Trilinear Higgs coupling: higher-order corrections and new constraints on BSM parameter spaces

Based on

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

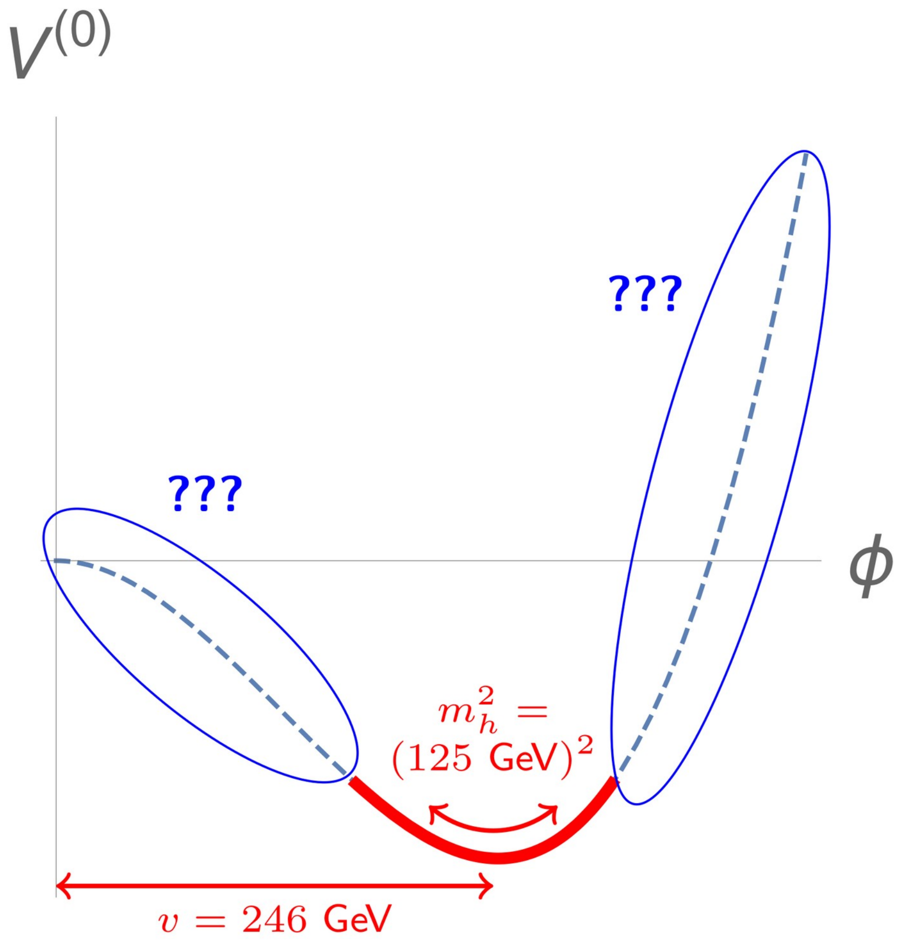
(as well as arXiv:1903.05417 (PLB) and 1911.11507 (EPJC) in collaboration with Shinya Kanemura)

Johannes Braathen

Workshop on Automatic Phenomenology, IHP, Paris, France | June 7, 2022

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!**

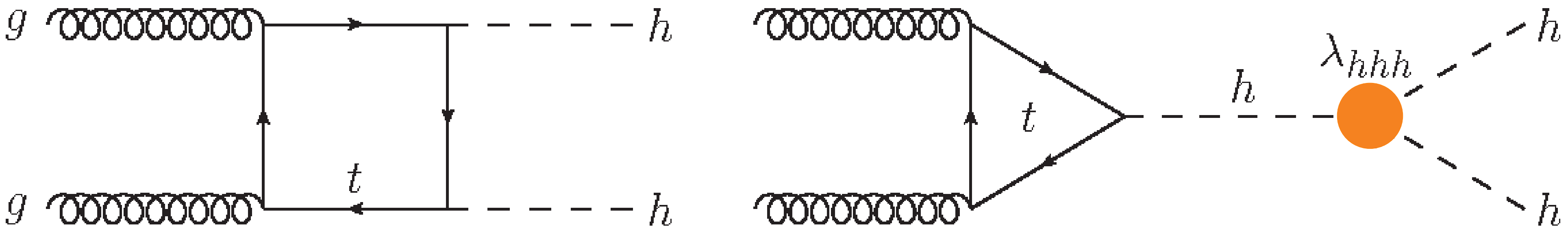
Outline of the talk

- Why study the Higgs trilinear coupling? ✓
- Constraining λ_{hhh} with experimental searches
- Computing λ_{hhh} in BSM models: an aligned 2HDM as a concrete example
- Using λ_{hhh} to constrain the parameter space of BSM models
- Conclusions

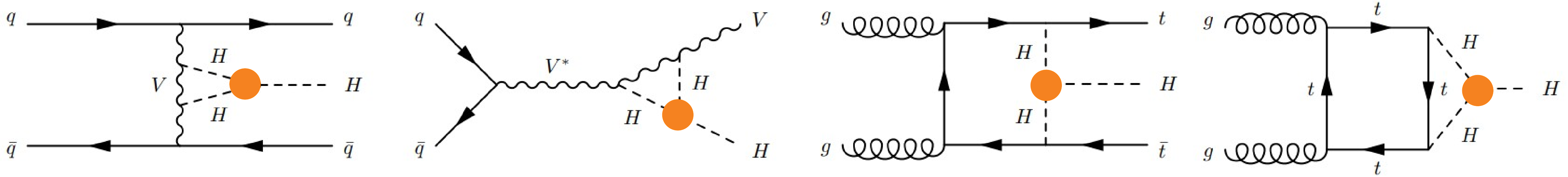
Constraining λ_{hhh}

Current methods to constrain λ_{hhh}

- **Double-Higgs production** → λ_{hhh} enters at <u>LO</u>

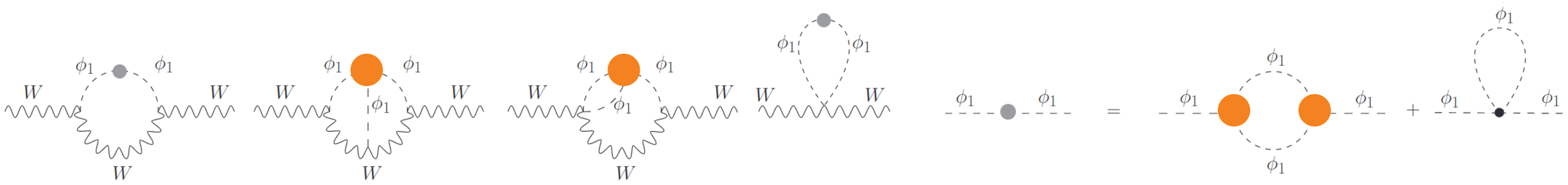


- **Single-Higgs production** → λ_{hhh} enters at <u>NLO</u>



[ATLAS-CONF-2019-049]

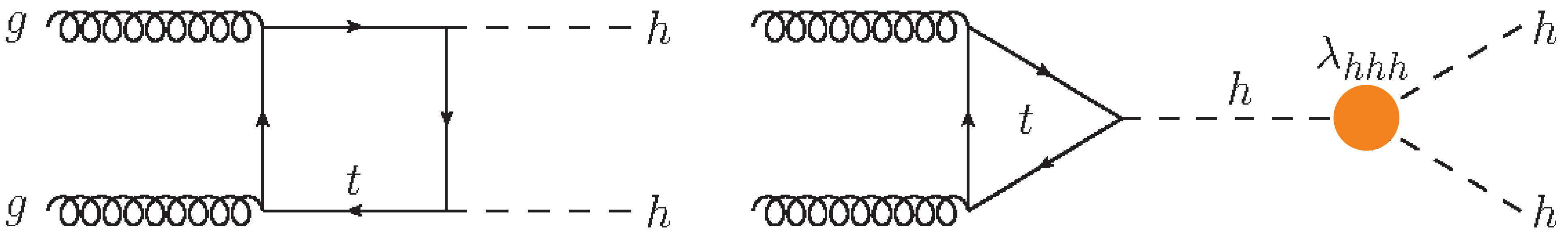
- **Electroweak Precision Observables** (EWPOs) → λ_{hhh} enters at <u>NNLO</u>



[Degrassi, Fedele, Giardino ‘17]

Accessing λ_{hhh} via double-Higgs production

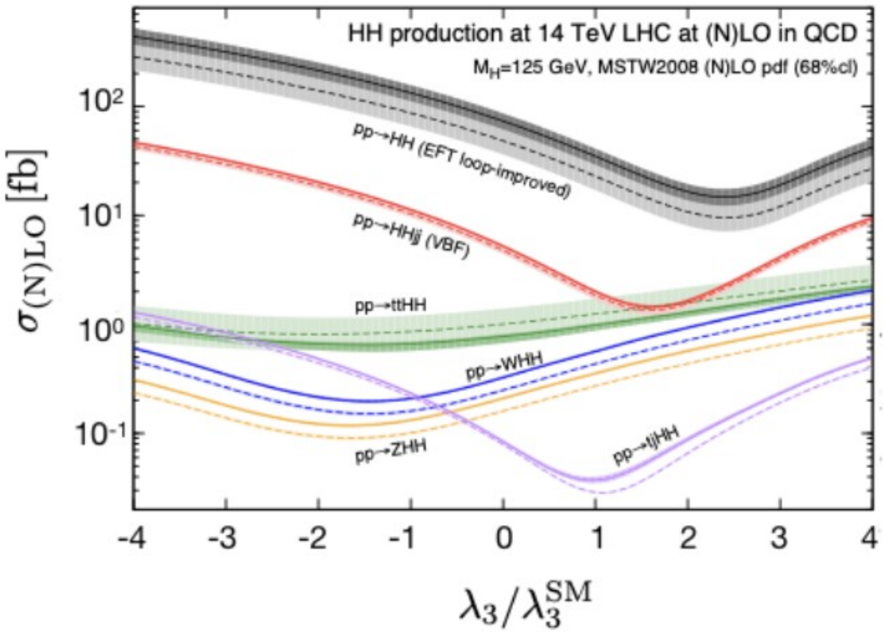
- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



- Box and triangle diagrams **interfere destructively**
  → small prediction in SM
  → BSM deviation in λ_{hhh} can **significantly alter hh-production!**

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

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



[Frederix et al., '14]

Accessing λ_{hhh} via double-Higgs production

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**

Recent results from ATLAS hh-searches [ATLAS-CONF-2021-052]
yield the limits:

-1.0 < κ_λ < 6.6 at 95% C.L.

→ factor ~2 improvement compared to
previously best ATLAS limits (from single-h prod.)
-3.2 < κ_λ < 11.9 at 95% C.L. [ATLAS-PHYS-PUB-2019-009]

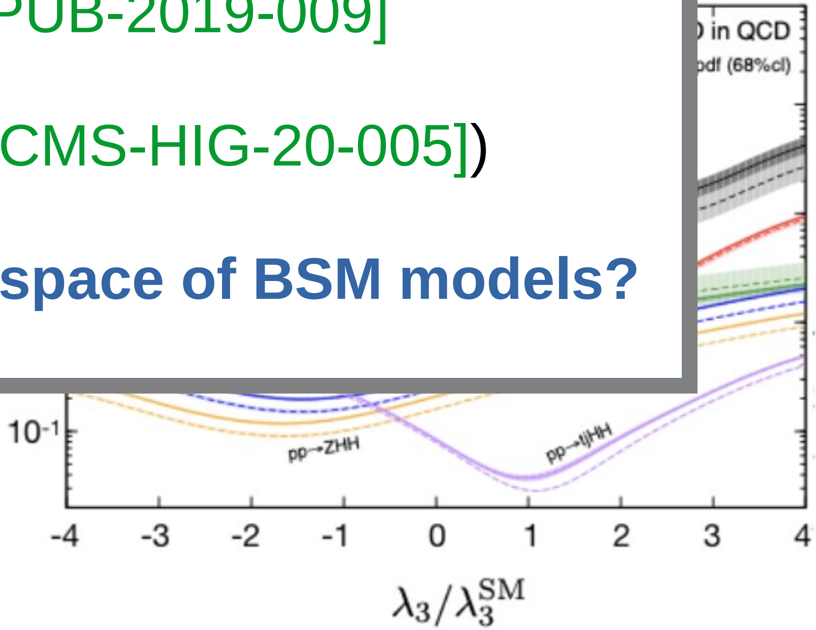
(CMS recently gave **-2.3 < κ_λ < 9.4** at 95% C.L. [CMS-HIG-20-005])

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

- Box
  → sr
  → B
  hh-p

- Uppe
  $\kappa_\lambda \equiv \lambda$

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



[Frederix et al., '14]

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

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

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

- **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 $\tan\beta = v_2/v_1$)

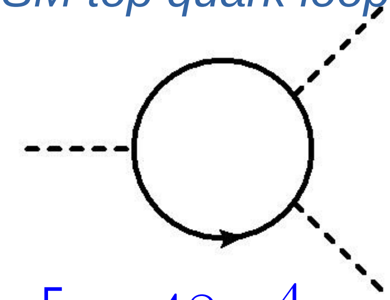
- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,,\quad \Phi \in \{H, A, H^\pm\}$

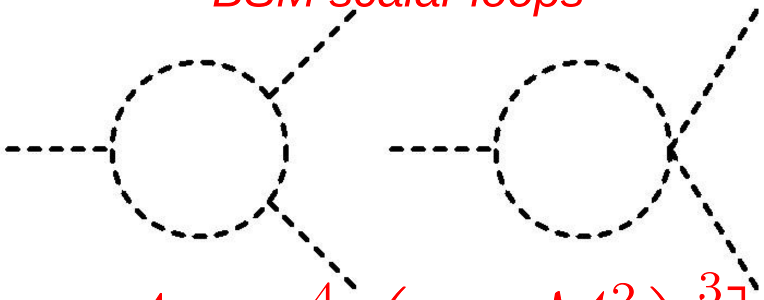
- We take the **alignment limit α=β-π/2** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data!

One-loop non-decoupling 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: $m_\Phi^2 = \mathcal{M}^2 + \tilde{\lambda}_\Phi v^2$

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

→ **Huge BSM effects possible!**

One-loop non-decoupling effects

- Leading one-loop c

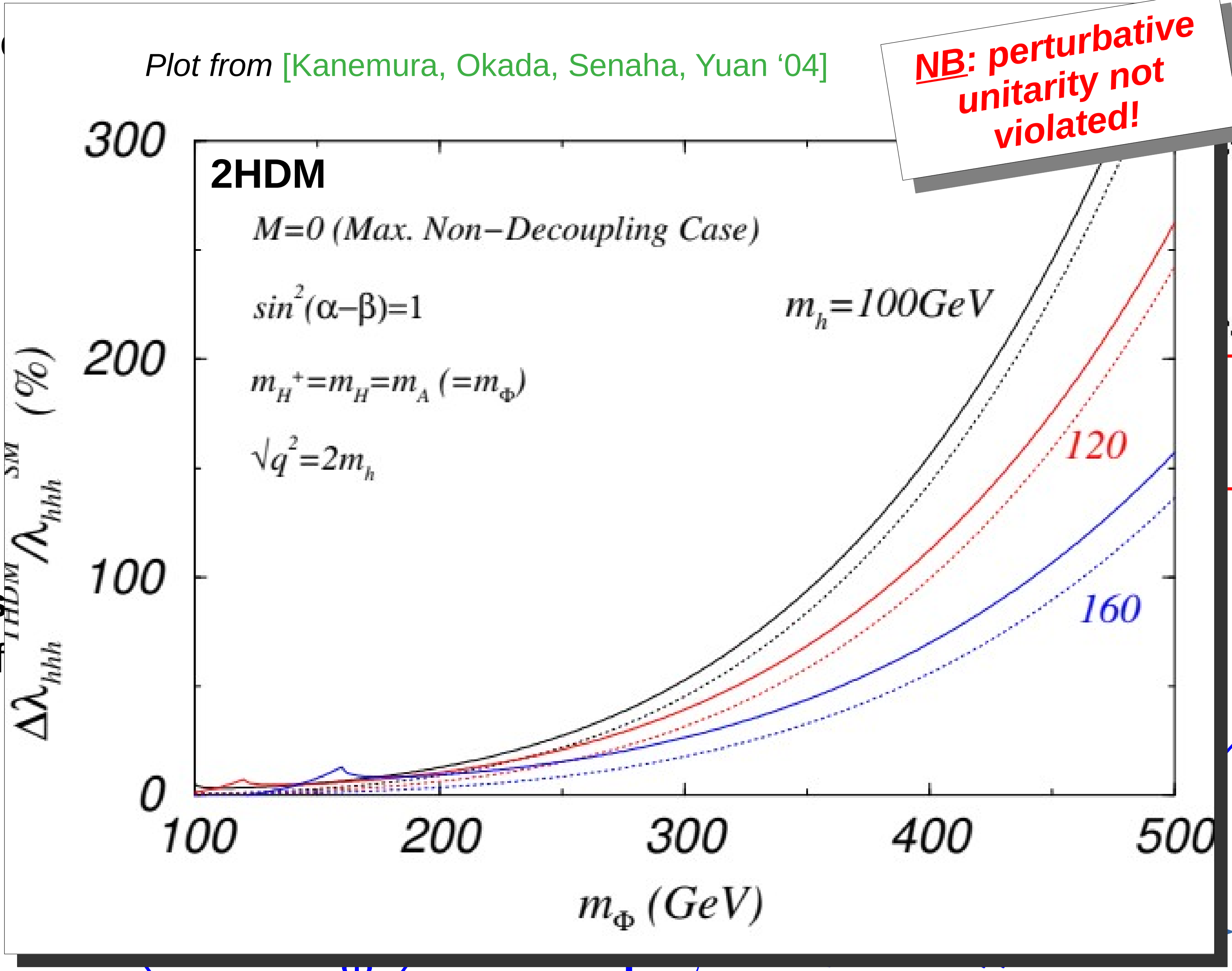
$\delta^{(1)}\lambda_{hhh} \supset$

$\mathcal{M}$: **BSM mass**

n_Φ : # of d.o.f of

- Size of new effects

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



***NB*: perturbative unitarity not violated!**

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

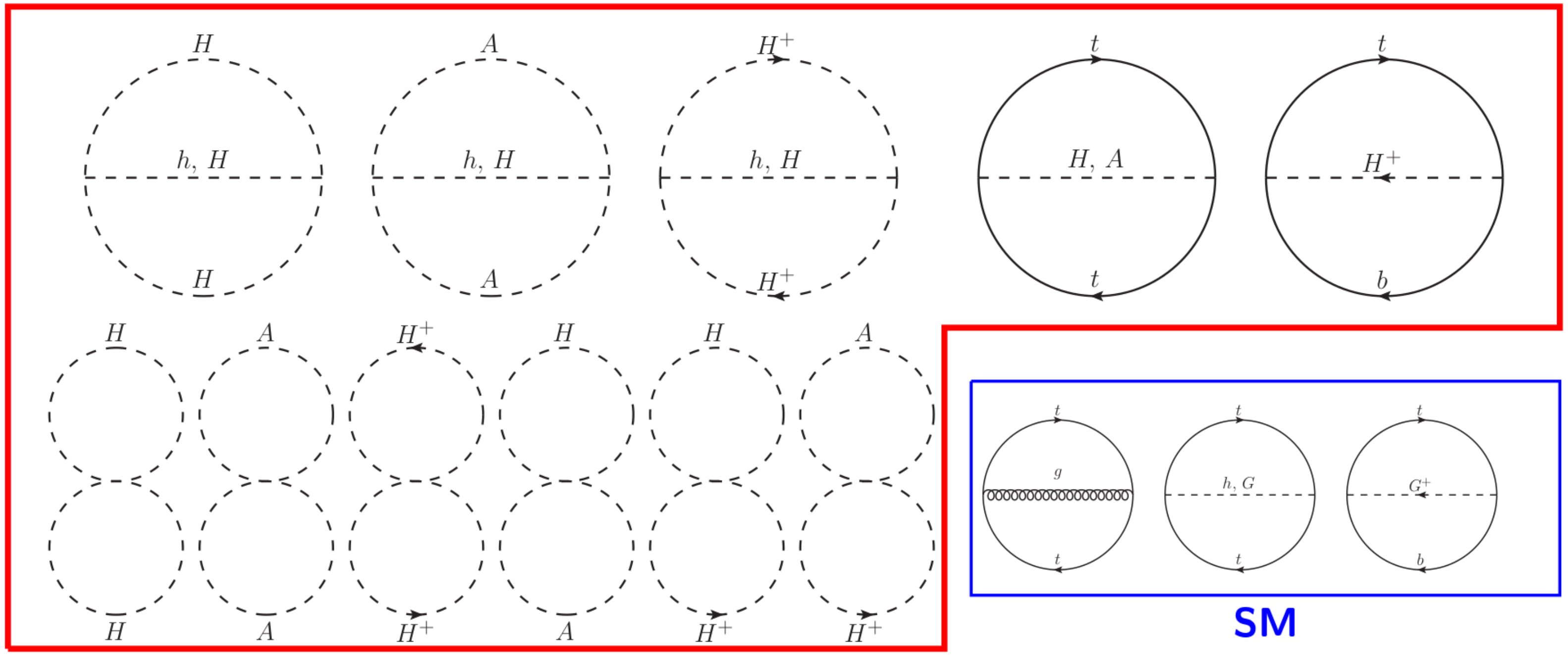
Huge BSM effects possible!

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**
  - **Aligned scenarios** → no mixing + compatible with experimental results
  - **Neglect masses of light states** (SM-like Higgs, light fermions, ...)

2HDM



SM

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  - $V^{(2)}$: 1PI vacuum bubbles
  - *Dominant BSM contributions to $V^{(2)}$* = diagrams involving **heavy BSM scalars and top quark**
  - *Aligned scenarios + neglect light masses*

- **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

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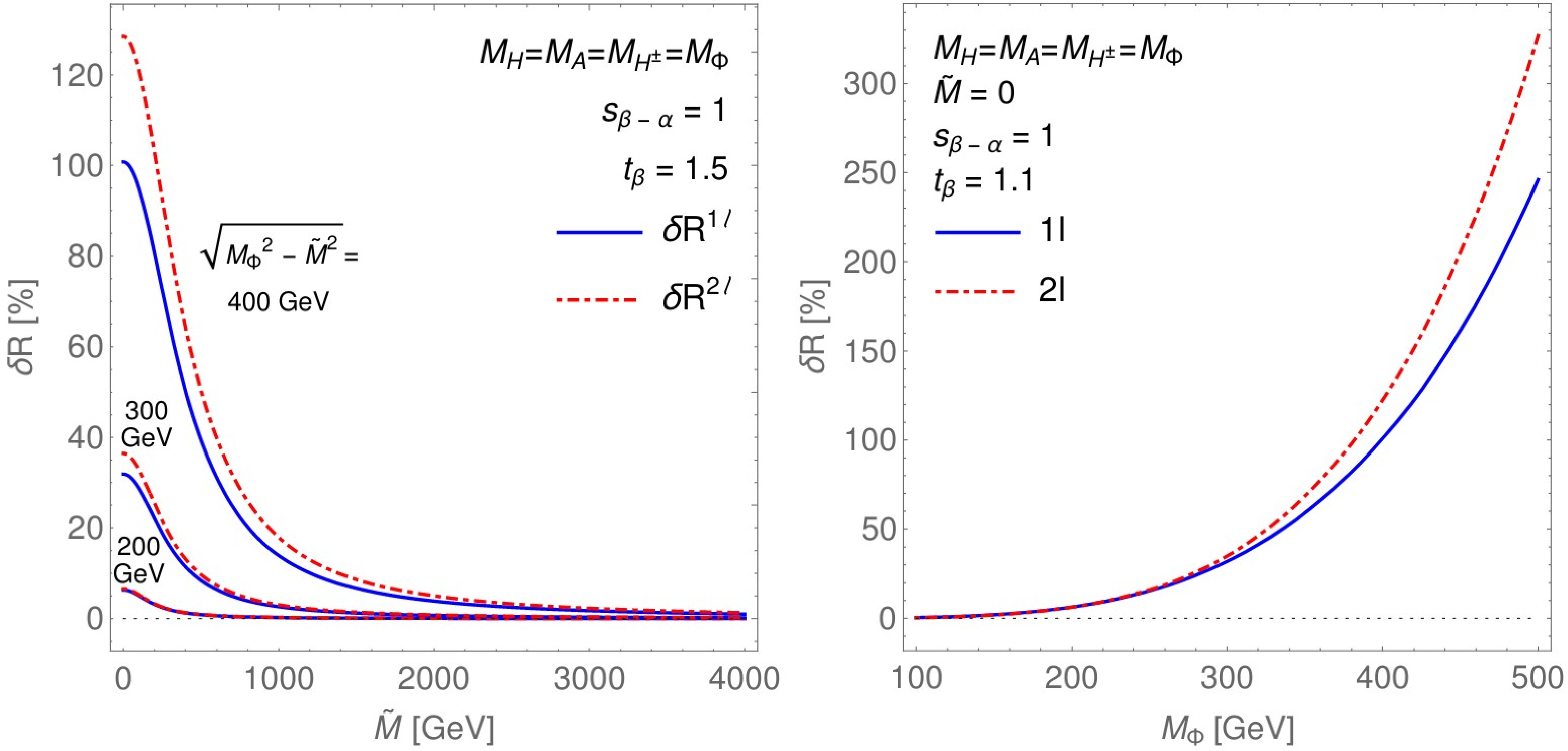
- **Step 2**: ($\overline{\rm MS}$ result too)

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

- **Step 3**: conversion from $\overline{\rm MS}$ to OS scheme
  - Express result in terms of **pole masses**: M_t, M_h, M_Φ (Φ=H,A,H$^\pm$); OS Higgs VEV $v_{\rm phys} = \frac{1}{\sqrt{\sqrt{2}G_F}}$
  - Include **finite WFR**: $\hat{\lambda}_{hhh} = (Z_h^{\rm OS}/Z_h^{\overline{\rm MS}})^{3/2}\lambda_{hhh}$
  - 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

[JB, Kanemura ‘19]



Constraining the 2HDM with λ_{hhh}

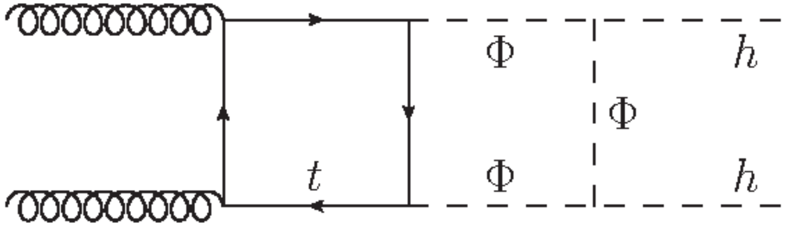
i. *Can we apply the limits on κ_λ, extracted from experimental searches for double-Higgs production, for BSM models?*

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

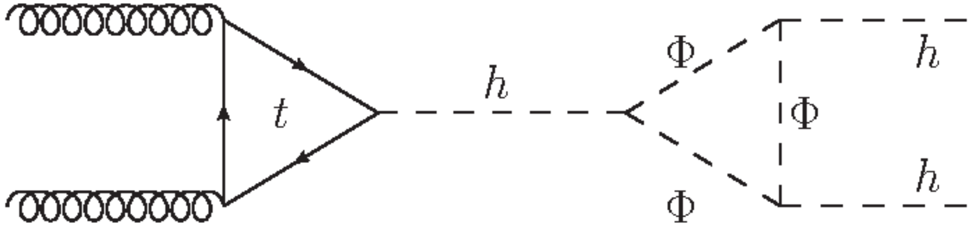
Can we apply hh-production results for the aligned 2HDM?

- What are the *assumptions* for the ATLAS limits $-1.0 < \kappa_\lambda < 6.6$ [ATLAS-CONF-2021-052] ?
  - 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]

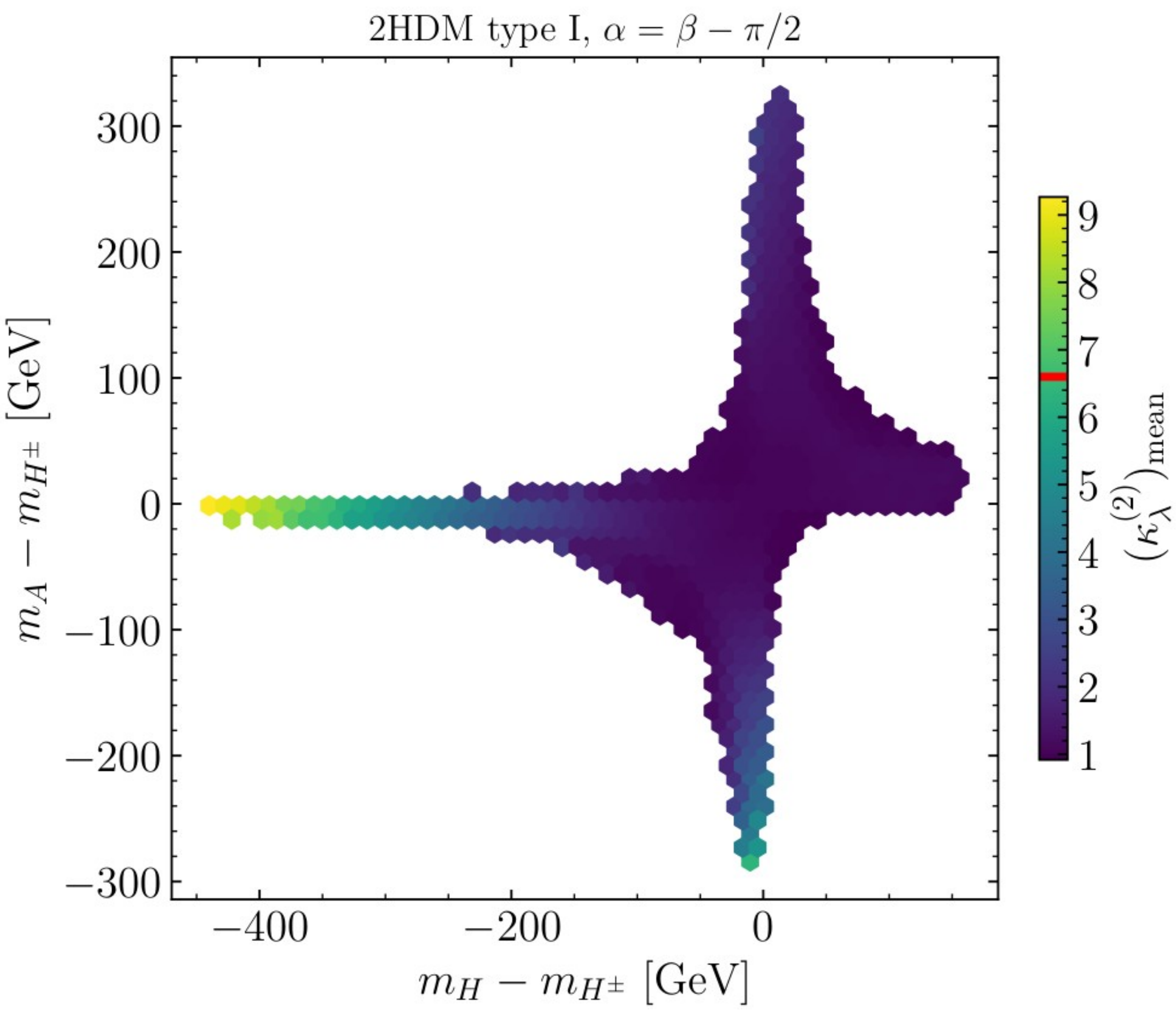
Checked with `ScannerS` (SM-like Higgs measurements through boundedness-from-below)

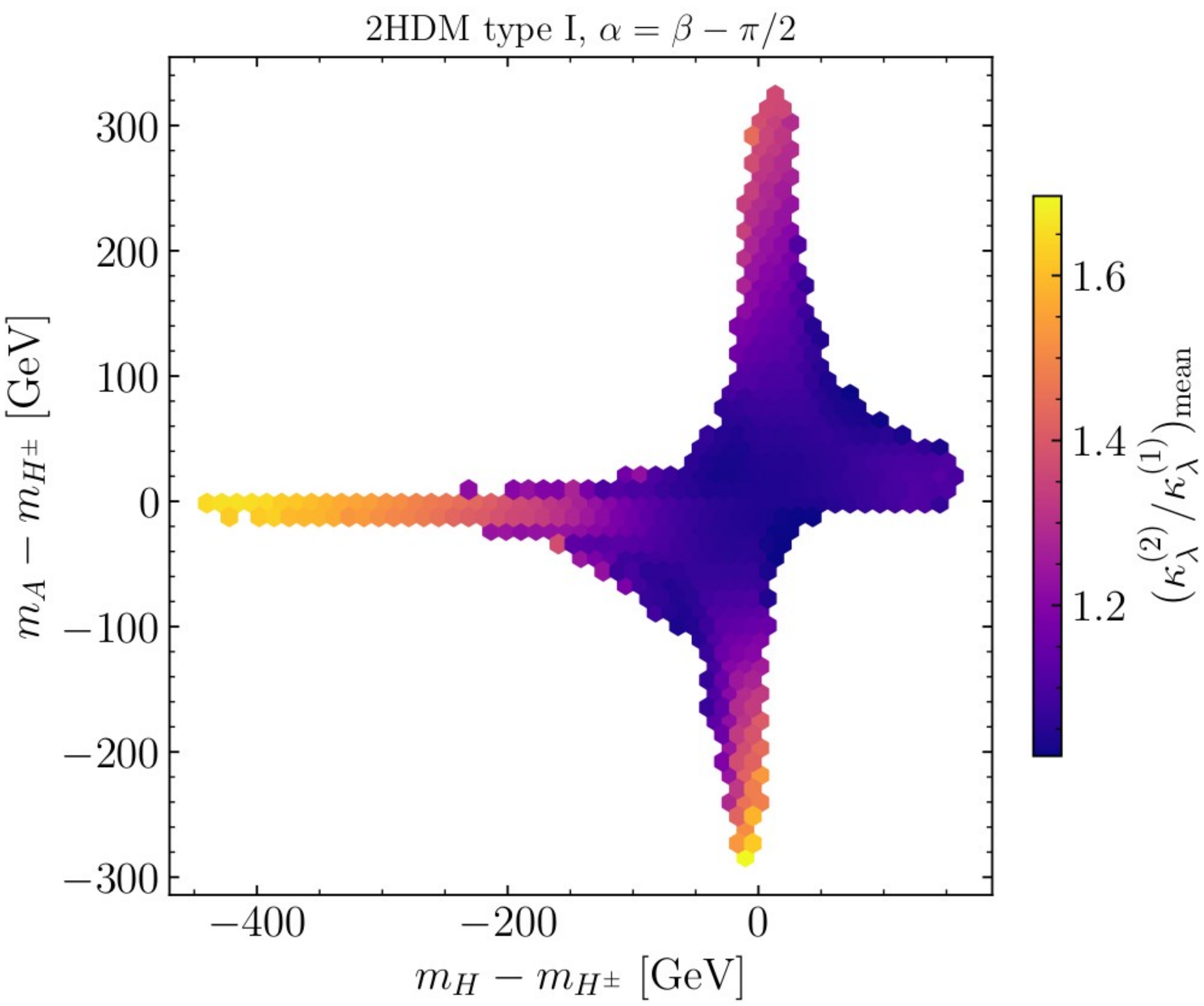
- For points passing these constraints, we compute κ_λ at 1L and 2L, using results from [JB, Kanemura ‘19]

Parameter scan results

[Bahl, JB, Weiglein 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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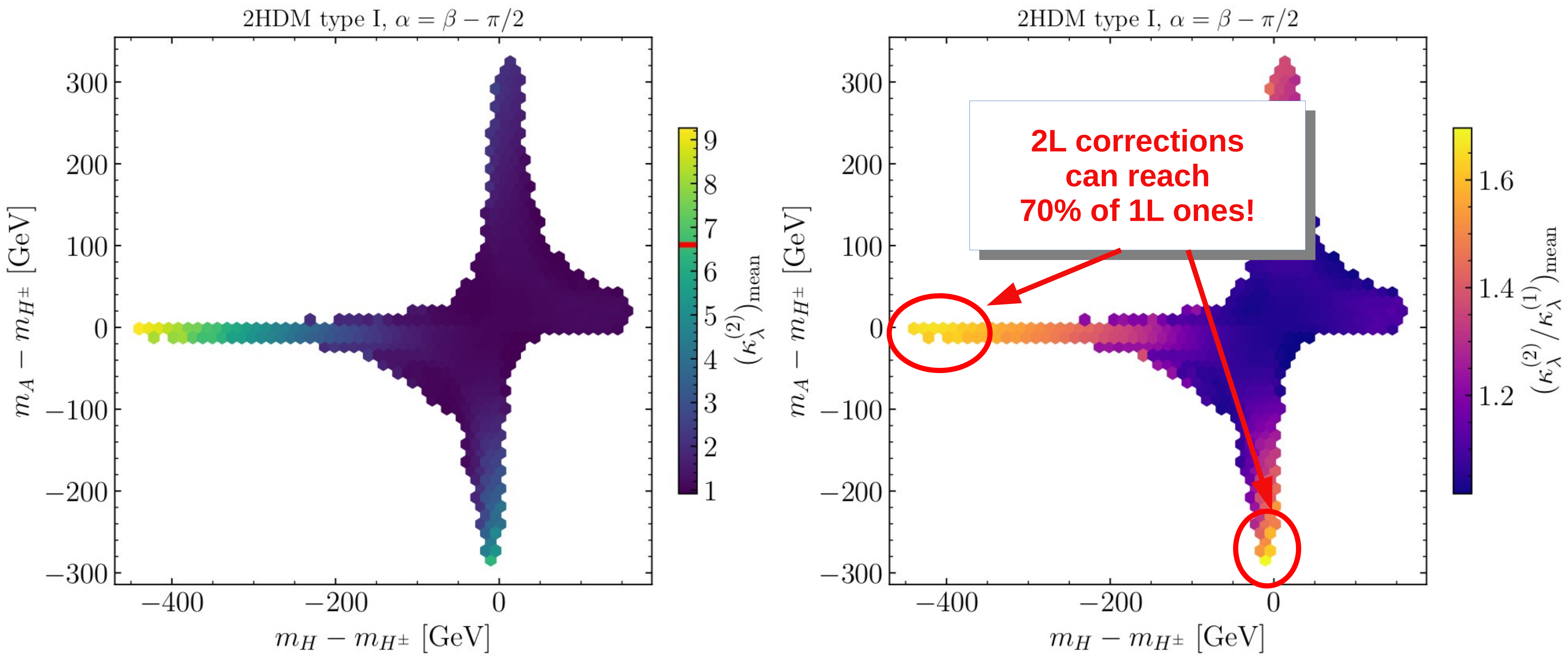

- 2L corrections can become **significant** (up to ~70% of 1L)

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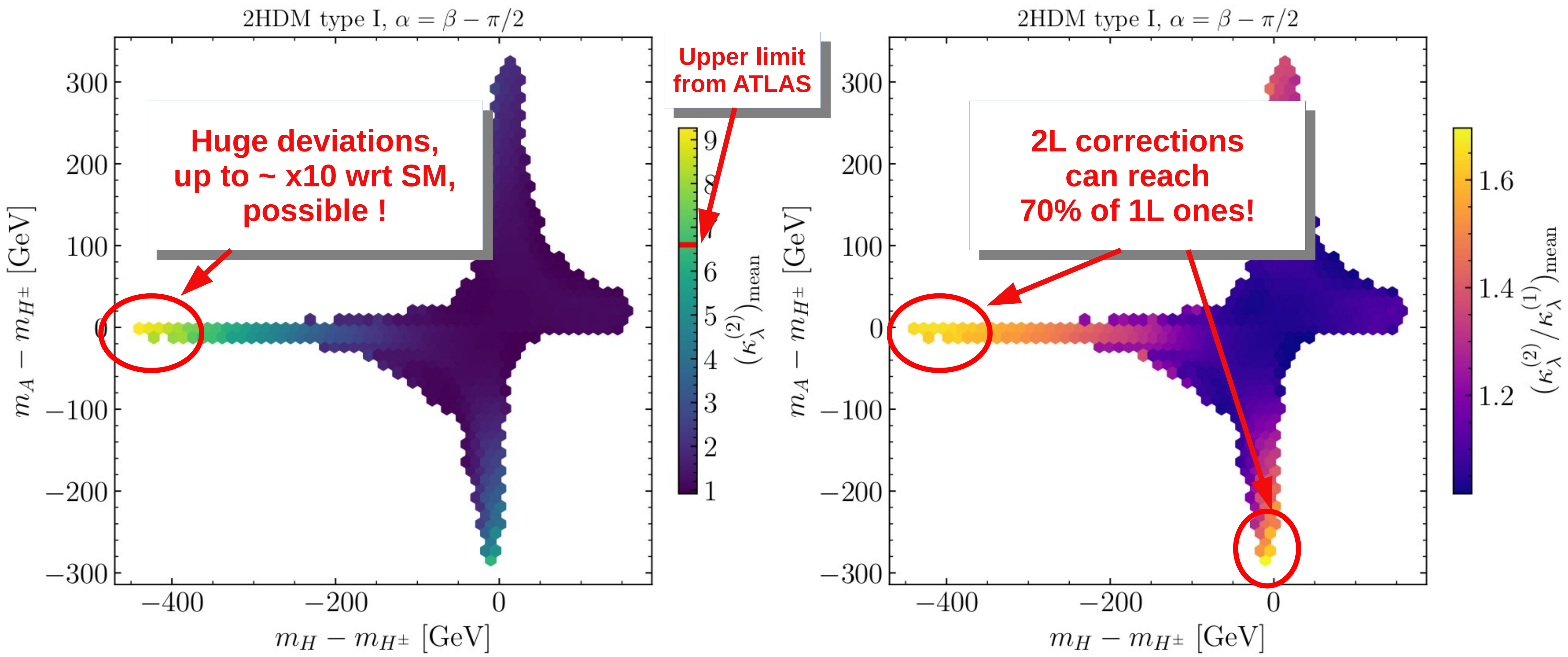


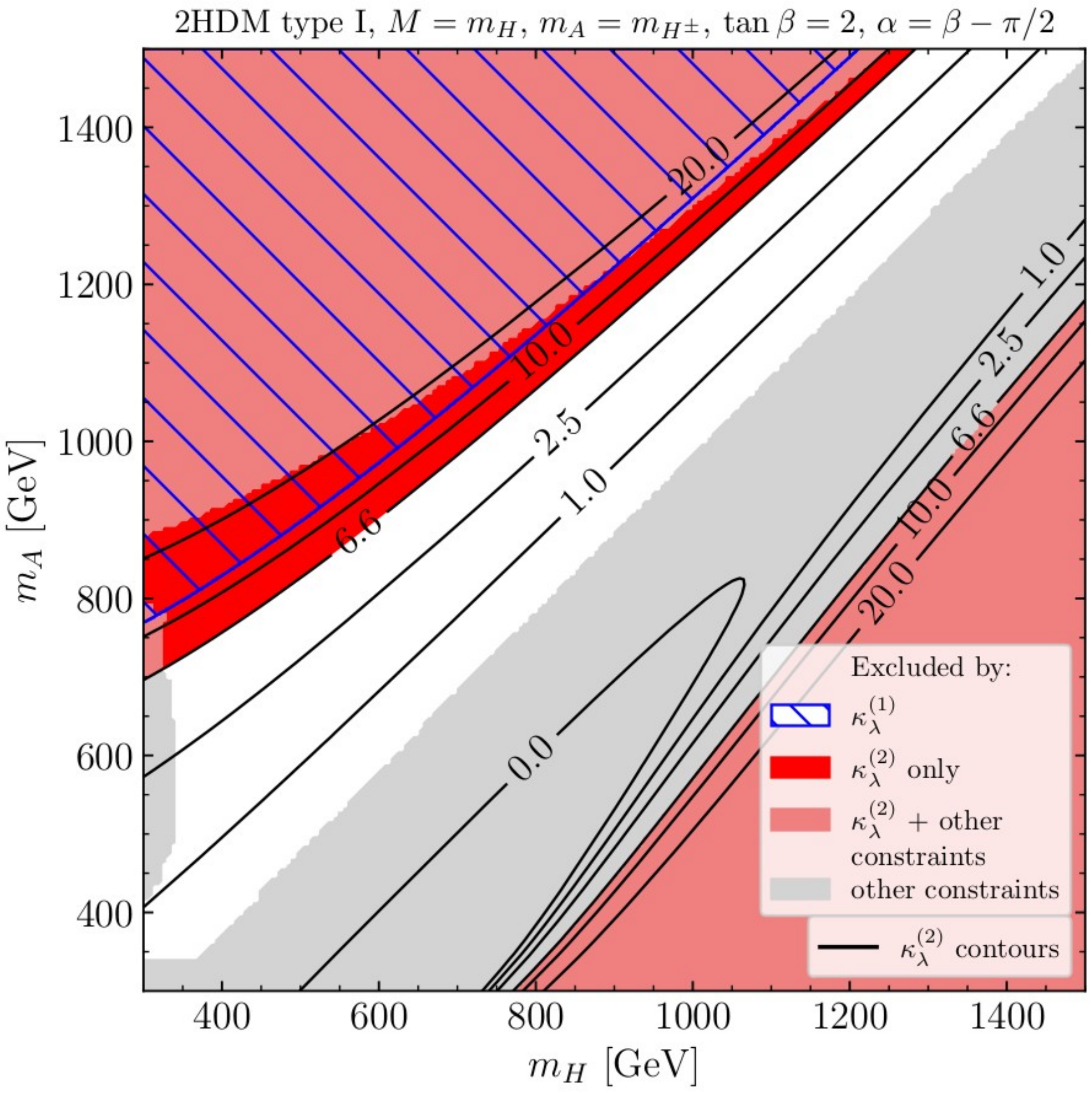
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark plane 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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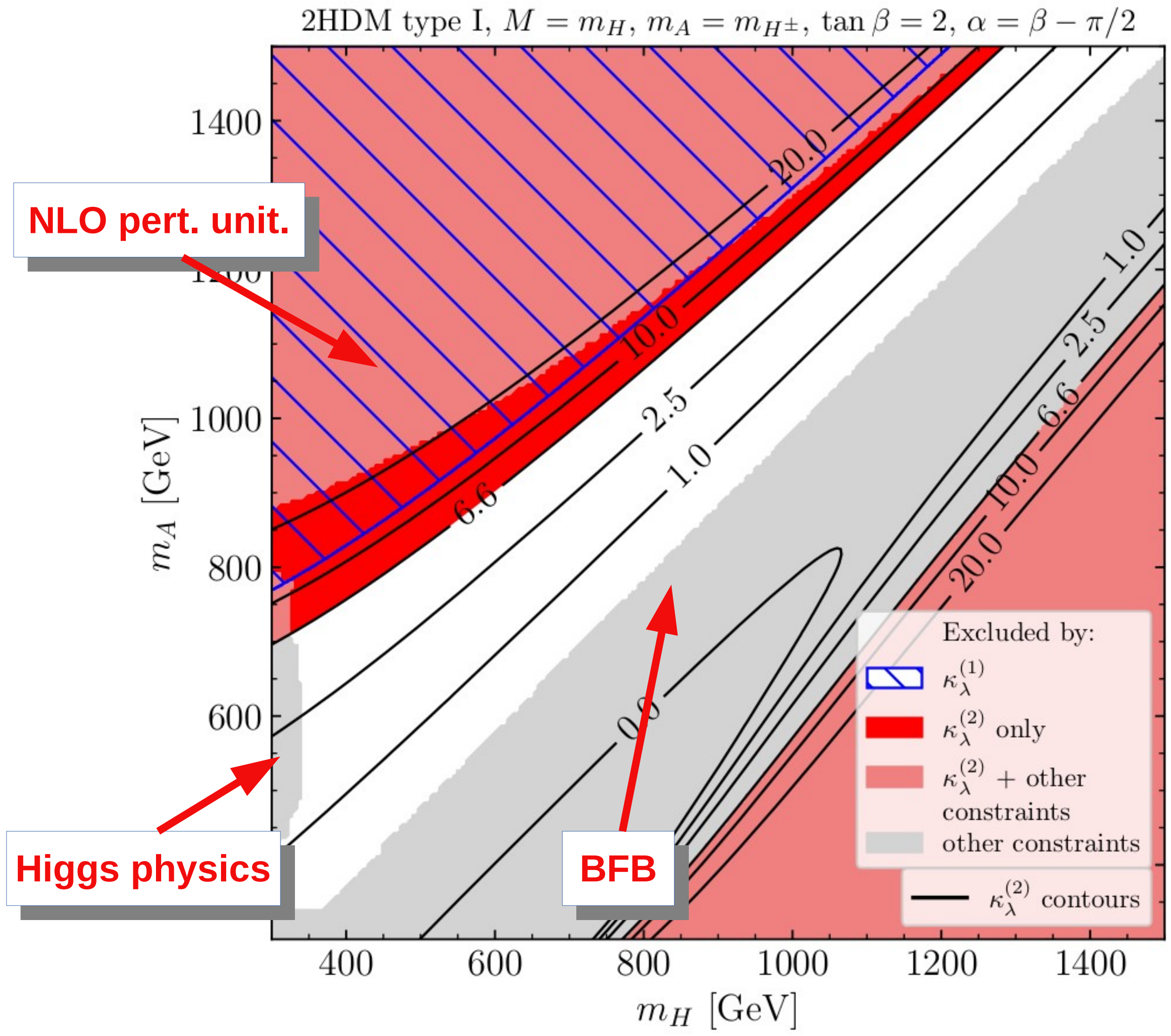

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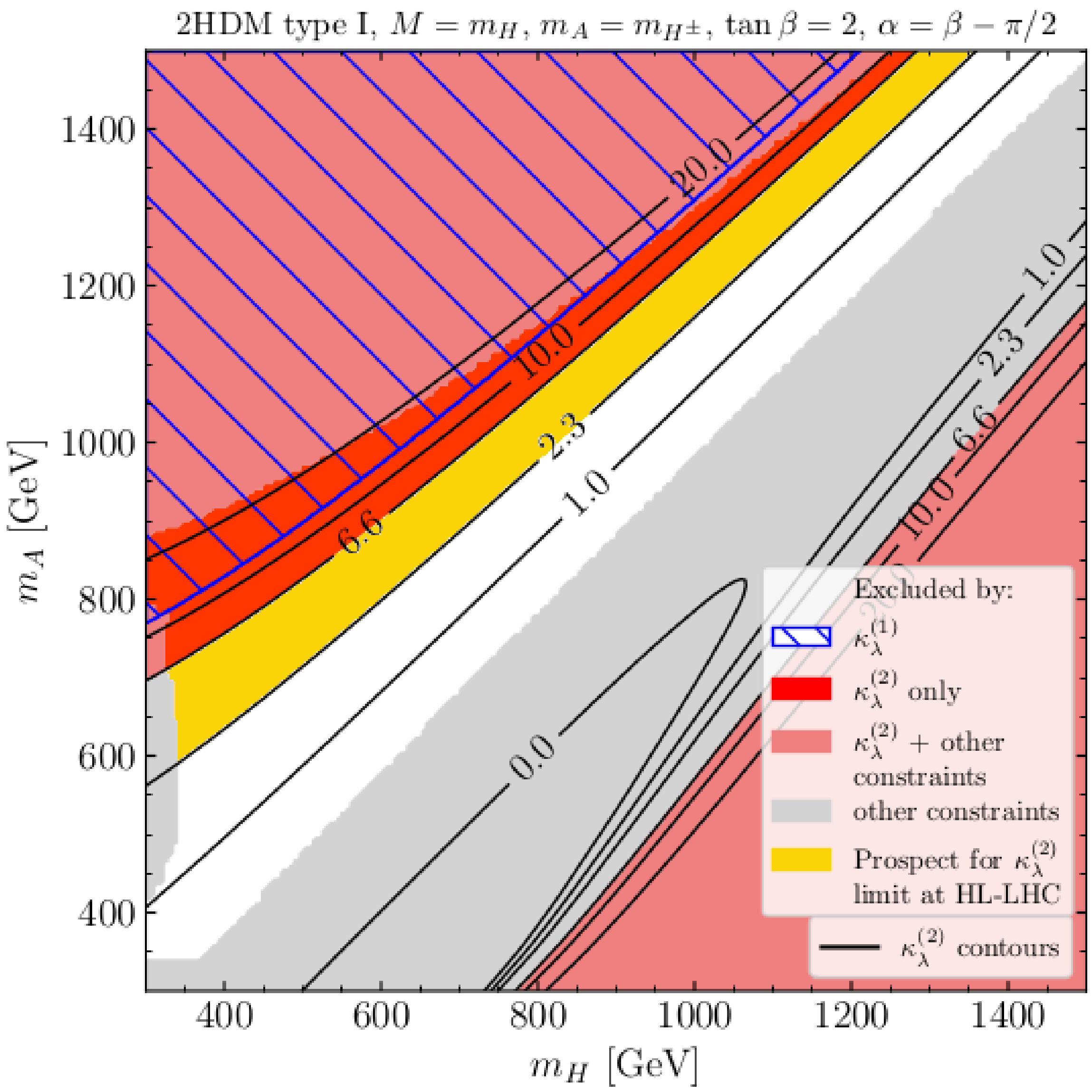
A benchmark scenario in the aligned 2HDM – future prospects

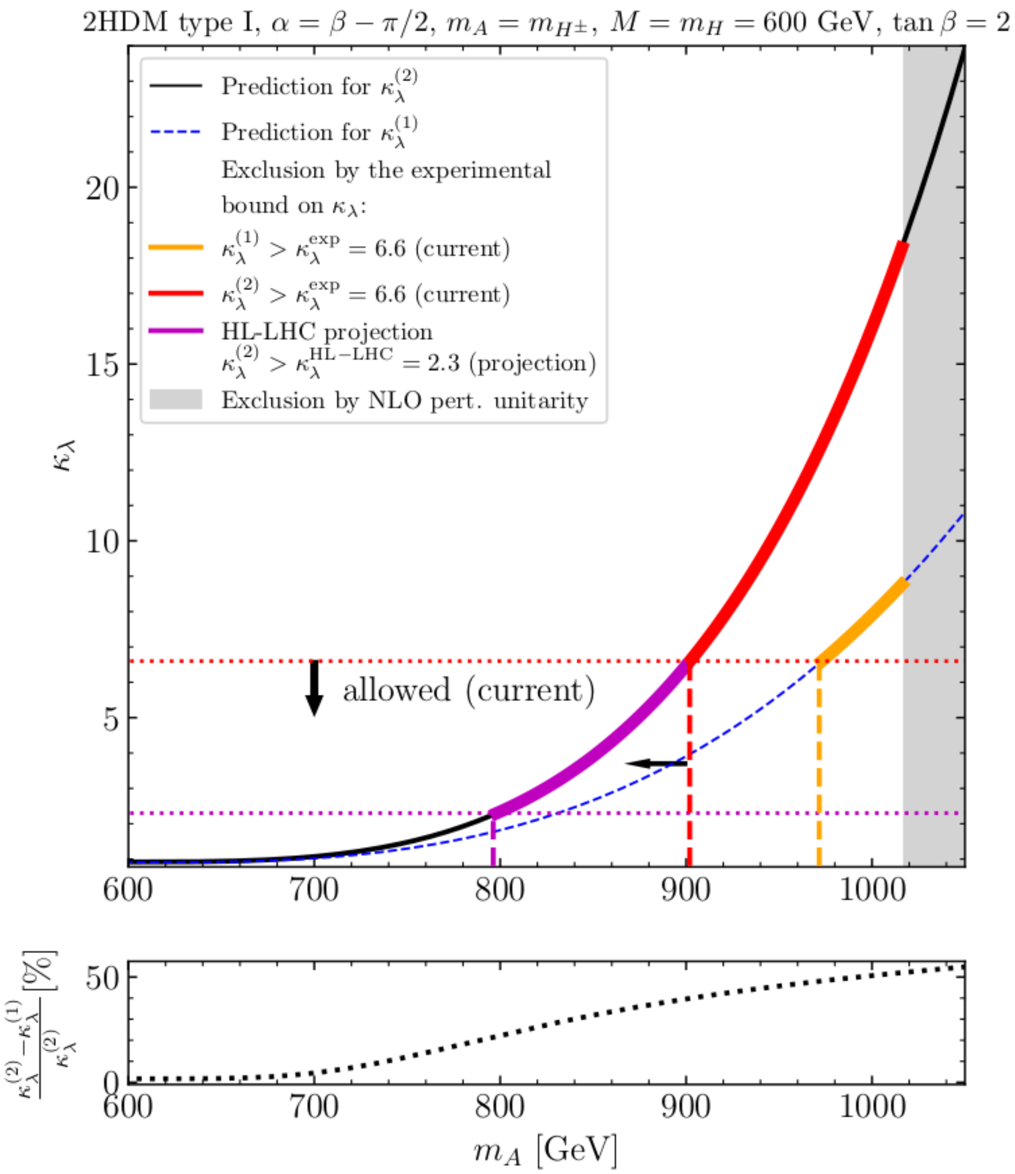
Suppose for instance the upper bound on κ_λ becomes $\kappa_\lambda < 2.3$



- ***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

Correlation between M_W and κ_λ

[Bahl, JB, Weiglein 2204.05269]

- Recent measurement of M_W by CDF collaboration sparked a lot of excitement:

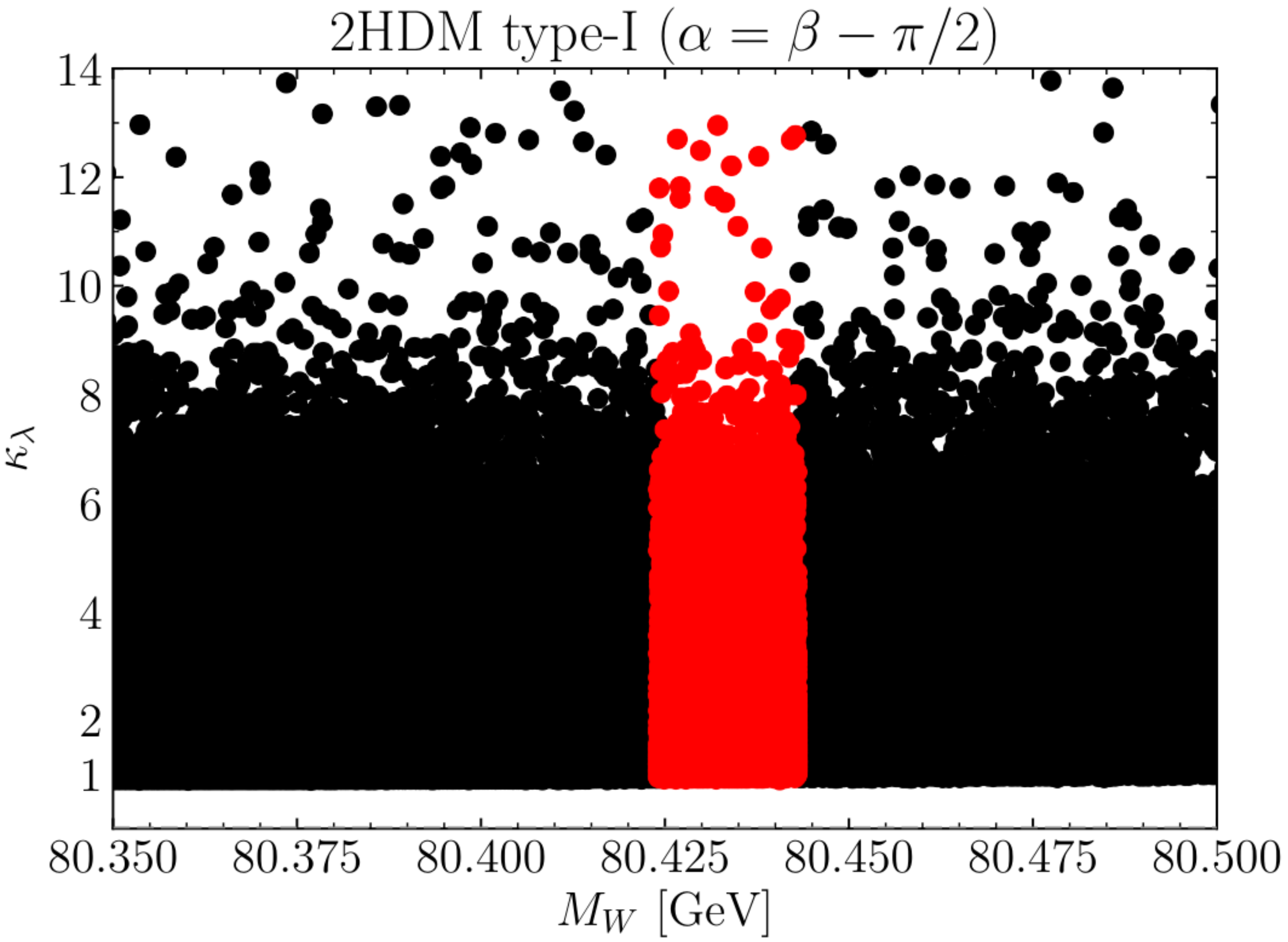
  M_W = 80 433 ± 9 MeV

- Most precise single measurement of M_W
- 7σ deviation from SM!

- In [Bahl, JB, Weiglein 2204.05269] we considered whether the 2HDM can accommodate the CDF result (or any value between the current world average and the CDF result) using a 2L calculation of EWPOs → it does! (*more in backup*)

- No apparent correlation between M_W and κ_λ

- Only few points excluded by $-1.0 < \kappa_\lambda < 6.6$ [ATLAS-CONF-2021-052]



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's talk!**

Thank you for your attention!

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