Trilinear Higgs coupling calculations @ two loops

Based on

arXiv:1903.05417 (PLB), 1911.11507 (EPJC), 2011.07580 (JHEP),in collaboration with Shinya Kanemura and Makoto Shimoda

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

WIPs in collaboration with Henning Bahl, Martin Gabelmann Sebastian Paßehr, and Georg Weiglein

Johannes Braathen

KUTS @ CERN | February 28, 2023

Outline of the talk

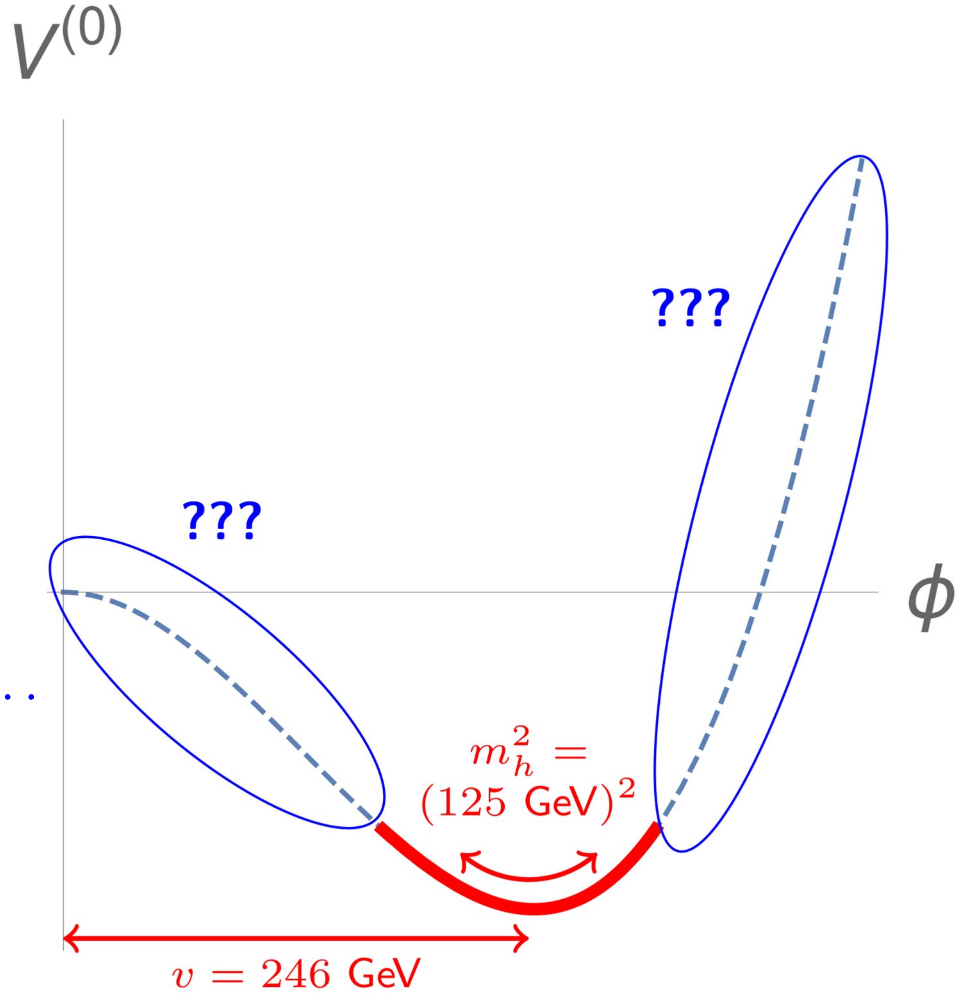
- Why study the trilinear Higgs coupling λ_{hhh} *(overlap with Martin's talks)*
- Two-loop corrections to λ_{hhh} in extensions of the SM
  - An aligned scenario of the 2HDM [JB, Kanemura '19, '19]
  - Classical scale-invariant theories [JB, Kanemura, Shimoda '20]
- New constraints on BSM models from λ_{hhh} [Bahl, JB, Weiglein '22], [Bahl, JB, Gabelmann, Weiglein, WIP]
- A word on automation @ 2 loops [Bahl, JB, Gabelmann, Paßehr, WIP]

Why investigate λ_{hhh}?

Probing the shape of 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}**



- In the SM: $V^{(0)}_{\text{SM}} = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\underbrace{\left(\frac{3m_h^2}{v}\right)}_{\equiv(\lambda^{(0)}_{hhh})^{\text{SM}}} h^3 + \frac{1}{4!}\left(\frac{3m_h^2}{v^2}\right) h^4 + \cdots$

- In general:

$$V^{(0)} = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\overbrace{\kappa_\lambda\left(\frac{3m_h^2}{v}\right)}^{\equiv\lambda_{hhh}} h^3 + \frac{1}{4!}\kappa_{\lambda_4}\left(\frac{3m_h^2}{v^2}\right) h^4 + \cdots$$

with $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda^{(0)}_{hhh})^{\text{SM}}$

The Higgs potential and the Electroweak Phase Transition

Possible thermal history of the Higgs potential:

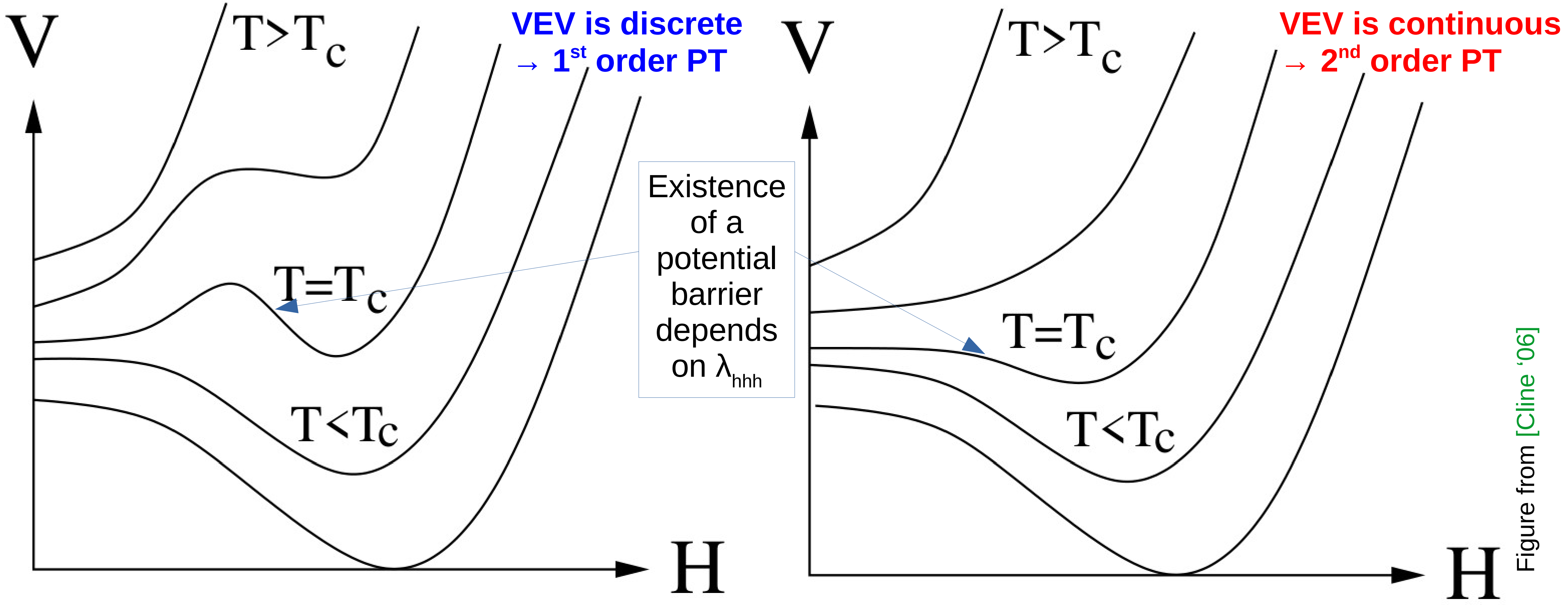


Figure from [Cline '06]

- **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

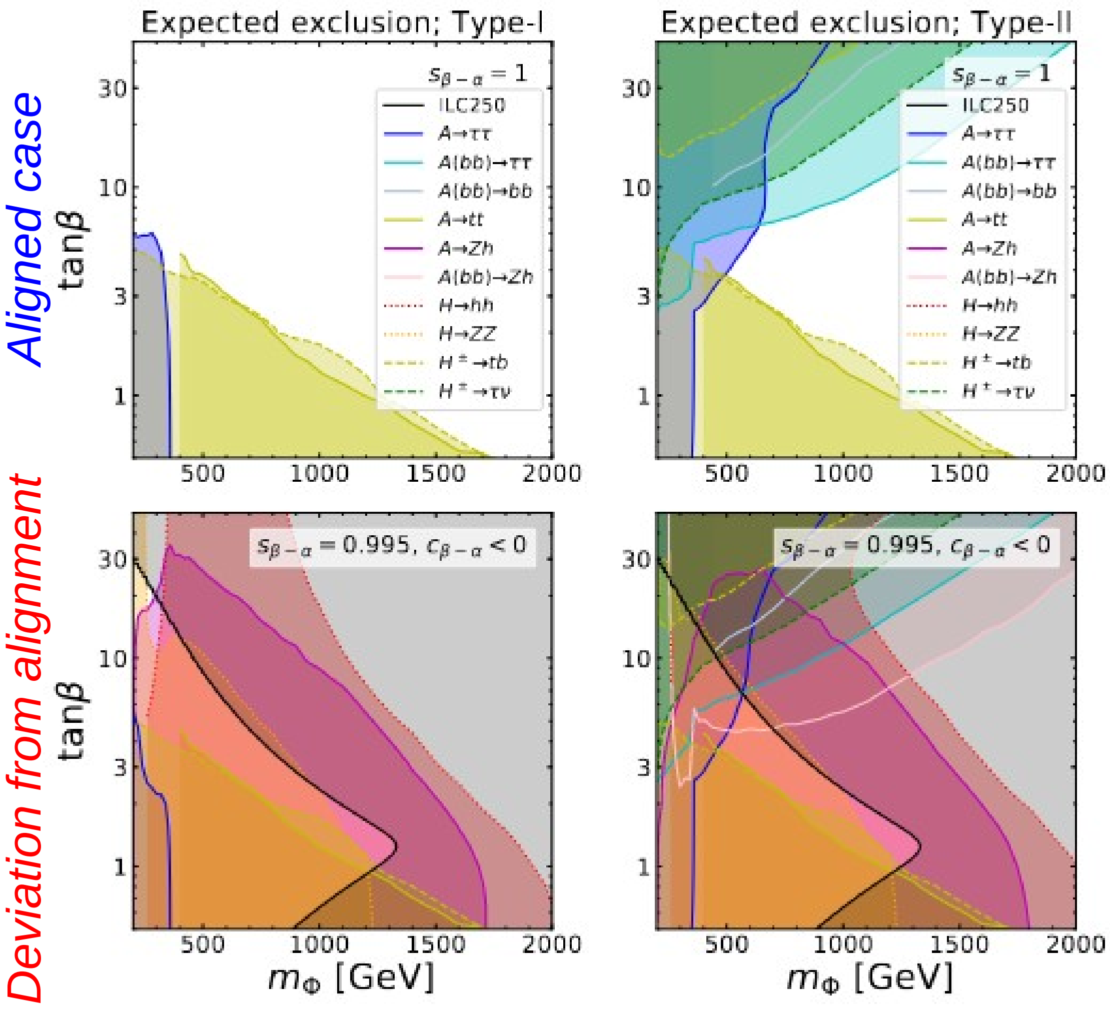
  [Grojean, Servant, Wells '04], [Kanemura, Okada, Senaha '04]

Distinguishing aligned scenarios with or without decoupling

- No concrete sign of BSM Physics so far + Higgs couplings are SM-like
  → favours ***aligned scenarios***, i.e. scenarios where Higgs couplings are *SM-like at tree-level*

- **Synergy** of **direct searches** (LHC, HL-LHC) and **indirect searches** (→ ILC) strongly constrain non-aligned scenarios (see e.g. for MSSM [Bagnaschi et al. '18], for 2HDM [Aiko et al. '20])
  → In some models, aligned scenarios could be almost entirely excluded in near future!

e.g. for Two-Higgs-Doublet Model (2HDM) variants



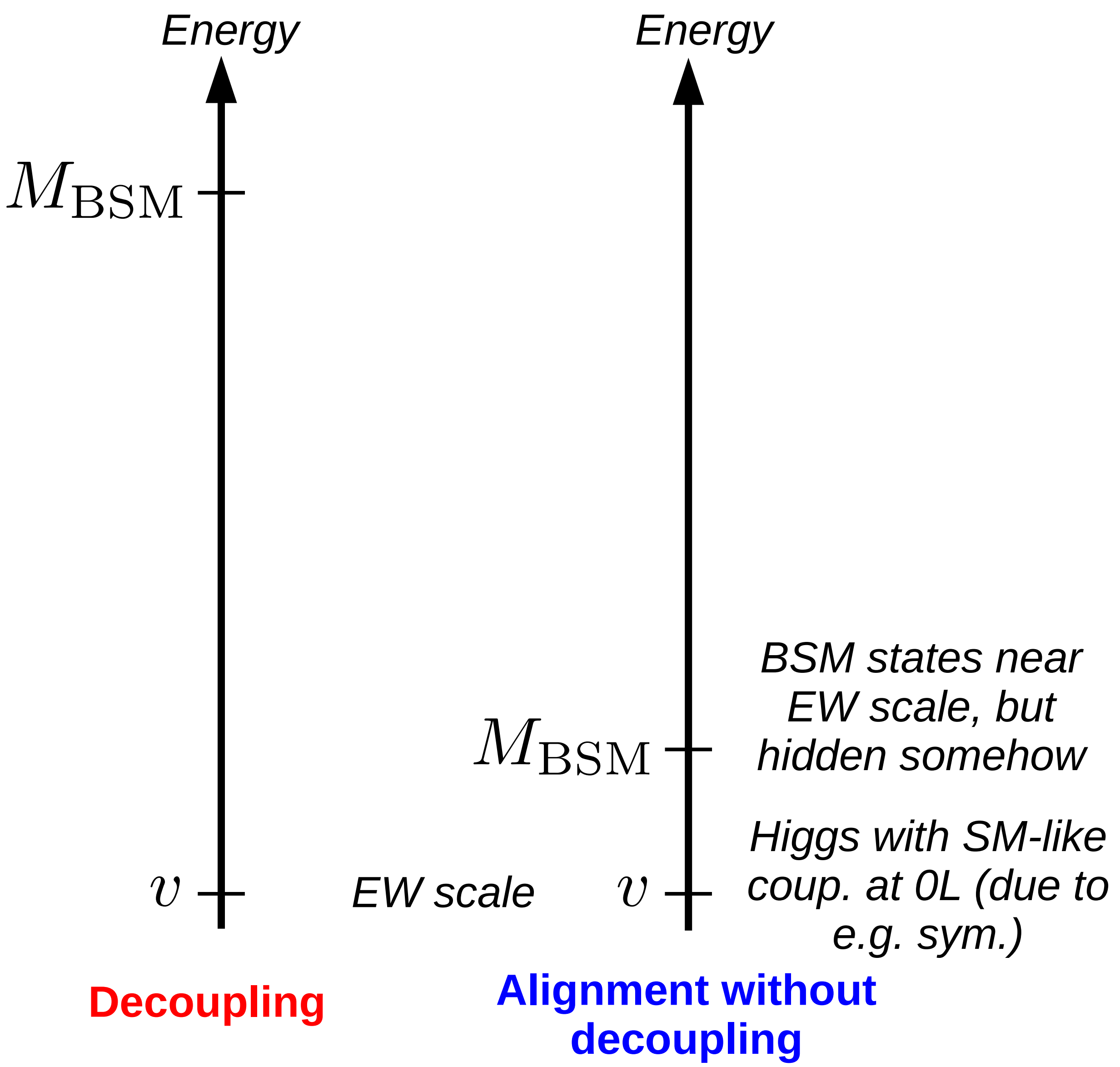
[Aiko et al. 2010.15057]

Distinguishing aligned scenarios with or without decoupling

- If alignment is favoured, how does it occur?
  → **Alignment through decoupling**? or **alignment without decoupling**?

- If *alignment without decoupling*, Higgs couplings **like λ_{hhh}** can still exhibit large deviations from SM predictions because of **non-decoupling effects from BSM loops**

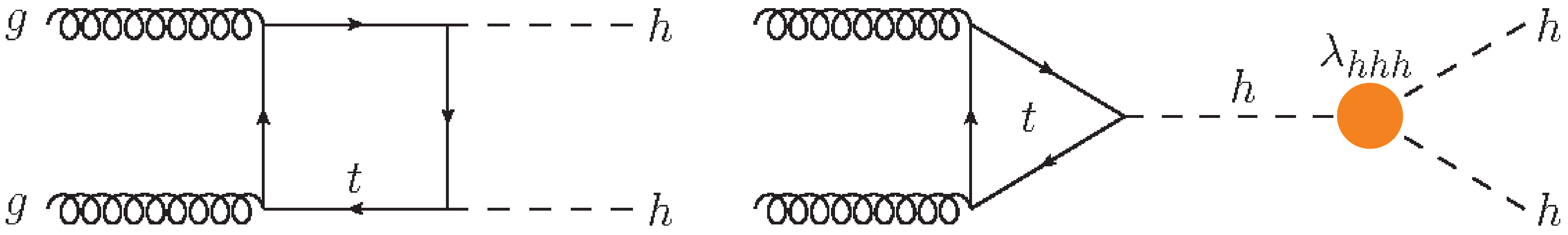
- λ_{hhh} could be a **prime target**: not very well measured yet but with prospects for drastical improvements in the future!



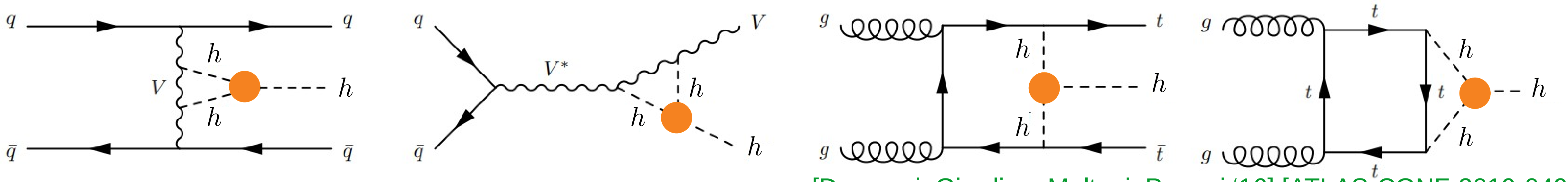
Accessing λ_{hhh} experimentally

Experimental probes of λ_{hhh}

- **Double-Higgs production** → λ_{hhh} enters at <u>leading order (LO)</u> → **most direct probe!**

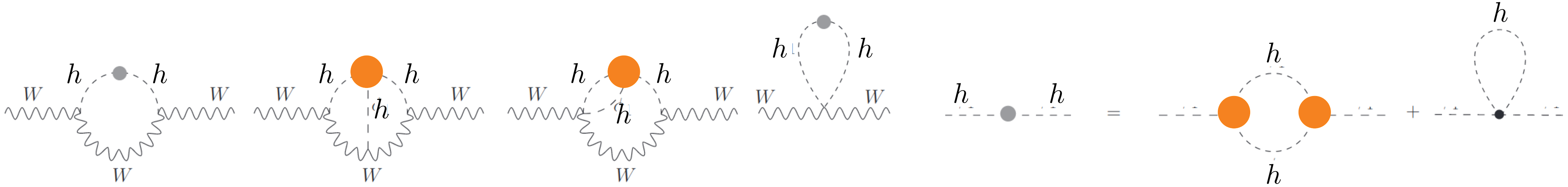


- **Single-Higgs production** → λ_{hhh} enters at <u>NLO</u>



[Degrassi, Giardino, Maltoni, Pagani '16] [ATLAS-CONF-2019-049]

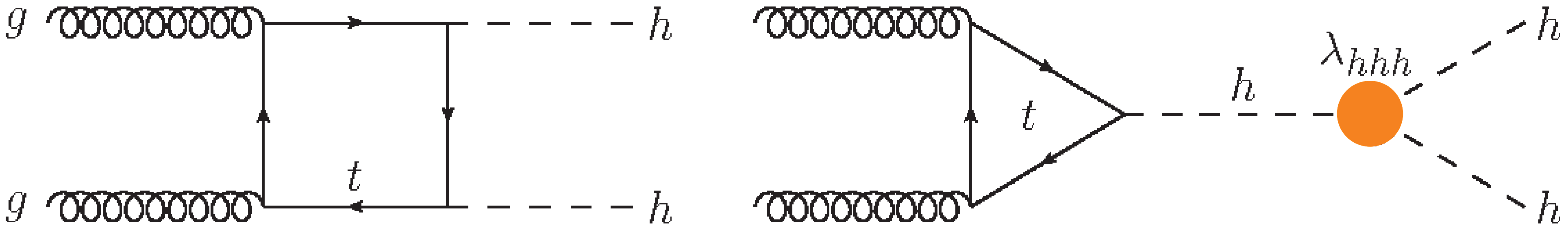
- **Electroweak Precision Observables** (EWPOs) → λ_{hhh} enters at <u>NNLO</u>



[Degrassi, Fedele, Giardino '17]

Accessing λ_{hhh} via double-Higgs production

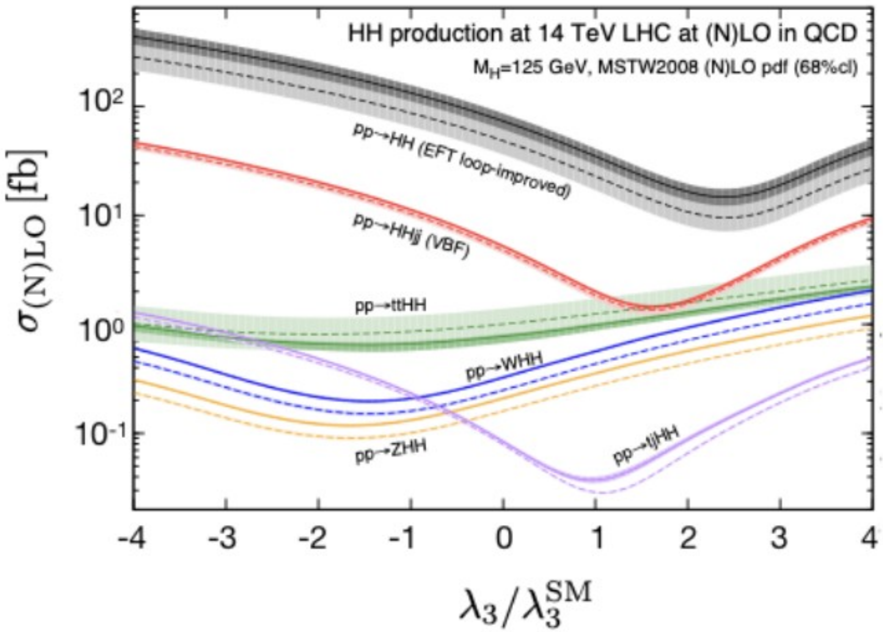
- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



- Box and triangle diagrams **interfere destructively**
  → small prediction in SM
  → BSM deviation in λ_{hhh} can **significantly alter di-Higgs 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-2022-050]
yield the limits:

-0.4 < κ_λ < 6.3 at 95% C.L.

→ factor ~2 improvement compared to
pre-2021 best ATLAS limits (from single-h prod.)
-3.2 < κ_λ < 11.9 at 95% C.L. [ATLAS-PHYS-PUB-2019-009]

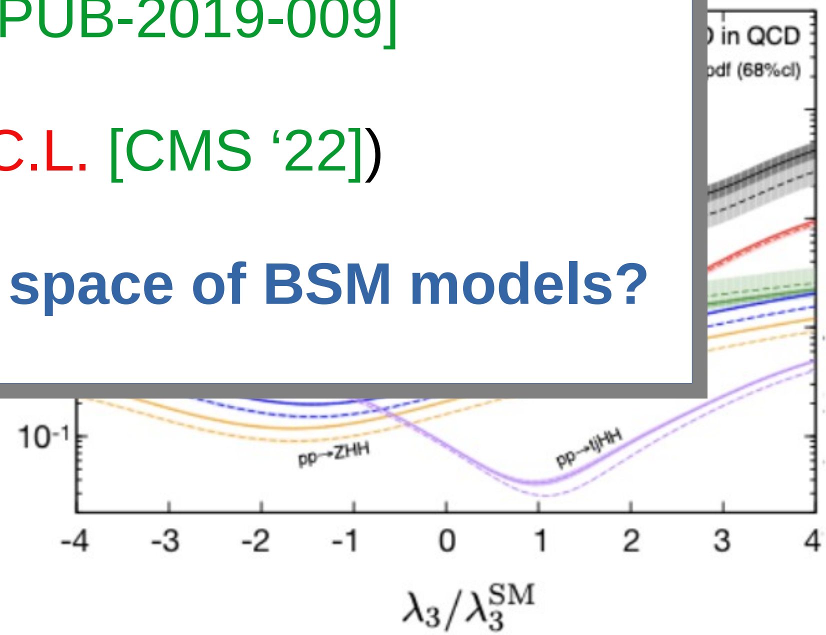
(CMS recently gave **-1.2 < κ_λ < 6.5** at 95% C.L. [CMS '22])

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

- Box
→ sı
→ B
hh-p

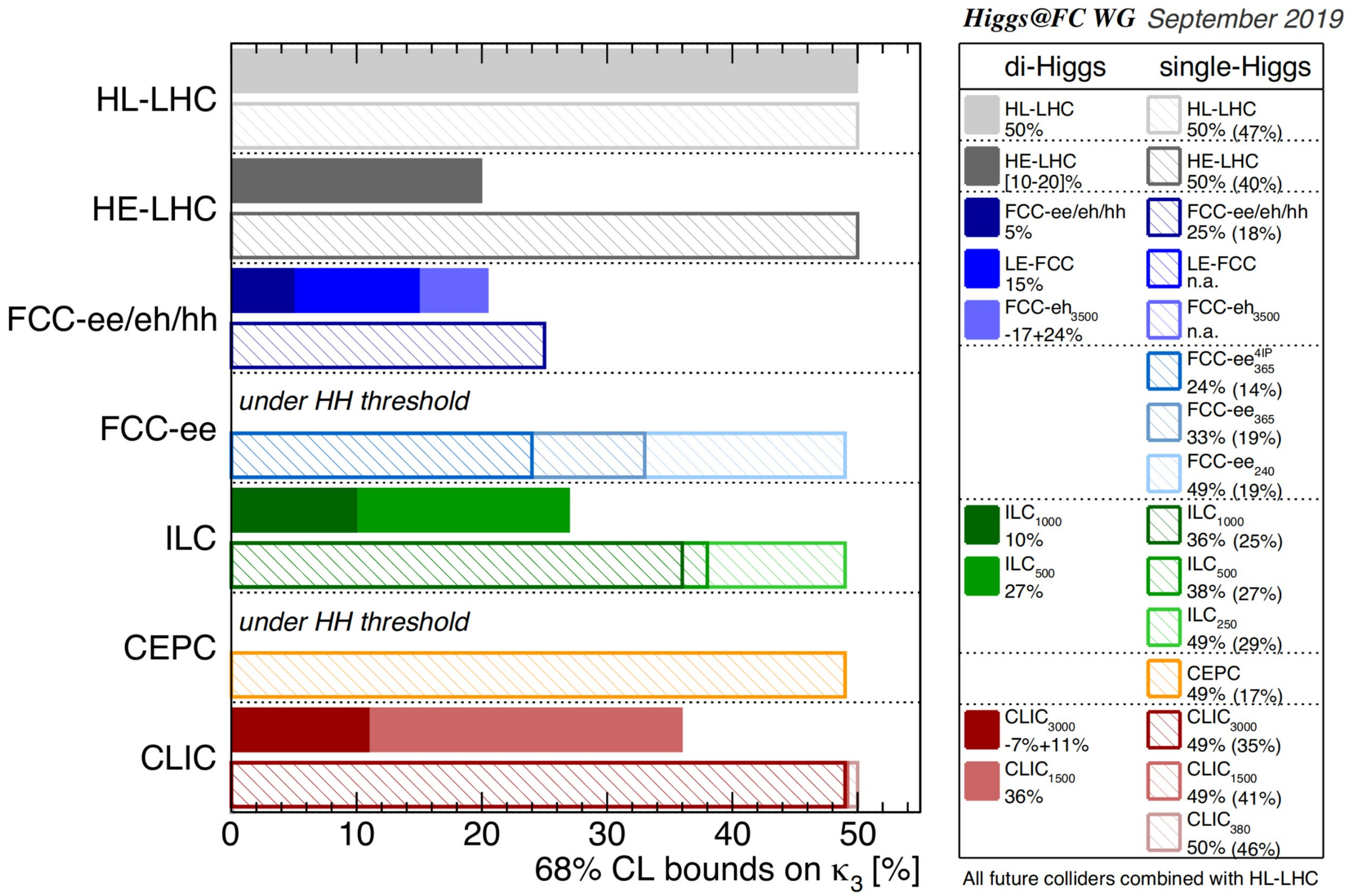
- Uppe
κ_λ≡λ

- 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]

Future determination of λ_{hhh}

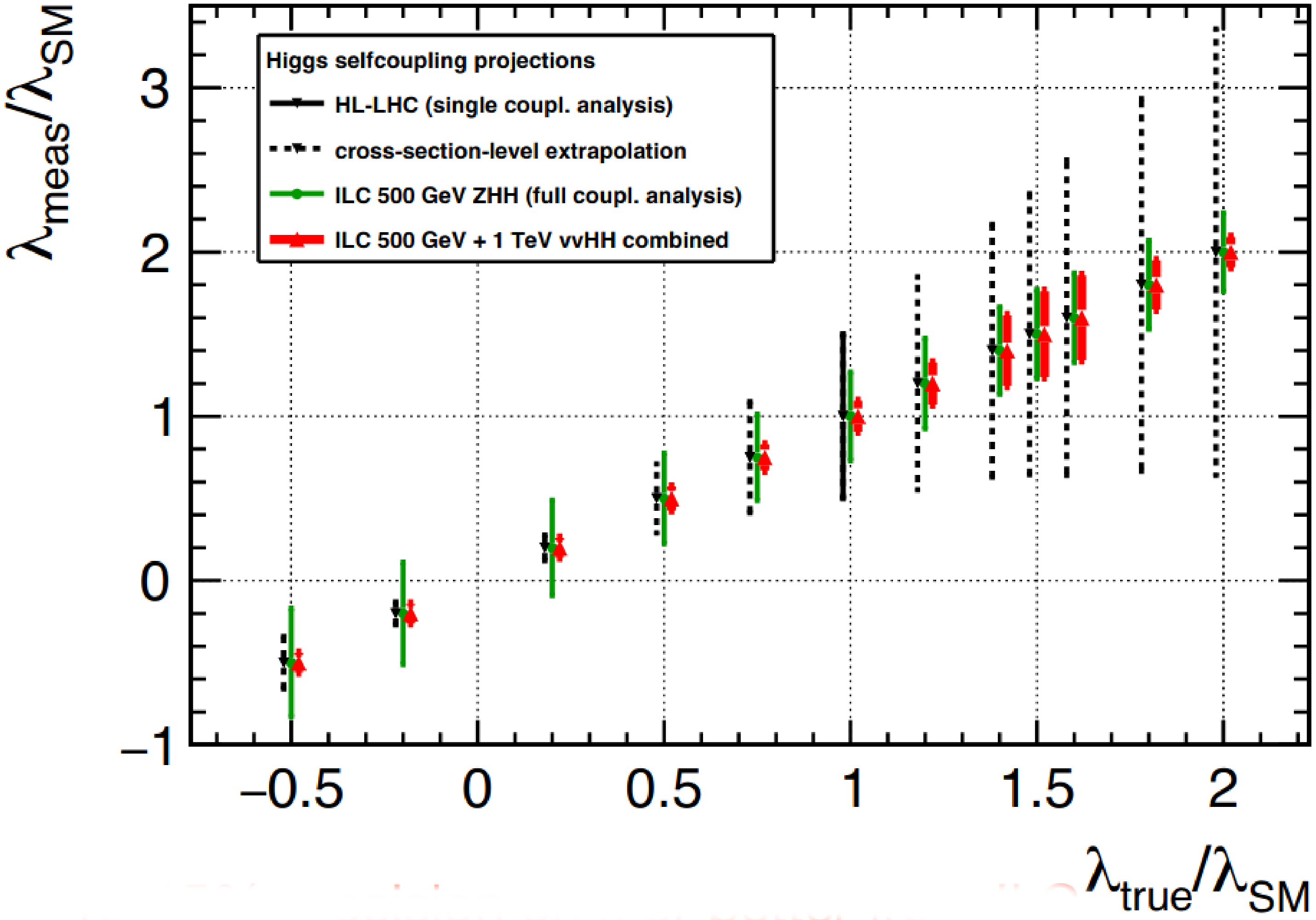


[de Blas et al., 1905.03764]

see also [Cepeda et al., 1902.00134], [Di Vita et al.1711.03978], [Fujii et al. 1506.05992, 1710.07621, 1908.11299], [Roloff et al., 1901.05897], [Chang et al. 1804.07130,1908.00753], *etc.*

Future determination of λ_{hhh}

Achieved accuracy actually depends on the value of λ_{hhh}



[J. List et al. ‘21]

See also [Dürig, DESY-THESIS-2016-027]

Calculating λ_{hhh} in models with extended scalar sectors

Based on

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

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 ($\Phi_1 \rightarrow \Phi_1$, $\Phi_2 \rightarrow -\Phi_2$) to avoid tree-level FCNCs

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

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

- **Mass eigenstates**:
  h, H: CP-even Higgs bosons *(h → 125-GeV SM-like state);* A: CP-odd Higgs boson;
  $H^\pm$: charged Higgs boson

- **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 (CP-even Higgs mixing angle) and β (defined by $\tan\beta = v_2/v_1$)

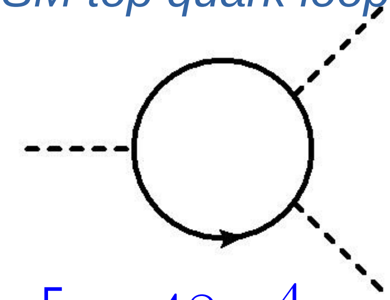
- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

- We take the **alignment limit $\alpha = \beta - \pi/2$** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data

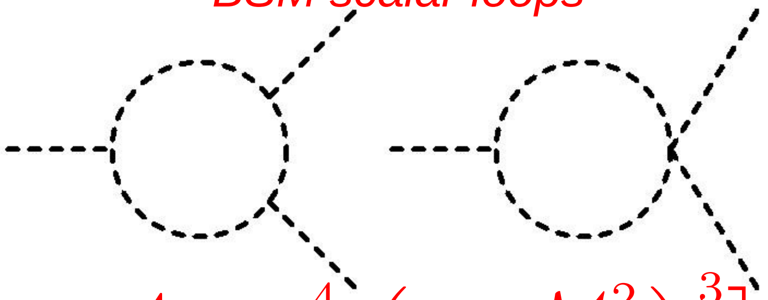
One-loop non-decoupling effects

- **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: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda}v^2$

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

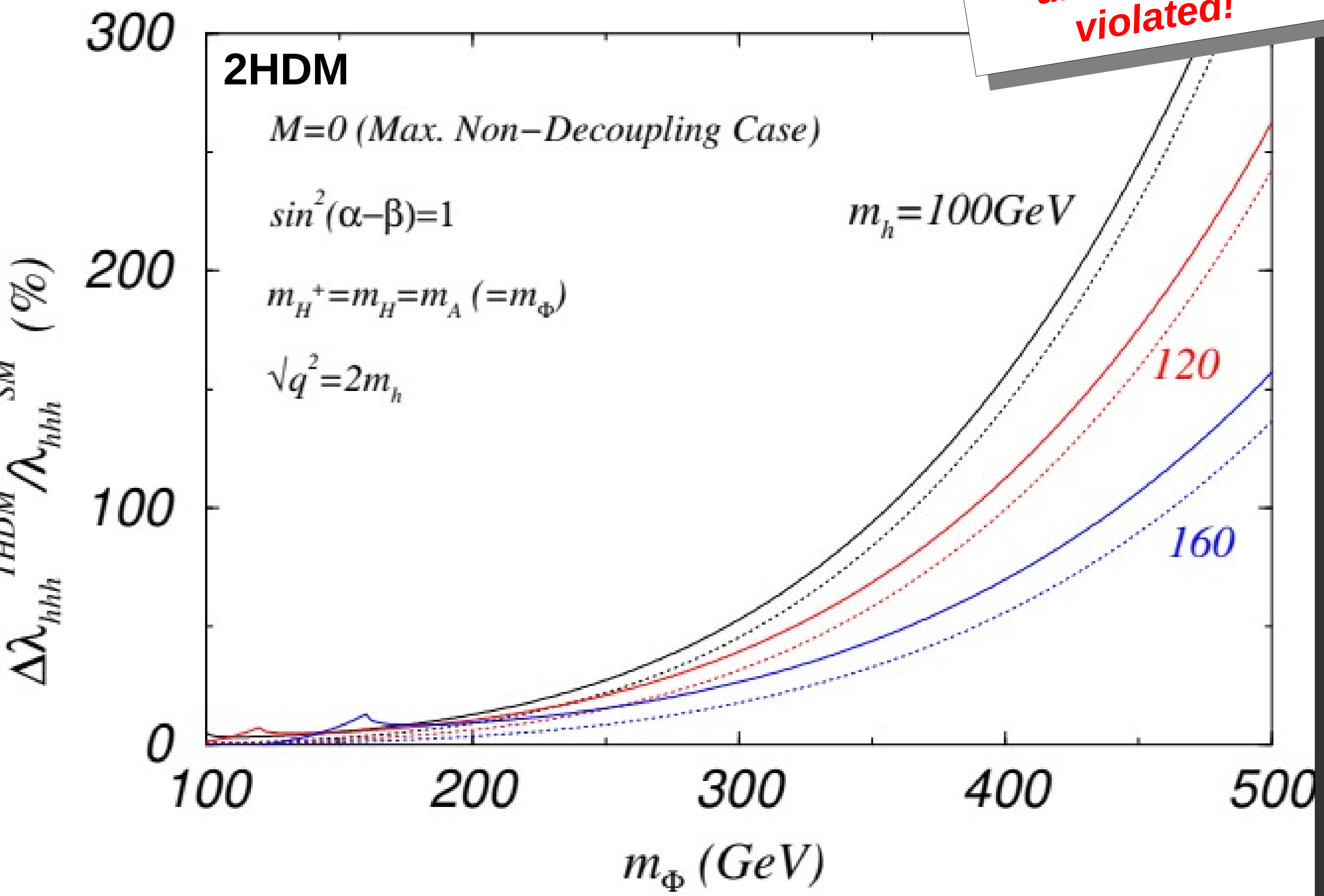
→ **Huge BSM effects possible!**

One-loop non-decoupling effects

- Leading one-loop c

Plot from [Kanemura, Okada, Senaha, Yuan '04]

NB: perturbative unitarity not violated!



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

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

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

n_Φ : # of d.o.f of

- Size of new effects

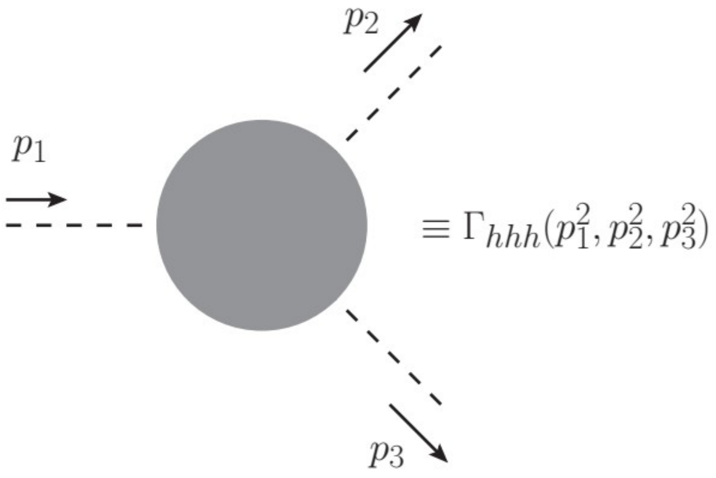
$^2 + \tilde{\lambda} v^2$

Huge BSM effects possible!

Our two-loop calculation

Goal: How large can the two-loop corrections to λ_{hhh} become?

An effective Higgs trilinear coupling



- In principle: consider 3-point function Γ_{hhh}
  but this is momentum dependent → very difficult beyond one loop

- Instead, consider an **effective trilinear coupling**

$$\lambda_{hhh} \equiv \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\bigg|_{\text{min}}$$

  entering the coupling modifier

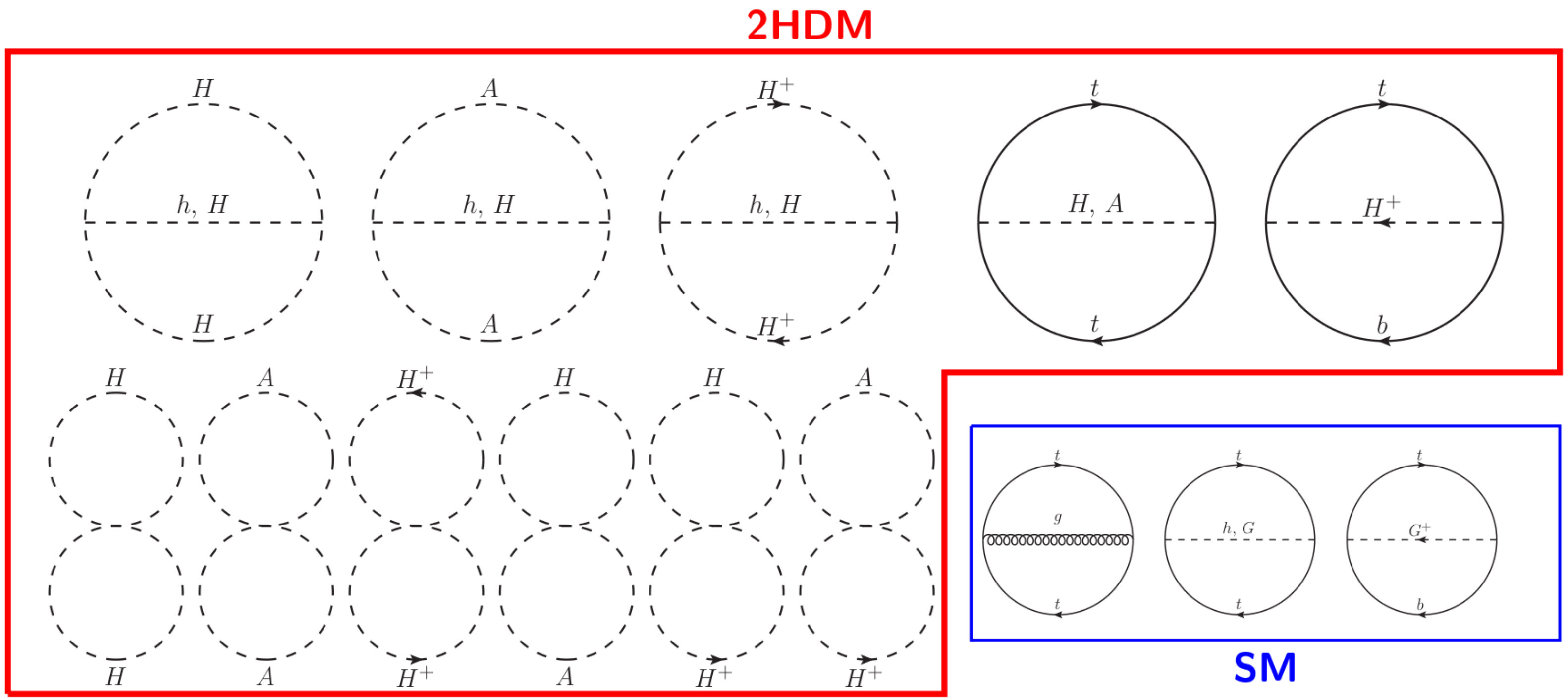
$$\kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda^{(0)}_{hhh})^{\text{SM}}} \qquad \text{with } (\lambda^{(0)}_{hhh})^{\text{SM}} = \frac{3m_h^2}{v}$$

  constrained by experiments (*applicability of this assumption discussed later*)

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** $\sin(\beta-\alpha) = 1 \rightarrow$ no mixing + compatible with experimental results
  - **Neglect masses of light states** (SM-like Higgs, light fermions, ...)



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 + 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

[JB, Kanemura '19]

- **Step 1**: compute $V_{\rm eff} = V^{(0)} + \frac{1}{16\pi^2} V^{(1)} + \frac{1}{(16\pi^2)^2} V^{(2)}$ ($\overline{\rm MS}$ result)
  - $V^{(2)}$: 1PI vacuum bubbles
  - *Dominant BSM contributions to $V^{(2)}$* = diagrams involving **heavy BSM scalars and top quark**
  - *Aligned scenarios + neglect light masses*

- **Step 2**:

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

($\overline{\rm MS}$ result too)

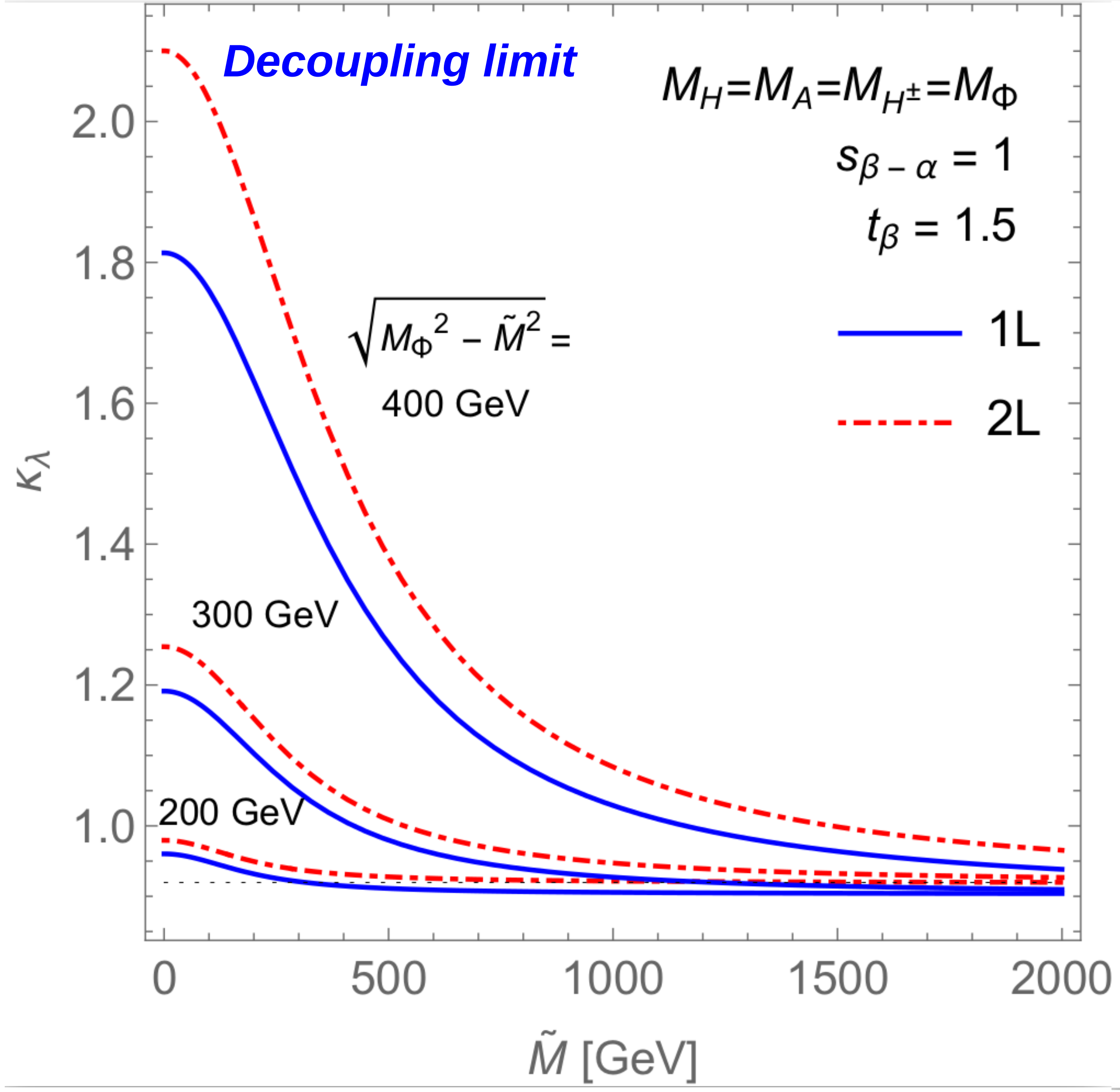
- **Step 3**: conversion from $\overline{\rm MS}$ to OS scheme
  - Express result in terms of **pole masses**: M_t, M_h, M_Φ (Φ=H,A,H$^\pm$); OS Higgs VEV $v_{\rm phys} = \frac{1}{\sqrt{\sqrt{2}G_F}}$
  - Include **finite WFR**: $\hat{\lambda}_{hhh} = (Z_h^{\rm OS}/Z_h^{\overline{\rm MS}})^{3/2}\lambda_{hhh}$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

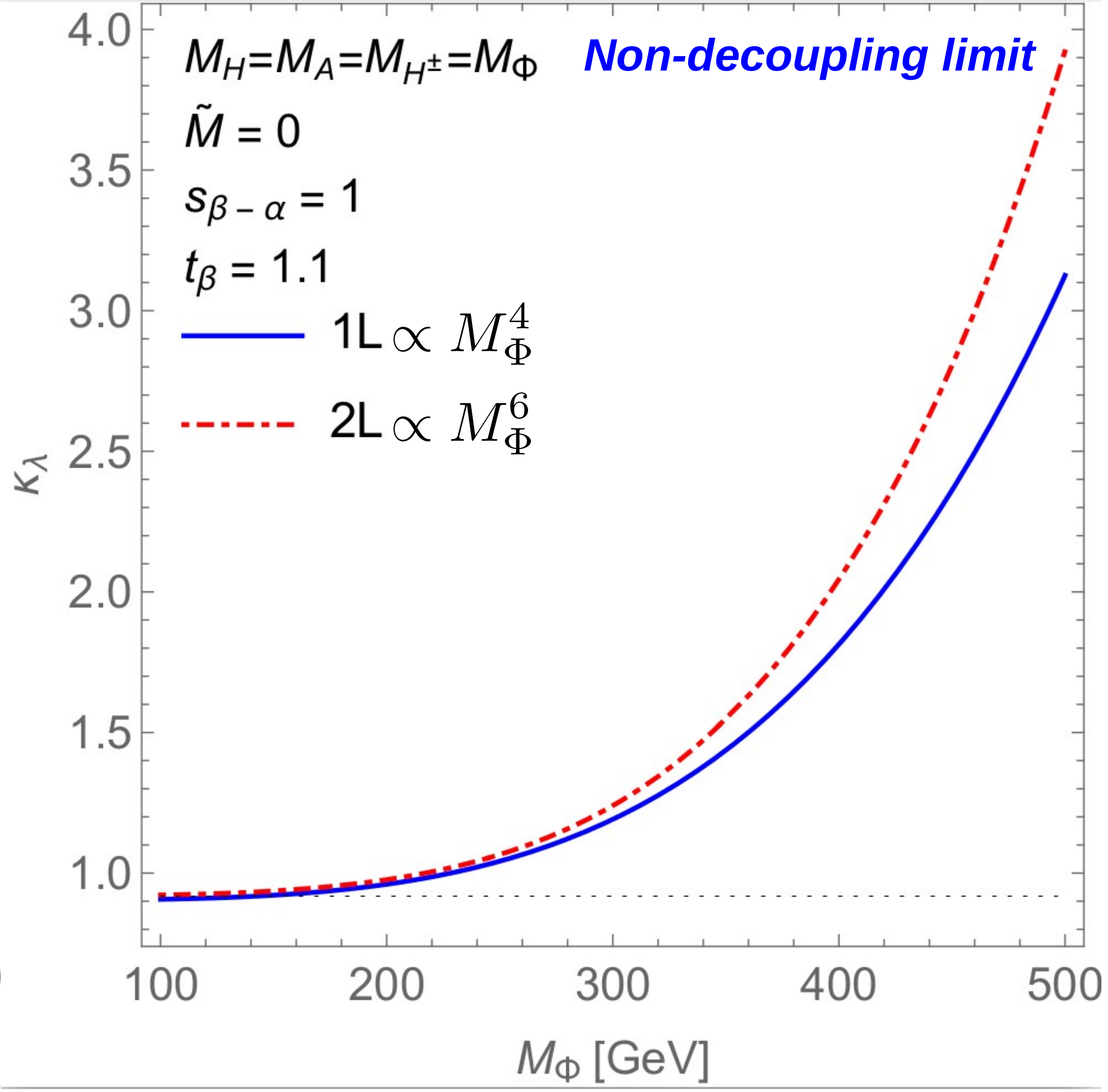
Numerical results in an aligned 2HDM

Our results

Taking degenerate BSM scalar masses: $M_\Phi = M_H = M_A = M_{H^\pm}$

[JB, Kanemura '19]



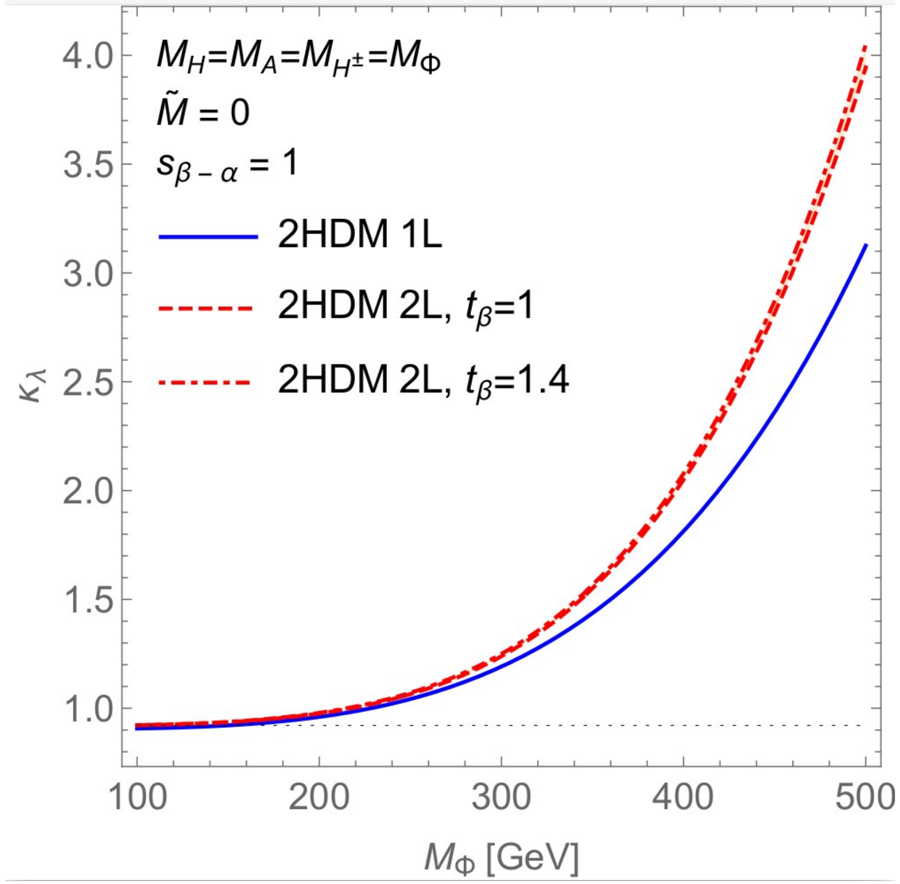


λ_{hhh} at two loops in more models

[JB, Kanemura 1911.11507]

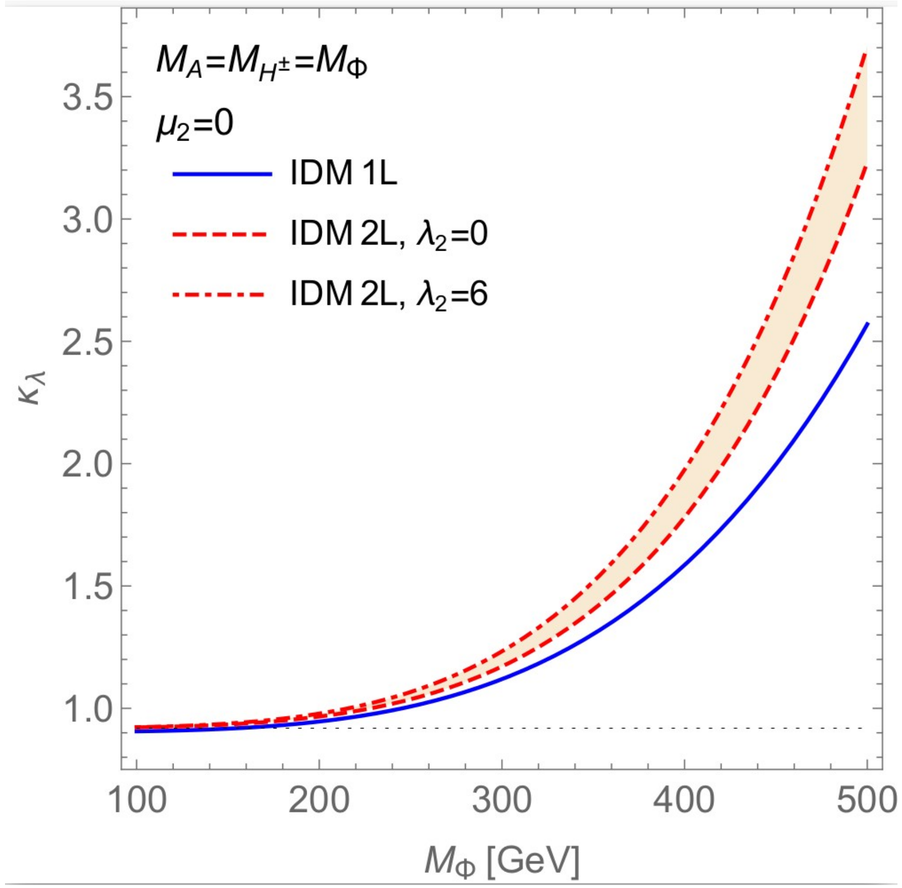
- Calculations in several other models: *IDM*, *singlet extension of SM*
- Each model contains a **new parameter appearing from two loops**:

Aligned 2HDM → tanβ



tanβ constrained by perturbative unitarity → only small effects

IDM → λ_2 (quartic coupling of inert doublet)



λ_2 is less contrained → **enhancement is possible**
(but 2l effects remains well smaller than 1l ones)

Calculating λ_{hhh} in CSI models

Based on

arXiv:2011.07580 (JHEP) in collaboration with Shinya Kanemura and Makoto Shimoda

Classical scale invariance

- CSI: forbid mass-dimensionful parameters at classical (= tree) level

  → tree-level potential: $V^{(0)} = \Lambda_{ijkl}\varphi_i\varphi_j\varphi_k\varphi_l$

- However broken **explicitly** at loop level

- EW symmetry breaking: (c.f. [Coleman, Weinberg '73], [Gildener, Weinberg '76])
  - Must occur along a flat direction of $V^{(0)}$ (= Higgs/scalon direction)
  - EW sym. broken à la Coleman-Weinberg along flat direction
  - EW scale generated by dimensional transmutation

- Here: **CSI assumed around EW scale, motivated by phenomenology**
  - Higgs (scalon) automatically aligned at tree level → compatible with current exp. results
  - BSM states can't be decoupled (no BSM mass term!)
  - CSI scenarios: **alignment with decoupling**

One-loop effective potential and λ_{hhh}

- Only source of mass = coupling to Higgs and its VEV $\Rightarrow$ $m_i^2(h) = m_i^2 \times \left(1+\frac{h}{v}\right)^2$

- Greatly simplifies the one-loop potential along Higgs (scalon) direction:

$$V^{(1)} = A(v+h)^4 + B(v+h)^4 \log\frac{(v+h)^2}{Q^2}$$

with

$$A \equiv \frac{1}{64\pi^2 v^4}\left\{\mathrm{tr}\left[M_S^4\left(\log\frac{M_S^2}{v^2}-\frac{3}{2}\right)\right] - 4\mathrm{tr}\left[M_f^4\left(\log\frac{M_f^2}{v^2}-\frac{3}{2}\right)\right] + 3\mathrm{tr}\left[M_V^4\left(\log\frac{M_V^2}{v^2}-\frac{5}{6}\right)\right]\right\}$$

$$B \equiv \frac{1}{64\pi^2 v^4}\left(\mathrm{tr}\left[M_S^4\right] - 4\mathrm{tr}\left[M_f^4\right] + 3\mathrm{tr}\left[M_V^4\right]\right)$$

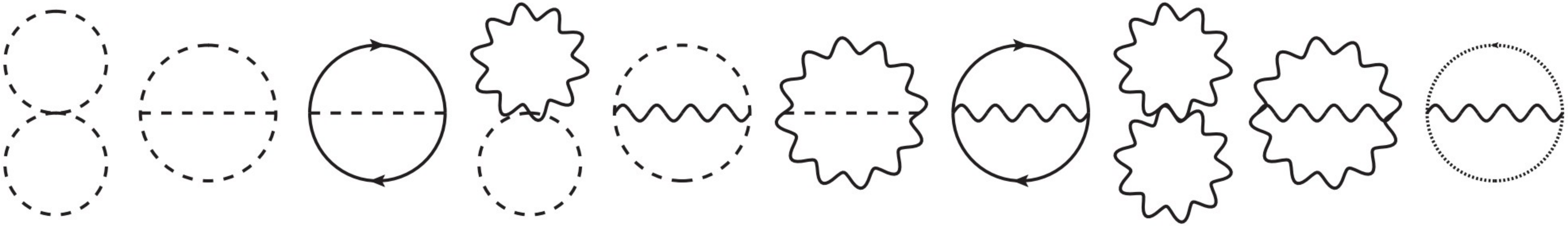
- Taking successive derivatives of the potential
  - 1st derivative = tadpole equation → fix A in terms of v and B
  - 2nd derivative = Higgs (effective potential) mass $[M_h^2]_{V_\mathrm{eff}}$ → fix B in terms of v and M_h
  - 3rd derivative = λ_{hhh} but $V^{(1)}$ is **entirely determined** by A, B →

$$\boxed{\lambda_{hhh} = \frac{5[M_h^2]_{V_\mathrm{eff}}}{v} = \frac{5}{3}\lambda_{hhh}^{\mathrm{SM,tree}}}$$

Universal one-loop result in CSI theories!

Effective potential at two loops

- Form of V_{eff} changes at two loops:



$V^{(2)}_{SS}$ $\quad V^{(2)}_{SSS}$ $\quad V^{(2)}_{F\bar{F}S}$ $\quad V^{(2)}_{VS}$ $\quad V^{(2)}_{SSV}$ $\quad V^{(2)}_{VVS}$ $\quad V^{(2)}_{F\bar{F}V}$ $\quad V^{(2)}_{gauge}$

- New type of contribution:

new log^2 term!

$$V_{\text{eff}} = A(v+h)^4 + B(v+h)^4 \log\frac{(v+h)^2}{Q^2} + C(v+h)^4 \log^2\frac{(v+h)^2}{Q^2}$$

λ_{hhh} at two loops in CSI models

[JB, Kanemura, Shimoda '20]

- Follow same procedure as at one loop:
  - ➔ Eliminate A with tadpole eq., B with Higgs mass
  - ➔ Still, **C remains!**
- One finds: $$\lambda_{hhh} = \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\bigg|_{\text{min}} = \frac{5[M_h^2]_{V_{\text{eff}}}}{v} + 32Cv$$
  - ➔ Deviation in λ_{hhh} depends on log^2 term in V_{eff}
  - ➔ **Universality found at one loop is lost at two loops!**

Example: a CSI-2HDM

Setup of our calculation

[JB, Kanemura, Shimoda '20]

- CSI-2HDM (see e.g. [Lee, Pilaftsis '12]):
  - similar to usual 2HDM, i.e. CP-even Higgses h, H; CP-odd Higgs A, charged Higgs H^+

  but
  - No mass terms in potential
  - Automatically **aligned** at tree level!

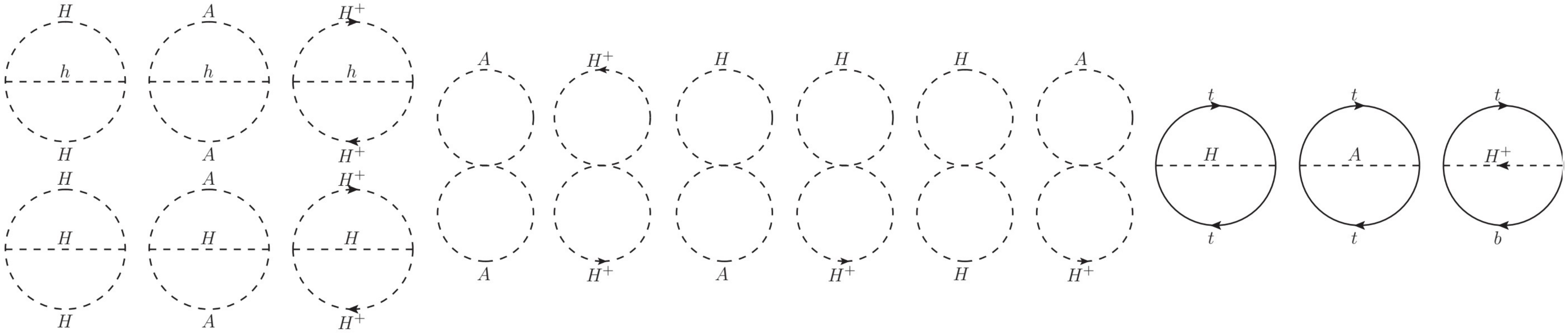
- **Derive $V^{(2)}$ ($\overline{\text{MS}}$) → extract log^2 coefficient C → compute λ_{hhh} ($\overline{\text{MS}}$)→ convert to OS scheme**

$$\lambda_{hhh} = \frac{5[M_h^2]_{V_{\text{eff}}}}{v} + 32Cv$$

(details in backup)

- Dominant corrections to $V^{(2)}$
  = diagrams involving BSM scalars (H,A,H^+) and top quark

$$V^{(2)} =$$



Theoretical and experimental constraints

- **Perturbative unitarity**: we constrain parameters entering only at two loops
  → tree-level perturbative unitarity suffices [Kanemura, Kubota, Takasugi ‘93]

- EW vacuum must be **true minimum of V_{eff}** i.e. check that

$$\underbrace{V_{\text{eff}}(v+h=0)}_{=0} - V_{\text{eff}}(h=0) > 0 \quad \Rightarrow \quad V_{\text{eff}}(h=0) < 0$$

- M_h, generated at loop level, must be **125 GeV**
  → imposes a relation between SM parameters, M_H, M_A, M_H^+, tanβ, e.g. we can extract:

$$[M_h^2]_{V_{\text{eff}}} = \frac{\partial^2 V_{\text{eff}}}{\partial h^2}\bigg|_{\text{min}} \quad \Rightarrow \quad \tan\beta = \tan\beta(\underbrace{M_h, M_t, \cdots}_{\text{measured SM values}}, \underbrace{M_H, M_A, M_{H^\pm}}_{\text{BSM inputs}})$$

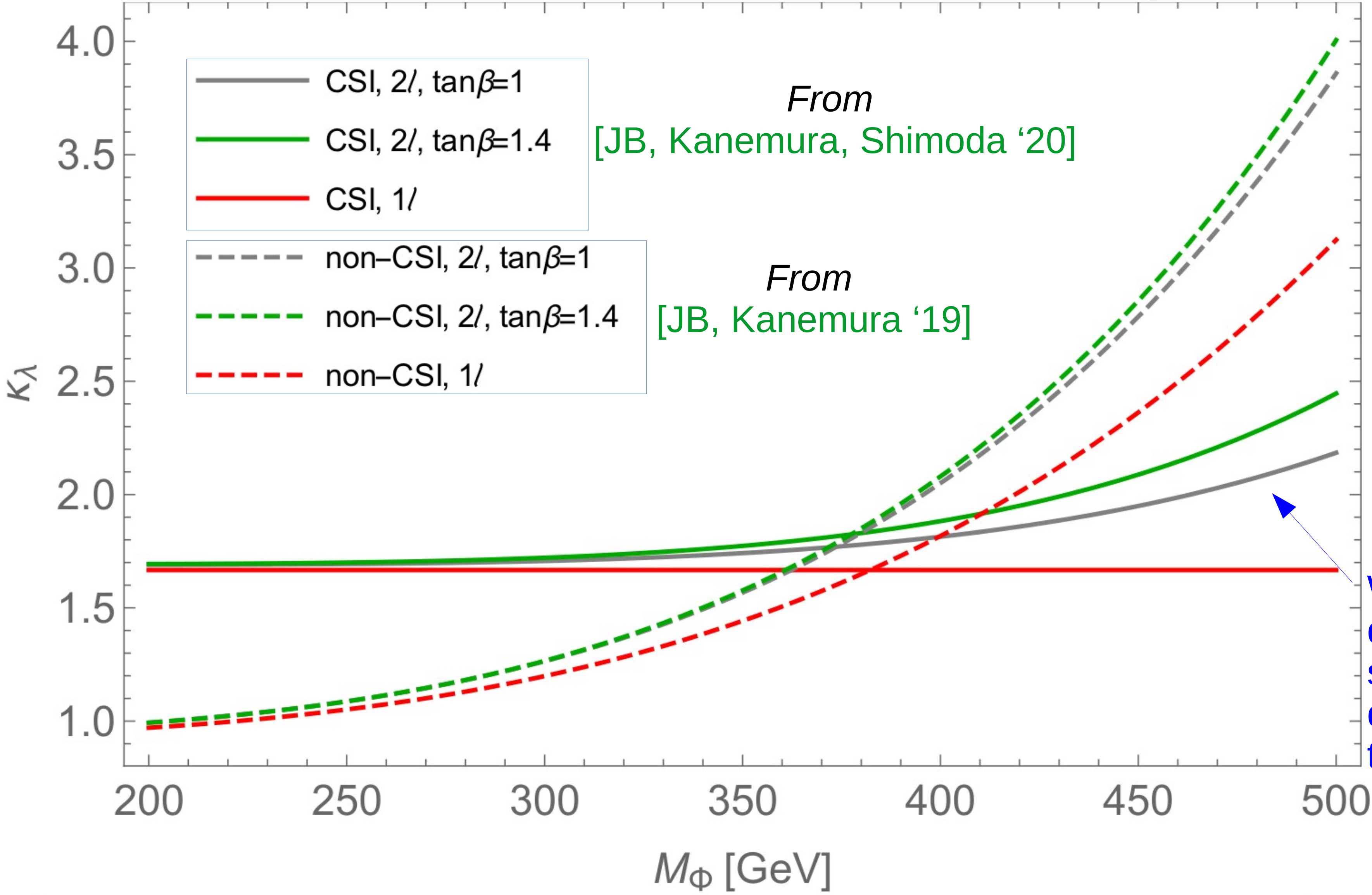
- Limits from **collider searches** with HiggsBounds and HiggsSignals

Numerical results

Comparing λ_{hhh} in 2HDM scenarios with or without CSI

Taking degenerate BSM masses: $M_\Phi = M_H = M_A = M_{H^+}$

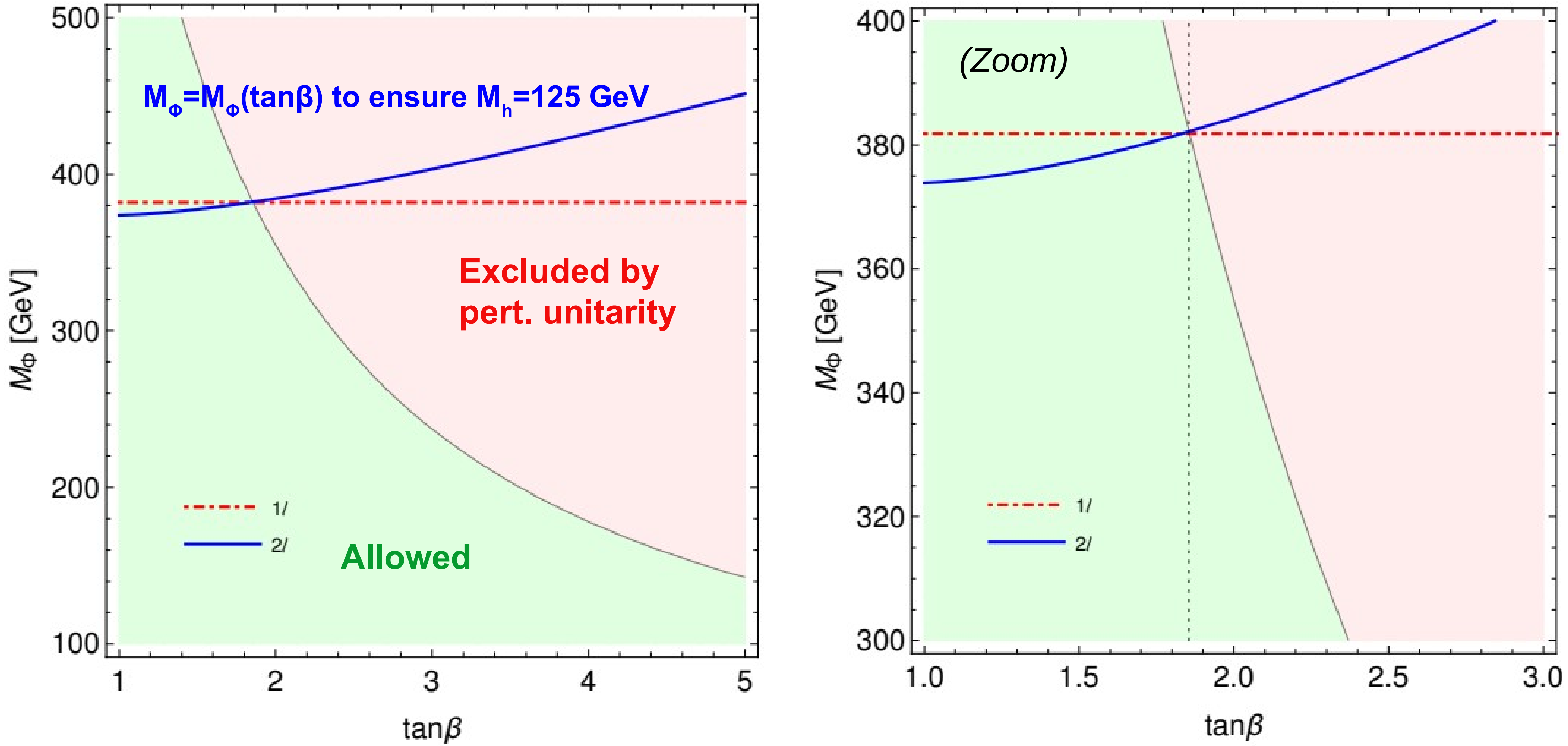
[JB, Kanemura, Shimoda '20]



We can now distinguish CSI scenarios with different values of tanβ or M_Φ!

Unitarity and constraint from M_h

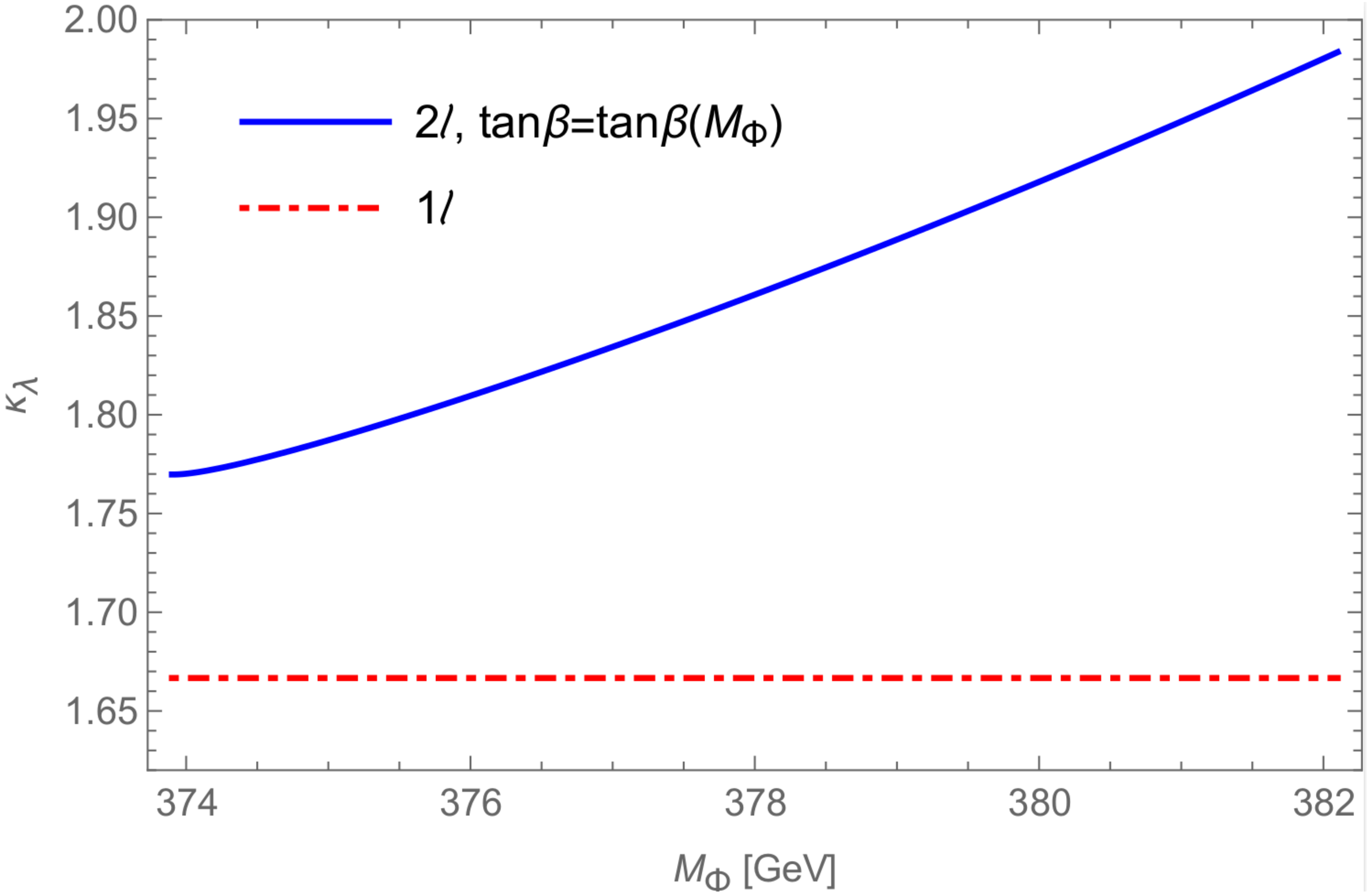
[JB, Kanemura, Shimoda ‘20]



Once all constraints are included

tanß uniquely constrained as a function of M_Φ

[JB, Kanemura, Shimoda '20]



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?*

Based on

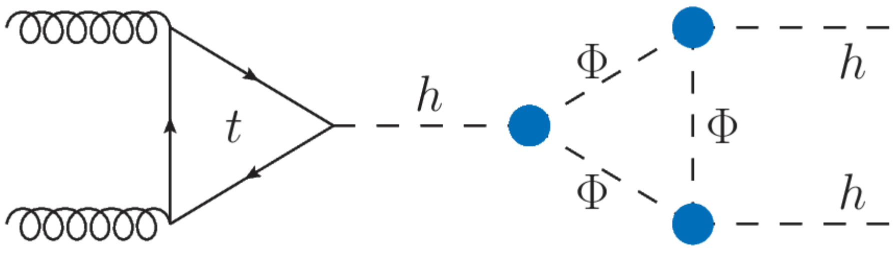
`arXiv:2202.03453` **(PRL) in collaboration with Henning Bahl and Georg Weiglein**

Can we apply di-Higgs results for the aligned 2HDM?

- Current strongest limit on κ_λ are from ATLAS double- (+ single-) Higgs searches

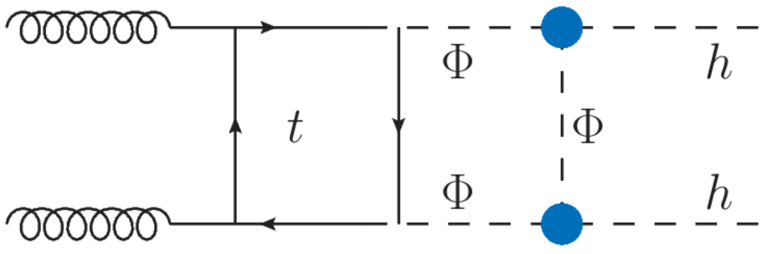
  $-0.4 < \kappa_\lambda < 6.3$ [ATLAS-CONF-2022-050] [where $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$]

- What are the *assumptions* for the ATLAS limits?
  - All other Higgs couplings (to fermions, gauge bosons) are SM-like → this is **ensured by alignment** ✓
  - The modification of λ_{hhh} is the only source of deviation of the *non-resonant Higgs-pair production cross section* from the SM



$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$

Correction to λ_{hhh} → included



$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$

not included

$g_{hh\Phi\Phi}$ drives large BSM contributions

→ 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 λ_{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]

Checked with `ScannerS` [Mühlleitner et al. 2007.02985]

- EW precision observables, computed at two loops with `THDM_EWPOS` [Hessenberger, Hollik '16, '22]

theoretical

- Vacuum stability
- Boundedness-from-below of the potential

Checked with `ScannerS`

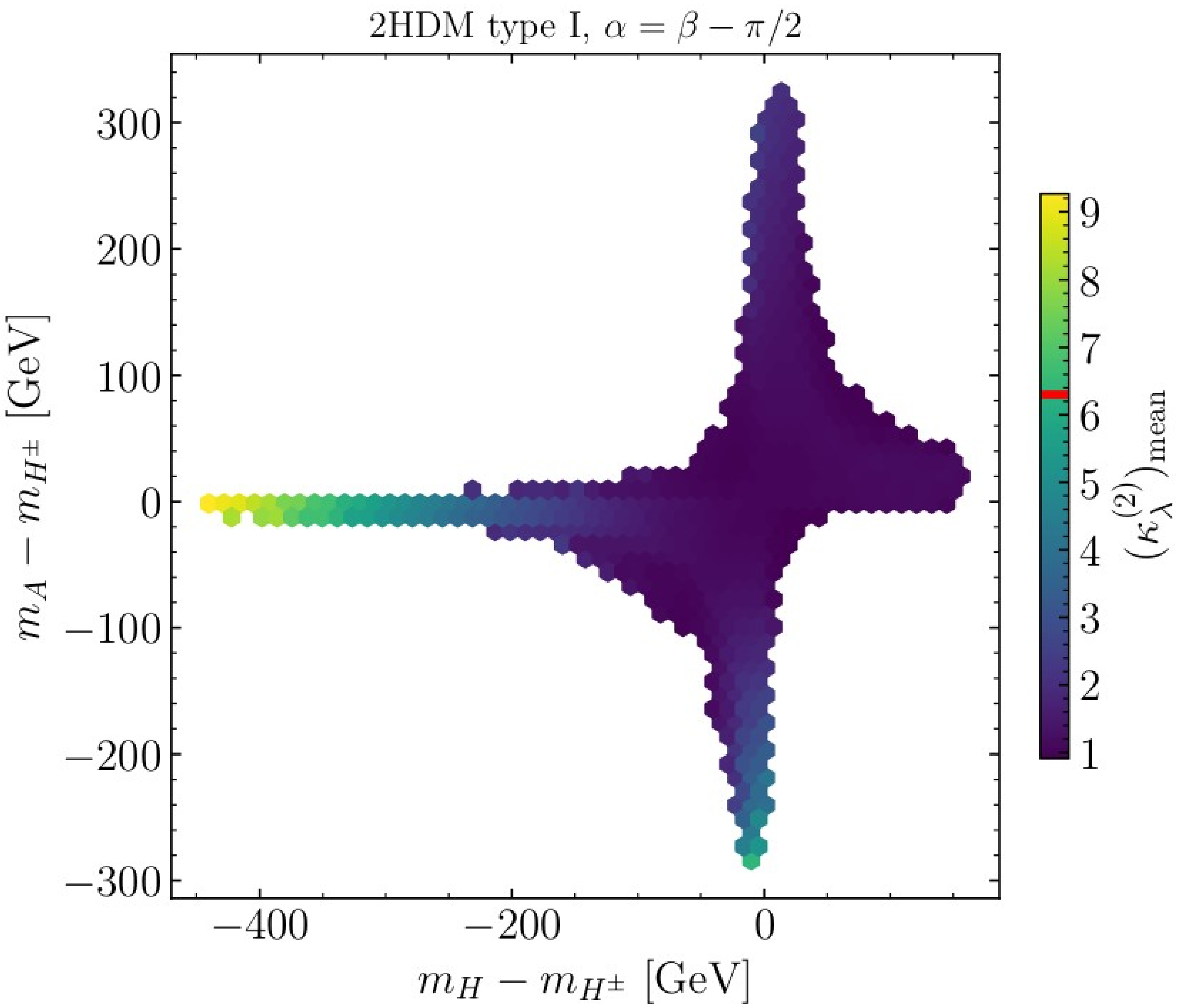
- NLO perturbative unitarity, using results from [Grinstein et al. 1512.04567], [Cacchio et al. 1609.01290]

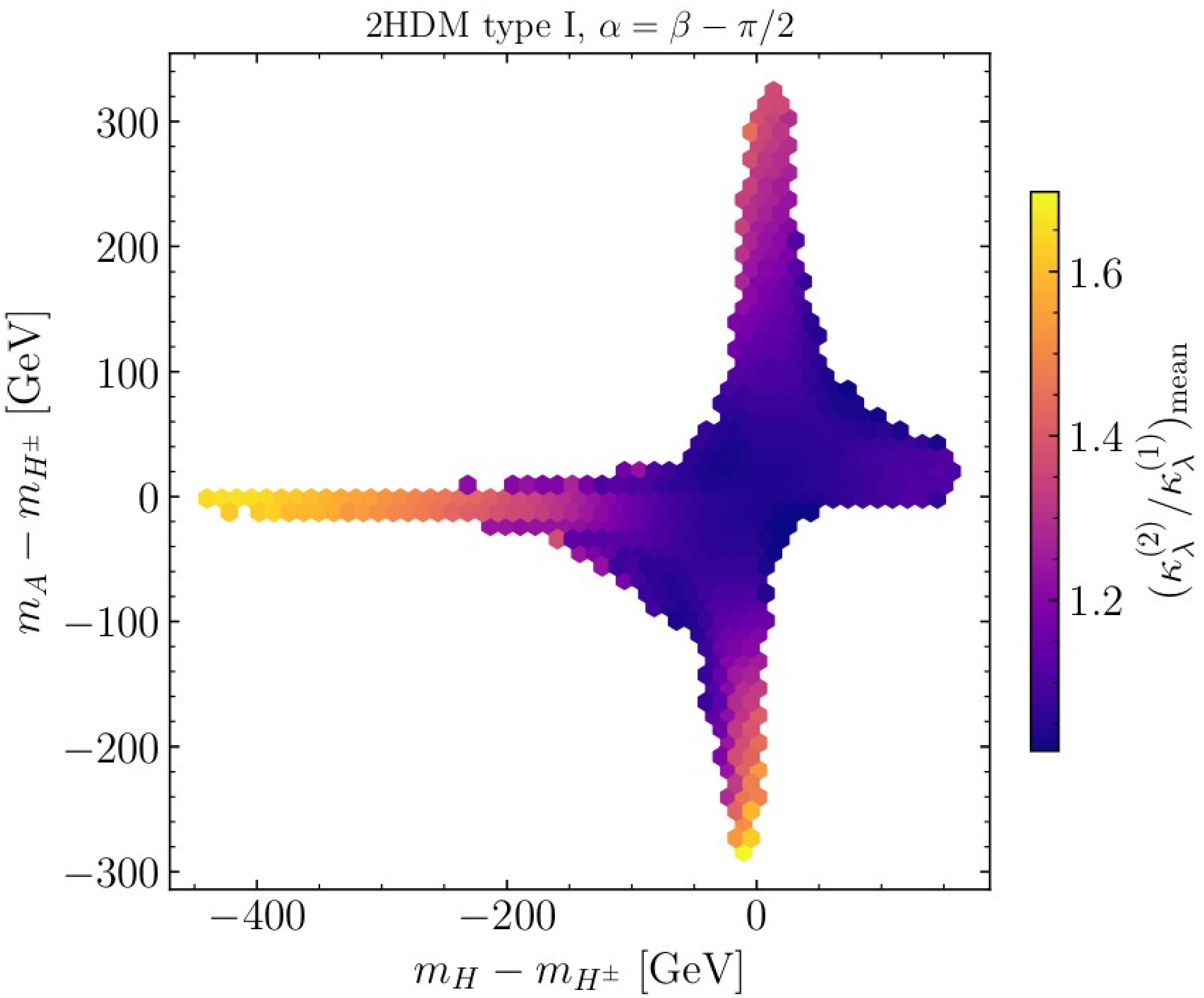
- For points passing these constraints, we **compute κ_λ at 1L and 2L**, using results from [JB, Kanemura '19]

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



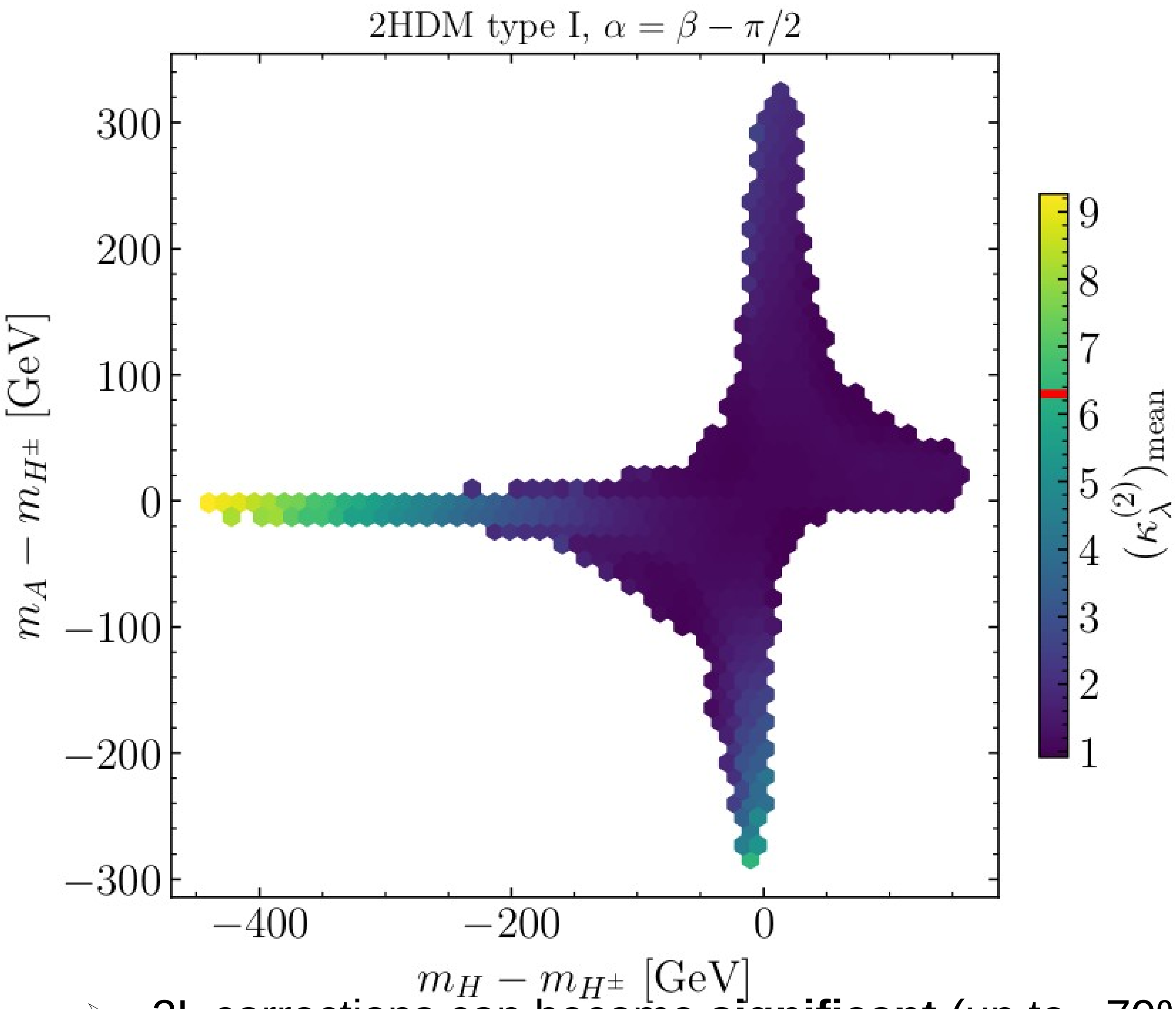


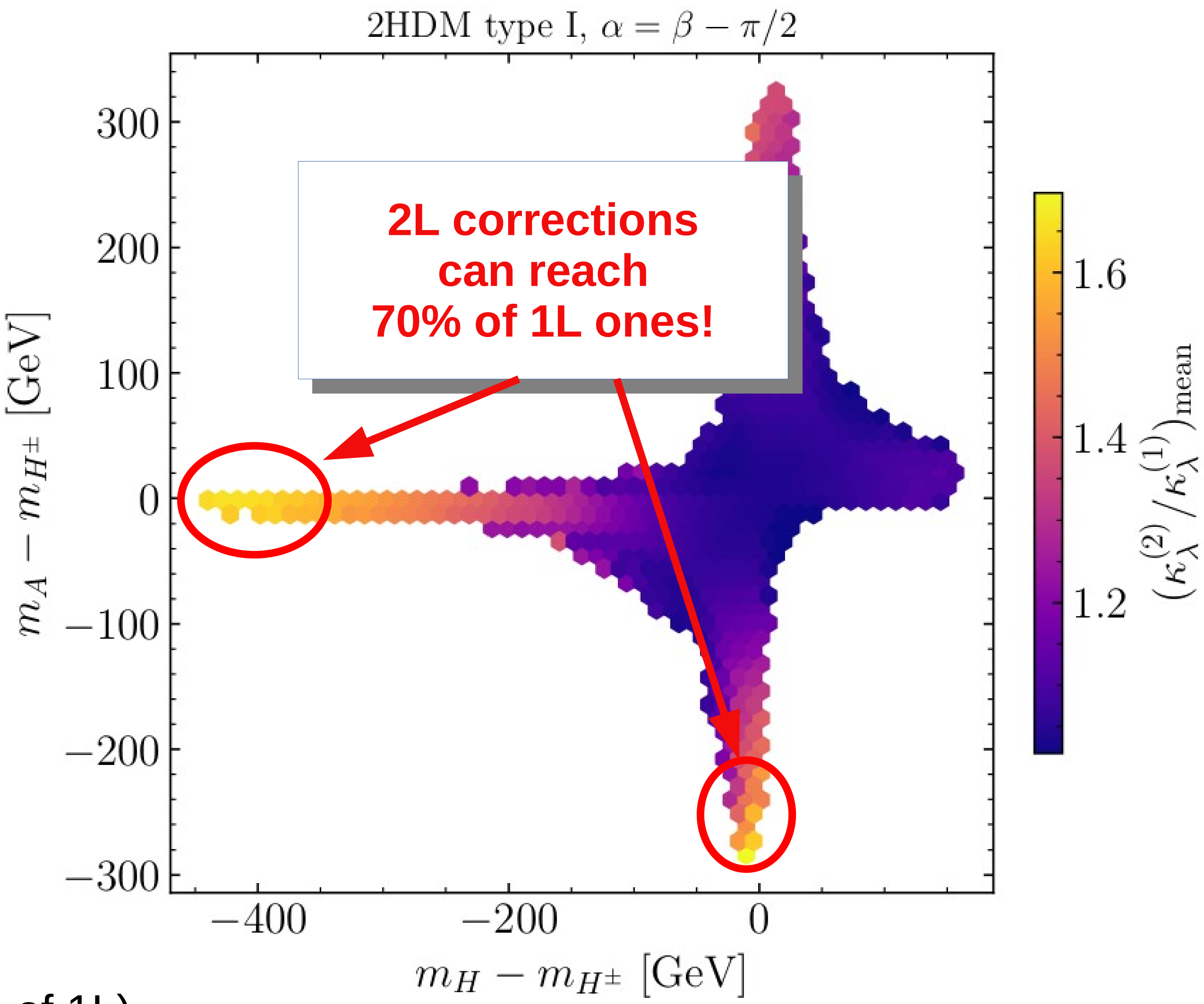
NB: all previously mentioned constraints are fulfilled by the points shown here

Parameter scan results

[Bahl, JB, Weiglein 2202.03453]

<u>Mean value</u> 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



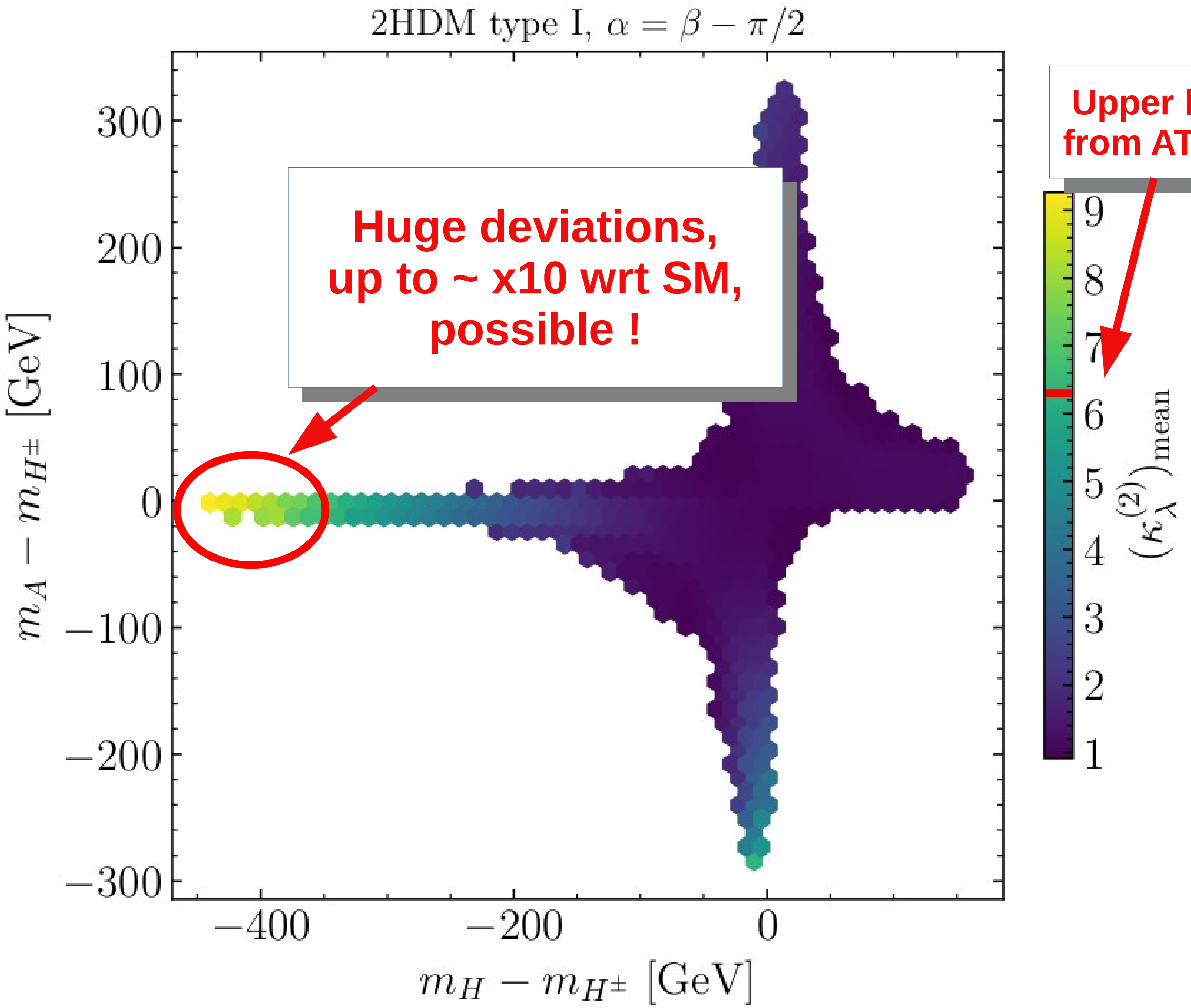


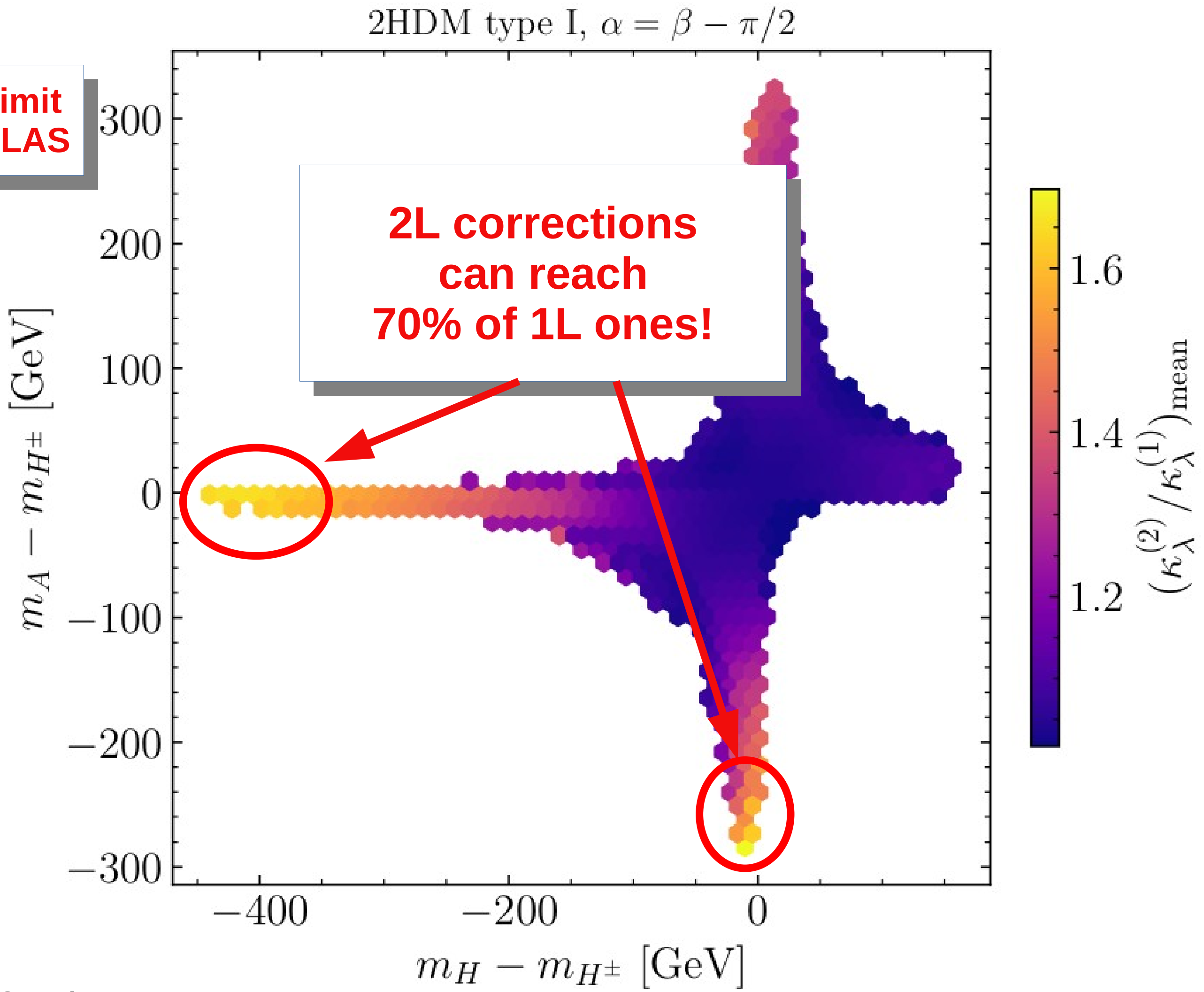
- 2L corrections can become **significant** (up to ~70% of 1L)

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





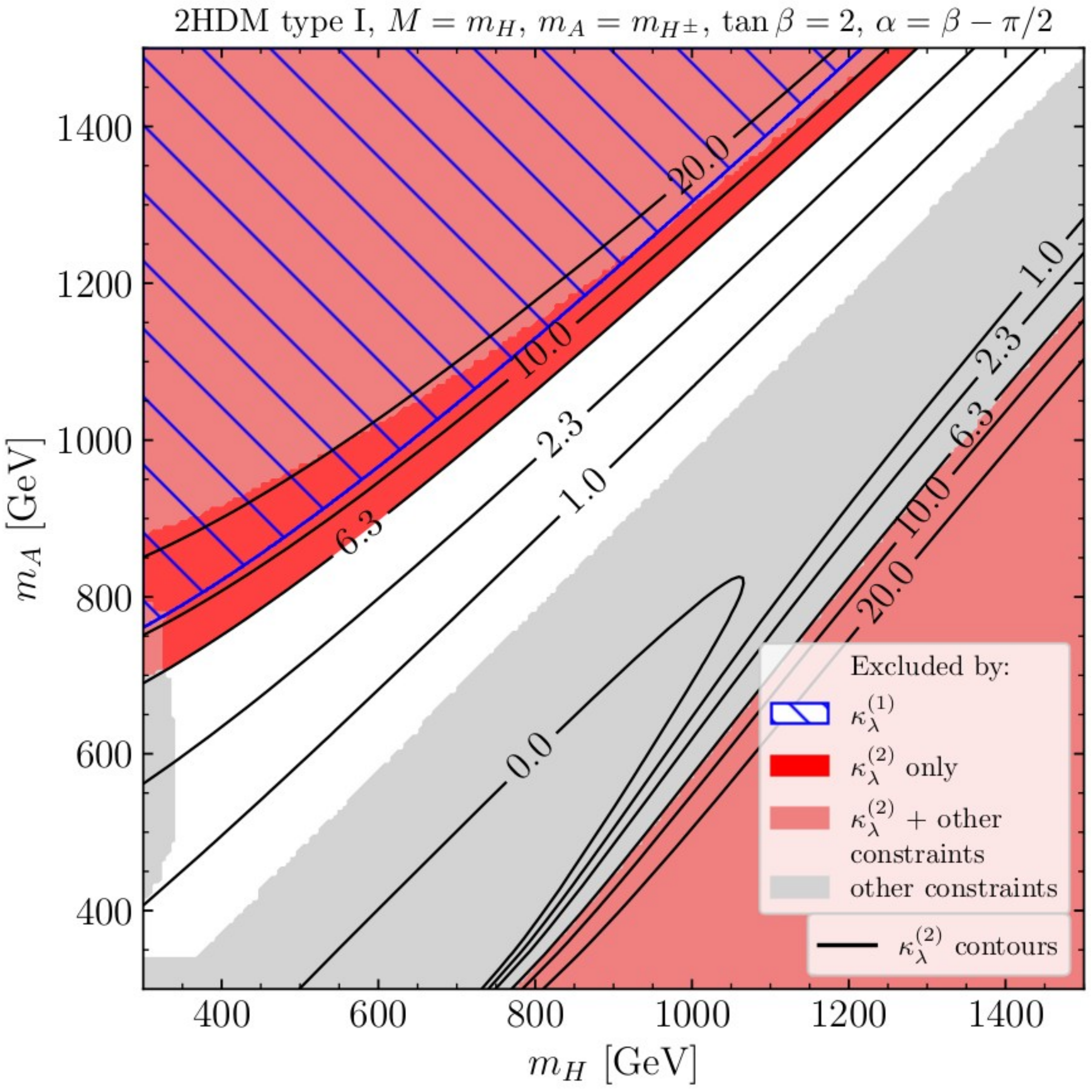
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark scenario 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 $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ the calculation isn't reliable]
- ***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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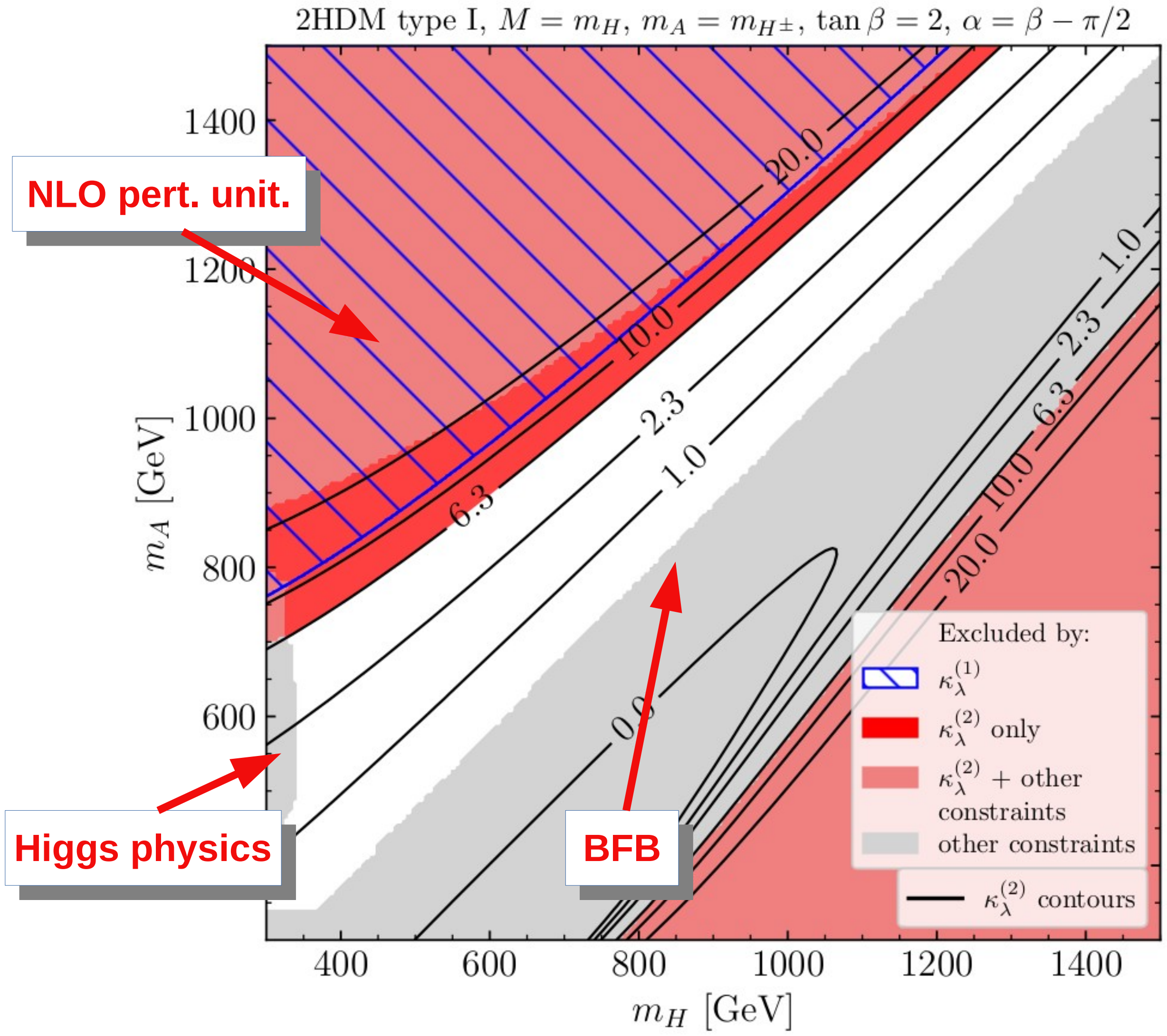

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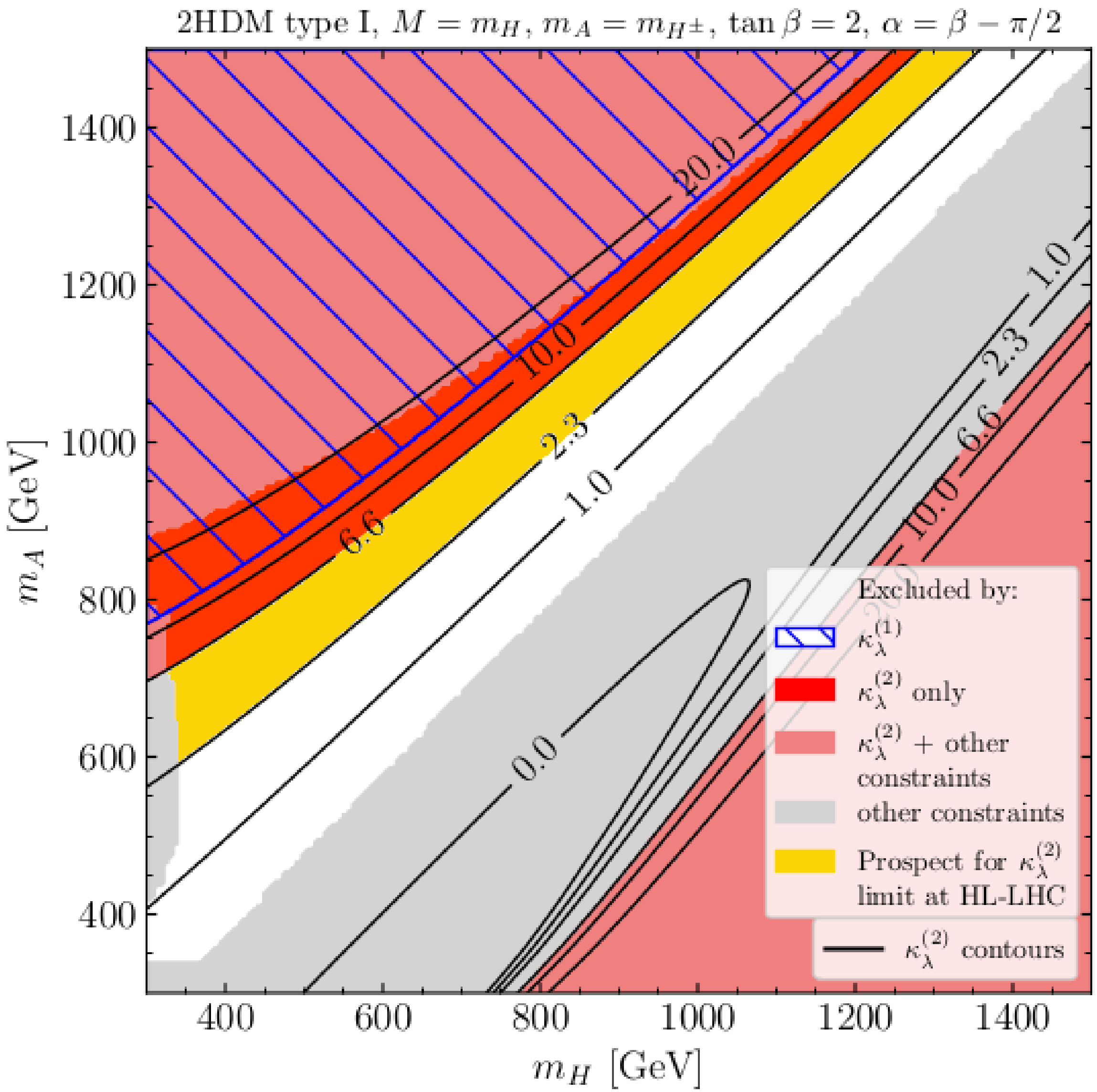
A benchmark scenario in the aligned 2HDM – future prospects

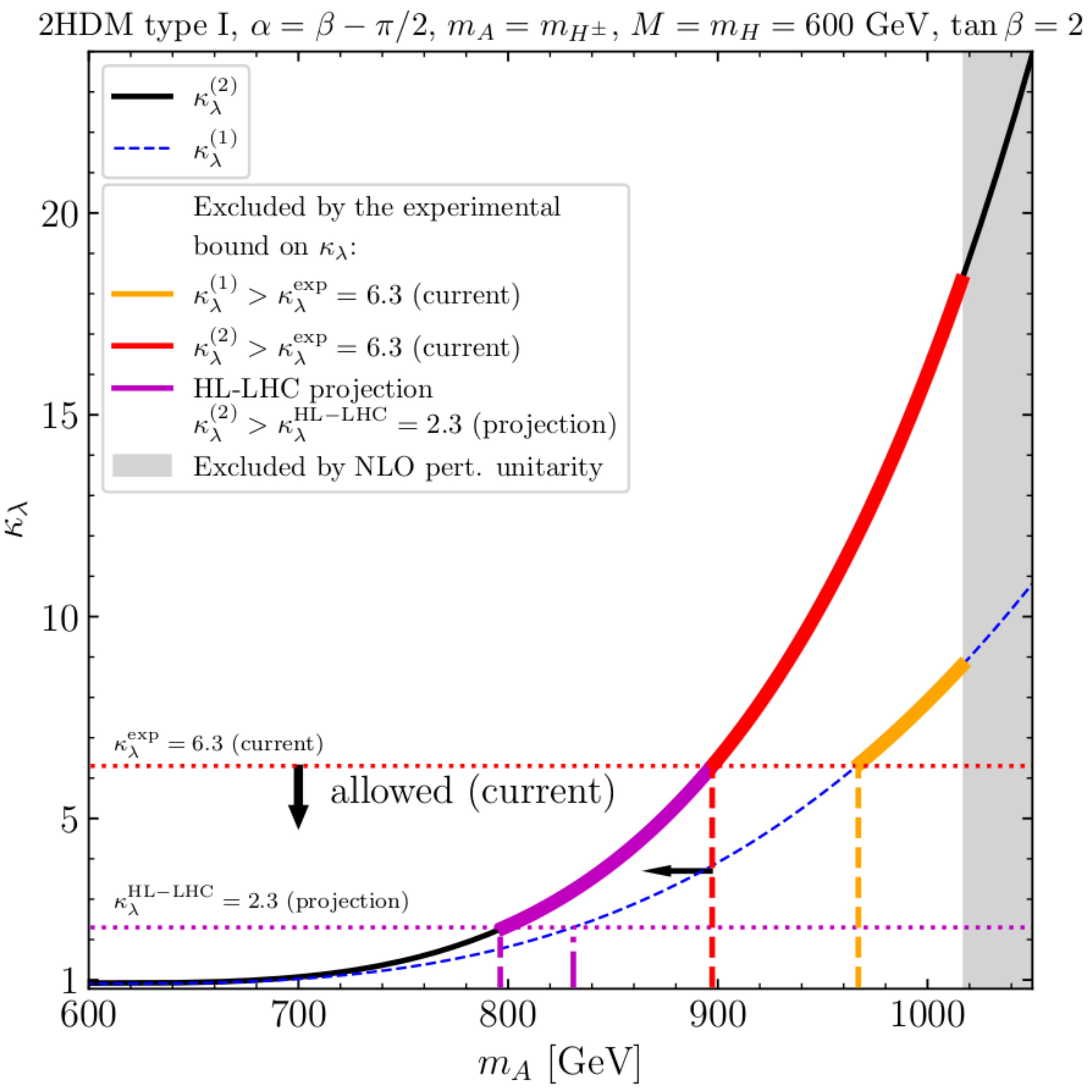
Suppose for instance the upper bound on κ_λ becomes $\kappa_\lambda < 2.3$



- ***Golden area:*** additional exclusion if the limit on κ_λ becomes $\kappa_\lambda^{(2)} < 2.3$ (achievable at HL-LHC)
- Of course, **prospects even better with an e^+e^- collider!**
- 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
- A stricter choice for the perturbative unitarity constraint (grey) does not significantly change the region excluded by $\kappa_\lambda^{(2)}$

anyH3: similar results in various BSM models (at 1L)

[Bahl, JB, Gabelmann, Weiglein]

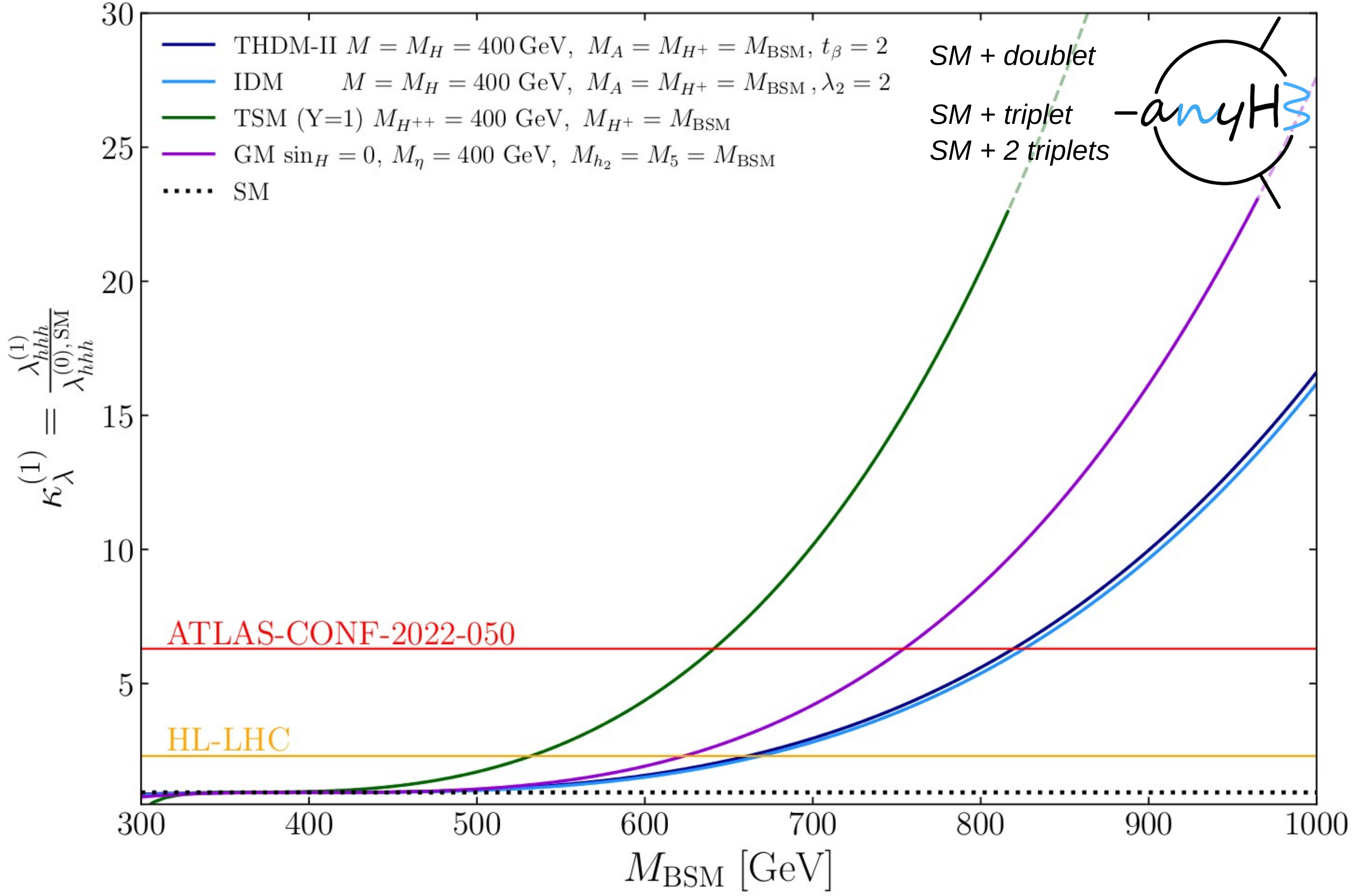
- Consider the non-decoupling limit in several BSM models

$$M_{\rm BSM}^2 = \mathcal{M}^2 + \tilde{\lambda} v^2$$

- Increase $M_{\rm BSM}$, keeping $\mathcal{M}$ fixed
  → large mass splittings
  → **large BSM effects!**

- Perturbative unitarity checks:
  - Solid: OK ✓
  - Dashed: not OK ✗

- **Constraints on BSM parameter space!**



Generic predictions for λ_{hhh} at 2L

Based on

Work in progress, in collaboration with Henning Bahl, Martin Gabelmann, and Sebastian Paßehr

Computing λ_{hhh} in BSM theories at 2L

[Bahl, JB, Gabelmann, Paßehr]

- Automation well underway at 1L (`anyH3` available soon), but **2L corrections** to λ_{hhh} can also be **important**
- Goal: **generic results** for λ_{hhh}, applicable at least for leading 2L corrections and beyond models currently studied (e.g. non-SUSY models with mixing, etc.)
- Extend work of [Goodsell, Paßehr '19] on 2L self-energies to 3-point and 4-point functions (at vanishing external momenta)
  - Generation of genuine, unrenormalised, 2L contributions + 1L subloop renormalisation contributions
  - Renormalisation by hand (at first)
- Cross-checks in progress
  - SM at $O(\alpha_s\alpha_t)$ and $O(\alpha_t^2)$ ✓
  - NMSSM at $O(\alpha_t^2)$ ✓
- Stay tuned!

Summary

- λ_{hhh} plays a crucial role to understand the shape of the Higgs potential, and probe indirectly signs of New Physics

- **Leading 2L corrections** now available in various BSM models (incl. CSI models)

- 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 has a significant impact.

- Similar results are expected for a wider range of BSM models with extended scalar sectors
  → motivates **automating calculations of $\boldsymbol{\lambda_{hhh}}$** → **anyH3** (c.f. Martin's talk) + WIP @ 2L

Thank you very much for your attention!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

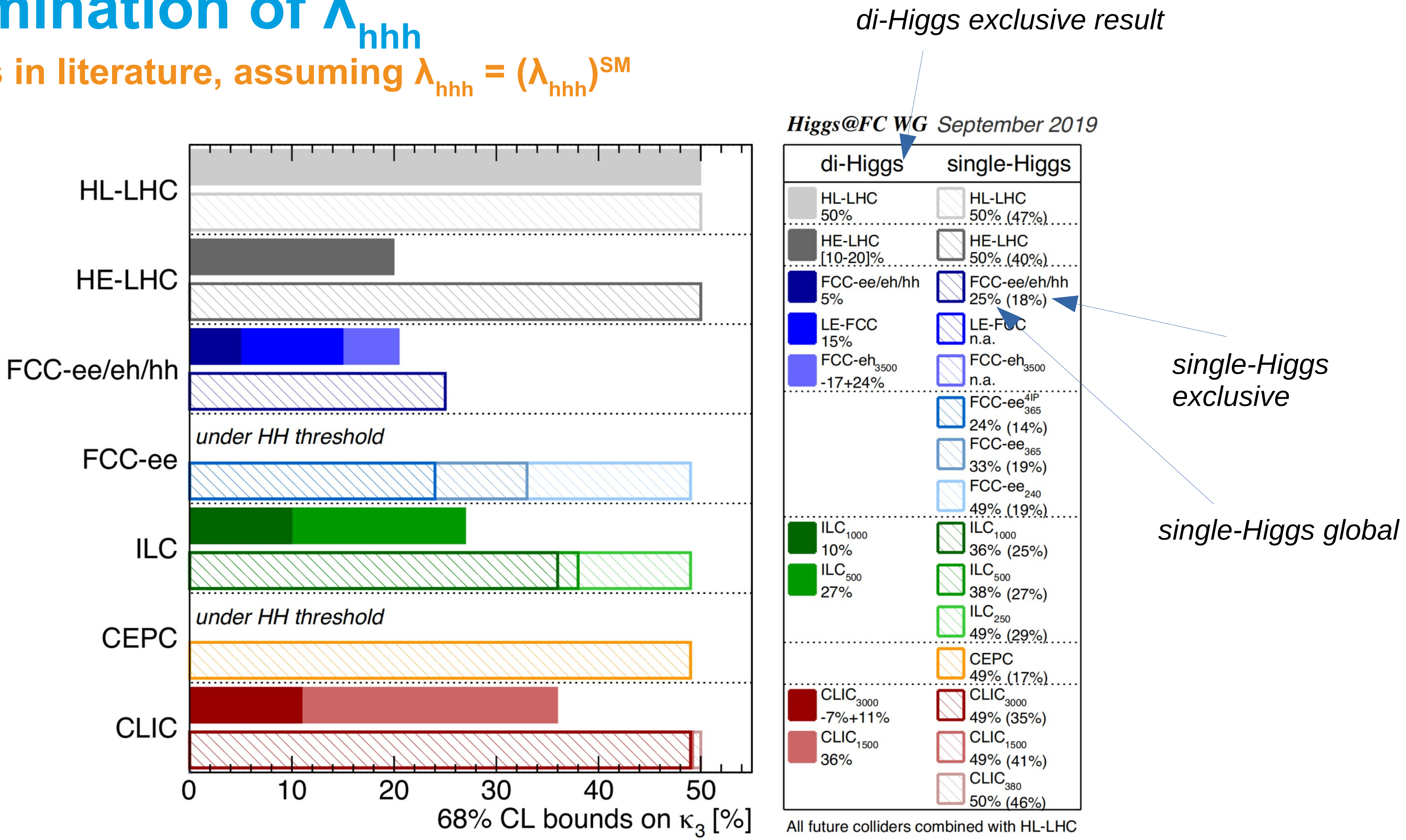
Johannes Braathen
DESY Theory group
Building 2a, Room 209
johannes.braathen@desy.de

Backup

Future determination of λ_{hhh}

Expected sensitivities in literature, assuming $\lambda_{hhh} = (\lambda_{hhh})^{SM}$

Plot taken from
[de Blas et al., 1905.03764]



see also [Cepeda et al., 1902.00134], [Di Vita et al.1711.03978], [Fujii et al. 1506.05992, 1710.07621, 1908.11299], [Roloff et al., 1901.05897], [Chang et al. 1804.07130,1908.00753], *etc.*

Future determination of λ_{hhh}

Higgs production cross-sections (here double Higgs production) depend on λ_{hhh}

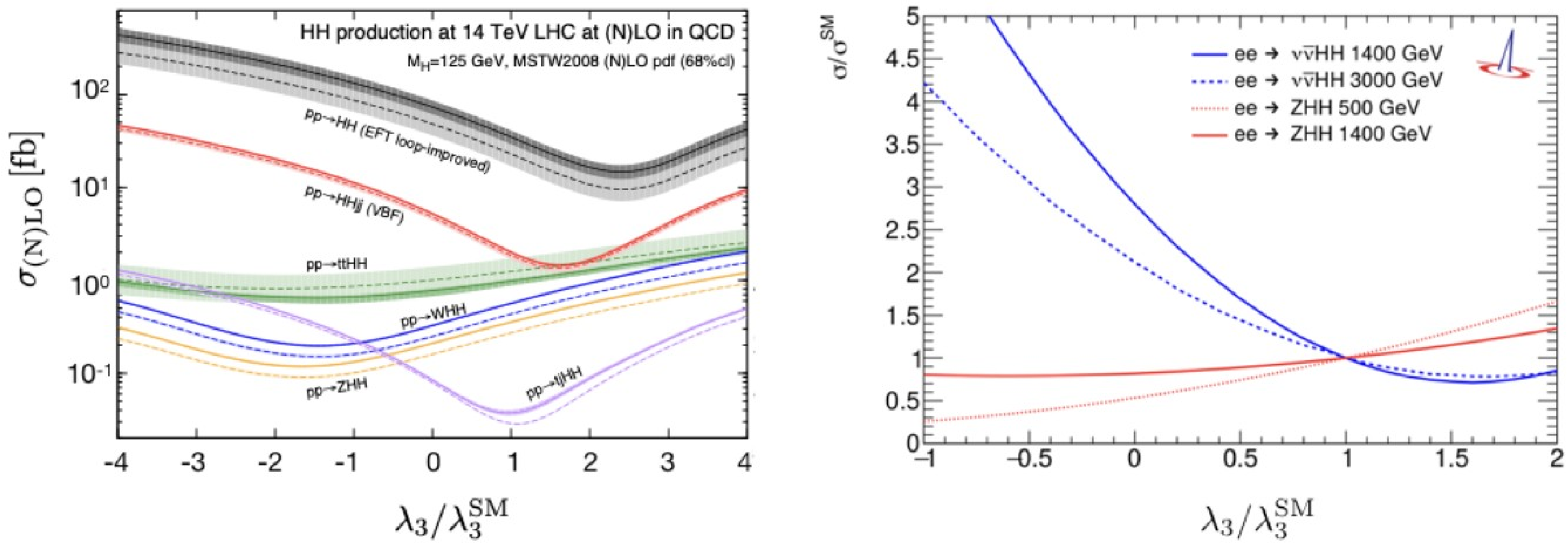
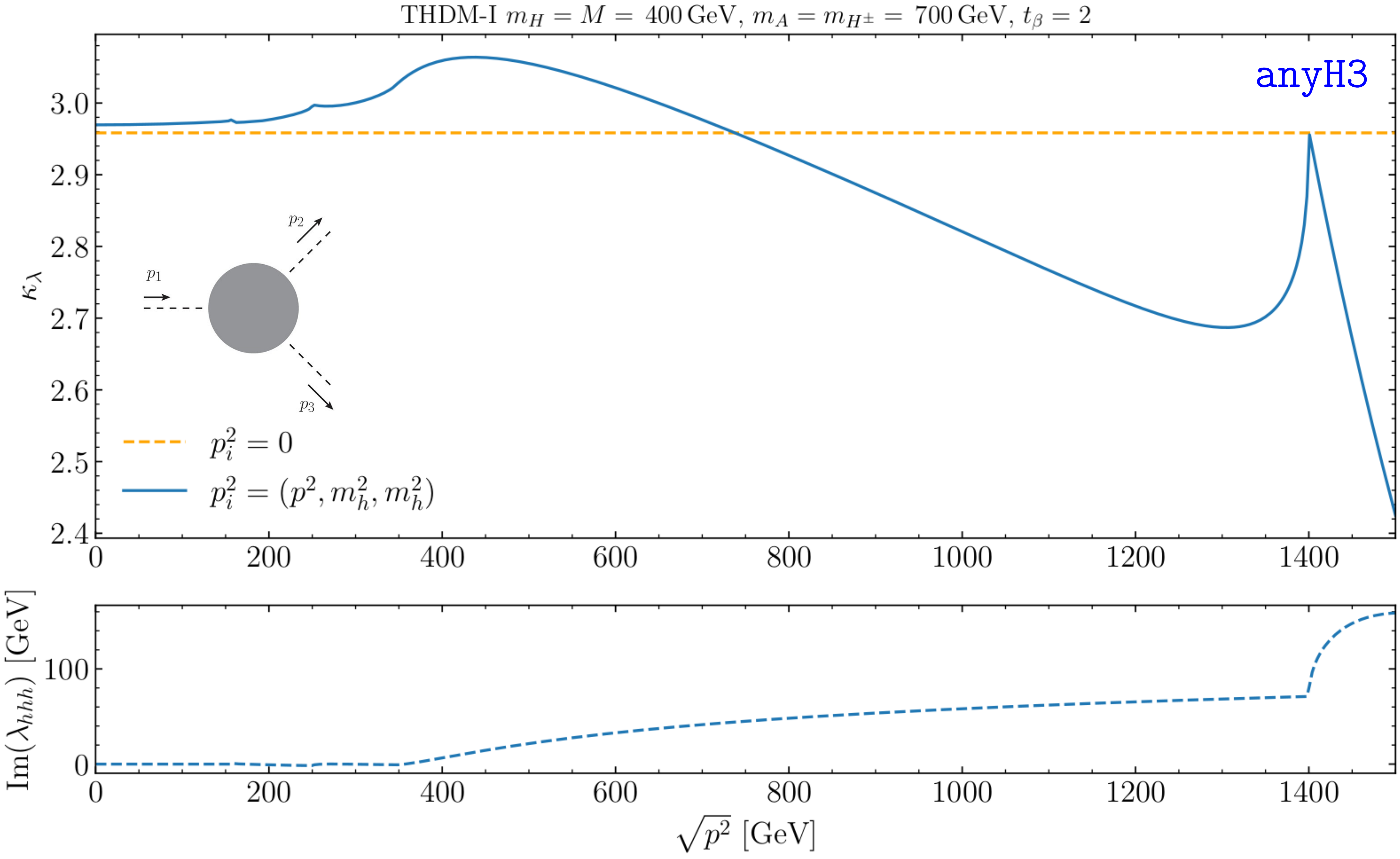


Figure 10. Double Higgs production at hadron (left) [65] and lepton (right) [66] colliders as a function of the modified Higgs cubic self-coupling. See Table 18 for the SM rates. At lepton colliders, the production cross sections do depend on the polarisation but this dependence drops out in the ratios to the SM rates (beam spectrum and QED ISR effects have been included).

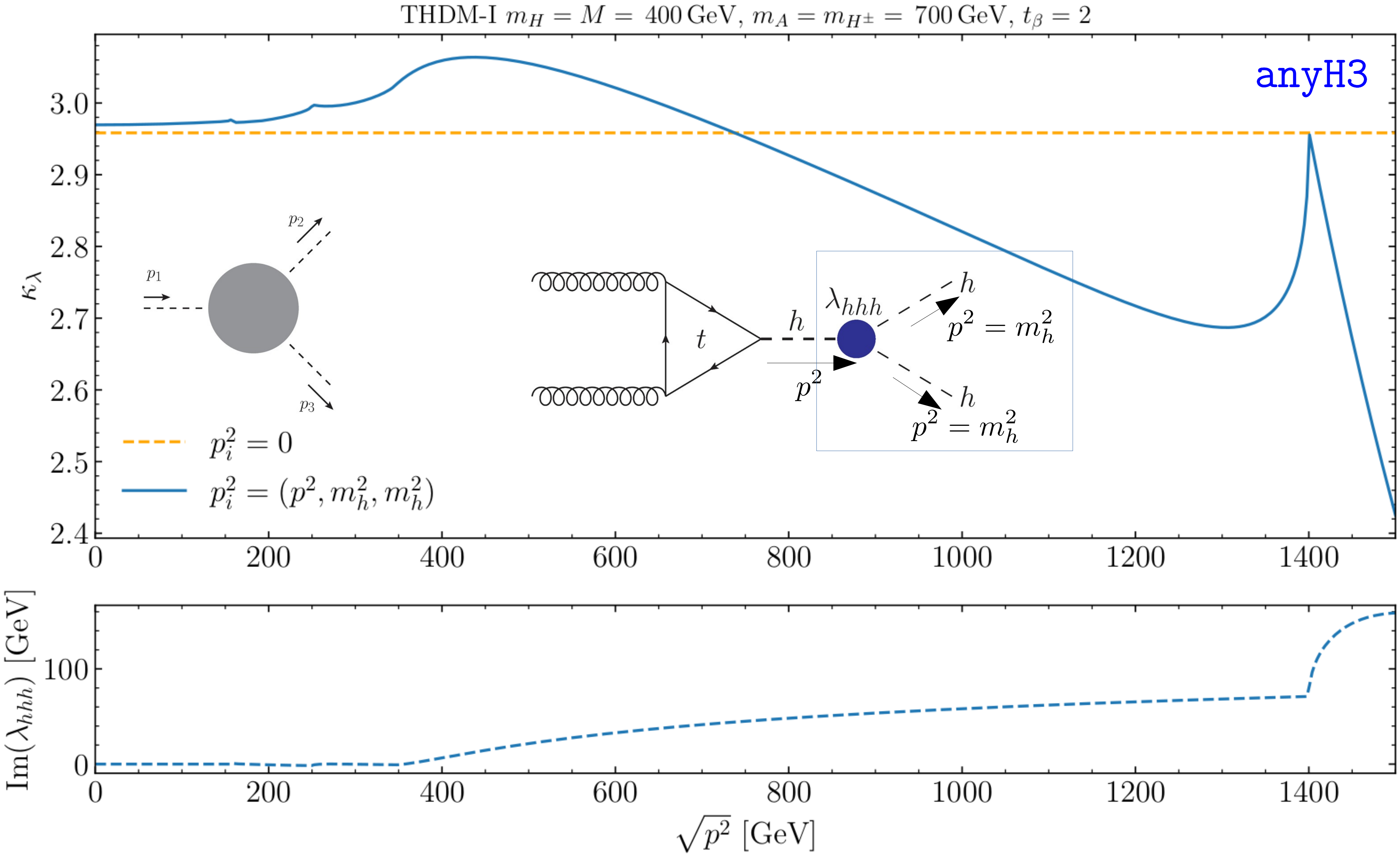
[Frederix et al., 1401.7340]

Plots taken from
[de Blas et al., 1905.03764]

anyH3: momentum dependence in the 2HDM (1L)



anyH3: momentum dependence in the 2HDM (1L)



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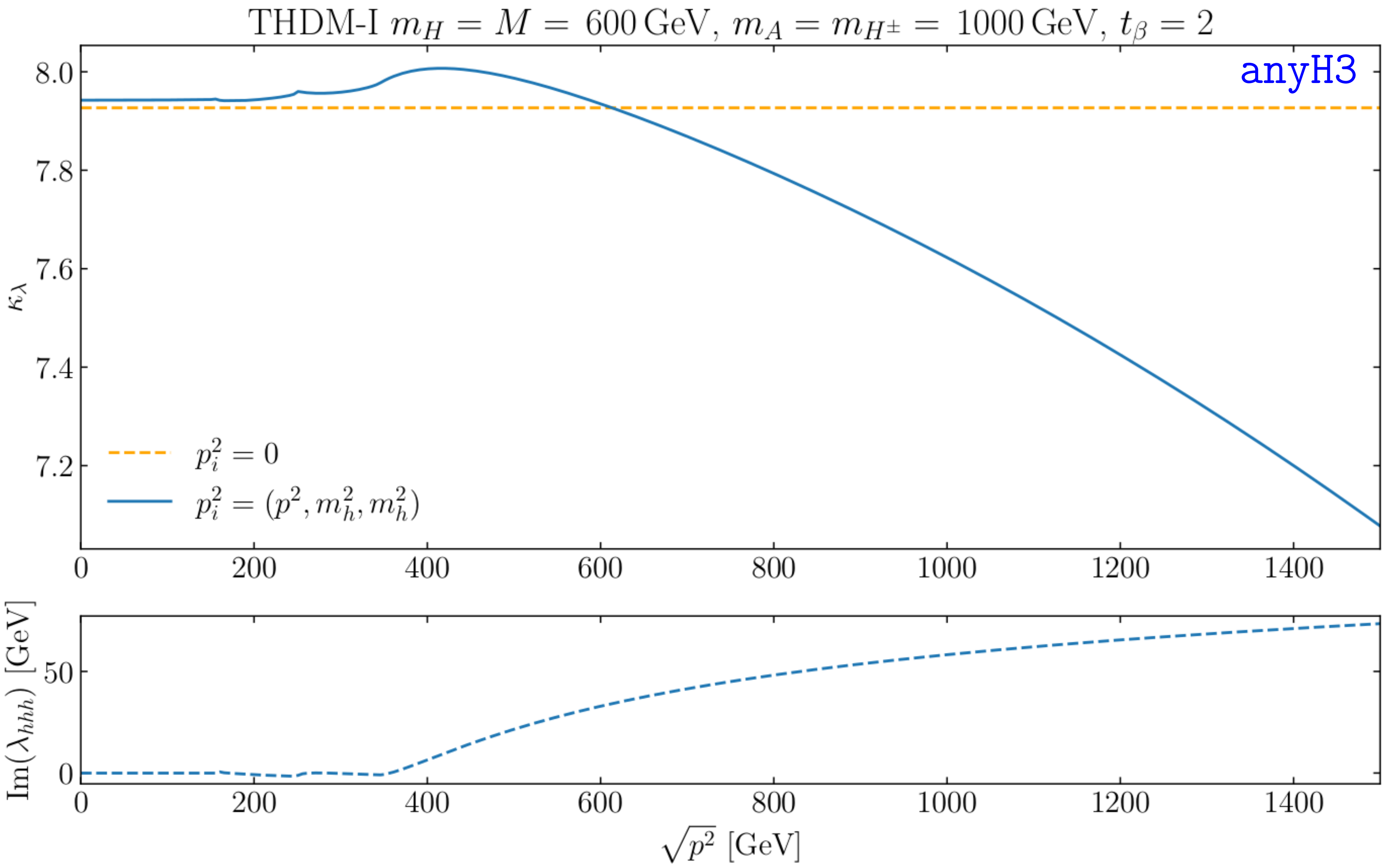
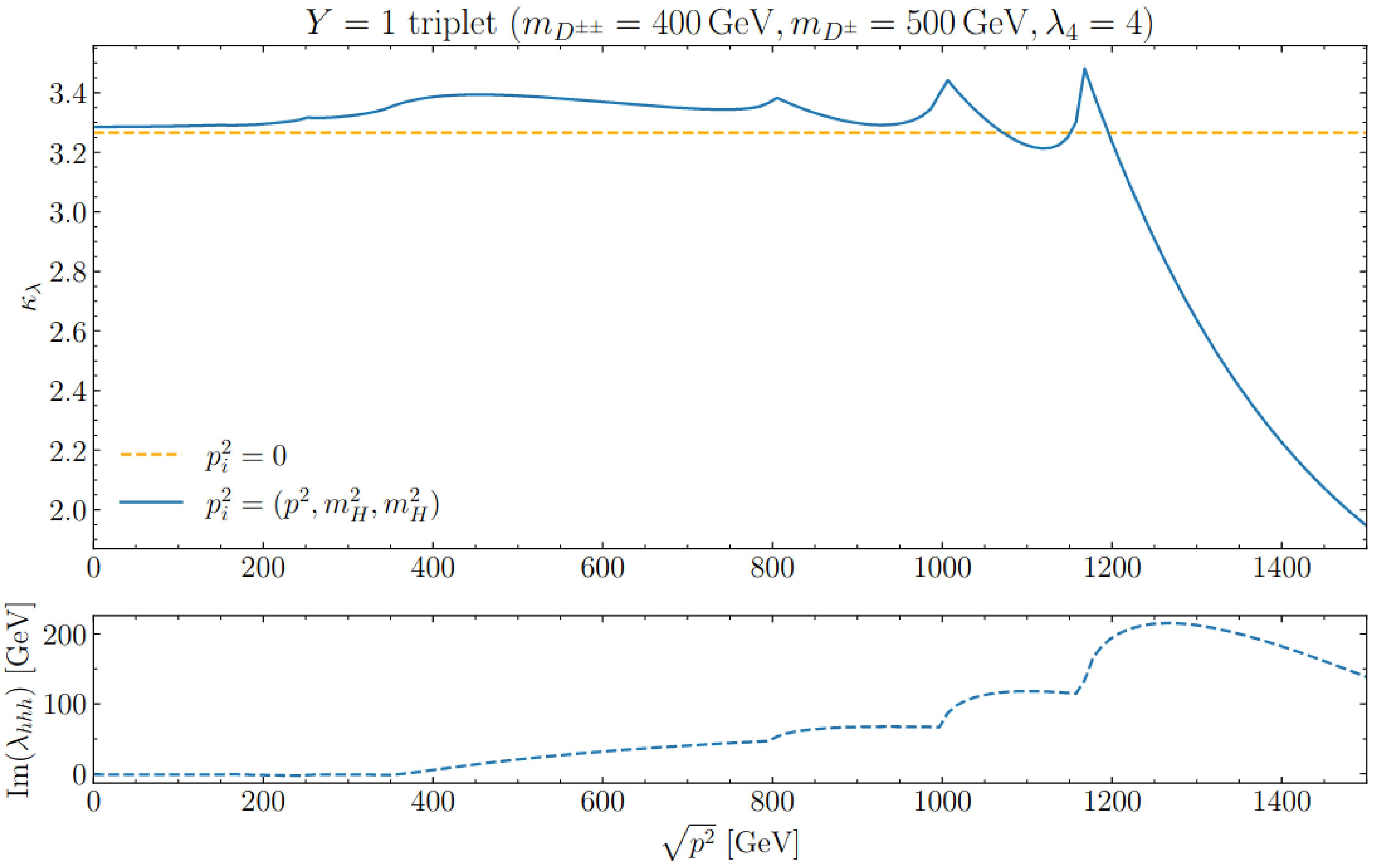


anyH3: momentum dependence in a Y=1 triplet extension (1L)



$\overline{\text{MS}}$ to OS scheme conversion

- V_{eff}: we use expressions in MS scheme hence results for λ_{hhh} also in $\overline{\text{MS}}$ scheme

- We include finite counterterms to express the Higgs trilinear coupling in terms of physical quantities

$$\underbrace{m_X^2}_{\overline{\text{MS}}} = \underbrace{M_X^2}_{\text{pole}} - \mathfrak{Re}[\Pi^{\text{fin.}}_{XX}(p^2 = M_X^2)], \qquad v^2 = \underbrace{(\sqrt{2}G_F)^{-1}}_{\equiv v^2_{\text{OS}}} + \frac{3M_t^2}{16\pi^2}\left(2\log\frac{M_t^2}{Q^2} - 1\right) + \cdots$$

- Also we include finite WFR effects → OS scheme

$$\underbrace{\hat{\lambda}_{hhh}}_{\text{OS}} = \underbrace{\left(\frac{Z_h^{\text{OS}}}{Z_h^{\overline{\text{MS}}}}\right)^{3/2}}_{\text{finite WFR}} \underbrace{\lambda_{hhh}}_{\overline{\text{MS}}} = -\underbrace{\Gamma_{hhh}(0,0,0)}_{\text{3-pt. func.}}$$

$\overline{\text{MS}}$ to OS scheme conversion

- OS result is obtained as

$$\hat{\lambda}_{hhh} = \underbrace{\left(\frac{Z_h^{\text{OS}}}{Z_h^{\overline{\text{MS}}}}\right)^{3/2}}_{\text{inclusion of WFR}} \times \underbrace{\lambda_{hhh}}_{\substack{\overline{\text{MS}}\text{ parameters} \\ \text{translated to OS ones}}}$$

- Let's suppose (for simplicity) that λ_{hhh} only depends on one parameter x, as

$$\lambda_{hhh} = f^{(0)}(x^{\overline{\text{MS}}}) + \kappa f^{(1)}(x^{\overline{\text{MS}}}) + \kappa^2 f^{(2)}(x^{\overline{\text{MS}}}) \qquad \left(\kappa = \frac{1}{16\pi^2}\right)$$

and

$$x^{\overline{\text{MS}}} = X^{\text{OS}} + \kappa\delta^{(1)}x + \kappa^2\delta^{(2)}x$$

then in terms of OS parameters

$$\lambda_{hhh} = f^{(0)}(X^{\text{OS}}) + \kappa\left[f^{(1)}(X^{\text{OS}}) + \frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x\right] + \kappa^2\left[f^{(2)}(X^{\text{OS}}) + \frac{\partial f^{(1)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x + \frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(2)}x + \frac{\partial^2 f^{(0)}}{\partial x^2}(X^{\text{OS}})(\delta^{(1)}x)^2\right]$$

$\overline{\text{MS}}$ to OS scheme conversion

- OS result is obtained as

$$\hat{\lambda}_{hhh} = \underbrace{\left(\frac{Z_h^{\text{OS}}}{Z_h^{\overline{\text{MS}}}}\right)^{3/2}}_{\text{inclusion of WFR}} \times \underbrace{\lambda_{hhh}}_{\substack{\overline{\text{MS}}\text{ parameters}\\ \text{replaced by OS ones}}}$$

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and

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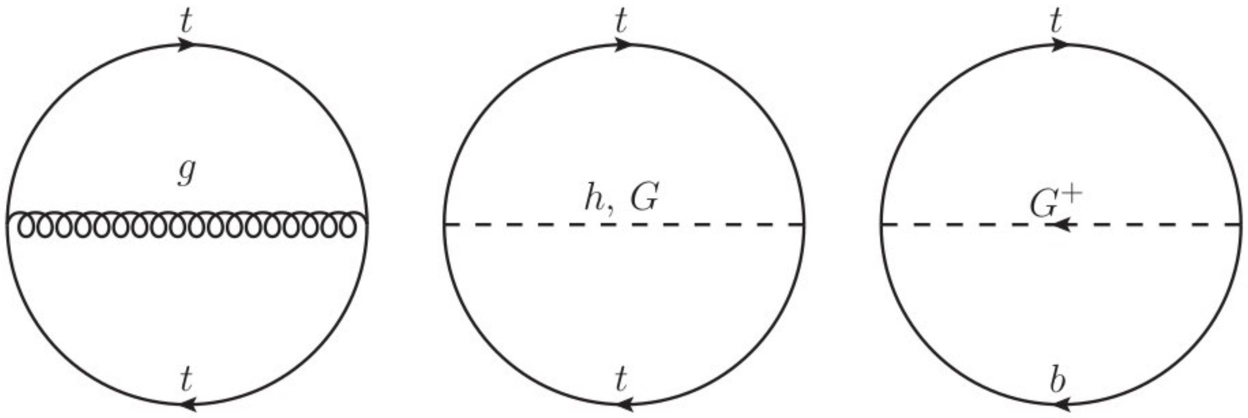
then in terms of OS parameters

$$\lambda_{hhh} = f^{(0)}(X^{\text{OS}}) + \kappa\left[f^{(1)}(X^{\text{OS}}) + \cancel{\frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x}\right]$$
$$+ \kappa^2\left[f^{(2)}(X^{\text{OS}}) + \frac{\partial f^{(1)}}{\partial x}(X^{\text{OS}})\delta^{(1)}x + \cancel{\frac{\partial f^{(0)}}{\partial x}(X^{\text{OS}})\delta^{(2)}x} + \cancel{\frac{\partial^2 f^{(0)}}{\partial x^2}(X^{\text{OS}})(\delta^{(1)}x)^2}\right]$$

because we neglect m_h in the loop corrections and $\lambda_{hhh}^{(0)} = 3m_h^2/v$ (in absence of mixing)

SM result at two loops

$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min.}}$$



- In the SM, 4 diagrams contribute to V_{eff} at order $\mathcal{O}(g_3^2 m_t^4)$ and $\mathcal{O}(m_t^6/v^2)$
- In the limit $m_t \gg m_h, m_G, \cdots$, their expression reads

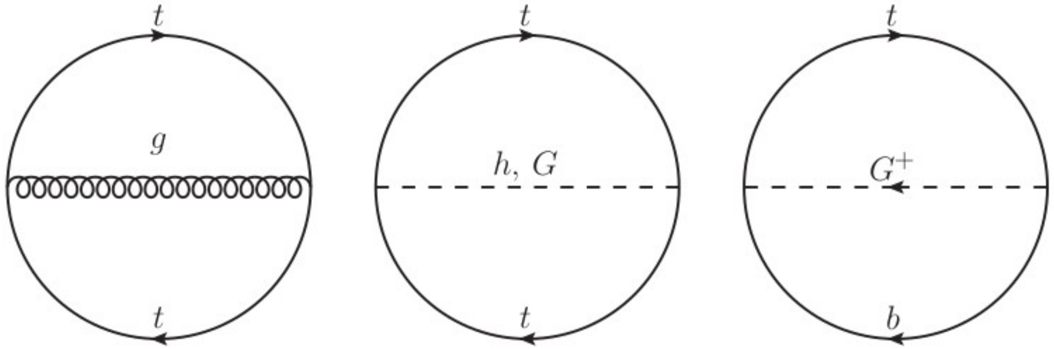
$$V^{(2)} = -4g_3^2 m_t^2 \left[4A(m_t^2) - 8m_t^2 - \frac{6A(m_t^2)^2}{m_t^2}\right] + 3y_t^2 \left[2m_t^2 I(m_t^2, m_t^2, 0) + m_t^2 I(m_t^2, 0, 0) + A(m_t^2)^2\right]$$

where $A(x) \equiv x(\log(x/Q^2) - 1)$, I: two-loop sunrise integral

- Then we find in the $\overline{\text{MS}}$ scheme

$$\delta^{(2)}\lambda_{hhh} = \frac{128 g_3^2 m_t^4 (1 + 6\,\overline{\log}\, m_t^2)}{v^3} - \frac{24 m_t^4 y_t^2 (-7 + 6\,\overline{\log}\, m_t^2)}{v^3} \qquad (\overline{\log}\, x \equiv \log x/Q^2)$$

SM result at two loops



- $\overline{\text{MS}}$ expression

$$\delta^{(2)}\lambda_{hhh} = \frac{128 g_3^2 m_t^4 (1 + 6\,\overline{\log}\, m_t^2)}{v^3} - \frac{24 m_t^4 y_t^2 (-7 + 6\,\overline{\log}\, m_t^2)}{v^3} \qquad (\overline{\log}\, x \equiv \log x/Q^2)$$

- Translate top quark mass and Higgs VEV from $\overline{\text{MS}}$ to OS scheme in $\delta^{(1)}\lambda_{hhh} = -\frac{48 m_t^4}{v^3}$

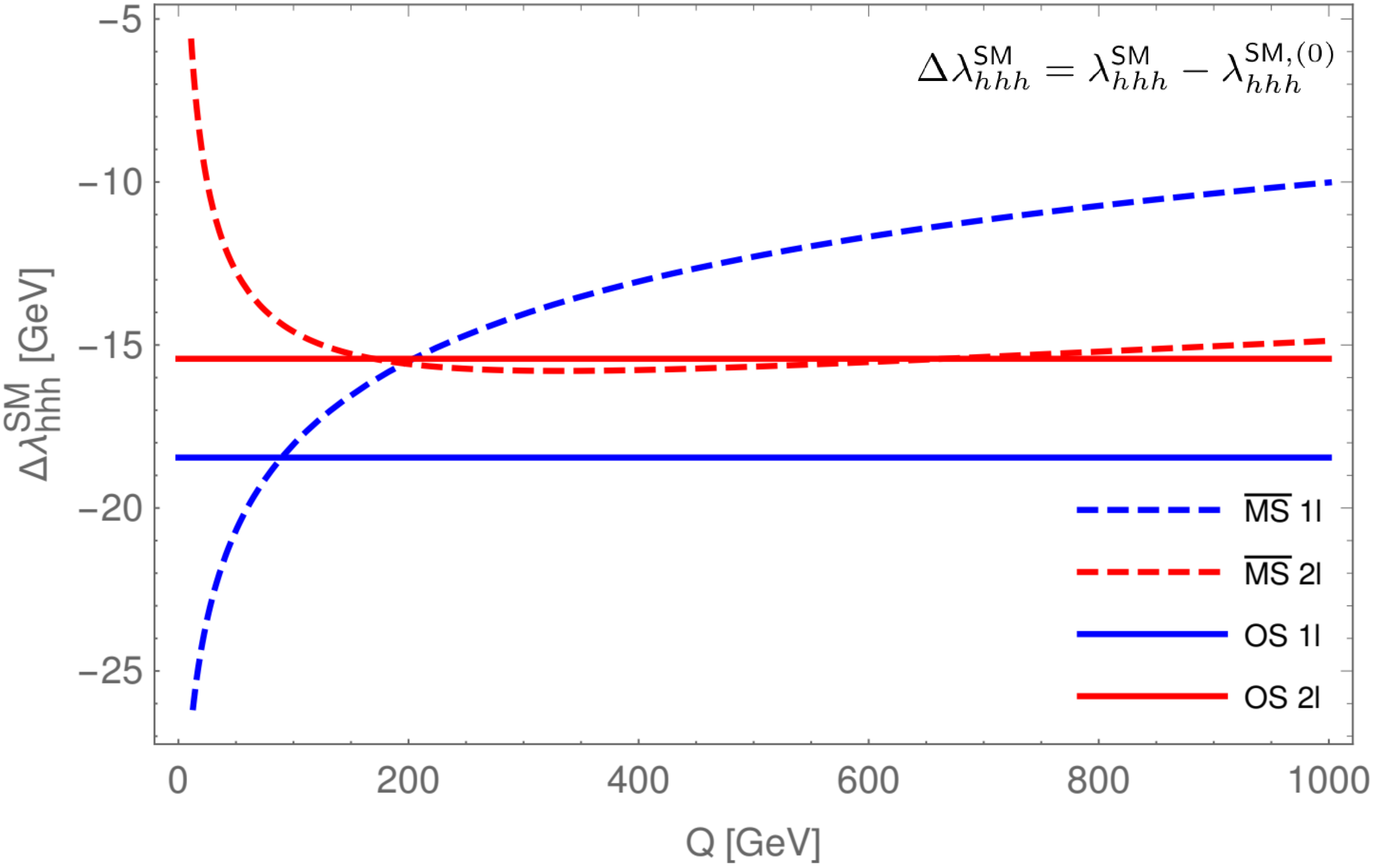
$$m_t^2 \to M_t^2 - \Pi_{tt}(p^2 = M_t^2) \qquad v \to \frac{1}{\sqrt{\sqrt{2}G_F}} - \delta v = v_{\text{phys}} - \delta v$$

$+$ include wave-function renormalisation
$\to$ OS-scheme result

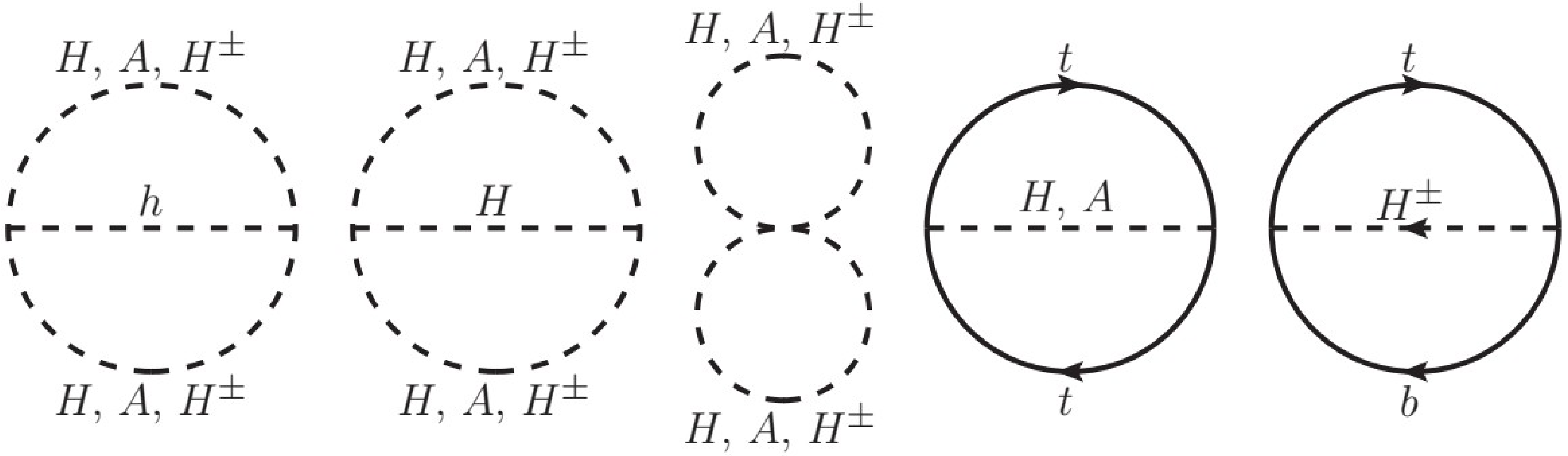
$$\delta^{(2)}\hat{\lambda}_{hhh} = \frac{72 M_t^4}{v_{\text{phys}}^3}\left(16 g_3^2 - \frac{13 M_t^2}{v_{\text{phys}}^2}\right)$$

SM result at two loops

[JB, Kanemura '19]



$\overline{\text{MS}}$ result



- Taking BSM scalars to be degenerate $M_\Phi = M_H = M_A = M_{H^\pm}$ we obtain in the $\overline{\text{MS}}$ scheme:
  (expressions for non-degenerate masses → see [JB, Kanemura 1911.11507])

$$
\begin{aligned}
\delta^{(2)}\lambda_{hhh} = {} & \frac{16 m_\Phi^4}{v^5}\left(4 + 9\cot^2 2\beta\right)\left(1 - \frac{M^2}{m_\Phi^2}\right)^4 \left[-2M^2 - m_\Phi^2 + (M^2 + 2m_\Phi^2)\,\overline{\log}\, m_\Phi^2\right] \\
& + \frac{192 m_\Phi^6 \cot^2 2\beta}{v^5}\left(1 - \frac{M^2}{m_\Phi^2}\right)^4 \left[1 + 2\,\overline{\log}\, m_\Phi^2\right] \\
& + \frac{96 m_\Phi^4 m_t^2 \cot^2\beta}{v^5}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \left[-1 + 2\,\overline{\log}\, m_\Phi^2\right] + \mathcal{O}\left(\frac{m_\Phi^2 m_t^4}{v^5}\right)
\end{aligned}
$$

Decoupling property in $\overline{\text{MS}}$ scheme

- Seeing whether corrections from additional BSM states decouple if said state is taken to be very massive is a good way to check the consistency of the calculation

$$\delta^{(2)}\lambda_{hhh} = \frac{16 m_\Phi^4}{v^5}\left(4 + 9\cot^2 2\beta\right)\left(1 - \frac{M^2}{m_\Phi^2}\right)^4\left[-2M^2 - m_\Phi^2 + (M^2 + 2m_\Phi^2)\,\overline{\log}\, m_\Phi^2\right]$$

$$\delta^{(1)}\lambda_{hhh} = \frac{16 m_\Phi^4}{v^3}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \qquad + \frac{192 m_\Phi^6 \cot^2 2\beta}{v^5}\left(1 - \frac{M^2}{m_\Phi^2}\right)^4\left[1 + 2\,\overline{\log}\, m_\Phi^2\right]$$

$$+ \frac{96 m_\Phi^4 m_t^2 \cot^2\beta}{v^5}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left[-1 + 2\,\overline{\log}\, m_\Phi^2\right] + \mathcal{O}\left(\frac{m_\Phi^2 m_t^4}{v^5}\right)$$

where $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2$

- To have $m_\Phi \to \infty$, then we must take $M \to \infty$, otherwise the quartic couplings grow out of control
- Fortunately all of these terms go like

$$(m_\Phi^2)^{n-1}\left(1 - \frac{M^2}{m_\Phi^2}\right)^n \underset{m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2}{=} \frac{(\tilde{\lambda}_\Phi v^2)^n}{M^2 + \tilde{\lambda}_\Phi v^2} \xrightarrow[\tilde{\lambda}_\Phi v^2 \text{ fixed}]{M\to\infty} 0$$

$\overline{\text{MS}} \to$ OS scheme conversion

- To express $\delta^{(2)}\lambda_{hhh}$ in terms of physical parameters (v_{phys}, M_t, $M_A = M_H = M_{H^\pm} = M_\Phi$), we replace

$$m_A^2 \to M_A^2 - \Pi_{AA}(M_A^2), \quad m_H^2 \to M_H^2 - \Pi_{HH}(M_H^2), \quad m_{H^\pm}^2 \to M_{H^\pm}^2 - \Pi_{H^+H^-}(M_{H^\pm}^2),$$

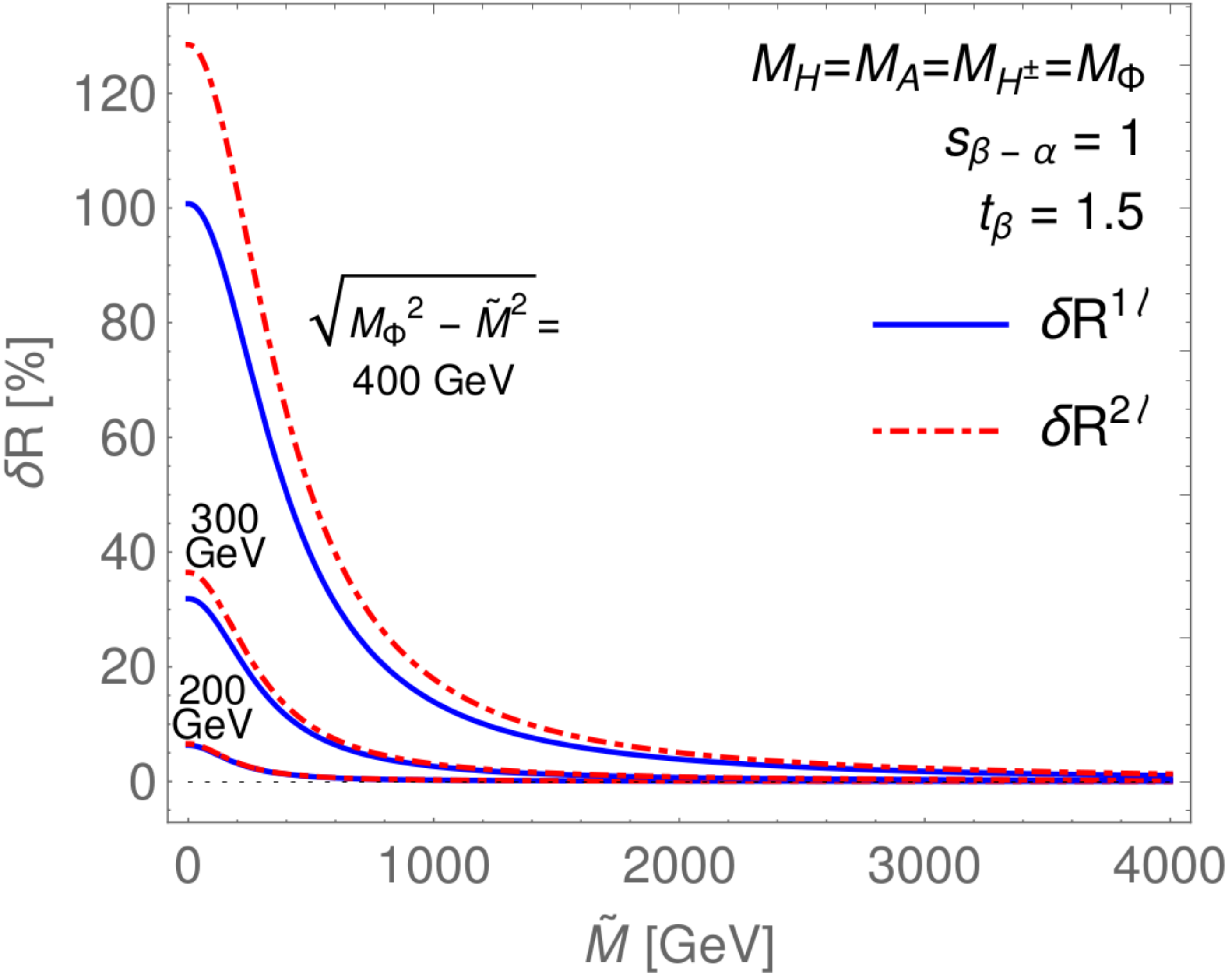
$$v \to v_{\text{phys}} - \delta v, \quad m_t^2 \to M_t^2 - \Pi_{tt}(M_t^2)$$

- A priori, M is still renormalised in $\overline{\text{MS}}$ scheme, because it is difficult to relate to physical observable

  ... but then, expressions do not decouple for $M_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2$ and $M \to \infty$!
- This is because we should relate M_Φ, renormalised in OS scheme, and M, renormalised in $\overline{\text{MS}}$ scheme, with a **one-loop relation** $\to$ then the two-loop corrections decouple properly
- We give a new "OS" prescription for the finite part of the counterterm for M be requiring that
  1. the decoupling of $\delta^{(2)}\hat{\lambda}_{hhh}$ (in OS scheme) is apparent using a relation $M_\Phi^2 = \tilde{M}^2 + \tilde{\lambda}_\Phi v^2$
  2. all the log terms in $\delta^{(2)}\hat{\lambda}_{hhh}$ are absorbed in δM^2

$$\delta^{(2)}\hat{\lambda}_{hhh} = \frac{48 M_\Phi^6}{v_{\text{phys}}^5}\left(1 - \frac{\tilde{M}^2}{M_\Phi^2}\right)^4 \left\{4 + 3\cot^2 2\beta\left[3 - \frac{\pi}{\sqrt{3}}\left(\frac{\tilde{M}^2}{M_\Phi^2} + 2\right)\right]\right\} + \frac{576 M_\Phi^6 \cot^2 2\beta}{v_{\text{phys}}^5}\left(1 - \frac{\tilde{M}^2}{M_\Phi^2}\right)^4$$
$$+ \frac{288 M_\Phi^4 M_t^2 \cot^2\beta}{v_{\text{phys}}^5}\left(1 - \frac{\tilde{M}^2}{M_\Phi^2}\right)^3 + \frac{168 M_\Phi^4 M_t^2}{v_{\text{phys}}^5}\left(1 - \frac{\tilde{M}^2}{M_\Phi^2}\right)^3 - \frac{48 M_\Phi^6}{v_{\text{phys}}^5}\left(1 - \frac{\tilde{M}^2}{M_\Phi^2}\right)^5 + \mathcal{O}\left(\frac{M_\Phi^2 M_t^4}{v_{\text{phys}}^5}\right)$$

Decoupling behaviour



- δR size of BSM contributions to λ_{hhh}:

$$\delta R \equiv \frac{\lambda_{hhh}^{\text{2HDM}}}{\lambda_{hhh}^{\text{SM}}} - 1$$

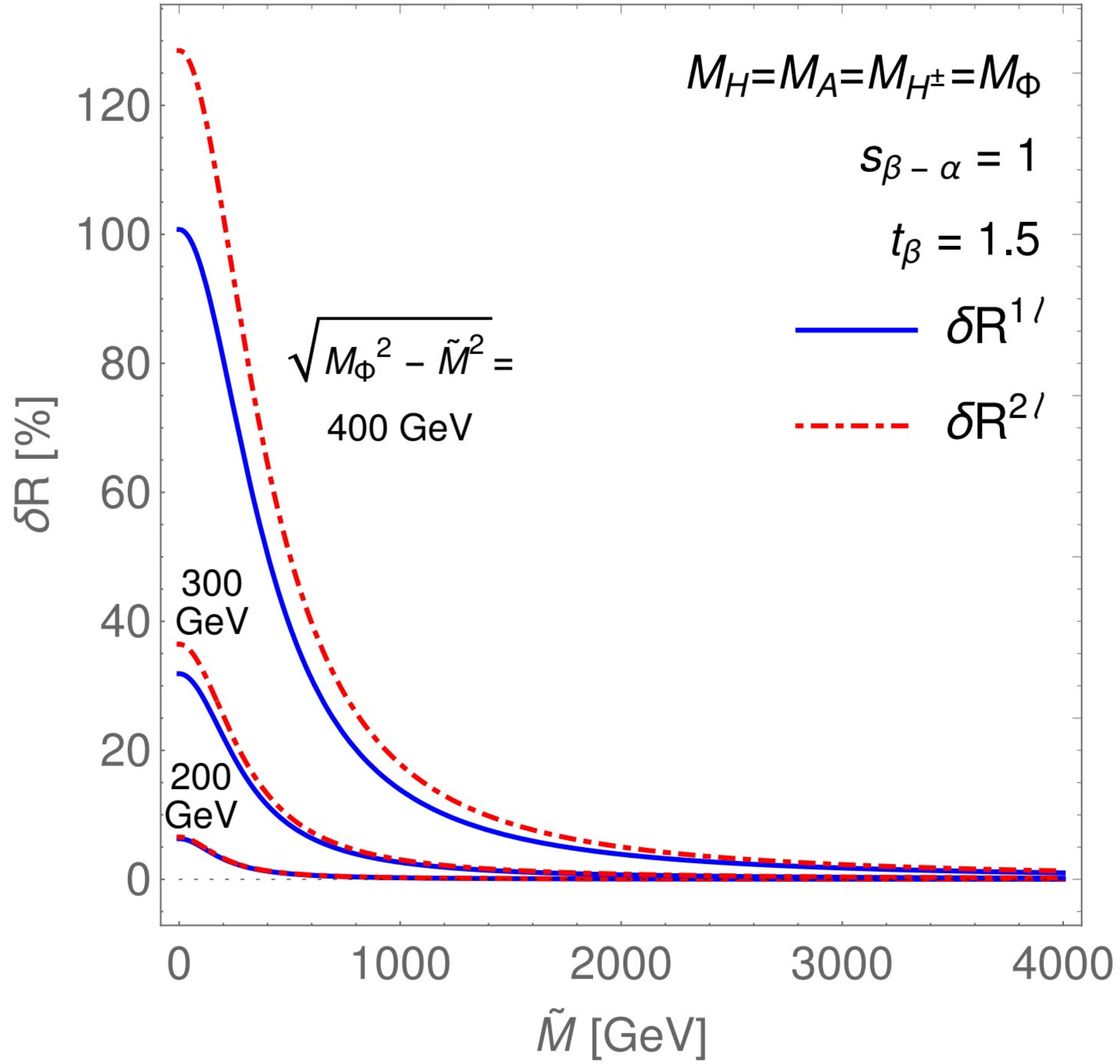
- $\tilde{M}$: "OS" version of M, defined so as to ensure proper decoupling for $M_\Phi^2 = \tilde{M}^2 + \tilde{\lambda}_\Phi v^2$ and $\tilde{M} \to \infty$

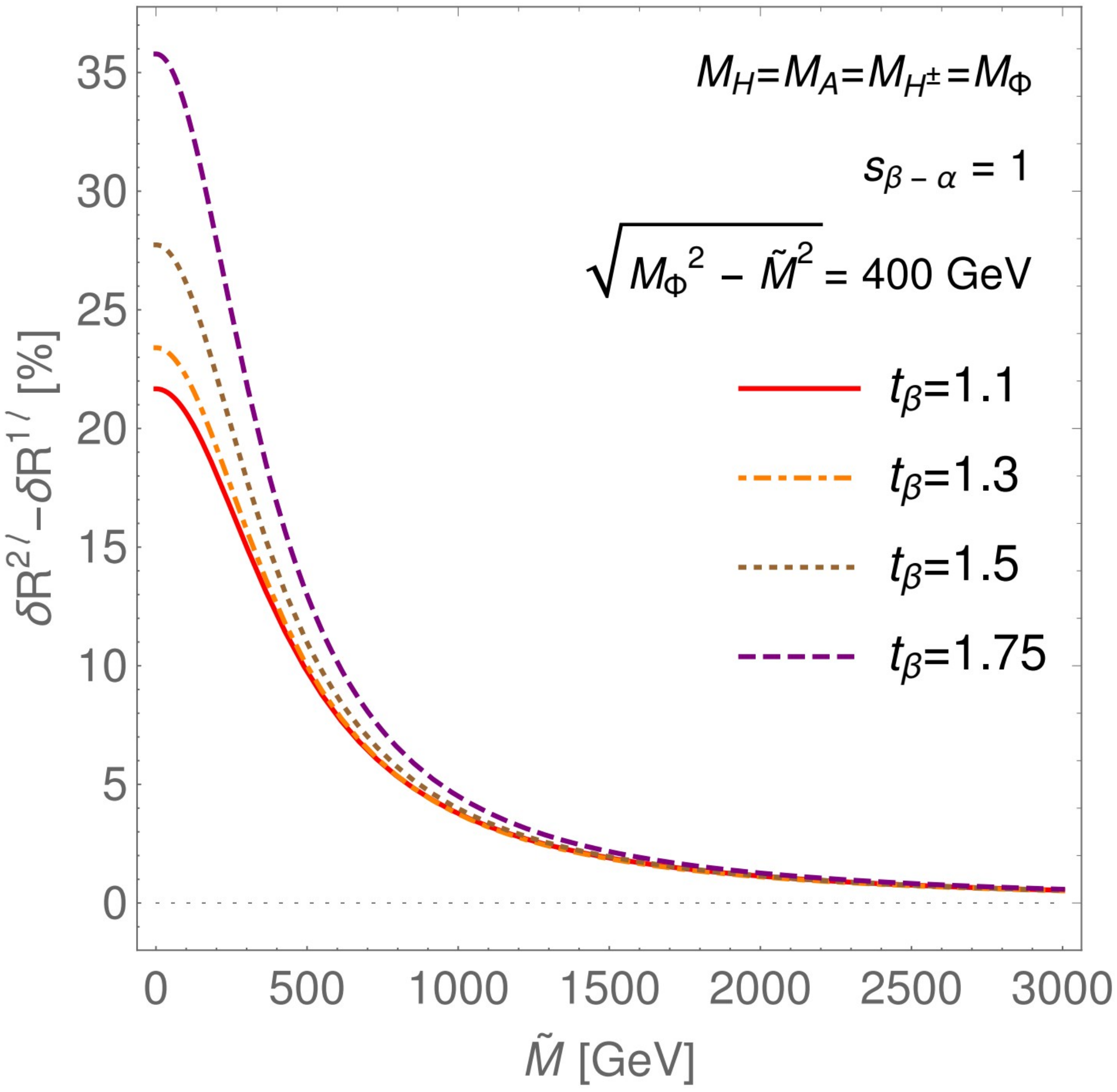
- Radiative corrections from additional scalars + top quark indeed decouple properly for $\tilde{M} \to \infty$

Decoupling of BSM effects

$\tilde{M}$: modified "OS" version of Z_2 breaking scale

[JB, Kanemura '19]

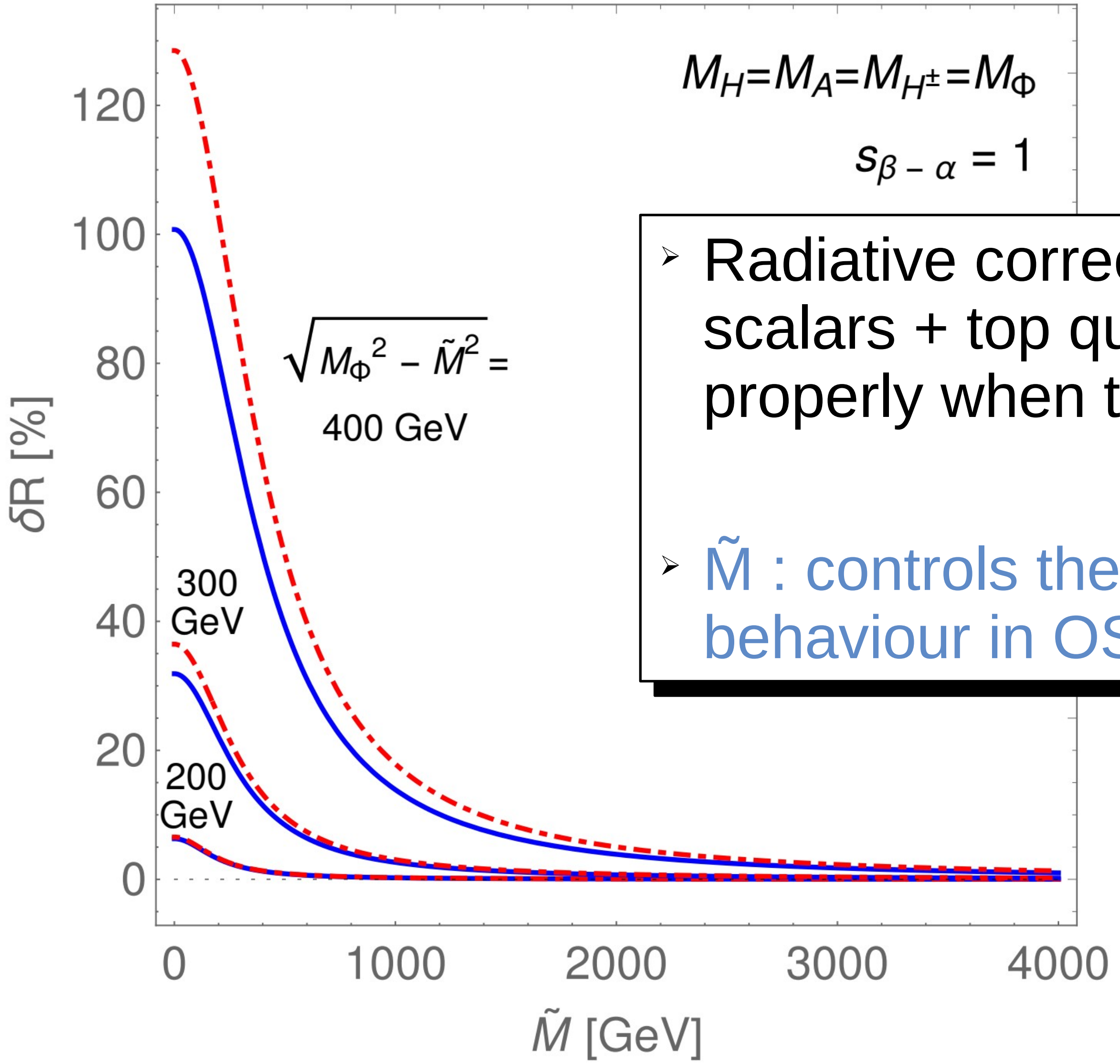




Decoupling of BSM effects

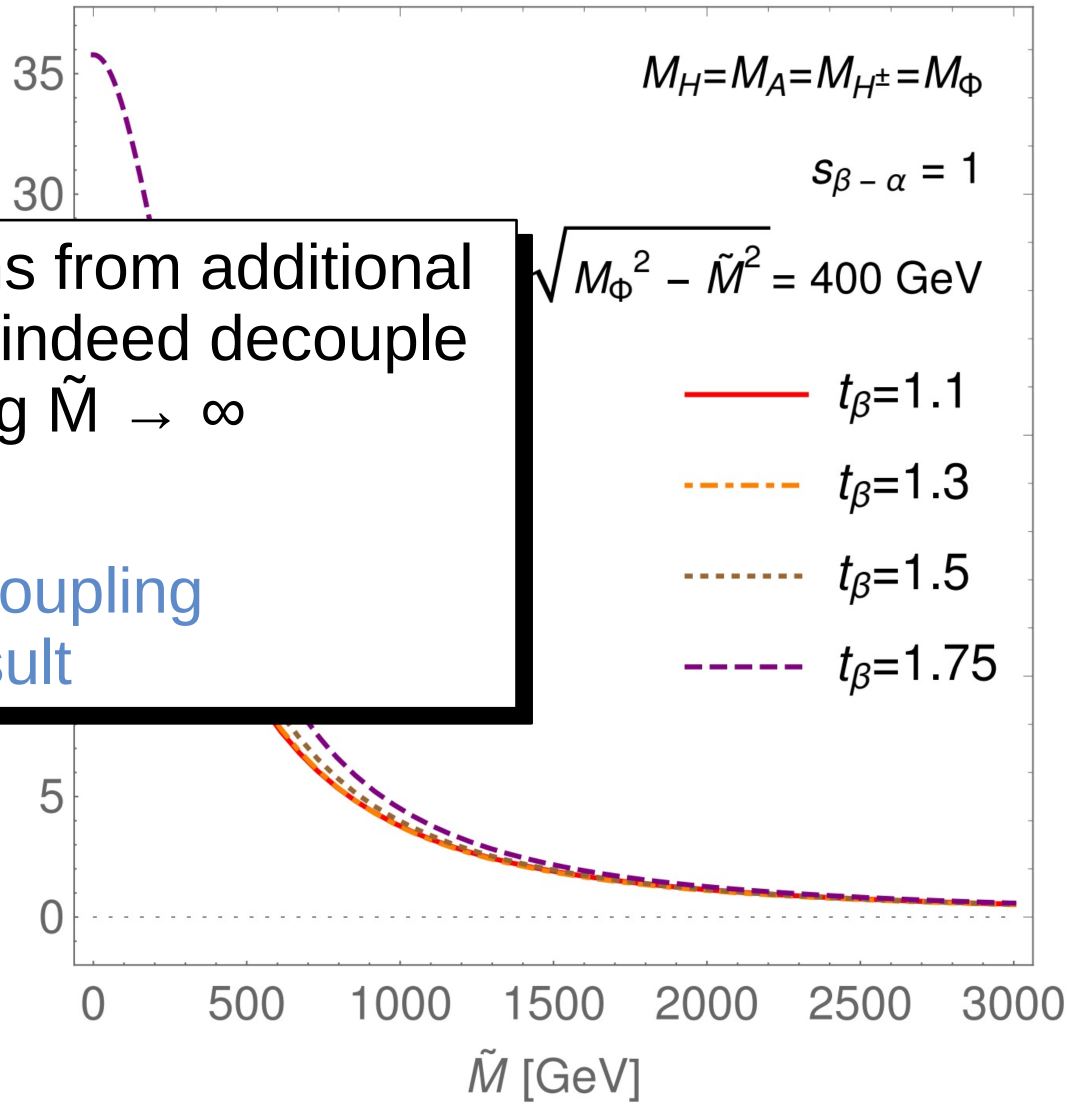
M̃ : modified "OS" version of Z_2 breaking scale

[JB, Kanemura '19]



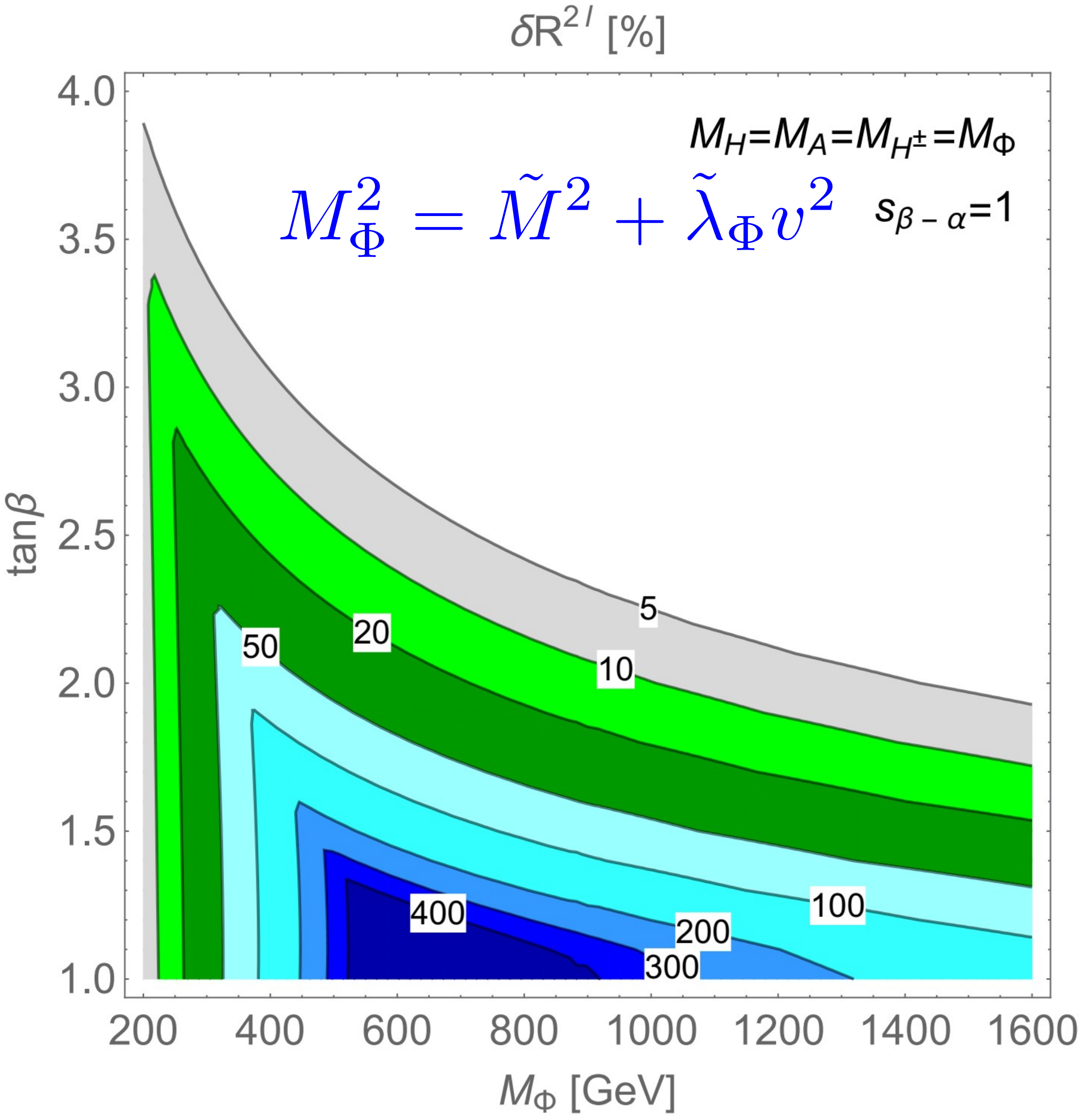
- Radiative corrections from additional scalars + top quark indeed decouple properly when taking $\tilde{M} \to \infty$

- $\tilde{M}$: controls the decoupling behaviour in OS result



Maximal BSM deviation in an aligned 2HDM scenario

[JB, Kanemura 1911.11507]



- Maximal δR (1l+2l) allowed while fulfilling perturbative unitarity [Kanemura, Kubota, Takasugi '93]
- Max. deviations for low tanβ and M_Φ~600-800 GeV → heavy BSM scalars acquiring their mass from Higgs VEV **only**
  - 1 loop: up to ~300% deviation at most
  - 2 loops: additional 100% (for same points)
- For increasing tanβ, unitarity constraints become more stringent → smaller δR
- **Blue region:** probed at **HL-LHC** (50% accuracy on λ_{hhh})
- **Green region:** probed at lepton colliders, e.g. **ILC** (50% accuracy at 250 GeV; 27% at 500 GeV; 10% at 1 TeV)

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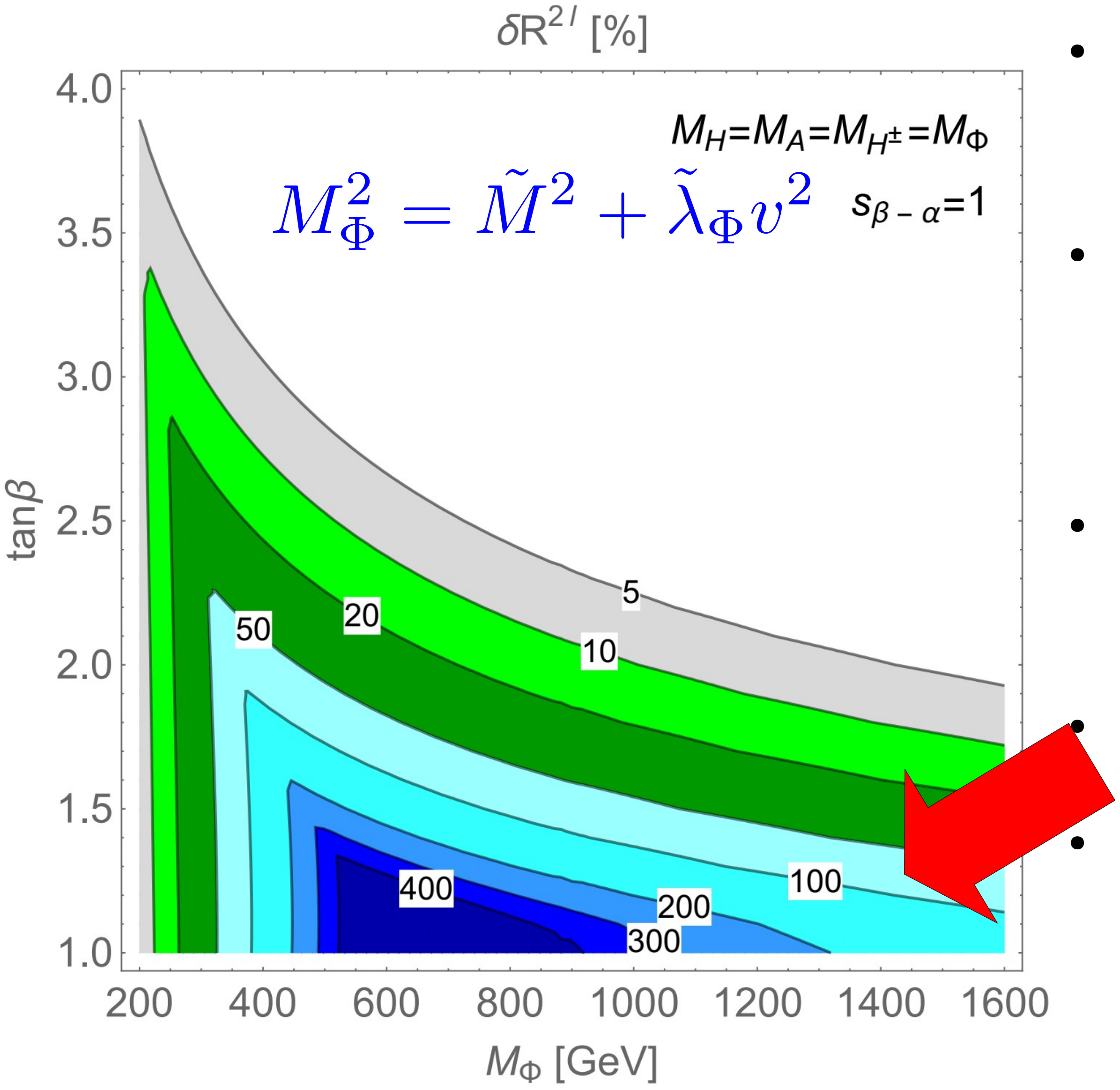

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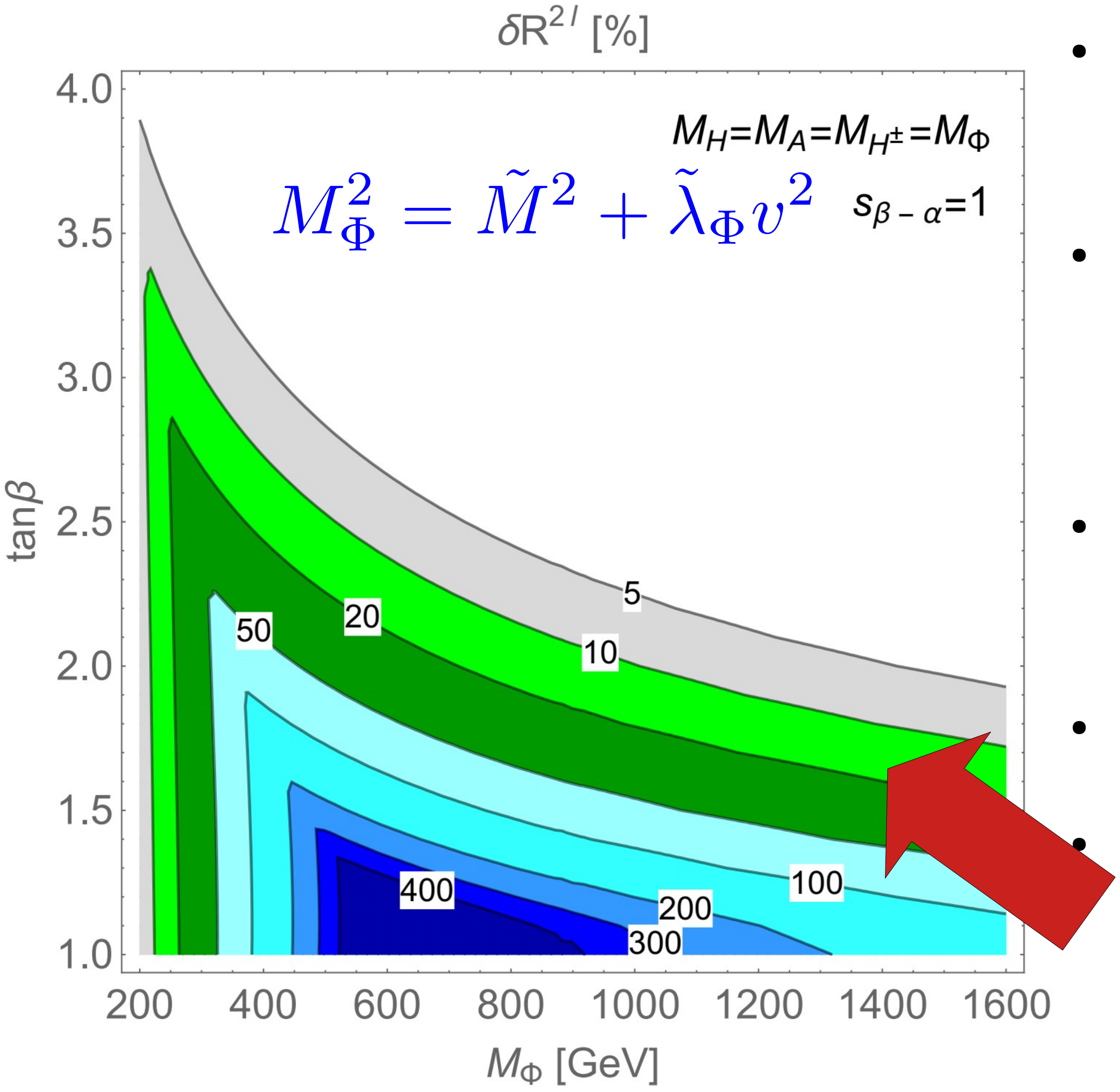

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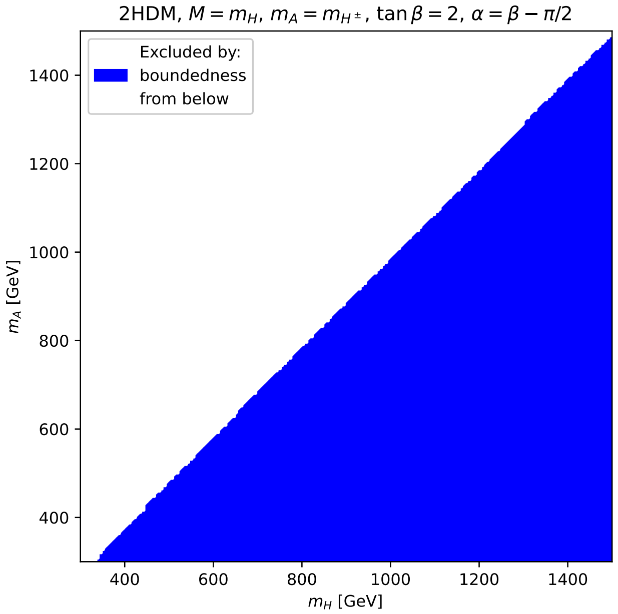
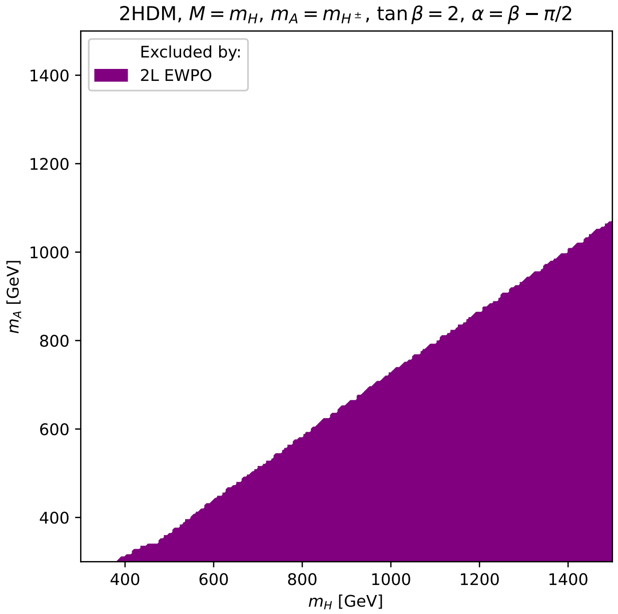
2HDM benchmark plane – individual theoretical constraints

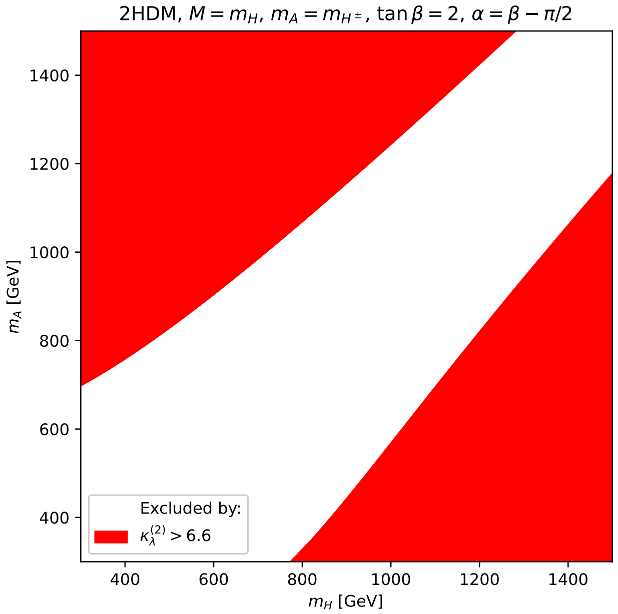
Constraints shown below are independent of 2HDM type



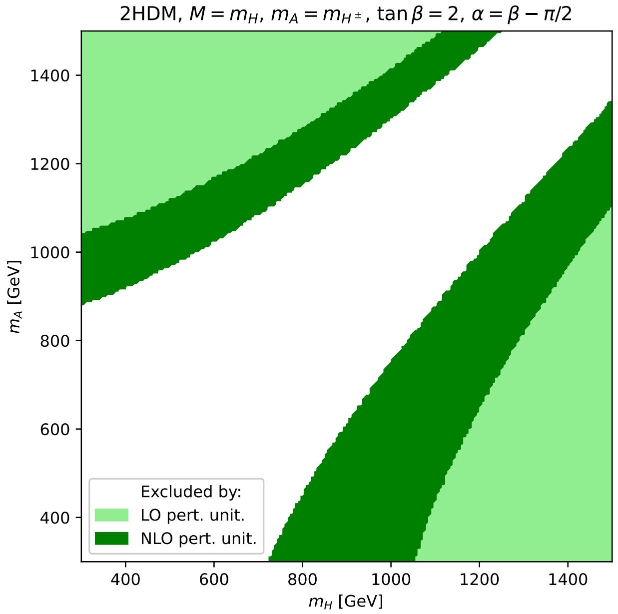
Boundedness from below



EW precision observables computed at 2L



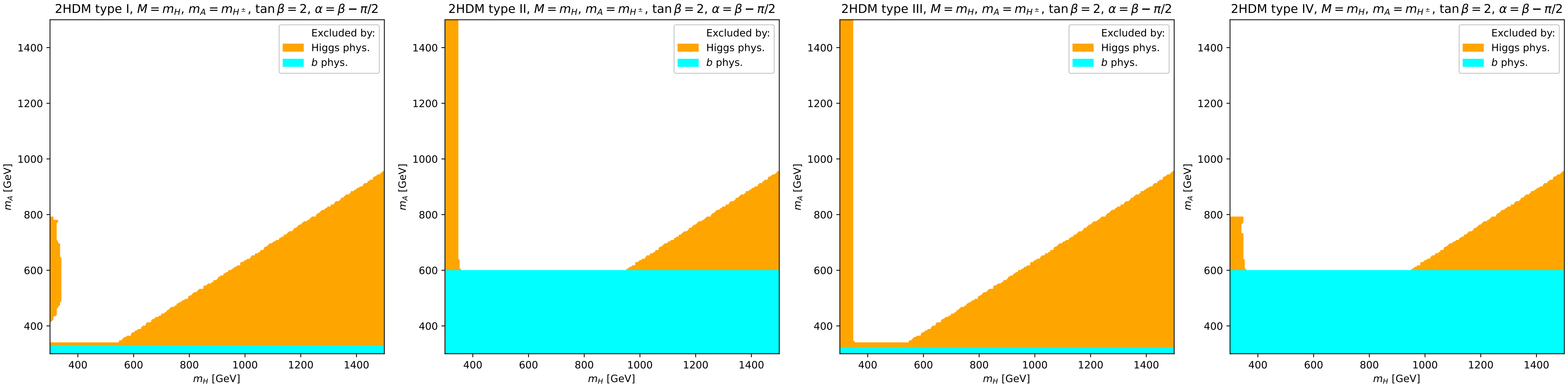
$\kappa_\lambda^{(2)} > 6.6$



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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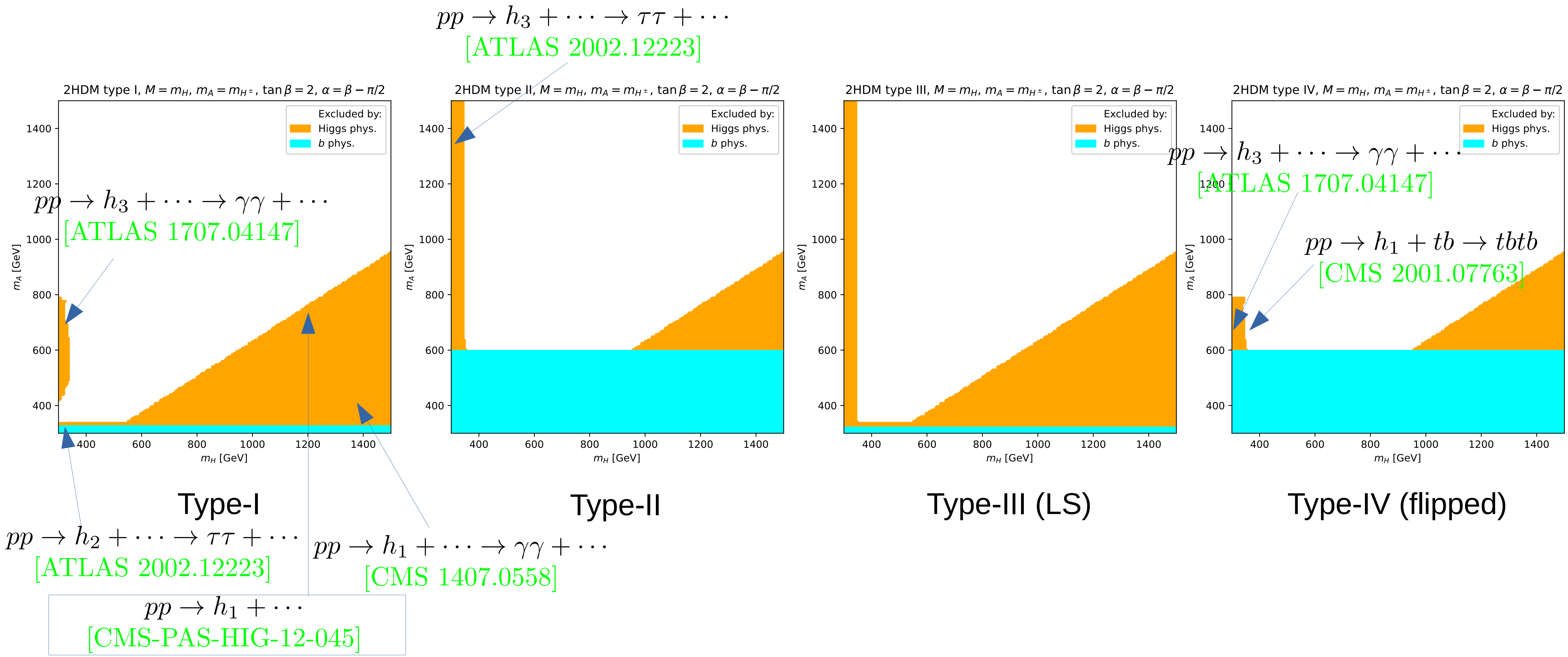
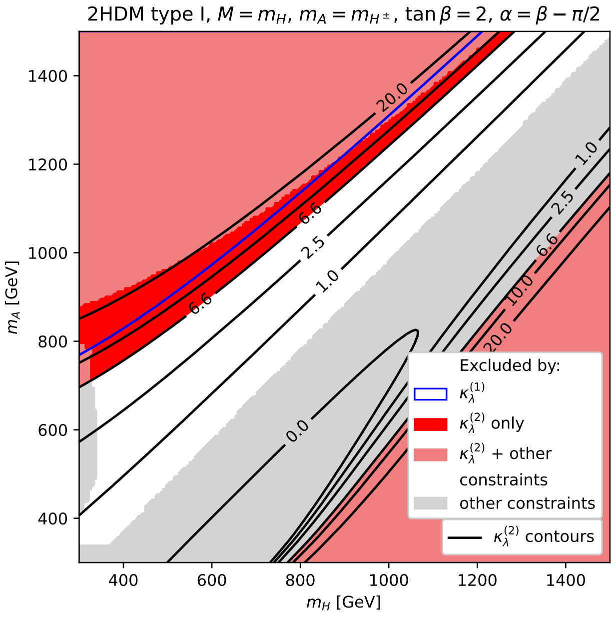
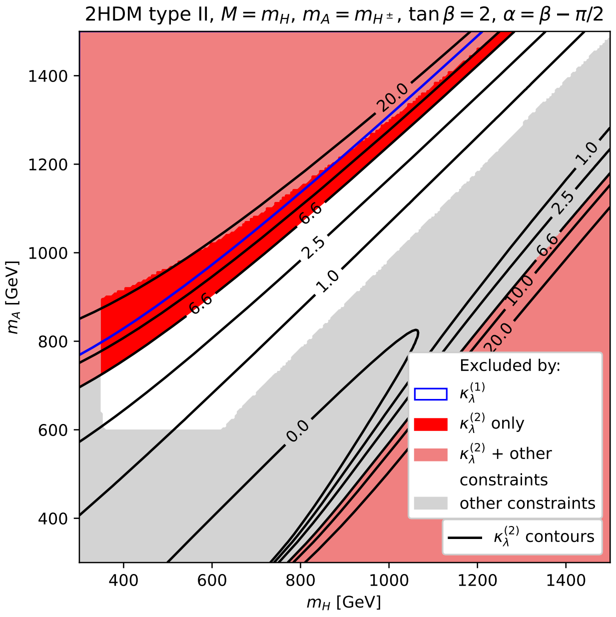


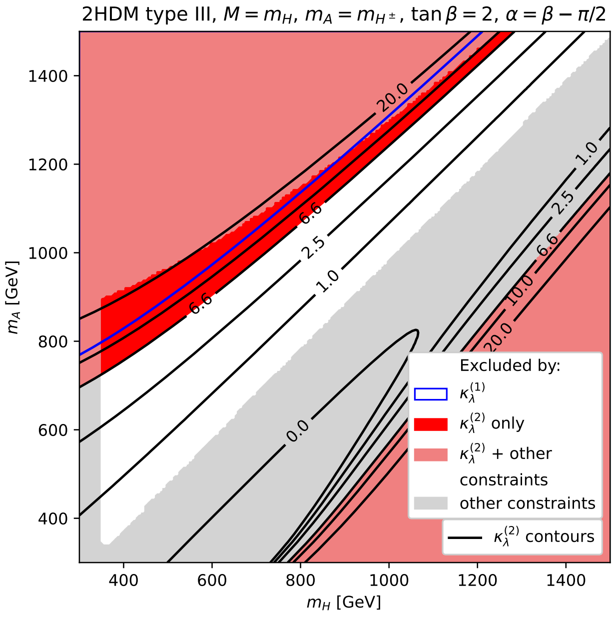
2HDM benchmark plane – results for all types



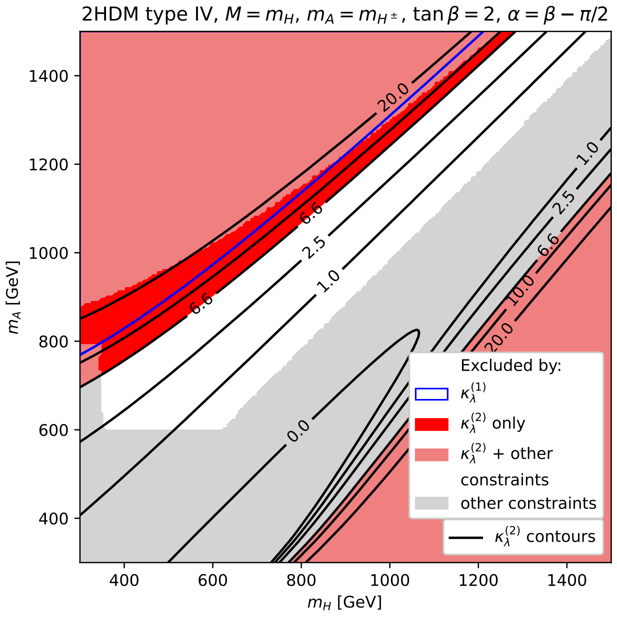
Type-I



Type-II



Type-III (LS)



Type-IV (flipped)