Two-loop corrections to the Higgs trilinear coupling in BSM models with classical scale invariance

Based on arXiv:2011.07580 (accepted in JHEP),

in collaboration with Shinya Kanemura and Makoto Shimoda

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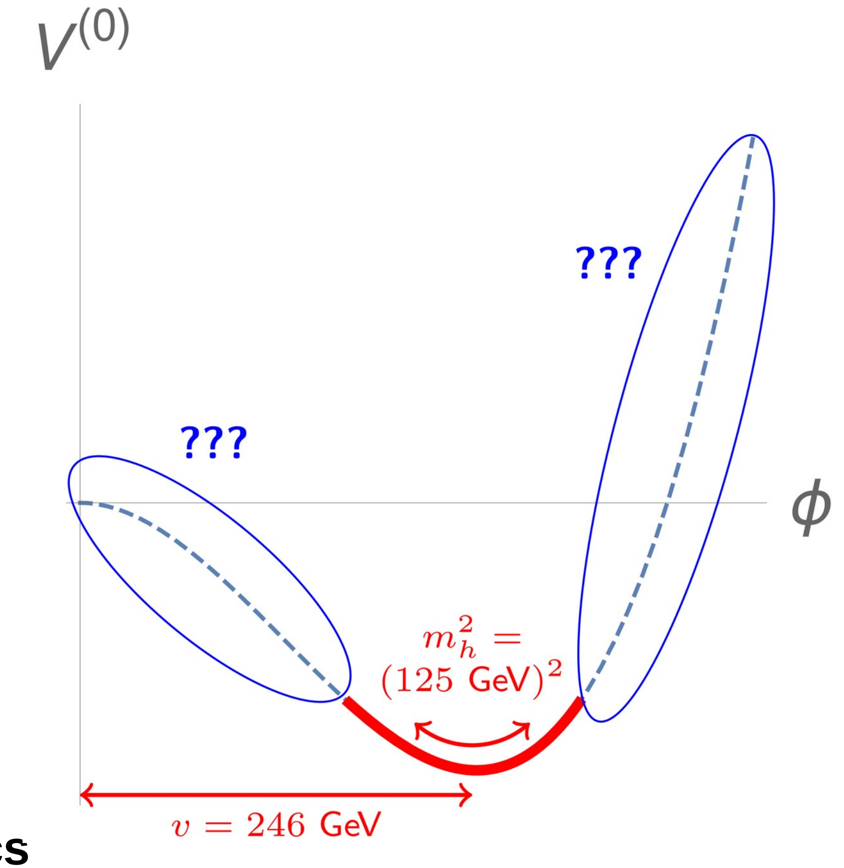
Why investigate λ_{hhh}?

- **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 → depends on λ_{hhh}



- **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]

- Higgs couplings, such as λ_{hhh}, can exhibit **large effects from BSM Physics**
  → Currently, $-3.7 < \lambda_{hhh}/(\lambda_{hhh})^{SM} < 11.5$ [ATLAS-CONF-2019-049]
  → But the determination will be drastically improved at future colliders:
  ~50% accuracy at **HL-LHC**; accuracy of some tens of % achievable at linear e^+e^- colliders (**ILC/CLIC**)

(more details in backup)

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, for 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**

λ_{hhh} in CSI models

One-loop effective potential and λ_{hhh}

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

- 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

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

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

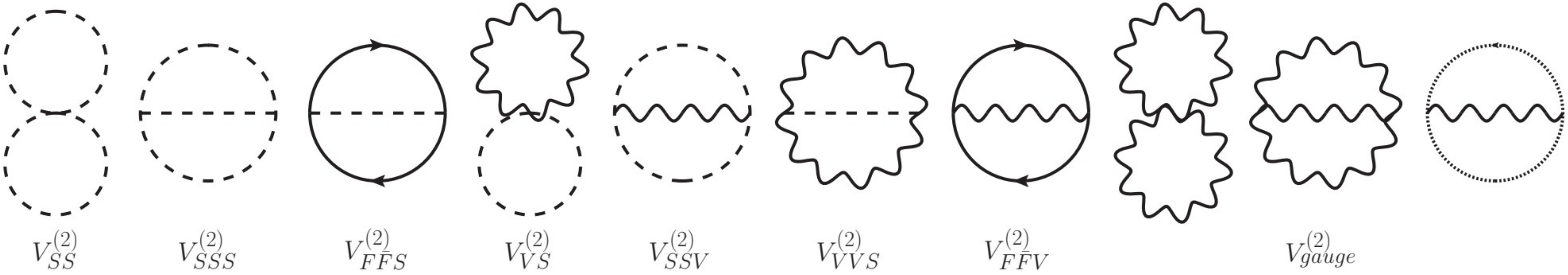
- Taking successive derivatives of the potential
  - 1st derivative = tadpole equation → fix A in terms of v and B
  - 2nd derivative = Higgs (effective potential) mass $[M_h^2]_{V_\mathrm{eff}}$ → fix B in terms of v and Mh
  - 3rd derivative = λ_{hhh} but $V^{(1)}$ is **entirely determined** by A,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

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

Universal one-loop result in CSI theories!

Effective potential at two loops

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



- 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

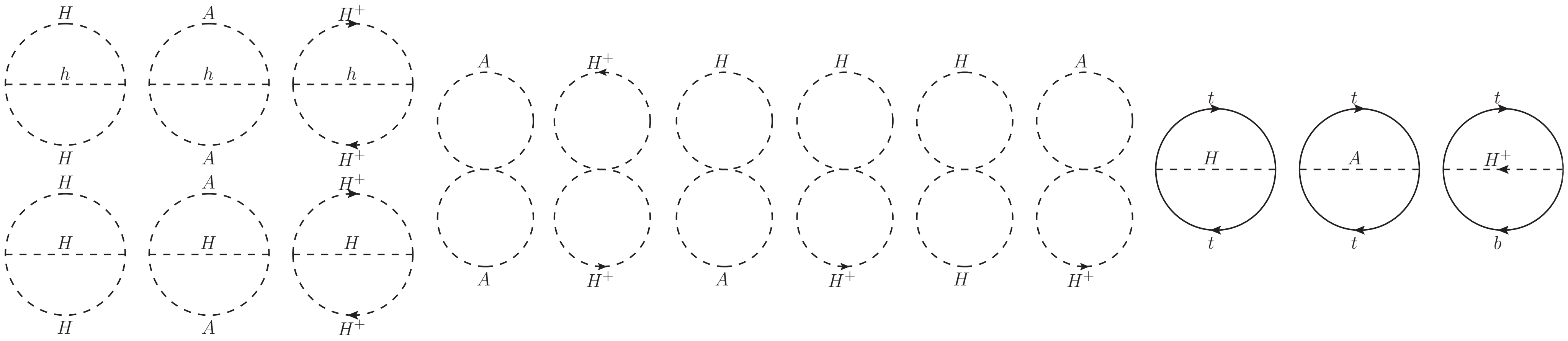
  - No mass terms in potential
  - Automatically **aligned** at tree level!

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

(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:

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

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

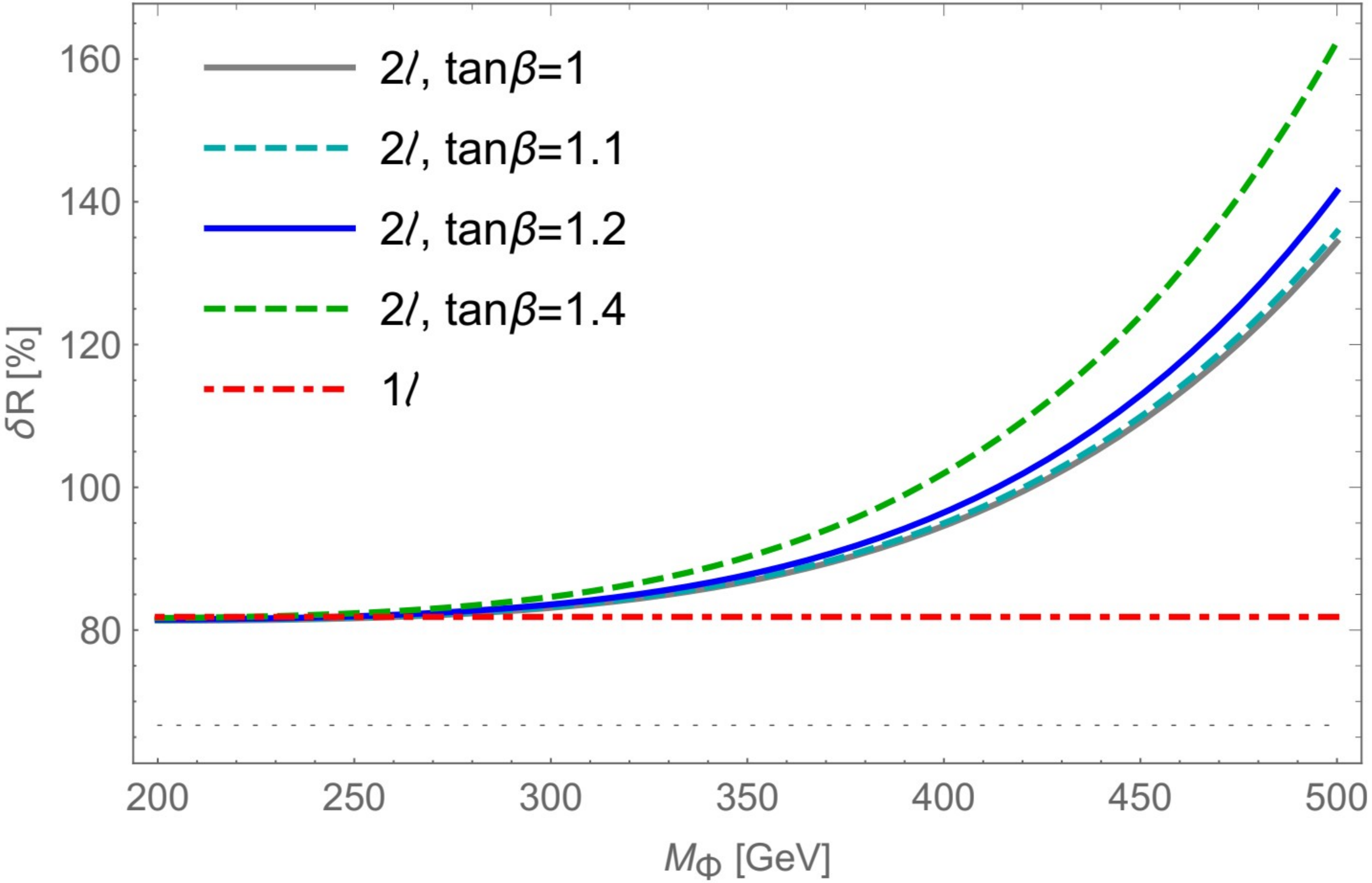
Numerical results

$$\delta R \equiv \frac{\hat{\lambda}_{hhh}^{\text{CSI-2HDM}} - \hat{\lambda}_{hhh}^{\text{SM}}}{\hat{\lambda}_{hhh}^{\text{SM}}}$$

No constraints

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

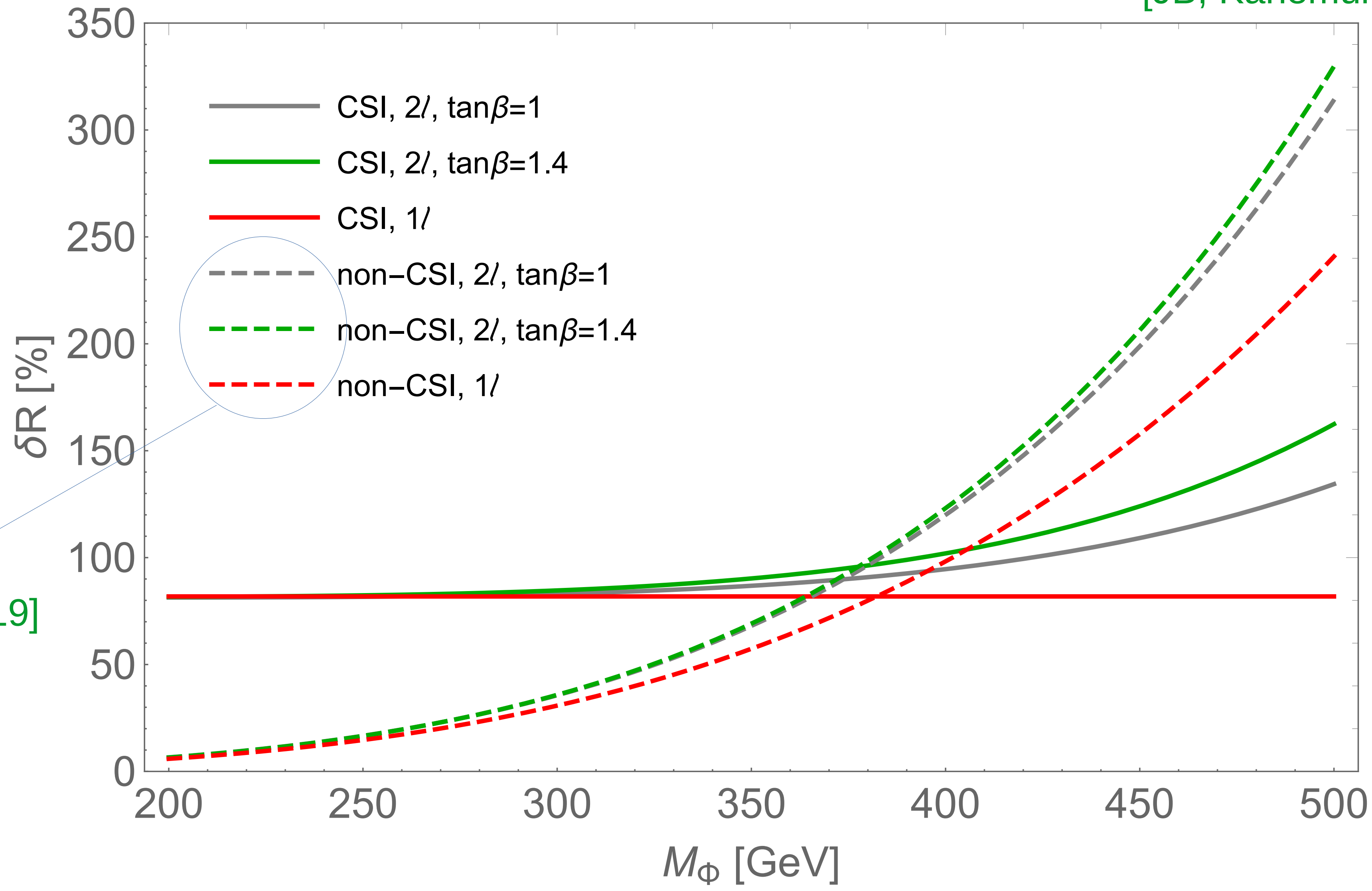
[JB, Kanemura, Shimoda '20]



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

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

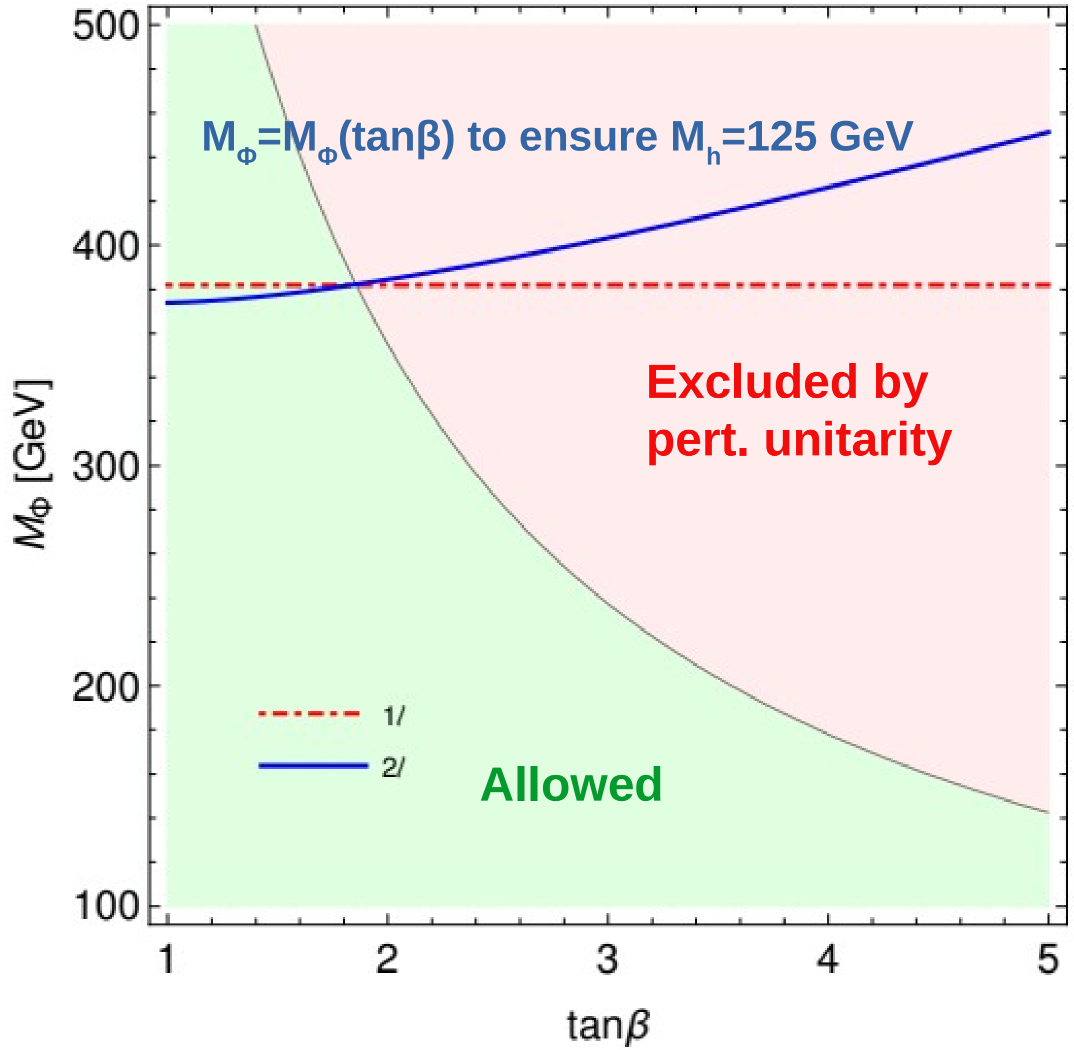
[JB, Kanemura, Shimoda '20]

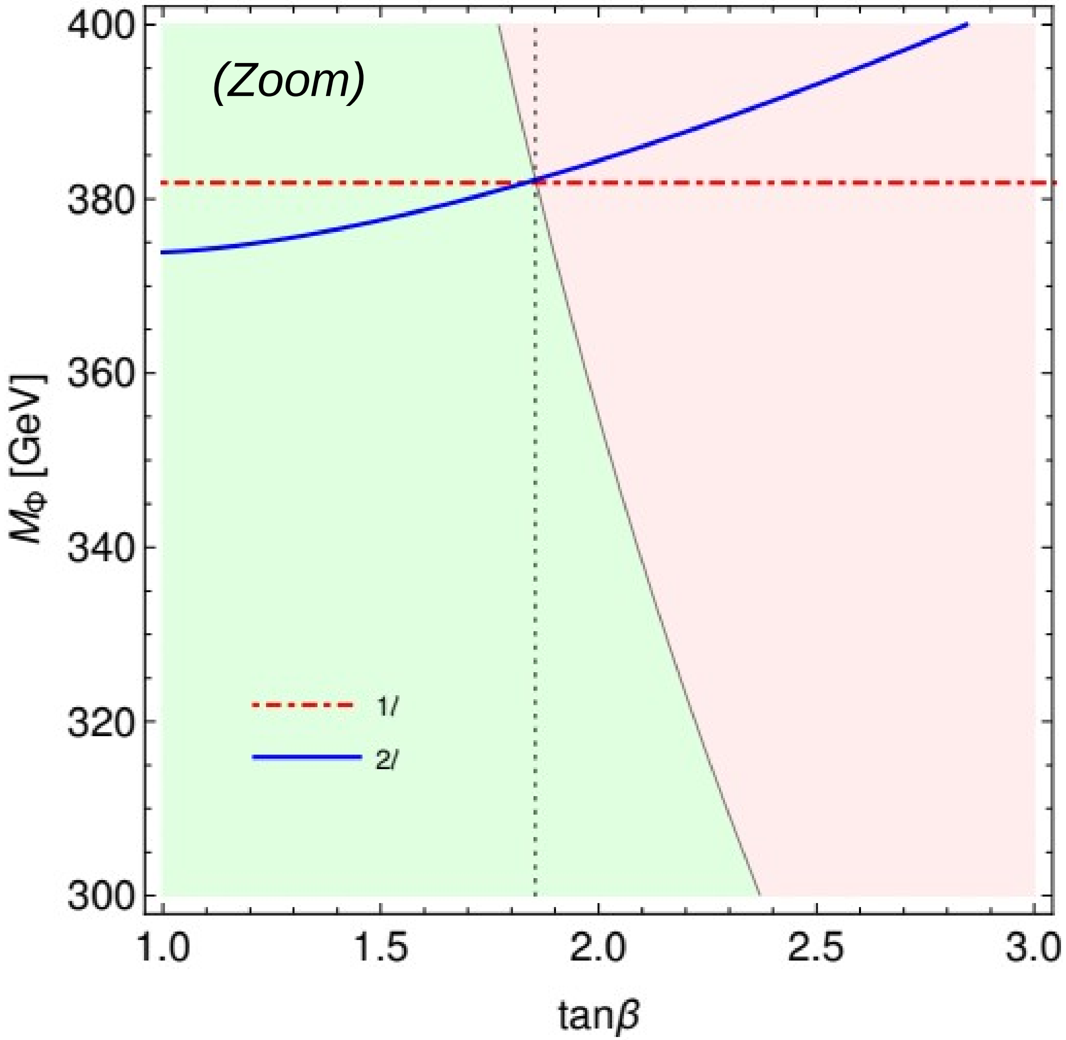


From
[JB, Kanemura '19]

Unitarity and constraint from M_h

[JB, Kanemura, Shimoda '20]

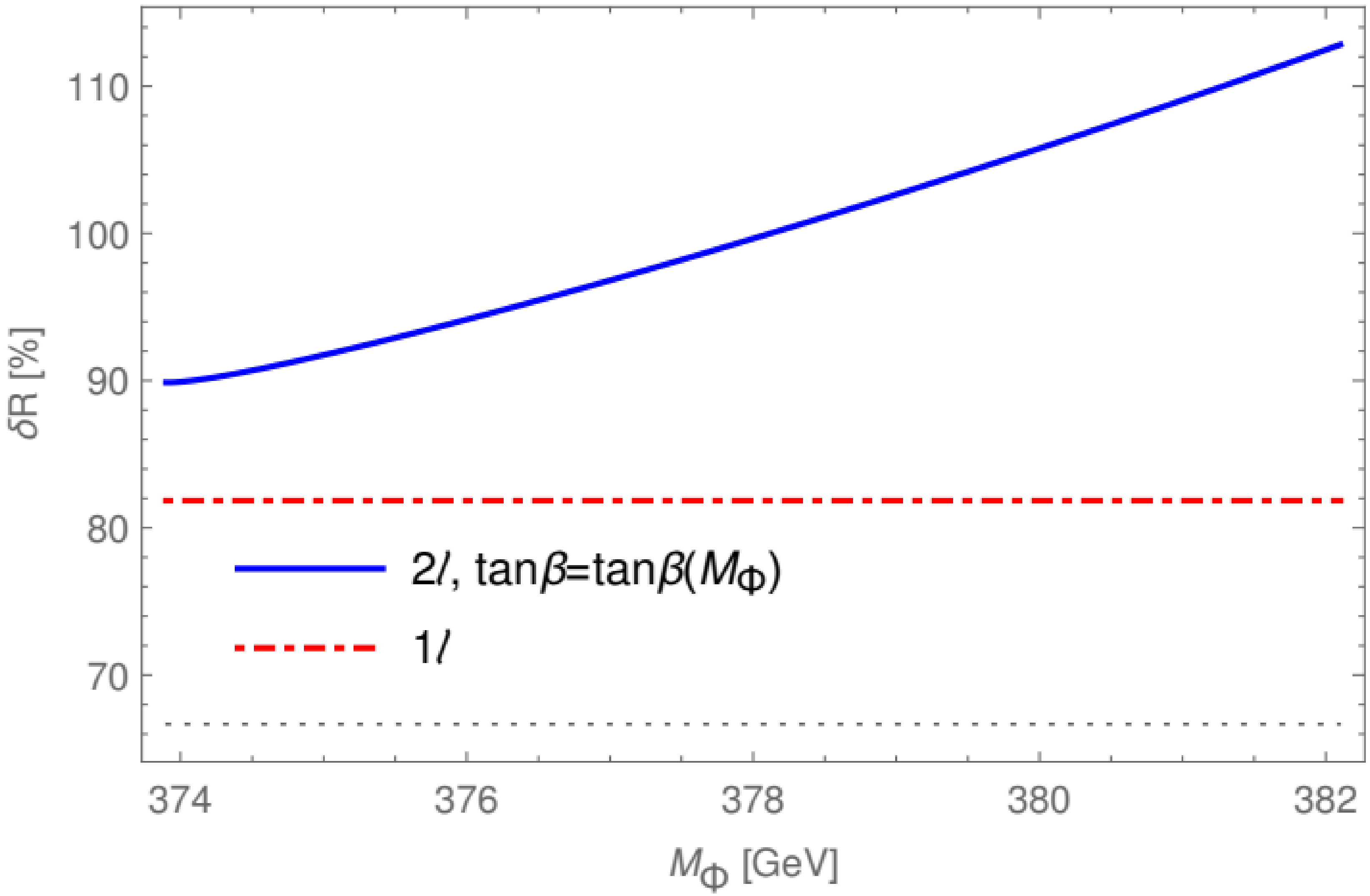




Once all constraints are included

tanß uniquely constrained as a function of M_Φ

[JB, Kanemura, Shimoda ‘20]



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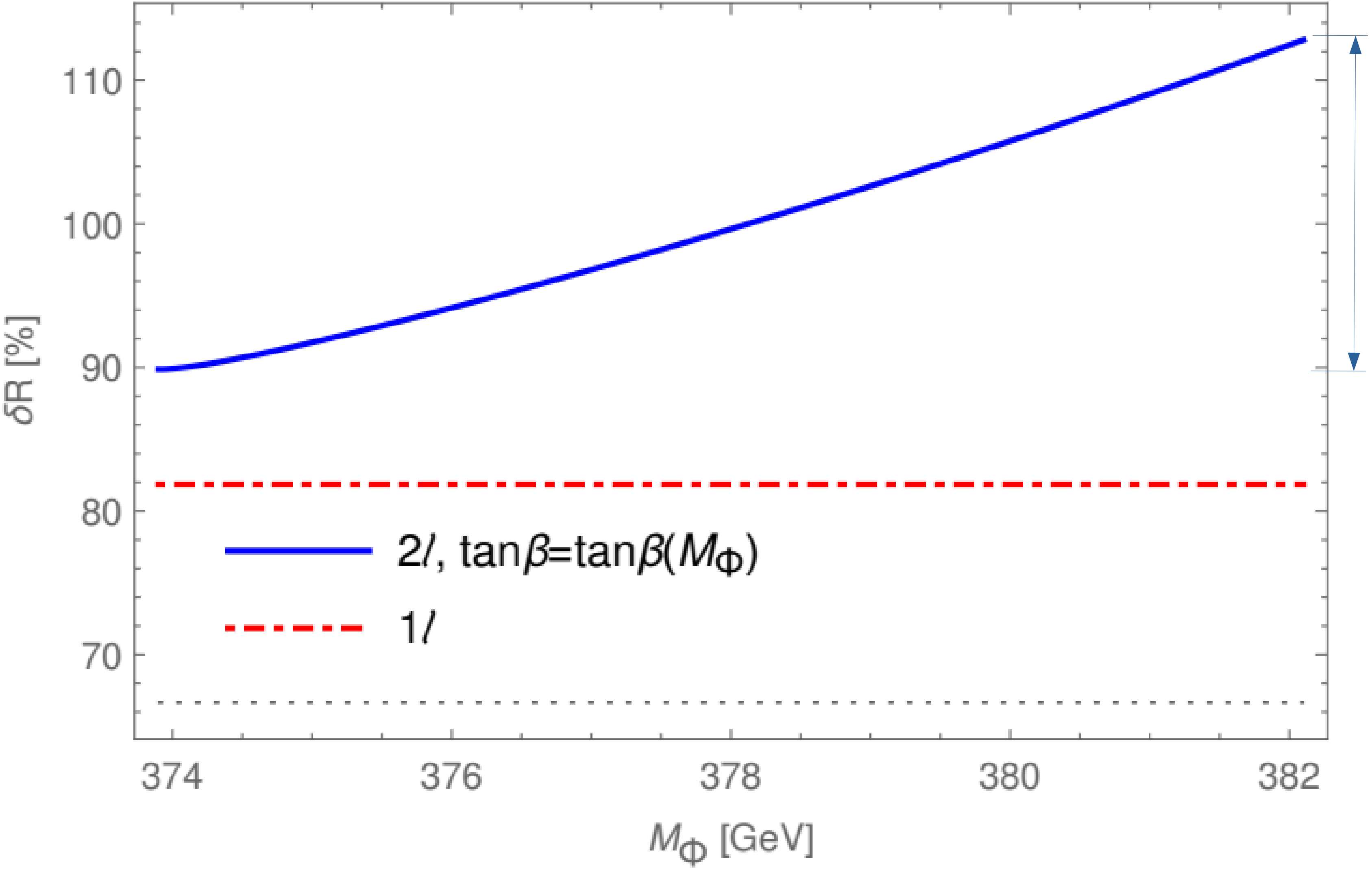
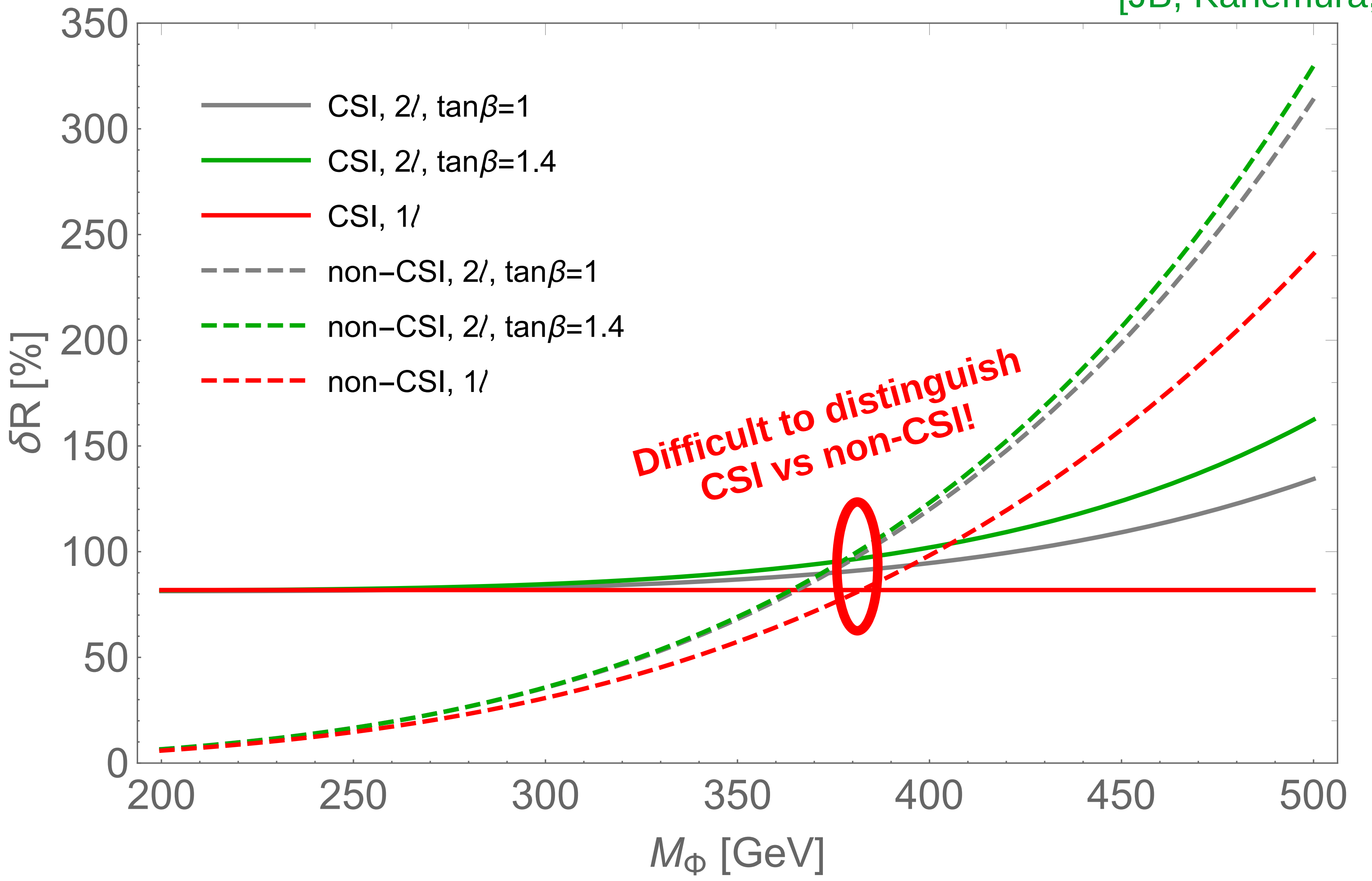


Could also be obtained in a non-CSI 2HDM [JB, Kanemura '19]

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

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

[JB, Kanemura, Shimoda '20]



Summary

First explicit two-loop calculation of Higgs trilinear coupling in theories with CSI

- Matches level of accuracy for non-CSI, non-SUSY, extensions of SM in [JB, Kanemura '19]
- Two-loop corrections allow distinguishing different scenarios with CSI
- Unitarity and M_h severely limit the allowed range of the two-loop corrections to λ_{hhh}
- Separate models w. or w/o. CSI difficult with only λ_{hhh}, but possible with synergy of λ_{hhh} and either collider or GW signals (see e.g. [Hashino, Kakizaki, Kanemura, Matsui '16])

Thank you

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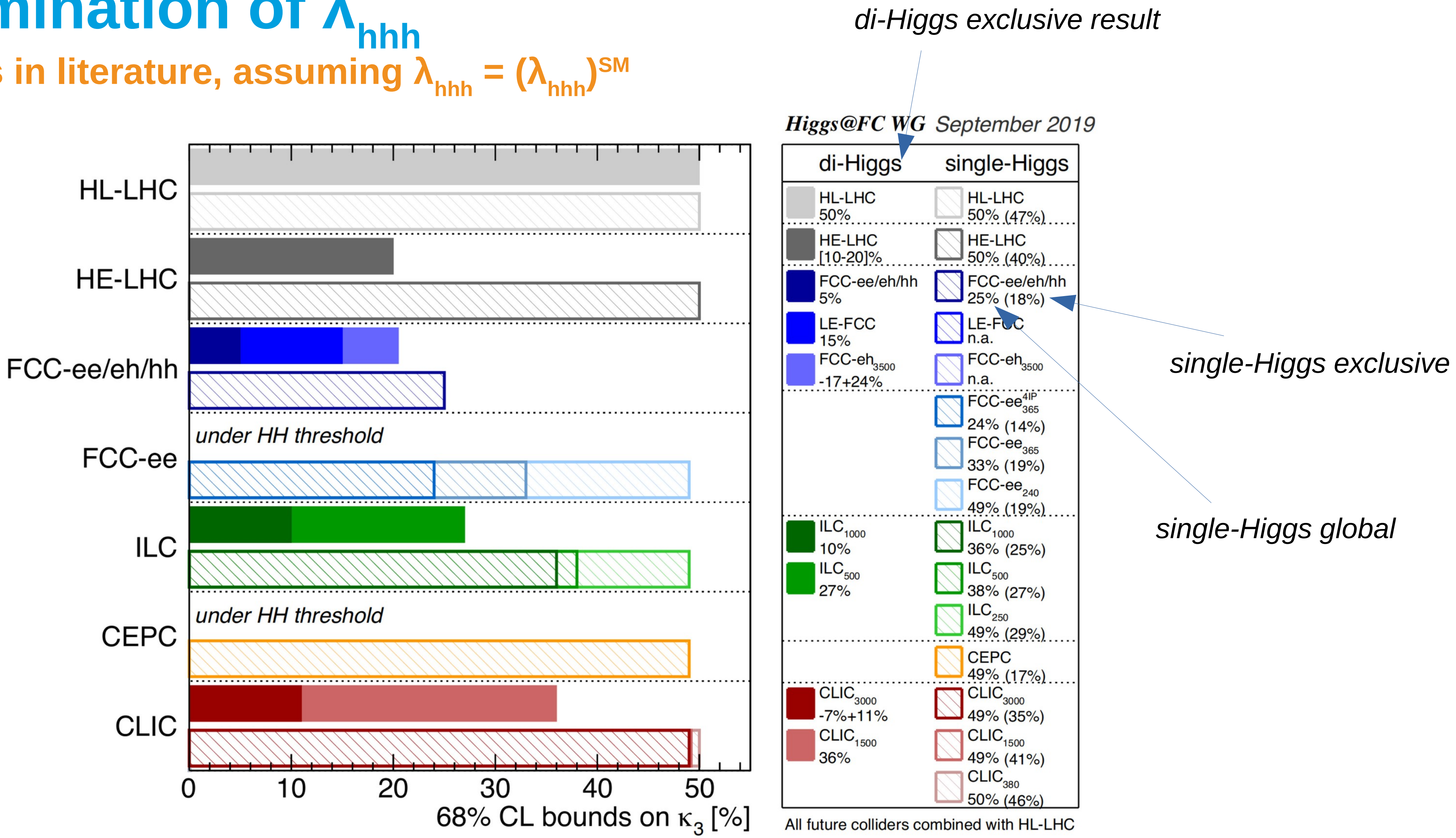
Future determination of λ_{hhh}

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}

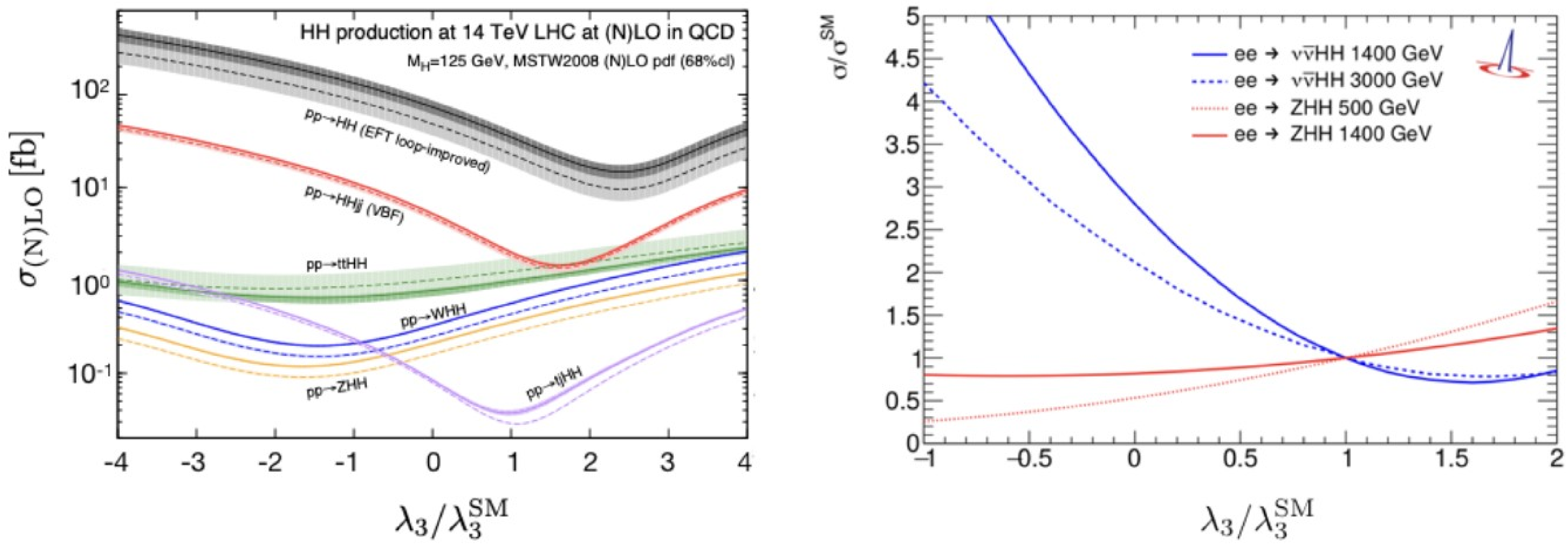
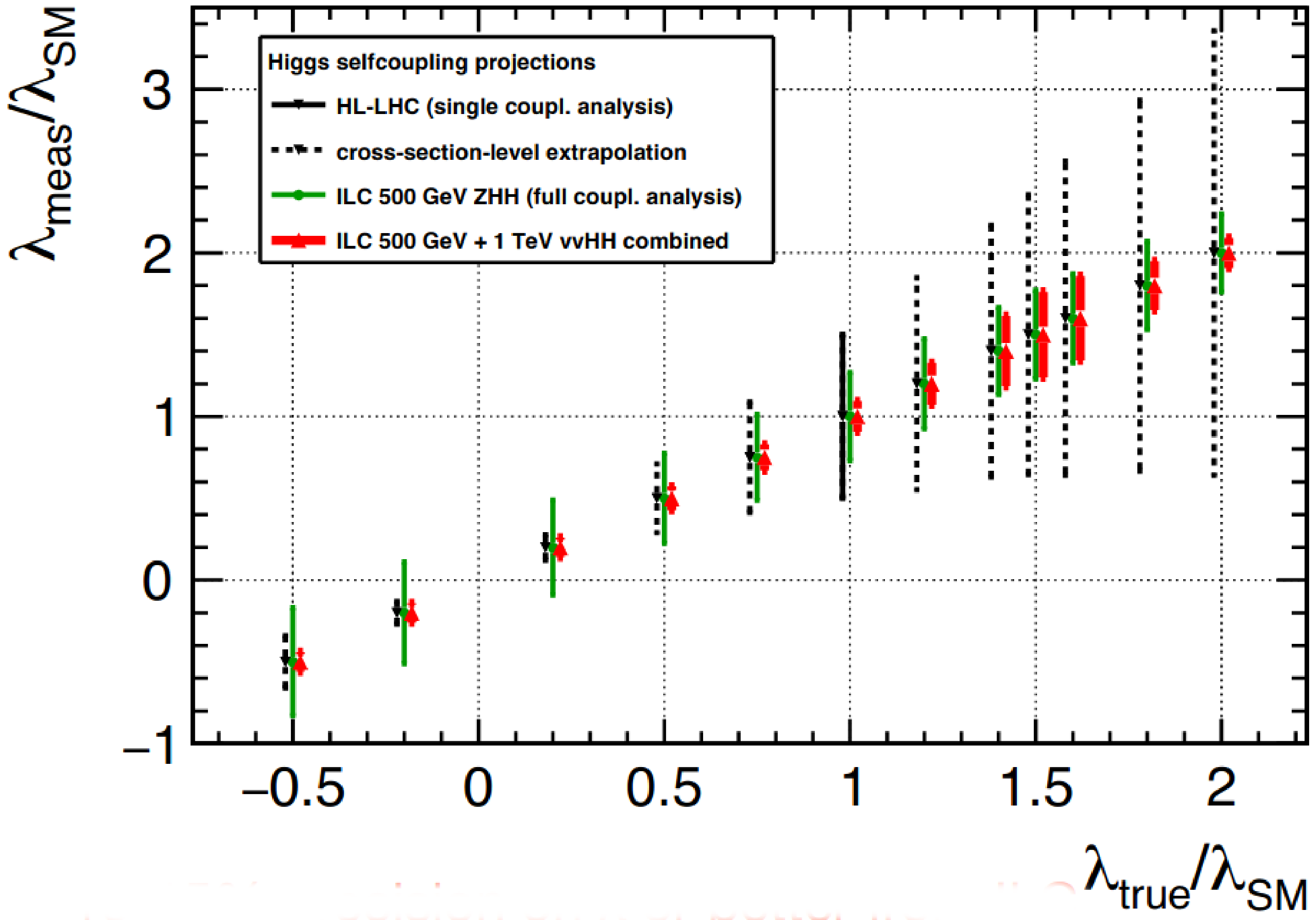


Figure 10. Double Higgs production at hadron (left) [65] and lepton (right) [66] colliders as a function of the modified Higgs cubic self-coupling. See Table 18 for the SM rates. At lepton colliders, the production cross sections do depend on the polarisation but this dependence drops out in the ratios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

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

Future determination of λ_{hhh}

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



[J. List et al. '21], *see also talk by G. Weiglein on Tuesday*

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

$\overline{\text{MS}}$ 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

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

- Also we include finite WFR effects → OS scheme

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