The Higgs Inverse Problem

Based mostly on

`arXiv:2007.01296, arXiv:2102.02823`

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In collaboration with

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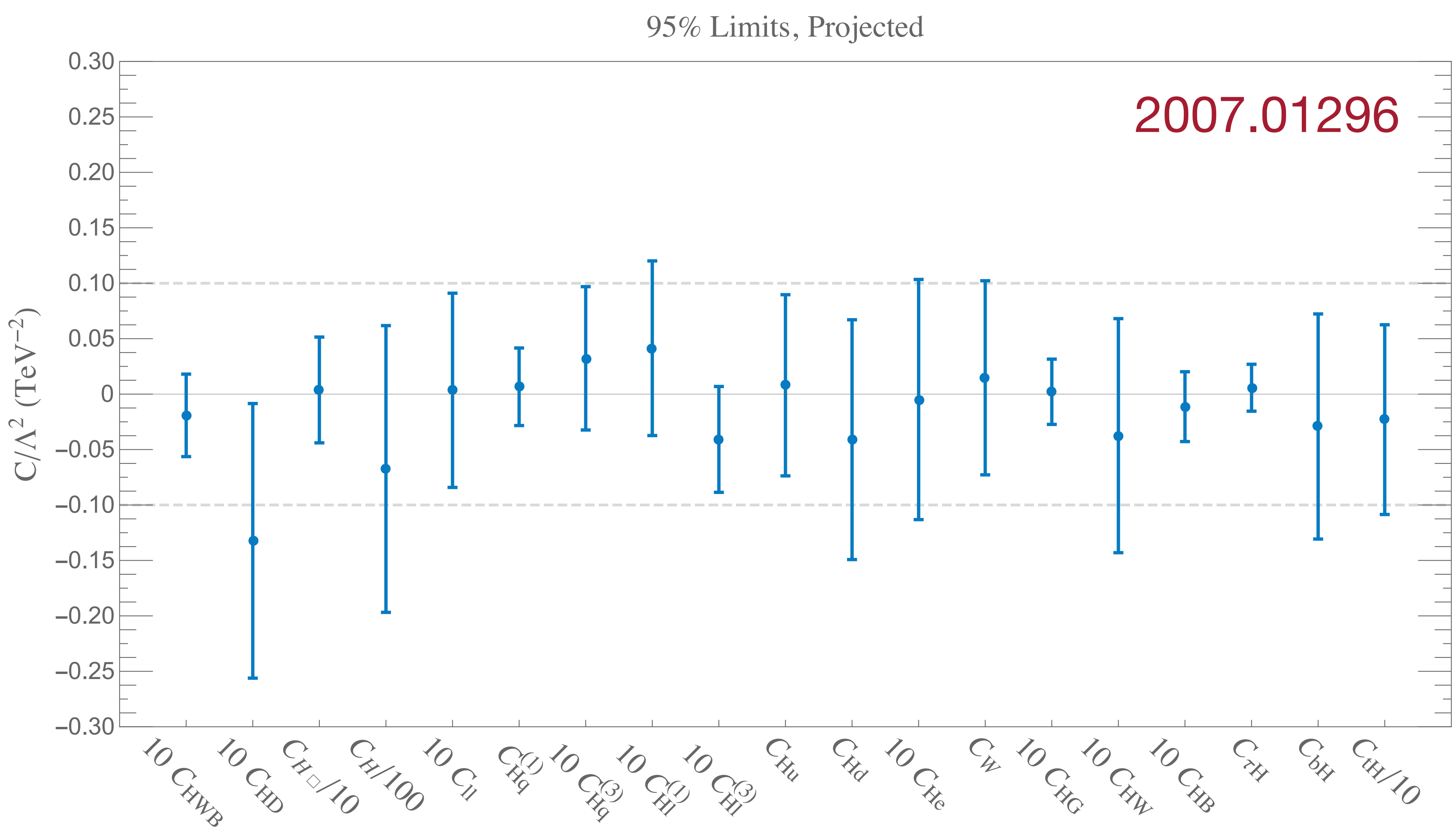
EF01 Meeting — August 18, 2021

The Higgs Inverse Problem:

What can we learn from precise measurements of the Higgs?



$\Longrightarrow$ *assuming* we observe some deviation in Higgs couplings, how can we make sense of what UV physics underlies it?

The SMEFT Framework

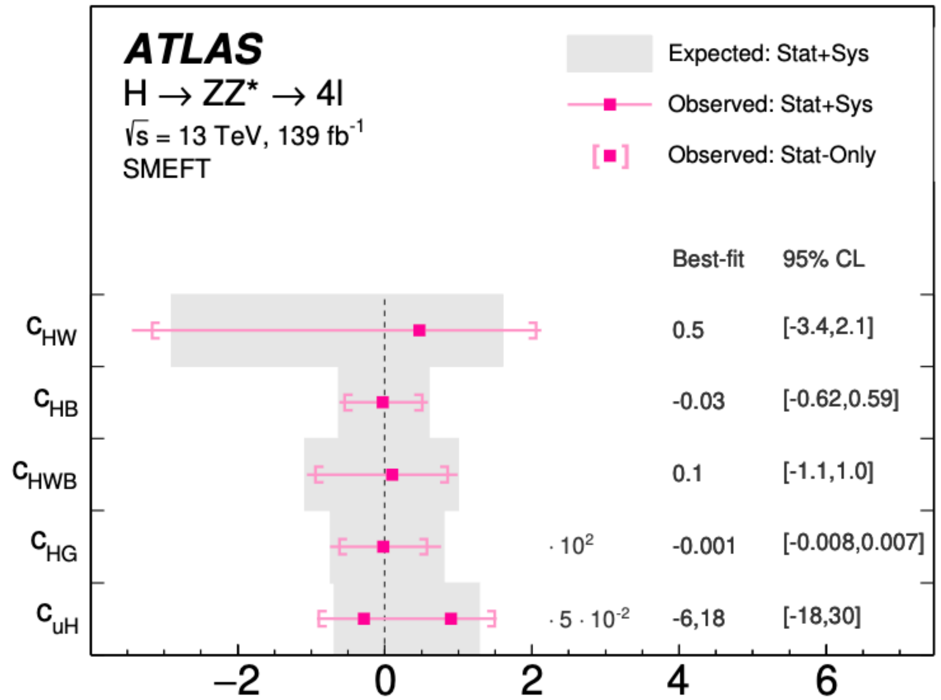
Complete (non-redundant) basis of effective operators that let us search for deviations

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

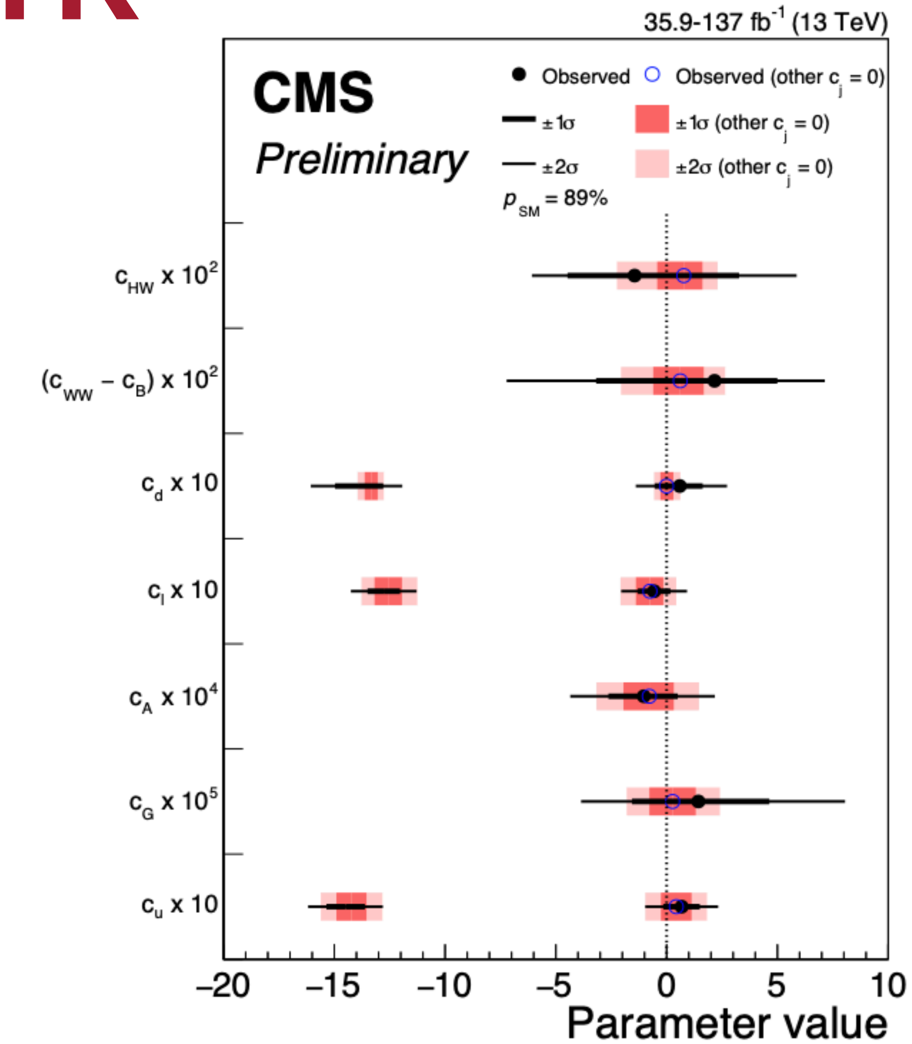
(Note: not the full set here — lots of flavor / model-based assumptions to limit the ~3000 operators in the full EFT!)

The SMEFT Framework

Experiments starting to present limits in this framework:



arXiv:2004.03447



CMS-PAS-HIG-19-005

Well-known procedures for matching theories onto SMEFT, and getting coefficients in terms of theory parameters

(see e.g., Henning, Lu, and Murayama, arXiv:1412.1837)

Tree-Level Dictionary: de Blas, Criado, Perez-Victoria, Santiago, arXiv:1711.10391

Beyond Tree Level Matching:

Lots of “higher-order” effects to consider:

- RG Evolution of Wilson Coefficients
- Linear vs. Quadratic Effects in $(1/\Lambda^2)$
- One-Loop Matching Effects
- Importance of Dimension-8 Operators
- Higher Order QCD / EW Corrections in the EFT

  See, e.g, Baglio, Dawson, SH, arXiv:1909.11576,
  Baglio, Dawson, SH, Lane, Lewis, arXiv:2003.07862, for importance in *VV*, *VH*

Focus on the impacts of these today

Strategy:

Example: *T* Vector-like Quark

Start with Lagrangian for new states at high scale, (*M* ~ few TeV)

$$\mathcal{L} \supset \lambda_3 \bar{Q}_L \tilde{H} T_R$$

Integrate out new states, generating a subset of SMEFT Coefficients

$$\left(C_{Hq}^{(1)}\right)_{33},\ \left(C_{Hq}^{(3)}\right)_{33},\ C_{tH},\ C_{HG}$$

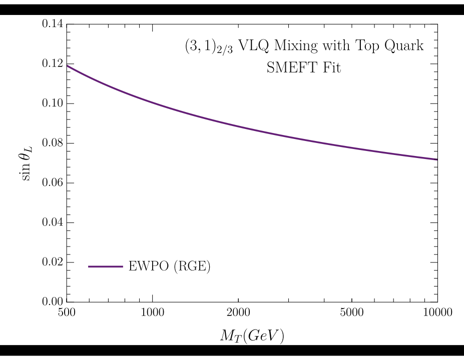
Evolve Coefficients down to EW scale

(Using Anomalous Dimensions from Trott et. al, 1308.2627+)

$$C_{HD},\ C_{H\Box}\ \cdots$$

Fit to Higgs + Diboson + EWPO Data

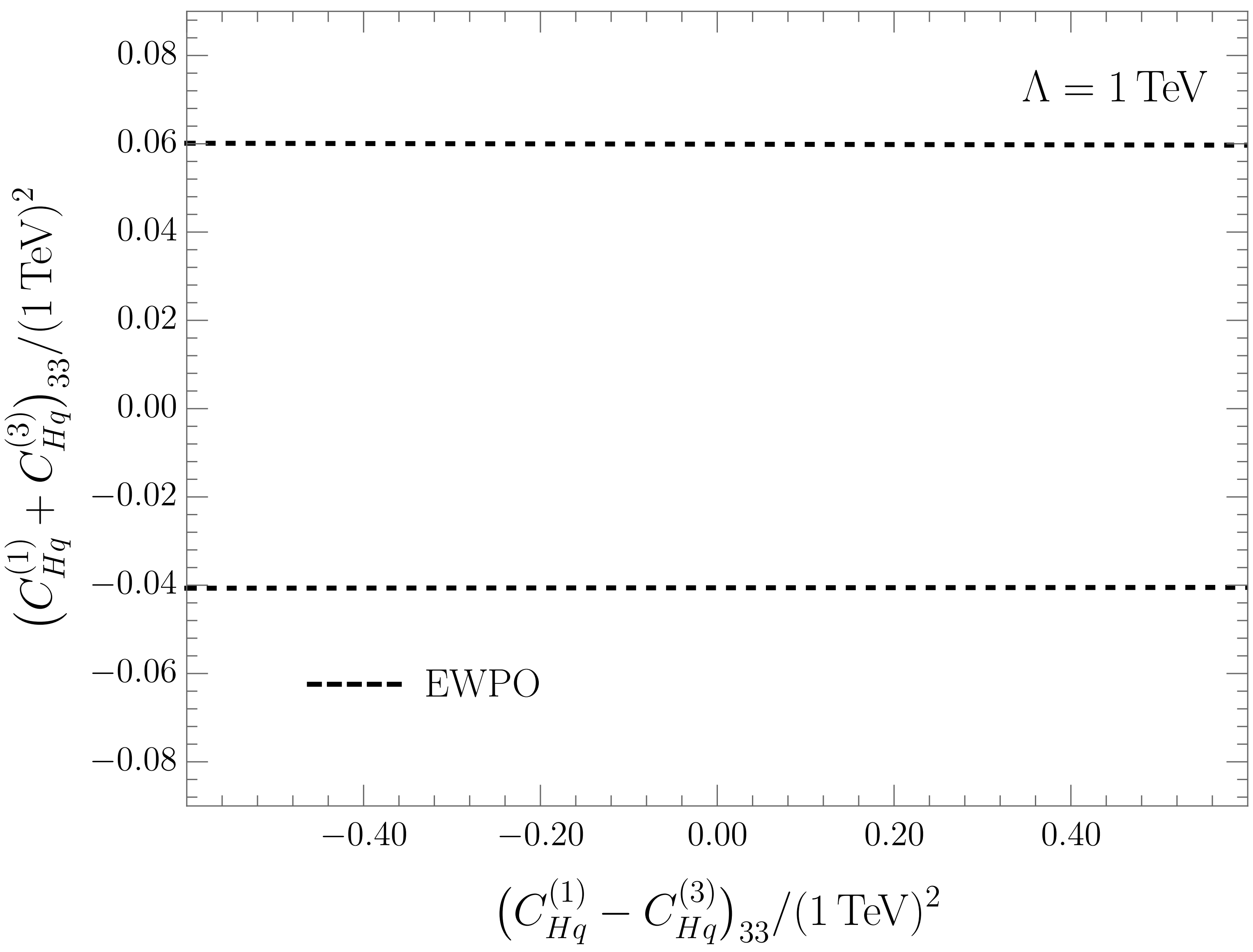
→ Limits on physical parameters!



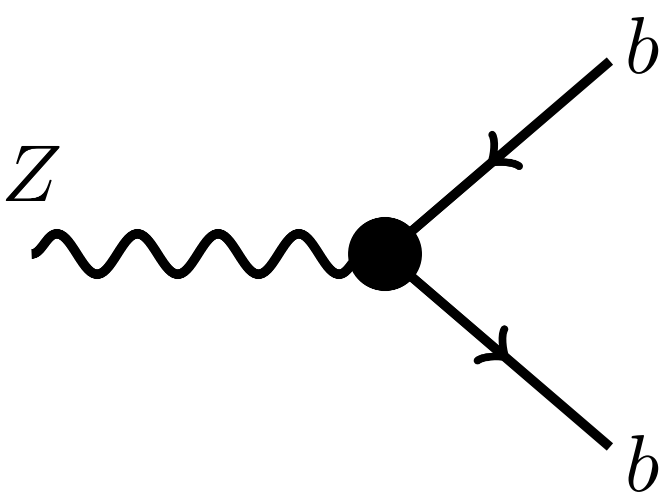
SM + VLQ Singlet Mixing with Top

Generates C_{tH}, $(C^{(1)}_{Hq})_{33}$, $(C^{(3)}_{Hq})_{33}$, C_{HG} at the matching scale

RG Effects on the LEP Bounds:



At tree level, only one way to measure operators $C^{(1)}_{Hq,33}$, $C^{(3)}_{Hq,33}$:



$Z \to b\bar{b}$ branching ratio constrains ***one*** combination of operators.

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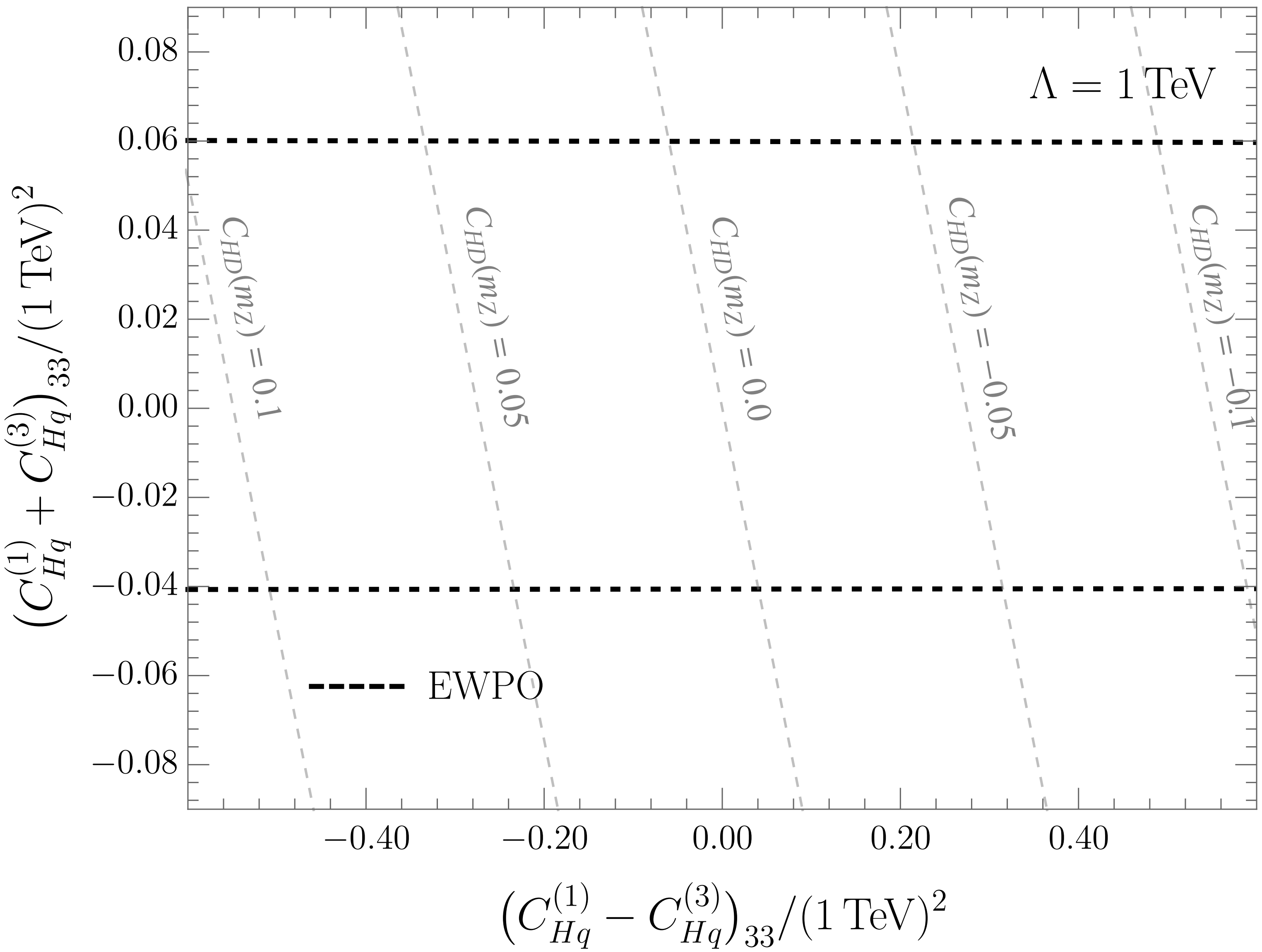

But if we evolve the operators down to the weak scale…

… we generate C_{HD} — strongly constrained by EW precision data!

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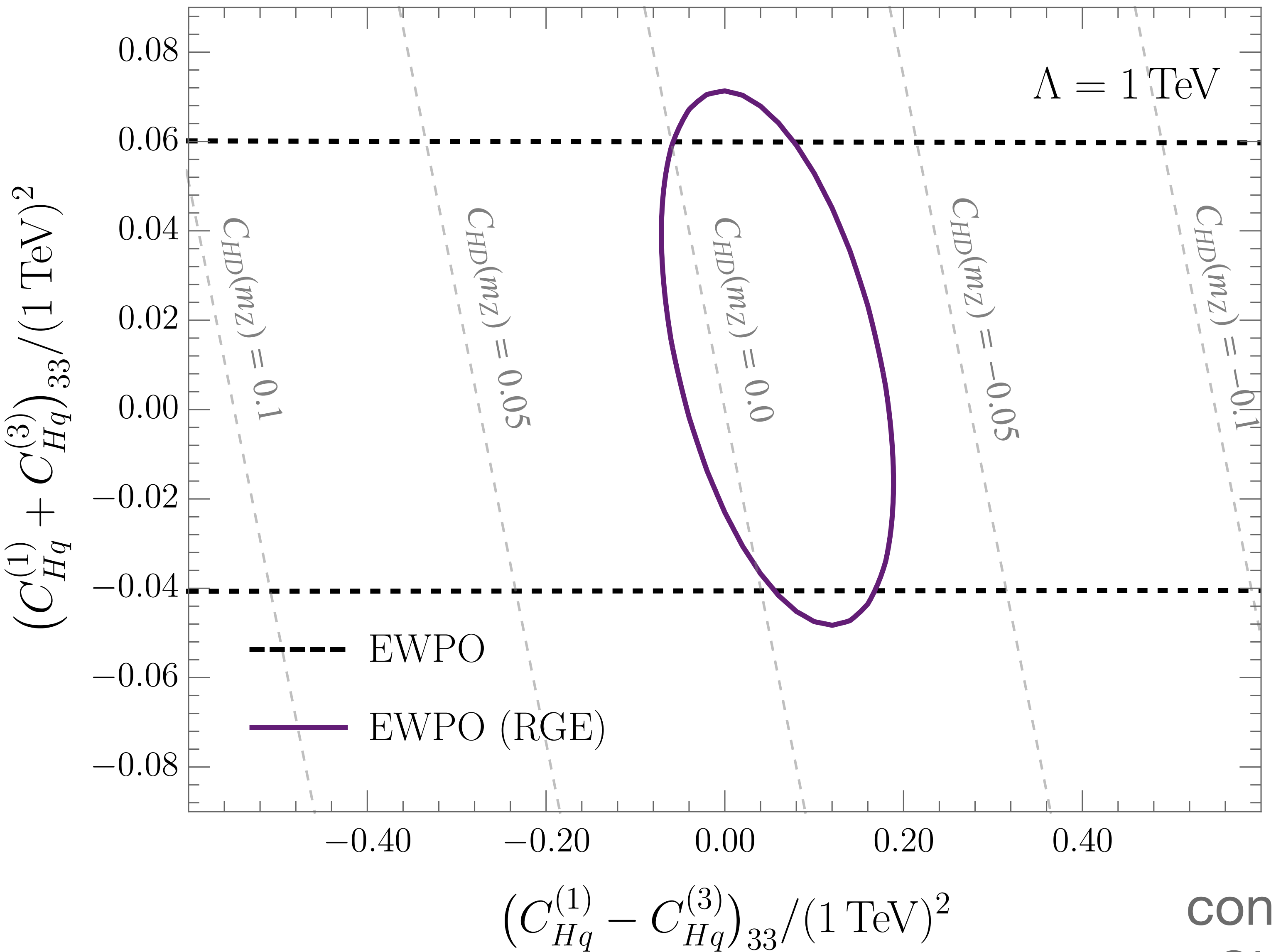

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(Well understood in UV theory — constraints from oblique parameters, e.g., Chen, Dawson, Furlan, arXiv:1406.3349

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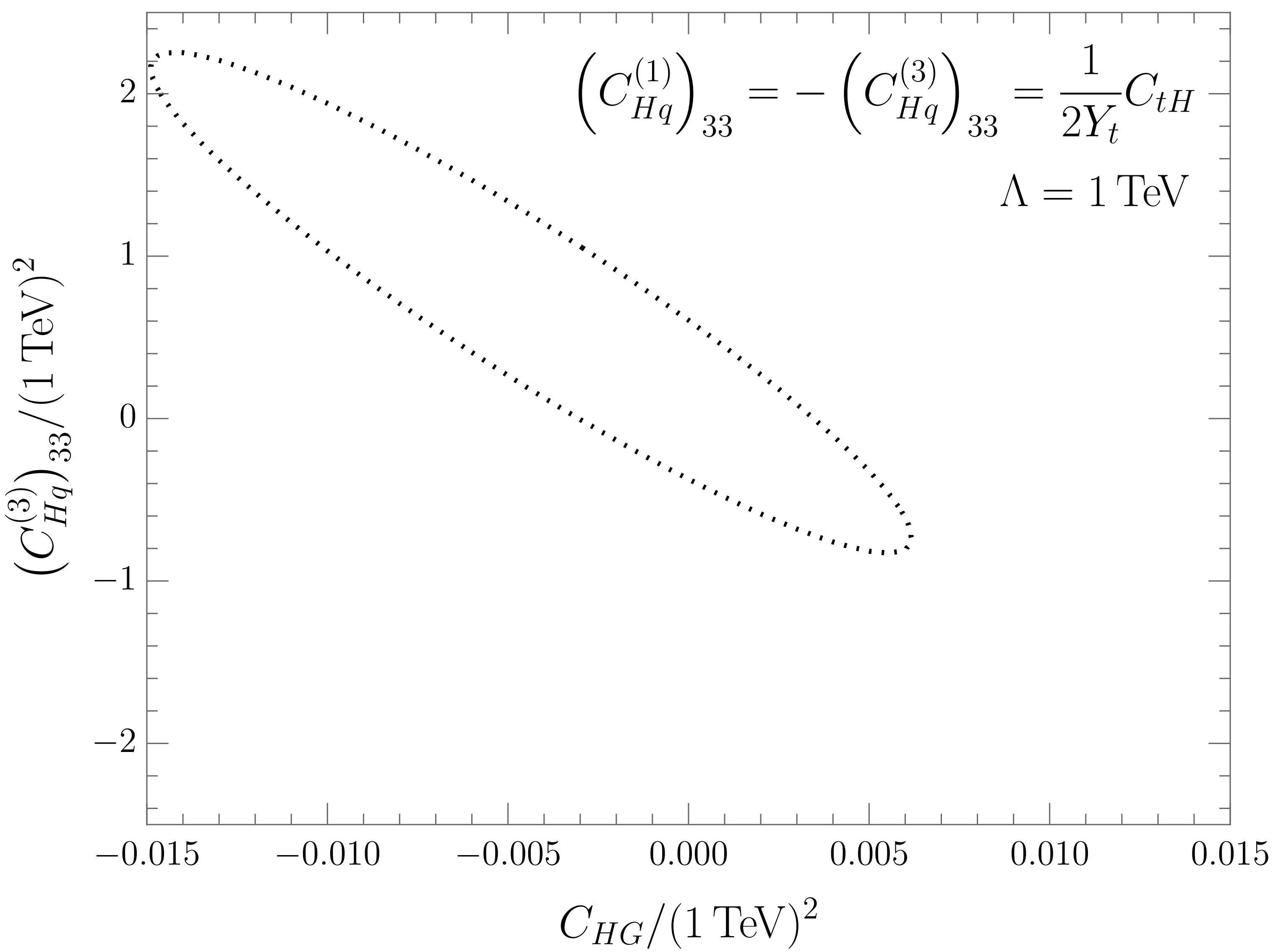
Similar lessons apply to LHC bounds:



Operators that arise at tree level constrained by Higgs coupling fits

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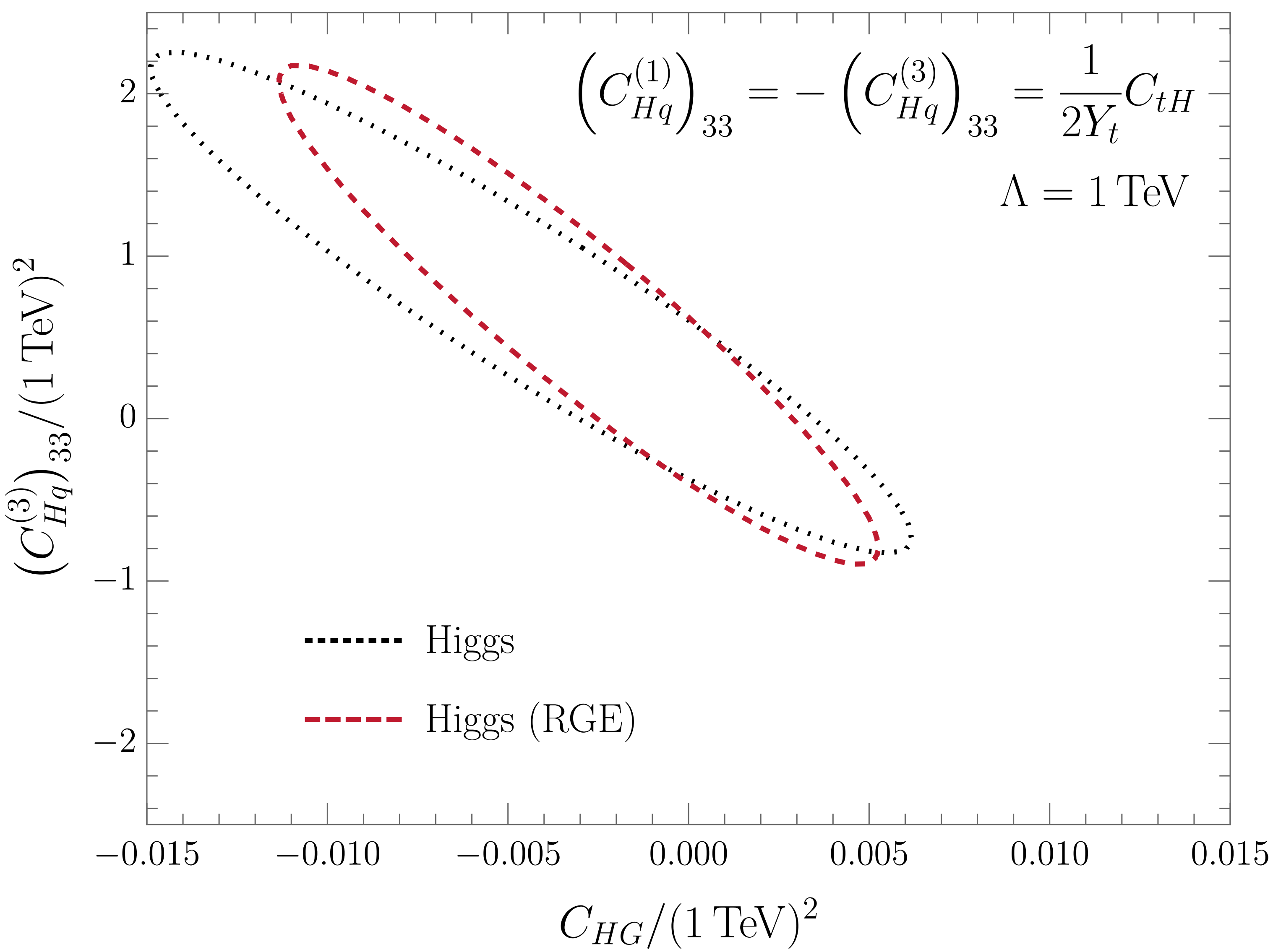

Operators that arise at tree level constrained by Higgs coupling fits

RG evolution changes the values of these operators at the weak scale, so the inferred bounds are different!

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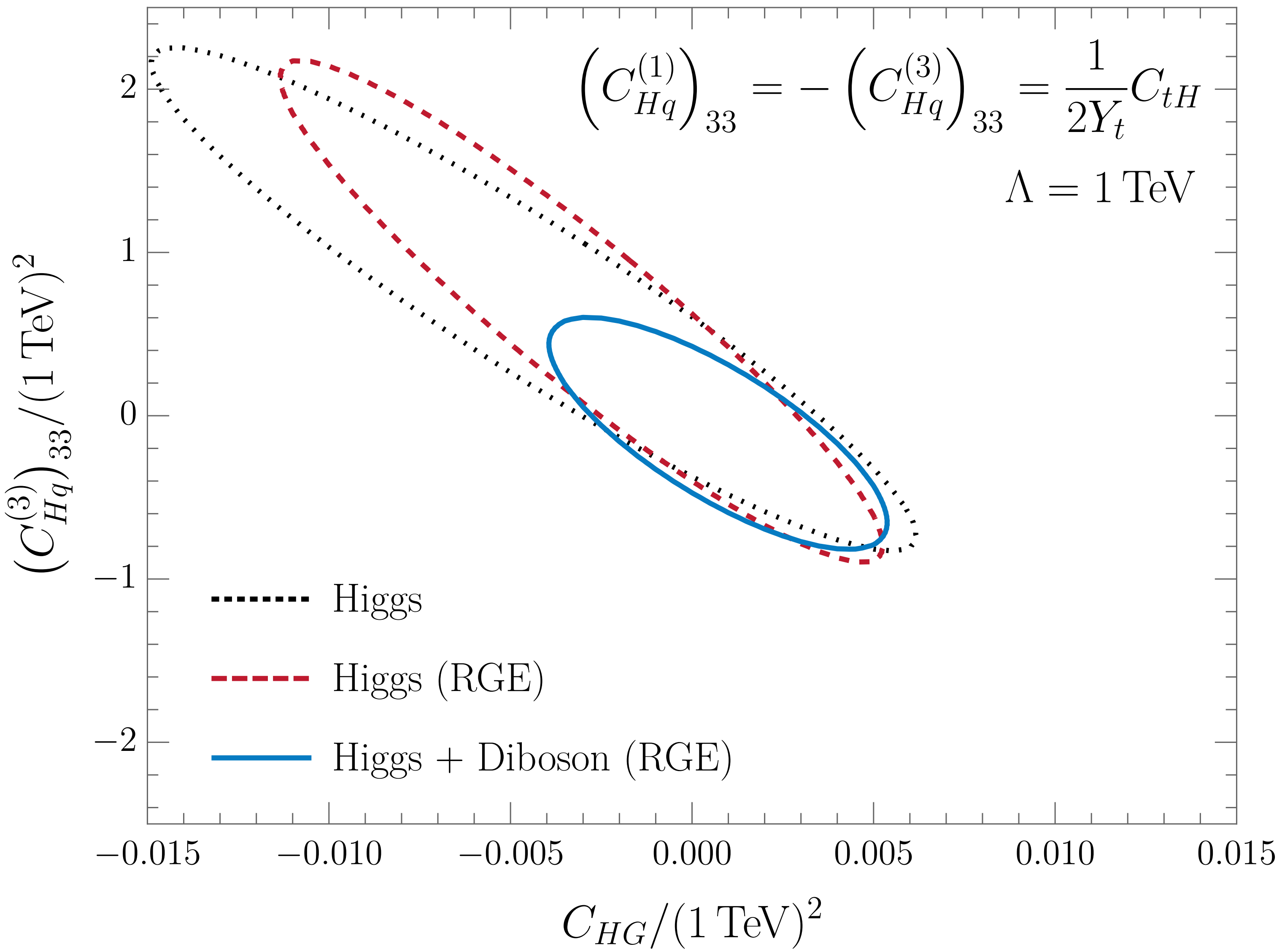


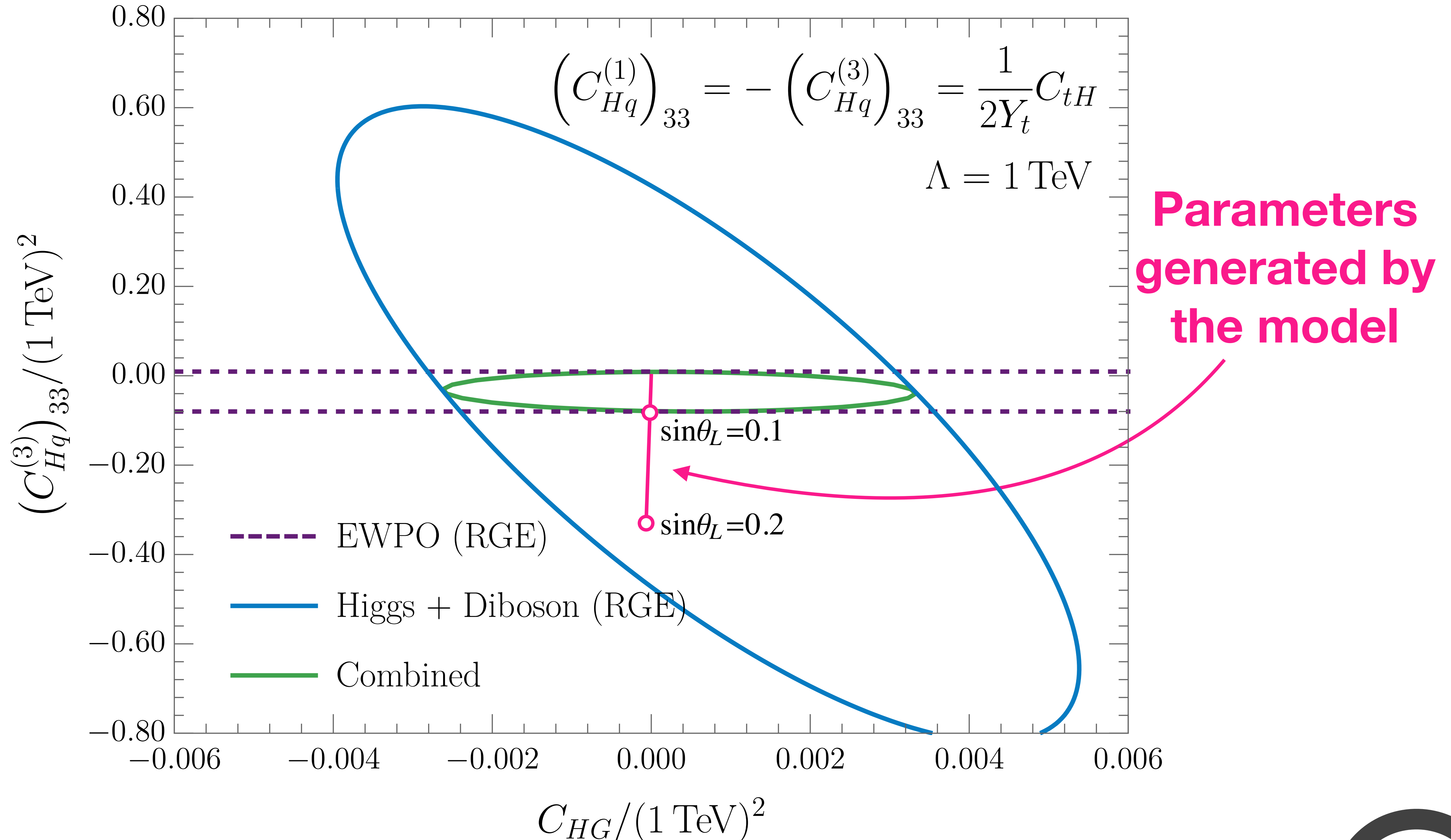
But RG evolution also generates *new* operators measured at the LHC in *WW*, *WZ*, *WH*, *ZH* production!

Strongest constraint from RGEs!

Note: NLO-QCD effects are *very* important for diboson limits (see arXiv:1909.11576, arXiv:2003.07862)

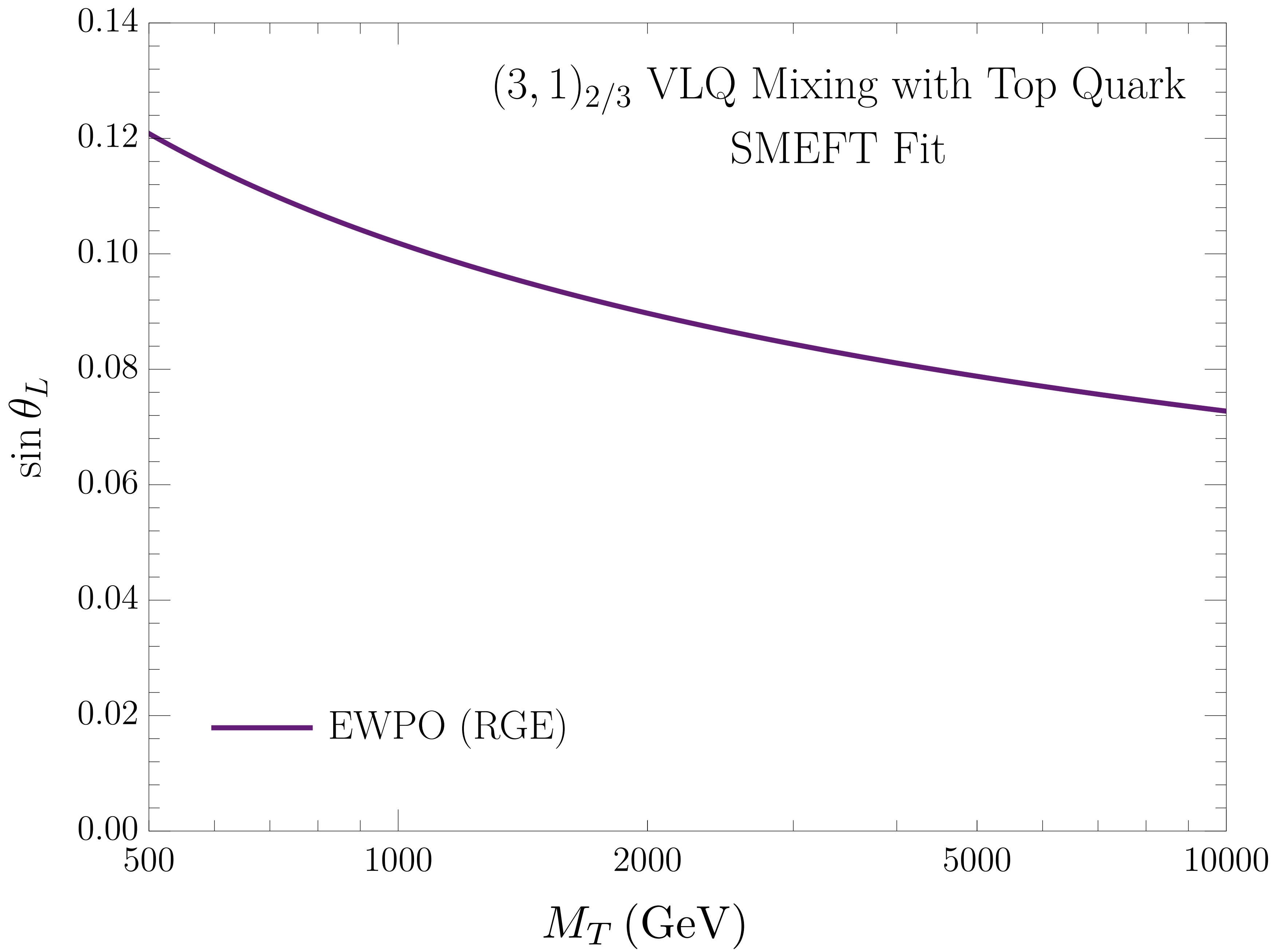
SM + VLQ Singlet Mixing with Top

Back to the inverse problem: the T VLQ is a 1-parameter model — sweeps out only 1D curve in operator space



SM + VLQ Singlet Mixing with Top

Now we can re-interpret the bounds on operators as bounds on the physical parameters of the model:



Example 2: The Singlet Model

arXiv:2102.02823

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)

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

Goal: understand numerical importance of 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 $\cos\theta$

Unitarity and Vacuum Stability

The physical parameters are not entirely arbitrary!

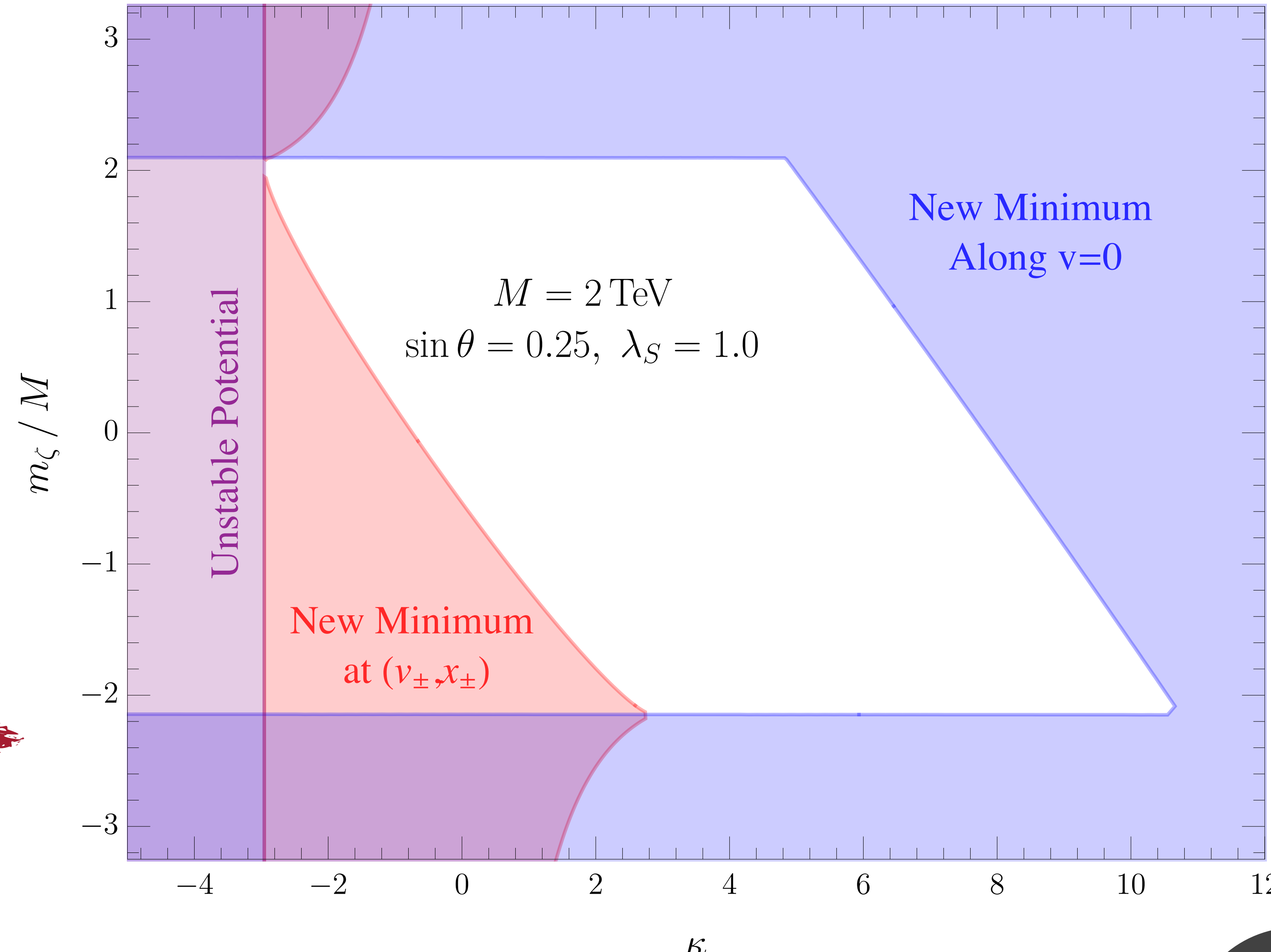
Unitarity of the *hh, hH, HH* amplitudes requires:

$$M_H^2 \sin^2\theta \lesssim \frac{16\pi}{3} v^2 - m_h^2 \cos^2\theta$$

$$\lambda_S, \lambda_H \lesssim 8\pi/3$$

$$|\kappa| \lesssim 8\pi$$

Furthermore, have to demand that the EWSB minimum be the global minimum of the potential



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

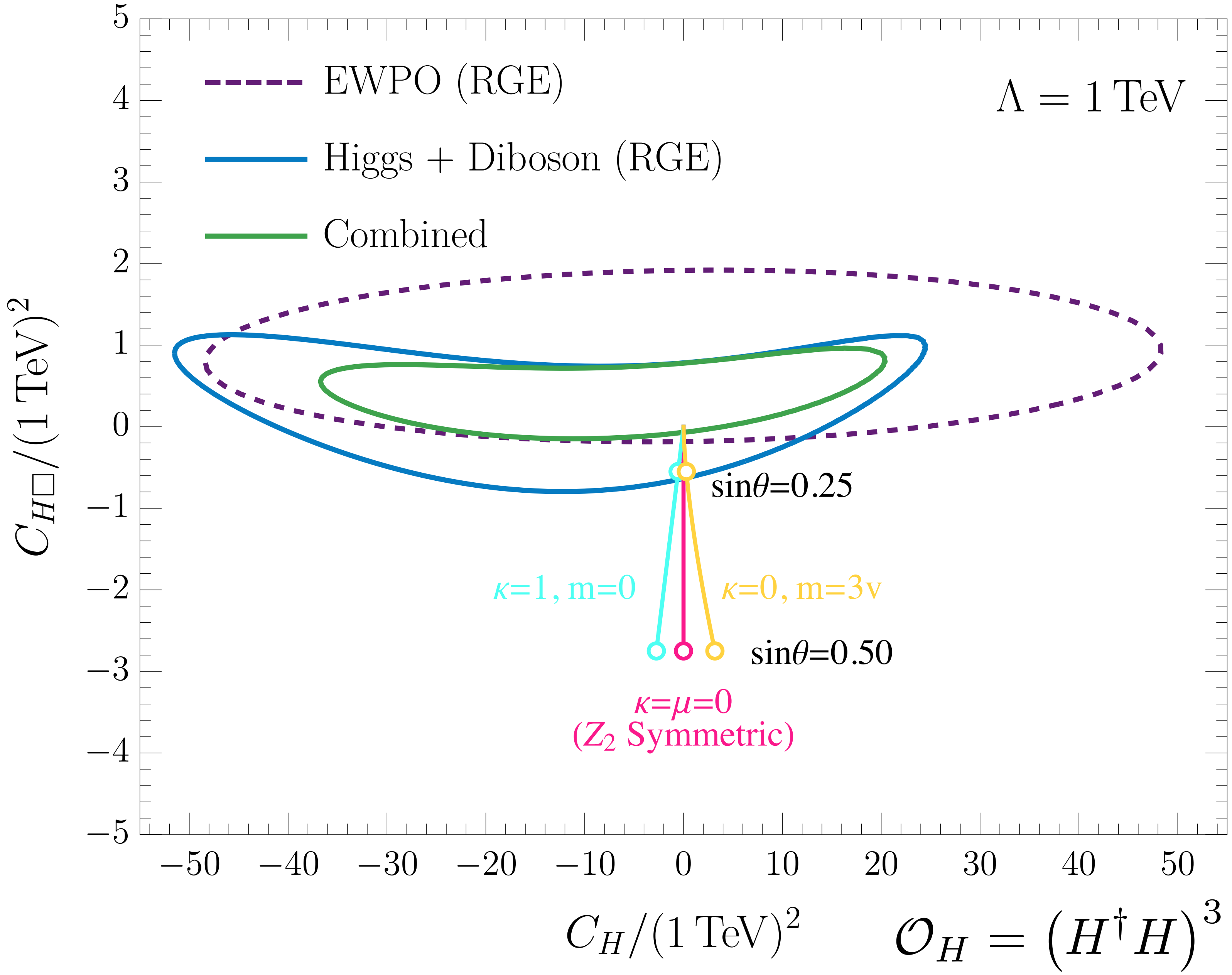
$$M^2 = m_h^2 \sin^2\theta + M_H^2 \cos^2\theta - \frac{\kappa}{2}v^2$$

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



$\mathcal{O}_H = (H^\dagger H)^3$

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

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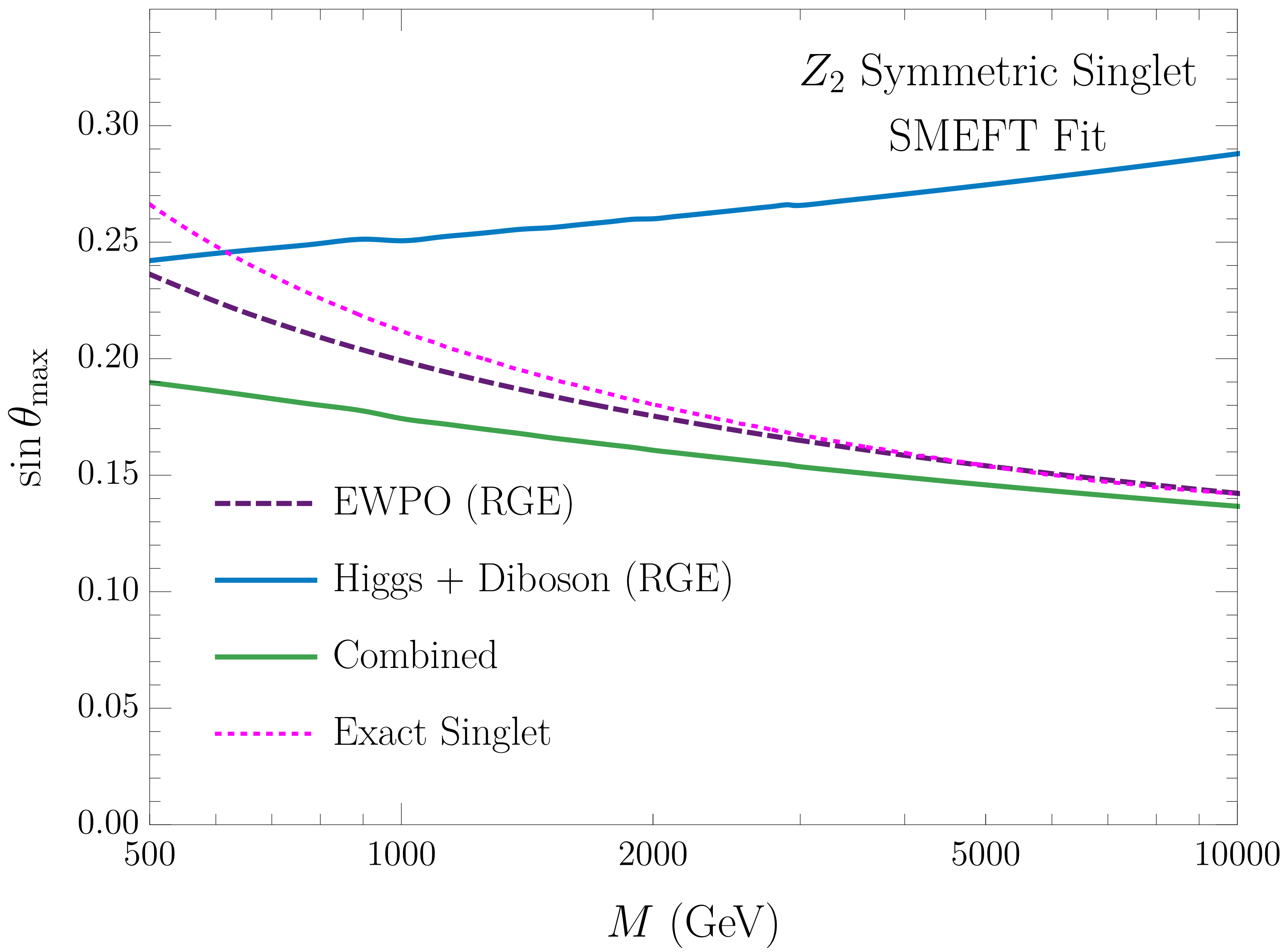

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One-Loop Matching

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…

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

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

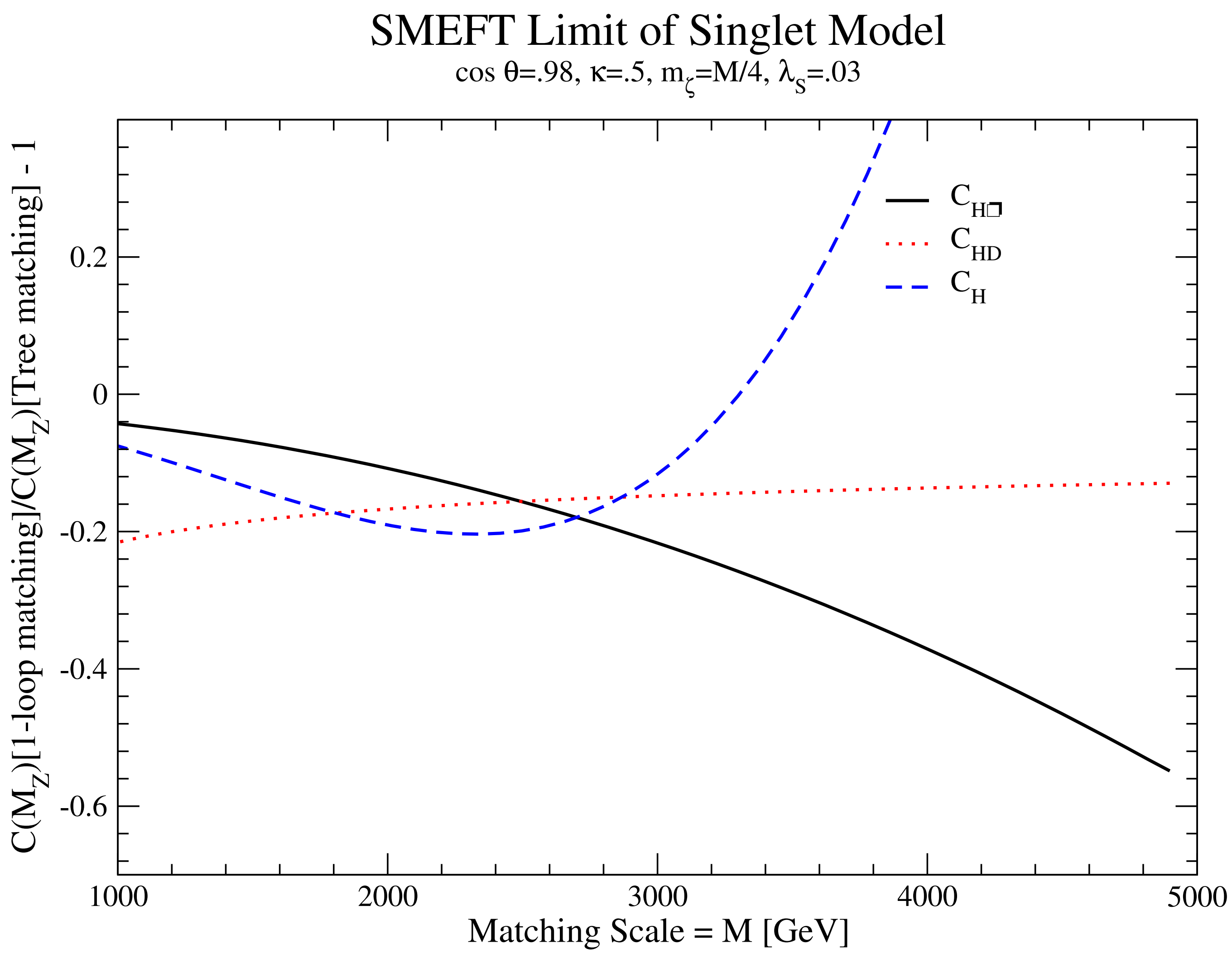
…as well as many operators that don't appear at tree-level

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

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

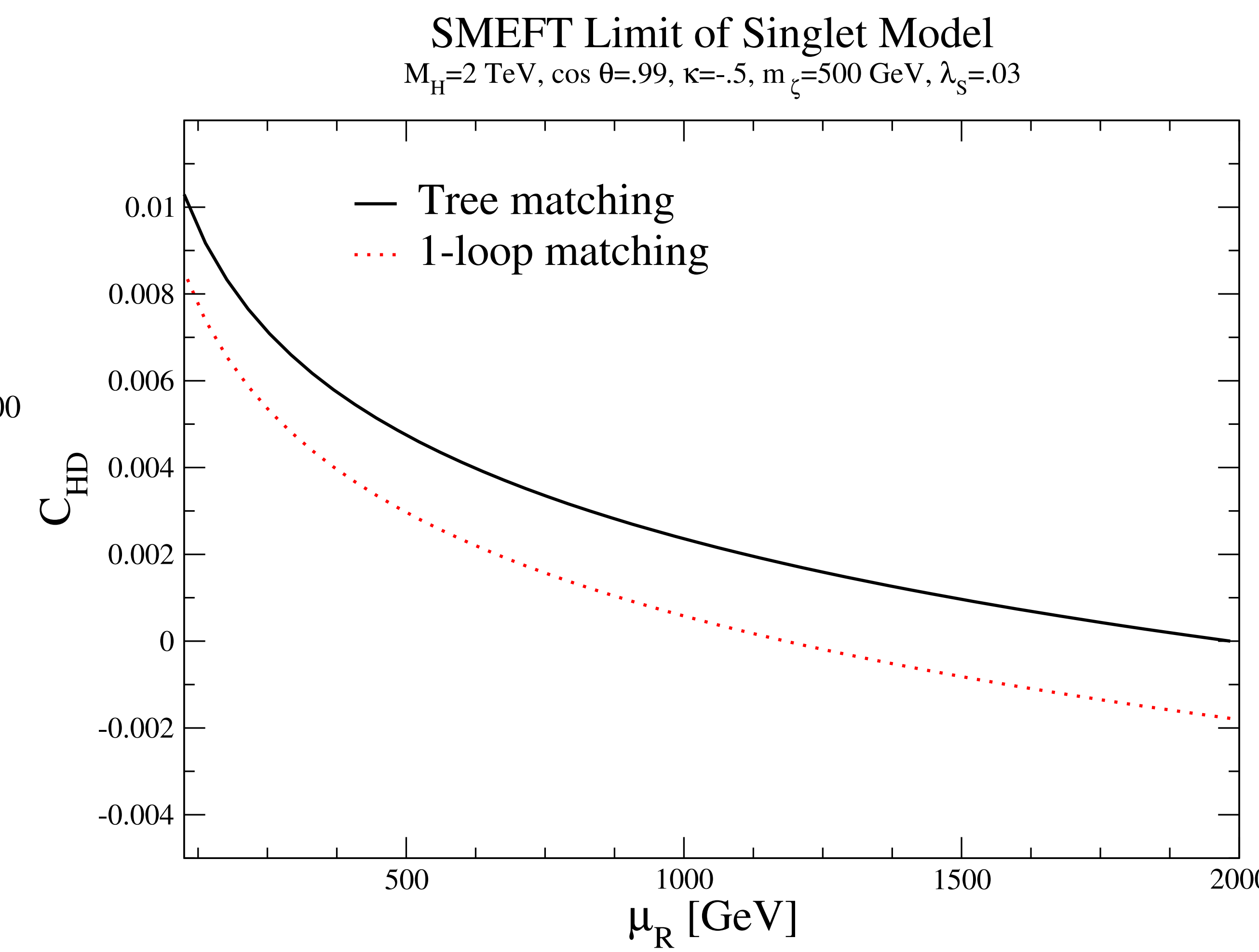
In principle of comparable size to RGE-induced contribution!

One-Loop Matching



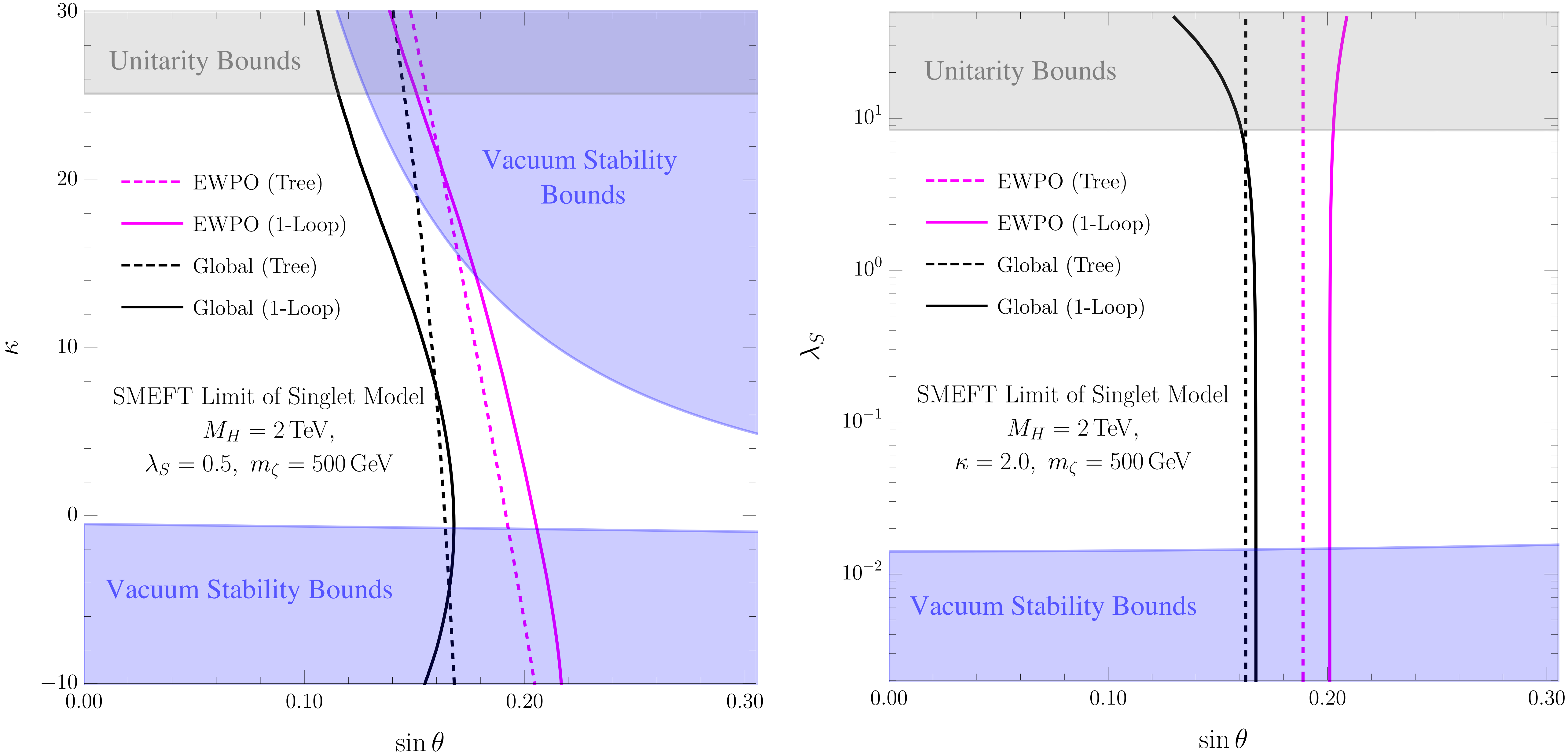
Include only one-loop RGEs

(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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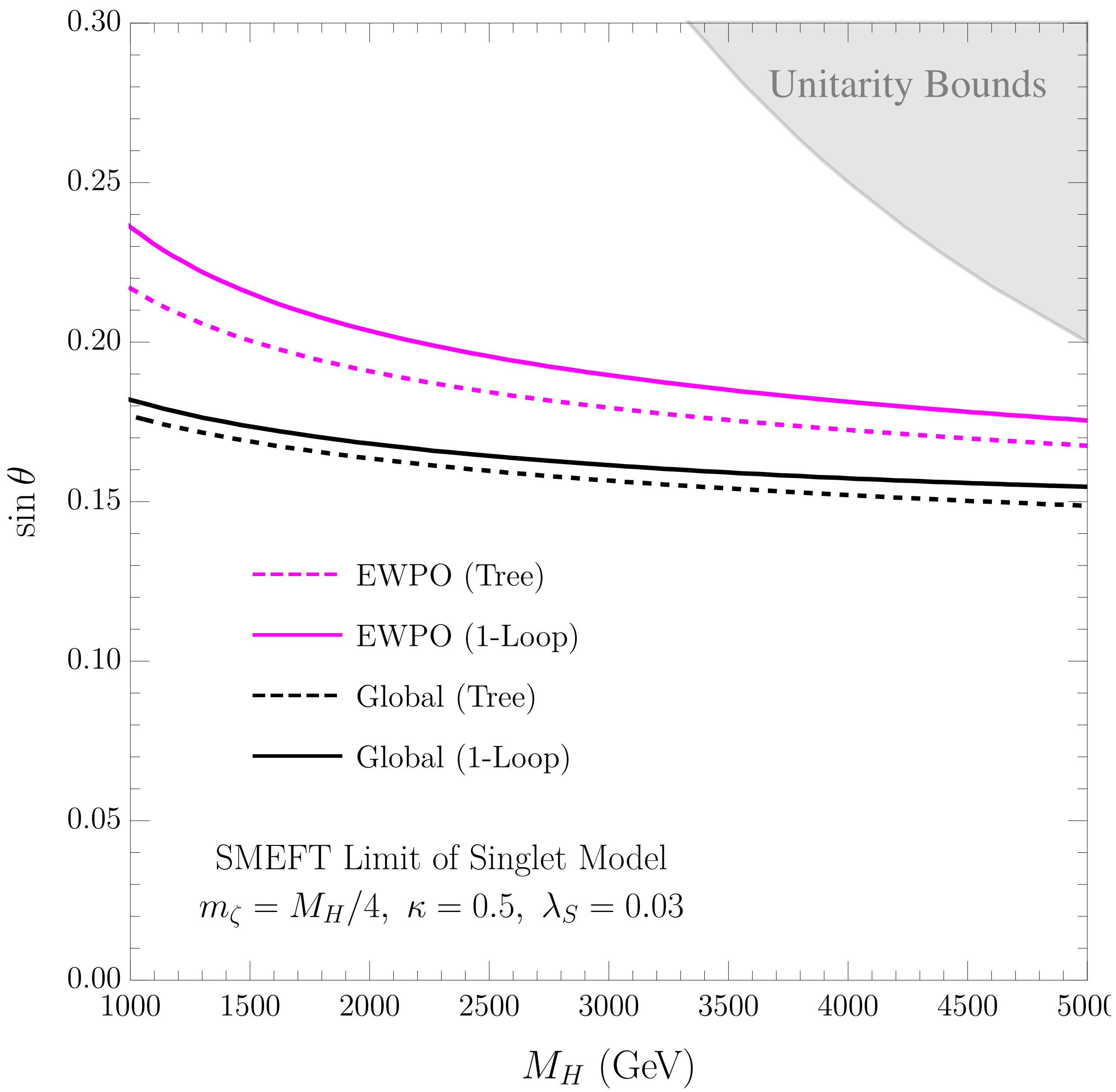

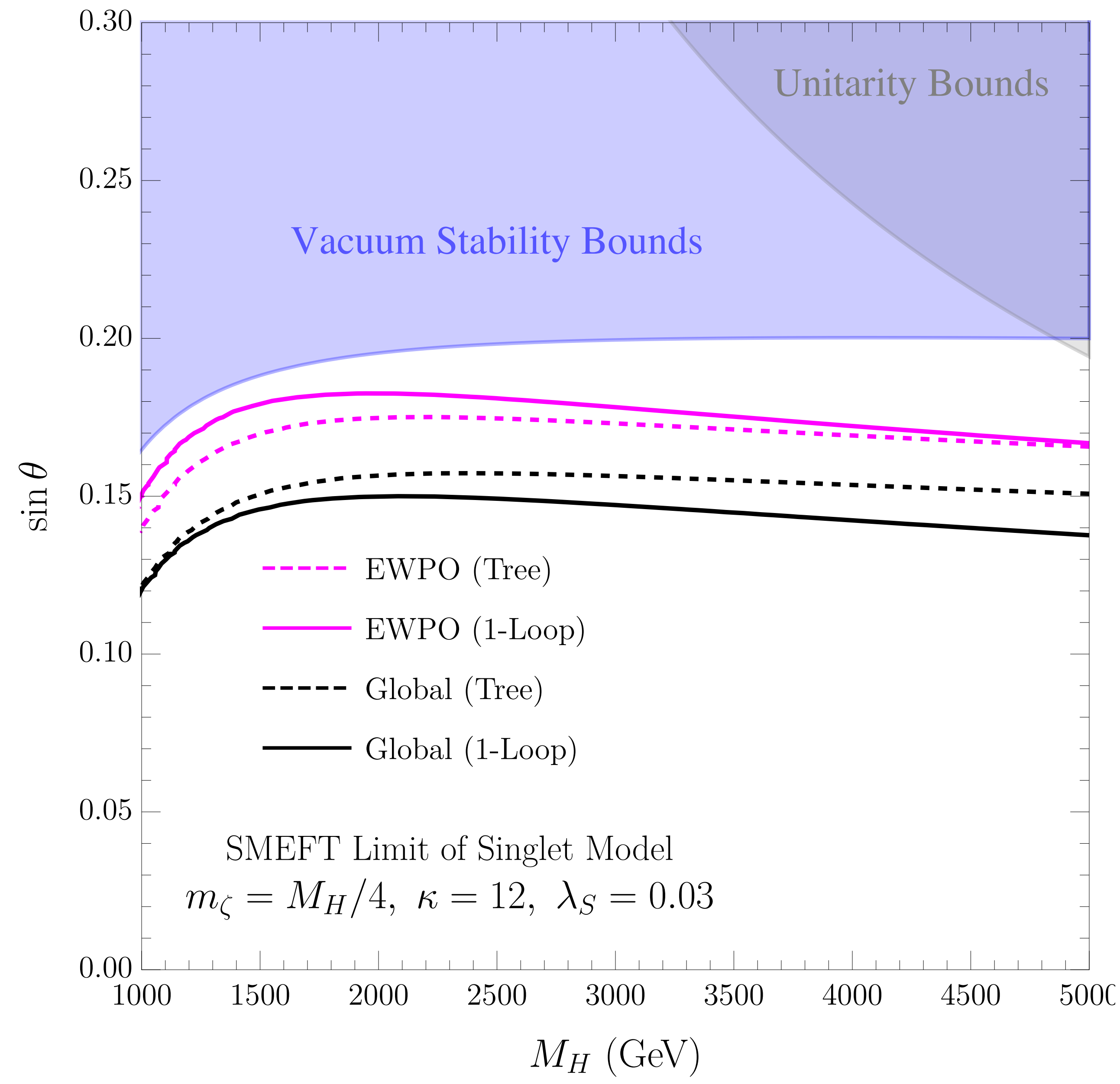

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Conclusions:

- The Higgs Inverse Problem is the next phase of LHC Higgs Physics
- 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!

Lots more work to do:

- More robust understanding what coefficients can be generated
- Understand linear vs. quadratic approximation in fits in context of models?
- Include complete one-loop matching for other models, more NLO effects in fits, and more distributions
- Importance of effects from dimension-8 operators?