New constraints on extended Higgs sectors from the trilinear Higgs coupling

Based on

arXiv:2202.03453 in collaboration with Henning Bahl and Georg Weiglein,

(as well as arXiv:1903.05417 (PLB), 1911.11507 (EPJC) in collaboration with Shinya Kanemura)

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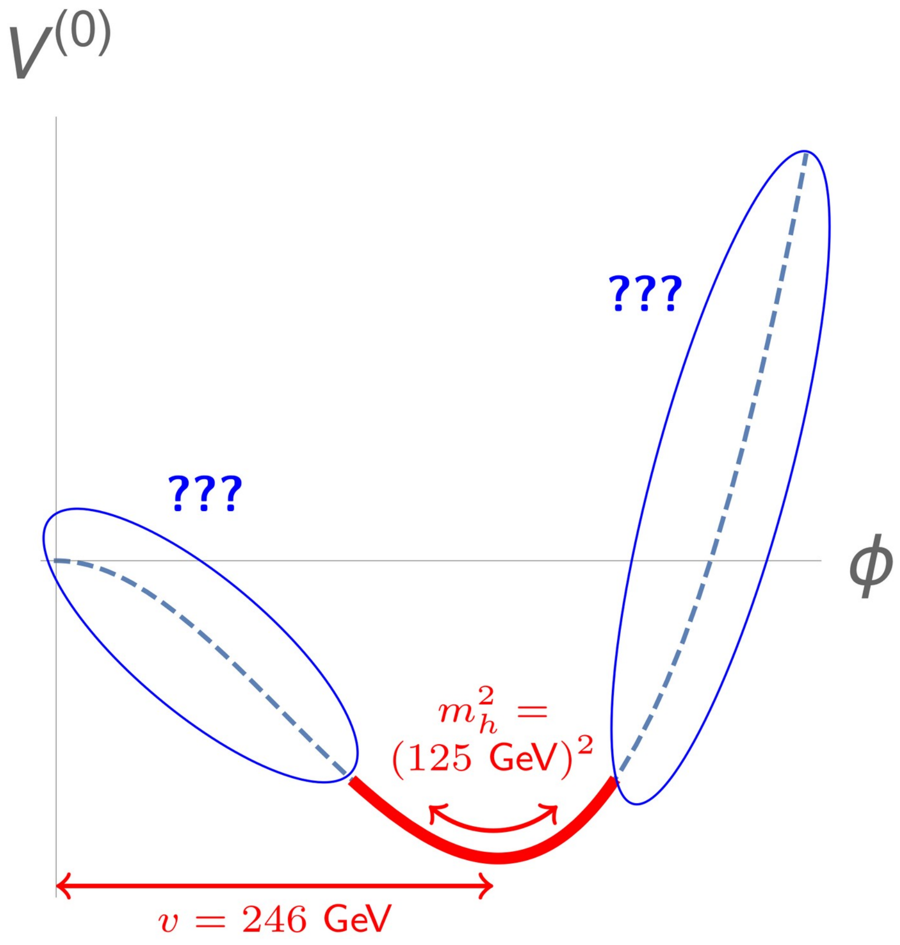
Why study the Higgs trilinear coupling?

- **Probing the Higgs potential:**
  Since the Higgs discovery, the existence of the Higgs potential is confirmed, but at the moment we only know:
  → the location of the EW minimum:
  v = 246 GeV
  → the curvature of the potential around the EW minimum:
  m_h = 125 GeV
  However we still don't know the **shape** of the potential, away from EW minimum → **depends on λ_{hhh}**



- **λ_{hhh} determines the nature of the EWPT**!
  ⇒ O(20%) deviation of λ_{hhh} from its SM prediction needed to have a strongly first-order EWPT → necessary for EWBG [Grojean, Servant, Wells '04], [Kanemura, Okada, Senaha '04]

- ***New in this talk***: **studying λ_{hhh} can also serve to constrain the parameter space of BSM models!**

BSM contributions to λ_{hhh}

The Two-Higgs-Doublet Model

- 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; α: CP-even Higgs mixing angle

- **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 and β (defined by $\tan\beta = v_2/v_1$)

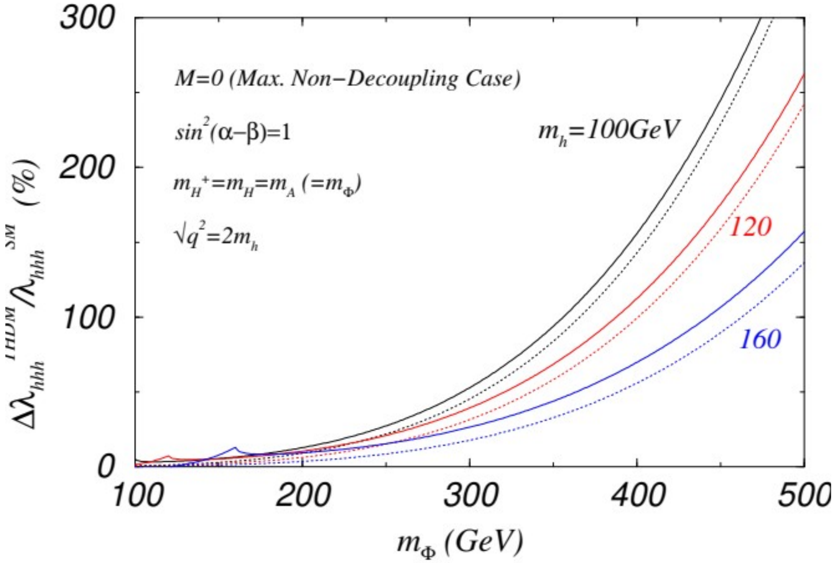
- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,,\quad \Phi \in \{H, A, H^\pm\}$

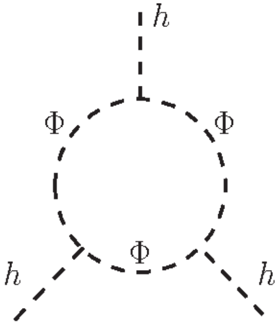
- We take the **alignment limit α=β-π/2** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data!

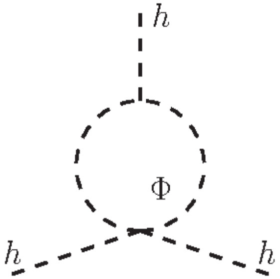
Non-decoupling effects in λ_{hhh}

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

BSM deviation =







- **Deviations of tens/hundreds of % from SM possible,** for **large $g_{h\Phi\Phi}$ or $g_{hh\Phi\Phi}$ couplings**

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

(new class of couplings not present at tree level
→ no issue with perturbativity!)

- **Non-decoupling effects**, now found in various models (2HDM, inert doublet model, singlet extensions, etc.)

Non-decoupling effects in λ_{hhh}

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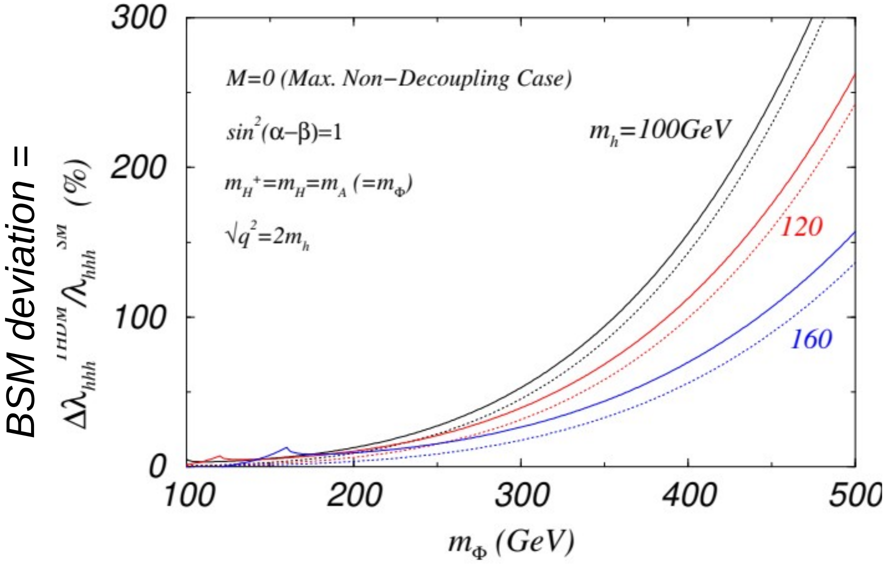

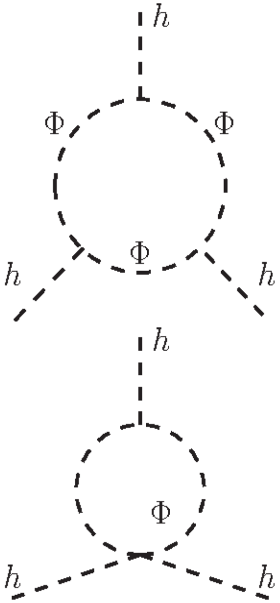

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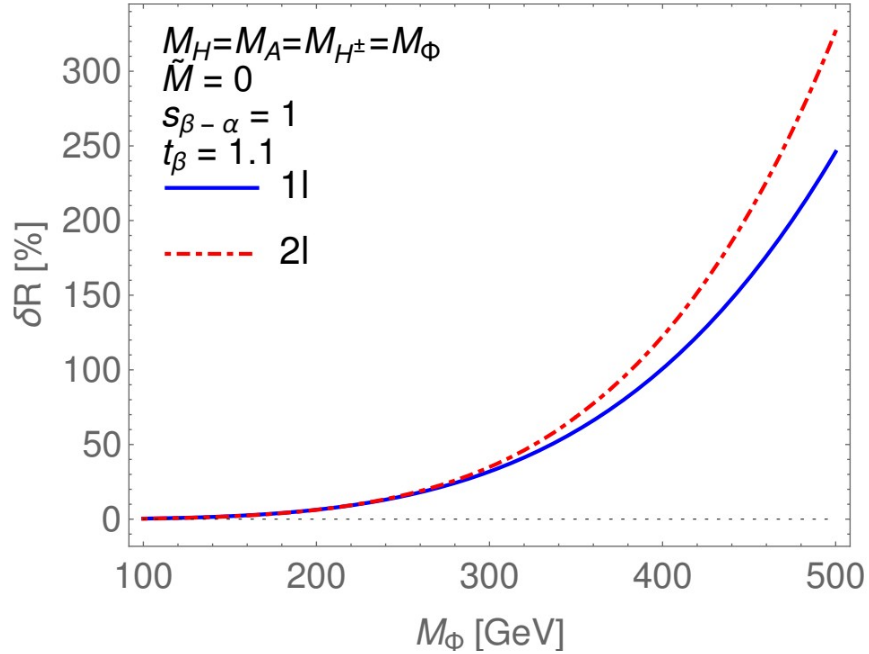
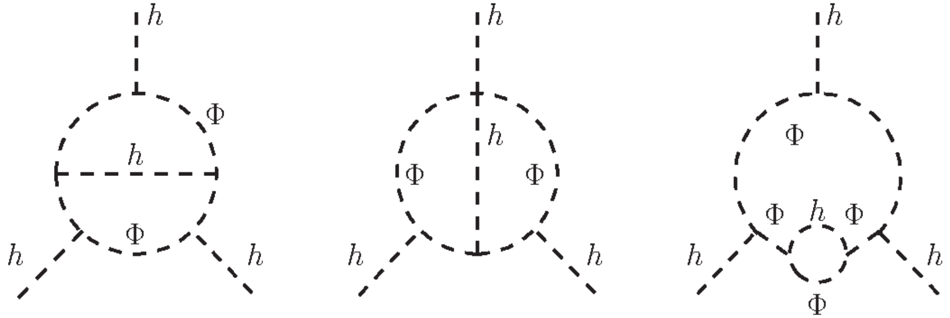
- **Non-decoupling effects**, now found in various models (2HDM, inert doublet model, singlet extensions, etc.)

- Non-decoupling 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





Constraining the 2HDM with λ_{hhh}

i. *Can we apply the limits on κ_λ, extracted from experimental searches for double-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?*

Can we apply hh-production results for the aligned 2HDM?

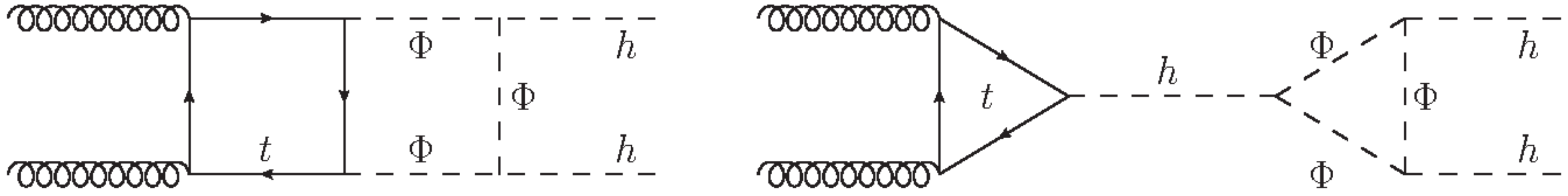
- Current strongest limit on κ_λ are from ATLAS double-Higgs searches **$-1.0 < \kappa_\lambda < 6.6$** [ATLAS-CONF-2021-052]

  [recall $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$]

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

    → this **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



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

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

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

  (Note: BSM resonant Higgs-pair production cross section also suppressed at LO, thanks to alignment)

A parameter scan in the aligned 2HDM

[Bahl, JB, Weiglein `2202.03453`]

- 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 $\boldsymbol{\lambda_{hhh}}$**
  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
  - SM-like Higgs measurements with `HiggsSignals`
  - Direct searches for BSM scalars with `HiggsBounds`
  - b-physics constraints, using results from [Gfitter group 1803.01853]

theoretical
  - Vacuum stability
  - Boundedness-from-below of the potential
  - EW precision observables, computed at two loops with `THDM_EWPOS` [Hessenberger, Hollik '16]
  - NLO perturbative unitarity, using results from [Grinstein et al. `1512.04567`], [Cacchio et al. `1609.01290`]

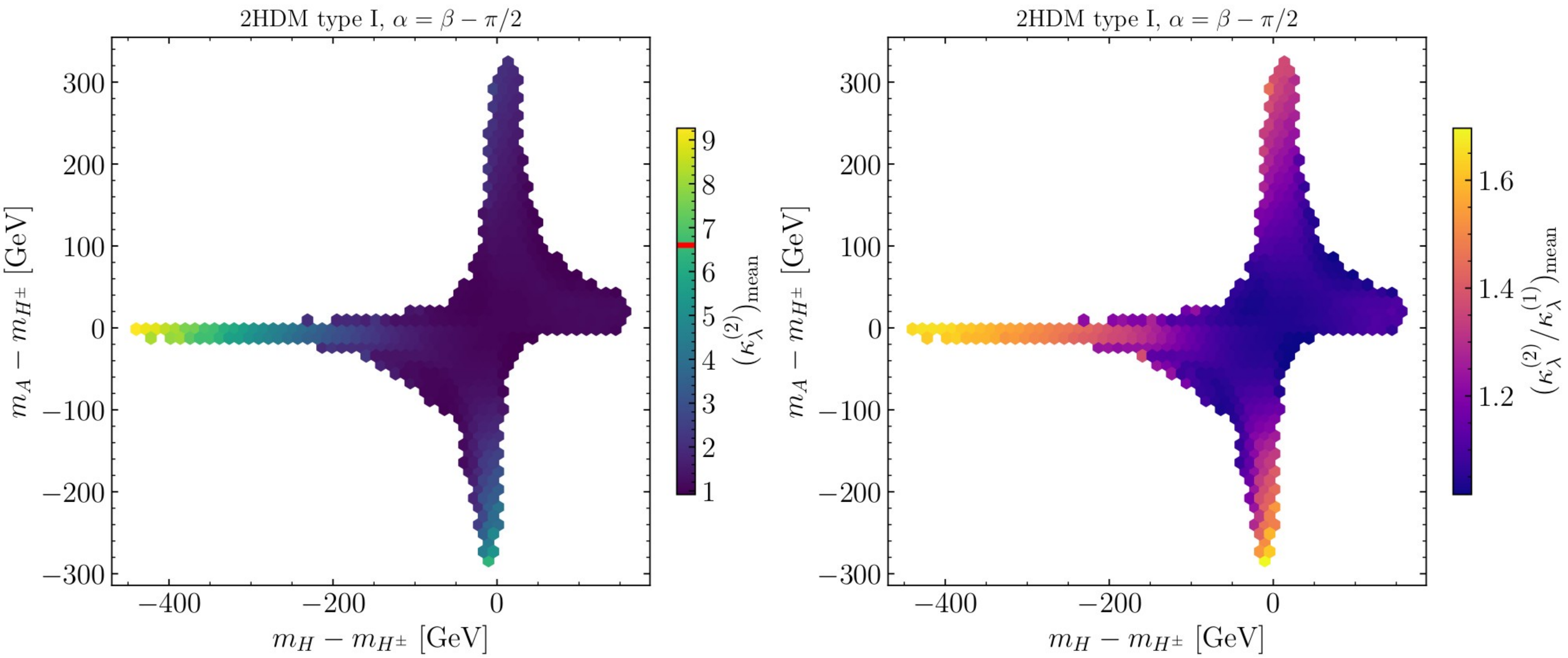
Checked with `ScannerS`

- For points passing these constraints, we **compute $\boldsymbol{\kappa_\lambda}$ at 1L and 2L**, using results from [JB, Kanemura '19]

Parameter scan results

[Bahl, JB, Weiglein 2202.03453]

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

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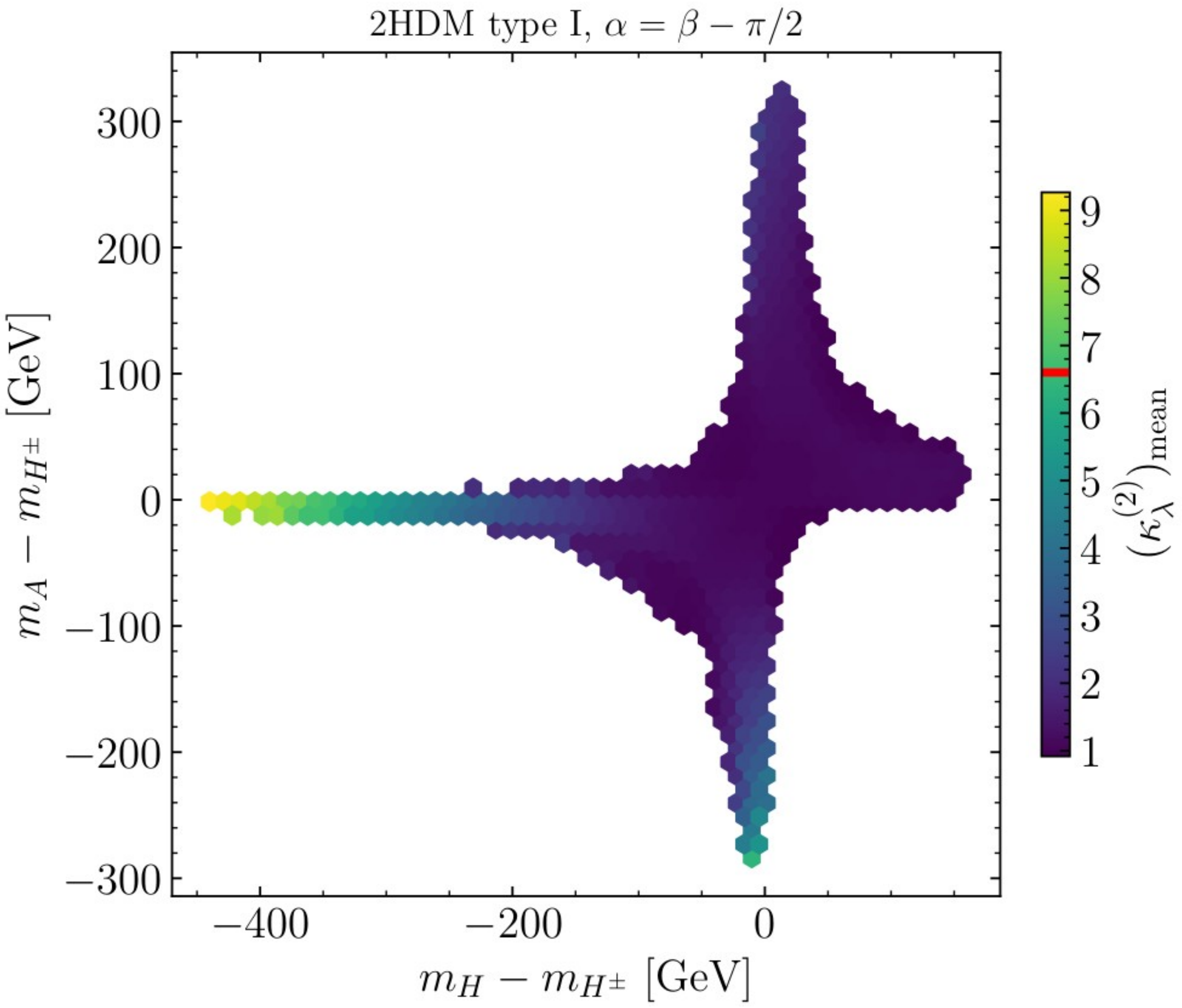

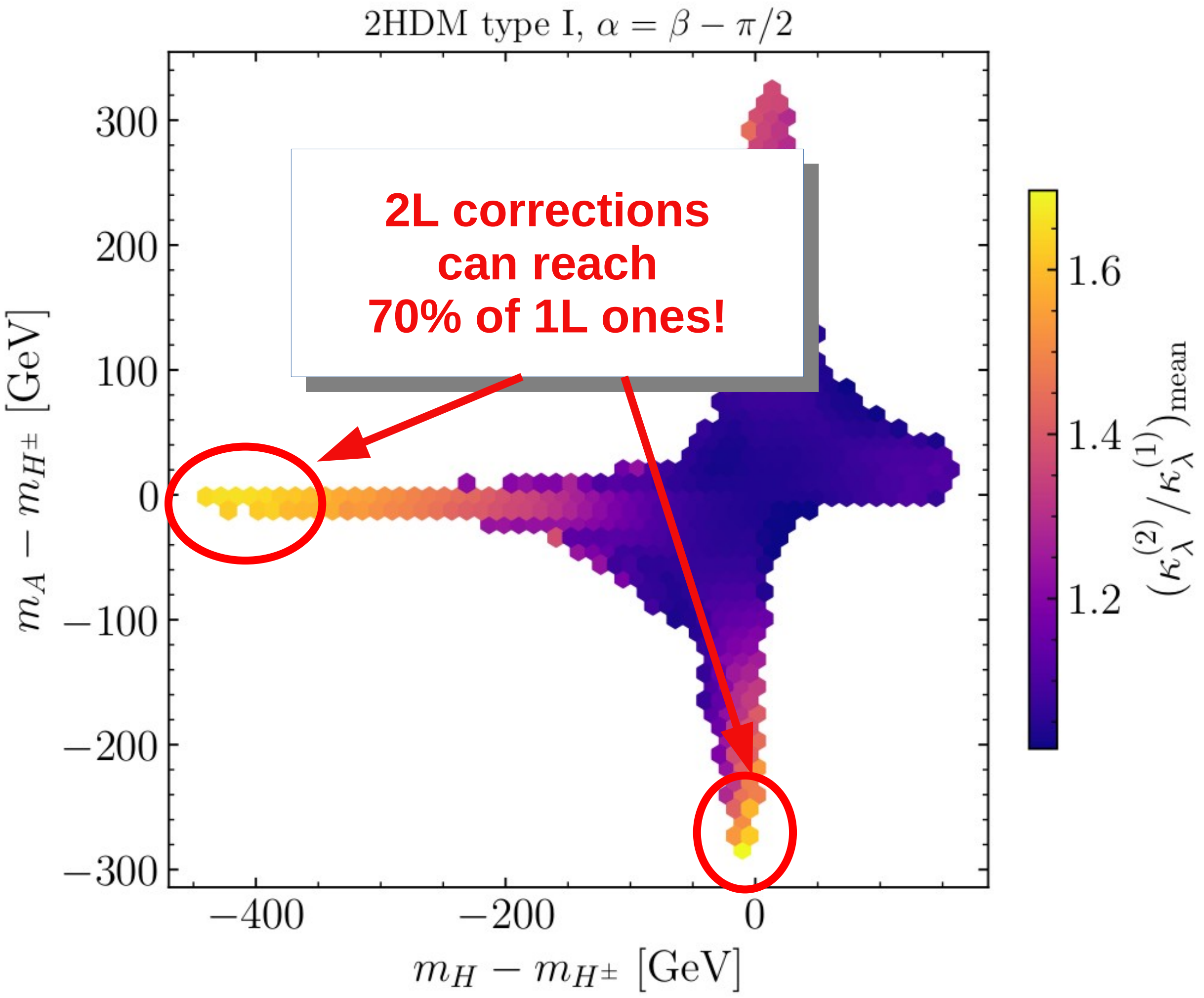

- 2L corrections can become **significant** (up to ~70% of 1L)

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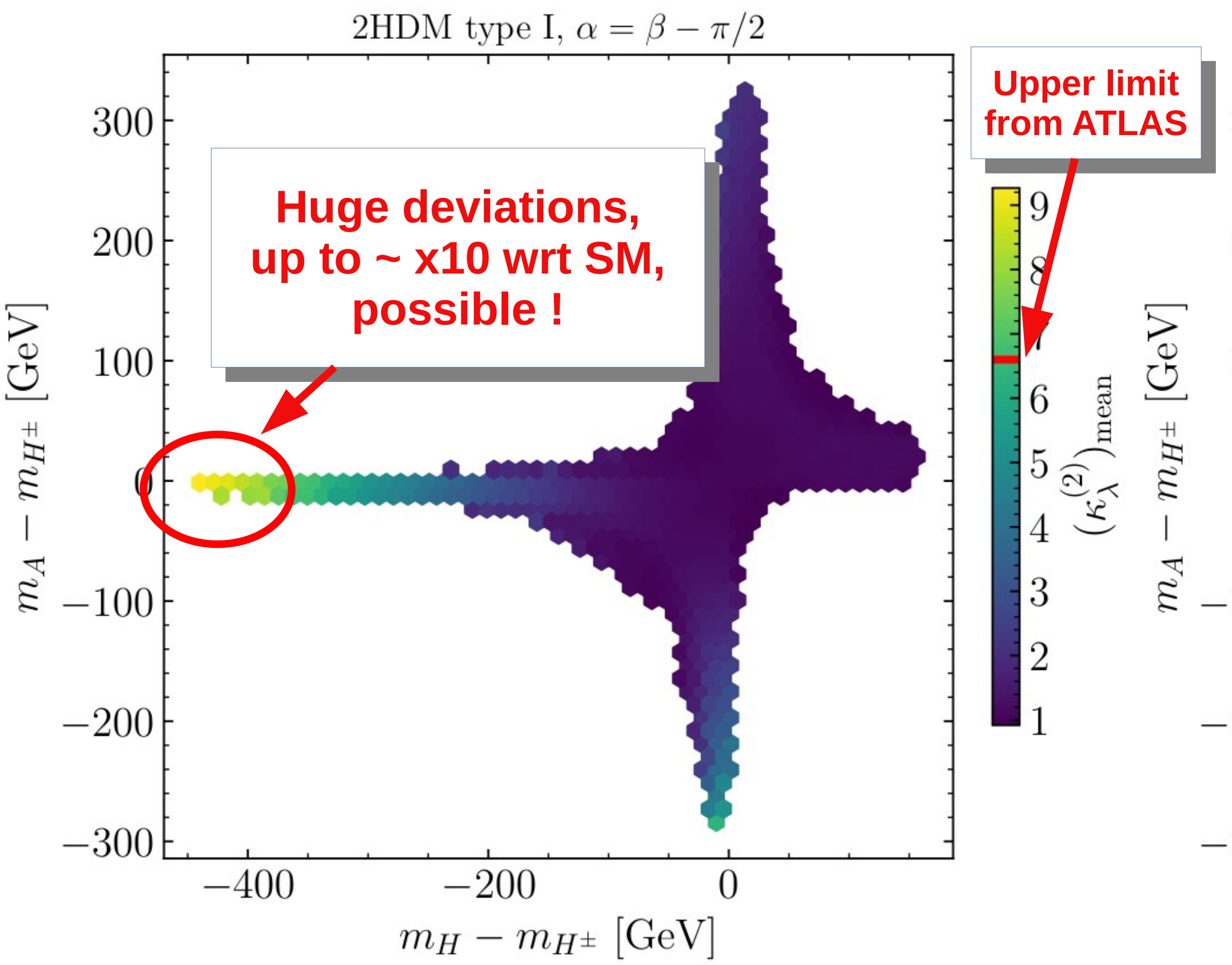
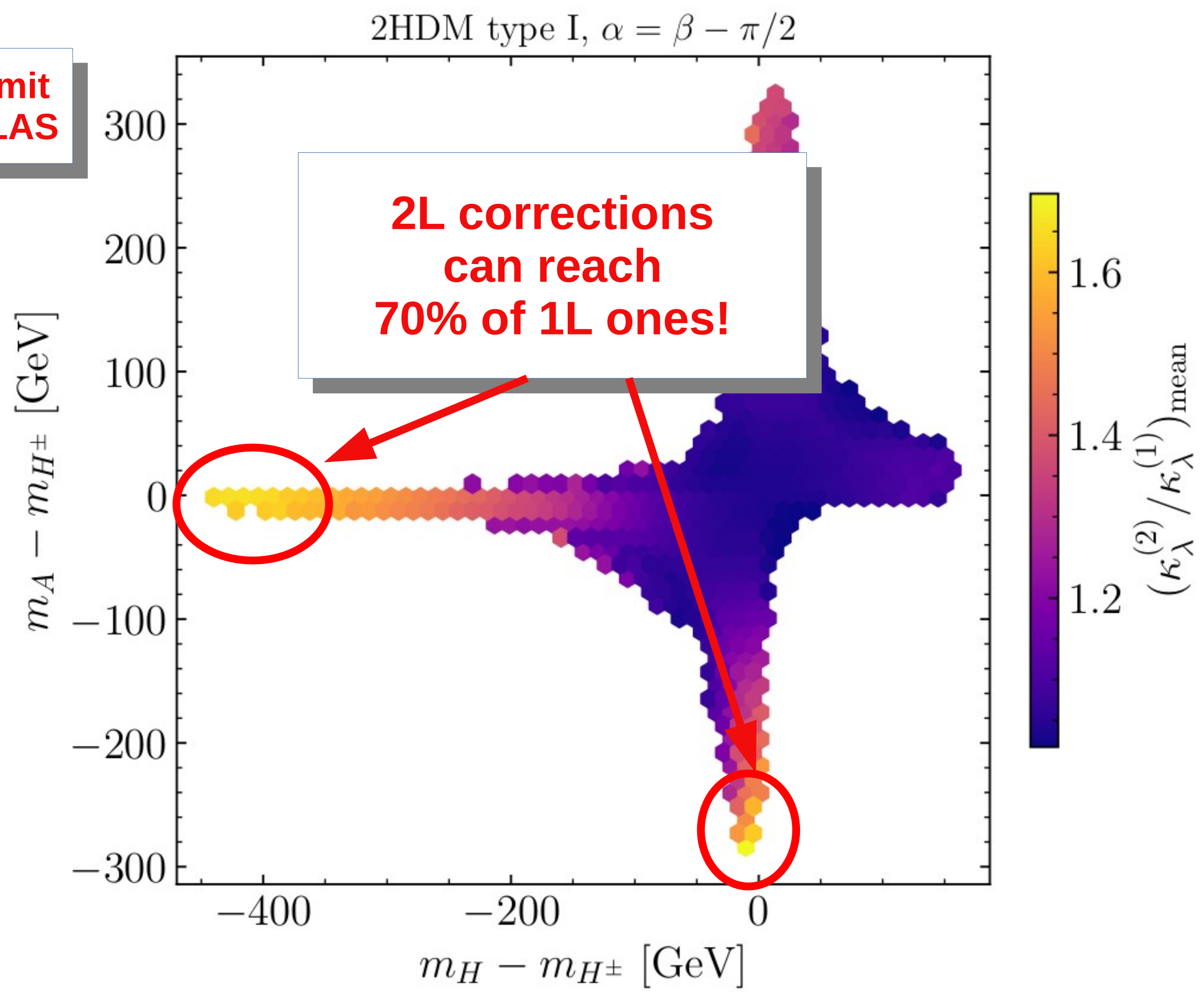




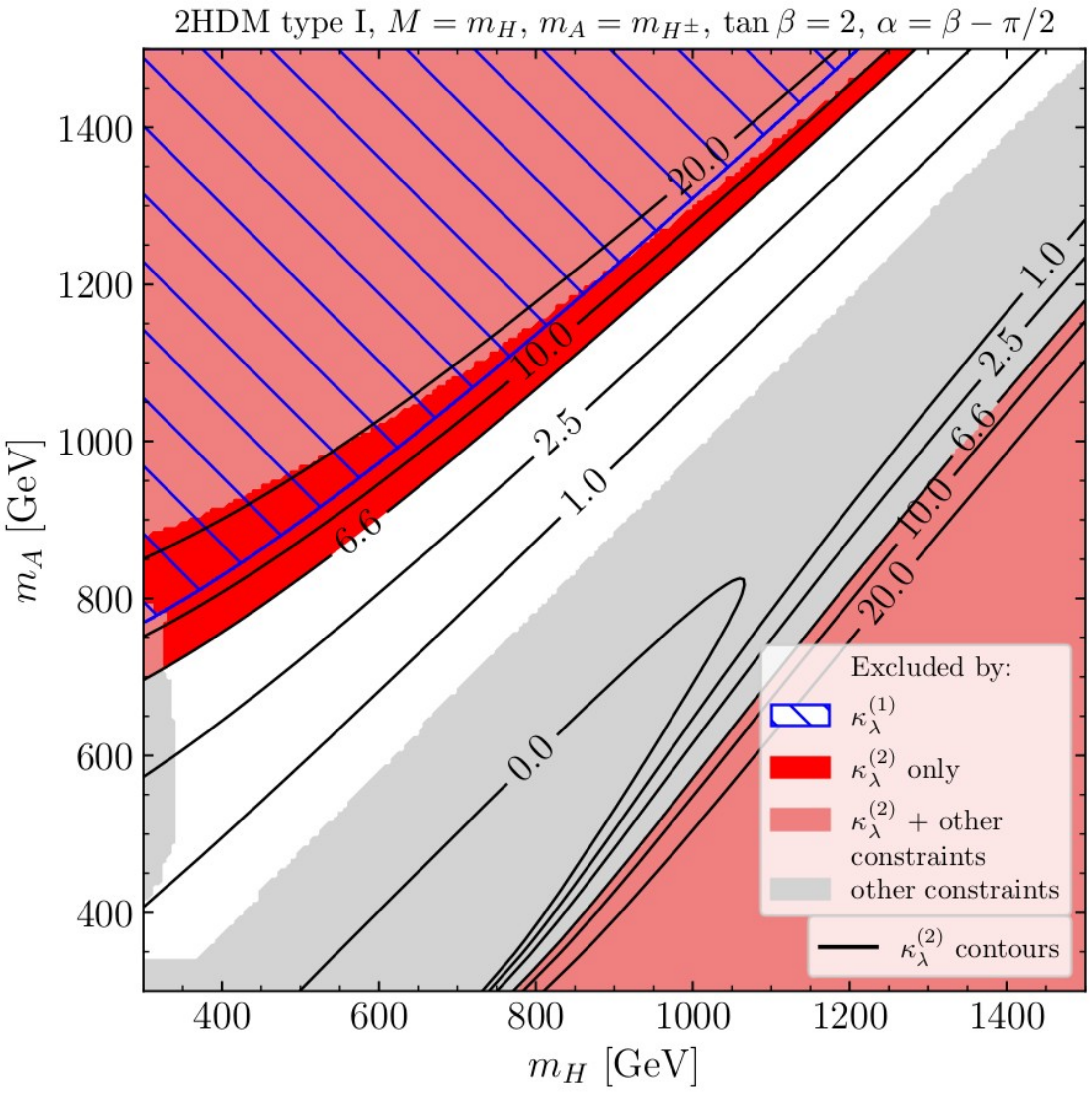
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark scenario in the aligned 2HDM

[Bahl, JB, Weiglein 2202.03453]

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 Higgs physics, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.6$ [in region where $\kappa_\lambda^{(2)} < -1.0$ the calculation isn't reliable]
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.6$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.6$ → impact of including 2L corrections is significant!

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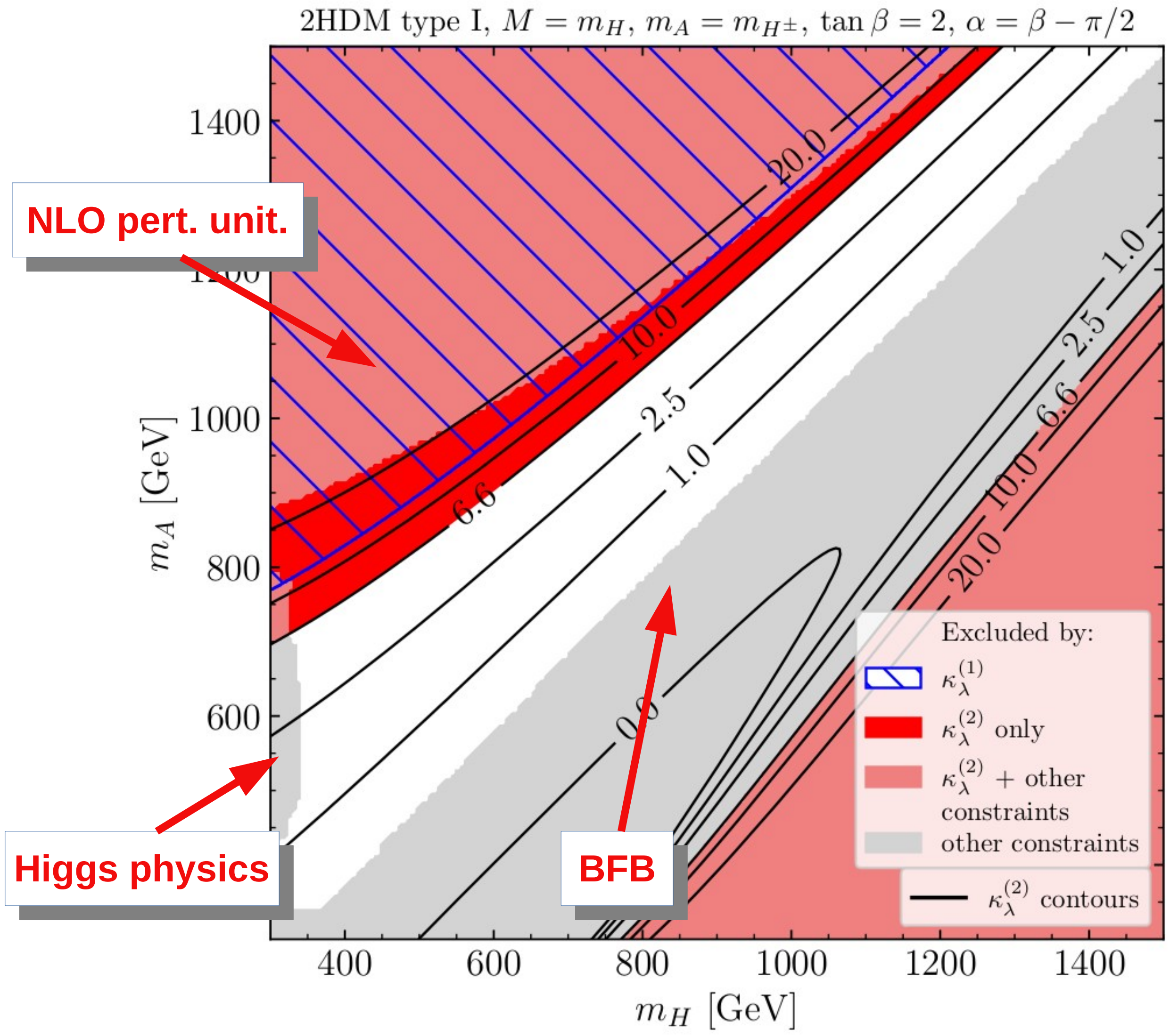

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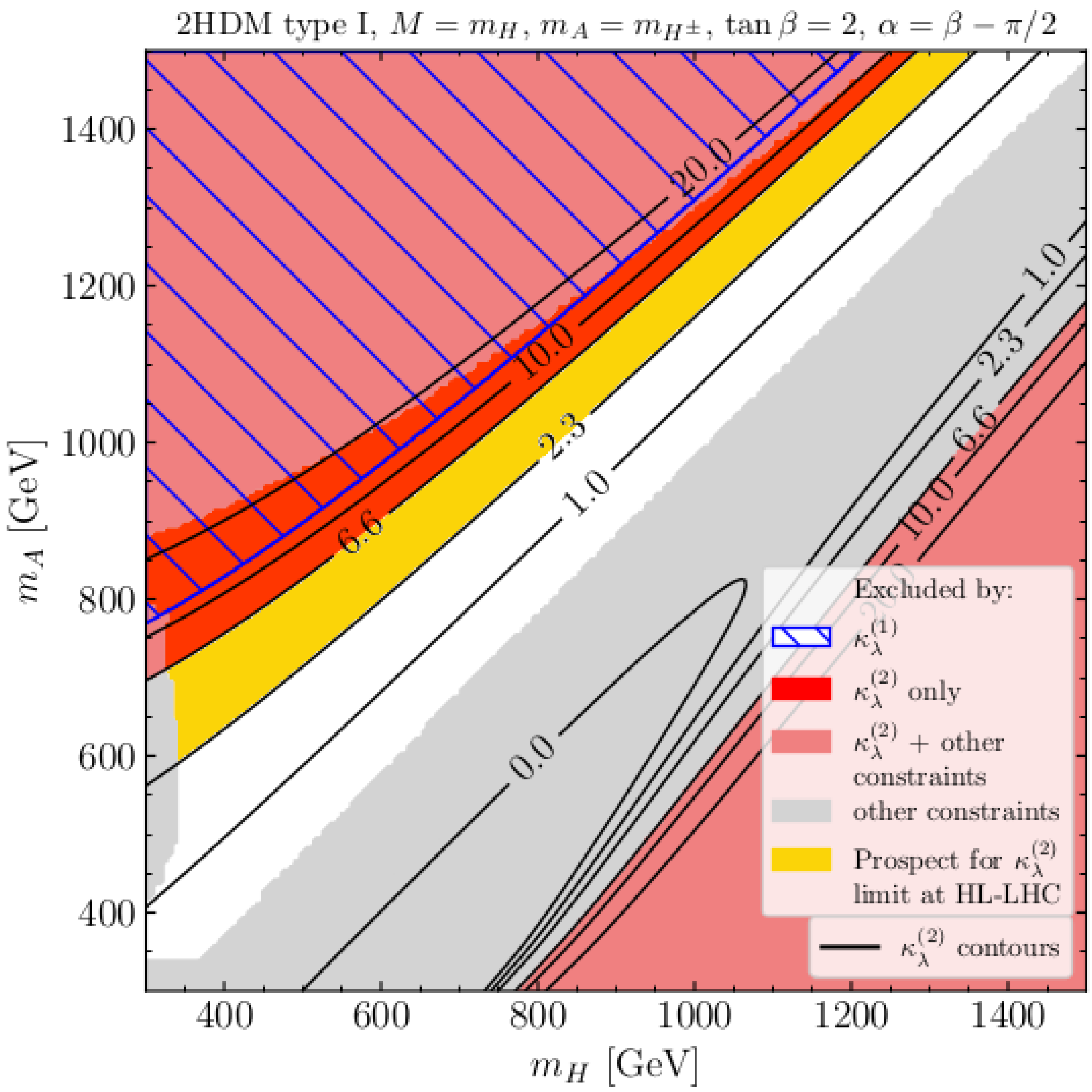
A benchmark scenario in the aligned 2HDM – future prospects

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

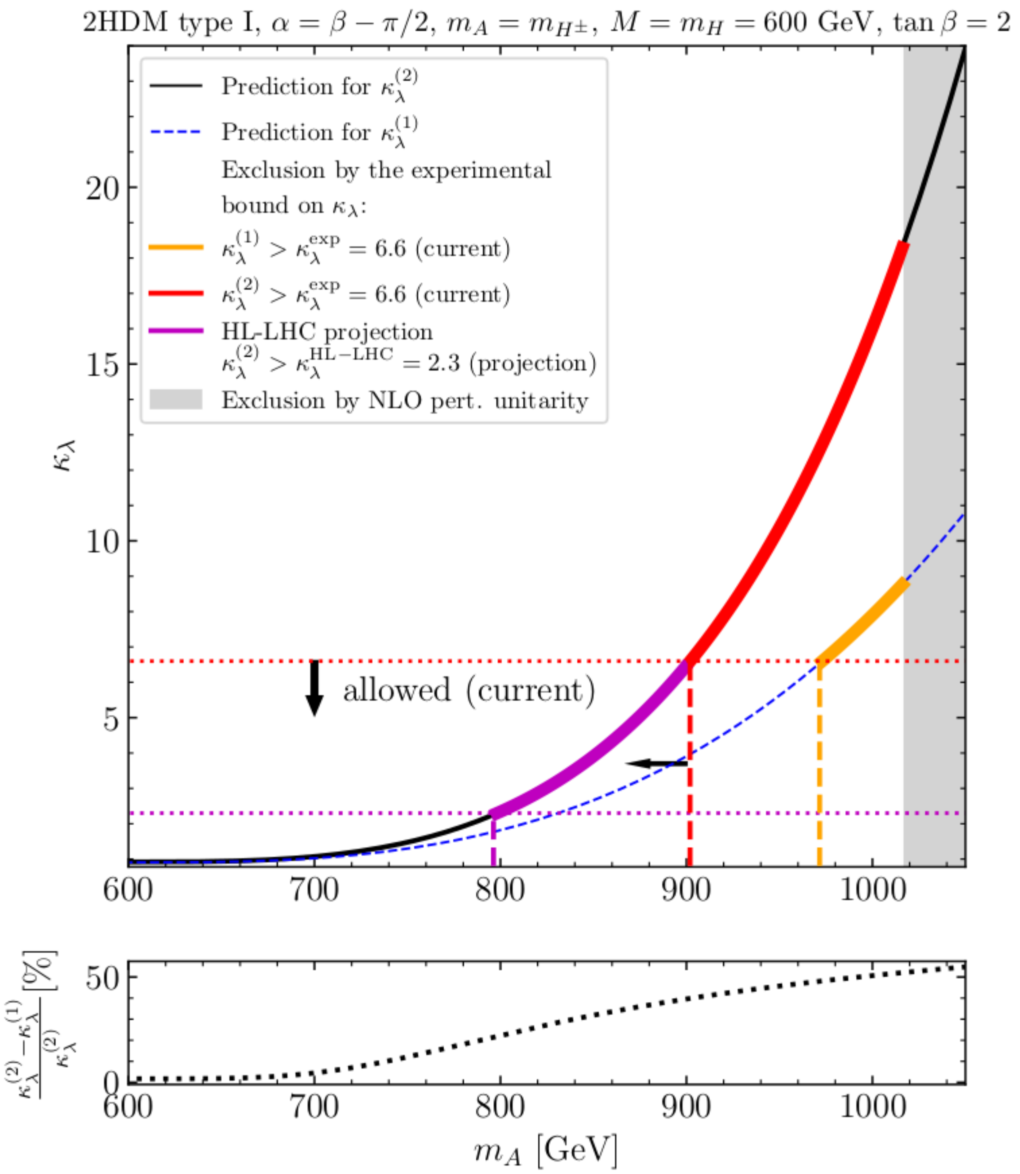


- ***Golden area:*** additional exclusion if the limit on κ_λ becomes $\kappa_\lambda^{(2)} < 2.3$ (achievable at HL-LHC)

- 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 $m_A=m_{H\pm}$



- Illustrates the significantly improved reach of the experimental limit when including **2L corrections** in calculation of κ_λ

Summary

- λ_{hhh} plays a crucial role to understand the shape of the Higgs potential, and probe indirectly 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 non-decoupling 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! Inclusion of 2L corrections [JB, Kanemura '19] has significant impact.

- In this talk, 2HDM taken as an *example*, but similar results are expected for a wider range of BSM models with extended scalar sectors
  → further motivates **automating calculations of λ_{hhh}** → see **Martin Gabelmann's talk!**

Thank you for your attention!

Contact

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