Interpreting SMEFT Results in Extended Scalar Sectors

Based on
arXiv:2007.01296, 2102.02823, 2205.01561

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In collaboration with
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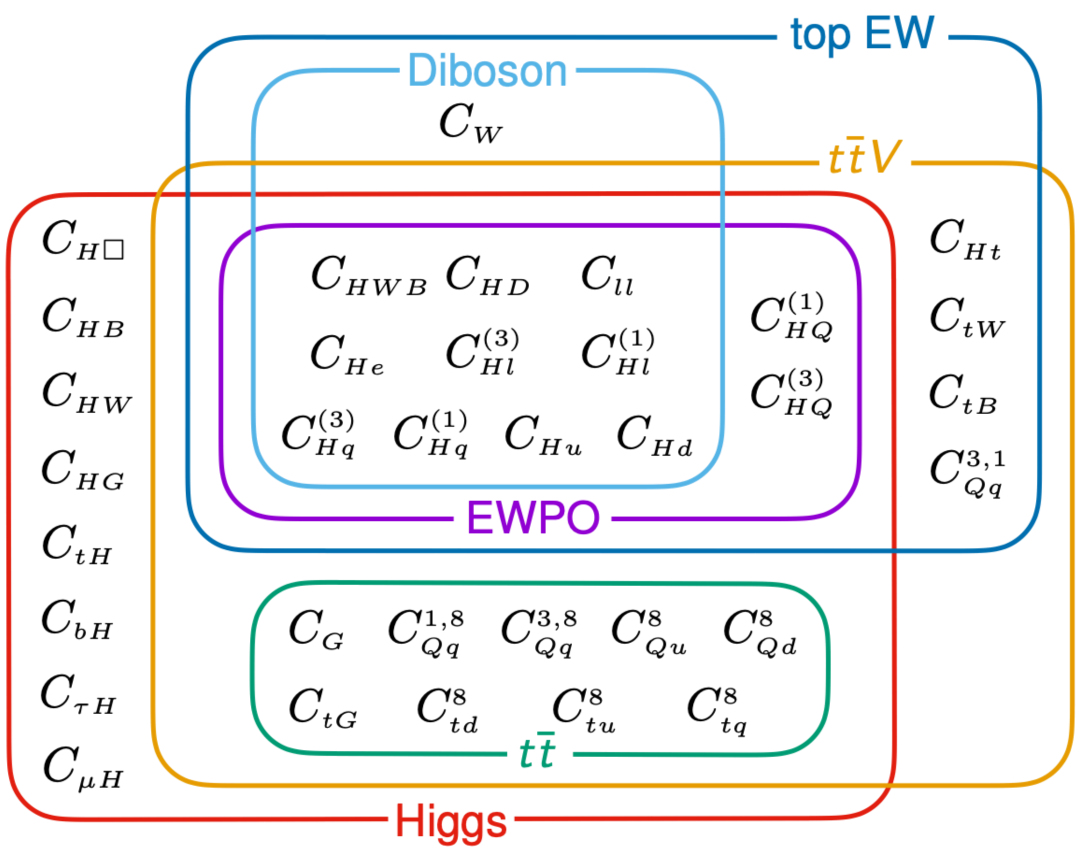
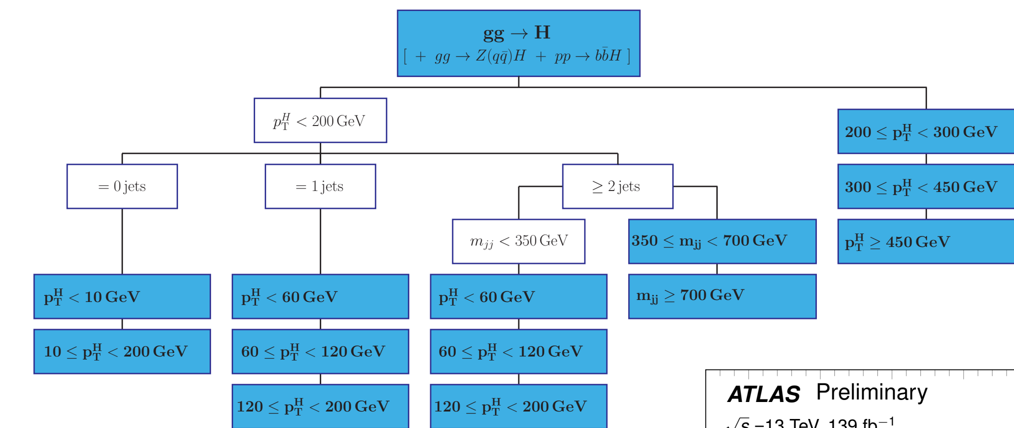
LHC Higgs Working Group, November 30, 2022

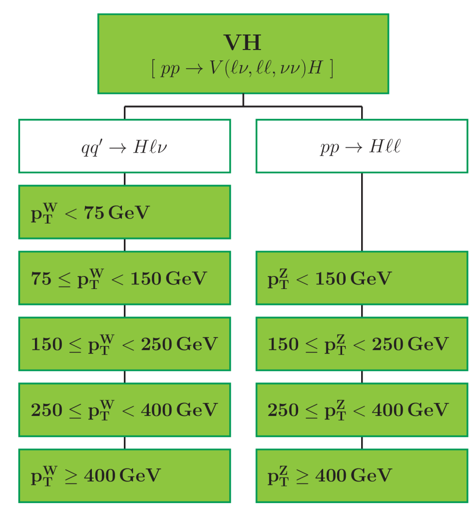
Higgs Physics in the Age of the SMEFT

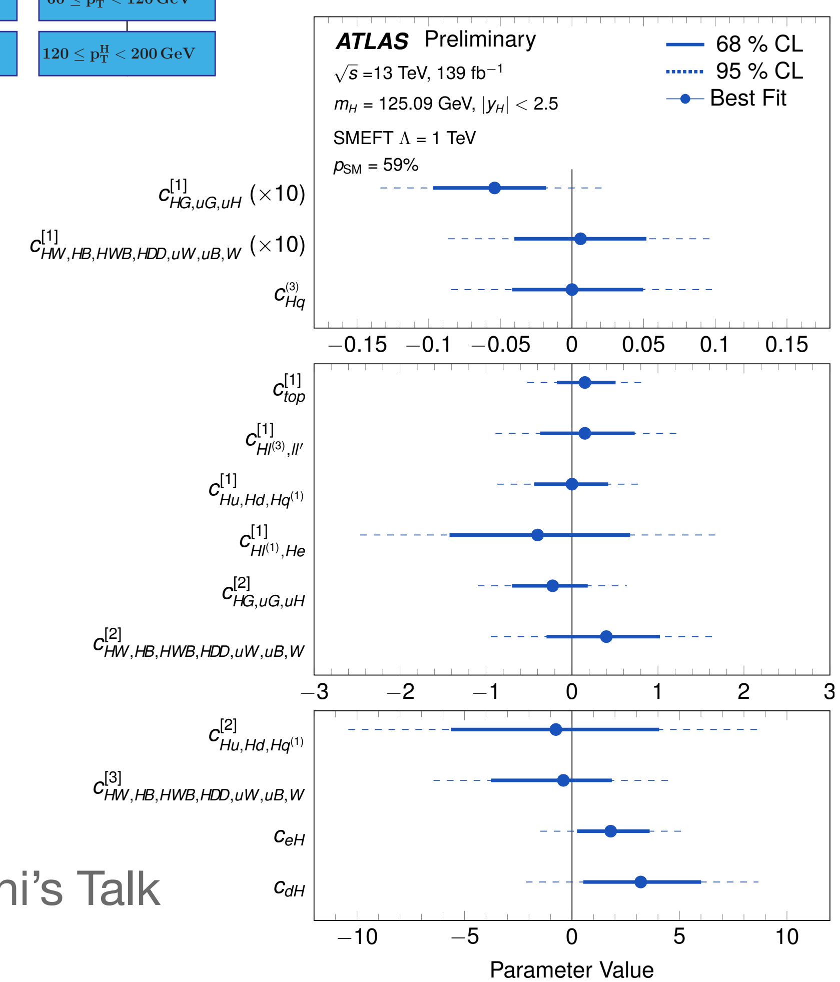
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d=6,8,\ldots} \sum_i \frac{C_i^{(d)}}{\Lambda^{d-2}} \mathcal{O}_i^{(d)}$$



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



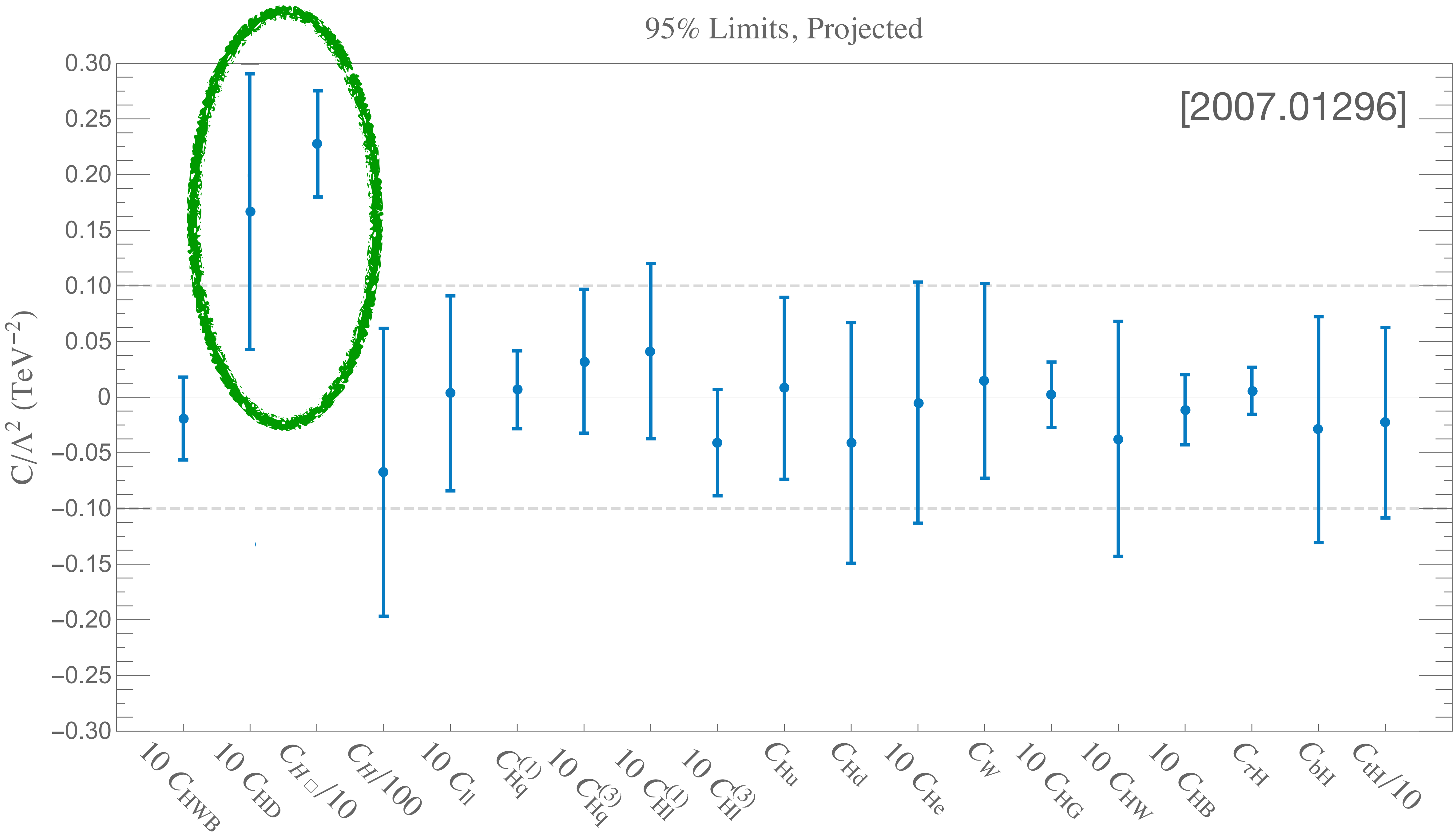




ATLAS-CONF-2021-053

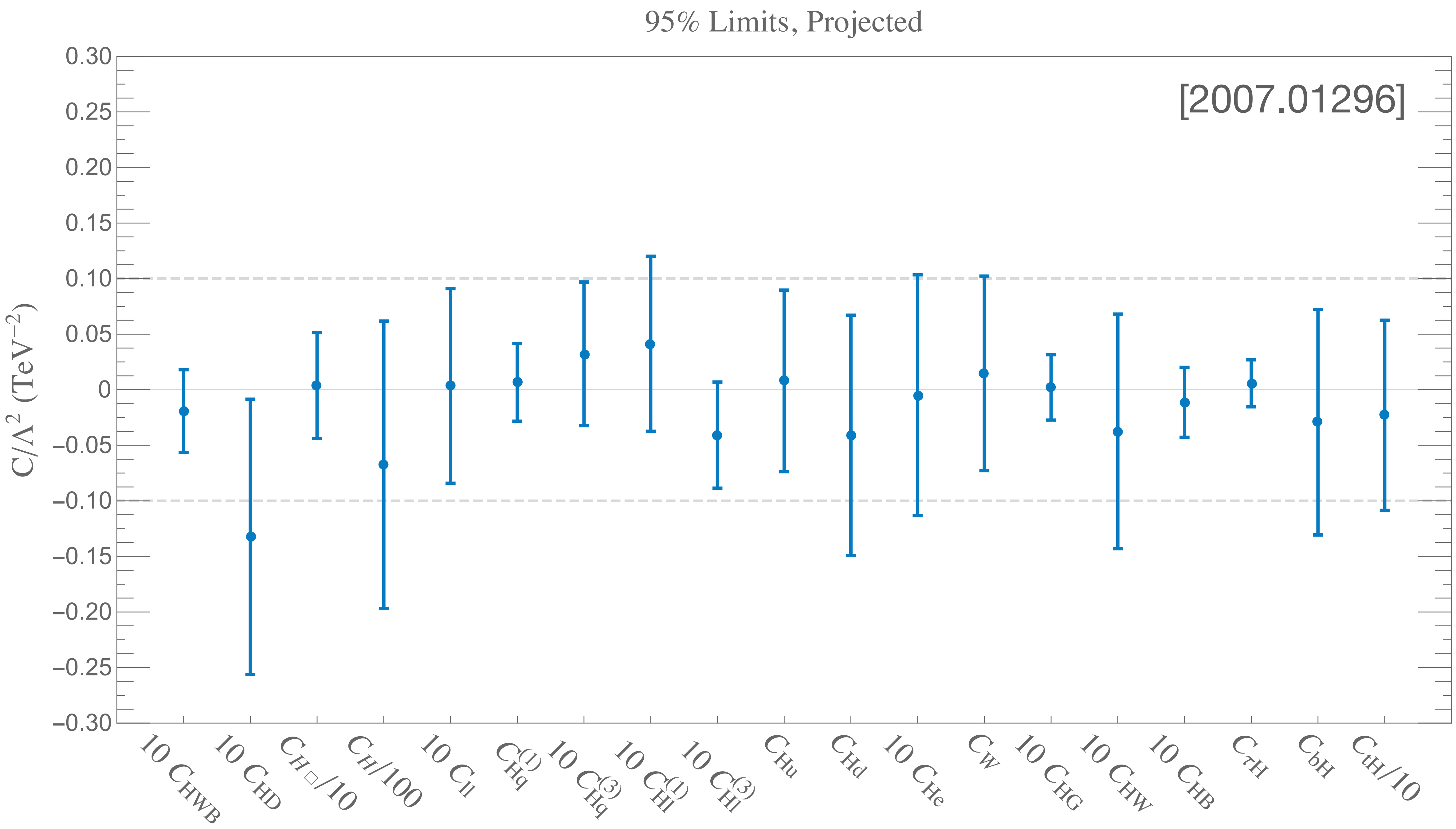
(See Alessandro Calandrini's Talk from Monday)

The Dream:



$\Longrightarrow$ Start model building! Focussed searches, make sure we understand the SM, …

Alas…



But we are still learning a lot about the Standard Model!

What are we learning about *New Physics?*

SMEFT allows for a robust, precision program at the LHC, but ultimately these operators arise from *some* underlying UV model.

Lots of interesting / challenging methodological questions:

- At what order do we truncate the amplitude / Lagrangian?
- What assumptions about flavor should we make to get a manageable set of operators?
- How should we account for EFT validity issues?

Also “higher-order” effects to consider:

- RG Evolution of Wilson Coefficients
- One-Loop Matching Effects
- Importance of Dimension-8 Operators
- Higher Order QCD / EW Corrections in the EFT

These questions are best studied in examples!

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Focus on the impacts of these today

These questions are best studied in examples!

Example 1: The Singlet Model

arXiv:2102.02823, Dawson, Giardino, SH

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Simplest extension to the SM — only one additional state

Ideal test case for investigating details of matching procedure

- theoretical constraints well understood
- one-loop matching results are known
  (Jiang et al., 1811.08878, Haisch et al., 2003.05936)

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

Goal: understand numerical importance of RGEs + 1-loop matching effects in the context of the singlet model

The Singlet Model

$$V(\Phi, S) = -\mu_H^2 \Phi^\dagger\Phi + \lambda_H \left(\Phi^\dagger\Phi\right)^2 + \frac{1}{2} m_\xi \Phi^\dagger \Phi S + \frac{1}{2}\kappa \Phi^\dagger\Phi S^2$$
$$+ t_S S + \frac{1}{2} M^2 S^2 + \frac{1}{3} m_\zeta S^3 + \frac{1}{4}\lambda_S S^4$$

In Z_2 non-symmetric case, use shift symmetry to set $v_S \to 0$

Physical states:

$$h = \cos\theta\, \Phi_0 + \sin\theta\, S$$
$$H = -\sin\theta\, \Phi_0 + \cos\theta\, S$$

Masses $m_h = 125$ GeV, M_H

Other physical parameters:

$$\sin\theta,\ \kappa,\ m_\zeta,\ \lambda_S$$

Higgs couplings universally suppressed by $\cos\theta$

Singlet Matching to SMEFT

Two coefficients are generated at tree-level:

$$c_{H\Box} = -\frac{m_\xi^2}{8M^2}$$

$$c_H = \frac{m_\xi^2}{8M^2}\left(\frac{m_\xi m_\zeta}{3M^2} - \kappa\right)$$

Perform matching at the scale *M*, related to the physical mass via

$$M^2 = m_h^2 \sin^2\theta + M_H^2 \cos^2\theta - \frac{\kappa}{2}v^2$$

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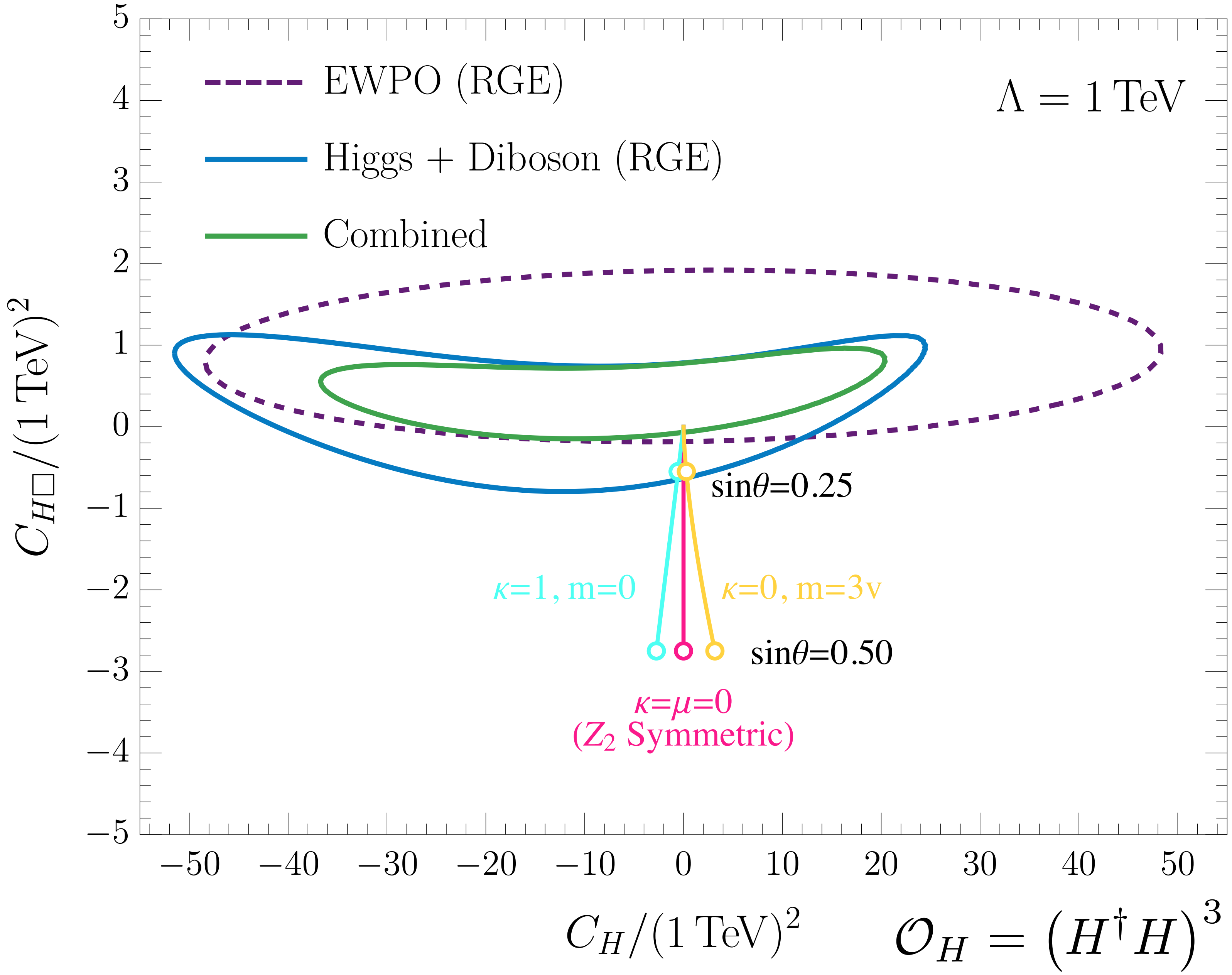
These operators introduce

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

at the weak scale from RG running

Tree Level (+RGE) Results



Limits on the singlet from EWPO and LHC competitive — but most allowed coefficients cannot be generated in the model

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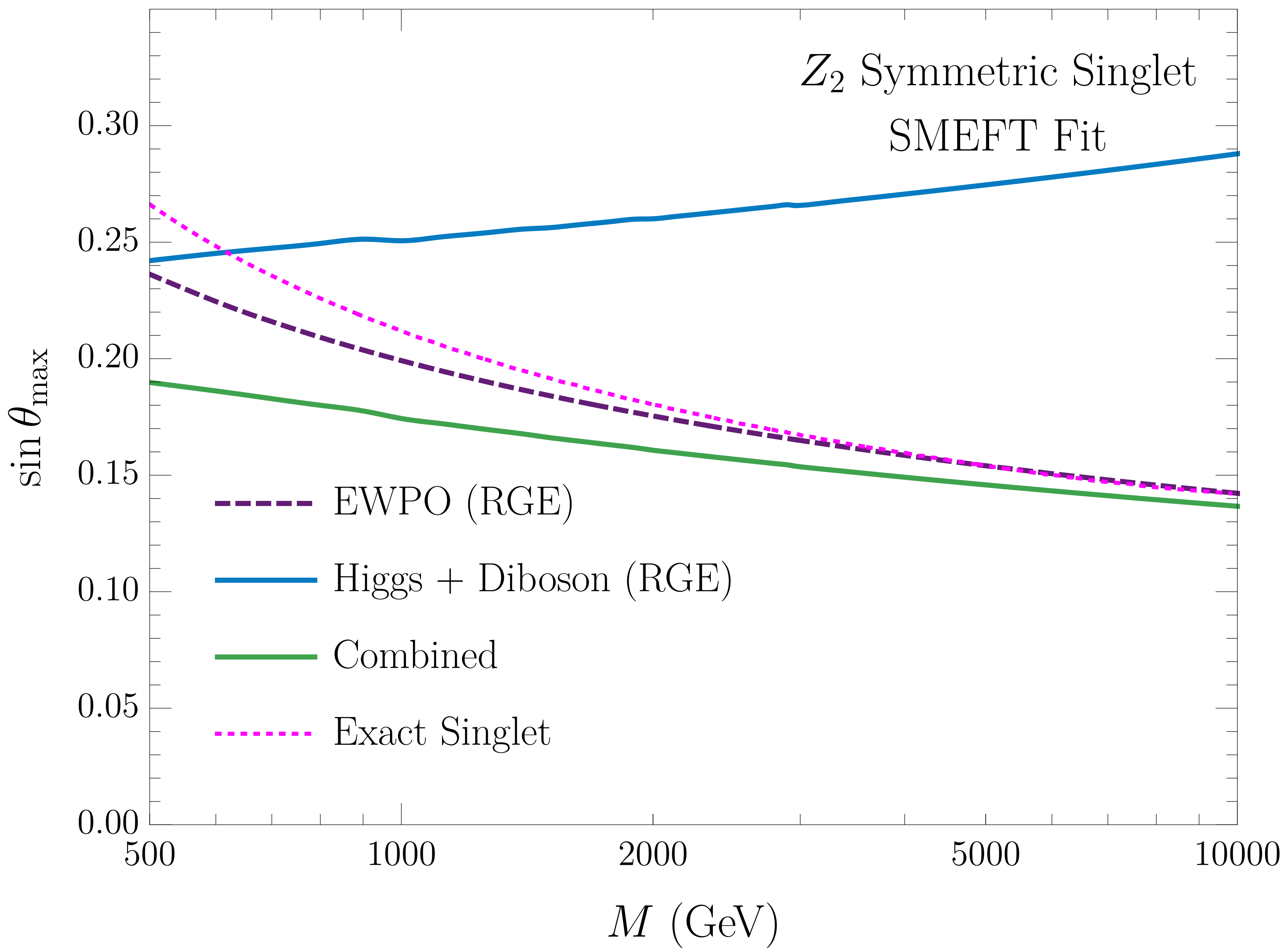


Limits on the singlet from EWPO and LHC competitive — but most allowed coefficients cannot be generated in the model

One-Loop Matching

Jiang, Craig, Li, Sutherland [1811.08878],
Haisch, Ruhdorfer, Salvioni, Venturini, Weiler [2003.05936]

New contributions to C_H, $C_{H\Box}$ at the matching scale…

$$d_{H\Box} = -\frac{9}{2}\lambda c_{H\Box} + \frac{31}{36}(3g^2 + g'^2)c_{H\Box} + \frac{3}{2}c_H + \delta d_H + \delta d_{H\Box}^{\text{shift}}$$

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

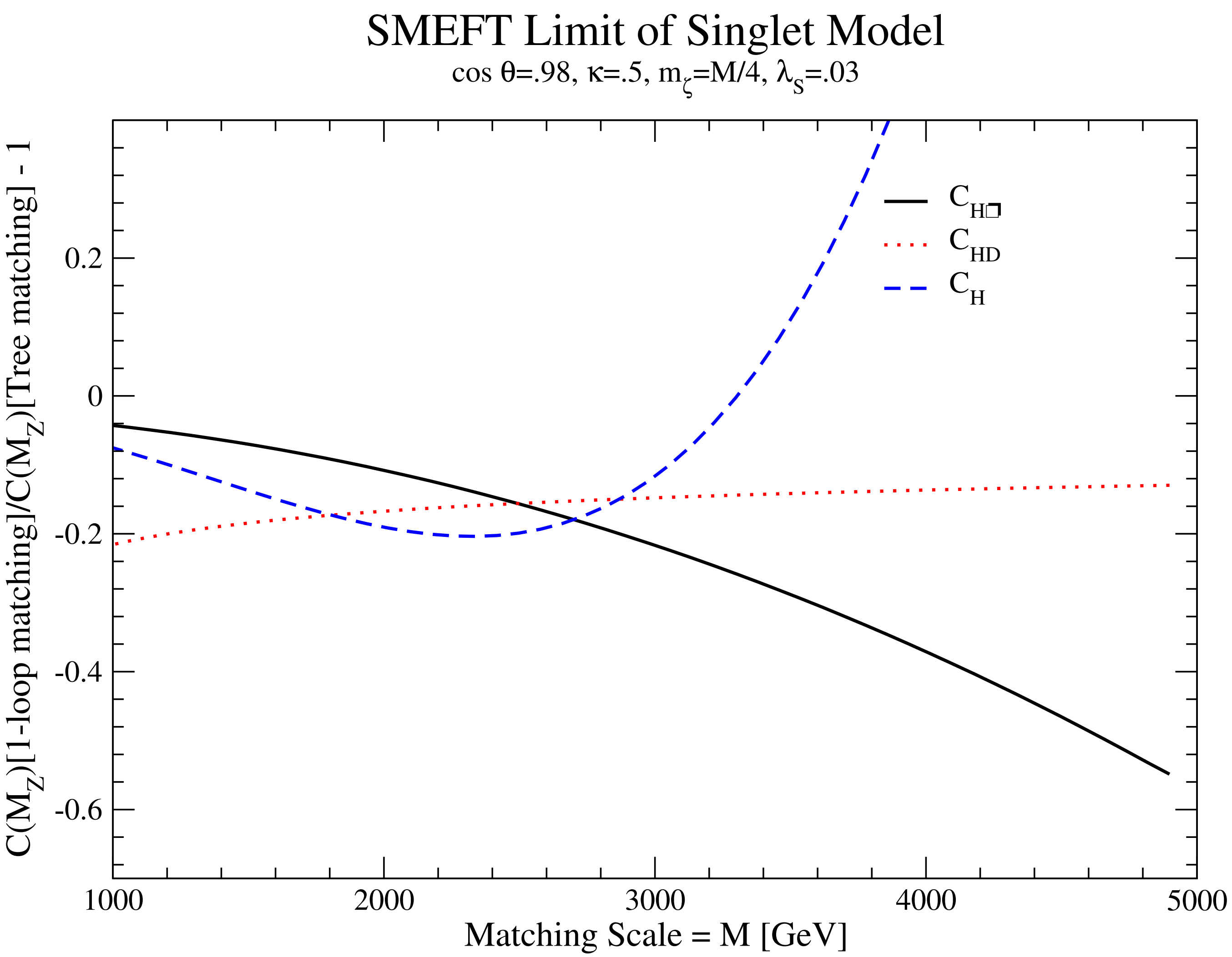
…as well as many operators that don't appear at tree-level

$$C_{HD},\ C_{HW},\ C_{HB},\ C_{HWB},\ C_{Hu},\ C_{Hd},$$

$$C_{Hq}^{(1)},\ C_{Hq}^{(3)},\ C_{Hl}^{(3)},\ C_{tH}$$

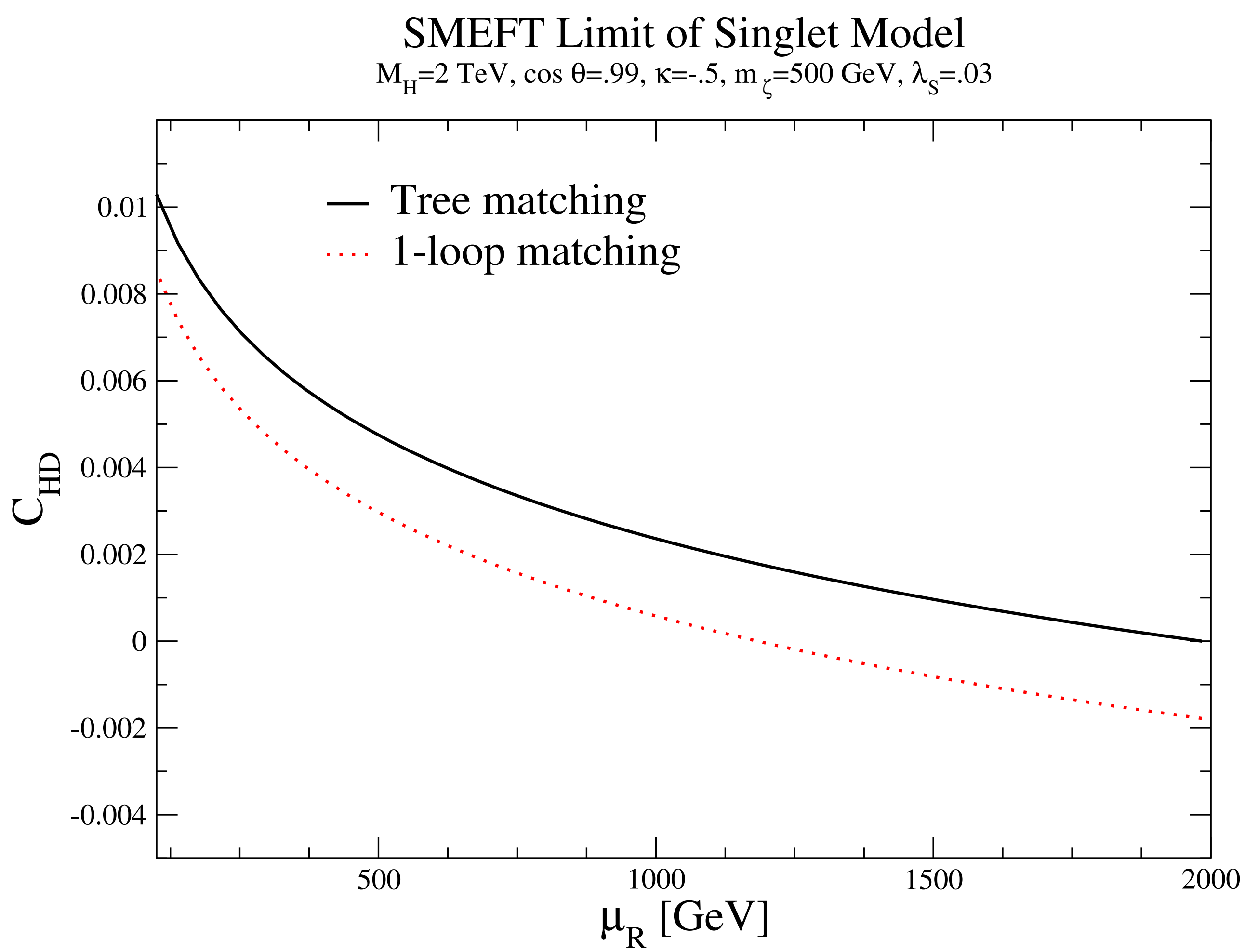
In principle of comparable size to RGE-induced contribution!

One-Loop Matching



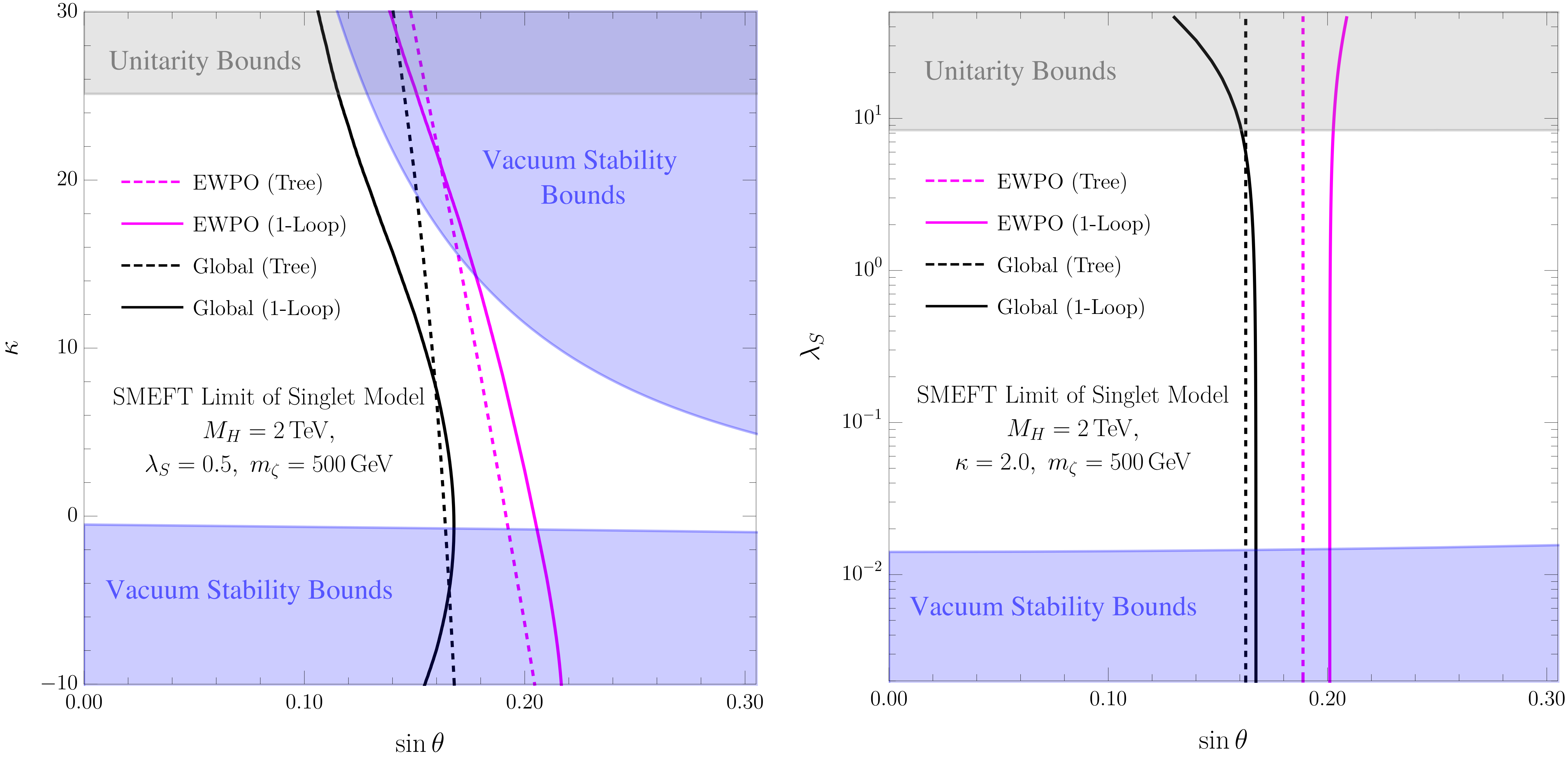
Include only one-loop RGEs

(two loops unavailable, but necessary to run one-loop induced operators)



One-loop matching changes operators by ~10-20% as measured at the weak scale

Effects on the Fit



Effects mostly O(10%), except for large values of portal coupling

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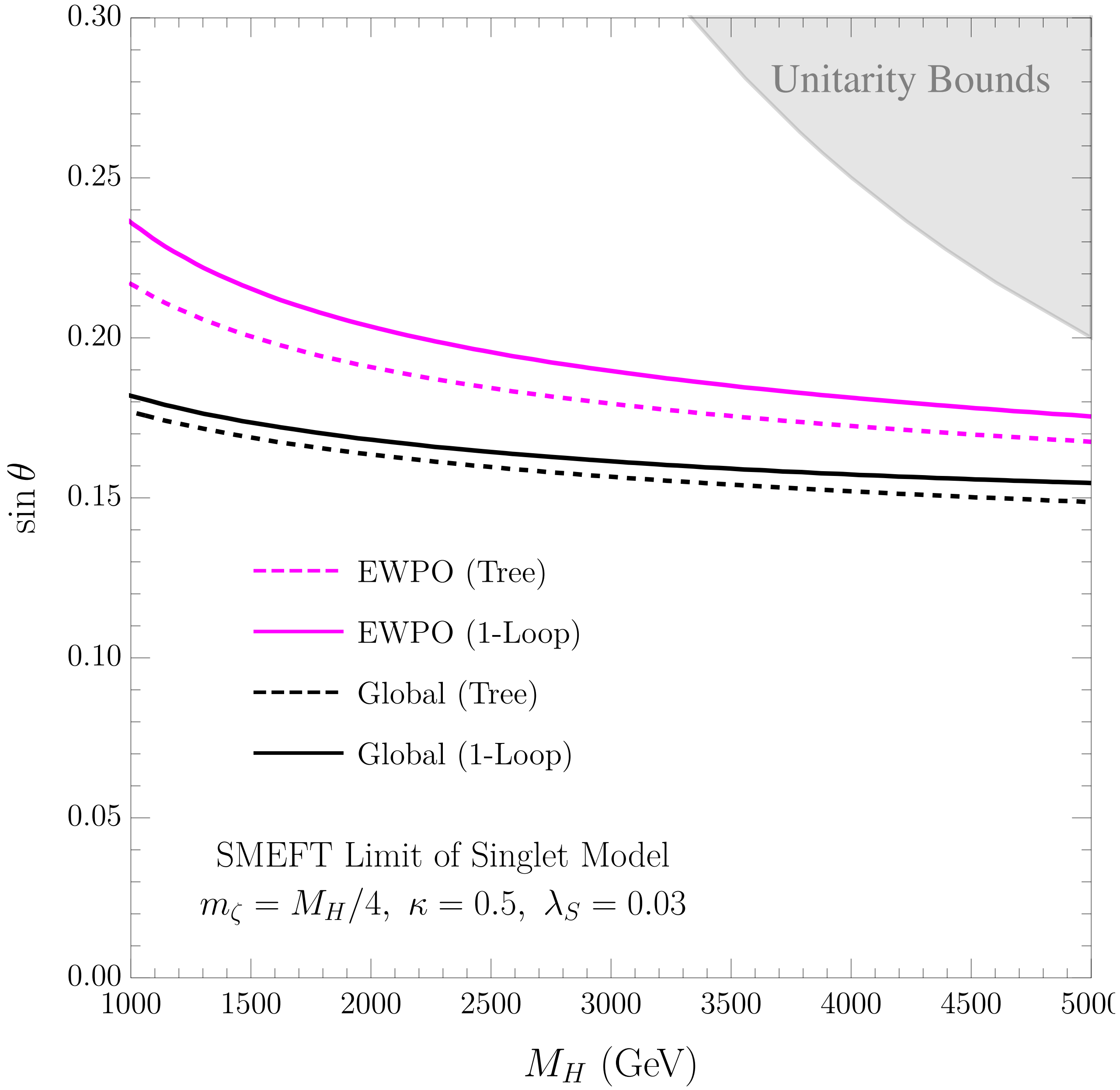

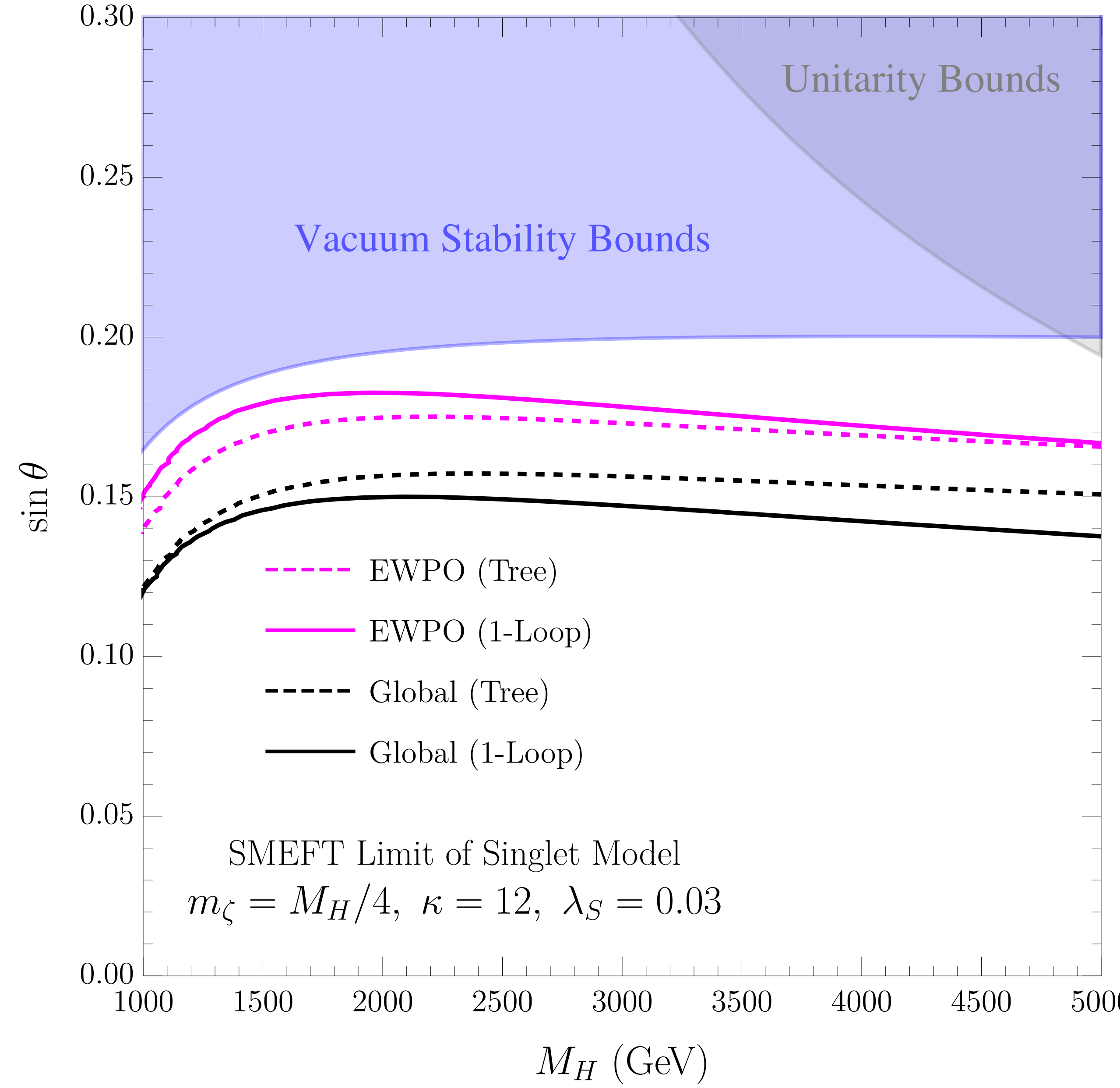

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Example 2: The 2HDM

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

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Four "standard" types of 2HDMs (I, II, L and F) distinguished by Z_2 symmetry acting on Φ_2 and the fermions.

Higgs coupling deviations can be written in terms of $\tan\beta,\ \cos(\beta-\alpha)$.

E.g., for Type-II:

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

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

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

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

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

Alignment parameter tells us how "SM-like" the 125-GeV Higgs is

Matching to Dimension-6

Ignoring light flavor, there are four operators generated:

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

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

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

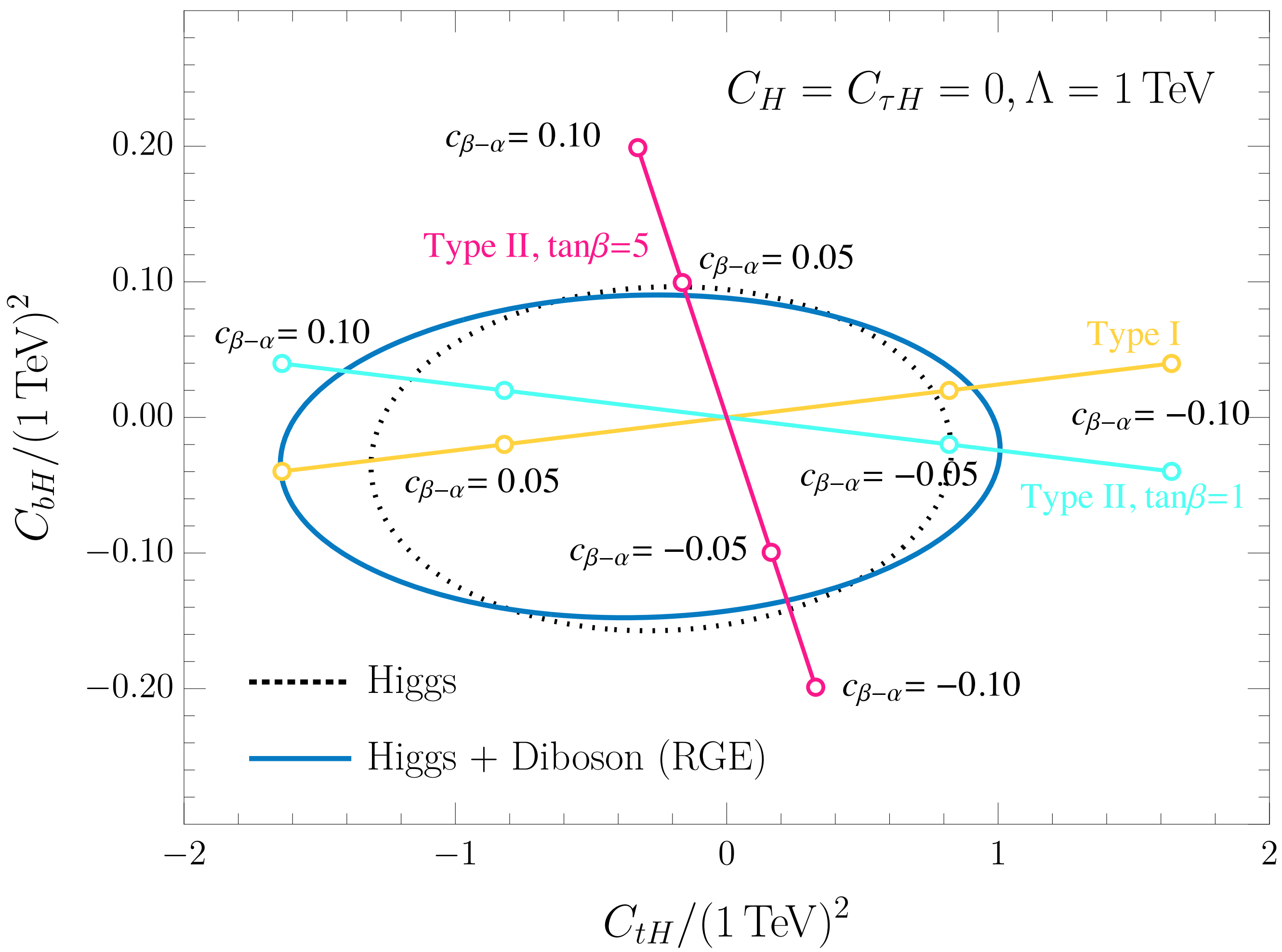
$$\mathcal{O}_{\tau H} = (H^\dagger H)(\bar{L}_3 \tau_R \tilde{H}), \qquad \frac{v^2}{\Lambda^2} C_{\tau H} = -y_\tau \eta_\tau \frac{\cos(\beta-\alpha)}{\tan\beta}$$

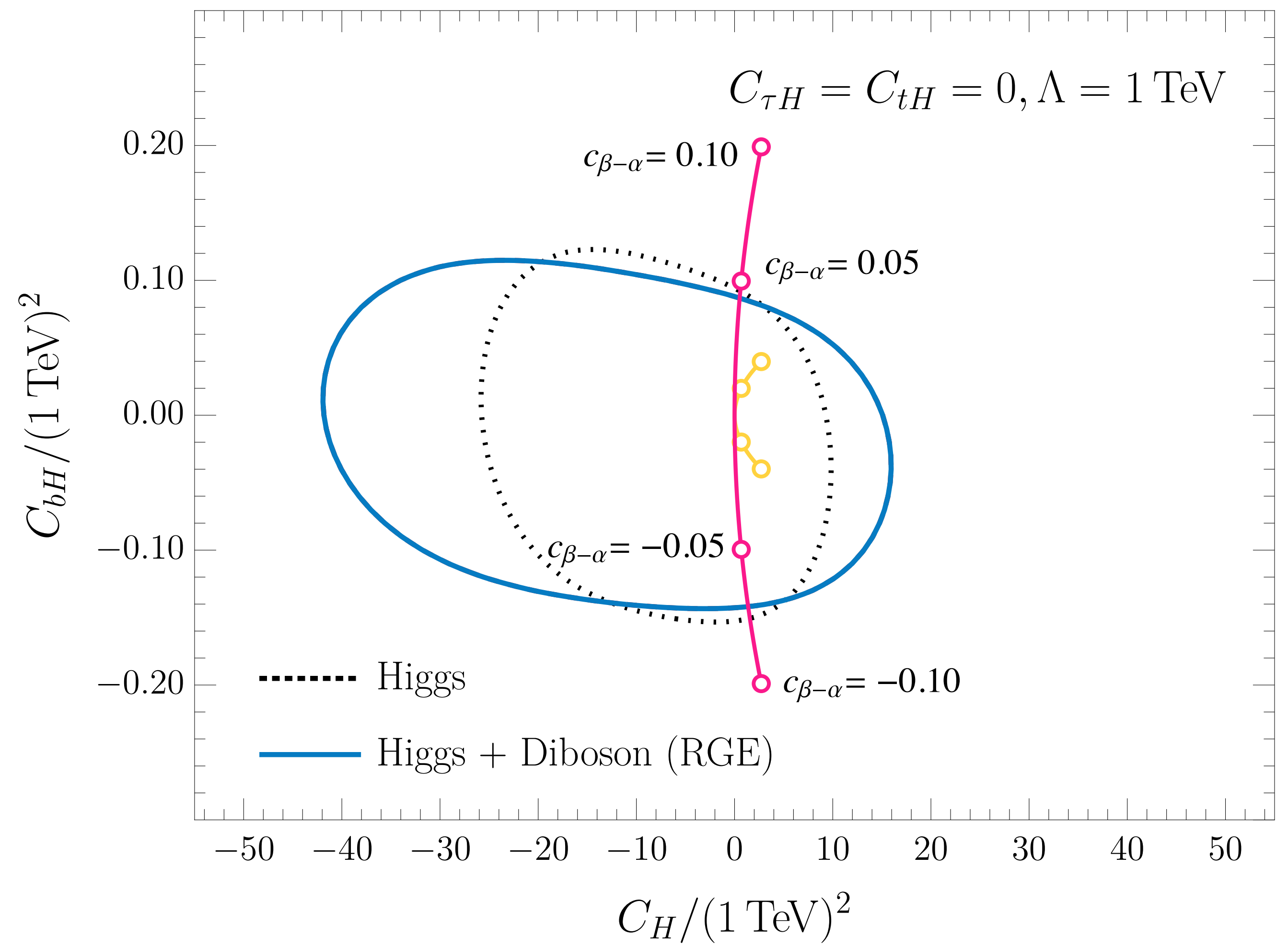
	η_t	η_b	η_τ
Type-I	1	1	1
Type-II	1	$-\tan^2\beta$	$-\tan^2\beta$
Lepton-specific	1	1	$-\tan^2\beta$
Flipped	1	$-\tan^2\beta$	1

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

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

Matching to Dimension-6

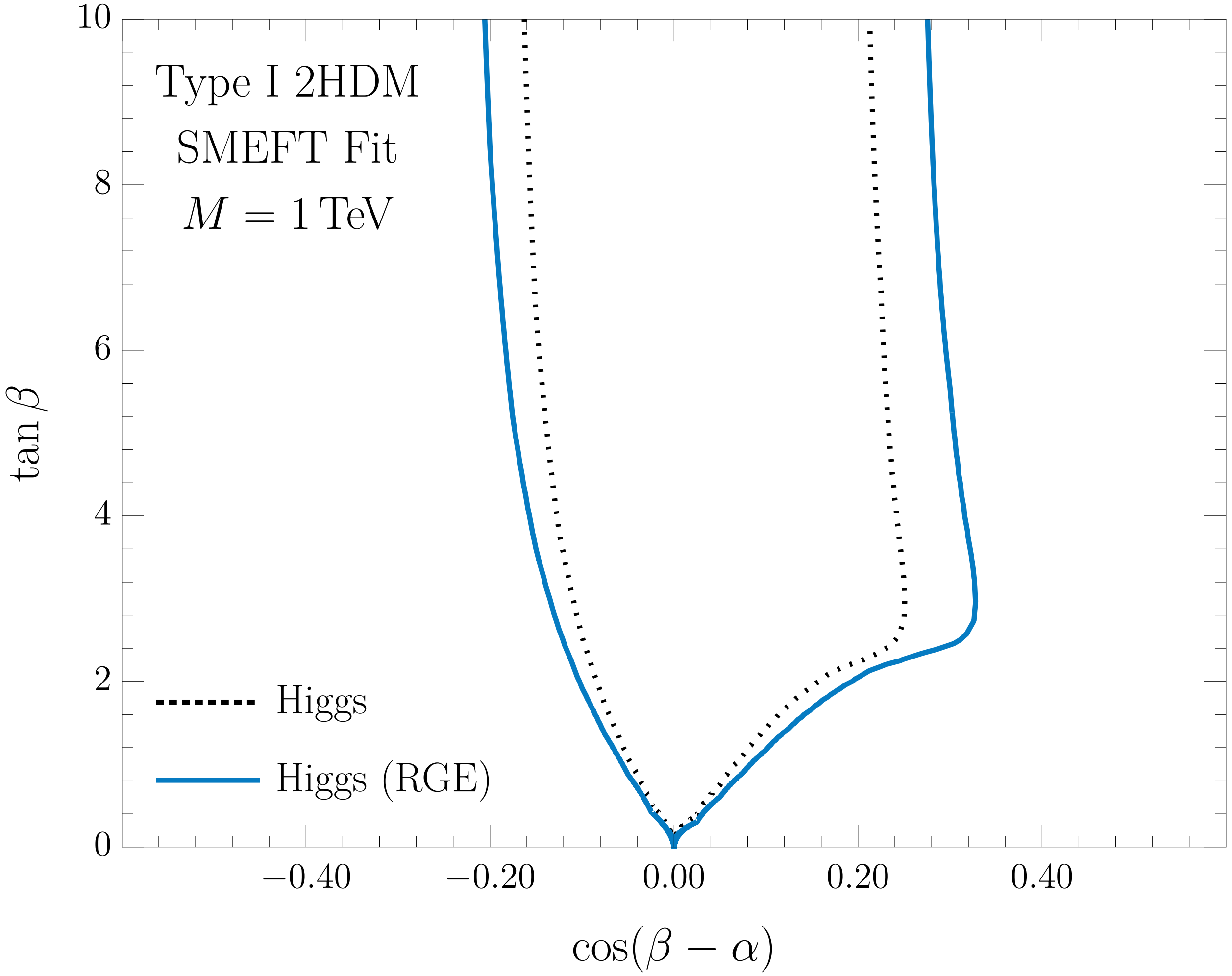


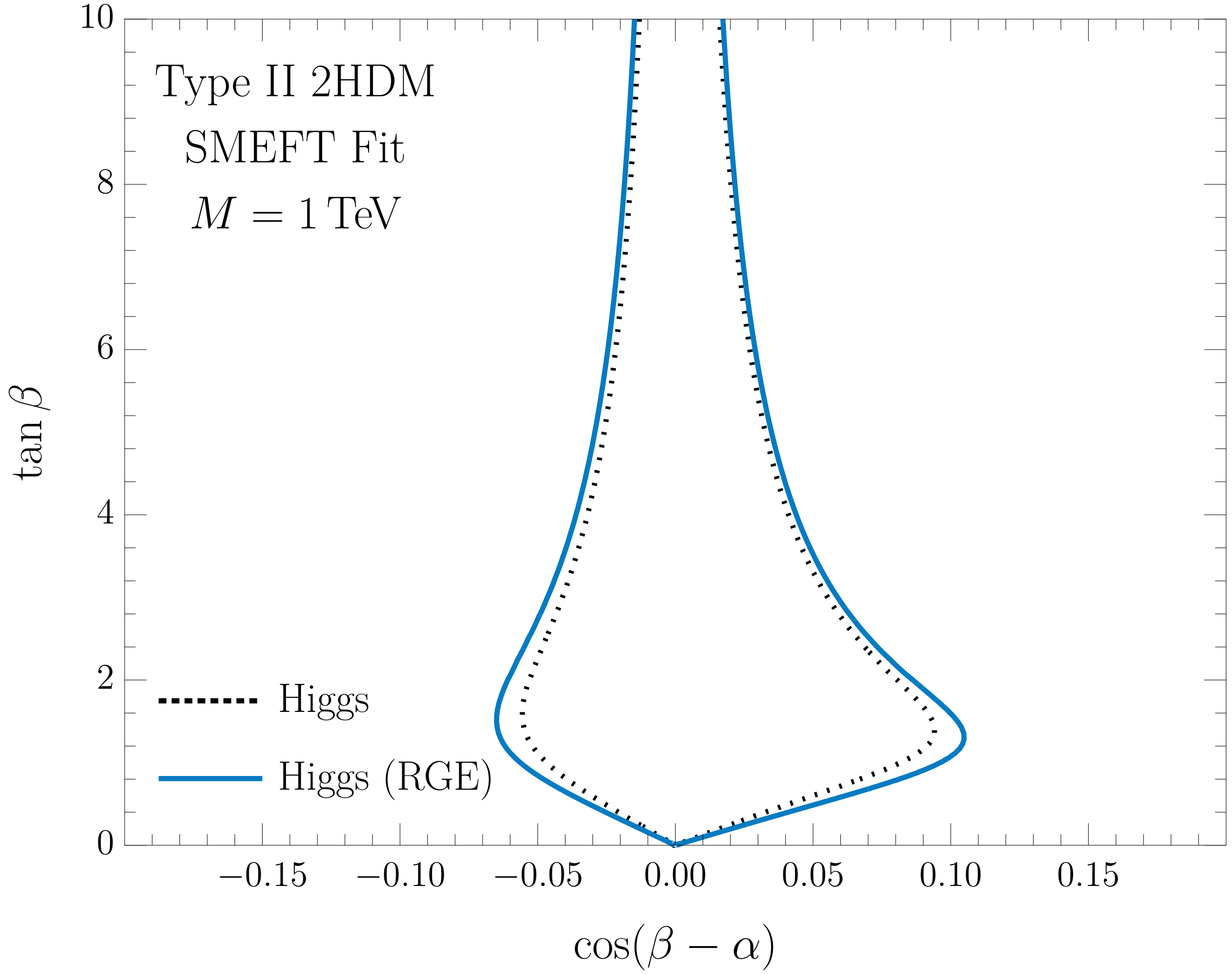


Different types of 2HDM sweep out different ranges of allowed coefficients

Matching to Dimension-6

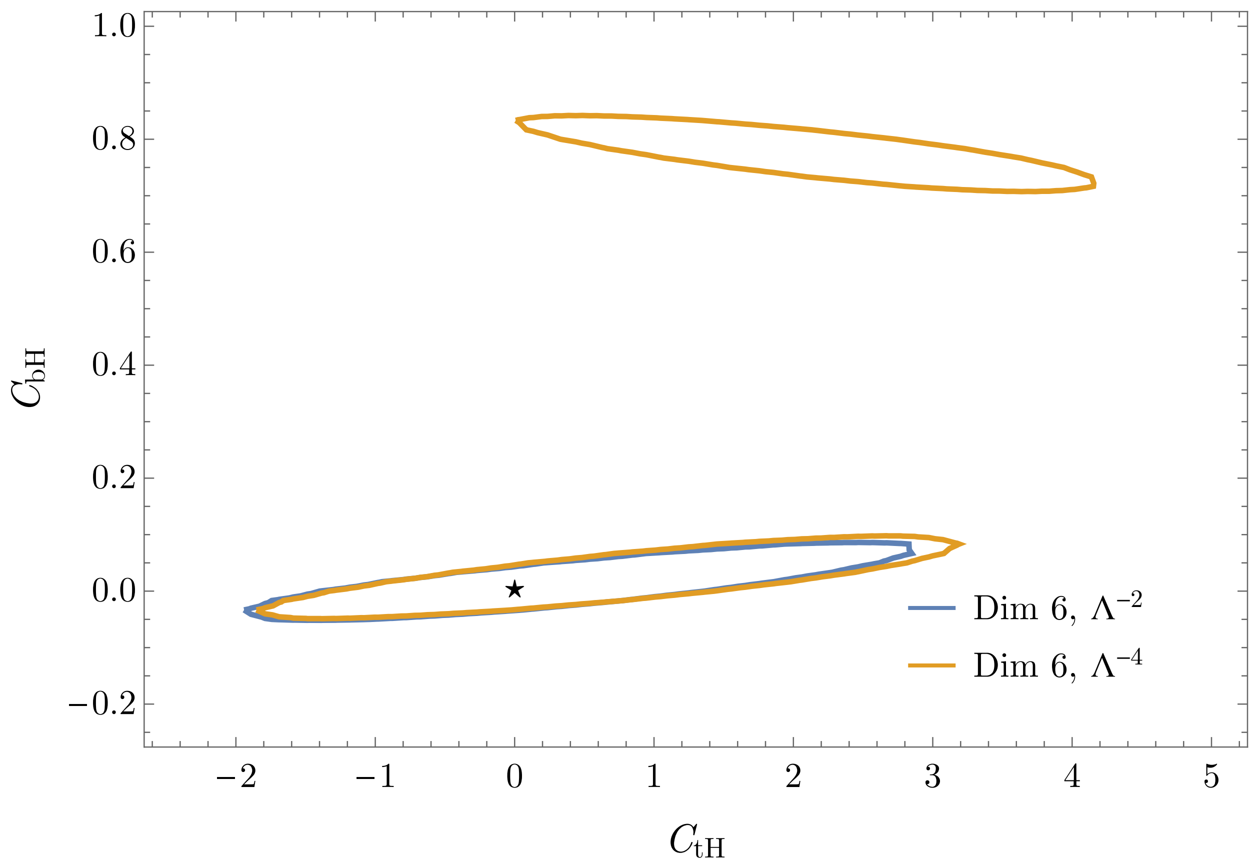
For a given type of 2HDM, easy to translate into the $\tan\beta, \cos(\beta-\alpha)$ plane





Effects of RGE are relatively small (logarithmic effects on Higgs couplings)

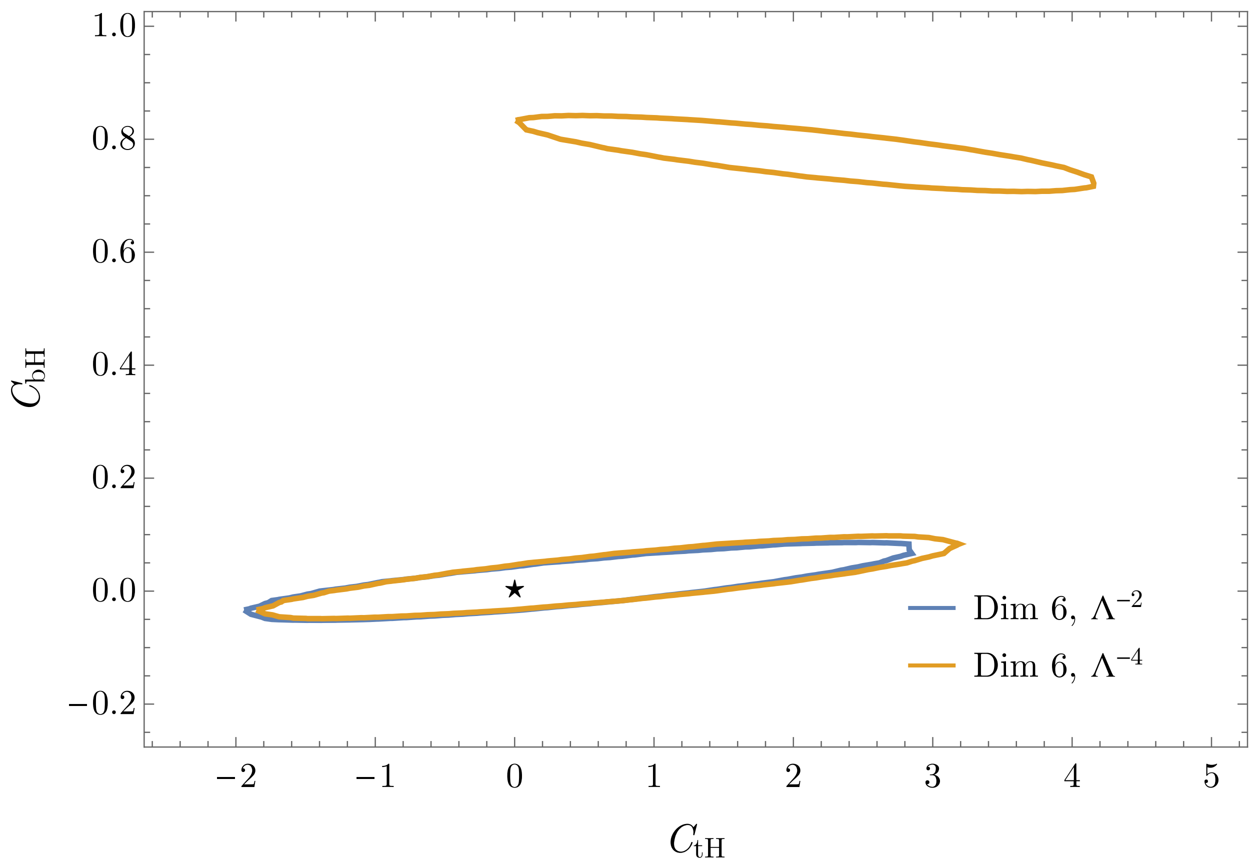
Effects at Large $\tan\beta$



There is a second minimum where the bottom Yukawa has the opposite sign

The well-known “wrong-sign” region of the Type-II 2HDM

Effects at Large tan β



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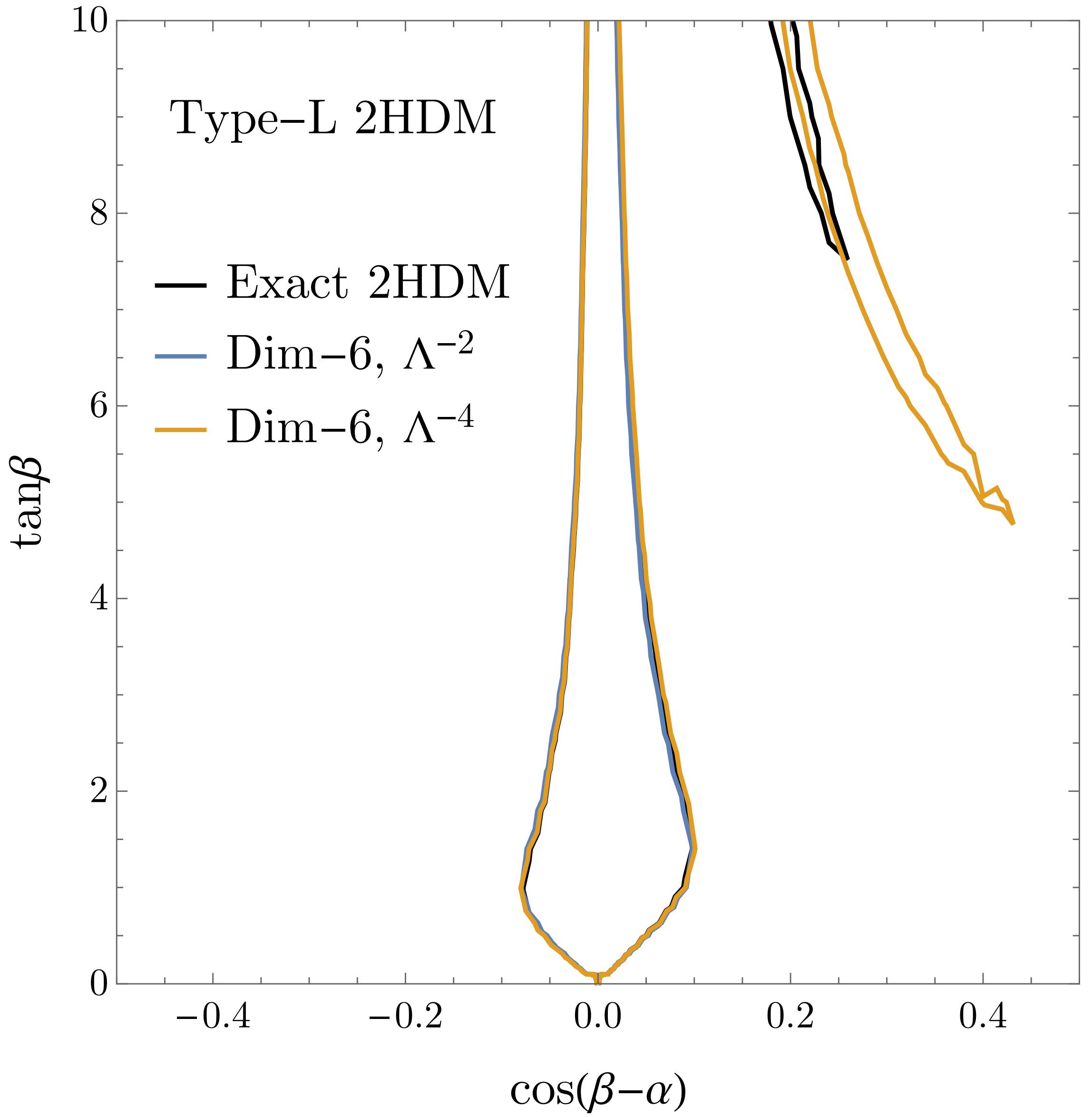
The well-known “wrong-sign” region of the Type-II 2HDM

Actually ruled out for Type-II by latest Higgs data, but appears still in e.g., Type-L:



But only if we include $\mathcal{O}(\Lambda^{-4})$ terms!

Effects at Large $\tan\beta$

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

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

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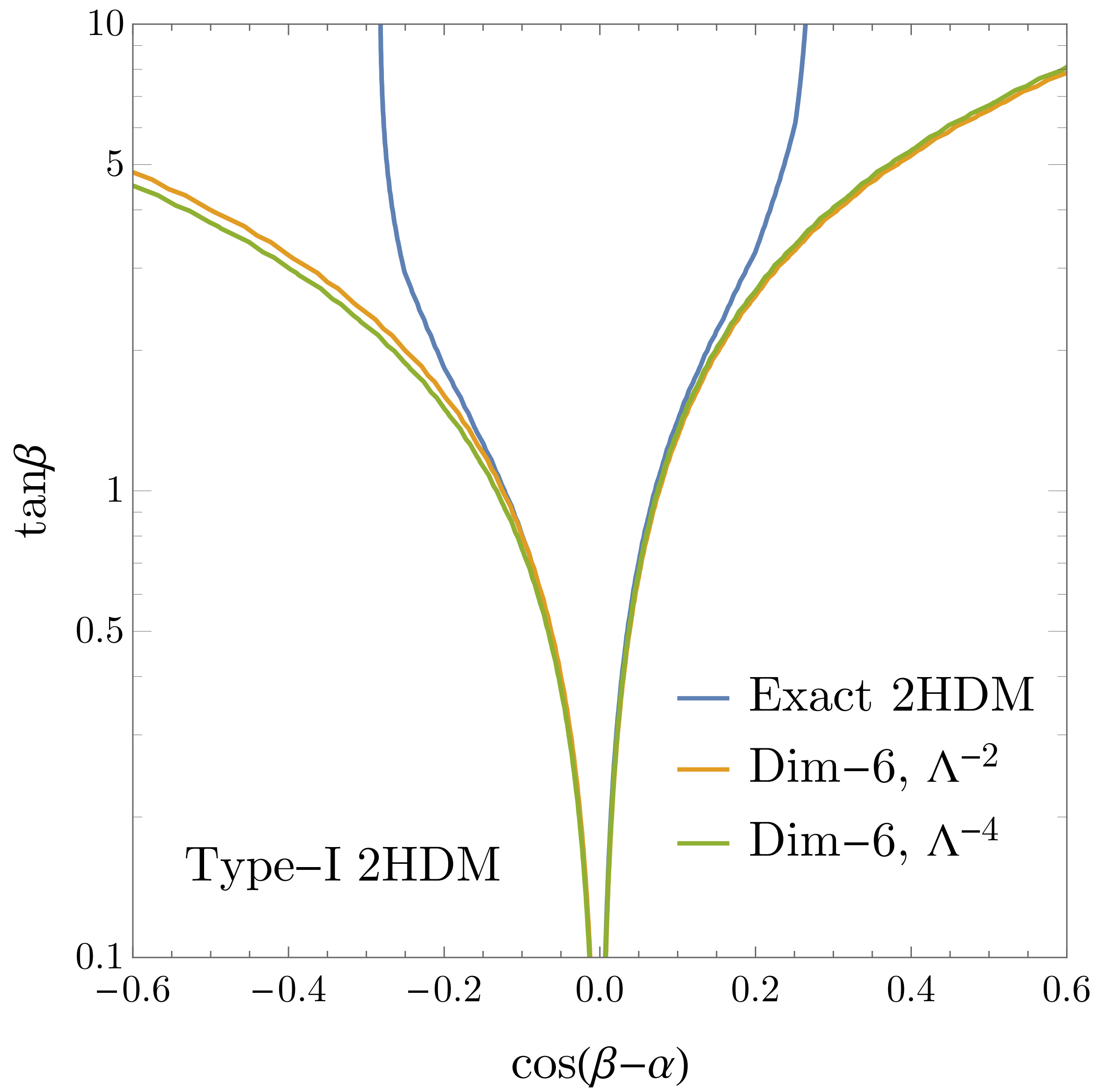
For large $\tan\beta$, approaches the SM!

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

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



λ_{hhh} Constraints are Important!

At dimension-6, the leading constraints for large $\tan\beta$ come from information about the Higgs self coupling encoded in C_H

Use indirect bounds from single-Higgs measurements based on [arXiv:1607.04251]
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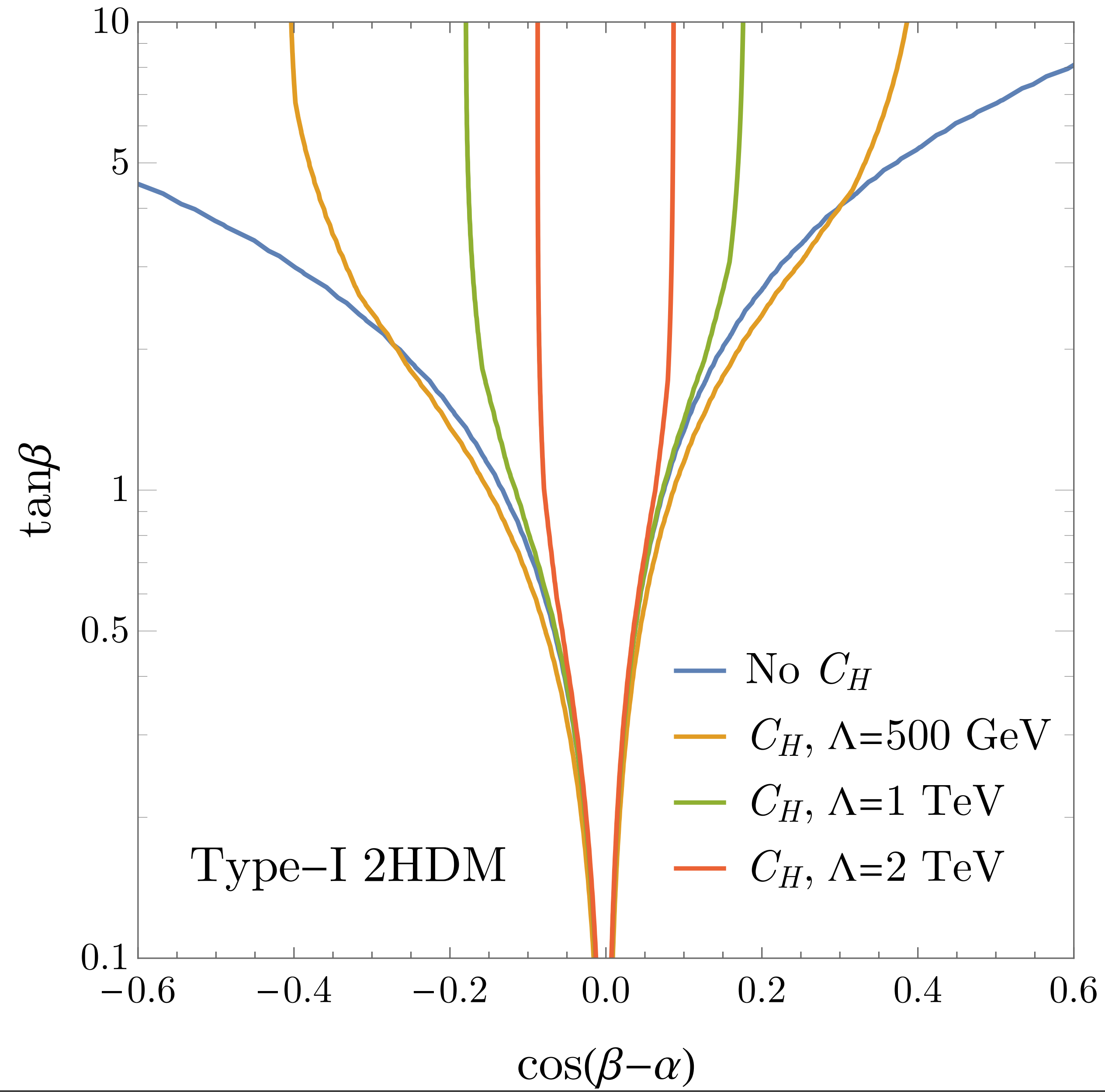


Matching the 2HDM to Dimension-8

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

Gauge coupling modifications make it clear matching to dimension-8 is important.

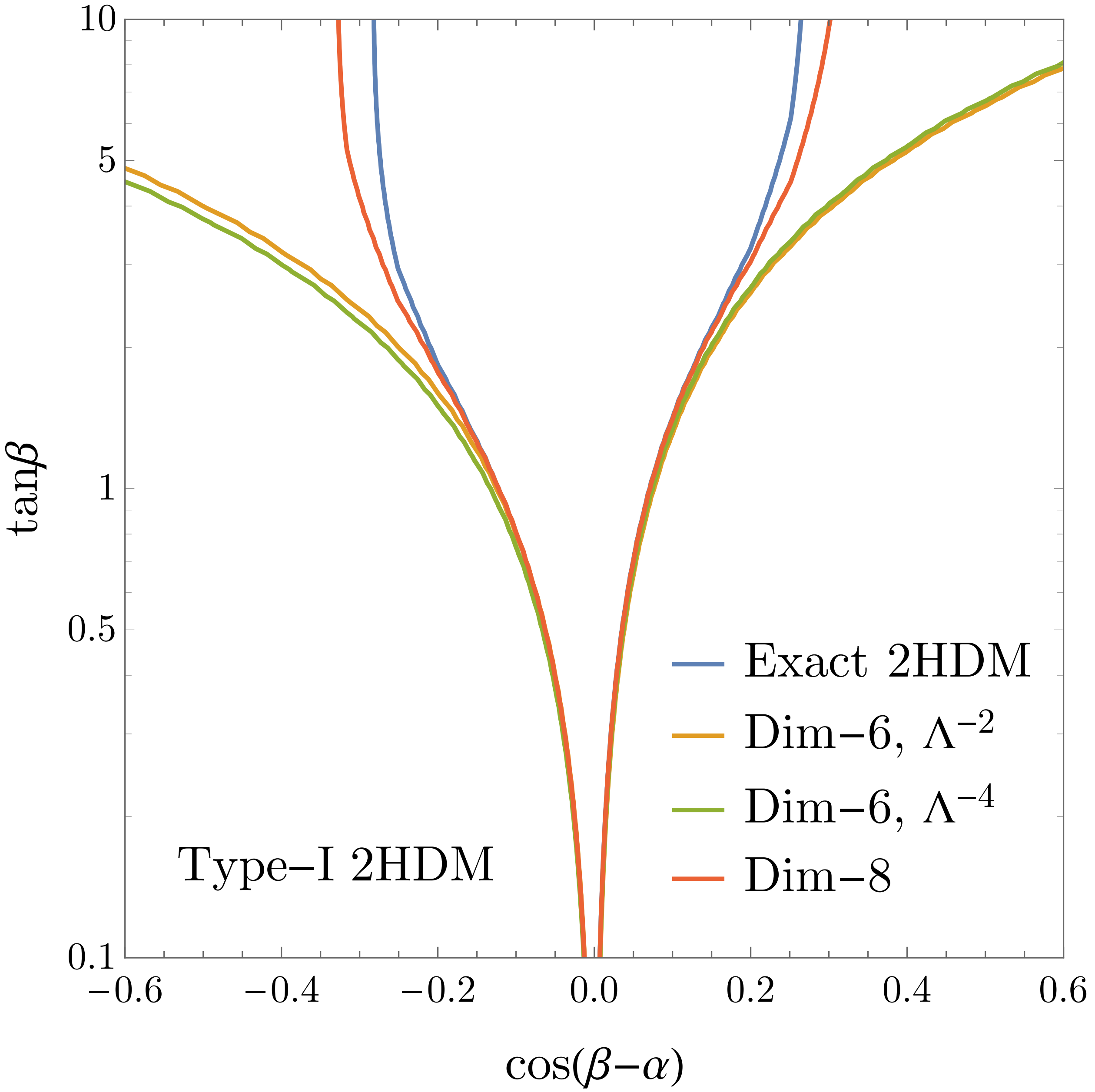
Perform complete matching of the 2HDM to dimension-8, and write operators in terms of "Murphy basis" in [2005.00059]

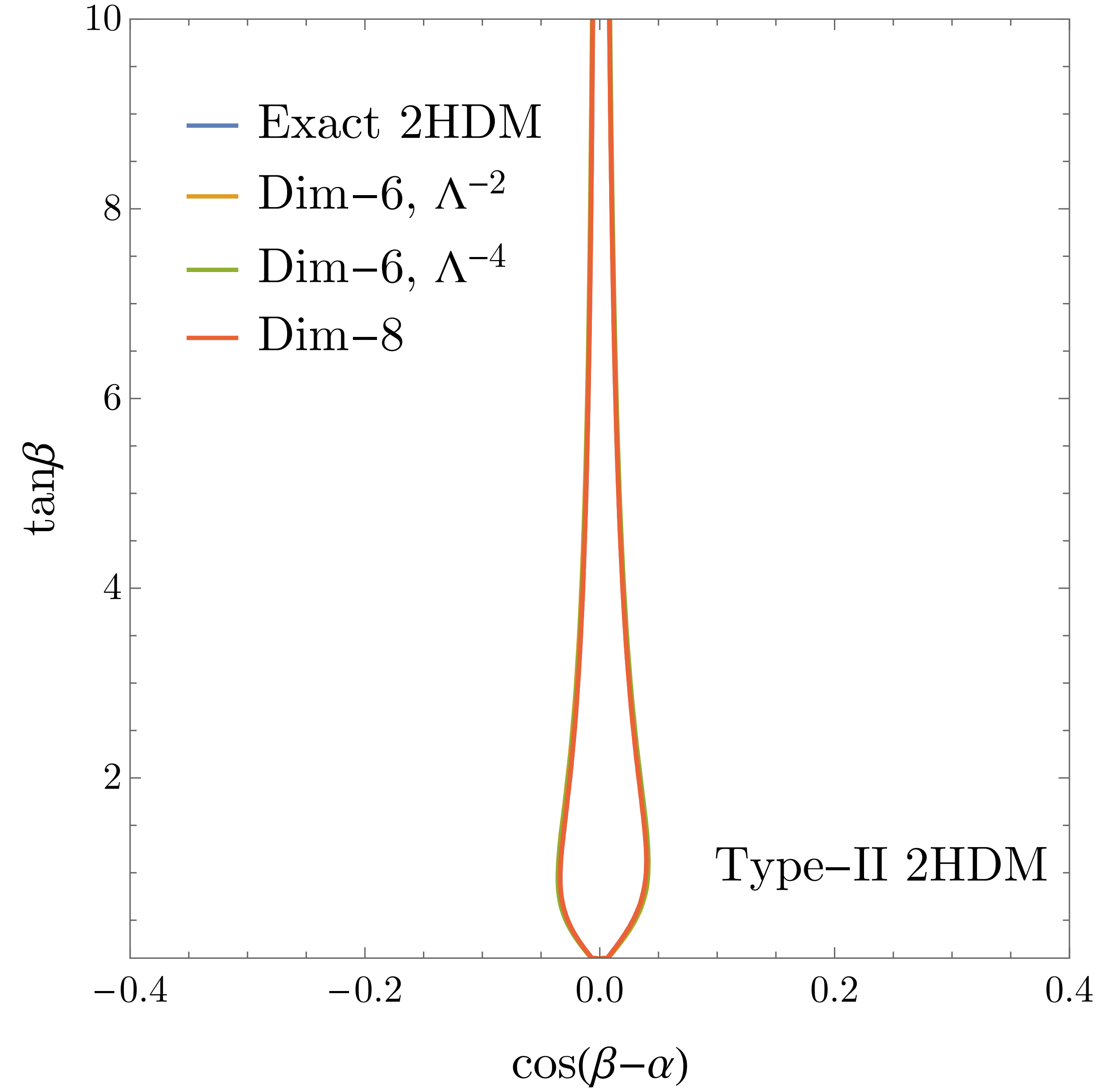
$$(D_\mu H^\dagger D^\mu H)(\bar{q}u\tilde{H}), \quad (D_\mu H^\dagger \tau^I D^\mu H)(\bar{q}u\tau^I \tilde{H}), \quad (D_\mu H^\dagger H)(\bar{q}uD^\mu \tilde{H})$$

$$(H^\dagger H)^2(\bar{q}u\tilde{H}), \qquad (H^\dagger H)^4$$

$$\mathcal{O}^{(1)}_{H^6} = (H^\dagger H)^2 (D_\mu H)^\dagger (D^\mu H), \quad C^{(1)}_{H^6} = -\frac{\Lambda^4}{v^4}\cos(\beta-\alpha)^2$$

Fit Results Including Dimension-8





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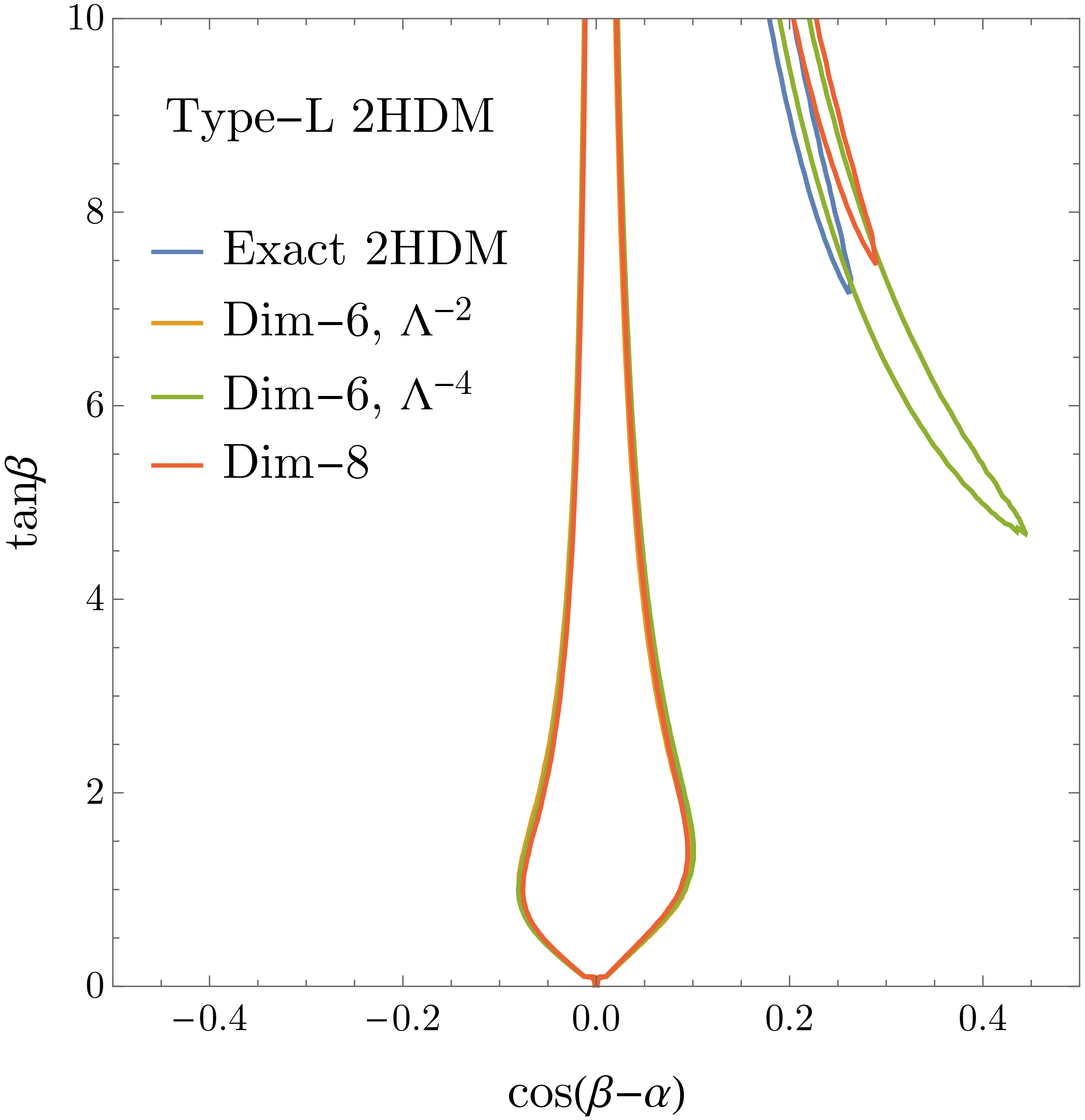

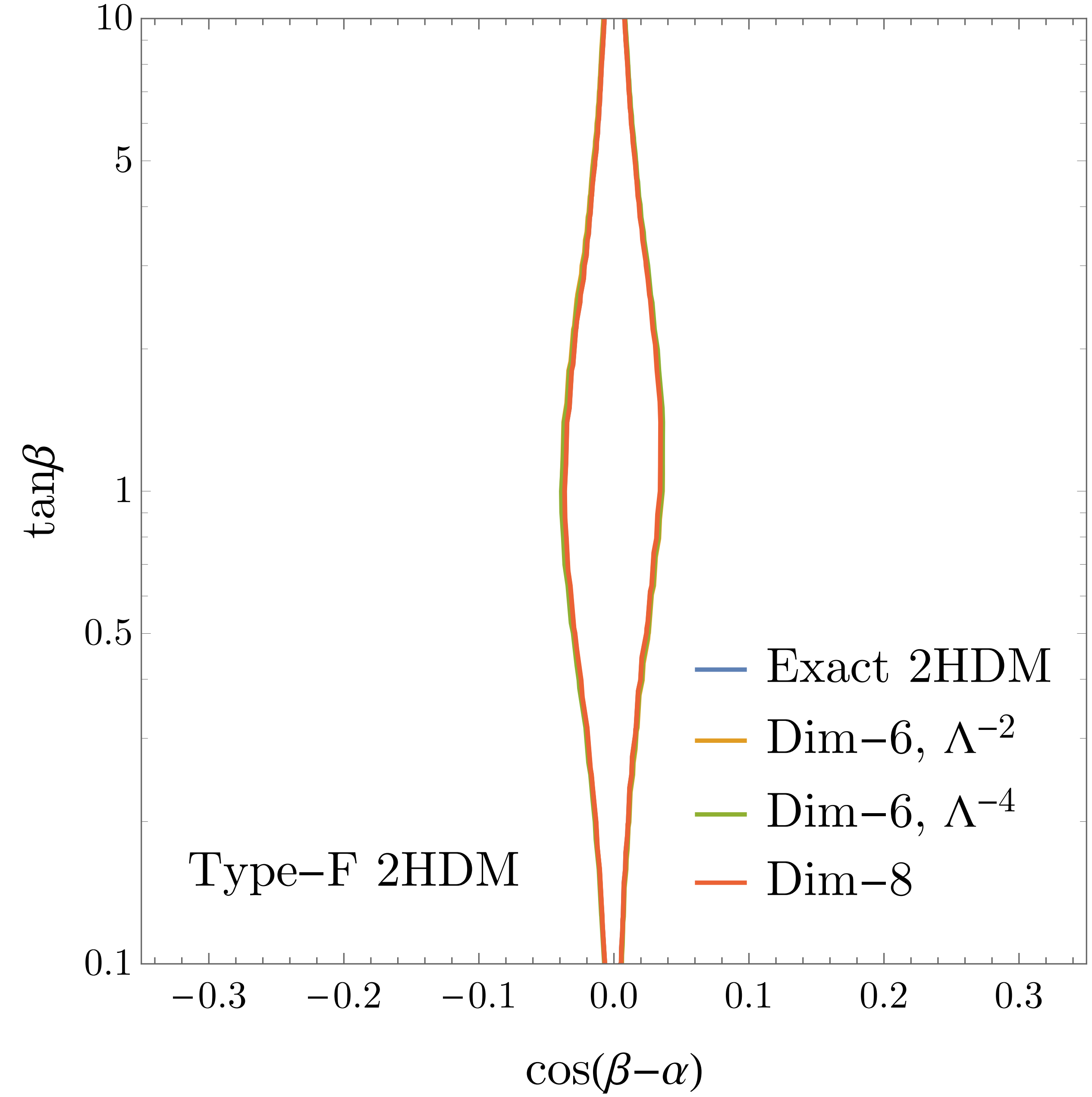

EFT of the 2HDM Summary

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

Rich structure of the 2HDM leads to interesting effects when interpreting SMEFT results:

- SMEFT formally valid only in the “alignment-limit”, requires light scales for large mixing angles
- “Wrong-sign” regions require going beyond $\mathcal{O}(\Lambda^{-2})$
- Gauge couplings only appear at dimension-8
- Self-coupling effects introduce a dependence on the heavy scale

Conclusions

- SMEFT Fits may be the "legacy" measurements of the LHC, but important to keep UV models in mind!
- Tree level interpretations of SMEFT Fits aren't the whole story! *RG evolution of coefficients is extremely important.*

Lots of other recent work on this topic!

See:

- Ellis, et al., [2012.02779]
- Das Bakshi, et al., [2012.03839]
- Marzocca, et al., [2009.01249]
- Brivio et al., [2108.01094]
- Almeida et al., [2108.04828],
- … and others!

- Considering explicit models lets us assess the importance of higher-order matching effects (1 loop, dim-8) in a concrete way.
- Higher order effects can change phenomenology / interpretation — what happens in even more complicated models?

Thanks for your attention!