New constraints on extended Higgs sectors from the trilinear Higgs coupling

Based on

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

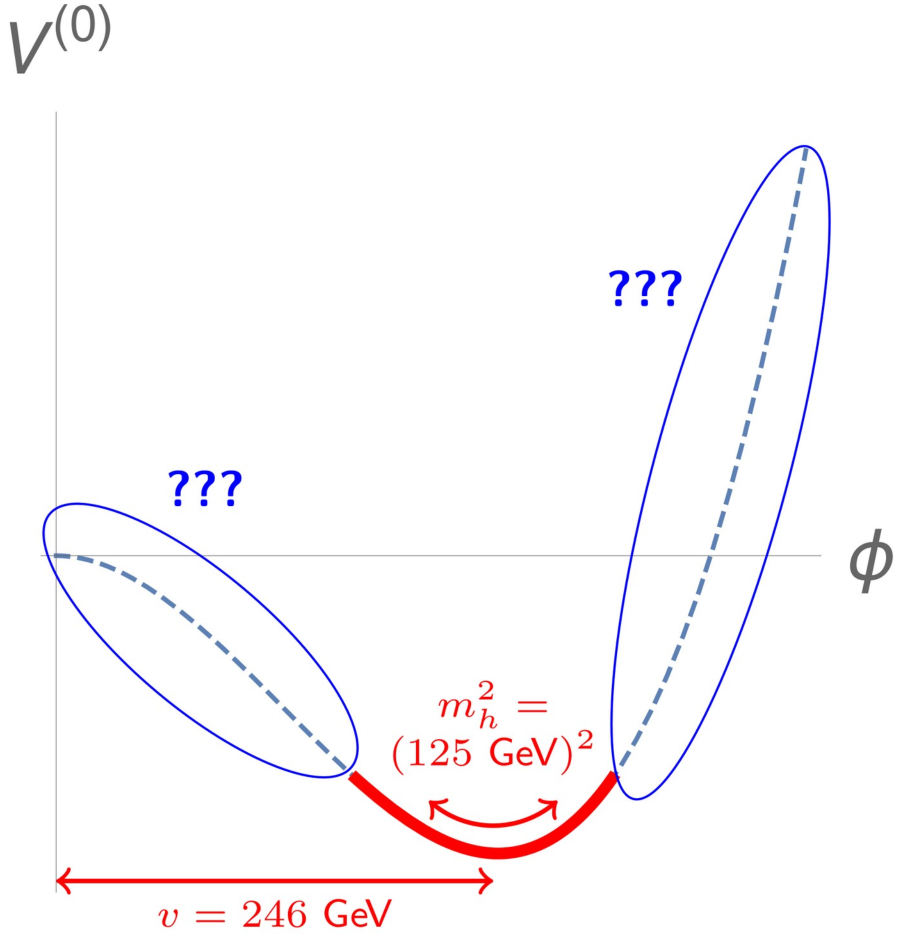
(as well as arXiv:1903.05417 (PLB), 1911.11507 (EPJC) in collaboration with Shinya Kanemura)

Johannes Braathen

Helmholtz program days "Matter and the Universe" 2022,
GSI, Darmstadt, Germany | October 20-21, 2022

Why study the trilinear Higgs coupling λ_{hhh}?

- **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 $\mathcal{L} \supset -\frac{1}{6}\lambda_{hhh}h^3$

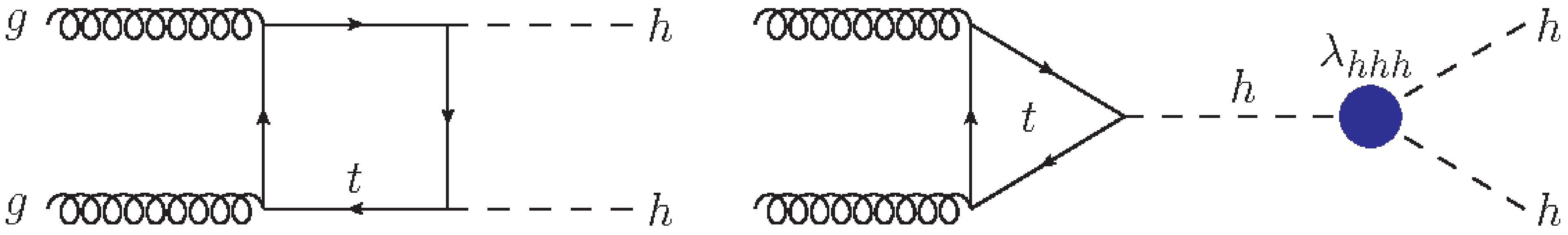


- **λ_{hhh} determines the nature of the EWPT!**
  ⇒ O(20%) deviation of λ_{hhh} from its SM prediction needed to have a strongly first-order EWPT → necessary for EWBG [Grojean, Servant, Wells '04], [Kanemura, Okada, Senaha '04]
  → see also **FT by L. Biermann!**

- ***New in this talk***: **studying λ_{hhh} can also serve to constrain the parameter space of Beyond-the-Standard-Model (BSM) theories!**

Experimental situation for λ_{hhh}

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



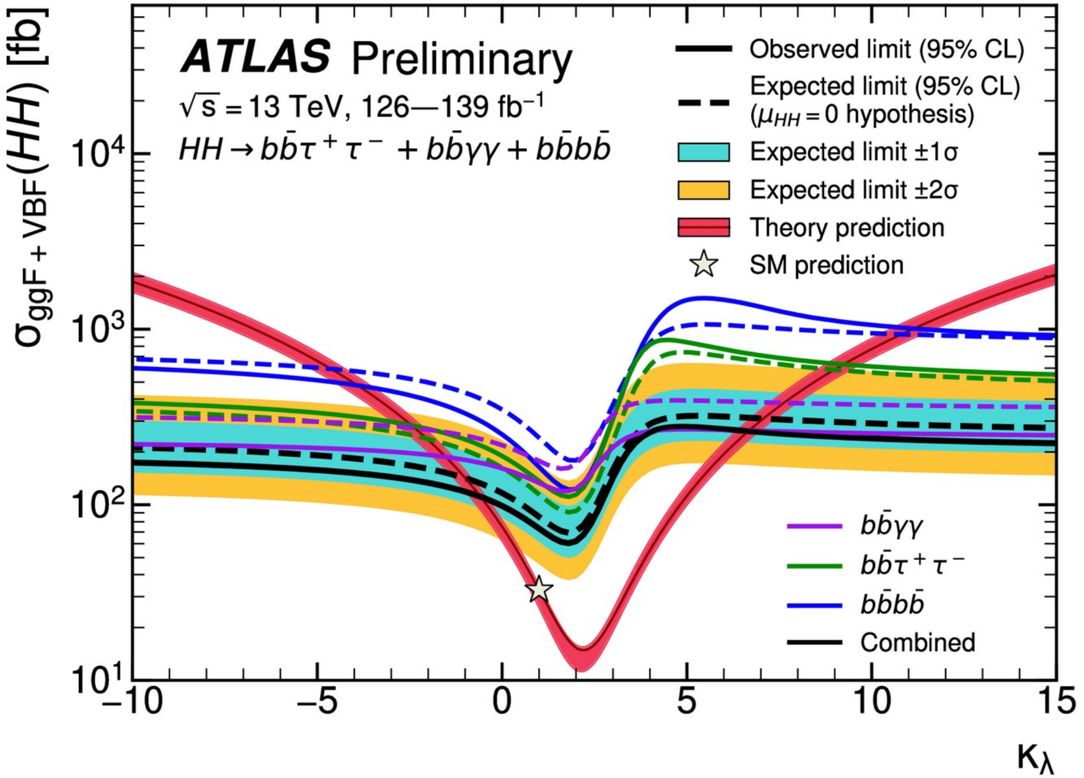
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

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

- Search limits on double-Higgs production
  → **limits on $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$**

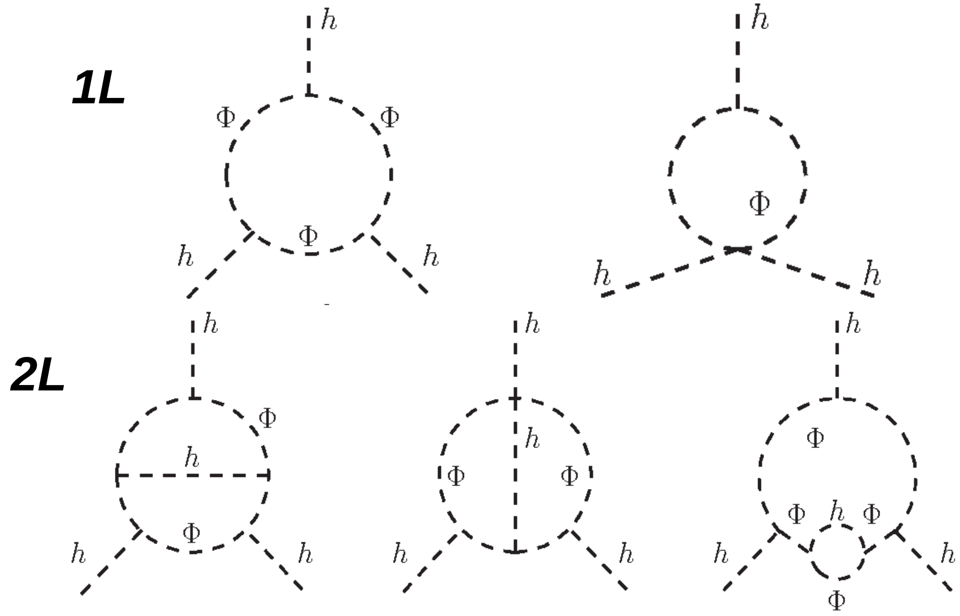
$-0.4 < \kappa_\lambda < 6.3$

[ATLAS-CONF-2022-050]



Non-decoupling effects in λ_{hhh}

- Calculations of BSM contributions at one loop (1L) in [Kanemura, Okada, Senaha, Yuan ‘04], and at two loops (2L) in [Senaha ‘18], [JB, Kanemura ‘19, ‘20]



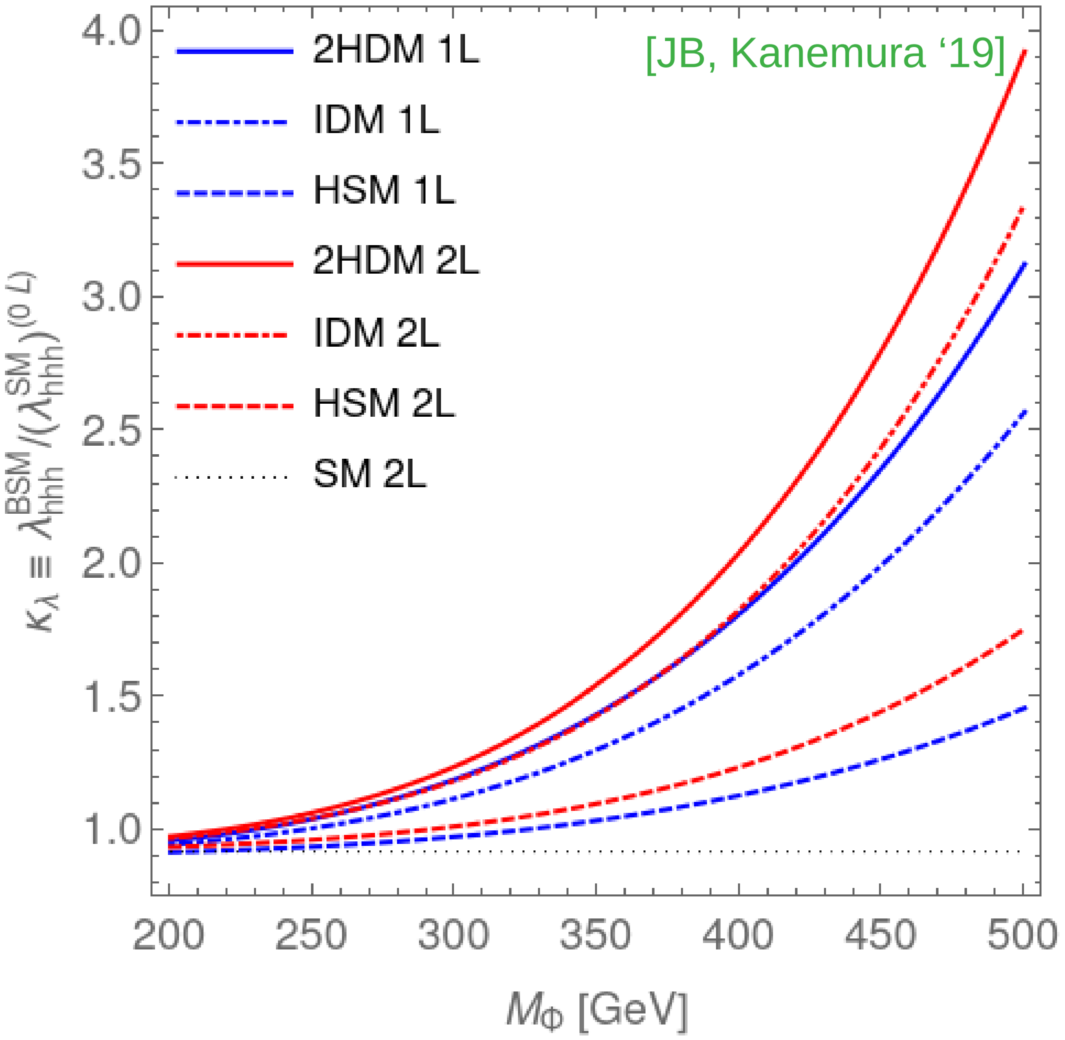
- Involve BSM scalars Φ and couplings

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

BSM mass parameter *BSM scalar mass*

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

- **Non-decoupling effects**, now found in various models, e.g. Two-Higgs-Doublet Model (2HDM), Inert Doublet Model (IDM), singlet extensions (like HSM), etc.



A benchmark scenario in the aligned 2HDM

[Bahl, JB, Weiglein 2202.03453]

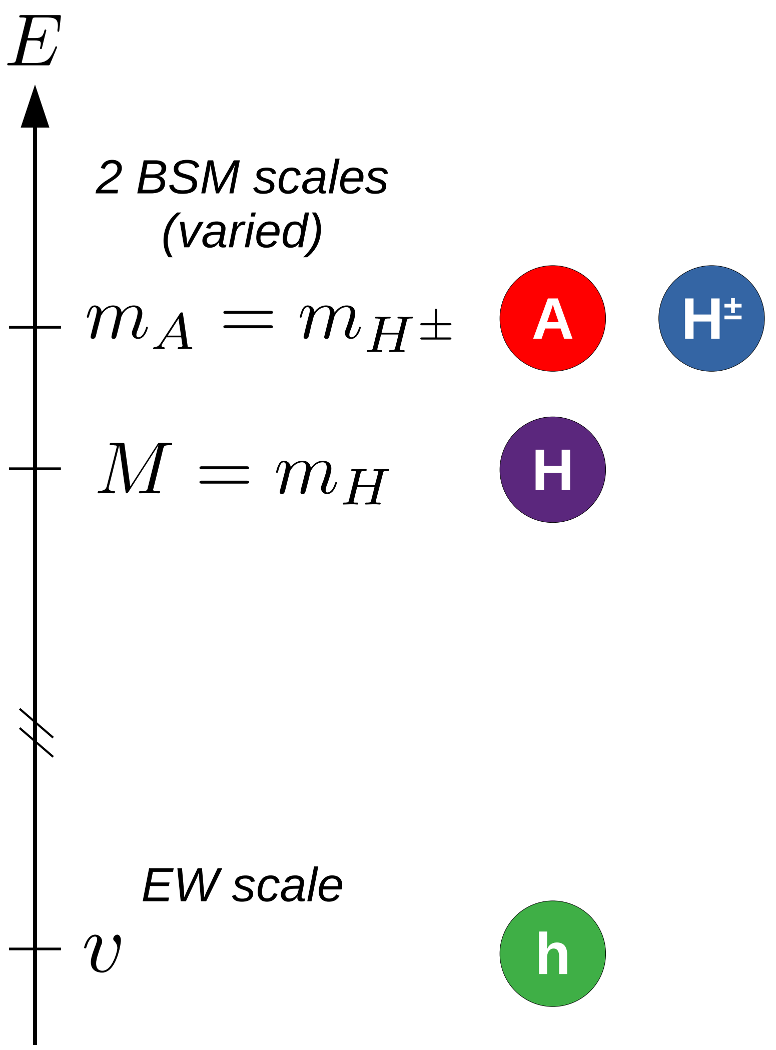
- **Two-Higgs-Doublet Model (2HDM)**:
  add a 2nd scalar doublet to the SM

  Here: CP conservation assumed, Yukawa couplings of type I

- Mass eigenstates:
  - 2 CP-even Higgs bosons

    h (125-GeV Higgs), H
  - CP-odd Higgs boson A
  - Charged Higgs bosons $H^{\pm}$
  - M: new mass term in 2HDM

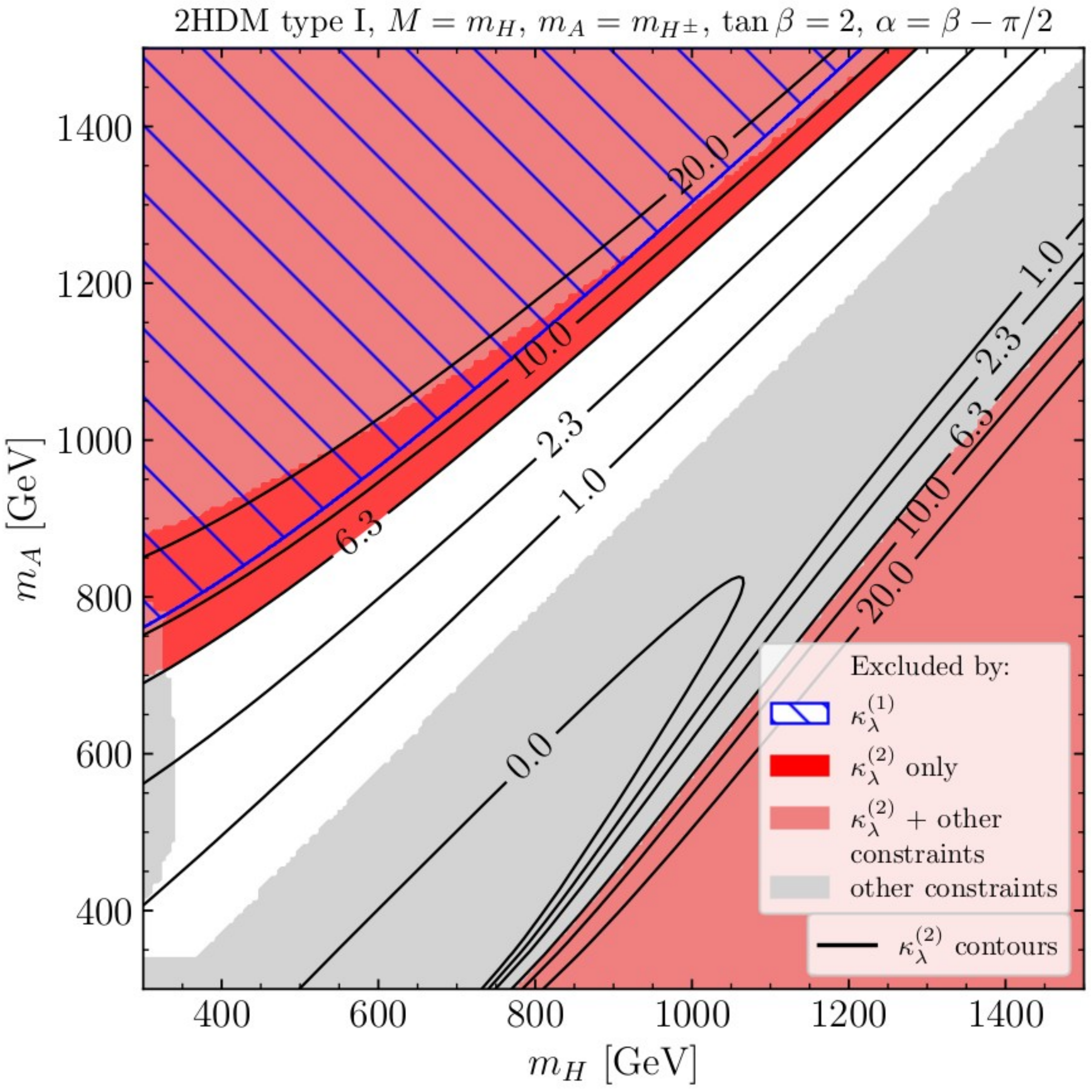
- Scenario with **alignment**: couplings of h are SM-like at tree level



A benchmark scenario in the aligned 2HDM

Results shown for aligned 2HDM of type-I, similar for other types or other models

[Bahl, JB, Weiglein 2202.03453]



- ***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 $\kappa_\lambda^{(2)} > 6.3$
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.3$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.3$ → impact of including 2L corrections is significant!

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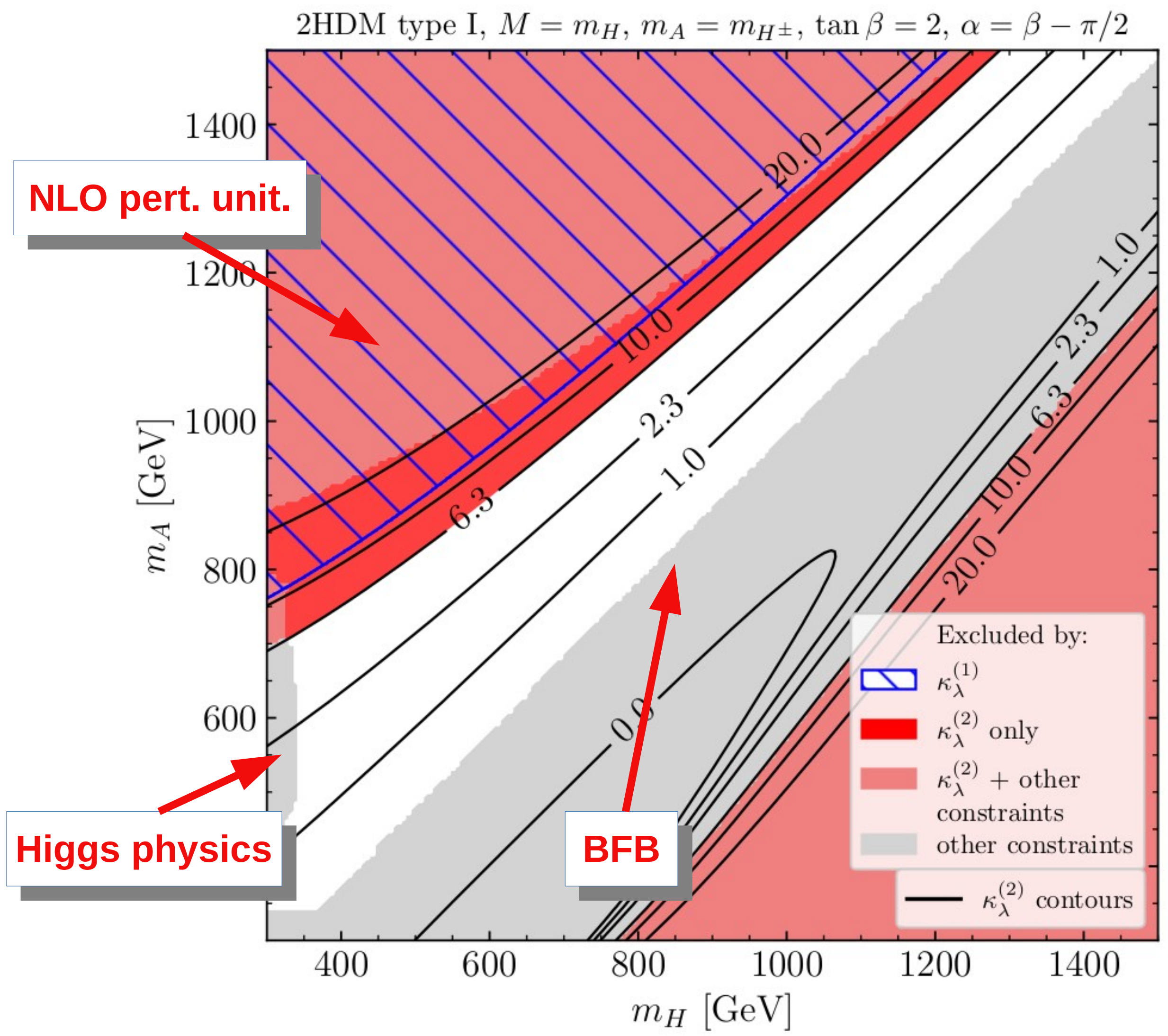

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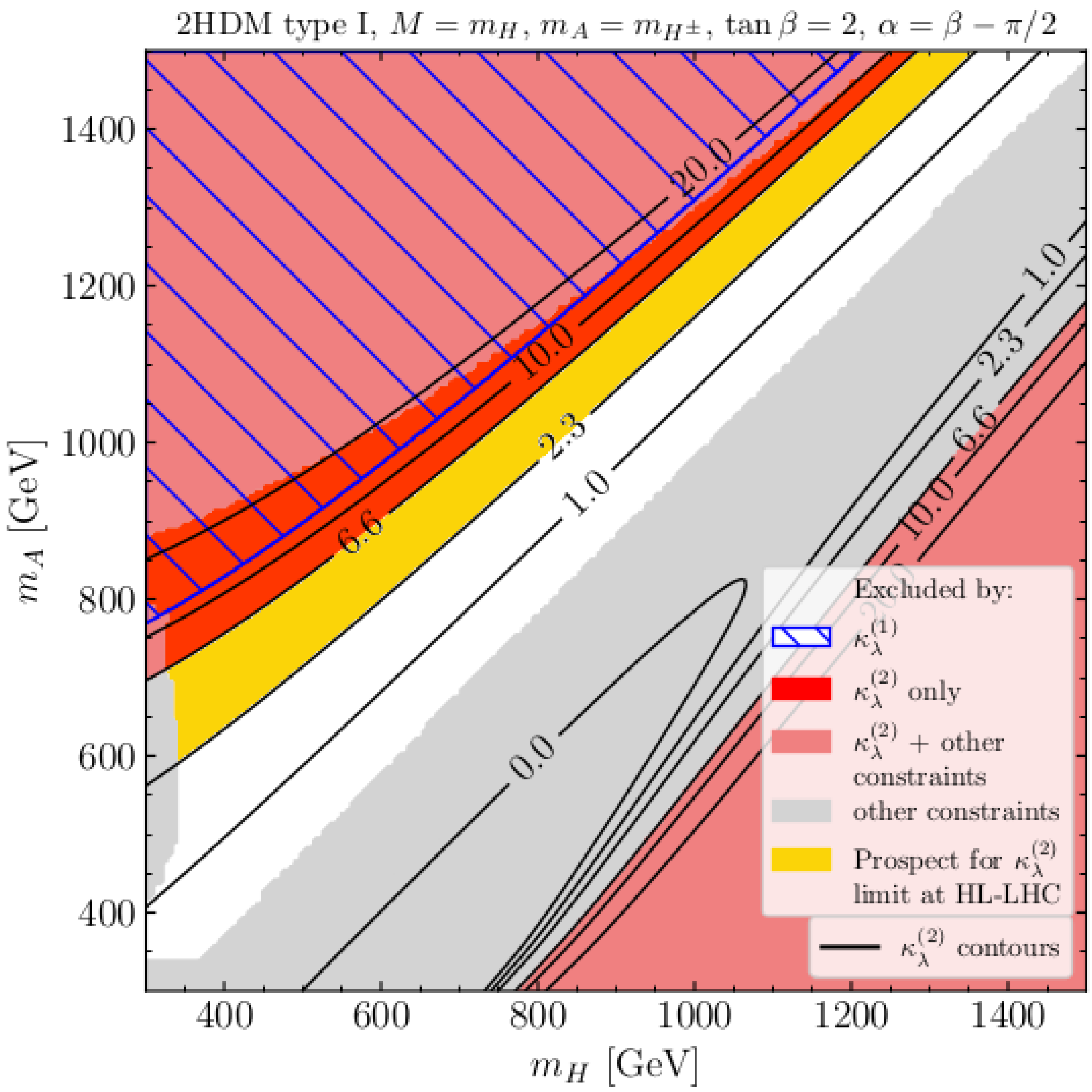
A benchmark scenario in the aligned 2HDM – future prospects



- ***Golden area:*** additional exclusion with the limit achievable at HL-LHC $\kappa_\lambda^{(2)} < 2.3$ (prospects even better with e^+e^- collider)
- Experimental constraints, such as Higgs physics, may also become more stringent, however **not** theoretical constraints (like BFB or perturbative unitarity)

Thank you for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Johannes Braathen
DESY Theory group
johannes.braathen@desy.de

Backup

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

$$\begin{aligned} V_{\text{2HDM}}^{(0)} = {} & m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2) \\ & + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \frac{\lambda_5}{2}\Big((\Phi_2^\dagger\Phi_1)^2 + \text{h.c.}\Big) \end{aligned}$$

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

- **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

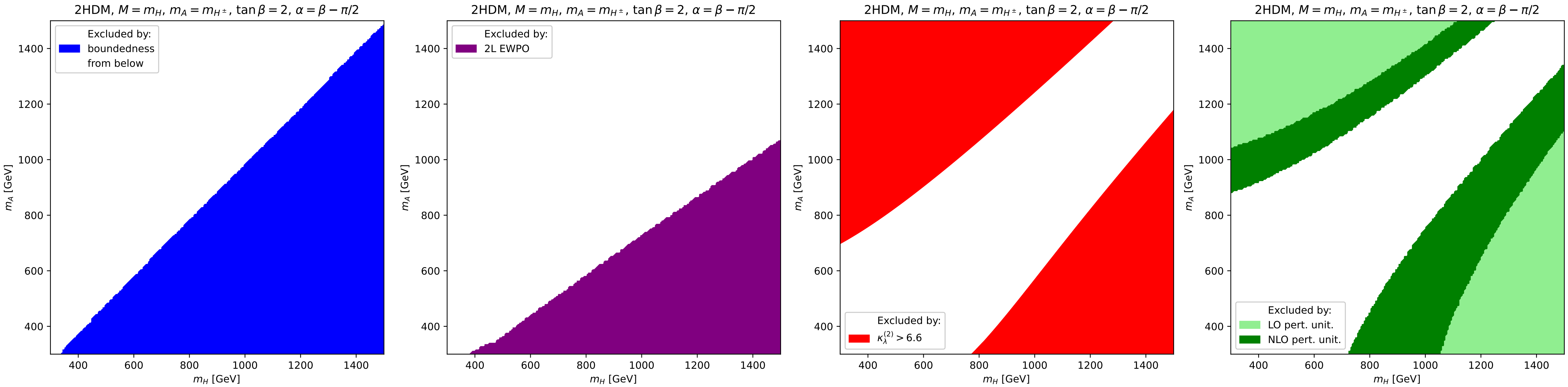
- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv 2m_3^2/s_{2\beta}$), angles α and β (defined by $\tan\beta = v_2/v_1$)

- **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!

2HDM benchmark plane – individual theoretical constraints

Constraints shown below are independent of 2HDM type



Boundedness from below

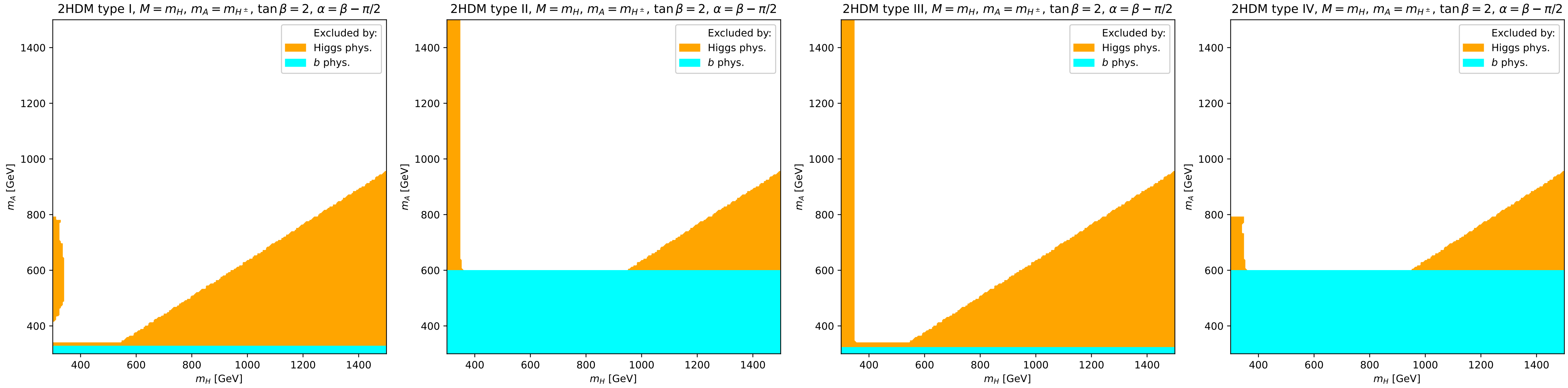
EW precision observables computed at 2L

$\kappa_\lambda^{(2)} > 6.6$

Perturbative unitarity at (N)LO

2HDM benchmark plane – experimental constraints

i.e. Higgs physics (via HiggsBounds and HiggsSignals) and *b* physics (from [Gfitter group 1803.01853])



Type-I Type-II Type-III (LS) Type-IV (flipped)

2HDM benchmark plane – experimental constraints

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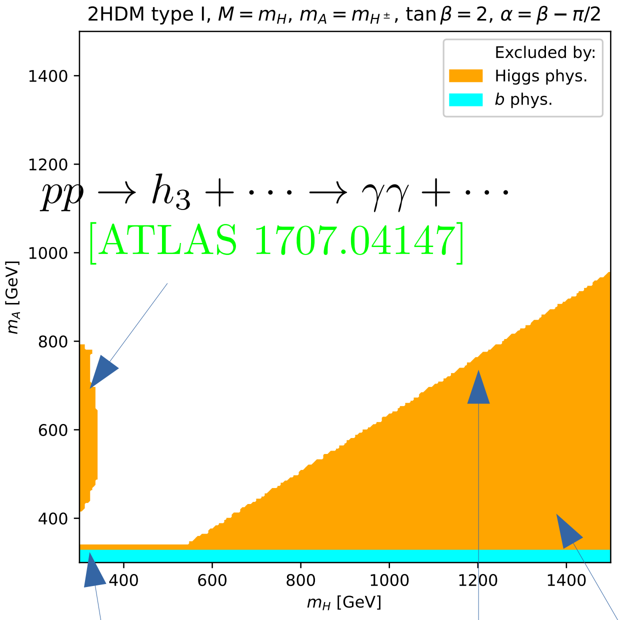
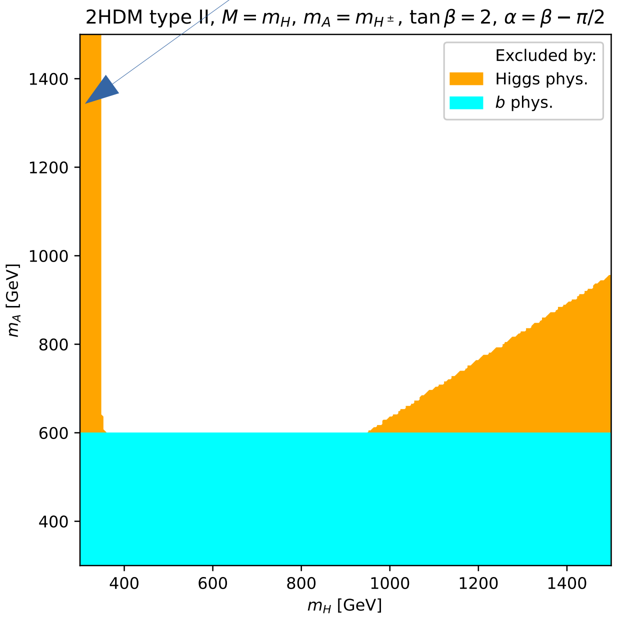
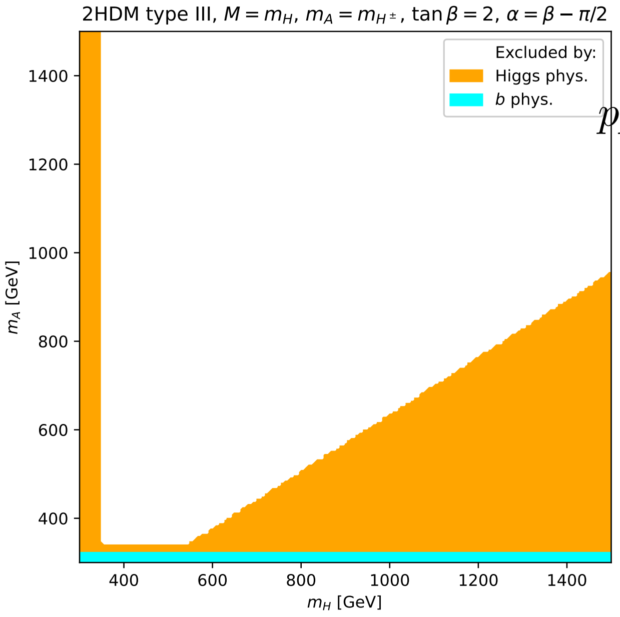
$pp \to h_3 + \cdots \to \tau\tau + \cdots$
[ATLAS 2002.12223]



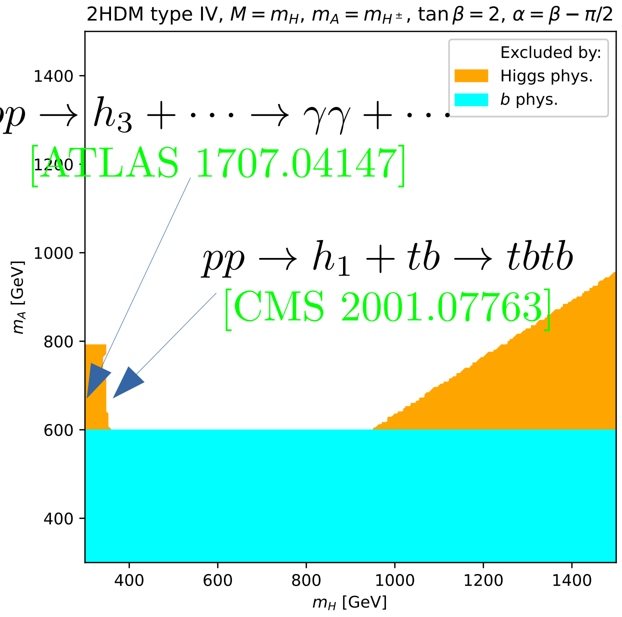
Type-I



Type-II



Type-III (LS)



Type-IV (flipped)

$pp \to h_3 + \cdots \to \gamma\gamma + \cdots$
[ATLAS 1707.04147]

$pp \to h_2 + \cdots \to \tau\tau + \cdots$
[ATLAS 2002.12223]

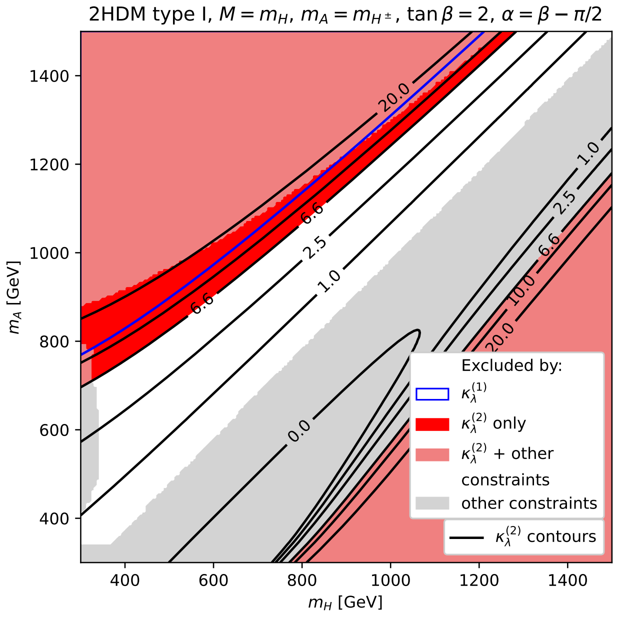
$pp \to h_1 + \cdots \to \gamma\gamma + \cdots$
[CMS 1407.0558]

$pp \to h_1 + \cdots$
[CMS-PAS-HIG-12-045]

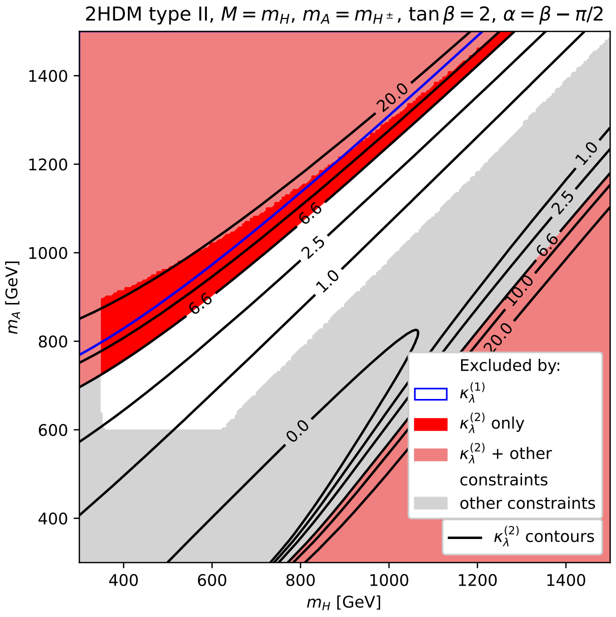
$pp \to h_3 + \cdots \to \gamma\gamma + \cdots$
[ATLAS 1707.04147]

$pp \to h_1 + tb \to tbtb$
[CMS 2001.07763]

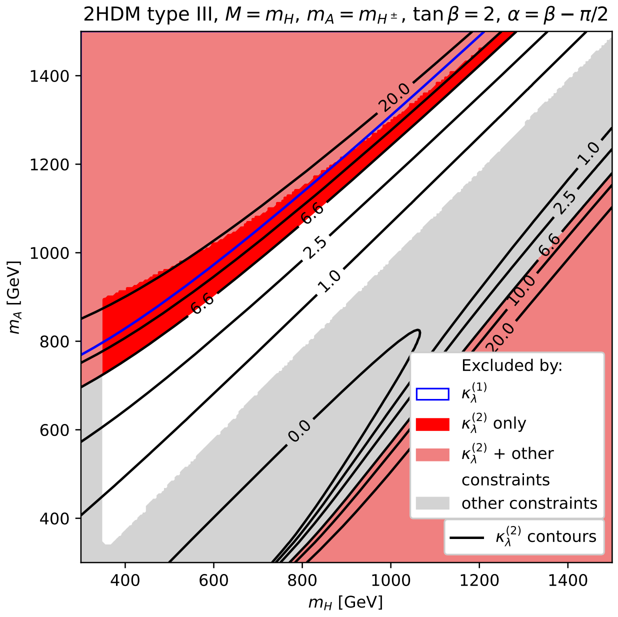
2HDM benchmark plane – results for all types



Type-I



Type-II



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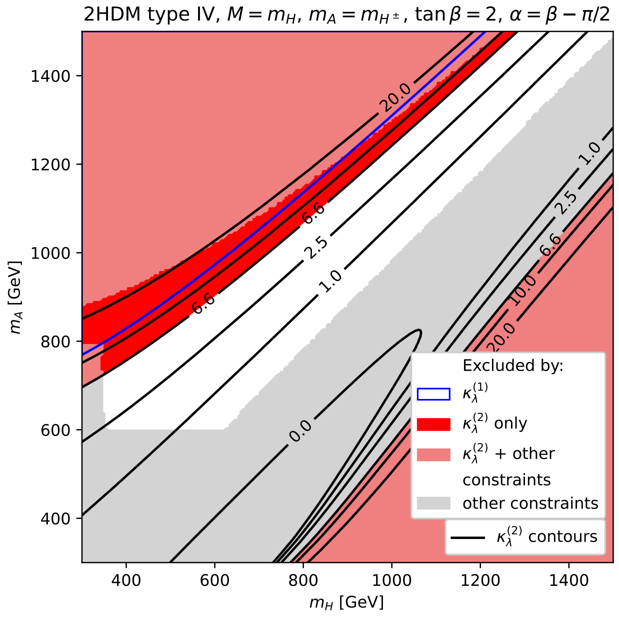

Type-IV (flipped)