Sensitivity to detecting New Physics effects first in the trilinear Higgs coupling

Based mainly on

arXiv:1903.05417 (PLB), 1911.11507 (EPJC), arXiv:2202.03453 (Phys. Rev. Lett.), arXiv:2305.03015 (EPJC), arXiv:2307.14976 and ongoing works

in collaboration with Masashi Aiko, Henning Bahl, Martin Gabelmann, Sven Heinemeyer, Shinya Kanemura, Kateryna Radchenko Serdula, Alain Verduras Schaeidt and Georg Weiglein

Johannes Braathen (DESY)

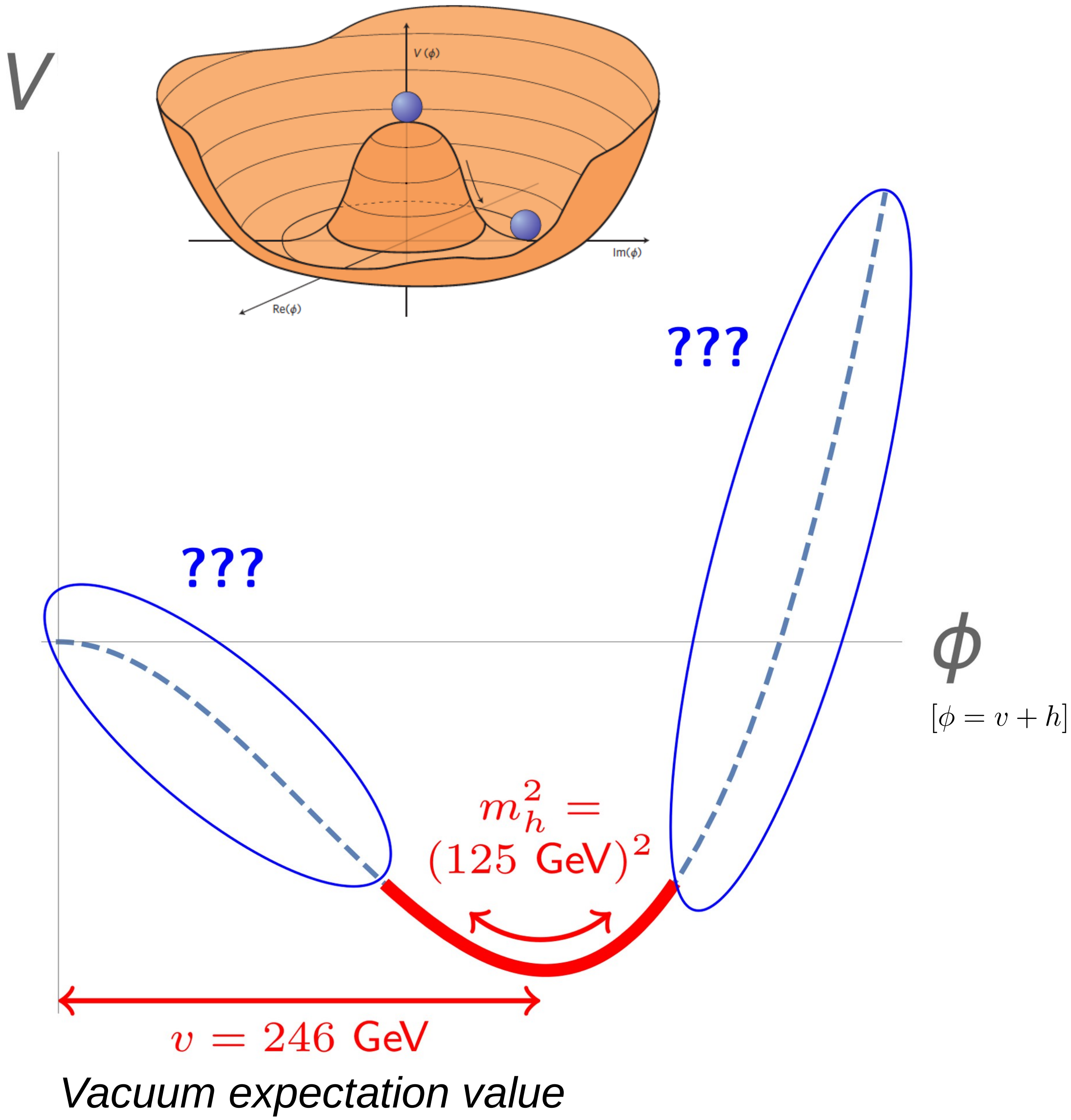
Third ECFA Workshop on e+e- Higgs/EW/Top factories

Paris, France | 10 October 2024

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)



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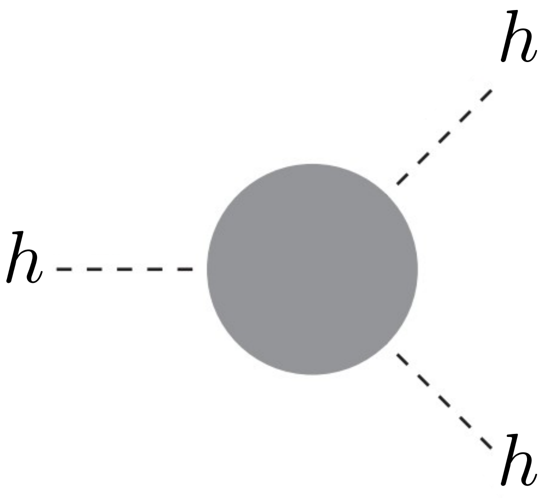
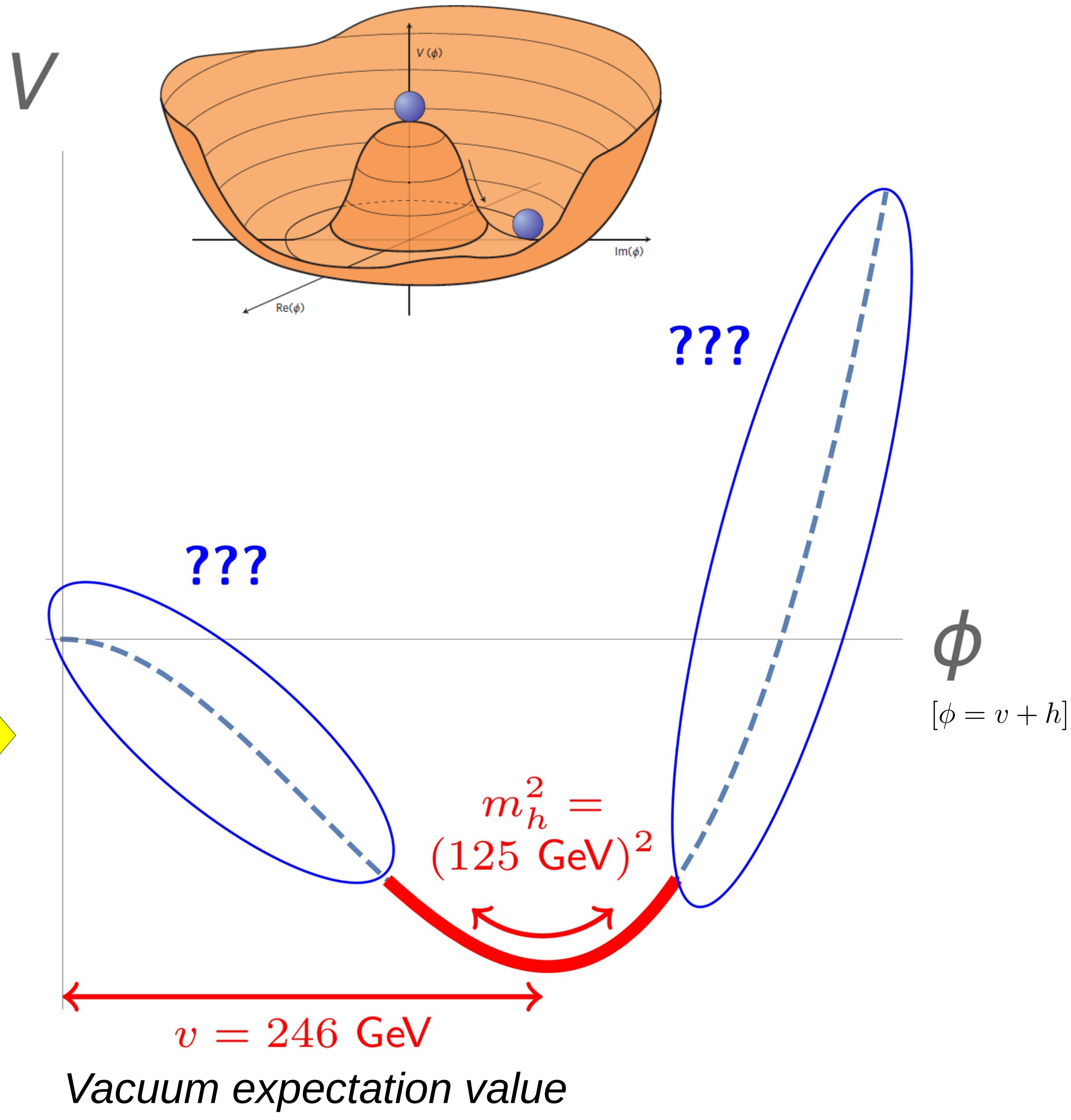
- **Trilinear Higgs coupling λ_{hhh}** crucial to understand the shape of the potential



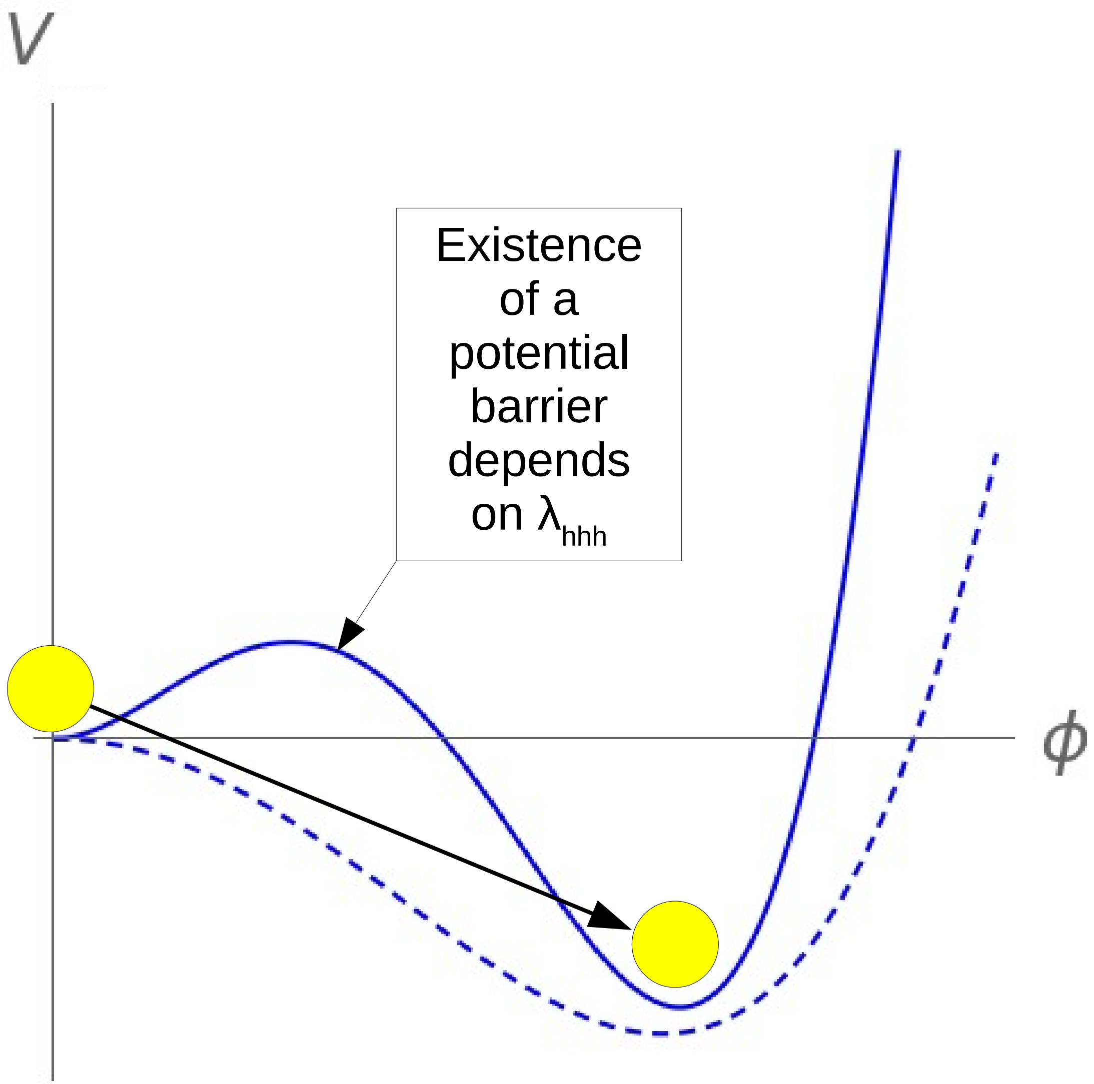


Form of the Higgs potential and baryon asymmetry

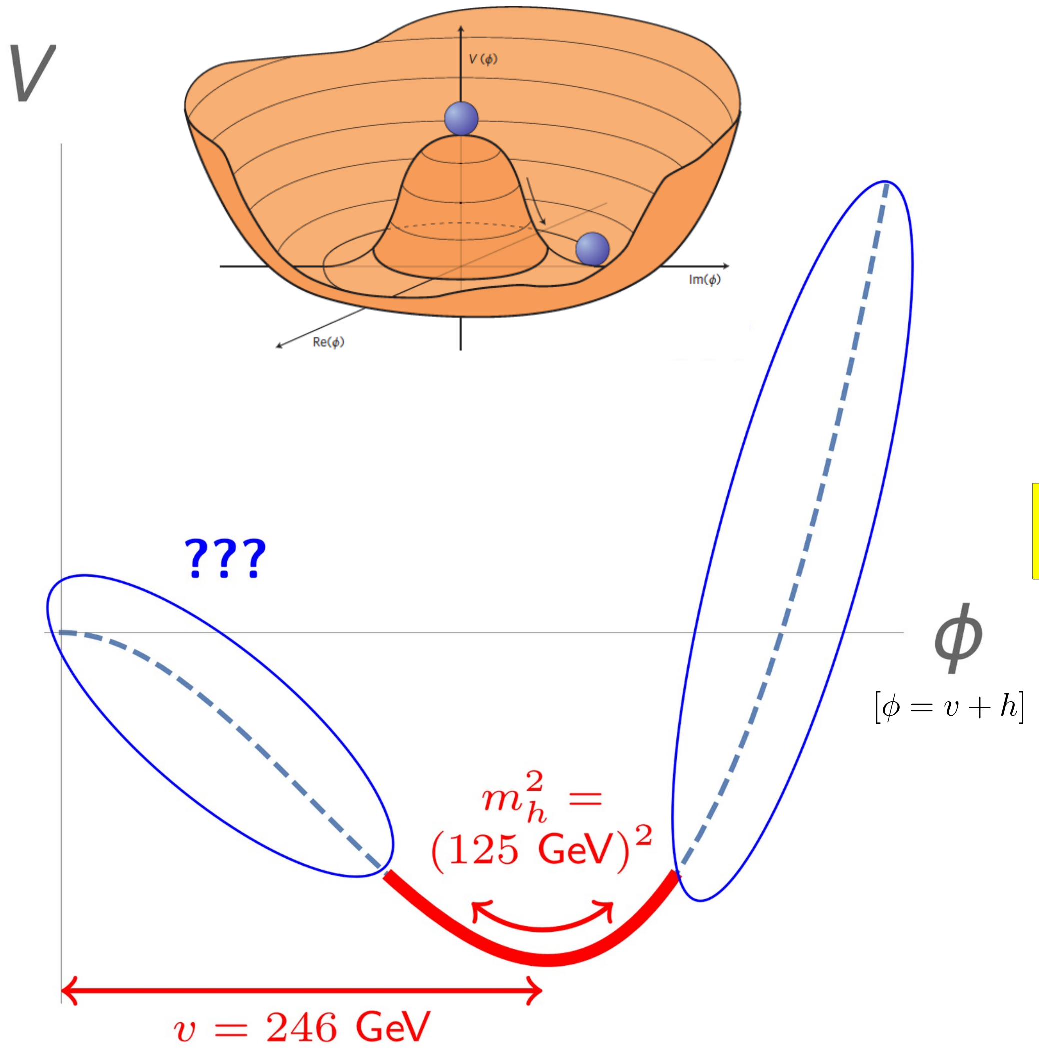
- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)

- **Trilinear Higgs coupling λ_{hhh}** crucial to understand the shape of the potential

- Among **Sakharov conditions** necessary to explain **baryon asymmetry of the Universe via electroweak phase transition** (= *electroweak baryogenesis*):
  - ***Strong first-order EWPT***
    → barrier in Higgs potential
    → typically significant deviation in λ_{hhh} from SM



Aparté: Form of the Higgs potential – a more realistic picture



***Beyond-the-Standard-Model theory**, here with 2 scalar states (as an example)*

→ *Multiple field directions*

→ *Multiple trilinear scalar couplings*

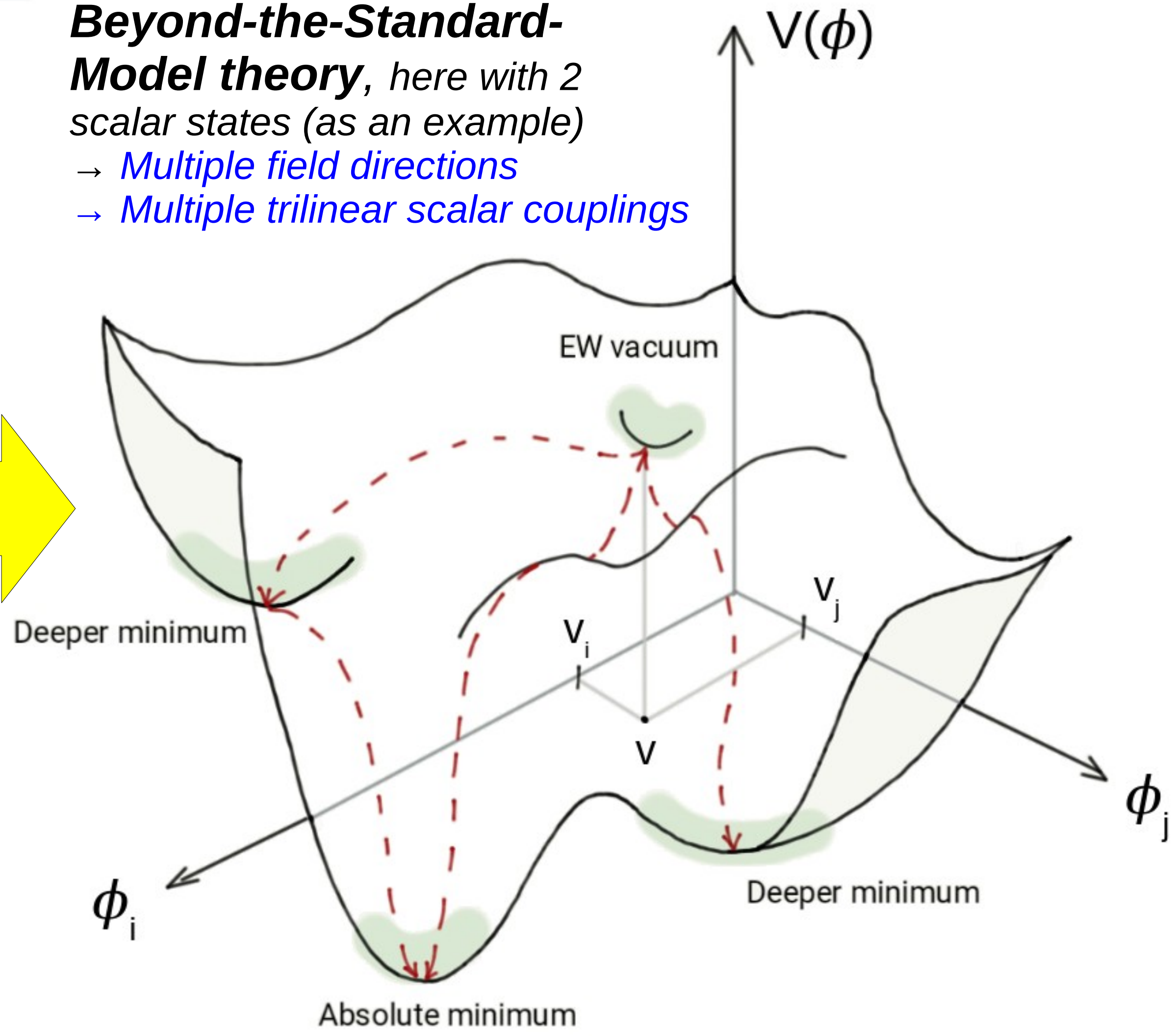


Figure by [K. Radchenko Serdula '24]

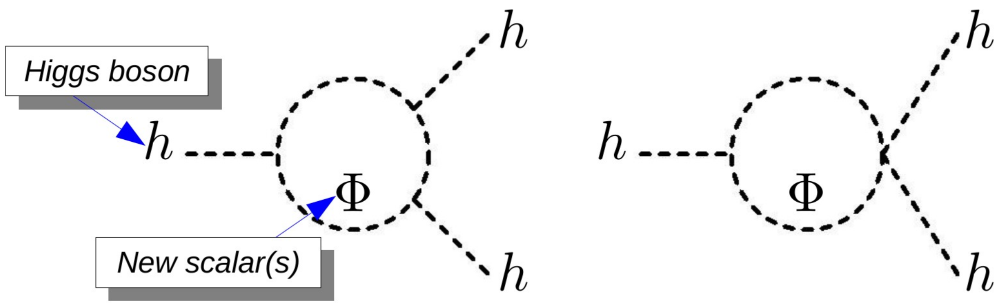
Probing New Physics with the trilinear Higgs coupling

- **In many models with extended Higgs sectors**

$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$$

m_Φ *: Physical mass of BSM state*
M *: BSM mass scale of the model*
$g_{hh\Phi\Phi}$ *: combination of Lagrangian quartic couplings*

- **Large effects from New Physics possible in λ_{hhh}**
  due to radiative corrections from extra scalars,
  e.g. at leading order

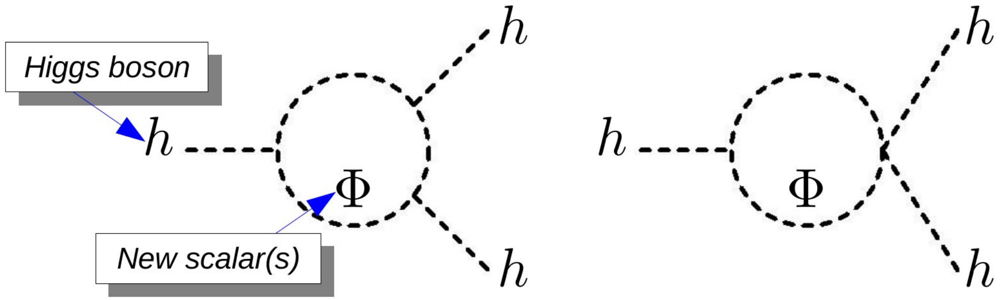


- Involves coupling $g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$

  which grows with **mass splitting between M and m_Φ**

Probing New Physics with the trilinear Higgs coupling

➢ **Large effects from New Physics possible in λ_{hhh}** due to radiative corrections from extra scalars, e.g. at leading order



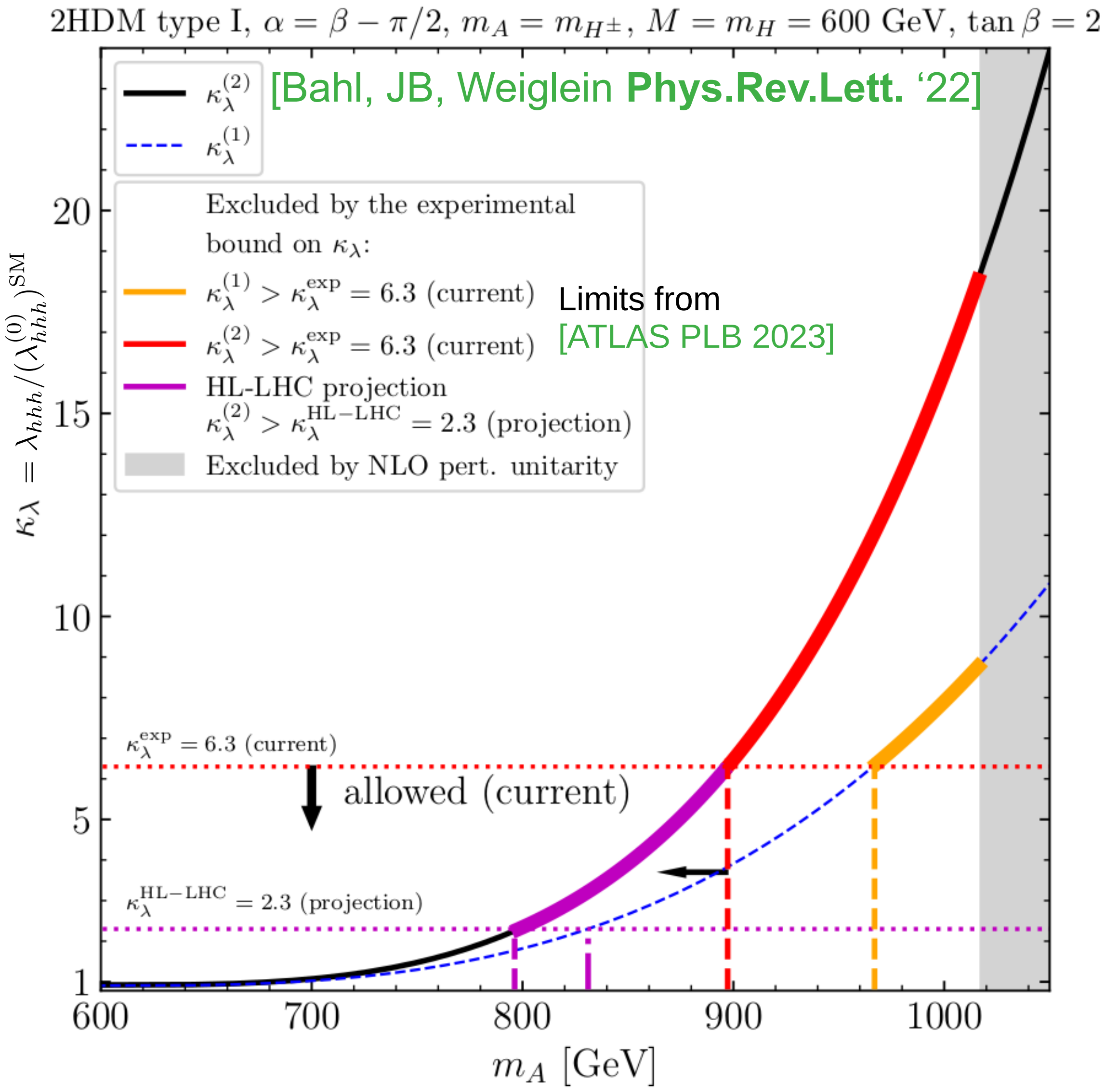
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

➢ Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}} < 7.2$$

[ATLAS 2024]

with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models** [Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]

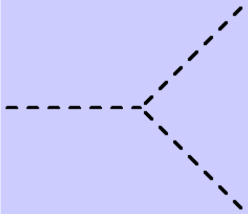
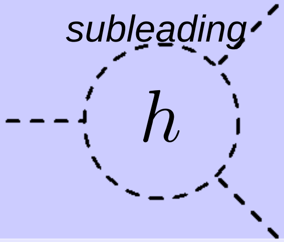
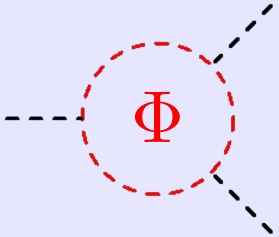
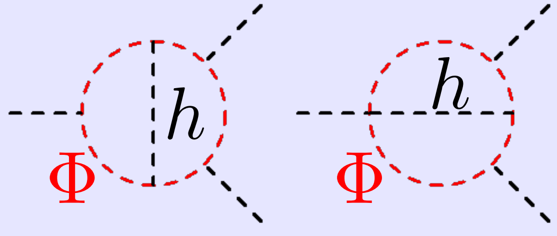
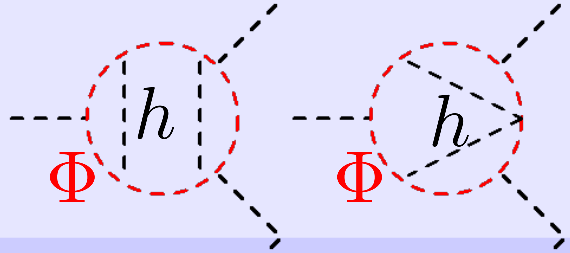
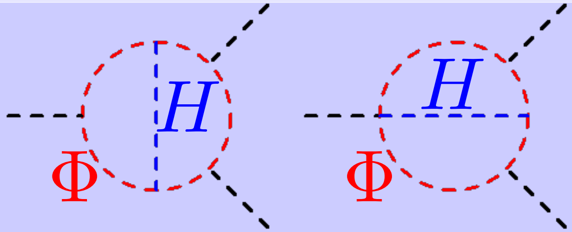
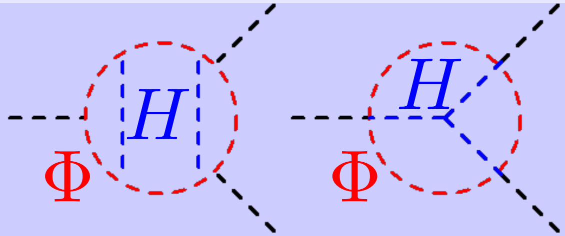
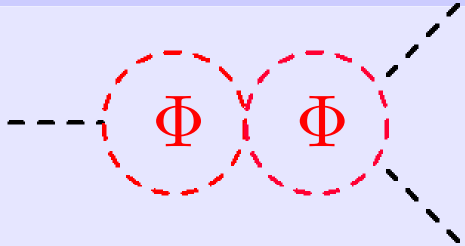
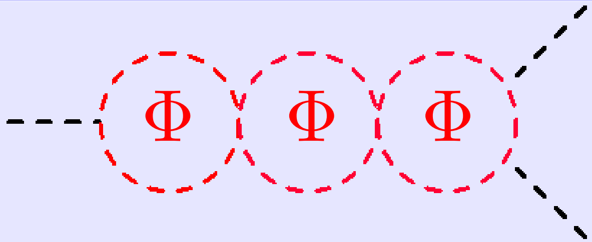


Examples of scalar contributions to λ_{hhh} in aligned 2HDM

BSM scalars:

$\Phi \in \{H, A, H^\pm\}$

$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2$

Coupling/Order	0L	1L	2L	3L
g_{hhhh}		*subleading* 	*subleading*	*subleading*
$g_{(h)h\Phi\Phi}$ $\left[g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}\right]$	-			
$g_{(h)H\Phi\Phi'}$ [$g_{(h)G\Phi\Phi'}$ case similar]	-	-		
$g_{\Phi\Phi\Phi'\Phi'}$ [2 BSM scalars of species Φ, 2 of species Φ’]	-	-		

[NB: 1 h can be replaced by a VEV]

→ *no further type of coupling entering after 2L*

→ *for each class of diagrams, perturbative convergence can be verified!*

e.g. in [Bahl, JB, Weiglein PRL ‘22]

Mass splitting effects for various BSM models with anyH3

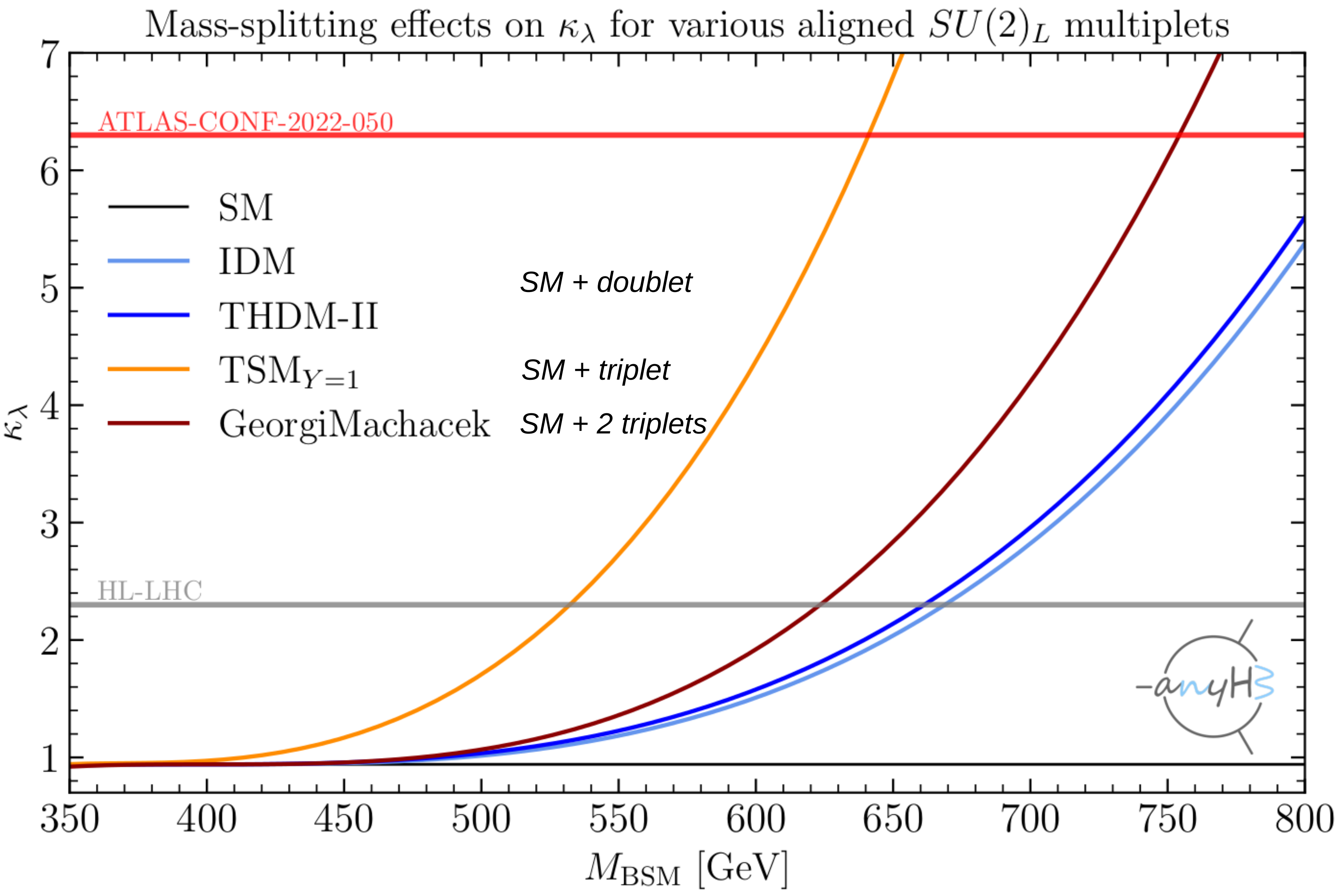
- anyH3 [Bahl, JB, Gabelmann, Weiglein '23]: public tool for full one-loop calculation of λ_{hhh} in arbitrary renormalisable models, using UFO inputs (*more details in backup*)

$$M^2_{\text{BSM}} = \mathcal{M}^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$$

- Increase M_{BSM}, keeping fixed $\mathcal{M}$
  → large mass splittings
  → **large BSM effects!**

- Perturbative unitarity checked within anyH3

- **Constraints on BSM parameter space!**



Here: scenarios with lightest BSM scalar mass + BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

Could BSM Physics be detected first in κ_λ ?

i. *How do BSM effects in the trilinear and single Higgs couplings scale?*

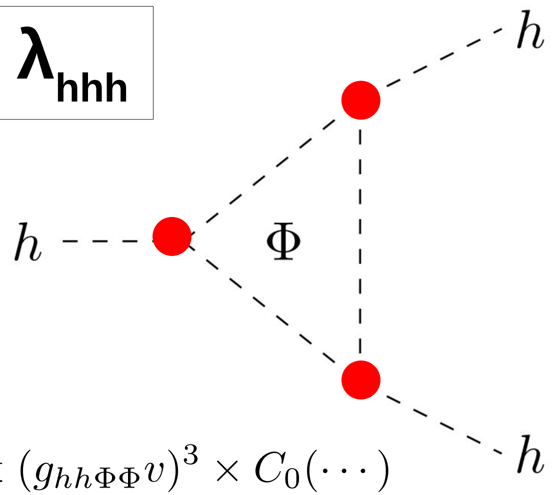
ii. *Example 1: Correlation κ_λ vs $\Gamma(h \to \gamma\gamma)$ in an Inert Doublet Model*

iii. *Example 2: Effective couplings at one and two loops in a Z_2-symmetric singlet model*

BSM effects in Higgs couplings: power counting

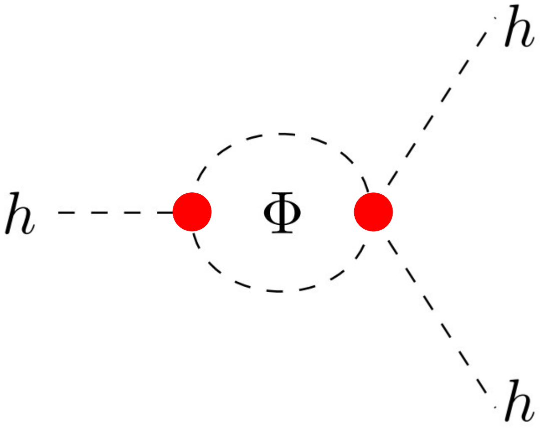
$$M^2_{\text{BSM}} = \mathcal{M}^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$$

λ_{hhh}



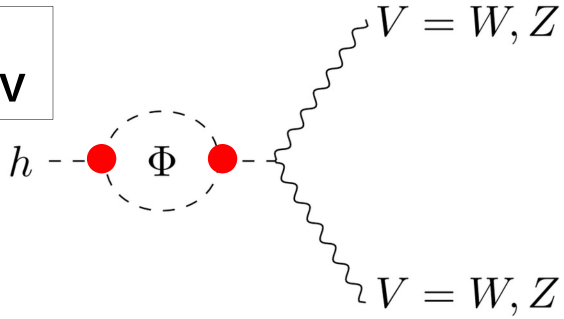
$$\propto (g_{hh\Phi\Phi} v)^3 \times C_0(\cdots)$$

$$\sim \frac{(g_{hh\Phi\Phi} v)^3}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi}v^2 \gg \mathcal{M}^2} \mathcal{O}(g^2_{hh\Phi\Phi})$$



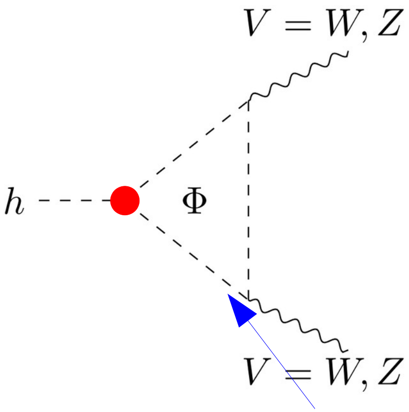
$$\propto g^2_{hh\Phi\Phi} v \times \underbrace{B_0(\cdots)}_{\text{mass. dim. } 0} \sim \mathcal{O}(g^2_{hh\Phi\Phi})$$

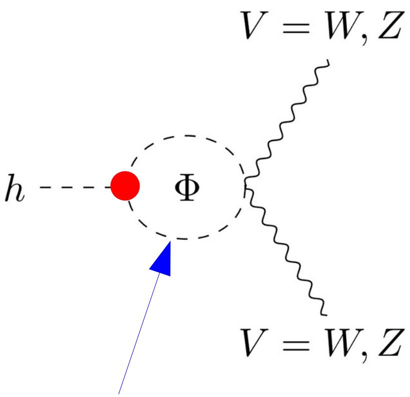
g_{hVV}



$$\propto (g_{hh\Phi\Phi} v)^2 \times g_{\text{EW}} \times B_0'(\cdots)$$

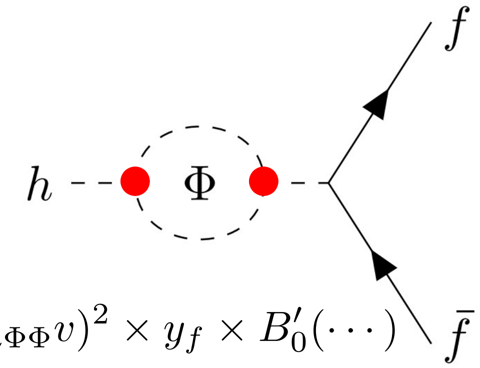
$$\propto \frac{(g_{hh\Phi\Phi} v)^2}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi}v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi})$$





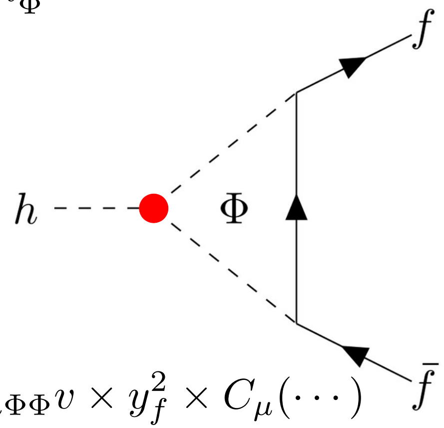
$$\propto g_{hh\Phi\Phi} v \times g^2_{\text{EW}} \times \underbrace{\{C_{\mu\nu}(\cdots) \text{ or } B_0(\cdots)\}}_{\text{mass. dim. } 0} \sim \mathcal{O}(g_{hh\Phi\Phi})$$

$g_{hf\bar{f}}$



$$\propto (g_{hh\Phi\Phi} v)^2 \times y_f \times B_0'(\cdots)$$

$$\propto \frac{(g_{hh\Phi\Phi} v)^2}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi}v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi})$$



$$\propto g_{hh\Phi\Phi} v \times y_f^2 \times C_\mu(\cdots)$$

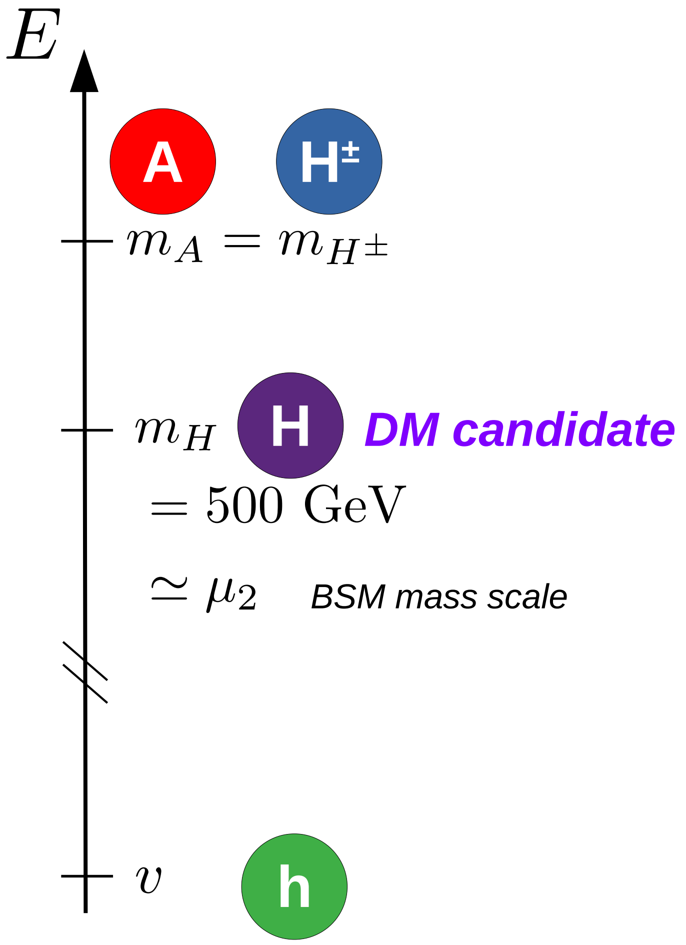
$$\sim \frac{g_{hh\Phi\Phi} v}{m_\Phi} \xrightarrow{g_{hh\Phi\Phi}v^2 \gg \mathcal{M}^2} O(g^{1/2}_{hh\Phi\Phi})$$

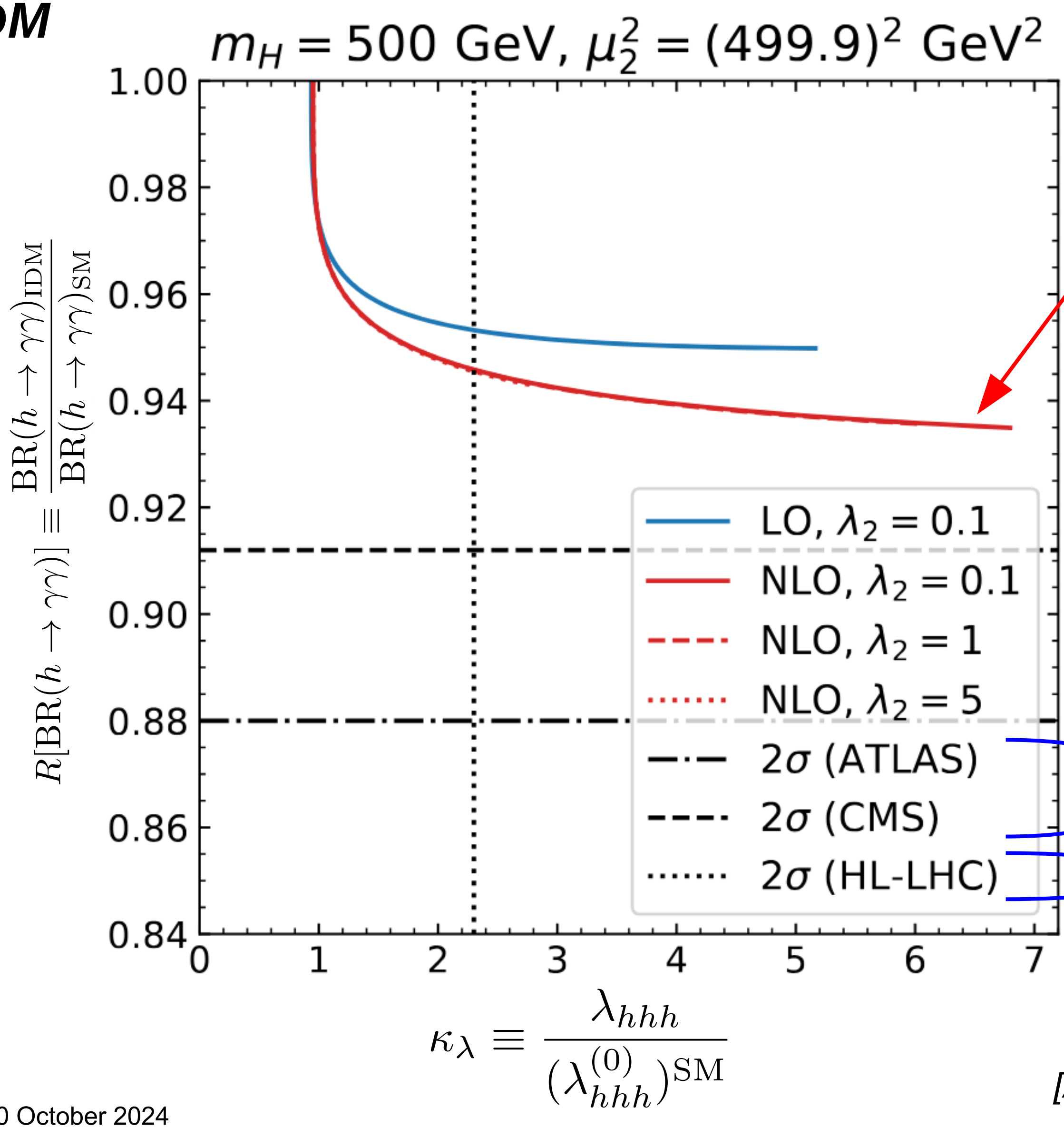
Note: similar arguments can be made from EFT perspective, c.f. talk of McCullough at ICHEP 2024 (link) or also next talk by G. Weiglein

Correlation between κ_λ and BR($h \to \gamma\gamma$) in the IDM

[Aiko, JB, Kanemura '23] + [JB, Kanemura '19]

Inert Doublet Model (IDM) in scenario with heavy DM candidate





$m_{H^\pm} = m_A$ varied along the curves (until limit from pert. unit.)

Expected bounds on R[BR($h \to \gamma\gamma$)] at HL-LHC

Expected bound on κ_λ at HL-LHC

[λ_2 : inert doublet self-coupling]

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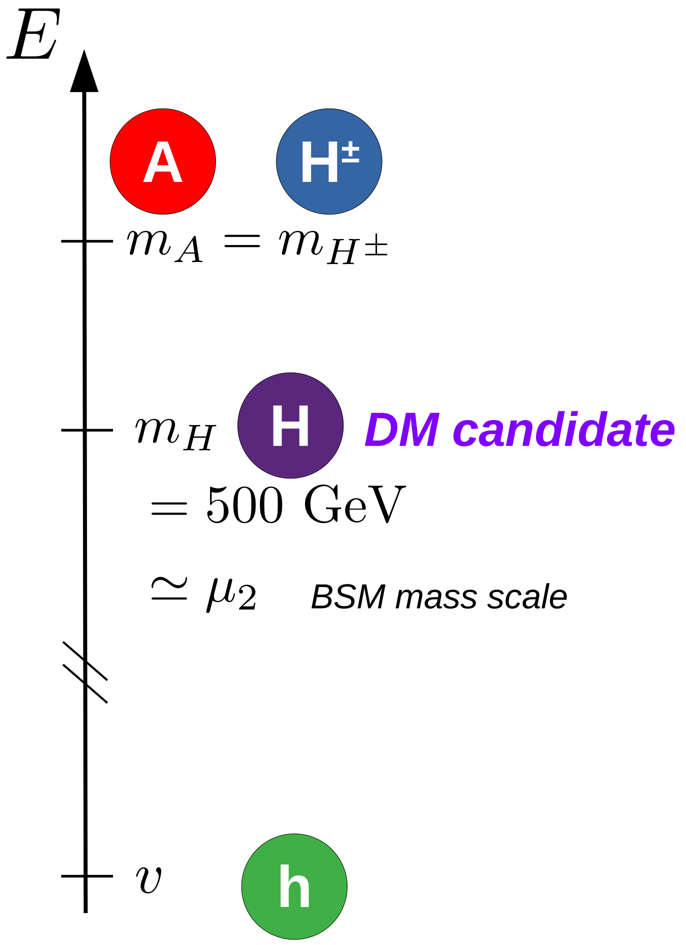
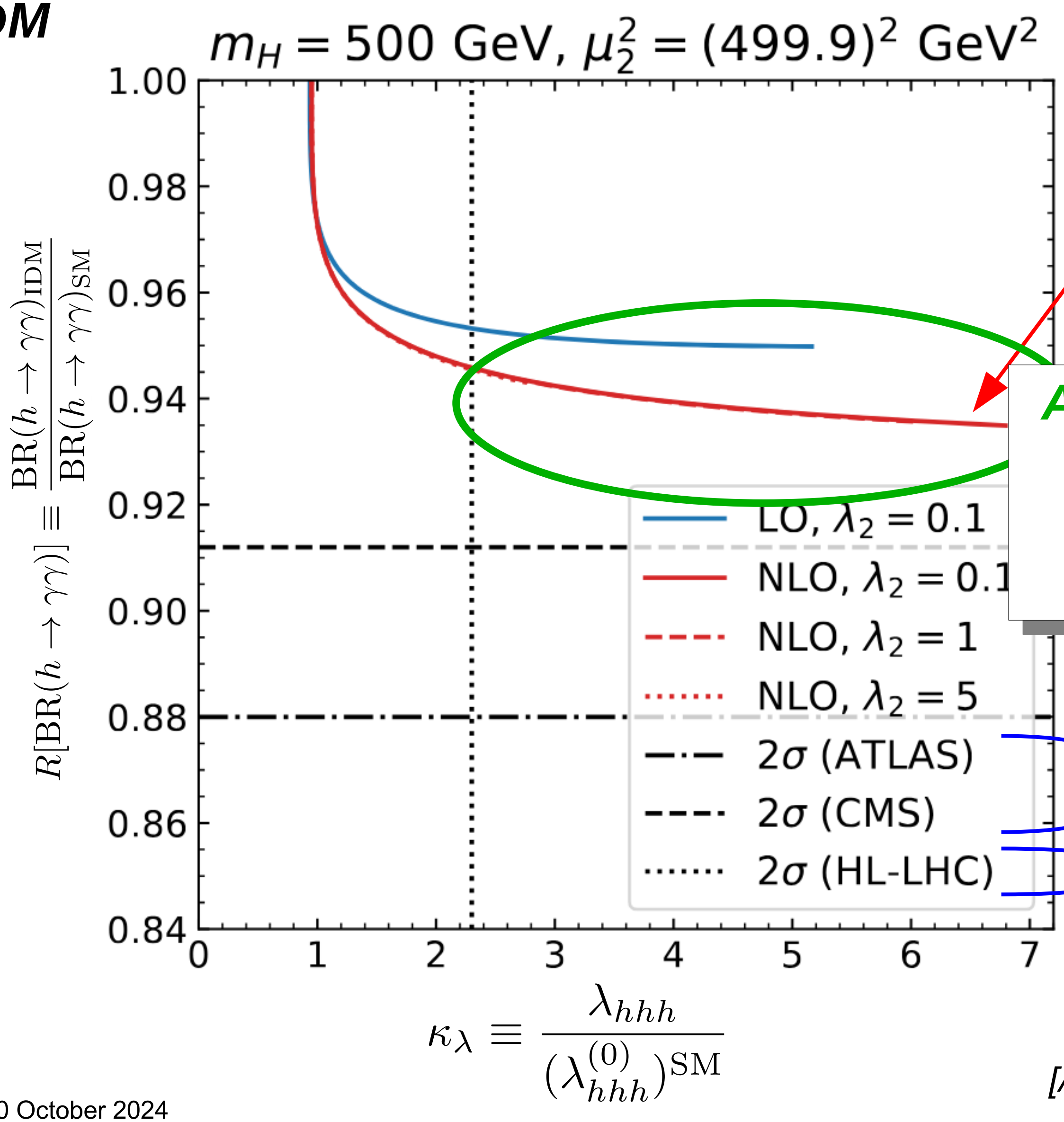




$m_{H\pm} = m_A$ varied along the curves (until limit from pert. unit.)

At HL-LHC, mass range above ~730 GeV is probed in κ_λ, but not with $\Gamma(h \to \gamma\gamma)$!

Expected bounds on R[BR($h \to \gamma\gamma$)] at HL-LHC

Expected bound on κ_λ at HL-LHC

[λ_2 : inert doublet self-coupling]

Correlation between κ_λ and BR($h\to\gamma\gamma$) in the IDM

What about the situation at an e^+e^- collider ?

	ΔBR/BR($h\to\gamma\gamma$) NB: $\Delta\kappa_\gamma \neq \Delta$BR($h\to\gamma\gamma$) !	$\Delta\lambda_{hhh}/\lambda_{hhh}$
ILC-250	4.5% [1]	*Indirect*
ILC-500	2.6% [1]	23% [4,5]
FCC-ee	3.1% [2]	*Indirect*

[Given here: 1σ prospects]

[1] "Physics Case for the 250 GeV Stage of the International Linear Collider," Fujii, Grojean, Peskin et al., 1710.07621

[2] "Higgs physics opportunities at the Future Circular Collider," G. Marchiori, talk at ICHEP 2024

[3] "Higgs Boson studies at future particle colliders," de Blas et al., 1905.03764

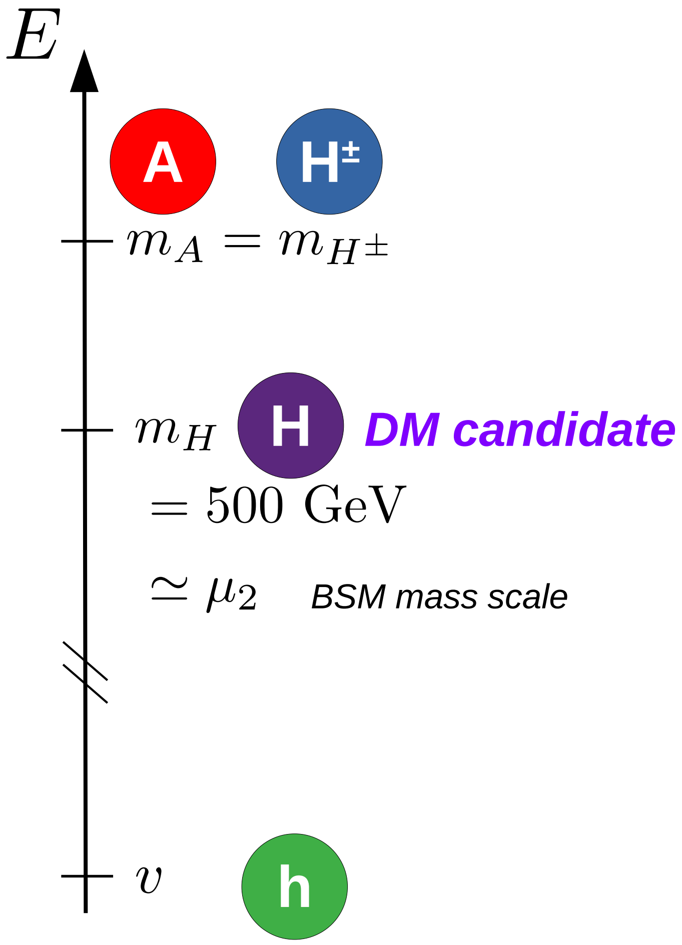
[4] B. Bliewert, J. List et al. 2024 + see previous talk by B. Bliewert

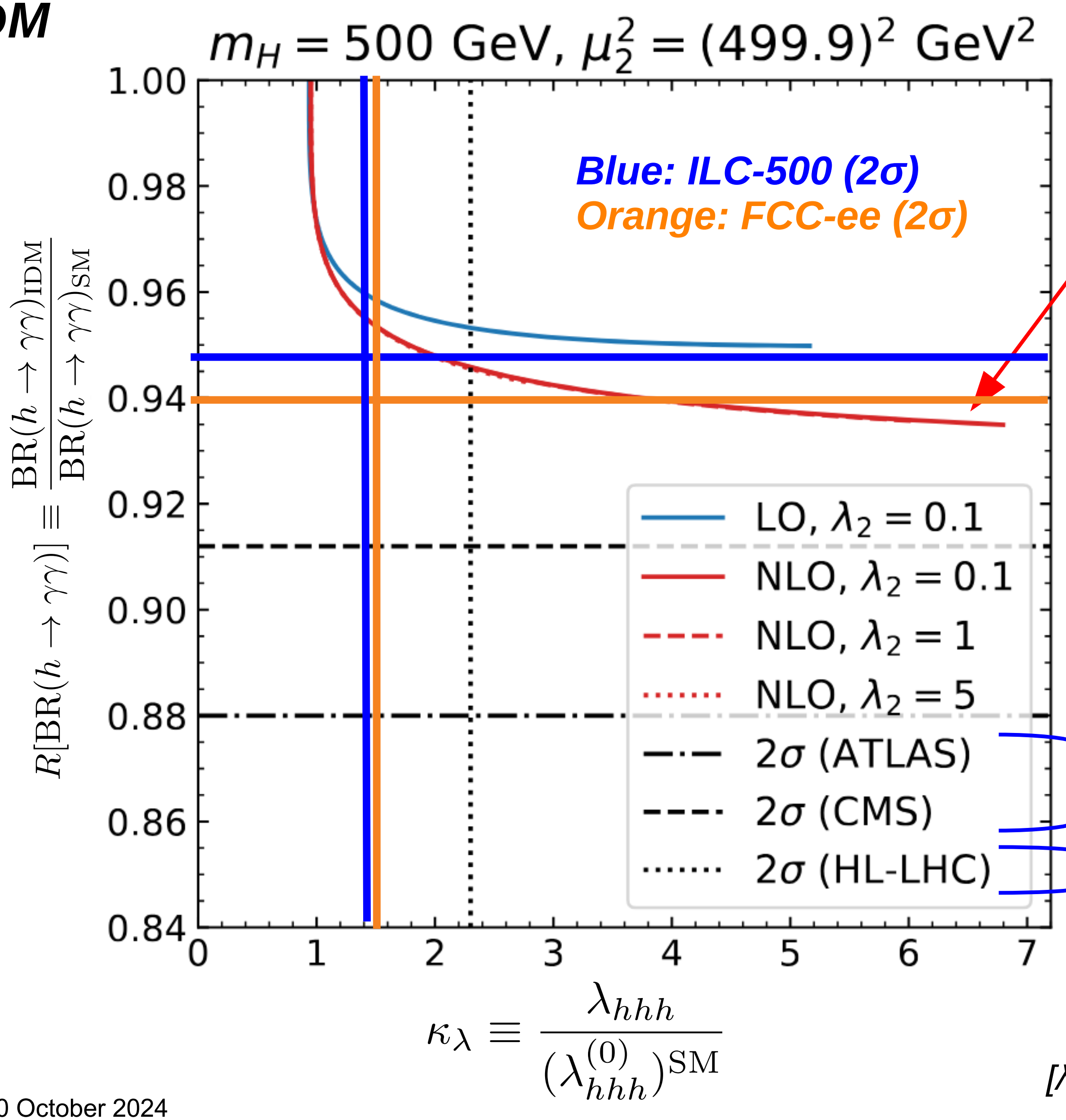
[5] "Opportunities & Experimental Challenges at the Higgs-Top interface," J. Tian, talk at LCWS 2024

Correlation between κ_λ and BR($h \to \gamma\gamma$) in the IDM

[Aiko, JB, Kanemura '23] + [JB, Kanemura '19]

Inert Doublet Model (IDM) in scenario with heavy DM candidate





$m_{H^\pm} = m_A$ varied along the curves (until limit from pert. unit.)

Prospects at e+e- Higgs factories		
	BR($h \to \gamma\gamma$)	λ_{hhh}
ILC-250	4.5%	*Indirect*
ILC-500	2.6%	23%
FCC-ee	3.1%	*Indirect*

Expected bounds on R[BR($h \to \gamma\gamma$)] at HL-LHC

Expected bound on κ_λ at HL-LHC

[λ_2 : inert doublet self-coupling]

Correlation between κ_λ and BR($h \to \gamma\gamma$) in the IDM

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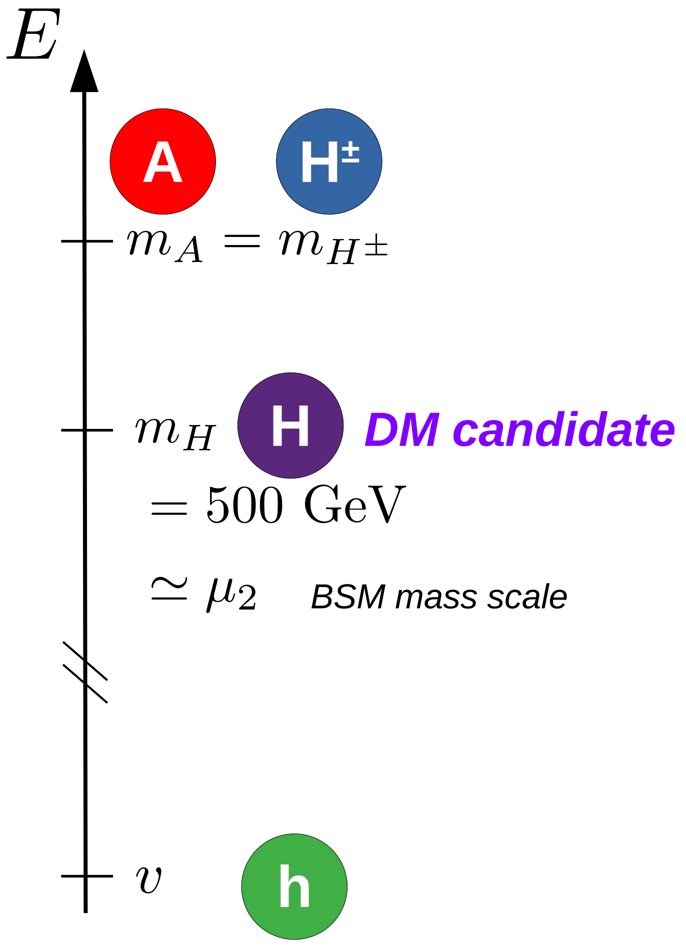

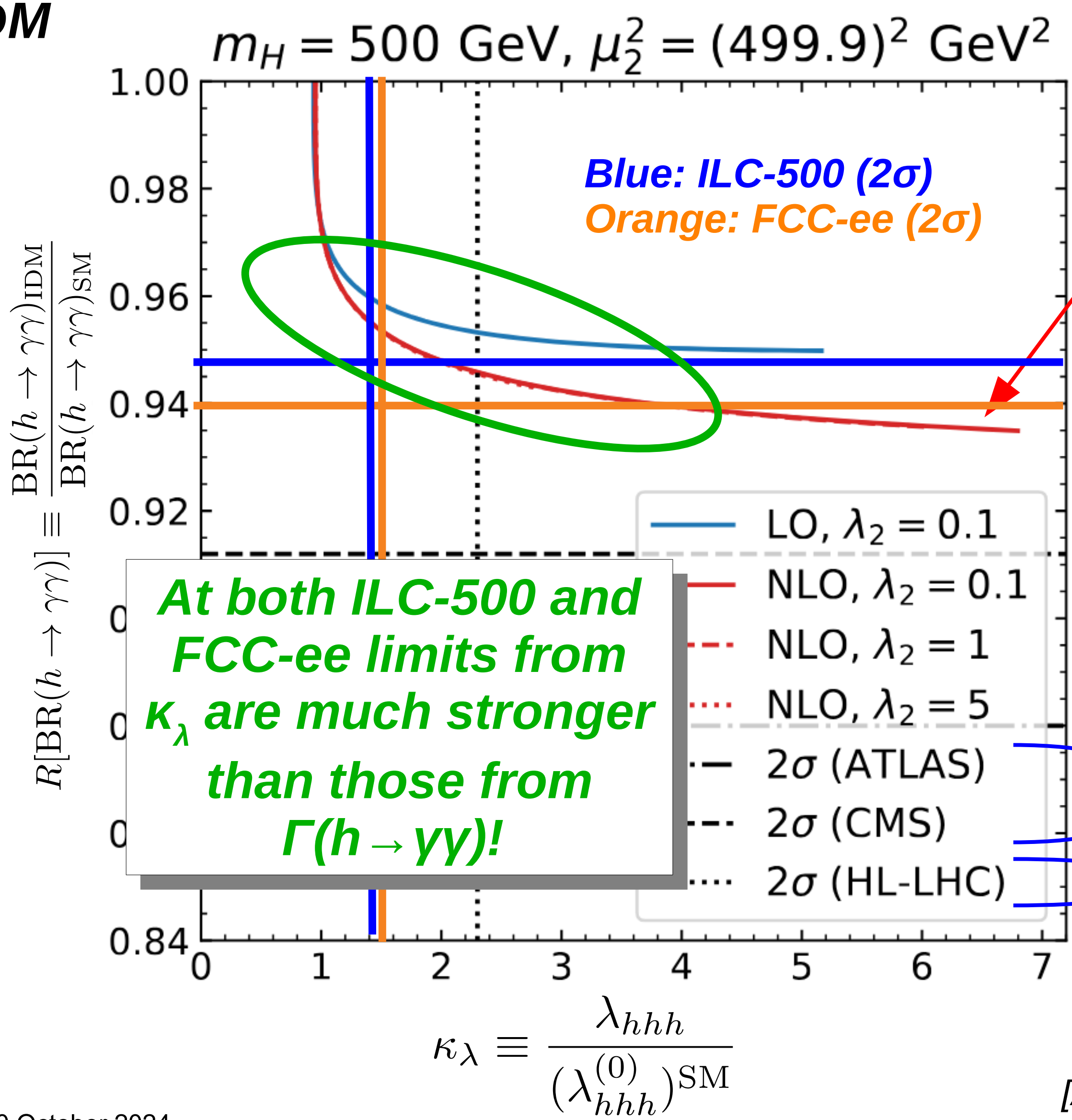

At both ILC-500 and FCC-ee limits from κ_λ are much stronger than those from $\Gamma(h \to \gamma\gamma)$!

$m_{H\pm} = m_A$ varied along the curves (until limit from pert. unit.)

Prospects at e+e- Higgs factories		
	BR($h \to \gamma\gamma$)	λ_{hhh}
ILC-250	4.5%	*Indirect*
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Expected bounds on R[BR($h \to \gamma\gamma$)] at HL-LHC

Expected bound on κ_λ at HL-LHC

[λ_2 : inert doublet self-coupling]

Effective couplings in the Z_2SSM

[Bahl, JB, Gabelmann, Heinemeyer, Radchenko Serdula, Verduras Schaeidt, Weiglein *WIP*]

- **Z_2SSM**: SM + real singlet S, charged under unbroken Z_2 symmetry

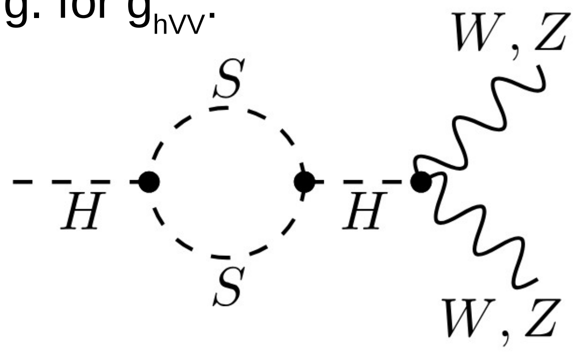
$$V_{\mathrm{SSM-}\mathbf{Z_2}}(\Phi, S) = V_{\mathrm{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi \qquad m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$$

- Corrections to κ_λ at 1L: $\kappa_\lambda^{(1)} \simeq 1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \frac{m_S^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$

  … and 2L: $\kappa_\lambda^{(2)} \simeq \kappa_\lambda^{(1)} + \frac{1}{256\pi^4}\left[\frac{16 m_S^6}{v^4 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^4 + \frac{24\lambda_S m_S^4}{v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 - \frac{2 m_S^6}{3 v^4 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^5\right]$

- **Single Higgs couplings** get leading BSM corrections ***only via external leg corrections***

e.g. for g_{hVV}:



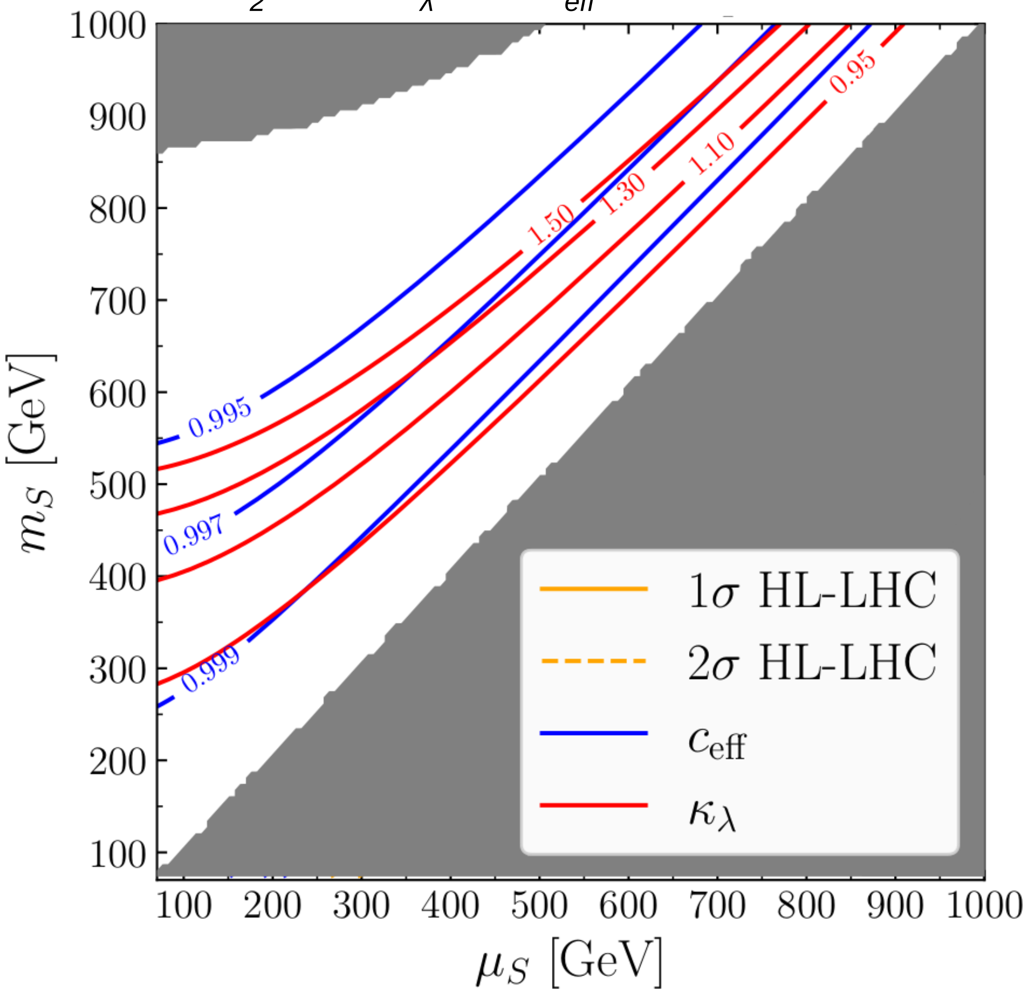
$$c_{\mathrm{eff}}^{(1)} \equiv \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}} \simeq 1 - \frac{m_S^2}{16\pi^2 v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

$$c_{\mathrm{eff}}^{(2)} \simeq c_{\mathrm{eff}}^{(1)} - \frac{1}{256\pi^4}\left[\frac{m_S^4}{v^4}\left(43 + \frac{5\mu_S^2}{m_S^2}\right)\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 + \frac{2\lambda_S m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2\right]$$

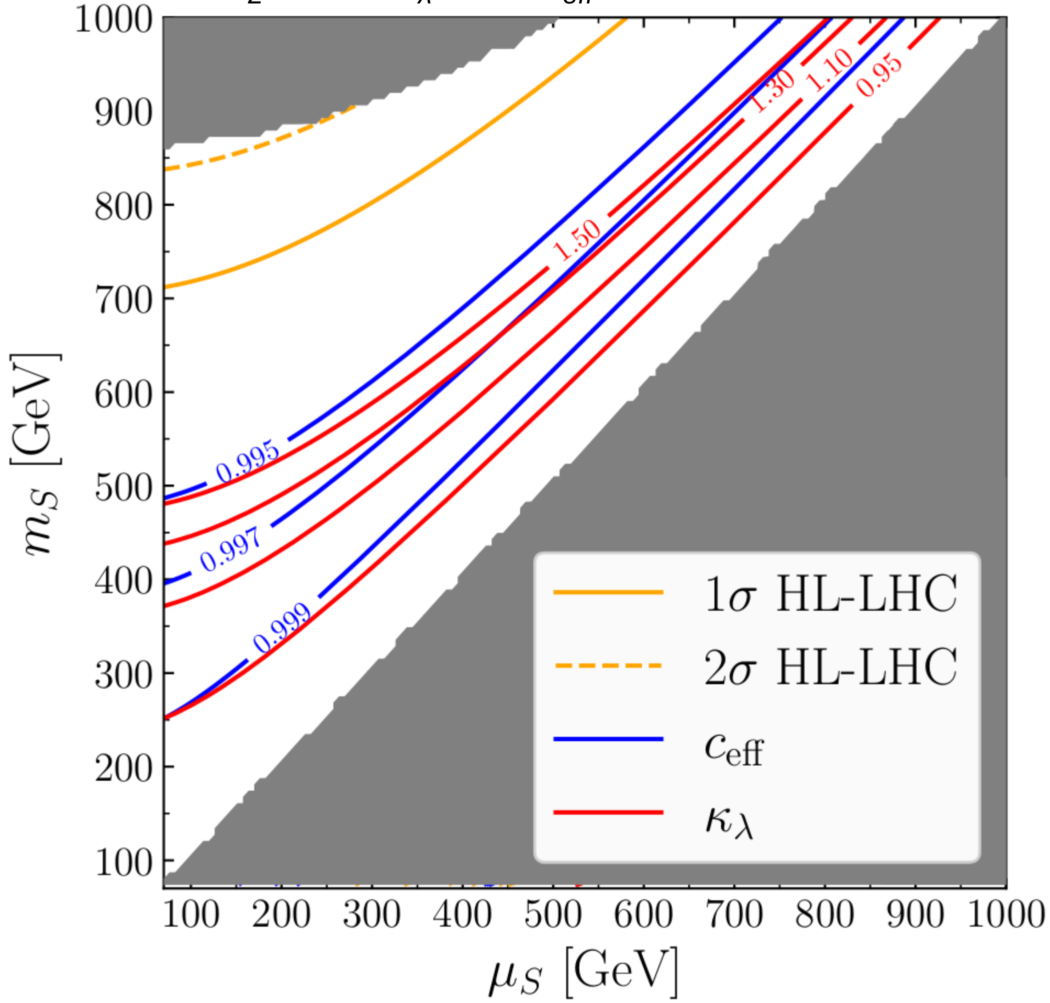
Effective couplings in the Z_2SSM

[Bahl, JB, Gabelmann, Heinemeyer, Radchenko Serdula, Verduras Schaeidt, Weiglein *WIP*]

Z_2SSM: κ_λ and c_{eff} evaluated at 1L



Z_2SSM: κ_λ and c_{eff} evaluated at 2L



- HL-LHC: no bound with 1L c_{eff}, only weak bound with 2L c_{eff}
- O(50%) accuracy on κ_λ is stronger than O(0.5%) accuracy on c_{eff} (i.e. g_{hVV})
- O(20%) accuracy on κ_λ is competitive with O(0.3%) accuracy on c_{eff} (i.e. g_{hVV}) for most of the parameter plane

Summary

- λ_{hhh} plays a crucial role to probe the **shape of the Higgs potential** and the **nature of the EW phase transition**, and search indirect **signs of New Physics**

- λ_{hhh} can **deviate significantly from SM prediction** (by up to a factor **~10**), for otherwise theoretically and experimentally allowed points, due to **mass-splitting effects in radiative corrections involving BSM scalars**

- Current experimental bounds on λ_{hhh} can **already exclude significant parts of otherwise unconstrained BSM parameter space**, and future prospects even better!

- **BSM Physics could potentially be found first in λ_{hhh}**, even with future precision measurements of other Higgs couplings or BRs like g_{hZZ} or $\Gamma(h \to \gamma\gamma)$

We could find BSM Physics in λ_{hhh}, *even if nothing shows up in precision measurements of Higgs properties like hZZ or hγγ*

Thank you very much for your attention!

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