EFT Complementarity & Relation to Underlying Models

Based on
arXiv:2007.01296, 2102.02823, 2110.06929, 2205.01561

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In collaboration with
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The SM Effective Field Theory (SMEFT)

In the absence of any signals, want to search for *indirect* signals of new physics in Standard Model processes.

Calls for an effective field theory approach:

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

Built-in assumptions:

- New physics at a scale $\sim \Lambda \gg E, v$
- Electroweak Symmetry Breaking is *linearly* realized (Higgs is an SU(2) doublet)

The SM Effective Field Theory (SMEFT)

arXiv:1008.4884, Grzadkowski, et. al — the Warsaw Basis

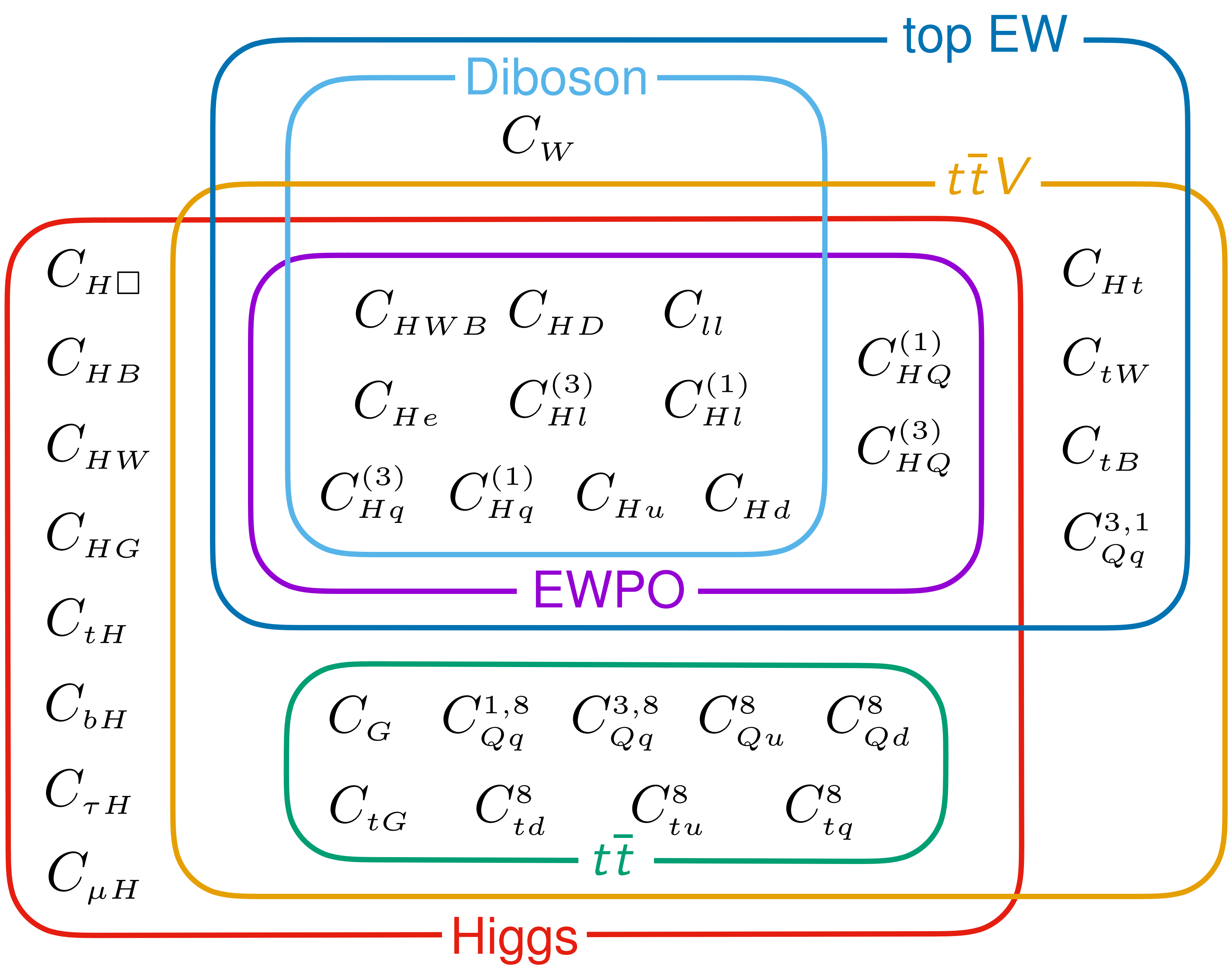
Complete (non-redundant) basis of effective operators exists:

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

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

Recently enumerated at dimension-8 as well:
Li et al [2005.00008] + Murphy [2005.00059]

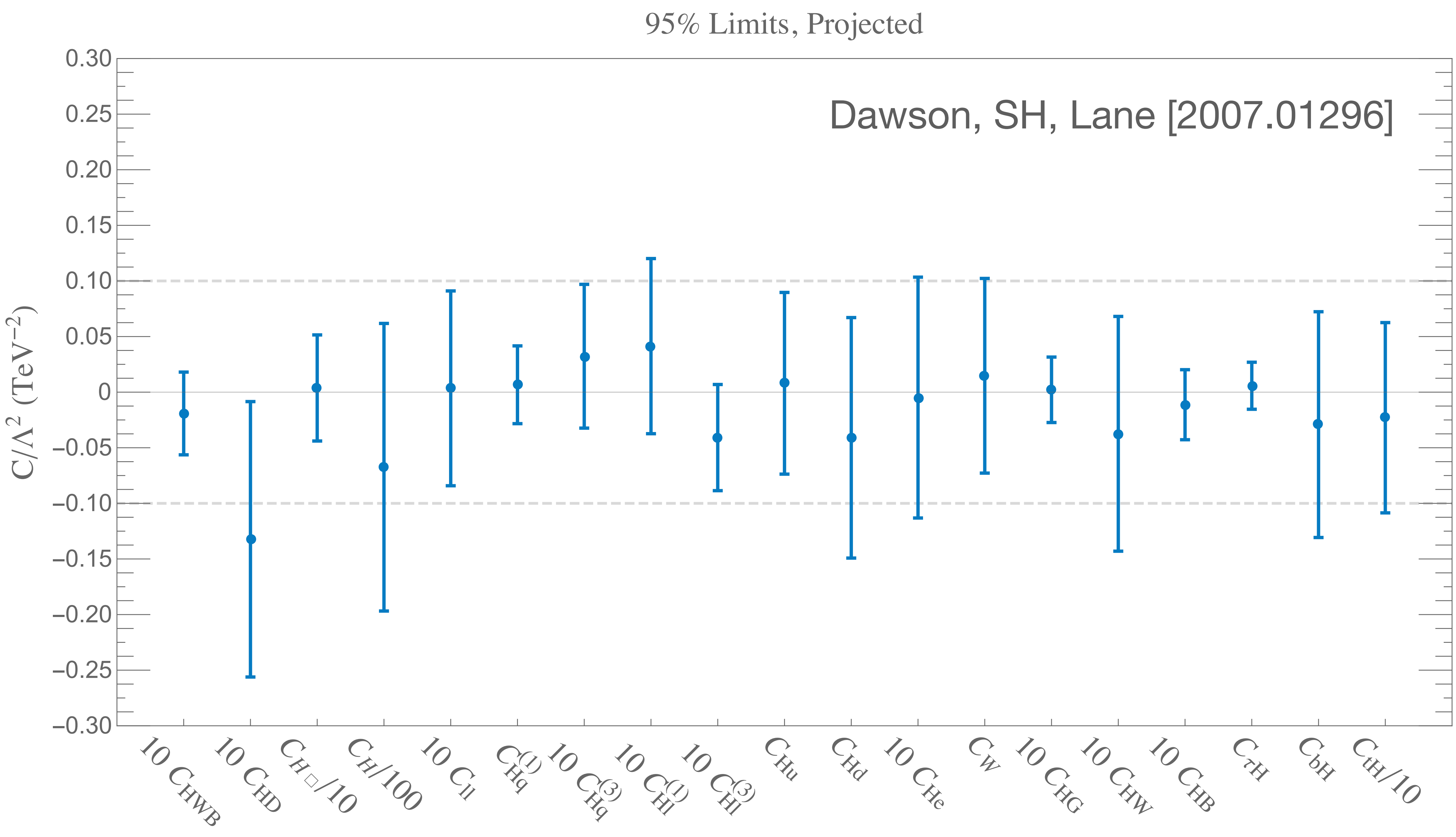
Complementarity in the SMEFT



Ellis, et al [2012.02779]

Measurements in different channels can be *consistently* combined in a “model-agnostic” way.

Combine into Global Fits:



See also 1803.03252, 1812.01009, 1910.14012, 1911.07866, 2012.02779, 2105.00006, …

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.**

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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

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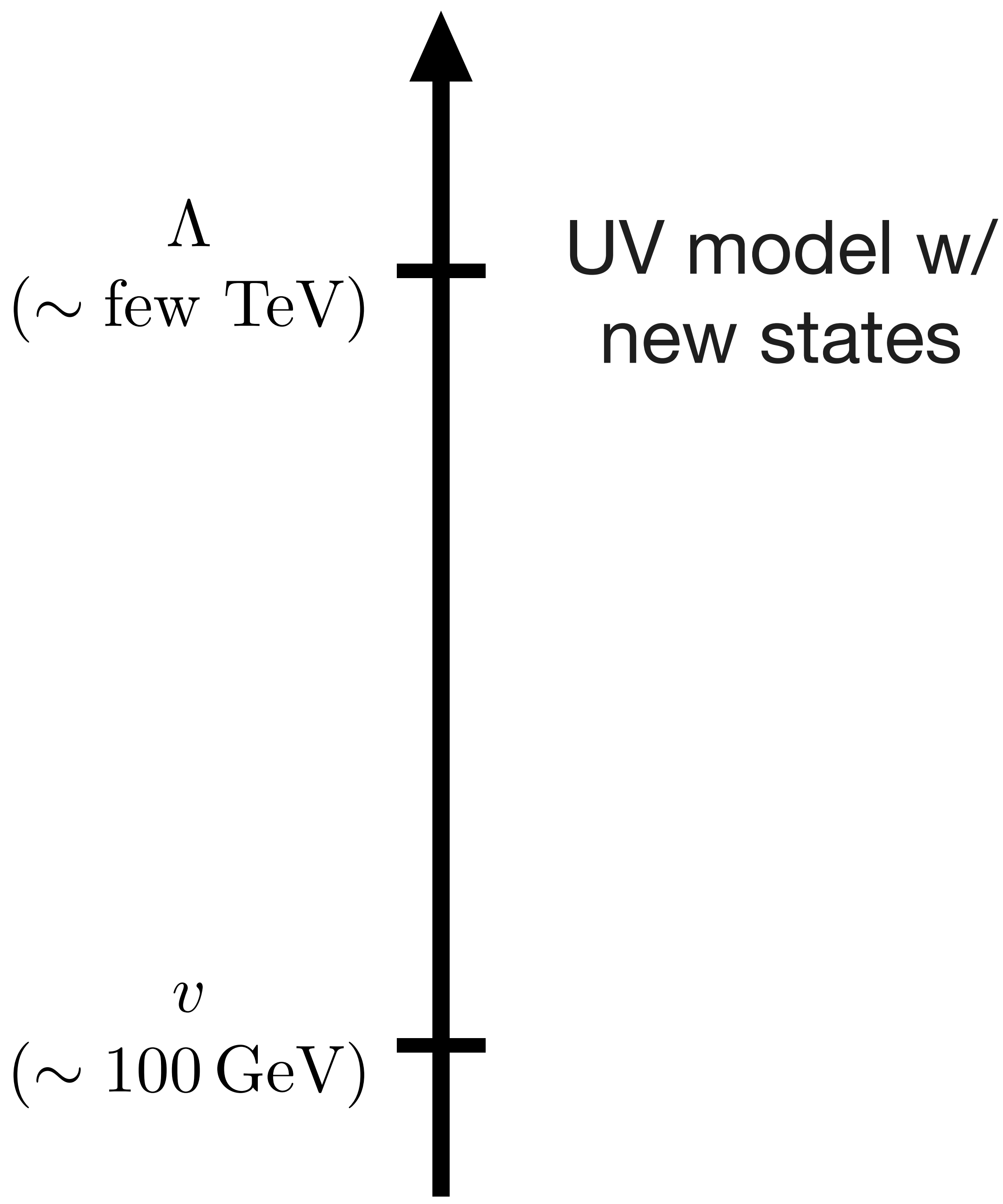
These questions are best studied in examples!

Interpreting Models in the SMEFT



Interpreting Models in the SMEFT

Matching with Covariant Derivative Expansion / UOLEA
(M. K. Gaillard, NPB 268 (1986)
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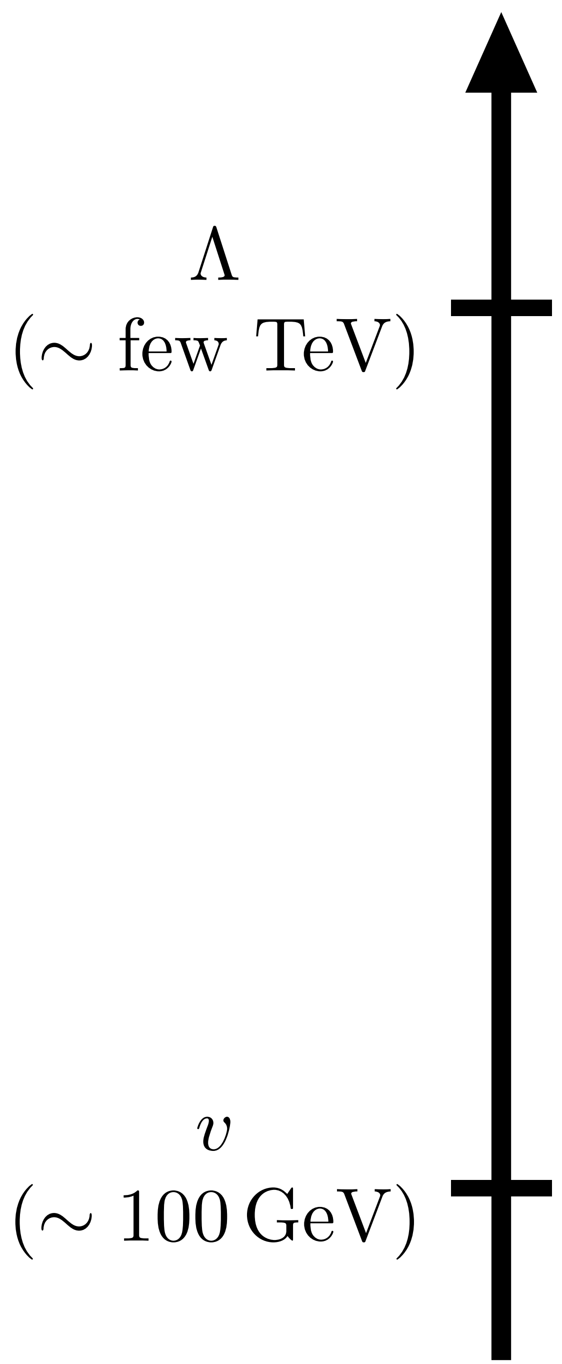

UV model w/ new states → Subset of EFT coefficients $C_i(\Lambda)$

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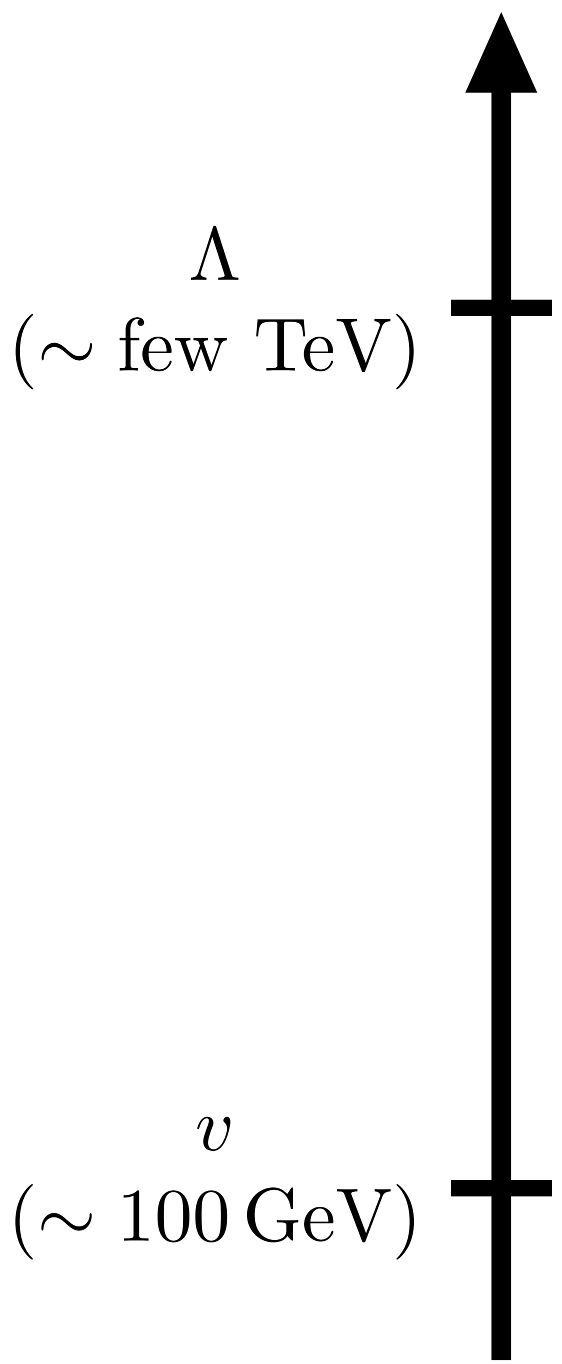

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RG Evolution to EW scale
(using anomalous dimensions given in Trott et. Al, 1308.2627+)

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$C_j(m_W)$

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Λ
$(\sim \text{few TeV})$

UV model w/ new states → Subset of EFT coefficients $C_i(\Lambda)$

RG Evolution to EW scale
(using anomalous dimensions given in Trott et. Al, 1308.2627+)

↓

v
$(\sim 100\,\text{GeV})$

Fit to experimental data at LHC, LEP ← $C_j(m_W)$

Computing observables in SMEFT using suite of available tools (SMEFTsim, SMEFT@NLO, …)

Matching Models to SMEFT

This process is systematic, and can be automated!
Lots of tools have been developed in the past few years:

(Apologies for any I have missed!)

Dictionaries:

- Tree-level: De Blas, Criado, Perez-Victoria, Santiago [1711.10391]
- Including one-loop: Guedes, Olgoso, Santiago [2303.16965]

Matching Tools:

- CoDEx (Das Bakshi, Chakrabortty, Kumar Patra [1808.04403])
- Matchete (Fuentes-Martín, König, Pagès, Thomsen, Wilsch [2212.04510]
  - Matchmakereft (Carmona, Lazopoulos, Oleoso, Santiago [2112.10787])

And many other advances in understanding
(see e.g., 2001.00017, 2110.02967, 2112.12724 , 2302.03485, …)

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Extend Standard Model with gauge-singlet scalar that mixes with the Higgs

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

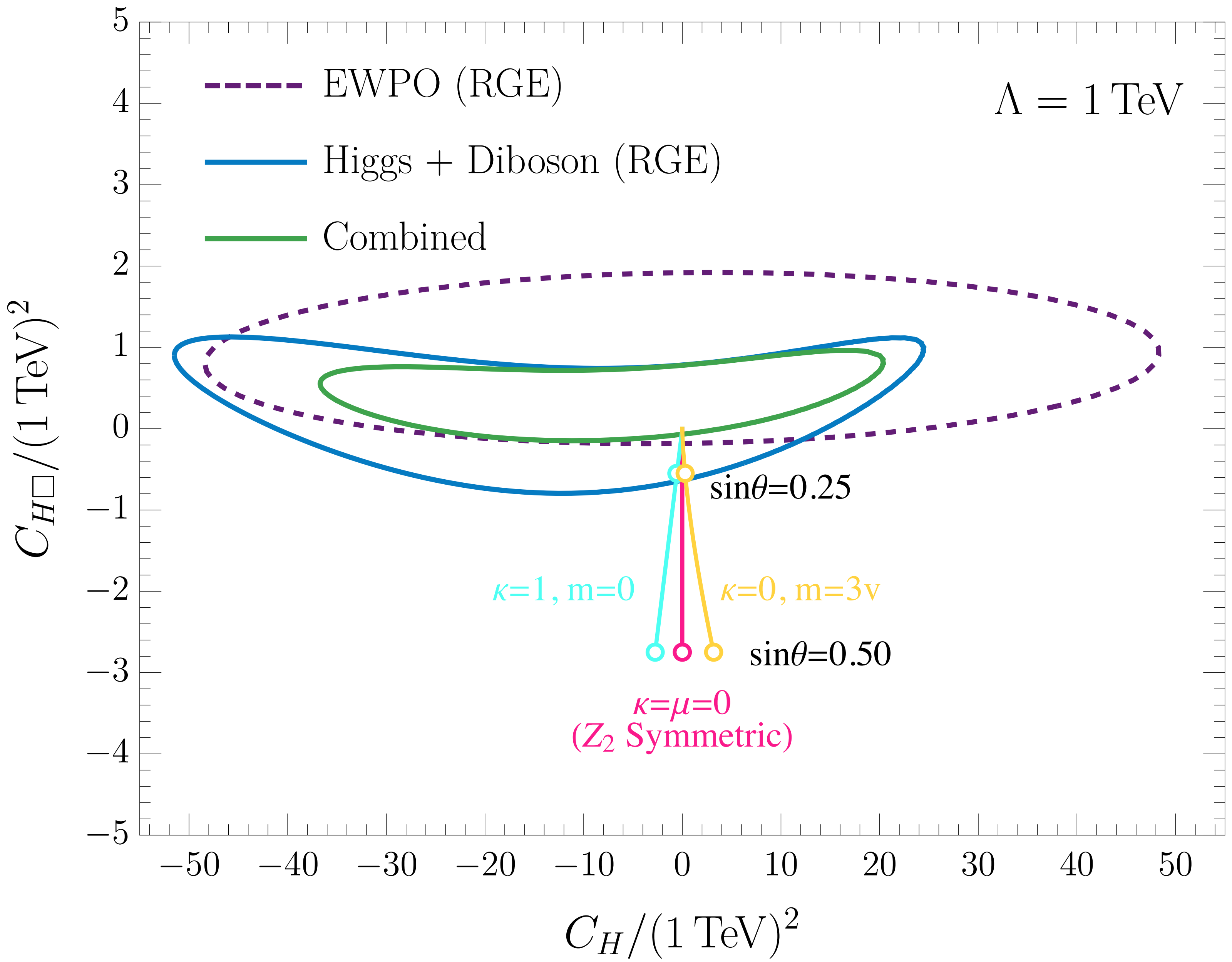
$$M^2 = m_h^2 \sin^2\theta + M_H^2 \cos^2\theta - \frac{\kappa}{2} v^2$$

Two coefficients are generated at tree-level:

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

Singlet Matching to SMEFT

Fit Results in Space of Wilson Coefficients



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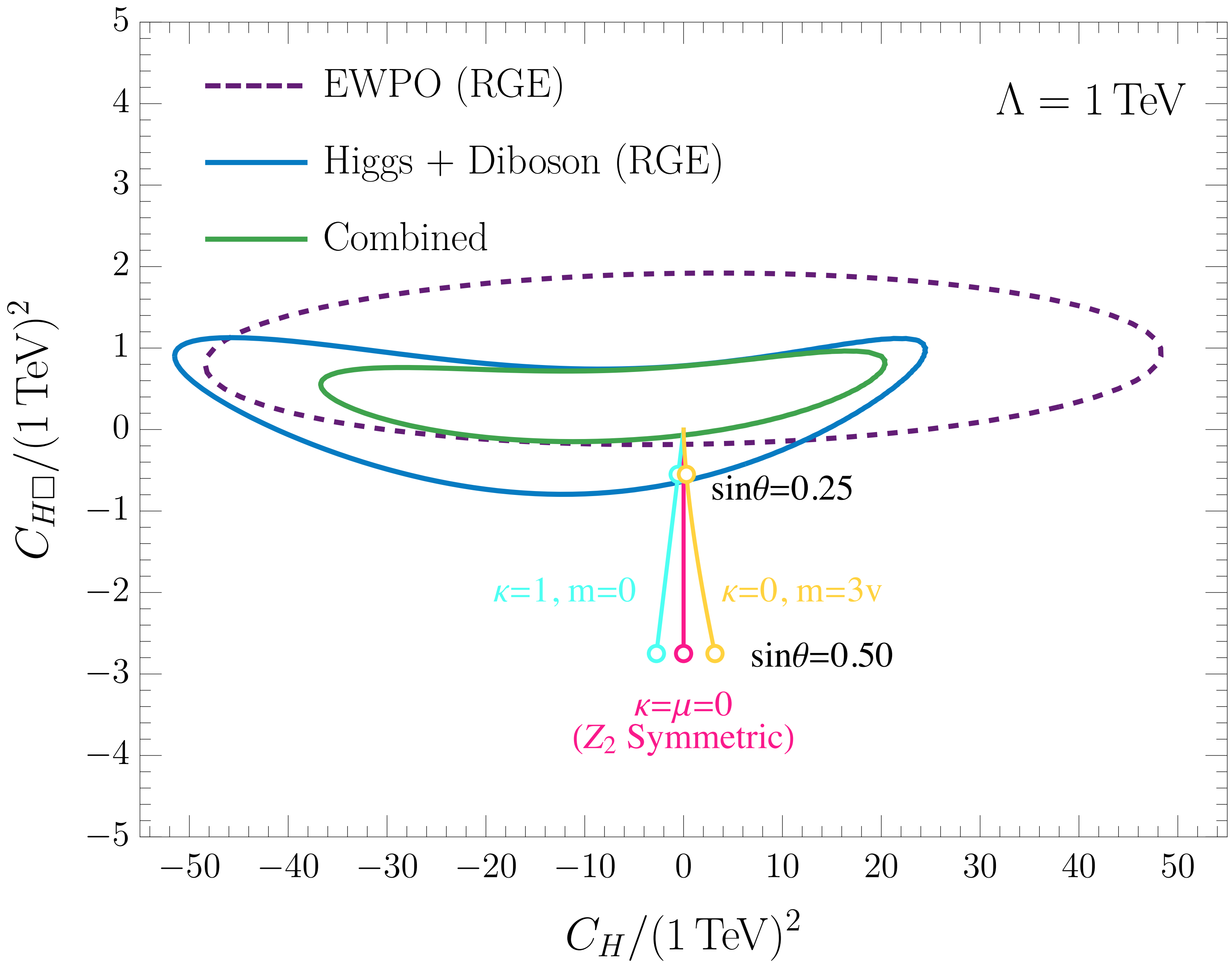

EW Precision Constraints (from M_W) arise from operators generated by the RGEs!

Includes

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

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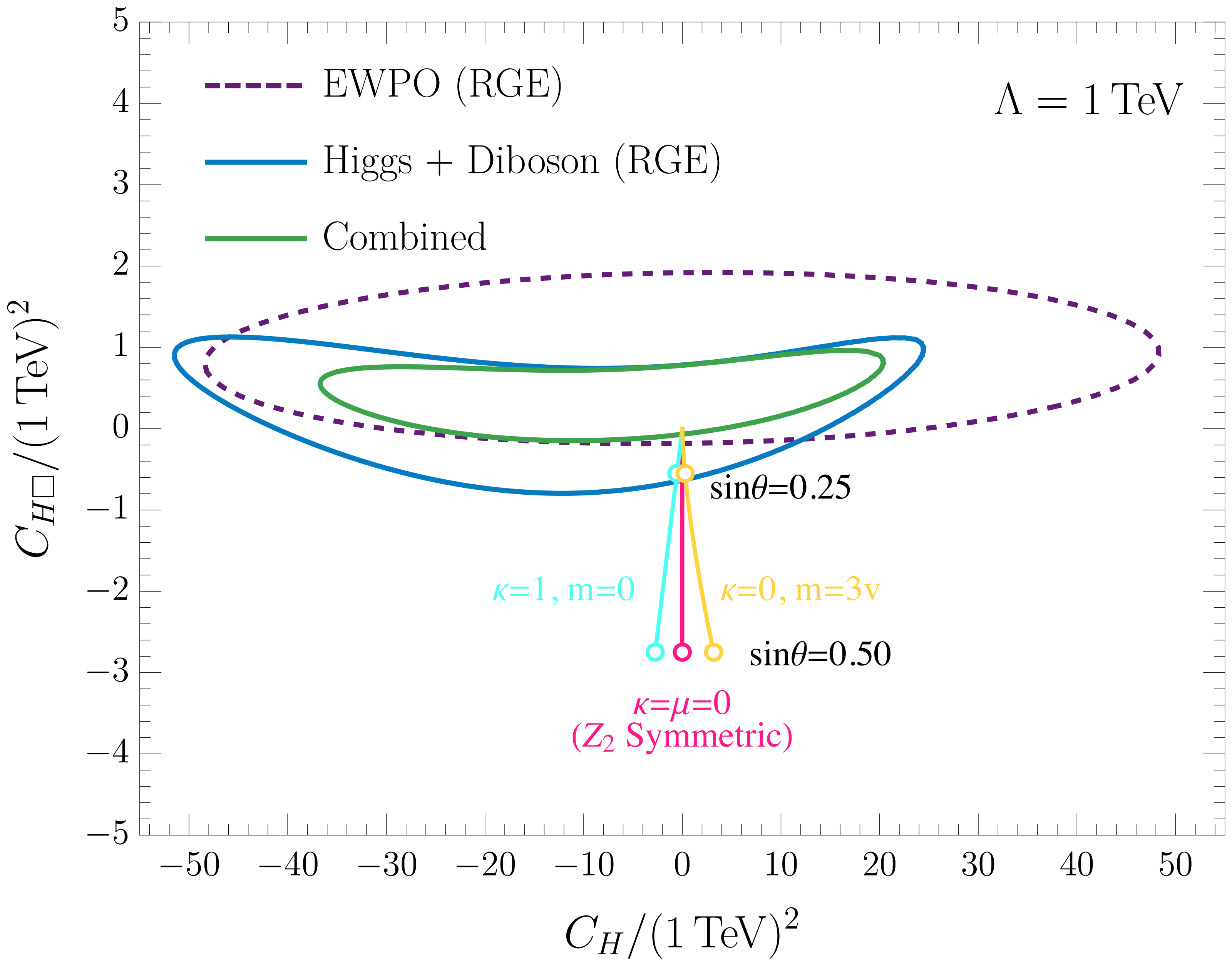

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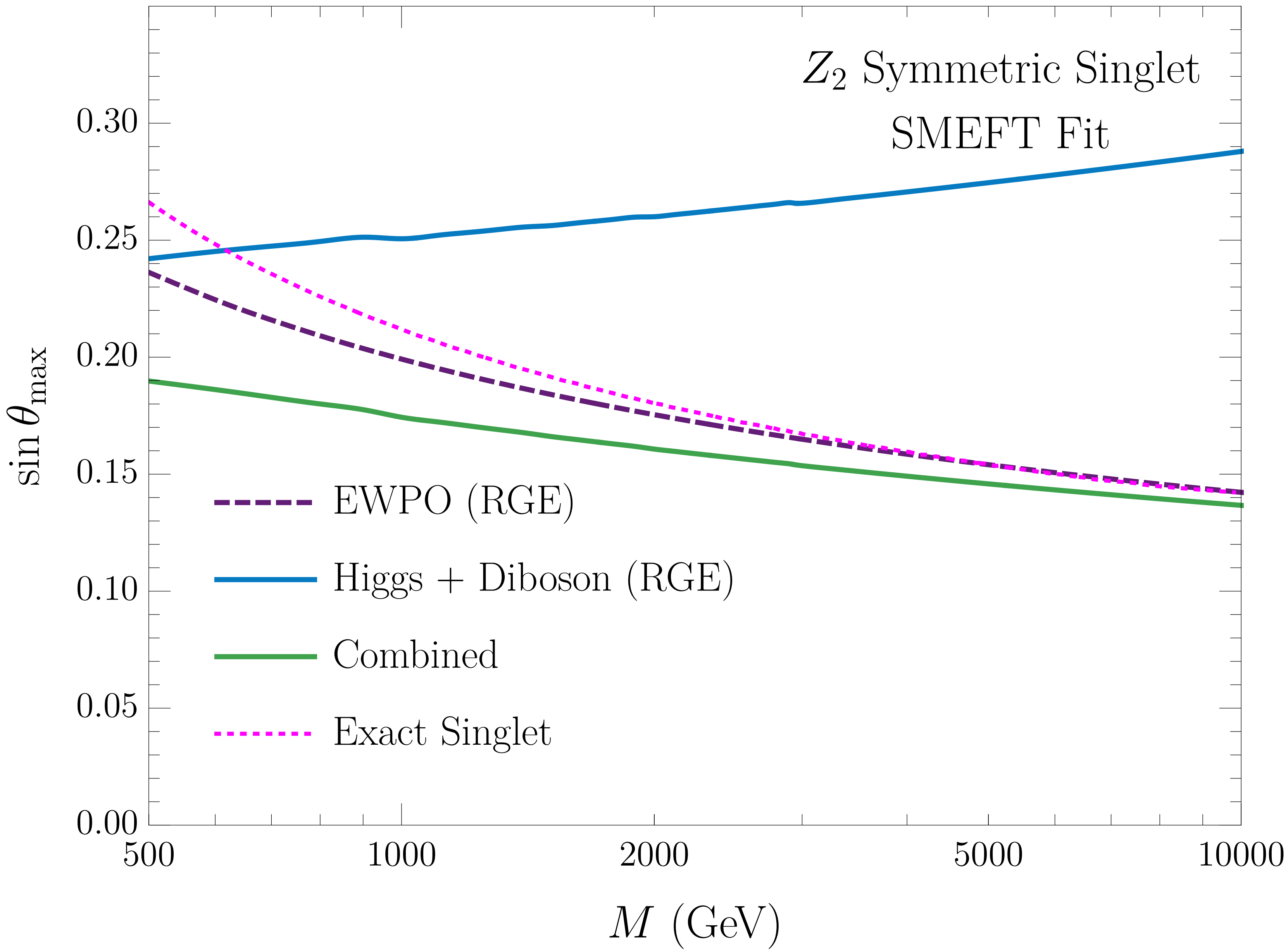
Limits from the LHC and EWPO are competitive, and complementary (but most of allowed parameter space is not generated in the model)

Singlet Matching to SMEFT

Bounds on Wilson Coefficients can be translated into bounds on model parameters:



Singlet Matching to SMEFT at One Loop

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

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

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

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

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

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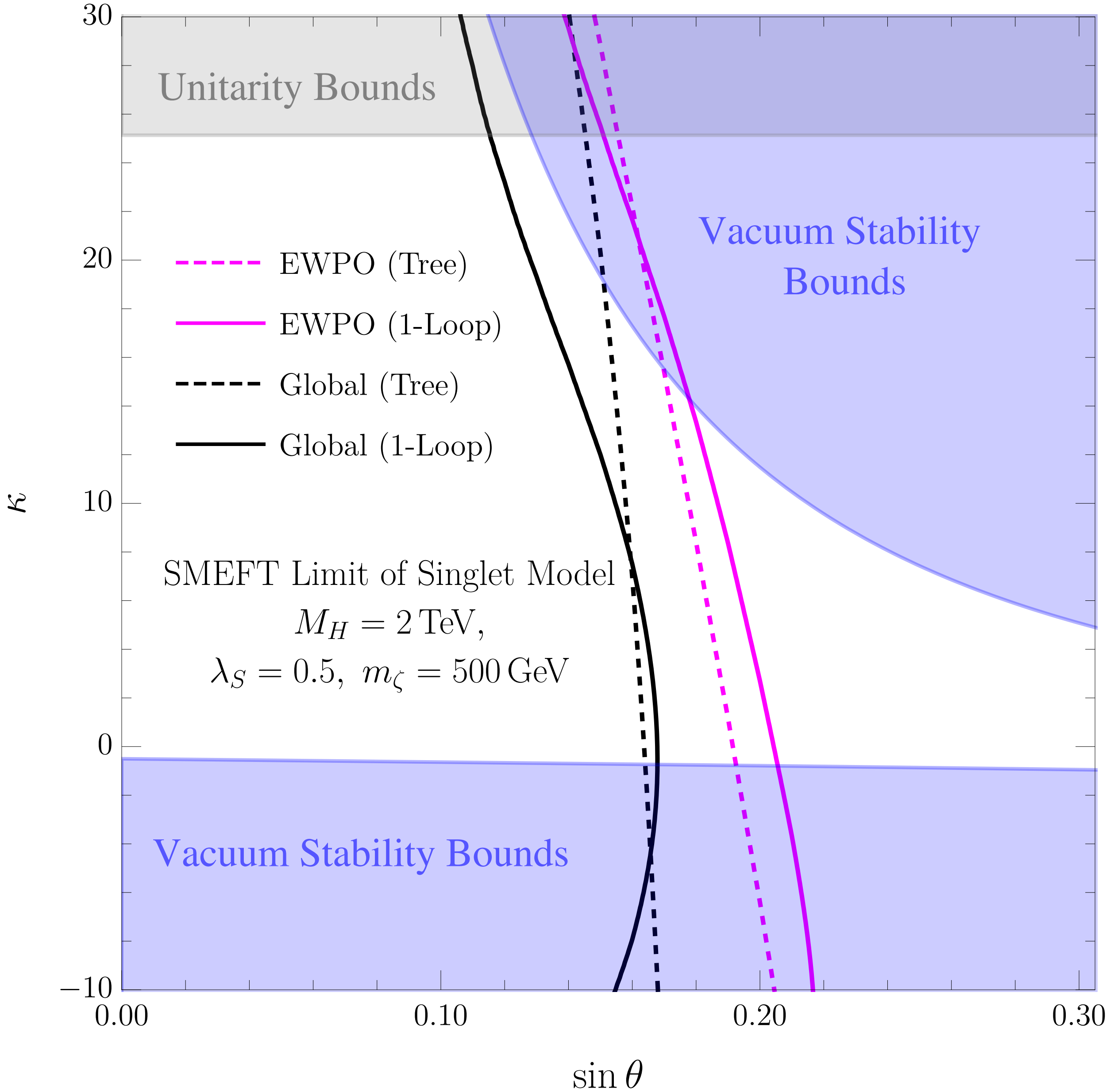
…as well as many operators that don't appear at tree-level:

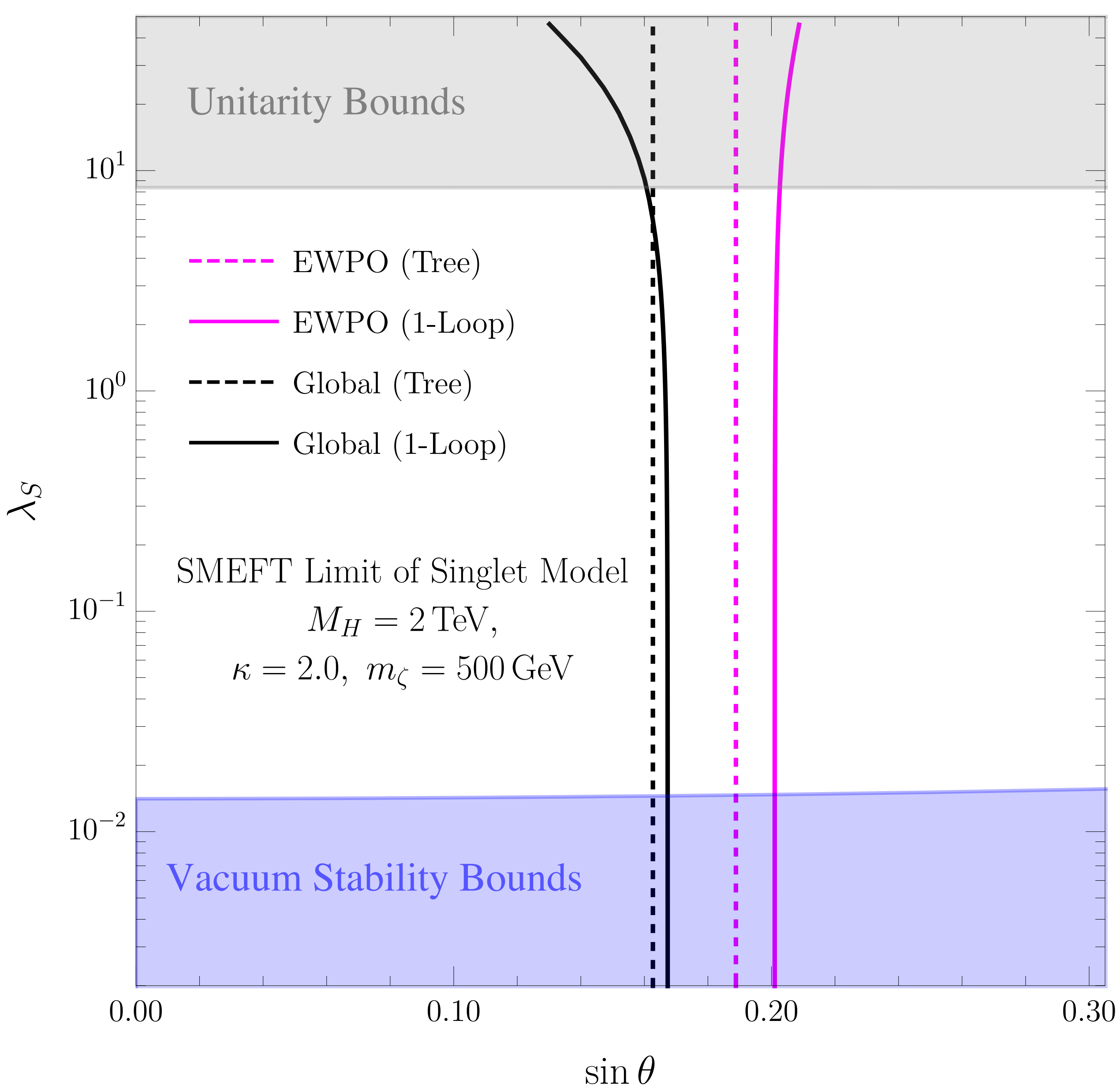
$$C_{HD},\ C_{HW},\ C_{HB},\ C_{HWB},\ C_{Hu},\ C_{Hd},\ C_{Hq}^{(1)},\ C_{Hq}^{(3)},\ C_{Hl}^{(3)},\ C_{tH}$$

In principle of comparable size to RGE-induced contribution!

Singlet Matching to SMEFT at One-Loop

Straightforward to implement in existing SMEFT Fit:





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

Singlet Matching to SMEFT at One-Loop

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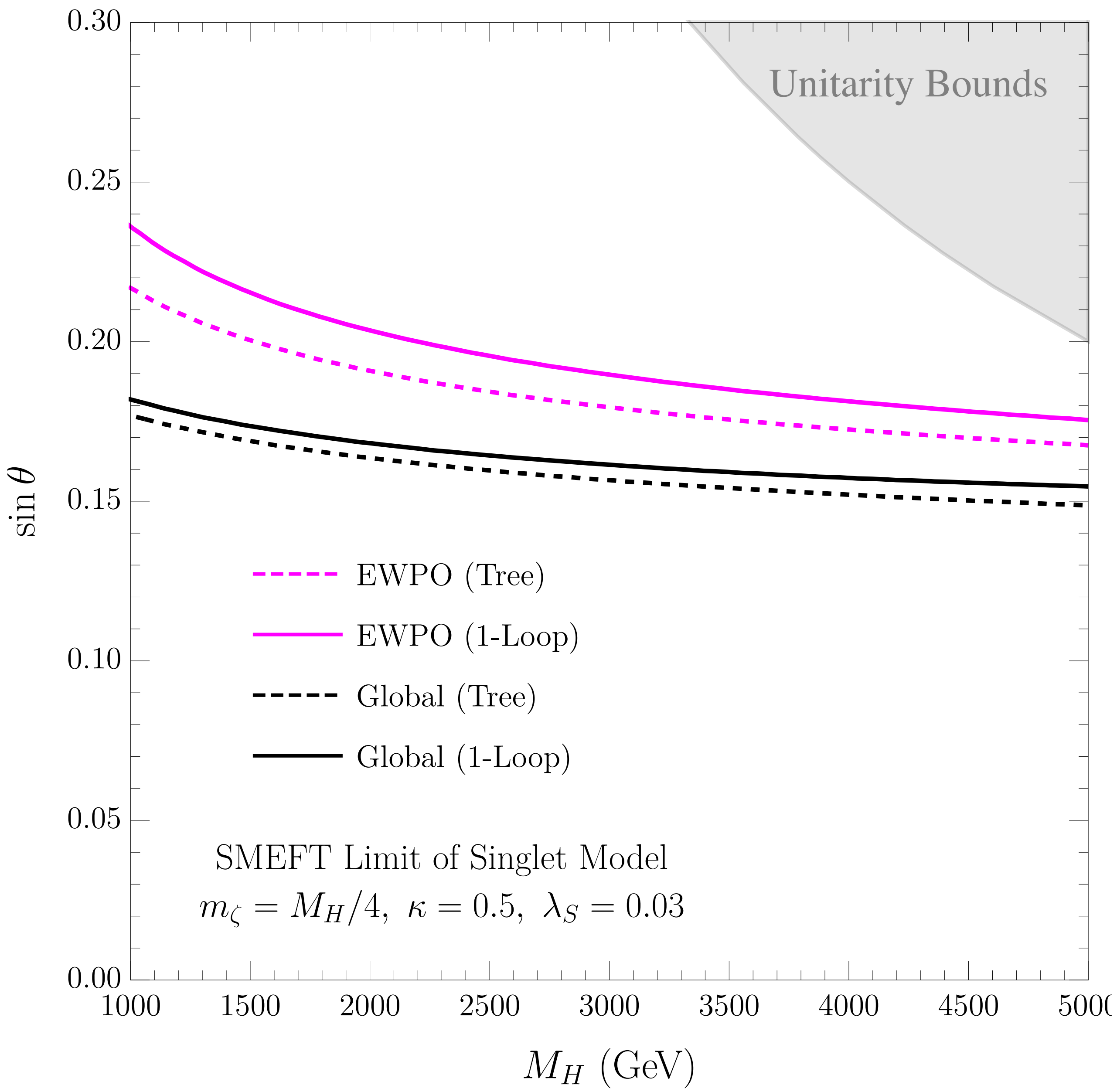

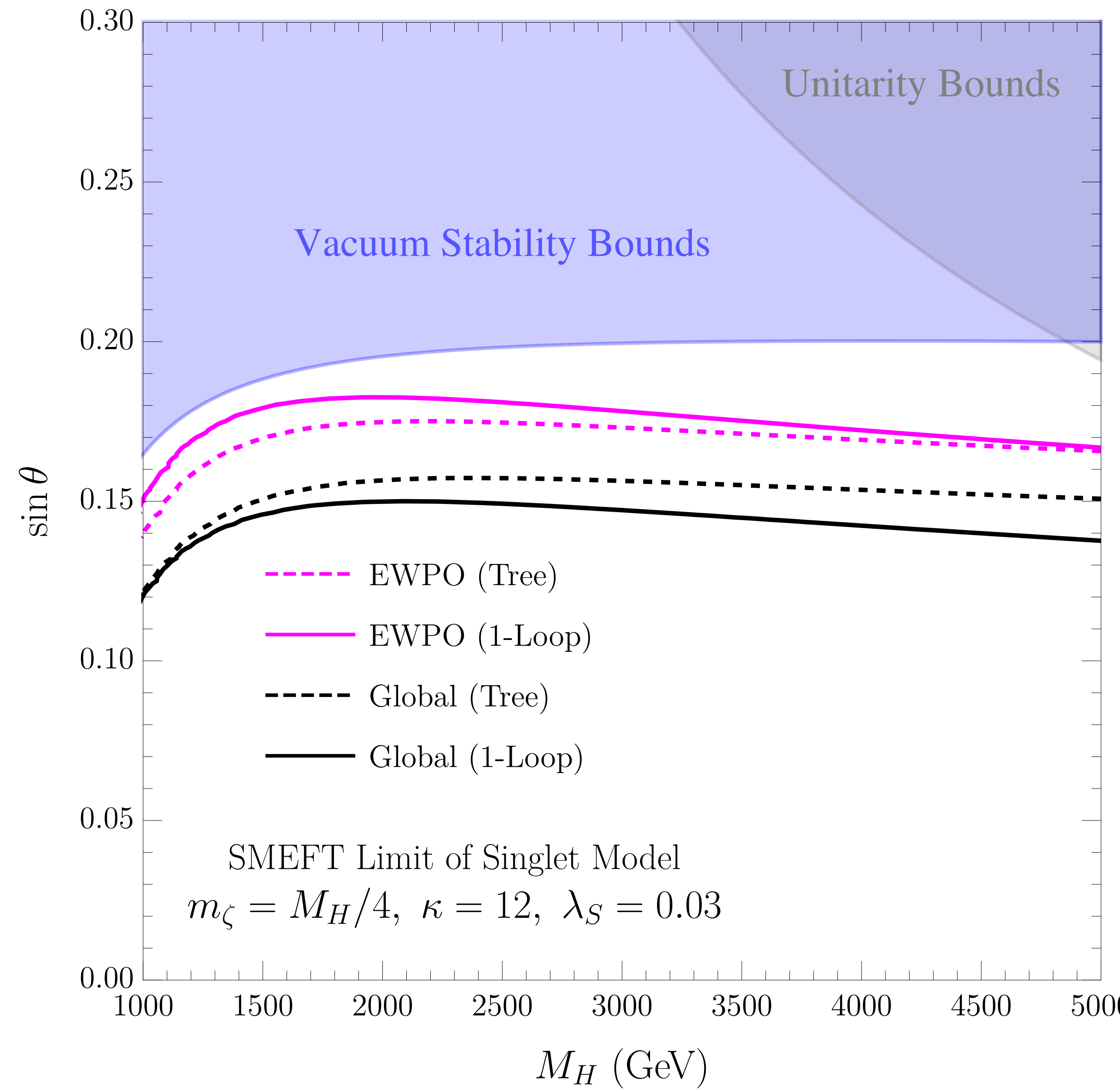

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Example 2: Vector-like Tops

Extend the SM with a pair of SU(2) singlet, $Q = 2/3$, vector-like quarks (VLQs):

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Diagonalize the left- and right-handed tops to find physical eigenstates with masses m_t $(= 173\,\text{GeV})$, M_T

$$\begin{pmatrix} t \\ T \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\theta_{L,R} & -\sin\theta_{L,R} \\ \sin\theta_{L,R} & \cos\theta_{L,R} \end{pmatrix} \begin{pmatrix} \mathcal{T}^1 \\ \mathcal{T}^2 \end{pmatrix}_{L,R}$$

$$\tan\theta_R = \frac{m_t}{M_T}\tan\theta_L$$

Three physical parameters: $m_t, M_T, \sin\theta_L$

(Alternatively, $\lambda_t,\ \lambda_T,\ m_{\mathcal{T}}$)

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(Alternatively, $\lambda_t,\ \lambda_T,\ m_{\mathcal{T}}$)

Note: expansions in M_T and $m_{\mathcal{T}}$ have different counting in inverse mass dimension for fixed $\sin\theta_L$

$$\frac{1}{m_{\mathcal{T}}^2} = \frac{1}{M_T^2} + \frac{s_L^2}{M_T^2}\left(1 - \frac{m_t^2}{M_T^2}\right)$$

Top VLQ Matching to SMEFT

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{i\lambda_T^2}{4m_{\mathcal{T}}^2}\left(\mathcal{O}_{Ht}^{1,(6)} - \mathcal{O}_{Ht}^{3,(6)}\right) + \frac{\lambda_t \lambda_T^2}{2m_{\mathcal{T}}^2}\mathcal{O}_{tH}^{(6)}$$

Note: all dim-6 corrections scale like $(\lambda_T / m_{\mathcal{T}})^2$!

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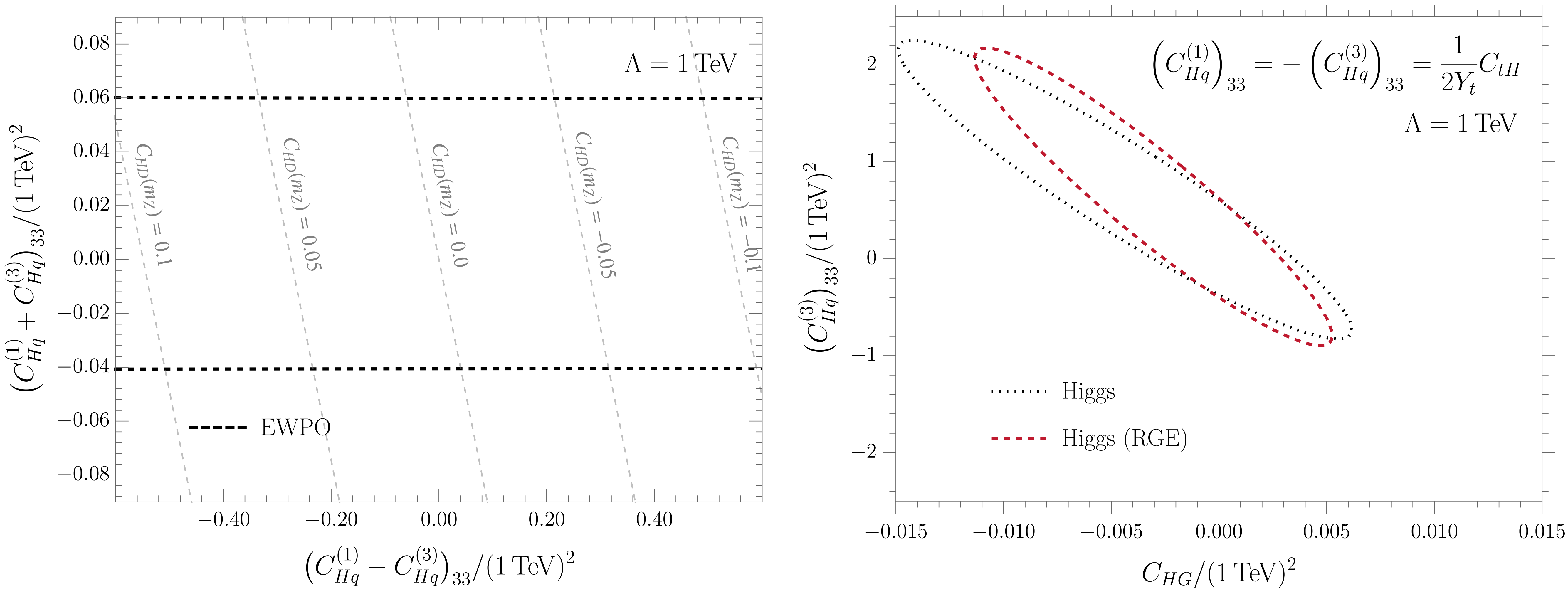

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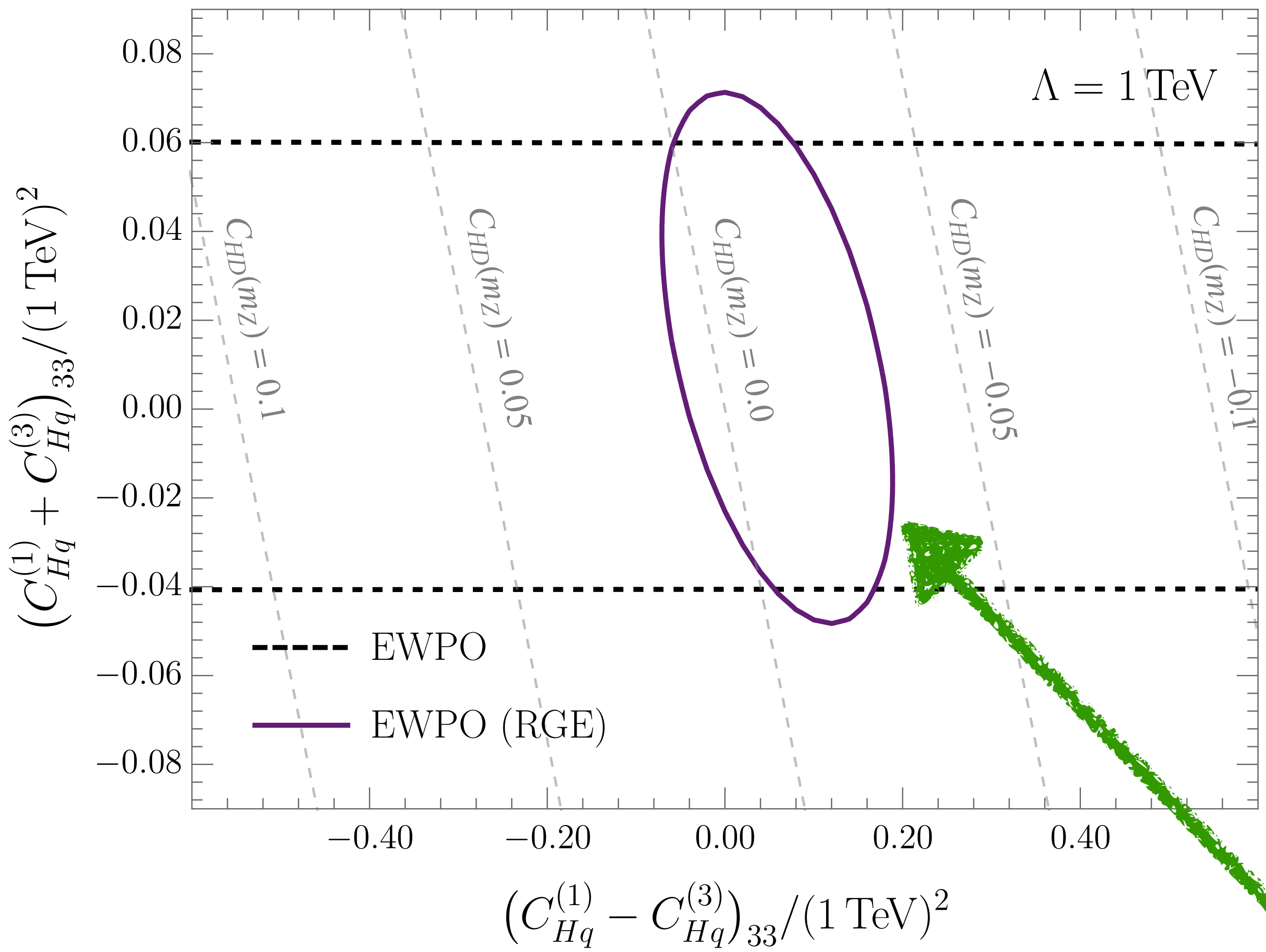

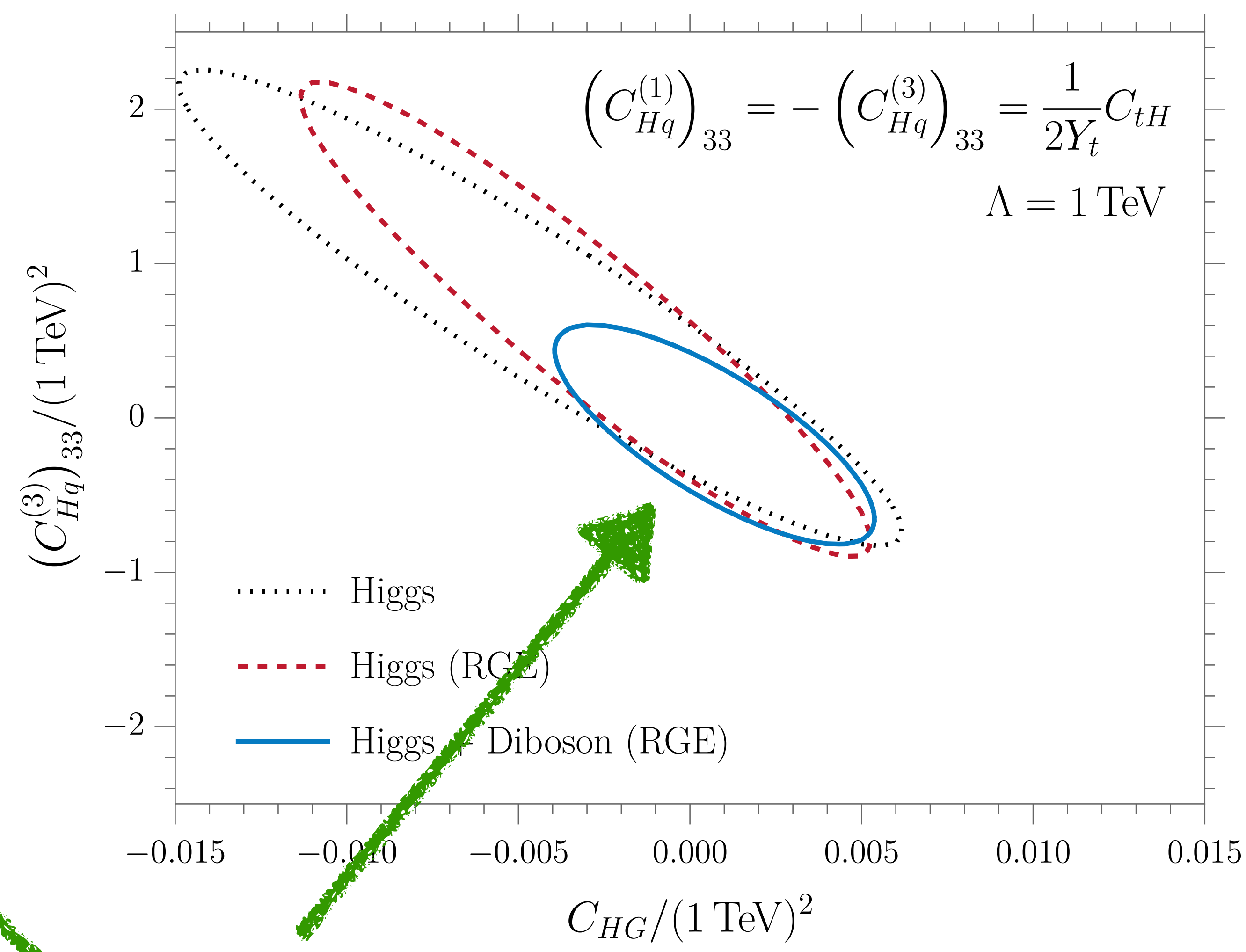

RG-induced contributions break flat direction in EWPO, and lead to Diboson constraints

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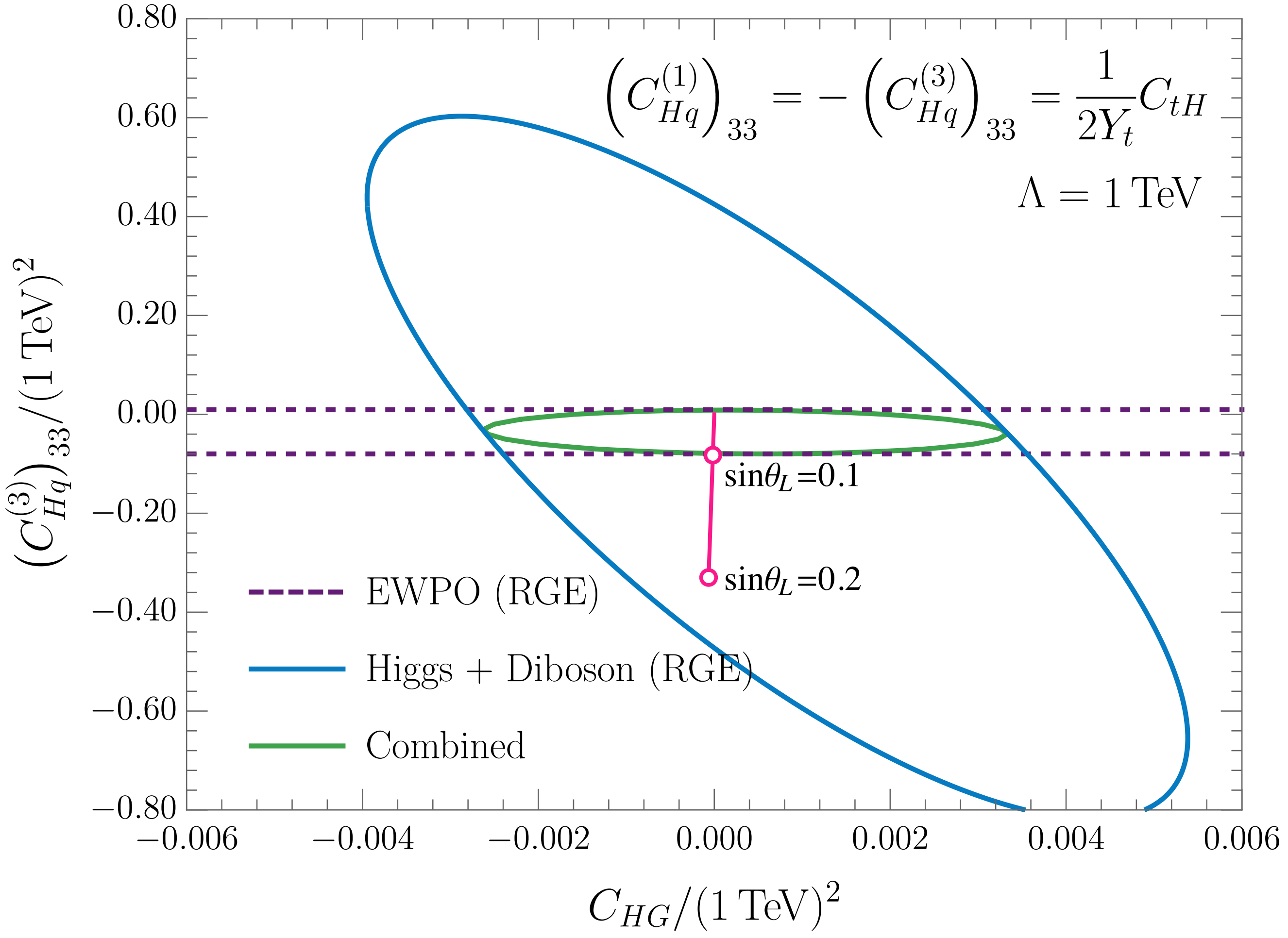

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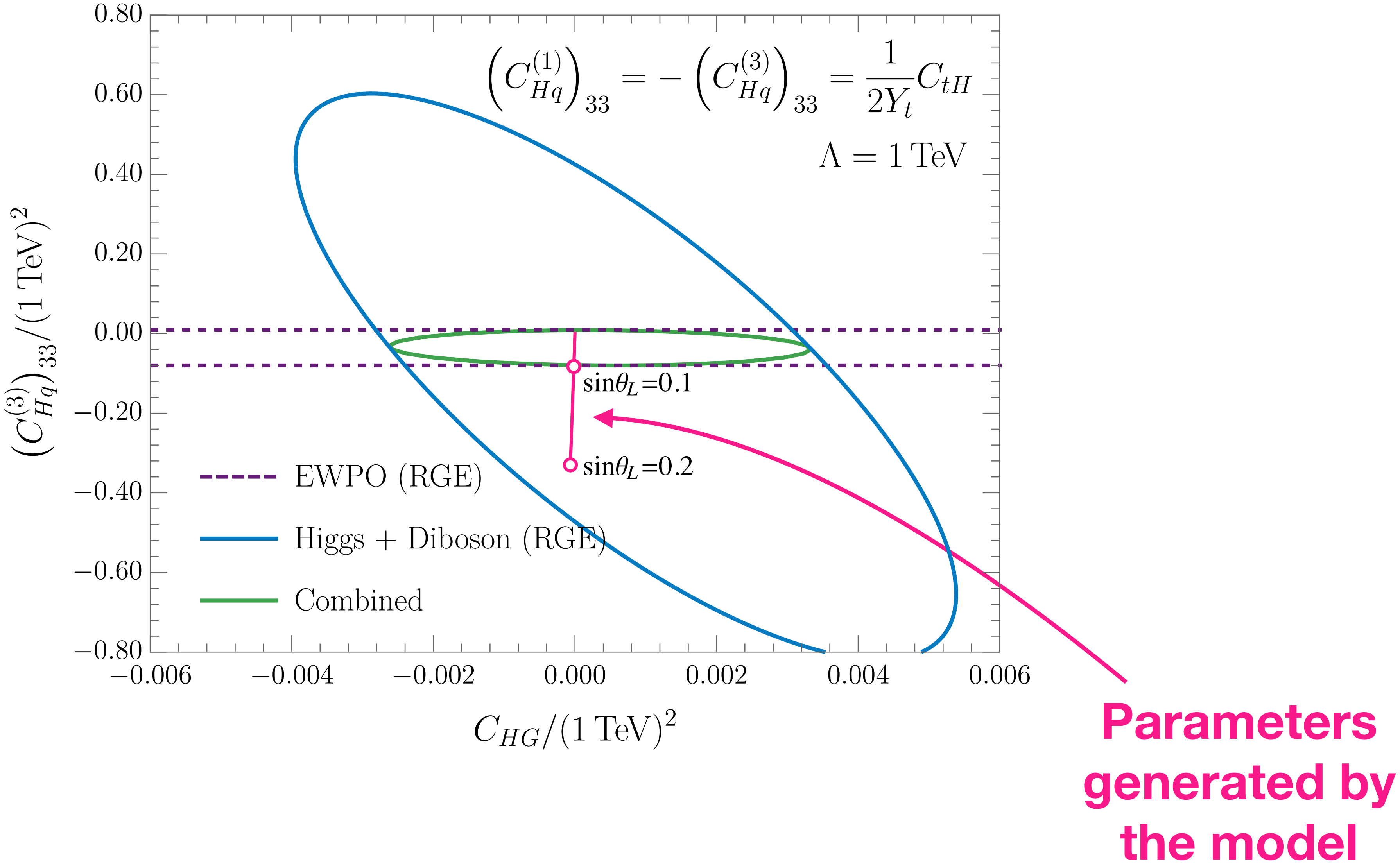

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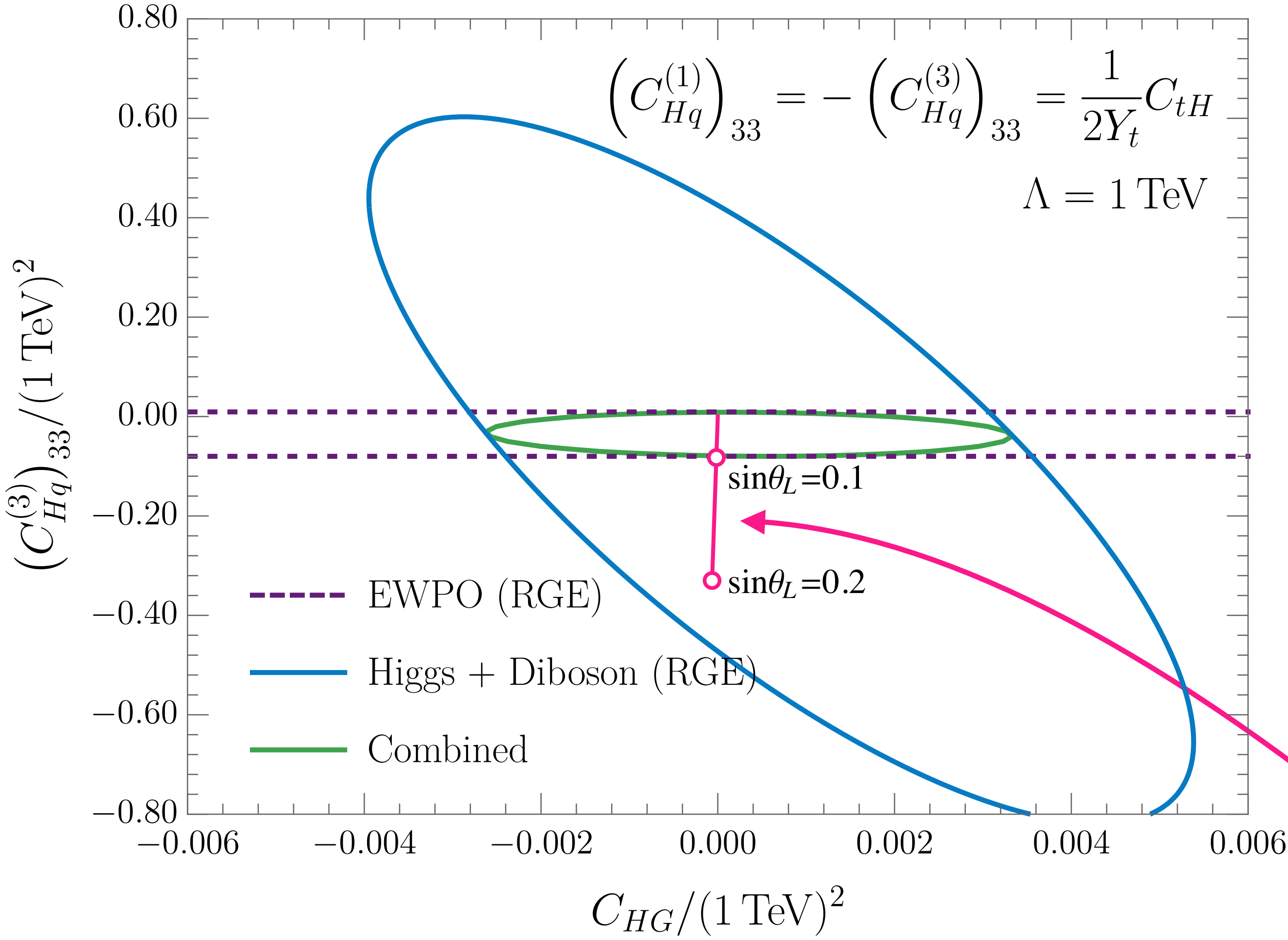
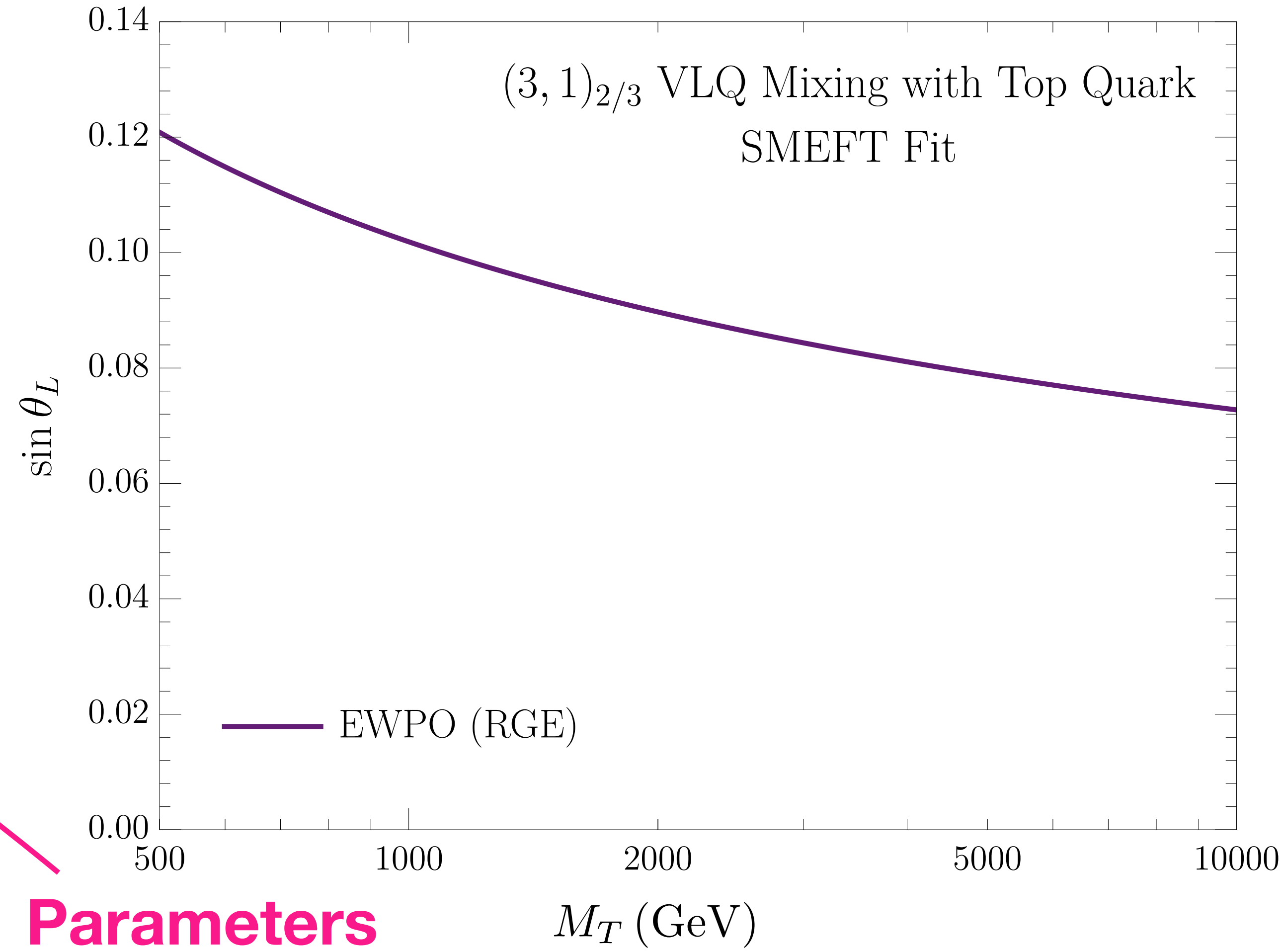




Parameters generated by the model

Constraints on the model driven almost entirely by EW precision observables

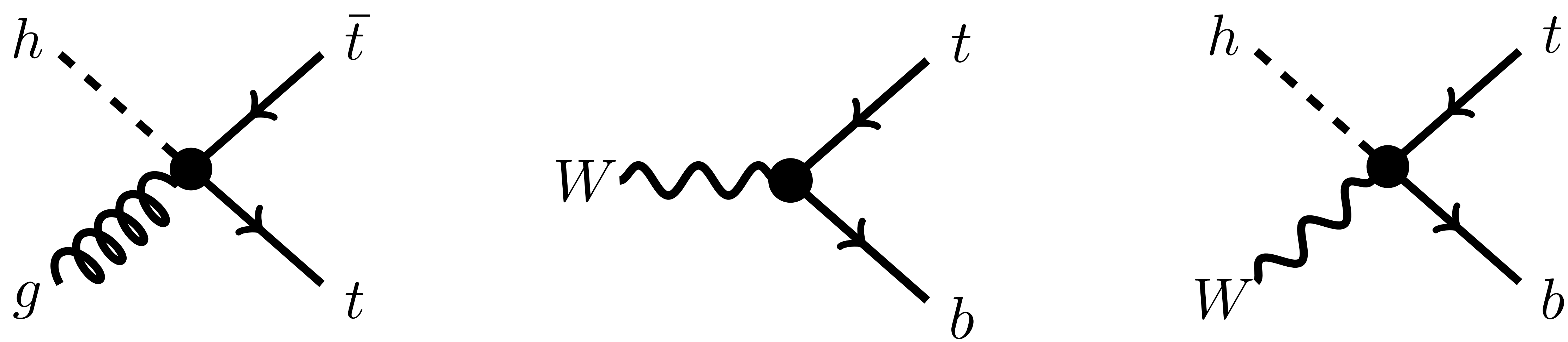
Top VLQ Matching to Dimension-8

arXiv:2110.06948, Dawson, SH, Sullivan

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_6 + \frac{\lambda_t \lambda_T^2}{8 m_T^4}(4\lambda_t^2 - 3\lambda_T^2)\overbrace{(H^\dagger H)^2 \bar{\psi}_L H^c t_R}^{\mathcal{O}^{(8)}_{quH^5}} + \ldots$$

Note: different scaling than at dim-6!

Additional momentum-dependent interactions, modified tbW couplings, modified top-gluon couplings, …



Effects are small for allowed parameters in this model, but illustrative of challenges & subtleties in consistent matching to dimension-8!

Example 3: The 2HDM

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

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

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E.g., for Type-II:

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

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

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

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

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

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

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

2HDM 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

2HDM Matching to Dimension-6

Ignoring light flavor, there are four operators generated:

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

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

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

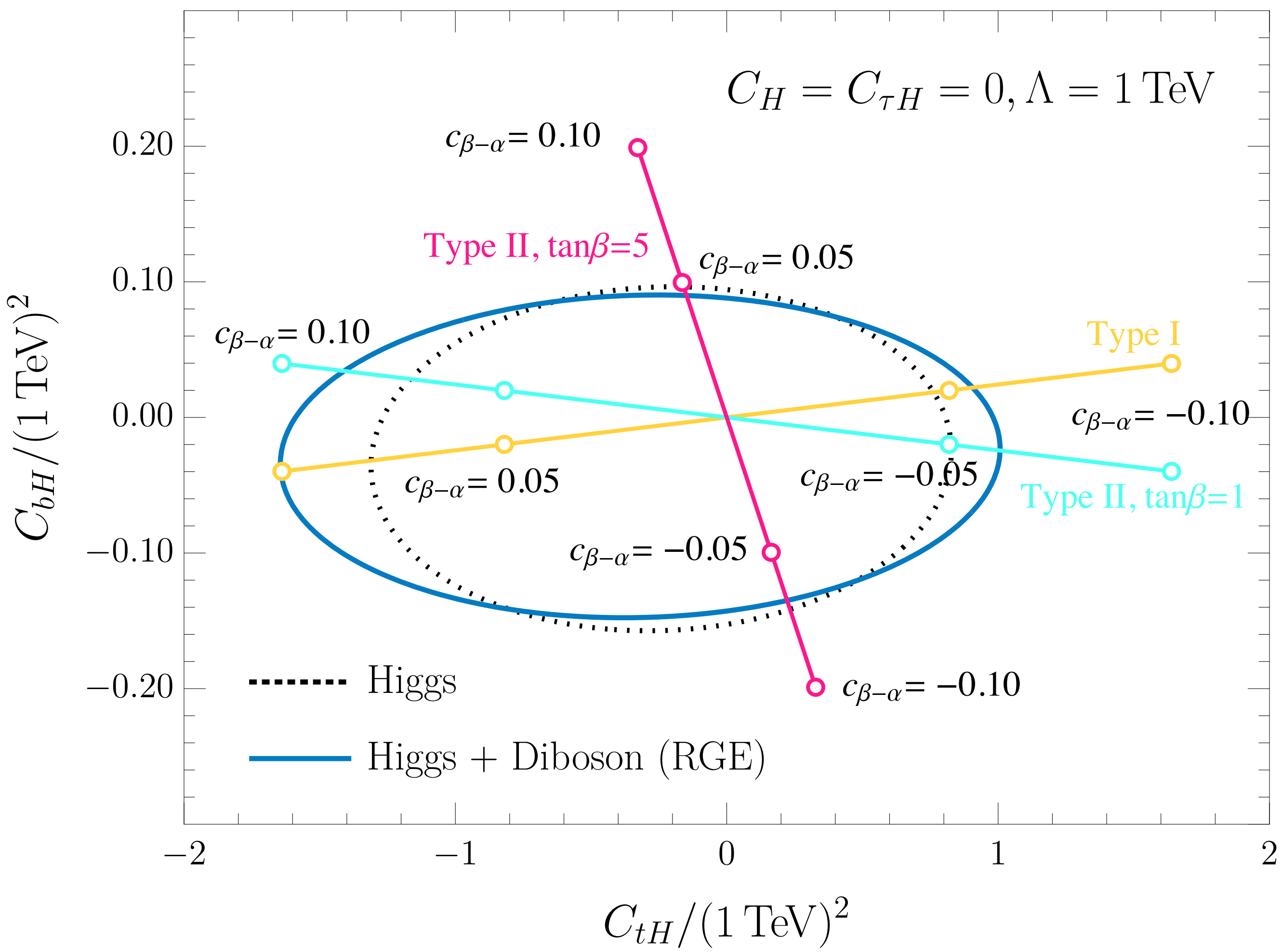
$$\mathcal{O}_{\tau H} = (H^\dagger H)(\bar{L}_3 \tau_R \tilde{H}), \qquad \frac{v^2}{\Lambda^2} C_{\tau H} = -y_\tau \eta_\tau \frac{\cos(\beta-\alpha)}{\tan\beta}$$

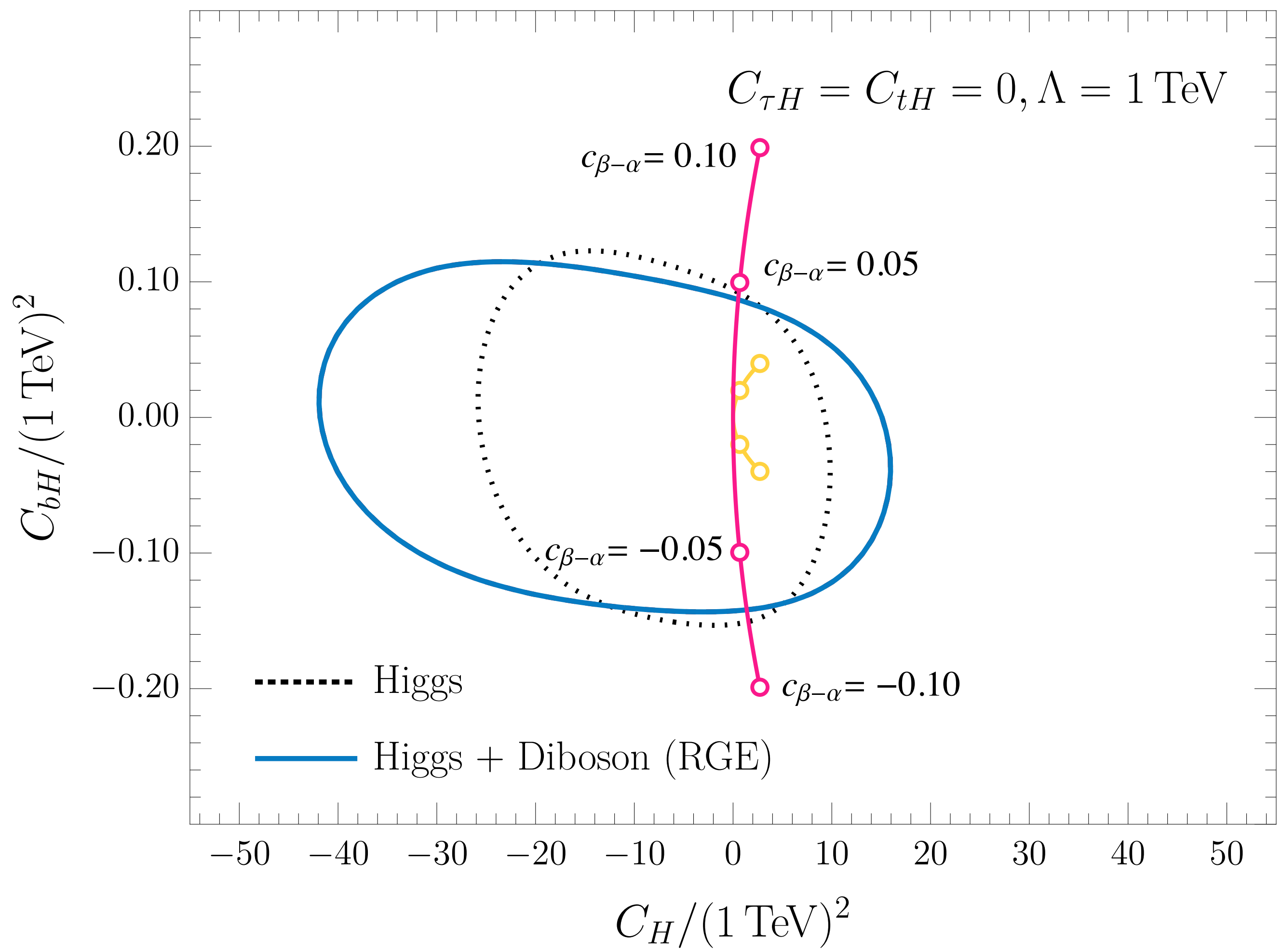
	η_t	η_b	η_τ
Type-I	1	1	1
Type-II	1	$-\tan^2\beta$	$-\tan^2\beta$
Lepton-specific	1	1	$-\tan^2\beta$
Flipped	1	$-\tan^2\beta$	1

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

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

2HDM Matching to Dimension-6

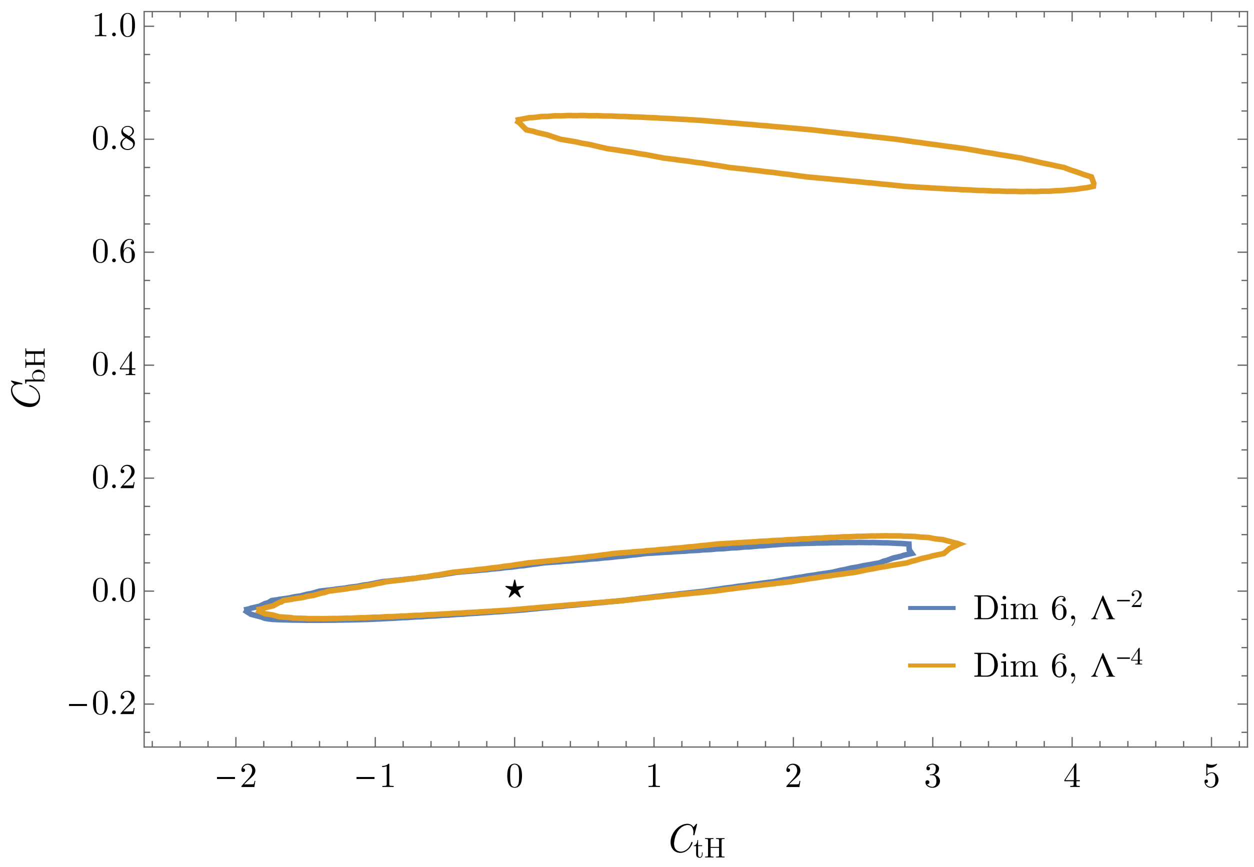




Different types of 2HDM sweep out different ranges of allowed coefficients

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

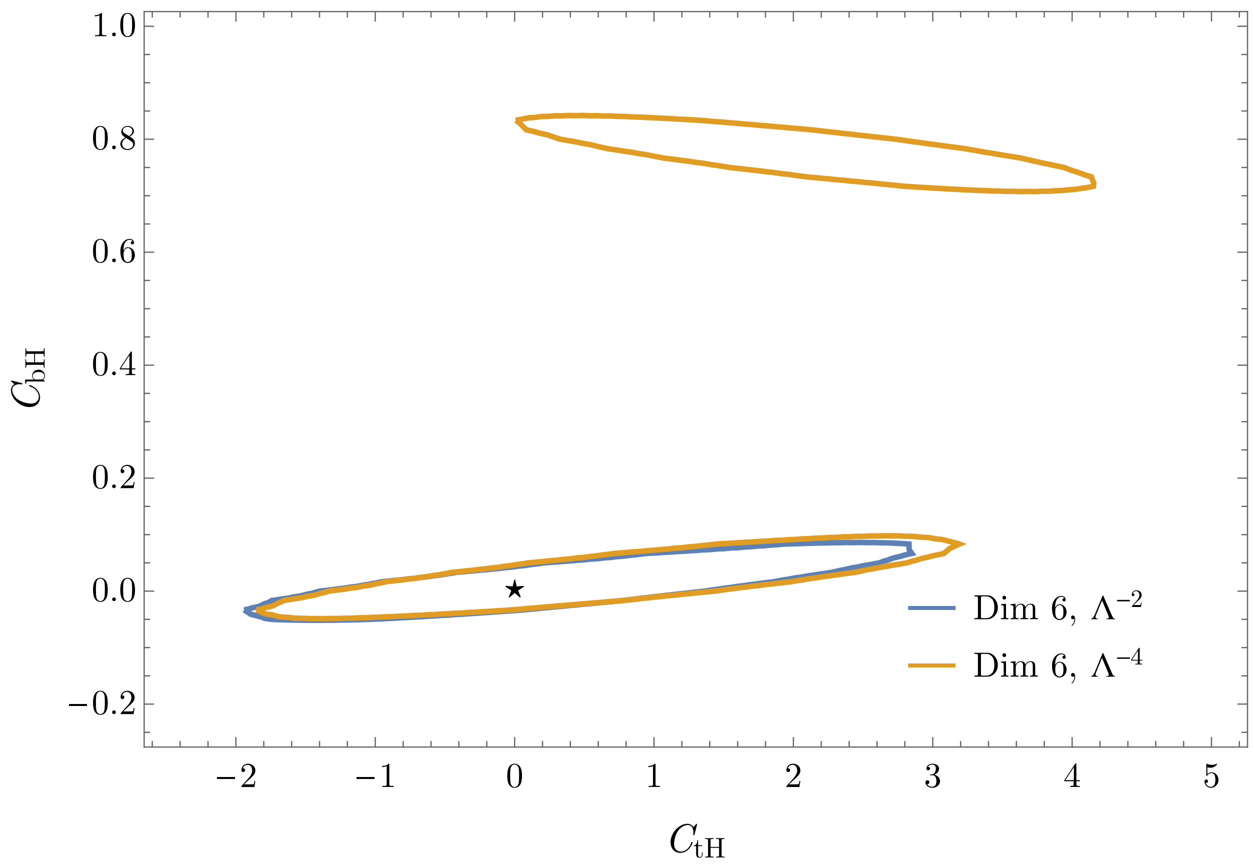
Matching Effects at Large $\tan\beta$



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

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

Matching Effects at Large $\tan\beta$



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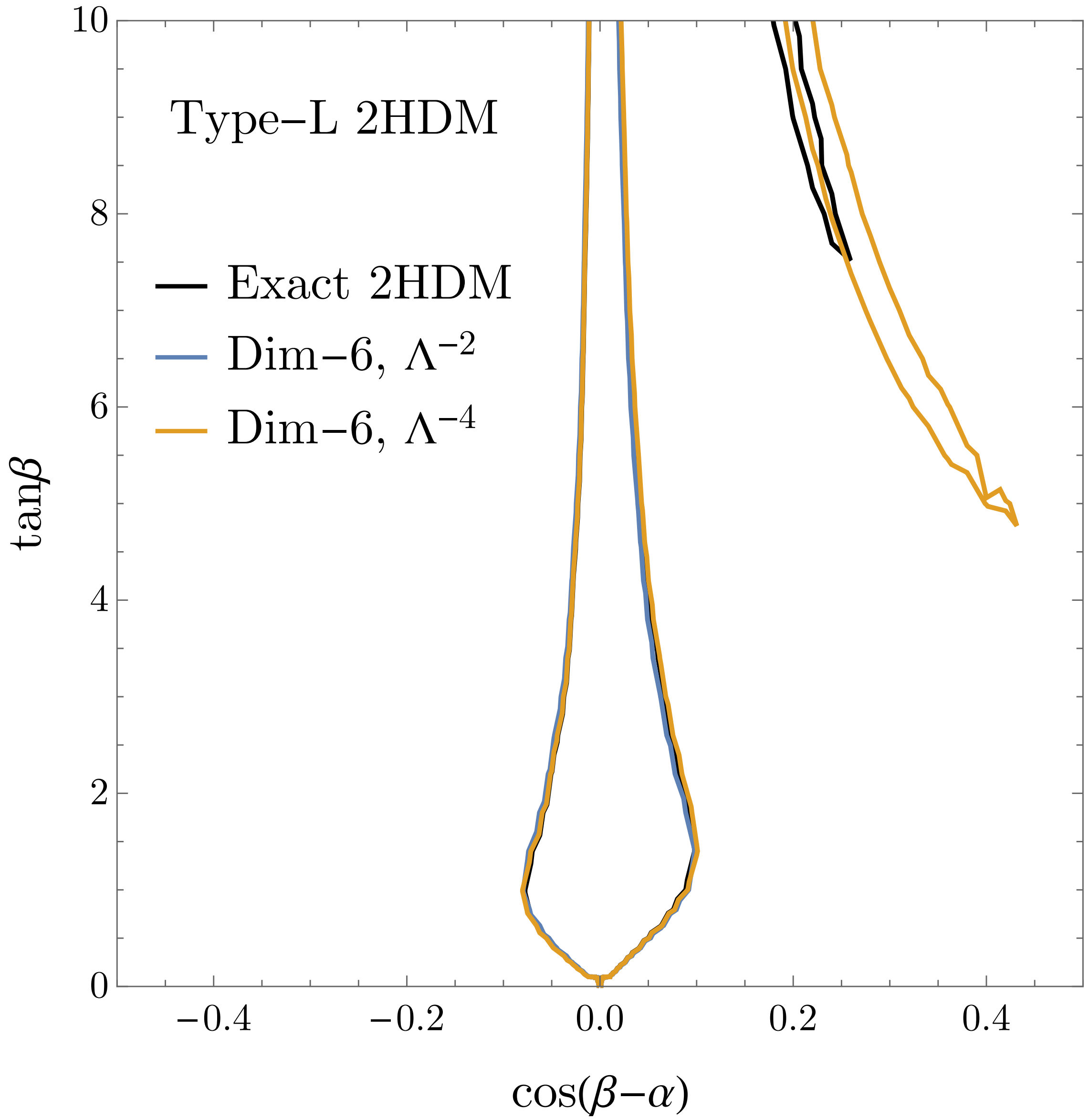

Ruled out for Type-II by latest Higgs data, but appears still in e.g., Type-L…

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

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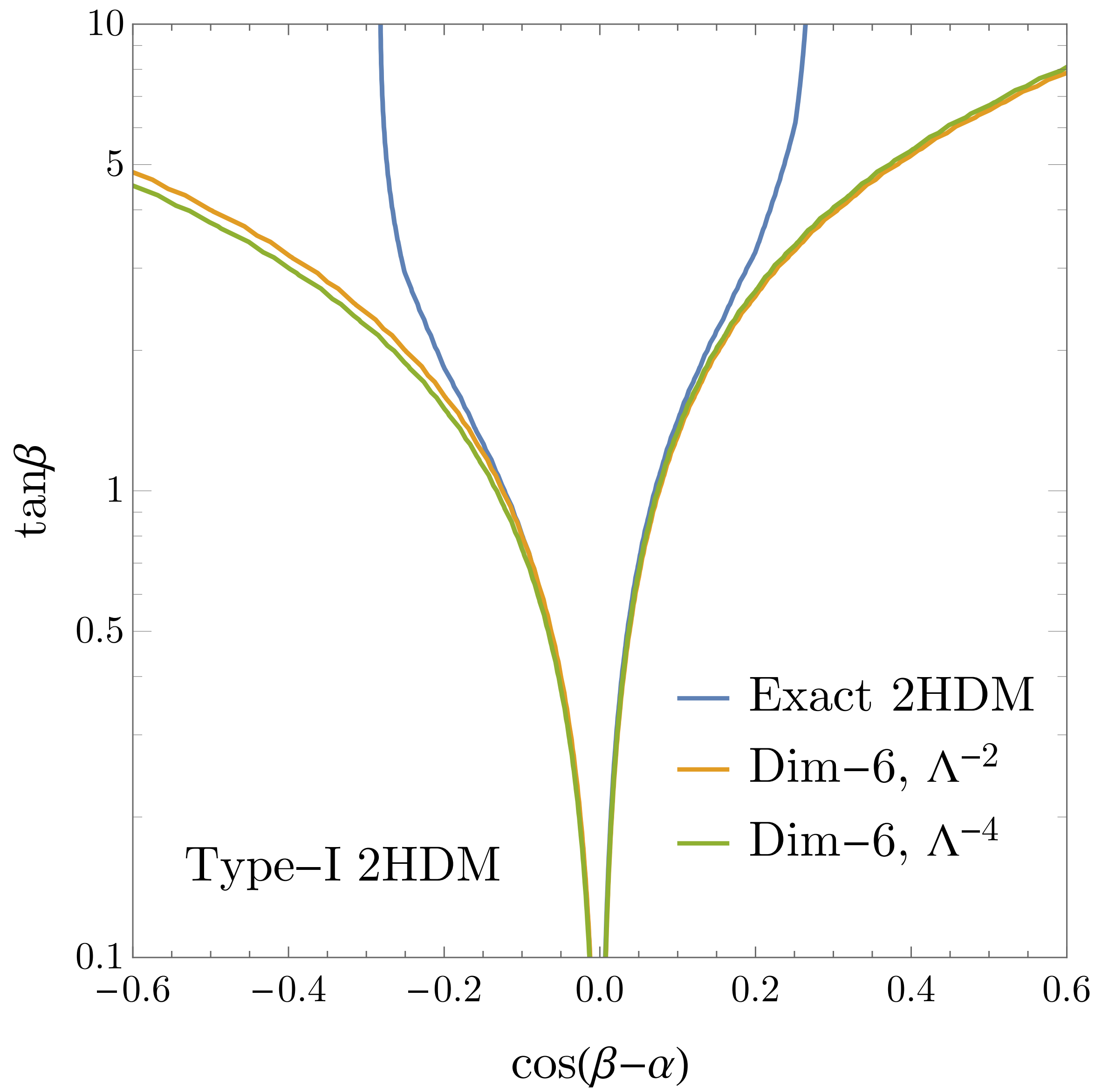
Ignoring the constraints on C_H, we see the dimension-6 description **completely fails**
(see e.g., [1611.01112])

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



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]
(Degrassi, Di Micco, Giardino, Rossi).

$$\frac{v^2}{\Lambda^2} C_H = \cos(\beta - \alpha)^2 \frac{(\Lambda^2 - 4m_h^2)}{v^2}$$

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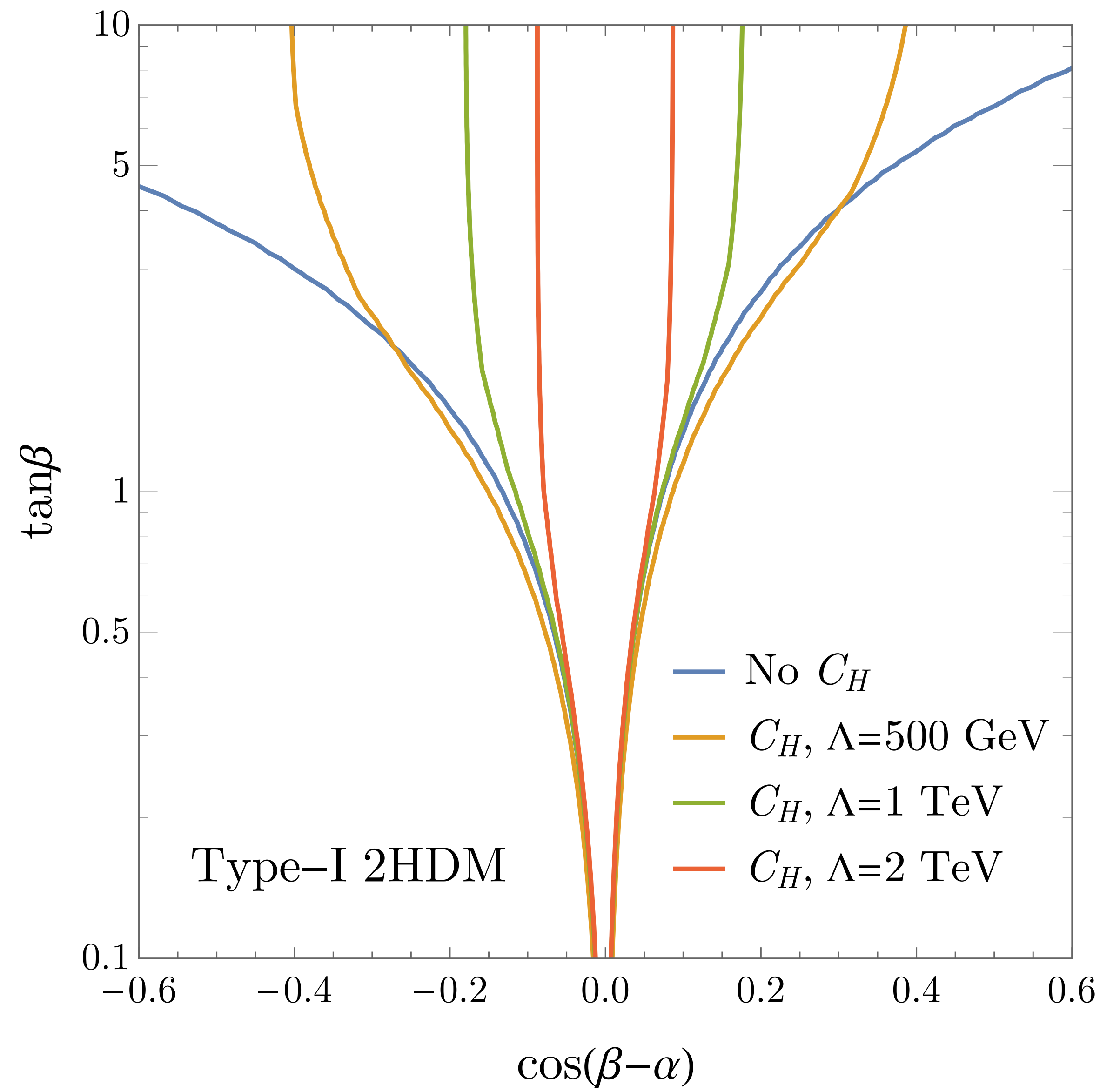
Direct hh measurements should have a big impact here!



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]

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

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

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

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Fit Results Including Dimension-8

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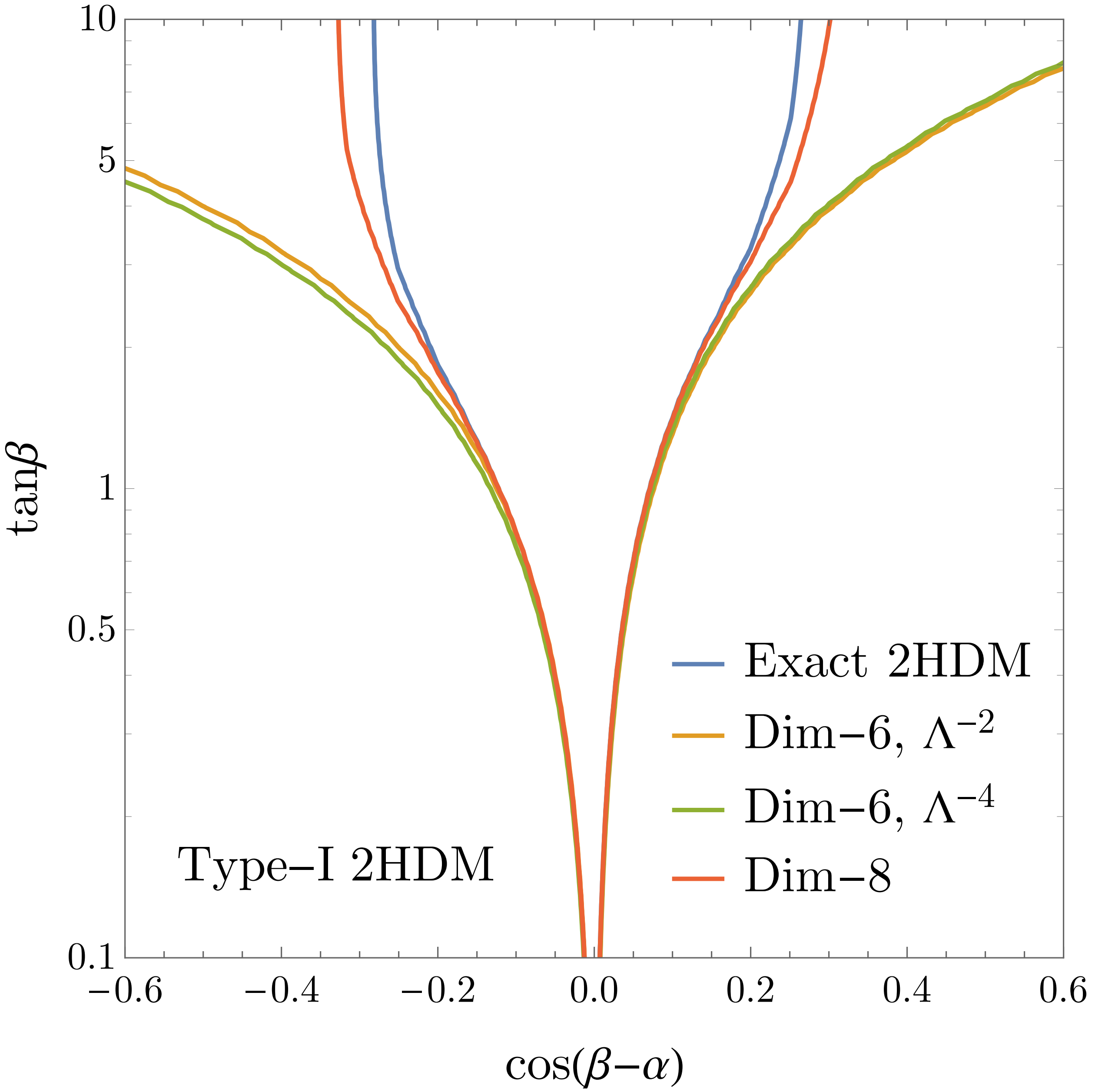

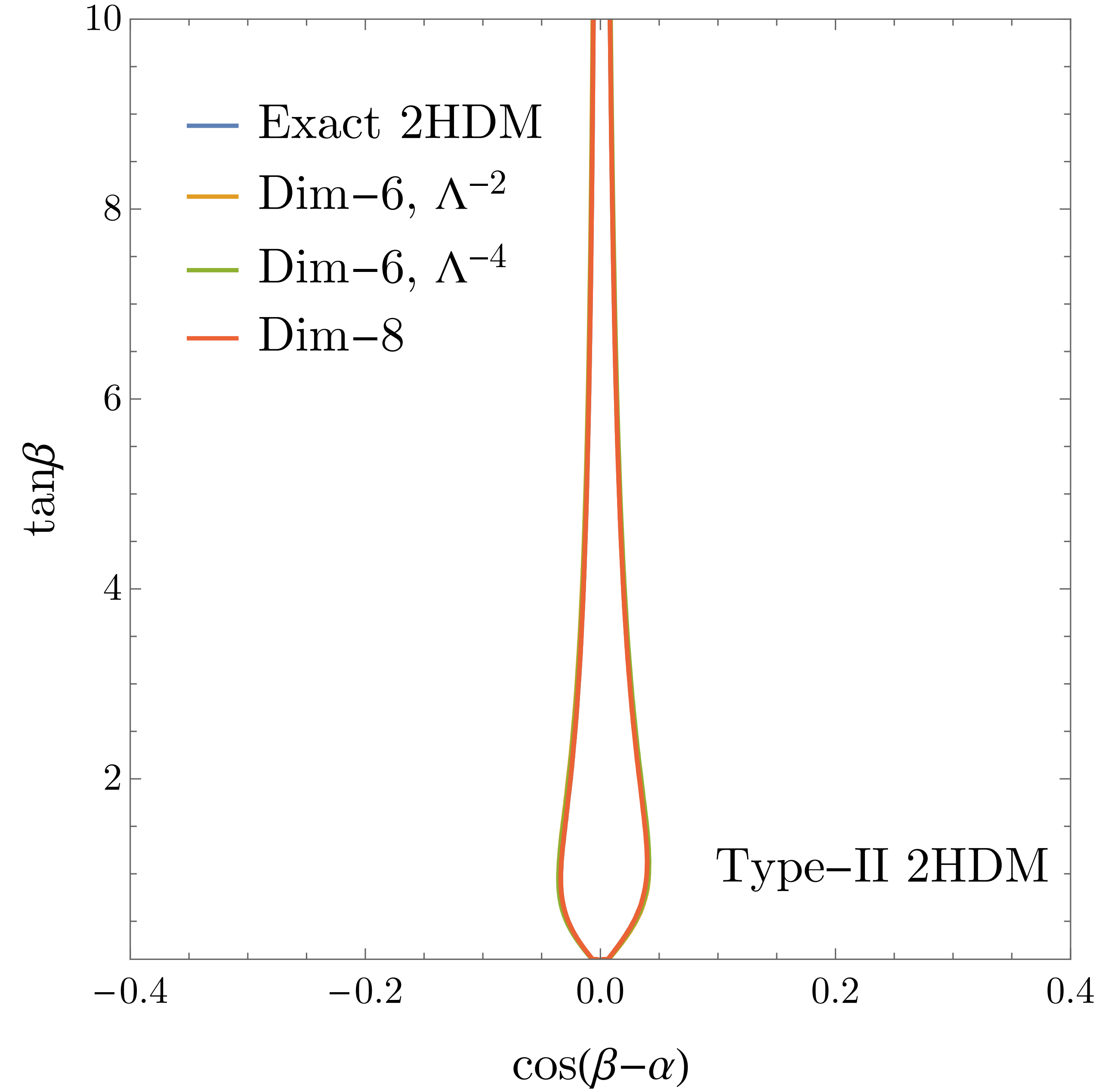

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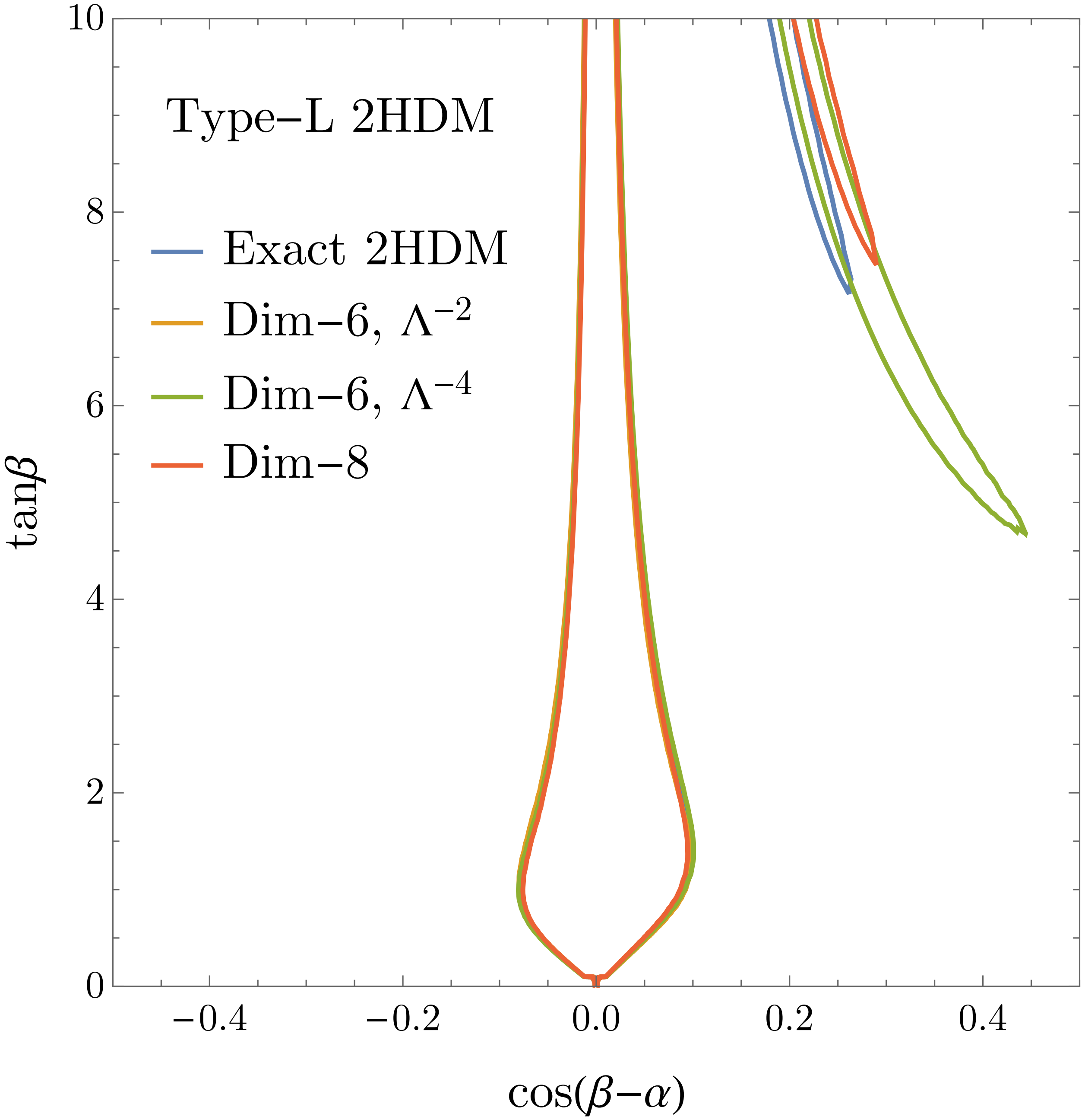

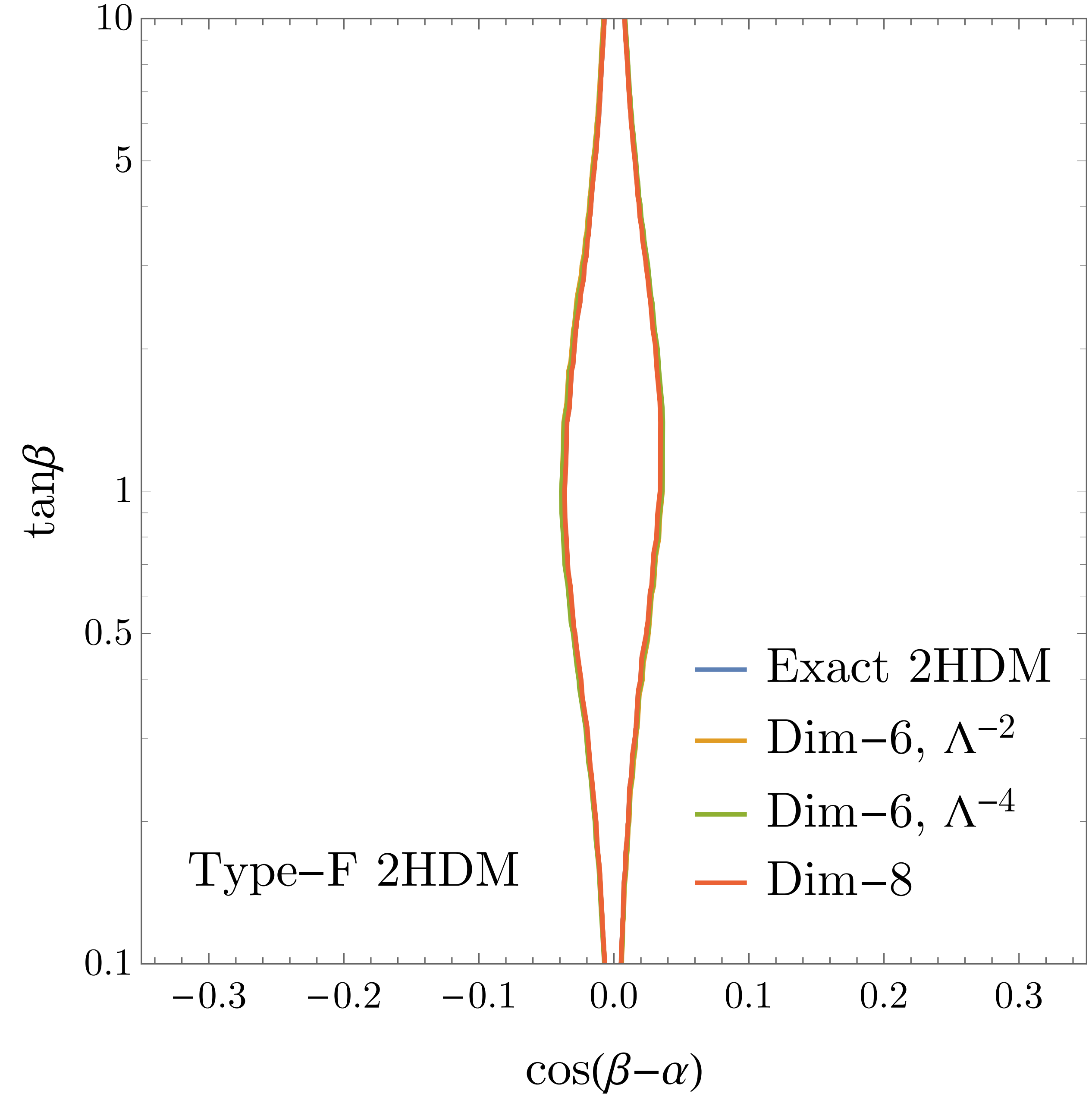

EFT of the 2HDM Summary

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

See also 2305.07689 (Talk by Duarte Fontes on Monday) for more details on the decoupling and relation to HEFT

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.*
- 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!

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:

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

- 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!