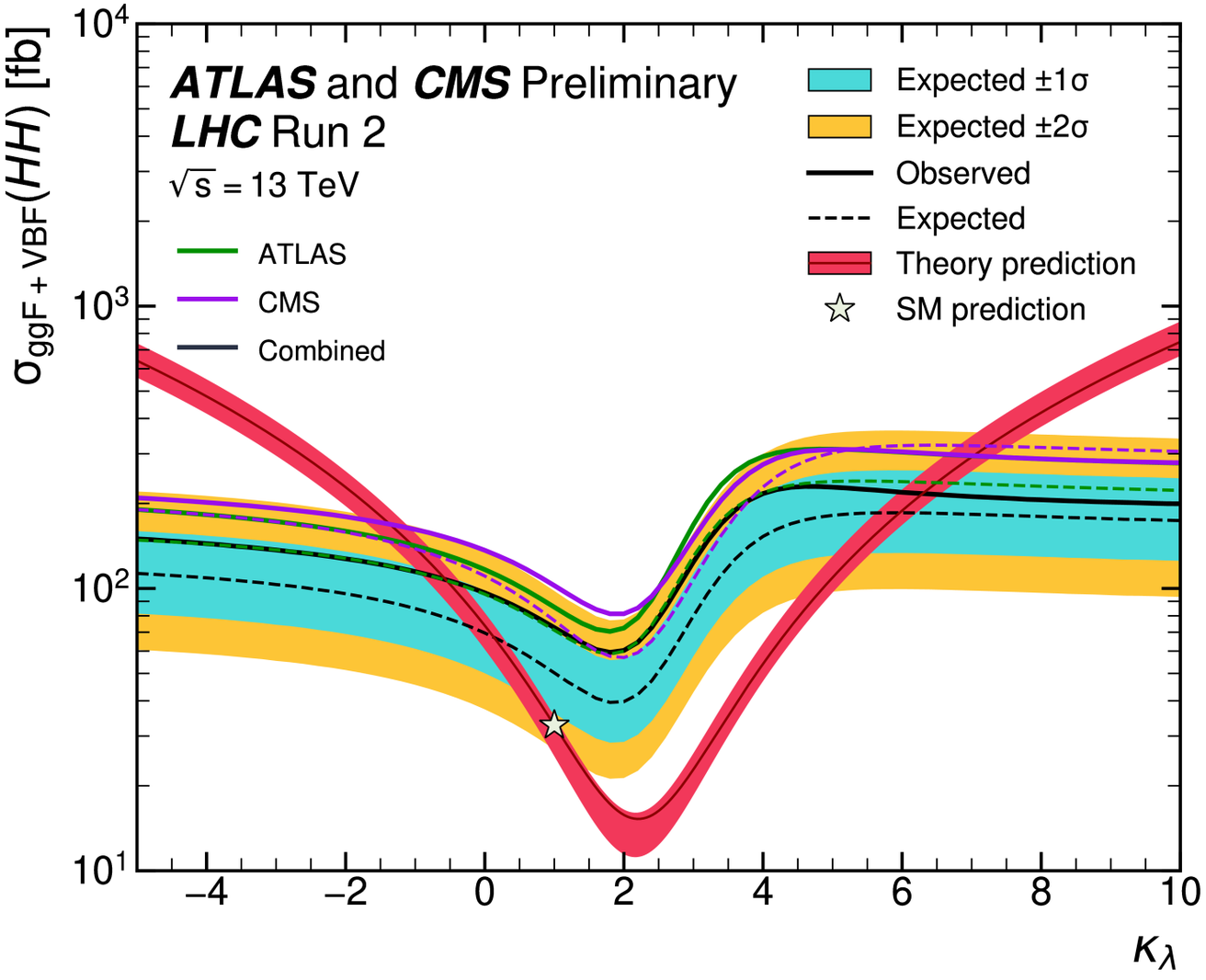
$\Rightarrow$ Need to take into account possible variations of other coupling modifiers (or EFT operators), in particular of the ones that are not well constrained by single Higgs production processes!

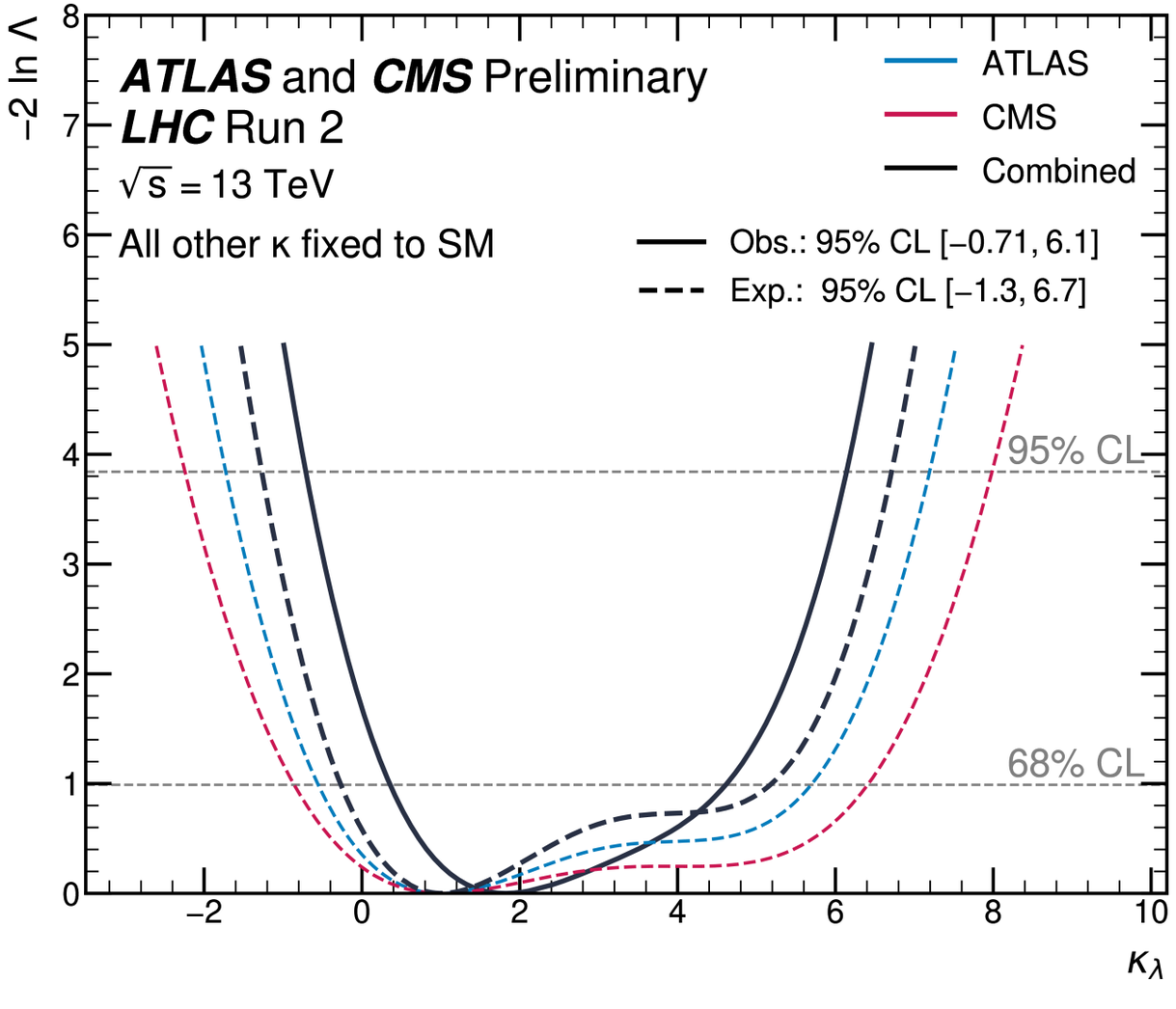
LHC: limits from non-resonant di-Higgs production

[ATLAS and CMS Collaborations '25]

Using only information from di-Higgs production and assuming that new physics only affects λ_{hhh} (only κ_λ allowed to vary):

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





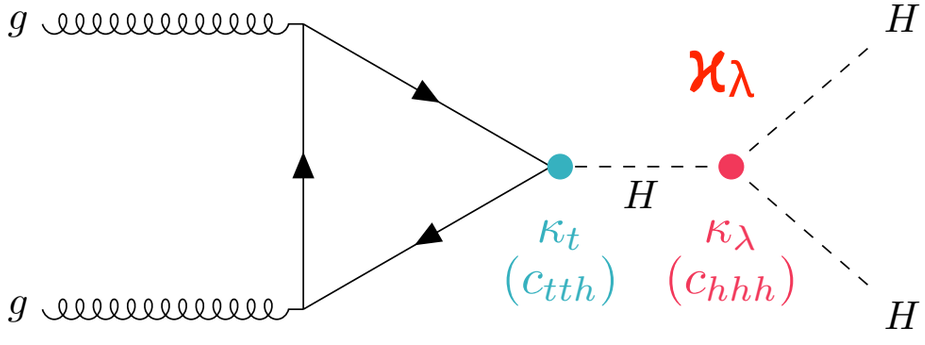
obs: $-0.7 < \kappa_\lambda < 6.1$ at 95% C.L., exp.: $-1.3 < \kappa_\lambda < 6.7$ at 95% C.L.

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

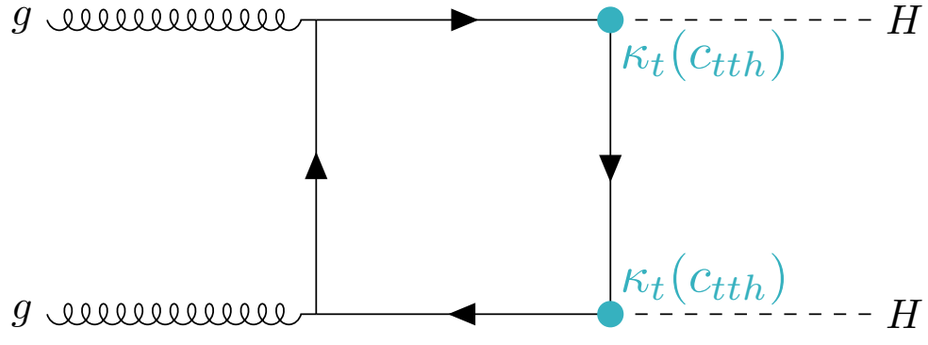
LHC: impact of relaxing the assumption that all other couplings are fixed to their SM values

Contributions at the LHC:

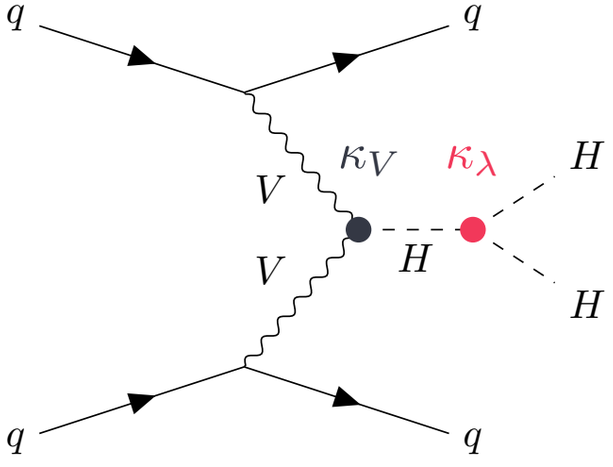
[ATLAS Collaboration '24]



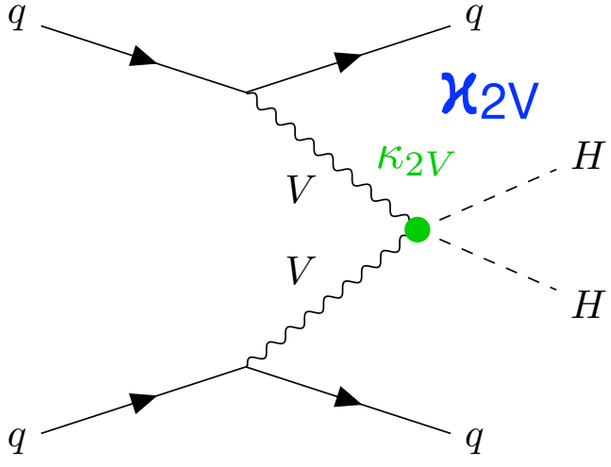
(a)



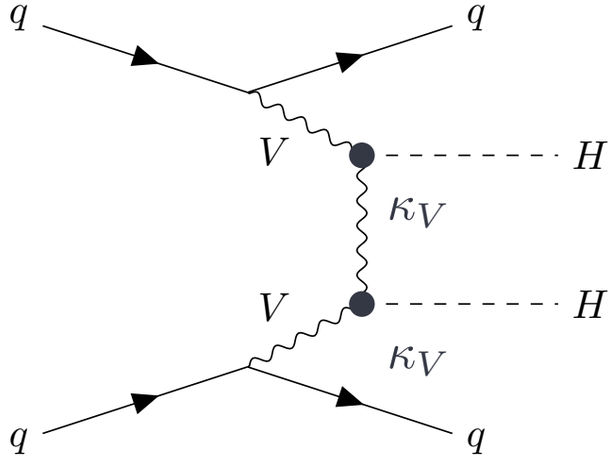
(b)



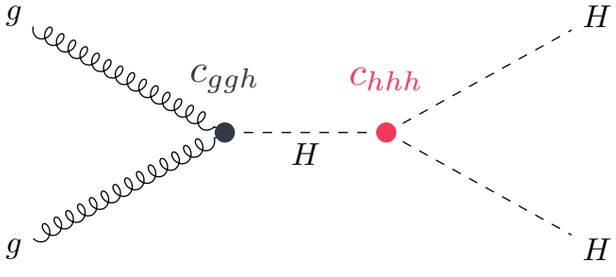
(c)



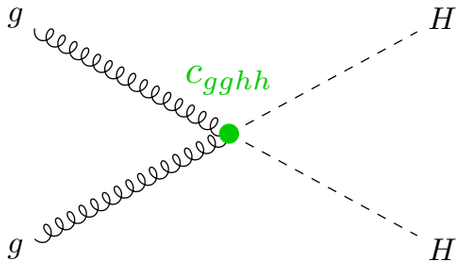
(d)



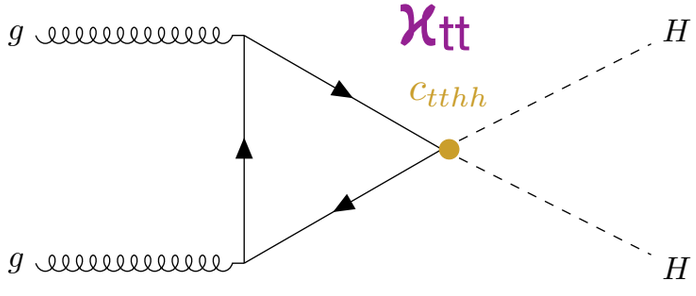
(e)



(f)



(g)

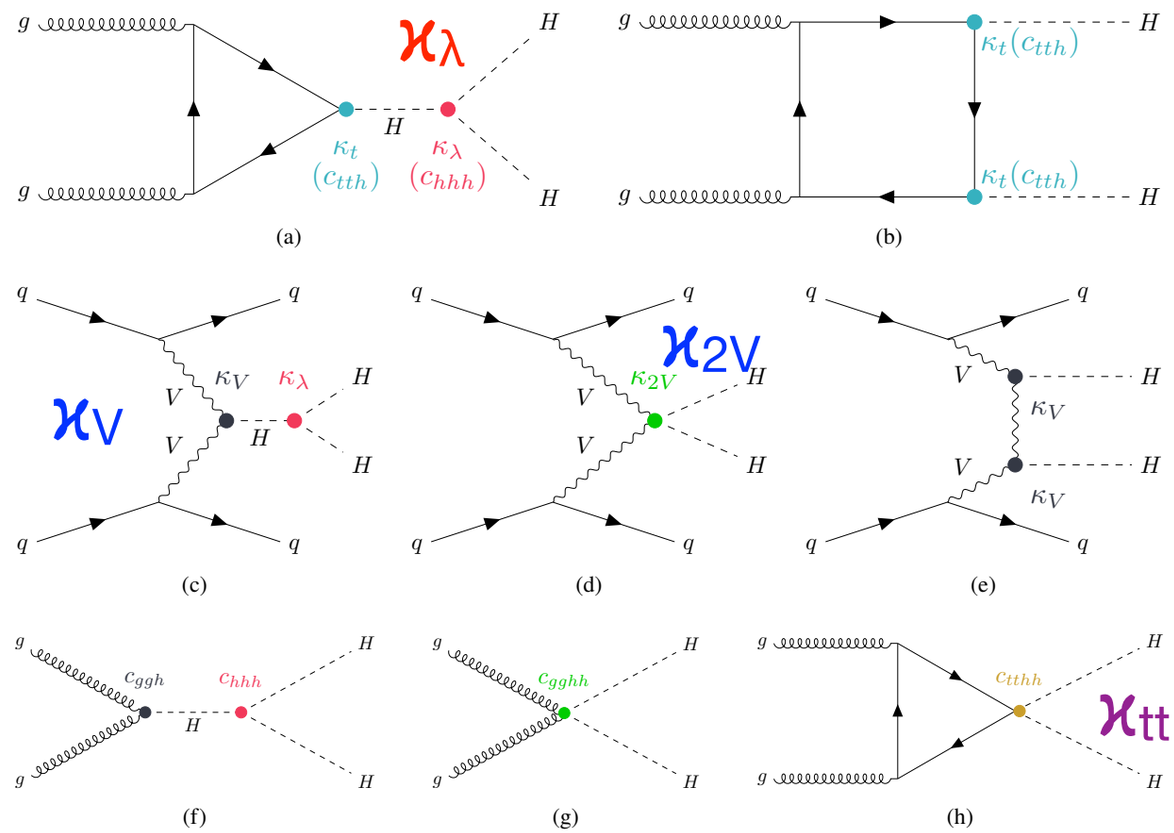


(h)

LHC: impact of relaxing the assumption that all other couplings are fixed to their SM values

Particularly important in this context: (effective) couplings that are not well constrained by single Higgs measurements: κ_{tt} and κ_{2V}

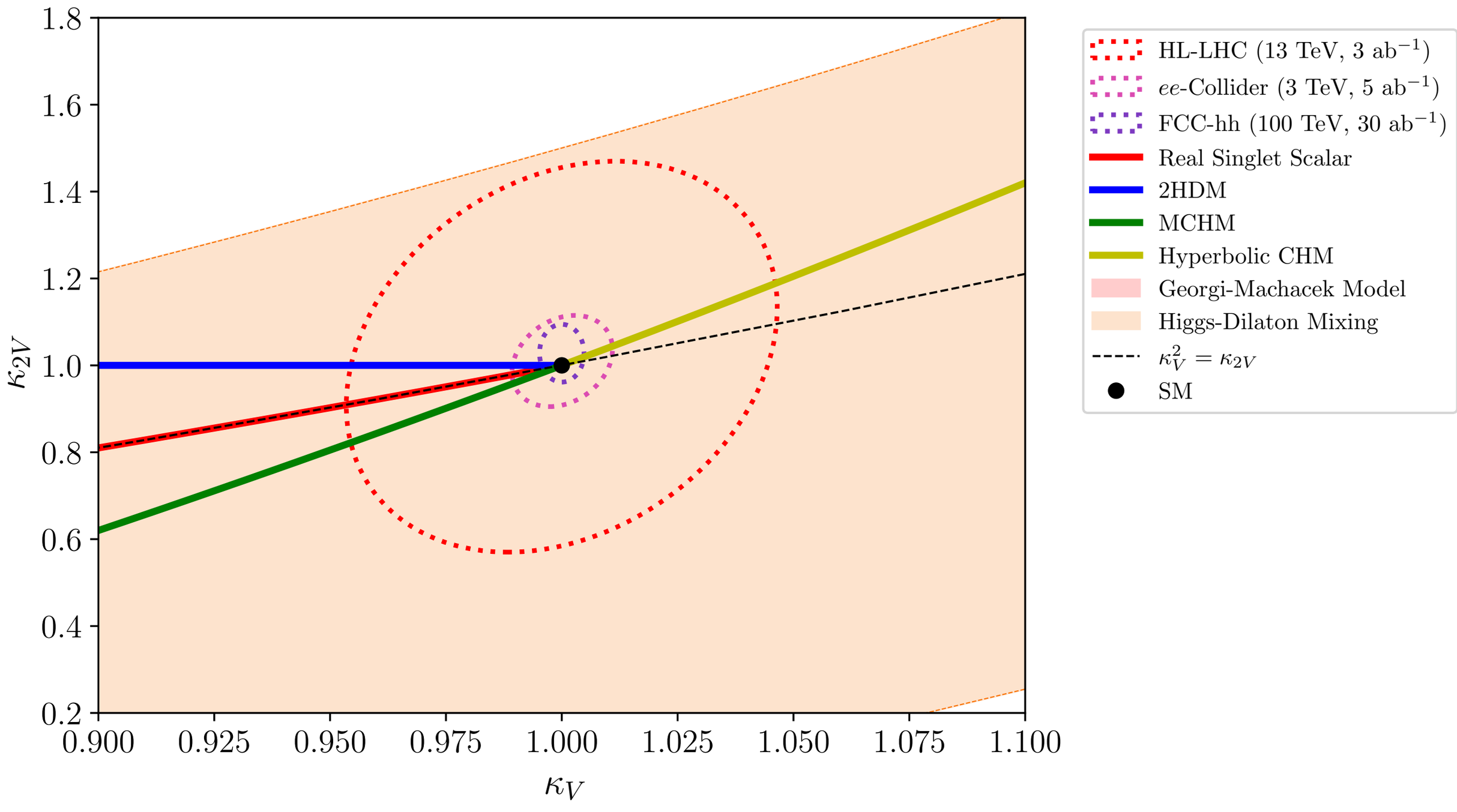
- κ_{tt} : $\kappa_{tt} = 0$ in the SM, can e.g. be generated by lowest-order contribution of additional neutral Higgs boson or loop contribution to the tthh coupling



- κ_{2V} : $\kappa_{2V} = 1$ in the SM, connection of the VVhh coupling (κ_{2V}) to the Vhh coupling (κ_V) via the BEH mechanism?

Possible variations of κ_V and κ_{2V}

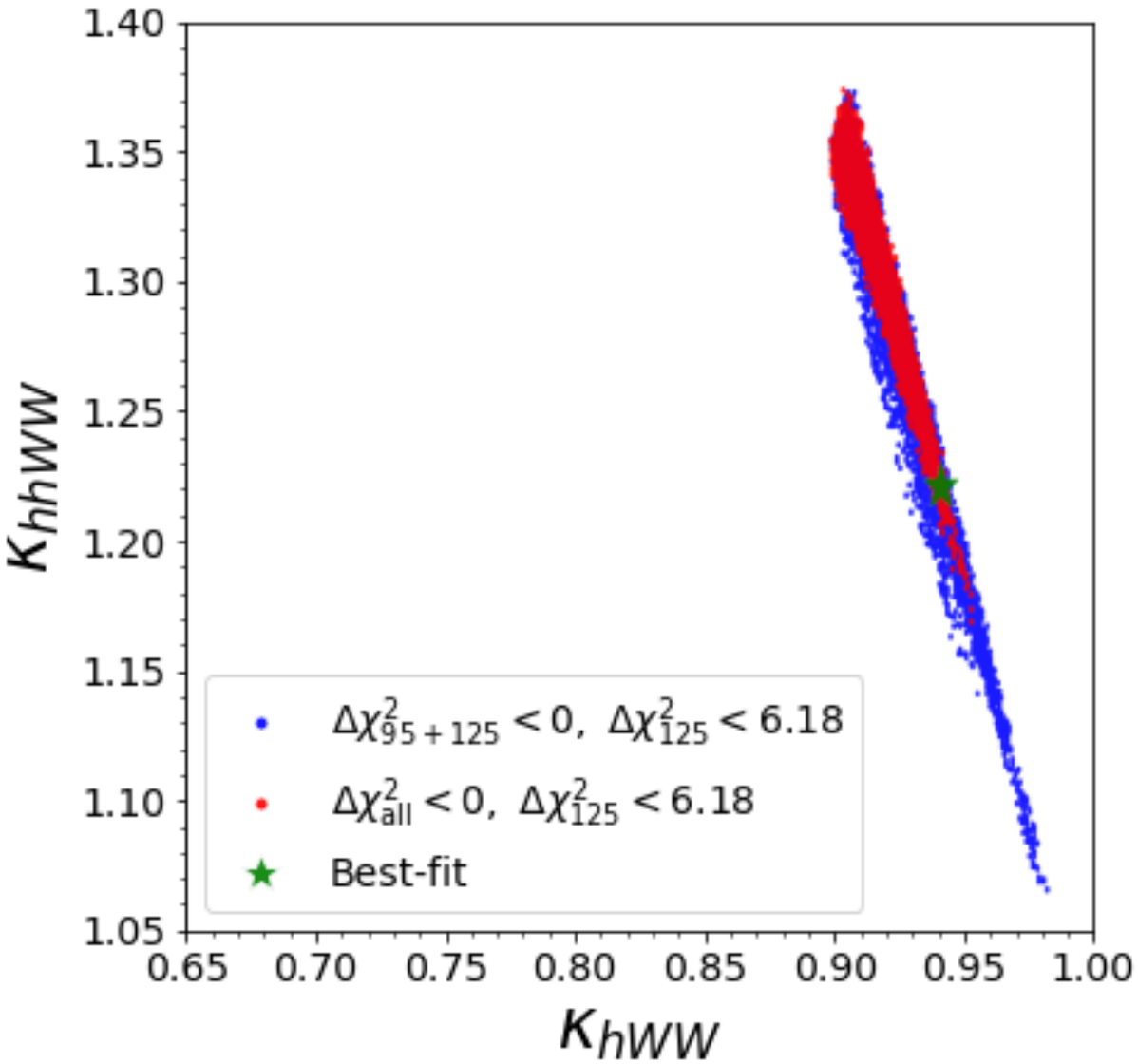
[C. Englert, W. Naskar, D. Sutherland '23]

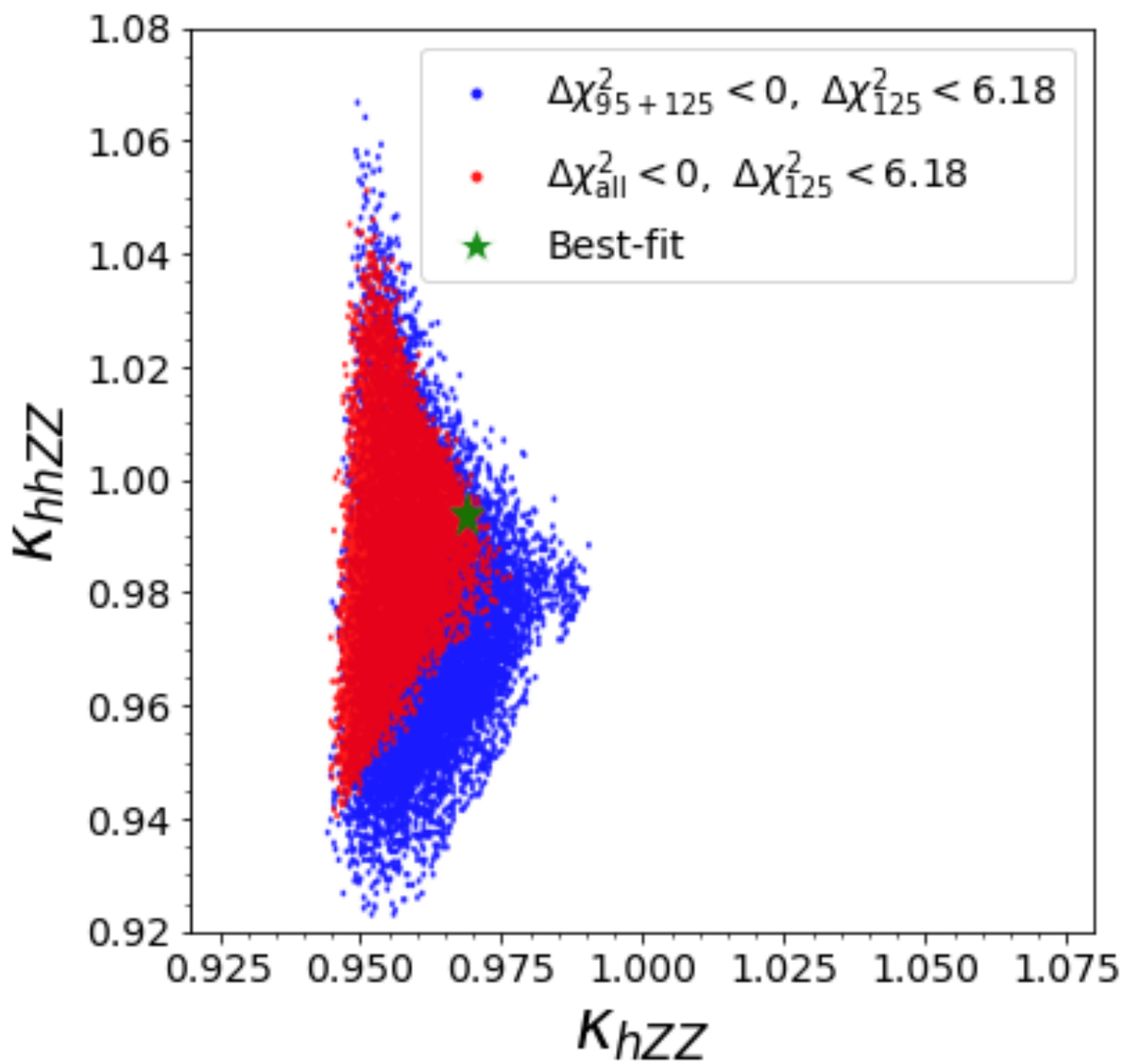


⇒ κ_{2V} can be independent of κ_V; example: Georgi-Machacek model

Extended Georgi-Machacek model

[T.-K. Chen, C.-W. Chiang, S. Heinemeyer, G. W. '26]

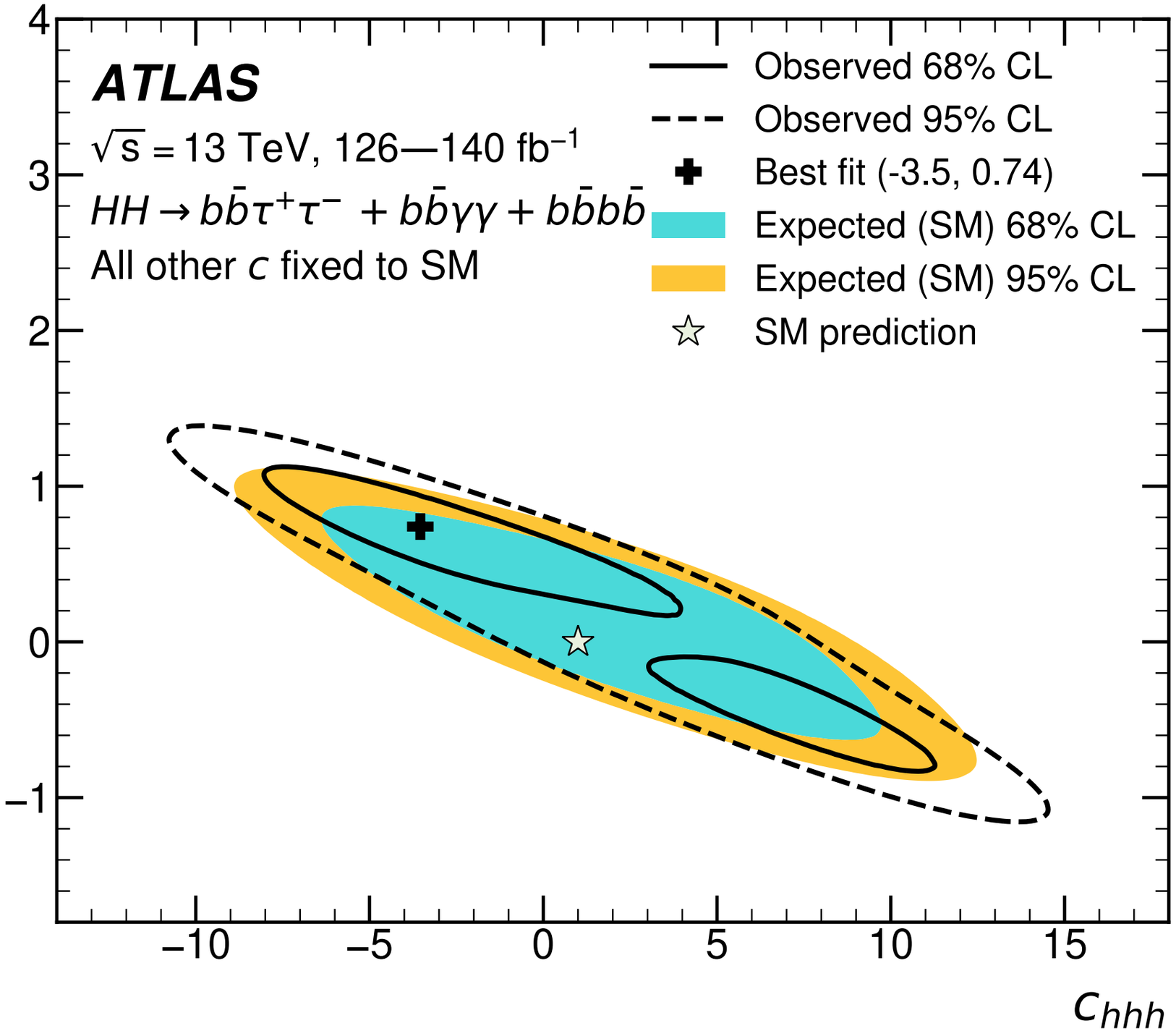




$\Rightarrow \kappa_{2V}$ does not have to be the same for W and Z, i.e. can have $\kappa_{2W} \neq \kappa_{2Z}$

LHC: combined determination of κ_λ and κ_{tt}

κ_{tt}



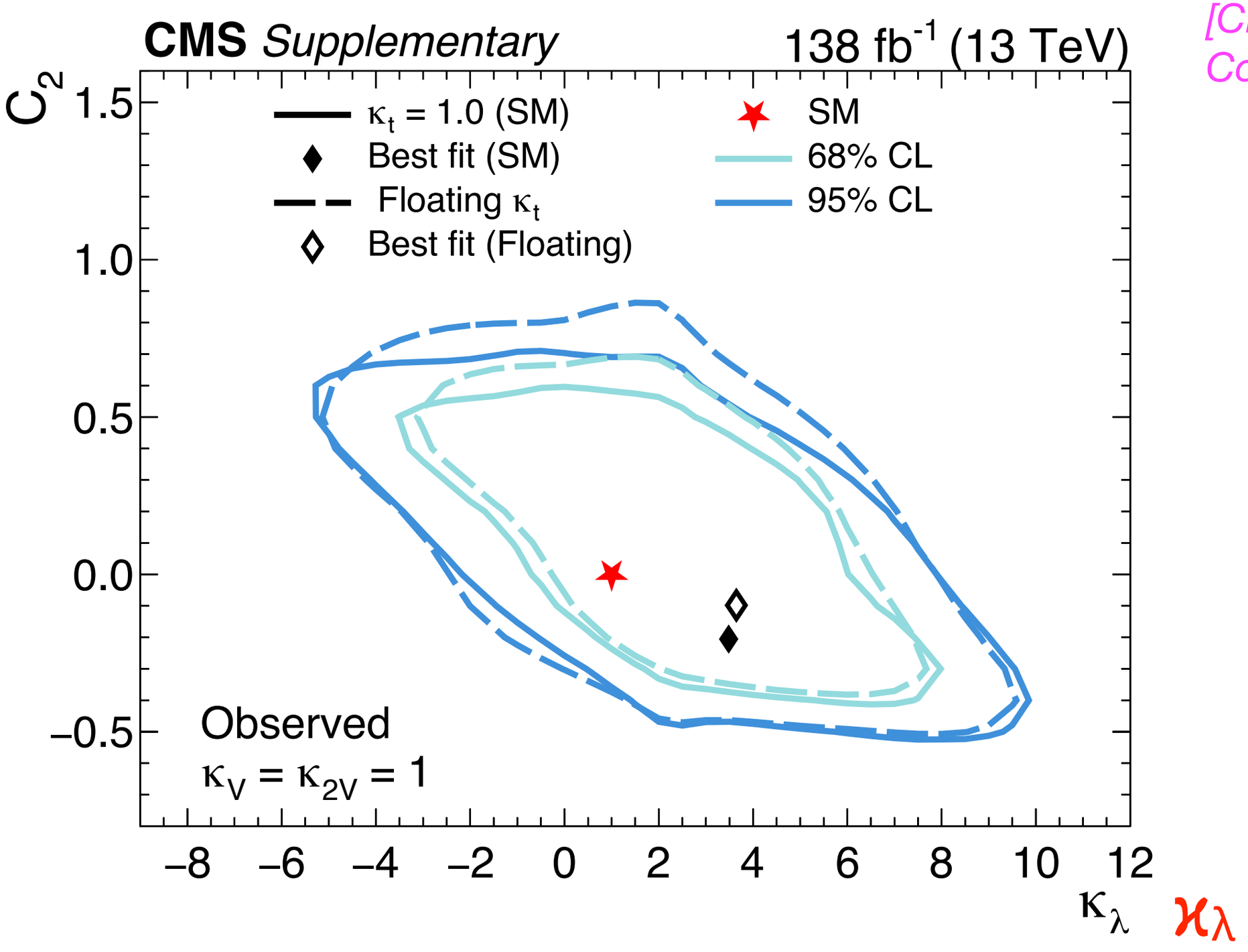
κ_λ

[ATLAS Collaboration '24]

⇒ Large degradation of the sensitivity to κ_λ!

LHC: combined determination of $\varkappa_\lambda$ and $\varkappa_{tt}$

$\varkappa_{tt}$



[CMS Collaboration '25]

$\varkappa_\lambda$

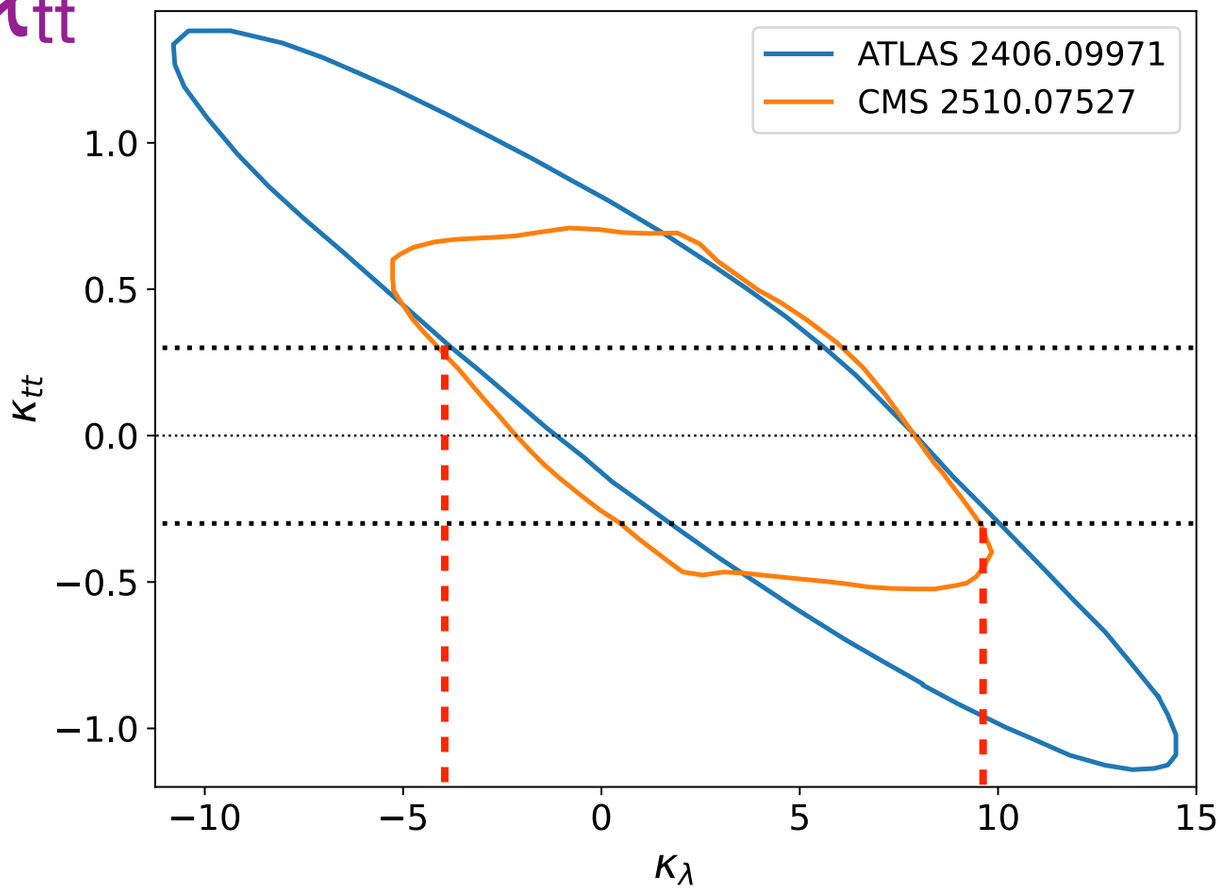
$\Rightarrow$ Large degradation of the sensitivity to $\varkappa_\lambda$!

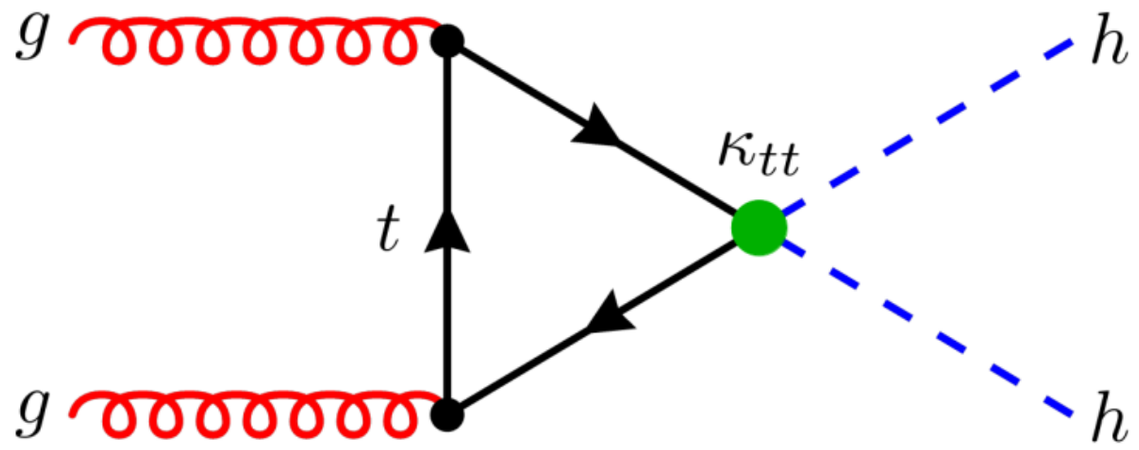
LHC: combined determination of κ_λ and κ_{tt}

[J. Braathen, W. Naskar, D. Nath, G. W. '26]

2HDM case: effective values of κ_{tt} up to $\kappa_{tt} = \approx \pm 0.3$ possible

κ_{tt}

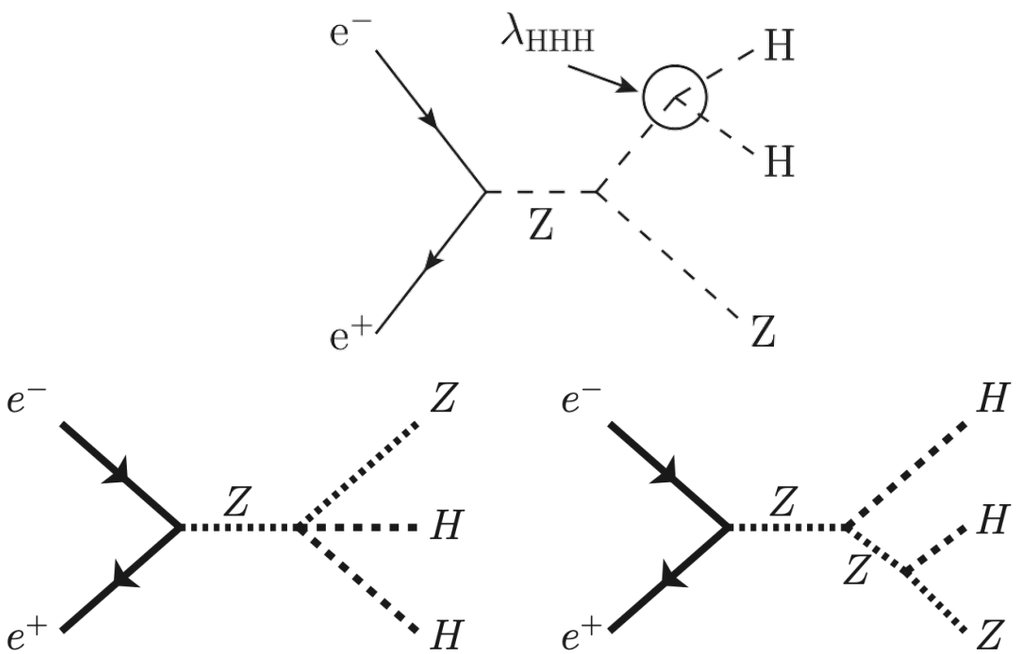


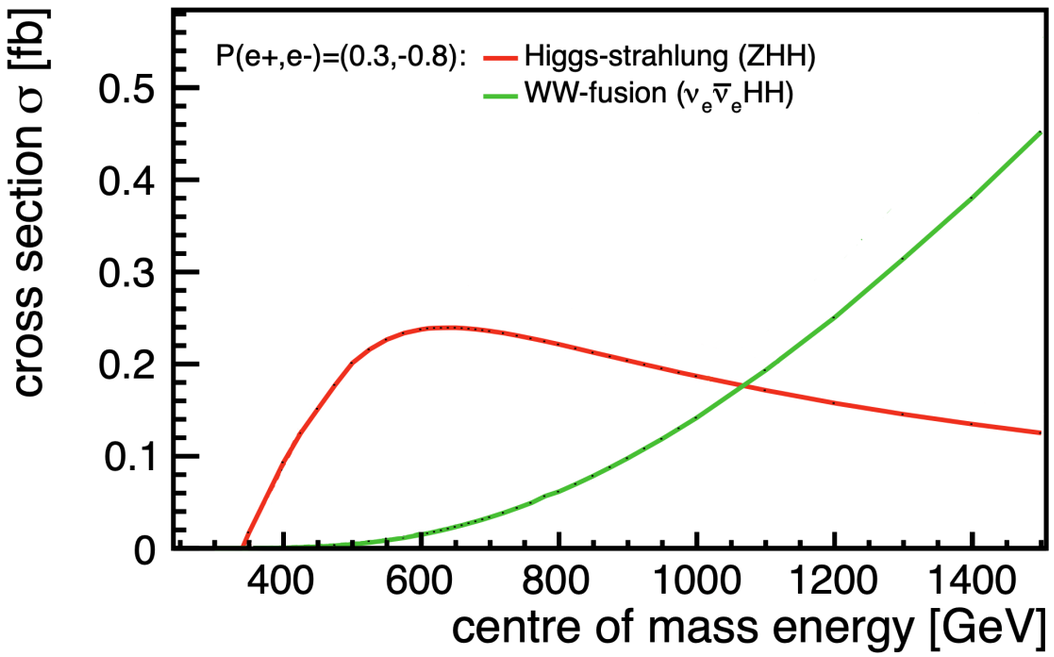


κ_λ

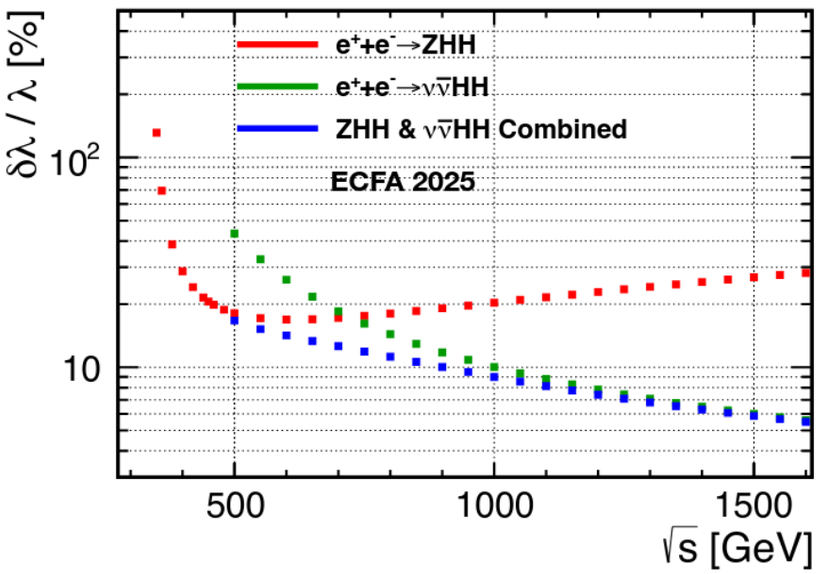
⇒ Possible BSM contributions to κ_{tt} have large impact on κ_λ determination!

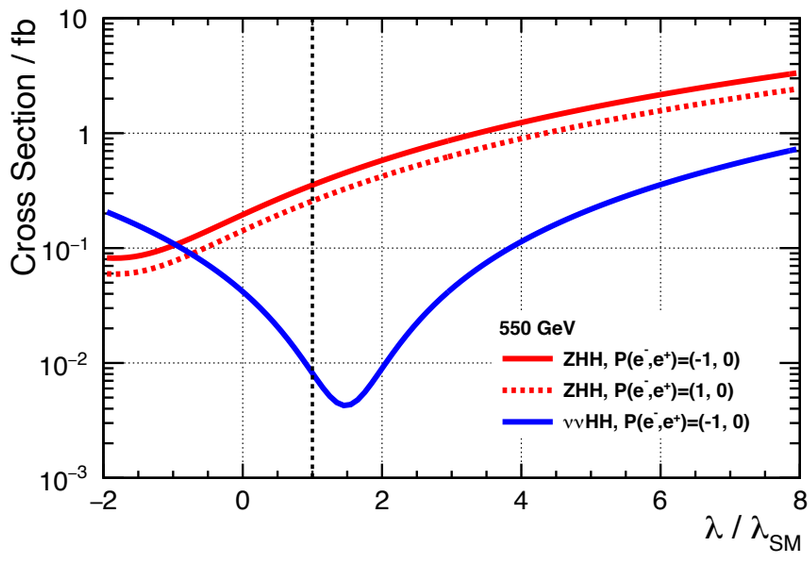
Higgs pair prod. at e^+e^- linear colliders ($E_{CM} \gtrsim 500$ GeV)

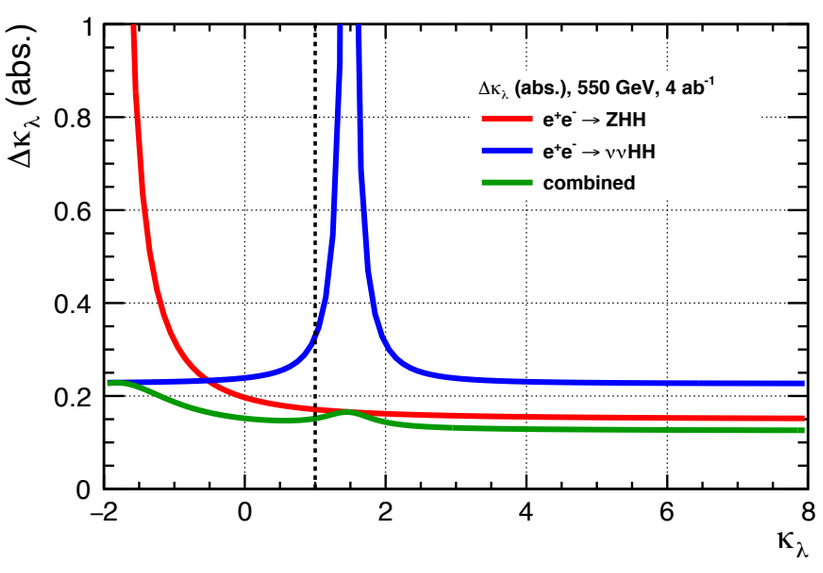




[LC Vision document '25]







$\kappa_{2V} = 1$ assumed!

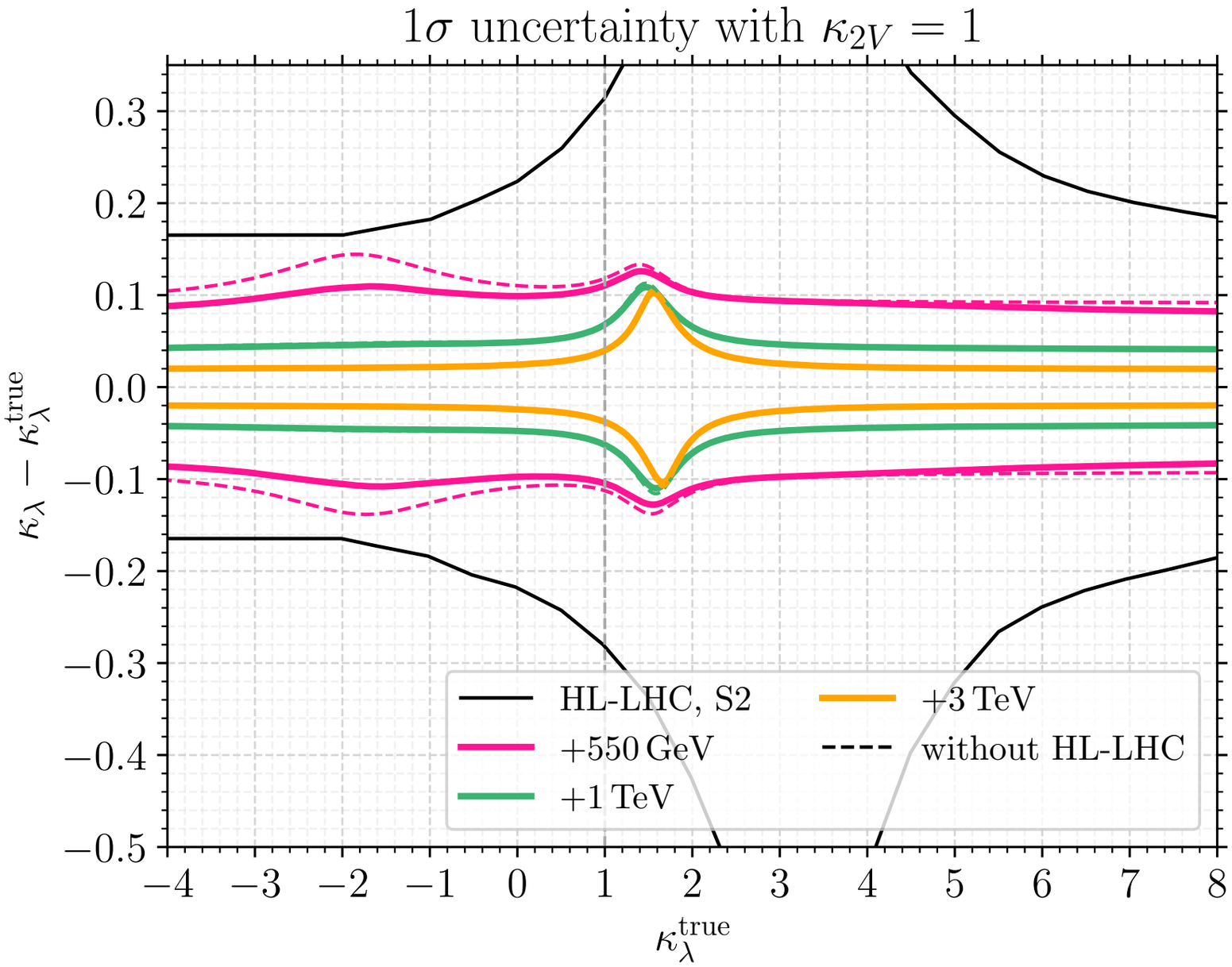
$\Rightarrow$ 11% accuracy on κ_λ for SM case, constructive interference for $\lambda > \lambda_{SM}$

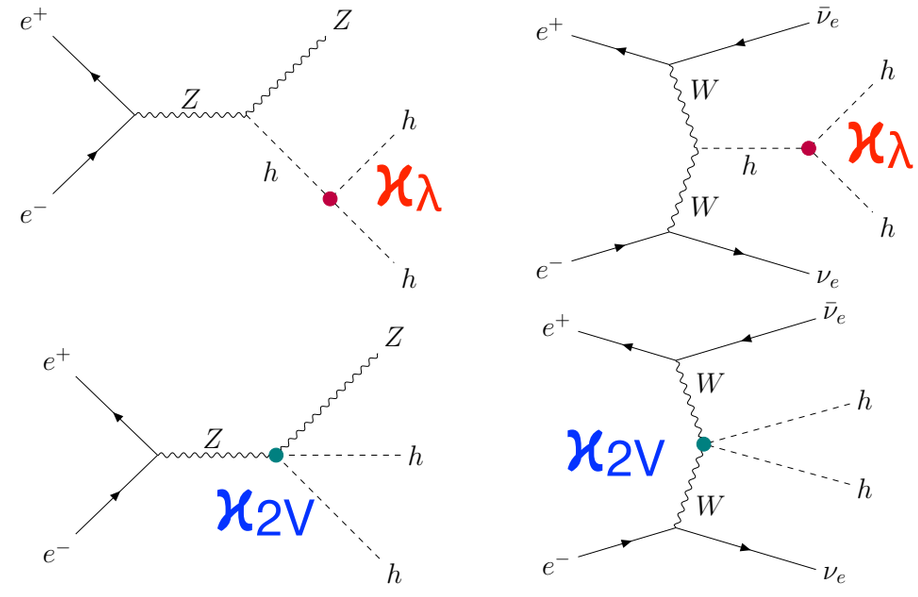
e^+e^- Linear Collider (LC) with 550 GeV (or higher)

[F. Arco, G. W. '26]

Here and for results above:

$\varkappa_{2V} = 1$ assumed



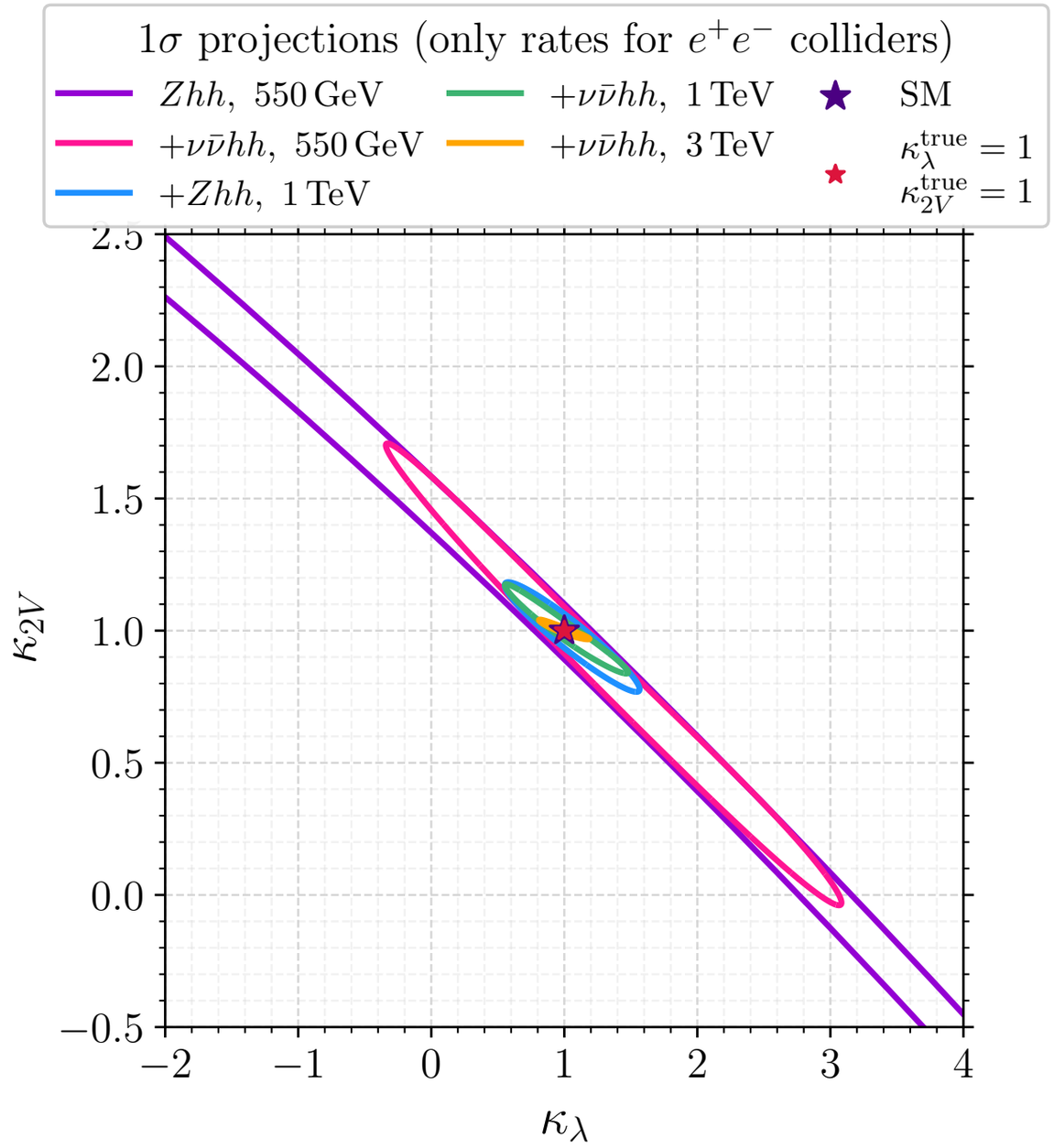


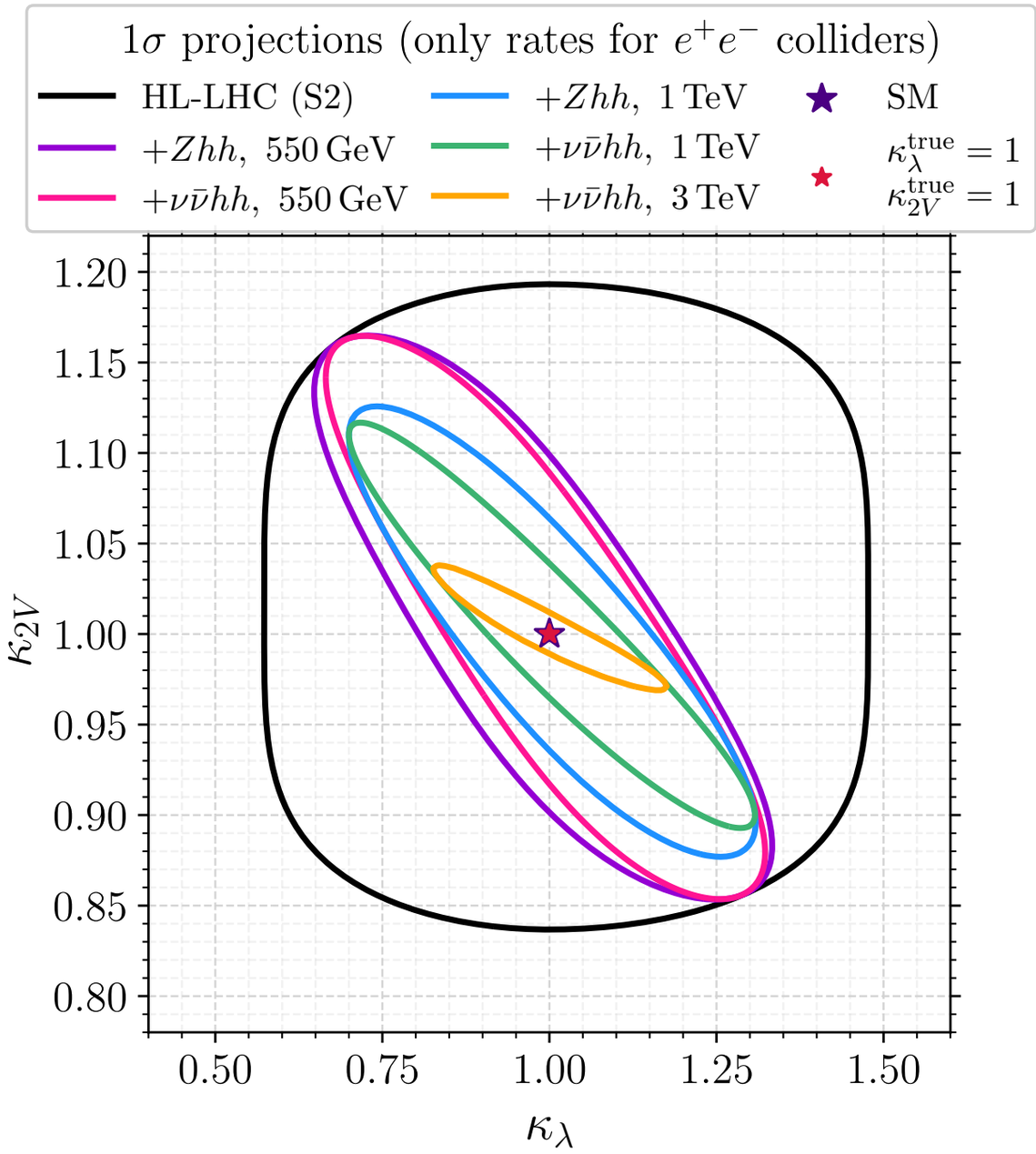
⇒ Good prospects for e^+e^- LC for $\varkappa_{2V} = 1$, large improvement over HL-LHC, input from HL-LHC plays minor role for LC results

e⁺e⁻ LC: impact of varying κ_{2V}

[F. Arco, G. W. '26]

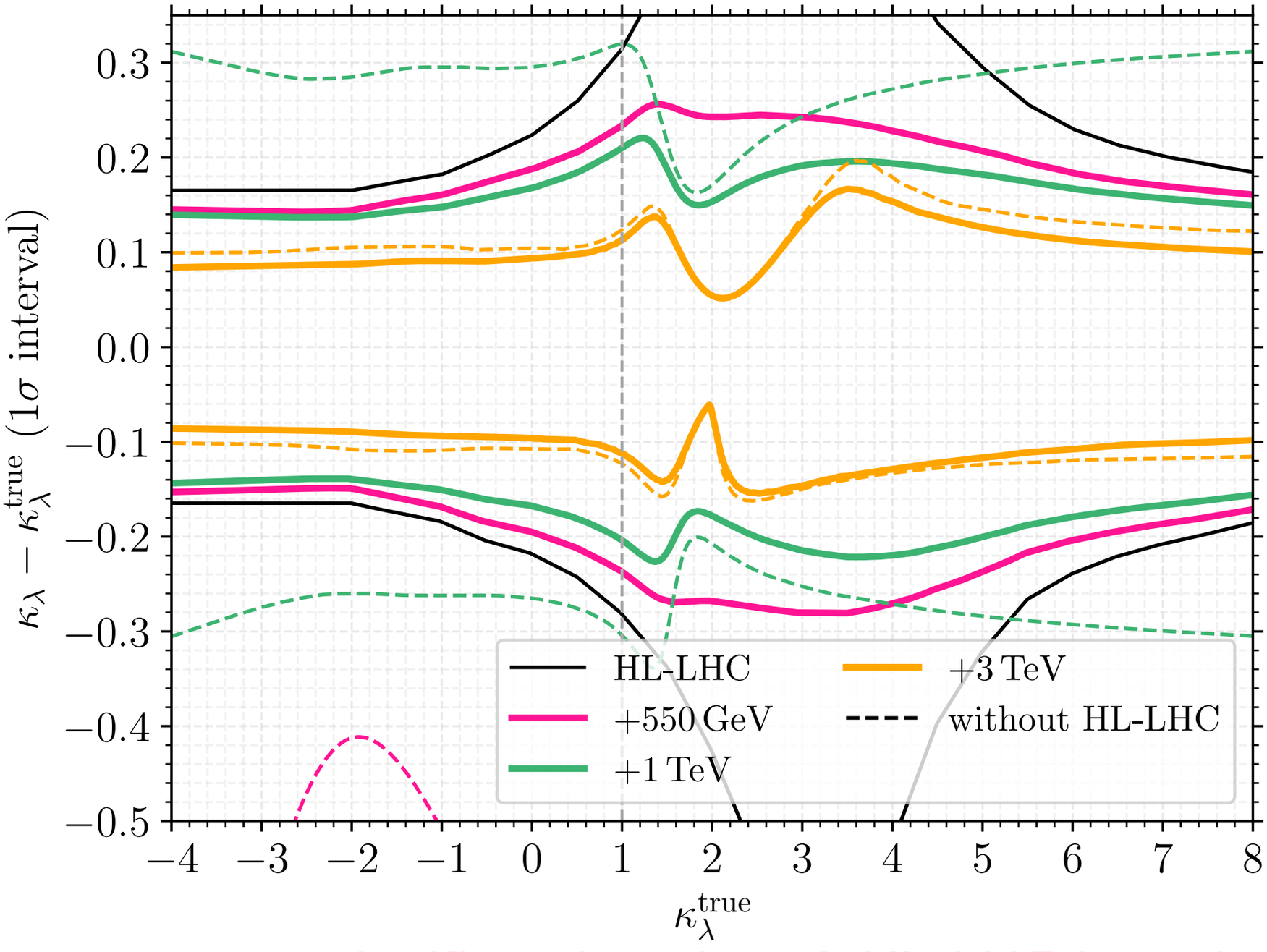
Without (left) and with (right) HL-LHC input:





⇒ Accuracy on κ_λ significantly reduced, HL-LHC input is crucial for LC550 results (here: ``pessimistic" HL-LHC projection, see below)

e^+e^- LC: impact of varying $\varkappa_{2V}$



[F. Arco, G. W. '26]

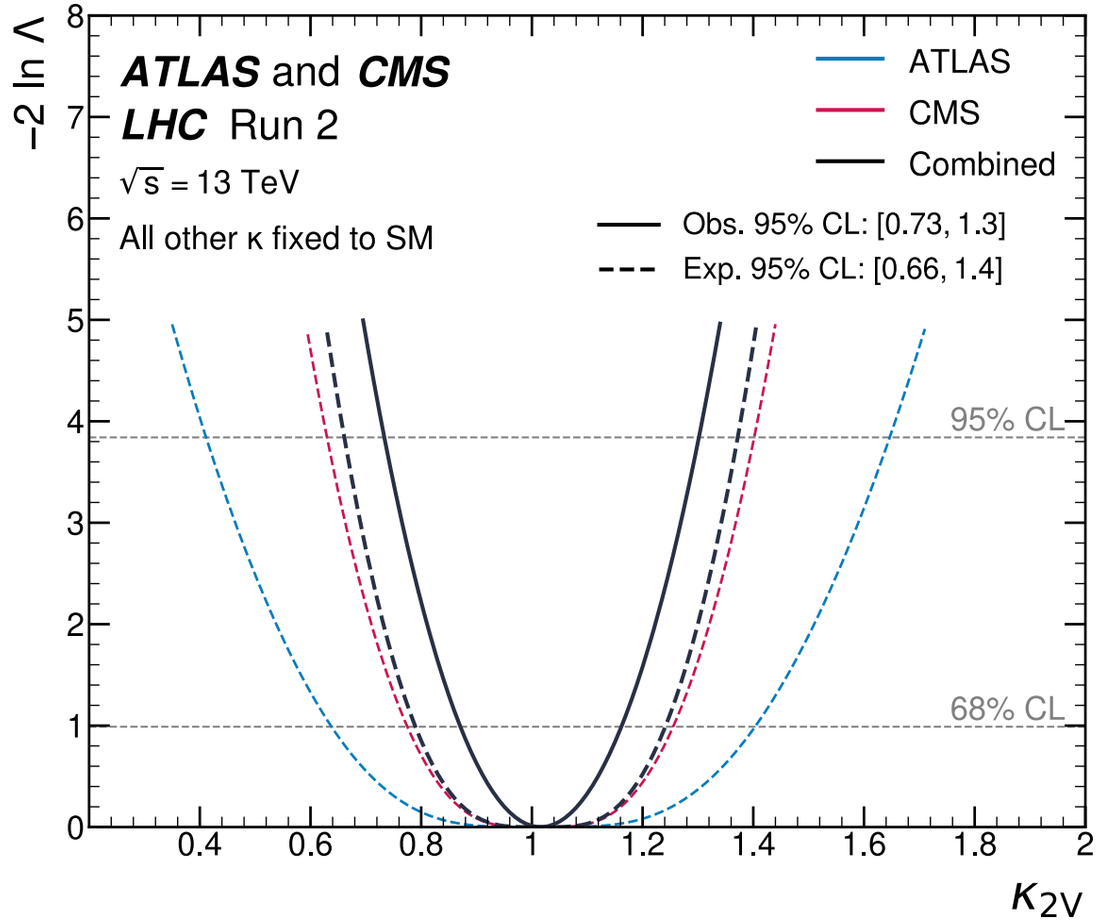
Similar results found by *[T. Barklow, K. Fujii, J. Tian '16]*

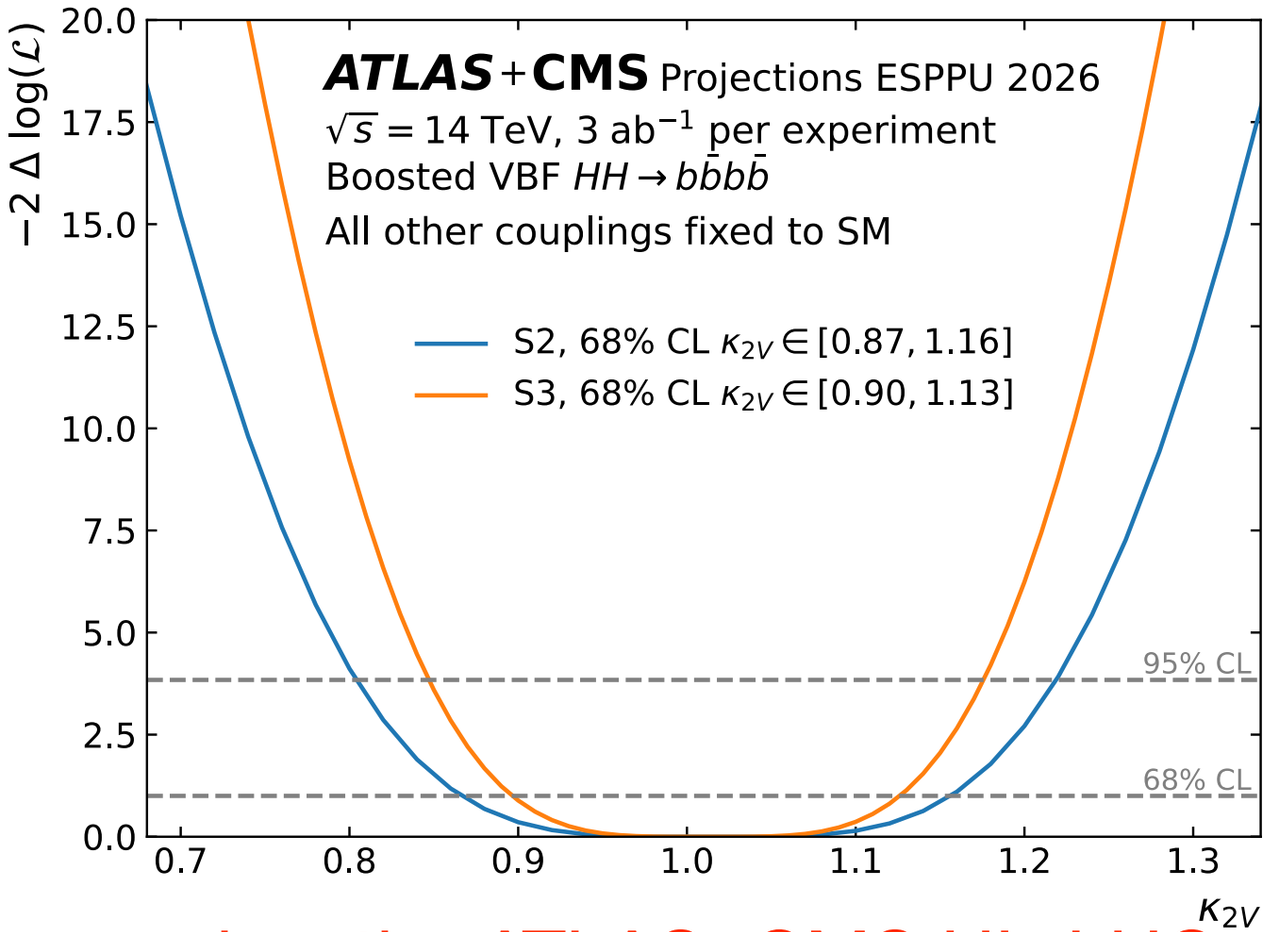
⇒ Accuracy on $\varkappa_\lambda$ significantly reduced, HL-LHC input is crucial for LC results, higher LC energy stages yield only rel. small improvement compared to LC550 + HL-LHC (reduce dependence on HL-LHC input)

κ_{2V}: LHC Run 2 combination and HL-LHC projection

[ATLAS and CMS Collaborations '26, '25]

Run 2 combination (left), observed limit at 68% C.L.: $0.87 < \kappa_{2V} < 1.16$



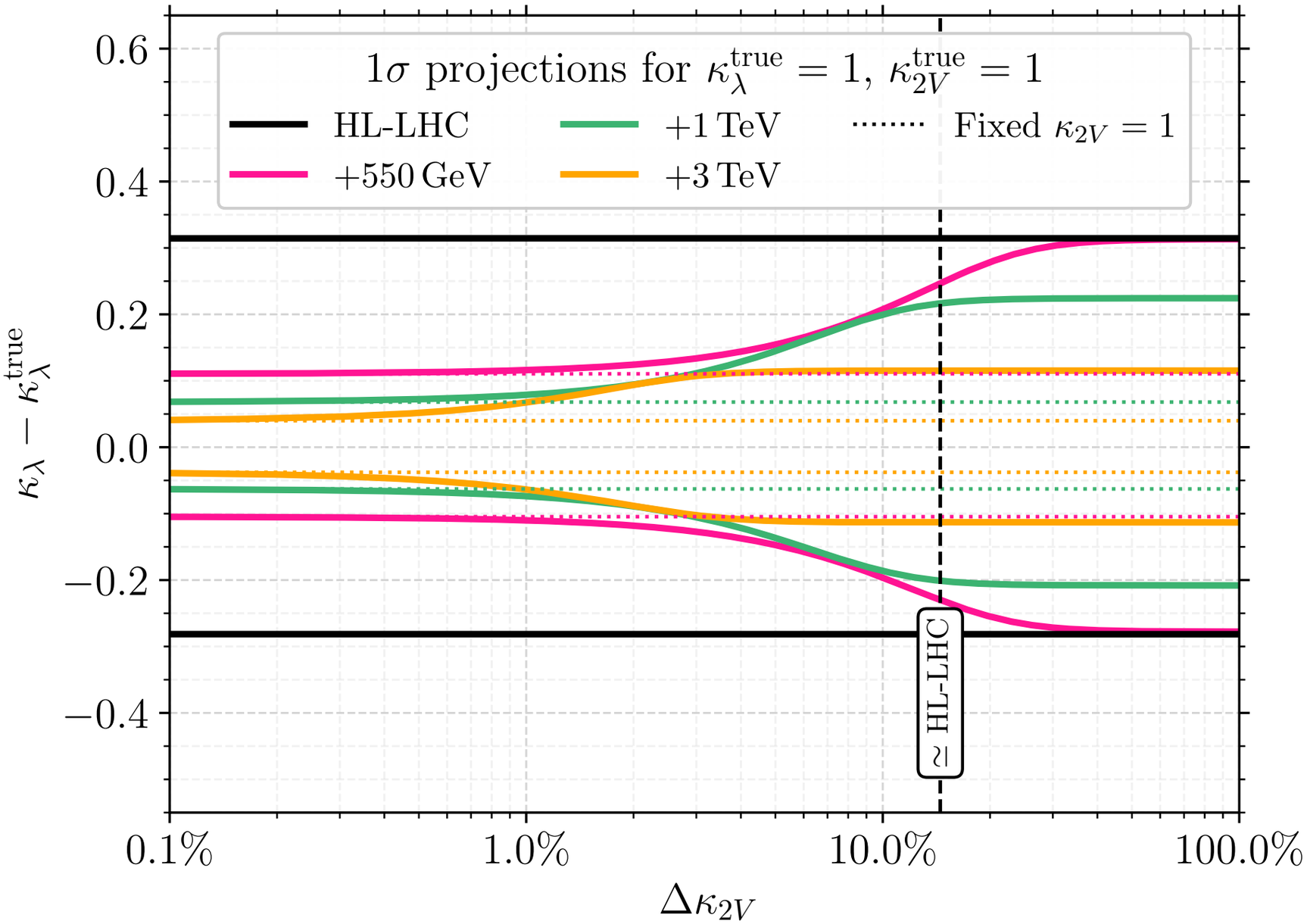


Observed Run 2 result is already as good as the ATLAS+CMS HL-LHC projection for S2 scenario of improved theoretical uncertainties!

Further significant improvements expected from 20 x Run 2 luminosity, analysis improvements (have already occurred in Run 3) and improved theoretical uncertainties!

e⁺e⁻ LC: accuracy for κ_λ depending on HL-LHC input for κ_{2V}

[F. Arco, G. W. '26]



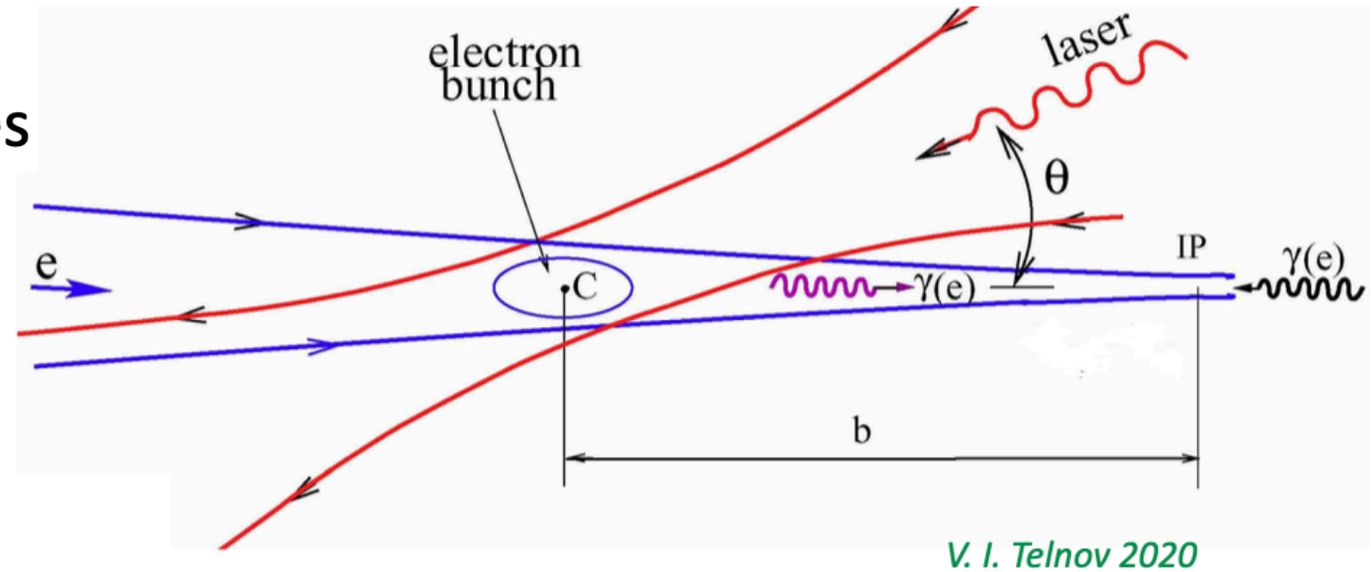
⇒ Improvement in accuracy on κ_{2V} (e.g. factor 2-3) w.r.t. (pessimistic) HL-LHC projection (based on only one channel, does not include latest analysis improvements) will significantly improve LC determination of κ_λ

Another possibility: $\gamma\gamma$ collider (combined with e^+e^- or stand-alone) *[M. Berger, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26]*

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

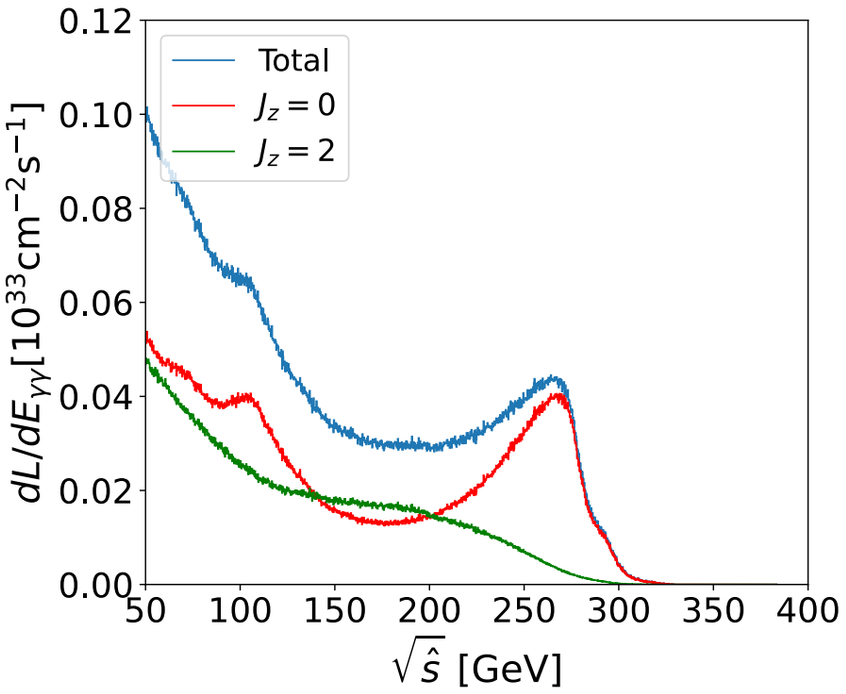
- the optical-laser setup, with $x \leq 4.8$
- the XFEL-based setup, or XCC (XFEL Compton Collider), with $x \geq 1000$.

$$x = \frac{4E_0\omega_0}{m_e^2c^4}\cos^2\frac{\theta}{2} \simeq 15.3\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\omega_0}{\text{eV}}\right] \simeq 19\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\mu}{}\right.$$

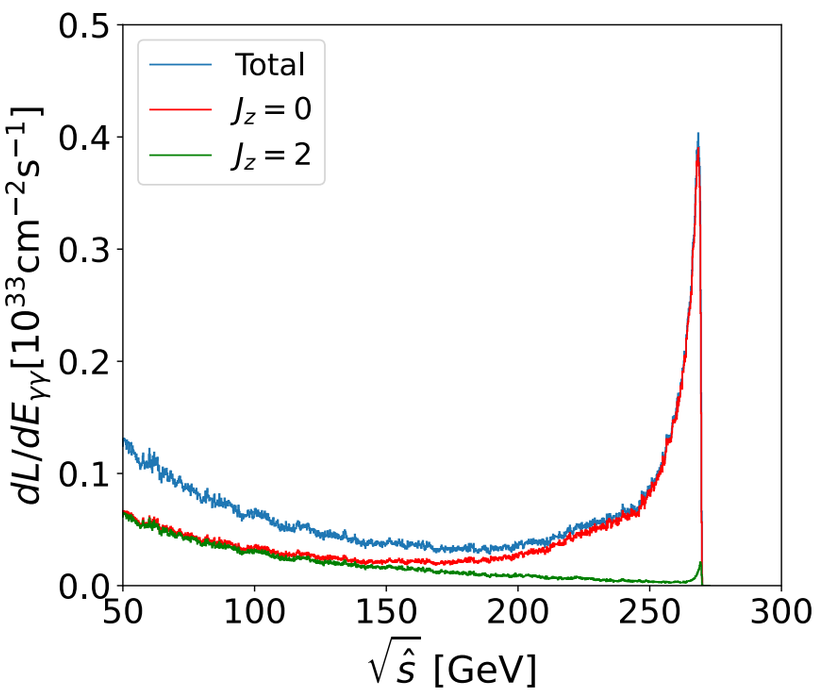


Optical or XFEL-like laser:

Optical, ee energy of 380 GeV:

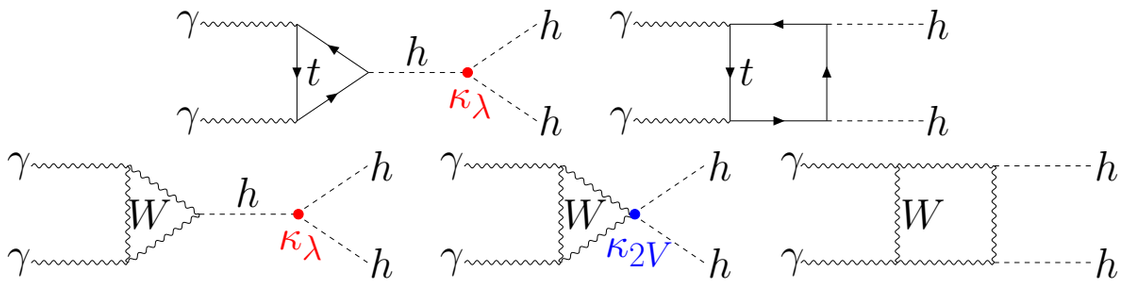


XFEL-like, ee energy of 270 GeV:



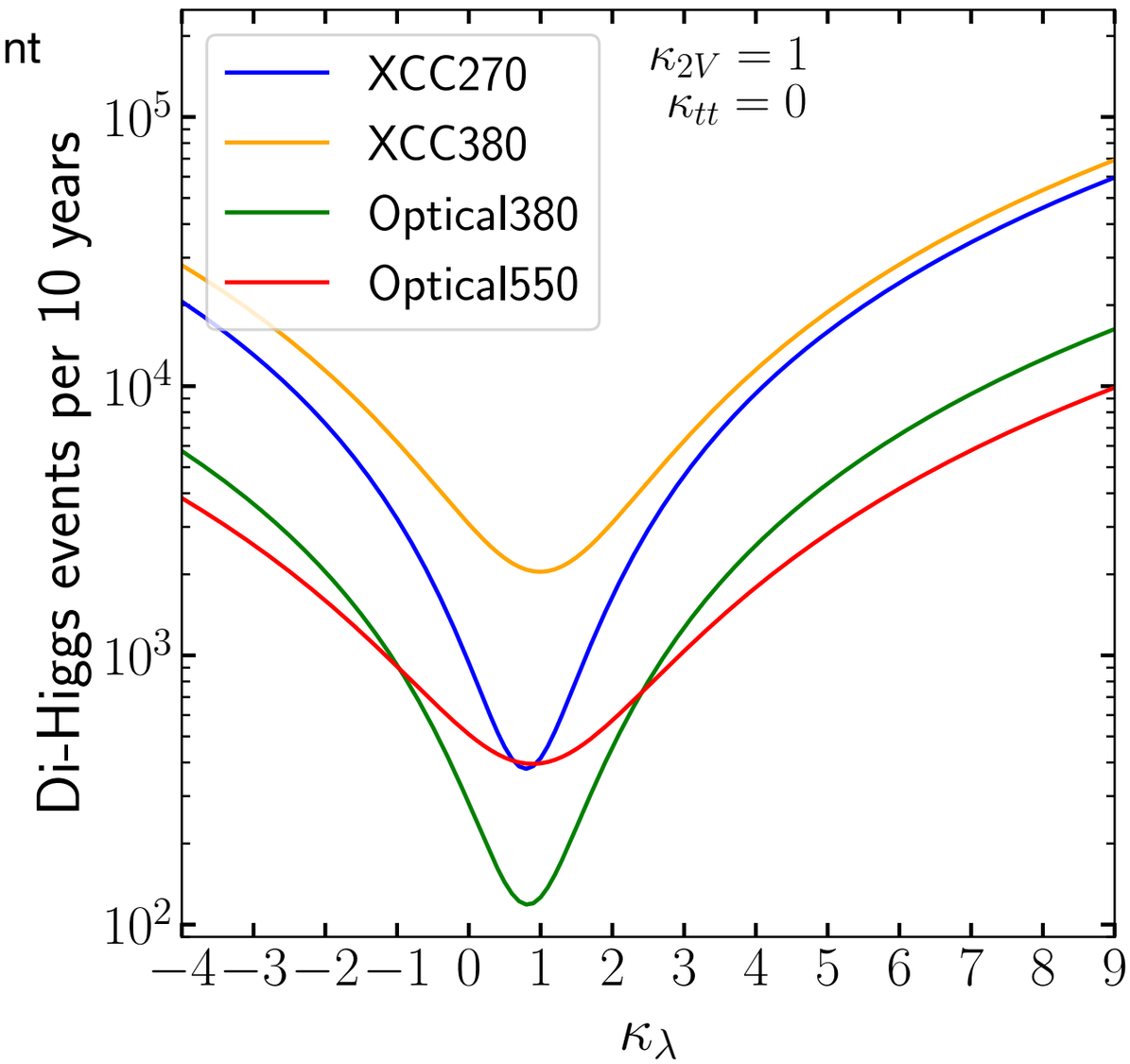
$\gamma\gamma \to$ hh at 380 GeV and 270 GeV: optical laser and XFEL (XCC)

[M. Berger, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26]



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

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



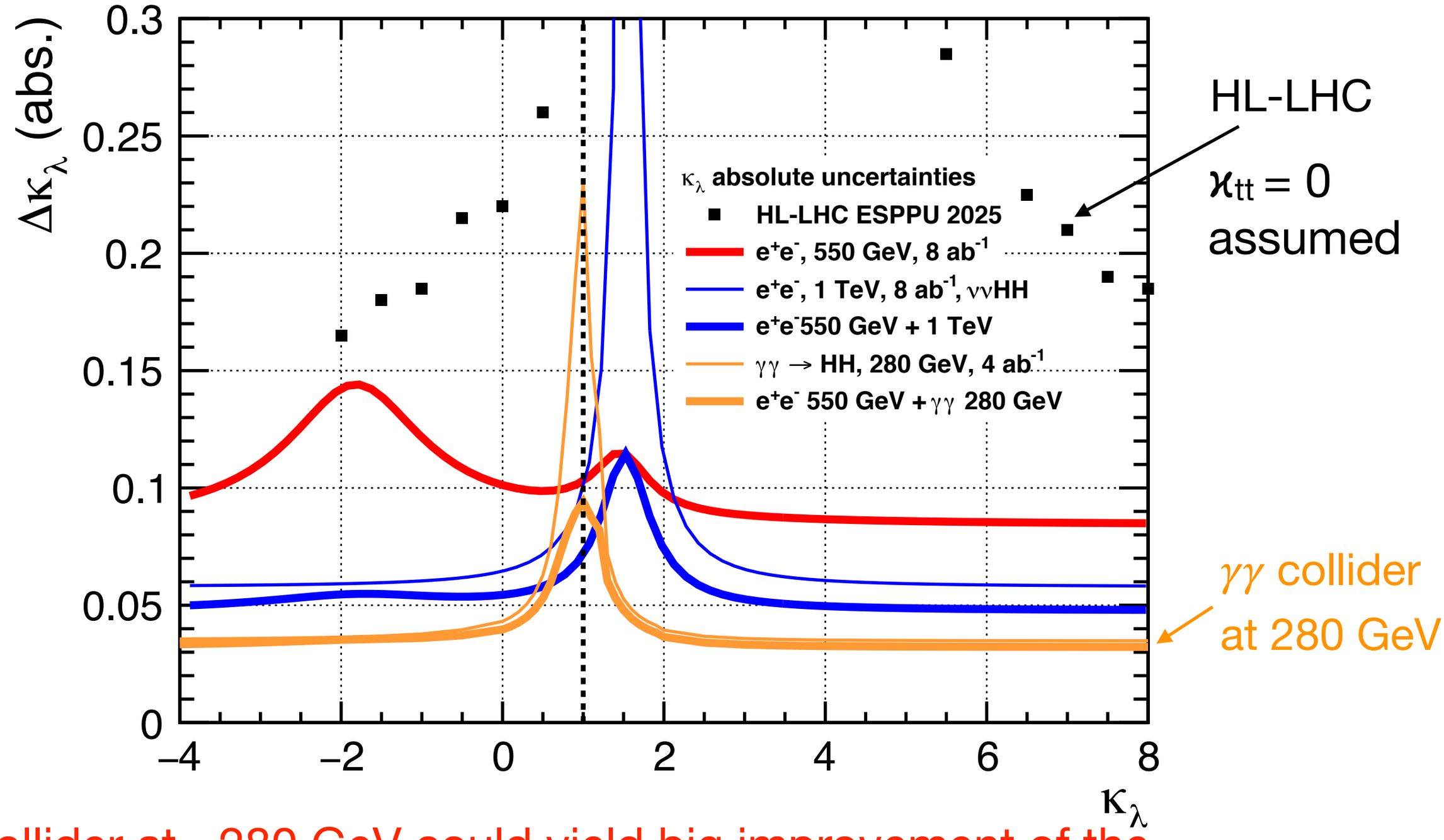
HEFT analysis

$\Rightarrow \gamma\gamma$ collider at 270 GeV has high sensitivity to κ_λ

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

$\kappa_{2V} = 1$ assumed

[LC Vision document '26]



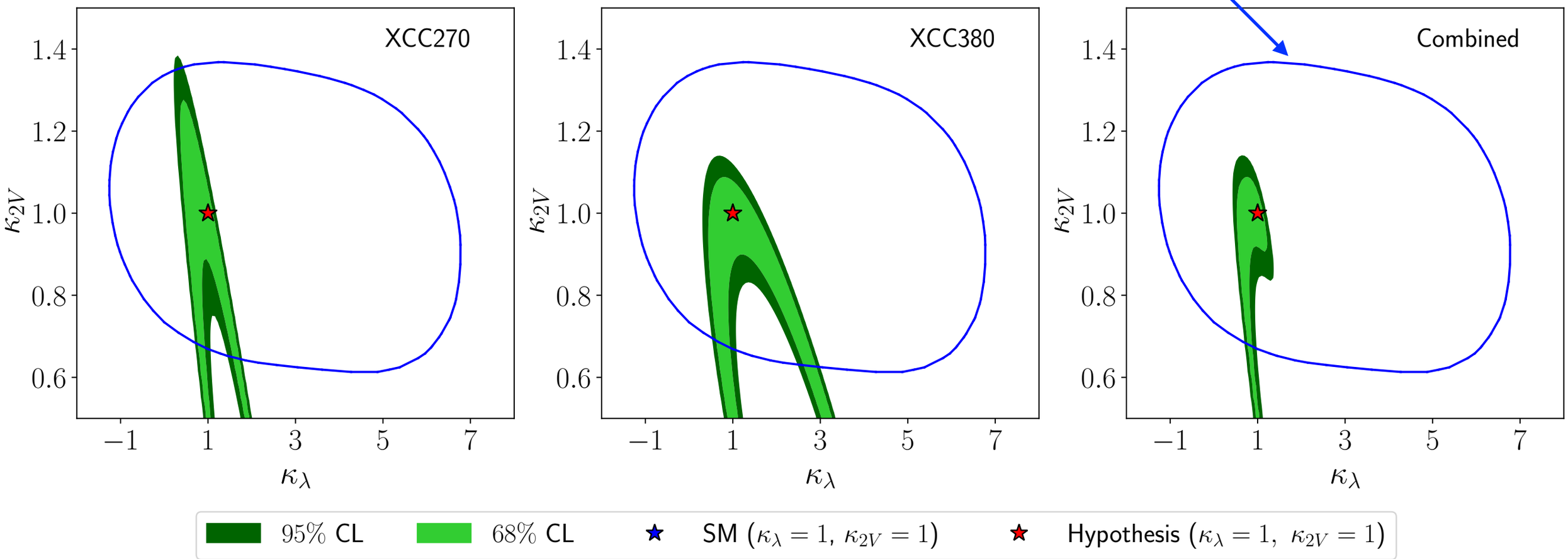
$\Rightarrow \gamma\gamma$ collider at ≈280 GeV could yield big improvement of the measurement of the trilinear Higgs coupling

$\gamma\gamma \rightarrow$ hh at two energies, HEFT analysis: simultaneous determination of κ_λ and κ_{2V}

[M. Berger, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26]

Assumed true values: $\kappa_\lambda^{\text{true}} = 1$, $\kappa_{2V}^{\text{true}} = 1$

95% C.L. limits from ATLAS + CMS



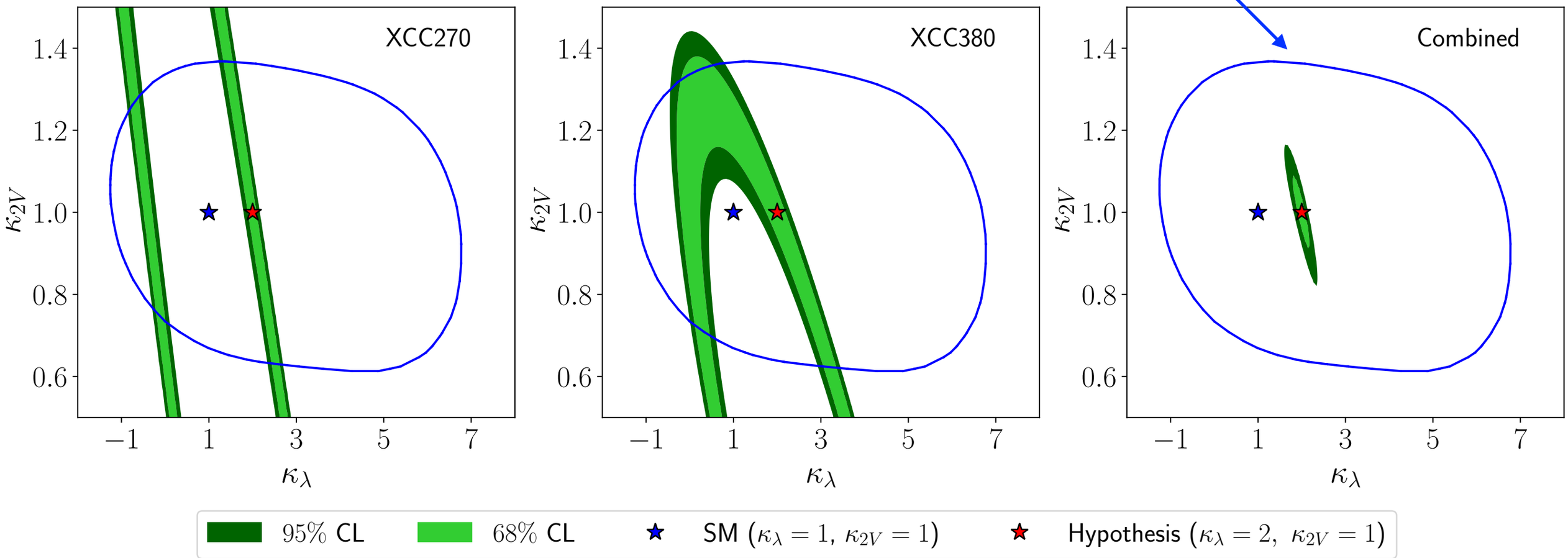
$\Rightarrow$ High sensitivity for simultaneous determination of κ_λ and κ_{2V}

$\gamma\gamma \to$ hh at two energies, HEFT analysis: simultaneous determination of κ_λ and κ_{2V}

[M. Berger, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26]

Assumed true values: $\kappa_\lambda^{\text{true}} = 2$, $\kappa_{2V}^{\text{true}} = 1$

95% C.L. limits from ATLAS + CMS



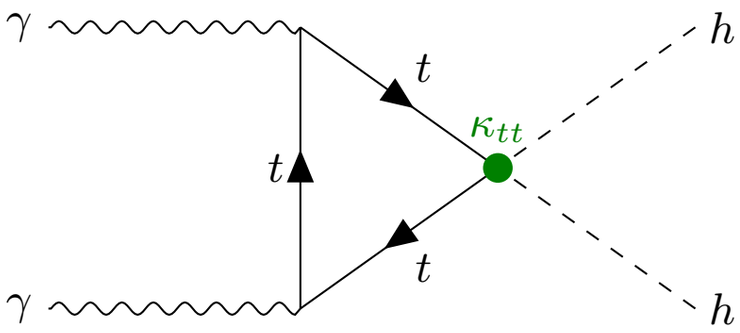
⇒ High sensitivity for simultaneous determination of κ_λ and κ_{2V}

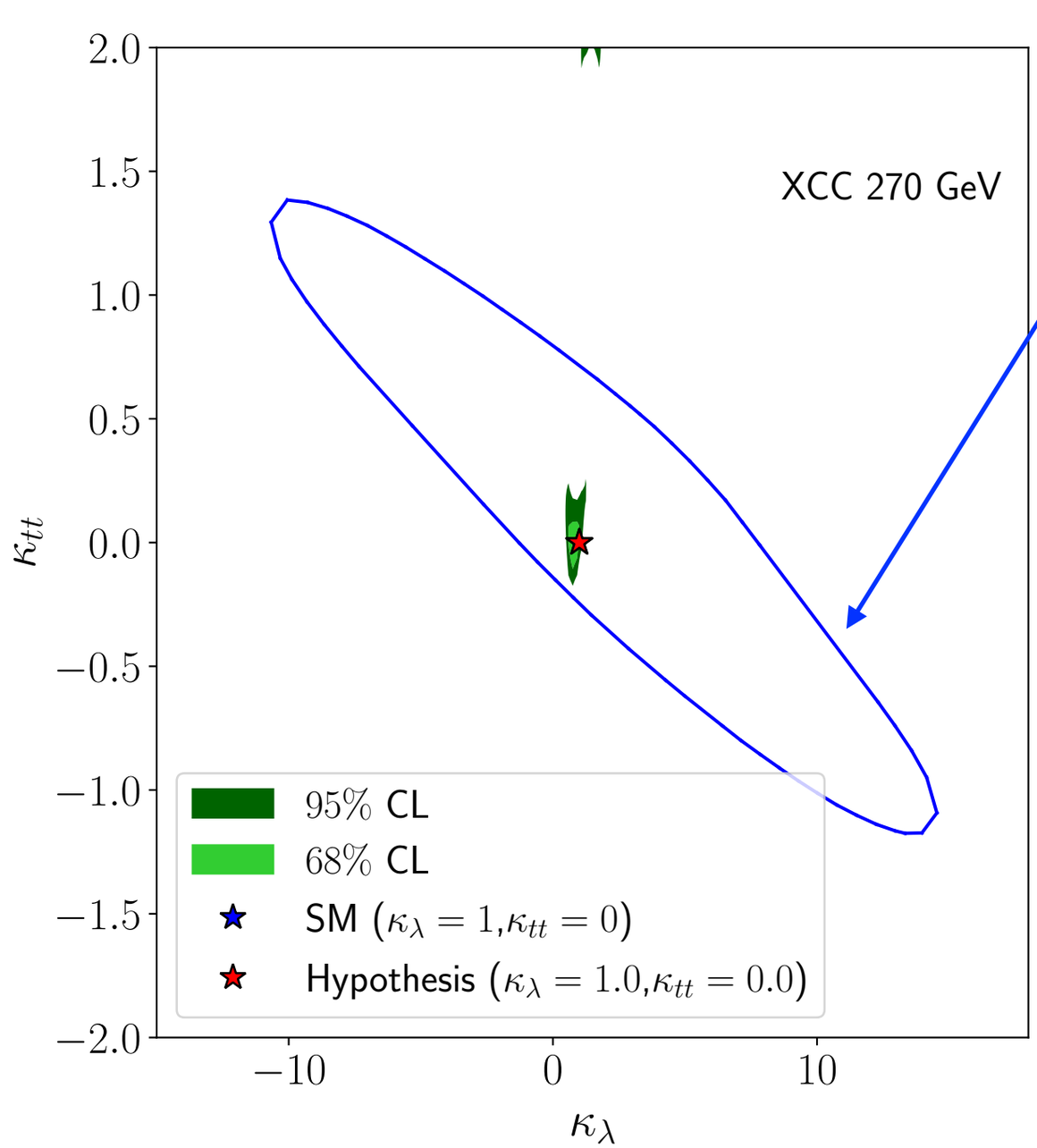
$\gamma\gamma \rightarrow$ hh at 270 GeV: HEFT analysis

[M. Berger, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26]

Constraints in (κ_λ, κ_{tt}) plane in comparison to current limit from ATLAS

$\kappa_{2V} = 1$ assumed





⇒ Large improvement compared to present situation, good prospects for simultaneous determination of κ_λ, κ_{tt}, κ_{2V}

Conclusions

Via the Higgs self-couplings we are starting at the LHC to probe the shape of the Higgs potential realised in nature and its connection to the EW phase transition and the thermal evolution of the early universe

Sensitivity to κ_λ can be limited by dependence on other coupling modifiers: κ_{tt} at the LHC, κ_{2V} at the LC

For e^+e^- LC stand-alone: going beyond the theoretical assumption of $\kappa_{2V} = 1$ leads to drastic reduction of the accuracy for κ_λ

HL-LHC results for κ_{2V} will be crucial for the κ_λ determination at e^+e^- LC!

$\gamma\gamma$ collider at 270 GeV and 380 GeV: good prospects for simultaneous determination of κ_λ, κ_{tt}, κ_{2V}!

Backup

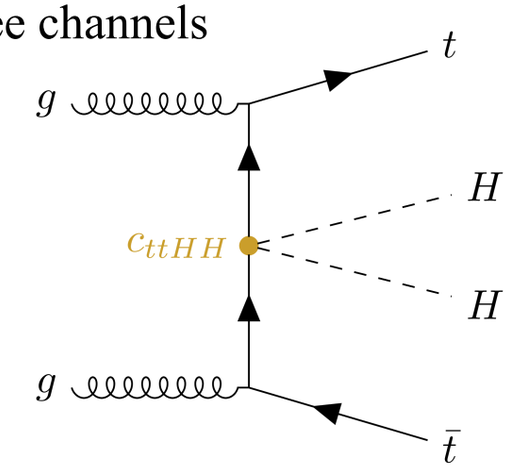
Constraints on κ_{tt} from tthh production

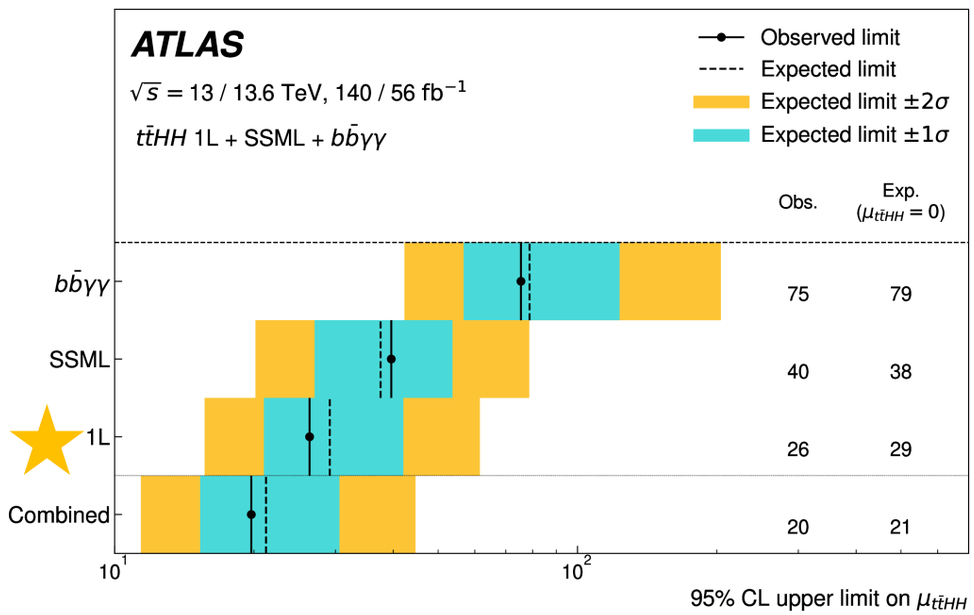
[G. Di Gregorio, MBI Workshop '26]

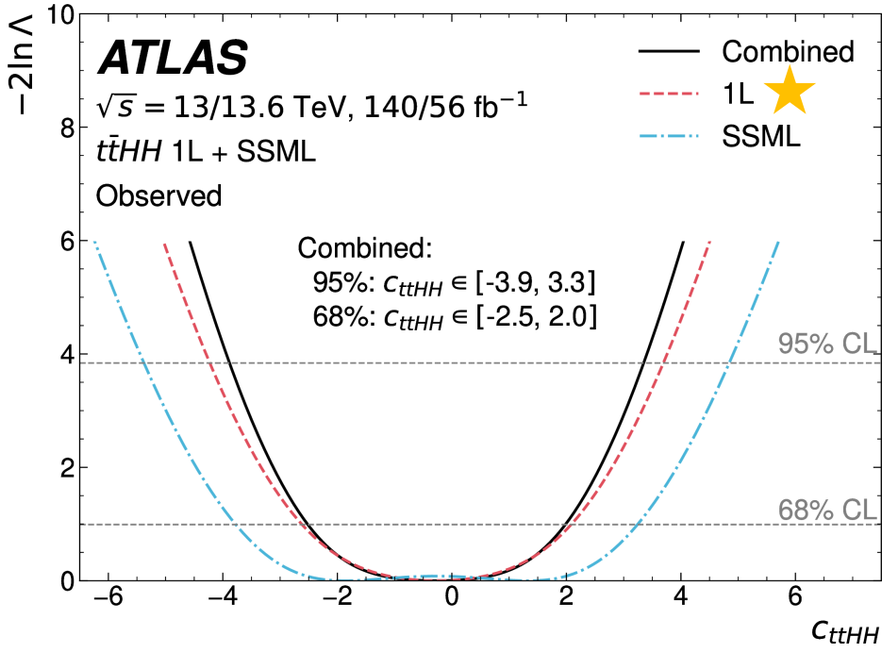
JHEP 08 (2026) 020

Results

- **Maximum likelihood fit** performed in all SRs + CRs in all the three channels
- No significant excess over the bkg-only hypothesis
- **Same contribution** from **statistics** and **systematics uncertainties**
- **Observed (expected) upper limits @ 95% CL on μ_{HH} < 20 (21)**
- Both 1L and SSML re-interpreted with HEFT to constrain $c_{t\bar{t}HH}$
  - **-3.9 < $c_{t\bar{t}HH}$ < 3.3 @ 95% CL**

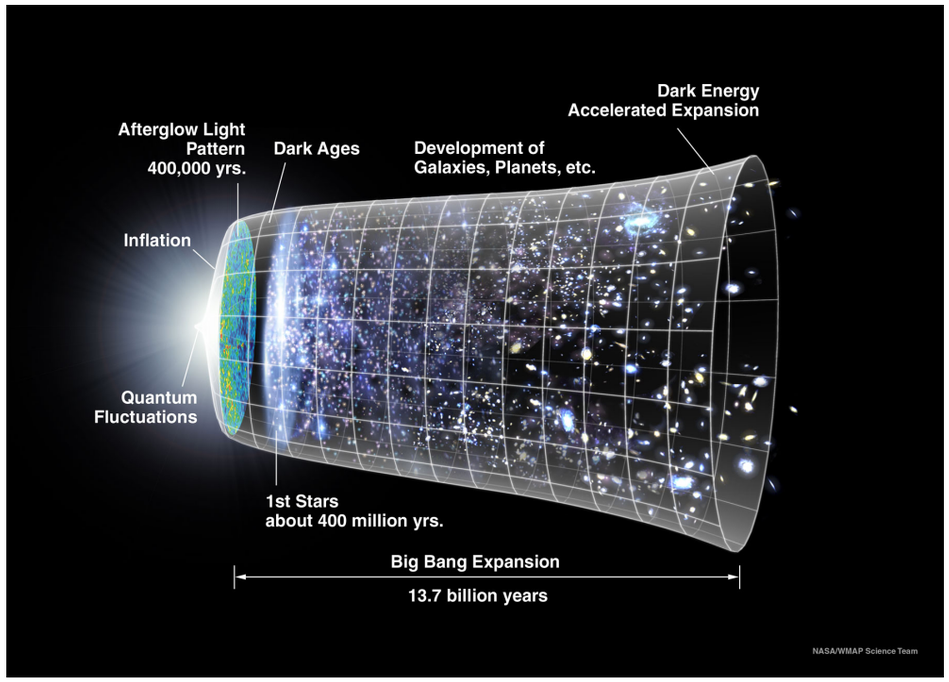


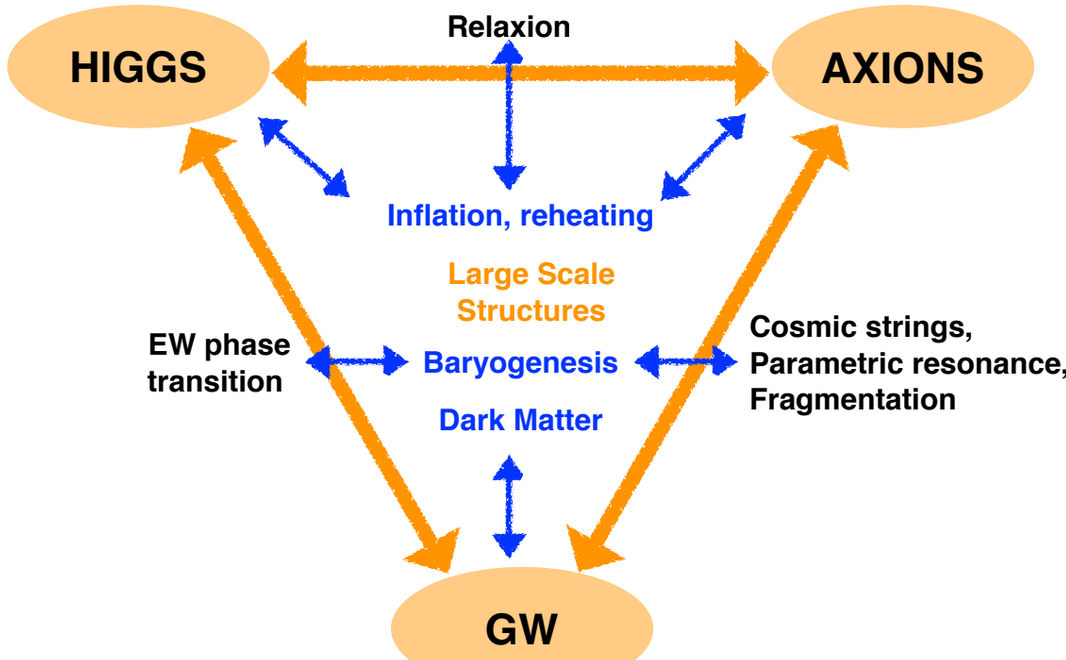


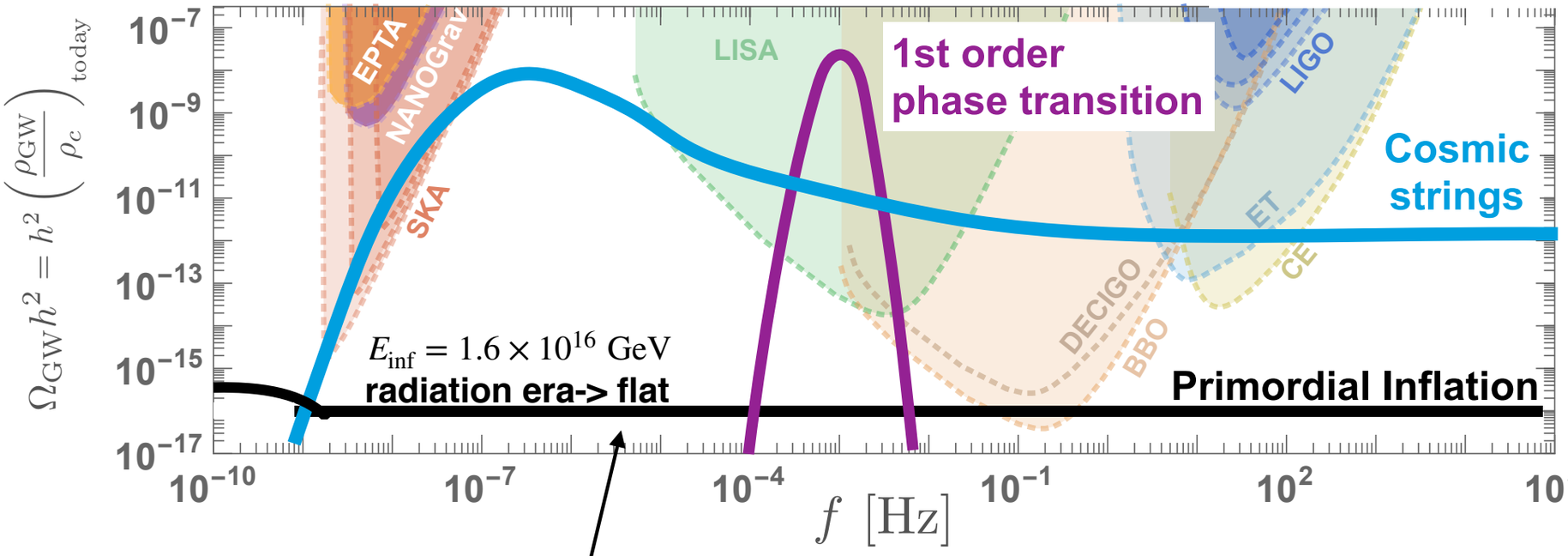


⇒ Accuracy not sufficient to help in combined (κ_λ, κ_{tt}) determination

Gravitational waves as a probe of the early universe

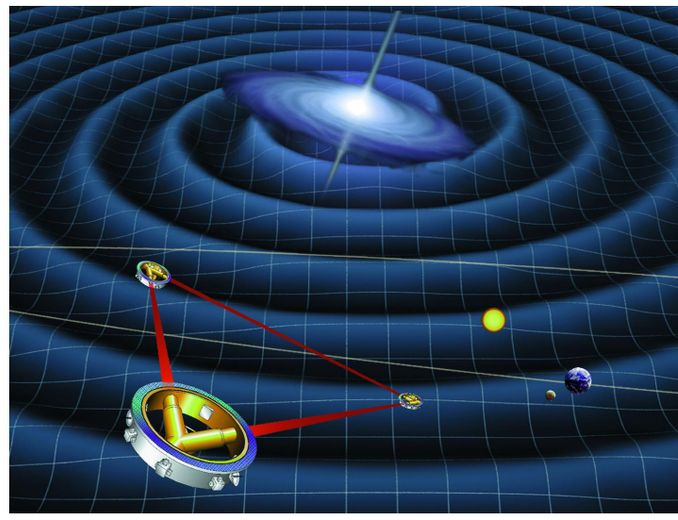






Irreducible GW background from amplification of initial quantum fluctuations of the gravitational field during inflation

LISA:



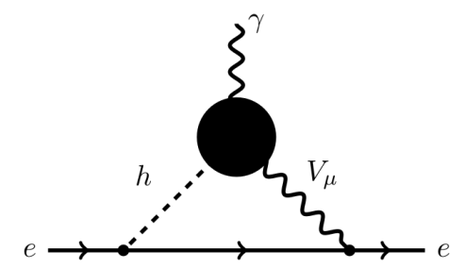
EWPT: are there additional sources for CP violation in the Higgs sector?

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



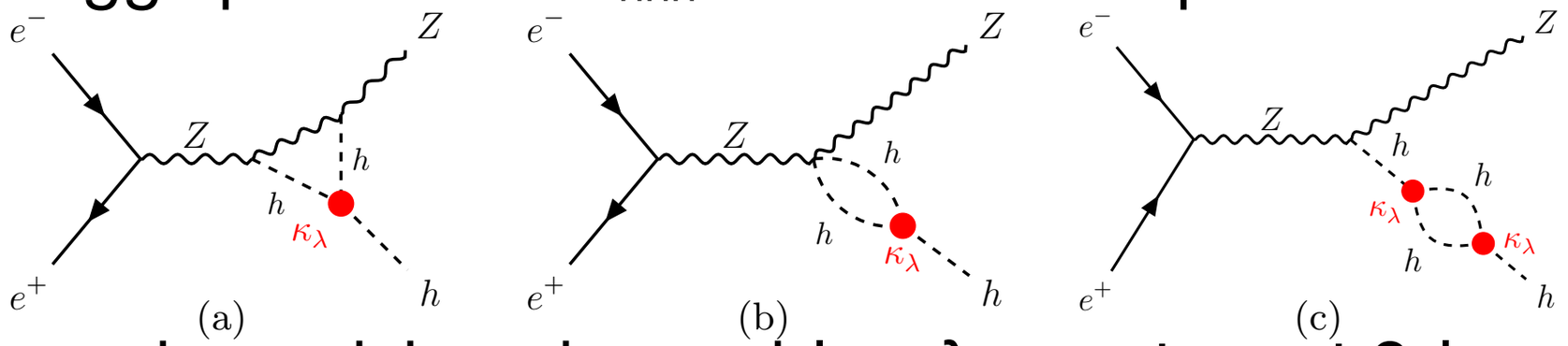
Two-loop "Barr-Zee" electron EDM contribution

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

How about indirect constraints on λ_{hhh} from circular Higgs factories (CEPC, FCC-ee) below hh threshold?

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, …)

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

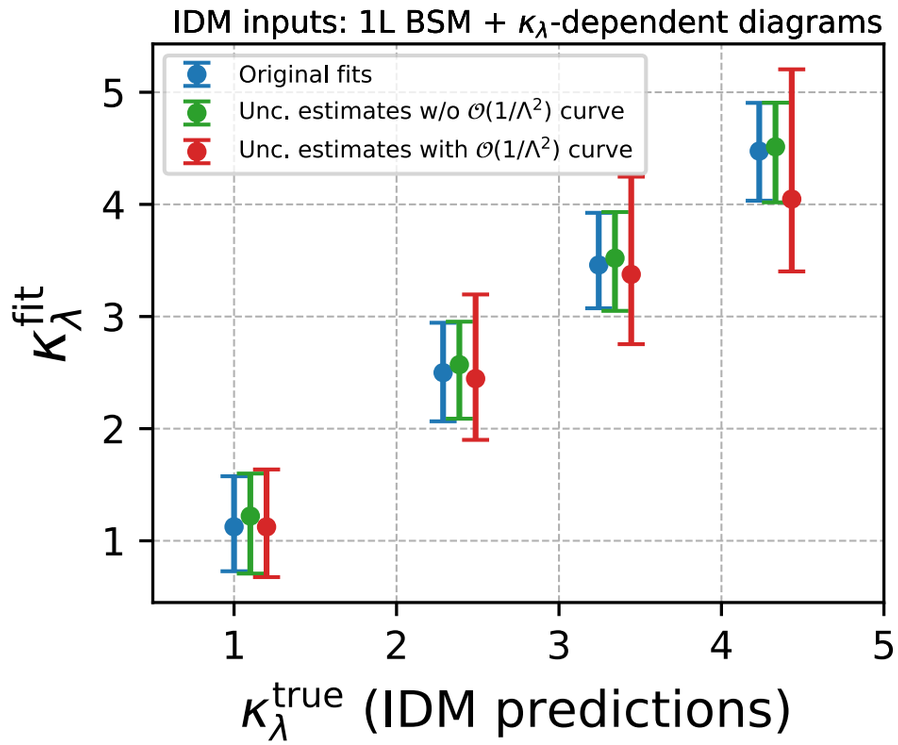
We want to determine λ_{hhh}, accounting for the fact that it may differ substantially from the SM value

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 $\kappa_\lambda \neq 1$

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

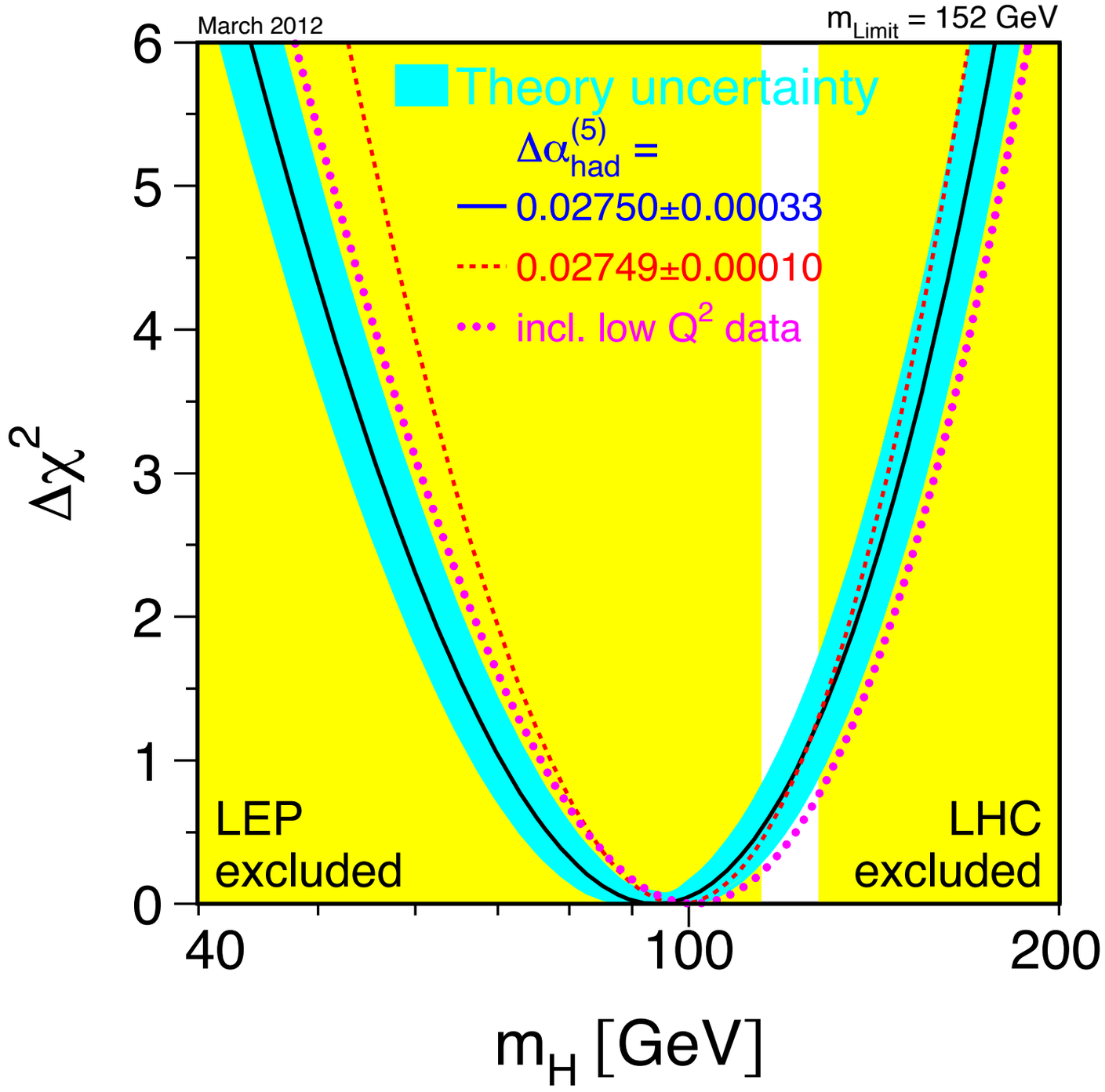


[H. Bahl, P. Bechtle, J. Braathen, S. Heinemeyer, J. List, M. Vellasco, G. W. '26, prelim.]

⇒ 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

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



[LEPEWWG '12]

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

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

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

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

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

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

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

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

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

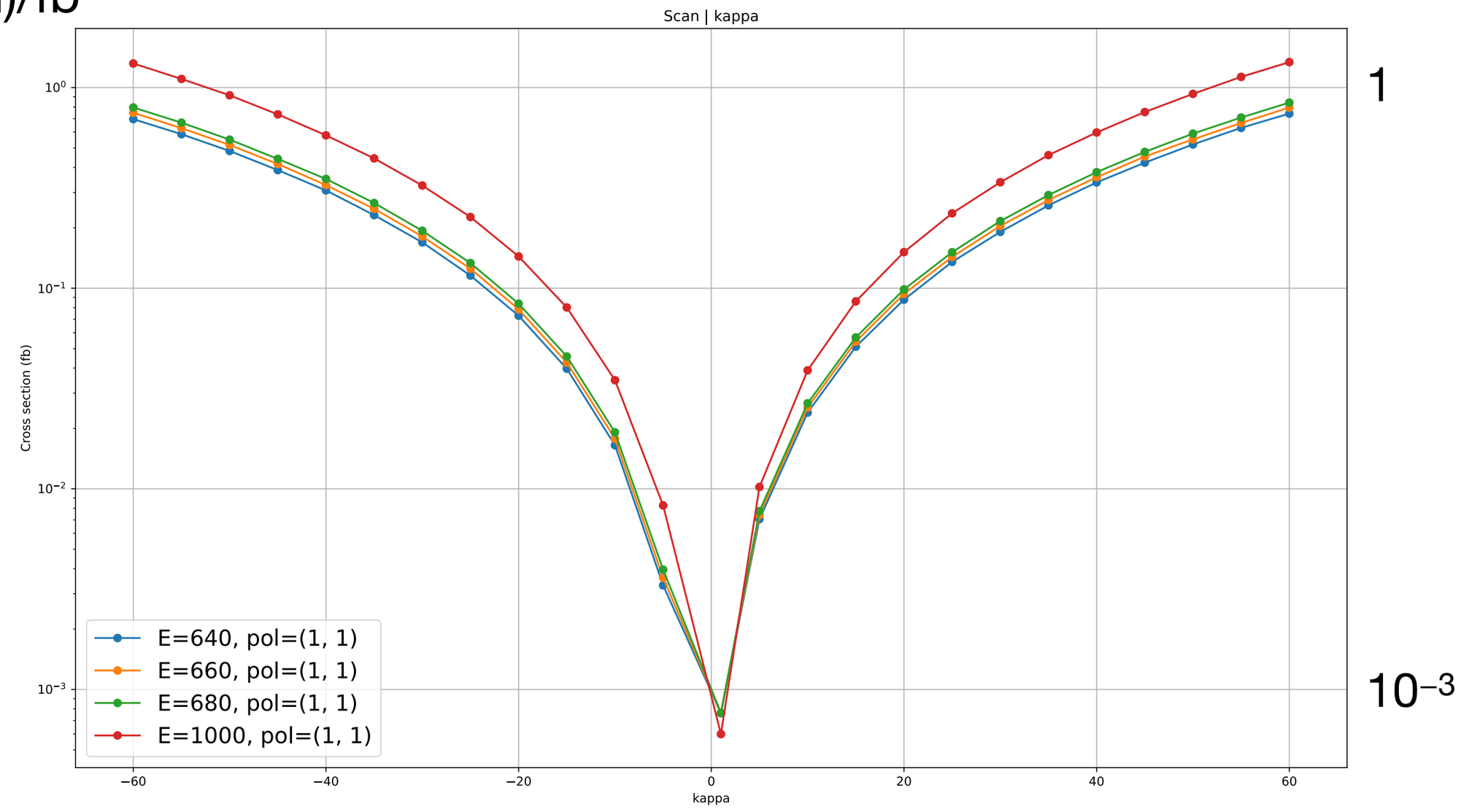
The actual physical observable in this context is the cross section for the Higgs pair production process, i.e. gg → hh at the LHC and e^+e^- → Zhh, e^+e^- → $\nu\nu$hh at an e^+e^- collider with a c.m. energy of at least 500 GeV (or $\gamma\gamma$ → hh at a 380 GeV $\gamma\gamma$ collider)

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!

Triple Higgs production at $\gamma\gamma$ collider

[M. Berger, P. Bossuyt, J. Braathen, G. Moortgat-Pick, W. Naskar, G. W. '26, pelim.]

$\sigma(\gamma\gamma \to hhh)$/fb



1

10^{-3}

$\varkappa_4$

⇒ Potential for constraining $\varkappa_4$ beyond unitarity bounds