Extended Higgs sectors and their corresponding trilinear scalar couplings

Based mainly on

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

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

Johannes Braathen (DESY)

QCD @ LHC 2024,

Universität Freiburg, Germany | 7 October 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

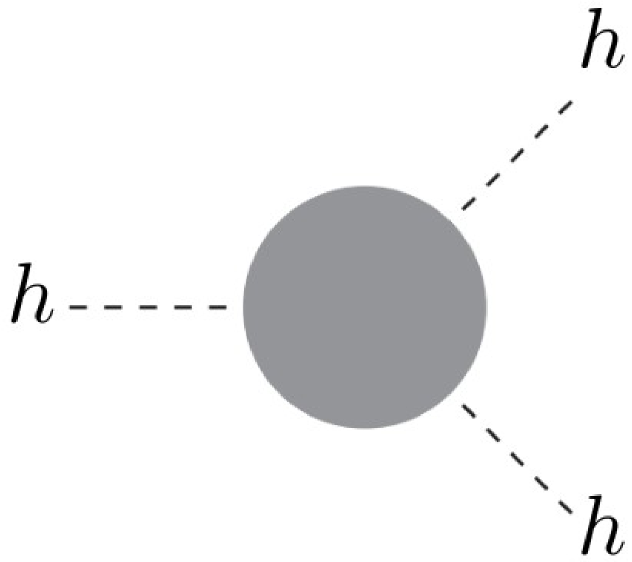
Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

DESY.

Outline of the talk

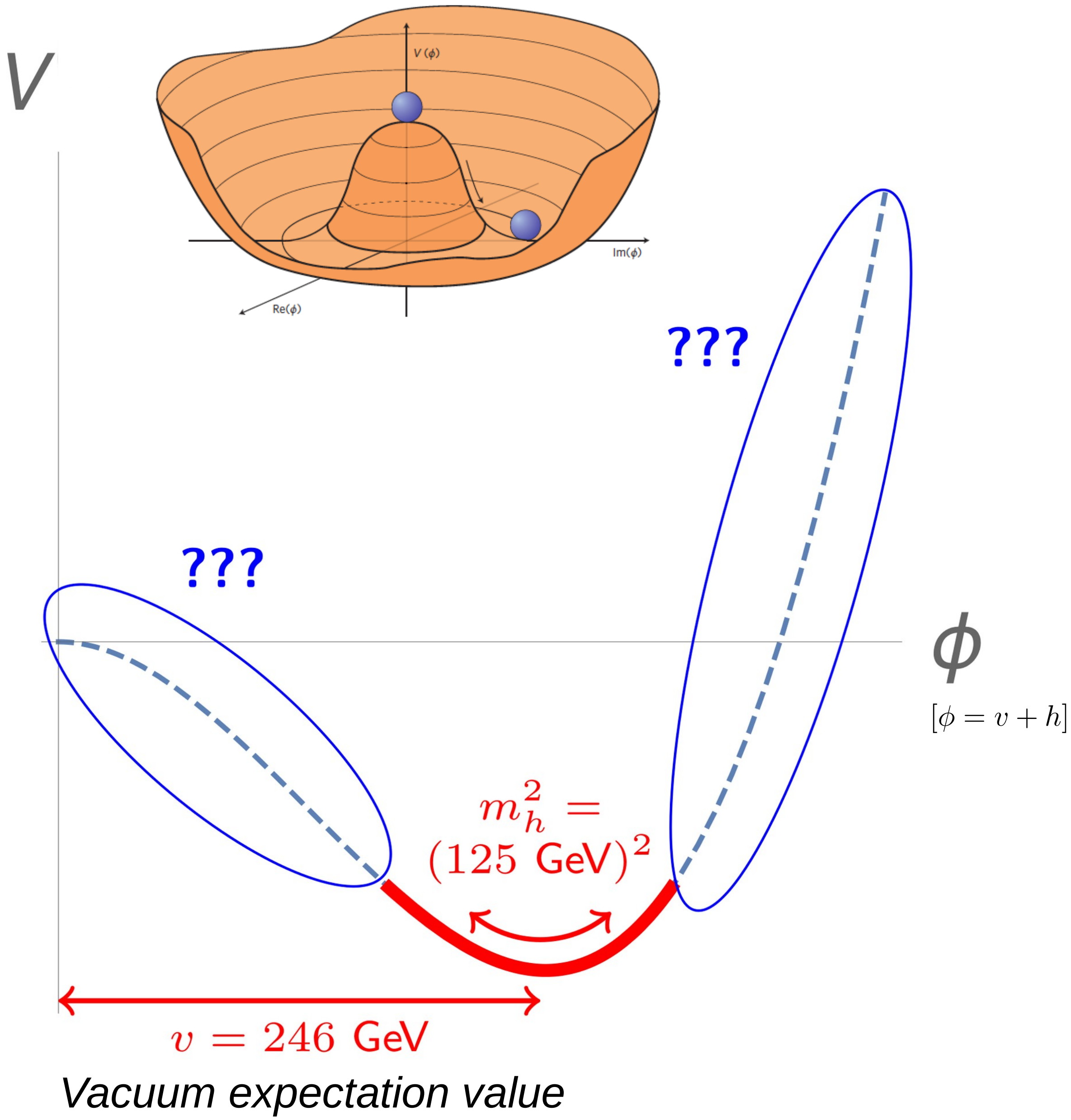
- Introduction: Why study the trilinear Higgs coupling λ_{hhh} and how to access it experimentally
- Calculating λ_{hhh} in BSM models
- How large can λ_{hhh} become for realistic scenarios
- Consequences for di-Higgs production at LHC

Why investigate λ_{hhh}?



Form of the Higgs potential and trilinear Higgs coupling

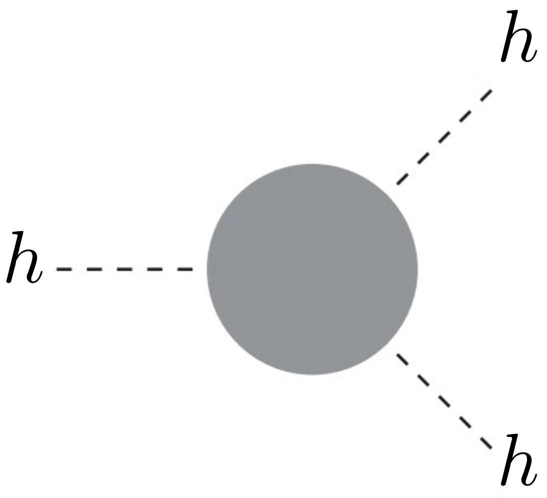
- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)

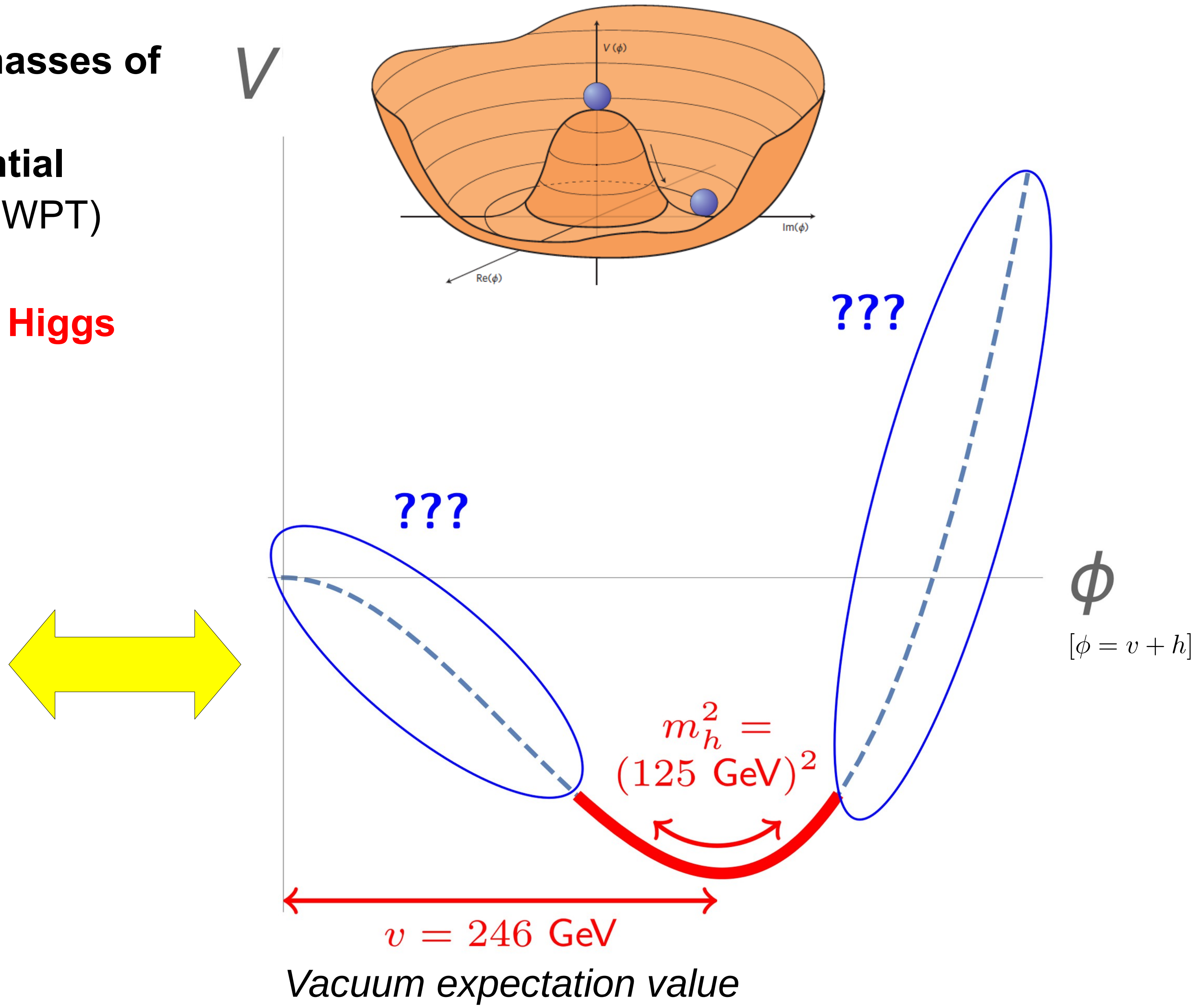


Form of the Higgs potential and trilinear Higgs coupling

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

- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**

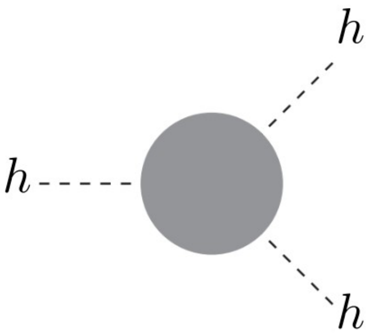


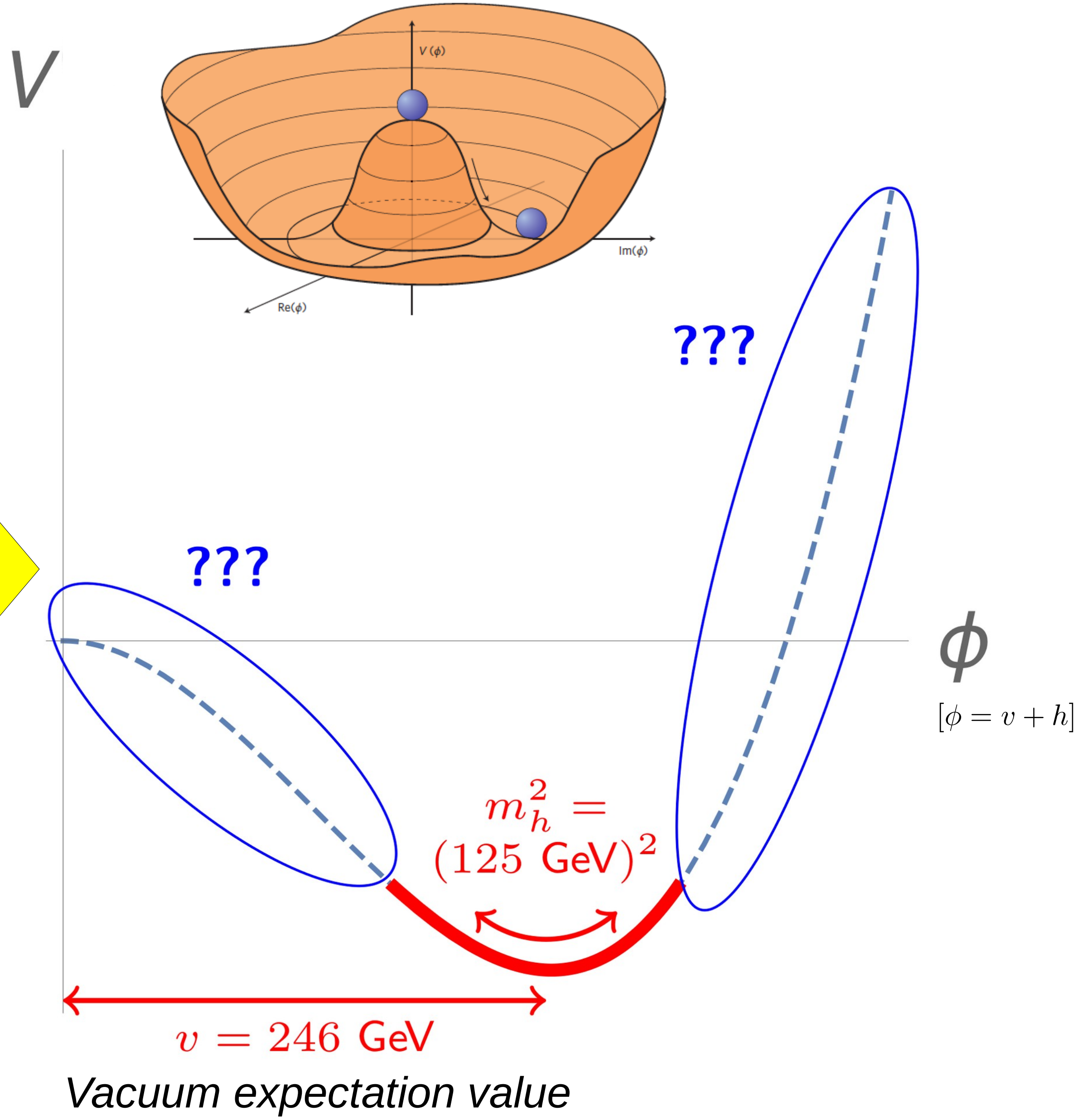


Form of the Higgs potential and trilinear Higgs coupling

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

- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**





In the SM: $V^{(0)}_{\rm SM} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \underbrace{\left(\frac{3m_h^2}{v}\right)}_{\equiv (\lambda^{(0)}_{hhh})^{\rm SM}} h^3 + \frac{1}{4!} \left(\frac{3m_h^2}{v^2}\right) h^4 + \cdots$

In general:

$$V^{(0)} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \overbrace{\kappa_\lambda \left(\frac{3m_h^2}{v}\right)}^{\equiv \lambda_{hhh}} h^3 + \frac{1}{4!} \kappa_{\lambda_4} \left(\frac{3m_h^2}{v^2}\right) h^4 + \cdots$$

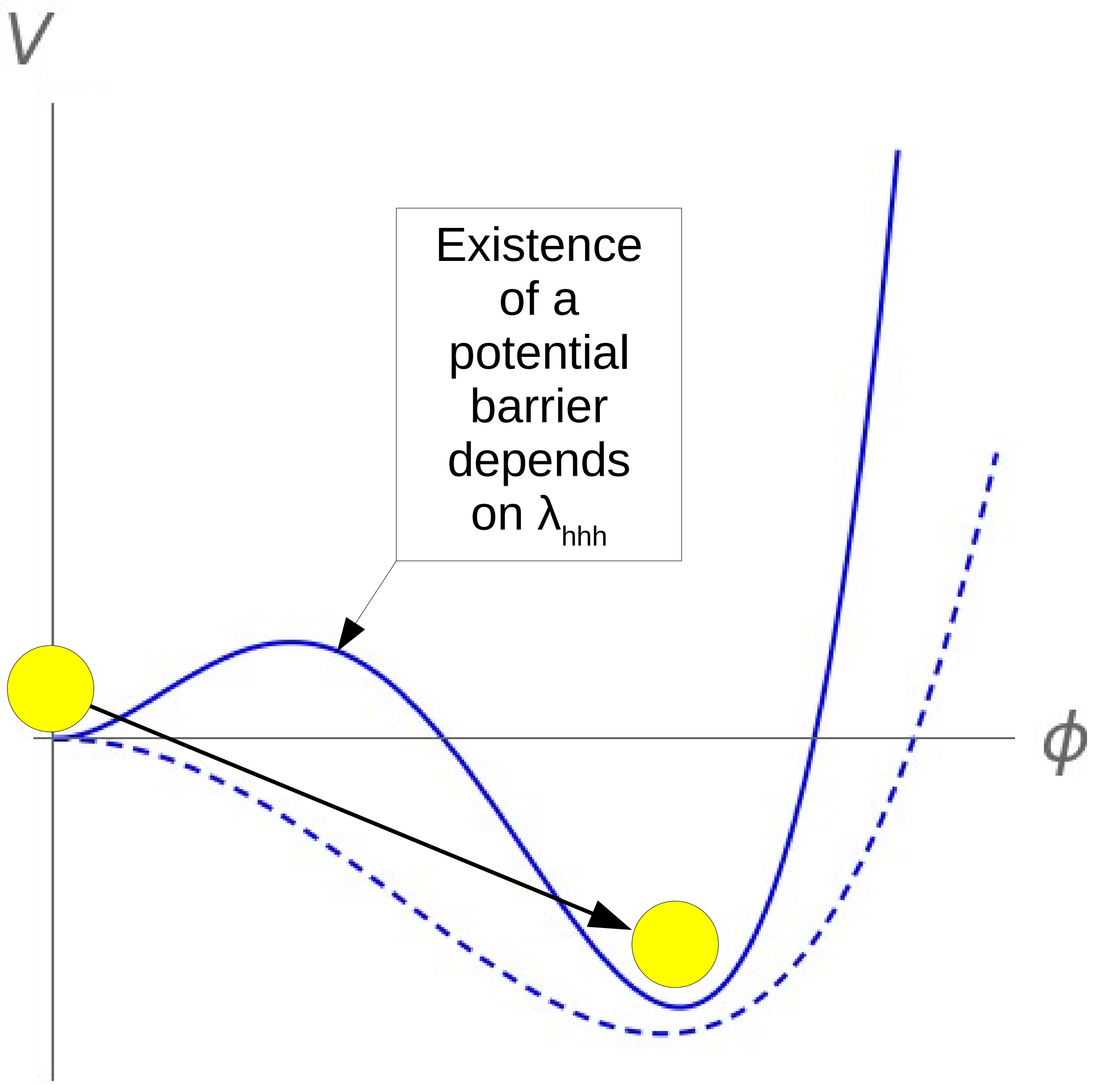
with $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda^{(0)}_{hhh})^{\rm SM}$

Form of the Higgs potential and baryon asymmetry

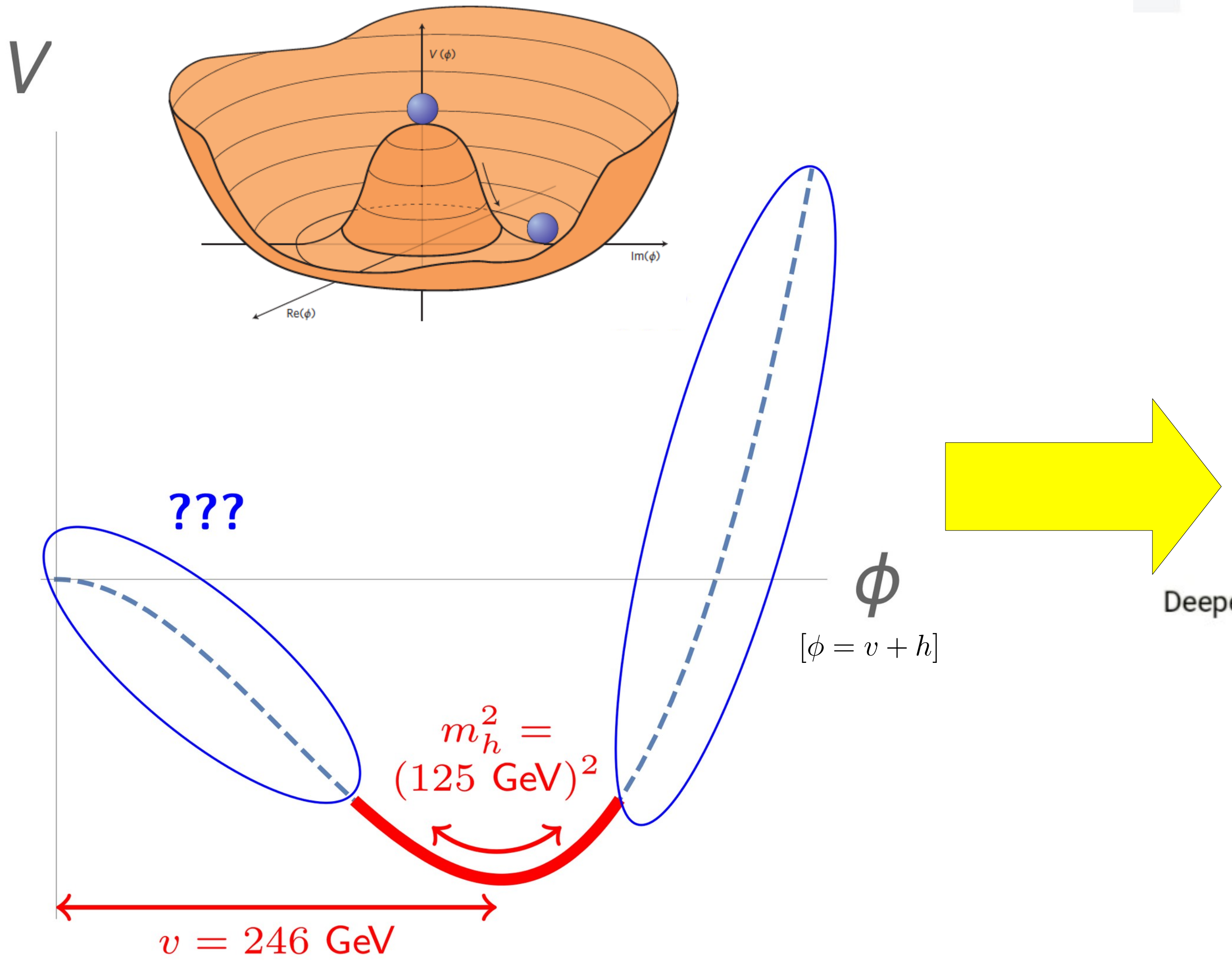
- Brout-Englert-Higgs mechanism = **origin of masses of elementary particles** ...
  … but very little known about the **Higgs potential** causing the **electroweak phase transition** (EWPT)

- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**

- 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)*

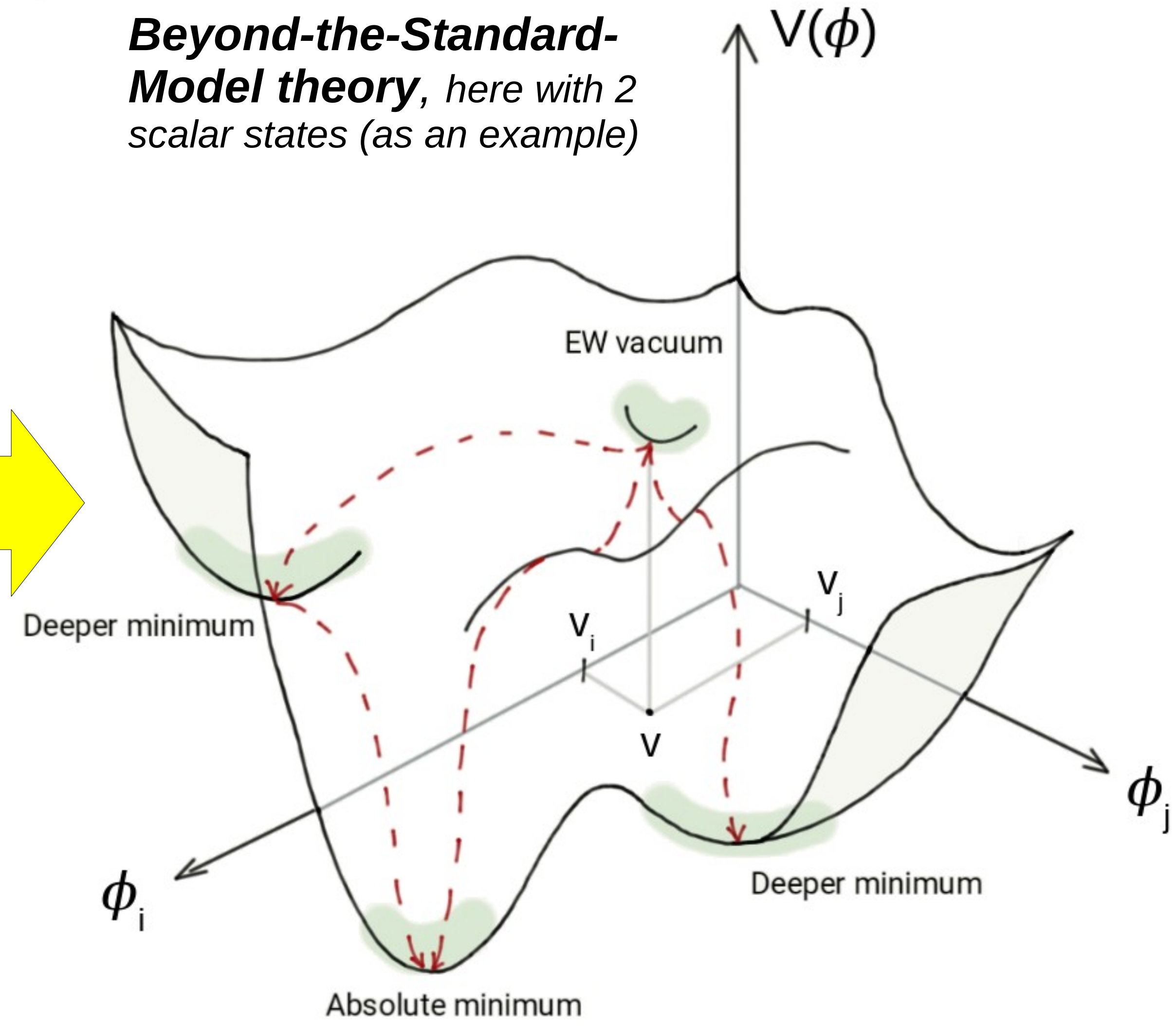
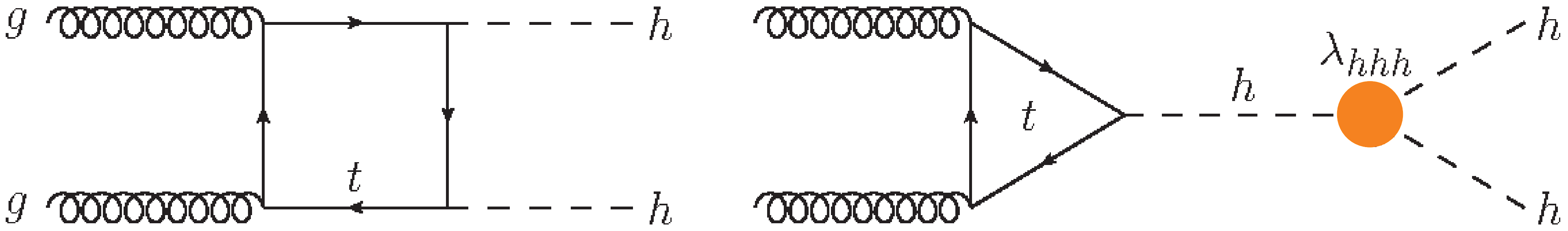


Figure by [K. Radchenko Serdula '24]

Accessing λ_{hhh} experimentally

Accessing λ_{hhh} via di-Higgs production

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



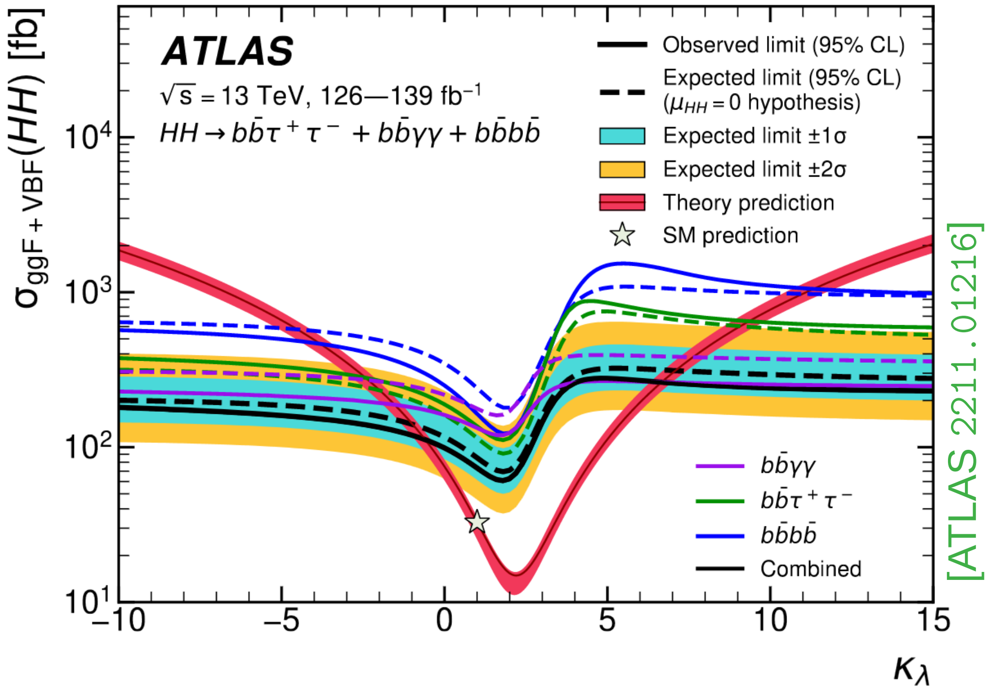
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

- 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

v^2

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.

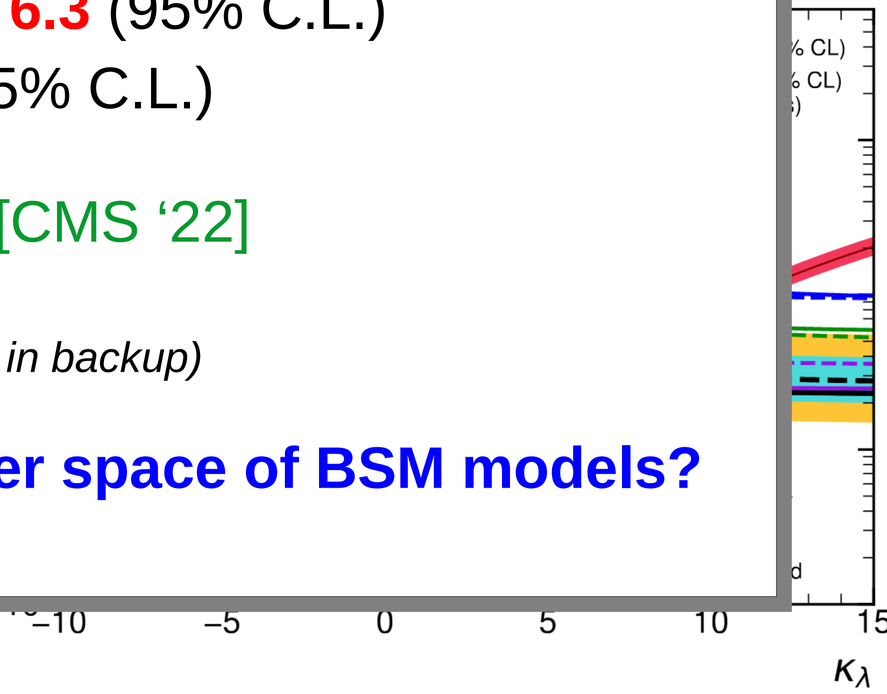
(all other κ's fixed to 1)

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]

Calculating λ_{hhh} in models with extended scalar sectors

The Two-Higgs-Doublet Model

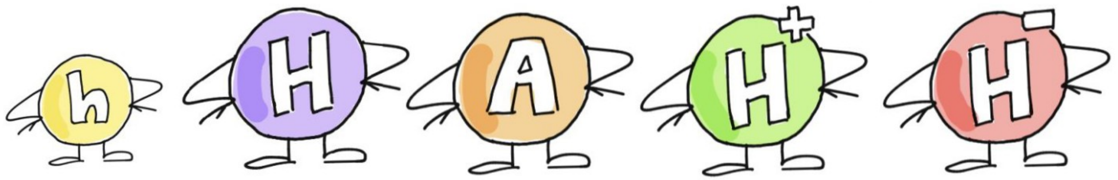


Figure by [K. Radchenko Serdula '24]

- 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

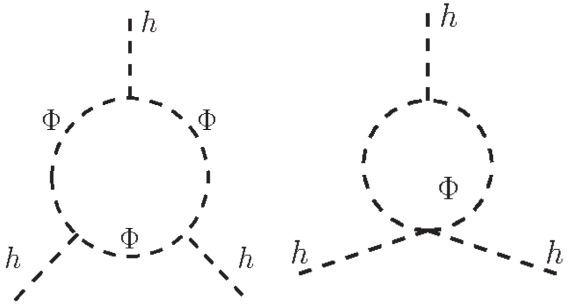
- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv 2m_3^2/s_{2\beta}$), angles α (CP-even Higgs mixing angle) and β (defined by $\tan\beta = v_2/v_1$)

- **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
  → compatible with current experimental data

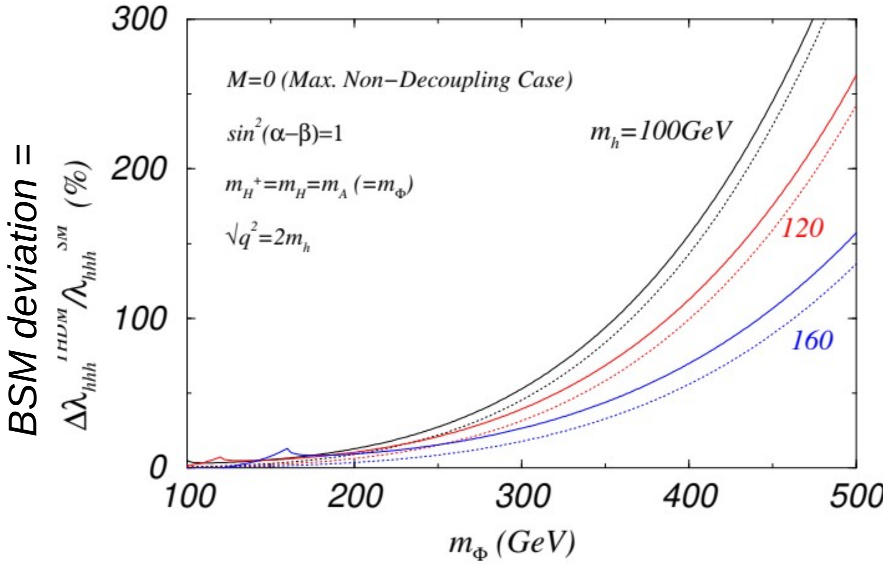
Mass splitting effects in λ_{hhh}

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



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

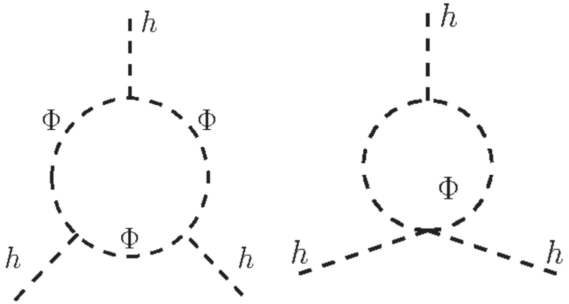
$$(\Phi \in \{H, A, H^\pm\})$$



- **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.)

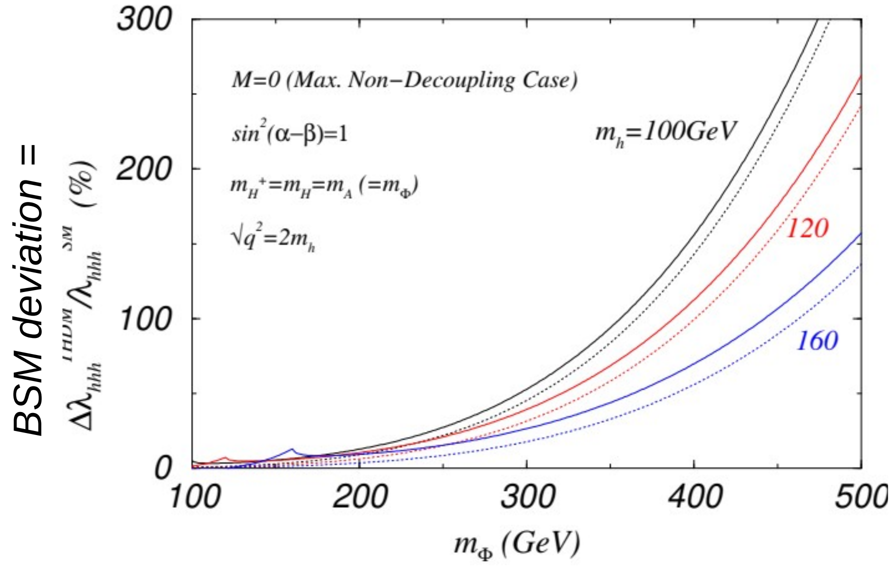
Mass splitting effects in λ_{hhh}

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



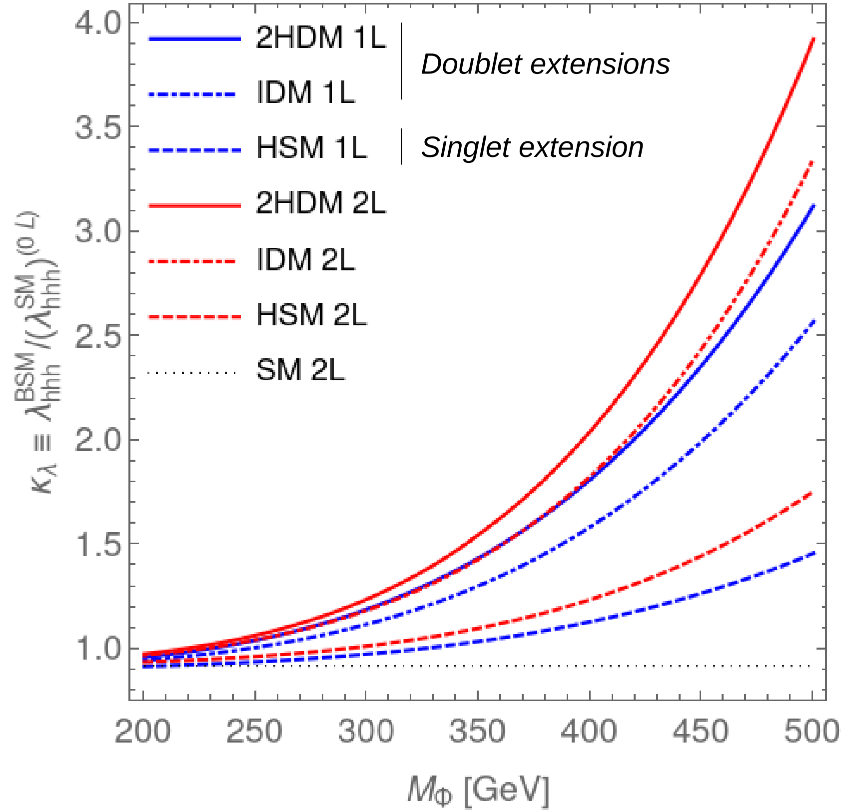
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

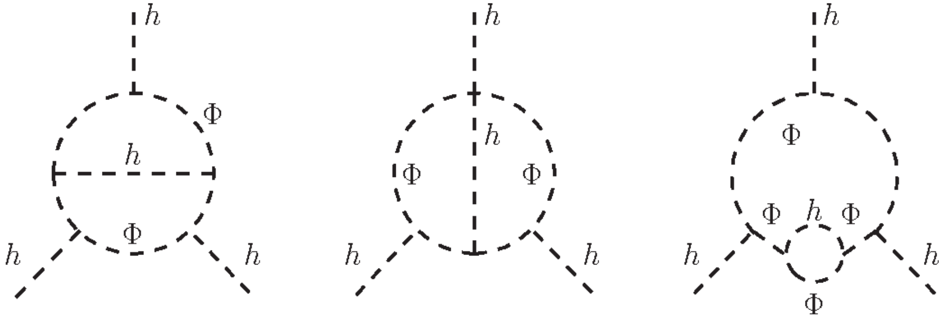
$$(\Phi \in \{H, A, H^\pm\})$$



- **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.)

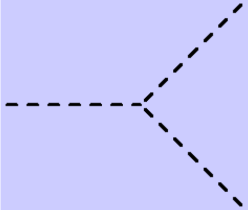
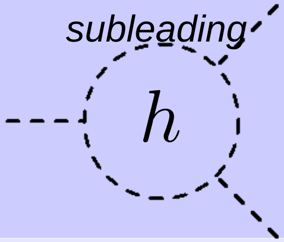
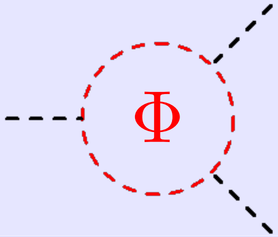
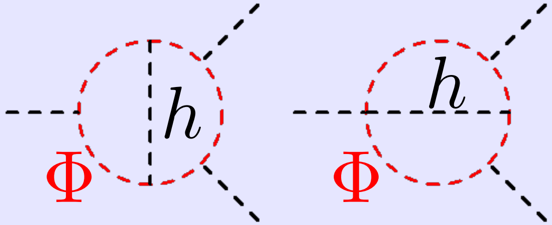
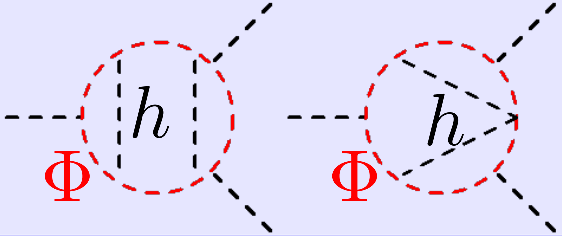
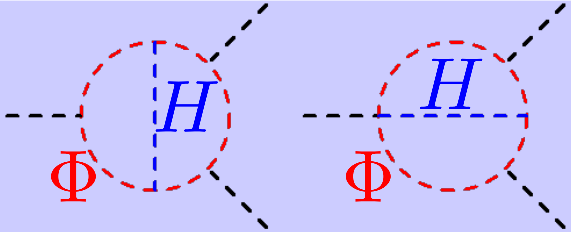
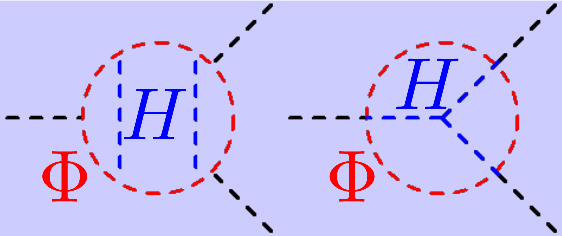
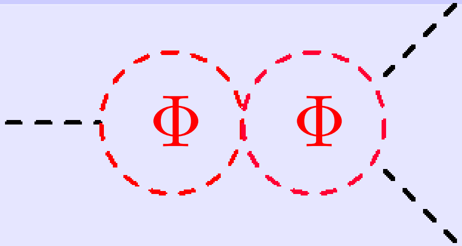
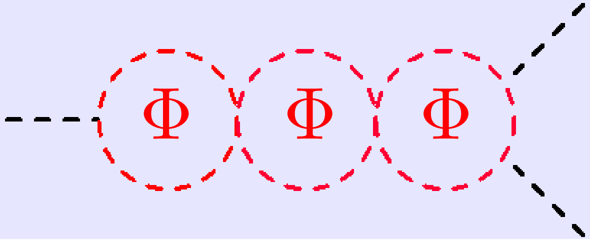
- Large effects **confirmed at 2L** in [JB, Kanemura '19]
→ **leading 2L corrections involving BSM scalars (H,A,H±) and top quark**, computed in effective potential approximation





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 checked!*

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

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?

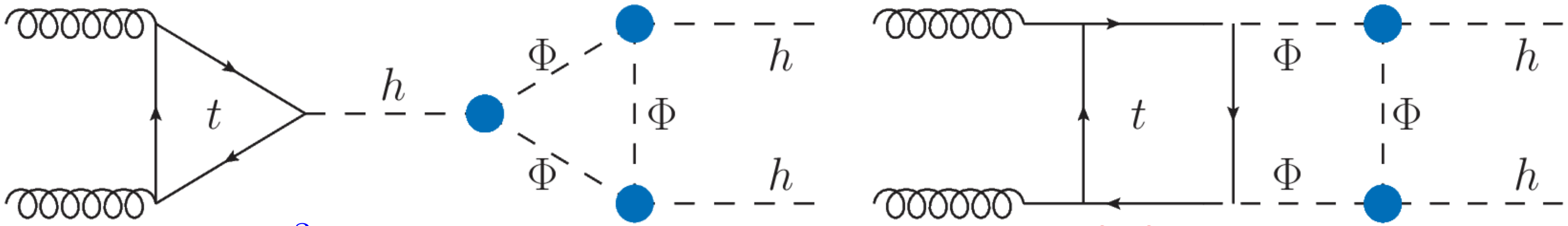
- Current strongest limits on κ_λ from ATLAS di-Higgs searches

  $-1.2 < \kappa_\lambda < 7.2$ [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

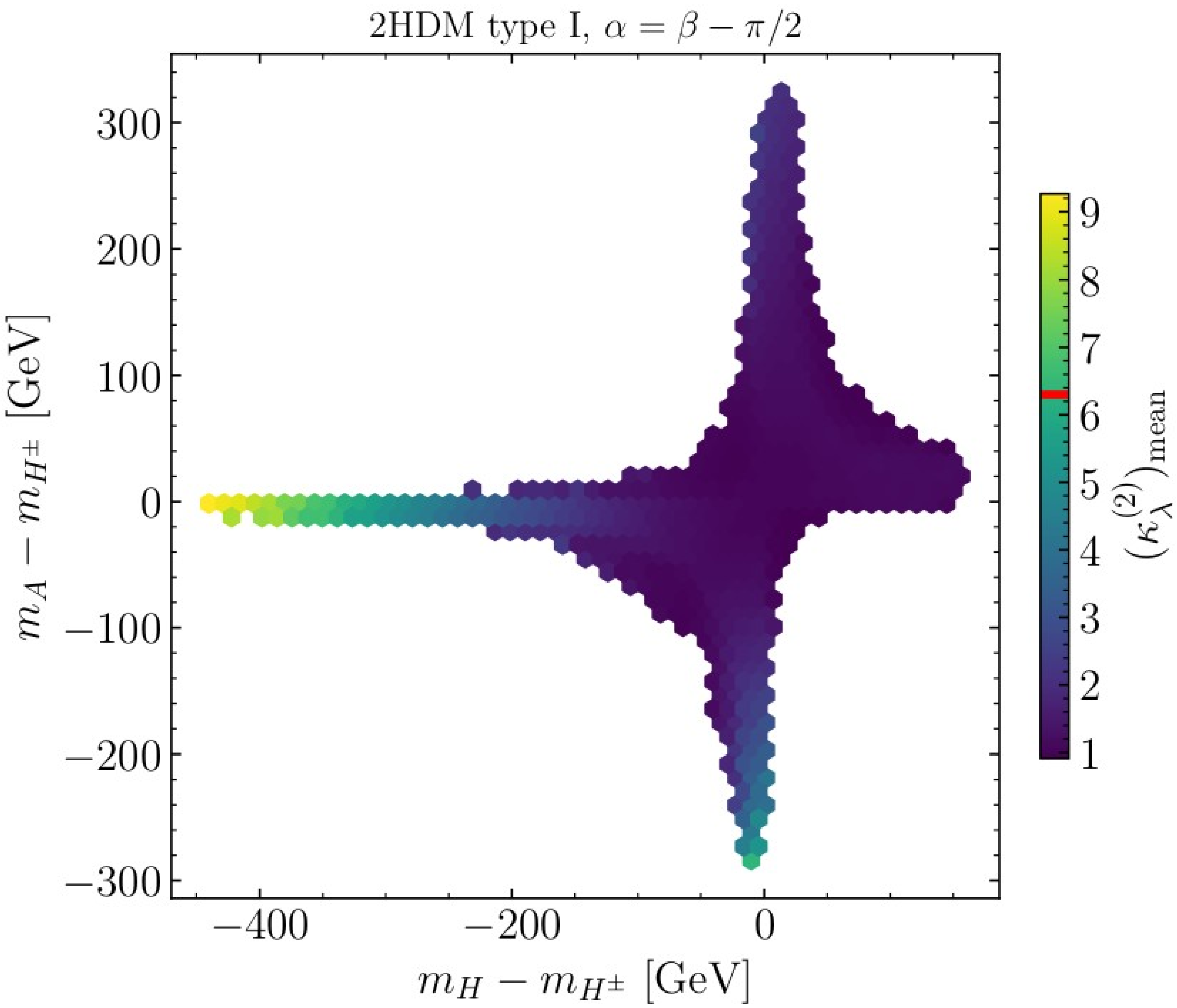
  (Checked with `ScannerS`)

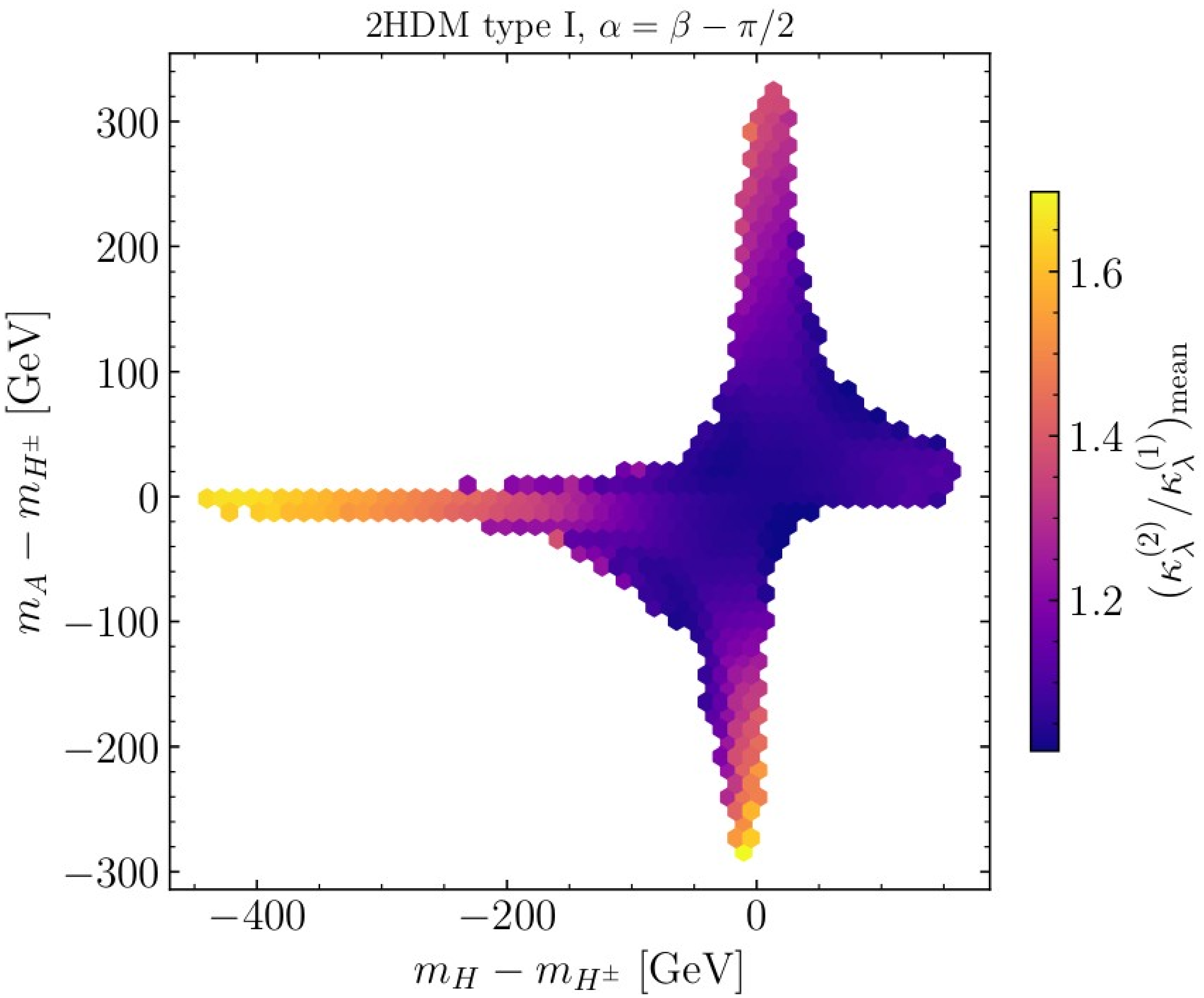
  - NLO perturbative unitarity, using results from [Grinstein et al. `1512.04567`], [Cacchio et al. `1609.01290`]
- For points passing these constraints, we **compute κ_λ at 1L and 2L**, using results from [JB, Kanemura '19]

Parameter scan results

[Bahl, JB, Weiglein PRL '22]

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



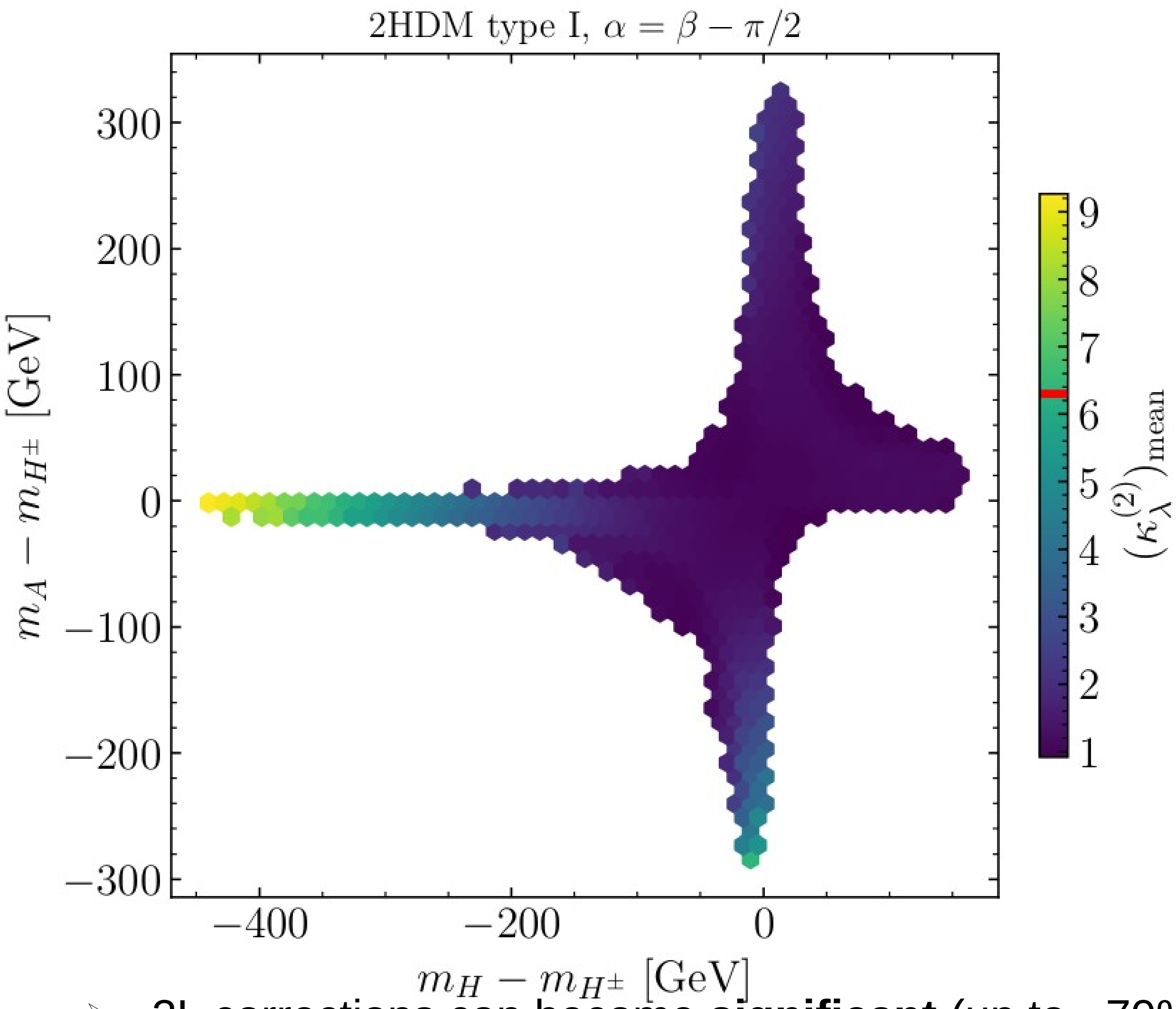


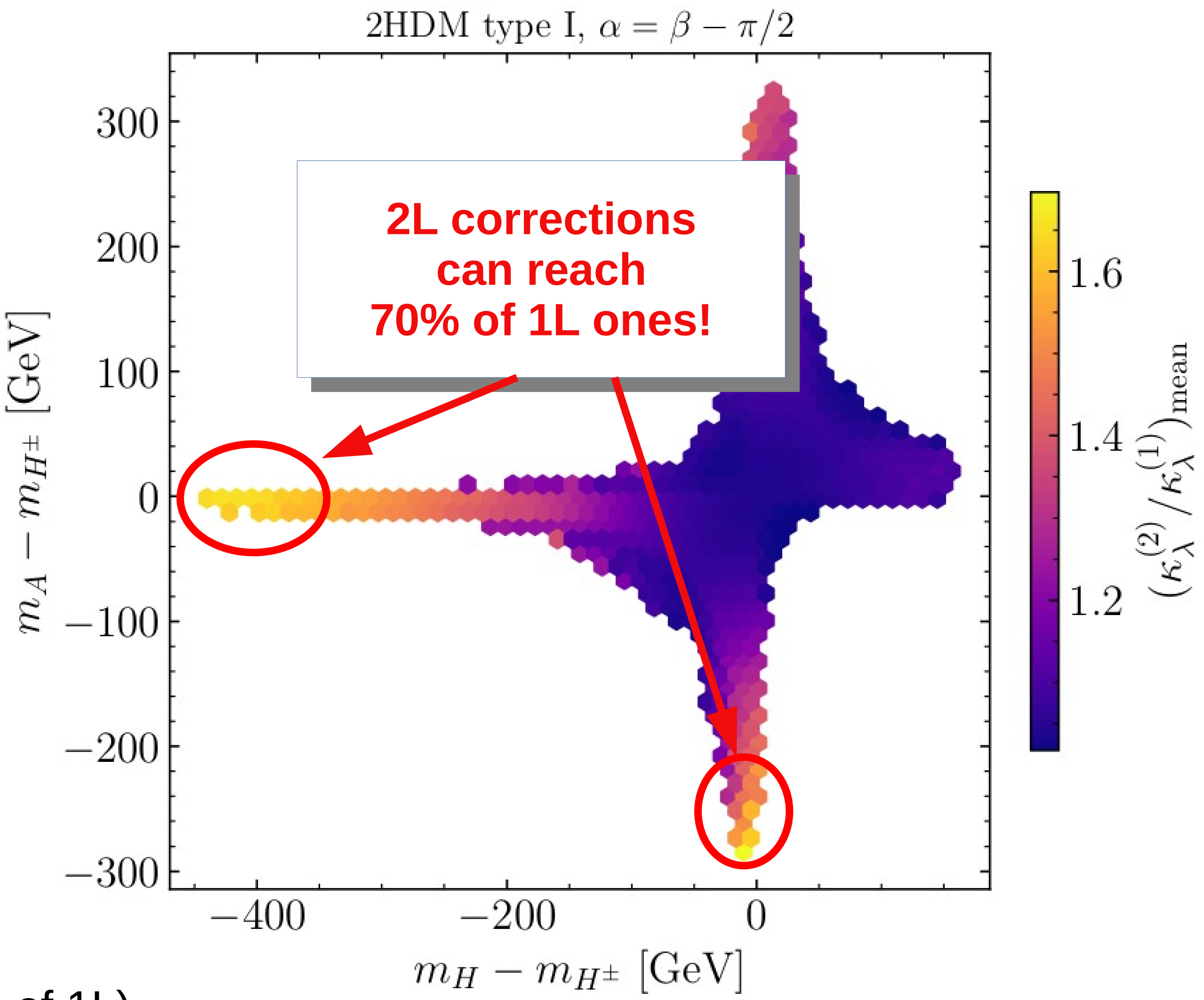
NB: all previously mentioned constraints are fulfilled by the points shown here

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



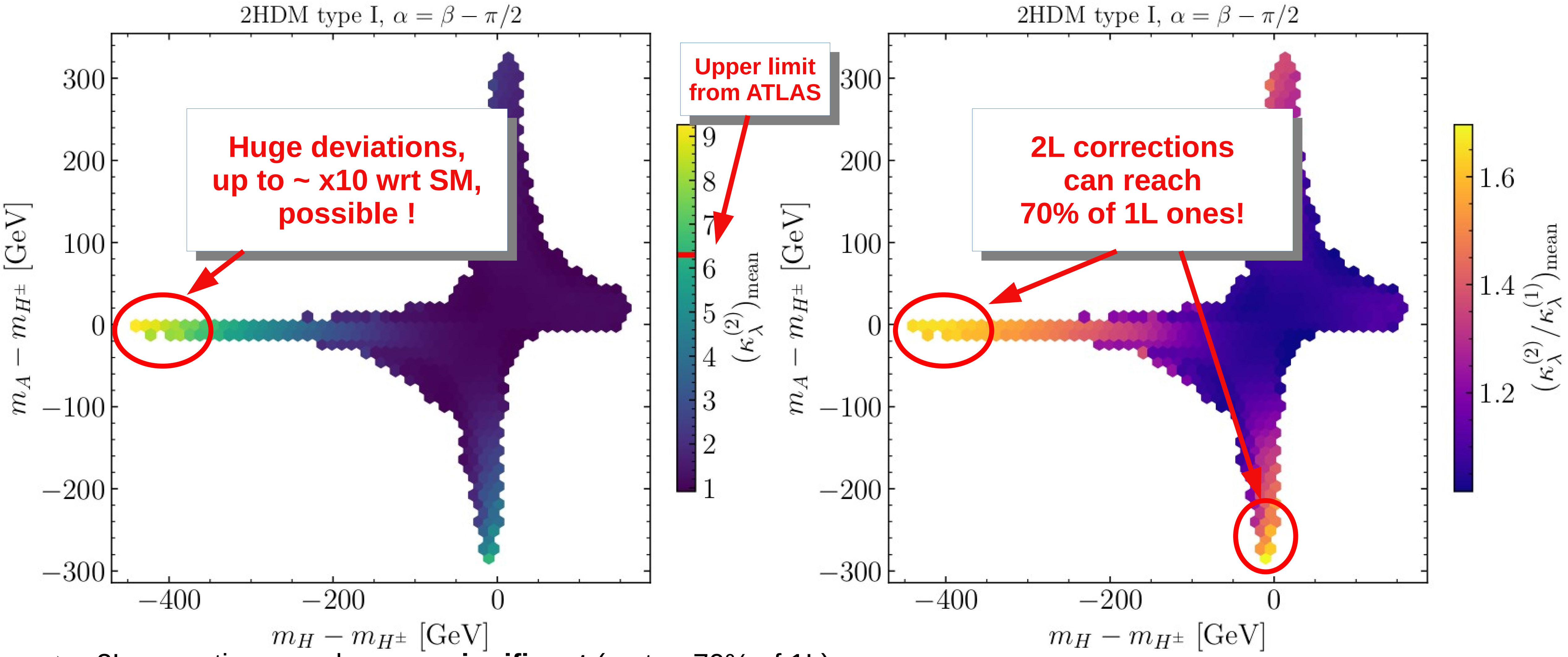


- 2L corrections can become **significant** (up to ~70% of 1L)

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



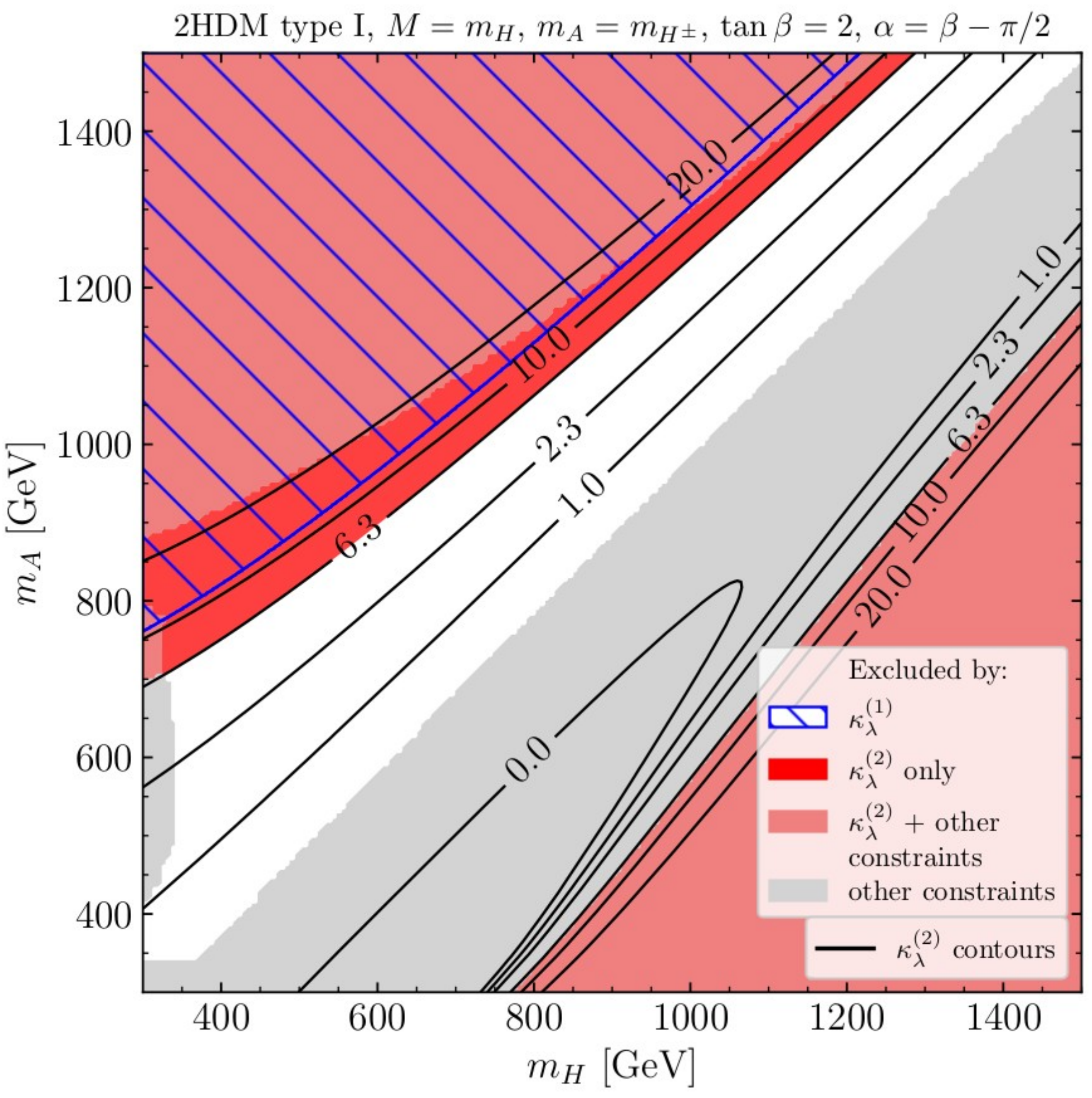
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

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



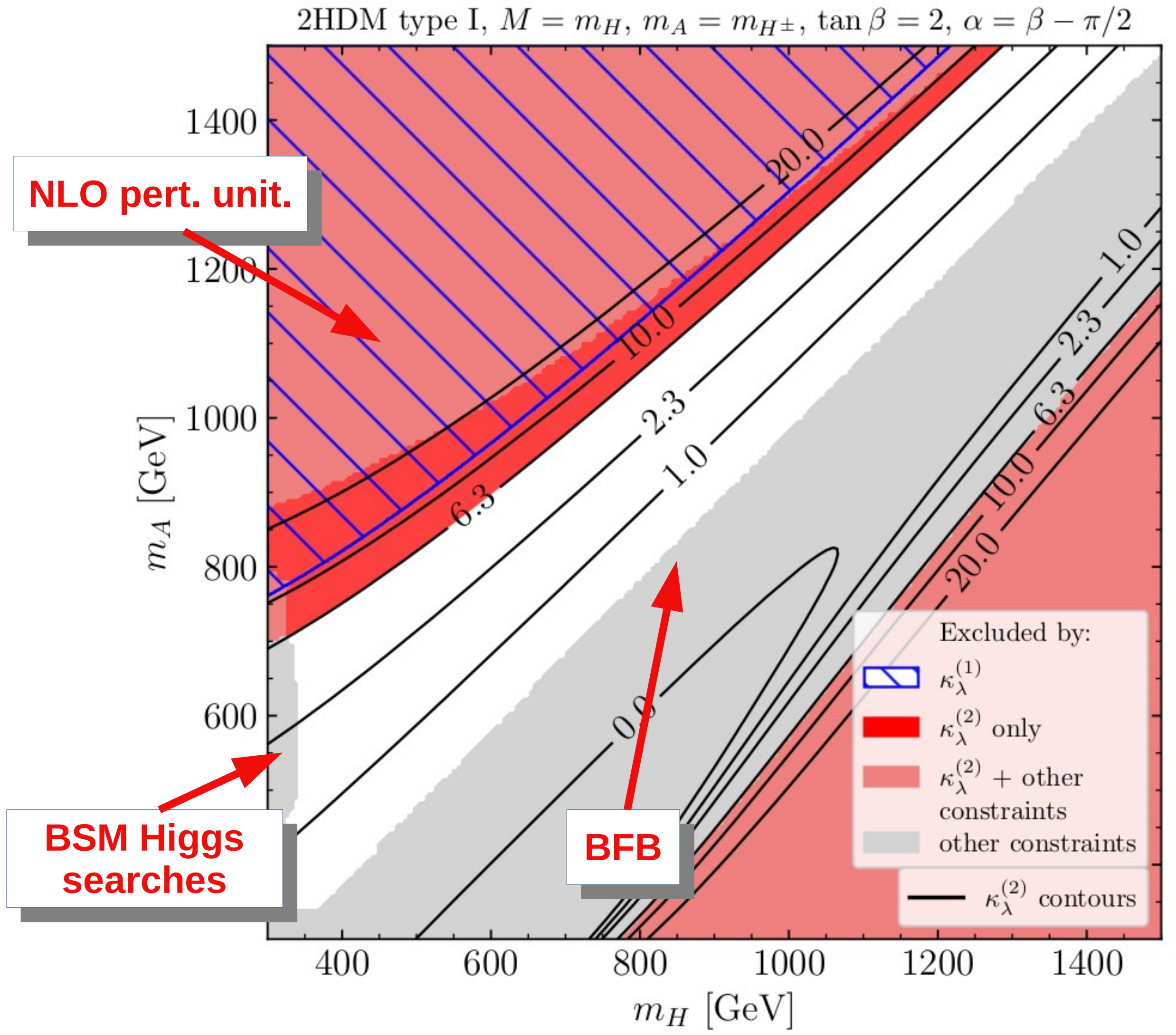
- ***Grey area:*** area excluded by other constraints, in particular BSM Higgs searches, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ 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

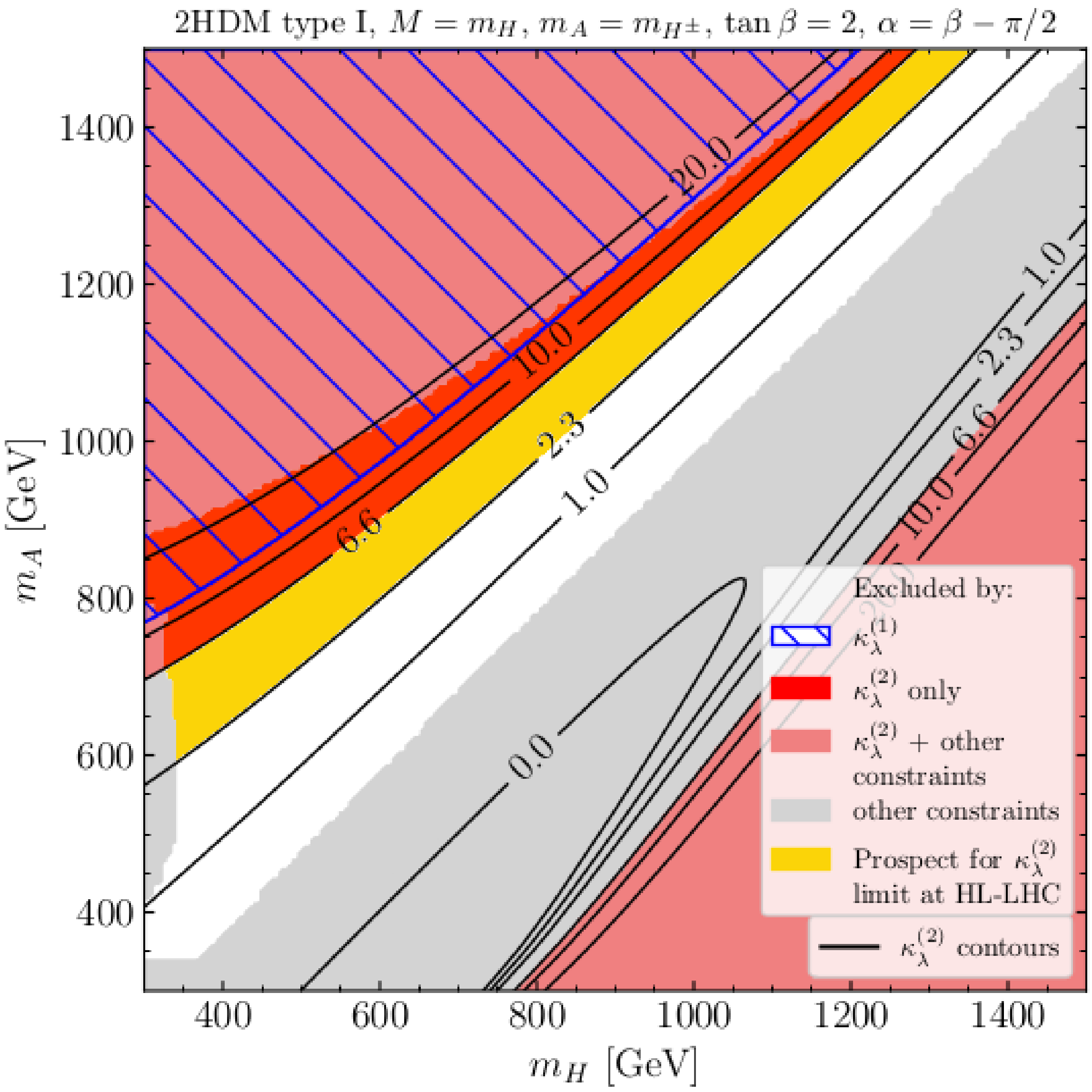
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ the calculation isn't reliable]

- ***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 $\kappa_\lambda < 2.3$



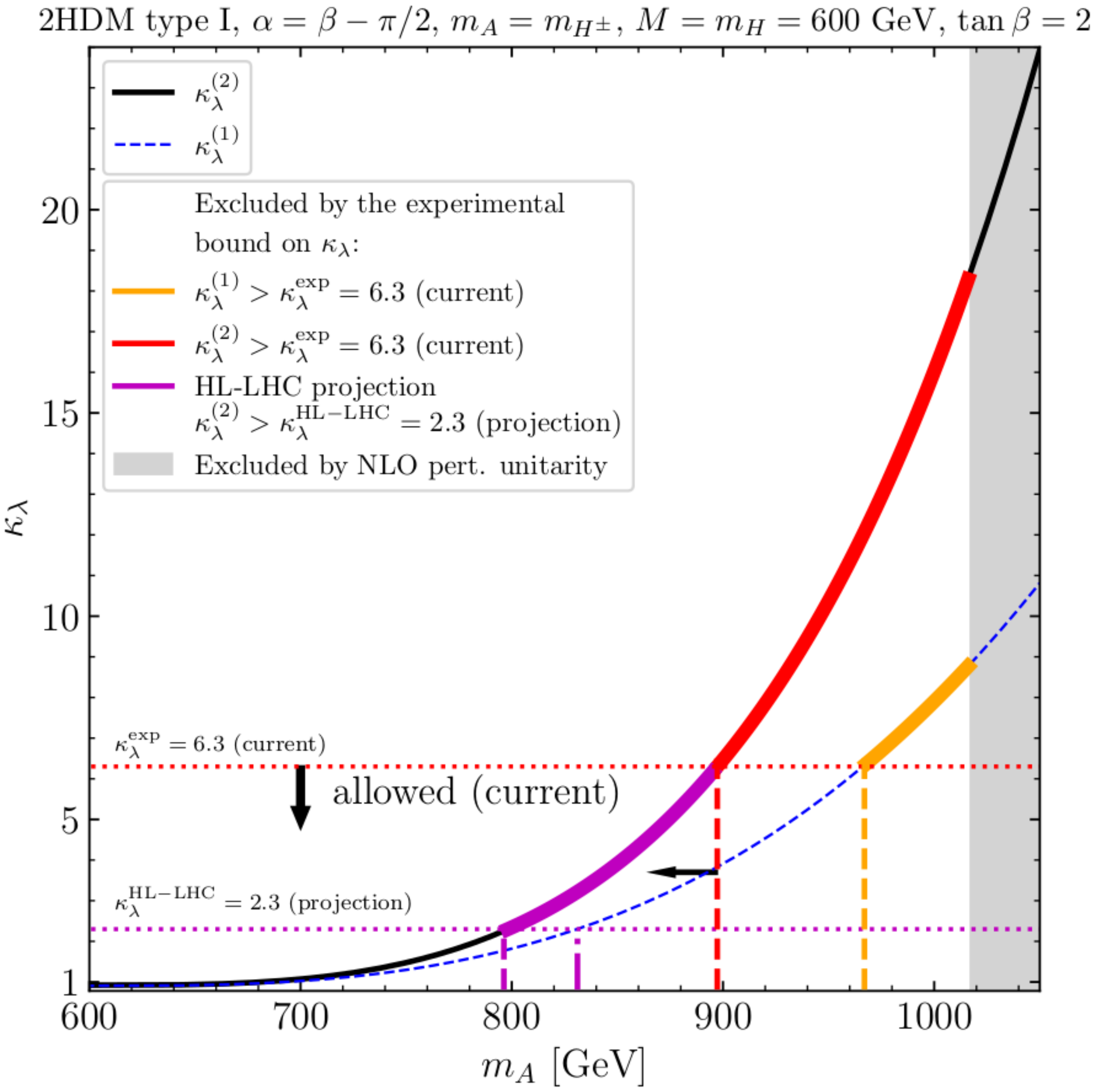
[Bahl, JB, Weiglein '23]

- ***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 $\kappa_\lambda^{(2)}$

Mass splitting effects for various BSM models with anyH3

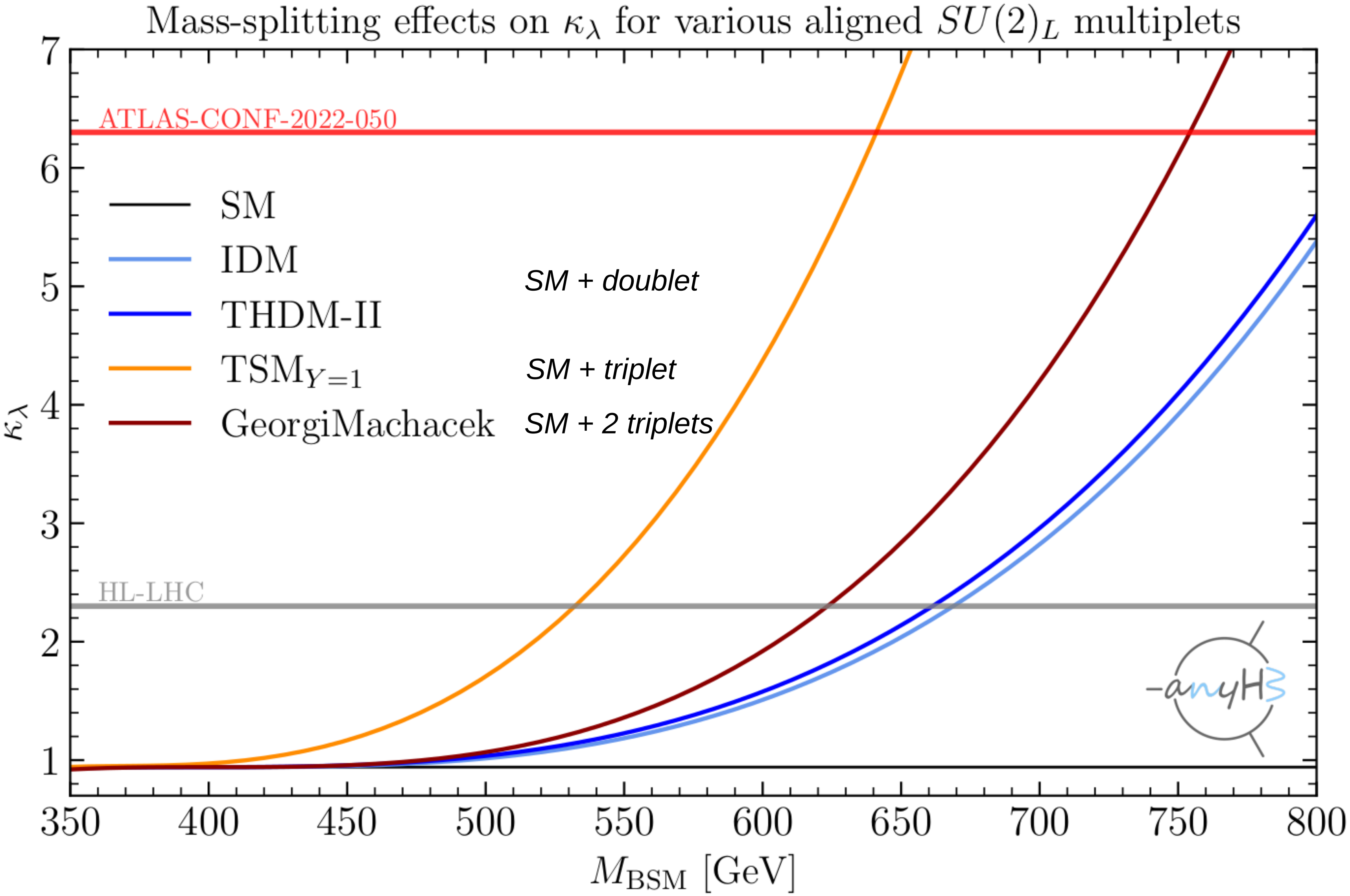
- anyH3 [Bahl, JB, Gabelmann, Weiglein '23]: public tool for full one-loop calculation of λ_{hhh} in arbitrary renormalisable models, using UFO inputs (*more details in backup*)

$$M_{\text{BSM}}^2 = \mathcal{M}^2 + \tilde{\lambda} v^2$$

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

- Perturbative unitarity checked within anyH3

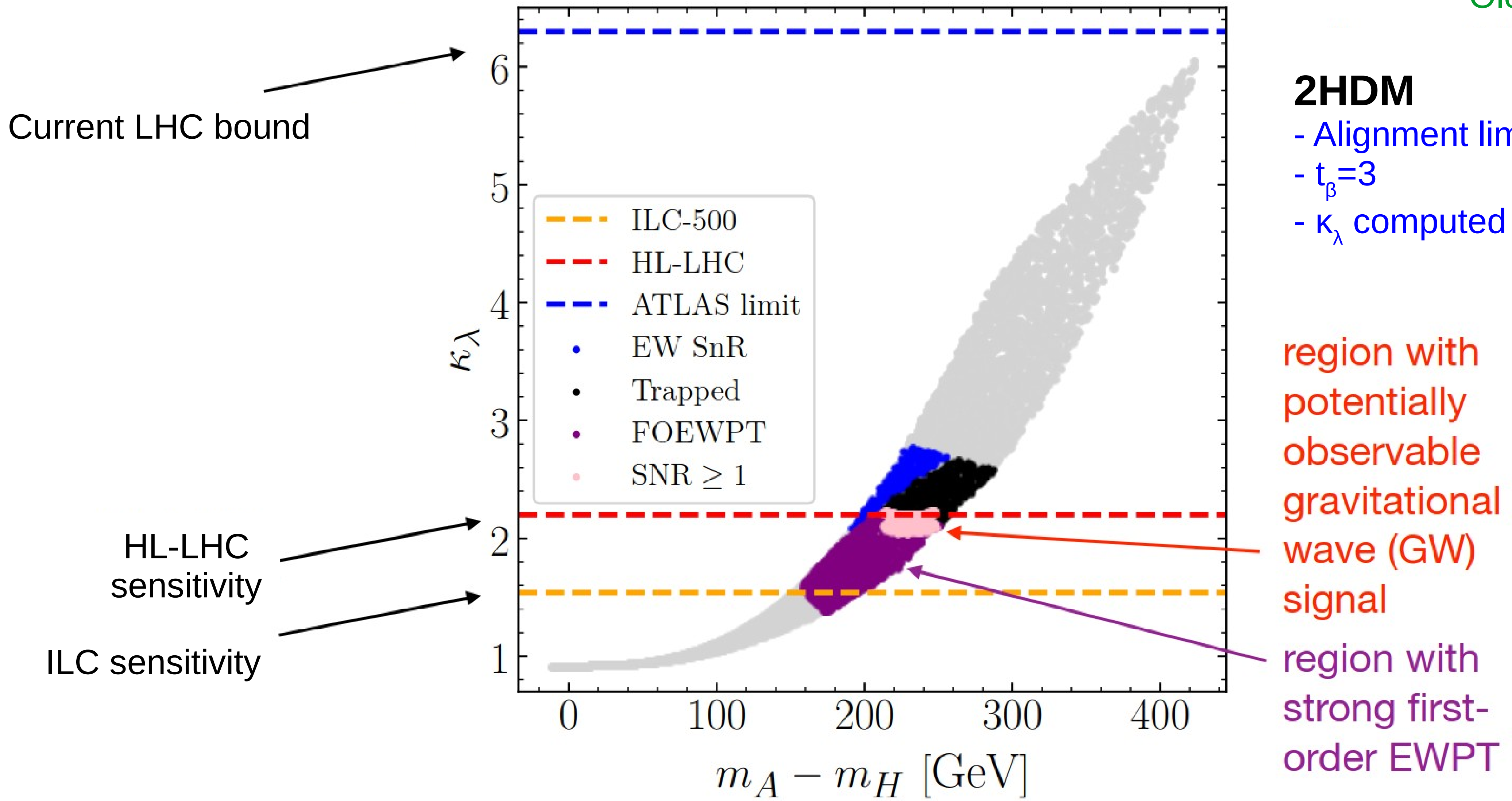
- **Constraints on BSM parameter space!**



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]



2HDM

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

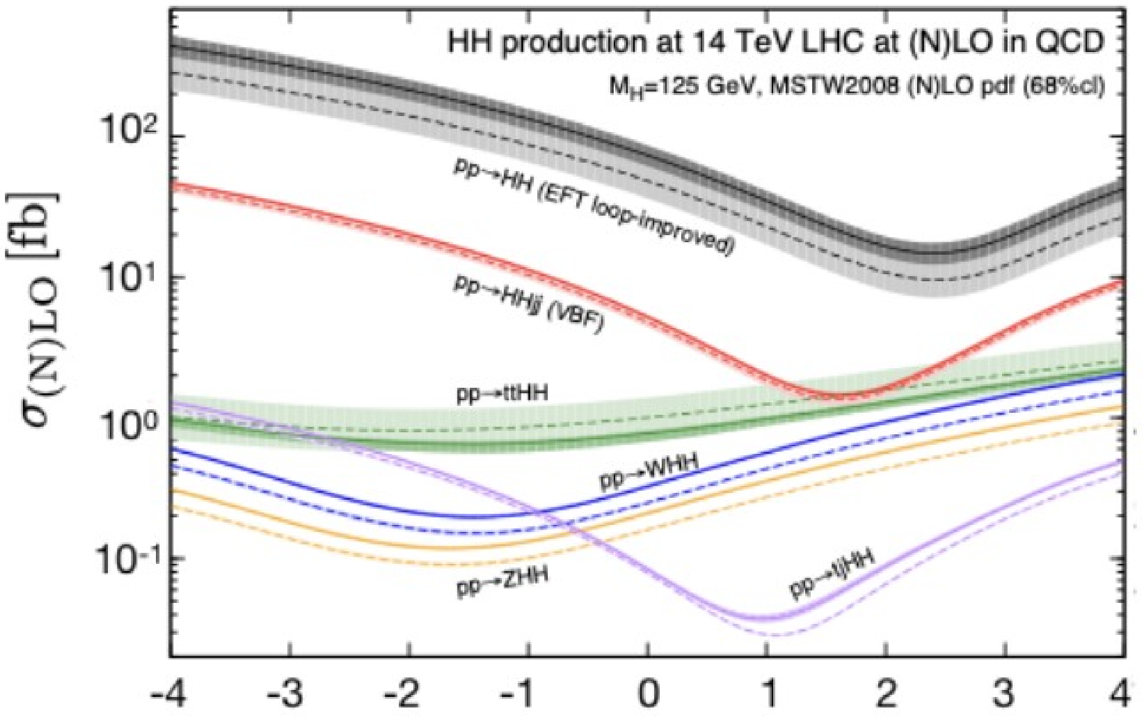
- **Region with a strong first-order EWPT and a potentially detectable GW signal is correlated with significant BSM deviation in κ_λ**

Large BSM effects in κ_λ: consequences on di-Higgs production at LHC

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

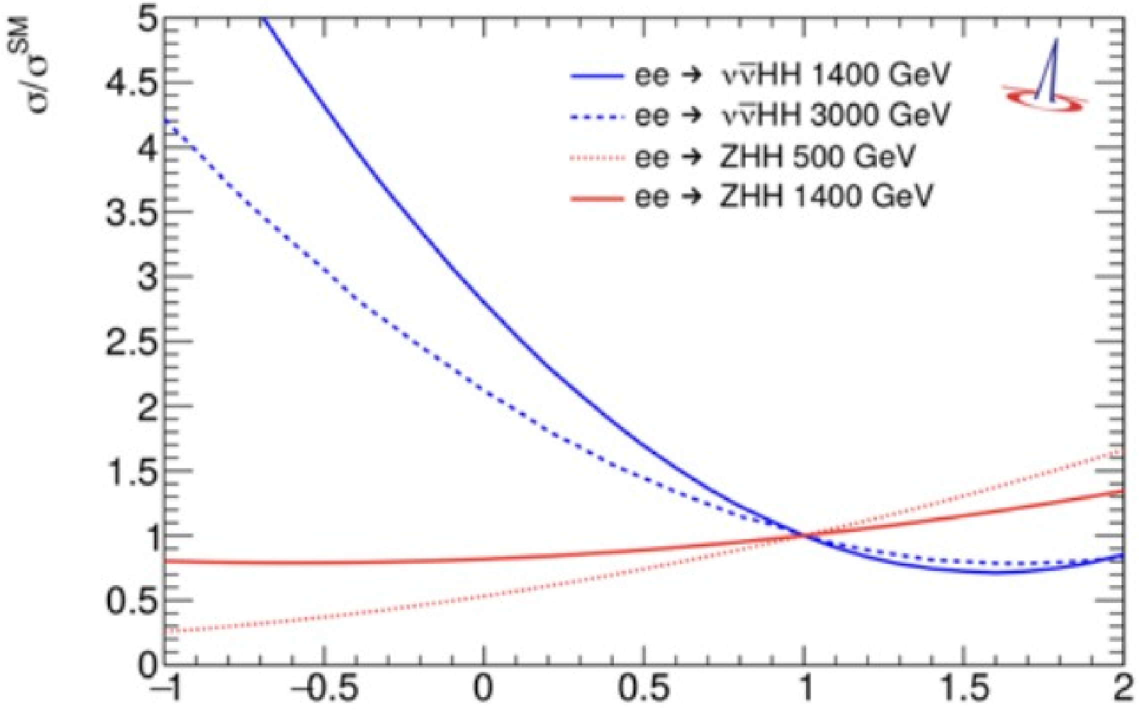
Plots taken from
[de Blas et al., 1905.03764]

Hadron collider



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

e^+e^- collider

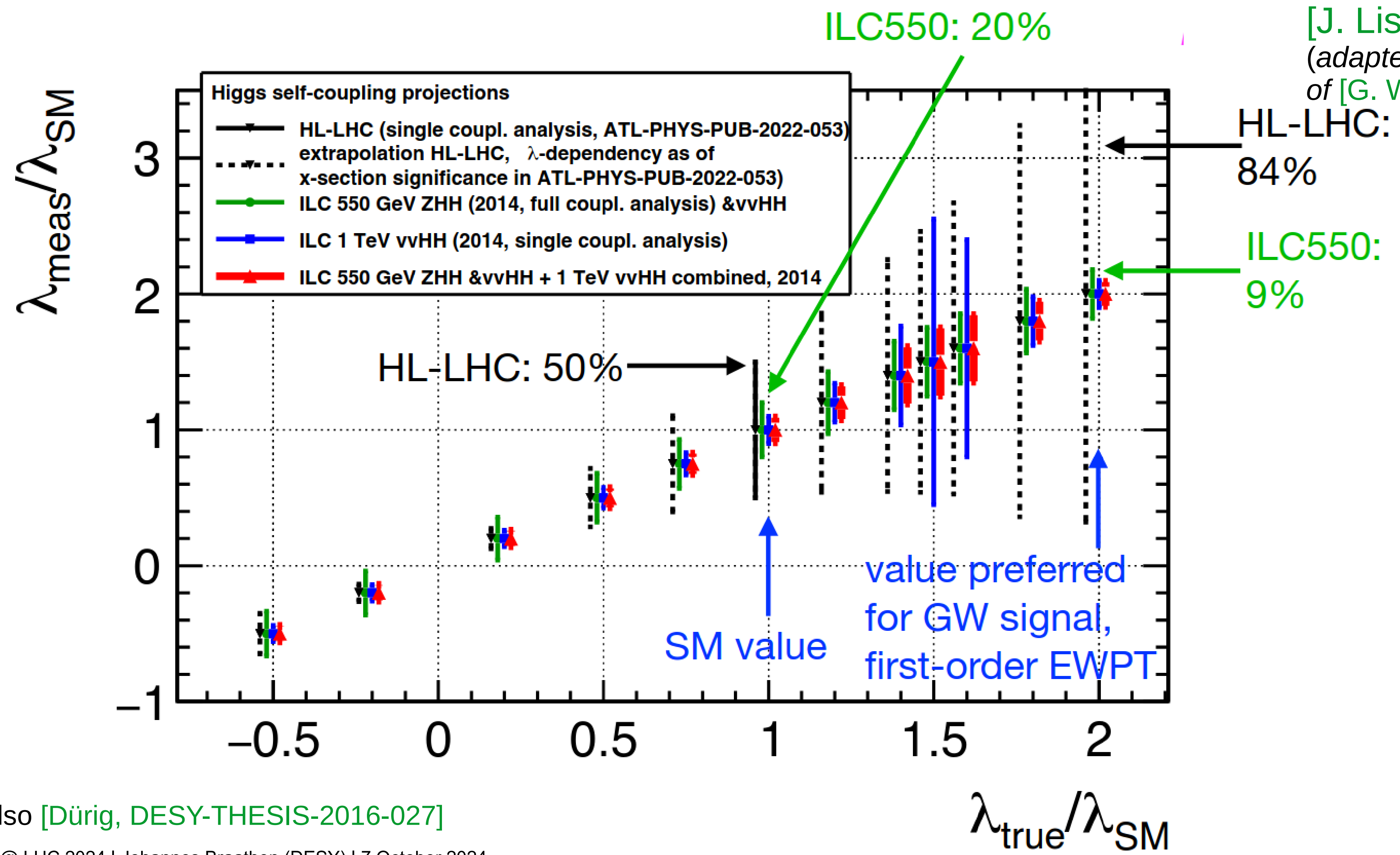


$\lambda_3/\lambda_3^{SM} = \kappa_\lambda$ [Reuter '19]

- **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)

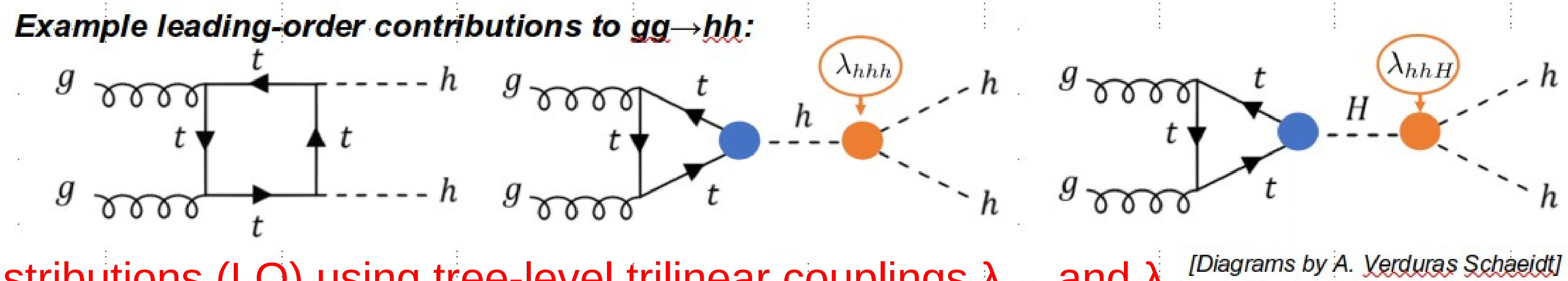
Precision on the determination of λ_{hhh} as a function of λ_{hhh}

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



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

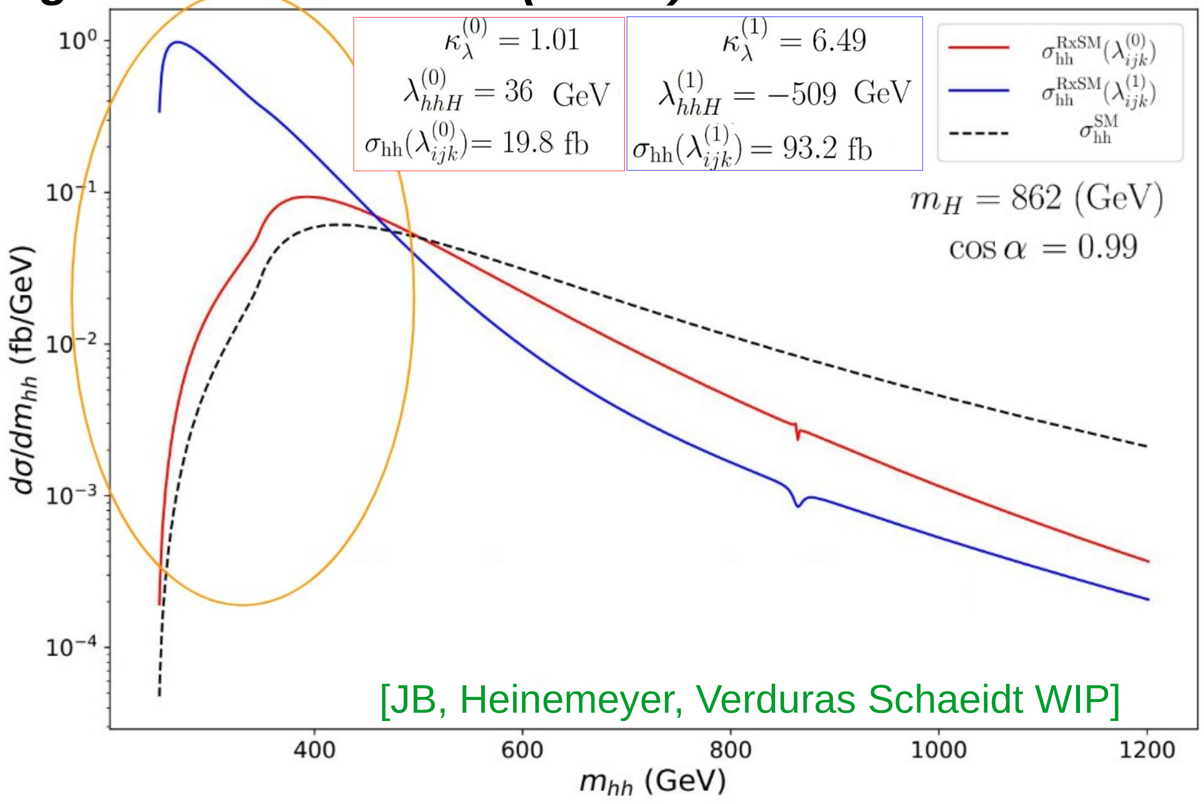
Di-Higgs invariant mass distributions

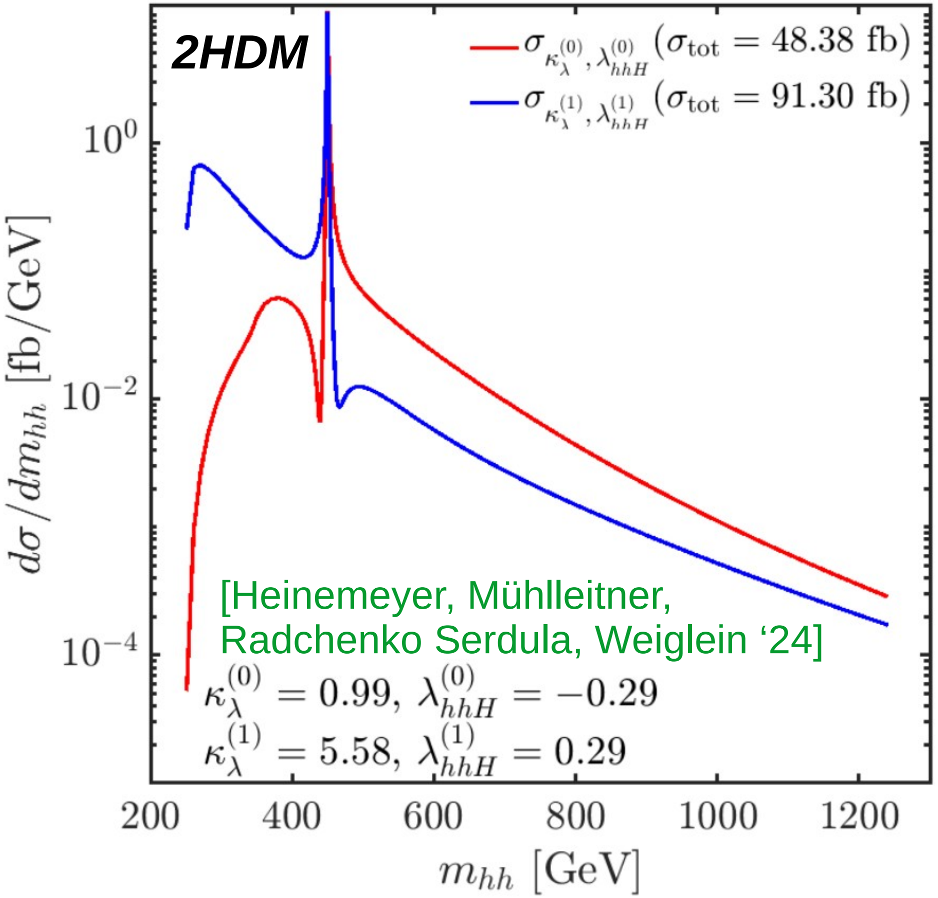


Red: differential distributions (LO) using tree-level trilinear couplings λ_{hhh} and λ_{hhH}

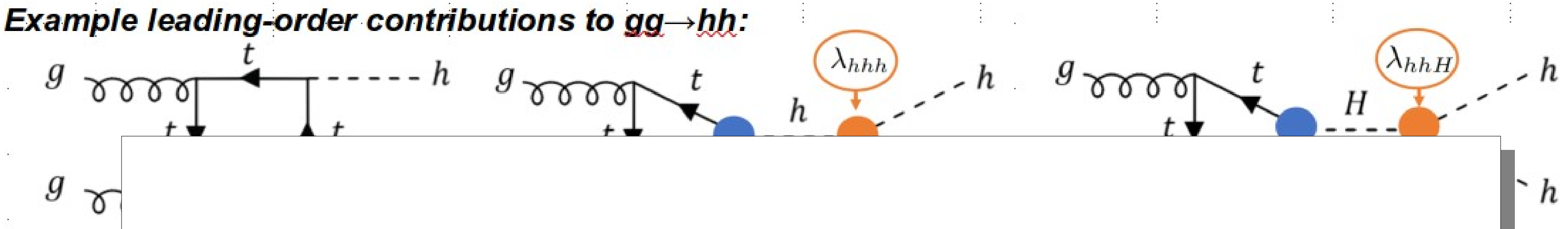
Blue: differential distributions (LO) using **loop-corrected** trilinear couplings λ_{hhh} and λ_{hhH}

Singlet extension of SM (RxSM)





Di-Higgs invariant mass distributions



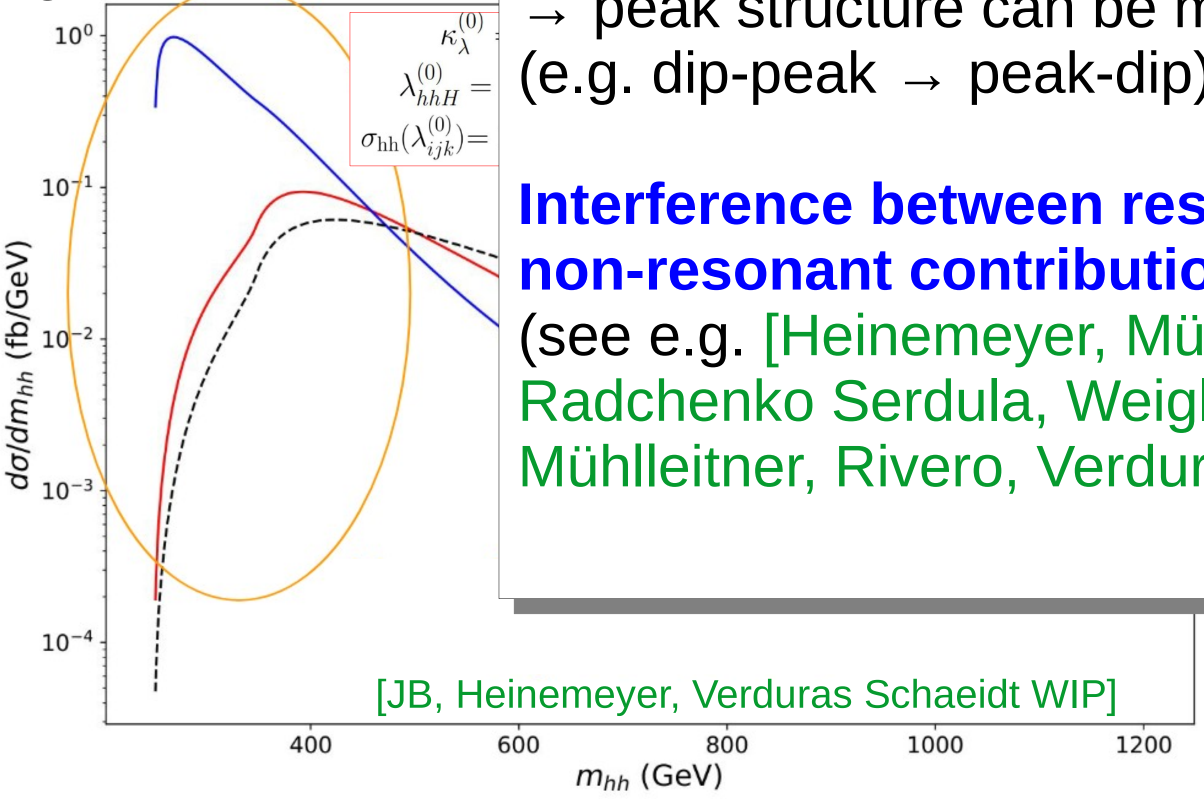
Red: differential distributi

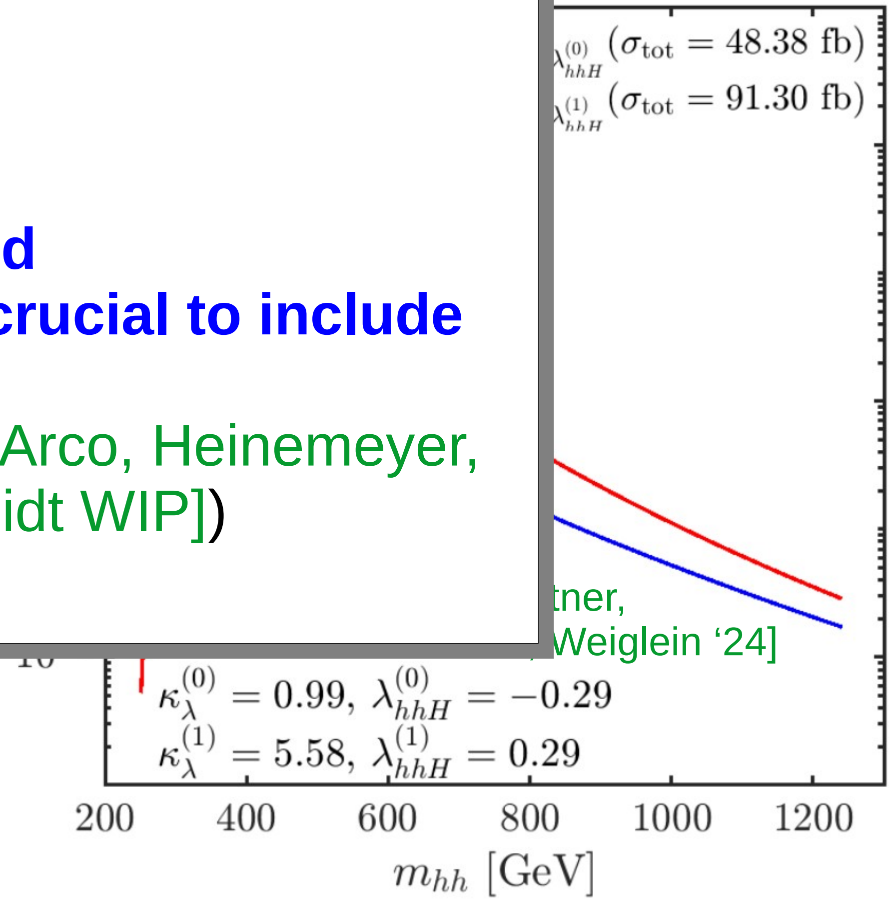
Blue: differential distribut

Singlet extension of SM

Strong impact also on differential distributions!
→change in destructive interference at hh threshold
→ peak structure can be modified (e.g. dip-peak → peak-dip)

Interference between resonant and non-resonant contributions also crucial to include
(see e.g. [Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein '24], [Arco, Heinemeyer, Mühlleitner, Rivero, Verduras Schaeidt WIP])

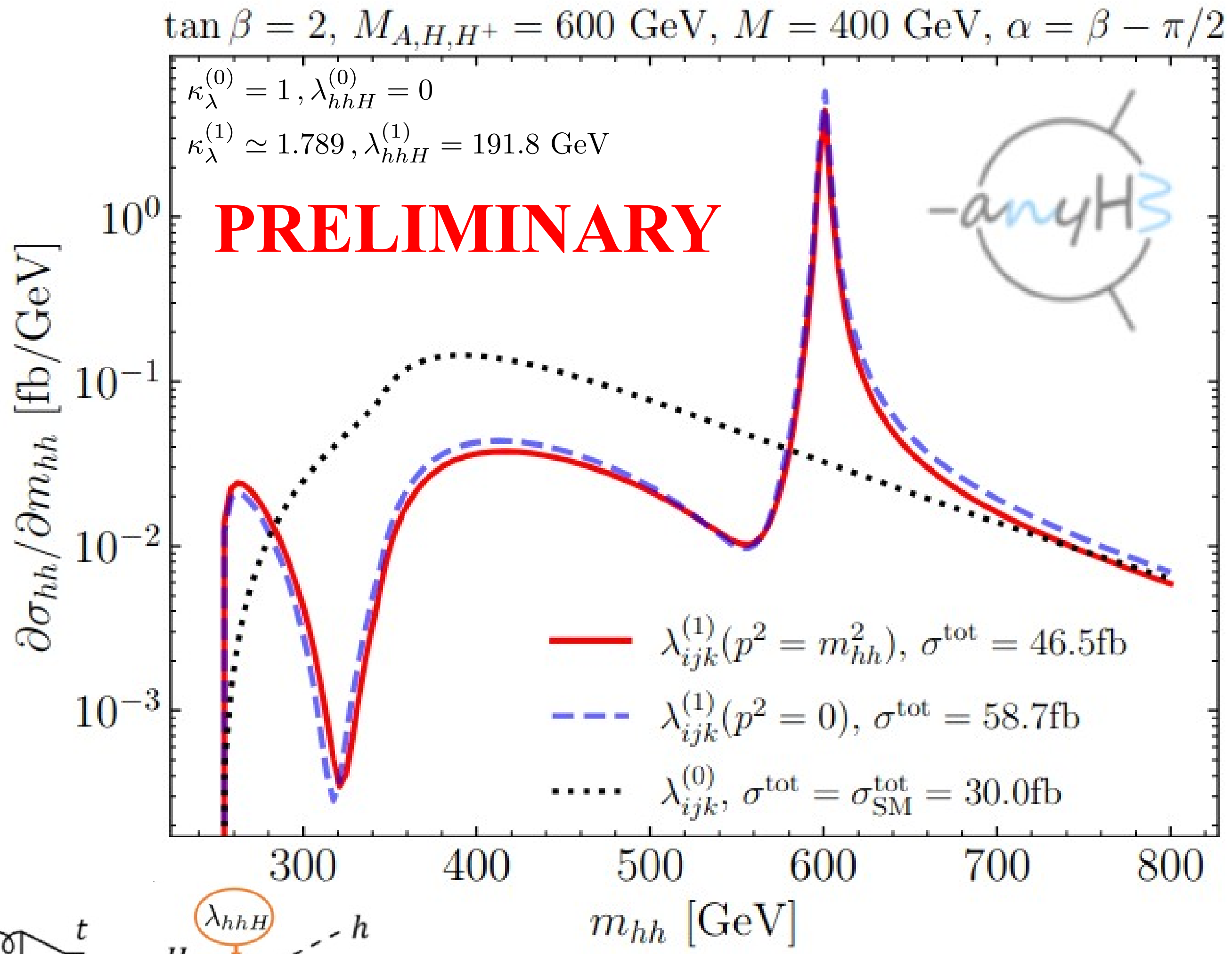


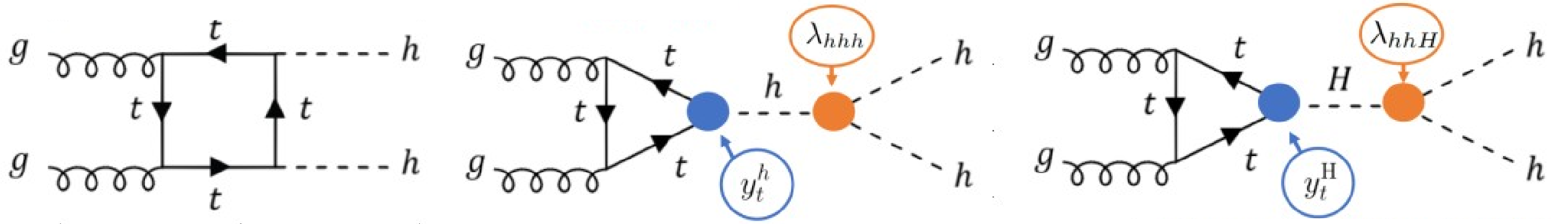


Di-Higgs production in arbitrary models: `anyHH`

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

- **`anyHH`: Total and differential cross-sections** for gg→hh including **1L corrections to λ_{ijk}** (computed by anyH3) and **BSM contributions in s-channel**
- Good agreement found with existing results in the literature (e.g. HPair [M. Mühlleitner, M. Spira, et al.]) – *details in backup*
- *Here:* **example in aligned 2HDM**
  Alignment limit:
  → $\kappa_\lambda^{(0)} = 1$; $\lambda_{hhH}^{(0)} = 0$
  → **huge impact of loop corrections to λ_{ijk}**
  → O(20%) impact of momentum in λ_{ijk}

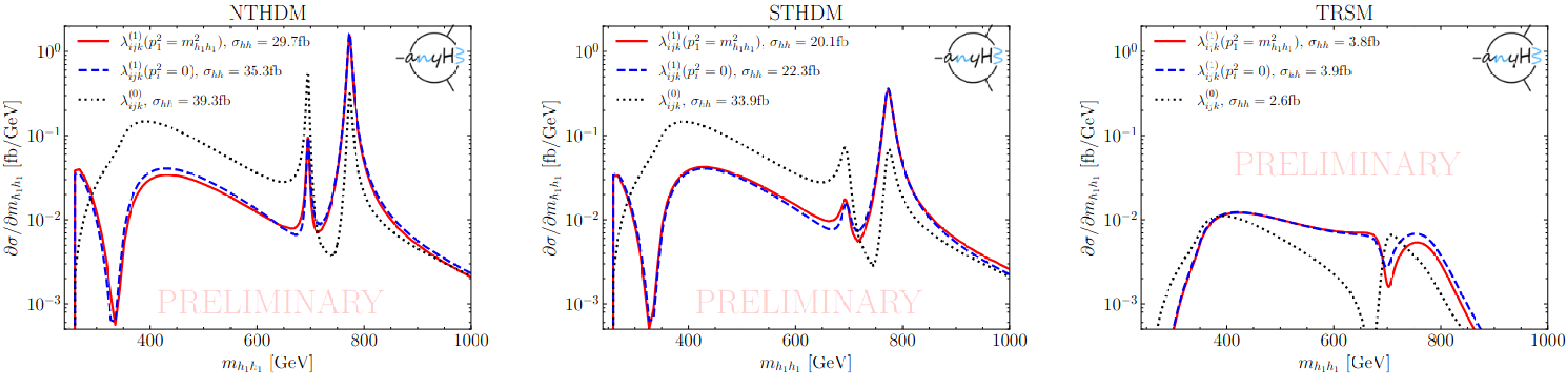




Ongoing developments: `anyHH` and link to `MadGraph`

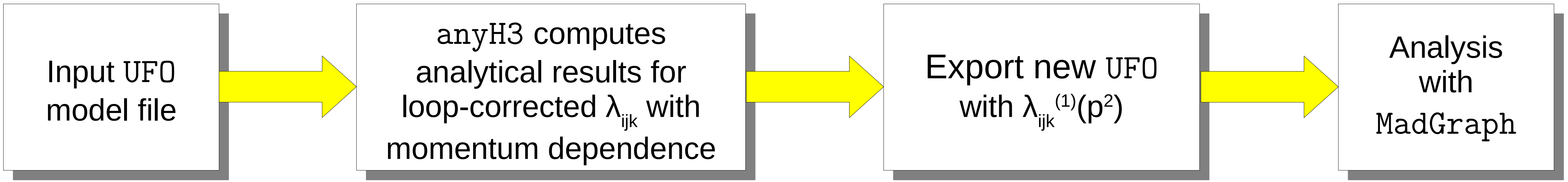
[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

- Results available in ***various new models*** for the 1st time!
  (NTHDM = 2HDM + real singlet; STHDM = 2HDM + complex singlet DM; TRSM: two-real singlet model)



(NB: these preliminary plots are meant for illustrations purposes only; not yet for phenomenological studies)

- **Link to MadGraph under development**:



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!
- Large BSM deviations in λ_{hhh}, as well as loop corrections to other BSM trilinear scalar couplings, can have a **strong impact on total and differential cross-sections for di-Higgs production**
  → the inclusion of these loop effects in theoretical and experimental analyses is paramount
  → possible with public tools `anyH3` and `anyHH`

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

Summary – anyH3

Python package anyH3 allows calculation of λ_{hhh} for arbitrary renormalisable theories with

- Full one-loop effects including external-momentum dependence
- Highly flexible choices of renormalisation schemes → predefined or by user
- Uses **UFO** model inputs (generated with SARAH, FeynRules or using custom ones)

- Part of wider **anyBSM framework**, including
  - **anyHH for di-Higgs production at hadron colliders**
  - **Interface to MadGraph** planned to allow direct use in experimental analyses of loop-corrected trilinear scalar couplings

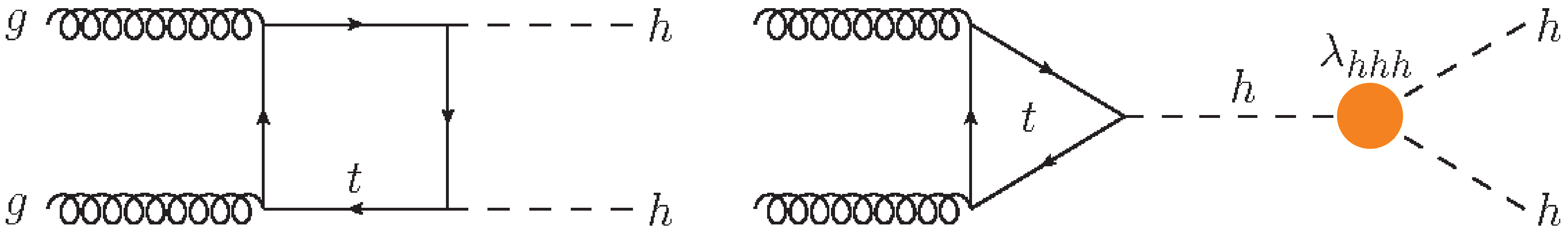
  and much more!
- Currently 14 models included (publicly), easy inclusion of further models → **new ideas/requests welcome!**

Get started at https://anybsm.gitlab.io/
or directly in terminal with
`pip install anyBSM` **&** `anyBSM --help` **!**

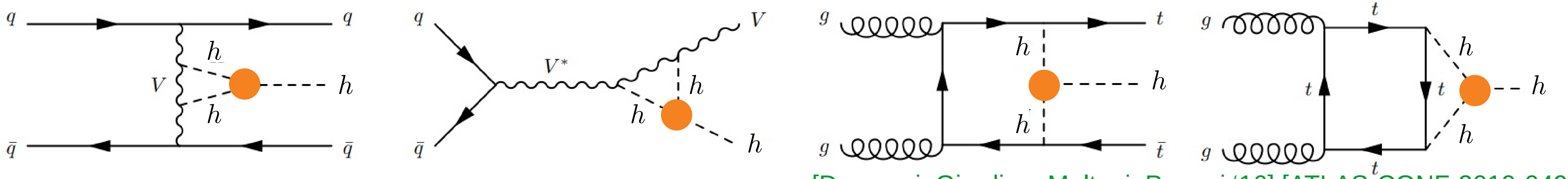
Backup

Experimental probes of λ_{hhh}

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

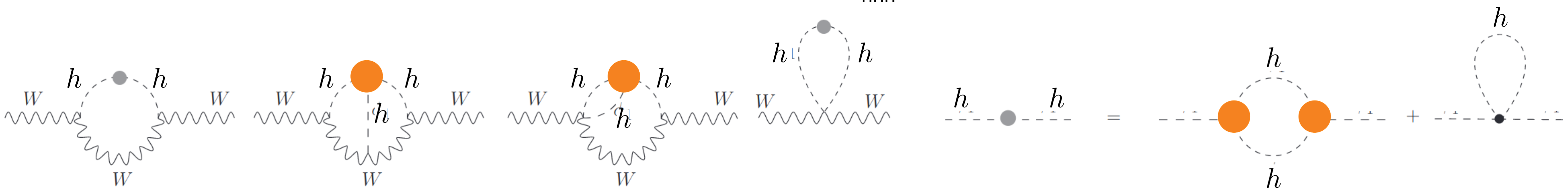


- **Single-Higgs production** → λ_{hhh} enters at <u>NLO</u>



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

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

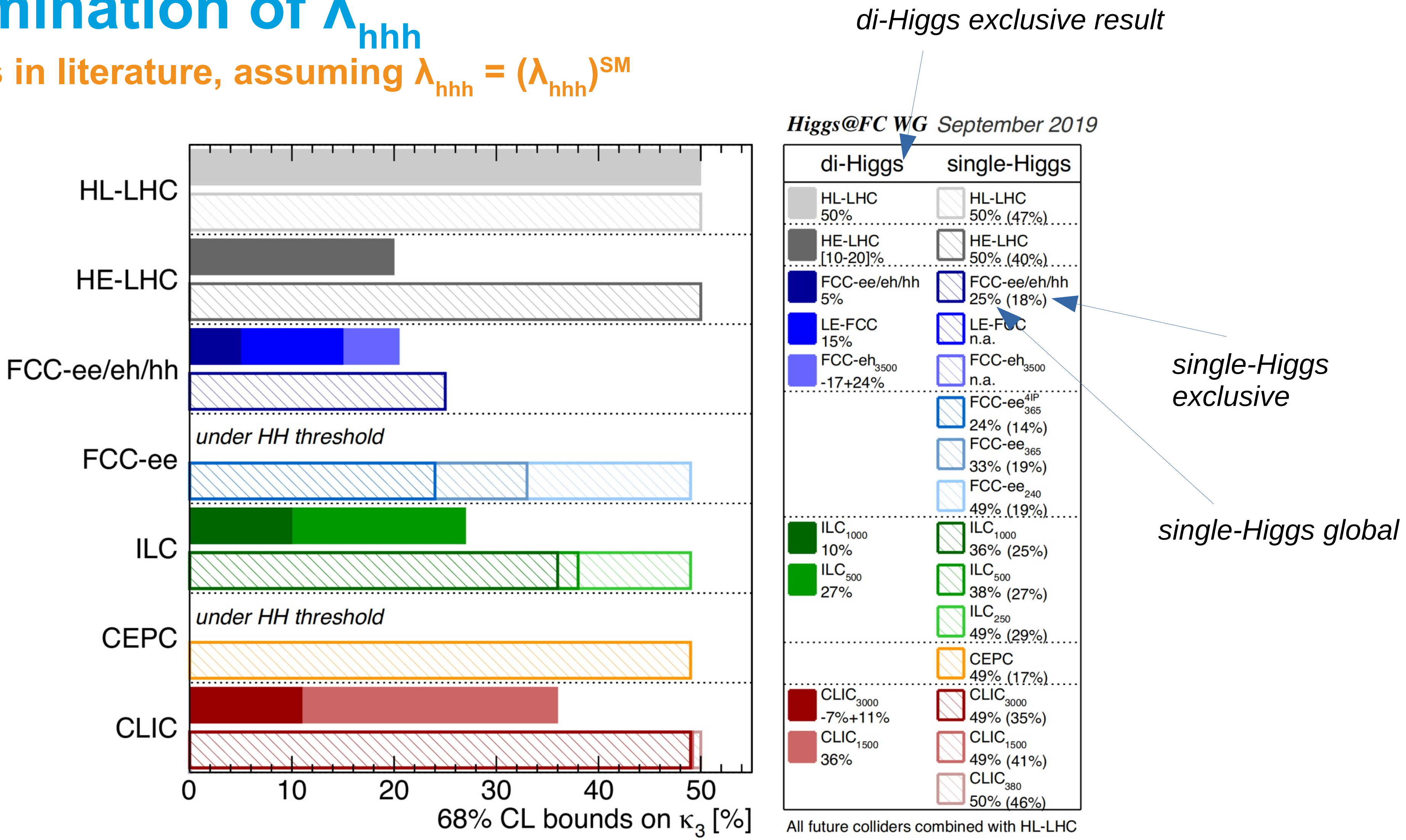


[Degrassi, Fedele, Giardino '17]

Future determination of λ_{hhh}

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

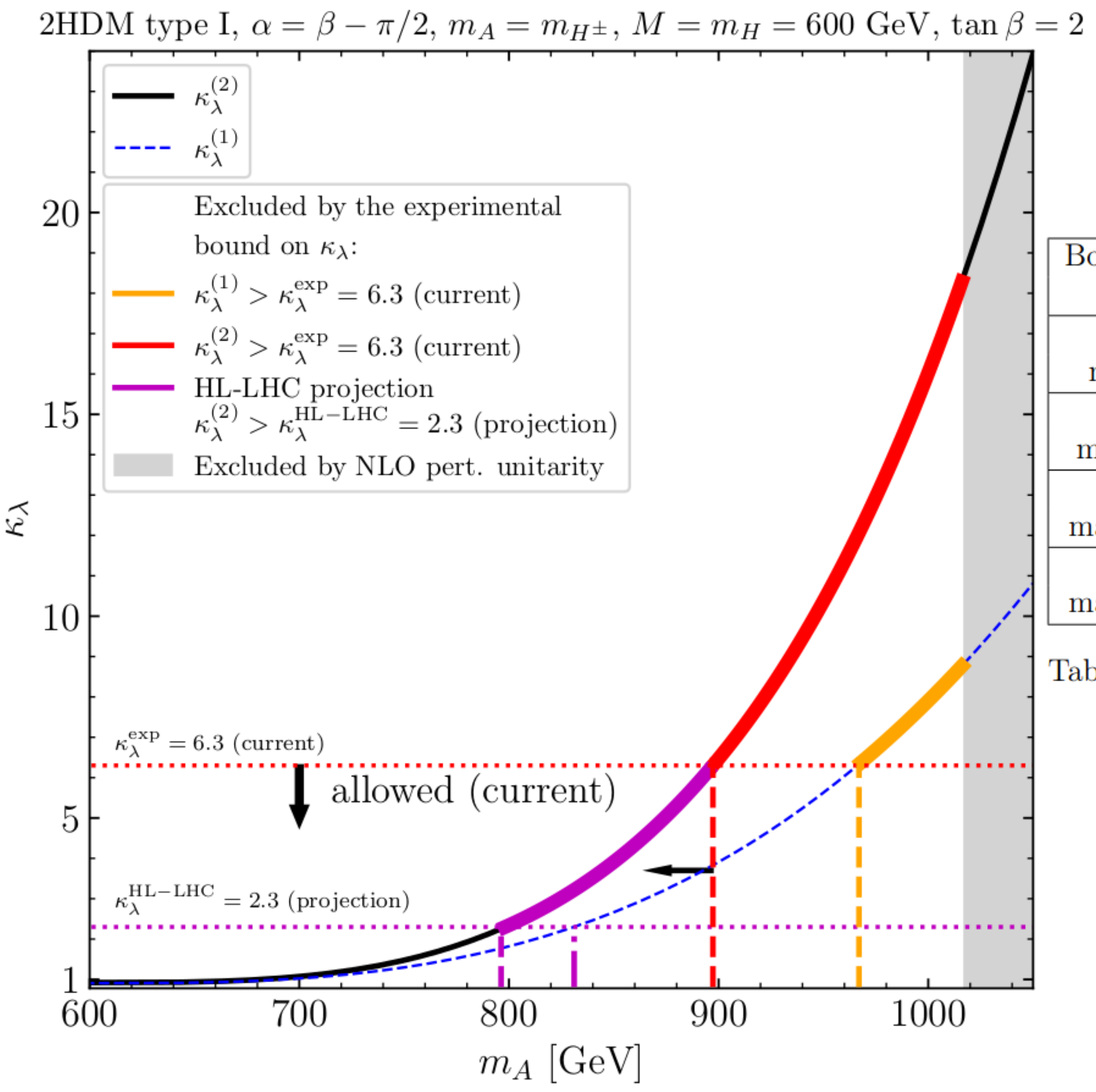
Plot taken from
[de Blas et al., 1905.03764]



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.*

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

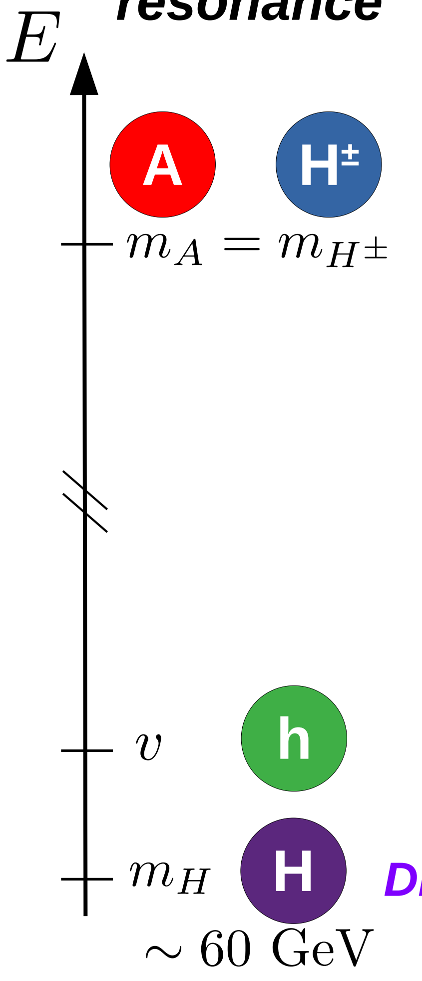
Table 1: Maximal values of m_A allowed in the benchmark scenario under the constraint of perturbative unitarity, at LO and NLO, and for different upper bounds on the $2 \to 2$ scattering eigenvalues used in the perturbative unitarity constraint. Note that tree-level scattering eigenvalues are all real,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

Correlation between κ_λ and BR($h \to \gamma\gamma$) at one and two loops

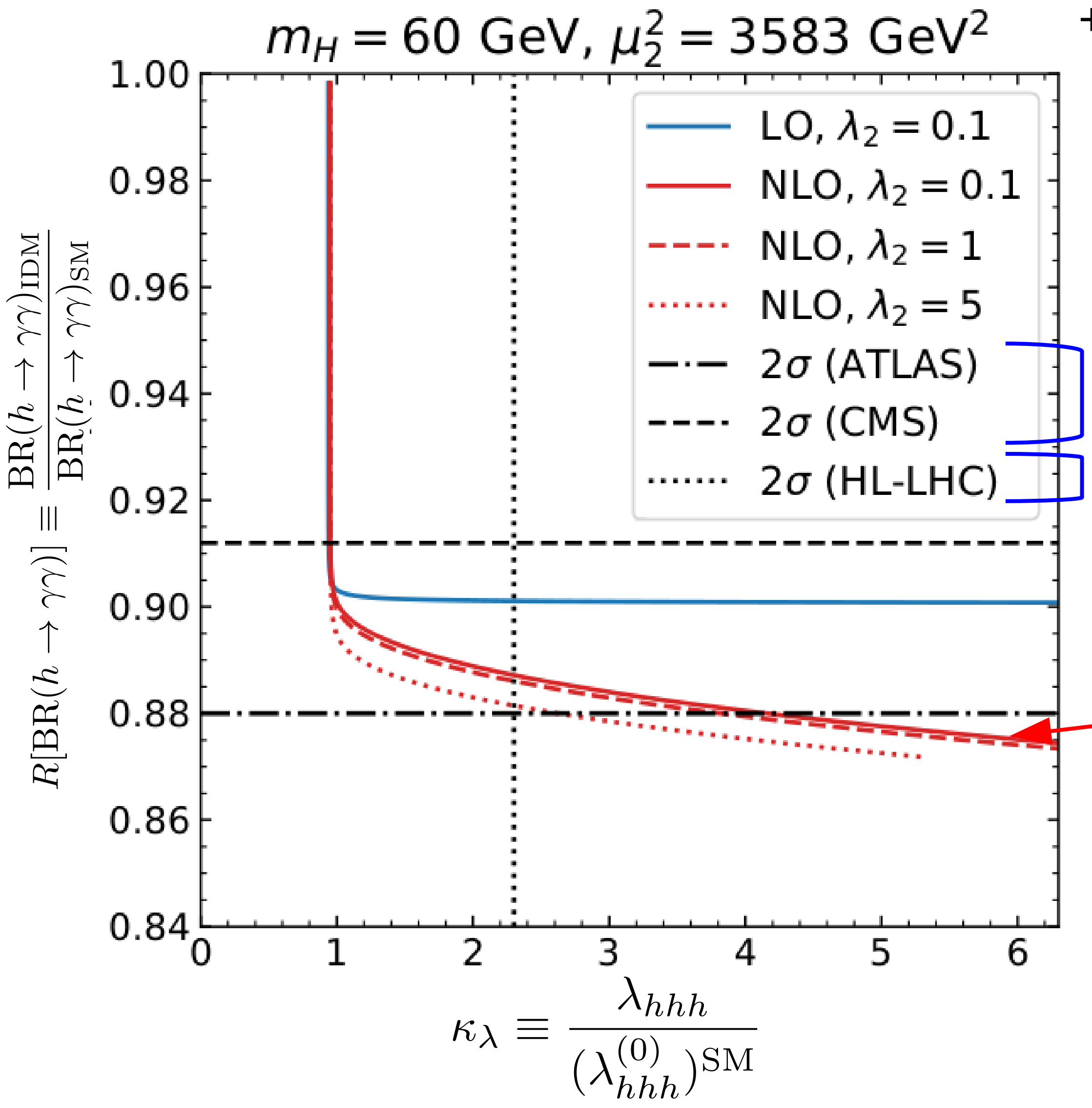
Could BSM Physics be observed first in κ_λ ?

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

Inert Doublet Model in DM-inspired "Higgs resonance" scenario



DM candidate



[λ_2 : inert doublet self-coupling]

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

Expected bound on κ_λ at HL-LHC

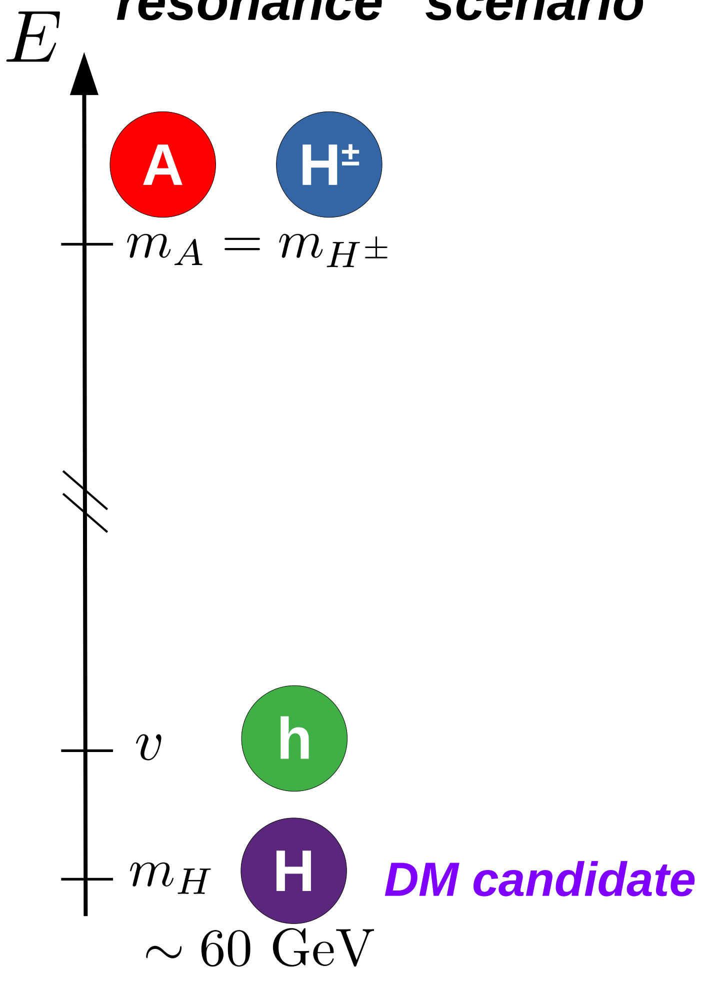
$m_{H\pm} = m_A$ varied along the curves (until limit from pert. unit.)

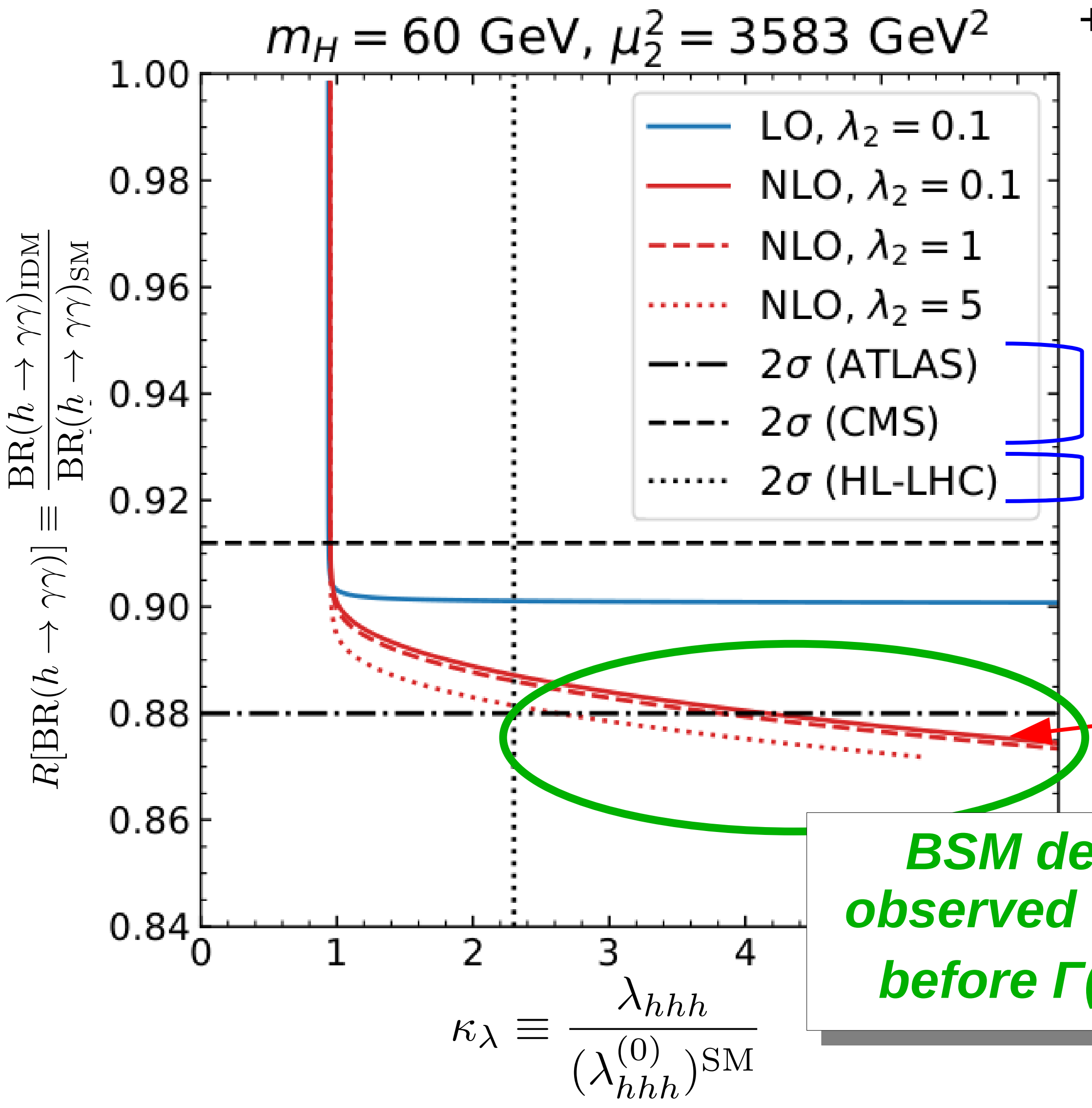
Correlation between κ$_\lambda$ and BR($h\to\gamma\gamma$) at one and two loops

Could BSM Physics be observed first in κ$_\lambda$?

[Aiko, JB, Kanemura ‘23 + WIP] + [JB, Kanemura ‘19]

Inert Doublet Model in DM-inspired “Higgs resonance” scenario





[λ_2 : inert doublet self-coupling]

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

Expected bound on κ$_\lambda$ at HL-LHC

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

BSM deviation observed first in κ$_\lambda$, before Γ($h\to\gamma\gamma$)!

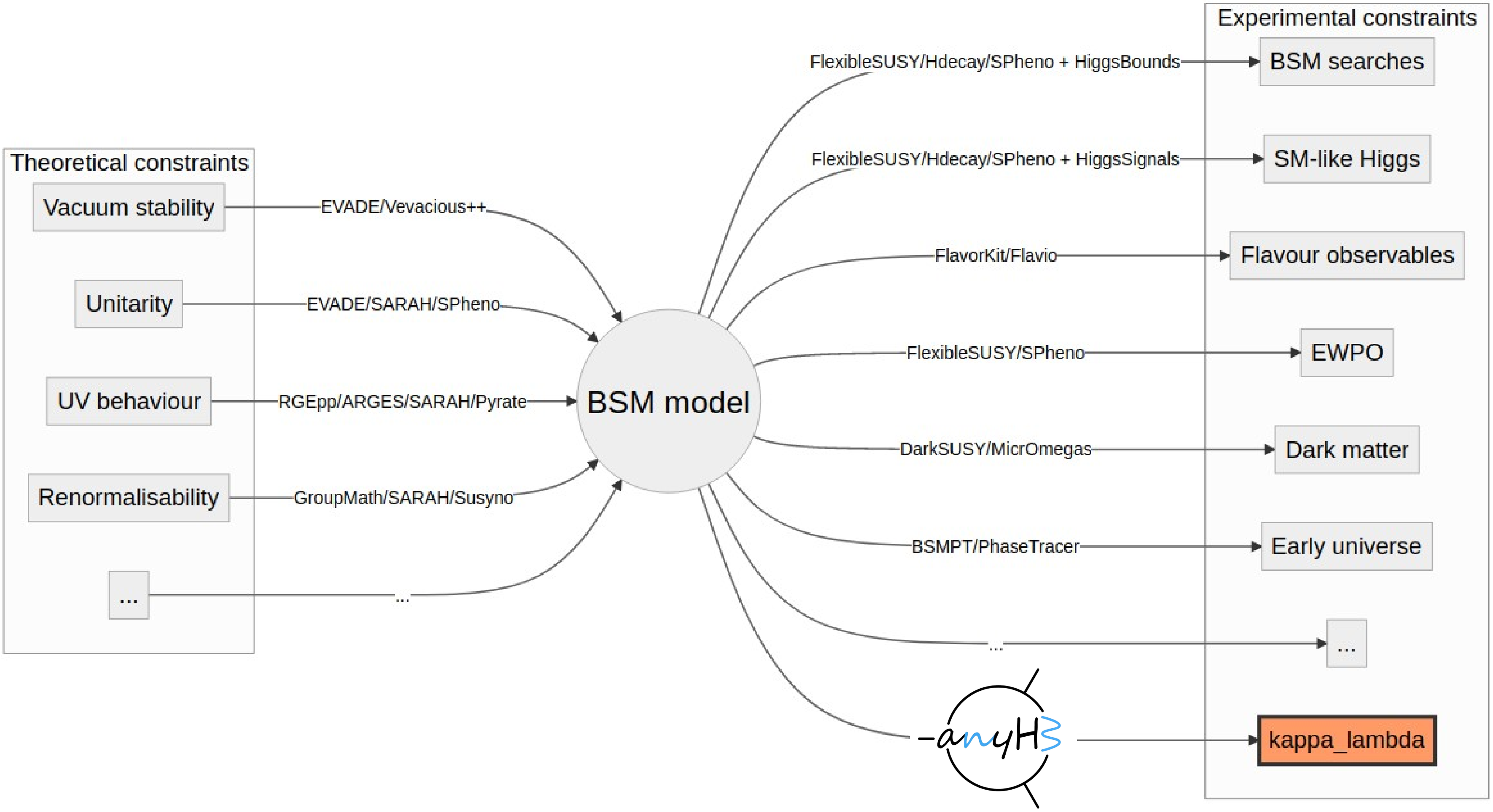
Generic predictions for λ_{hhh}

Based on

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

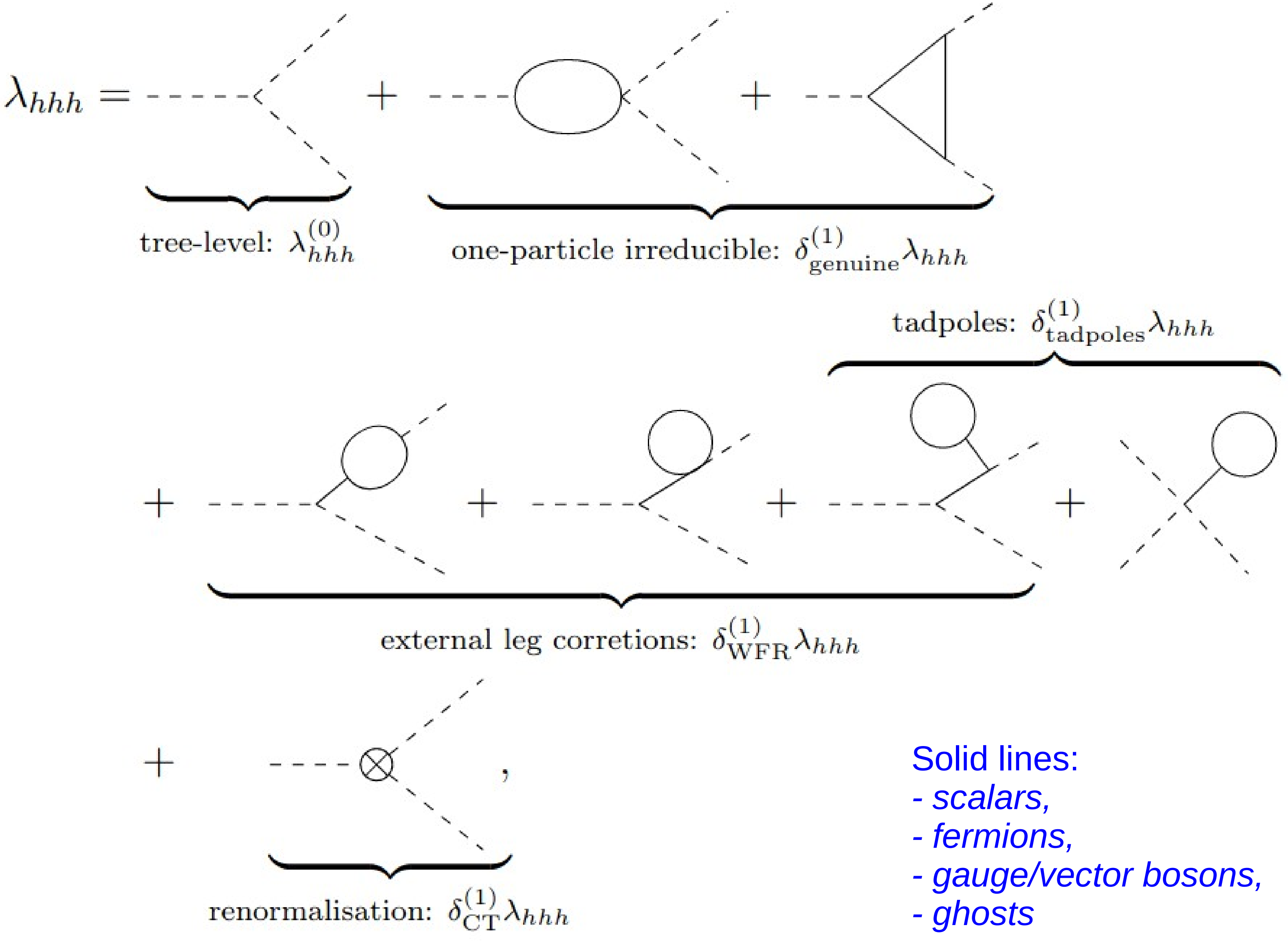
in collaboration with Henning Bahl, Martin Gabelmann, Kateryna Radchenko Serdula and Georg Weiglein

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*)

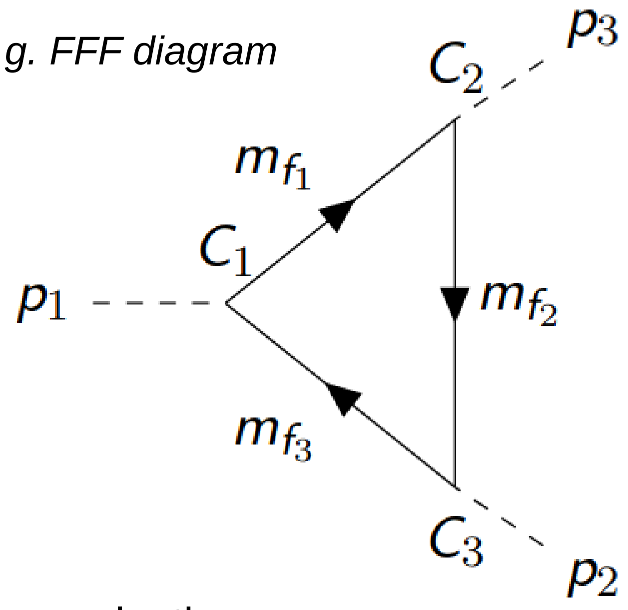


Solid lines:
- *scalars,*
- *fermions,*
- *gauge/vector bosons,*
- *ghosts*

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

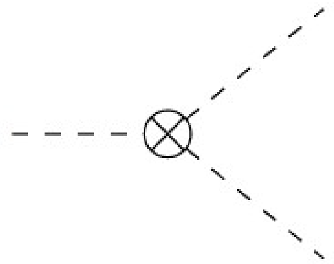
$$= 2\mathbf{B0}(p_3^2, m_2^2, m_3^2)(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3})) + m_{f_1}\mathbf{C0}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L)(p_1^2 + p_2^2 -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

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)

  $\rightarrow$ 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

```yaml
# 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

```python
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

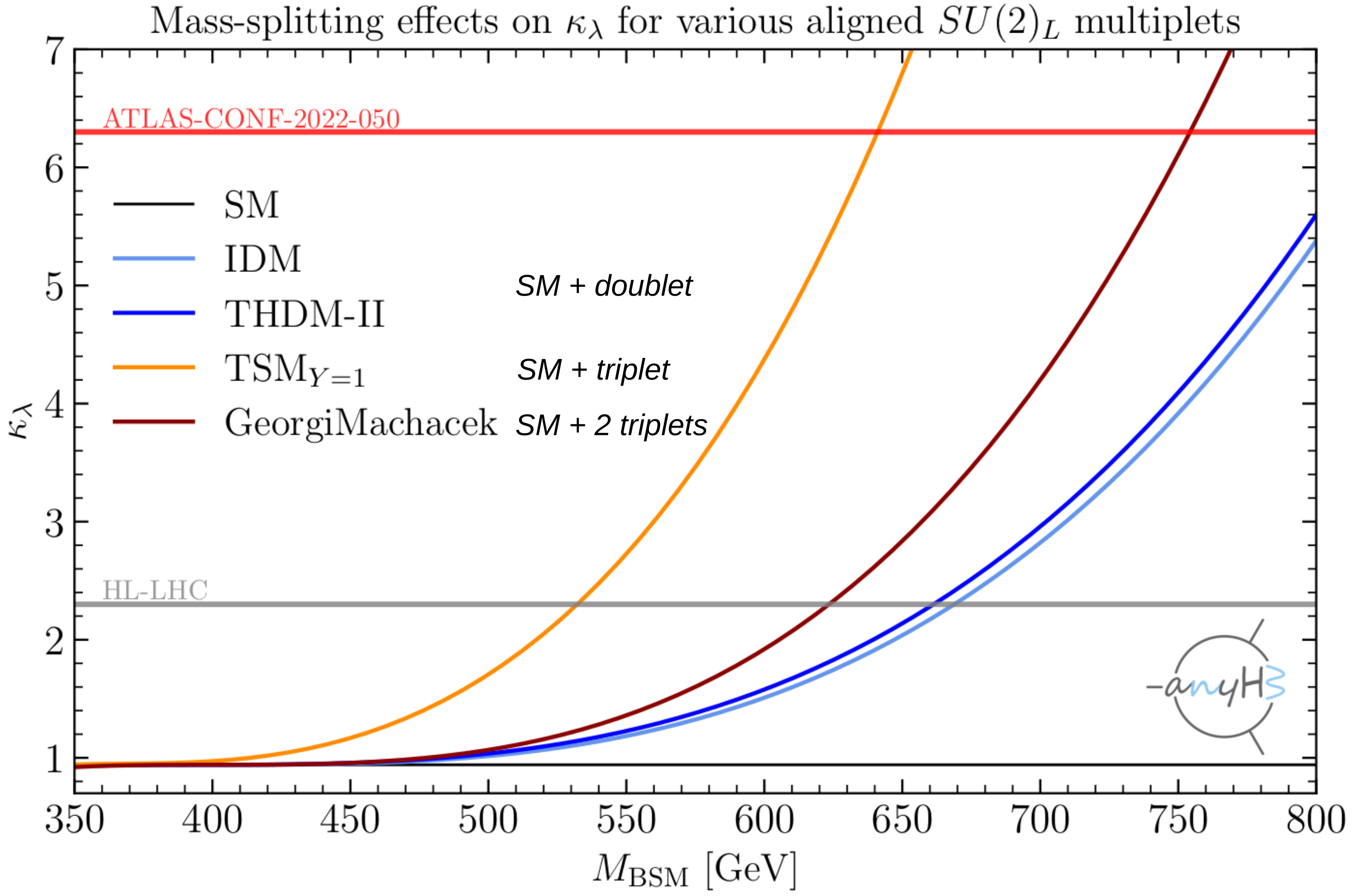
- Consider the non-decoupling limit in several BSM models

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

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

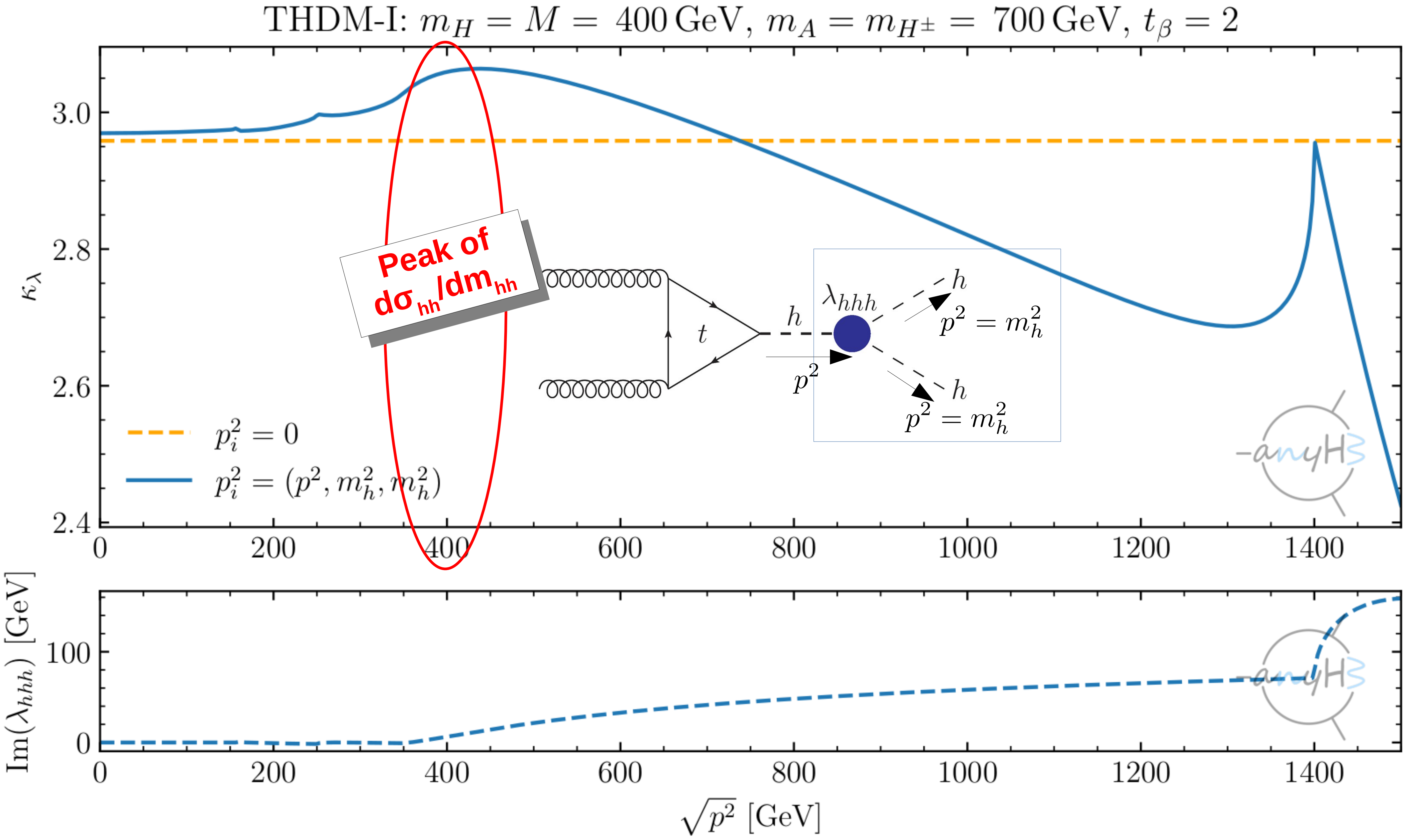
- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**

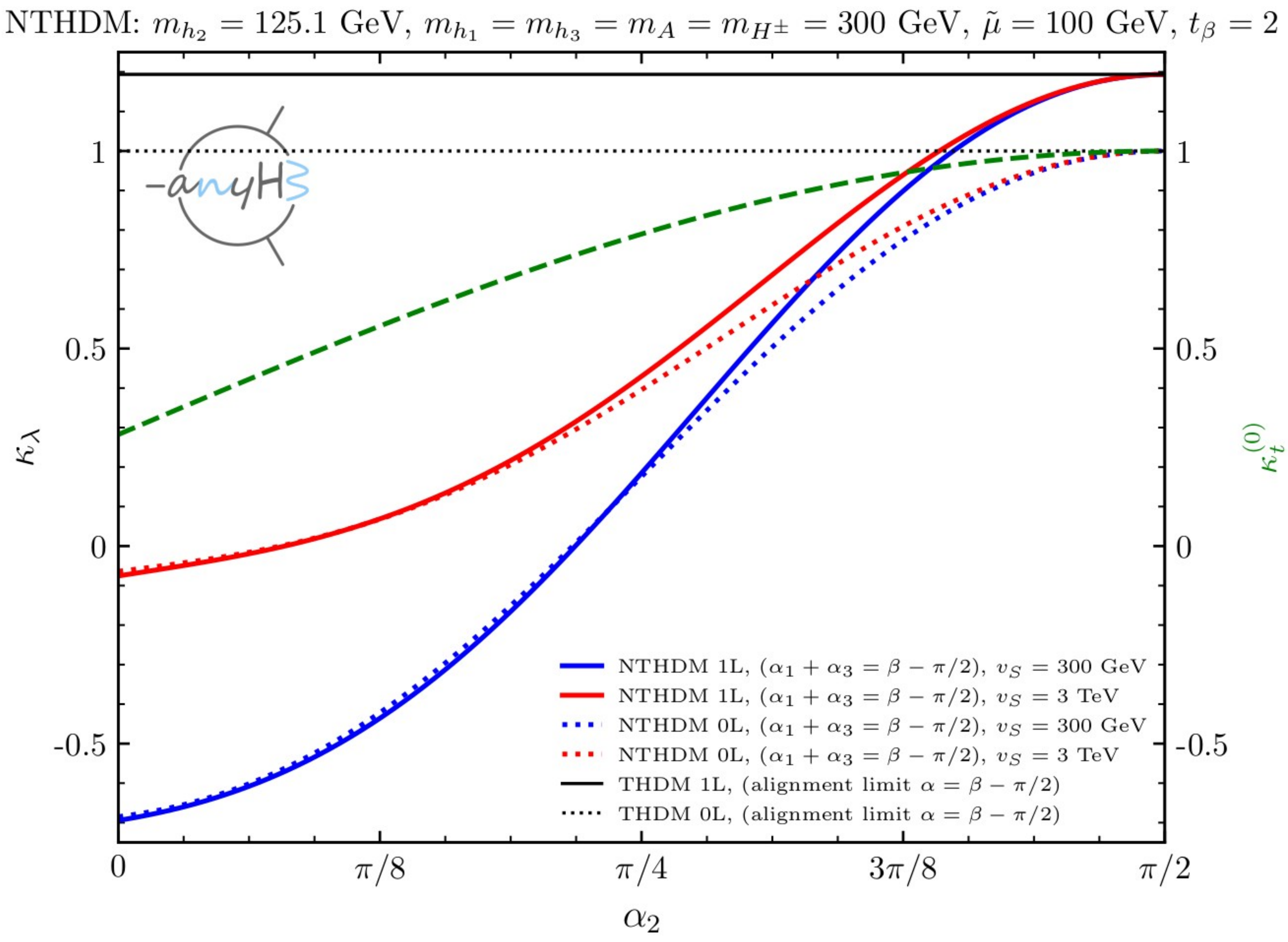


Here: scenarios with lightest BSM scalar mass & BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

New results II: momentum dependence in the 2HDM

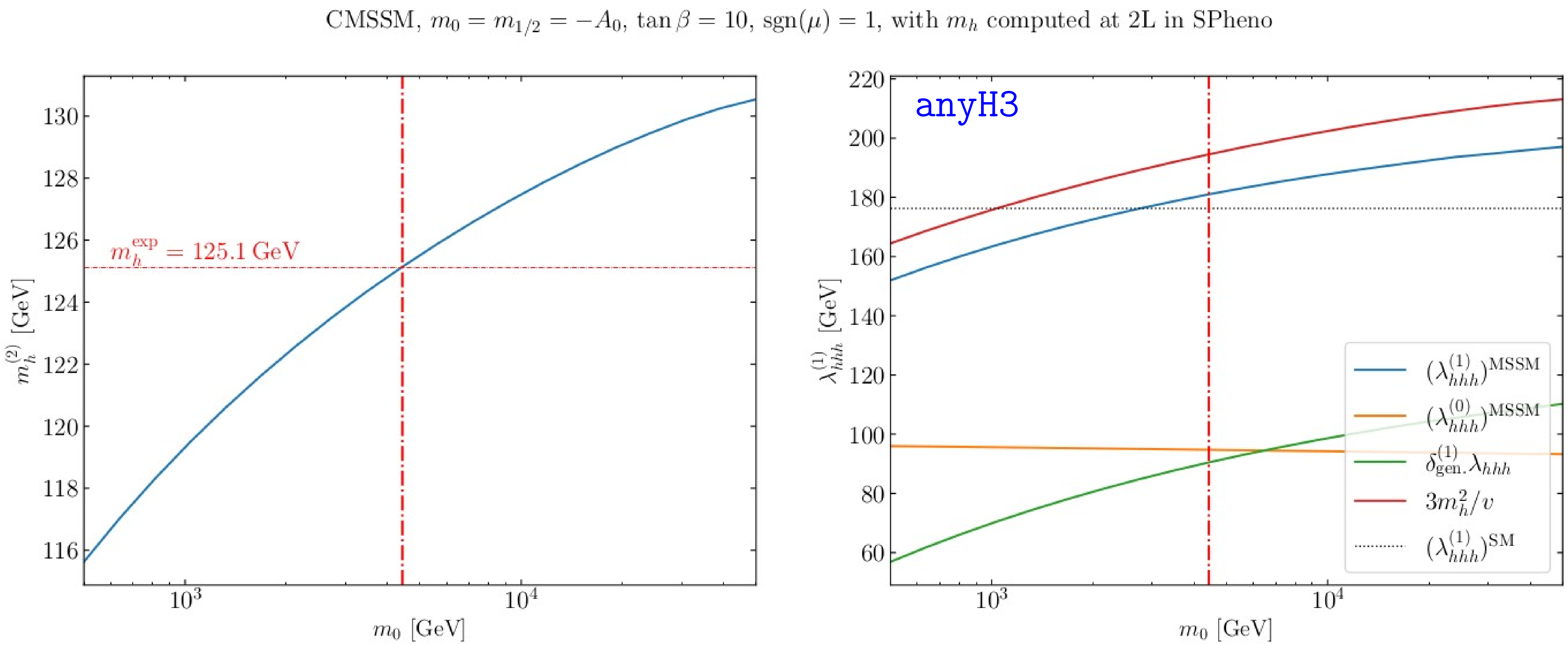


More new results with anyH3: an example in the N2HDM



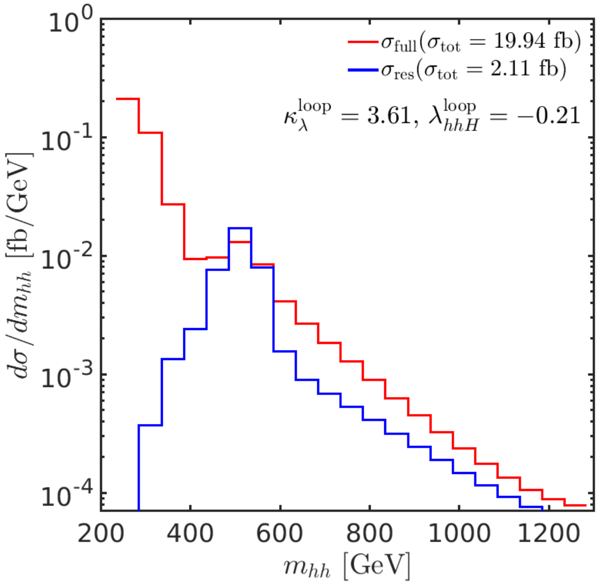
- **N2HDM = 2HDM + real singlet**
- CP-even sector: 3 states h_1, h_2, h_3, with 3 mixing angles α_1, α_2, α_3
- Here $\alpha_2 \to \pi/2$ → recover 2HDM (itself in alignment limit)
- We can study e.g. the relative sign of κ_λ and κ_t → affects double-Higgs production
- κ_t too far away from 1 excluded

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



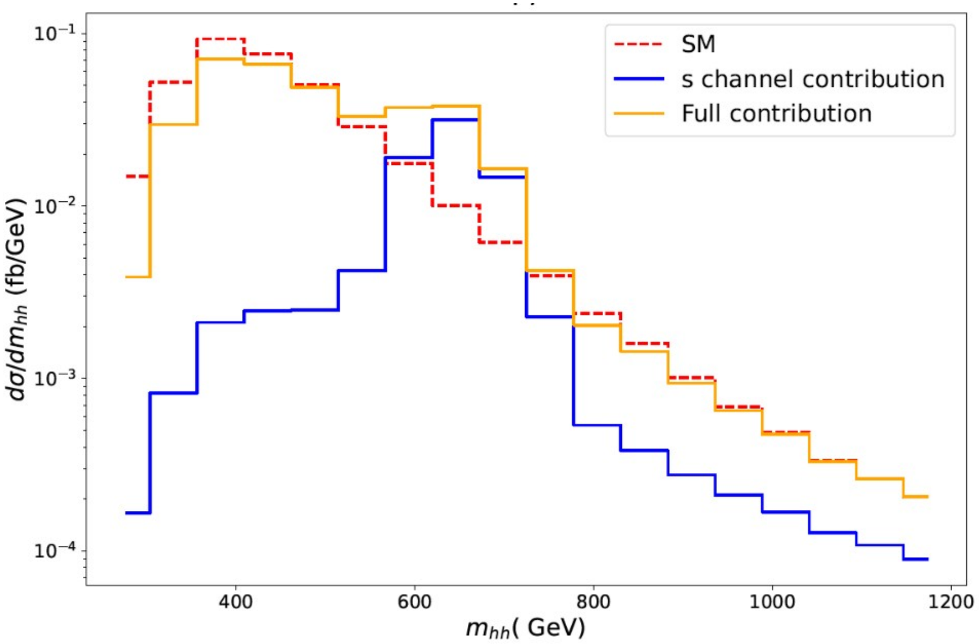
- Example for a very simple version of the constrained MSSM → BSM parameters m_0, $m_{1/2}$, A_0, sgn(μ), tanβ
- For each point, M_h computed at 2L with SPheno, and SLHA output of SPheno used as input of anyH3

Ongoing developments in `anyBSM`

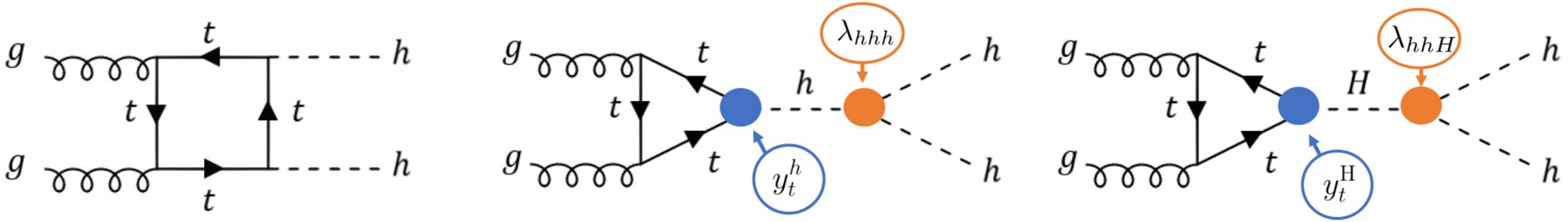


Left: 2HDM
[Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein '24]
plot from talk of K. Radchenko Serdula at 20th LHC Higgs WG workshop

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



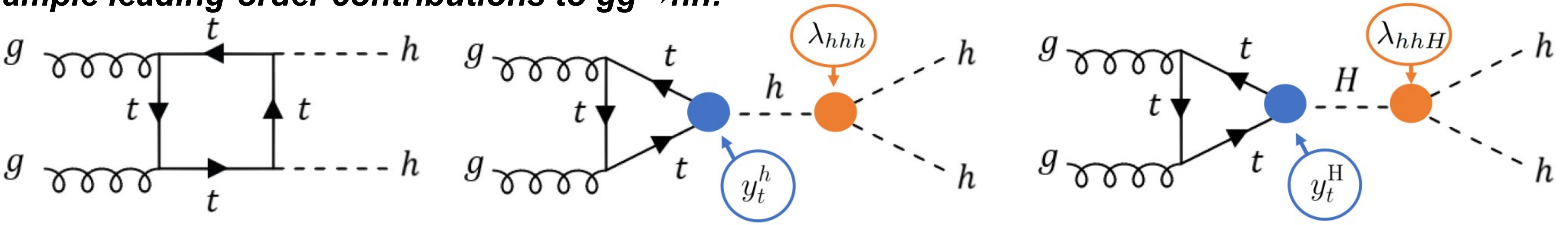
Example leading-order contributions:



[Figure by A. Verduras]

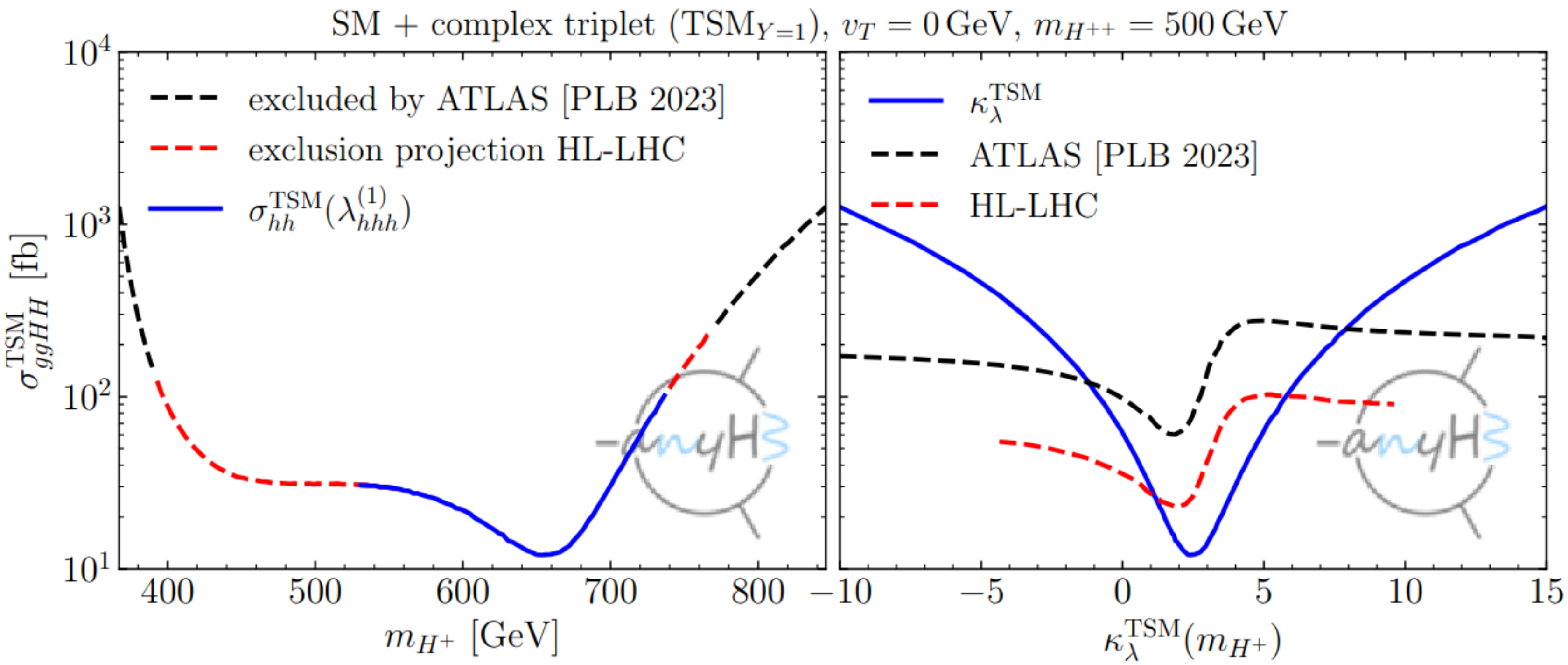
Ongoing developments in `anyBSM`: `anyLambdaijk` and `anyHH`

Example leading-order contributions to gg→hh:



[Diagrams by A. Verduras Schaeidt]

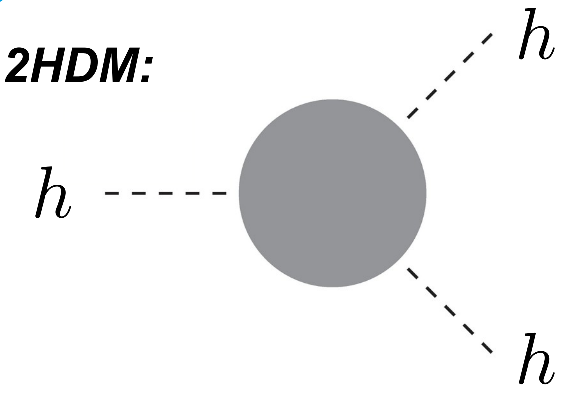
Having predictions for di-Higgs production, including **all (i.e. resonant + non-resonant) contributions + 1L corrections to trilinear scalar couplings** in **arbitrary models** would be highly desirable
→ new modules `anyLambdaijk` and `anyHH`
[Bahl, Braathen, Gabelmann, Radchenko Serdula, GW *WIP*]

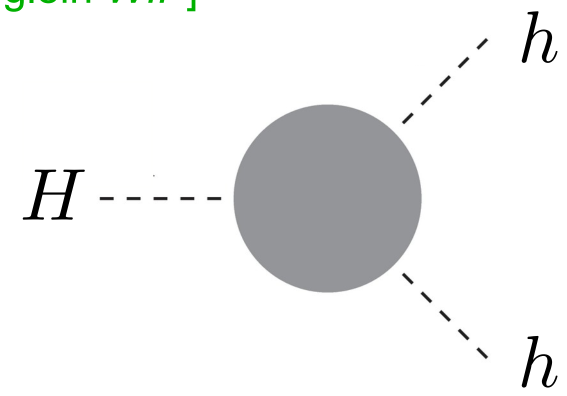


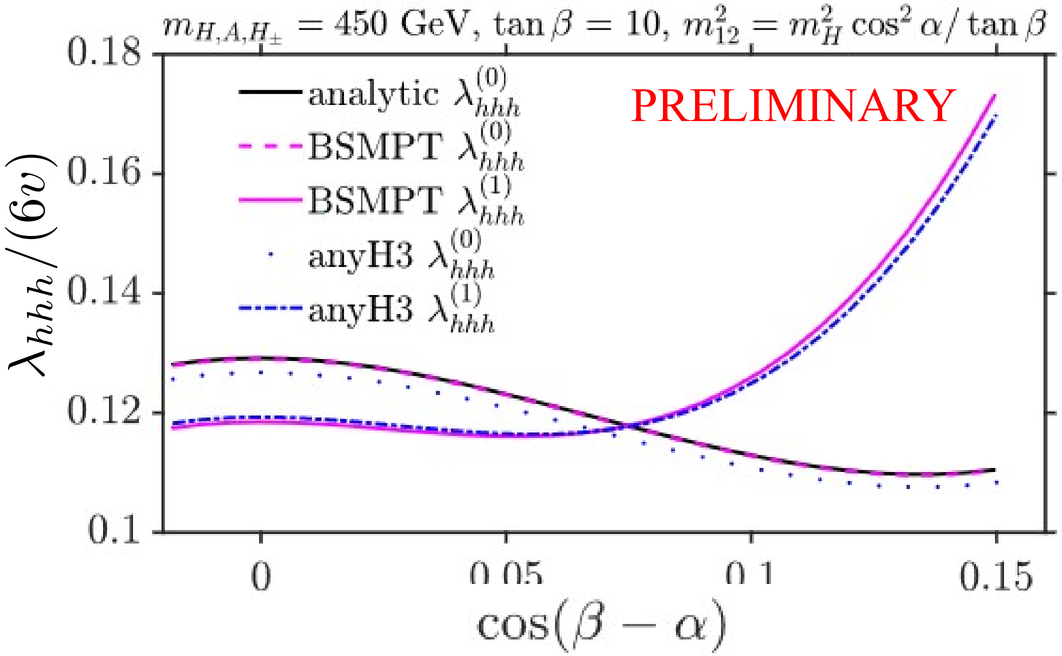
Ongoing developments: `anyLamijk`

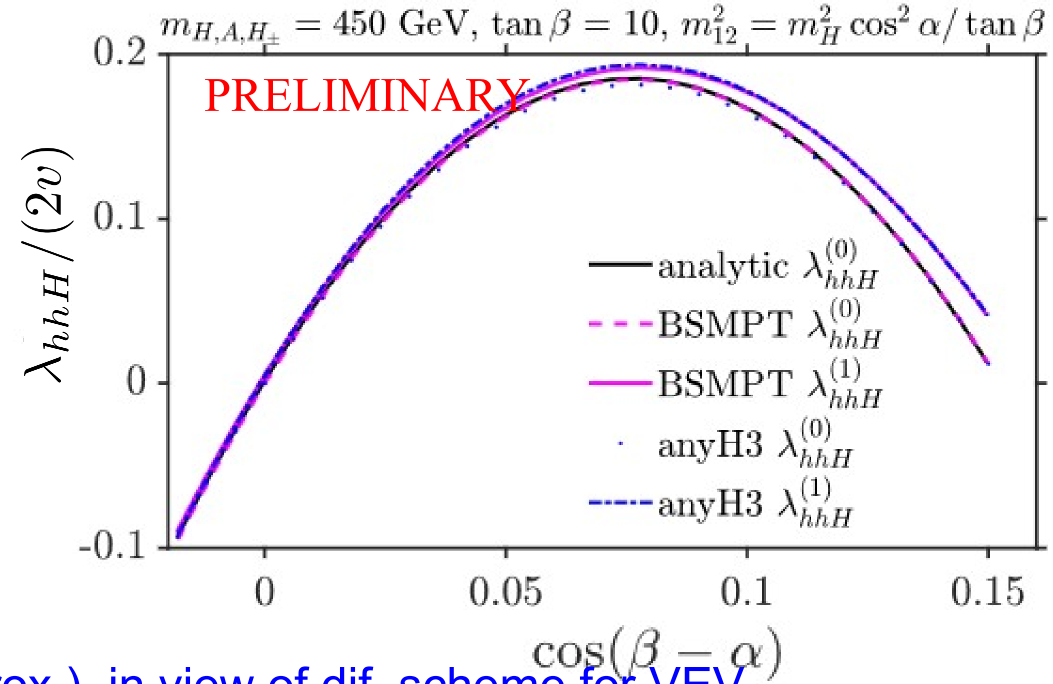
[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

Example in a 2HDM:







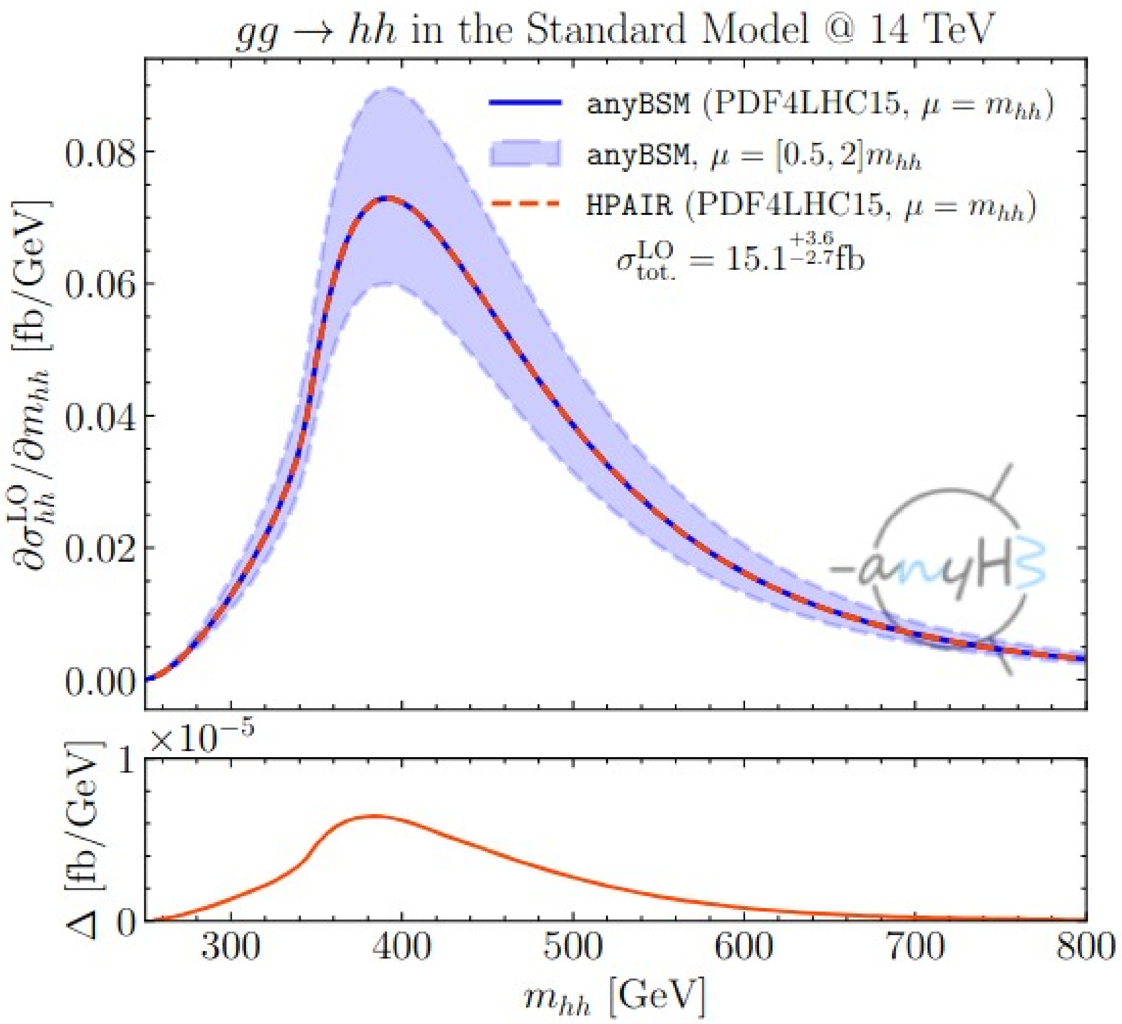


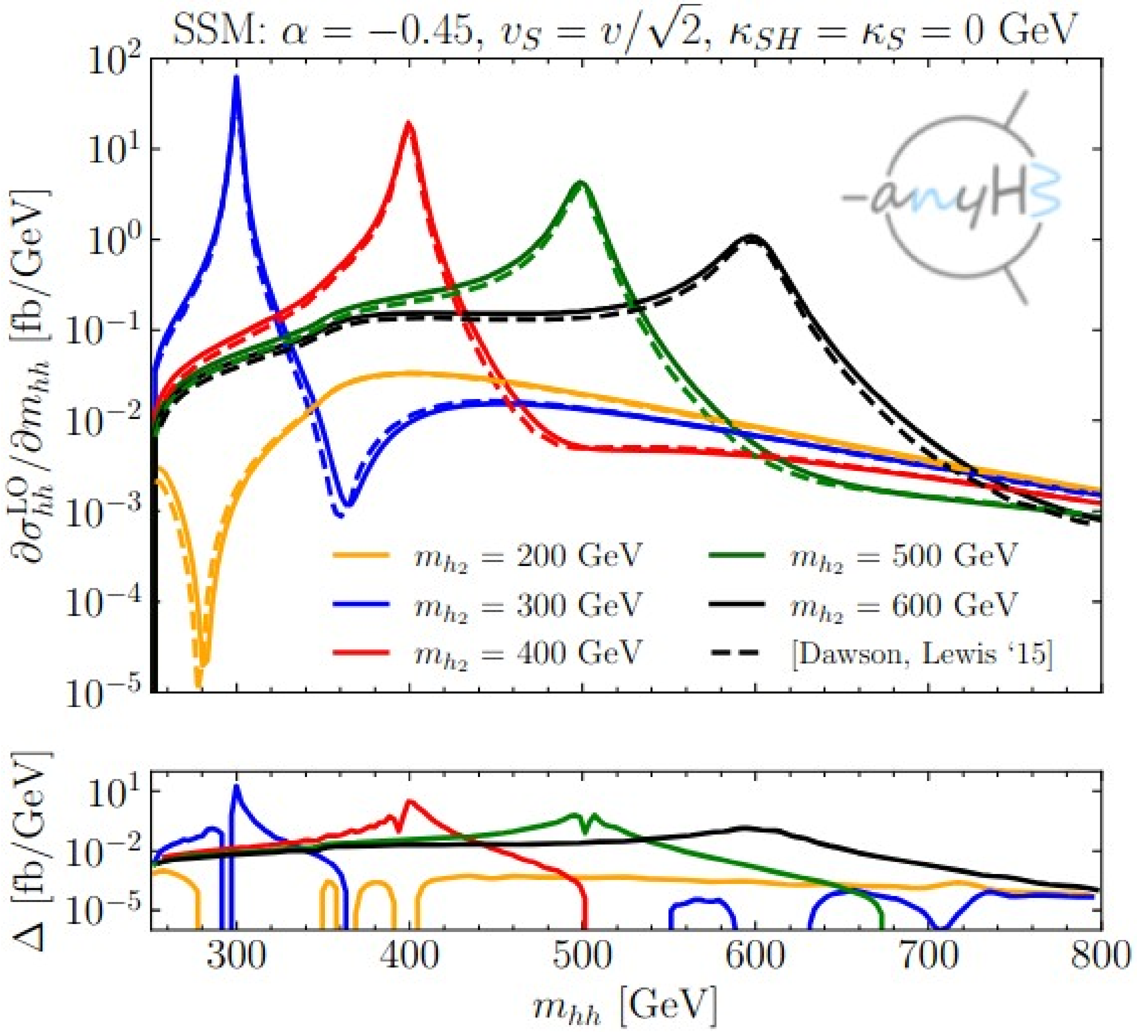
→ excellent agreement with BSMPT results (in eff. pot. approx.), in view of dif. scheme for VEV

→ 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

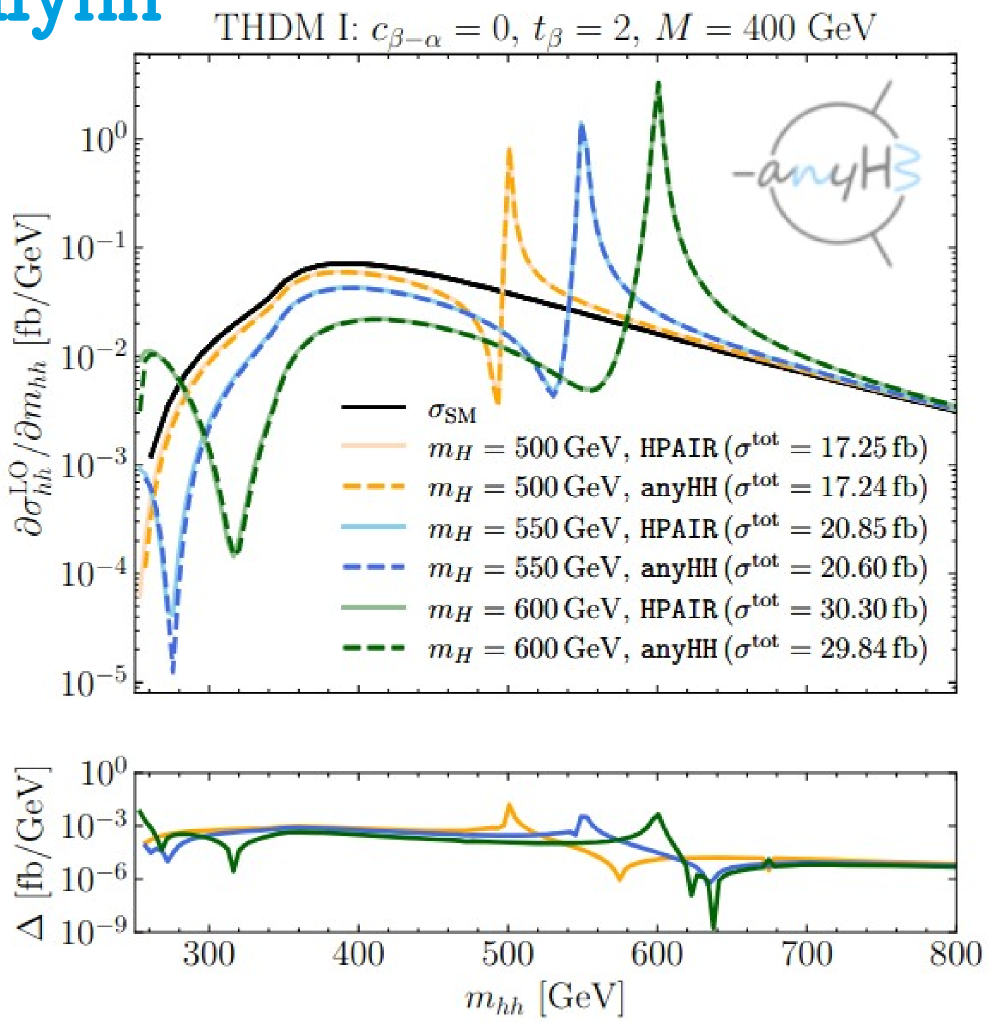
$$\Delta \equiv |\partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{HPAIR}) - \partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{anyHH})|$$

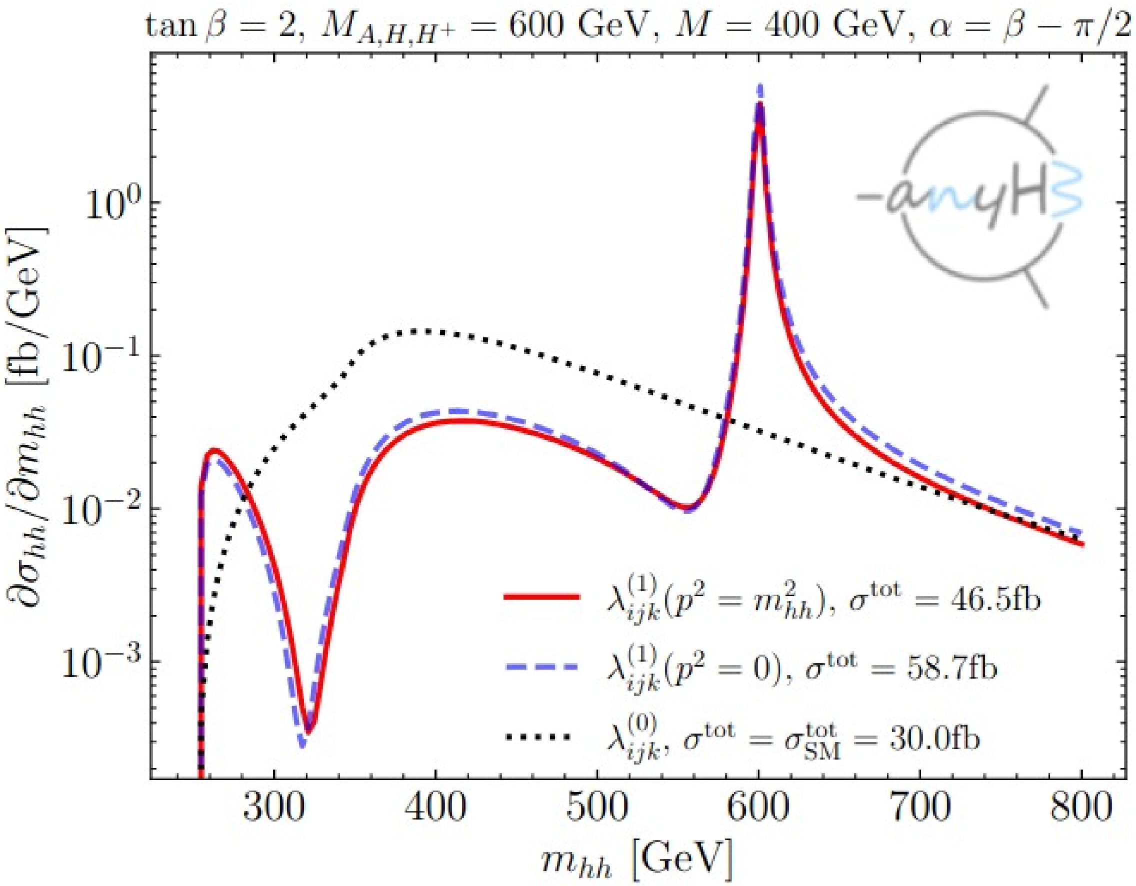




- Excellent agreement with LO HPair result, once one ensures that running of α_s + choice of PDFs are same
- Very good agreement results of [Dawson, Lewis '15] for singlet extension of SM (remaining difference because PDF sets can't be taken to be the same)

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)

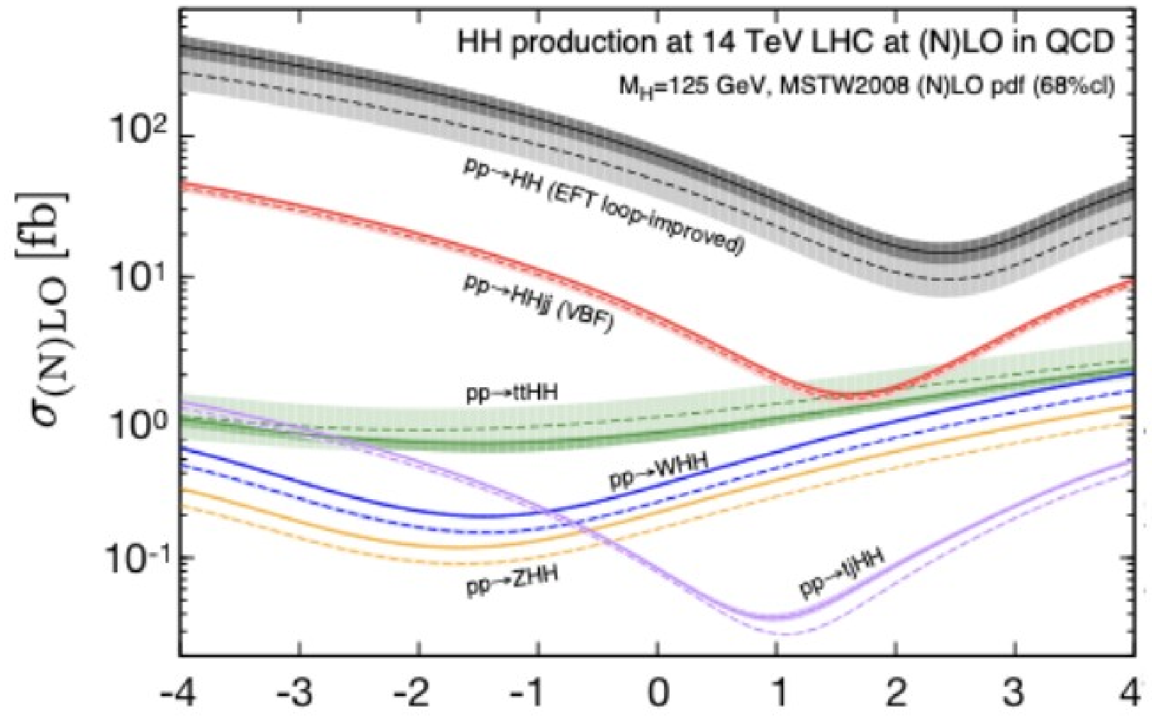
- Strong impact of inclusion of one-loop corrections to trilinear scalar couplings on differential distribution

- 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

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

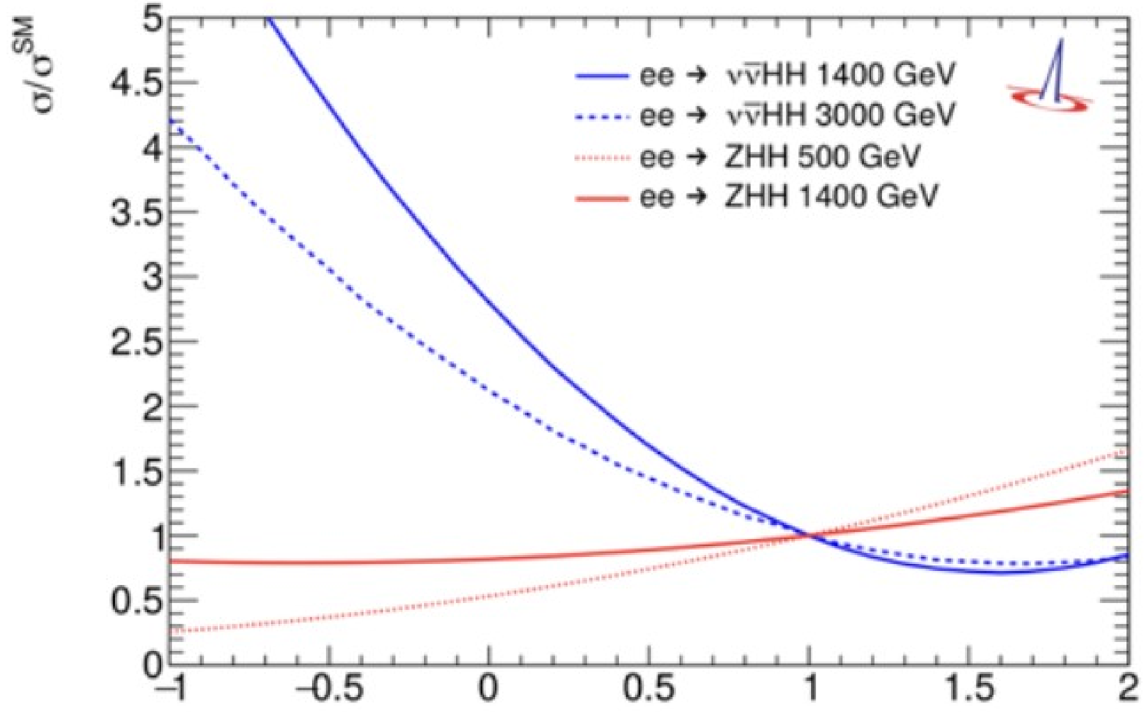
Plots taken from
[de Blas et al., 1905.03764]

Hadron collider



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

e^+e^- collider

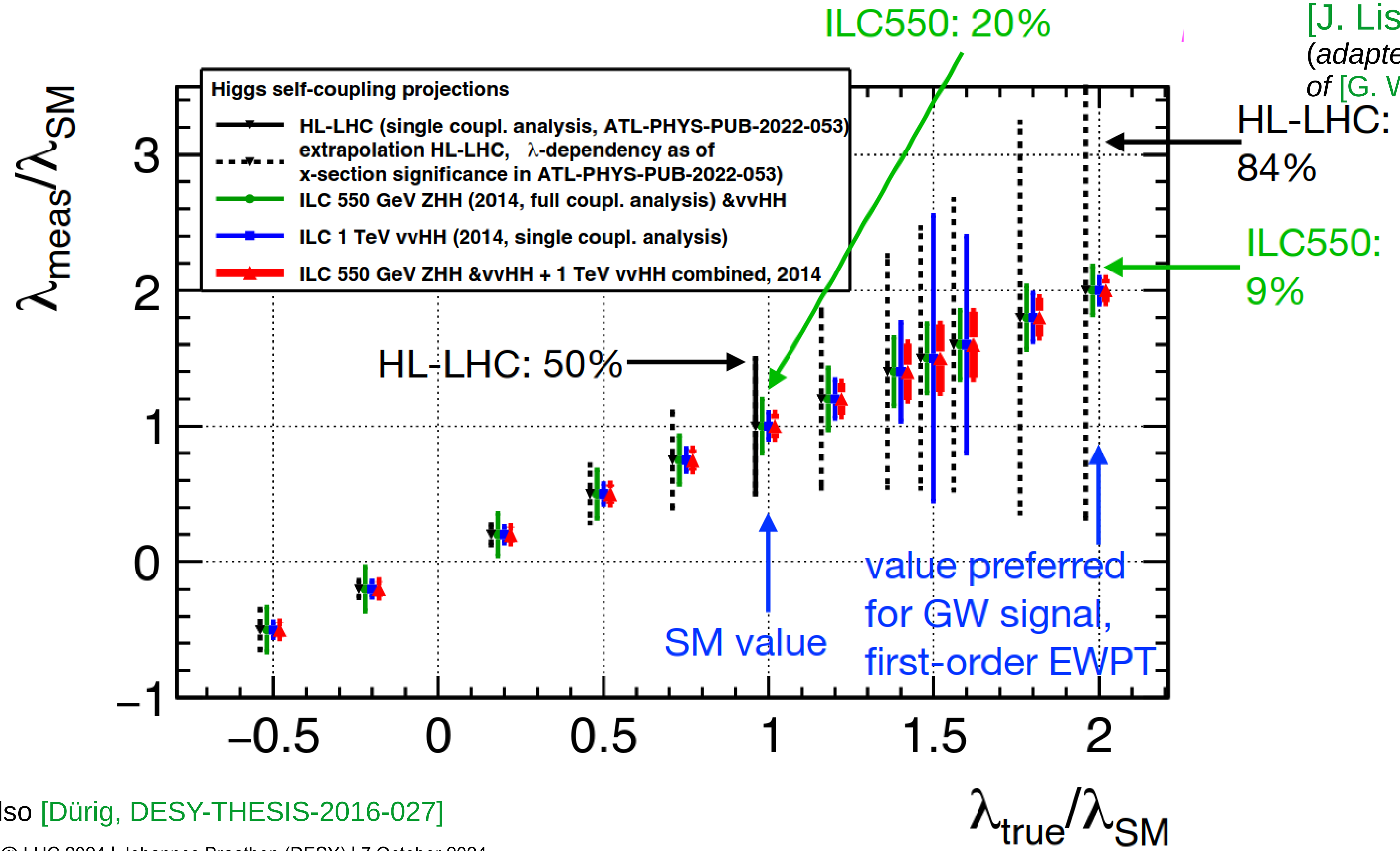


$\lambda_3/\lambda_3^{SM} = \kappa_\lambda$ [Reuter '19]

- **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])

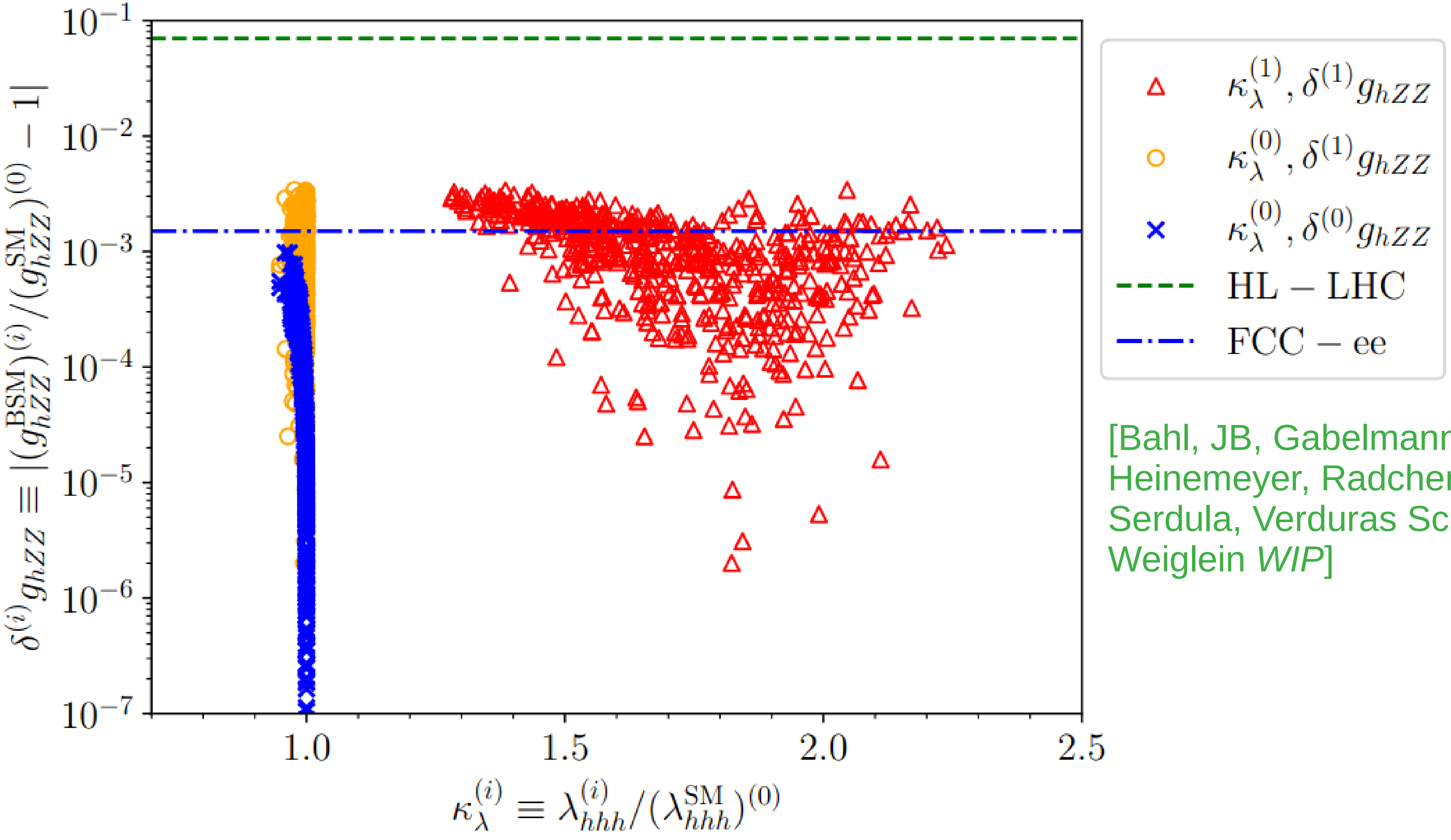


See also [Dürig, DESY-THESIS-2016-027]

Correlation between κ_λ and g_{hZZ} at tree level and one loop

Could BSM Physics be observed first in κ_λ ?

2HDM type II
All points shown here feature a strong first-order EWPT

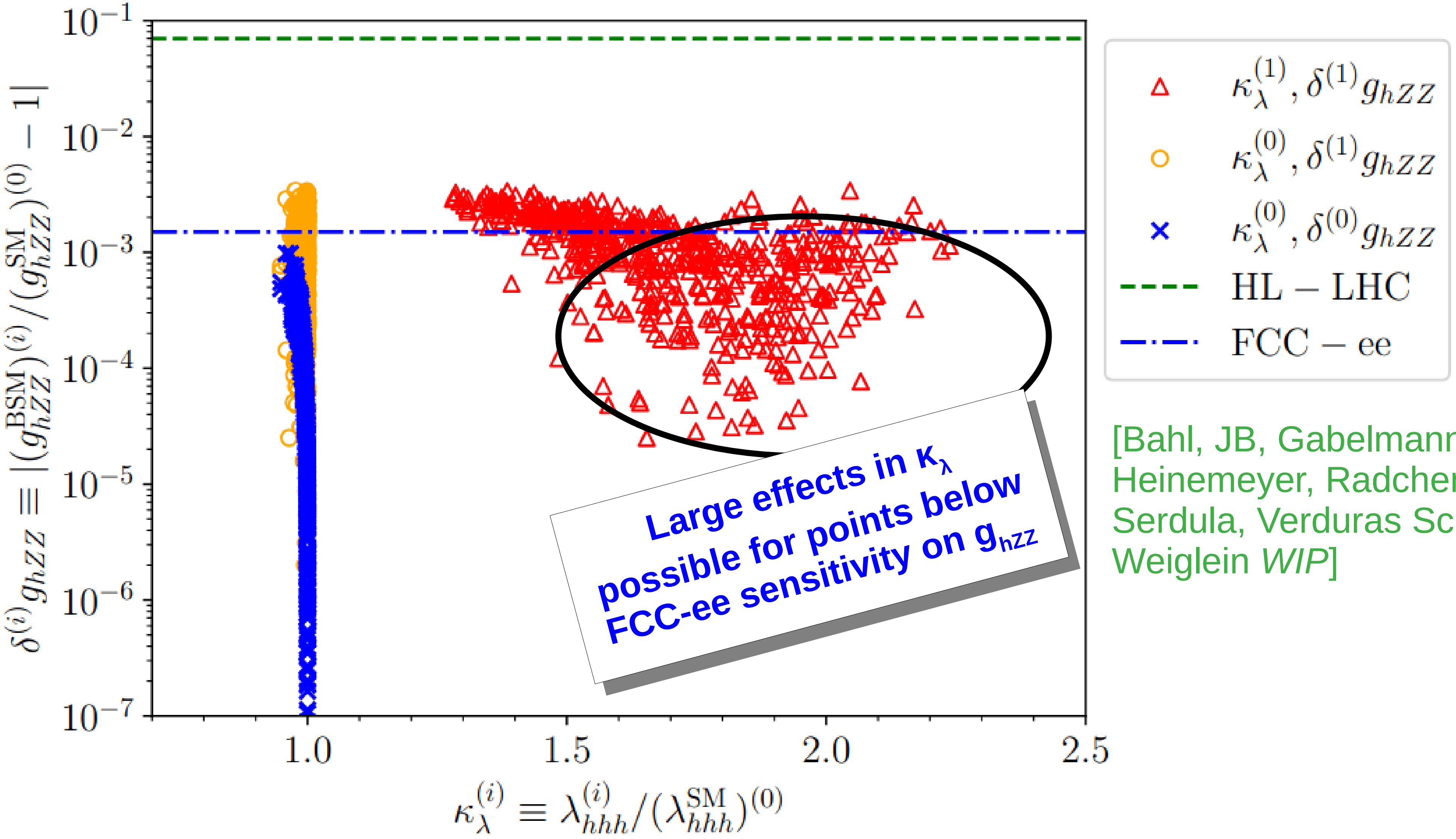


[Bahl, JB, Gabelmann, Heinemeyer, Radchenko Serdula, Verduras Schaeidt, Weiglein *WIP*]

Correlation between κ_λ and g_{hZZ} at tree level and one loop

Could BSM Physics be observed first in κ_λ ?

2HDM type II
All points shown here feature a strong first-order EWPT



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

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]

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

Deviation in λ_{hhh}

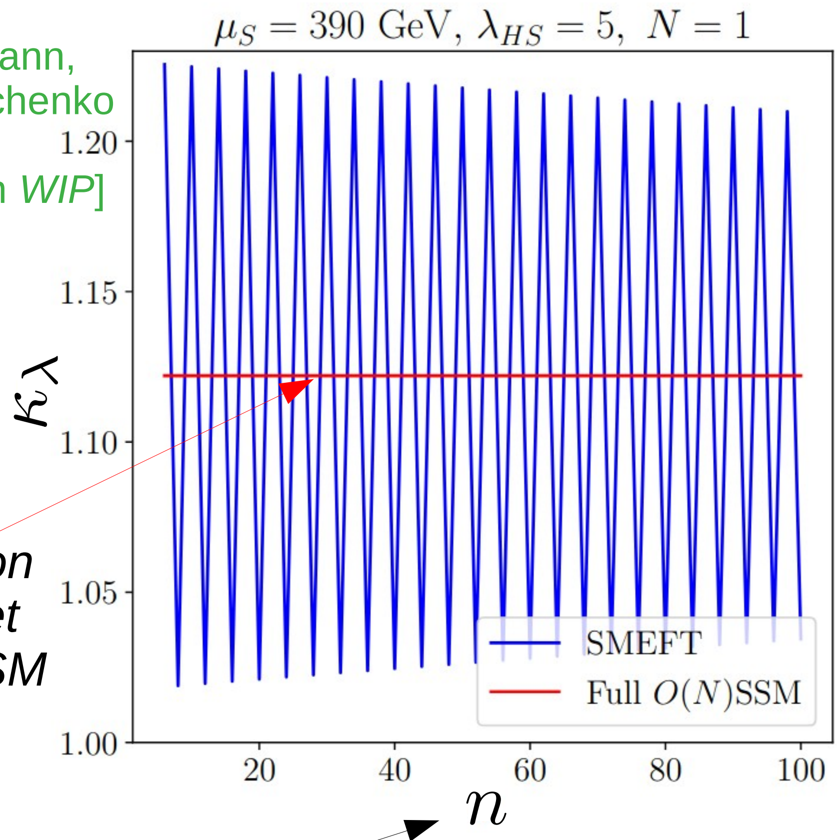
~ 600

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

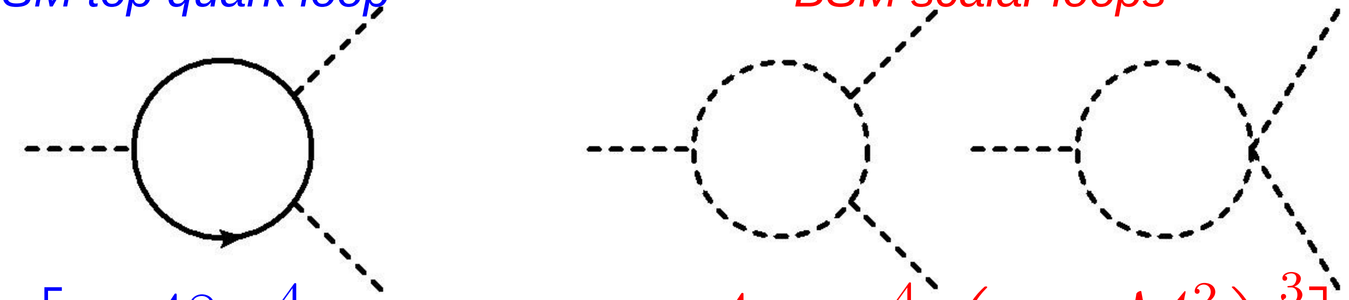
Order to which we do the calculation in SMEFT

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

One-loop mass-splitting effects

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

SM top quark loop *BSM scalar loops*



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48m_t^4}{v^3} + \sum_\Phi \frac{4n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

First found in 2HDM: [Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\mathcal{M}$: **BSM mass scale**, e.g. soft breaking scale M of Z_2 symmetry in 2HDM
n_Φ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda} v^2$

$$\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3 \longrightarrow \begin{cases} 0, \text{ for } \mathcal{M}^2 \gg \tilde{\lambda}v^2 \\ 1, \text{ for } \mathcal{M}^2 \ll \tilde{\lambda}v^2 \end{cases}$$

→ **Huge BSM effects possible!**

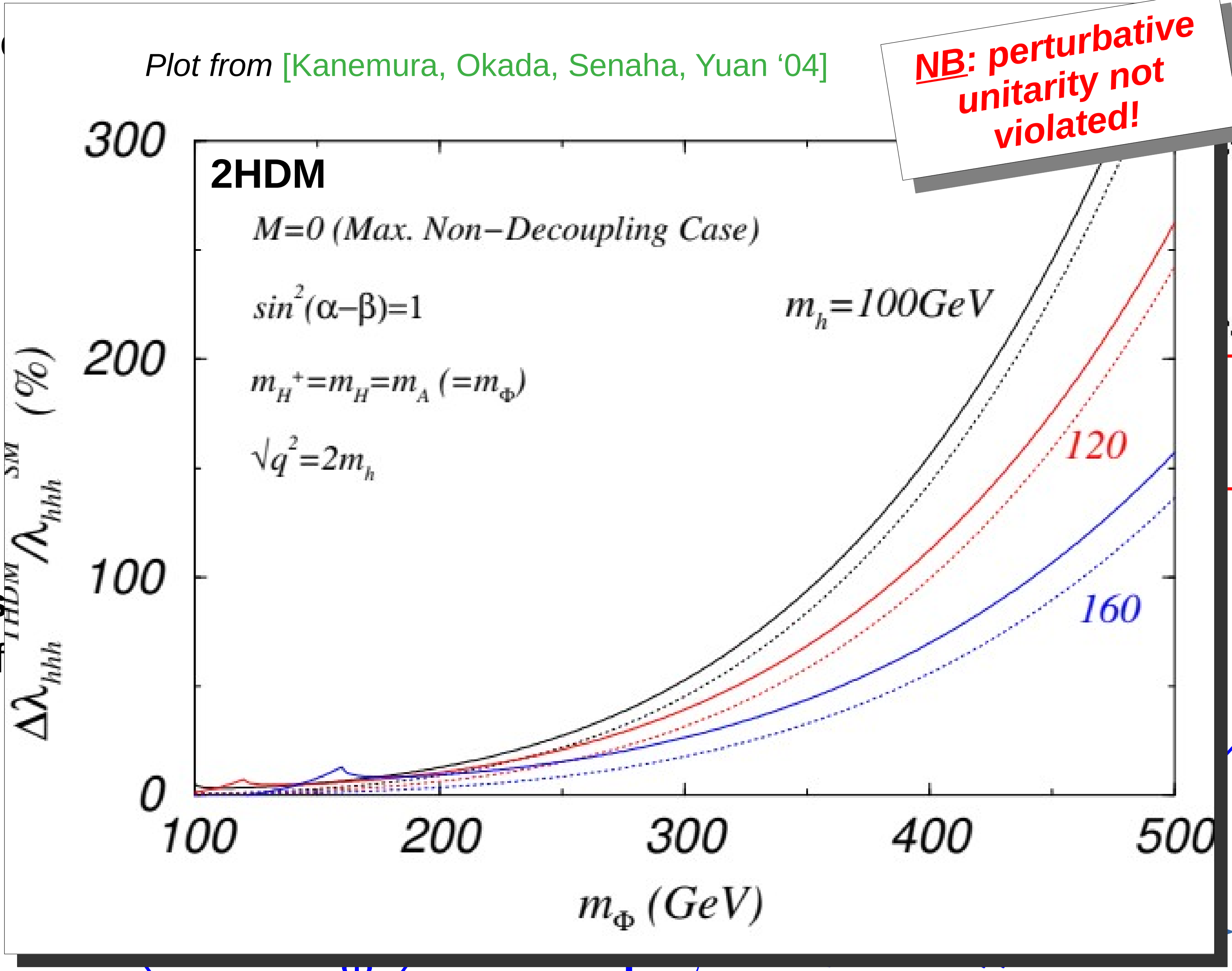
One-loop mass-splitting effects

- Leading one-loop c

$\delta^{(1)}\lambda_{hhh} \supset$

$\mathcal{M}$: **BSM mass**
n_Φ : # of d.o.f of

- Size of new effects



NB: perturbative unitarity not violated!

First found in 2HDM: [Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\Lambda^2 + \tilde{\lambda}v^2$

Huge BSM effects possible!

Two-loop calculation of λ_{hhh}

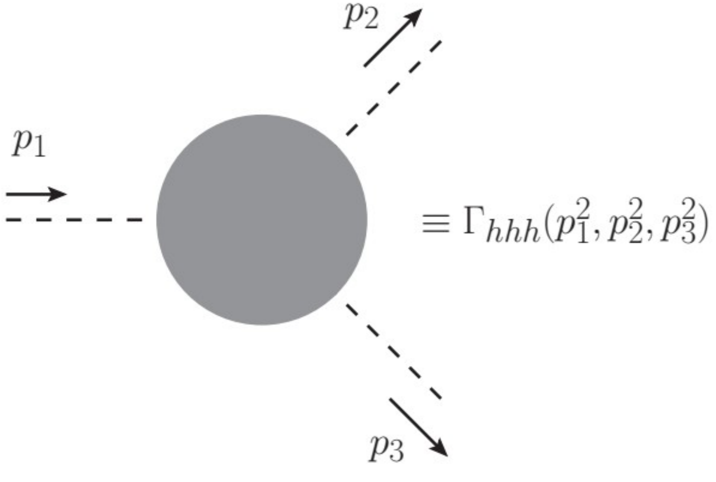
Goal: How large can the two-loop corrections to λ_{hhh} become?

Based on

arXiv:1903.05417 (PLB) and arXiv:1911.11507 (EPJC) in collaboration with Shinya Kanemura

An effective Higgs trilinear coupling

- In principle: consider 3-point function Γ_{hhh}
  but this is momentum dependent → very difficult beyond one loop



- Instead, consider an **effective trilinear coupling**

$$\lambda_{hhh} \equiv \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\bigg|_{\text{min}}$$

entering the coupling modifier

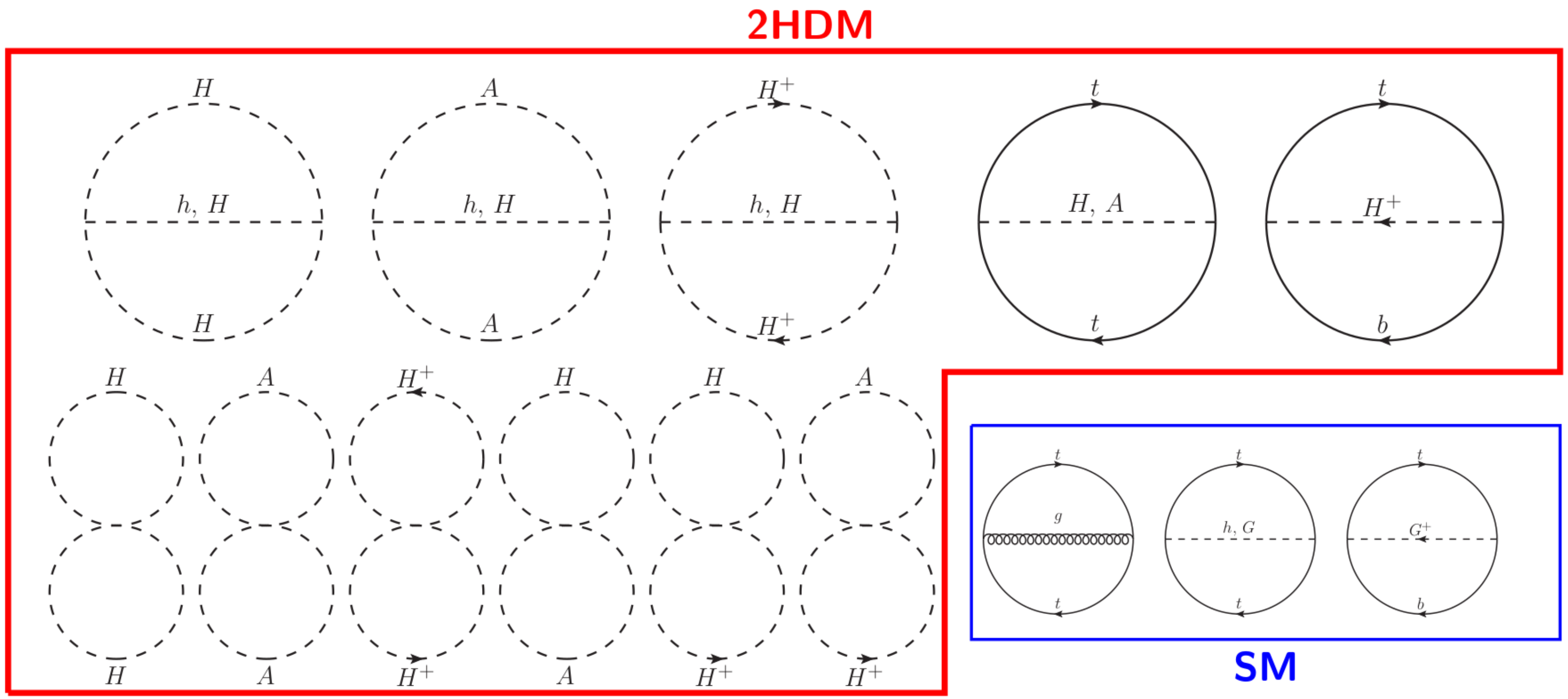
$$\kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\text{SM}}} \qquad \text{with } (\lambda_{hhh}^{(0)})^{\text{SM}} = \frac{3m_h^2}{v}$$

constrained by experiments (*applicability of this assumption discussed later*)

Our effective-potential calculation

[JB, Kanemura '19]

- **Step 1**: compute $V_{\text{eff}} = V^{(0)} + \frac{1}{16\pi^2} V^{(1)} + \frac{1}{(16\pi^2)^2} V^{(2)}$ ($\overline{\text{MS}}$ result)
  - $V^{(2)}$: 1PI vacuum bubbles
  - *Dominant BSM contributions to* $V^{(2)}$ = diagrams involving **heavy BSM scalars and top quark**
  - **Neglect masses of light states** (SM-like Higgs, light fermions, ...)



Our effective-potential calculation

[JB, Kanemura '19]

- **Step 1**: compute $V_{\text{eff}} = V^{(0)} + \frac{1}{16\pi^2} V^{(1)} + \frac{1}{(16\pi^2)^2} V^{(2)}$ ($\overline{\text{MS}}$ result)
  - $V^{(2)}$: 1PI vacuum bubbles
  - *Dominant BSM contributions to* $V^{(2)}$ = diagrams involving **heavy BSM scalars and top quark**

- **Step 2**: derive an effective trilinear coupling

$$\lambda_{hhh} \equiv \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\bigg|_{\text{min.}} = \frac{3[M_h^2]_{V_{\text{eff}}}}{v} + \left[\frac{\partial^3}{\partial h^3} - \frac{3}{v}\left(\frac{\partial^2}{\partial h^2} - \frac{1}{v}\frac{\partial}{\partial h}\right)\right]\Delta V\bigg|_{\text{min.}}$$

($\overline{\text{MS}}$ result too)

Express tree-level result in terms of effective-potential Higgs mass

Our effective-potential calculation

[JB, Kanemura '19]

- **Step 1**: compute $V_{\text{eff}} = V^{(0)} + \frac{1}{16\pi^2}V^{(1)} + \frac{1}{(16\pi^2)^2}V^{(2)}$ ($\overline{\text{MS}}$ result)
  - $V^{(2)}$: 1PI vacuum bubbles
  - *Dominant BSM contributions to $V^{(2)}$* = diagrams involving **heavy BSM scalars and top quark**

- **Step 2**: $\lambda_{hhh} \equiv \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\Big|_{\text{min.}} = \frac{3[M_h^2]_{V_{\text{eff}}}}{v} + \left[\frac{\partial^3}{\partial h^3} - \frac{3}{v}\left(\frac{\partial^2}{\partial h^2} - \frac{1}{v}\frac{\partial}{\partial h}\right)\right]\Delta V\Big|_{\text{min.}}$

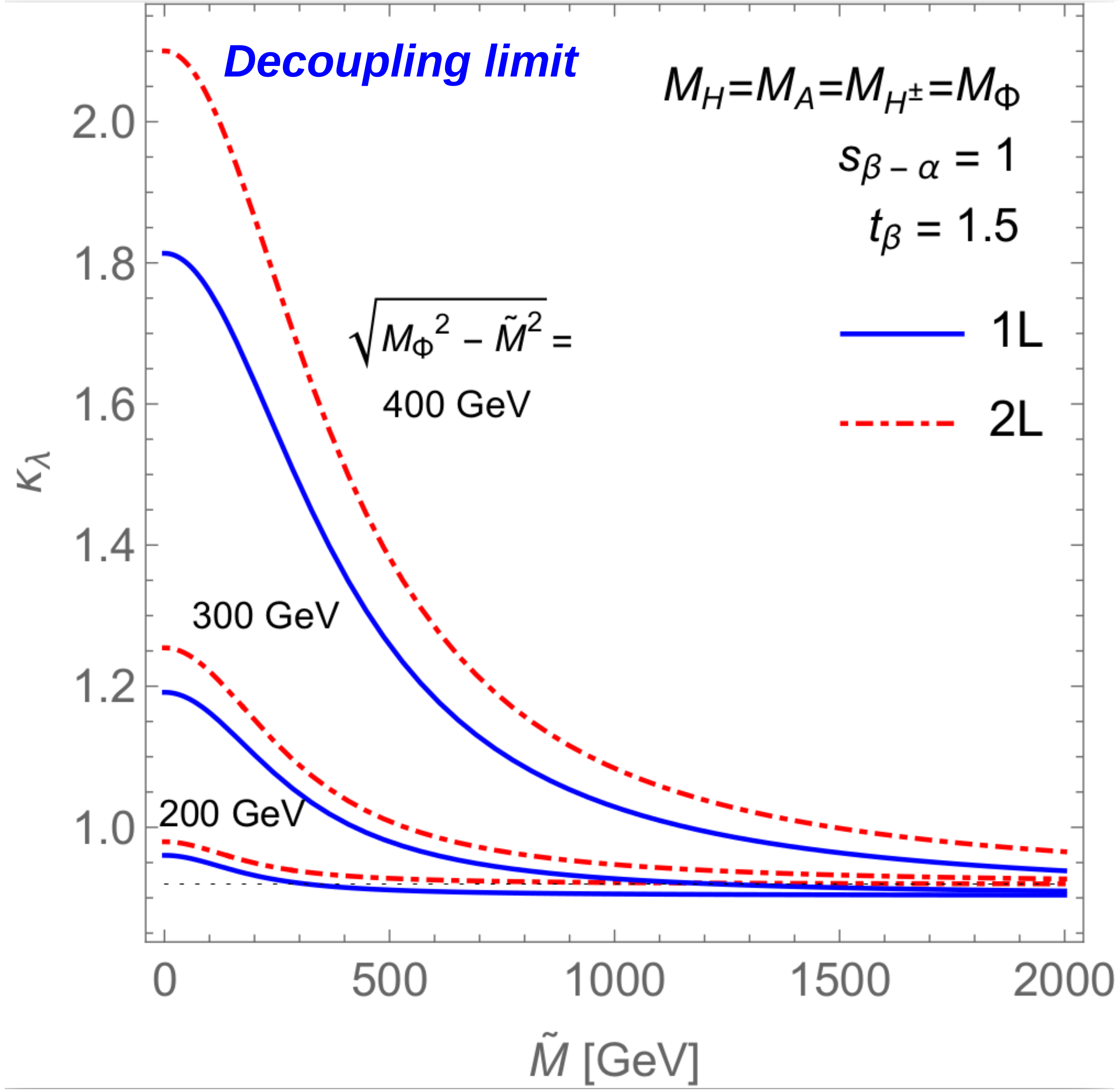
  ($\overline{\text{MS}}$ result too)

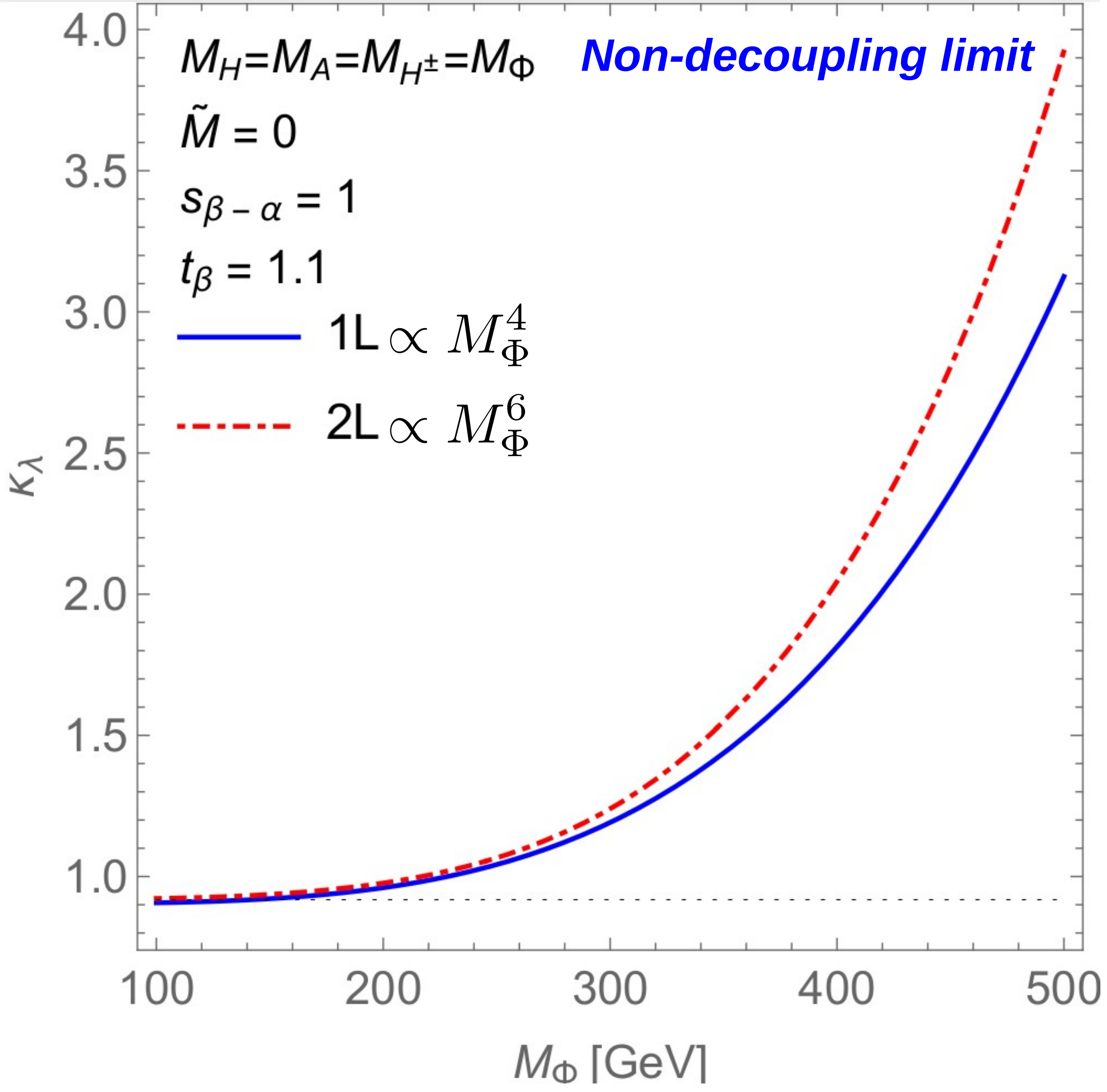
- **Step 3**: conversion from $\overline{\text{MS}}$ to OS scheme
  - Express result in terms of **pole masses**: M_t, M_h, M_Φ (Φ=H,A,H$^\pm$); OS Higgs VEV $v_{\text{phys}} = \frac{1}{\sqrt{\sqrt{2}G_F}}$
  - Include **finite WFR**: $\hat{\lambda}_{hhh} = (Z_h^{\text{OS}}/Z_h^{\overline{\text{MS}}})^{3/2}\lambda_{hhh}$
  - Prescription for M to ensure **proper decoupling** with $M_\Phi^2 = \tilde{M}^2 + \tilde{\lambda}_\Phi v^2$ and $\tilde{M} \to \infty$

Our results in the aligned 2HDM

[JB, Kanemura '19]

Taking degenerate BSM scalar masses: $M_\Phi = M_H = M_A = M_{H^\pm}$





$\overline{\text{MS}}$ to OS scheme conversion

- V_{eff}: we use expressions in MS scheme hence results for λ_{hhh} also in $\overline{\text{MS}}$ scheme

- We include finite counterterms to express the Higgs trilinear coupling in terms of physical quantities

$$\underbrace{m_X^2}_{\overline{\text{MS}}} = \underbrace{M_X^2}_{\text{pole}} - \mathfrak{Re}[\Pi_{XX}^{\text{fin.}}(p^2 = M_X^2)], \qquad v^2 = \underbrace{(\sqrt{2}G_F)^{-1}}_{\equiv v_{\text{OS}}^2} + \frac{3M_t^2}{16\pi^2}\left(2\log\frac{M_t^2}{Q^2} - 1\right) + \cdots$$

- Also we include finite WFR effects → OS scheme

$$\underbrace{\hat{\lambda}_{hhh}}_{\text{OS}} = \underbrace{\left(\frac{Z_h^{\text{OS}}}{Z_h^{\overline{\text{MS}}}}\right)^{3/2}}_{\text{finite WFR}} \underbrace{\lambda_{hhh}}_{\overline{\text{MS}}} = -\underbrace{\Gamma_{hhh}(0,0,0)}_{\text{3-pt. func.}}$$

$\overline{\text{MS}}$ to OS scheme conversion

- OS result is obtained as

$$\hat{\lambda}_{hhh} = \underbrace{\left(\frac{Z_h^{\text{OS}}}{Z_h^{\overline{\text{MS}}}}\right)^{3/2}}_{\text{inclusion of WFR}} \times \underbrace{\lambda_{hhh}}_{\substack{\overline{\text{MS}}\text{ parameters} \\ \text{replaced by OS ones}}}$$

- Let's suppose (for simplicity) that λ_{hhh} only depends on one parameter x, as

$$\lambda_{hhh} = f^{(0)}(x^{\overline{\text{MS}}}) + \kappa f^{(1)}(x^{\overline{\text{MS}}}) + \kappa^2 f^{(2)}(x^{\overline{\text{MS}}}) \qquad \left(\kappa = \frac{1}{16\pi^2}\right)$$

and

$$x^{\overline{\text{MS}}} = X^{\text{OS}} + \kappa\delta^{(1)}x + \kappa^2\delta^{(2)}x$$

then in terms of OS parameters

$$\lambda_{hhh} = f^{(0)}(X^{\text{OS}}) + \kappa\left[f^{(1)}(X^{\text{OS}}) + \cancel{\frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x}\right]$$
$$+\kappa^2\left[f^{(2)}(X^{\text{OS}}) + \frac{\partial f^{(1)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x + \cancel{\frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(2)}x} + \cancel{\frac{\partial^2 f^{(0)}}{\partial x^2}(X^{\text{OS}})(\delta^{(1)}x)^2}\right]$$

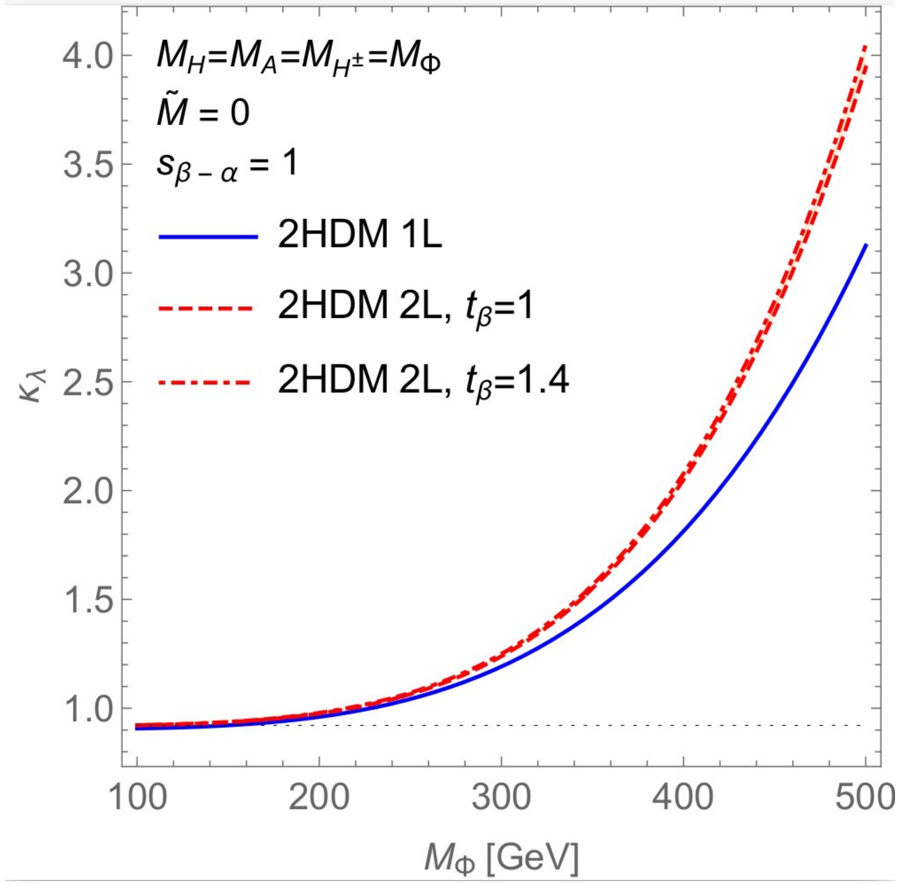
because we neglect m_h in the loop corrections and $\lambda_{hhh}^{(0)} = 3m_h^2/v$ (in absence of mixing)

λ_{hhh} at two loops in more models

[JB, Kanemura '19]

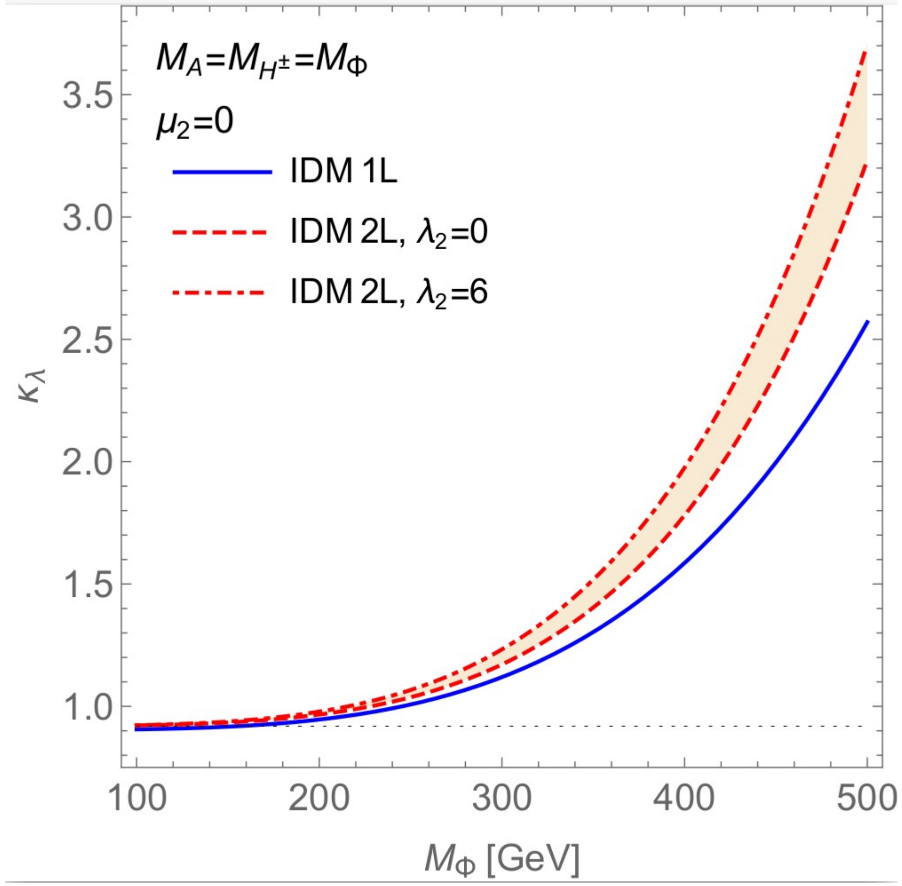
- Calculations in several other models: *Inert Doublet Model (IDM)*, *singlet extension of SM*
- Each model contains a **new parameter appearing from two loops**:

Aligned 2HDM → tanβ



tanβ constrained by perturbative unitarity → only small effects

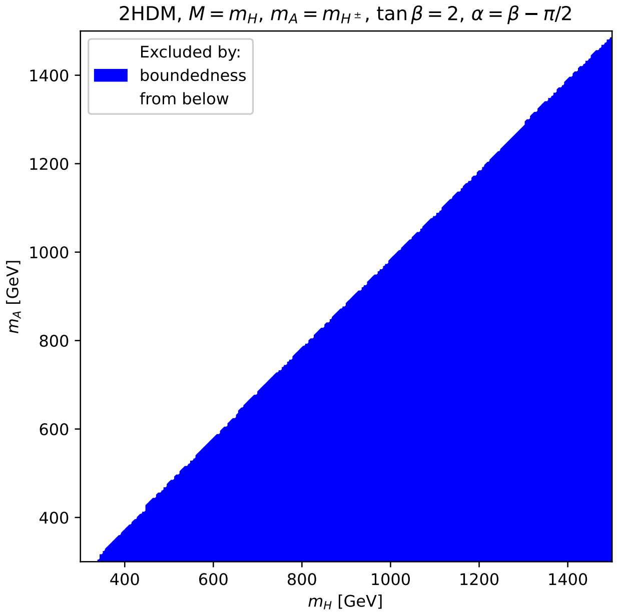
IDM → λ_2 (quartic coupling of inert doublet)



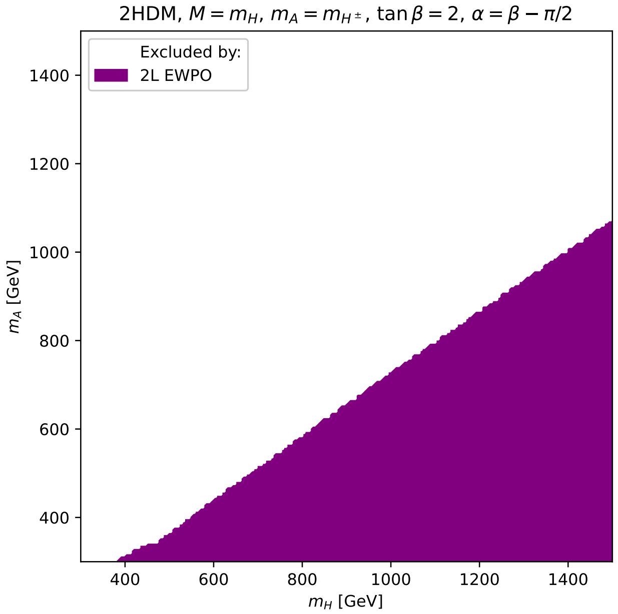
λ_2 is less contrained → **enhancement is possible**
(but 2L effects remain <u>well smaller</u> than 1L ones)

2HDM benchmark plane – individual theoretical constraints

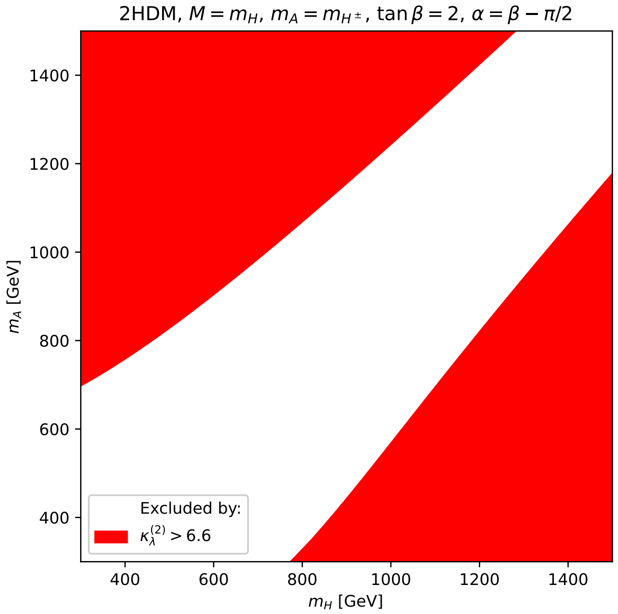
Constraints shown below are independent of 2HDM type



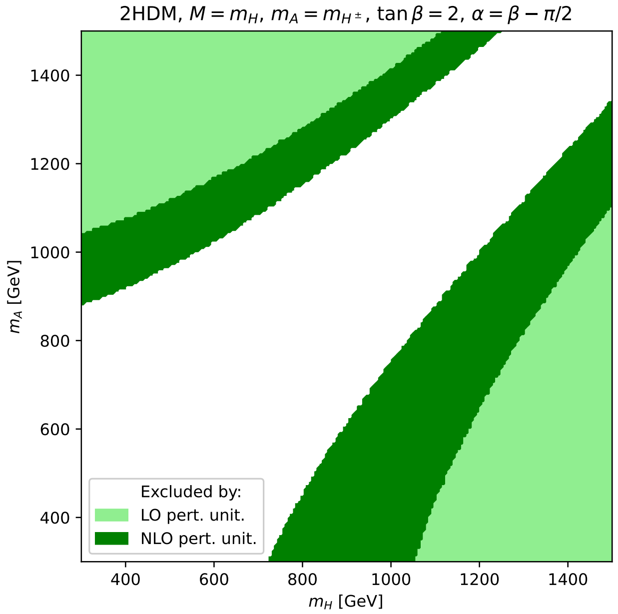
Boundedness from below



EW precision observables computed at 2L



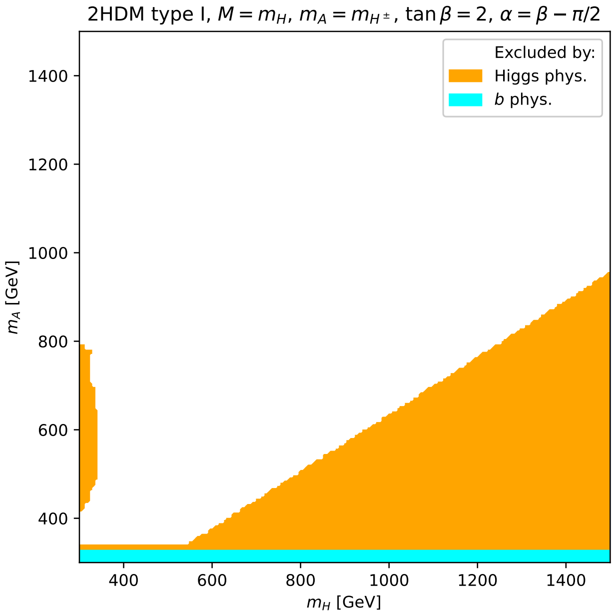
$\kappa_\lambda^{(2)} > 6.6$



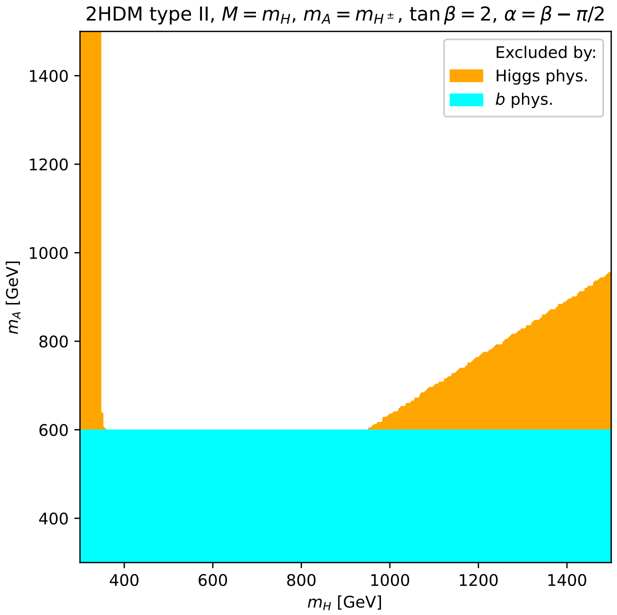
Perturbative unitarity at (N)LO

2HDM benchmark plane – experimental constraints

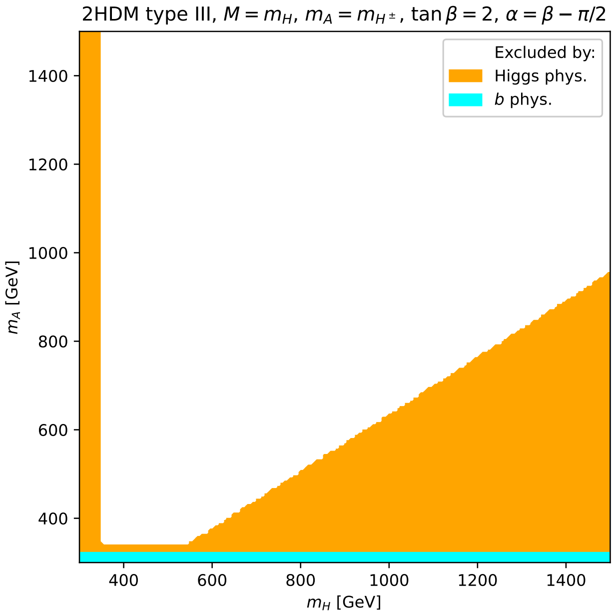
i.e. Higgs physics (via HiggsBounds and HiggsSignals) and *b* physics (from [Gfitter group 1803.01853])



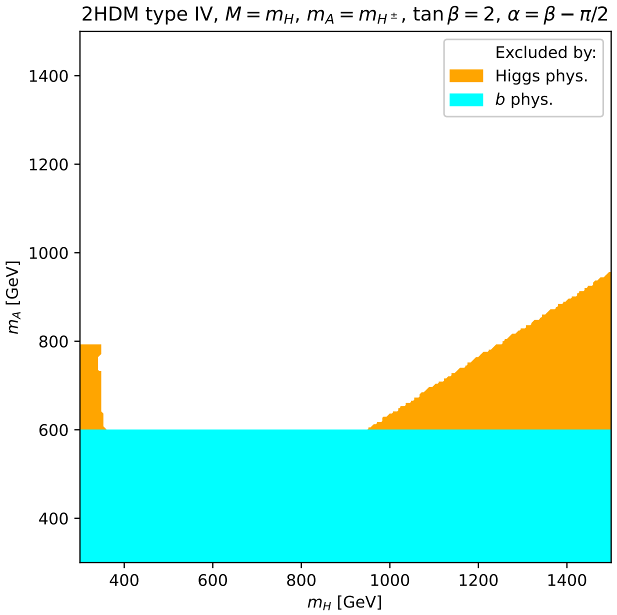
Type-I



Type-II



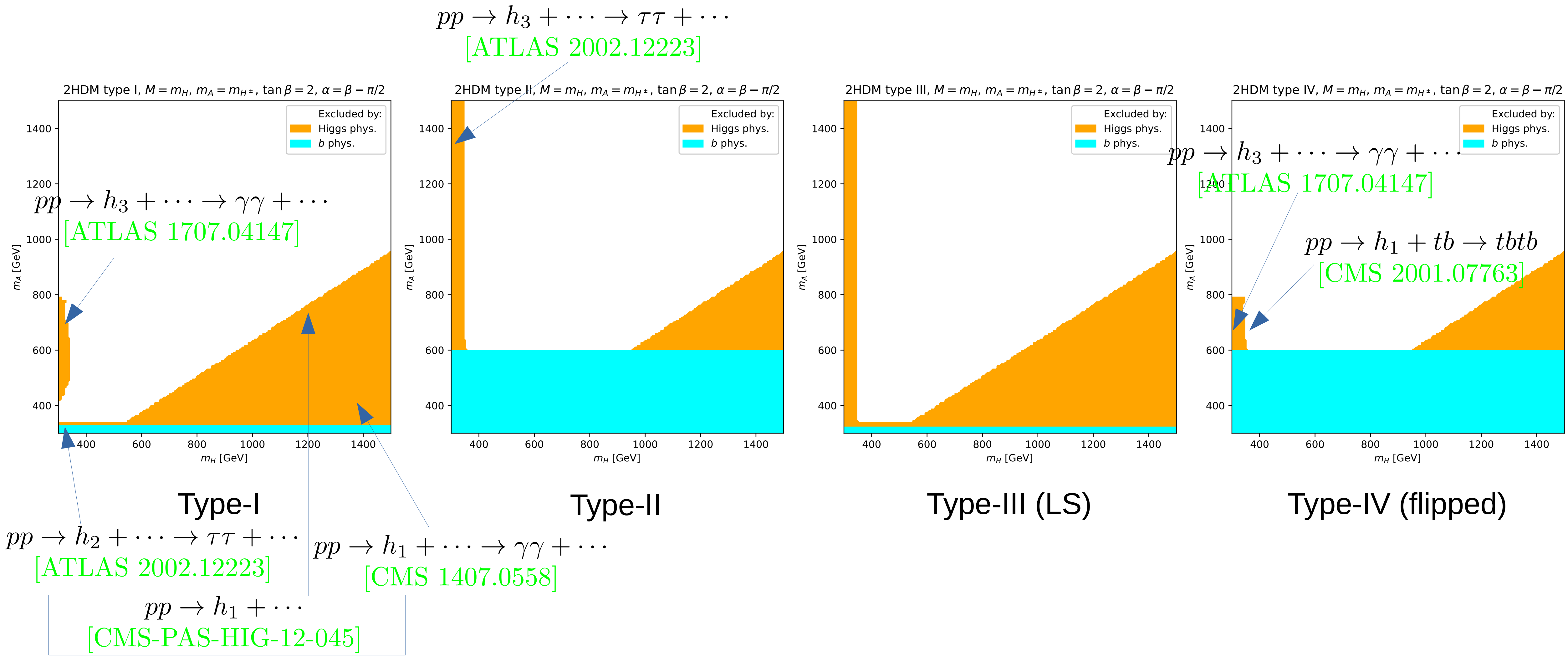
Type-III (LS)



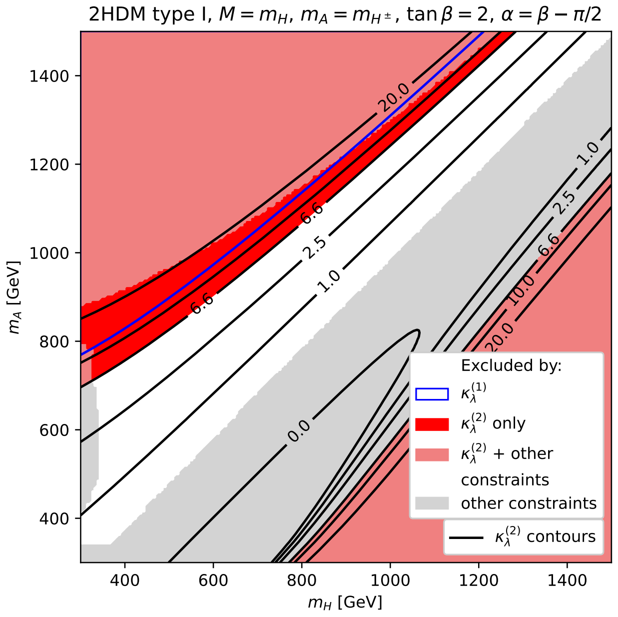
Type-IV (flipped)

2HDM benchmark plane – experimental constraints

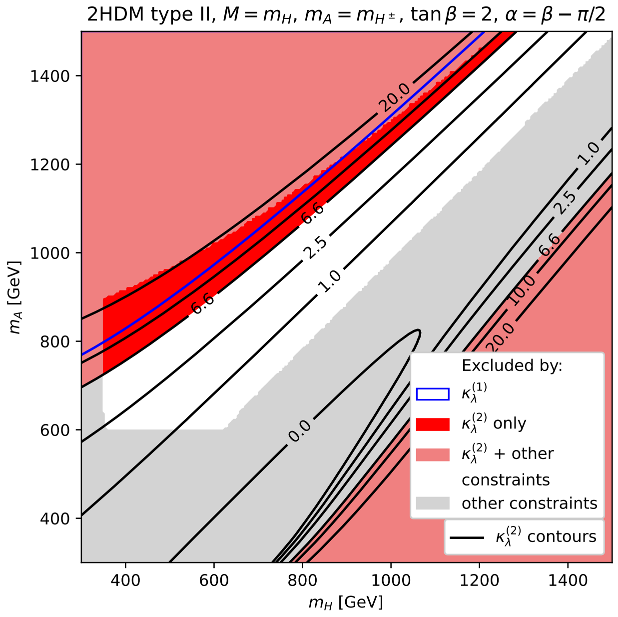
i.e. Higgs physics (via HiggsBounds and HiggsSignals) and *b* physics (from [Gfitter group 1803.01853])



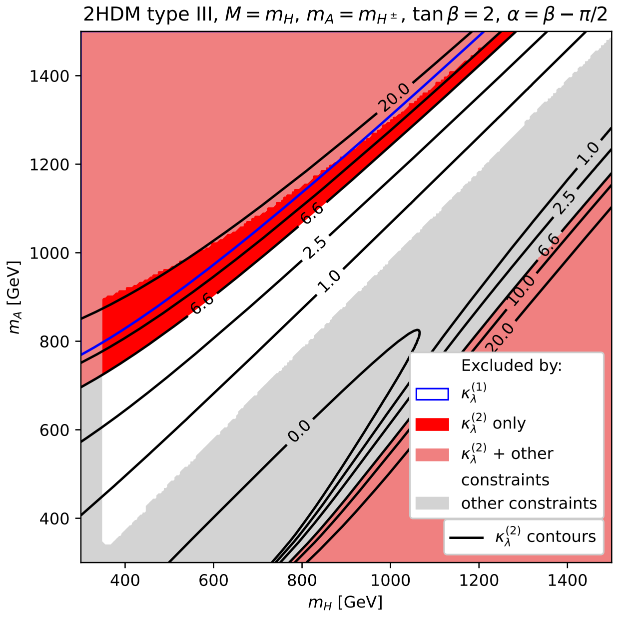
2HDM benchmark plane – results for all types



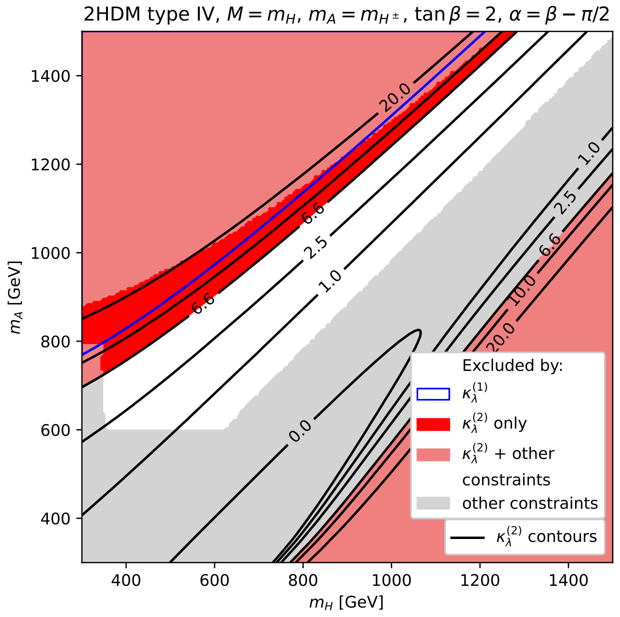
Type-I



Type-II



Type-III (LS)



Type-IV (flipped)

Baryogenesis

- **Observed Baryon Asymmetry of the Universe (BAU)**

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

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

- **Sakharov conditions** [Sakharov '67] for a theory to explain BAU:
  1) Baryon number violation
  2) C and CP violation
  3) Loss of thermal equilibrium

In the SM
→ Sphaleron transitions (break B+L)
→ C violation (SM is chiral), but not enough CP violation
→ No loss of th. eq. → in SM, the EWPT is a crossover

SM phase diagram

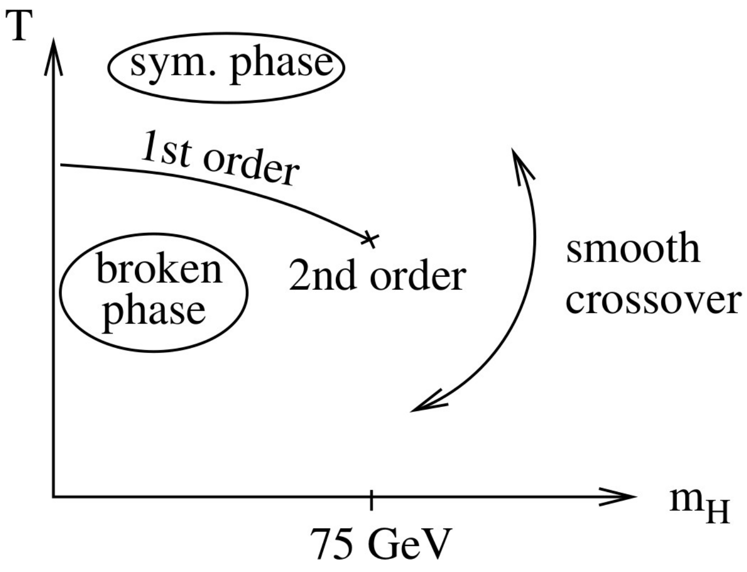


Figure from [Cline '06]

- SM cannot reproduce the BAU → **BSM physics needed!**

Electroweak Baryogenesis

- Many scenarios proposed, including:
  - Grand Unified Theories
  - Leptogenesis
  - **Electroweak Baryogenesis** (EWBG) [Kuzmin, Rubakov, Shaposhnikov, ‘85], [Cohen, Kaplan, Nelson ‘93]

- **Sakharov conditions** in EWBG

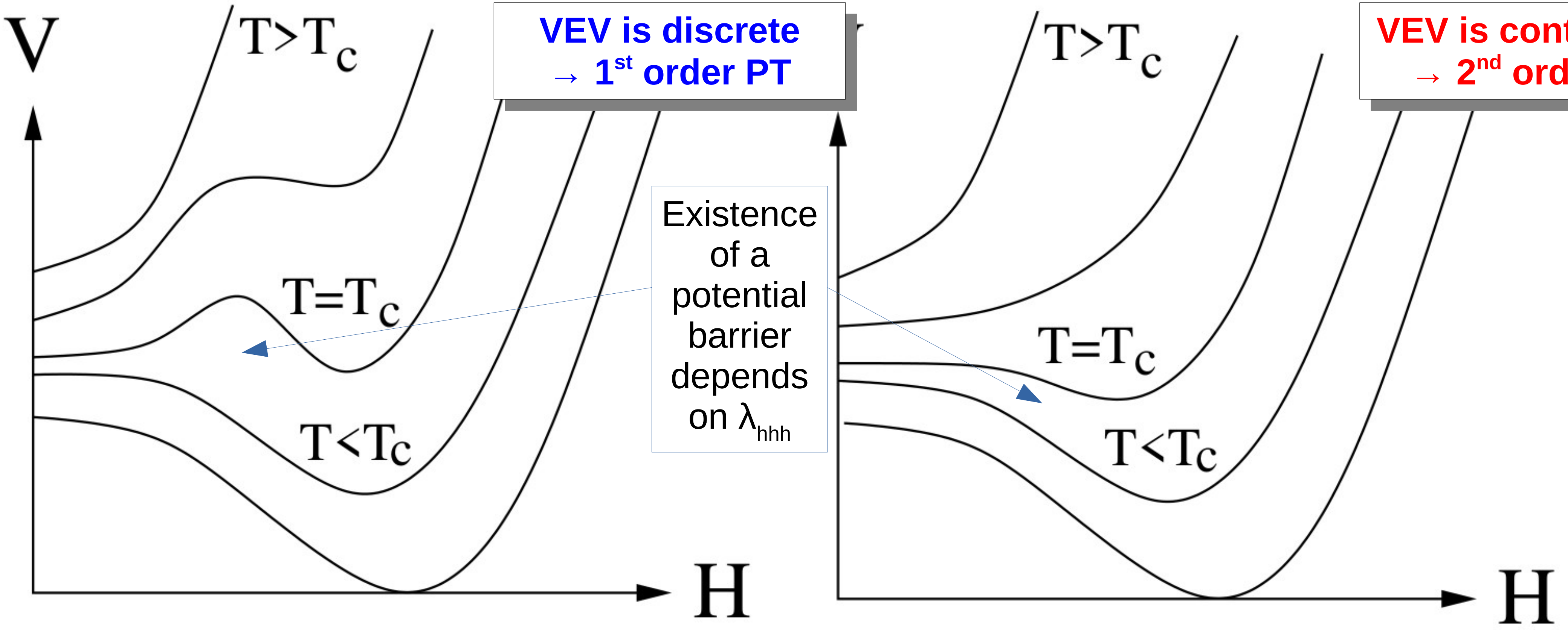
1) Baryon number violation → Sphaleron transitions (break B+L)

2) C and CP violation → C violation + CP violation in extended Higgs sector

3) Loss of thermal equilibrium → Loss of th. eq. via a strong 1st order EWPT

The Higgs potential and the Electroweak Phase Transition

Possible thermal history of the Higgs potential:



VEV is discrete → 1st order PT

VEV is continuous → 2nd order PT

Existence of a potential barrier depends on λ_{hhh}

Figure from [Cline '06]

- **λ_{hhh} determines the nature of the EWPT!**

  ⇒ deviation of λ_{hhh} from its SM prediction typically needed to have a strongly first-order EWPT [Grojean, Servant, Wells '04], [Kanemura, Okada, Senaha '04]

  ⇒ required for **electroweak baryogenesis** scenario

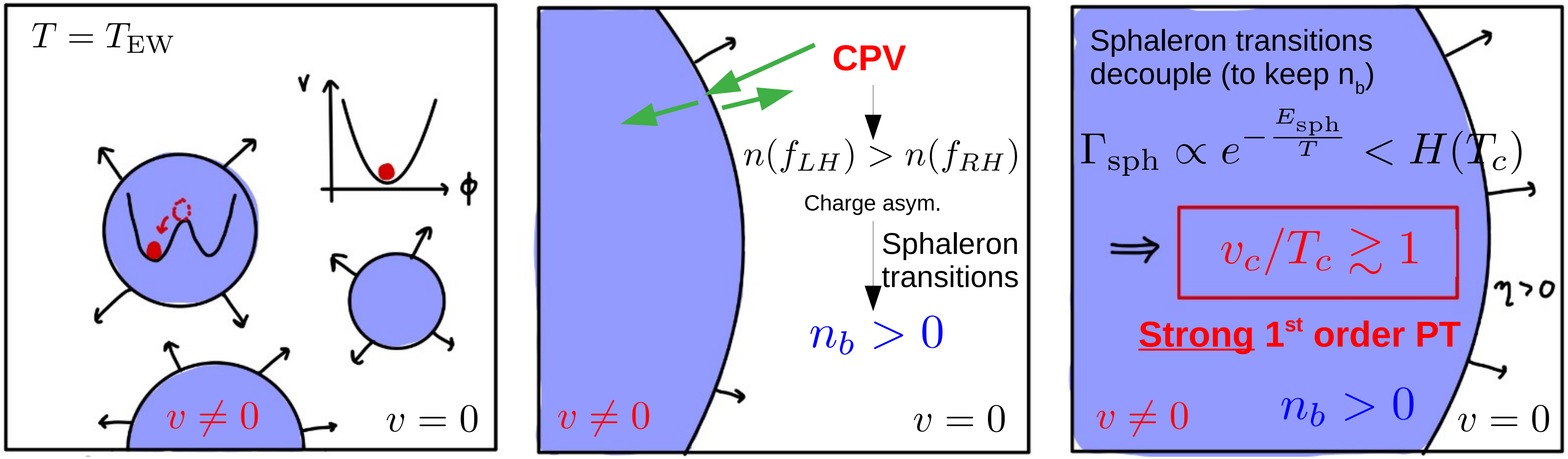
Electroweak Baryogenesis – a brief sketch

- **Sakharov conditions** in EWBG

  1) Baryon number violation → Sphaleron transitions (break B+L)

  2) C and CP violation → C violation + CP violation in extended Higgs sector

  3) Loss of thermal equilibrium → Loss of th. eq. via a strong 1st order EWPT



1) Bubble nucleation *2) Baryon number generation* *3) Baryon number conservation*

Figure adapted from [Biermann '22]

- EWBG only involves phenomena around the EW scale → **testable in the foreseeable future** via $\boldsymbol{\lambda_{hhh}}$, collider searches, gravitational waves or primordial black holes (sourced by 1st order EWPT)