New constraints on extended Higgs sectors from the trilinear Higgs coupling

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based on 2202.03453

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The Higgs boson – what we know so far.

- A scalar behaving similar as the SM Higgs boson was discovered at the LHC.
- What we know about this scalar:
  - Its mass: $m_h \simeq 125\ \mathrm{GeV}$.
  - Its vacuum expectation value: $v \simeq 246\ \mathrm{GeV}$
  - Its spin: $S = 0$.
  - It's not a $\mathcal{CP}$-odd state.
  - Its couplings to gauge bosons ($WW, ZZ, gg, \gamma\gamma$): $\mathcal{O}(10)\ \%$
  - Its coupling to third generation fermions: $\mathcal{O}(20)\ \%$
  - Its coupling to muons: $\mathcal{O}(50)\ \%$
- What we don't know about this scalar:
  - Its exact $\mathcal{CP}$ nature.
  - Its couplings to first and second generation fermions.
  - Its width (are there any decays to non-SM particles?).
  - The shape of its potential.

The Higgs potential

In the SM, the Higgs potential is completely determined by the Higgs mass and its vev:

$$V_h^{\mathrm{SM}} = \frac{1}{2} m_h^2 h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4 + \cdots$$

Relation between the different terms can easily be modified by BSM physics
→ add modifier κ_λ (and κ_{λ_4}):

known

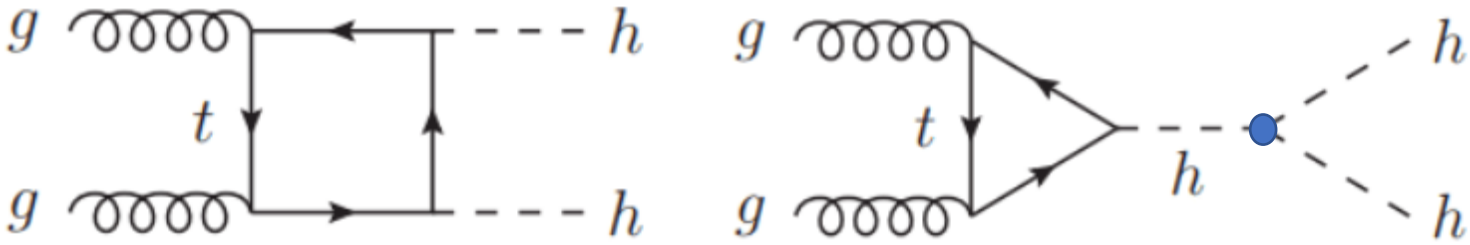
$$V_h = \frac{1}{2} m_h^2 h^2 + \kappa_\lambda \frac{m_h^2}{2v} h^3 + \kappa_{\lambda_4} \frac{m_h^2}{8v^2} h^4 + \cdots$$

unknown

How can we constraint κ_λ experimentally?

Double-Higgs production

Most direct probe of trilinear Higgs coupling: double-Higgs production via gluon fusion.



In the SM: large destructive interference between box and triangle contribution.

⇒ Deviations from SM trilinear Higgs coupling can significantly enhance the hh cross section.

Interpret upper limits on hh cross section as limits on κ_λ.

Experimental bound on κ_λ

Current strongest limit: $-1.0 < \kappa_\lambda < 6.6$ at 95% CL [ATLAS-CONF-2021-052].

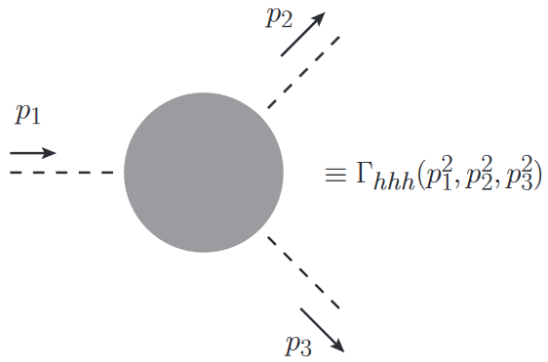
Assumptions:

- All other Higgs couplings are SM-like.
- Non-resonant Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling.

Can we use this limit to constrain BSM models?

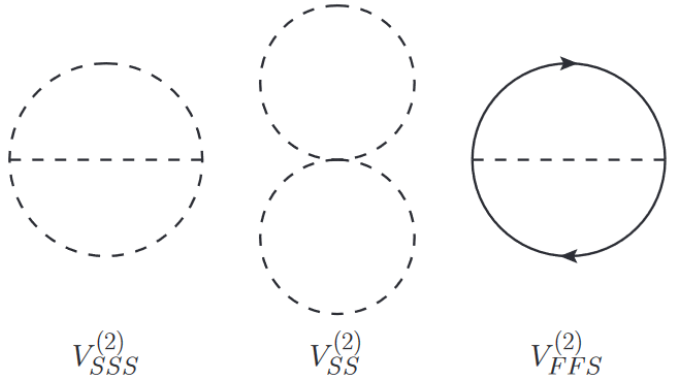
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



- Alternatively, employ zero momentum approximation and then use effective potential:

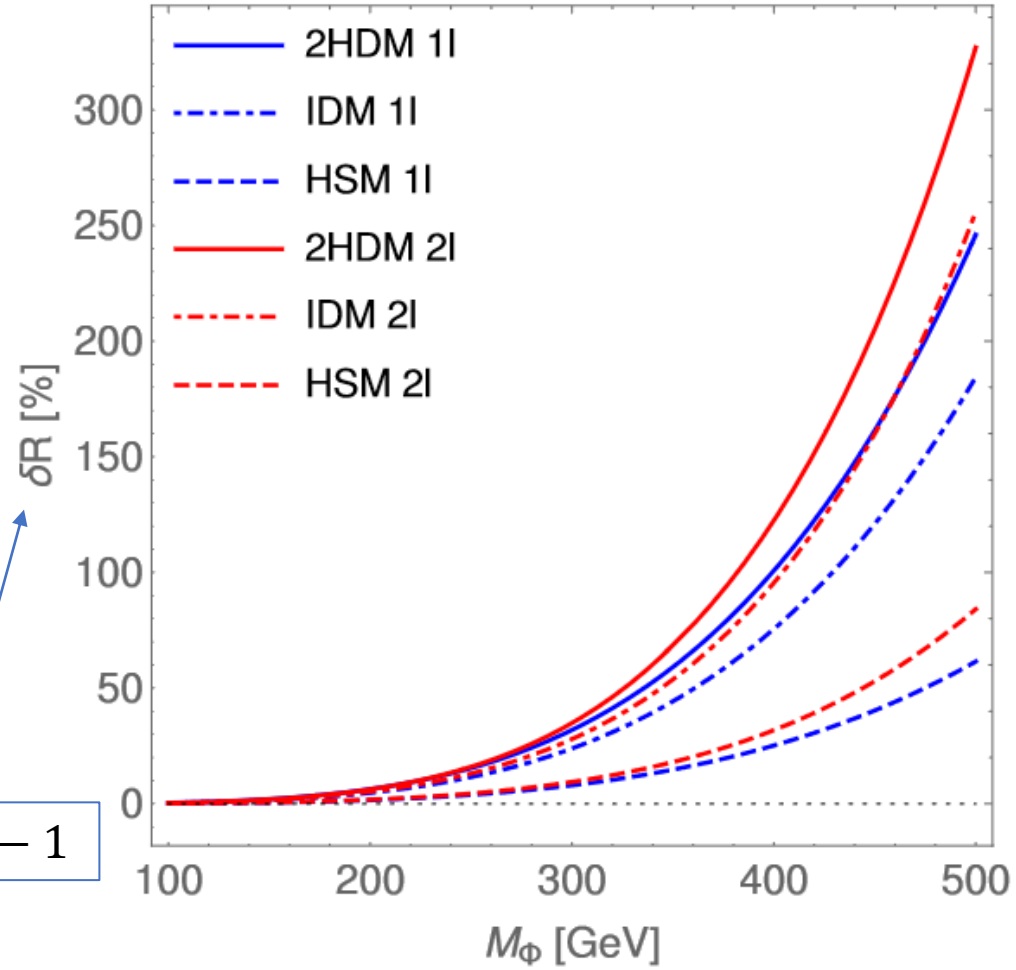
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda_{hhh}^{(0)} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- Using V_{eff}, 1L and 2L corrections have been calculated in various BSM Higgs models (see e.g. [Braathen,Kanemura,1911.11507]).

Calculating BSM corrections to κ_λ

[Braathen,Kanemura,1911.11507]



$\delta R = \kappa_\lambda - 1$

- Large non-decoupling corrections found in several BSM models.
- Analysis assumed that all BSM masses are equal M_Φ.
- No phenomenological analysis has been performed.

Idea of this work:

Can we constrain these models based on the large corrections to κ_λ?

κ_λ constraints in the 2HDM

- Focus first on **2HDM type I** in the alignment limit (similar results expected for other types/models).

- Most relevant/largest couplings ($\Phi \in \{H, A, H^{\pm}\}$, $M^2 = m_{12}^2/(s_\beta c_\beta)$):

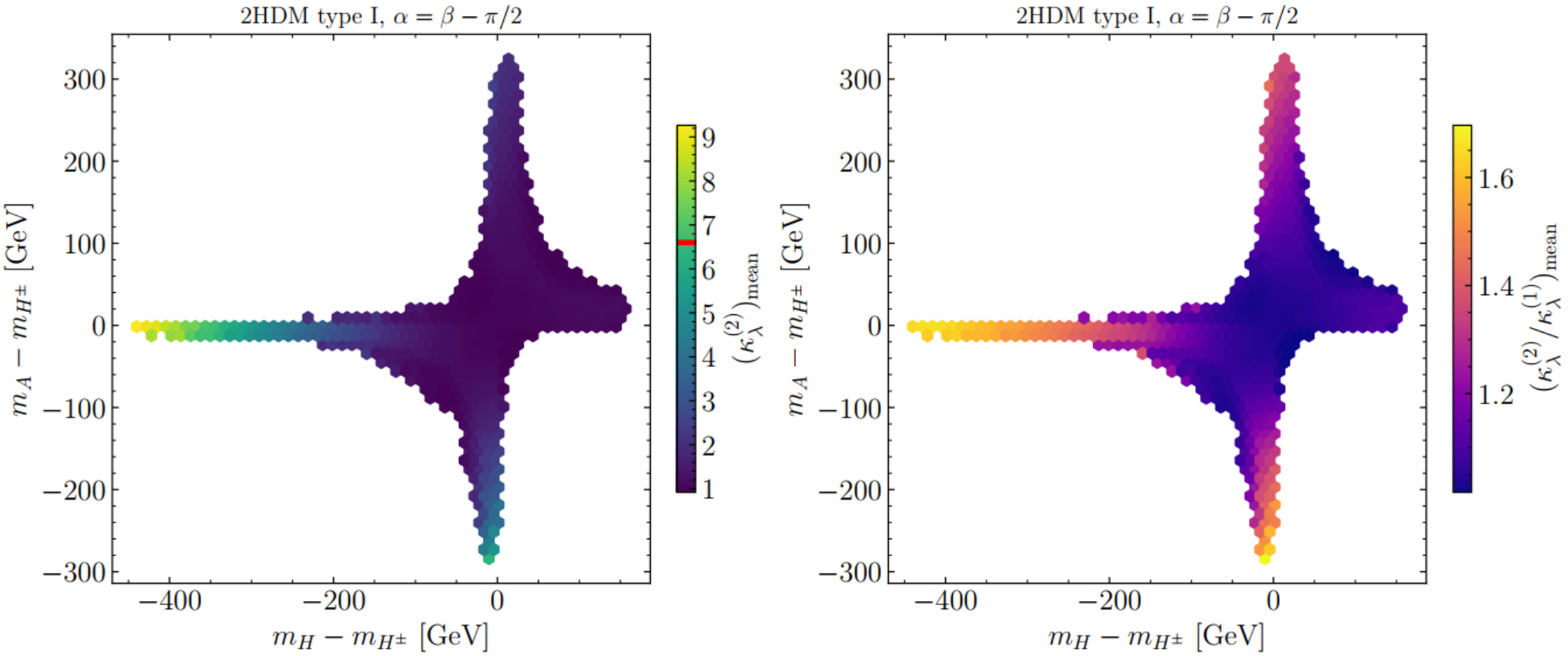
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Strategy:
  1. Scan parameter space applying various theoretical and experimental constraints.
  2. Identify regions with large deviations of κ_λ , which is calculated at the 2L level.
  3. Define a benchmark scenario and apply constraints on κ_λ.

2HDM parameter scan

- We checked for:
  - Vacuum stability and boundedness-from-below.
  - NLO perturbative unitarity.
  - Electroweak precision observables (calculated at the 2L level using `THDM_EWPOS` [Hessenberger,Hollik,1607.04610]).
  - SM-like Higgs measurements via `HiggsSignals`.
  - Direct searches for BSM scalars via `HiggsBounds`.
  - b-physics constraints.
- Most constraints checked using `ScannerS`.
- For each point passing the constraints, we calculate κ_λ at the 1L and 2L level ($\kappa_\lambda^{(1)}$ and $\kappa_\lambda^{(2)}$) using results from [Braathen,Kanemura,1911.11507].

2HDM parameter scan - results

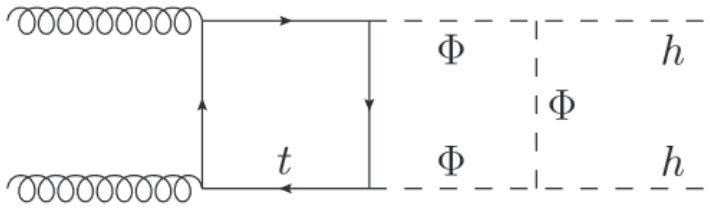


Largest corrections for $m_A \simeq m_{H^\pm}$, $m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}$, $m_A < m_{H^\pm}$. 2L corrections have sizeable impact.

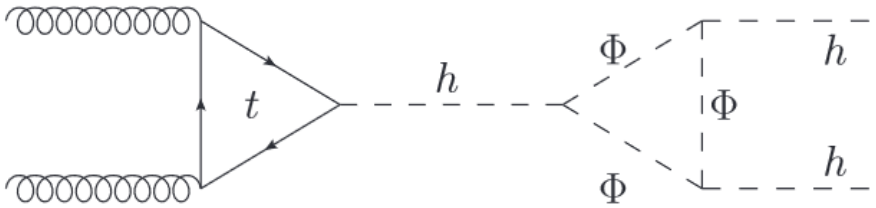
Applying the constraints on κ_λ

Assumptions of experimental bound:

- All other Higgs couplings are SM-like.
  - 2HDM in the alignment limit with heavy BSM masses. ✓
- Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling.
  - No resonant contribution because Hhh coupling is zero in alignment limit. ✓
  - Other BSM contributions to hh production?



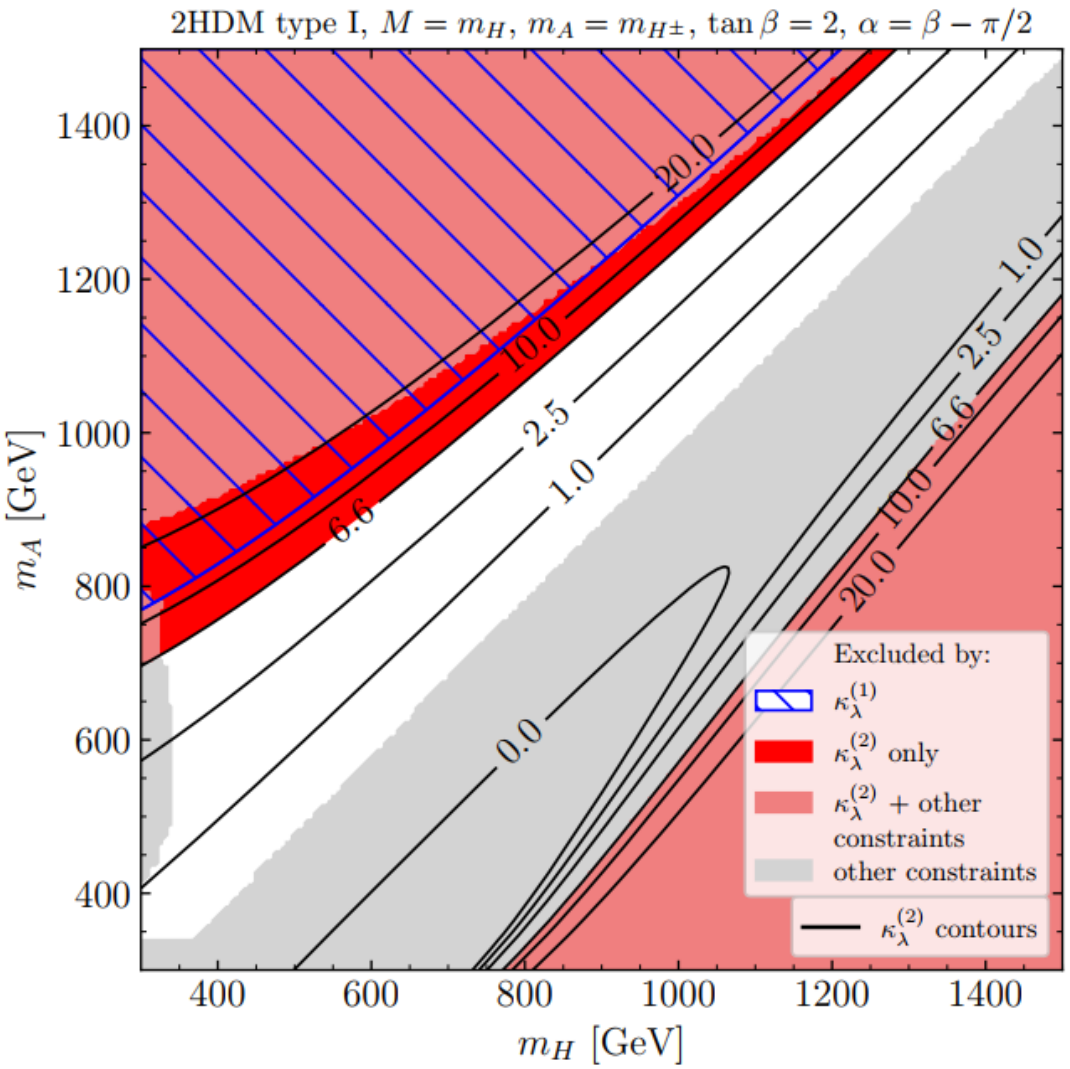
$\propto y_t^2 g_{hh\Phi\Phi}^2$ (not included)



$\propto y_t g_{hh\Phi\Phi}^3$ (included)

  - We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level. ✓

Constraints on κ_λ - benchmark scenario



Experimental bound on κ_λ excludes so far unconstrained parameter space!

Conclusions

- Measurement of the **trilinear Higgs coupling** crucial to determine shape of Higgs potential.
- Large deviations from the SM possible in many BSM models.
- We showed that already current bounds exclude significant parts of so far unconstrained 2HDM parameter space.
- Including 2L corrections important for precise prediction.
- We expect similar results in other BSM Higgs models.
- More precise bounds expected in the future ⇒ more precise theory predictions will be needed.

Thanks for your attention!