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, vev, spin.
  - 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.

→ Modification of Higgs potential can have implications for e.g. cosmology.

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

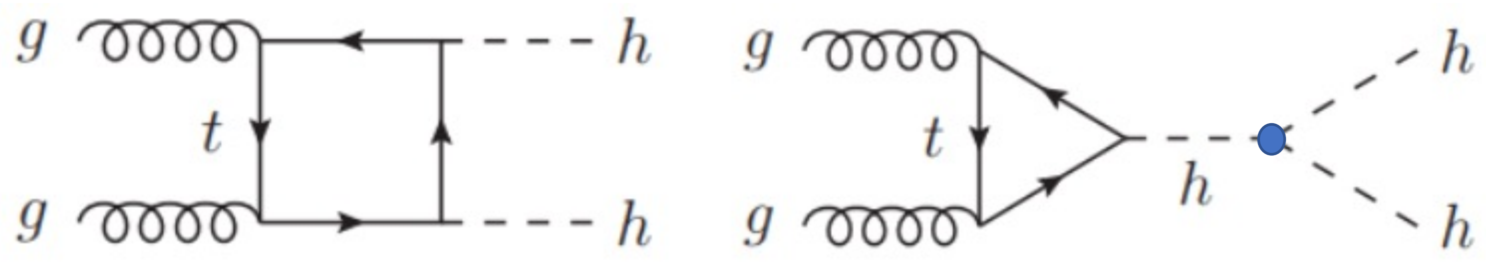
$$V_h = \frac{1}{2} m_h^2 h^2 + \kappa_\lambda \frac{m_h^2}{2v} h^3 + \kappa_{\lambda_4} \frac{m_h^2}{8v^2} h^4 + \cdots$$

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 experimental 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?

κ_λ in the 2-Higgs-doublet-model (2HDM)

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

$$V_{\rm 2HDM}(\Phi_1,\Phi_2) = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5\left((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right).$$

- 2 Higgs doublets → 5 physical Higgs bosons: CP-even h, H; CP-odd A; charged $H^\pm$.
- Most relevant/largest couplings:

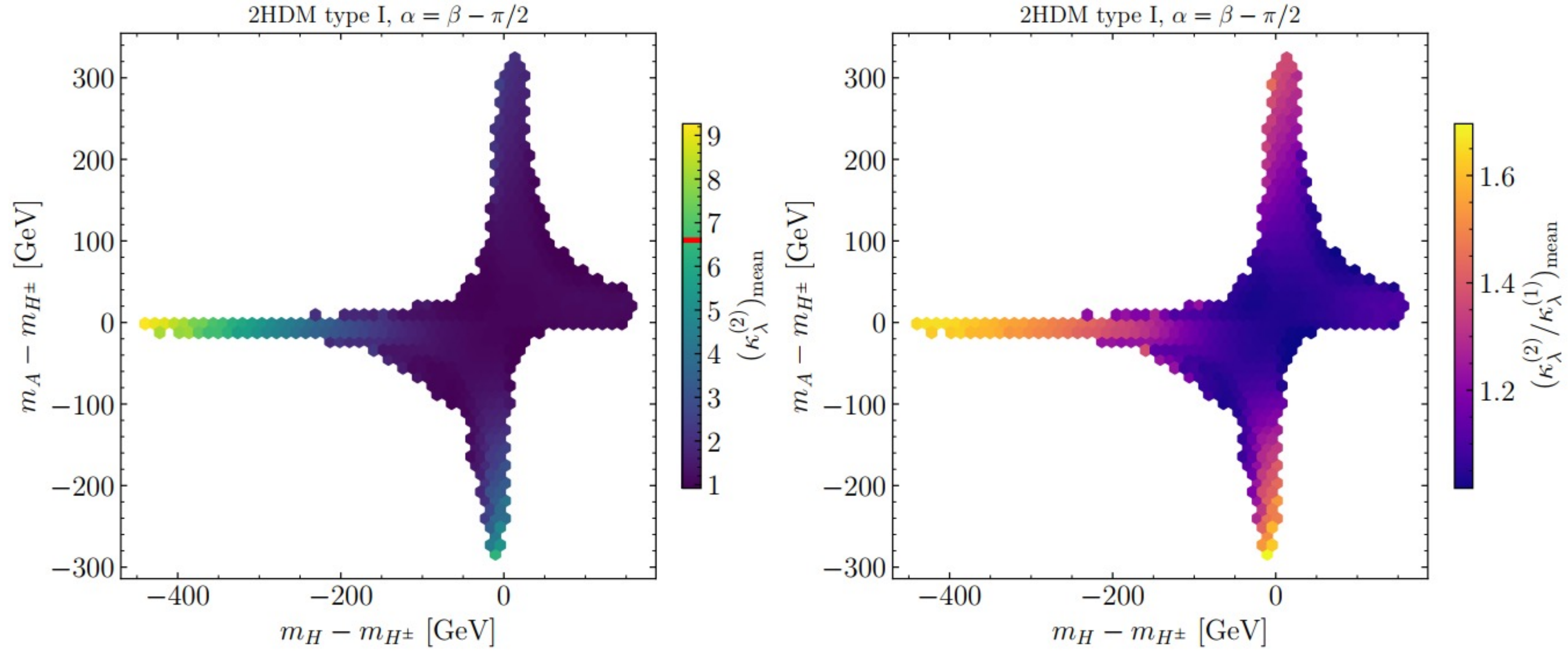
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2} \quad \text{with} \quad \Phi\in\{H,A,H^\pm\} \quad \text{and} \quad M^2 = \frac{m_{12}^2}{s_\beta c_\beta}$$

- 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

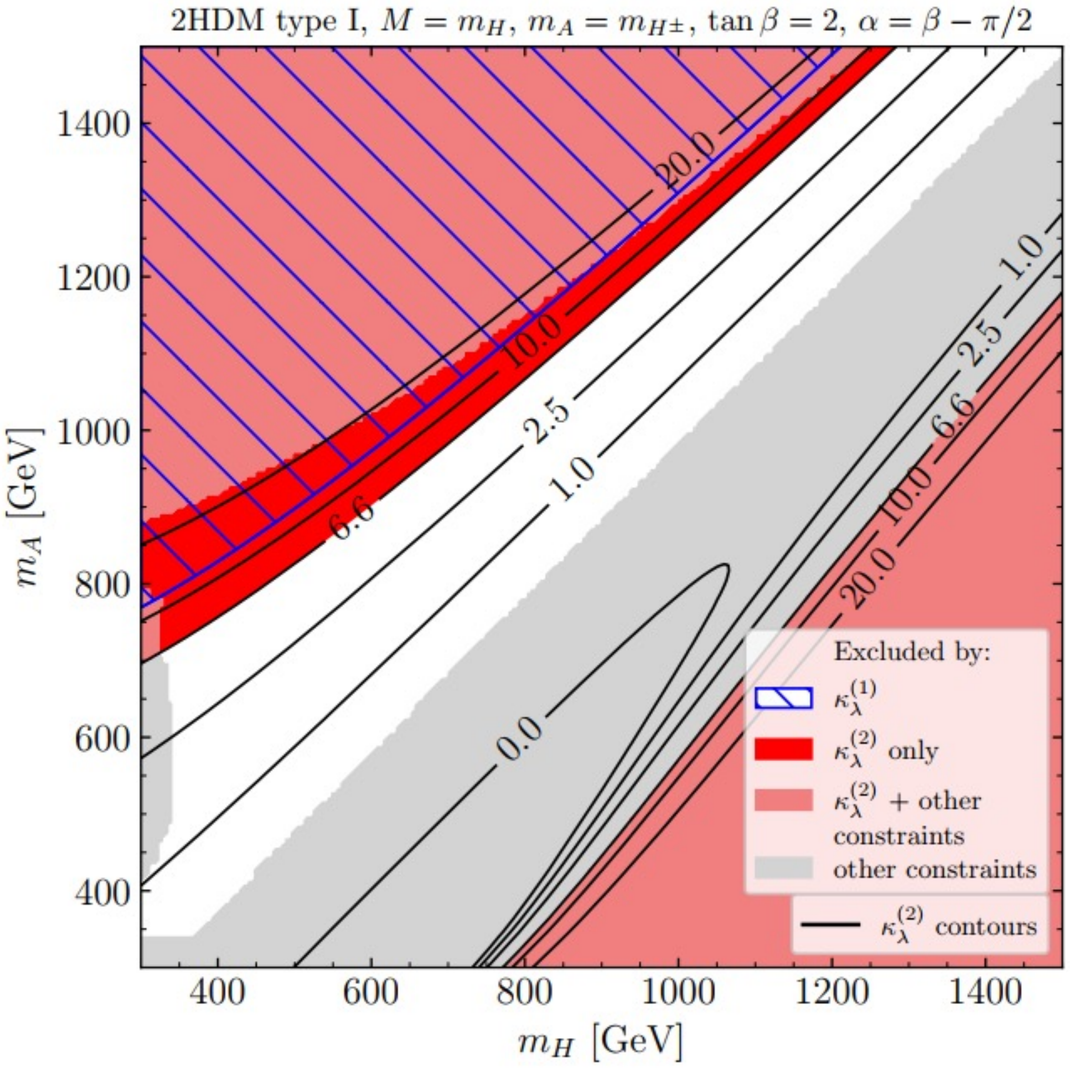
- We checked for:
  - Vacuum stability and boundedness-from-below.
  - NLO perturbative unitarity.
  - Electroweak precision observables (calculated at the 2L level using THDM_EWPOS [Hessenberger,Hollik,1607.04610]).
  - SM-like Higgs measurements via HiggsSignals.
  - Direct searches for BSM scalars 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.

Constraints on κ_λ - benchmark scenario



Experimental bound on κ_λ excludes so far unconstrained parameter space!

Conclusions

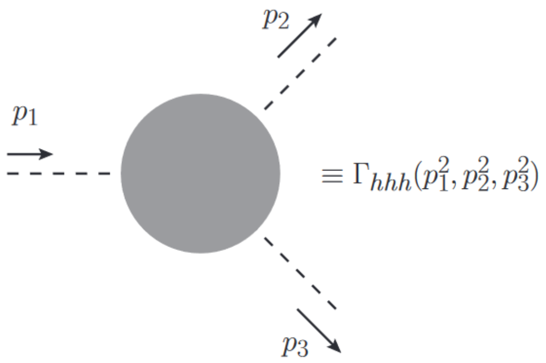
- Measurement of the **trilinear Higgs coupling** crucial to determine shape of Higgs potential.
- Large deviations from the SM possible in many BSM models.
- We showed that already current bounds exclude significant parts of so far unconstrained 2HDM parameter space.
- Including 2L corrections important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

Thanks for your attention!

Appendix

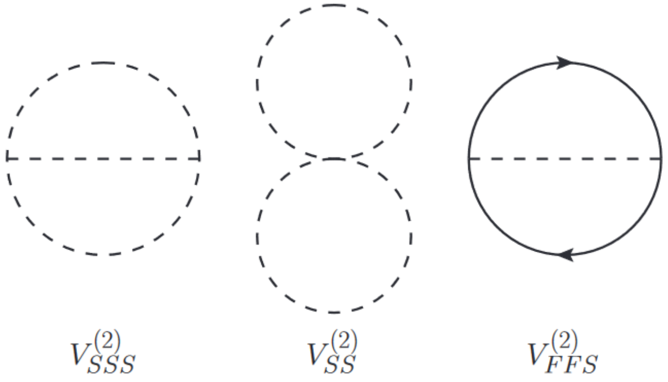
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



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

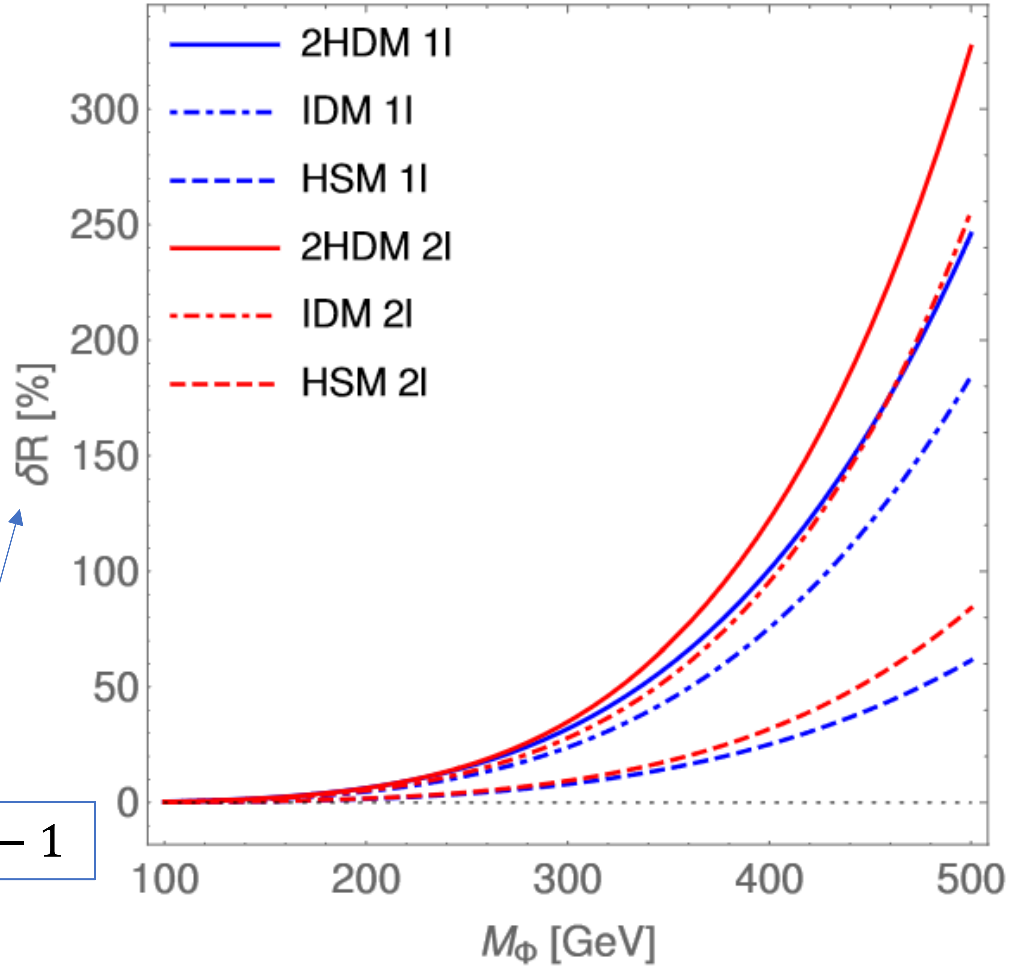
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda_{hhh}^{(0)} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- 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.

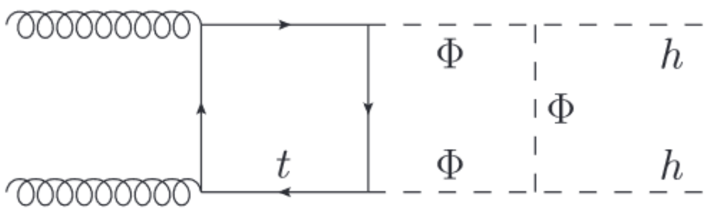
Idea of this work:

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

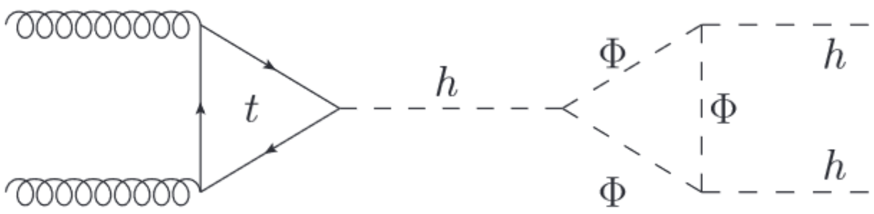
Applying the constraints on κ_λ

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)

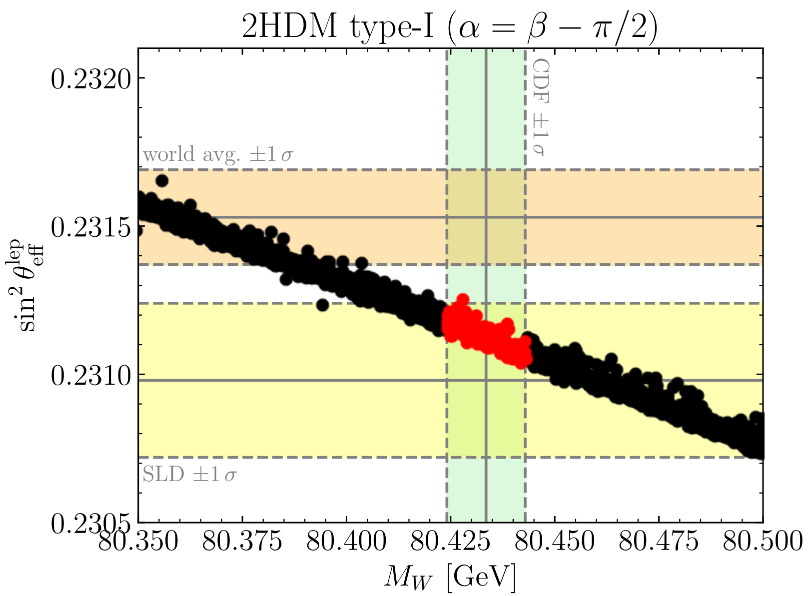
  - We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level. ✓

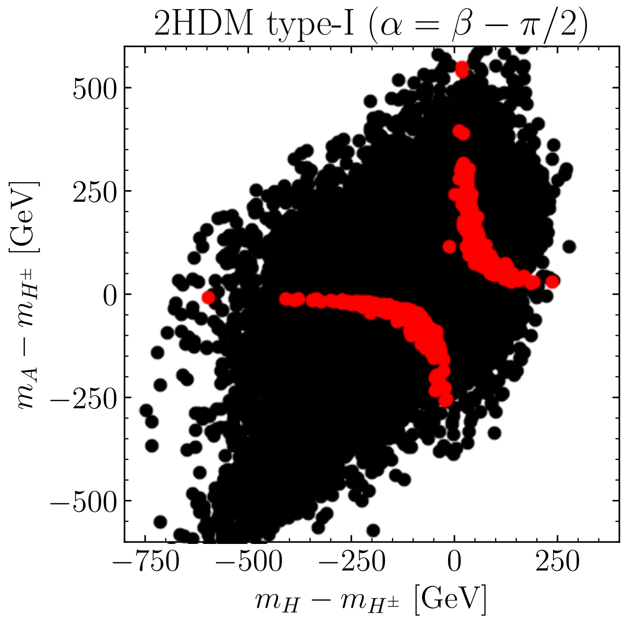
M_W in the 2HDM

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2}\left\{\frac{m_A^2 m_H^2}{m_A^2 - m_H^2}\ln\frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H\pm}^2}{m_A^2 - m_{H\pm}^2}\ln\frac{m_A^2}{m_{H\pm}^2} - \frac{m_H^2 m_{H\pm}^2}{m_H^2 - m_{H\pm}^2}\ln\frac{m_H^2}{m_{H\pm}^2} + m_{H\pm}^2\right\},$$

$$\Delta M_W \simeq \frac{1}{2} M_W \frac{c_W^2}{c_W^2 - s_W^2}\Delta\rho\,.$$

$\Delta M_W \simeq 0$ if $m_A = m_{H^\pm}$ or $m_H = m_{H^\pm}$





M_W in the 2HDM – correlation with κ_λ?