BSM effects 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 M. Aiko, H. Bahl, P. Bechtle, M. Gabelmann, S. Heinemeyer, S. Kanemura, J. List, K. Radchenko Serdula, M. Vellasco, A. Verduras Schaeidt and G. Weiglein

Johannes Braathen (DESY)

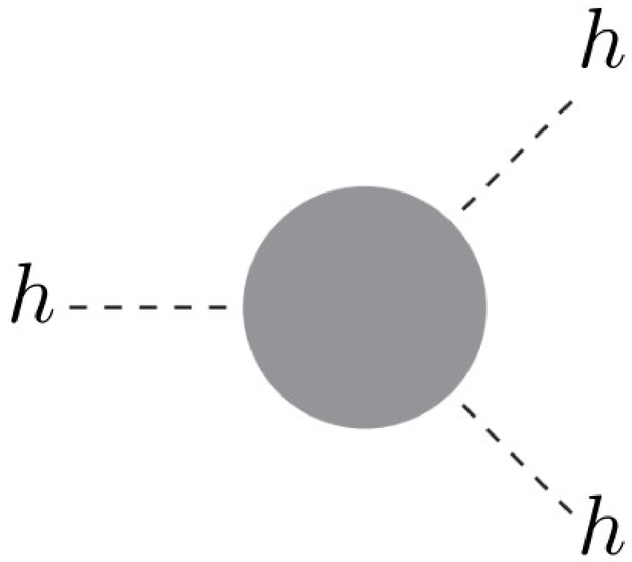
IDT-WG3-Phys Open Meeting

15 November 2024

Outline of the talk

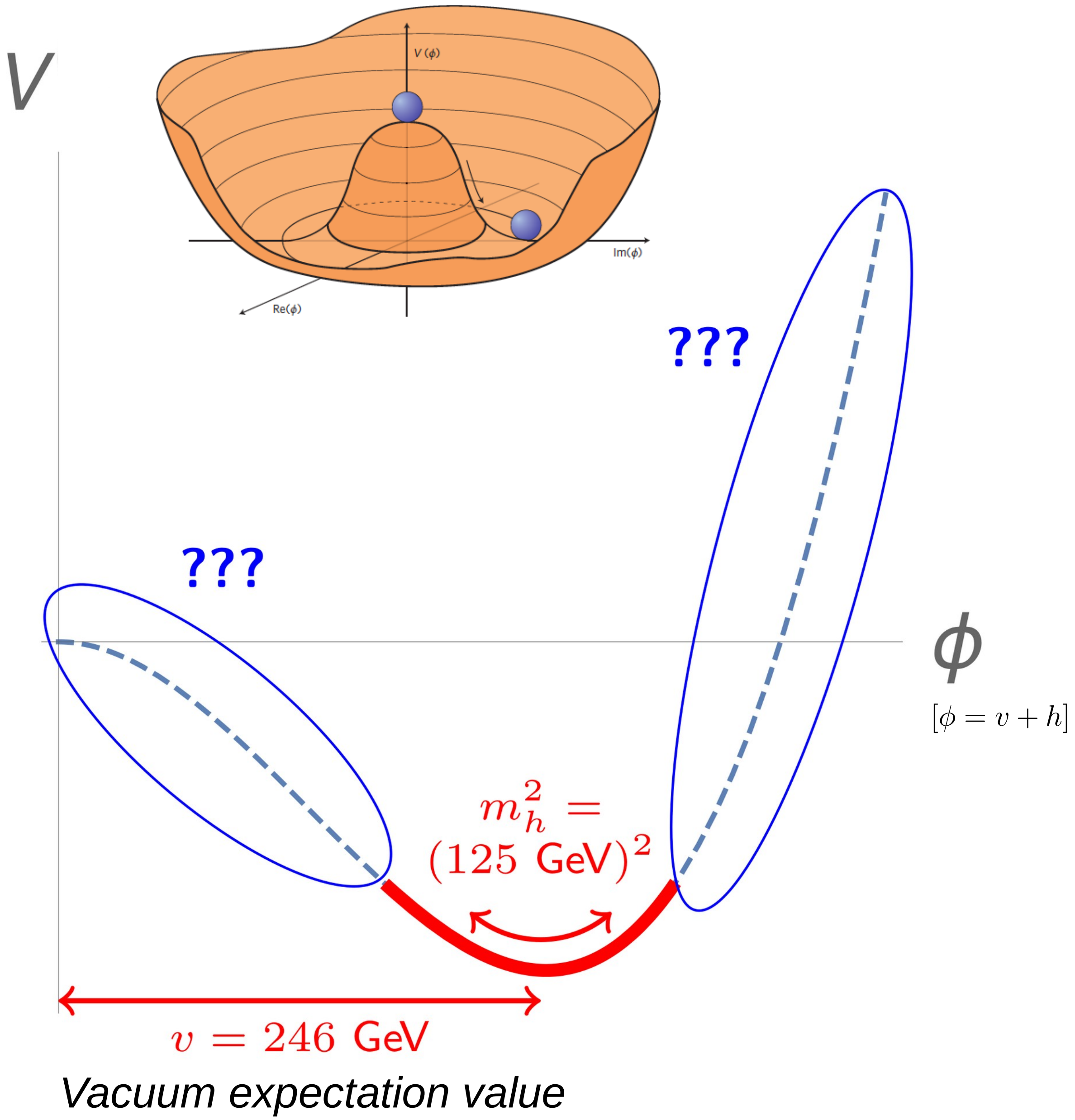
- Introduction: Why study the trilinear Higgs coupling λ_{hhh}
- λ_{hhh} in BSM models with extended scalar sectors
- Could BSM Physics be found first in λ_{hhh}?

Why investigate λ_{hhh}?



Form of the Higgs potential and trilinear Higgs coupling

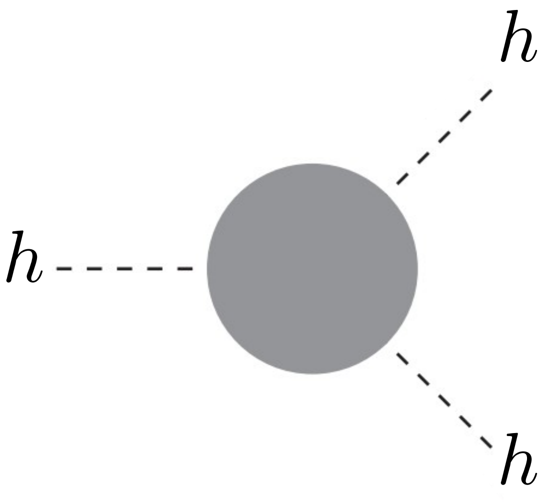
- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)

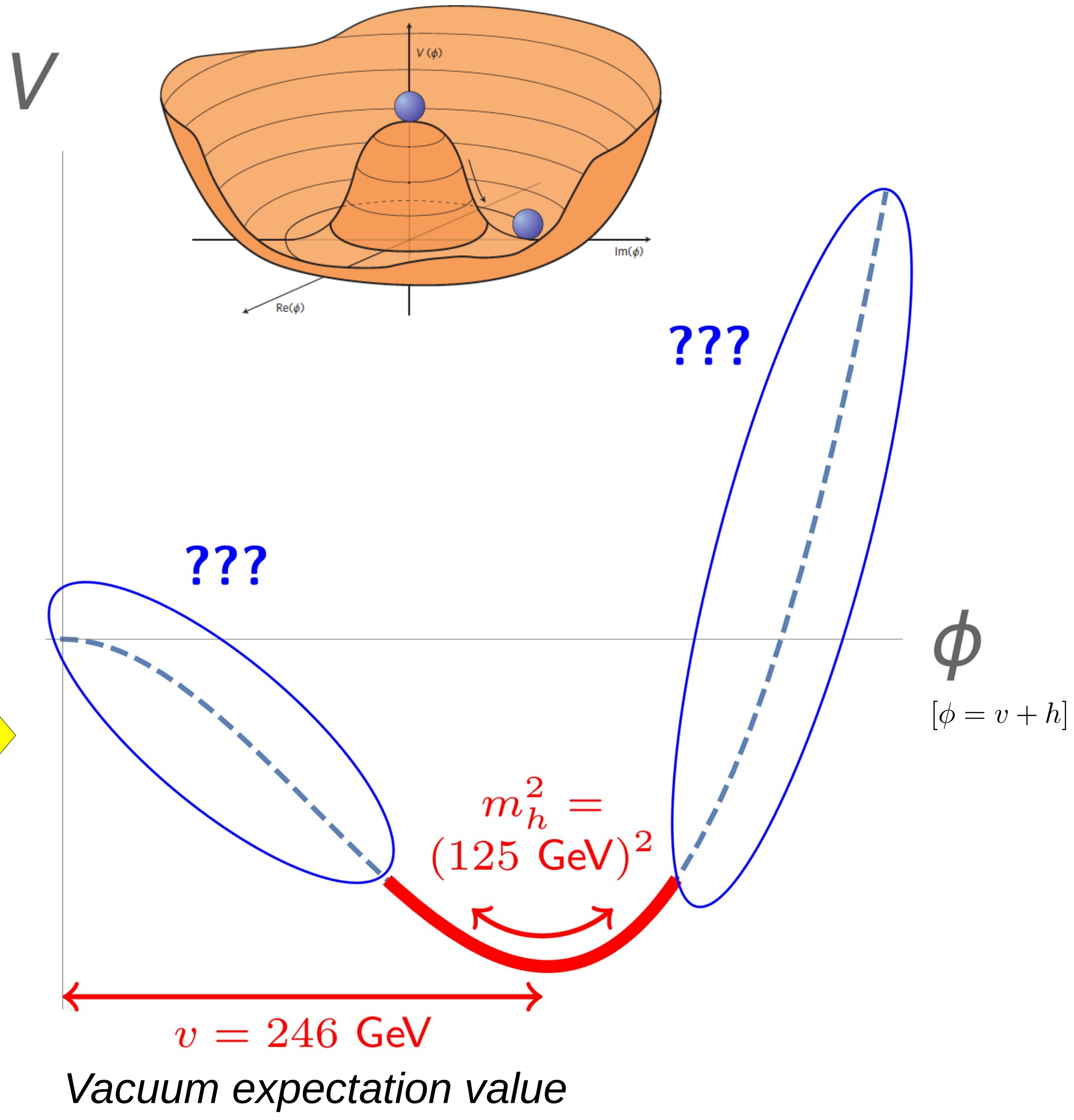


Form of the Higgs potential and trilinear Higgs coupling

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

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



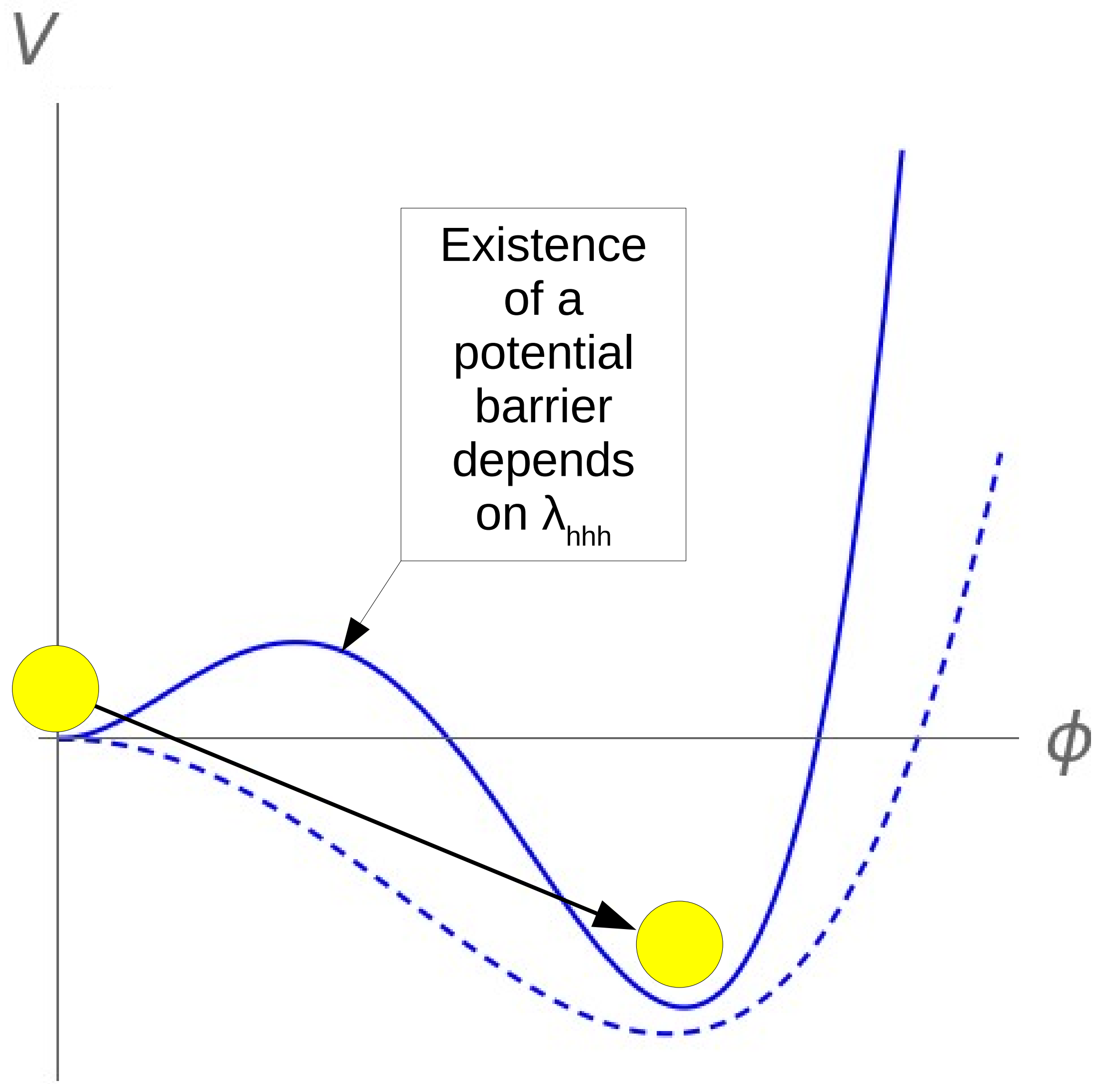


Form of the Higgs potential and baryon asymmetry

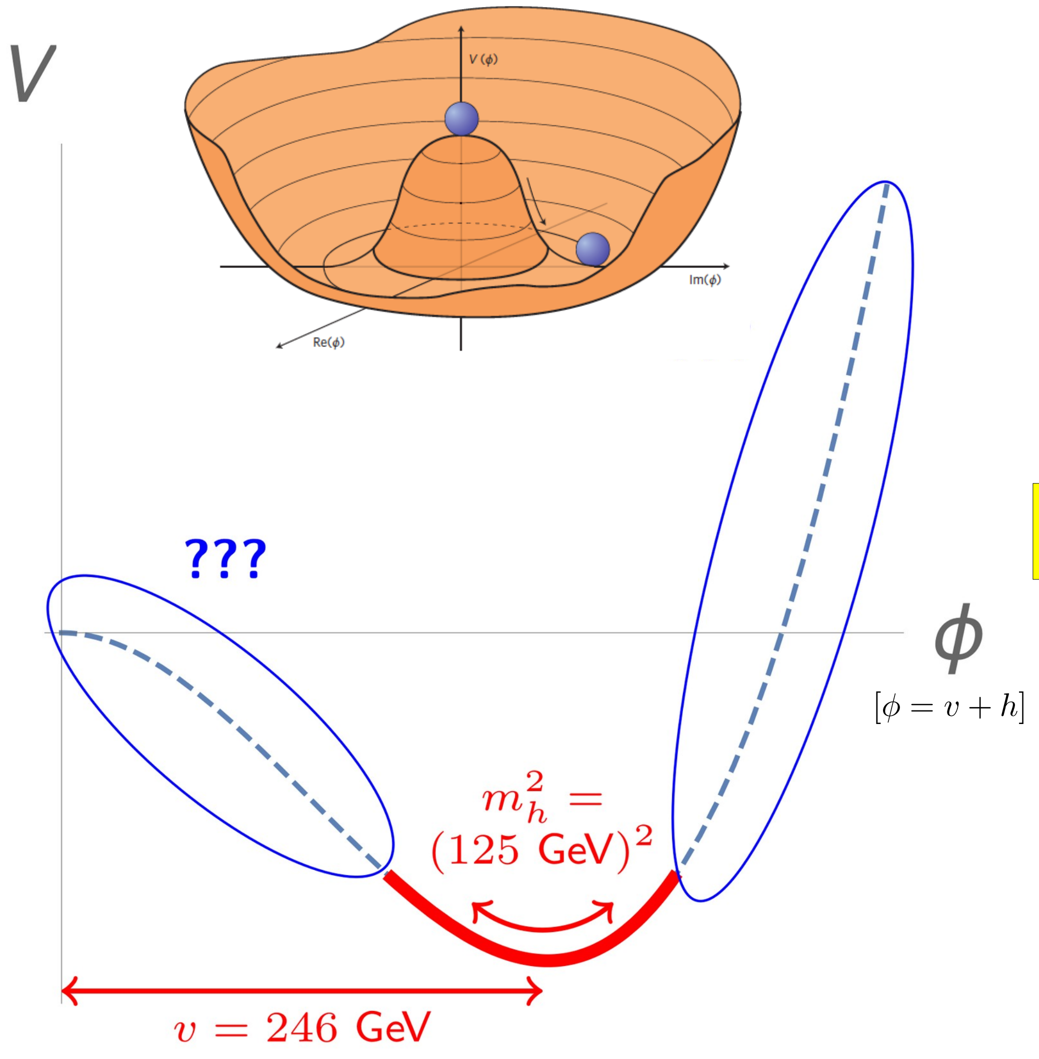
- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)

- **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*

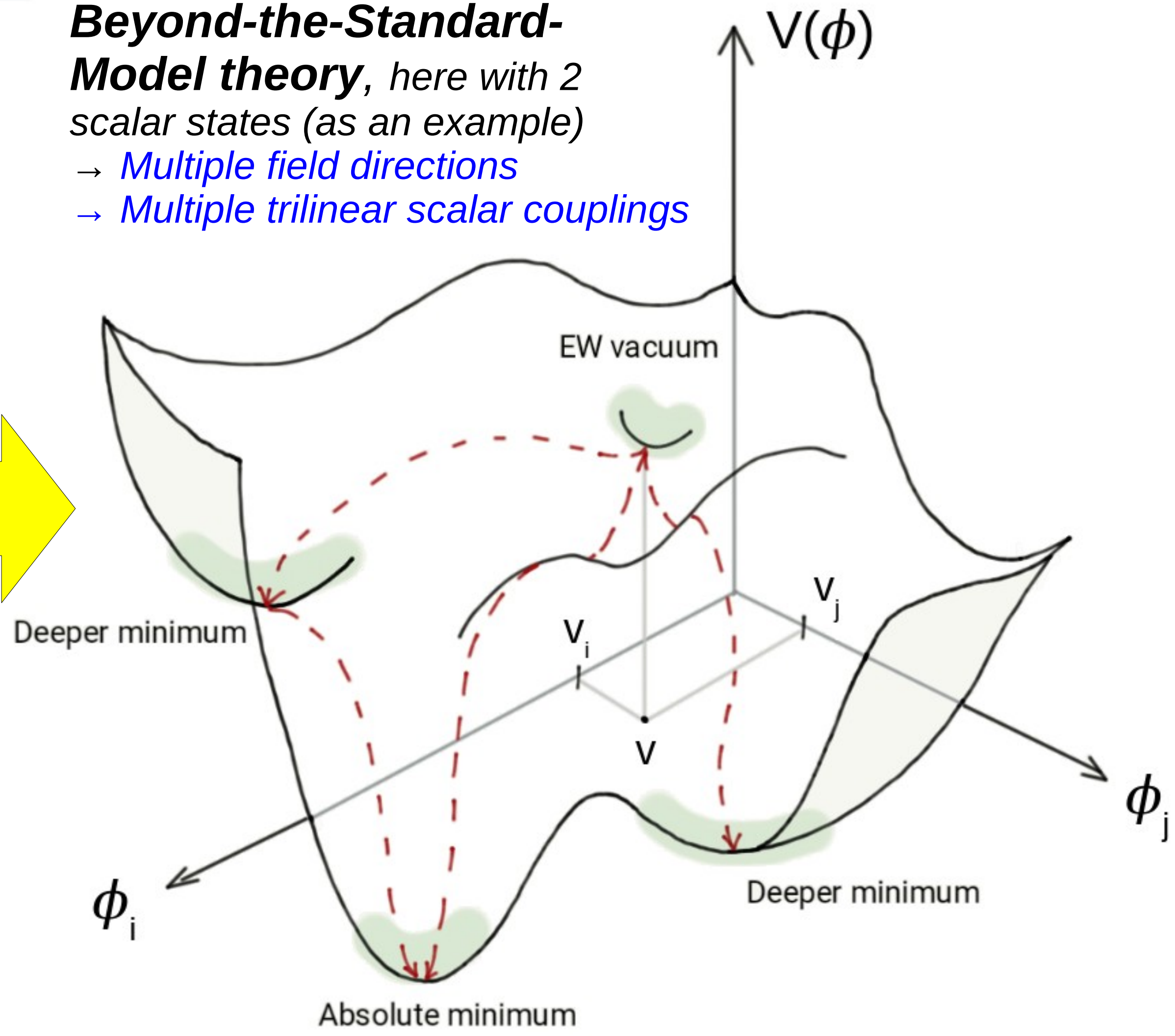


Figure by [K. Radchenko Serdula ‘24]

λ_{hhh} in models with extended scalar sectors

The Two-Higgs-Doublet Model

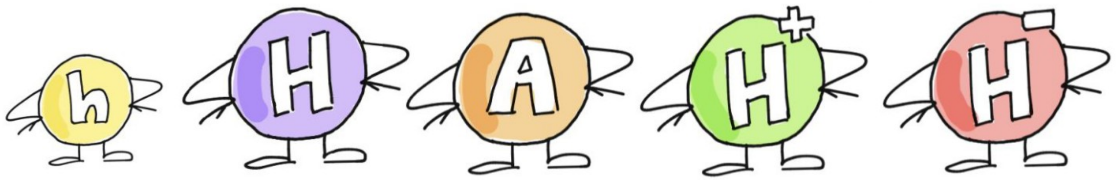


Figure by [K. Radchenko Serdula '24]

- 2 $SU(2)_L$ doublets $\Phi_{1,2}$ of hypercharge ½
- CP-conserving 2HDM, with softly-broken Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) to avoid tree-level FCNCs

$$V^{(0)}_{\text{2HDM}} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \frac{\lambda_5}{2}\Big((\Phi_2^\dagger\Phi_1)^2 + \text{h.c.}\Big)$$

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

- **Mass eigenstates**:
  h, H: CP-even Higgs bosons *(h → 125-GeV SM-like state);* A: CP-odd Higgs boson;
  $H^\pm$: charged Higgs boson

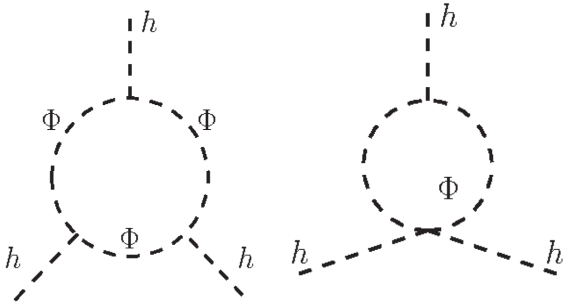
- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv 2m_3^2/s_{2\beta}$), angles α (CP-even Higgs mixing angle) and β (defined by $\tan\beta = v_2/v_1$)

- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

- We take the **alignment limit α = β - π/2** → all Higgs couplings are SM-like at tree level

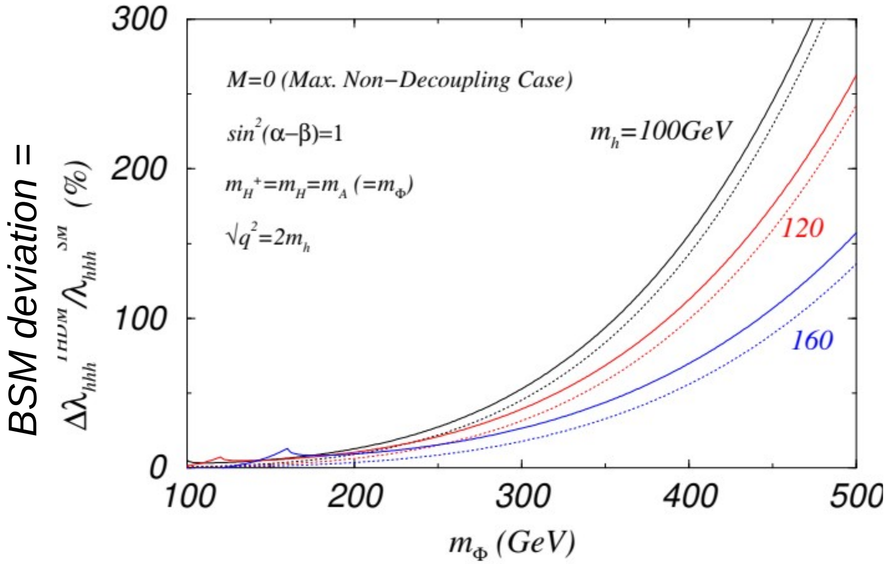
Mass splitting effects in λ_{hhh}

- First investigation of 1L BSM contributions to λ_{hhh} in 2HDM: [Kanemura, (Kiyoura), Okada, Senaha, Yuan '02, '04]



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

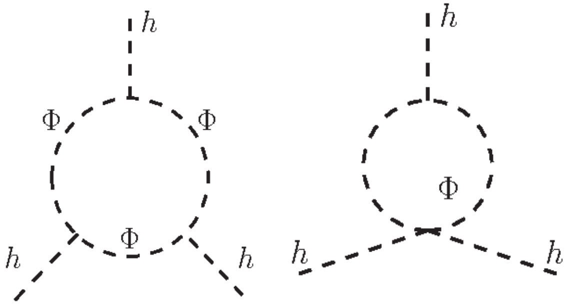
$(\Phi \in \{H, A, H^\pm\})$



- **Deviations of tens/hundreds of % from SM possible,** for **large $g_{h\Phi\Phi}$ or $g_{hh\Phi\Phi}$ couplings**
- **Mass splitting effects**, now found in various models (2HDM, inert doublet model, singlet extensions, etc.)

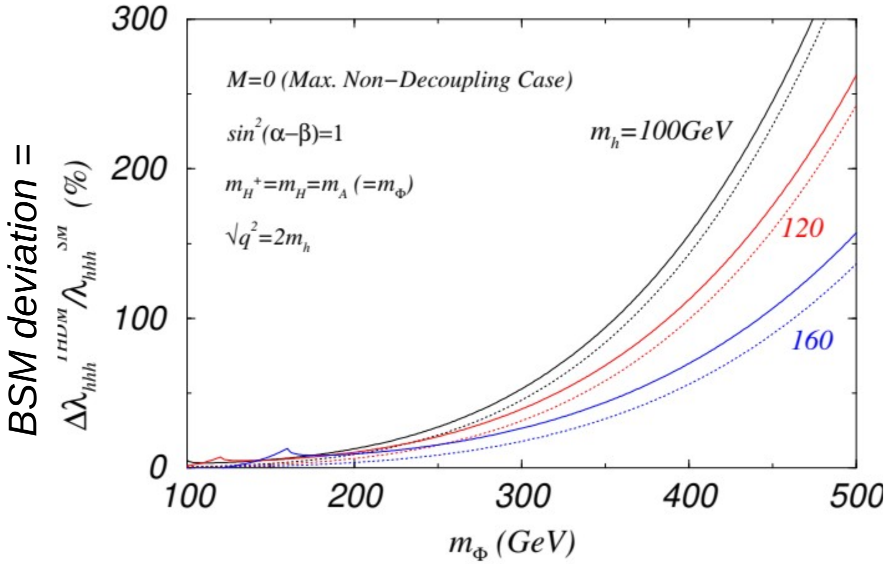
Mass splitting effects in λ_{hhh}

- First investigation of 1L BSM contributions to λ_{hhh} in 2HDM: [Kanemura, (Kiyoura), Okada, Senaha, Yuan '02, '04]

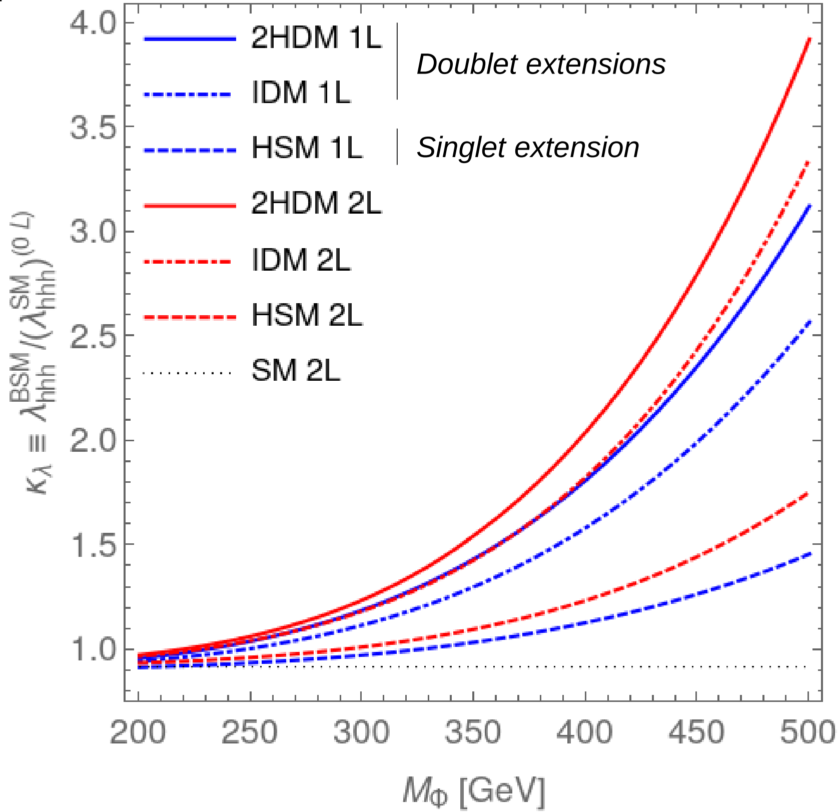


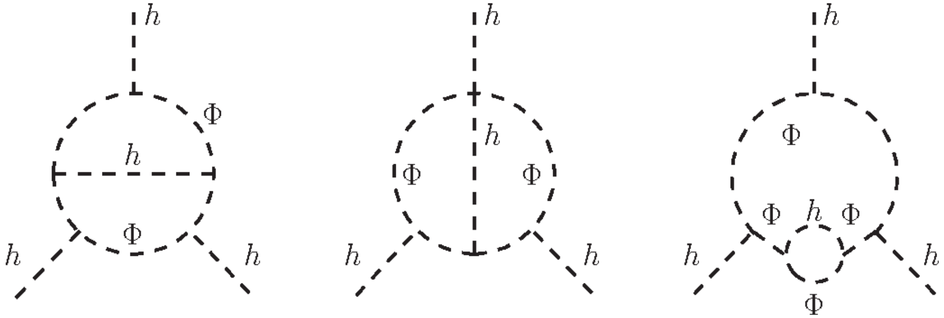
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

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



- Large effects **confirmed at 2L** in [JB, Kanemura '19]
→ leading 2L corrections involving BSM scalars (H,A,H±) and top quark, computed in effective potential approximation

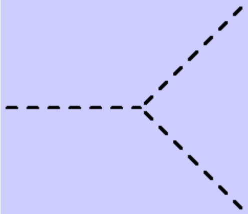
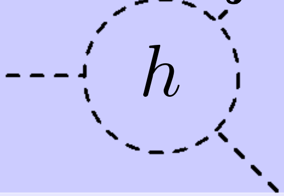
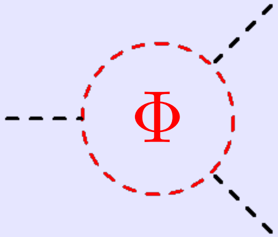
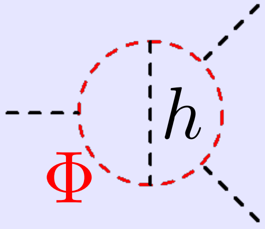
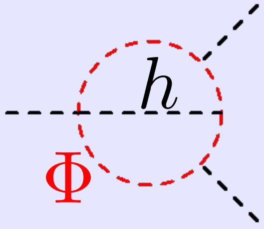
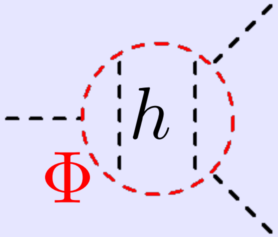
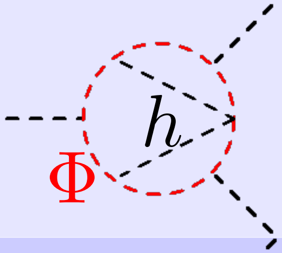
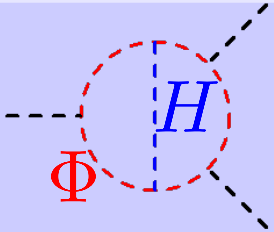
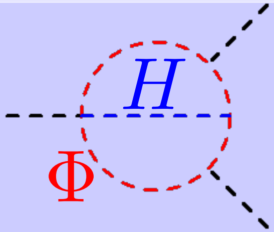
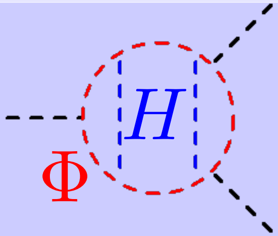
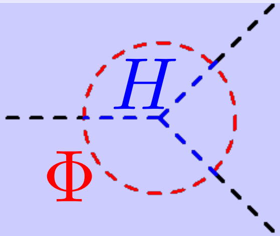
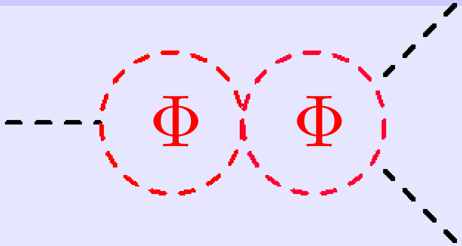
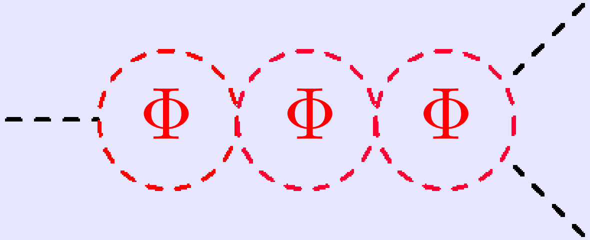




- **Deviations of tens/hundreds of % from SM possible,** for **large $g_{h\Phi\Phi}$ or $g_{hh\Phi\Phi}$ couplings**
- **Mass splitting effects**, now found in various models (2HDM, inert doublet model, singlet extensions, etc.)

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]

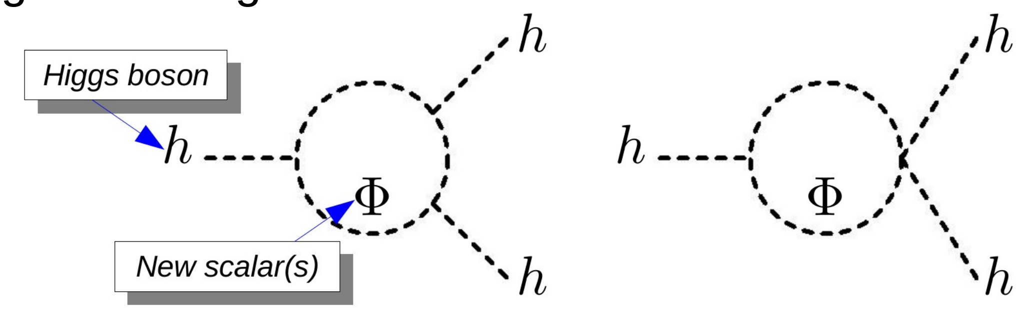
→ *no further type of coupling entering after 2L*

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

e.g. in [Bahl, JB, Weiglein PRL '22]

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



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

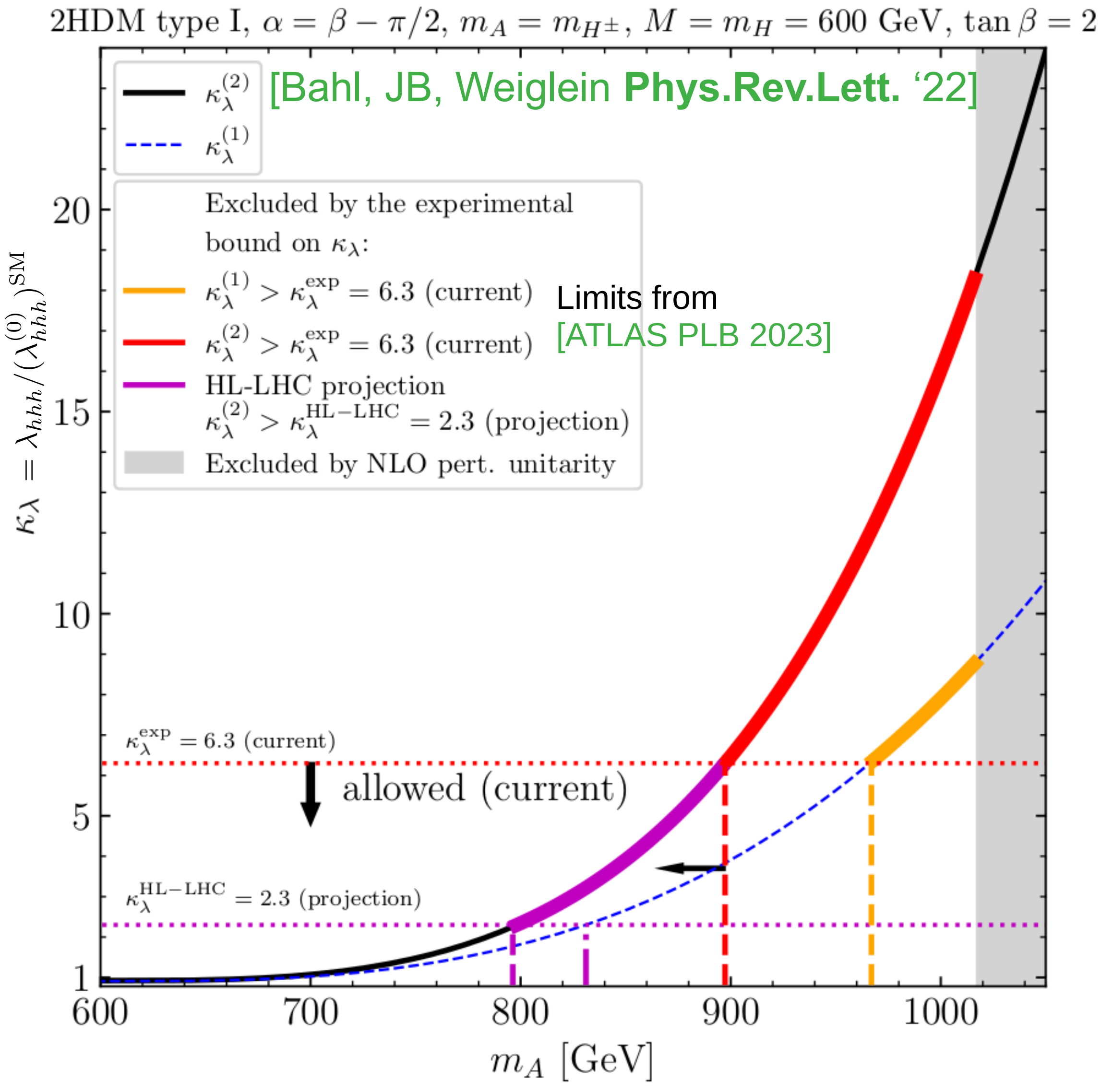
- Comparing latest exp. bounds

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

[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]



Mass splitting effects for various BSM models with `anyH3`

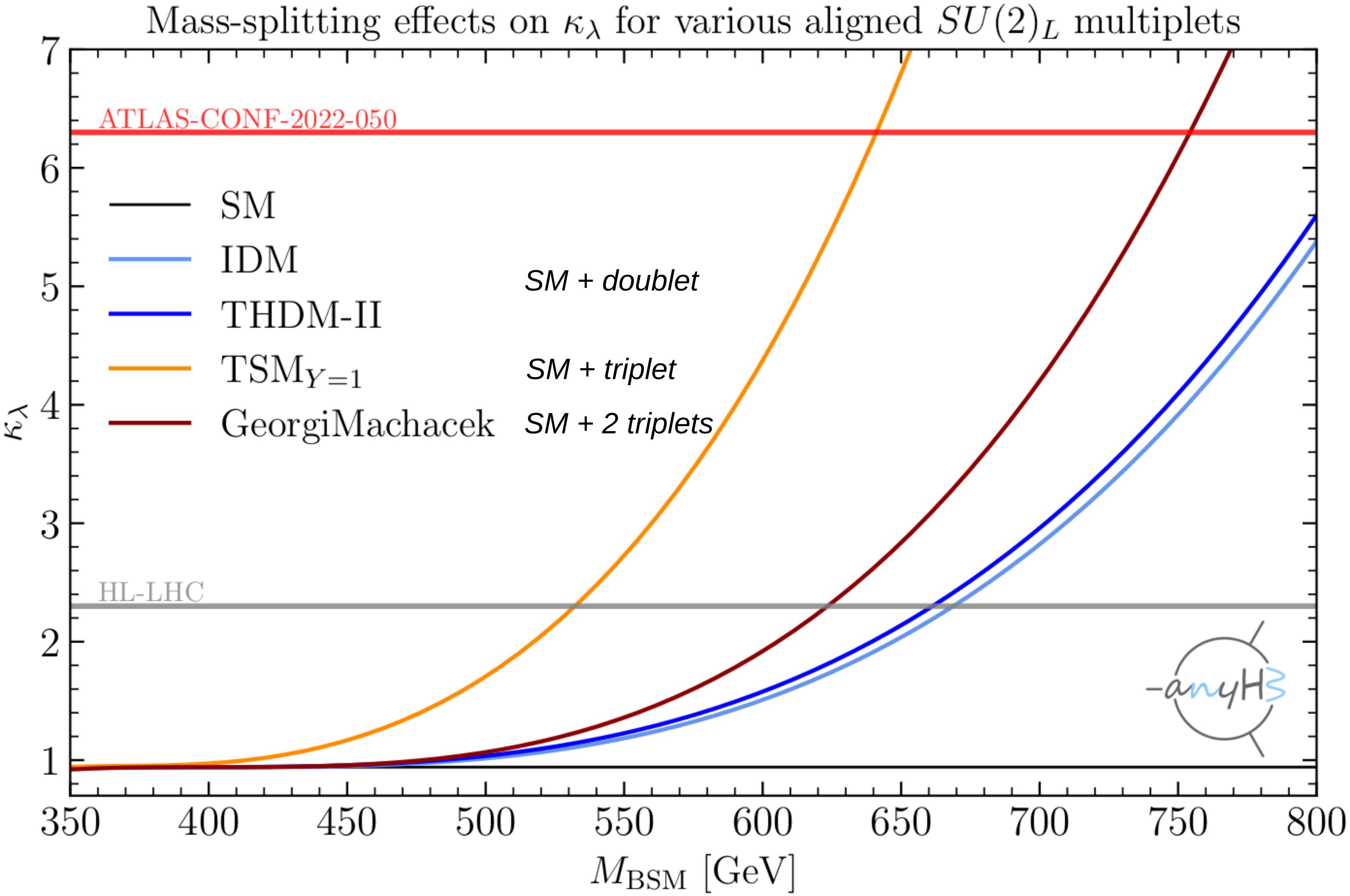
- `anyH3` [Bahl, JB, Gabelmann, Weiglein '23]: public tool for full one-loop calculation of λ_{hhh} in arbitrary renormalisable models, using UFO inputs (*more details in backup*)

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

- 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}

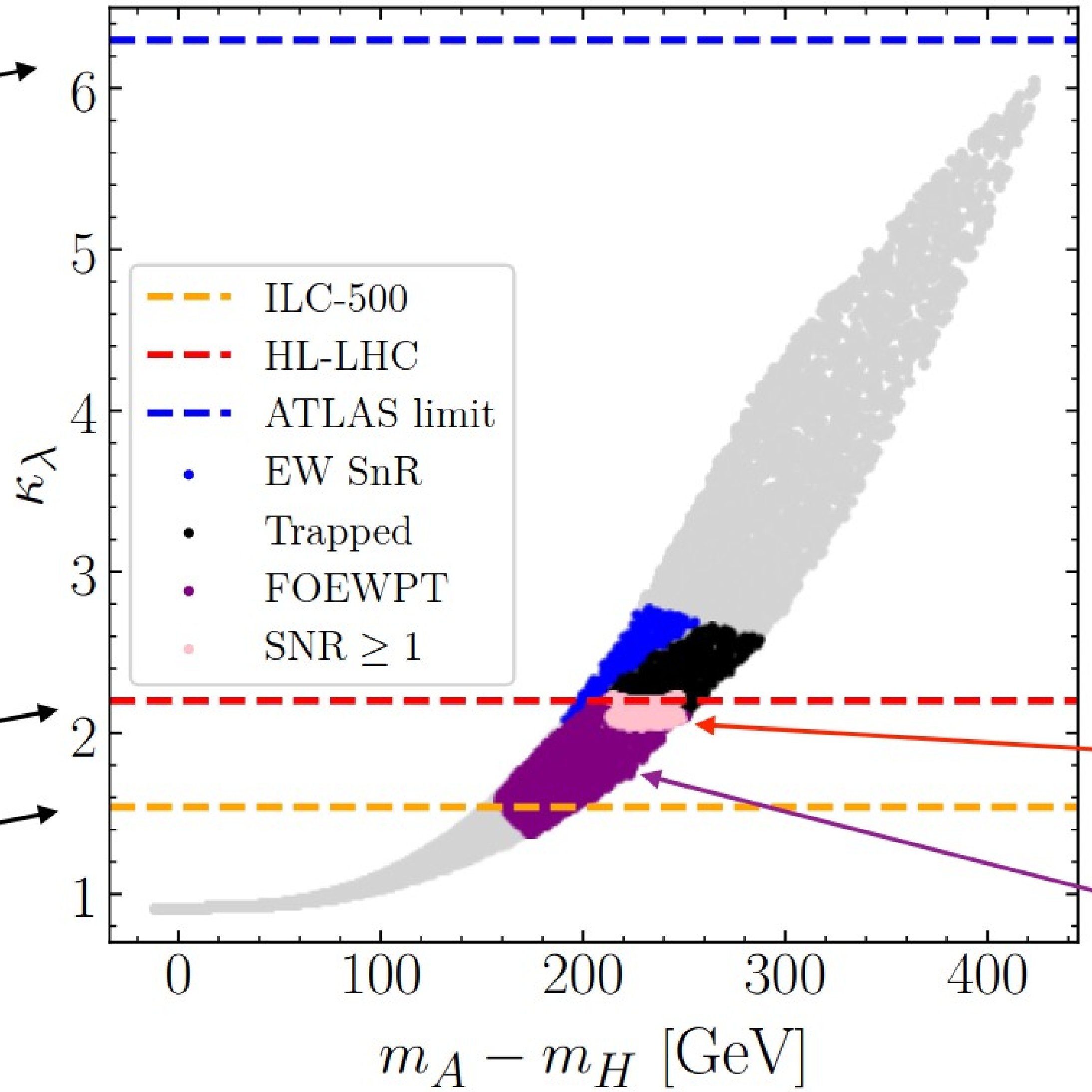
Relation between κ_λ and strong first-order EWPT

[Biekötter, Heinemeyer, No, Olea, Weiglein '22]

Current LHC bound

HL-LHC sensitivity

ILC sensitivity



2HDM

- Alignment limit α=β-π/2
- t_β=3
- κ_λ computed at 1L

region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

- **Region with a strong first-order EWPT and a potentially detectable GW signal is correlated with significant BSM deviation in κ_λ**

Could BSM Physics be detected first in κ_λ ?

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

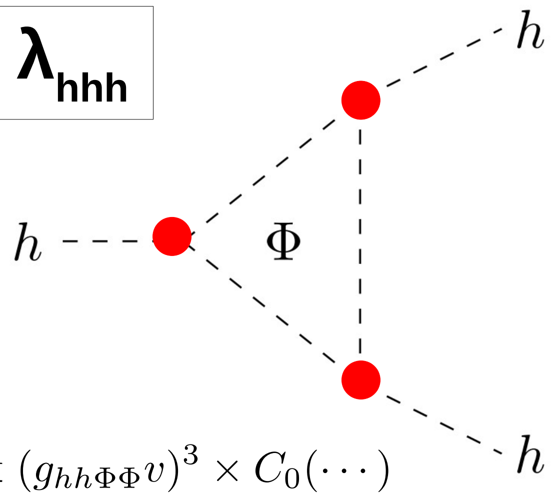
ii. *Example 1: Correlation κ_λ vs $\Gamma(h\to\gamma\gamma)$ in an Inert Doublet Model*

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

BSM effects in Higgs couplings: power counting (1L)

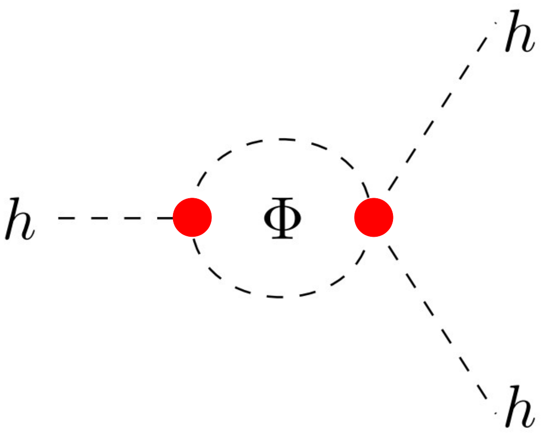
$M^2_{\rm BSM} = \mathcal{M}^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$

λ_{hhh}



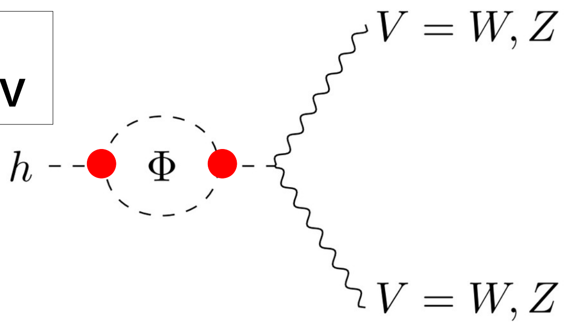
$\propto (g_{hh\Phi\Phi} v)^3 \times C_0(\cdots)$

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



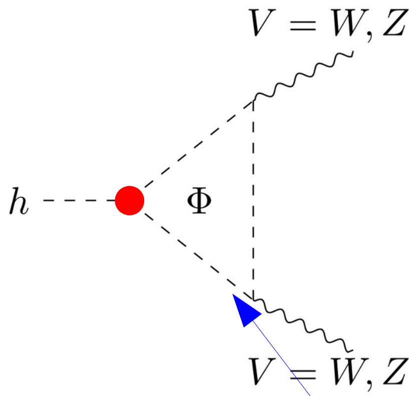
$\propto g^2_{hh\Phi\Phi} v \times \underbrace{B_0(\cdots)}_{\text{mass. dim. 0}} \sim \mathcal{O}(g^2_{hh\Phi\Phi})$

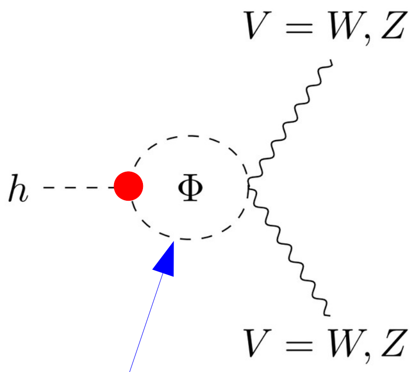
g_{hVV}



$\propto (g_{hh\Phi\Phi} v)^2 \times g_{\rm EW} \times B'_0(\cdots)$

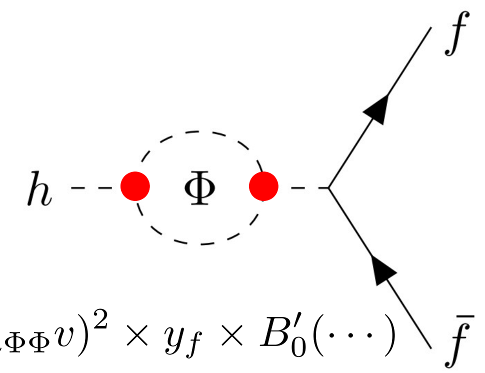
$\propto \frac{(g_{hh\Phi\Phi} v)^2}{m^2_\Phi} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi})$





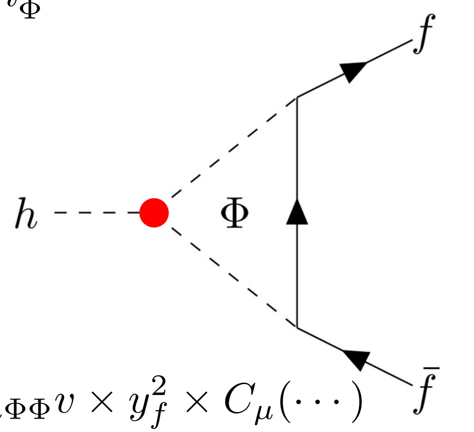
$\propto g_{hh\Phi\Phi} v \times g^2_{\rm EW} \times \underbrace{\{C_{\mu\nu}(\cdots) \text{ or } B_0(\cdots)\}}_{\text{mass. dim. 0}} \sim \mathcal{O}(g_{hh\Phi\Phi})$

$g_{hf\bar{f}}$



$\propto (g_{hh\Phi\Phi} v)^2 \times y_f \times B'_0(\cdots)$

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



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

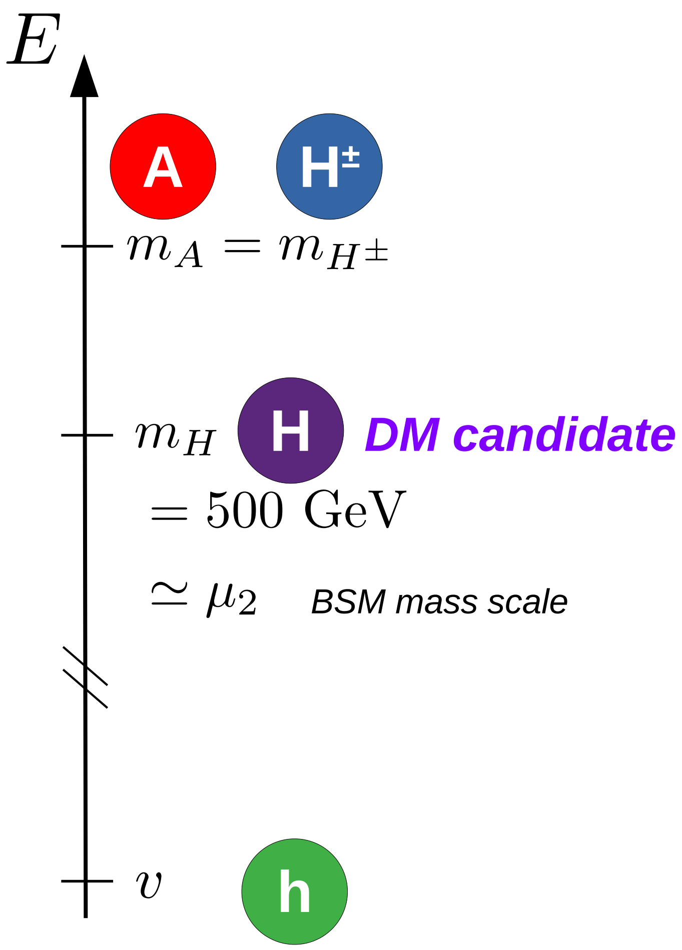
$\sim \frac{g_{hh\Phi\Phi} v}{m_\Phi} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} O(g^{1/2}_{hh\Phi\Phi})$

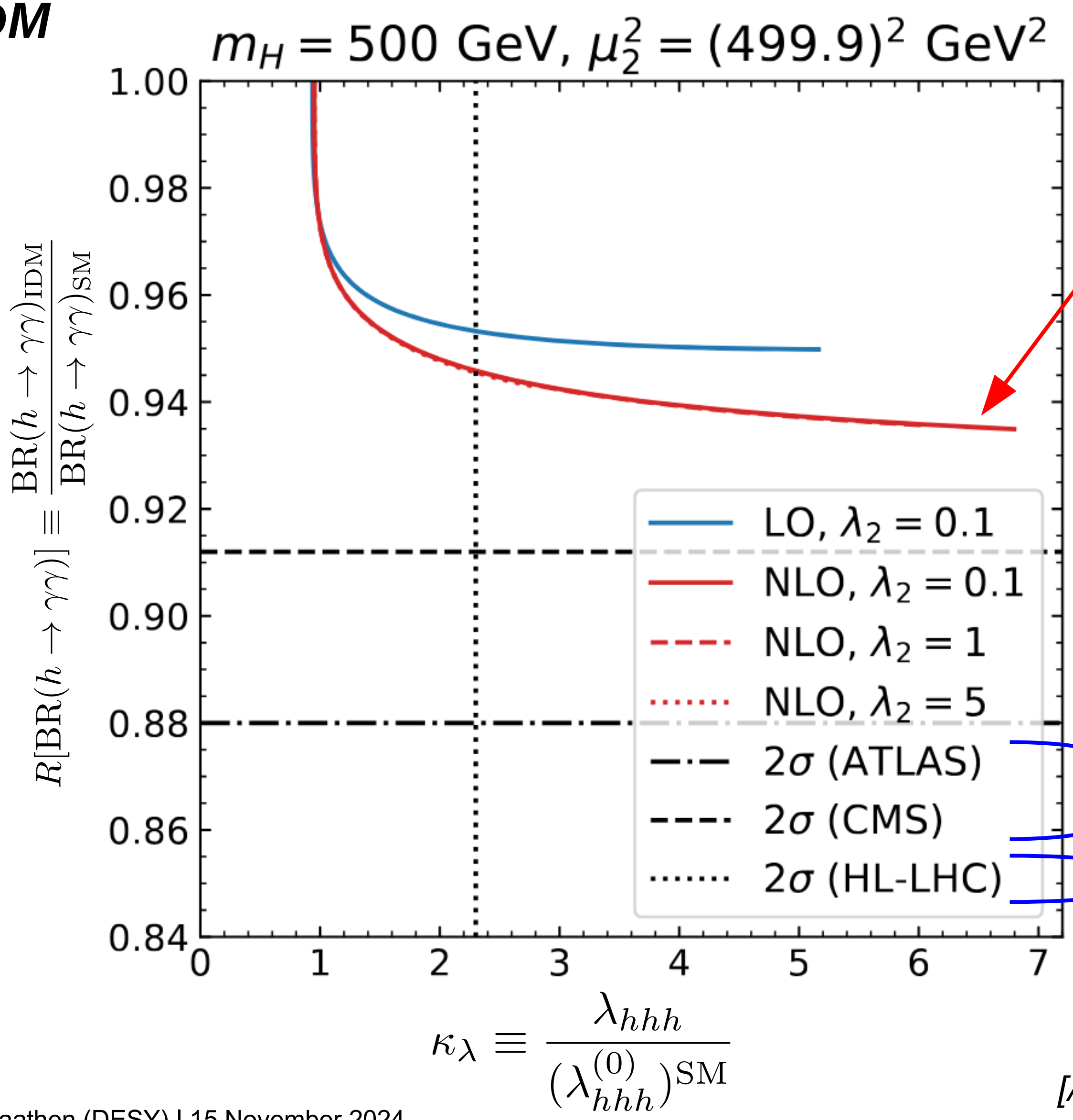
__Note__: similar arguments can be made from EFT perspective

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

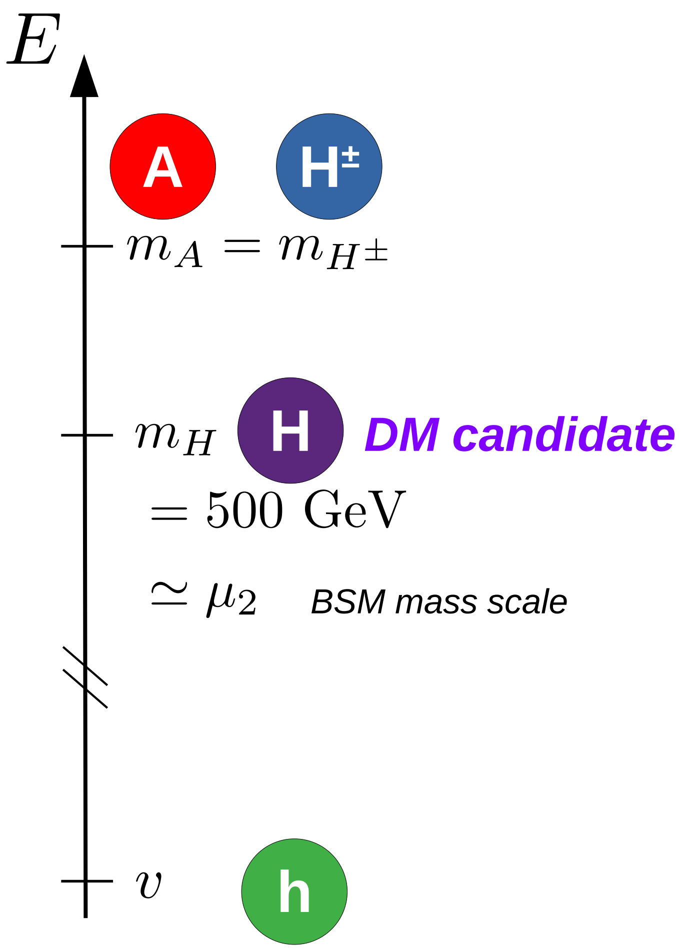
Expected bound on κ_λ at HL-LHC

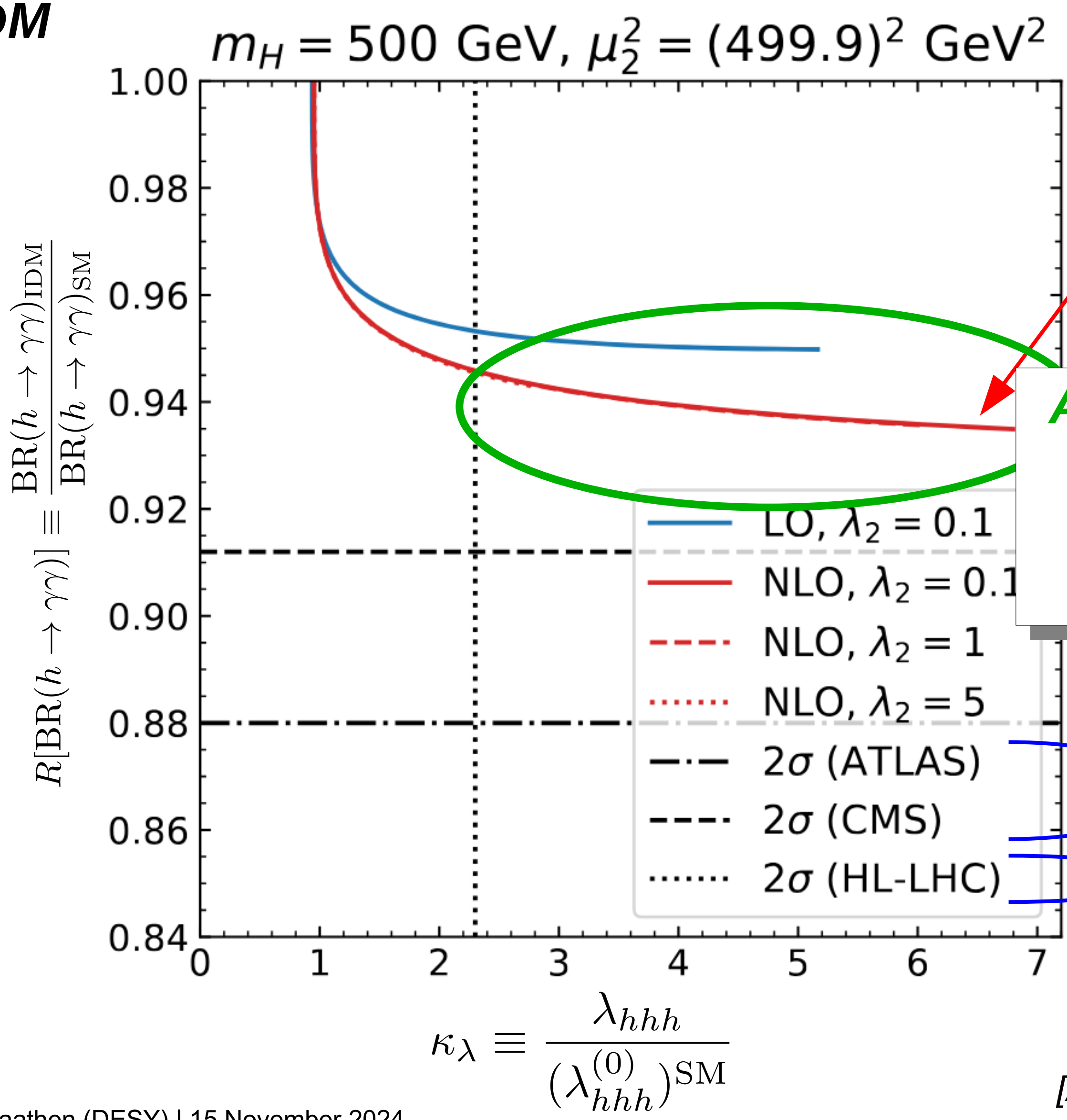
[λ_2 : inert doublet self-coupling]

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.)

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 ?

	$\Delta BR/BR(h \to \gamma\gamma)$ 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*

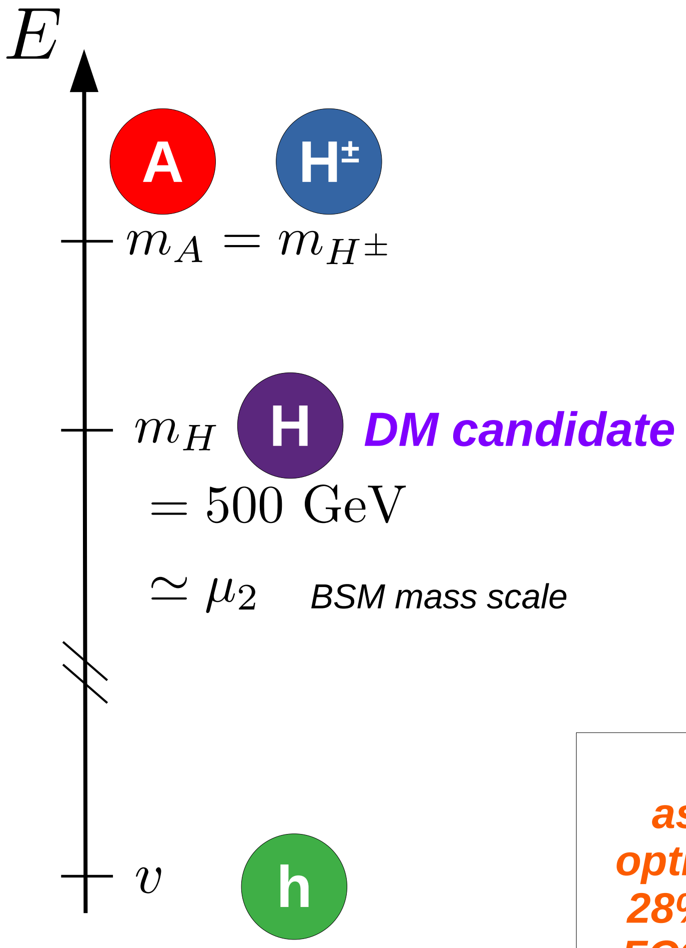
[Given here: 1σ prospects]

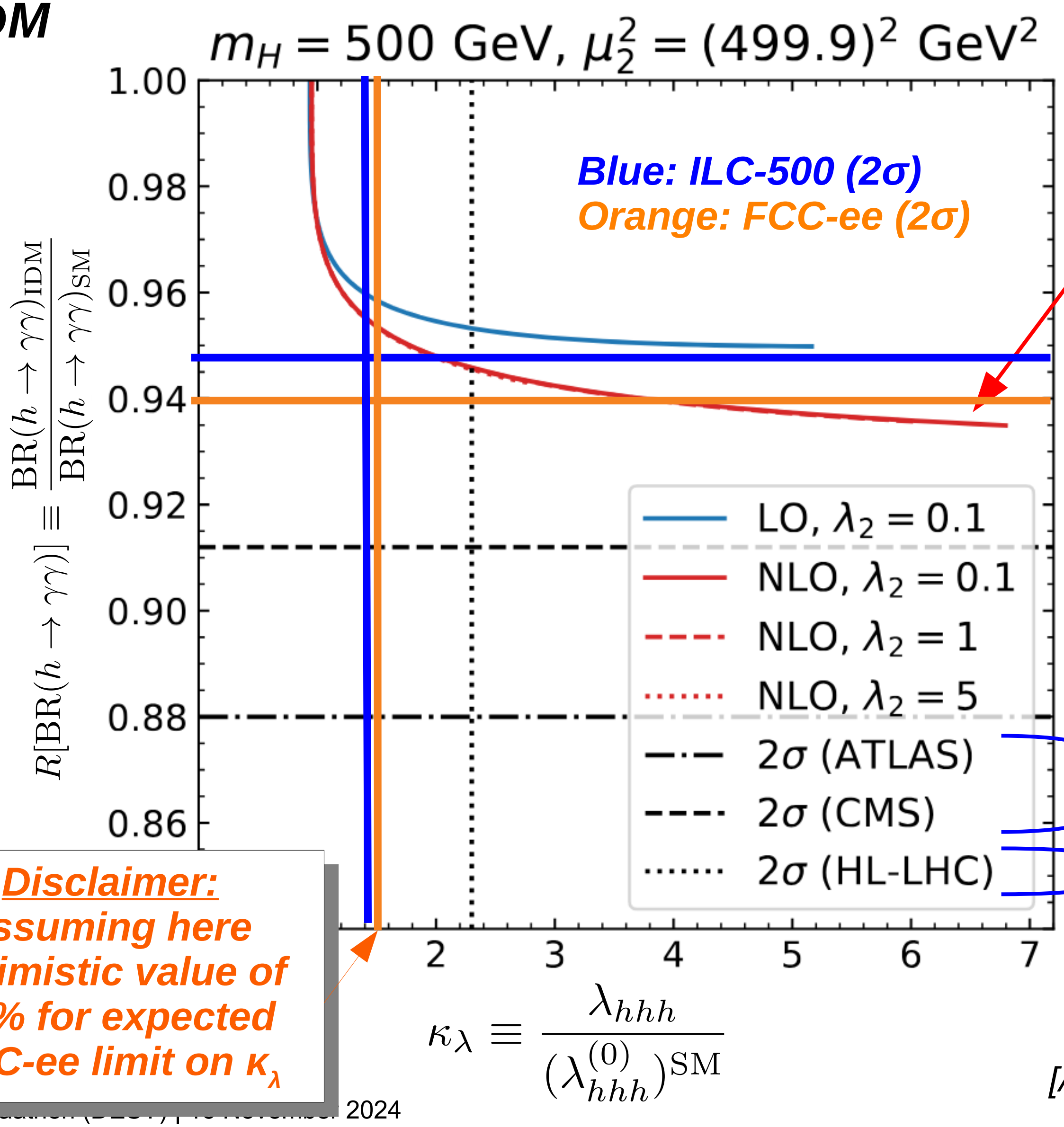
[1] "Physics Case for the 250 GeV Stage of the International Linear Collider," Fujii, Grojean, Peskin et al., 1710.07621
[2] "Higgs physics opportunities at the Future Circular Collider," G. Marchiori, talk at ICHEP 2024
[3] "Higgs Boson studies at future particle colliders," de Blas et al., 1905.03764
[4] B. Bliewert, J. List et al. 2024
[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.)

***Disclaimer:* assuming here optimistic value of 28% for expected FCC-ee limit on κ_λ**

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

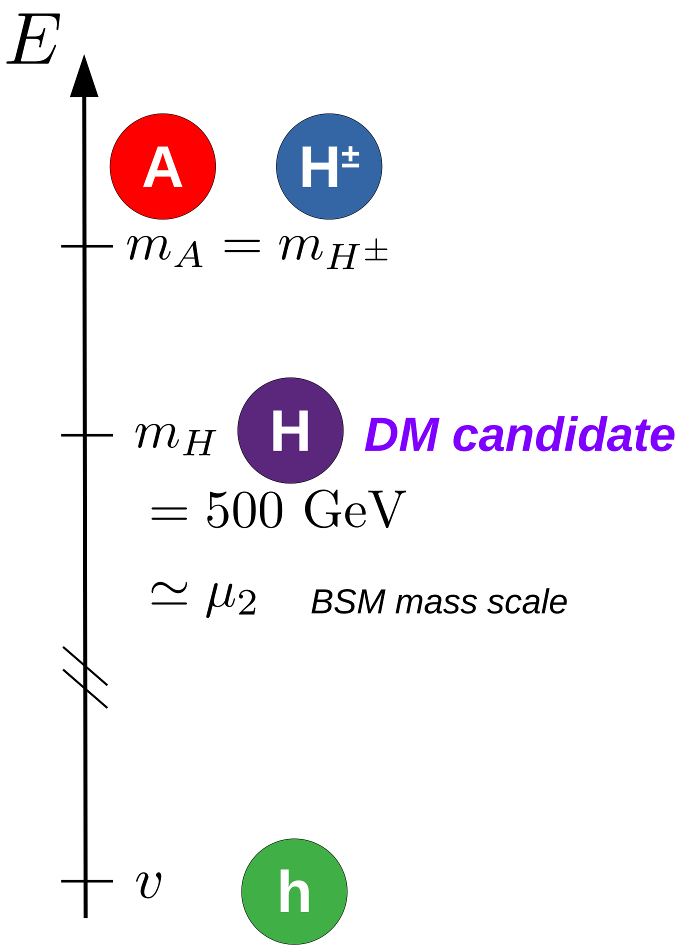
Expected bound on κ_λ at HL-LHC

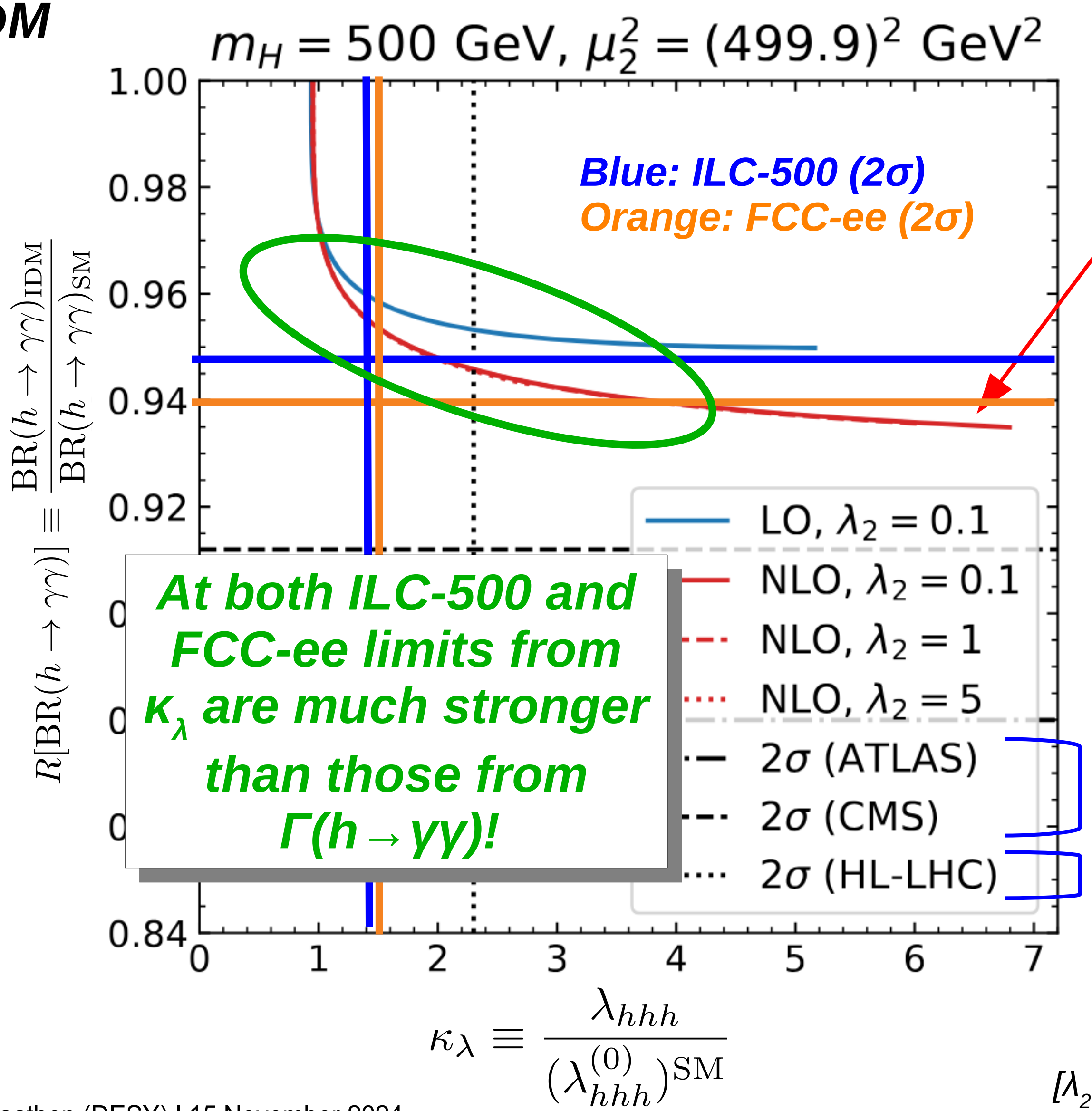
[λ_2 : inert doublet self-coupling]

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

[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→γγ)	λ_{hhh}
ILC-250	4.5%	*Indirect*
ILC-500	2.6%	23%
FCC-ee	3.1%	*Indirect*

[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

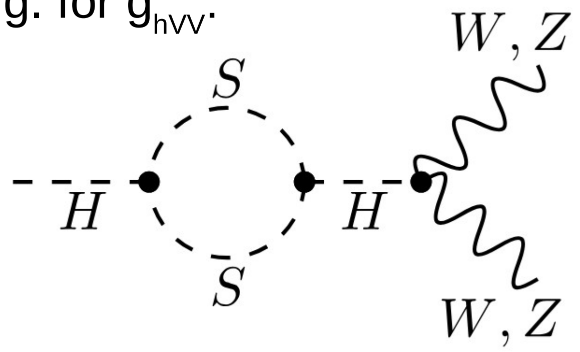
$$V_{\mathrm{SSM}-\mathbf{Z}_2}(\Phi, S) = V_{\mathrm{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi \qquad m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$$

- 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}:

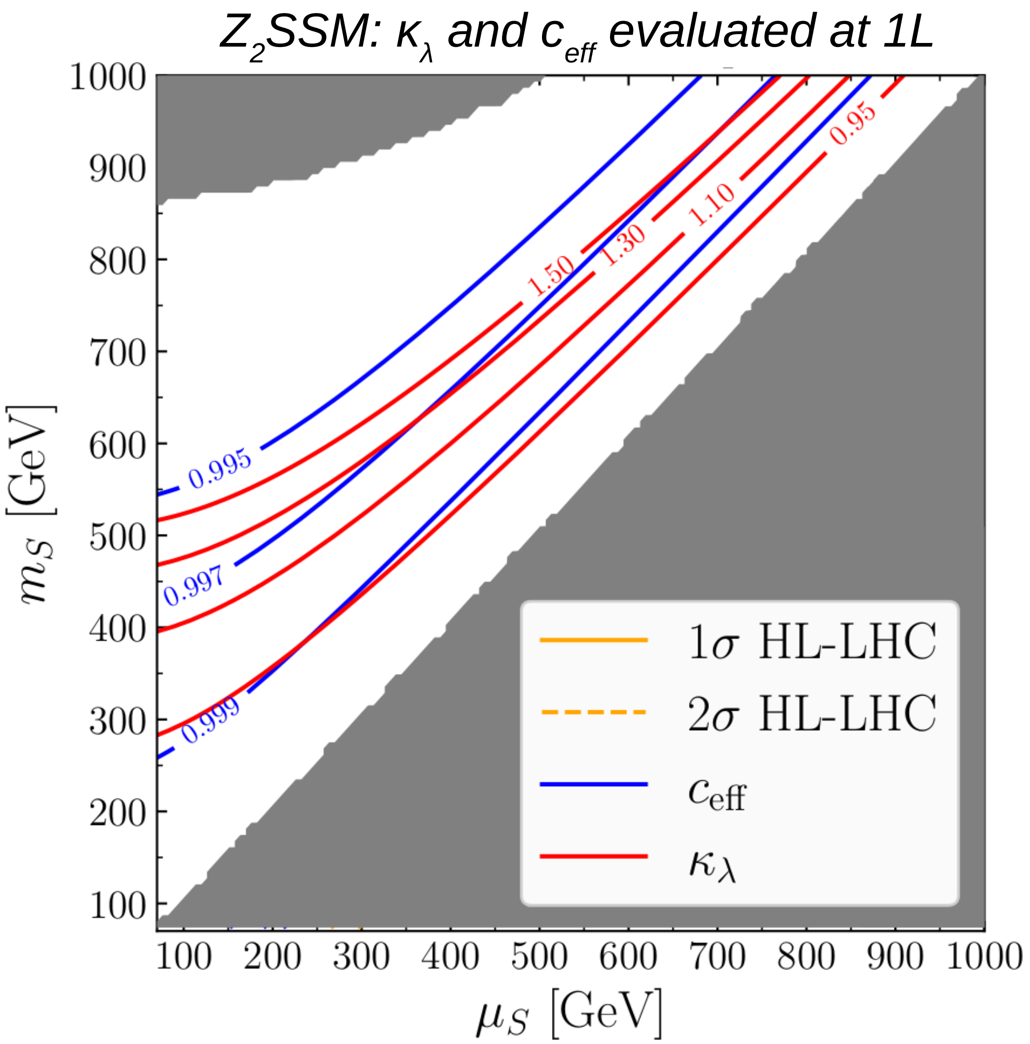


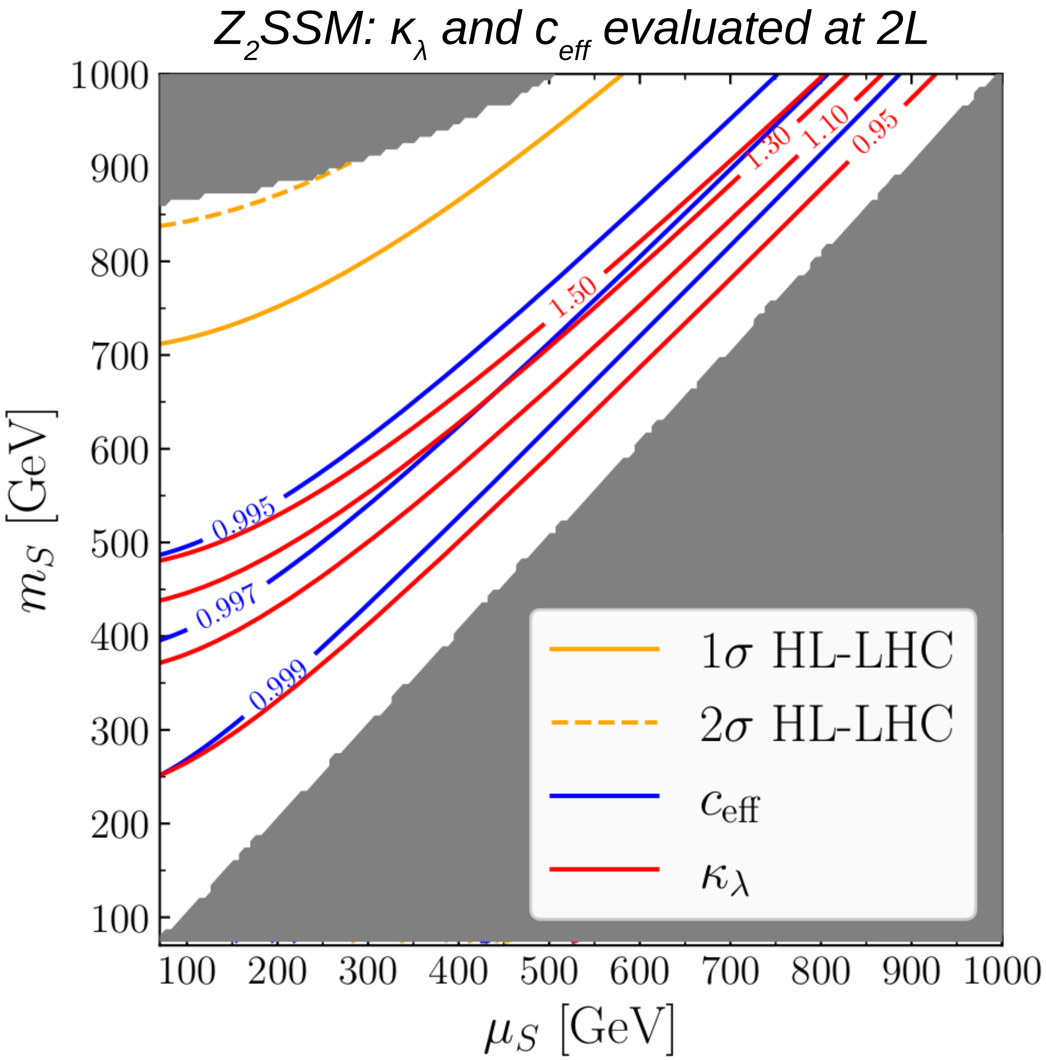
$$c_{\mathrm{eff}}^{(1)} \equiv \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}} \simeq 1 - \frac{m_S^2}{16\pi^2 v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

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

Effective couplings in the Z_2SSM

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

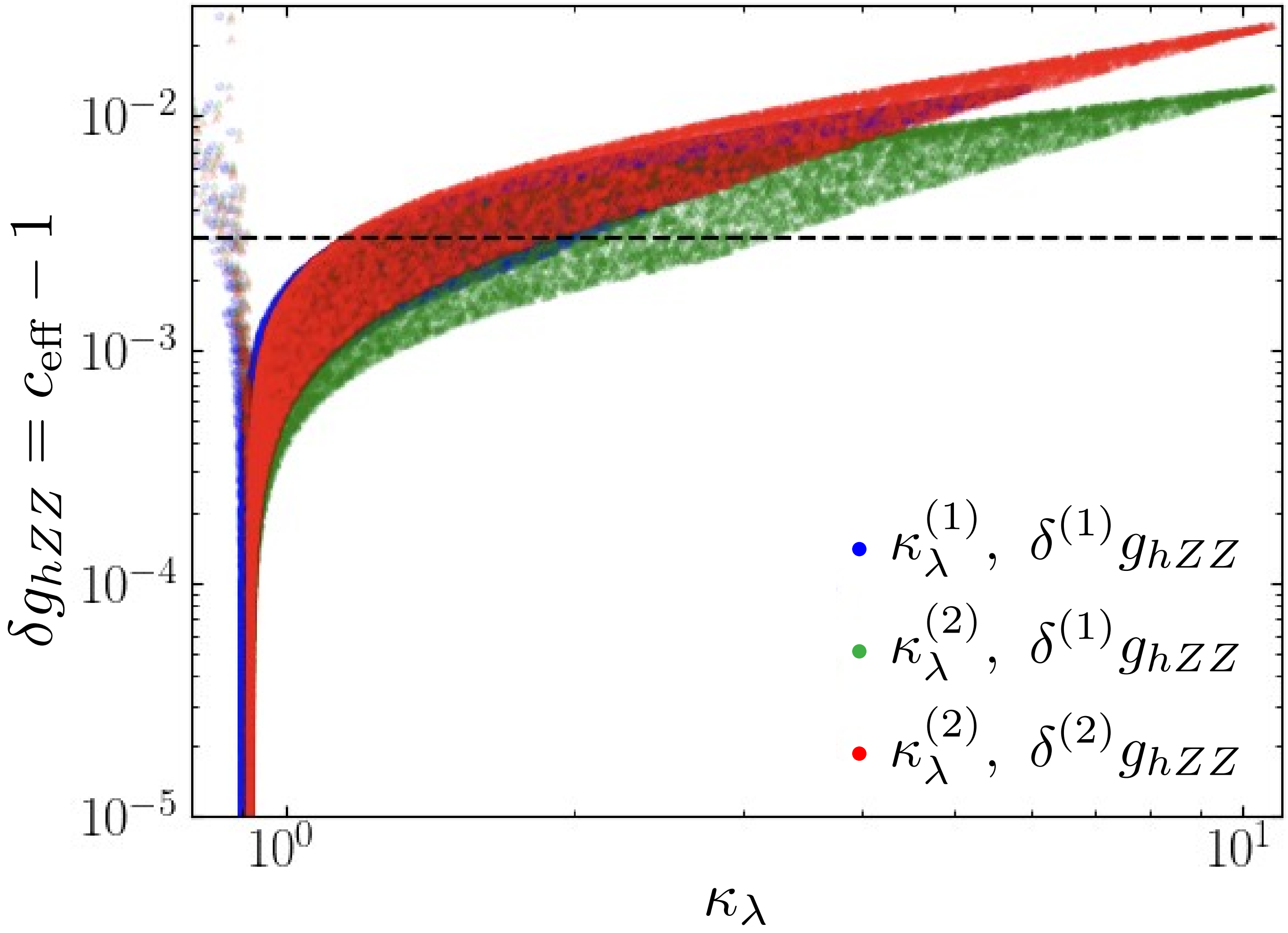




- HL-LHC: no bound with 1L c_{eff}, only weak bound with 2L c_{eff}
- O(50%) accuracy on κ_λ is stronger than O(0.5%) accuracy on c_{eff} (i.e. g_{hVV})
- O(20%) accuracy on κ_λ is competitive with O(0.3%) accuracy on c_{eff} (i.e. g_{hVV}) for most of the parameter plane

Effective couplings in the Z_2SSM – parameter scan

[Bahl, Bechtle, JB, Heinemeyer, List, Vellasco, Weiglein *WIP*]



- Parameter scan of Z_2SSM
- Leading 1L and 2L corrections included in λ_{hhh} and g_{hZZ}
- Values of κ_λ up to ~2 possible while keeping δg_{hZZ} below 3‰

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 other precision measurements of Higgs properties like hZZ or hγγ*

Thank you very much for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

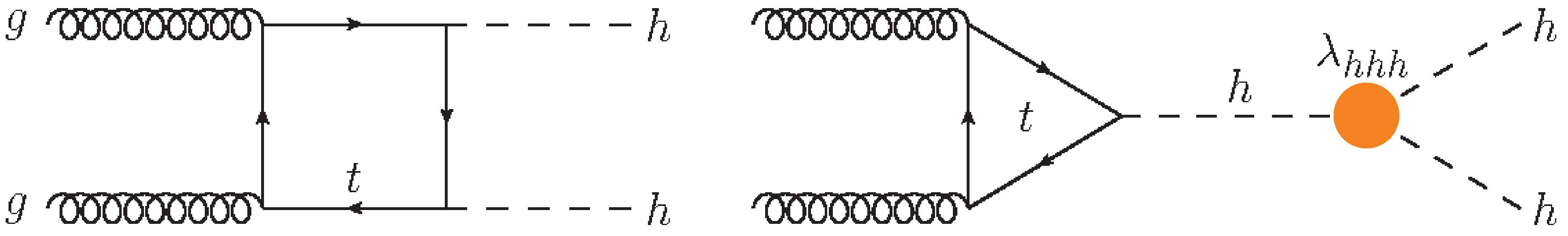
www.desy.de

Johannes Braathen
DESY Theory group
Building 2a, Room 208a
johannes.braathen@desy.de

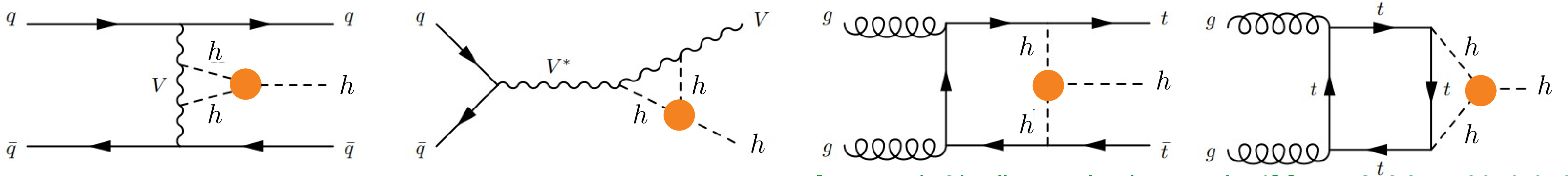
Backup

Experimental probes of λ_{hhh}

- **Double-Higgs production** → λ_{hhh} enters at <u>leading order (LO)</u> → **most direct probe!**

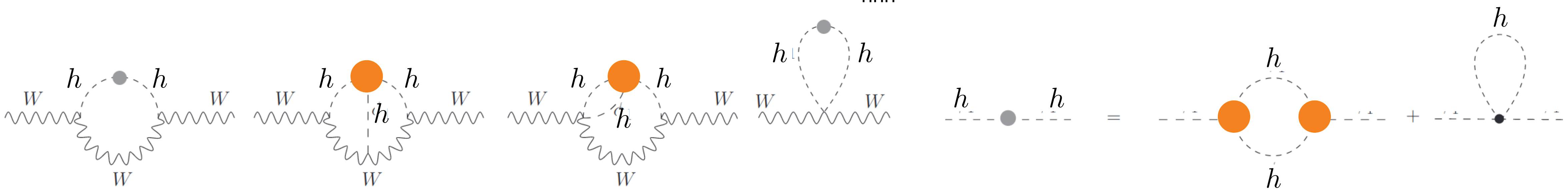


- **Single-Higgs production** → λ_{hhh} enters at <u>NLO</u>



[Degrassi, Giardino, Maltoni, Pagani '16] [ATLAS-CONF-2019-049]

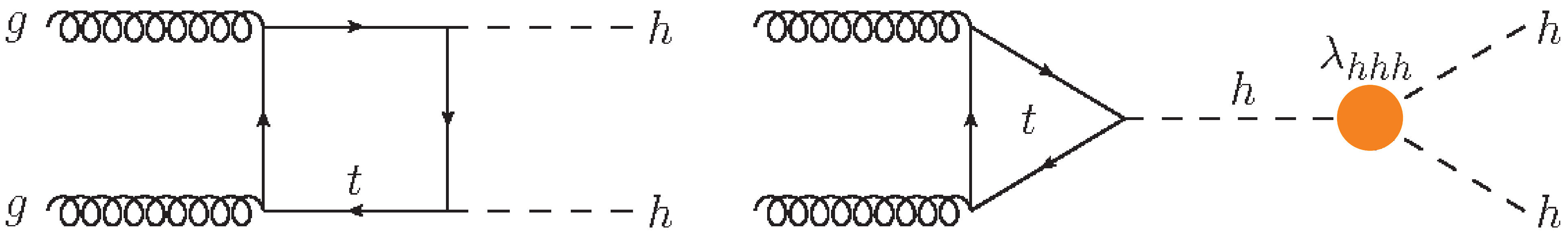
- **Electroweak Precision Observables** (EWPOs) → λ_{hhh} enters at <u>NNLO</u>



[Degrassi, Fedele, Giardino '17]

Accessing λ_{hhh} via di-Higgs production

- **Di-Higgs production** → λ_{hhh} enters at leading order (LO) → **most direct probe of λ_{hhh}**



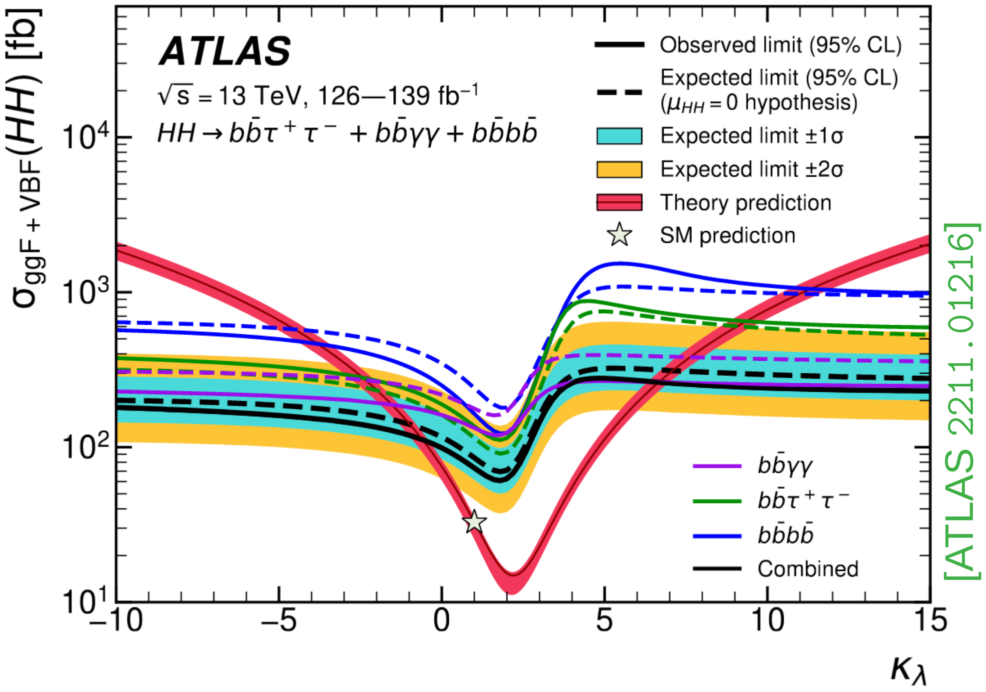
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

- Box and triangle diagrams **interfere destructively**
  → small di-Higgs cross-section σ_{hh} in SM

  → BSM deviation in λ_{hhh} can **significantly alter di-Higgs production!**

- Upper limit on di-Higgs cross-section
  → **limits on $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$**

- κ_λ as an *effective coupling*: $\mathcal{L} \supset -\kappa_\lambda \times \frac{3m_h^2}{v^2} \cdot h^3 + \cdots$



Accessing λ_{hhh} via di-Higgs production

- **Di-**

Not

- Bo
  →
  →
  di-
- Up
  →
- κ_λ a

Most recent and reliable results from
ATLAS di-Higgs searches [ATLAS-CONF-2024-006] yield the limits:

-1.2 < κ_λ < 7.2 at 95% C.L.

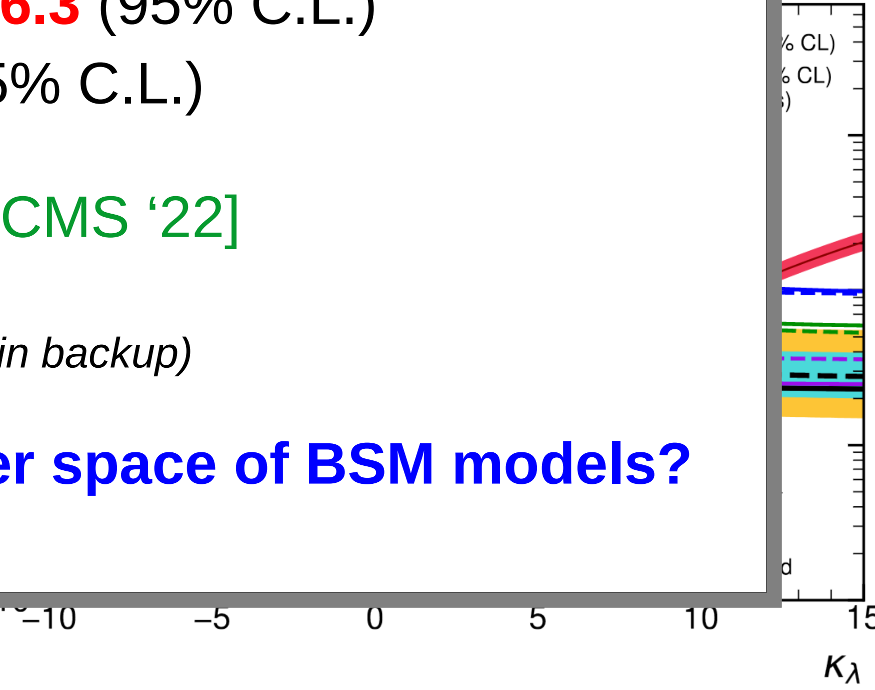
(all other κ's fixed to 1)

Also from [ATLAS PLB '23]:
With all other κ's fixed to 1: **-0.4 < κ_λ < 6.3** (95% C.L.)
With κ_t floating: -1.4 < κ_λ < 6.1 (95% C.L.)

CMS: **-1.2 < κ_λ < 6.5** at 95% C.L. [CMS '22]

NB: future determination even better (details in backup)

→ **Can κ_λ now be used to constrain the parameter space of BSM models?**

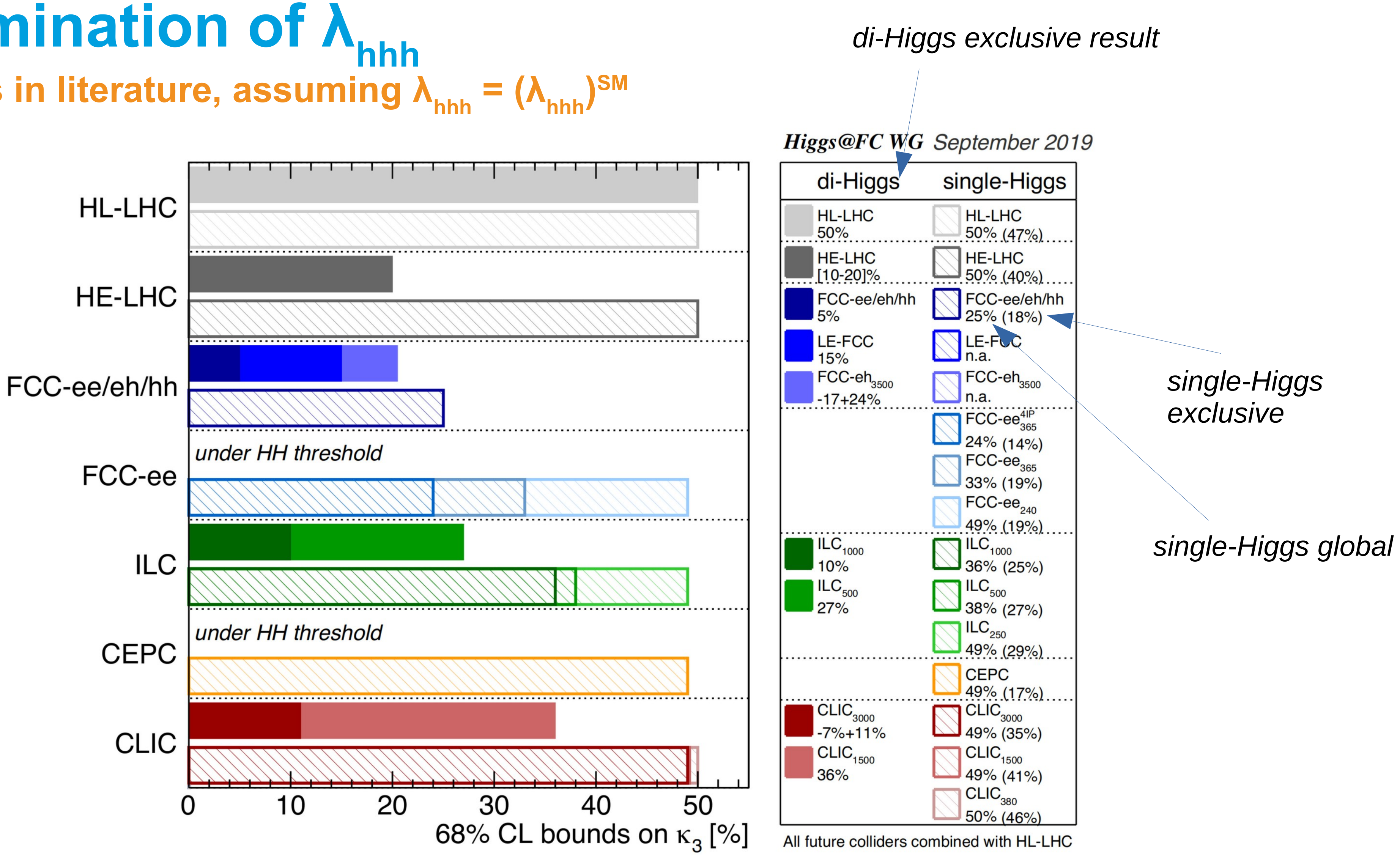


[ATLAS 2211.01216]

Future determination of λ_{hhh}

Expected sensitivities in literature, assuming $\lambda_{hhh} = (\lambda_{hhh})^{SM}$

Plot taken from
[de Blas et al., 1905.03764]

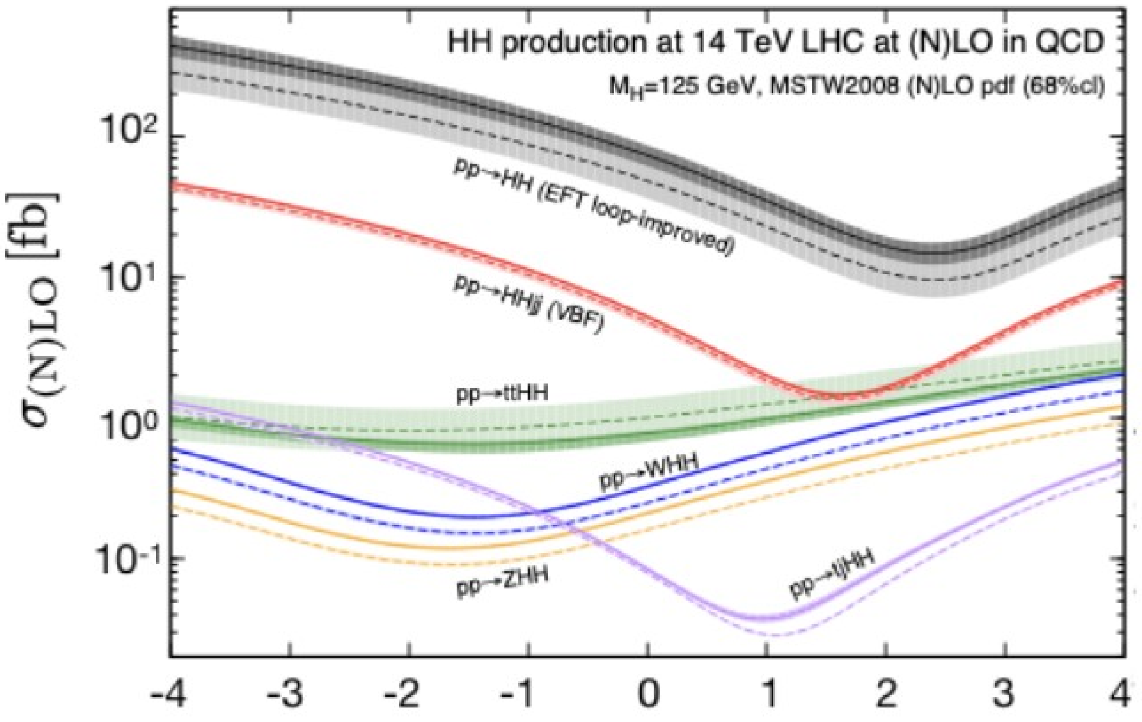


see also [Cepeda et al., 1902.00134], [Di Vita et al.1711.03978], [Fujii et al. 1506.05992, 1710.07621, 1908.11299], [Roloff et al., 1901.05897], [Chang et al. 1804.07130,1908.00753], *etc.*

Di-Higgs production cross-sections as a function of λ_{hhh}

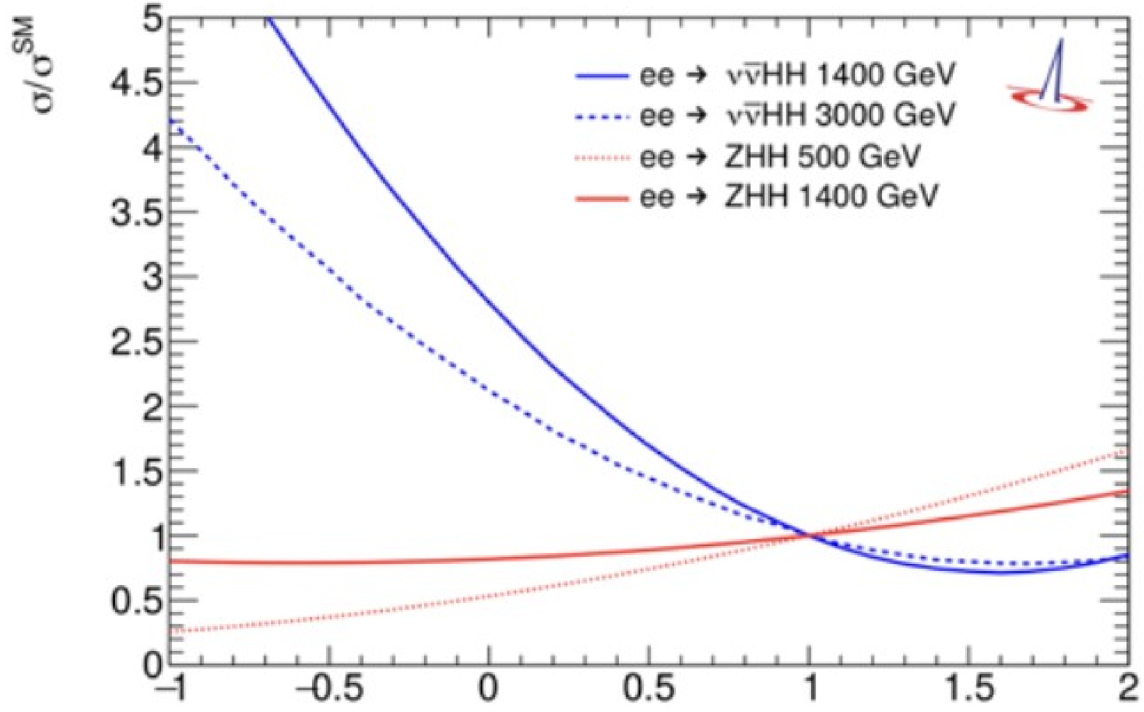
Plots taken from
[de Blas et al., 1905.03764]

Hadron collider



[Frederix et al., 1401.7340] $\lambda_3/\lambda_3^{SM} = \kappa_\lambda$

e⁺e⁻ collider

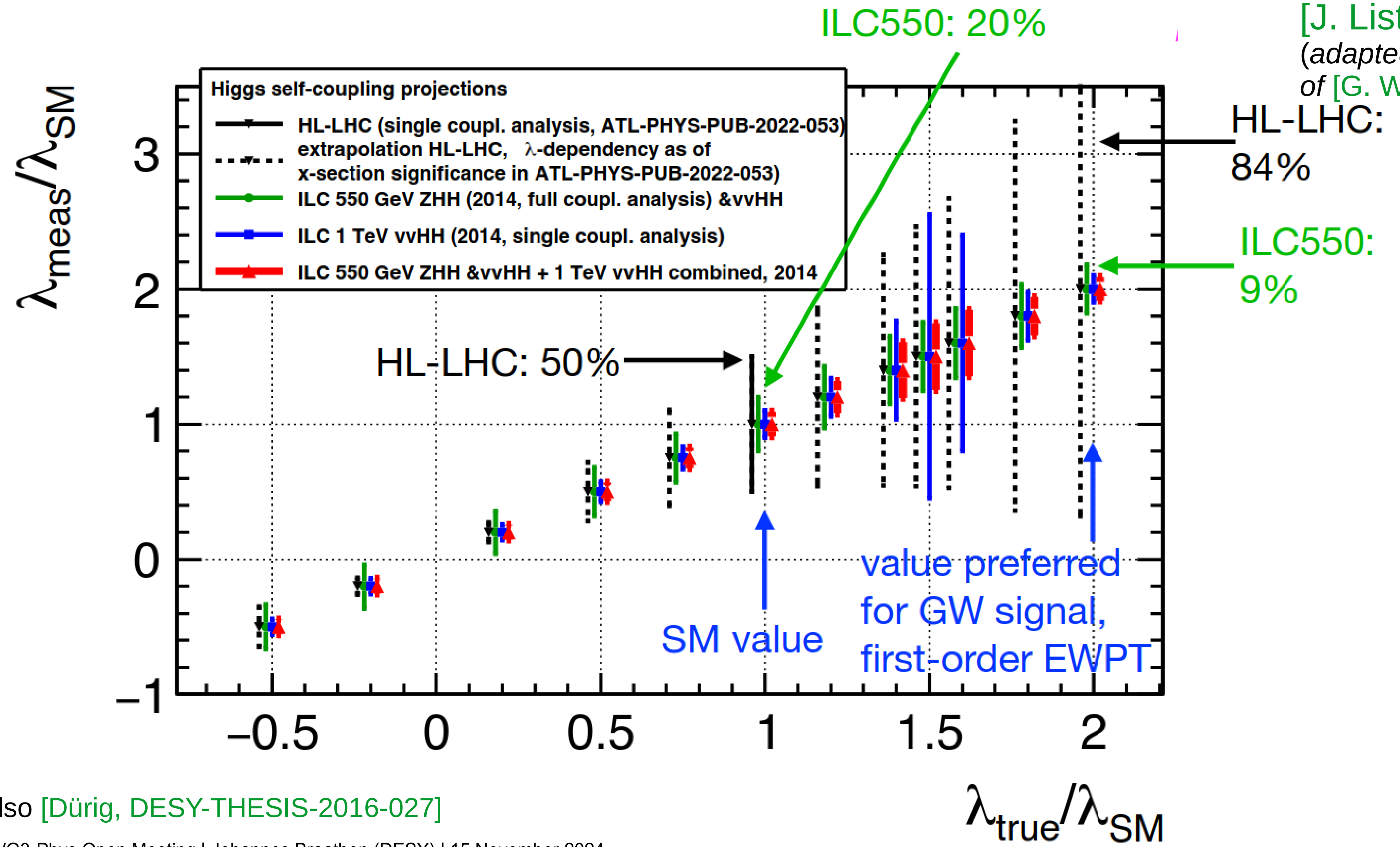


$\lambda_3/\lambda_3^{SM} = \kappa_\lambda$ [Reuter '19]

- **BSM deviation in κ_λ modifies the interference between different contributions to di-Higgs production**
- Strong impact on total cross-sections (and also on differential distributions, see later slides)

Precision on the determination of λ_{hhh} as a function of λ_{hhh}

[J. List et al '24]
(*adapted from slide of* [G. Weiglein '24])



See also [Dürig, DESY-THESIS-2016-027]

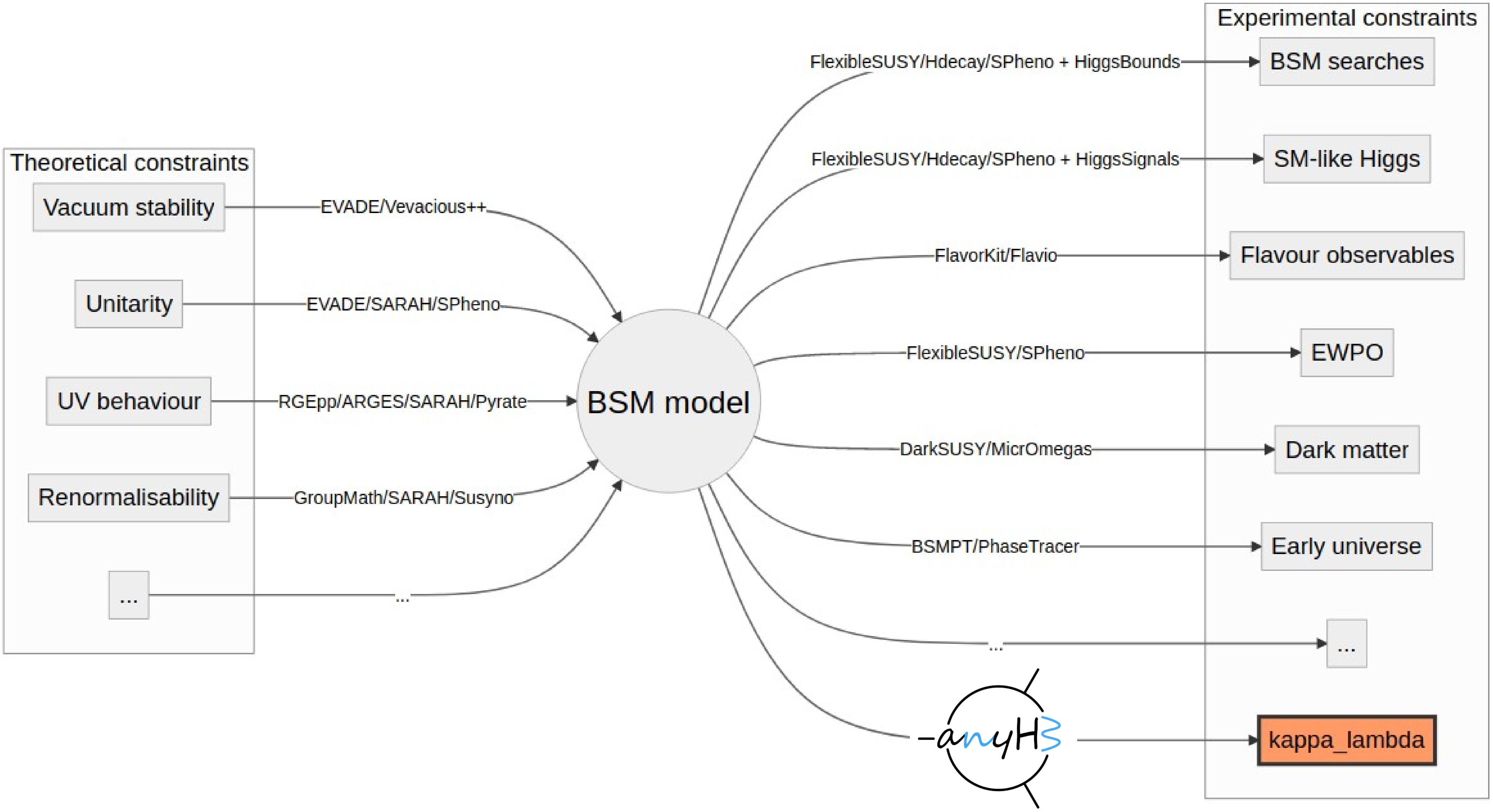
Generic predictions for λ_{hhh}

Based on

`arXiv:2305.03015` **(EPJC) + WIP**

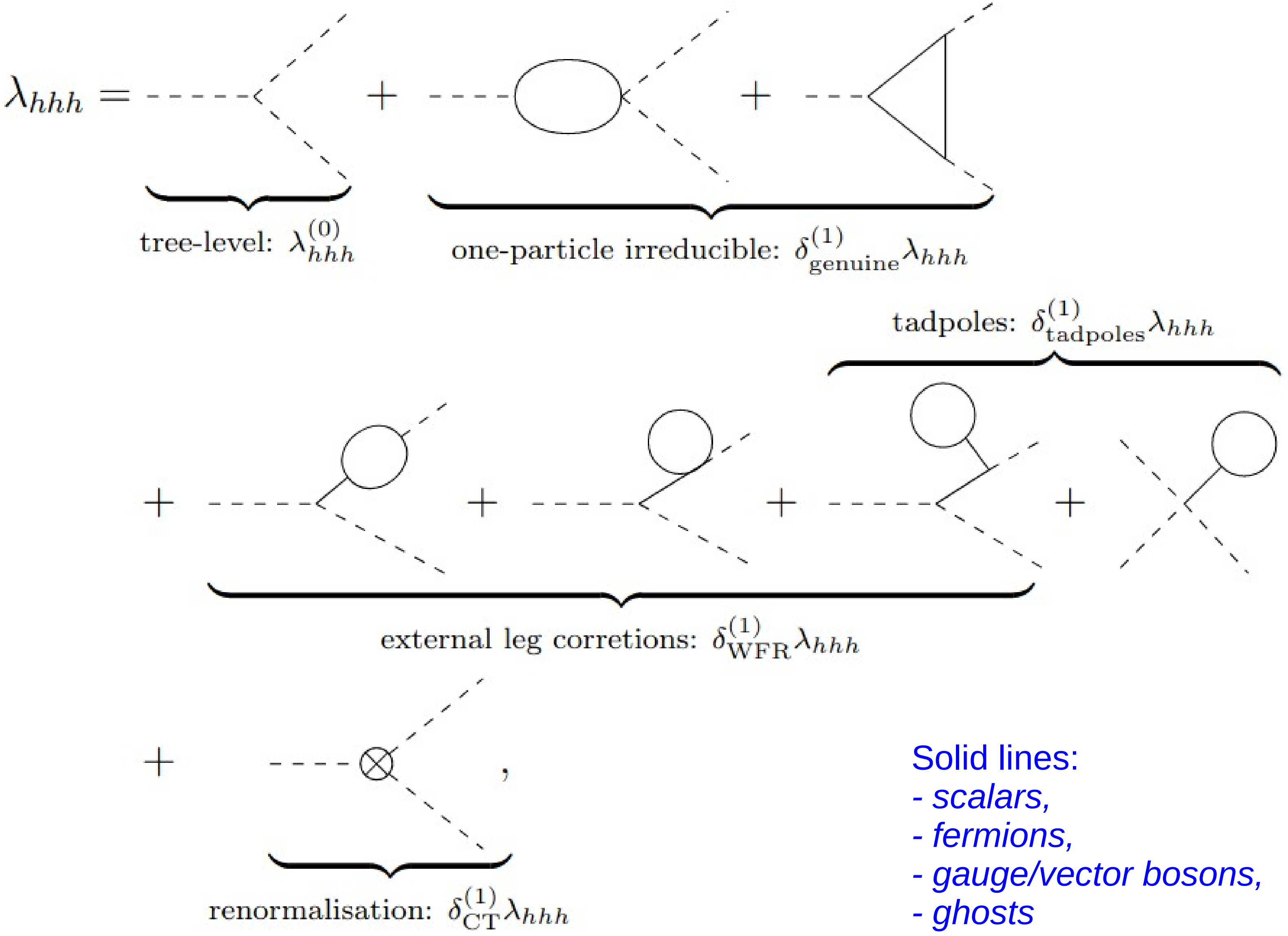
in collaboration with Henning Bahl, Martin Gabelmann, Kateryna Radchenko Serdula and Georg Weiglein

λ_{hhh} within the landscape of automated tools



Full one-loop calculation of λ_{hhh} with `anyH3`: how does it work?

- Generic results applied to concrete (B)SM model, using inputs in `UFO` format [Degrande et al., ‘11], [Darmé et al. ‘23]
- Loop functions evaluated via `COLLIER` [Denner et al ‘16] interface, `pyCollier`
- Restrictions on **particles** and/or **topologies** possible
- **Renormalisation performed automatically** (*more in backup*)

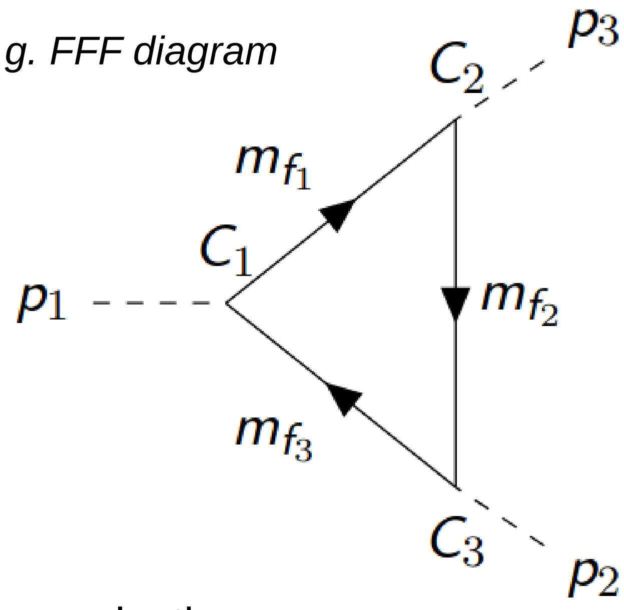


Solid lines:
- *scalars,*
- *fermions,*
- *gauge/vector bosons,*
- *ghosts*

Computing λ_{hhh} in general renormalisable theories: method

Our method: we derive and implement analytic results for **generic diagrams**, i.e. assuming generic

e.g. FFF diagram



- Couplings $C_i = C_i^L P_L + C_i^R P_R,\ \text{where}\ P_{L,R} \equiv \frac{1}{2}(1 \mp \gamma_5)$
- Masses on the internal lines m_{f_i}, i=1,2,3
- External momenta p_i, i=1,2,3

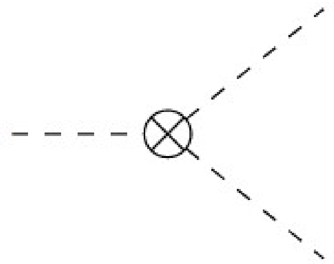
$$= 2\mathbf{B0}(p_3^2, m_2^2, m_3^2)\big(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3})\big) + m_{f_1}\mathbf{C0}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)\big((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L)(p_1^2 + p_2^2 - p_3^2) + 2(C_1^L C_2^L C_3^L + C_1^R C_2^R C_3^R) m_{f_2} m_{f_3} + 2m_{f_1}(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3}))\big) + \mathbf{C1}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)\big(2p_2^2(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + (p_1^2 + p_2^2 - p_3^2)((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L) m_{f_1} + (C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3})\big) + \mathbf{C2}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)\big((p_1^2 + p_2^2 - p_3^2)(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + 2p_1^2((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L) m_{f_1} + (C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3})\big)$$

For evaluation:

- Apply to concrete (B)SM model, using inputs in `UFO` format [Degrande et al., '11], [Darmé et al. '23]
- Evaluate loop functions via `COLLIER` [Denner et al '16] interface, `pyCollier`
- All included in public tool `anyH3` [Bahl, JB, Gabelmann, Weiglein '23]

(**B0**, **C0**, **C1**, **C2**: loop functions)

Flexible choice of renormalisation schemes

$\delta^{(1)}_{\rm CT}\lambda_{hhh} =$  $= \;?$

- **1L calculation** → renormalisation of all parameters entering λ_{hhh} at tree-level
- In general:

$$(\lambda^{(0)}_{hhh})^{\rm BSM} = (\lambda^{(0)}_{hhh})^{\rm BSM}(\underbrace{m_h \simeq 125\text{ GeV}, v \simeq 246\text{ GeV}}_{\text{SM sector}}, \underbrace{m_{\Phi_i}}_{\substack{\text{BSM}\\ \text{masses}}}, \underbrace{\alpha_i}_{\substack{\text{BSM}\\ \text{mixing angles}}}, \underbrace{v_i}_{\substack{\text{BSM}\\ \text{VEVs}}}, \underbrace{g_i}_{\substack{\text{indep.}\\ \text{BSM coups.}}})$$

- Most automated codes: $\overline{\rm MS}/\overline{\rm DR}$ only
- `anyH3`: much more flexibility, following **user choice**:
  - **SM sector** (m_h, v): fully OS or $\overline{\rm MS}/\overline{\rm DR}$
  - **BSM masses**: OS or $\overline{\rm MS}/\overline{\rm DR}$
  - **Additional couplings/vevs/mixings**: by default $\overline{\rm MS}$, but **user-defined ren. conditions** also possible!

$$\delta^{(1)}_{\rm CT}\lambda_{hhh} = \sum_x \left(\frac{\partial}{\partial x}(\lambda^{(0)}_{hhh})^{\rm BSM}\right)\delta^{\rm CT}x\,, \qquad \text{with } x \in \{m_h, v, m_{\Phi_i}, v_i, \alpha_i, g_i, \text{etc.}\}$$

Renormalised in $\overline{\rm MS}$, OS, in custom schemes, etc.

(Default) Renormalization choice of $(v^{\text{SM}})^{\text{OS}}$ and $(m_i^2)^{\text{OS}}$

- $v^{\text{OS}} \equiv \frac{2M_W^{\text{OS}}}{e}\sqrt{1-\frac{M_W^{2\,\text{OS}}}{M_Z^{2\,\text{OS}}}}$ with
  - $\delta^{(1)} M_V^{2\,\text{OS}} = \frac{\Pi_V^{(1),T}}{M_V^{2\,OS}}(p^2 = M_V^{2\,OS})\,,\, V = W, Z$
  - $\delta^{(1)} e^{\text{OS}} = \frac{1}{2}\dot{\Pi}_\gamma(p^2=0) + \text{sign}(\sin\theta_W)\frac{\sin\theta_W}{M_Z^2\cos\theta_W}\Pi_{\gamma Z}(p^2=0)$
- attention *(i)*: $\rho^{\text{tree-level}} \neq 1 \rightarrow$ further CTs needed (depends on the model)

  $\longrightarrow$ ability to define *custom* renormalisation conditions
- scalar masses: $m_i^{\text{OS}} = m_i^{\text{pole}}$
  - $\delta^{\text{OS}} m_i^2 = -\widetilde{\text{Re}}\Sigma_{h_i}^{(1)}|_{p^2=m_i^2}$
  - $\delta^{\text{OS}} Z_i = \widetilde{\text{Re}}\frac{\partial}{\partial p^2}\Sigma_{h_i}^{(1)}|_{p^2=m_i^2}$
- attention *(ii)*: scalar mixing may also require further CTs/tree-level relations

All bosonic one- & two-point functions and their derivatives for general QFTs are required for flexible OS renormalisation.

Features of `anyH3`, so far

- Import/conversion of any UFO model
- Definition of renormalisation schemes

```
# schemes.yml
```

```
renormalization_schemes:
  MS:
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: MS
    mass_counterterms:
      h1: MS
      h2: MS
  OS:
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: OS
    custom_CT_hhh: 'dbetaH =
f"({Sigma(''Hm1'',''Hm2'',momentum=''0'')} +
{Sigma(''Hm1'',''Hm2'',momentum=''MHm2**2'')})/-
(2*MHm2**2)"

      dTanBeta = f"({dbetaH})/cos(betaH)**2"
```

(extract from schemes.yml for 2HDM)

...

- Analytical / numerical / LaTeX outputs
- **3 user interfaces**:
  - Python library

```
from anyBSM import anyH3
myfancymodel = anyH3('path/to/UFO/model')
result = myfancymodel.lambdahhh()
```

  - Command line
  - Mathematica interface
- **Perturbative unitarity checks** available (at tree level and in high-energy limit for now)
- Can be used together with a spectrum generator and **handles SLHA format**
- Efficient **caching** available
- Lots more!

New results I: mass-splitting effects in various BSM models

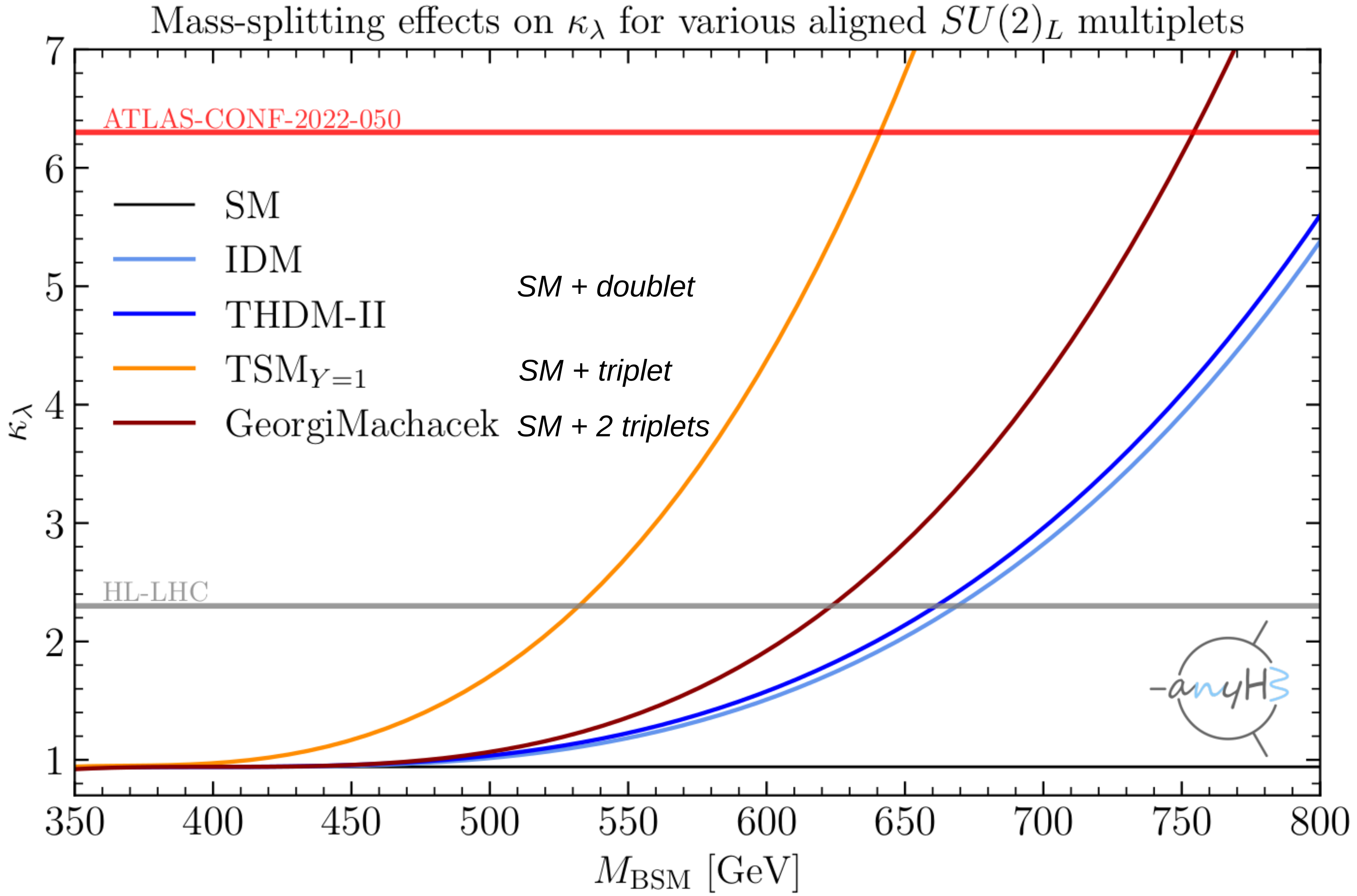
- Consider the non-decoupling limit in several BSM models

$$M^2_{\mathrm{BSM}} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

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

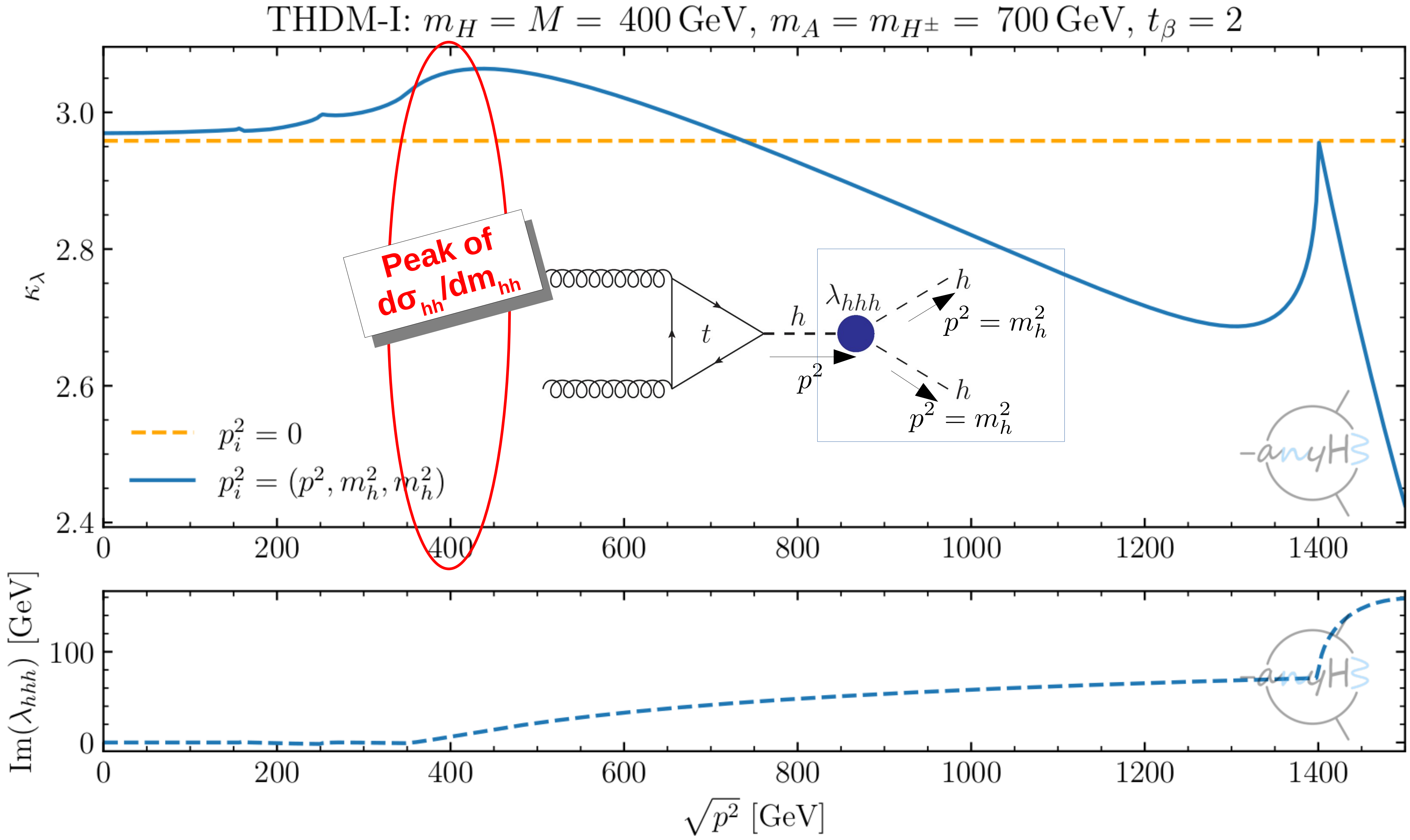
- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**

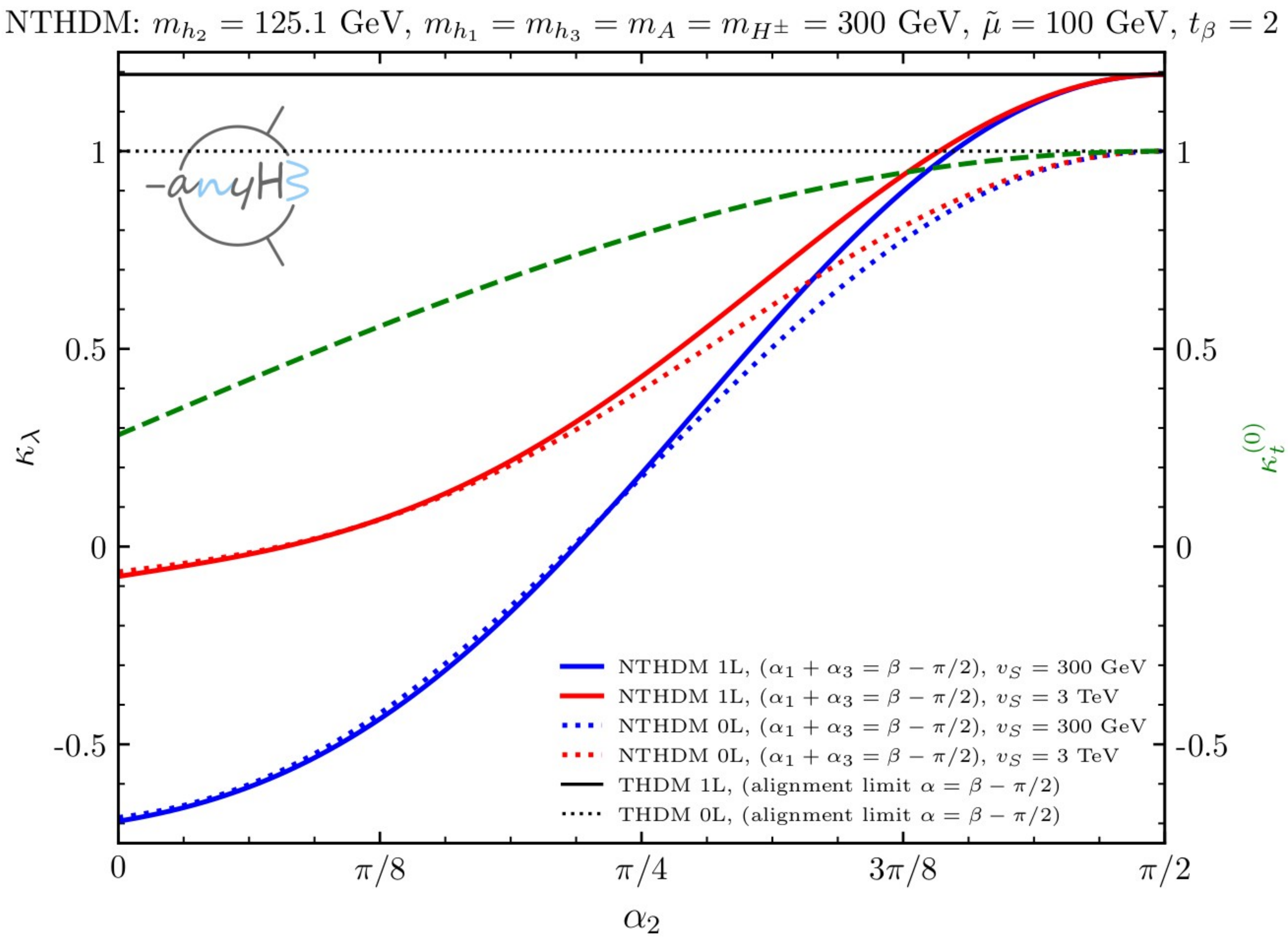


Here: scenarios with lightest BSM scalar mass & BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

New results II: momentum dependence in the 2HDM



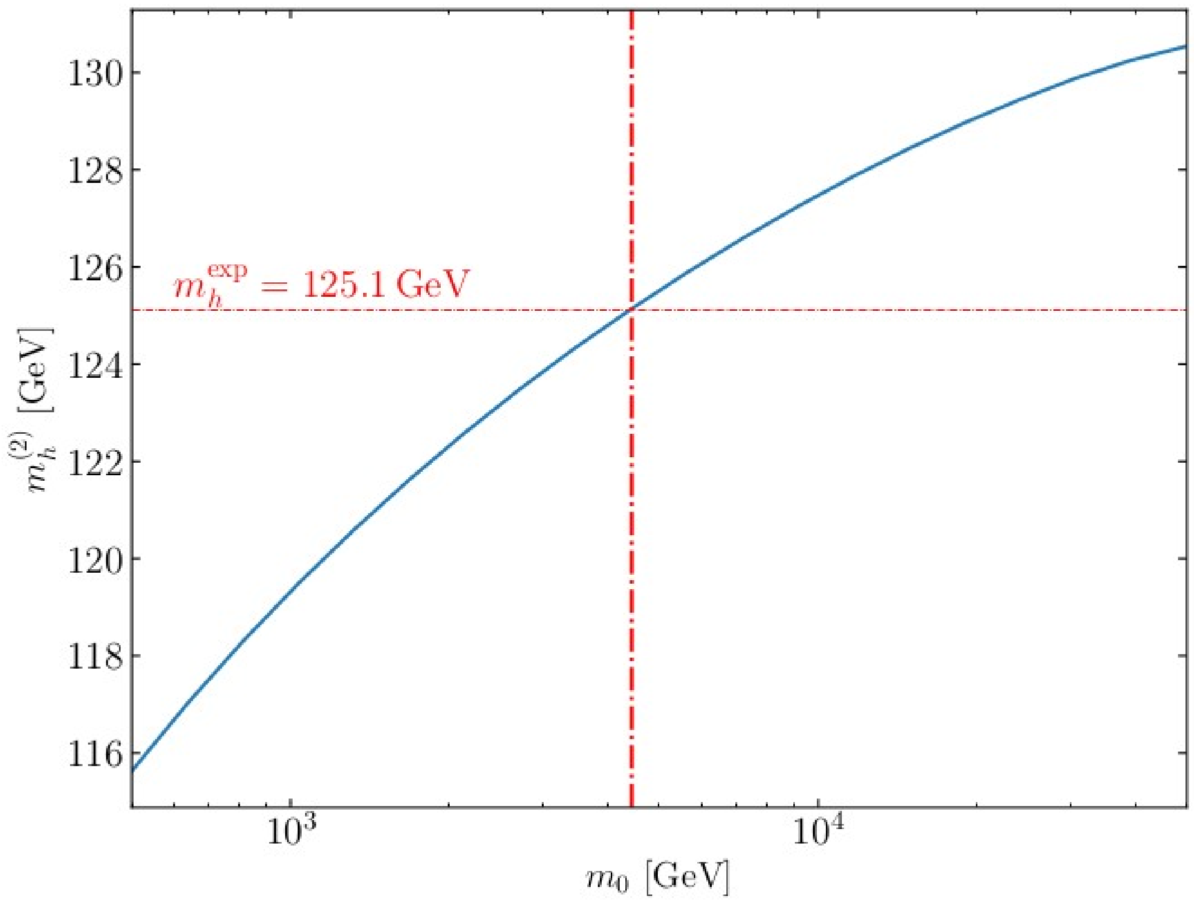
More new results with `anyH3`: an example in the N2HDM

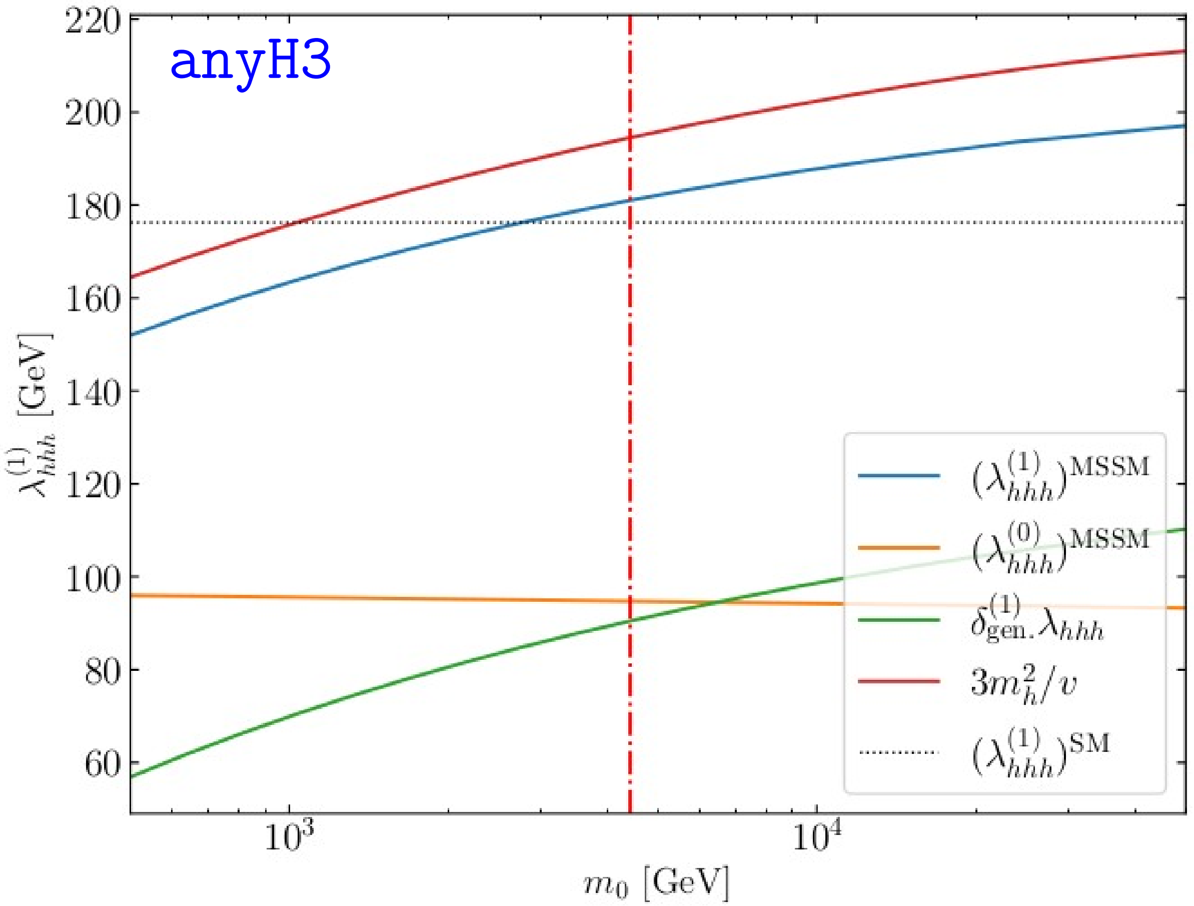


- **N2HDM = 2HDM + real singlet**
- CP-even sector: 3 states h_1, h_2, h_3, with 3 mixing angles α_1, α_2, α_3
- Here $\alpha_2 \to \pi/2$ → recover 2HDM (itself in alignment limit)
- We can study e.g. the relative sign of κ_λ and κ_t → affects double-Higgs production
- κ_t too far away from 1 excluded

Full one-loop calculation of λ_{hhh} in the MSSM

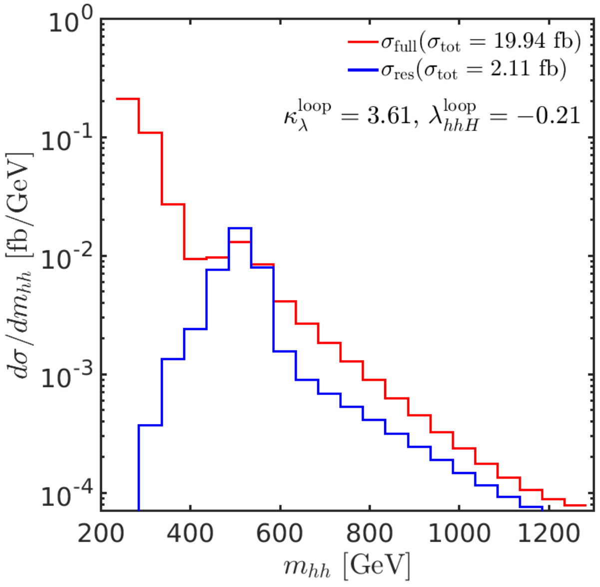
CMSSM, $m_0 = m_{1/2} = -A_0$, $\tan\beta = 10$, $\mathrm{sgn}(\mu) = 1$, with m_h computed at 2L in SPheno





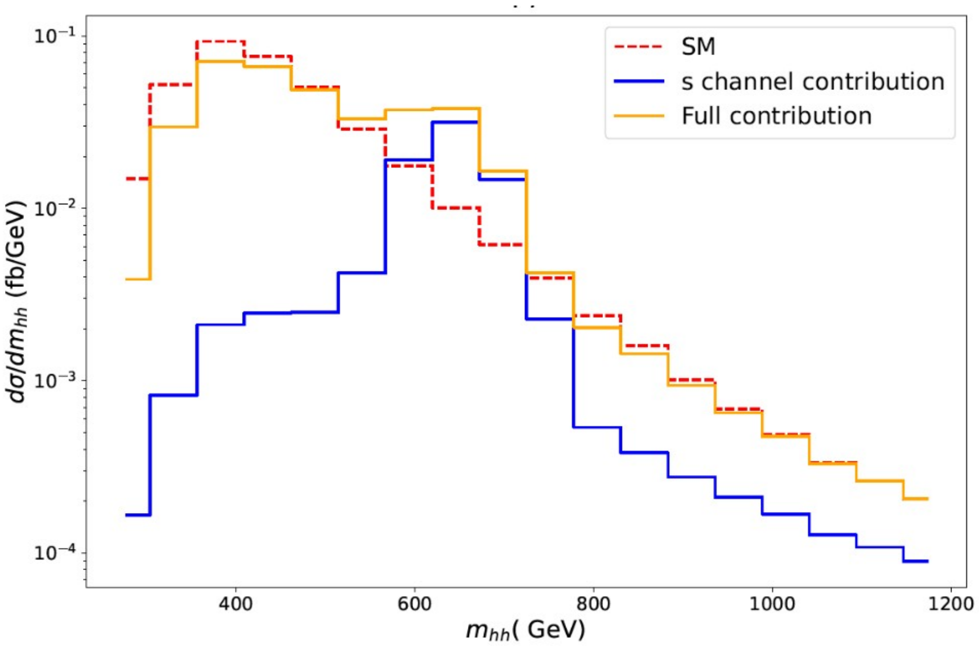
- Example for a very simple version of the constrained MSSM → BSM parameters m_0, $m_{1/2}$, A_0, sgn(μ), tanβ
- For each point, M_h computed at 2L with SPheno, and SLHA output of SPheno used as input of anyH3

Ongoing developments in anyBSM

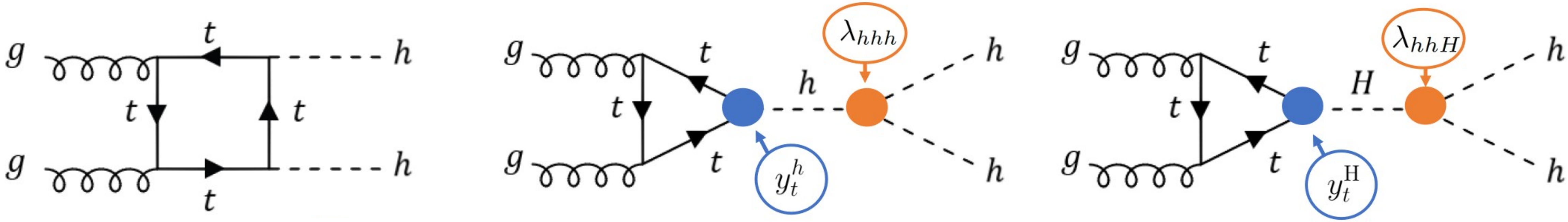


Left: 2HDM
[Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein '24]
plot from talk of K. Radchenko Serdula at 20th LHC Higgs WG workshop

Right: singlet extension
[Arco, Heinemeyer, Mühlleitner, Rivero, Verduras *WIP*]



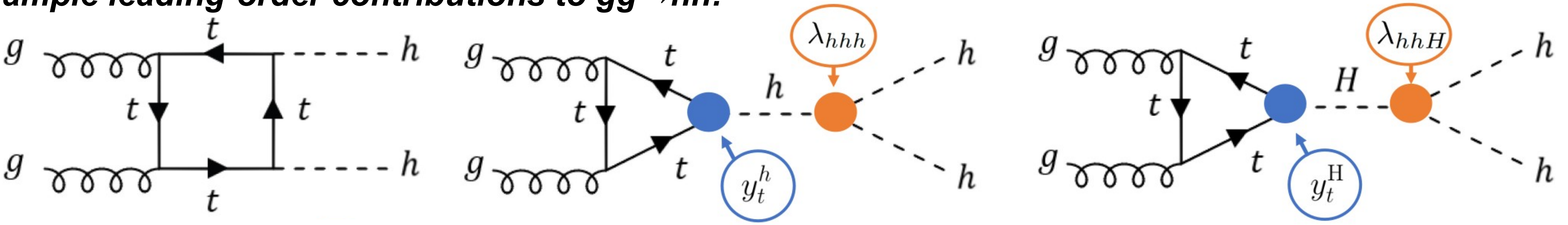
Example leading-order contributions:



[Figure by A. Verduras]

Ongoing developments in `anyBSM`: `anyLambdaijk` and `anyHH`

Example leading-order contributions to gg→hh:

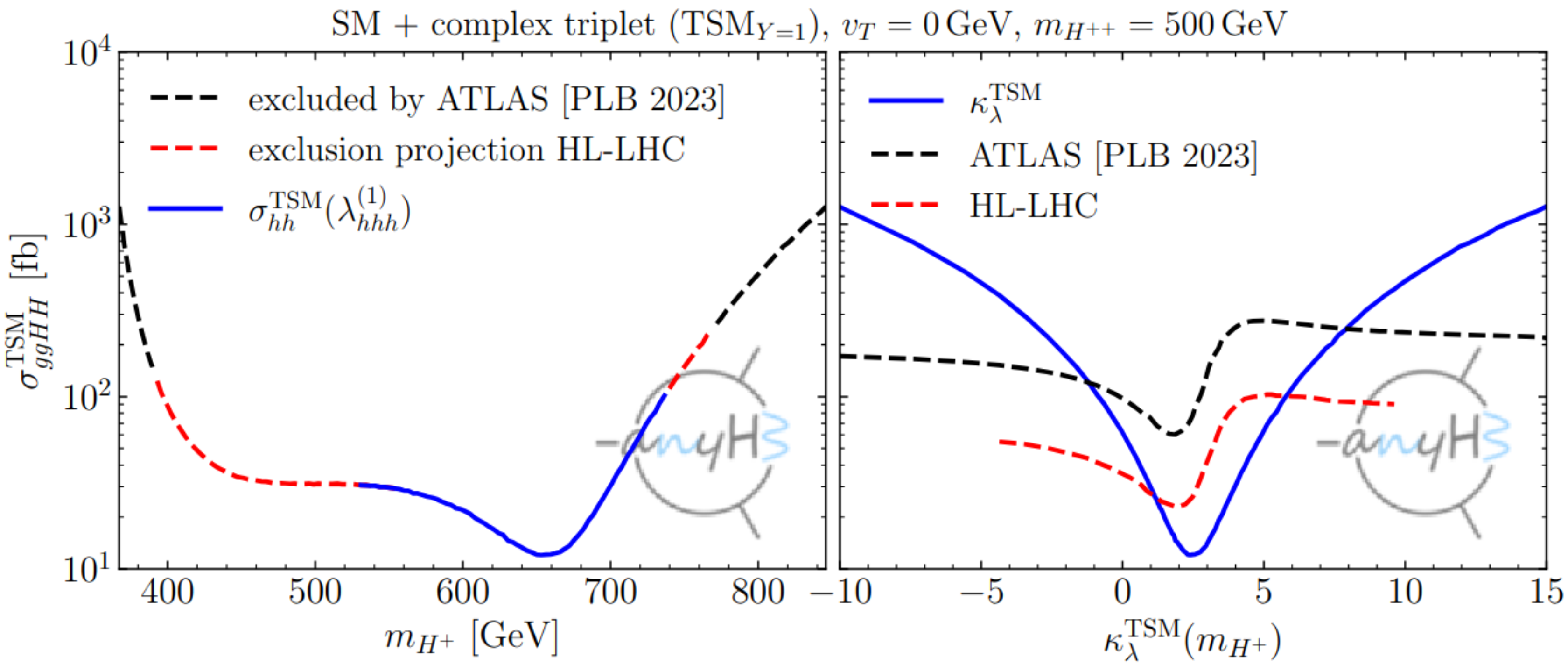


[Diagrams by A. Verduras Schaeidt]

Having predictions for di-Higgs production, including **all (i.e. resonant + non-resonant) contributions + 1L corrections to trilinear scalar couplings** in **arbitrary models** would be highly desirable

→ new modules `anyLambdaijk` and `anyHH`

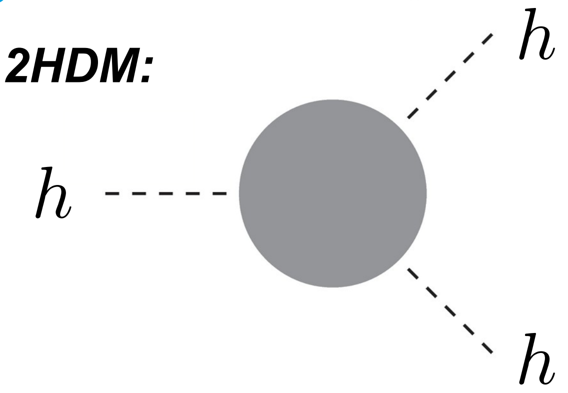
[Bahl, Braathen, Gabelmann, Radchenko Serdula, GW *WIP*]

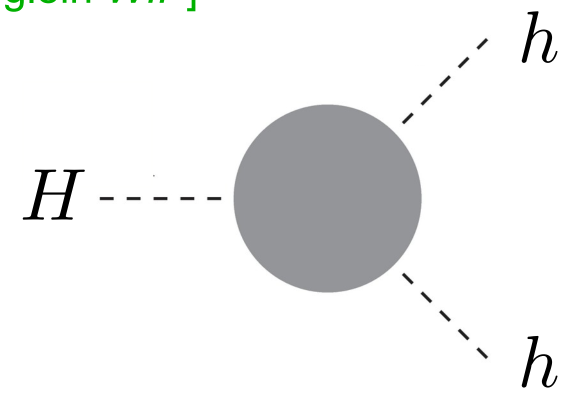


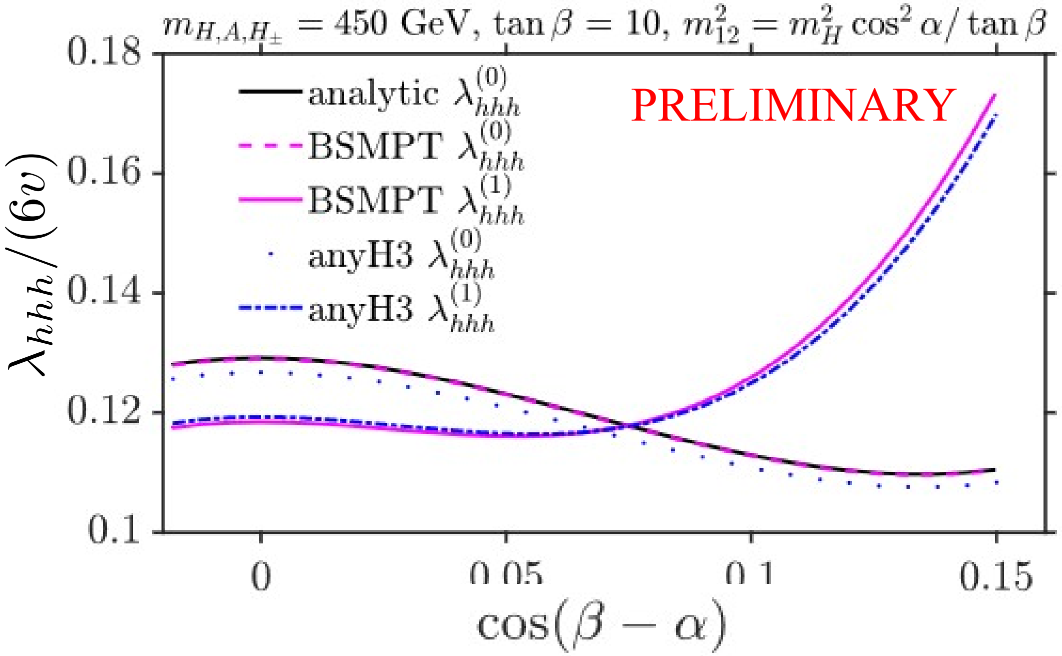
Ongoing developments: `anyLamijk`

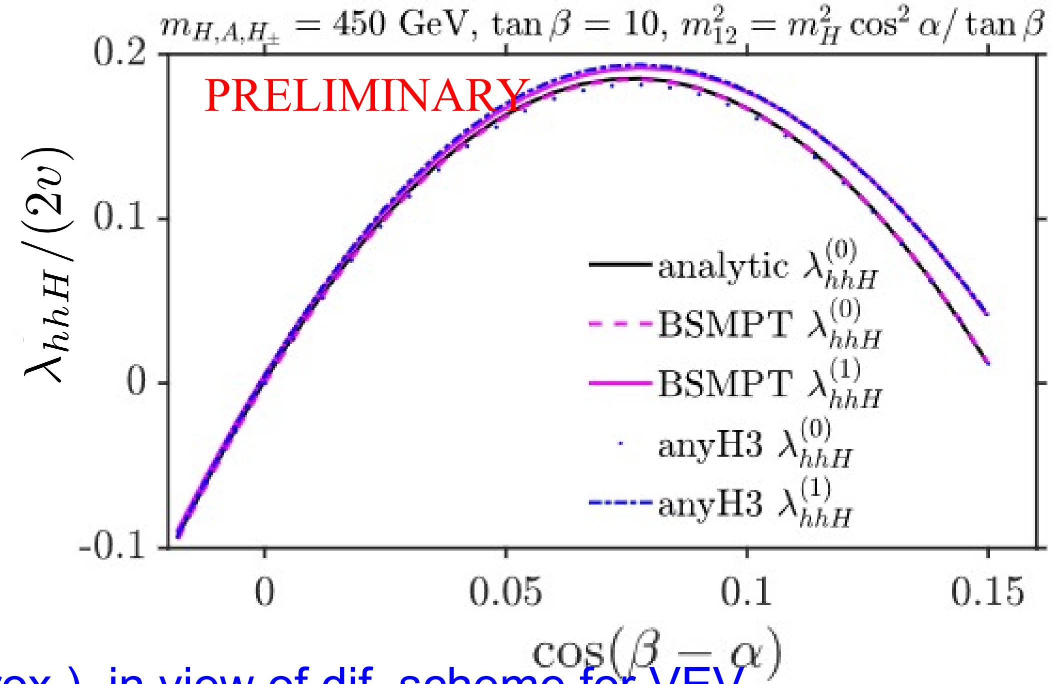
[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

Example in a 2HDM:







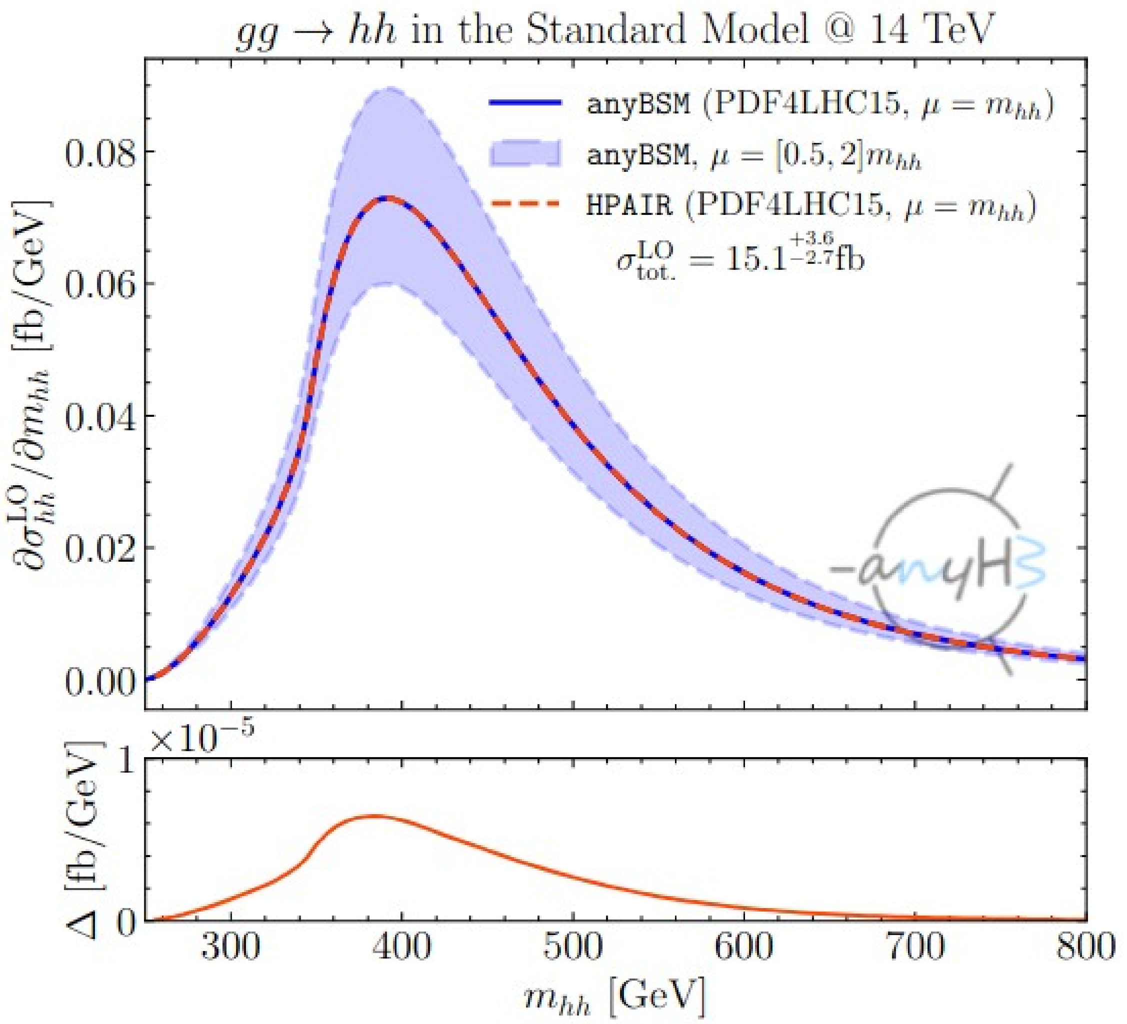


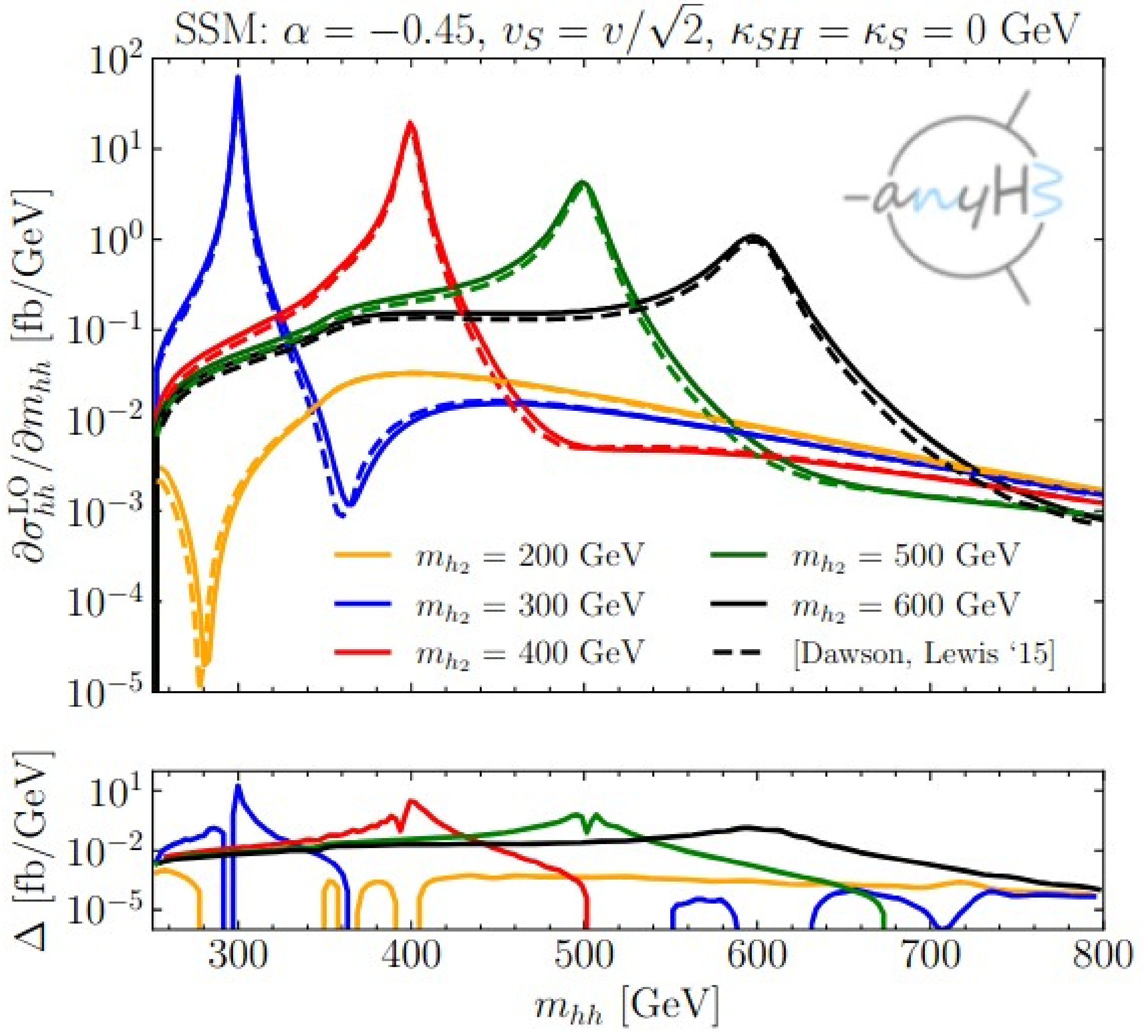
→ excellent agreement with BSMPT results (in eff. pot. approx.), in view of dif. scheme for VEV

→ full OS schemes for λ_{hhh} and λ_{hhH} couplings worked out in 2HDM [Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein], RxSM [JB, Heinemeyer, Verduras Schaeidt], and more [Bosse, JB, Gabelmann, Hannig, Weiglein]!

Ongoing developments: tests of anyHH with leading order trilinear couplings

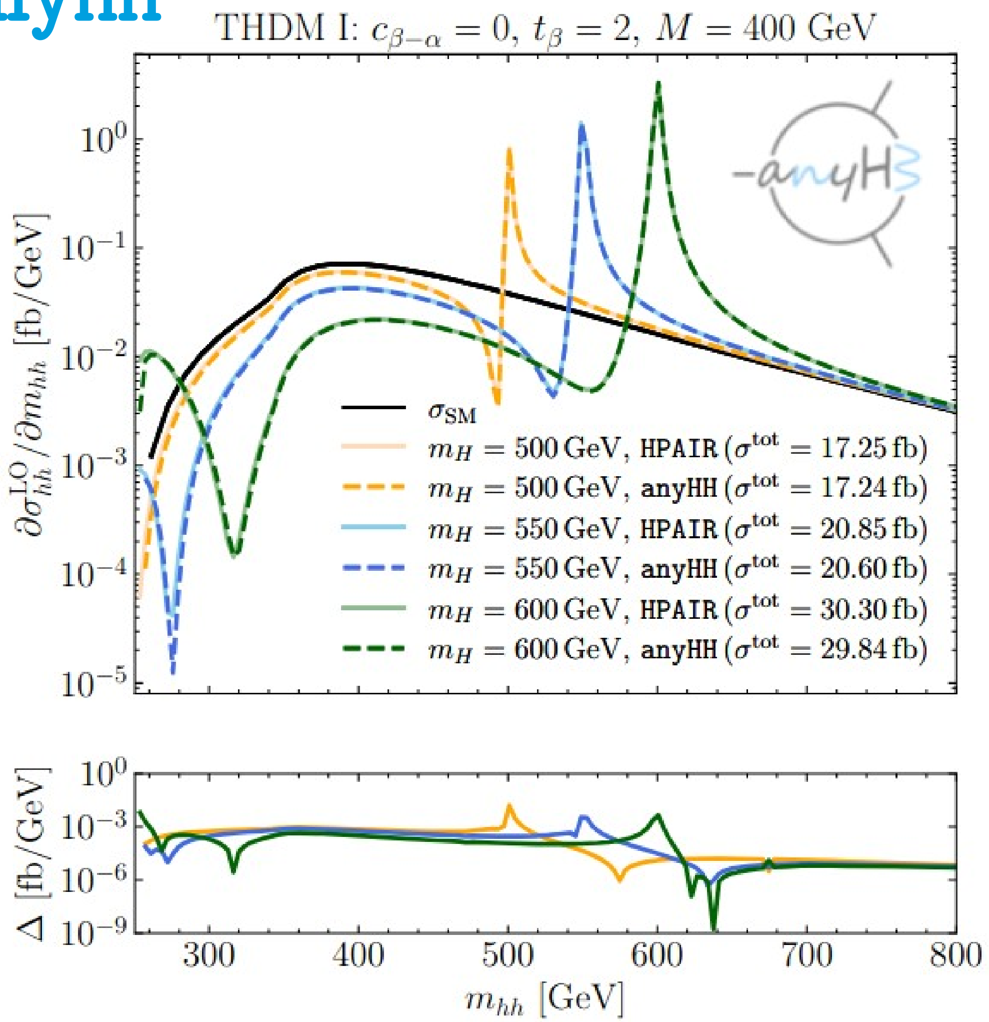
$$\Delta \equiv |\partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{HPAIR}) - \partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{anyHH})|$$

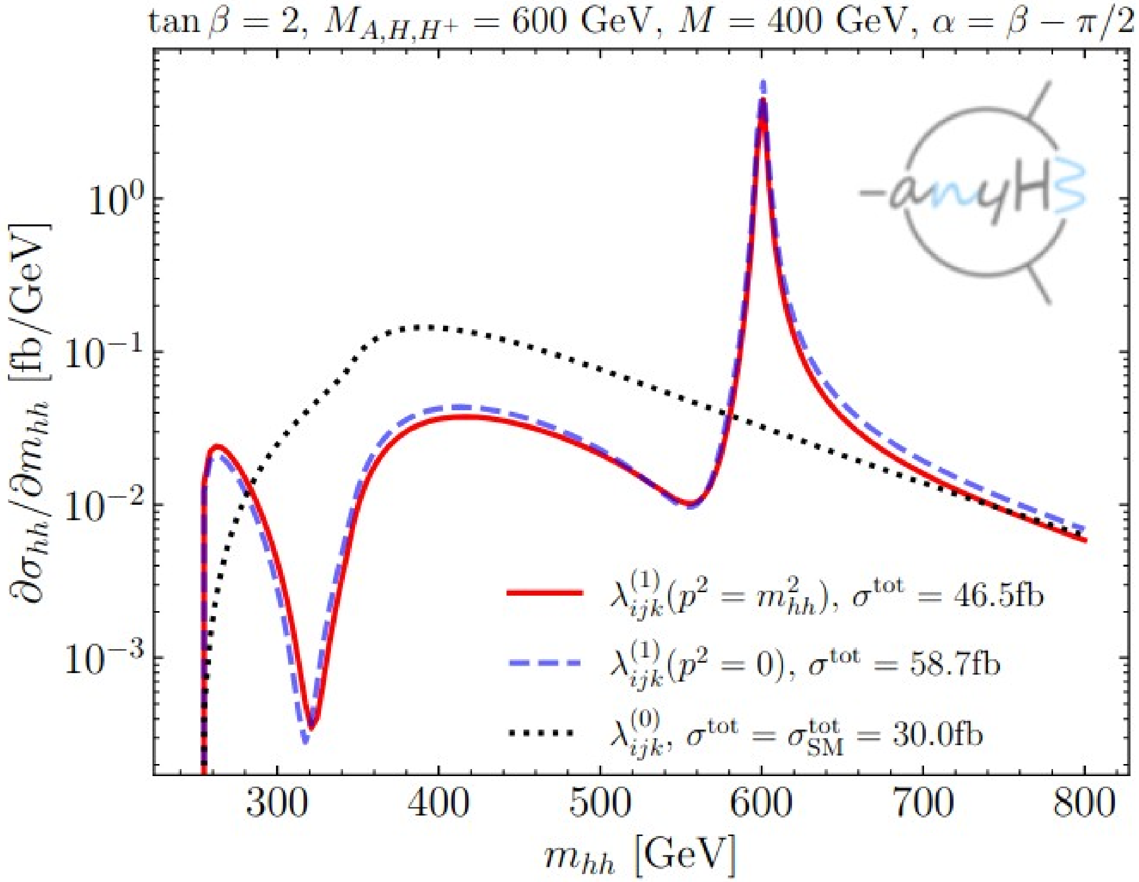




- Excellent agreement with LO HPair result, once one ensures that running of α_s + choice of PDFs are same
- Very good agreement results of [Dawson, Lewis '15] for singlet extension of SM (remaining difference because PDF sets can't be taken to be the same)

Ongoing developments: tests and new results in 2HDM with anyHH





- Very good agreement with HPair, using one-loop trilinear scalar couplings computed by anyH3/anyLambdaijk, for 2HDM benchmarks (here in alignment limit)

- Strong impact of inclusion of one-loop corrections to trilinear scalar couplings on differential distribution

- Impact of momentum dependence of trilinear scalar couplings (only possible with anyHH, not with HPair) can be as large as 20% on total cross-section

A word on EFTs

- Effects in κ_λ much larger than in other Higgs couplings can also be understood in terms of EFT/dimensional analysis

- See e.g. [Durieux, McCullough, Salvioni 2022] and [McCullough @ LCWS'24]

$$\left|\frac{\delta_{h^3}}{\delta_{hVV}}\right| \lesssim \min\left\{\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M_{\mathrm{BSM}}}{m_h}\right)^2\right\}$$

Deviation in λ_{hhh}

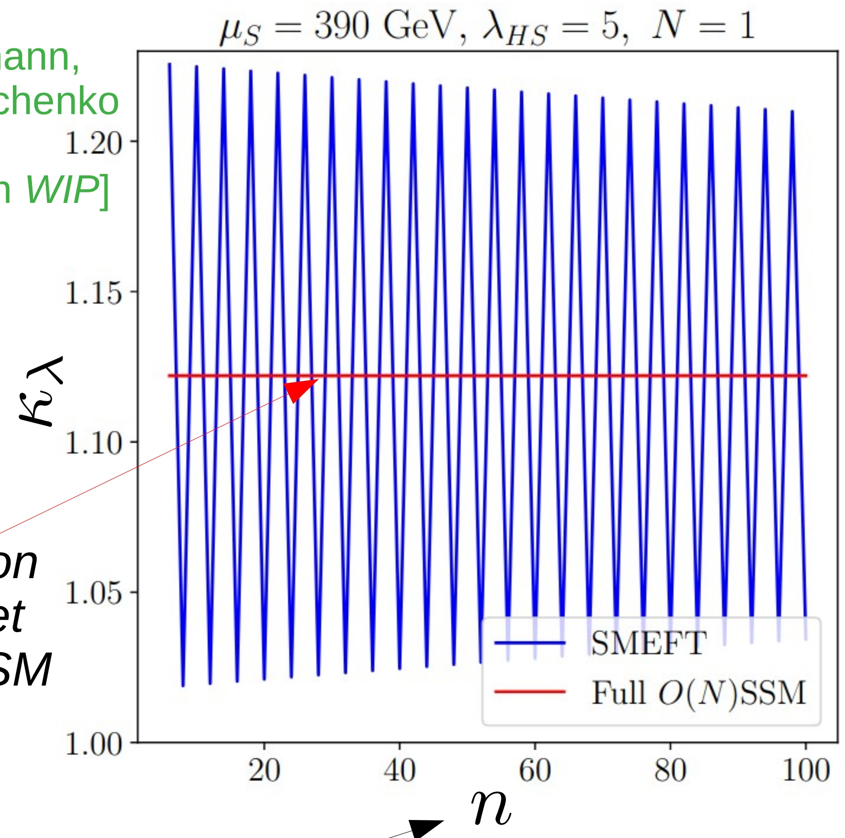
~ 600

Deviation in g_{hVV}

- But beware also about the **range of applicability** of different EFTs!

- E.g. an additional scalar of M~300-500 GeV is not necessarily excluded by experimental searches, but is also not well captured by SMEFT!
→ one should use **Higgs EFT** (HEFT) instead

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



Full calculation (1L) in singlet extension of SM

Order to which we do the calculation in SMEFT

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \sum_{n>3} c^{(2n)} \frac{|\Phi|^{2n}}{\Lambda^{2n-4}}$$

The Two-Higgs-Doublet Model

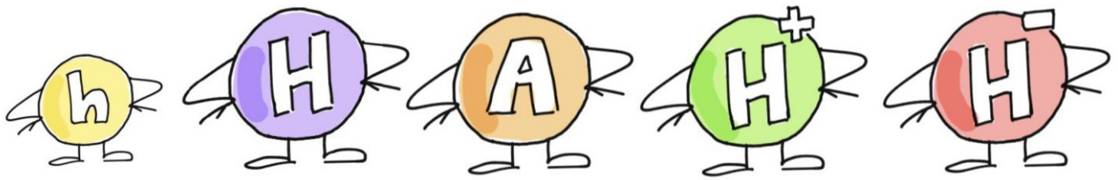


Figure by [K. Radchenko Serdula '24]

- 2 $SU(2)_L$ doublets $\Phi_{1,2}$ of hypercharge ½
- CP-conserving 2HDM, with softly-broken Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) to avoid tree-level FCNCs

$$V^{(0)}_{\rm 2HDM} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \frac{\lambda_5}{2}\Big((\Phi_2^\dagger\Phi_1)^2 + \text{h.c.}\Big)$$

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

- **Mass eigenstates**:
  h, H: CP-even Higgs bosons *(h → 125-GeV SM-like state);* A: CP-odd Higgs boson;
  $H^\pm$: charged Higgs boson

- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv 2m_3^2/s_{2\beta}$), angles α (CP-even Higgs mixing angle) and β (defined by $\tan\beta = v_2/v_1$)

- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

- We take the **alignment limit α = β - π/2** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data

Constraining BSM models with λ_{hhh}

i. *Can we apply the limits on κ_λ, extracted from experimental searches for di-Higgs production, for BSM models?*

ii. *Can large BSM deviations occur for points still allowed in light of theoretical and experimental constraints? If so, how large can they become?*

As a concrete example, we consider an aligned 2HDM

Based on

arXiv:2202.03453 **(Phys. Rev. Lett.) in collaboration with Henning Bahl and Georg Weiglein**

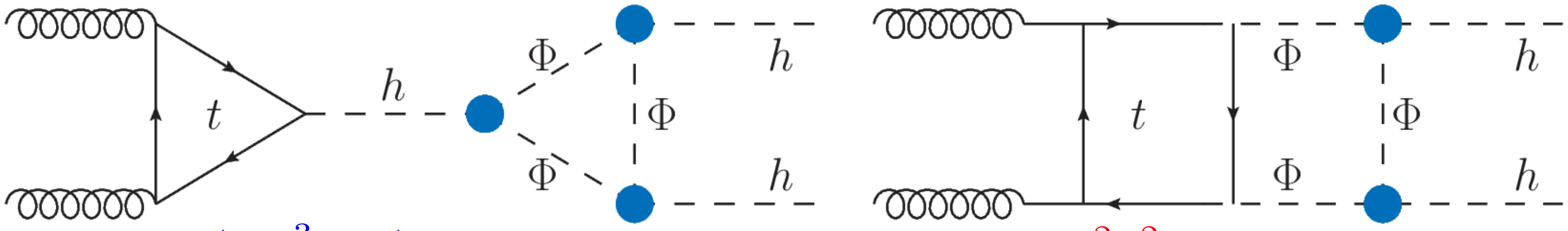
Can we apply di-Higgs results for the aligned 2HDM?

- Current strongest limits on κ_λ from ATLAS di-Higgs searches

  $-1.2 < \kappa_\lambda < 7.2$ [ATLAS-CONF-2024-006]   [where $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$]

- What are the *assumptions* for the ATLAS limits?
  - All other Higgs couplings (to fermions, gauge bosons) are SM-like

    → this is **ensured by the alignment** ✓
  - The modification of λ_{hhh} is the only source of deviation of the *non-resonant Higgs-pair production cross section* from the SM



$\propto \mathcal{O}(y_t g_{hh\Phi\Phi}^3)$ ***included*** $\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ *not included*

→ We **correctly include all leading BSM effects to di-Higgs production, in powers of $g_{hh\Phi\Phi}$, up to NNLO!** ✓

- **We can apply the ATLAS limits to our setting!**

A parameter scan in the aligned 2HDM

[Bahl, JB, Weiglein PRL '22]

- Our strategy:
  1. **Scan BSM parameter space**, keeping only points passing various theoretical and experimental constraints (*see below*)
  2. Identify regions with **large BSM deviations in λ_{hhh}**
  3. Devise a **benchmark scenario** allowing large deviations and investigate impact of experimental limit on λ_{hhh}
- *Here*: we consider an **aligned 2HDM of type-I**, but similar results expected for other 2HDM types, or other BSM models with extended Higgs sectors
- Constraints in our parameter scan:

experimental
  - 125-GeV Higgs measurements with `HiggsSignals`
  - Direct searches for BSM scalars with `HiggsBounds`
  - b-physics constraints, using results from [Gfitter group 1803.01853]

  (Checked with `ScannerS` [Mühlleitner et al. 2007.02985])
  - EW precision observables, computed at two loops with `THDM_EWPOS` [Hessenberger, Hollik '16, '22]

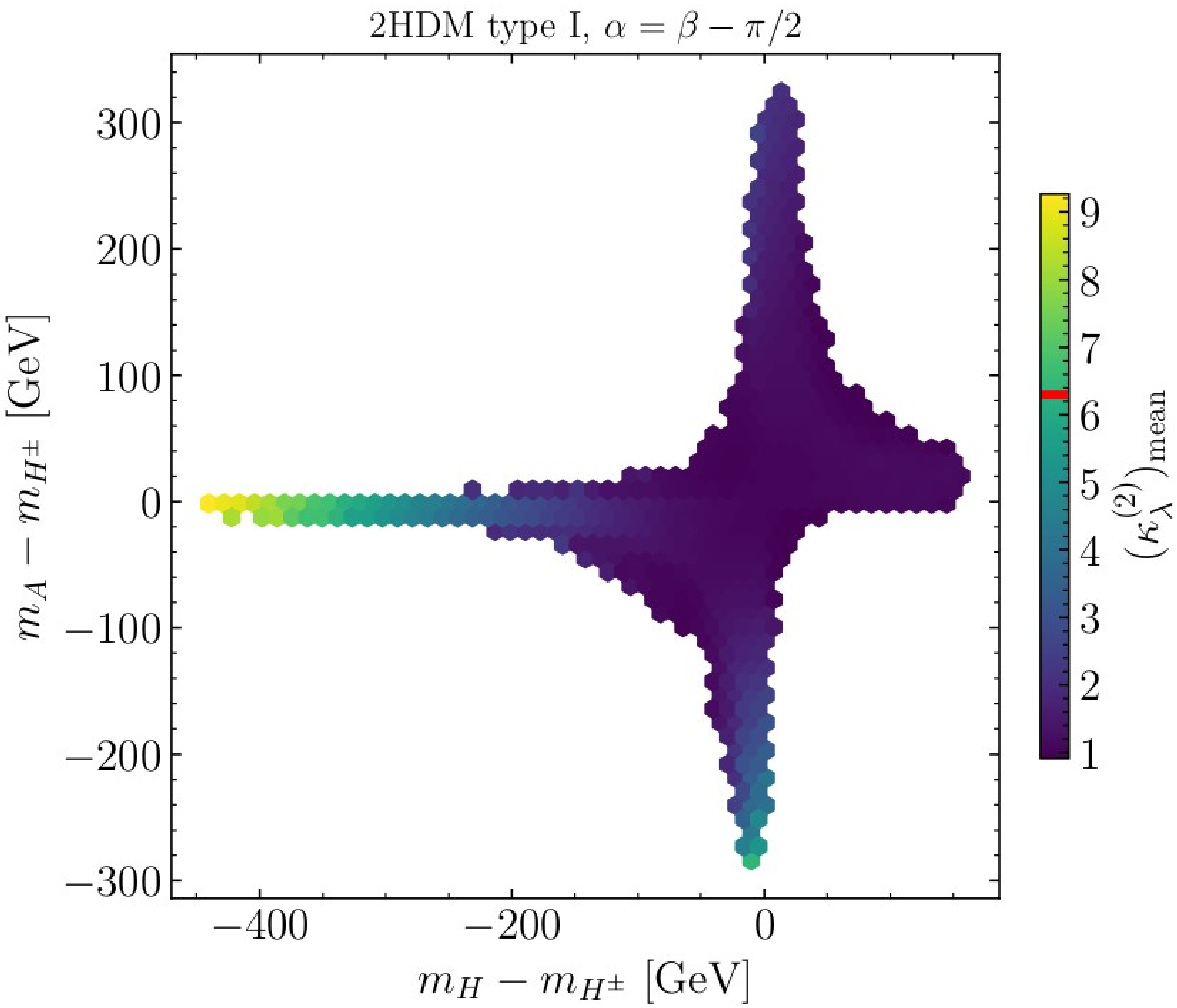
theoretical
  - Vacuum stability
  - Boundedness-from-below of the potential

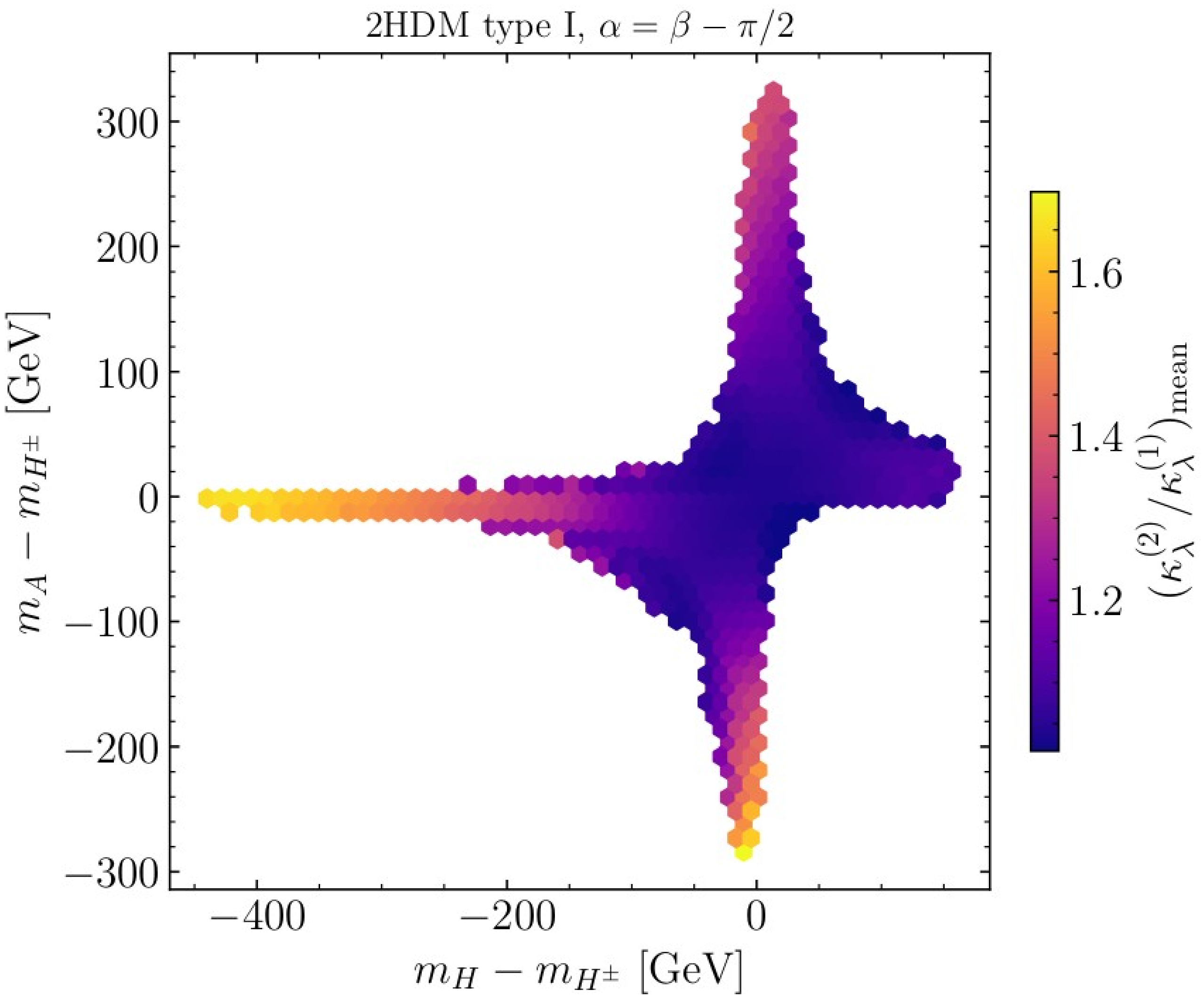
  (Checked with `ScannerS`)
  - NLO perturbative unitarity, using results from [Grinstein et al. 1512.04567], [Cacchio et al. 1609.01290]
- For points passing these constraints, we **compute κ_λ at 1L and 2L**, using results from [JB, Kanemura '19]

Parameter scan results

[Bahl, JB, Weiglein PRL '22]

<u>Mean value</u> for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(1)})^{2HDM}$ [right] in (m_H-$m_{H\pm}$, m_A-$m_{H\pm}$) plane



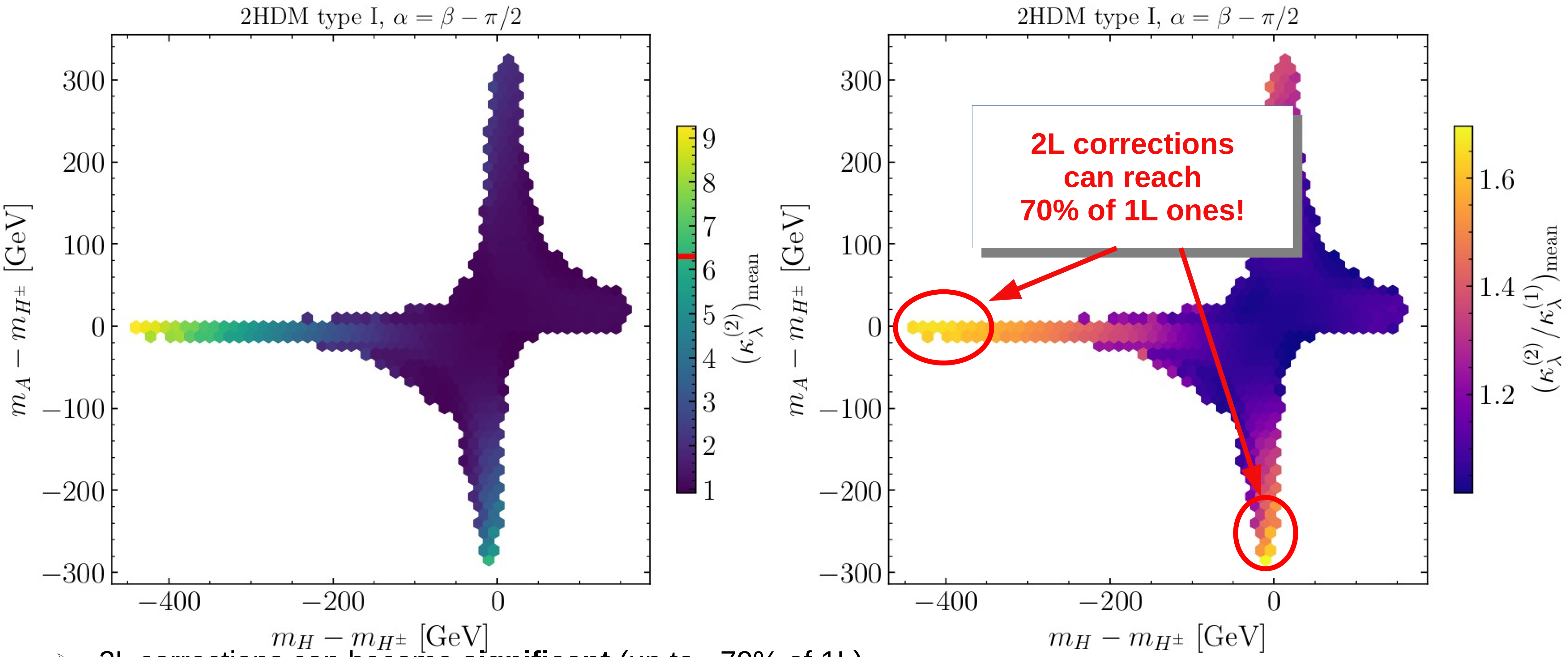


NB: all previously mentioned constraints are fulfilled by the points shown here

Parameter scan results

[Bahl, JB, Weiglein PRL '22]

Mean value for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(1)})^{2HDM}$ [right] in ($m_H - m_{H\pm}$, $m_A - m_{H\pm}$) plane

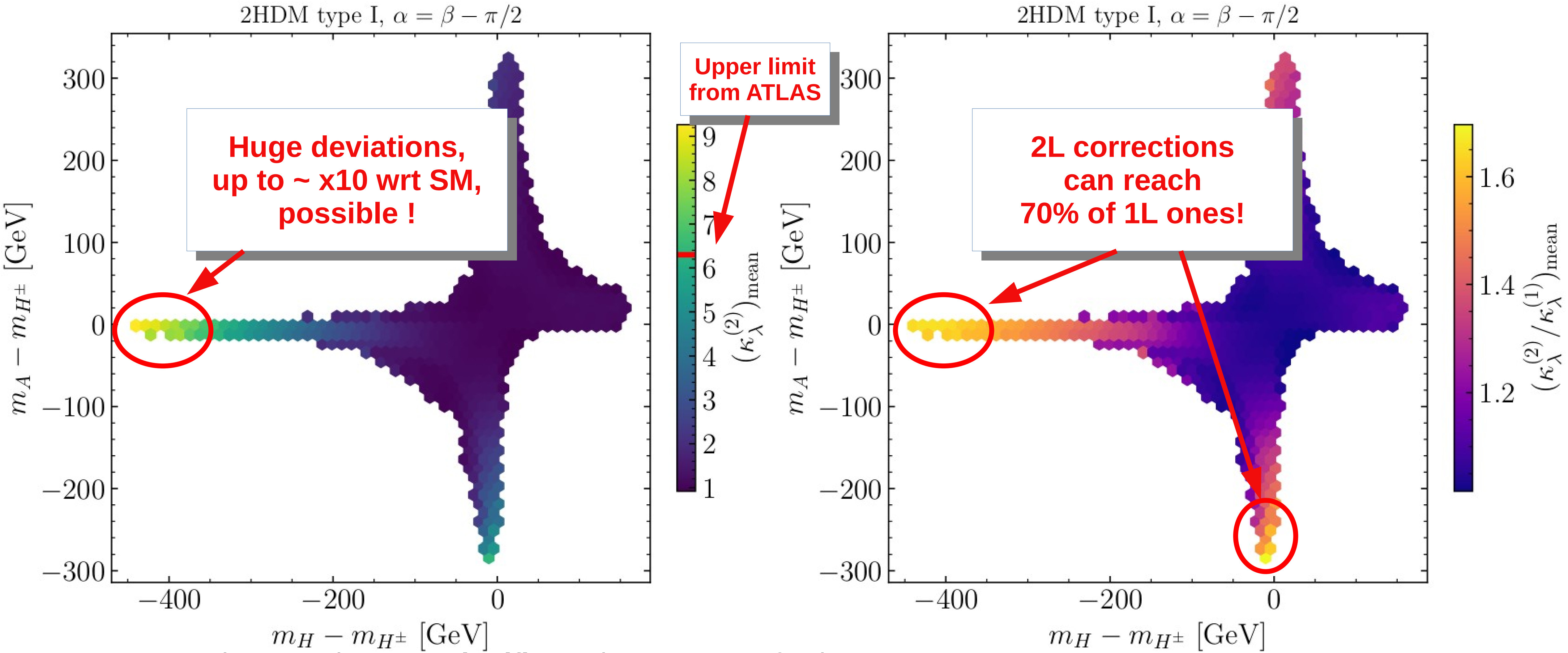


- 2L corrections can become **significant** (up to ~70% of 1L)

Parameter scan results

[Bahl, JB, Weiglein PRL '22]

Mean value for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM} / (\lambda_{hhh}^{(1)})^{2HDM}$ [right] in ($m_H - m_{H\pm}$, $m_A - m_{H\pm}$) plane



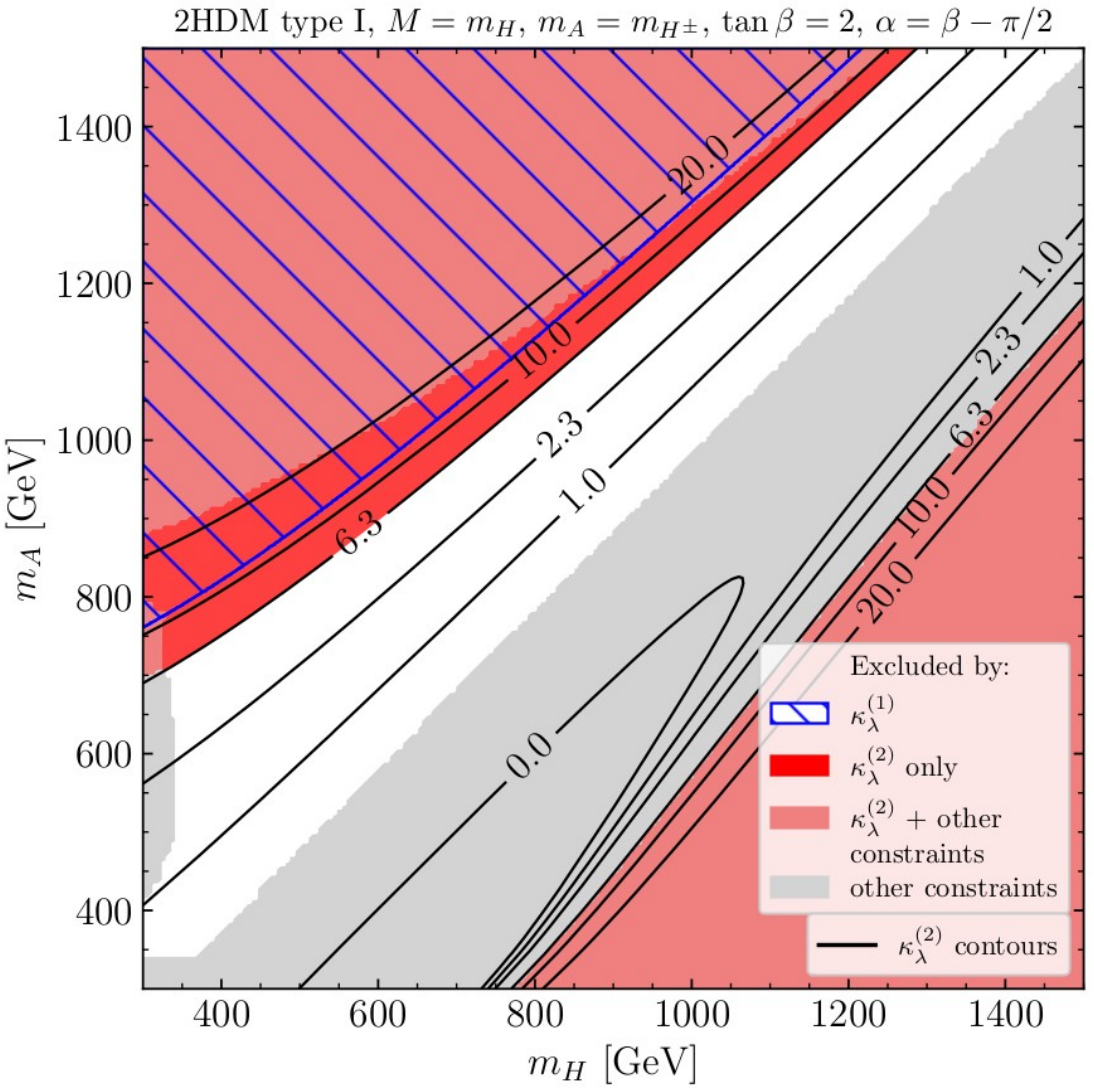
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark scenario in the aligned 2HDM

[Bahl, JB, Weiglein PRL '22]

Results shown for aligned 2HDM of type-I, similar for other types (*available in backup*)

We take $m_A = m_{H\pm}$, $M = m_H$, $\tan\beta = 2$



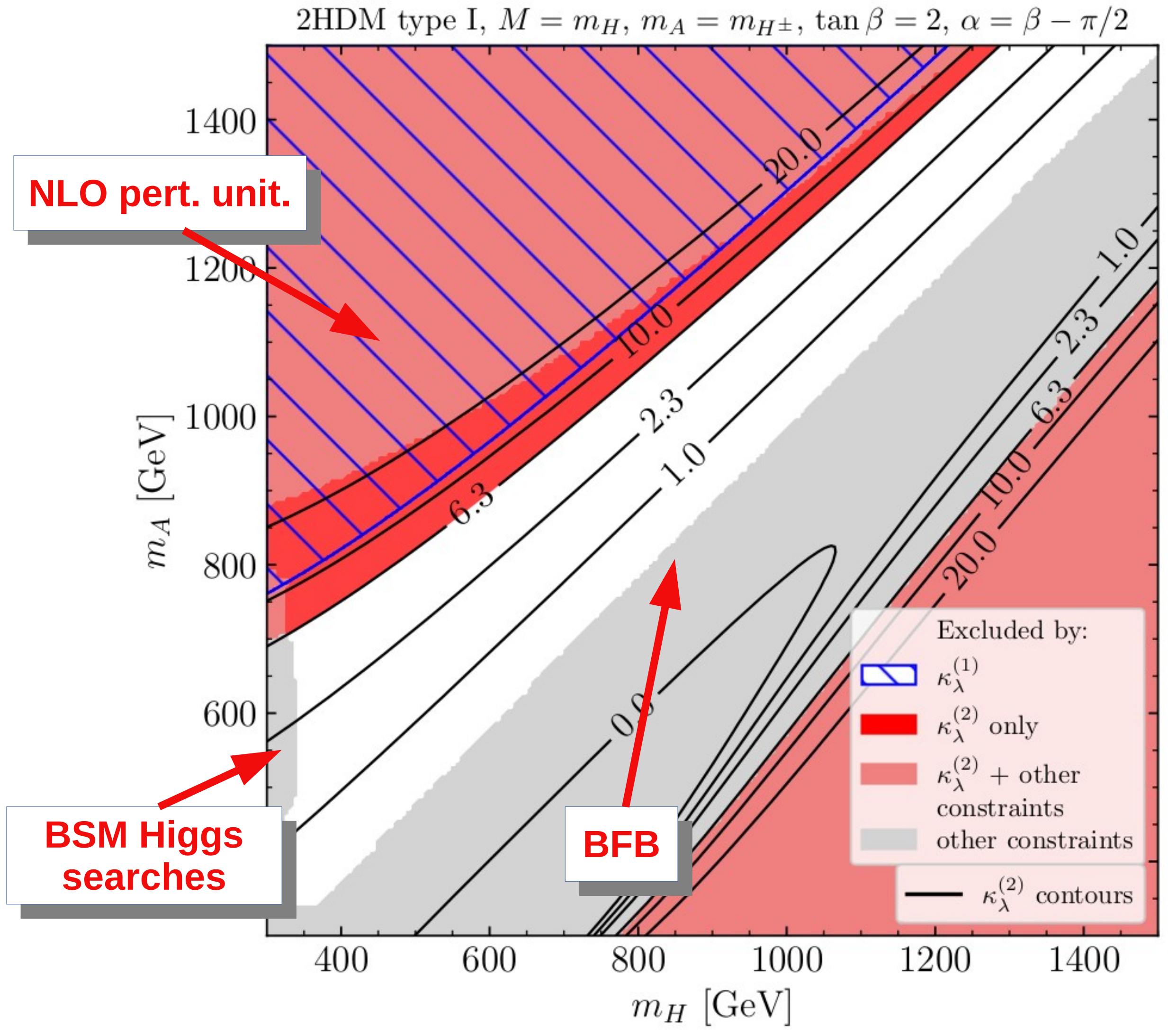
- ***Grey area:*** area excluded by other constraints, in particular BSM Higgs searches, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ the calculation isn't reliable]
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.3$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.3$ → impact of including 2L corrections is significant!

A benchmark scenario in the aligned 2HDM

[Bahl, JB, Weiglein PRL '22]

Results shown for aligned 2HDM of type-I, similar for other types (*available in backup*)

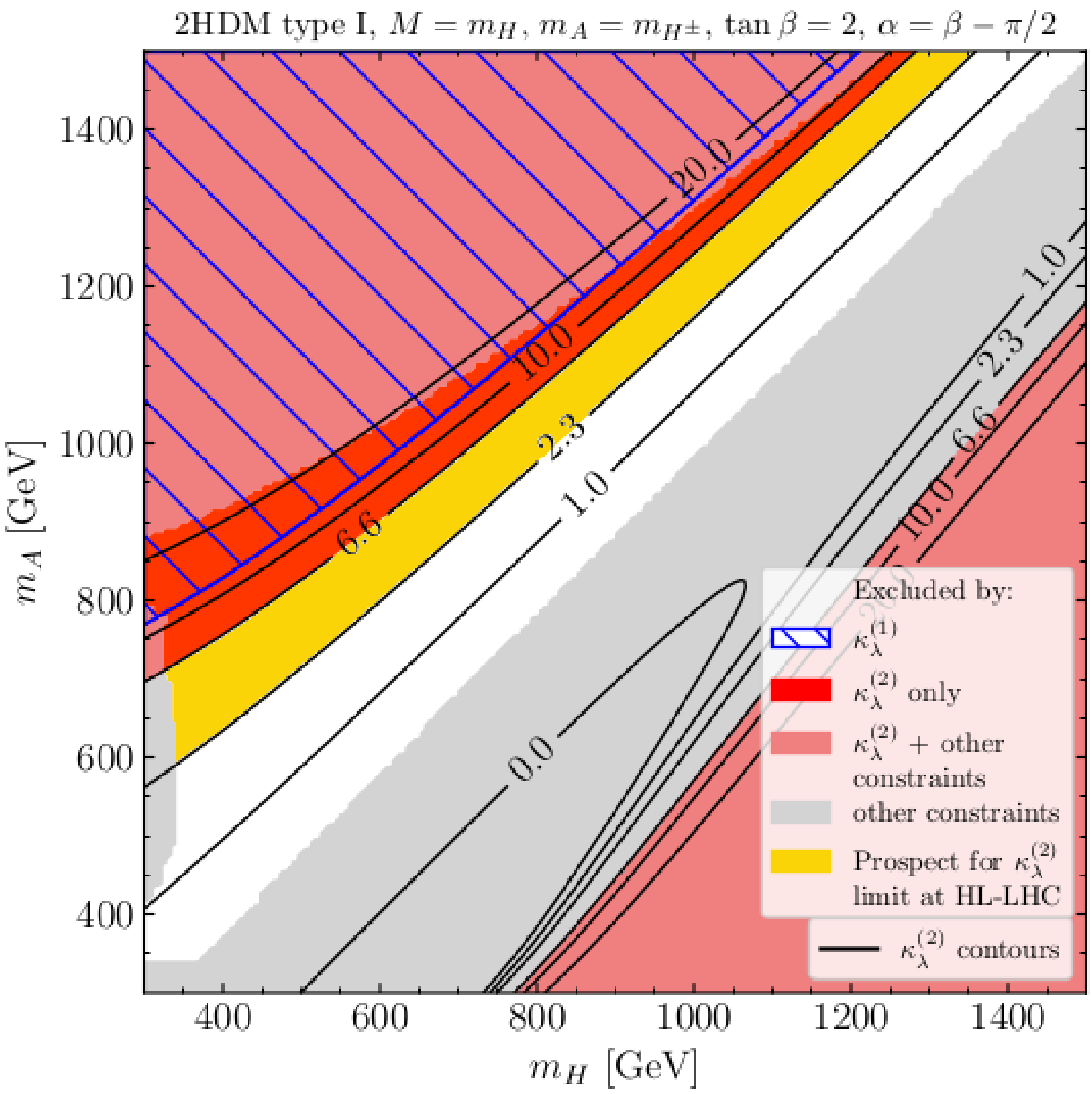
We take $m_A = m_{H\pm}$, $M = m_H$, $\tan\beta = 2$



- ***Grey area:*** area excluded by other constraints, in particular BSM Higgs searches, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ the calculation isn't reliable]
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.3$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.3$ → impact of including 2L corrections is significant!

A benchmark scenario in the aligned 2HDM – future prospects

Suppose for instance the upper bound on κ_λ becomes $\kappa_\lambda < 2.3$



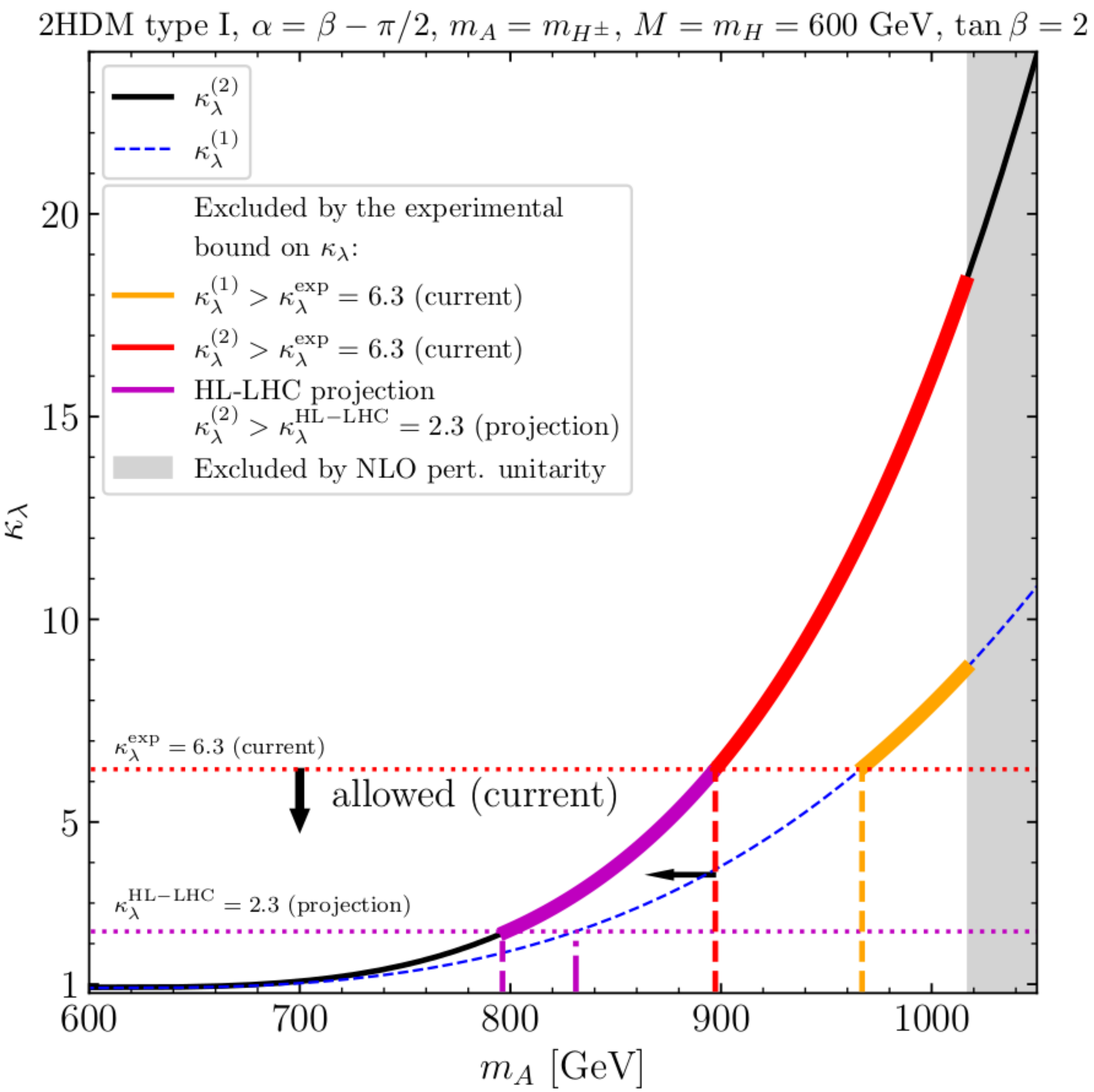
[Bahl, JB, Weiglein '23]

- ***Golden area:*** additional exclusion if the limit on κ_λ becomes $\kappa_\lambda^{(2)} < 2.3$ (achievable at HL-LHC)
- Of course, **prospects even better with an e^+e^- collider!**
- Experimental constraints, such as Higgs physics, may also become more stringent, however **not** theoretical constraints (like BFB or perturbative unitarity)

A benchmark scenario in the aligned 2HDM – 1D scan

Within the previously shown plane, we fix $M=m_H=600$ GeV, and vary $m_A=m_{H\pm}$

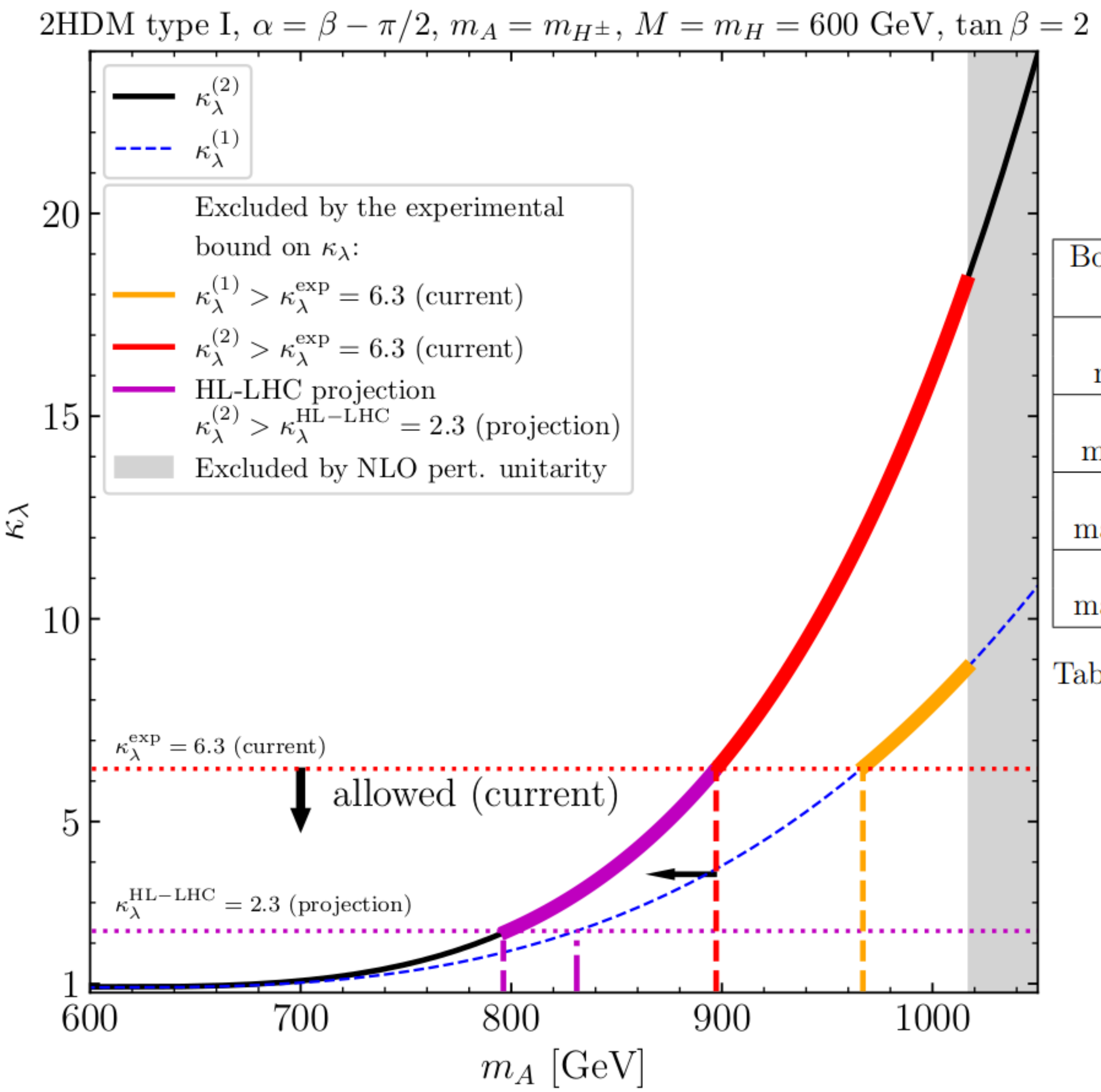
[Bahl, JB, Weiglein PRL '22]



- Illustrates the significantly improved reach of the experimental limit when including **2L corrections** in calculation of κ_λ
- A stricter choice for the perturbative unitarity constraint (grey) does not significantly change the region excluded by $\kappa_\lambda^{(2)}$

A benchmark scenario in the aligned 2HDM – 1D scan

[Bahl, JB, Weiglein PRL '22]

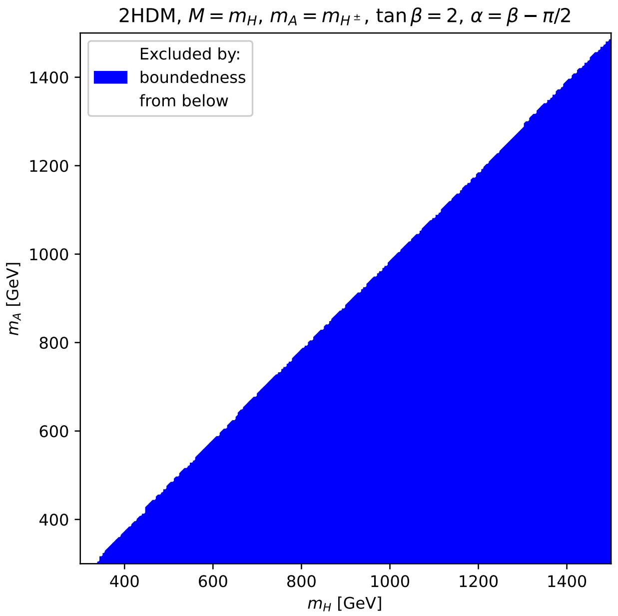


Bound on eigenvalues	$\max(m_A)$ with LO pert. unit.	$\max(m_A)$ with NLO pert. unit.	$\max(m_A)$ with with finite $\sqrt{s} \in [3\text{ TeV}, 10\text{ TeV}]$
$\max(\lvert a_i \rvert) < 1$	1161 GeV	1017 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 1$	1161 GeV	1033 GeV	1260 GeV
$\max(\lvert a_i \rvert) < 0.5$	917 GeV	937 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.5$	917 GeV	958 GeV	929 GeV
$\max(\lvert a_i \rvert) < 0.49$	911 GeV	933 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.49$	911 GeV	956 GeV	922 GeV
$\max(\lvert a_i \rvert) < 0.45$	889 GeV	912 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.45$	889 GeV	948 GeV	897 GeV

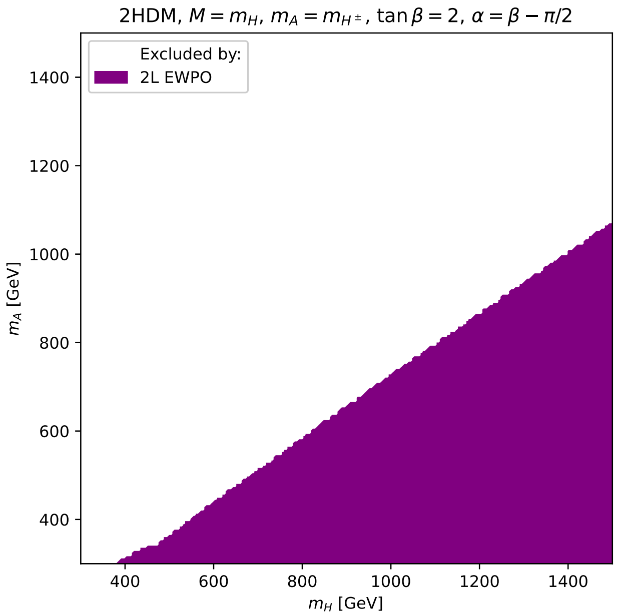
Table 1: Maximal values of m_A allowed in the benchmark scenario under the constraint of perturbative unitarity, at LO and NLO, and for different upper bounds on the $2 \to 2$ scattering eigenvalues used in the perturbative unitarity constraint. Note that tree-level scattering eigenvalues are all real, so there is no difference between using max or $\mathfrak{Re}$(max) for the left column.

2HDM benchmark plane – individual theoretical constraints

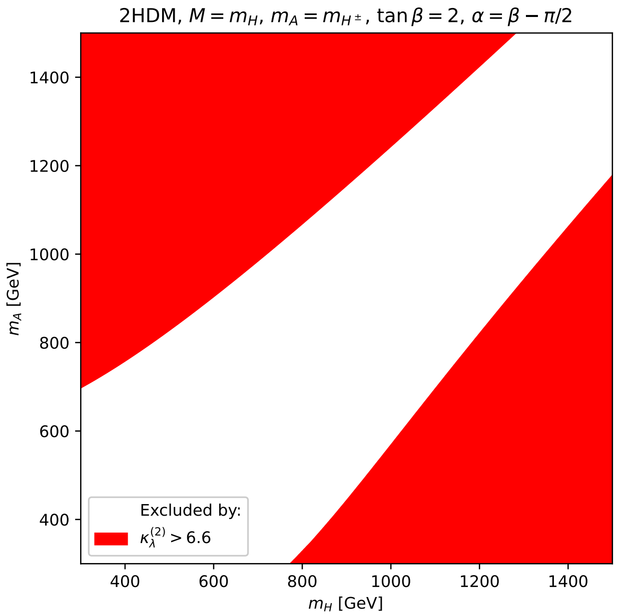
Constraints shown below are independent of 2HDM type



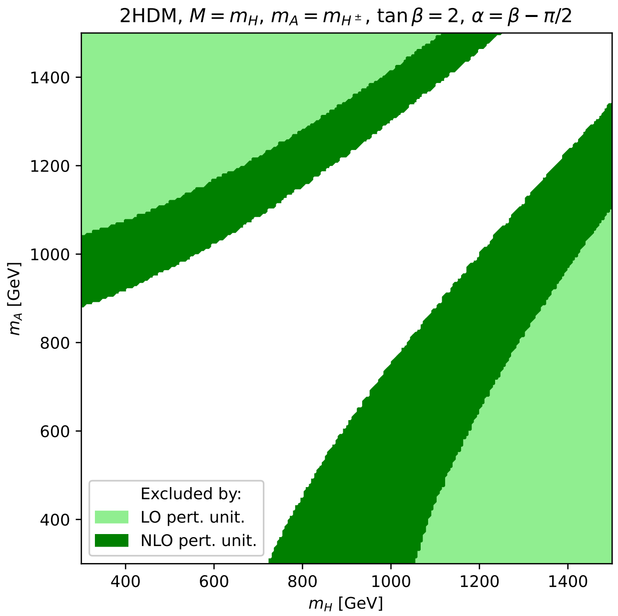
Boundedness from below



EW precision observables computed at 2L



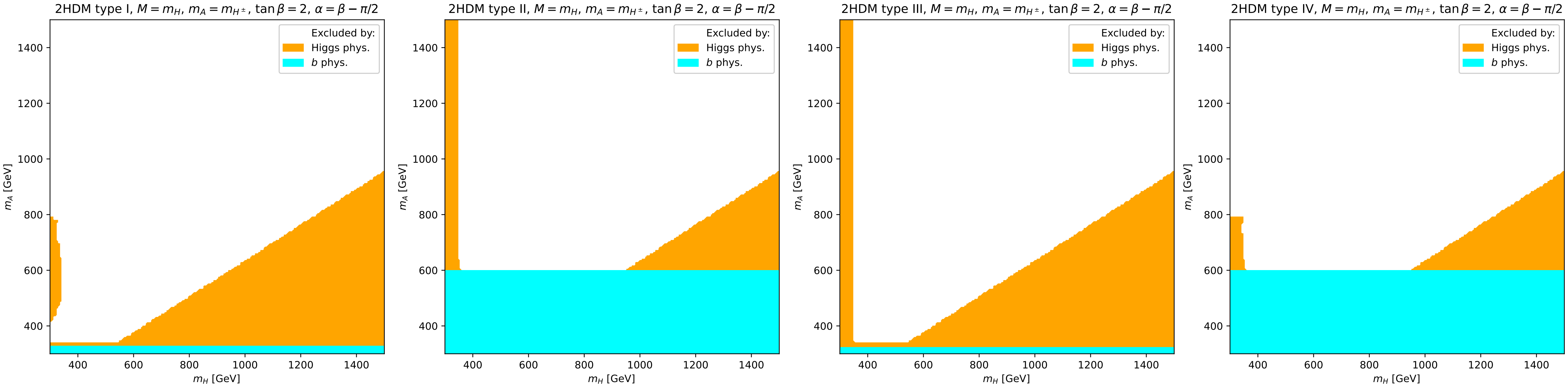
$\kappa_\lambda^{(2)} > 6.6$



Perturbative unitarity at (N)LO

2HDM benchmark plane – experimental constraints

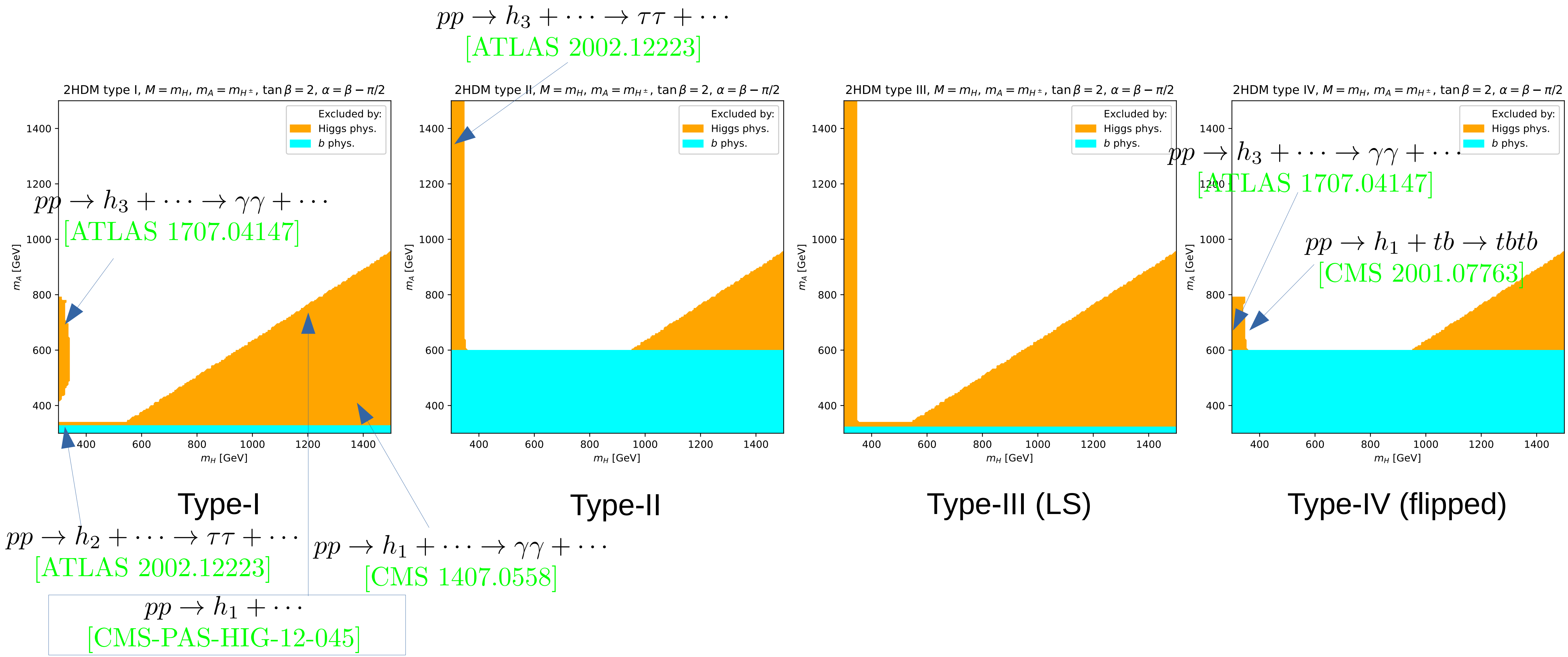
i.e. Higgs physics (via HiggsBounds and HiggsSignals) and *b* physics (from [Gfitter group 1803.01853])



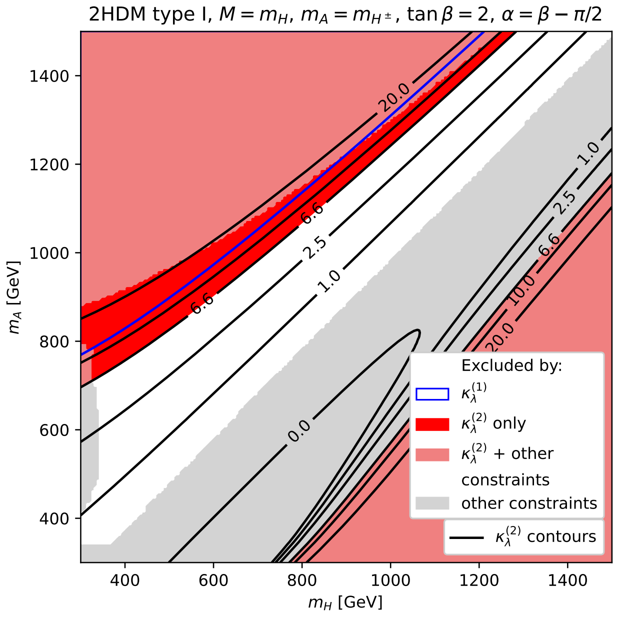
Type-I Type-II Type-III (LS) Type-IV (flipped)

2HDM benchmark plane – experimental constraints

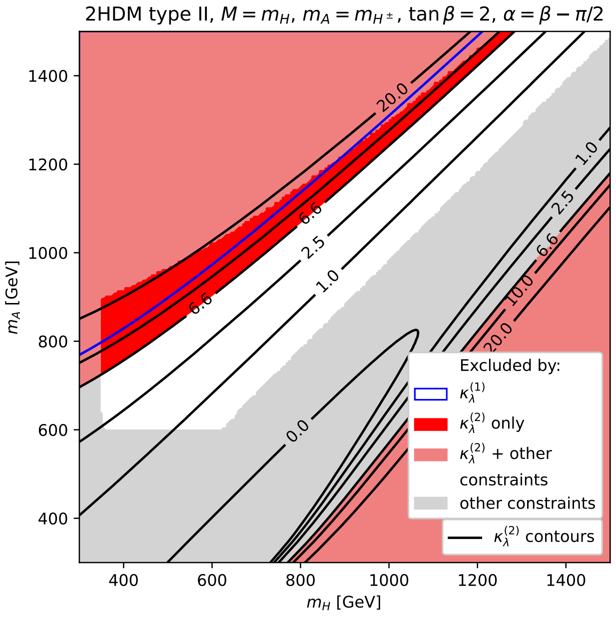
i.e. Higgs physics (via HiggsBounds and HiggsSignals) and *b* physics (from [Gfitter group 1803.01853])



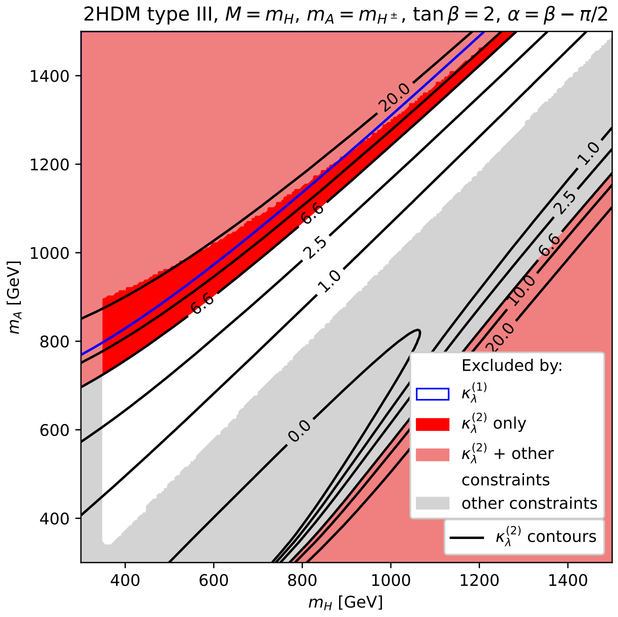
2HDM benchmark plane – results for all types



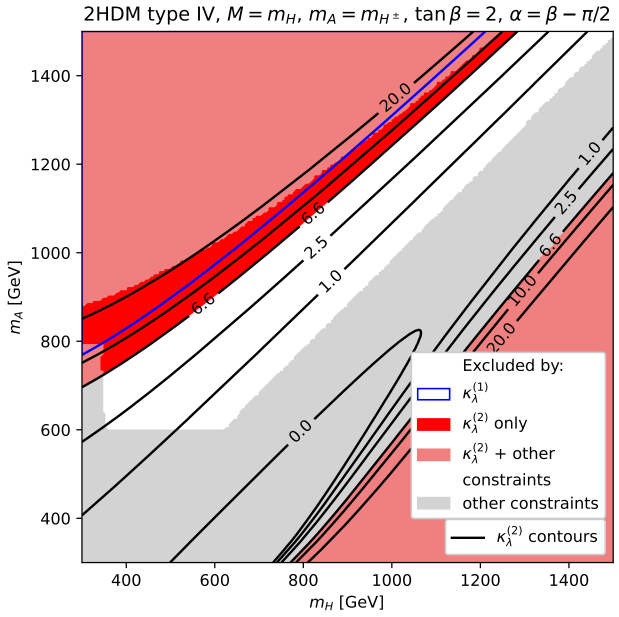
Type-I



Type-II



Type-III (LS)



Type-IV (flipped)