Putting SMEFT Fits to Work

Based on

`arXiv:2007.01296, arXiv:2102.02823`

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In collaboration with

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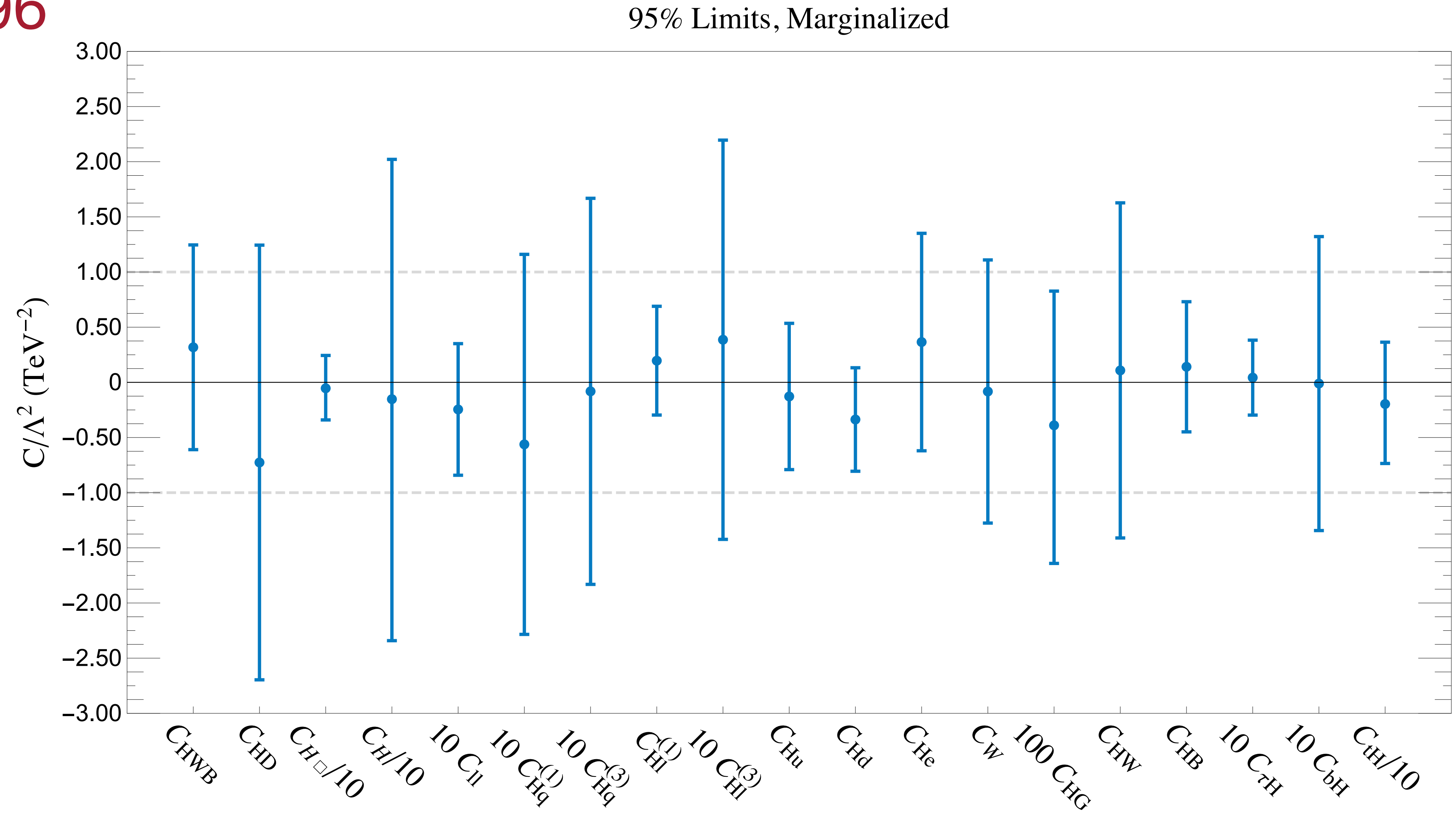
SMEFT: The Legacy of the LHC?

- Without clear signals of BSM physics, the SMEFT is playing an increasingly prominent role in Higgs + EWK Physics
- Lots of progress in recent years:
    - Experimental Constraints
    - Sophisticated Global Fits
    - Theoretical Understanding
    - Higher-Order Effects
    - ….
- Important questions remain on the theory side:
    - What does the space of models that UV-complete the SMEFT look like?
    - How can we best use LHC constraints moving forward?
    - **What are we really learning about BSM physics?**

Updated Global Fit

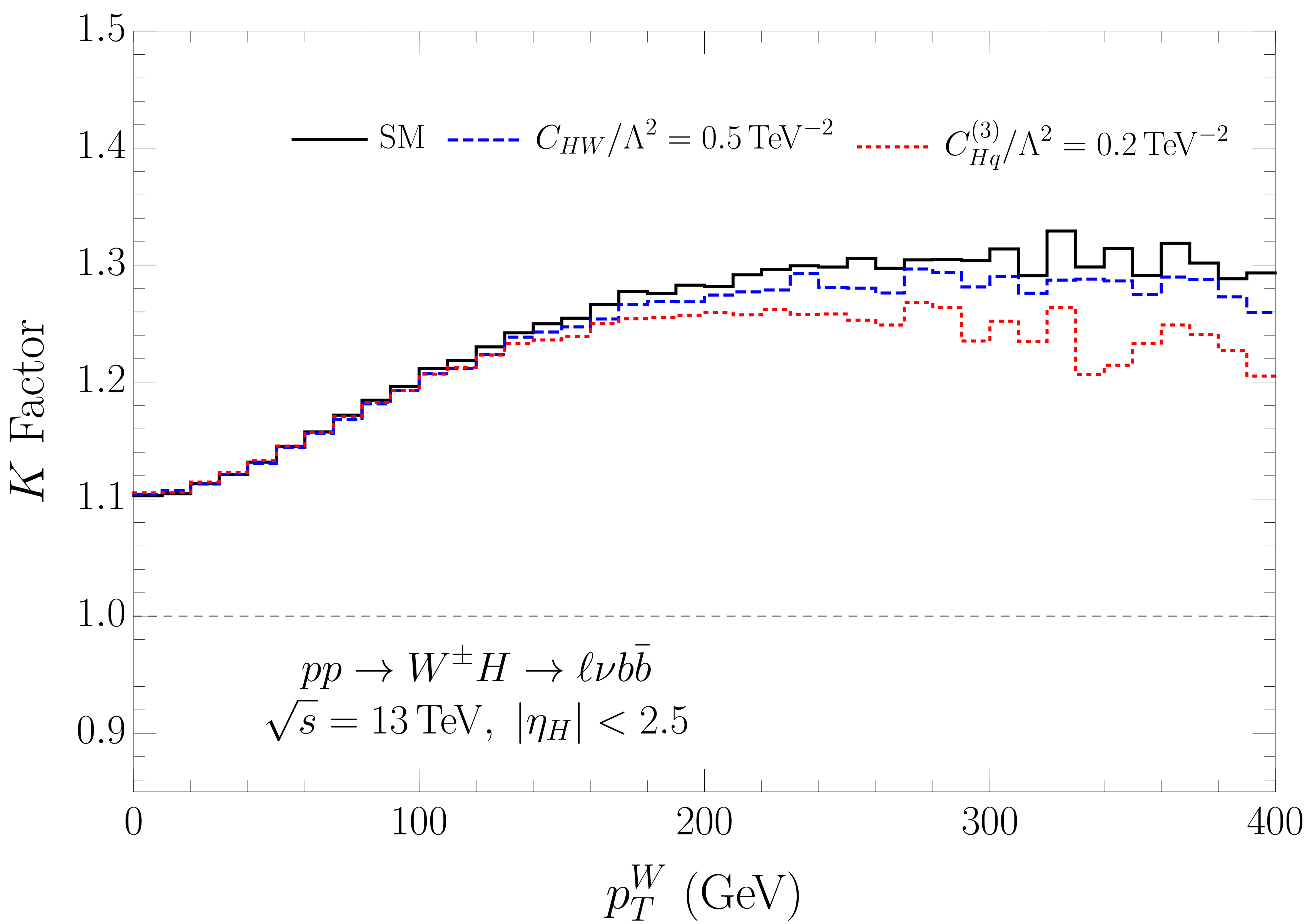
2007.01296



What's new here?

- Full NLO QCD Corrections in the SMEFT for *VH*, *VV* production (2003.07862)
- Leading Log NLO QCD + EW corrections to W, Z pole observables in the SMEFT (1909.02000)
- Loop-level contributions to the self-coupling (1607.04251)
- Higgs data using up to 137 fb^{-1} of data from ATLAS & CMS at 13 TeV

Including NLO Effects is Important!



Ratio of NLO/LO prediction in high bins is sensitive to presence of new operators

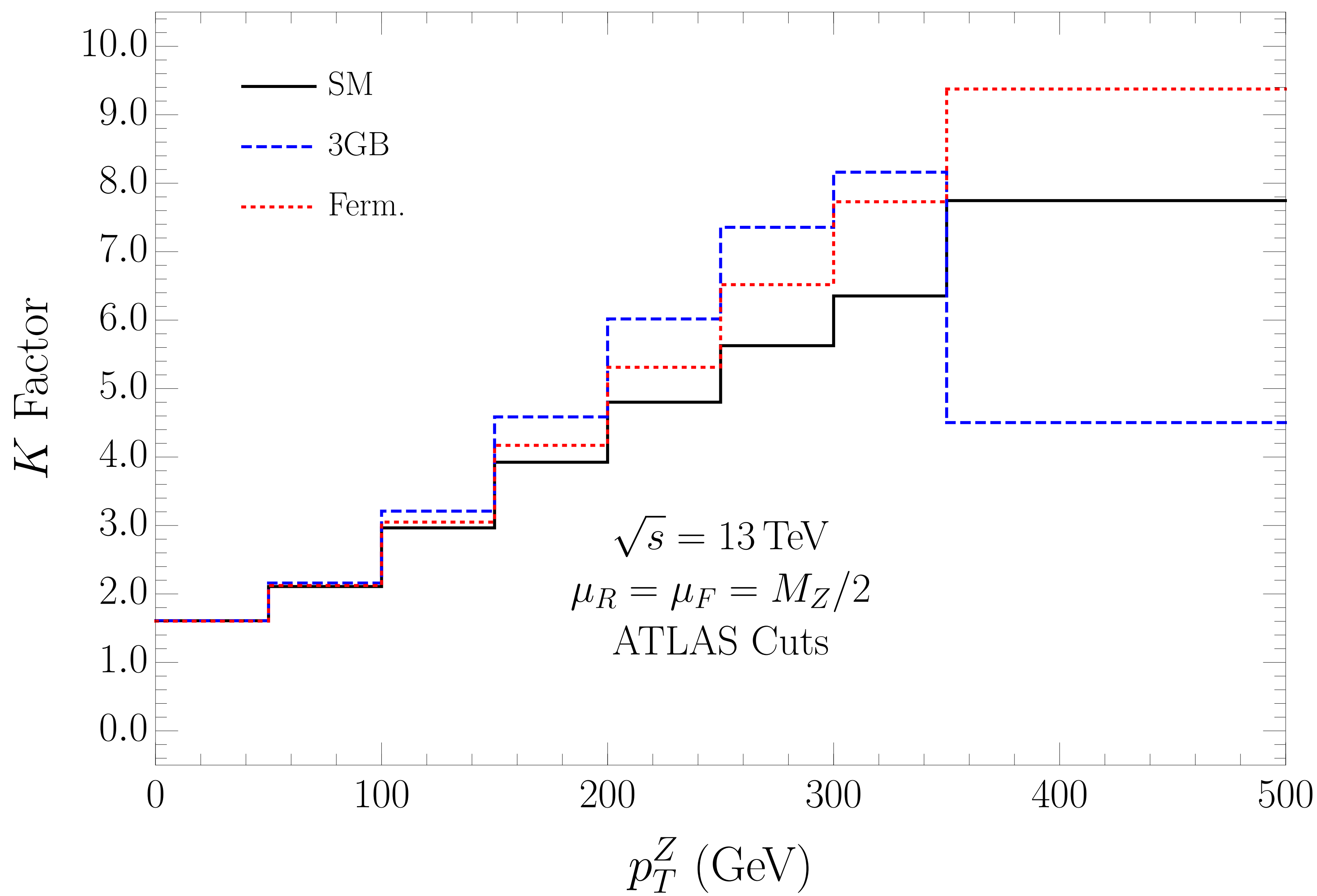
But these are also the bins that give the most constraining power!

QCD Corrections and anomalous coupling effects don't commute

Important to use full SMEFT@NLO predictions when setting limits

Including NLO Effects is Important!

Particularly in WZ Production



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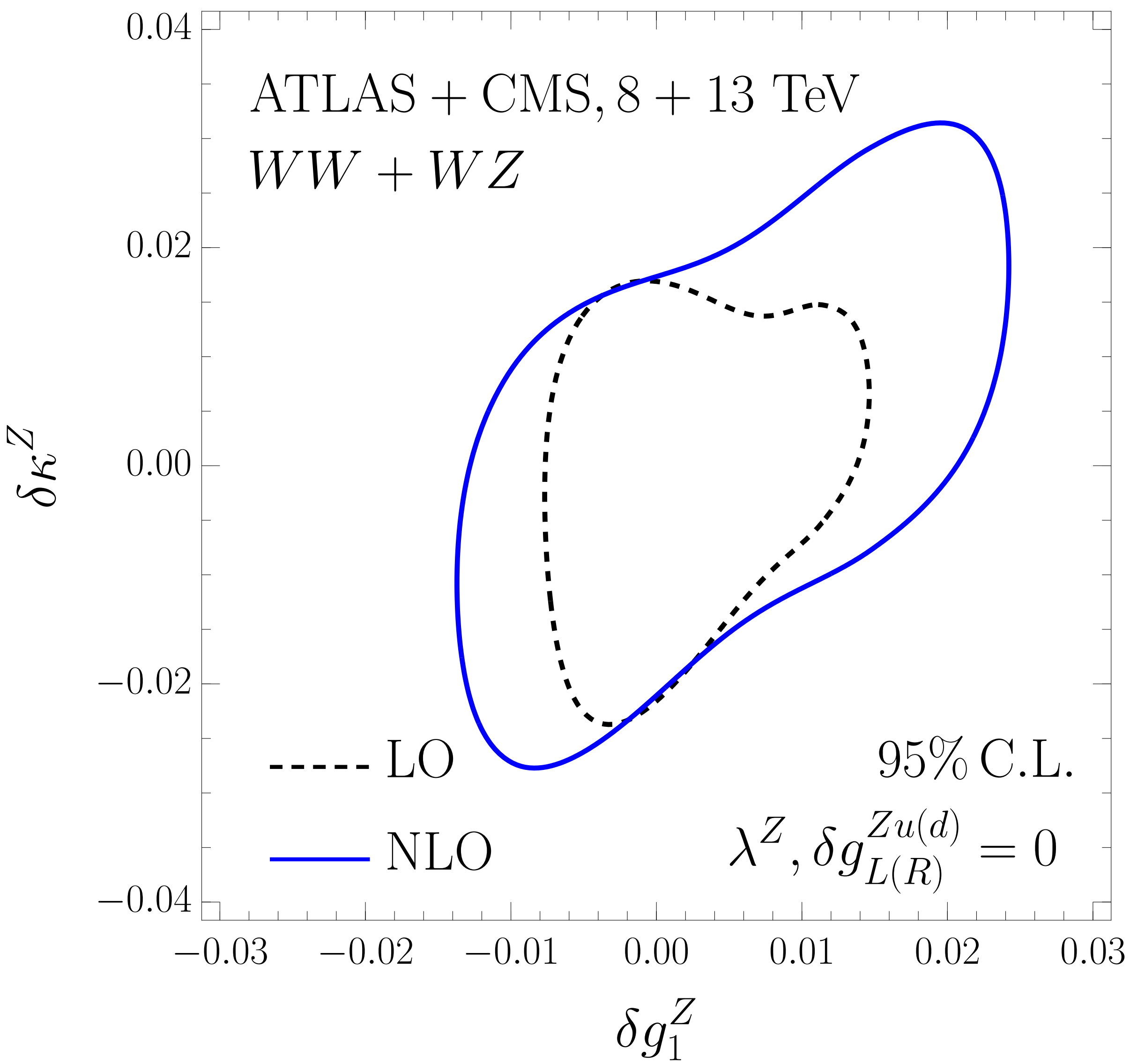
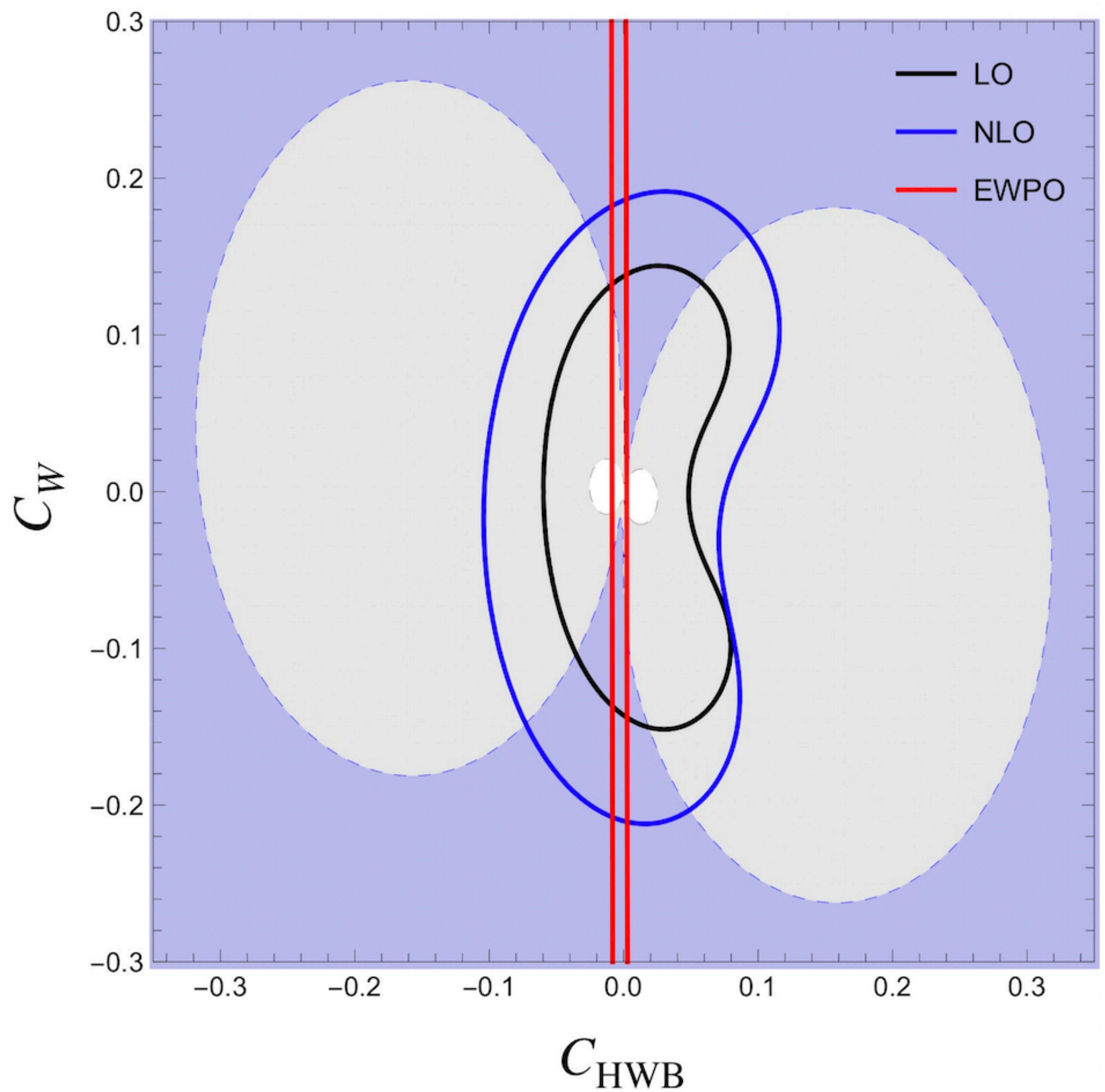
Including NLO Effects is Important!

Effects in Diboson Data Quantified in 1909.11576, 2003.07862

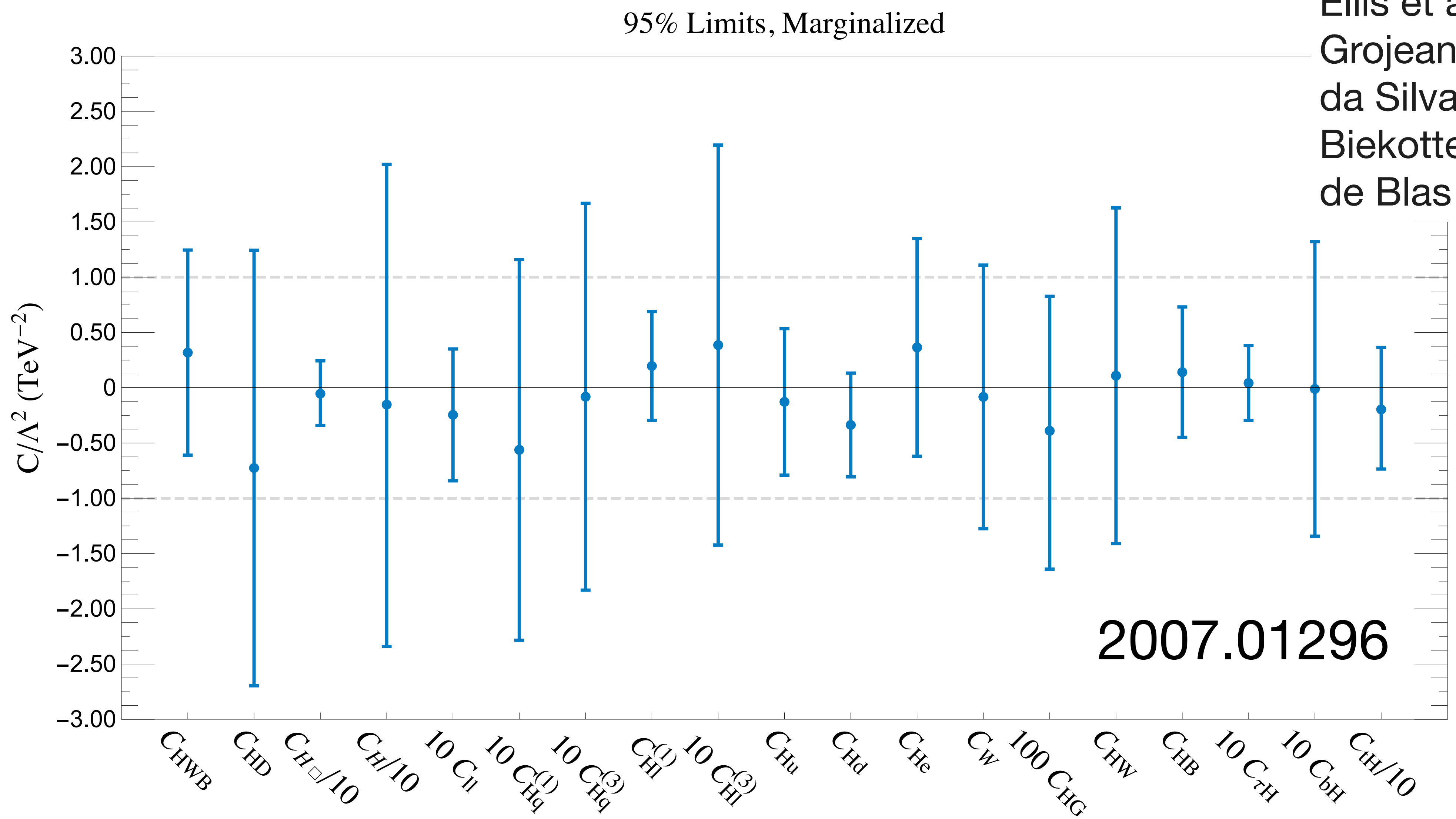




QCD Corrections and anomalous coupling effects don't commute

Important to use full SMEFT@NLO predictions when setting limits

A Number of Global Fits in the Literature…



See also:
Ellis et al., 1803.03252
Grojean et al., 1810.05149
da Silva Almeida et al.,1812.01009,
Biekotter et al., 1812.07587,
de Blas et al., 1905.03764

Important to remember that ultimately we’re looking for *new physics!*

How do we interpret these limits in the context of particular models?

Strategy:

Example: *T* Vector-like Quark

Integrate out new particles at matching scale (M ~ few TeV)

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

Generate subset of SMEFT Coefficients

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

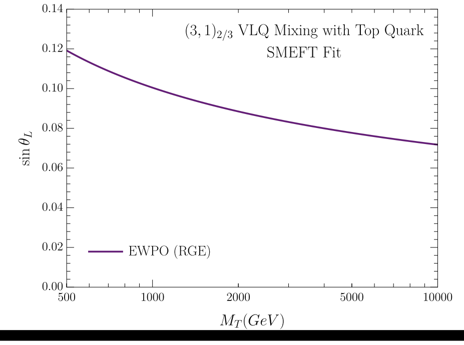
Evolve Coefficients down to EW scale

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

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

Fit to Higgs + Diboson + EWPO Data

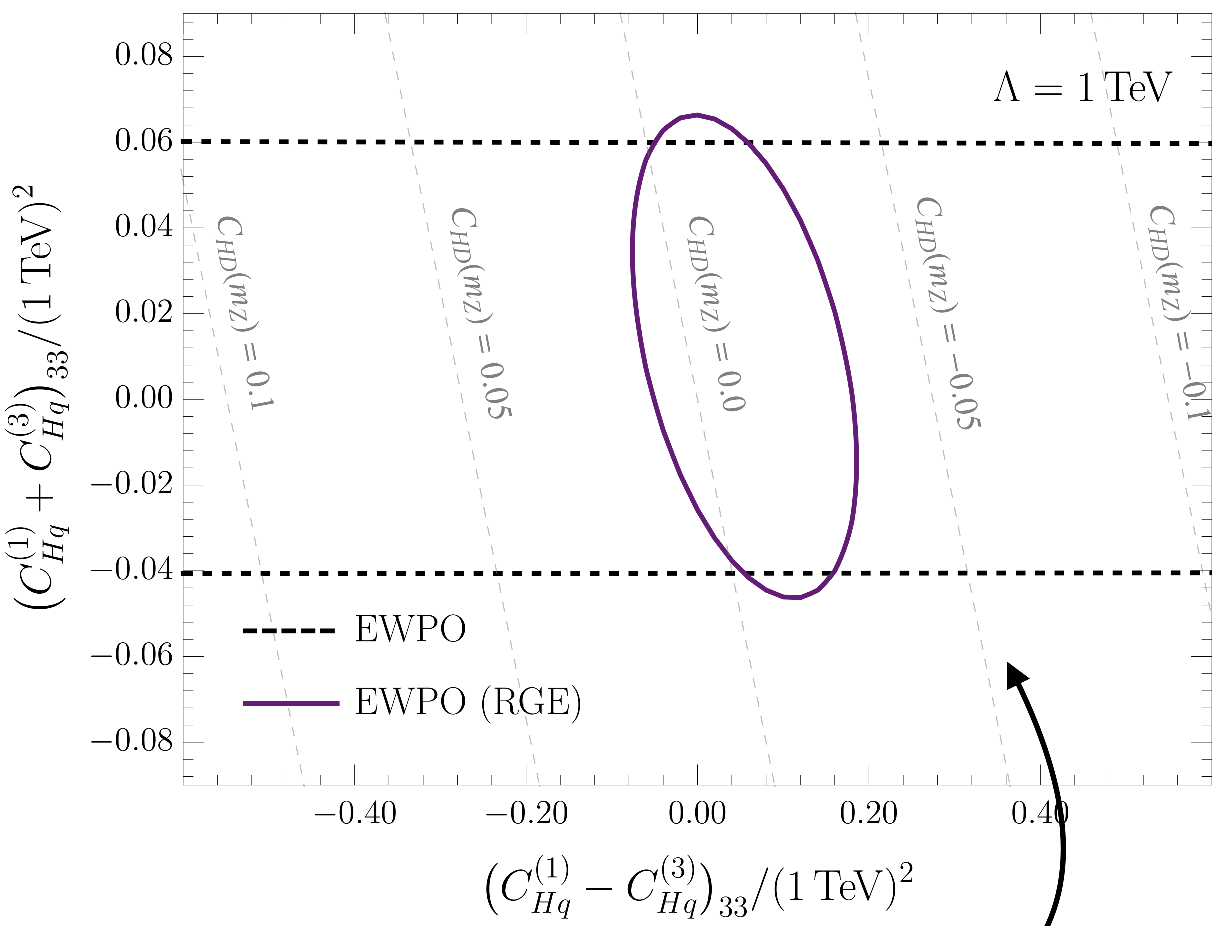
→ Limits on physical parameters!



SM + VLQ Singlet Mixing with Top

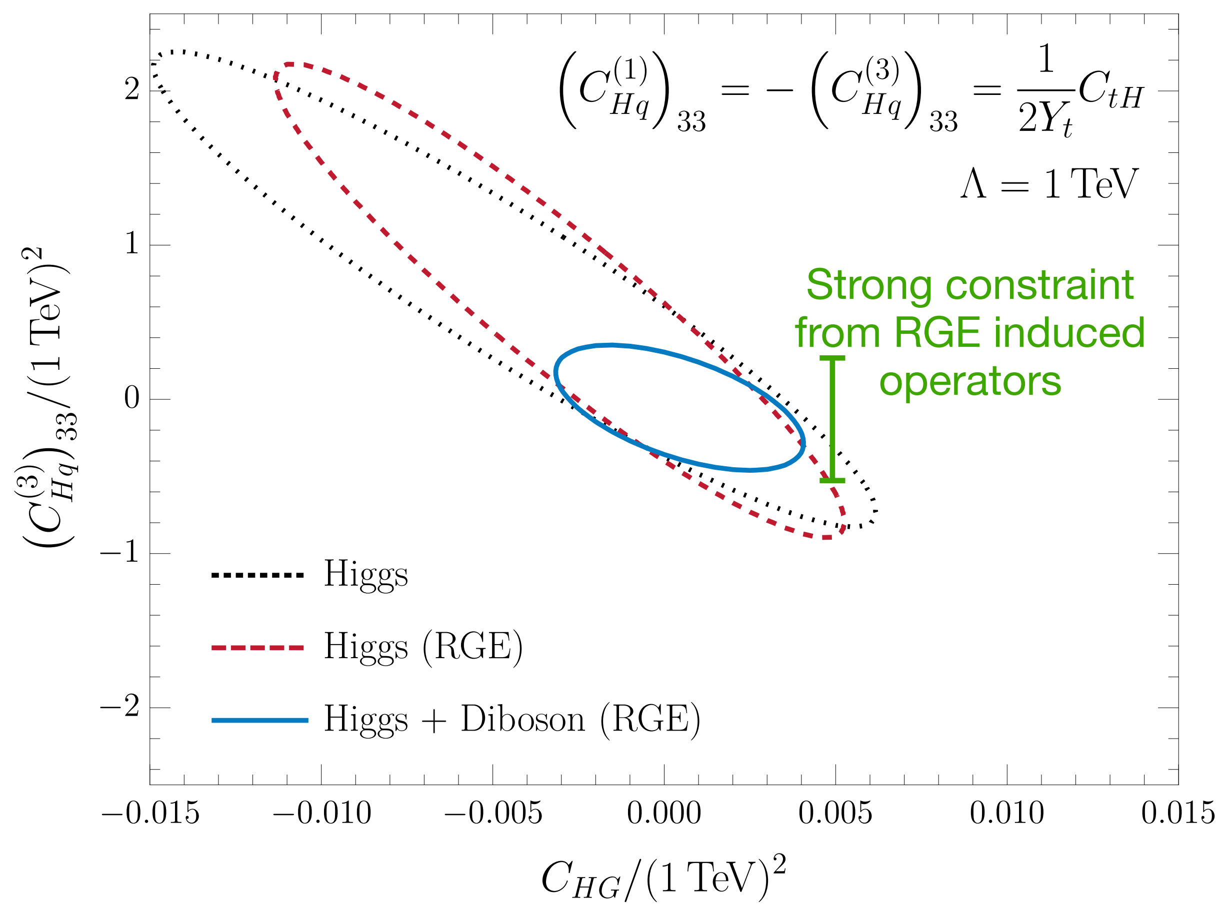
Generates C_{tH}, $(C_{Hq}^{(1)})_{33}$, $(C_{Hq}^{(3)})_{33}$, C_{HG} at the matching scale

EWPO Constraints:



LEP sensitivity via Z to bb — flat direction broken by RGEs

LHC Constraints:

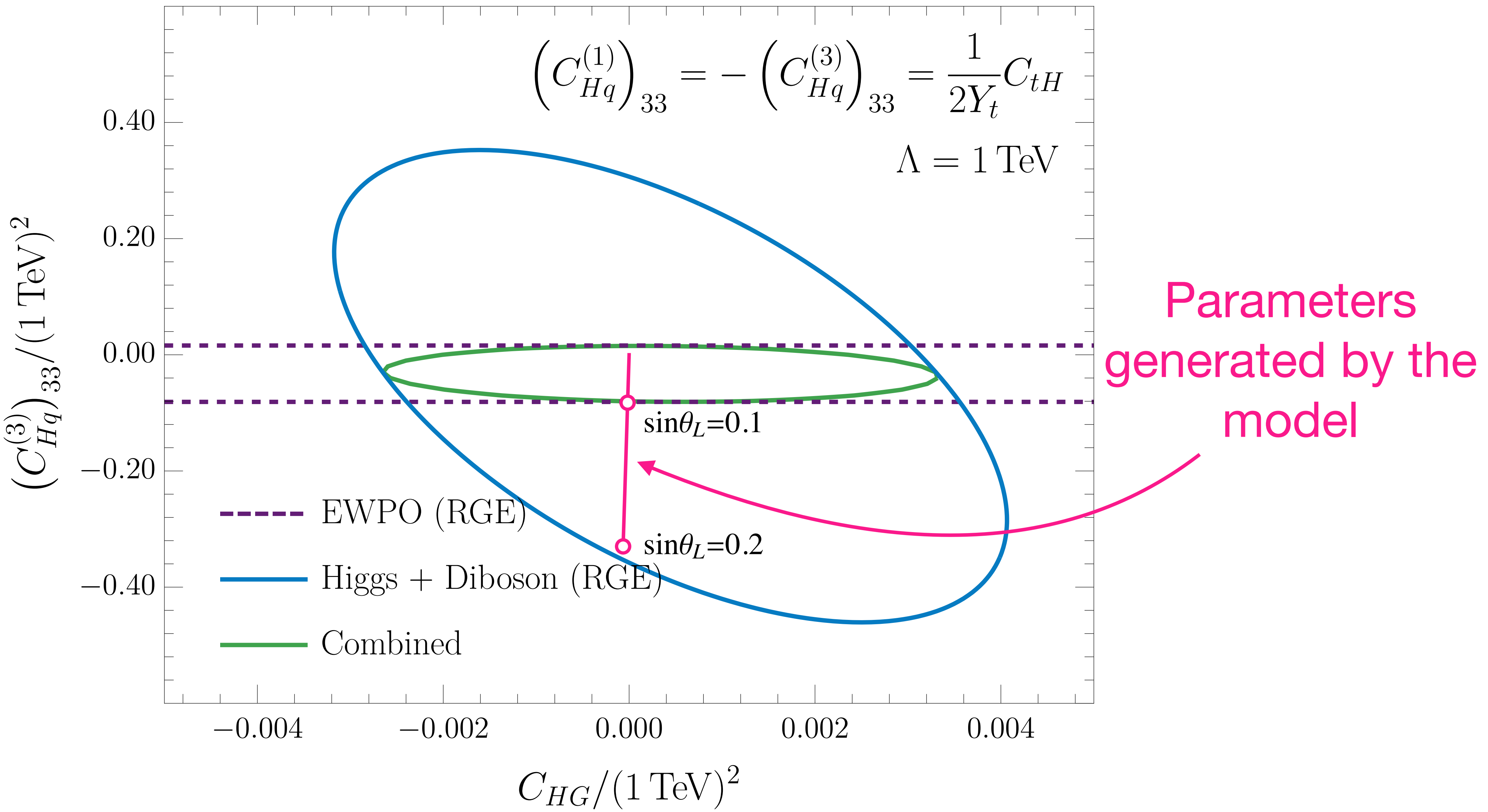


Note: NLO effects important for these diboson limits! (1909.11576)

SM + VLQ Singlet Mixing with Top

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

The T VLQ is a 1-parameter model — sweeps out only a line in this plane



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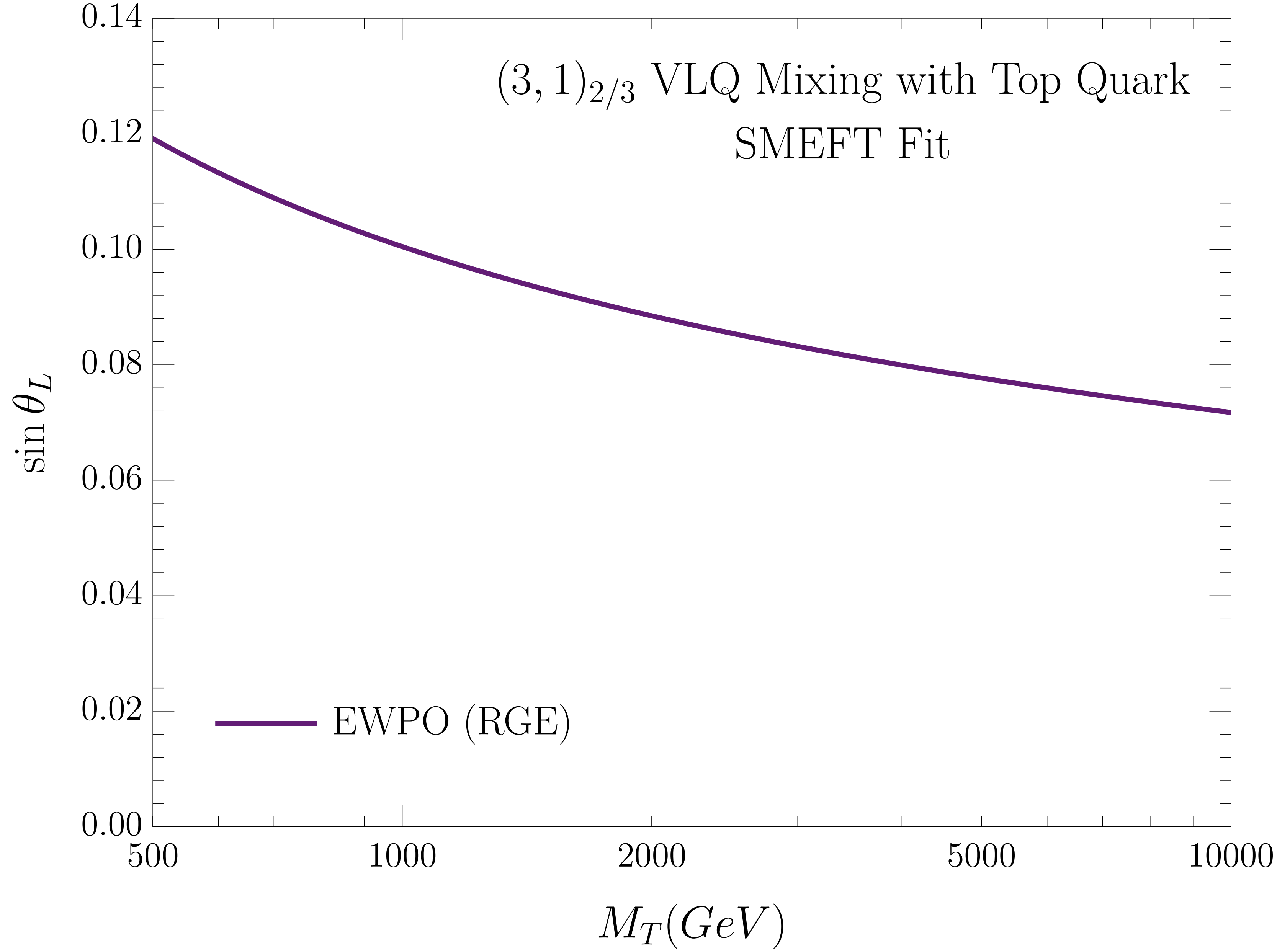
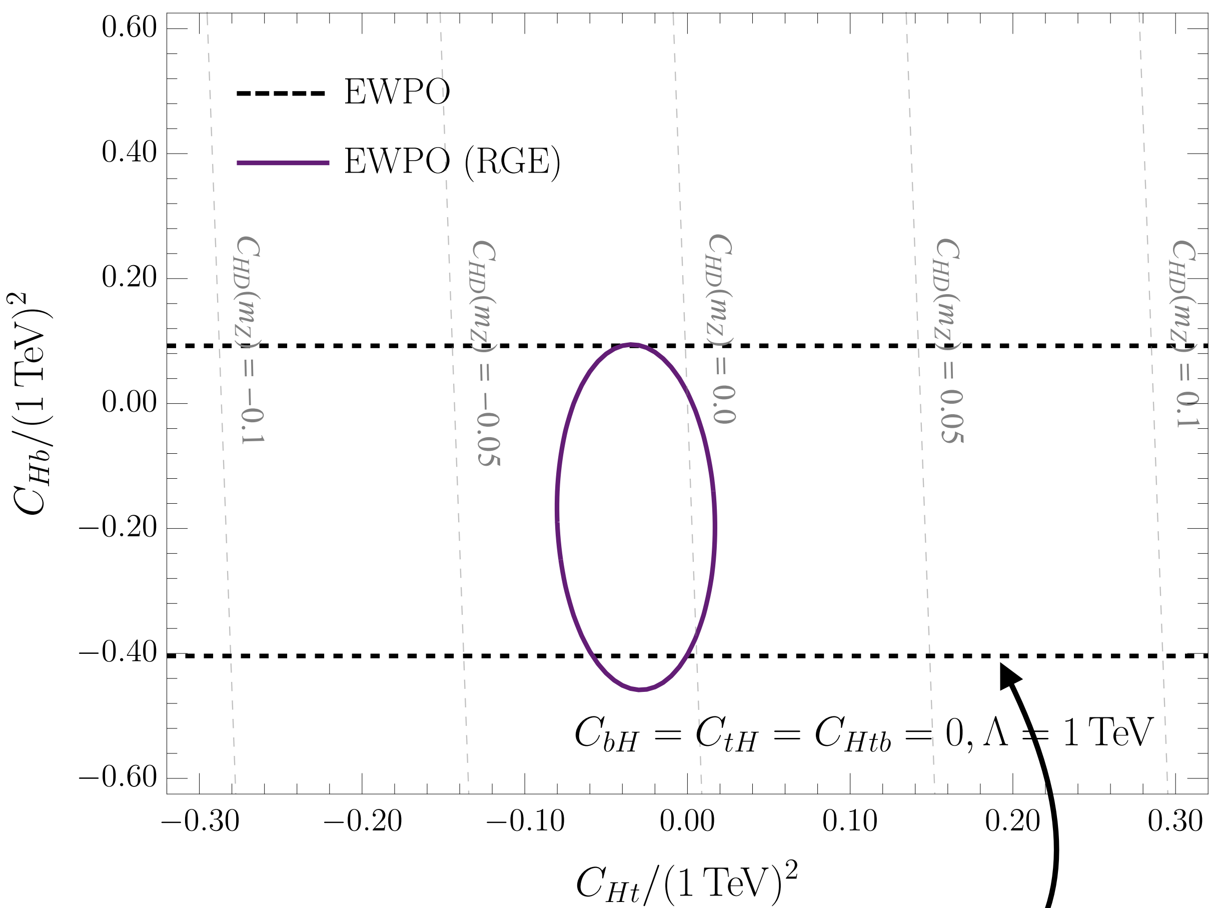


SM + VLQ Doublet Mixing with (t,b)

Generates C_{bH}, C_{tH}, C_{Hb}, C_{Ht}, C_{Htb}, C_{HG} at the matching scale

EWPO Constraints:



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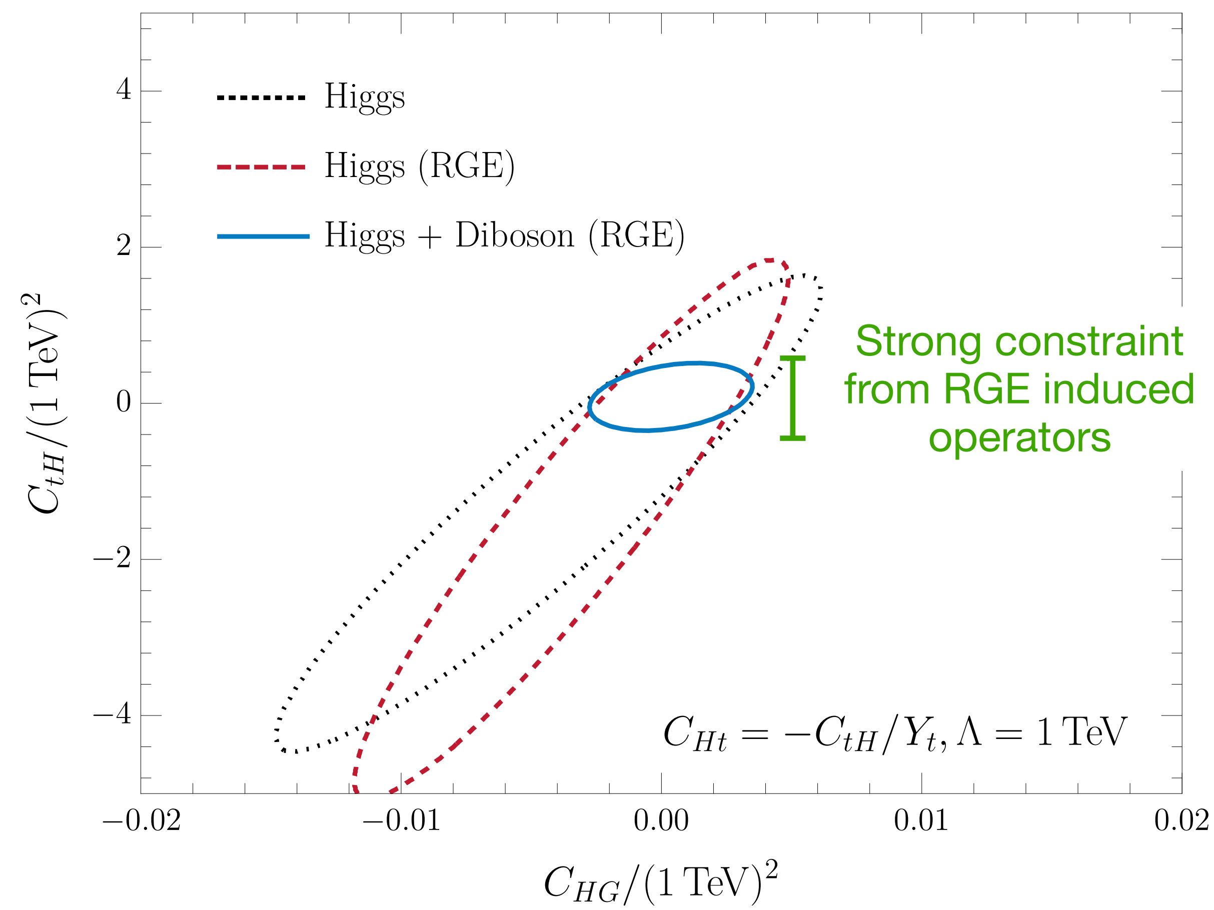

SM + VLQ Doublet Mixing with (t,b)

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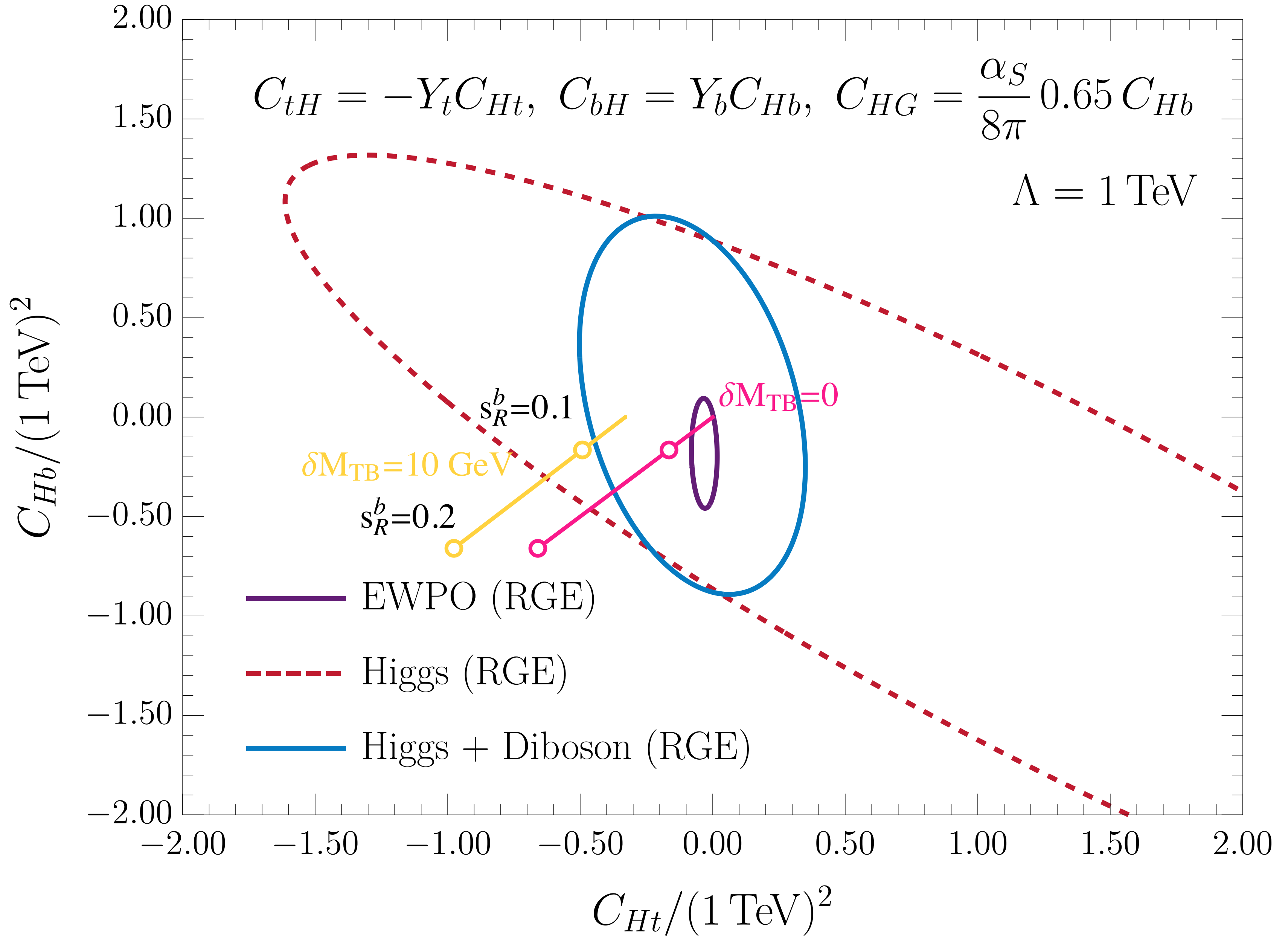
Model described by *two* parameters — mixing angle and mass splitting



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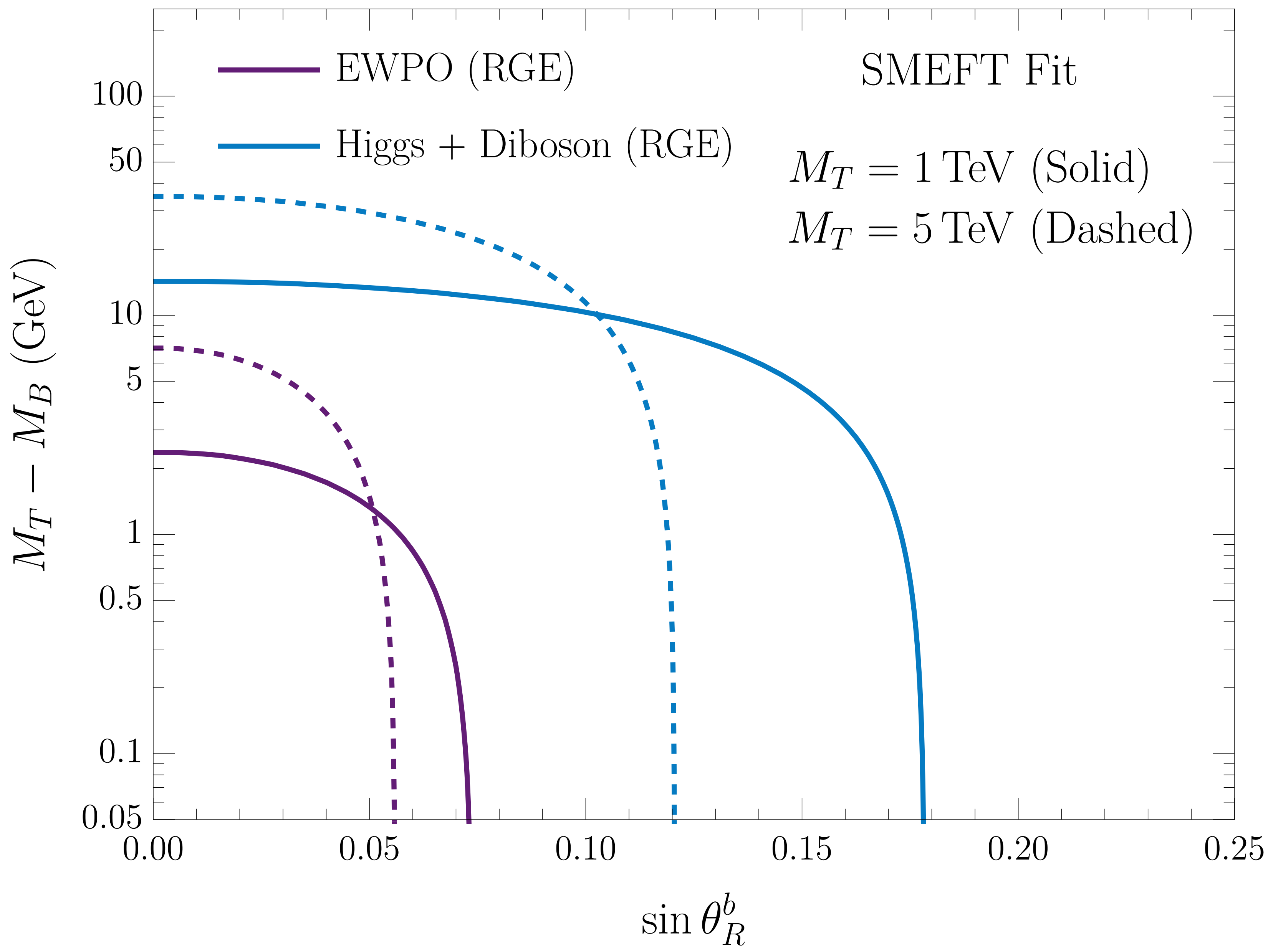
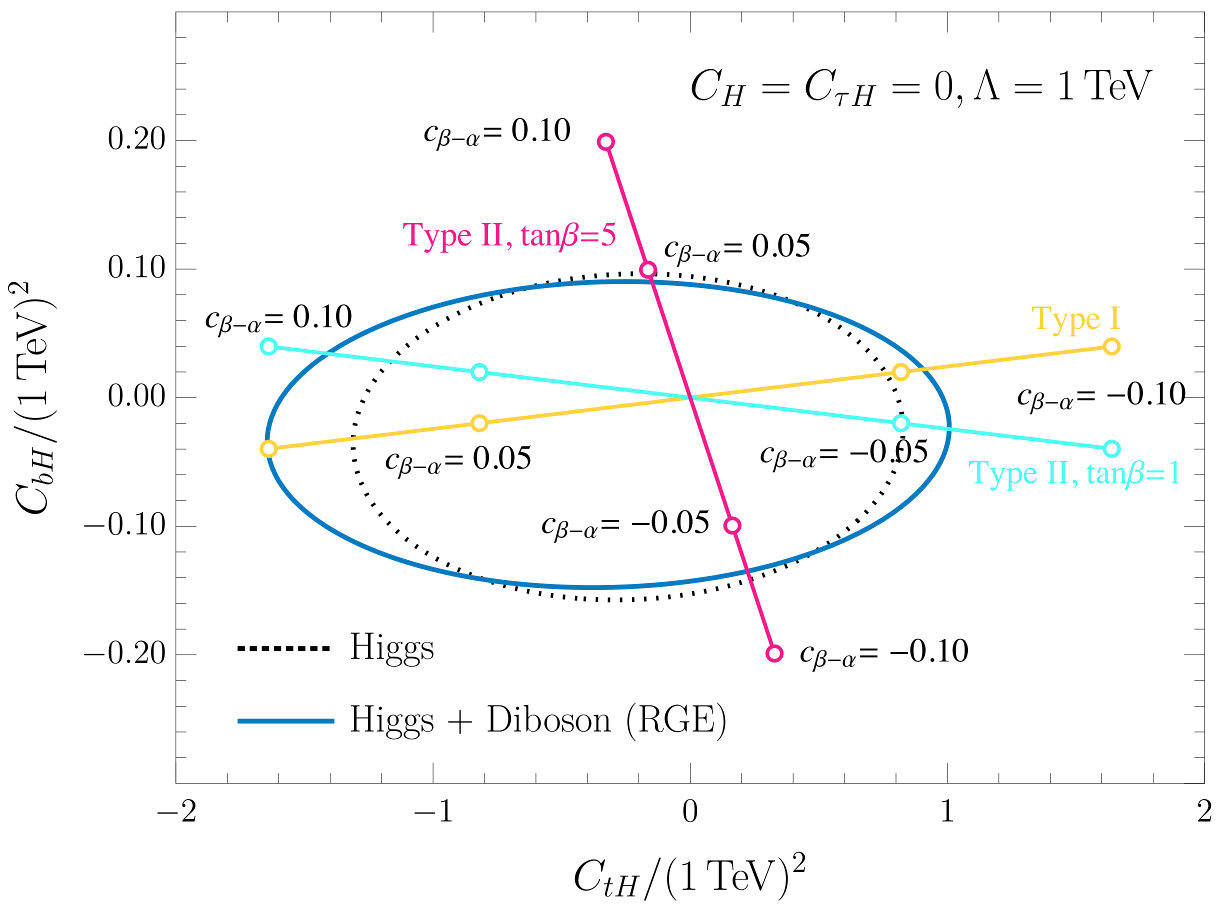
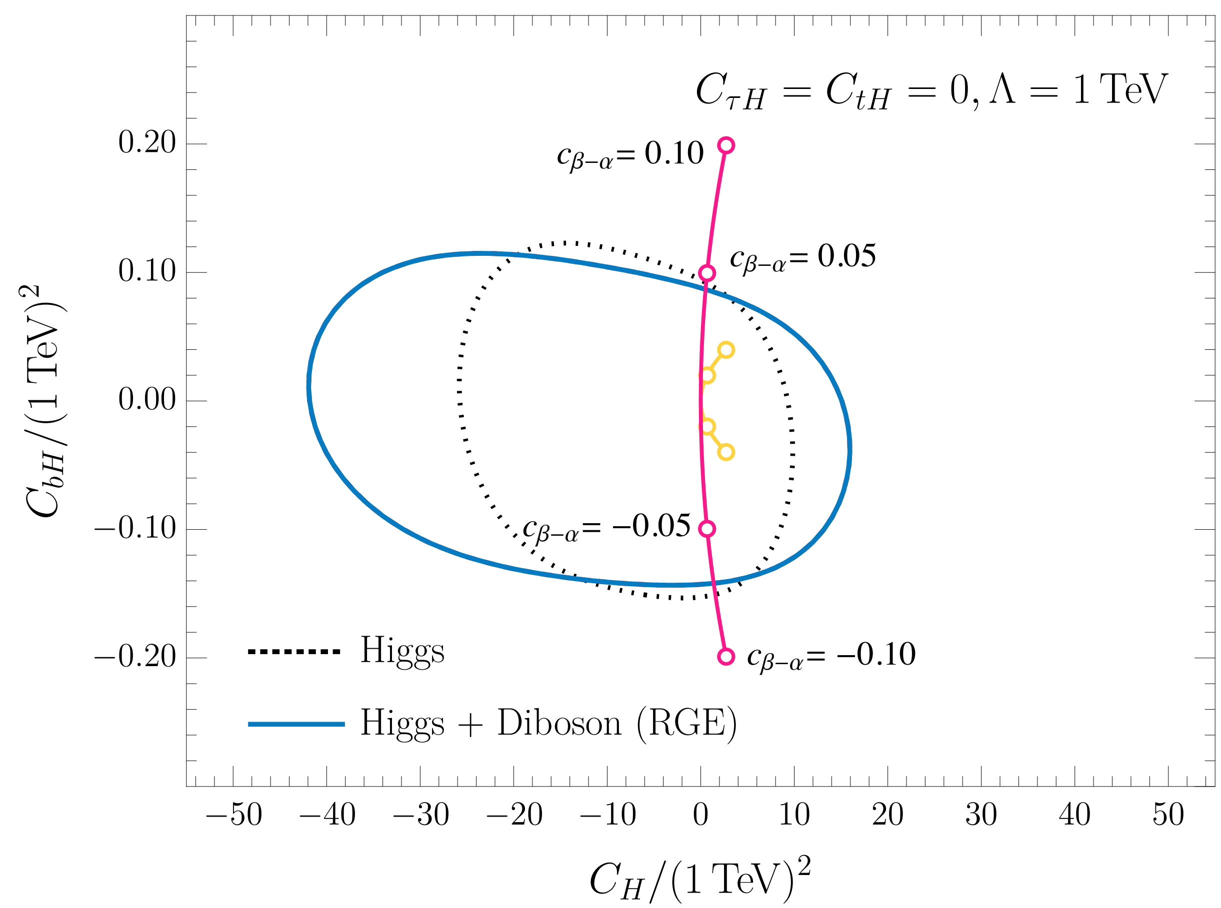


Two Higgs Doublet Models

Generates C_H, C_{bH}, C_{tH}, $C_{\tau H}$ at the matching scale





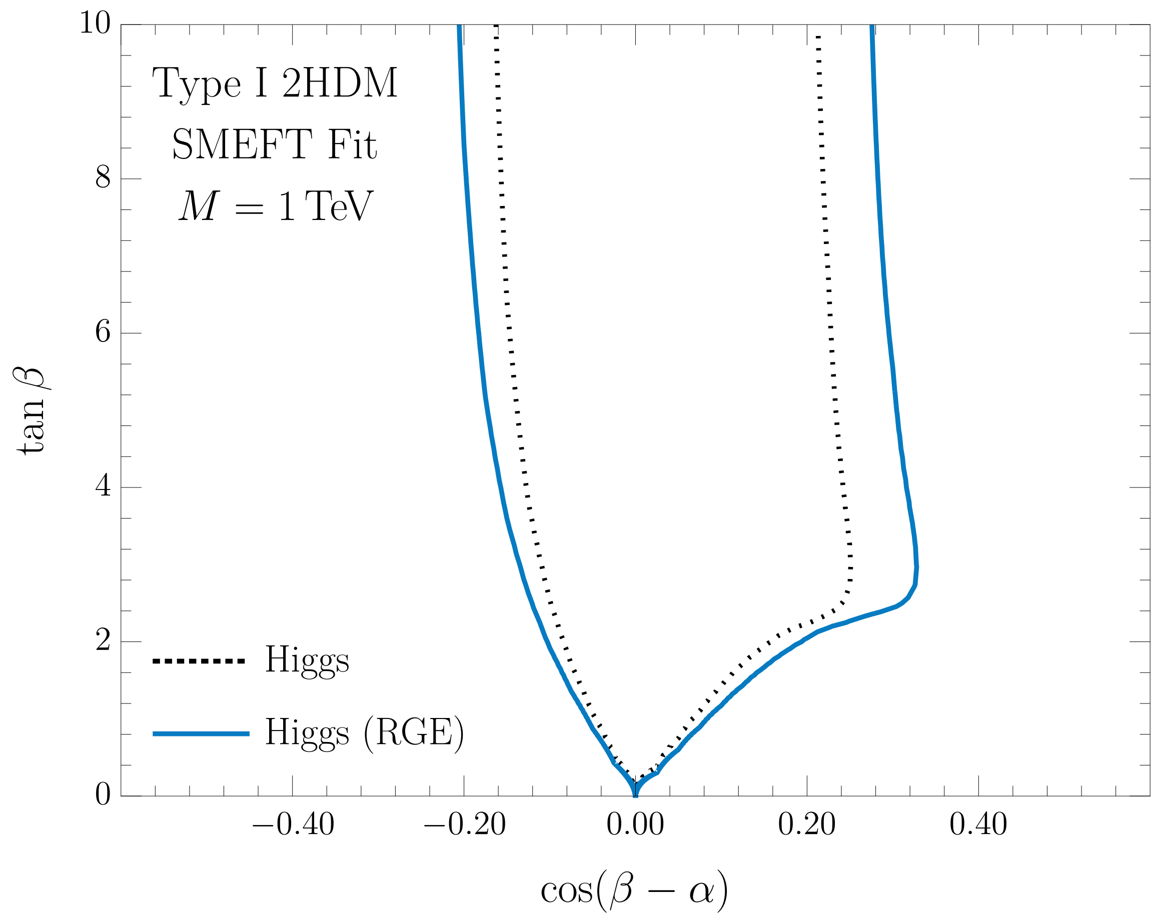
2HDM limits come entirely from Higgs data

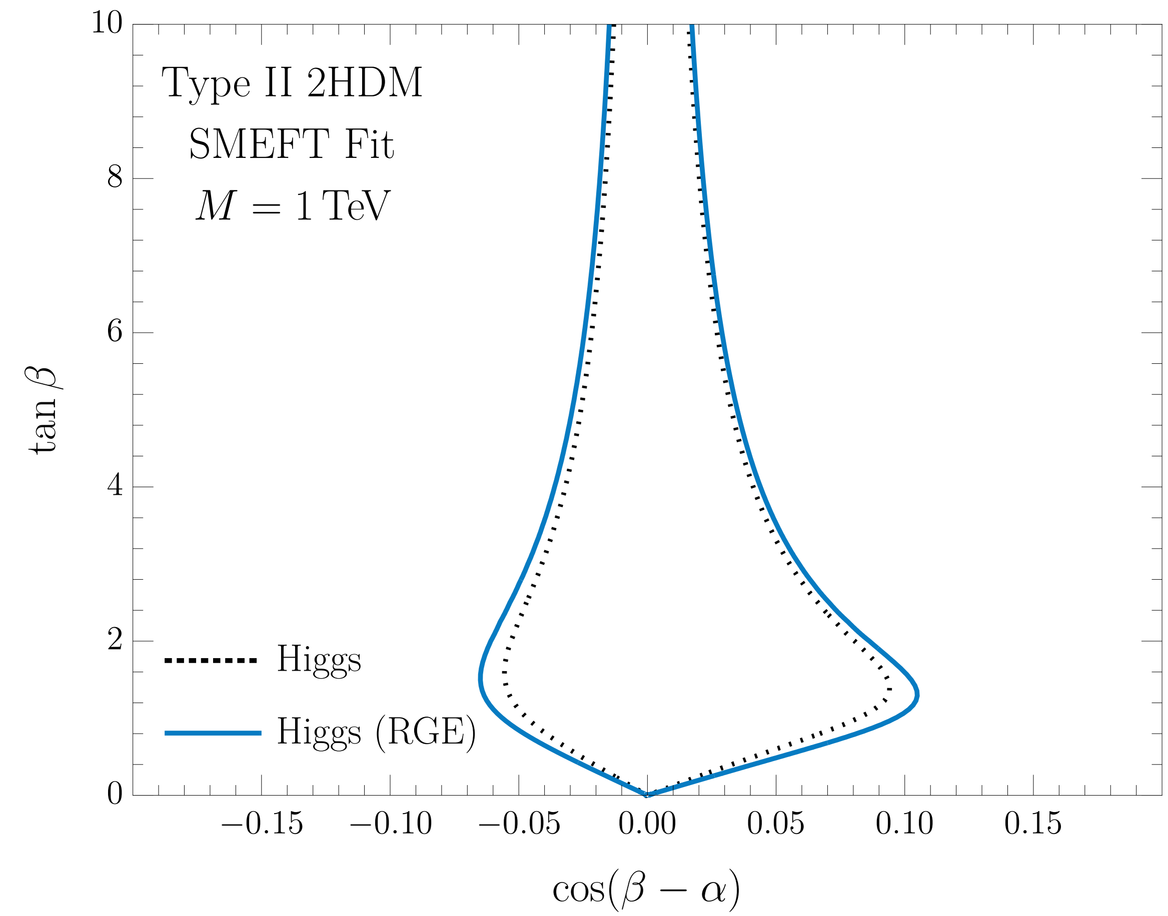
Different types of models sweep out wide range of allowed coefficients

Two Higgs Doublet Models

Generates C_H, C_{bH}, C_{tH}, $C_{\tau H}$ at the matching scale

Note that these are SMEFT Fits — not 2HDM fits!





Bounds can be reinterpreted in the usual physical parameter space

RGE effects slightly change the limits

Interlude: 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)

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

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

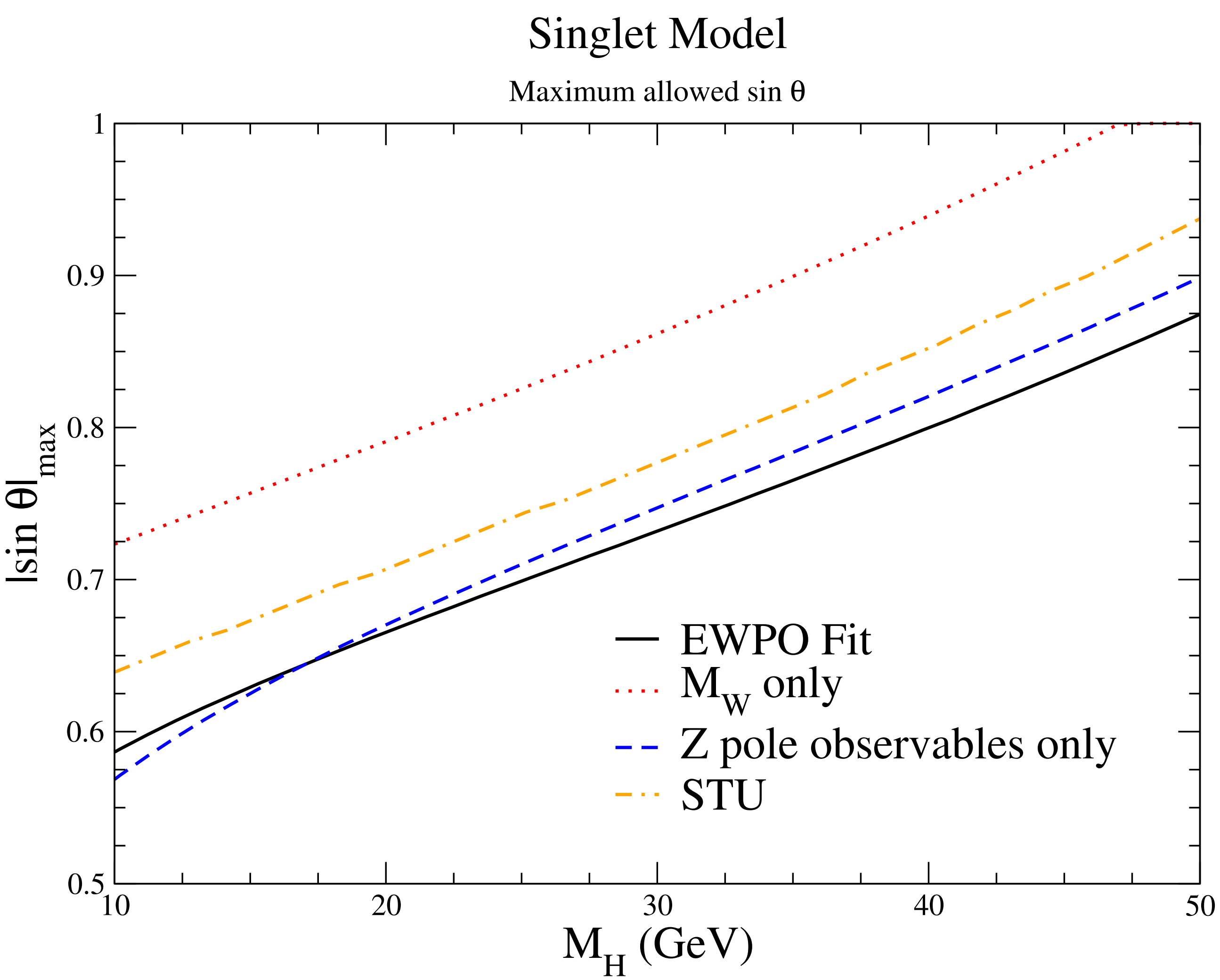
Other physical parameters:

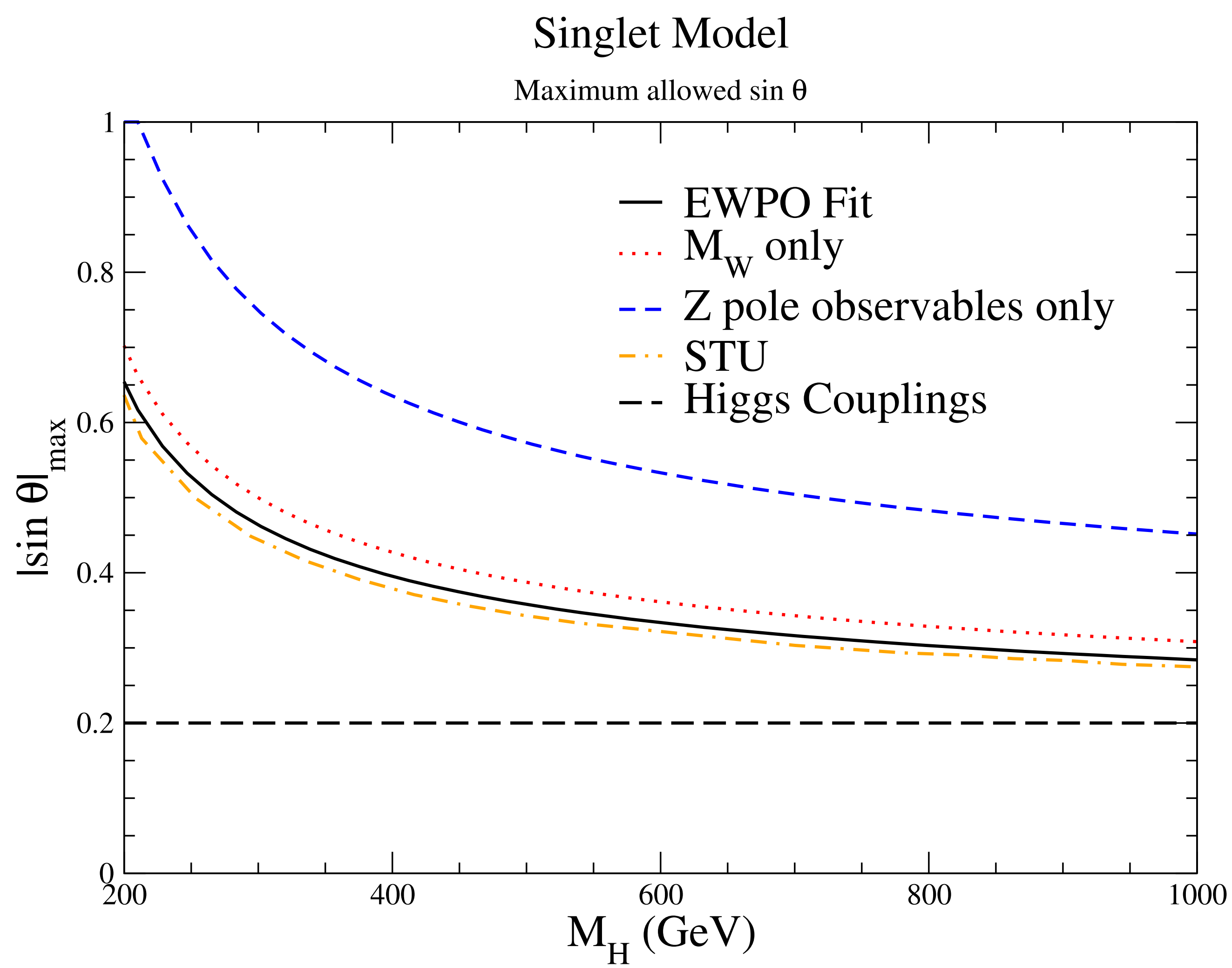
$$\sin\theta, \;\; \kappa, \;\; m_\zeta, \;\; \lambda_S$$

Higgs couplings universally suppressed by $\cos\theta$

The Singlet Model

Constraints in the context of the exact model:





Can also be directly probed via resonant di-Higgs production in the 250 to ~700 GeV range (e.g., ATLAS: 1906.02025)

Unitarity and Vacuum Stability

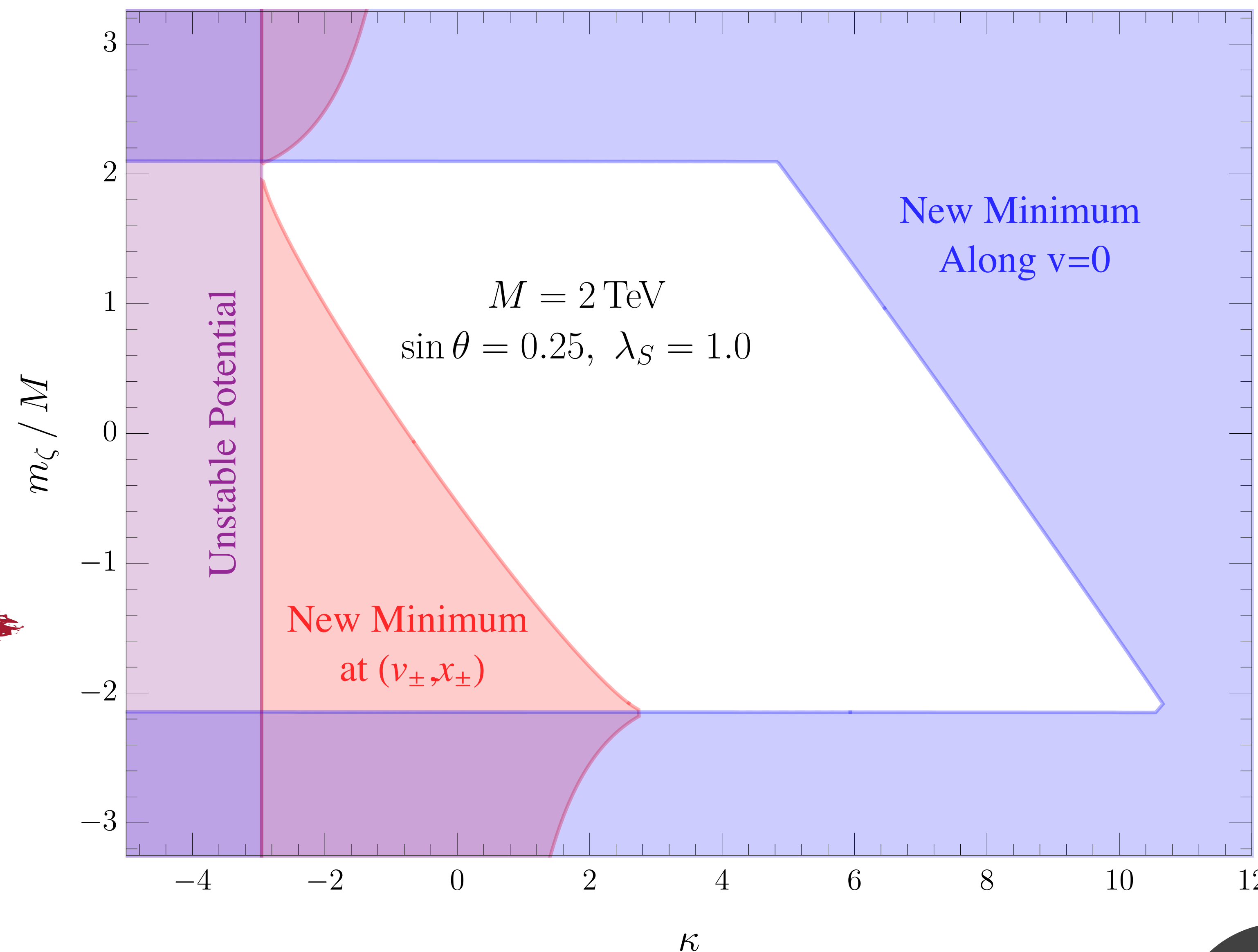
Unitarity of the *hh, hH, HH* amplitudes requires:

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

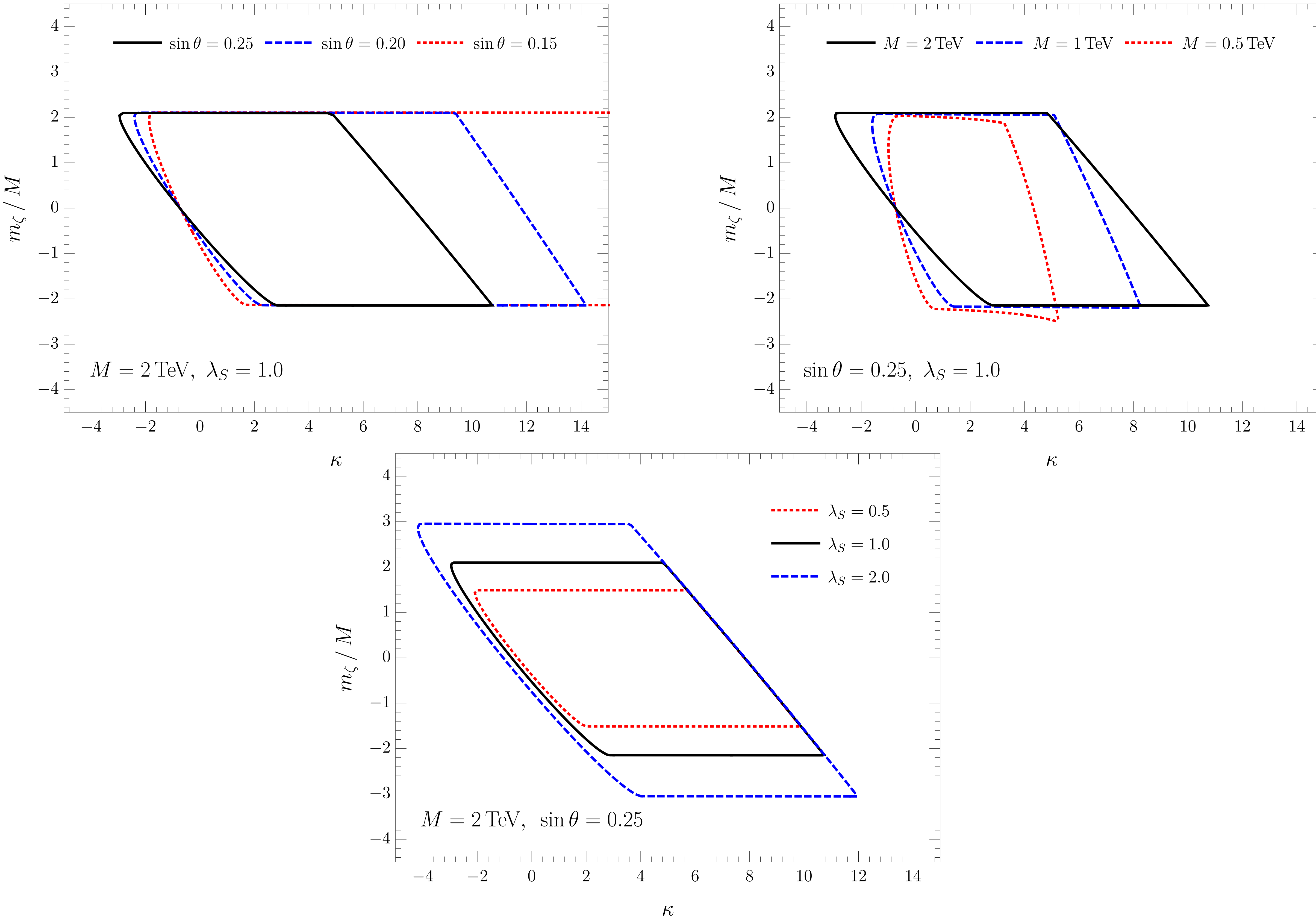
$$\lambda_S, \lambda_H \lesssim 8\pi/3$$

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

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



Unitarity and Vacuum Stability



Tree-Level Matching

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

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Note: matching at *M*, **not** the physical mass, M_H

(eliminates factors of $\log(\mu^2/M^2)$)

See, however, Brehmer et al, [1510.03443]

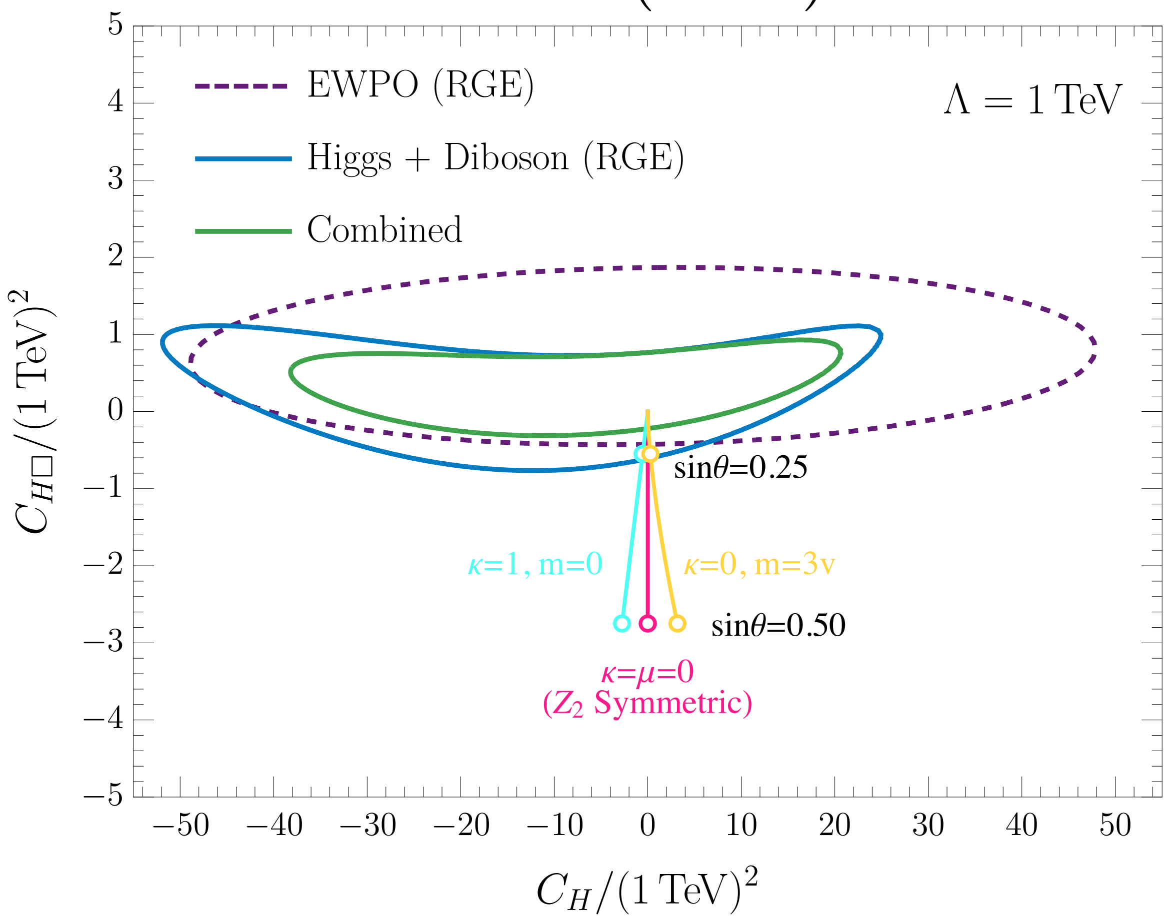
When $\kappa v^2 \gg M^2$, the singlet does not map onto the SMEFT, but the HEFT

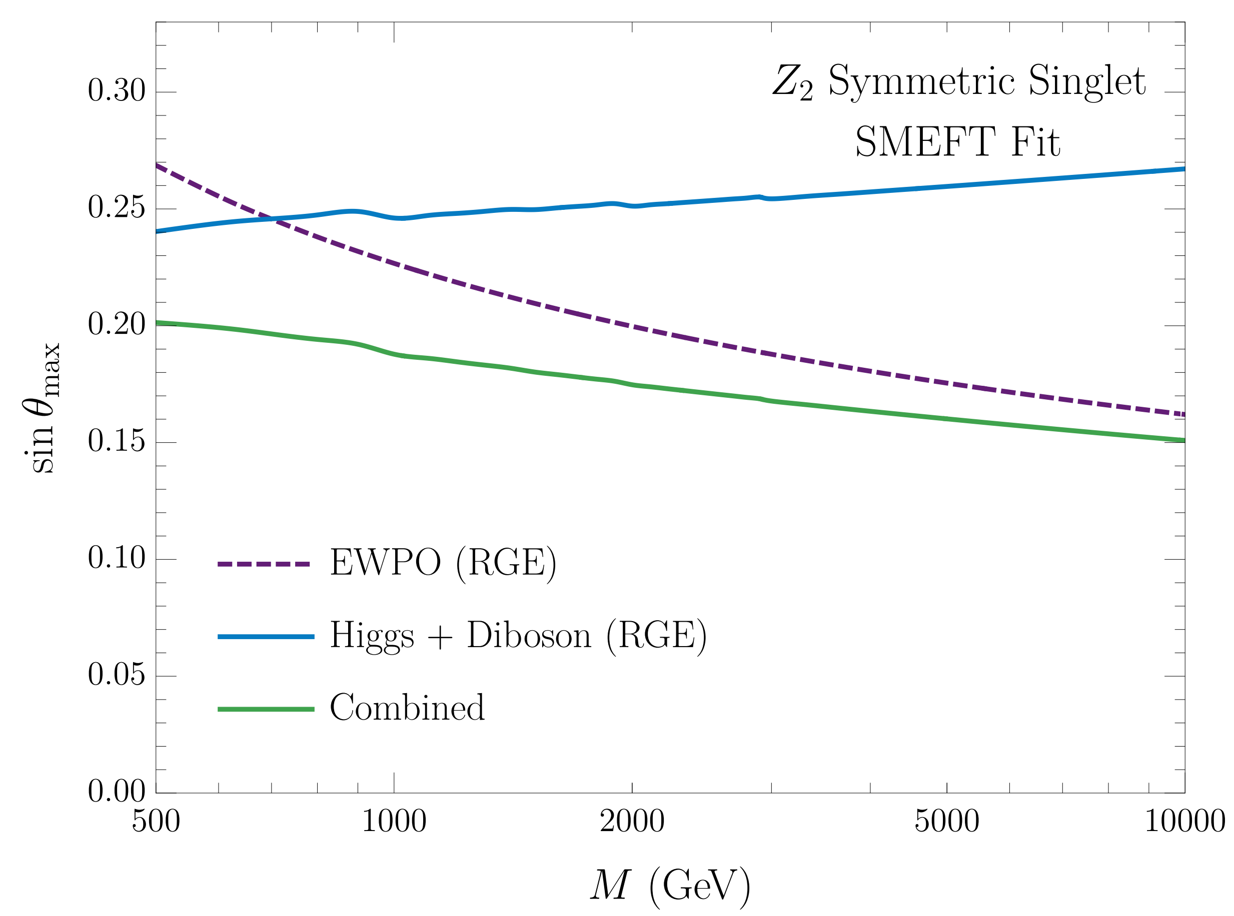
(1608.03564, 2011.02484)

Tree Level Results

Generates C_H, $C_{H\Box}$ at the matching scale

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





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…

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

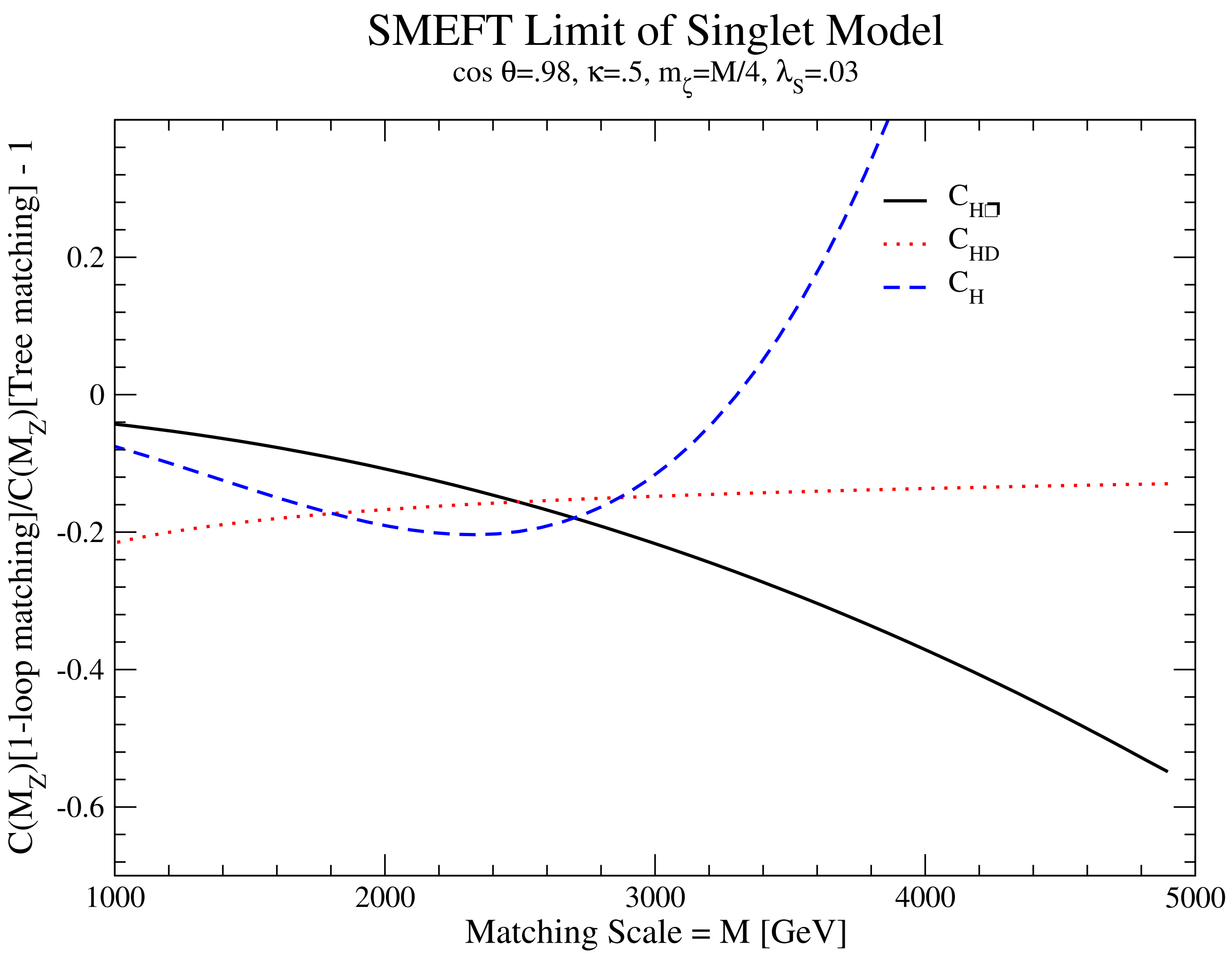
$$d_H = \lambda\left[\frac{1}{9}\left(62g^2 - 336\lambda\right)c_{H\Box} + 6c_H\right] + \delta d_H + \delta d_H^{\text{shift}}$$

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

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

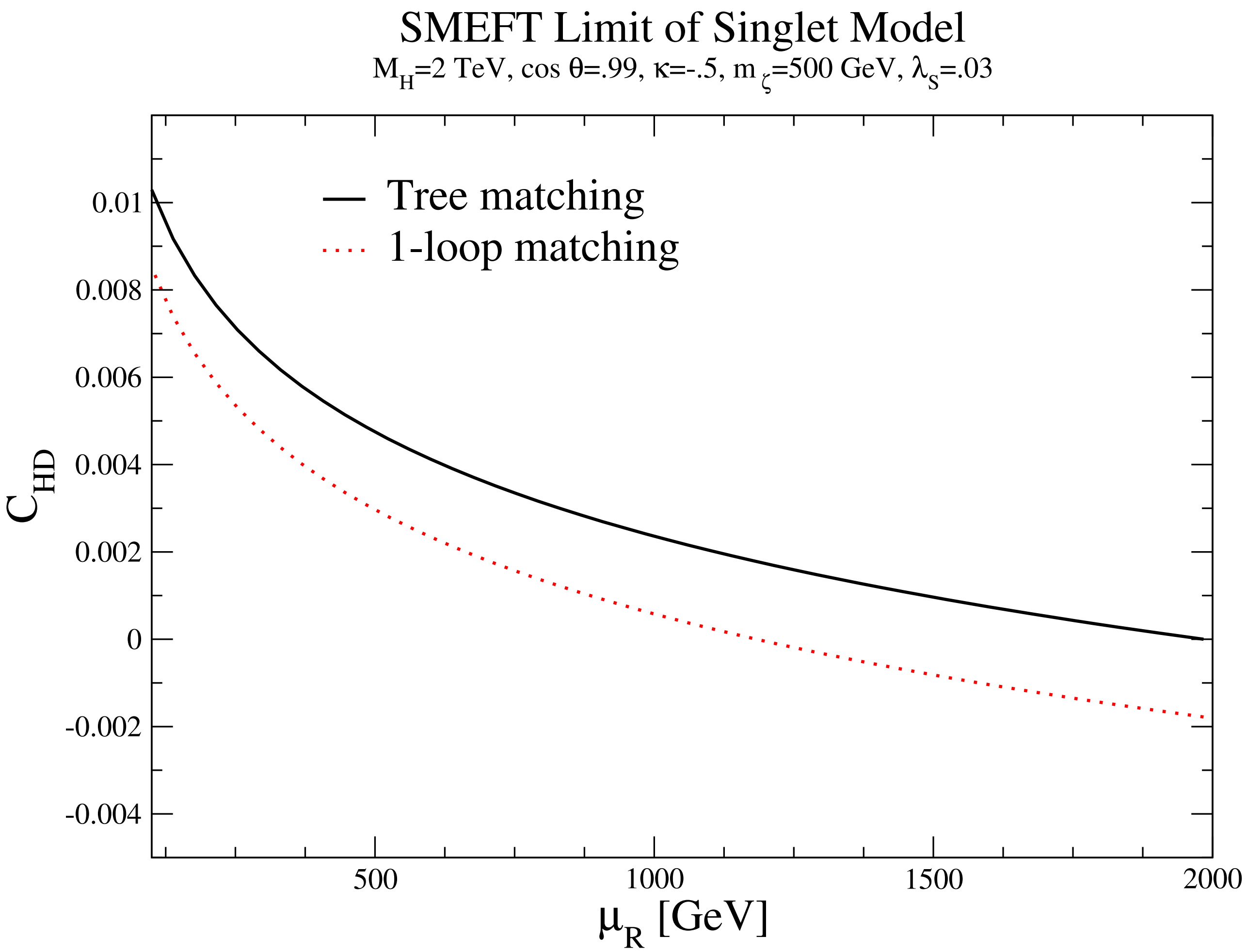
In principle of comparable size to RGE-induced contribution!

One-Loop Matching



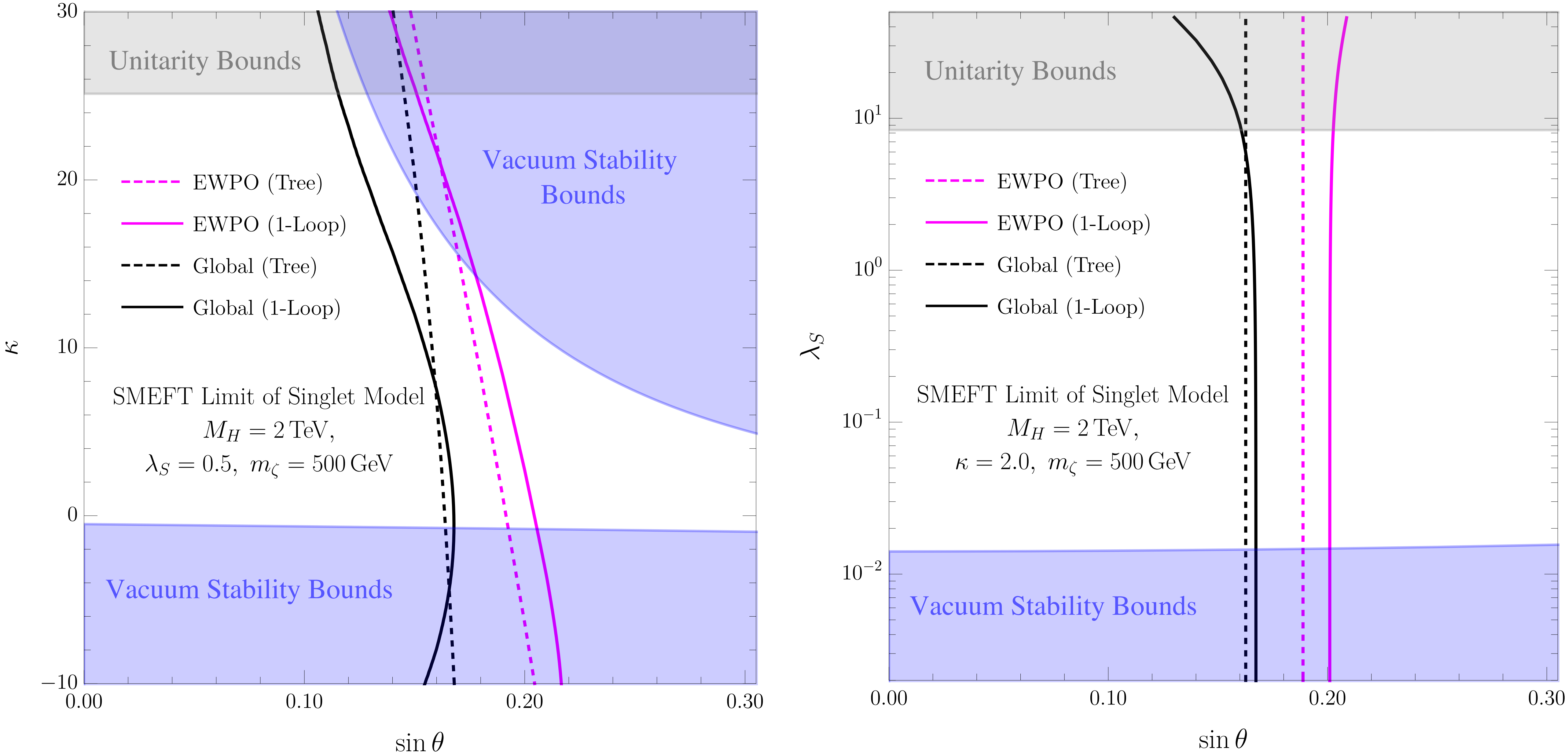
Include only one-loop RGEs

(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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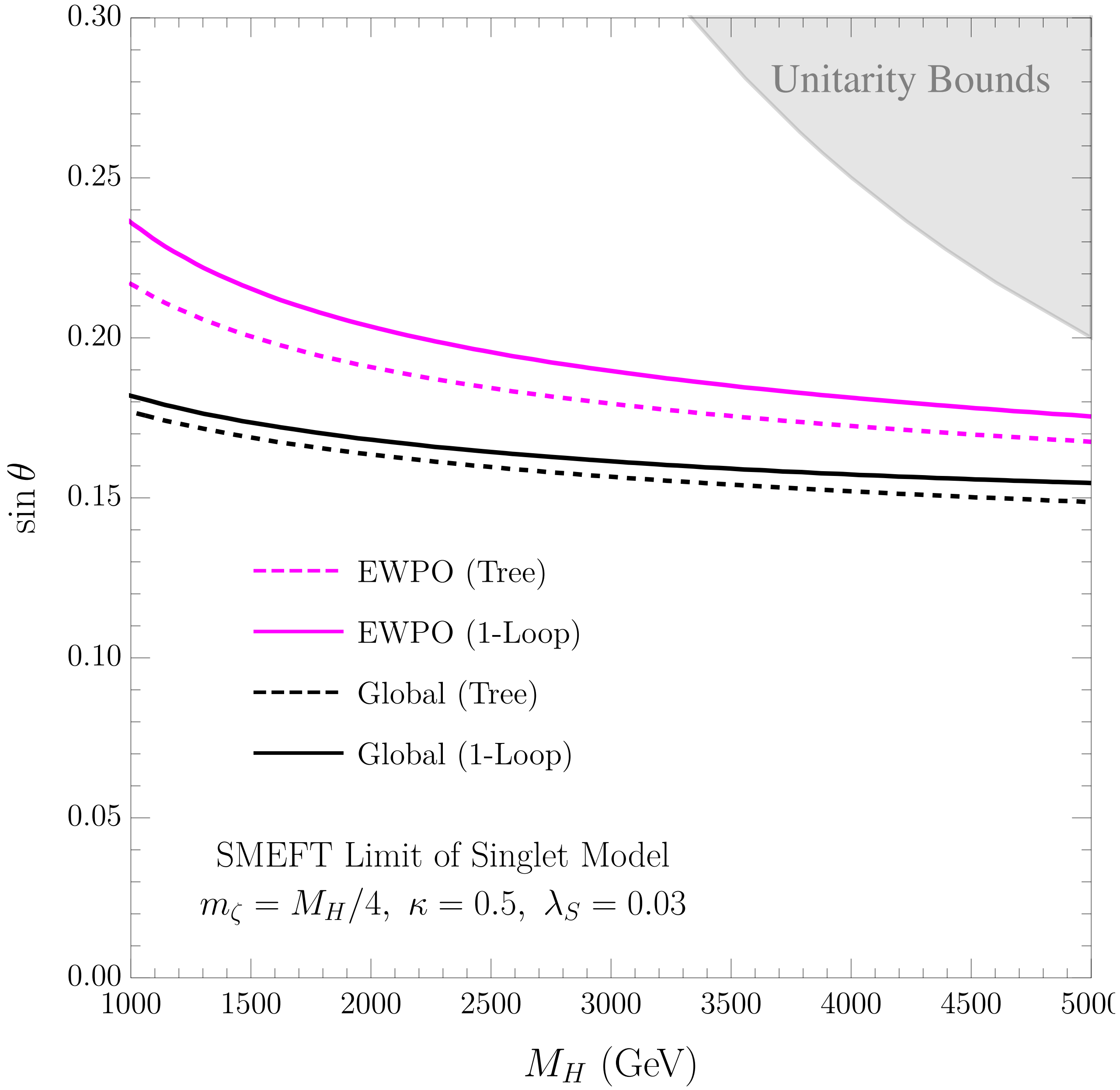

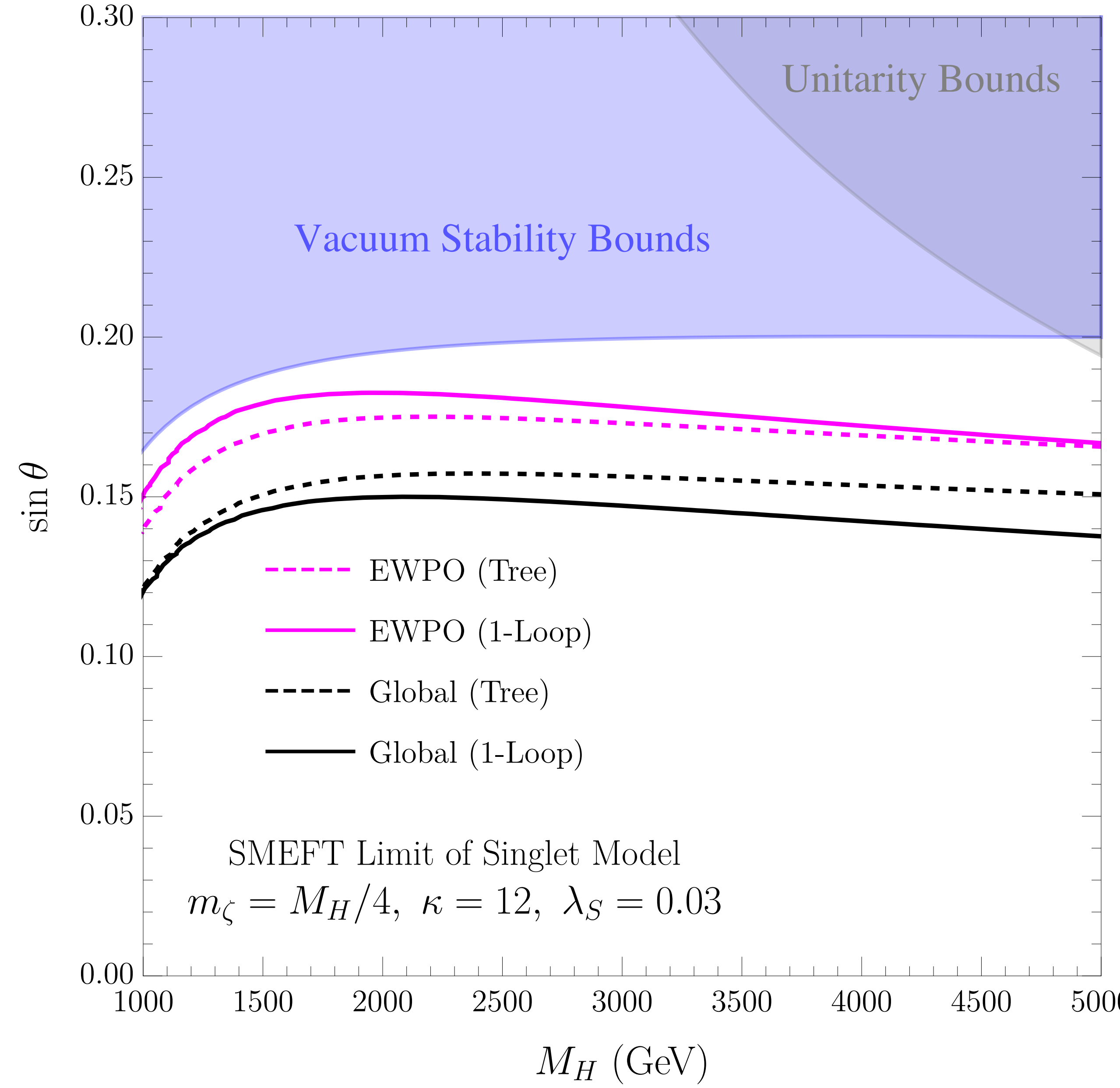

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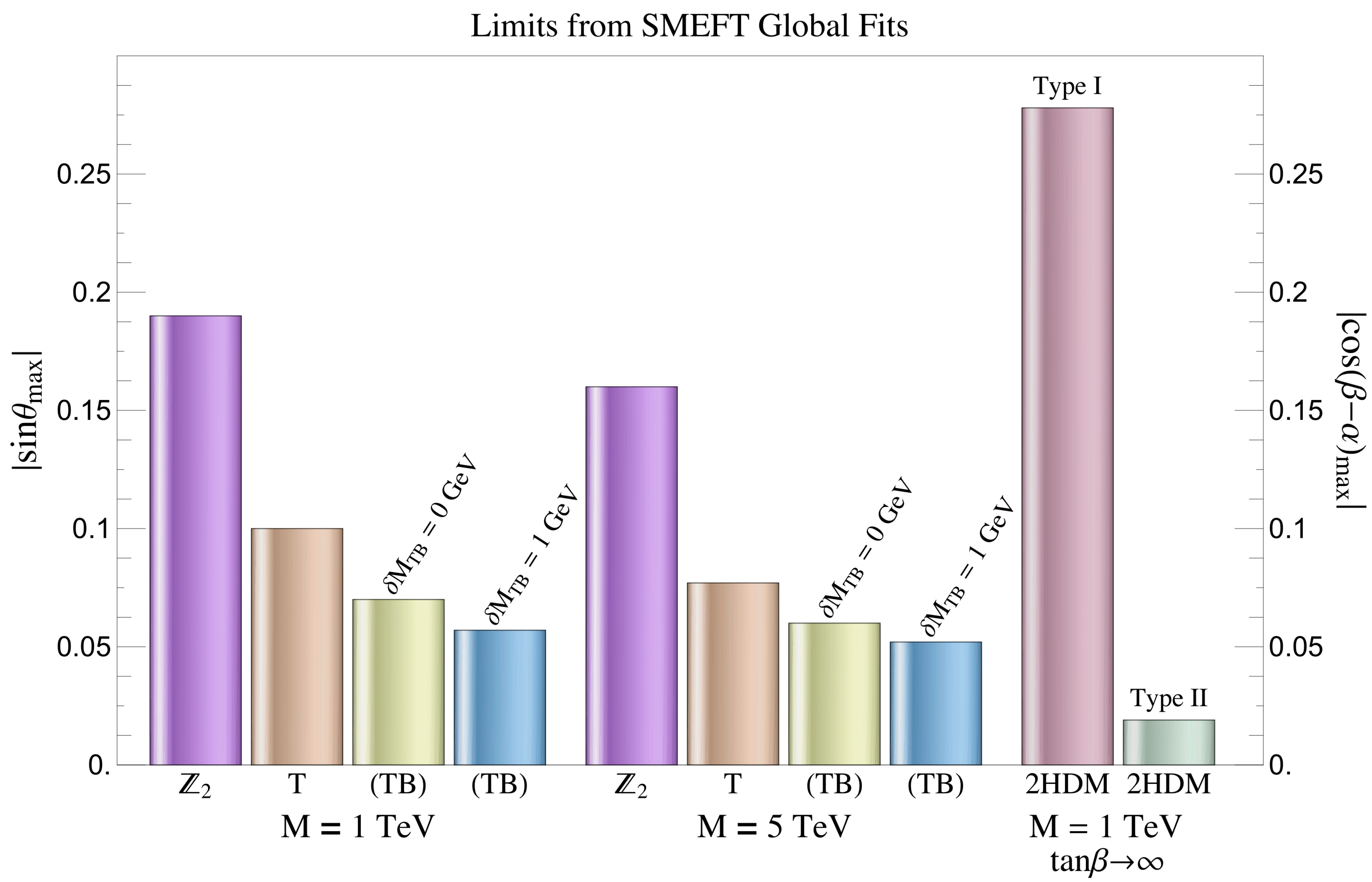
Conclusions:

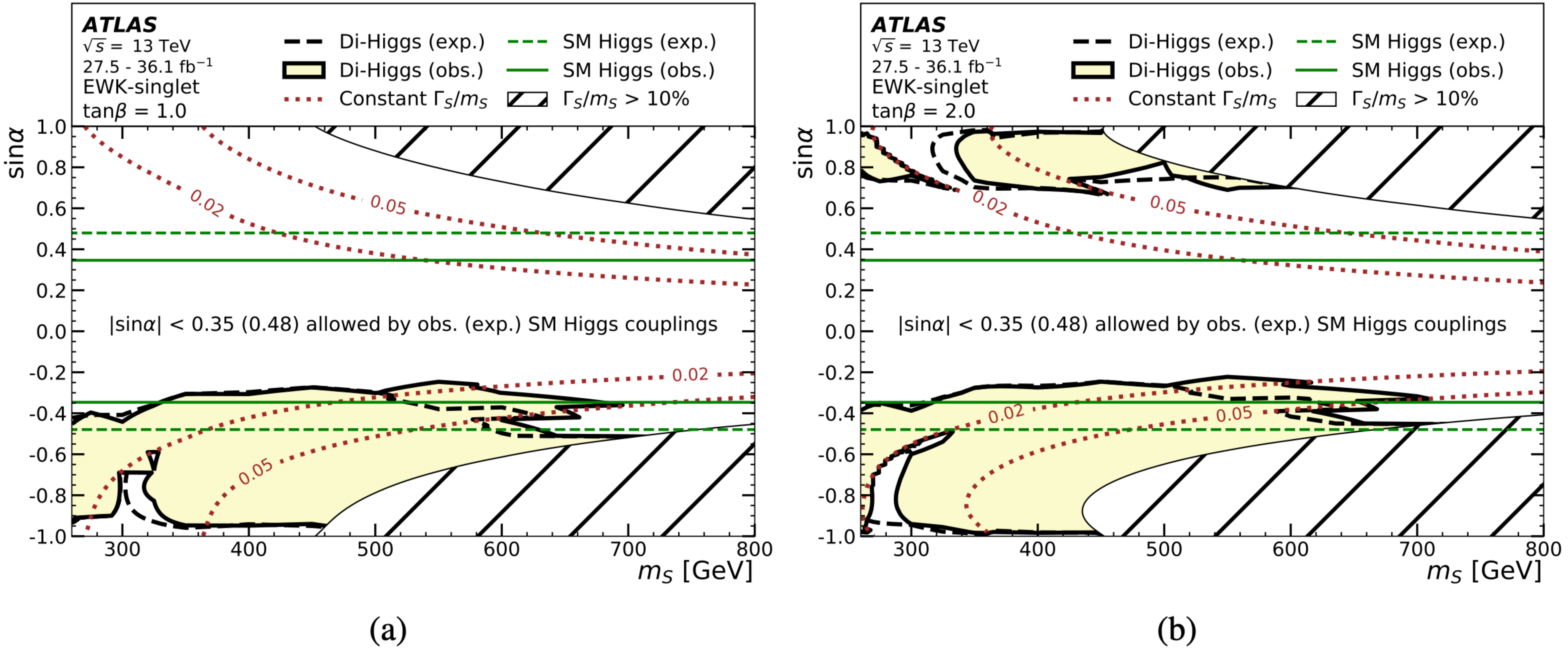


Lots more work to do:

- 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
- Compare effects of dimension-8 operators
- Top data is important for many of our models too, and should be included in global fits

Backup: Resonant Di-Higgs Limits

ATLAS: 1906.02025



Backup: Warsaw Basis Definitions

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

Backup: Anomalous Dimensions

$$
\begin{aligned}
\dot{C}_{HD} &= \frac{8}{3}g'^{\,2}\left[2C_{Ht} - C_{Hb} + (C_{Hq}^{(1)})_{33}\right] + \frac{20}{3}g'^{\,2}C_{H\Box} \\
&\quad -24\left[Y_t^2 C_{Ht} - Y_b^2 C_{Hb} + Y_b Y_t C_{Htb}\right] \\
&\quad +24\left(Y_t^2 - Y_b^2\right)(C_{Hq}^{(1)})_{33} \\
\dot{C}_{H\Box} &= 6g^2 (C_{Hq}^{(3)})_{33} + \frac{2}{3}g'^{\,2}\left[2C_{Ht} - C_{Hb} + (C_{Hq}^{(1)})_{33}\right] \\
&\quad +\left[-\frac{4}{3}g'^{\,2} - 4g^2 + 12\left(Y_t^2 + Y_b^2\right) + 4Y_\tau^2\right]C_{H\Box} \\
&\quad -6\left[(Y_b^2 - Y_t^2)(C_{Hq}^{(1)})_{33} + 3(Y_b^2 + Y_t^2)(C_{Hq}^{(3)})_{33} + Y_t^2 C_{Ht} - Y_b^2 C_{Hb} - 2Y_b Y_t C_{Htb}\right]
\end{aligned}
$$

$$
\begin{aligned}
(\dot{C}_{Hq}^{(3)})_{33} &= 3\left[Y_b^2 - Y_t^2\right](C_{Hq}^{(1)})_{33} + \left[-\frac{11}{3}g^2 + 8Y_t^2 + 8Y_b^2 + 2Y_\tau^2\right](C_{Hq}^{(3)})_{33} \\
&\quad -\frac{1}{6}\left[3Y_t^2 + 3Y_b^2 - g^2\right]C_{H\Box} \\
(\dot{C}_{Hq}^{(1)})_{33} &= \left[\frac{5}{9}g'^{\,2} + 10Y_t^2 + 10Y_b^2 + 2Y_\tau^2\right](C_{Hq}^{(1)})_{33} - 9\left[Y_t^2 - Y_b^2\right](C_{Hq}^{(3)})_{33} \\
&\quad -\frac{1}{2}\left[\frac{g'^{\,2}}{9} + Y_b^2 - Y_t^2\right]C_{H\Box} - (Y_t^2 + \frac{4}{9}g'^{\,2})C_{Ht} - (Y_b^2 + \frac{2}{9}g'^{\,2})C_{Hb}\,, \qquad (6)
\end{aligned}
$$