New constraints on extended Higgs sectors from the trilinear Higgs coupling

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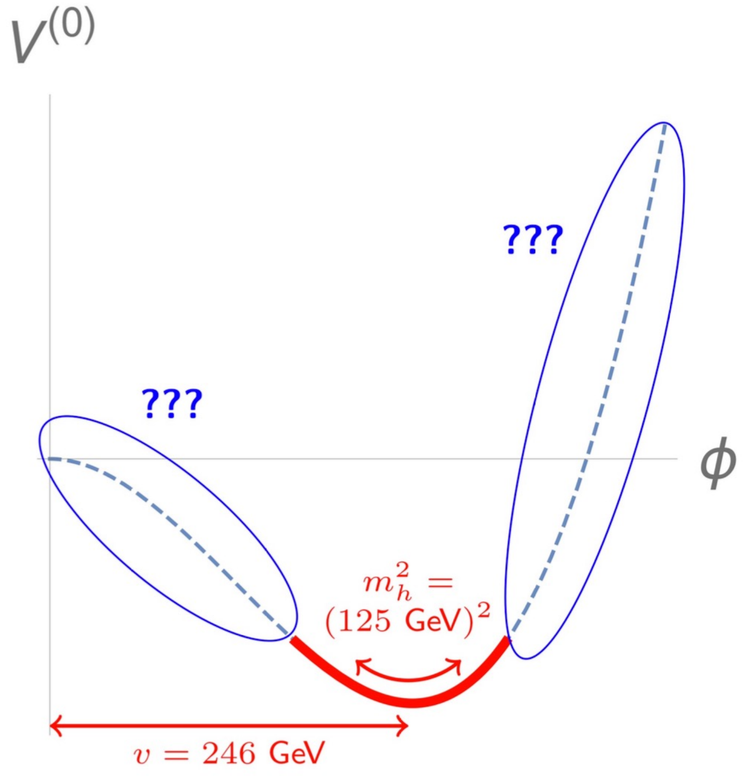
What can we learn form the trilinear Higgs coupling?

- After the Higgs discovery, we know
  - → the location of the EW minimum: $v = 246$ GeV,
  - → the curvature of the potential close to the minimum: $m_h = 125$ GeV.
- Away from the minimum, the shape of the potential is, however, unknown so far.
  - → Determination of trilinear Higgs coupling λ_{hhh} crucial.
- λ_{hhh} determines nature of EW phase transition.
  - → Deviations of λ_{hhh} from the SM prediction needed to allow for a strong EW phase transition, which is necessary for EW baryogenesis.

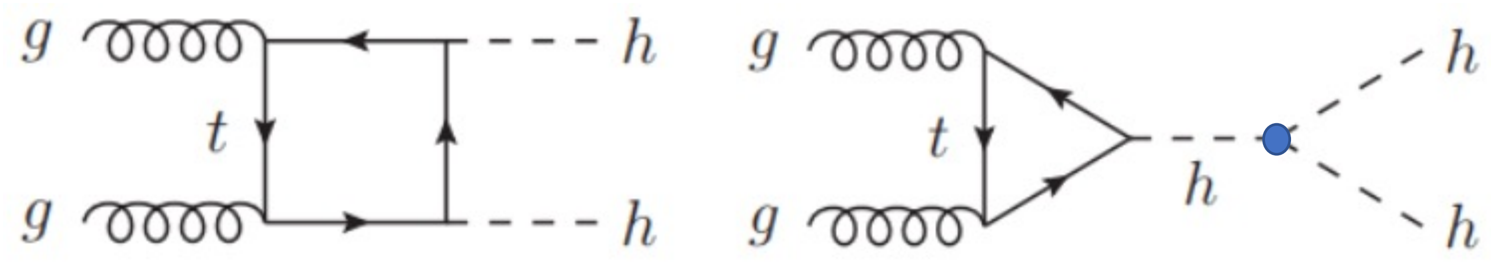


[figure by J. Braathen]

Focus of this talk: λ_{hhh} as a new constraint on BSM Higgs models.

Probing λ_{hhh} via 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.

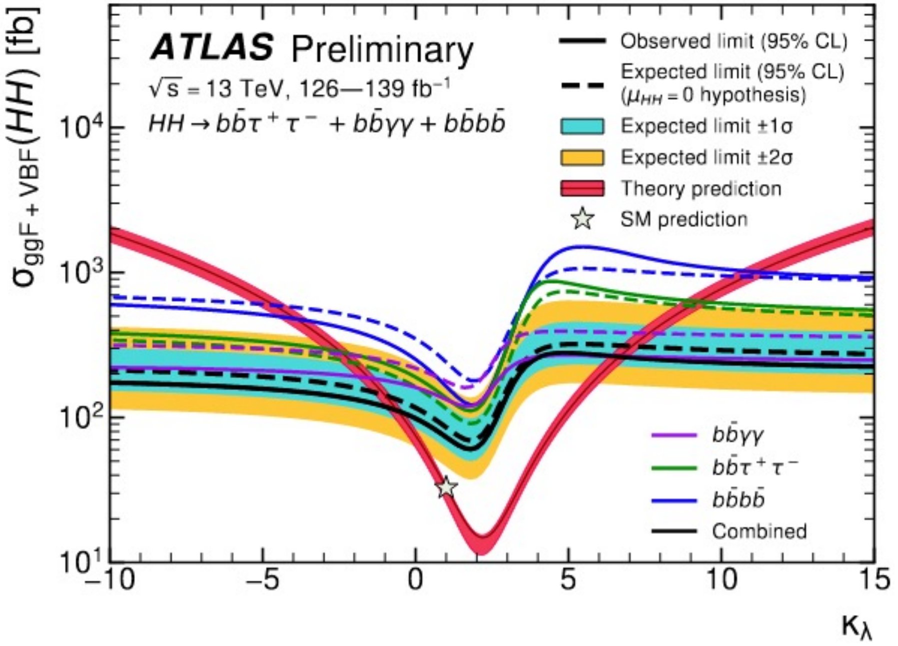
→ Interpret experimental upper limits on hh cross section as limits on κ_λ.

Experimental bound on $\kappa_\lambda \equiv \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$

Current strongest limit: $-0.4 < \kappa_\lambda < 6.3$ at 95% CL [ATLAS-CONF-2022-050].

Assumptions:

- Simplest analysis assumes that all other Higgs couplings are SM-like.
- Non-resonant Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling (i.e., no heavy resonances).



- Can we use this limit to constrain BSM models?
- Can large BSM deviations occur given other theoretical and experimental constraints?

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:

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

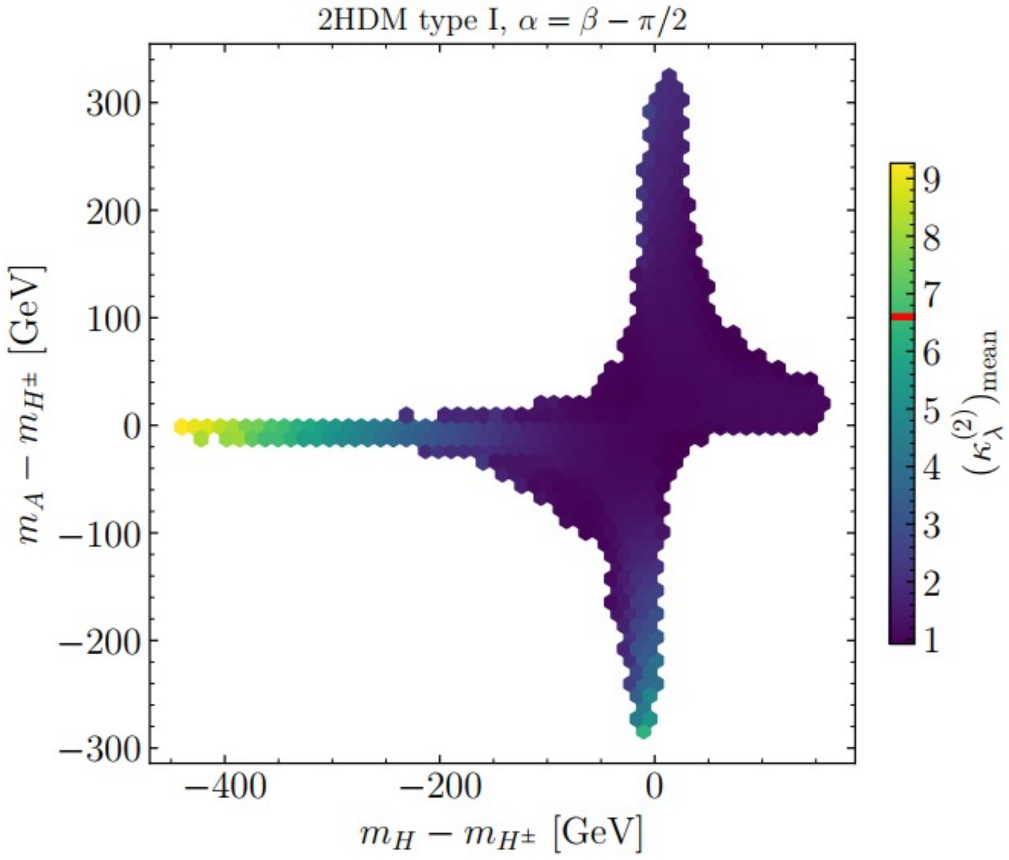
- Strategy:
  1. Scan parameter space applying various theoretical and experimental constraints.
  2. Identify regions with large deviations of κ_λ , which is calculated at the 2L level.
  3. Define a benchmark scenario and apply constraints on κ_λ.

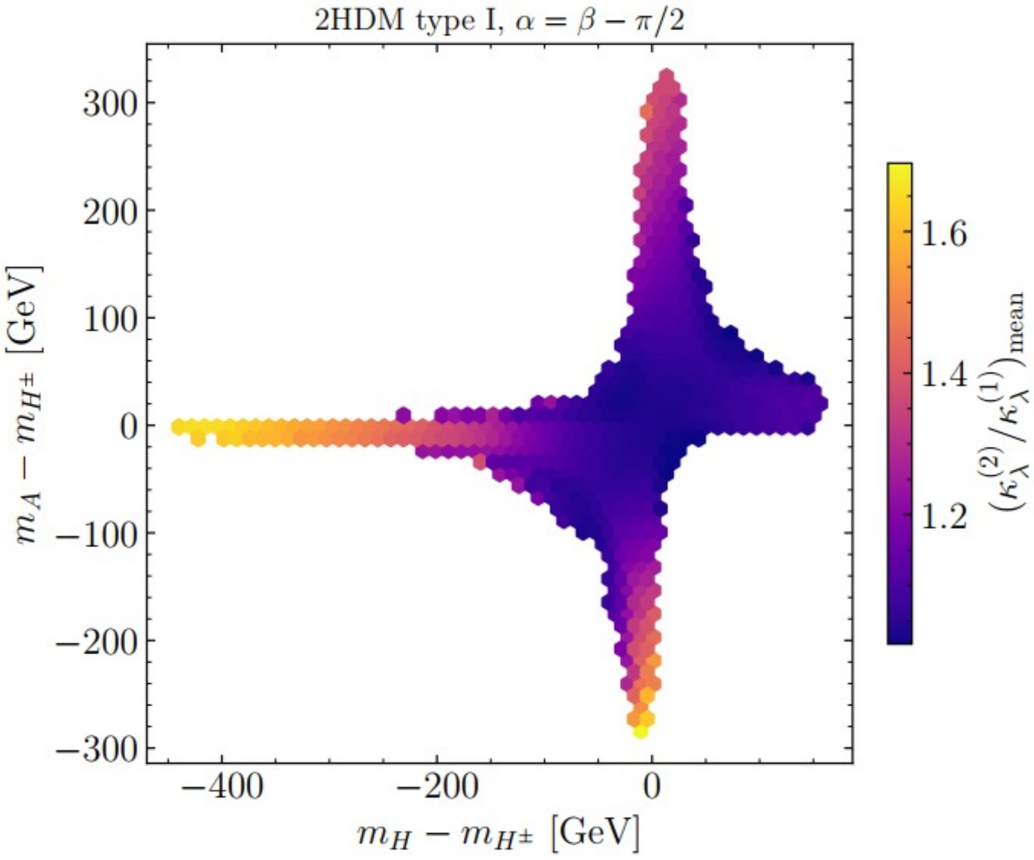
2HDM parameter scan

- We checked for
  - vacuum stability and boundedness-from-below,
  - NLO perturbative unitarity, [Grinstein et al., 1512.04567; Cacchio et al., 1609.01290]
  - electroweak precision observables (calculated at the 2L level using THDM_EWPOS), [Hessenberger & Hollik,1607.04610,2207.03845]
  - SM-like Higgs measurements via HiggsSignals, [Bechtle et al., 2012.09197]
  - direct searches for BSM scalars via HiggsBounds, [Bechtle et al., 2006.06007]
  - b-physics constraints.
- Most constraints checked using ScannerS. [Mühlleitner et al., 2007.02985]
- For each point passing the constraints, we calculate κ_λ at the 1L and 2L level ($\kappa_\lambda^{(1)}$ and $\kappa_\lambda^{(2)}$). [Braathen,Kanemura,1911.11507]

2HDM parameter scan — results

(showing only points passing all constraints mentioned on previous slide)



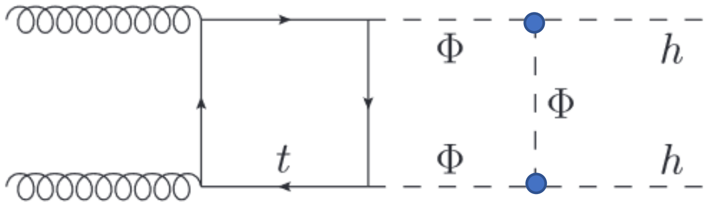


- Largest corrections for $m_A \simeq m_{H^\pm}, m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}, m_A < m_{H^\pm}$ (κ_λ of up to 9).
- 2L corrections have sizeable impact (up to 70%).

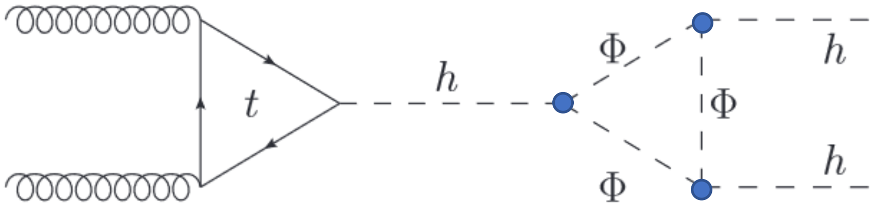
Can we apply the experimental constraints on κ_λ?

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?



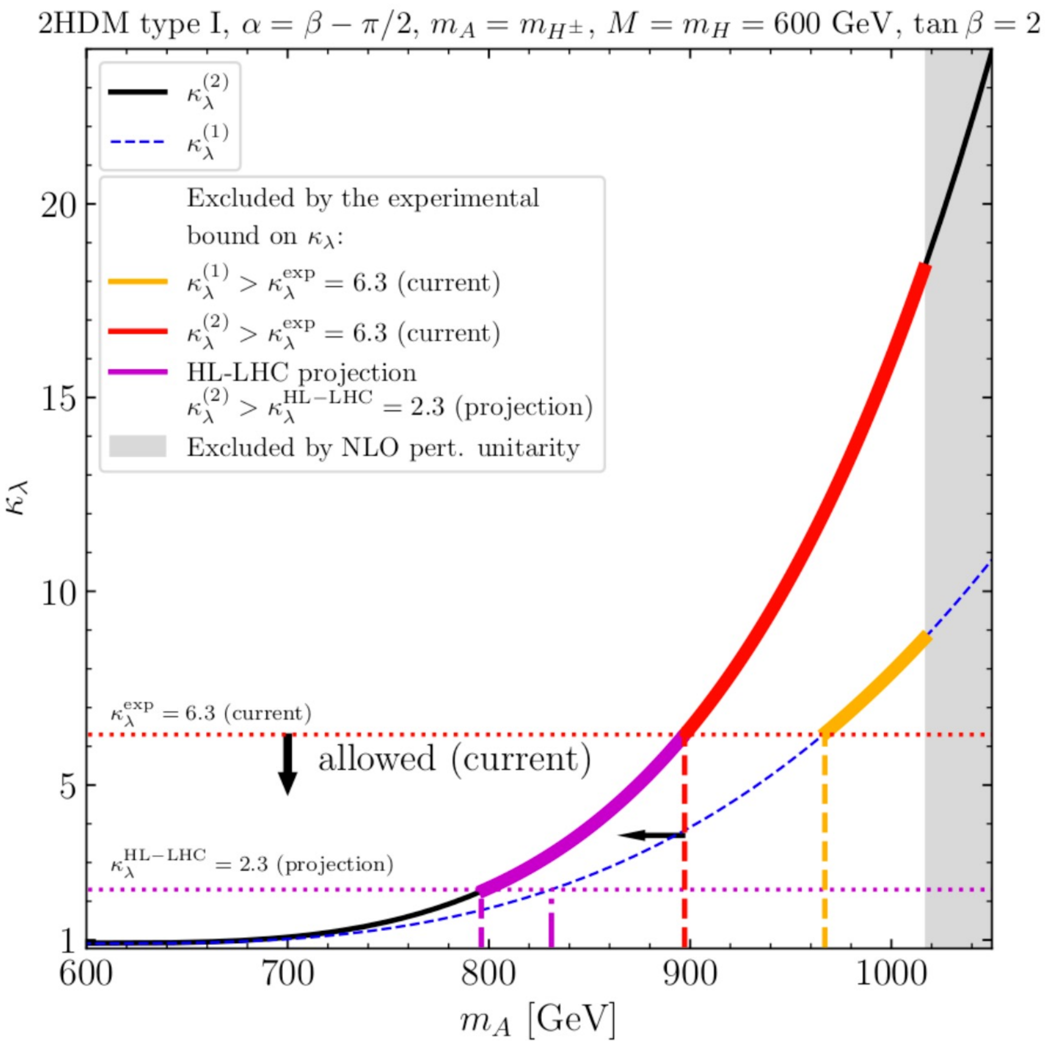
$\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ (not included)



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

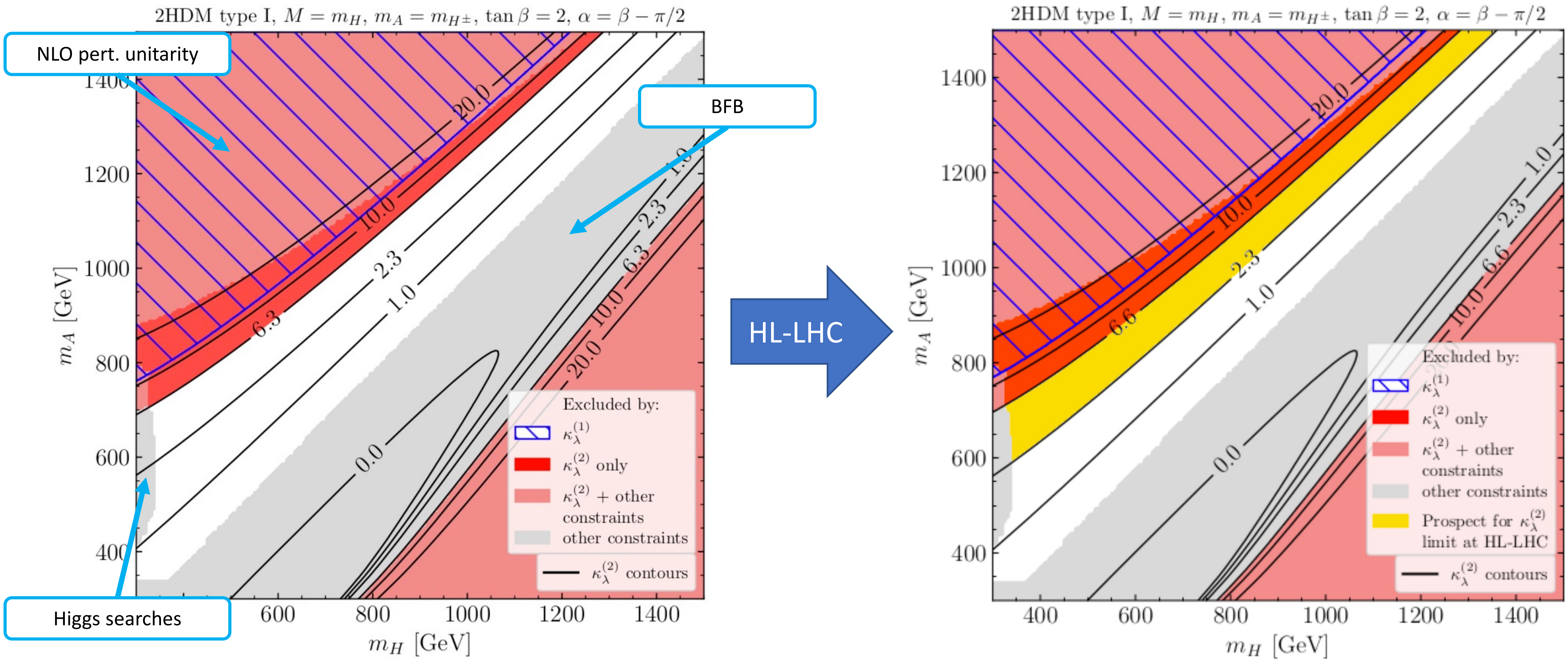
  - ➢ We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level.

Constraints on κ_λ — 1D scan



Experimental bound on κ_λ excludes so far unconstrained parameter space!

Constraints on κ_λ — benchmark scenario



Conclusions

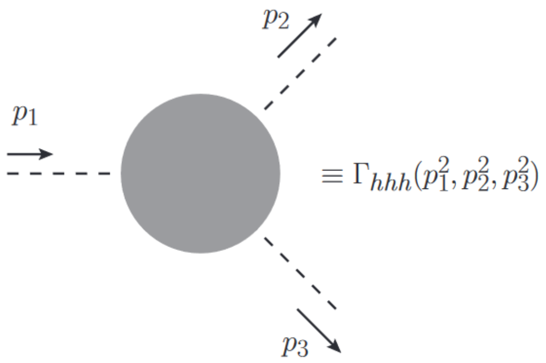
- Measurement of the **trilinear Higgs coupling** crucial to determine shape of Higgs potential.
- Large deviations from the SM possible in many BSM models.
- We showed that already current bounds exclude significant parts of so far unconstrained 2HDM parameter space.
- Including 2L corrections important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

Thanks for your attention!

Appendix

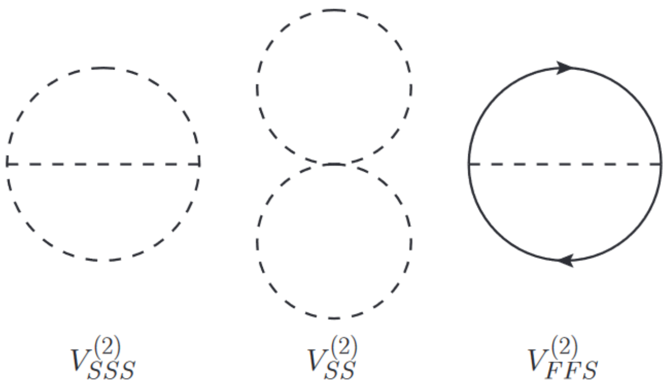
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



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

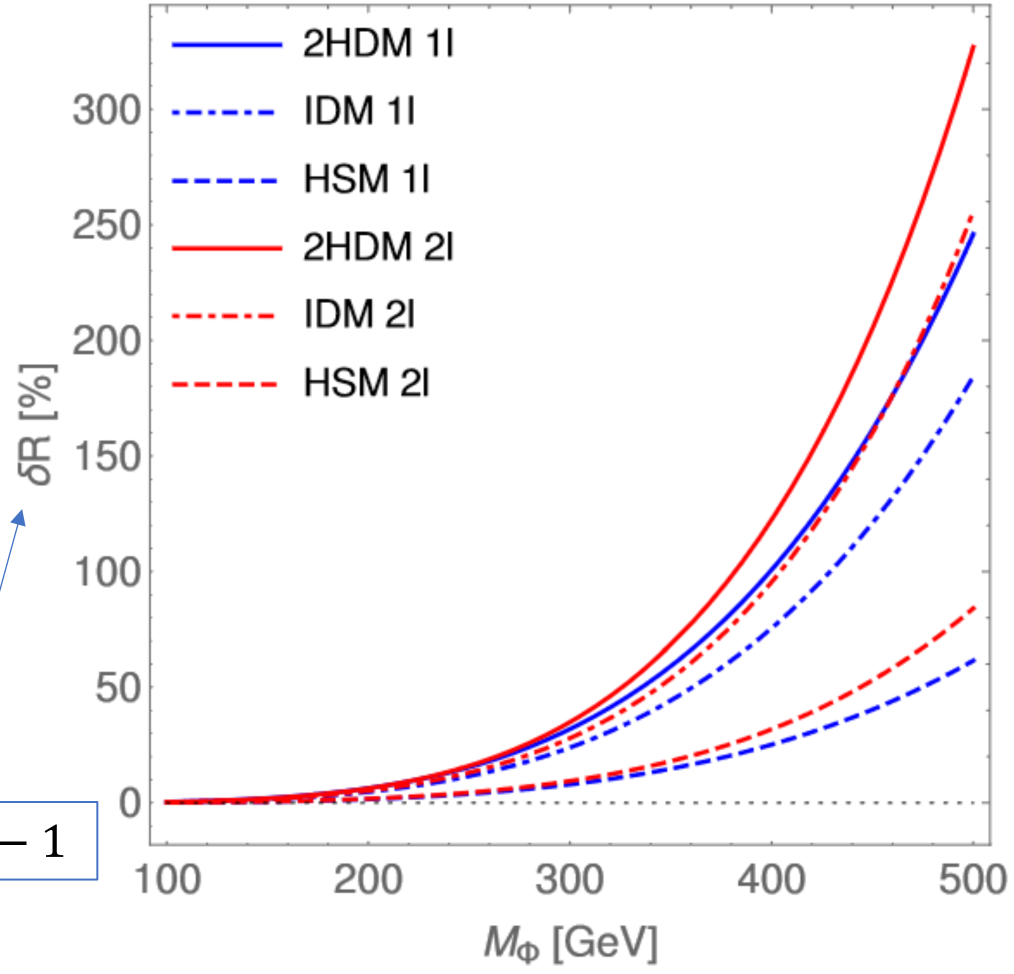
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda_{hhh}^{(0)} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- 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]



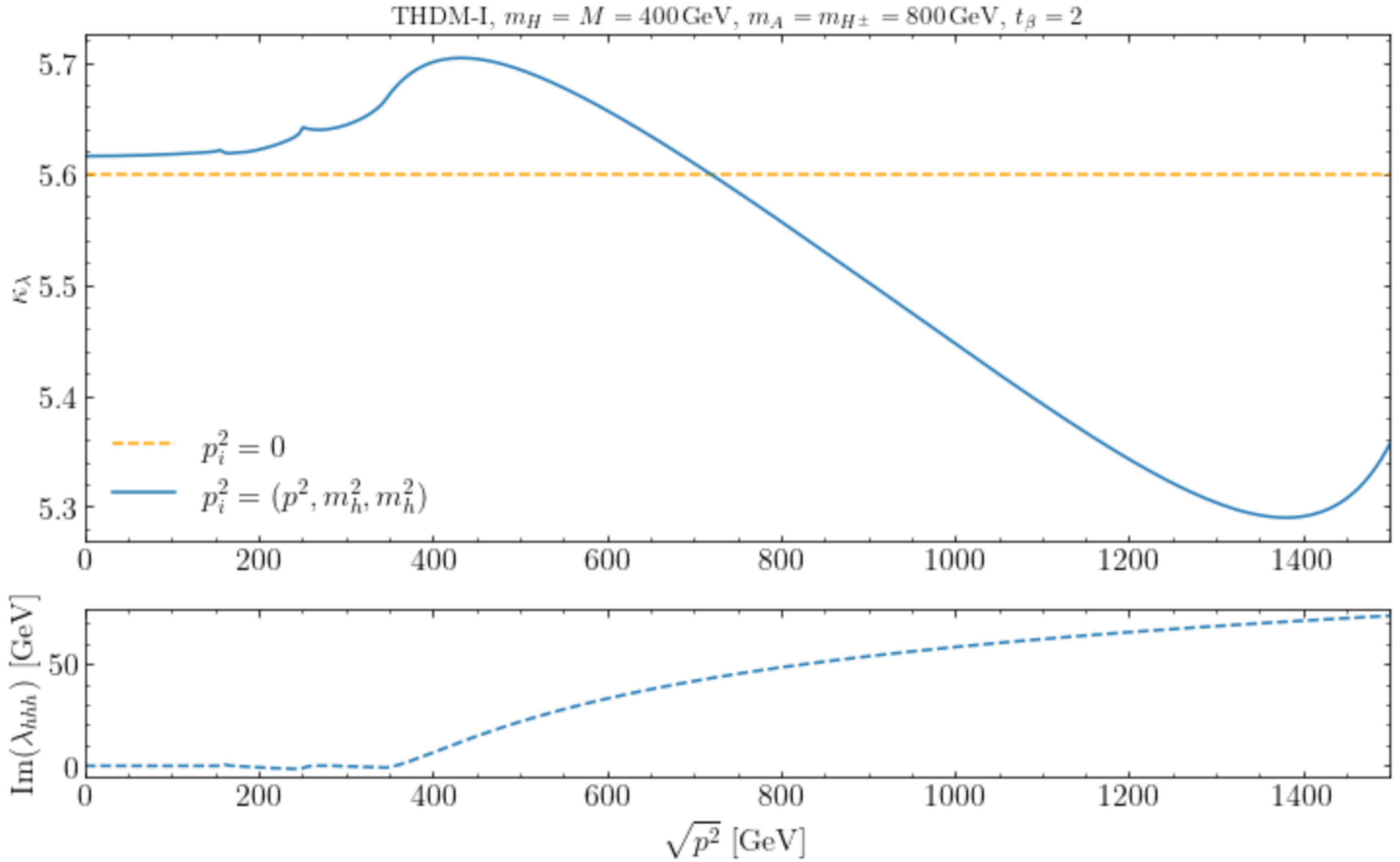
$\delta R = \kappa_\lambda - 1$

- 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.

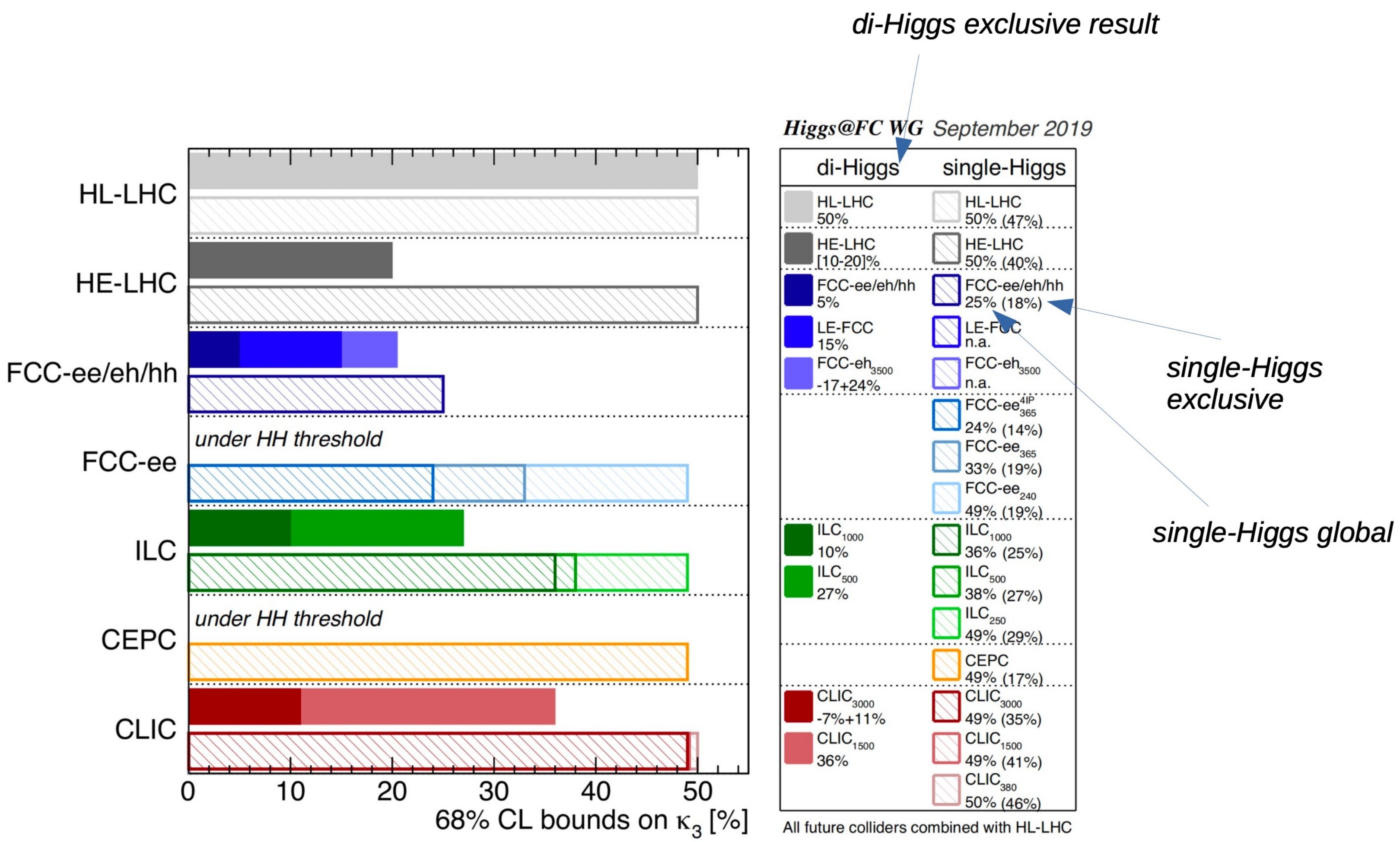
Idea of this work:

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

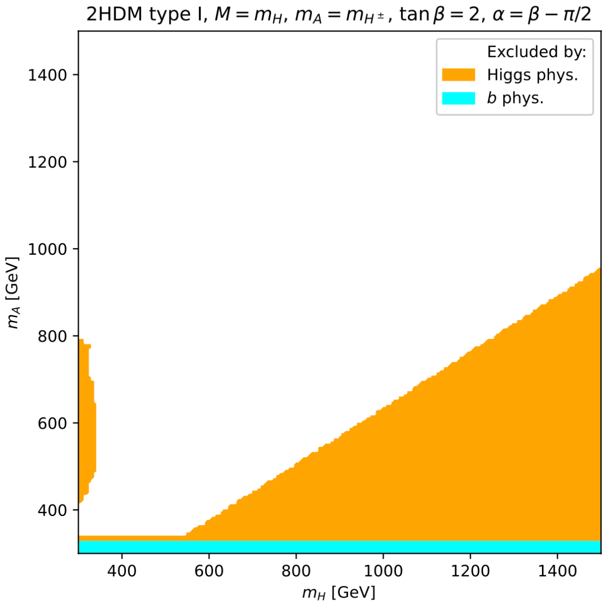
Momentum dependence



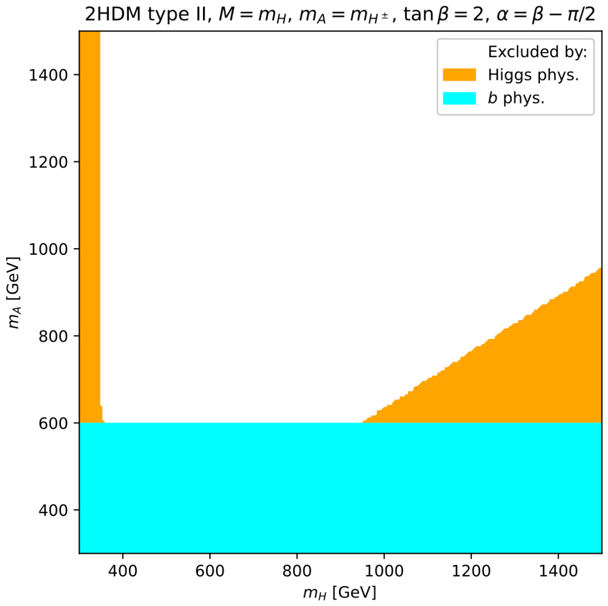
Projections for future colliders



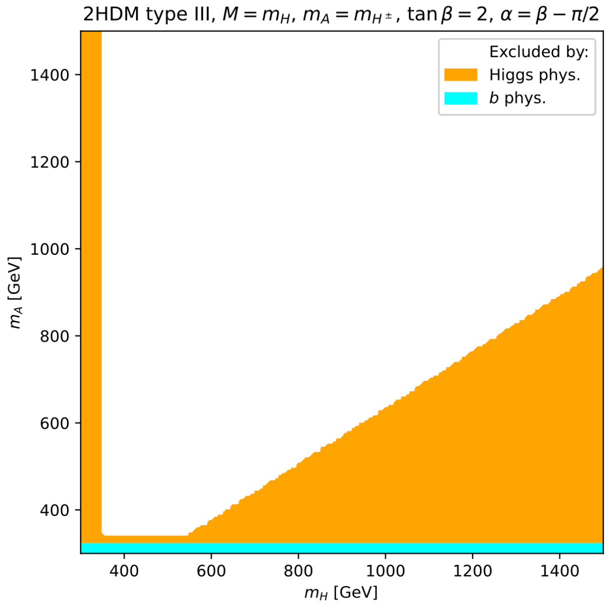
Comparison of 2HDM types



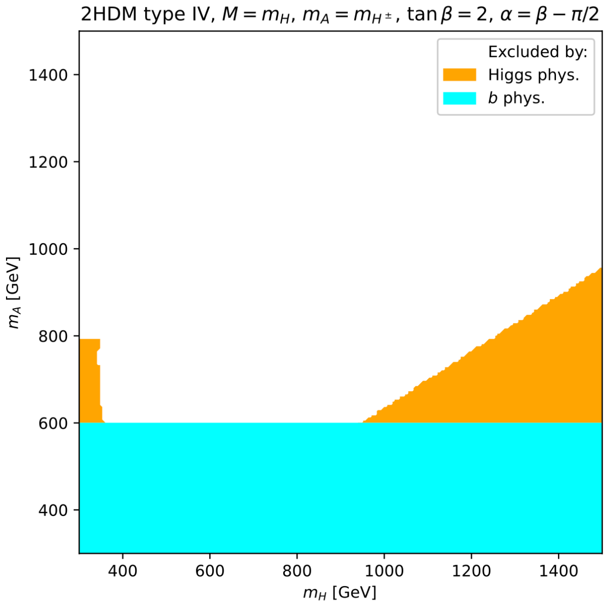
Type-I



Type-II



Type-III (LS)



Type-IV (flipped)