Extended Scalar Sectors and EFTs

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Based in part on work with Sally Dawson, Samuel Lane,
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Why Effective Field Theories?

In the absence of any clear* signal of new physics, we want to look for *indirect* signals of new physics in Standard Model processes.

EFT formalism allows for this with very inclusive assumptions:

- Local, Lorentz-invariant quantum field theory
- SM **gauge symmetries** and matter content (no additional fields**)
- Work at energy scales, $E \ll \Lambda$

Under these assumptions, parameterize interactions via tower of operators:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{n_{\mathcal{O}}^{(6)}} \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_{i=1}^{n_{\mathcal{O}}^{(8)}} \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

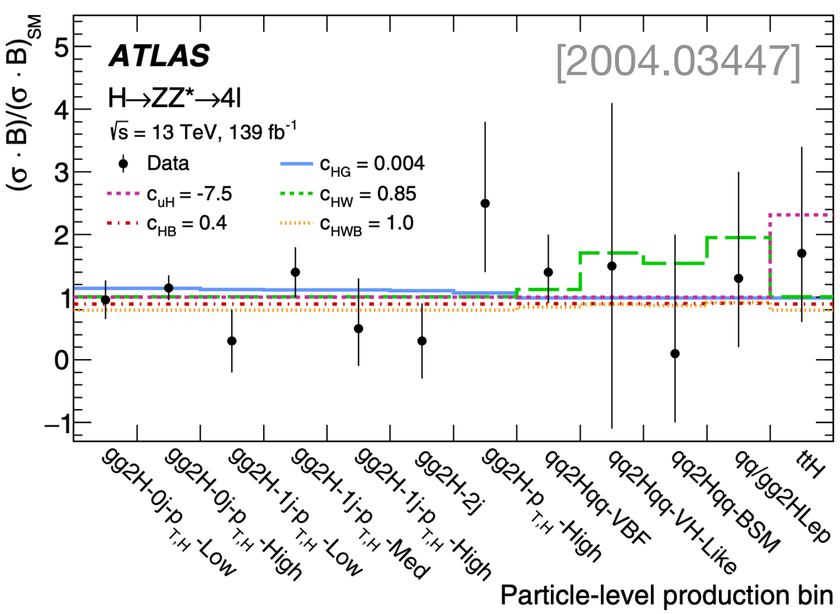
Unknown Wilson coefficients parameterizing new physics, fit to data

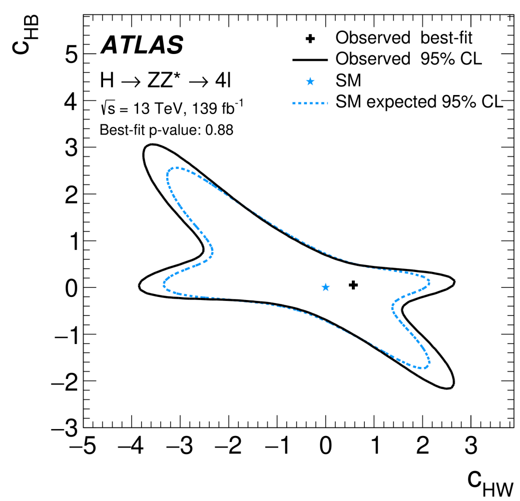
Gauge-invariant operators built out of SM fields

Why Effective Field Theories?

These simple principles immediately bring enormous advantages:

Allow for parameterization of BSM physics in *distributions:*

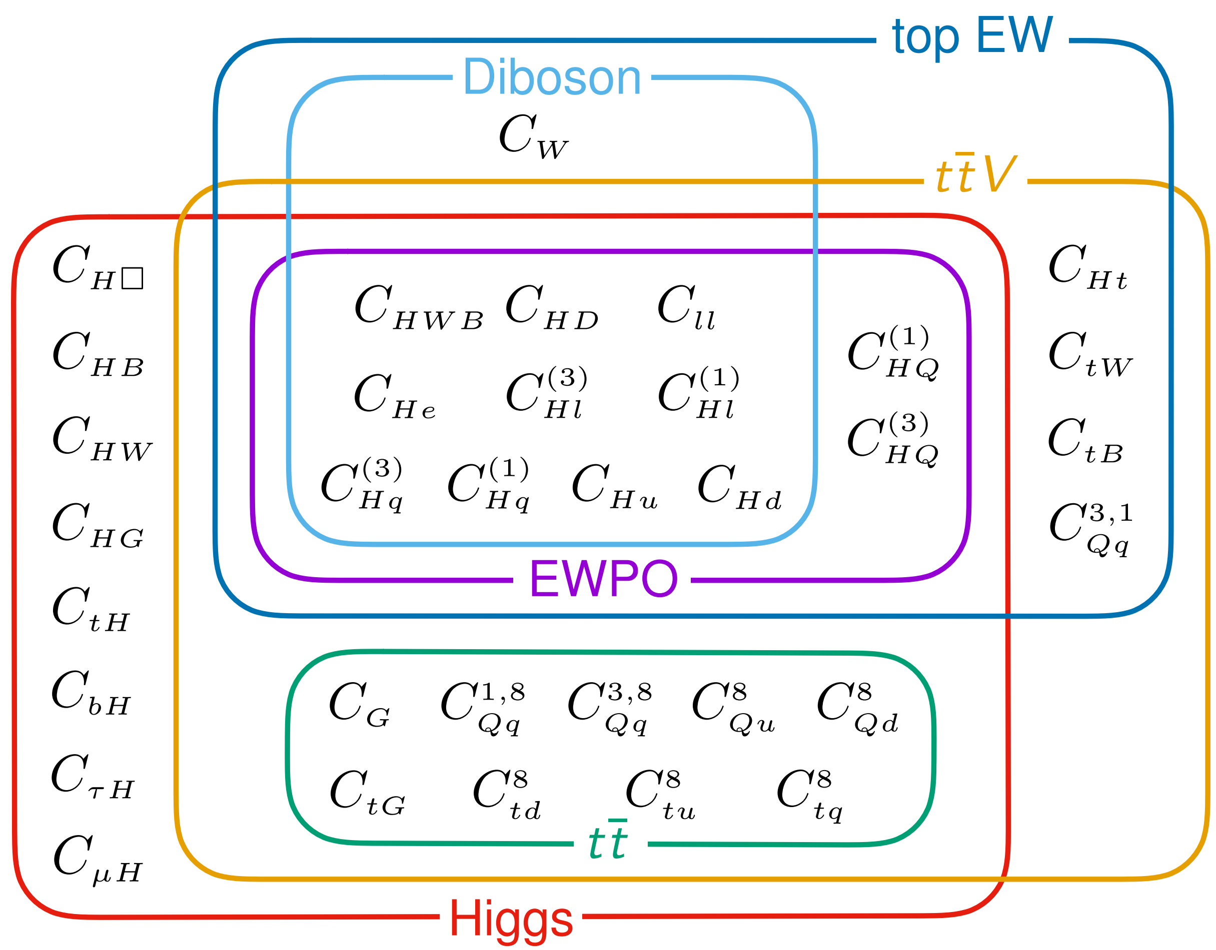




Theory predictions are systematically improvable:

$$d\sigma = \sum_n \sum_m \left(\frac{\alpha_S}{4\pi}\right)^n \left(\frac{C_i^{(6)}}{\Lambda^2}\right)^m d\sigma^{(6)} + \left(\frac{\alpha_S}{4\pi}\right)^n \left(\frac{C_i^{(8}}{\Lambda^4}\right)^{m-1} d\sigma^{(8)} + \ldots$$

Consistent combinations of different measurements at the LHC, LEP, …



Ellis, et al [2012.02779]

Which Effective Theory?

Defining the EFT requires some choices, most of which we all agree on:

Underlying $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ gauge invariance, with fermion matter fields:

$$Q_i, \quad \bar{u}^i, \quad \bar{d}^i, \quad L_i, \quad \bar{e}^i$$

Gauge group is spontaneously broken, $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \rightarrow \mathrm{U}(1)_{\mathrm{EM}}$

$\Longrightarrow$ Here we have choices!

EW Symmetry Broken *Linearly* — operators built out of

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

"SMEFT"

EW Symmetry Broken *non-linearly* — operators built out of

$$h, \ \mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots$$

$$U = \exp\left[iG^a\sigma^a/v\right]$$

"HEFT"

Linear or Non-Linear?

“Is SMEFT Enough?” (Cohen, Craig, Lu, Sutherland [2008.08597])

EW Symmetry Broken *Linearly* — operators built out of

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

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“HEFT”

One takeaway: HEFT expansion converges much faster than SMEFT when new states get significant portion of their mass from the Higgs mechanism.

$\Longrightarrow$ Important for many of our favorite scalar sectors, especially if not too decoupled. (See e.g., [2110.02967] for explicit examples)

Nevertheless, the rest of this talk I will focus on SMEFT examples.

SMEFT Interpretations of Data

Once we've chosen an EFT, a non-redundant basis of operators must be chosen, e.g., the "Warsaw Basis" (Grzadkowski, et al. [arXiv:1008.4884])

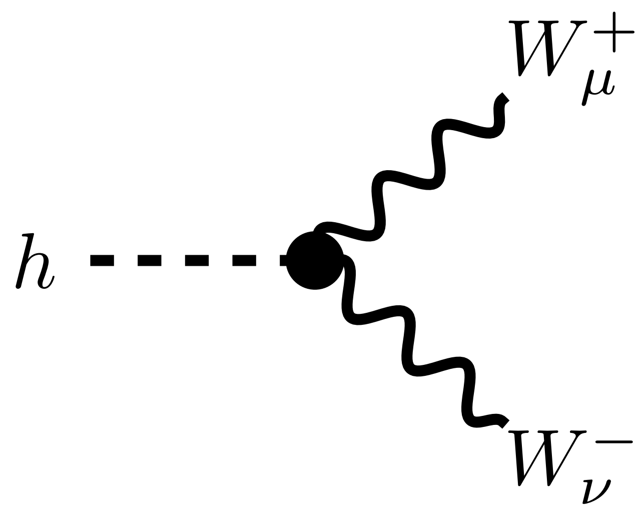
$\mathcal{O}_{ll}$	$(\bar{l}_L\gamma_\mu l_L)(\bar{l}_L\gamma^\mu l)_L$	$\mathcal{O}_{HWB}$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{q}_L\tau^a\gamma^\mu q_L)$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{l}_L\tau^a\gamma^\mu l_L)$
$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_L\gamma^\mu l_L)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{eH}$	$(H^\dagger H)\bar{l}_L\tilde{H}e_R$
$\mathcal{O}_{HG}$	$(H^\dagger H)G^A_{\mu\nu}G^{\mu\nu,A}$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_L\tilde{H}u_R)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_L H d_R)$
$\mathcal{O}_{HB}$	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{HW}$	$(H^\dagger H)W^a_{\mu\nu}W^{\mu\nu,a}$	$\mathcal{O}_W$	$\epsilon_{abc}W^{\nu,a}_\mu W^{\rho,b}_\nu W^{\mu,c}_\rho$
$\mathcal{O}_H$	$(H^\dagger H)^3$				

(Note: not the full set here — lots of flavor / model-based assumptions to limit the ~3000 operators in the full EFT!)

This enumeration has been extended to dimension-8 (Li et al., [2005.00008], Murphy [2005.00059]) and beyond (Harlander et al. [2305.06832]) …

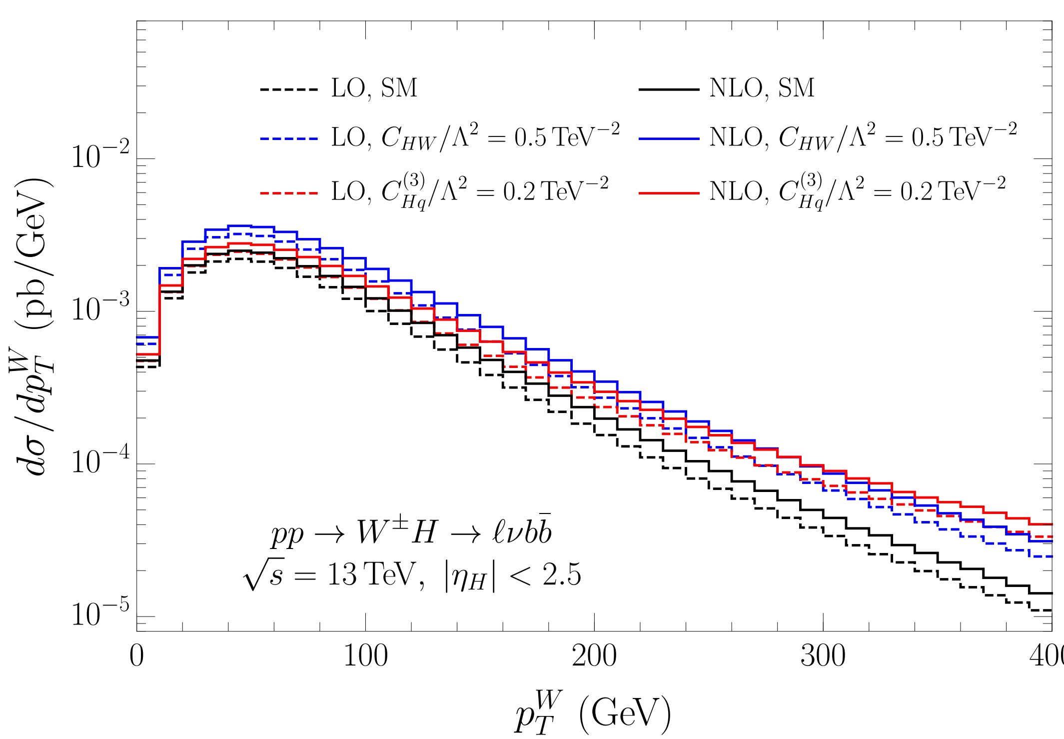
SMEFT Interpretations of Data

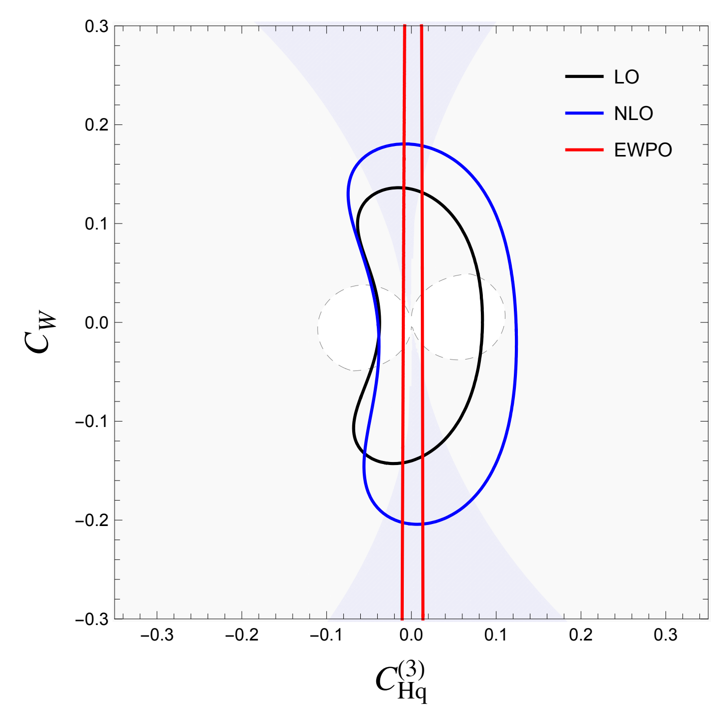
Then the Feynman rules can be computed to the desired order:



$$= \frac{1}{2} i g^2 v\, \eta_{\mu\nu} + \frac{1}{2} i g^2 v^3 \eta_{\mu\nu} \left(C^{H\Box} - \frac{1}{4} C^{HD}\right) + 4ivC^{HW}\left(p_{2\,\mu} p_{3\,\nu} - (p_2 \cdot p_3)\eta_{\mu\nu}\right)$$

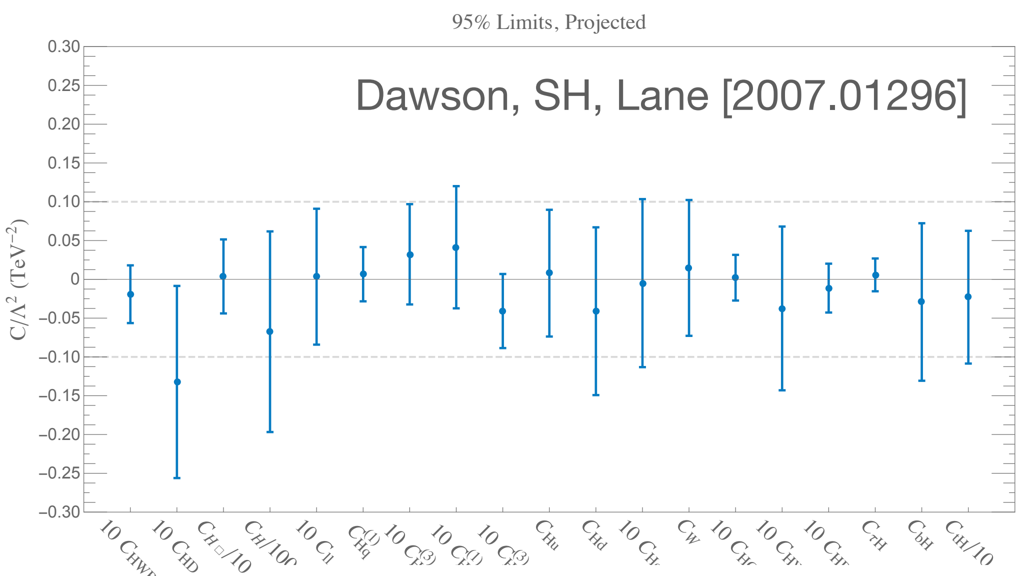
$\Longrightarrow$ Implemented in packages (SMEFTsim, SMEFT@NLO) that interface with generators, allow for direct comparison with data:



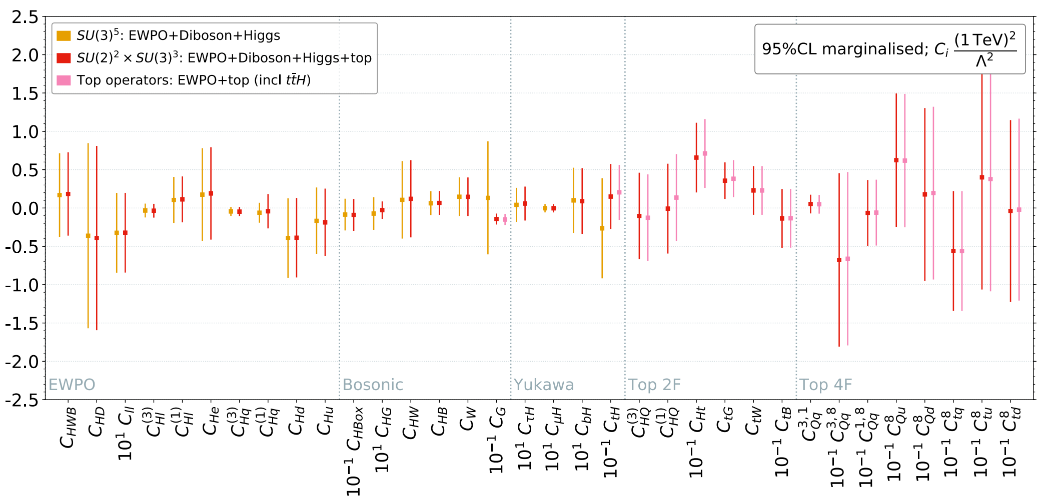


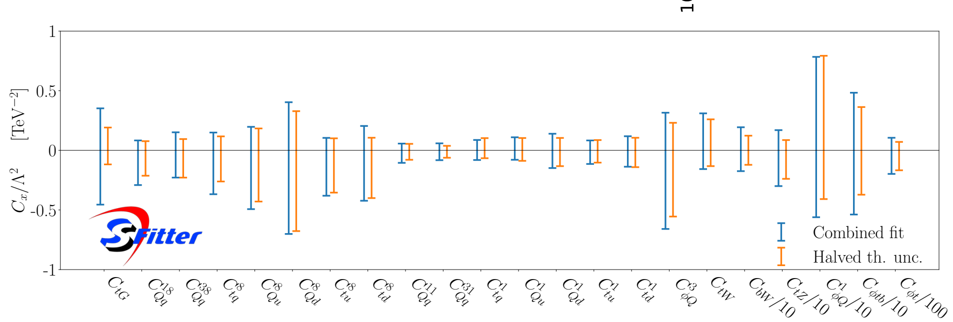
Baglio, Dawson, SH, Lane, Lewis [2003.07862]

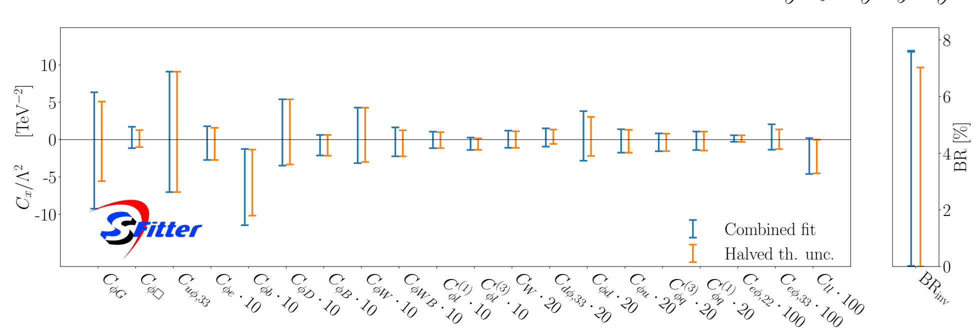
Global Fits / EFT Combinations



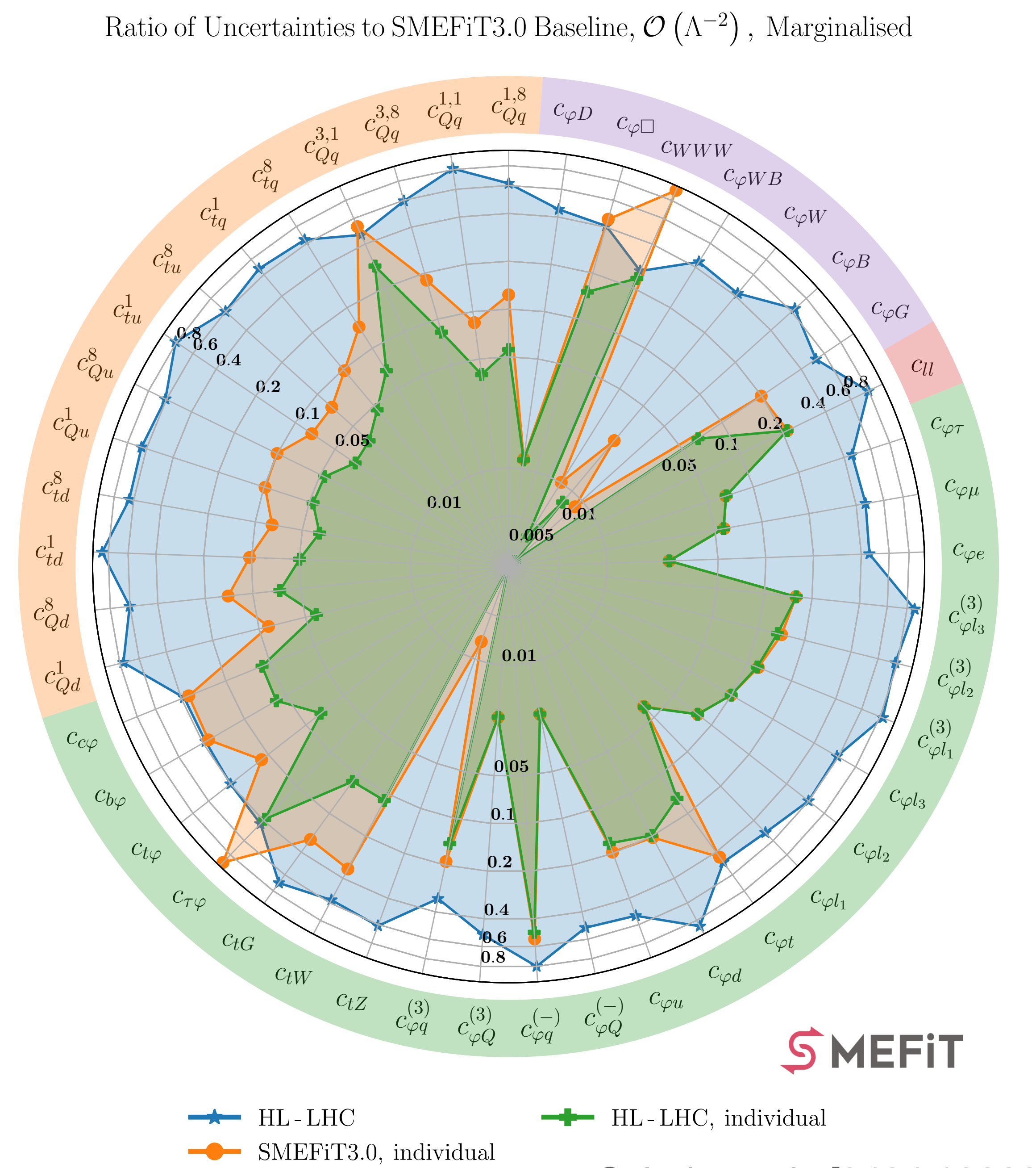
Ellis, Madigan, Mimasu, Sanz, You [2012.02779]







Elmer, Madigan, Plehn, Schmal [2312.12502]



Celada et al., [2404.12809]

(And many others, apologies for omissions..)

EFTs Meet UV Models

(This is an ***extended*** scalar sector workshop, after all!)

Two approaches to matching onto EFTs:

- Diagrammatic approach: carefully define EFT and UV theory at matching scale, and compute a (potentially large) set of amplitudes in terms of both theories using Feynman diagrams.

- Functional Method Approach
  (Covariant Derivative Expansion → Universal One-Loop Effective Action → Functional Supertraces)

Key references: M.K. Gaillard (NPB 268, 1986), Henning, Lu, Murayama [1412.1837], Drozd, Ellis, Quevillon, You [1512.03003], Cohen, Lu, Zhang [2011.02484]

Both of these methods are *automatable*, and implemented in public codes: `MatchingTools` [1710.06445], `CoDEx` [1808.04403], `Matchmakereft` [2112.10787], `Matchete` [2212.04510]

Example: Matching with a Singlet Scalar

Tree-Level Matching at dimension-6

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} m_\xi S H^\dagger H + \frac{1}{2}\kappa S^2 H^\dagger H + \frac{1}{2} M^2 S^2 + \frac{1}{3} m_\zeta S^3 + \frac{1}{4}\lambda_S S^4$$

Assume M is the high scale, and integrate out S at tree level:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_H (H^\dagger H)^3 + \ldots$$

with

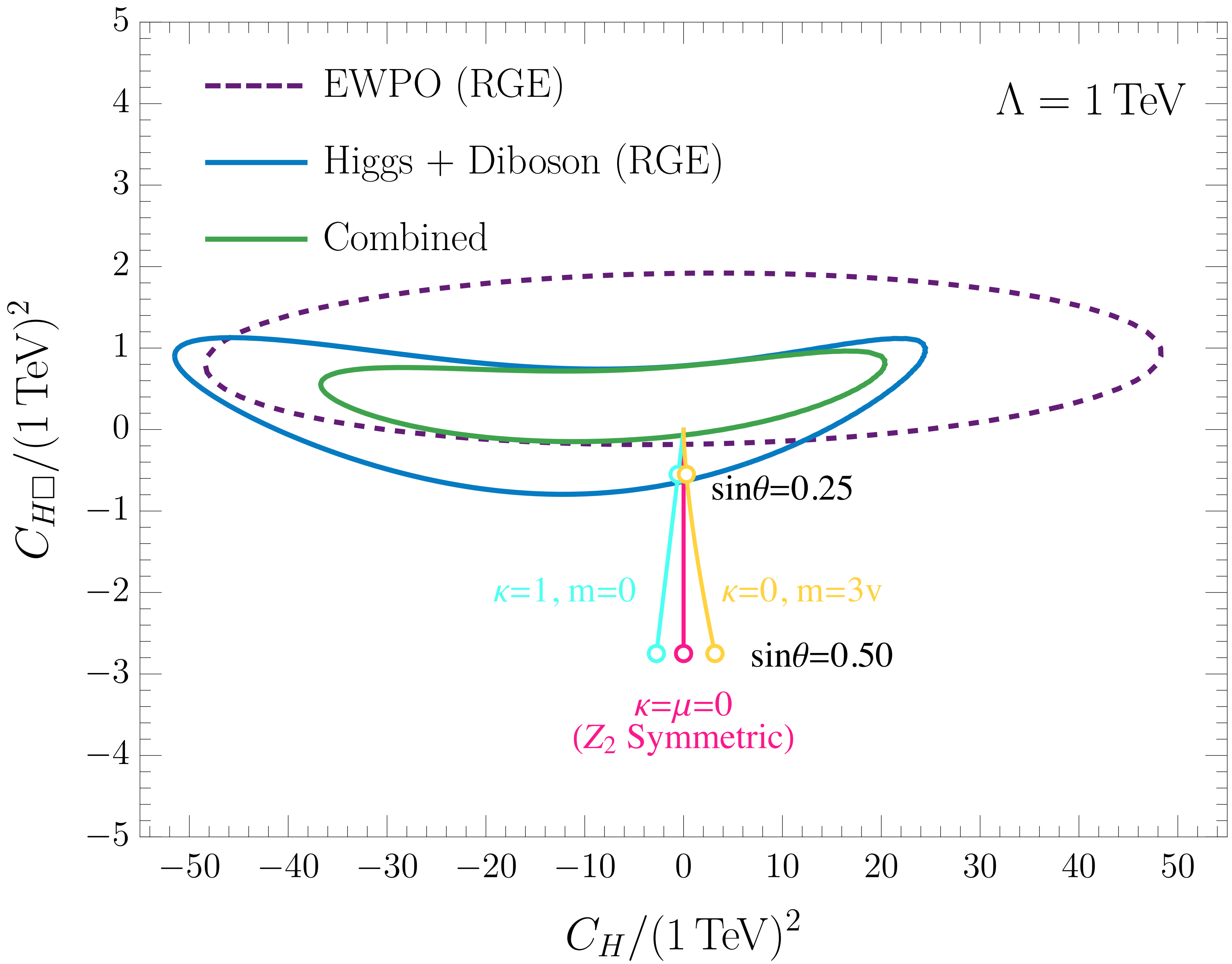
$$C_{H\Box} = -\frac{m_\xi^2}{8M^2}, \qquad C_H = \frac{m_\xi^2}{8M^2}\left(\frac{m_\xi m_\zeta}{3M^2} - \kappa\right)$$

Constant rescaling of all Higgs couplings

Modification to the Higgs trilinear interaction

Example: Matching with a Singlet Scalar

Constrained Global Fits



EW Precision Constraints (from M_W) arise from operators generated by the RGEs!

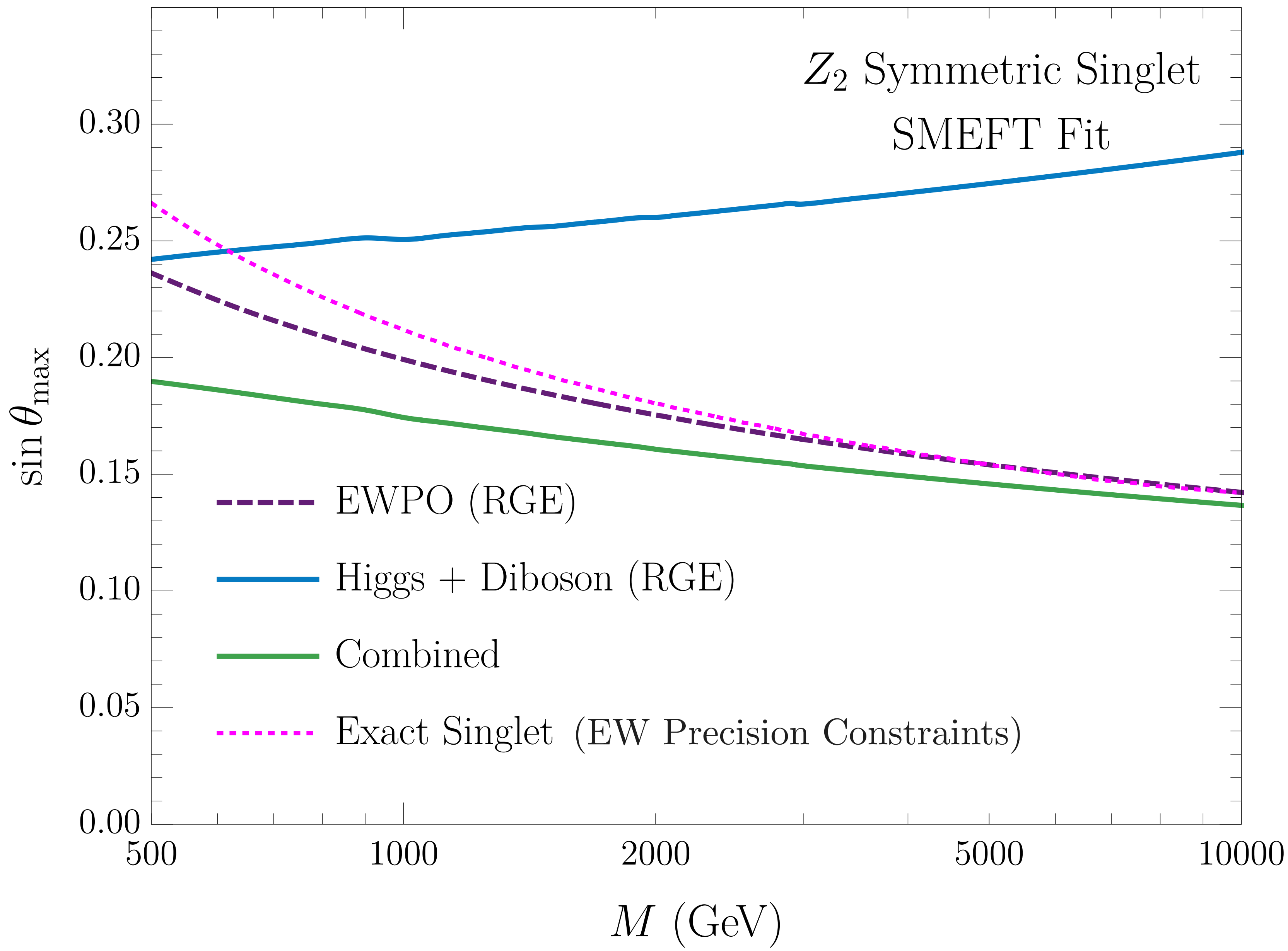
Includes

C_{HD}, C_{tH}, C_{bH}, $C_{\tau H}$, $C_{Hl}^{(3)}$, $C_{Hq}^{(3)}$, C_{Htb}

Limits from the LHC and EWPO are competitive, and complementary (but most of allowed parameter space is not generated in the model)

Example: Matching with a Singlet Scalar

Constrained Global Fits ➞ Constraints on Model Parameters



Example: Matching with a Singlet Scalar

Higher-Order Matching Effects

Higher order effects are important for bringing in EW Precision data:

$$C_i(\mu_R) = c_i(M) + \frac{1}{16\pi^2} d_i(M) + \frac{1}{32\pi^2} \gamma_{ij} c_j(M) \log\left(\frac{\mu_R^2}{M^2}\right)$$

The complete one-loop matching has been performed:

- Covariant derivative expansion / UOLEA
  Jiang, Craig, Li, Sutherland [1811.08878]
- Diagrammatic approach
  Haisch, Ruhdorfer, Salvioni, Venturini, Weiler [2003.05936]

New contributions to C_H, $C_{H\Box}$

$$d_{H\Box} = -\frac{9}{2}\lambda c_{H\Box} + \frac{31}{36}(3g^2 + g'^2)c_{H\Box} + \ldots$$

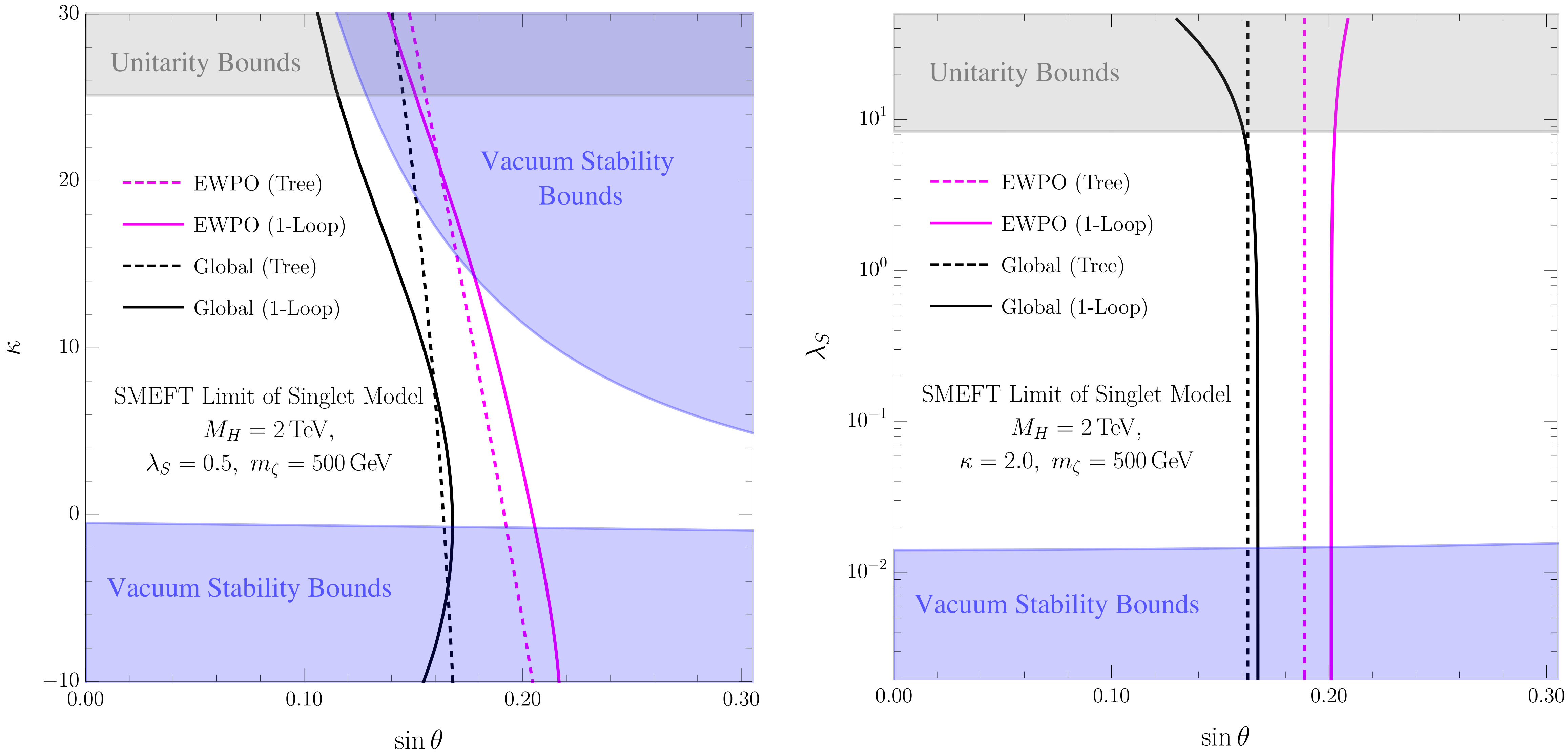
$$d_H = \lambda\left[\frac{1}{9}(62g^2 - 336\lambda)c_{H\Box} + 6c_H\right] + \ldots$$

(Many details I'm glossing over here on arriving at agreement between approaches, including mixed heavy-light loops, etc…
See Cohen, Lu, Zhang [2011.02484] for details!)

Example: Matching with a Singlet Scalar

Higher-Order Matching Effects

Straightforward to implement in existing SMEFT Fit:



Effects of $\mathcal{O}(10\%)$, except large values of portal couplings

Example: Matching with a Singlet Scalar

Higher-Order Matching Effects

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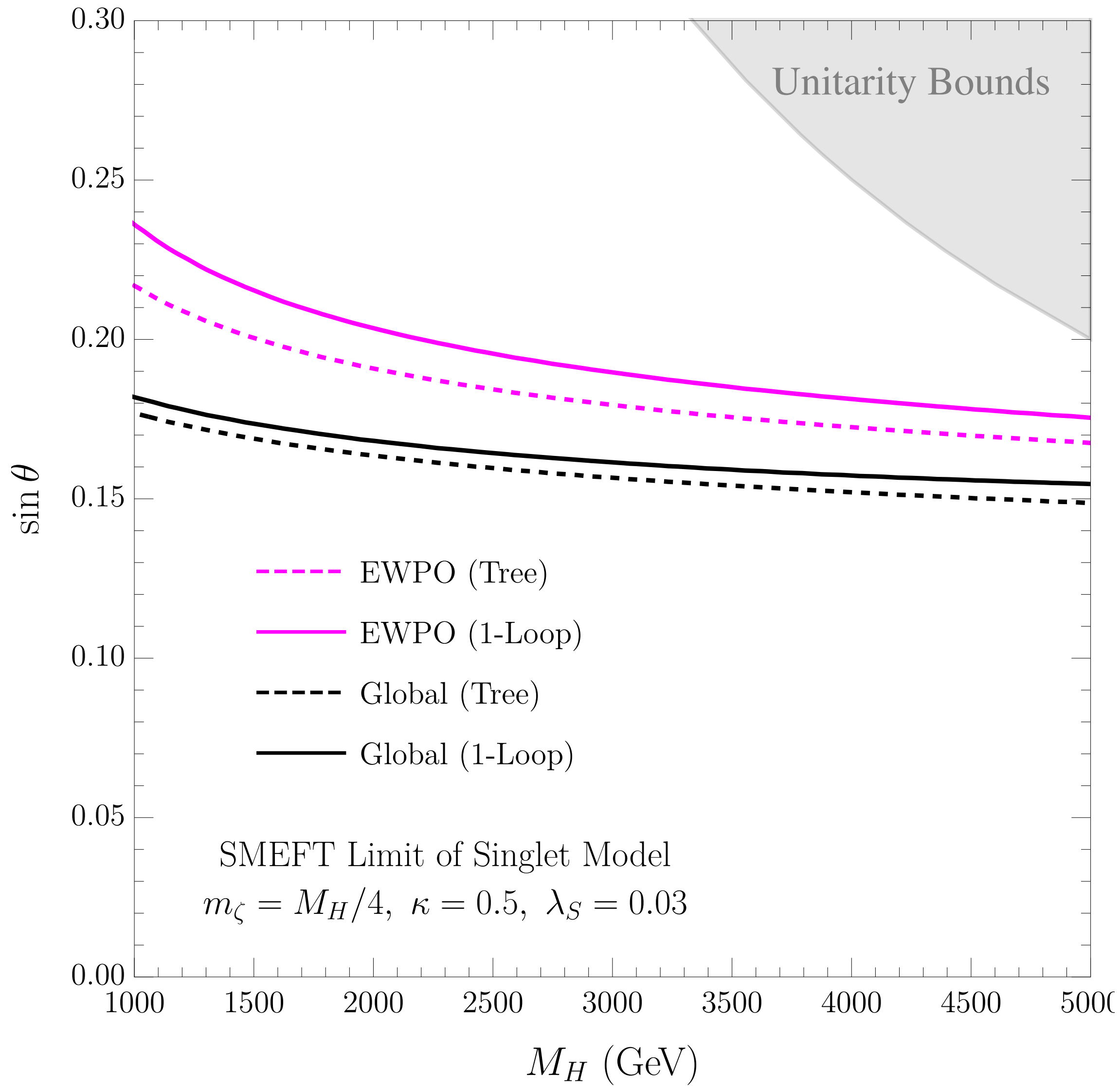
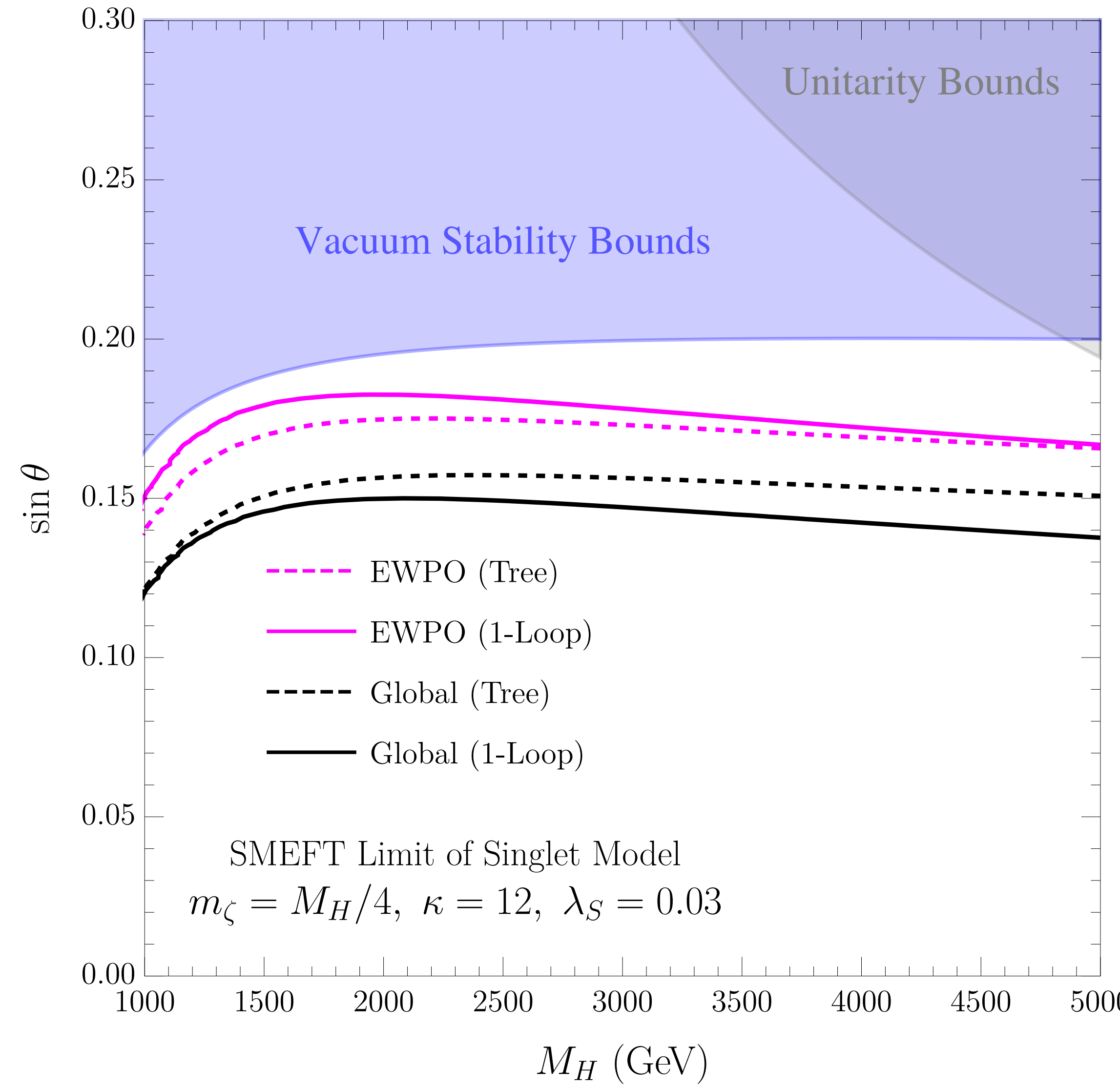




Effects of $\mathcal{O}(10\%)$, except large values of portal couplings

Example: Matching with a 2HDM

Let's turn to a more complicated model:

$a = 1{,}2$

$$\mathcal{L} \supset -\left[\lambda_a^u Q H_a \bar{u} + \lambda_a^{d\dagger} Q H_a^c \bar{d} + \lambda_a^{\ell\dagger} L H_a^c \bar{e} + \text{h.c.}\right] - V(H_1, H_2)$$

proportional to SM Yukawas if Z_2 symmetry is assumed

Observed Higgs couplings determined by $\cos(\beta-\alpha)$, $\tan\beta$, e.g., for type-II:

$$\kappa_u = \sin(\beta-\alpha) + \frac{\cos(\beta-\alpha)}{\tan\beta}$$

$$\kappa_d = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

$$\kappa_\ell = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

$$\kappa_V = \sin(\beta-\alpha)$$

(All approach 1 as $\cos(\beta-\alpha) \to 0$)

Example: Matching with a 2HDM

Tree-Level Matching at dimension-6

Ignoring light flavor, there are four operators generated:

$$\mathcal{O}_H = (H^\dagger H)^3, \qquad \frac{v^2}{\Lambda^2} C_H = \frac{\Lambda^2}{v^2}\cos^2(\beta-\alpha)$$

$$\mathcal{O}_{bH} = (H^\dagger H)(\bar{Q}_3 b_R H), \qquad \frac{v^2}{\Lambda^2} C_{bH} = -y_b \eta_b \frac{\cos(\beta-\alpha)}{\tan\beta}$$

$$\mathcal{O}_{tH} = (H^\dagger H)(\bar{Q}_3 t_R \tilde{H}), \qquad \frac{v^2}{\Lambda^2} C_{tH} = -y_t \eta_t \frac{\cos(\beta-\alpha)}{\tan\beta}$$

$$\mathcal{O}_{\tau H} = (H^\dagger H)(\bar{L}_3 \tau_R \tilde{H}), \qquad \frac{v^2}{\Lambda^2} C_{\tau H} = -y_\tau \eta_\tau \frac{\cos(\beta-\alpha)}{\tan\beta}$$

	η_t	η_b	η_τ
Type-I	1	1	1
Type-II	1	$-\tan^2\beta$	$-\tan^2\beta$
Lepton-specific	1	1	$-\tan^2\beta$
Flipped	1	$-\tan^2\beta$	1

Requiring all the additional states to lie at a common high scale enforces the “decoupling limit”:

$$\cos(\beta-\alpha) \sim \frac{v^2}{\Lambda^2} \ll 1$$

Example: Matching with a 2HDM

Warning: matching to SMEFT requires a careful approach to decoupling

The 2HDM potential contains multiple scales — in practice, we choose the dimensional coefficient of $H_2^\dagger H_2$ in the Higgs basis.

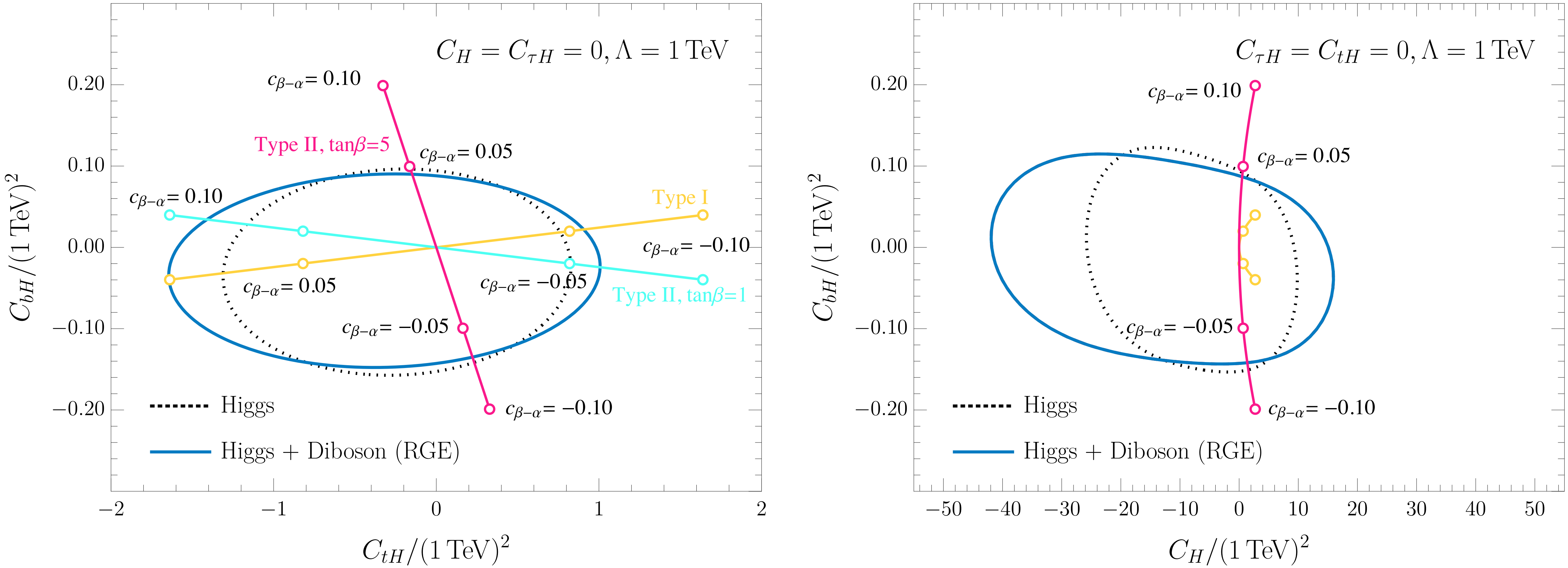
But remember: $$\cos(\beta - \alpha) \sim \frac{Z_6 v^2}{m_H^2 - m_h^2}$$

$\Longrightarrow$ Simultaneously going to high scales and large mixing angles rapidly leads to problems with perturbative unitarity!

Even defining the EFT carefully in the presence of all the heavy scales is subtle: see e.g., Banta, Cohen, Craig, Lu, Sutherland [2304.09884] and Dawson, Fontes, Quezada-Calogne, Sanz-Cillero [2305.07689]

Example: Matching with a 2HDM

Constrained Global Fits

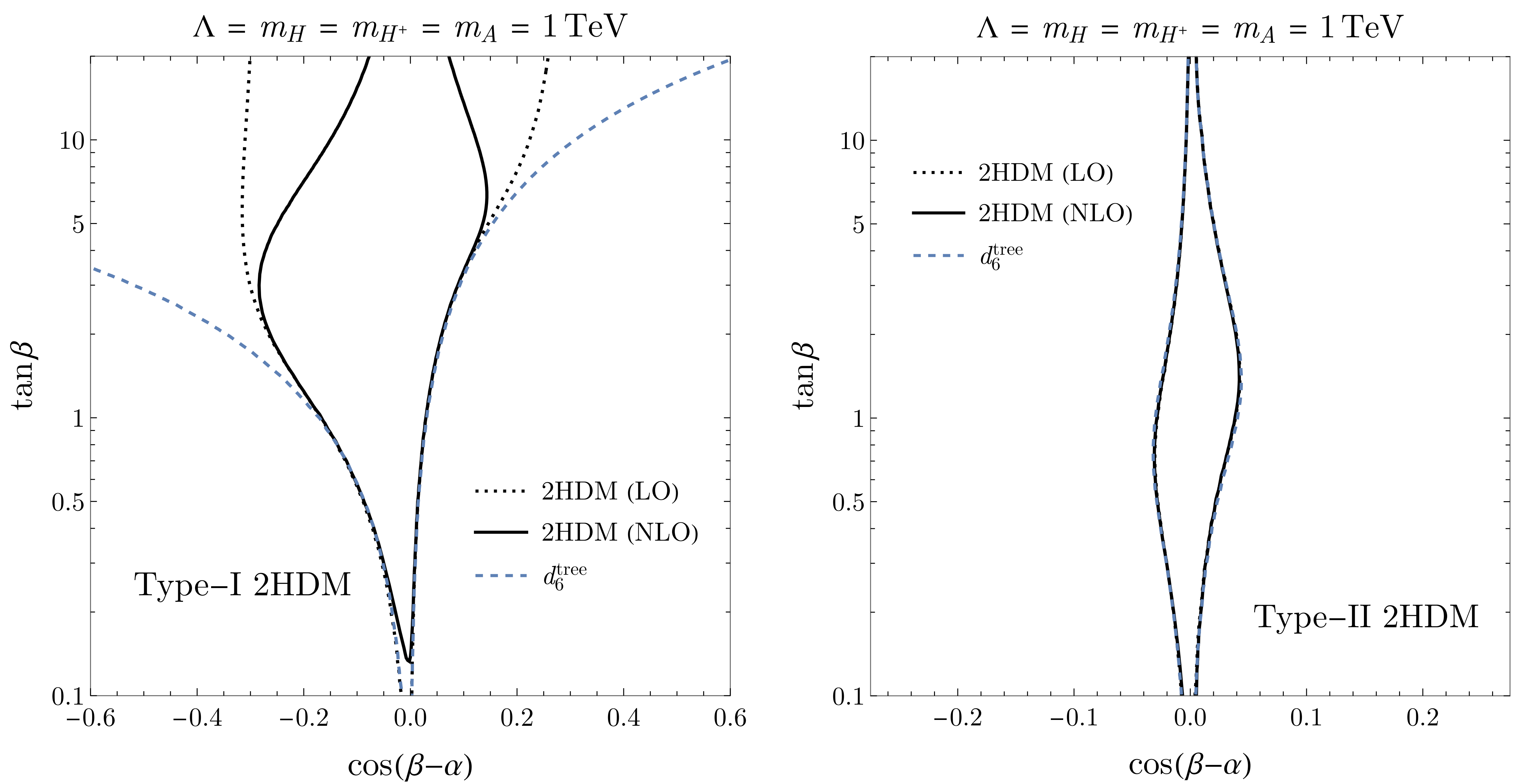


Different types of 2HDM sweep out different ranges of allowed coefficients

RGE Effects tend to be small (logarithmic changes in Higgs couplings)

Example: Matching with a 2HDM

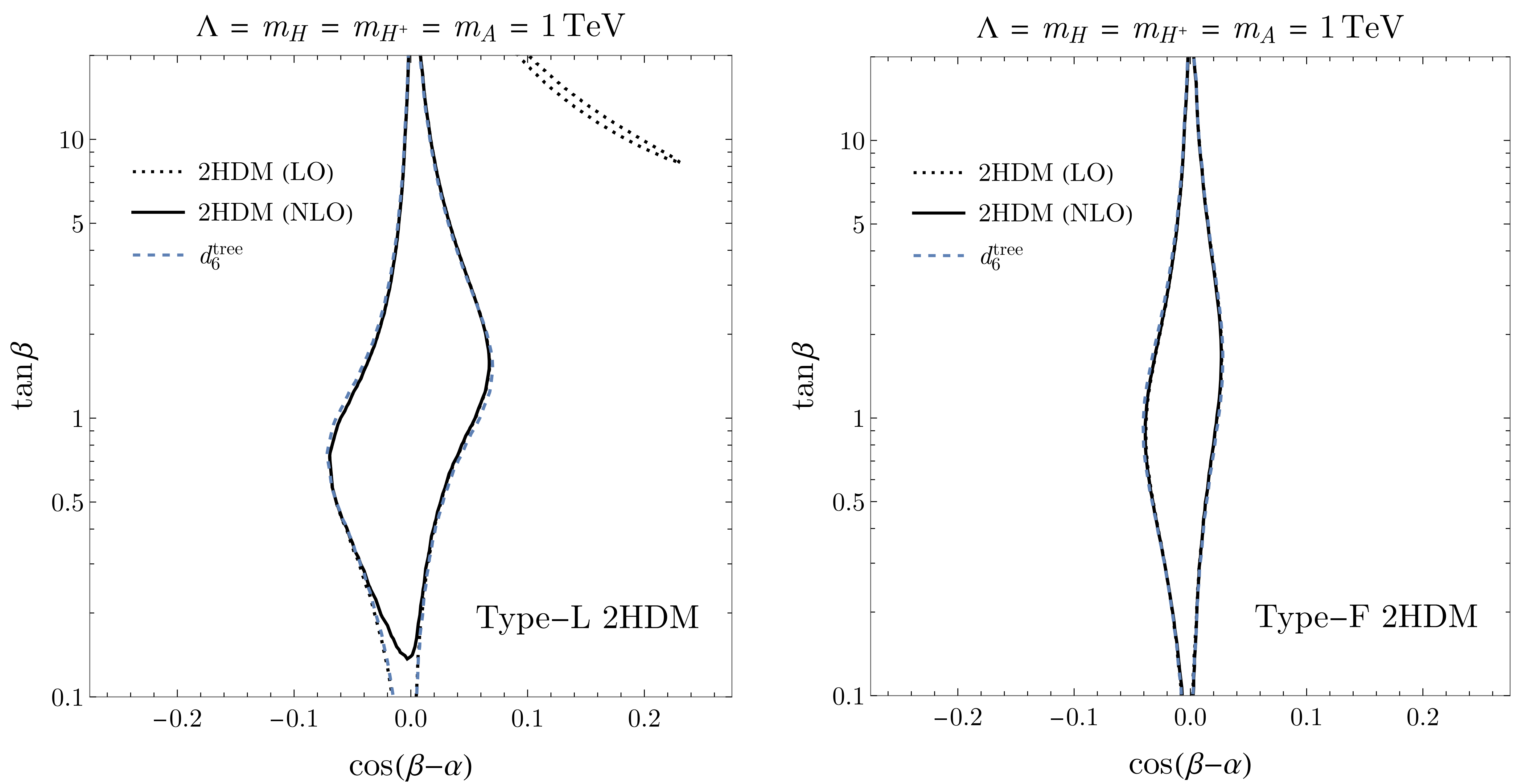
Constraints on Model Parameters from Dimension-6 Interpretation



One-loop expressions for signal strengths (valid in the alignment limit) are taken from Kanemura, Kikuchi, Yagyu [arXiv:1502.07716]

Example: Matching with a 2HDM

Constraints on Model Parameters from Dimension-6 Interpretation



Example: Matching with a 2HDM

Effects at large $\tan\beta$

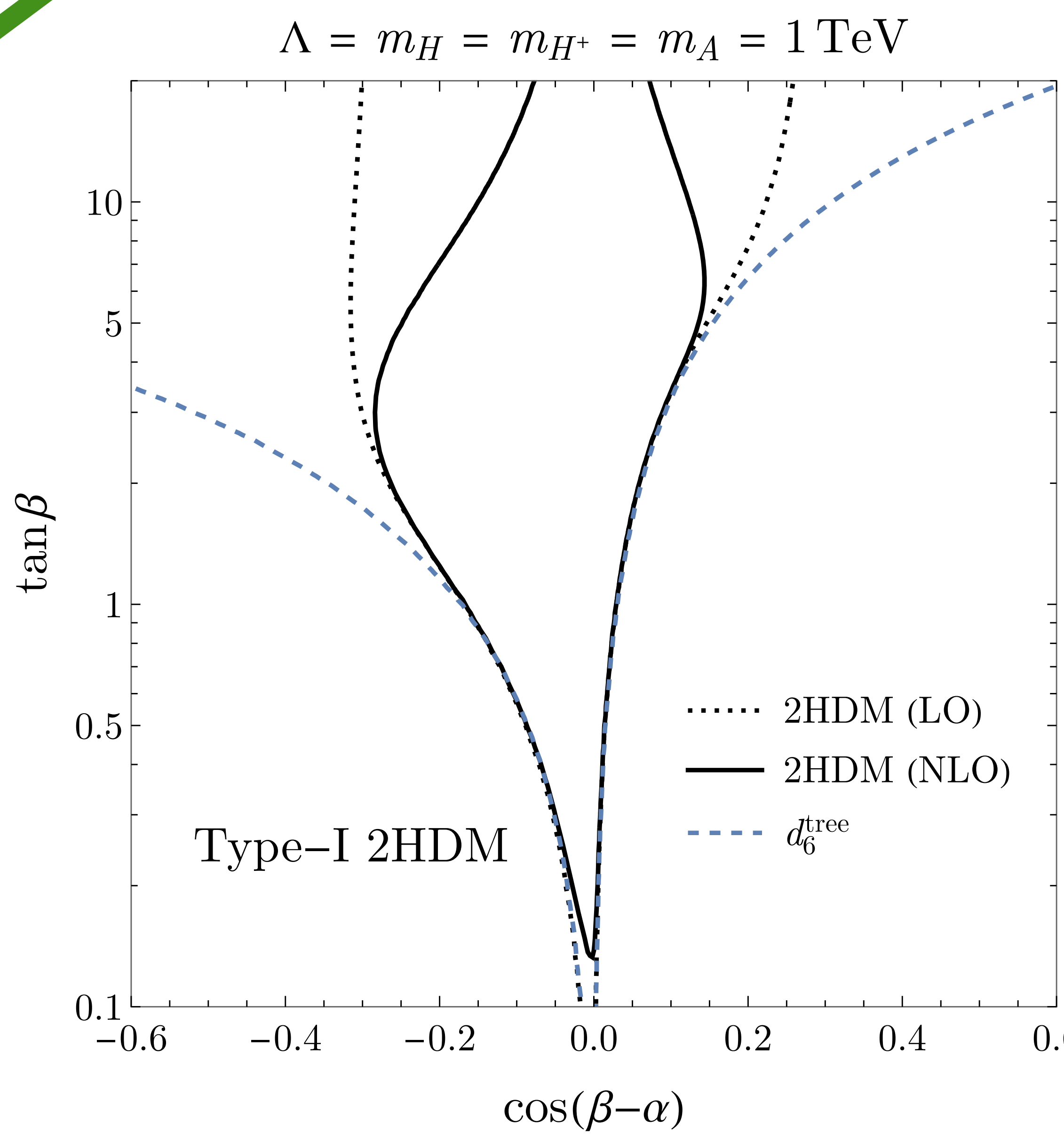
In the type-I 2HDM, all of the fermionic operators scale like:

$$\frac{v^2}{\Lambda^2} C_{fH} = -y_f \frac{\cos(\beta-\alpha)}{\tan\beta}$$

For large $\tan\beta$, approaches the SM!

Ignoring the constraints on C_H, we see the dimension-6 description **completely fails** (see e.g., [1611.01112])

$\Longrightarrow$ need to include gauge couplings! (Dimension-8)



Example: Matching with a 2HDM

Matching to Dim.-8: Dawson, Fontes, SH, Sullivan [arXiv:2205.01561]

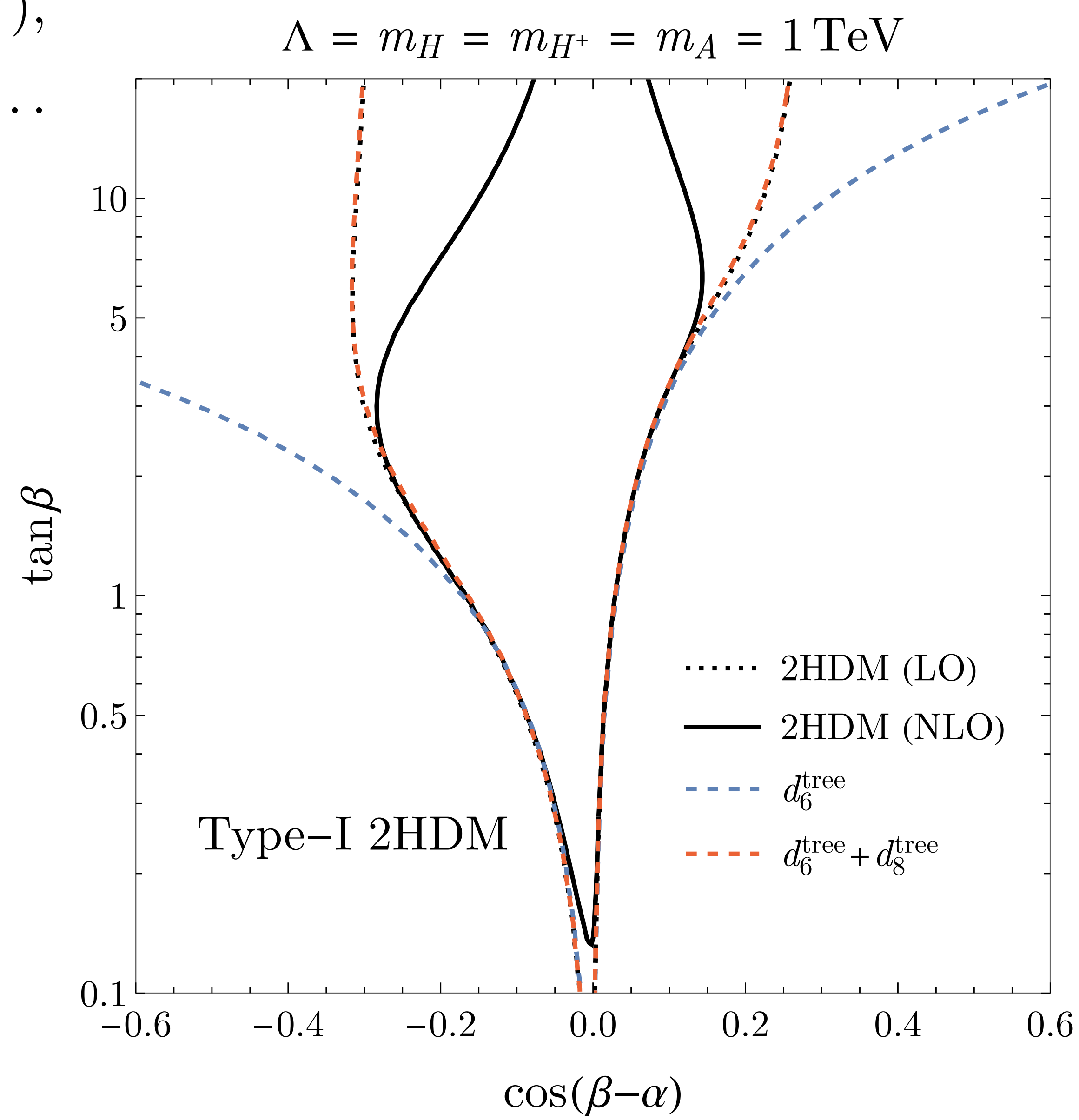
Extended the matching to dimension-8, and translated to the complete basis of Murphy [arXiv:2005.00059]. Many new operators generated:

$$(D_\mu H^\dagger D^\mu H)(\bar{q}uH^c), \quad (D_\mu H^\dagger \tau^I D^\mu H)(\bar{q}u\tau^I H^c),$$
$$(D_\mu H^\dagger H)(\bar{q}uD^\mu H^c), \quad (H^\dagger H)^2(\bar{q}uH^c), \quad (H^\dagger H)^4, \ldots$$

$$\mathcal{O}^{(1)}_{H^6} = (H^\dagger H)^2 (D_\mu H)^\dagger (D^\mu H)$$

$$C^{(1)}_{H^6} = -\frac{\Lambda^4}{v^4}\cos(\beta-\alpha)^2$$

Dimension-8 is the first order where gauge couplings are modified!



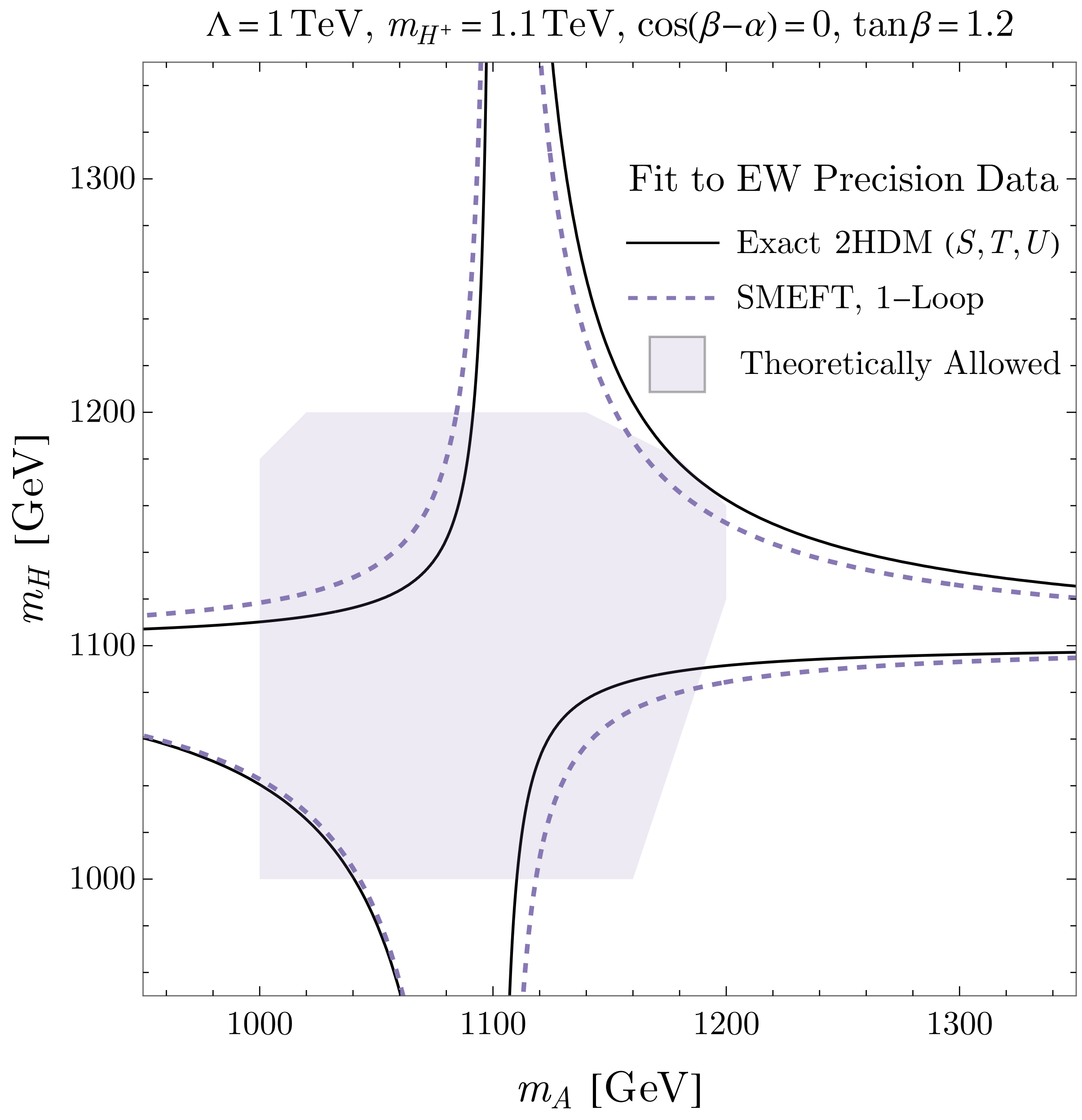
Example: Matching with a 2HDM

Matching at 1-loop: Das Bakshi, Dawson, Fontes, SH

To extend the matching calculation to 1-loop, we utilize two software packages: `Matchmakereft` (Diagrammatic) and `Matchete` (Functional) — results from each checked for agreement.

Work exclusively in the *decoupling limit* (small $c_{\beta-\alpha}$)

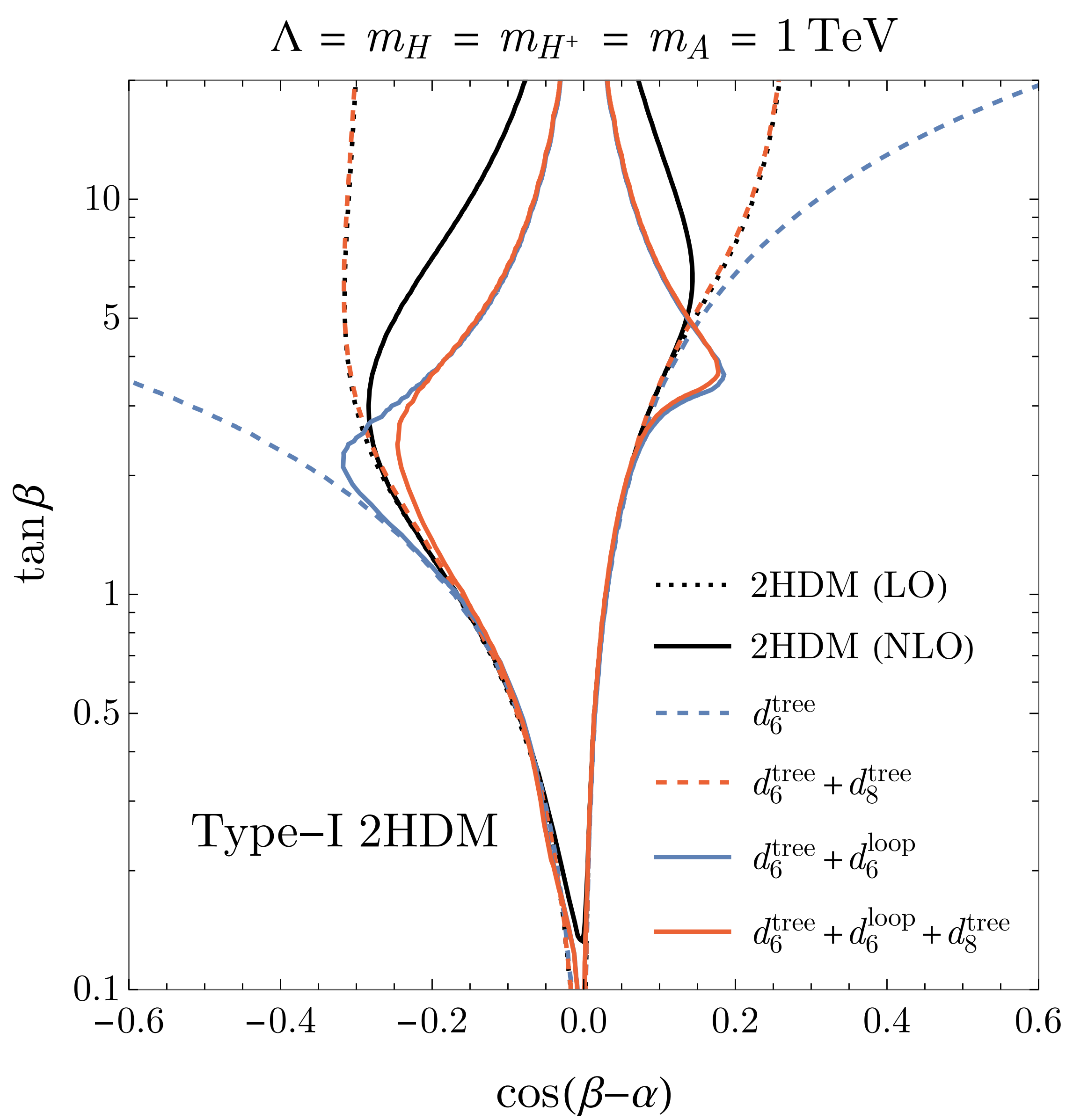
At one-loop, we are sensitive to differences in the masses of the heavy states, which generate operators (e.g., C_{HD}) constrained by EW precision data:

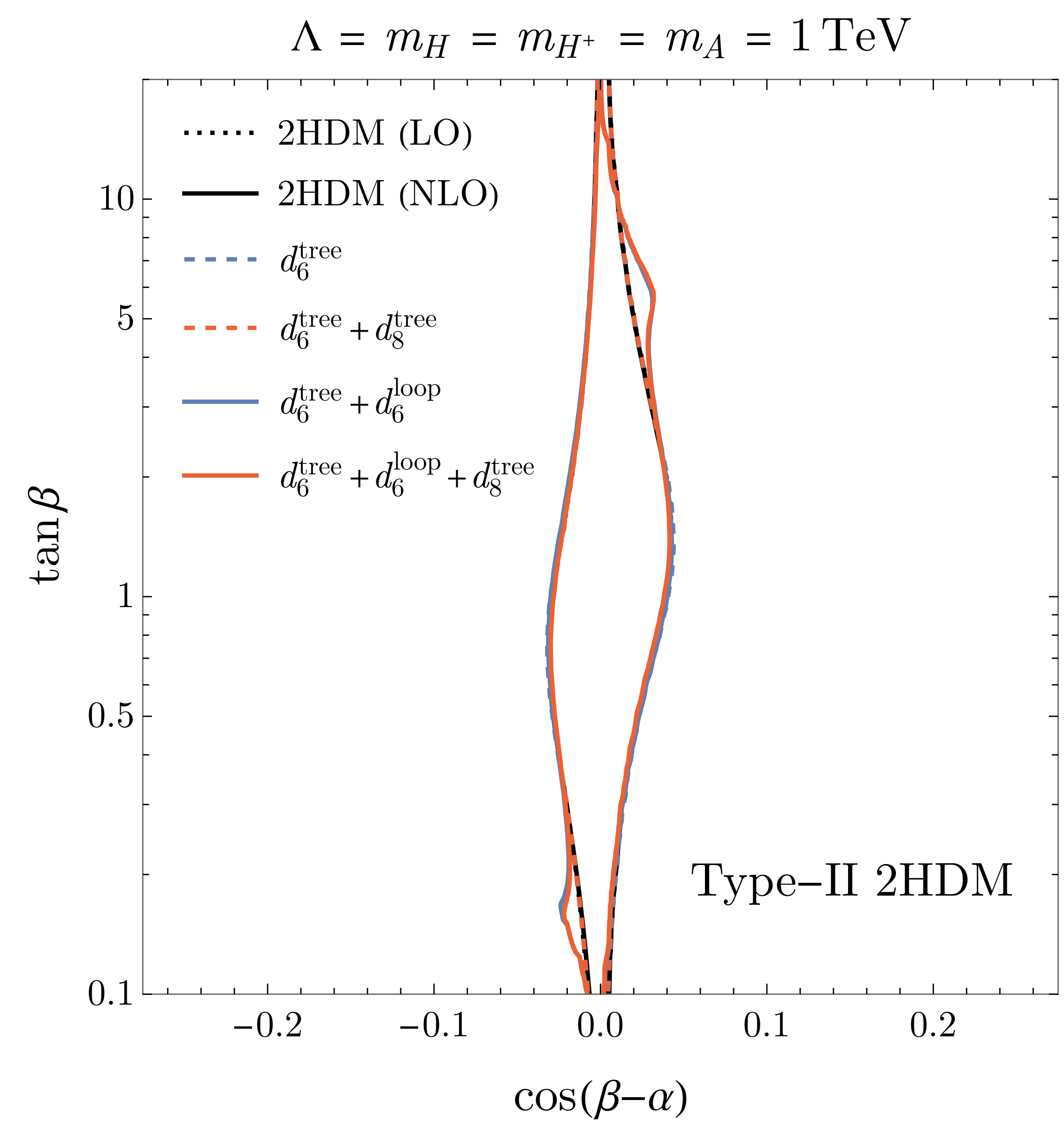


Example: Matching with a 2HDM

Matching at 1-loop: Das Bakshi, Dawson, Fontes, SH

With the full set of results, we can compare with the exact model:





Good agreement, and allows for inclusion of additional data (e.g., λ_{hhh})

Example: Matching with a 2HDM

Matching at 1-loop: Das Bakshi, Dawson, Fontes, SH

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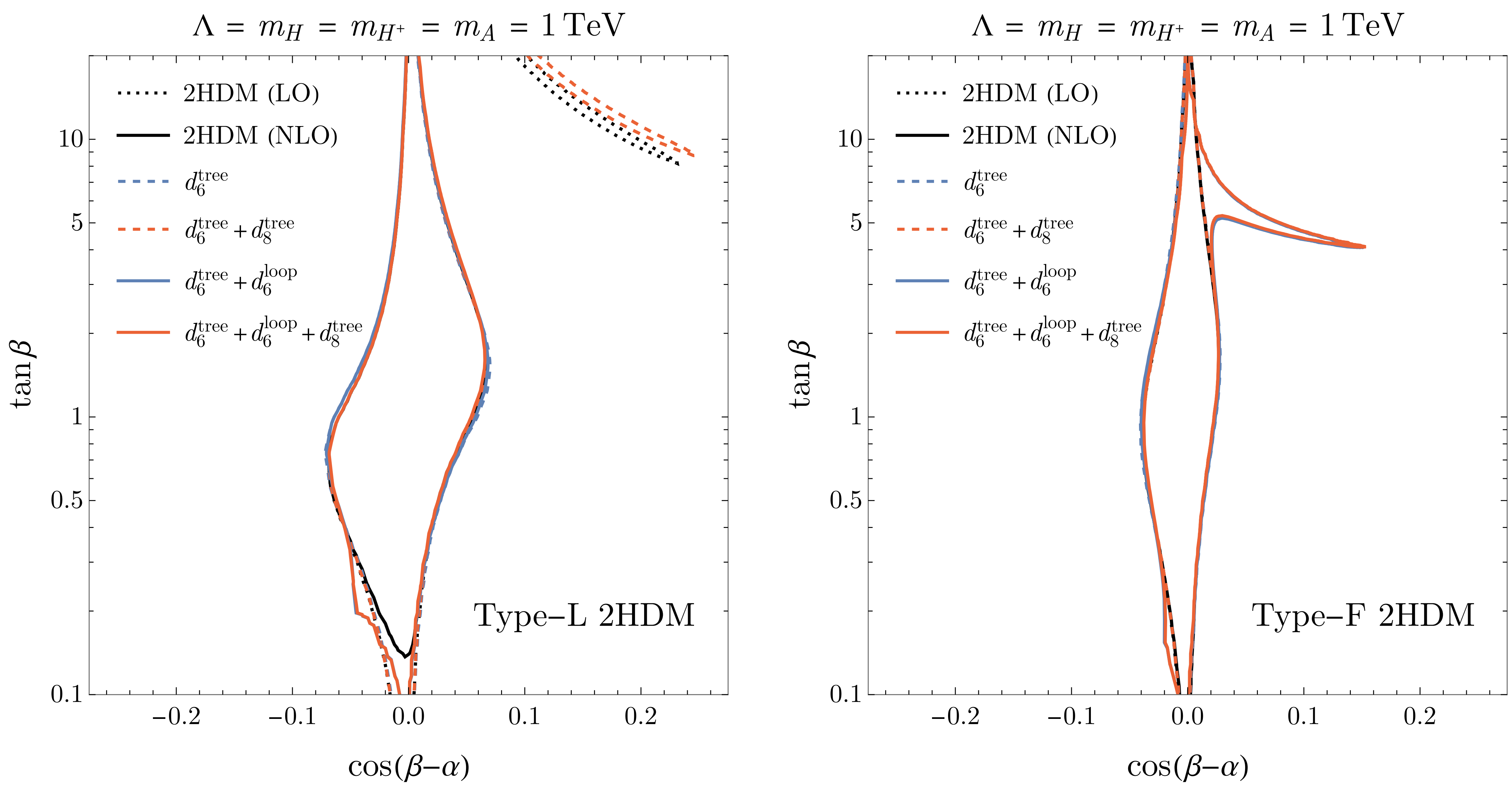

Good agreement, and allows for inclusion of additional data (e.g., λ_{hhh})

Outlook and Conclusions:

- SMEFT interpretations are increasingly common in Higgs/EWK/Top precision measurements at the LHC — must keep our goals in mind!
    - Identify new observables, get the most out of LHC data, make sure we aren't missing anything in inclusive observables!
    - Search for *new physics* (not measure coefficients)
- Higher-order effects can change both the phenomenology and the interpretation of data — but with effort, constraints on operators can be translated into bounds on models.
- Going beyond: if additional light fields are present, we can include them in the EFT!
  (See e.g., Adhikari, Lewis, Sullivan [2003.10449], Dermisek, Hermanek, [2405.20511])
- Lots of other fun work in this direction I didn't have time to include

Thanks for your attention!