Putting SMEFT Fits to Work

Lessons from Matching Simple Models

Based on
arXiv:2007.01296, 2102.02823, 2110.06929, 2205.01561

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In collaboration with
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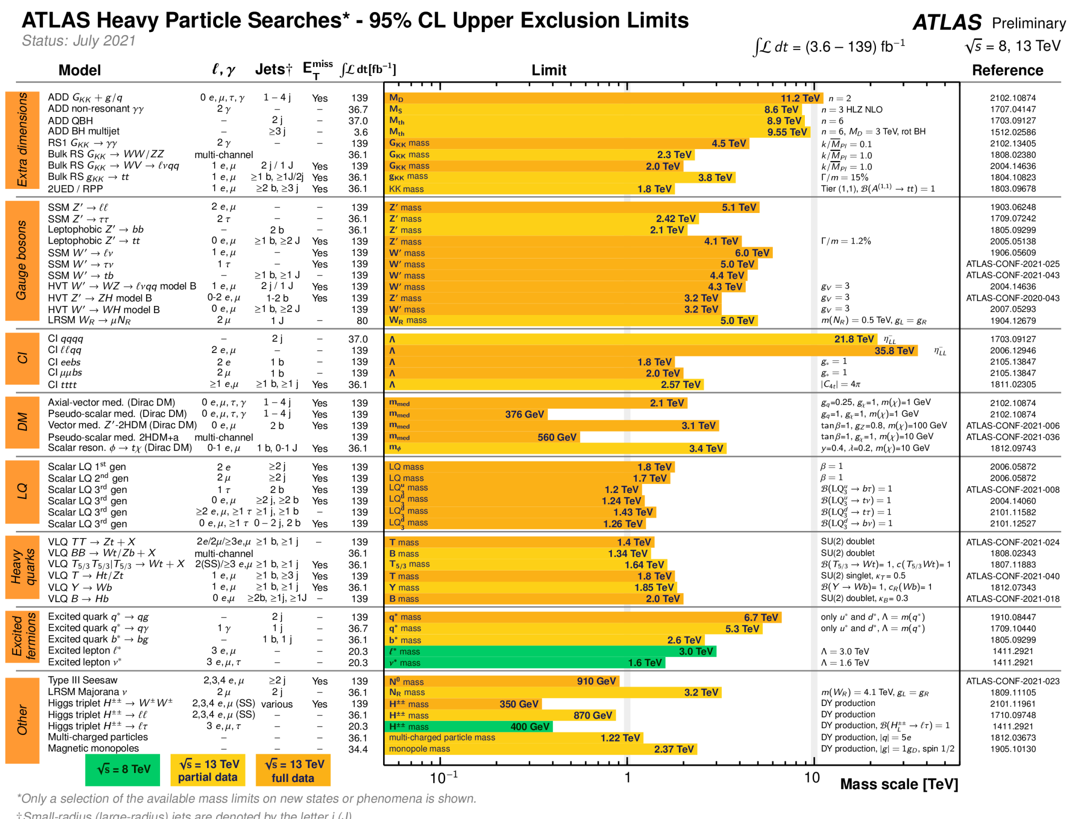
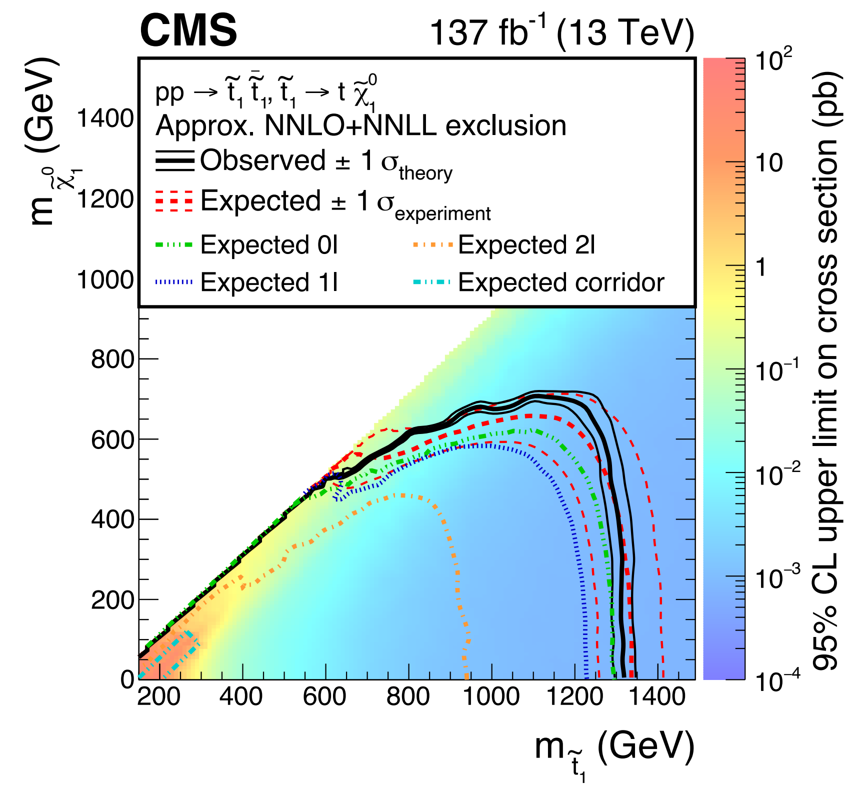
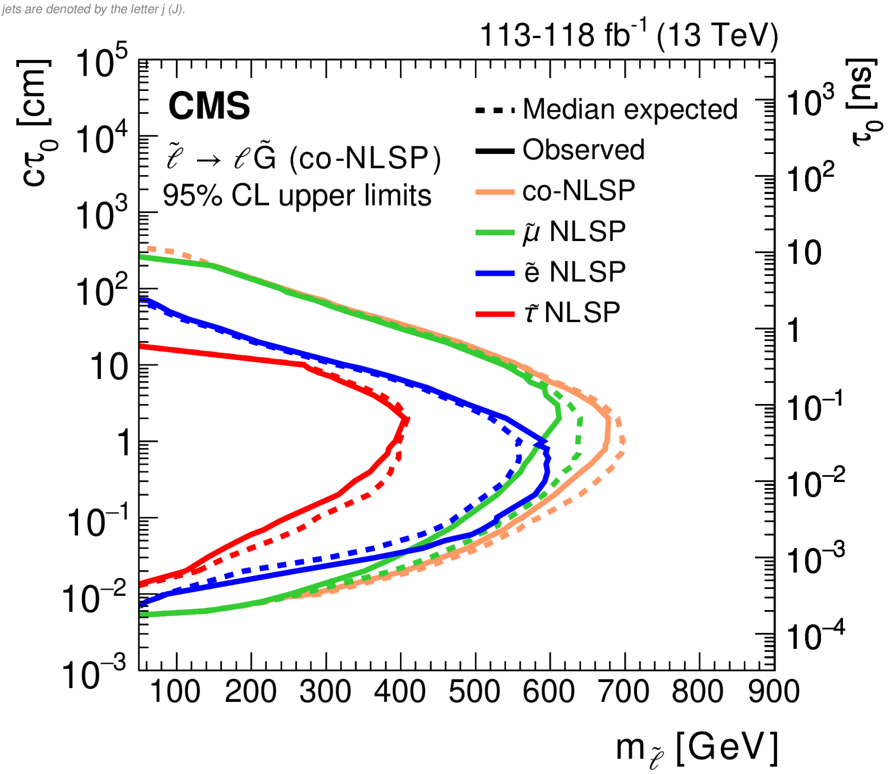
University of Cambridge, December 8, 2021

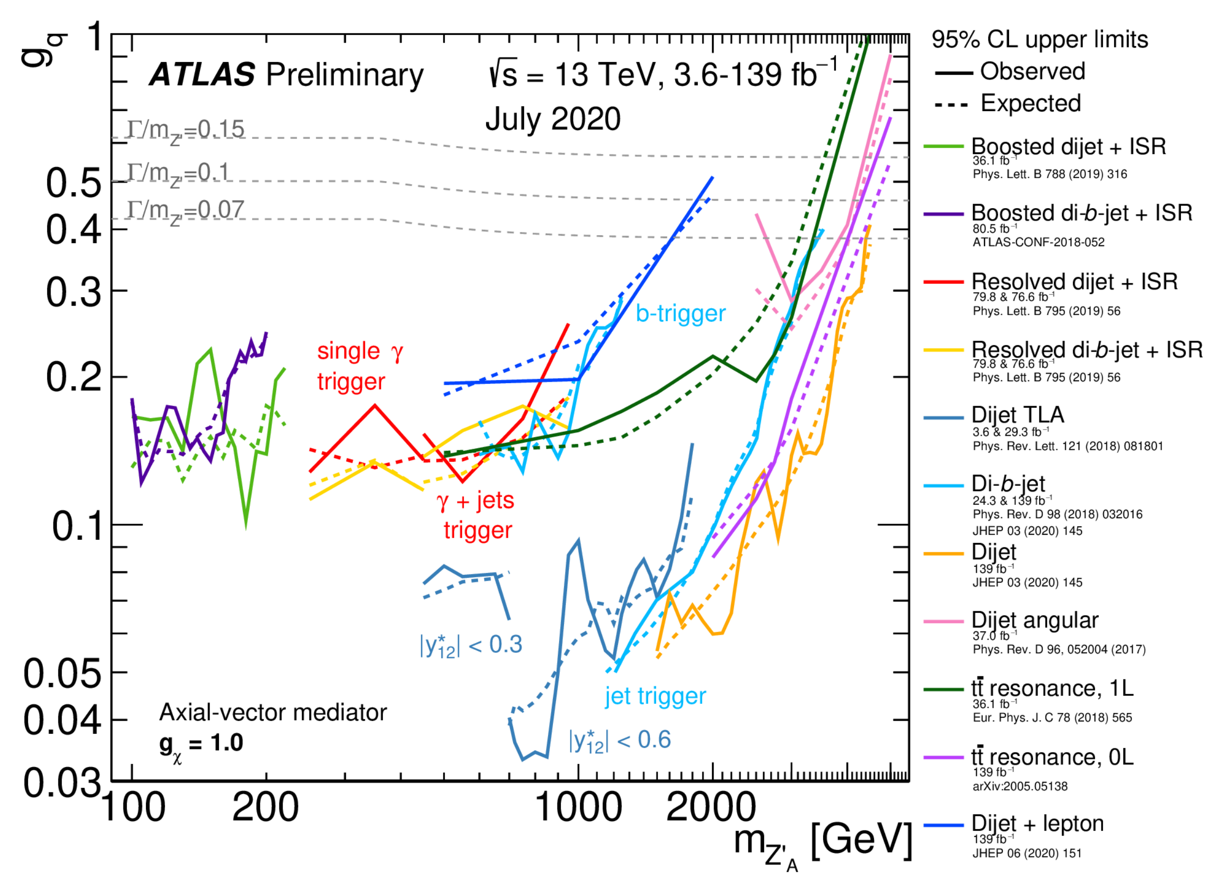
The State of LHC Physics

Have yet to find anything truly unexpected…



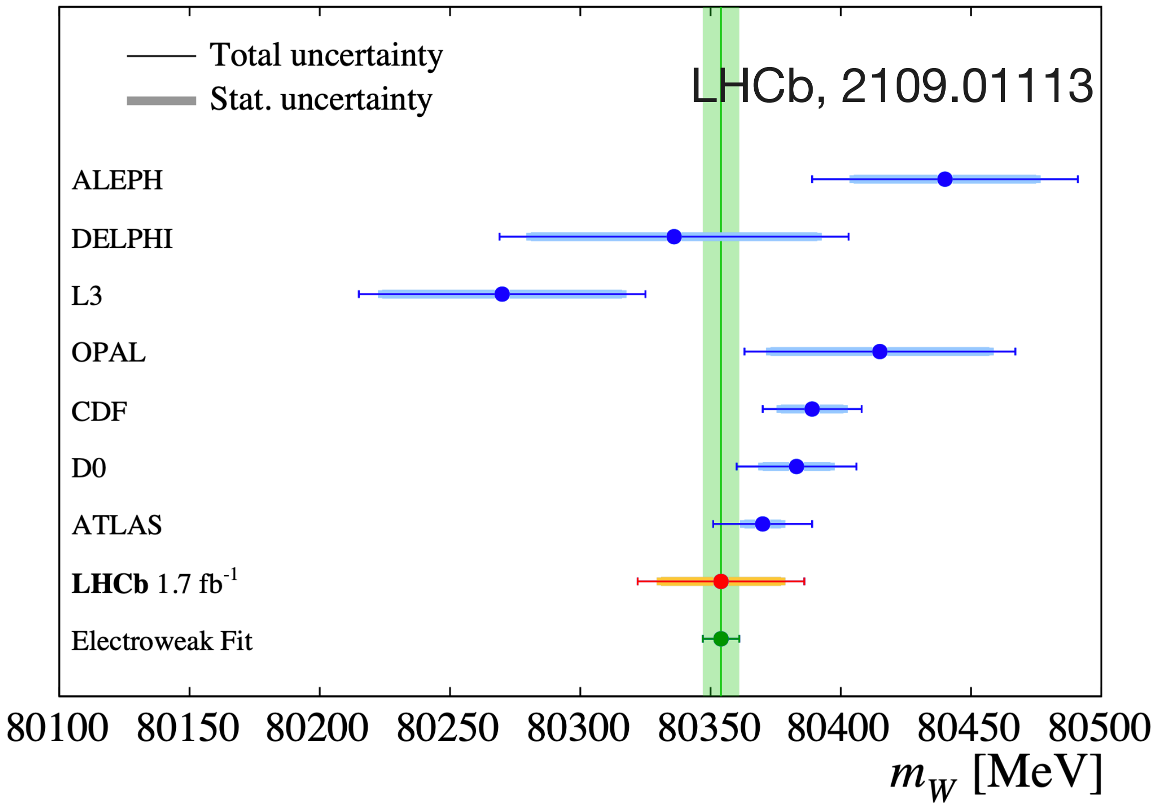


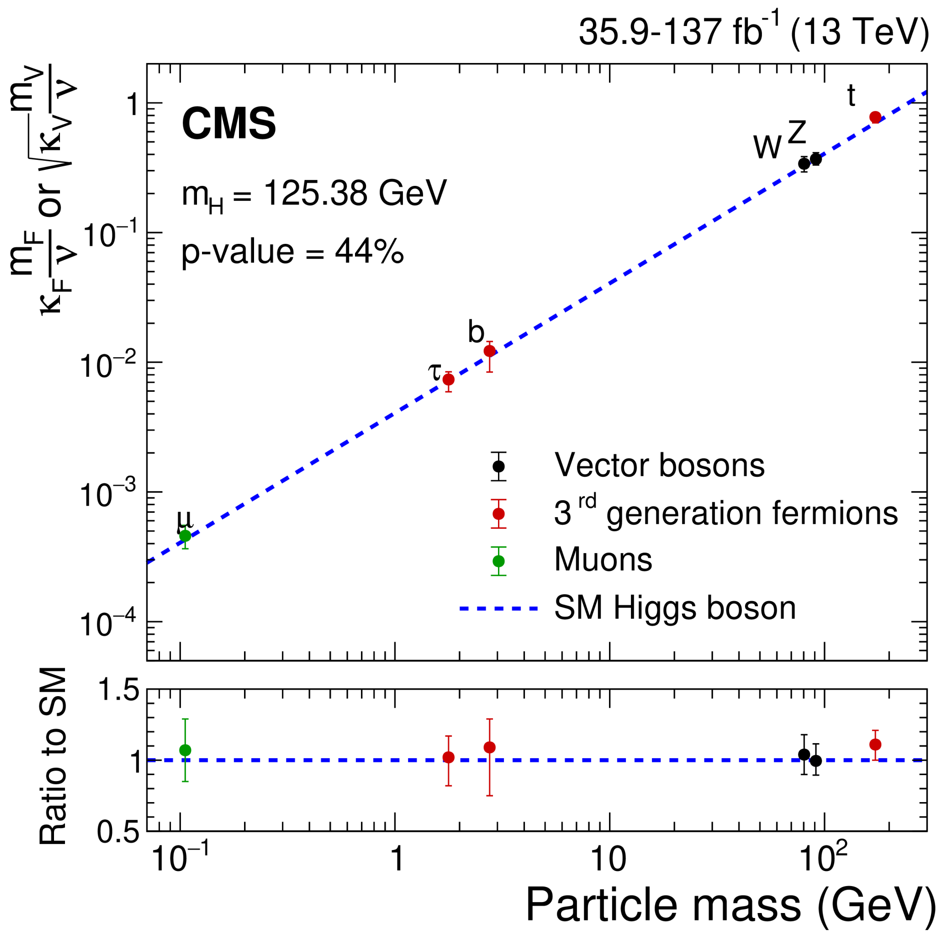


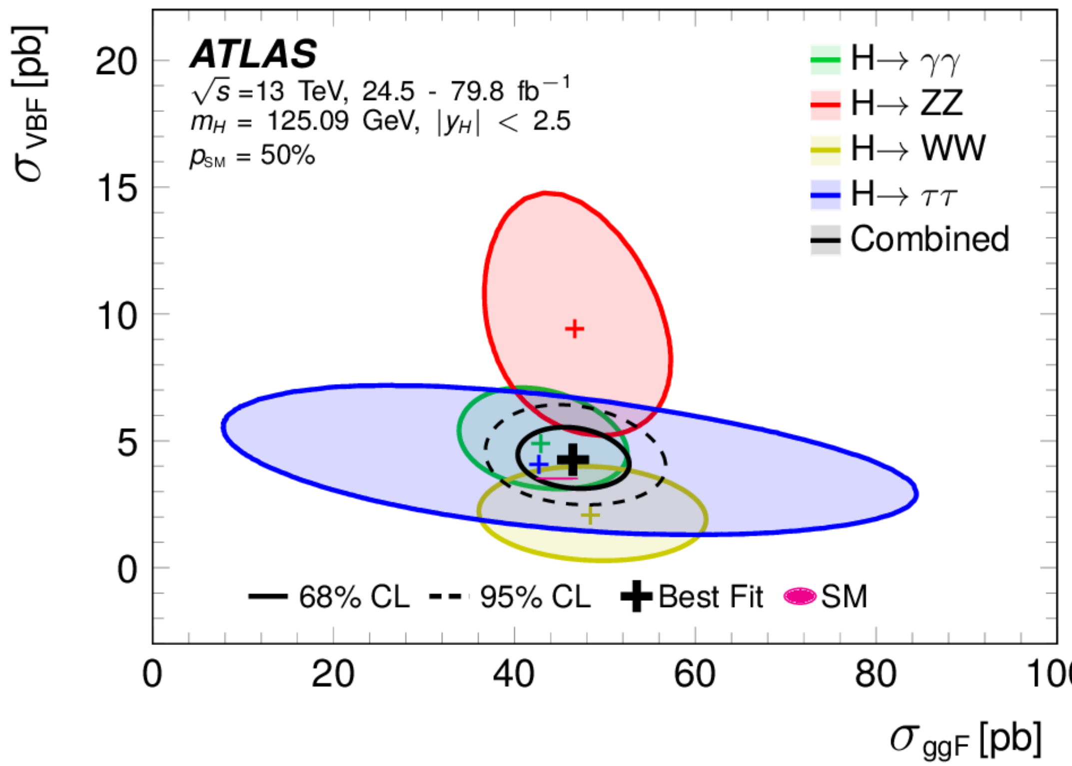


The State of LHC Physics

But learning a great deal about the SM!







Given the wealth of data, in many different channels, need a framework to search for deviations from the SM…

Enter the SMEFT

Treat the SM as an effective theory, with new physics at a scale $\Lambda \gg v, E$

Assuming $SU(2)_L \times U(1)_Y$ gauge + Lorentz invariance, with the Higgs transforming as a doublet (i.e., EWSB *linearly* realized), expand:

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

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Coefficients treated as independent parameters, depend on underlying UV theory

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

Counting in powers of Λ
(odd-dimension operators violate Lepton number)

Operators of given dimension built out of *only* SM fields

Enter the SMEFT

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

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

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

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

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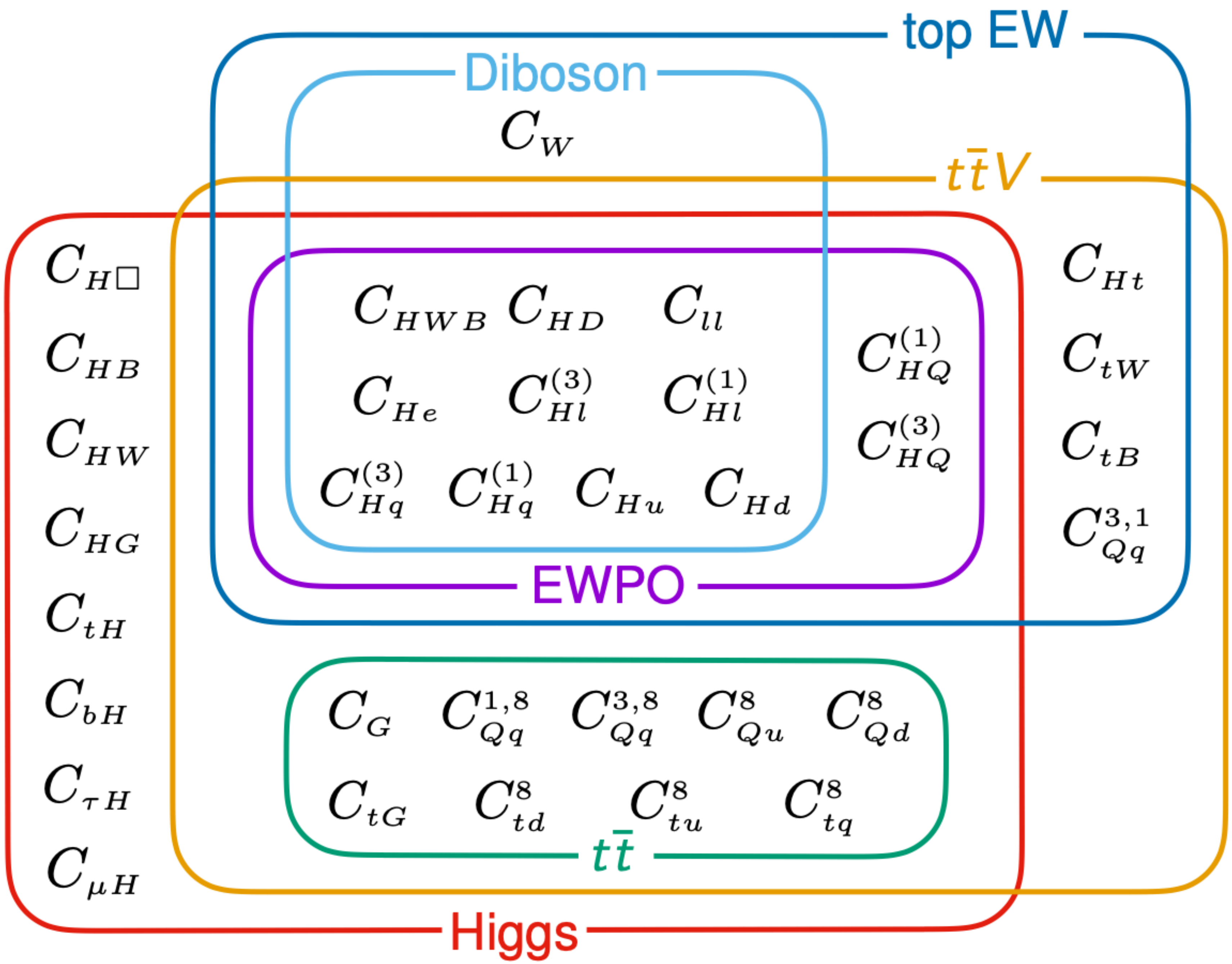
Recently enumerated at dimension-8 as well:
Li et al [2005.00008] + Murphy [2005.00059]

Enter the SMEFT

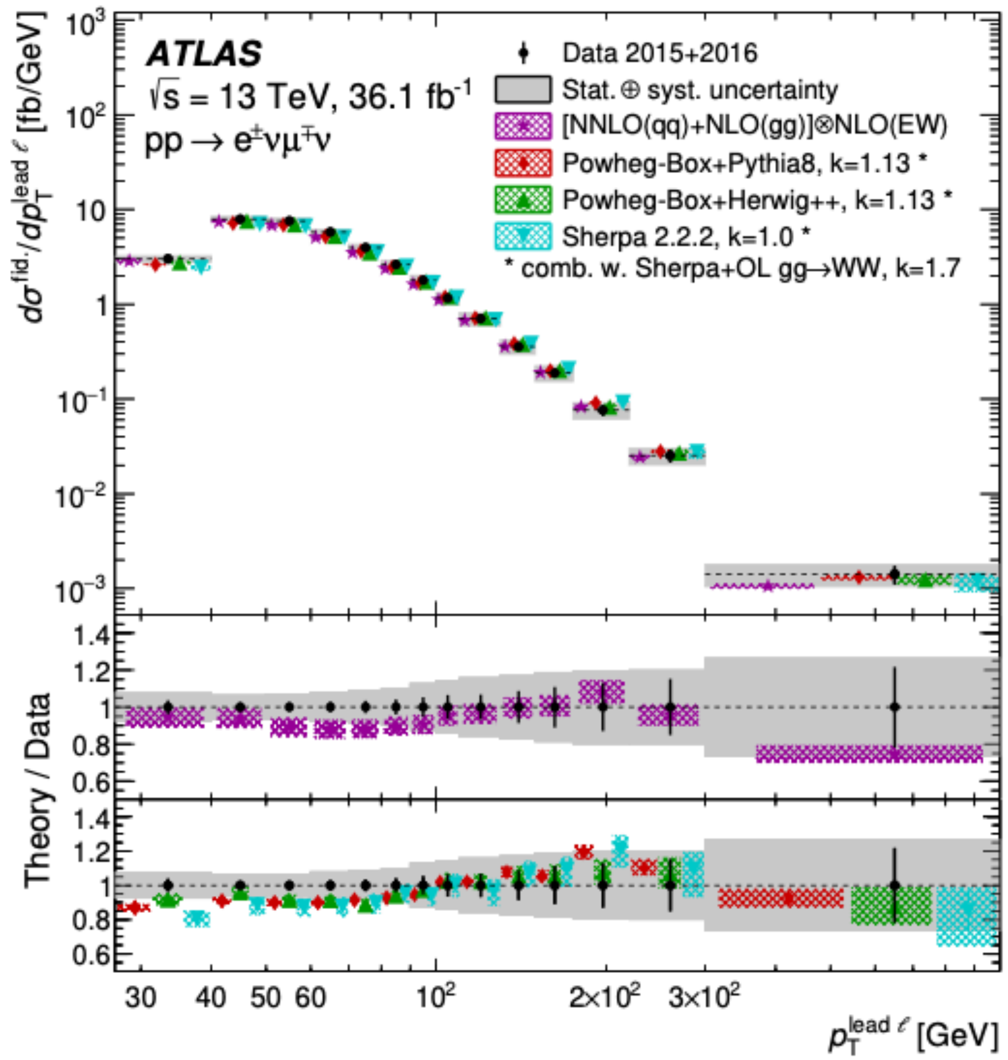
Effective operators allow for consistent combination of measurements

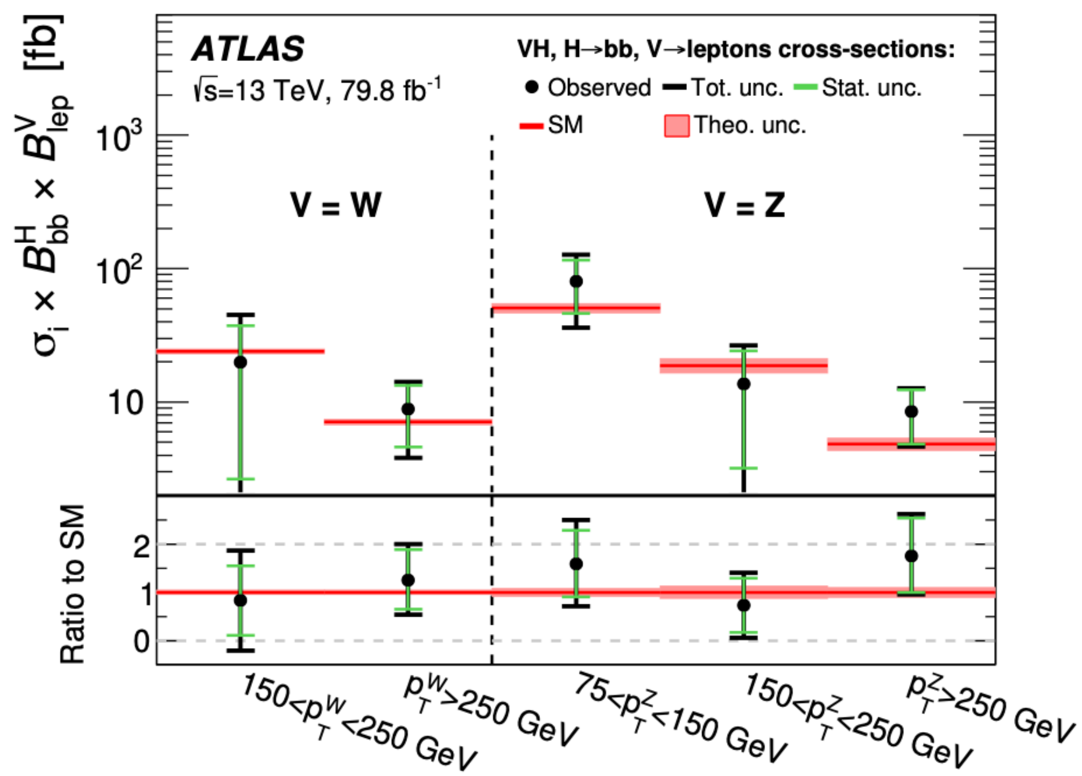


Ellis, Madigan, Mimasu, Sanz, You [2012.02779]

Enter the SMEFT

… and can also parameterize deviations in kinematic distributions!





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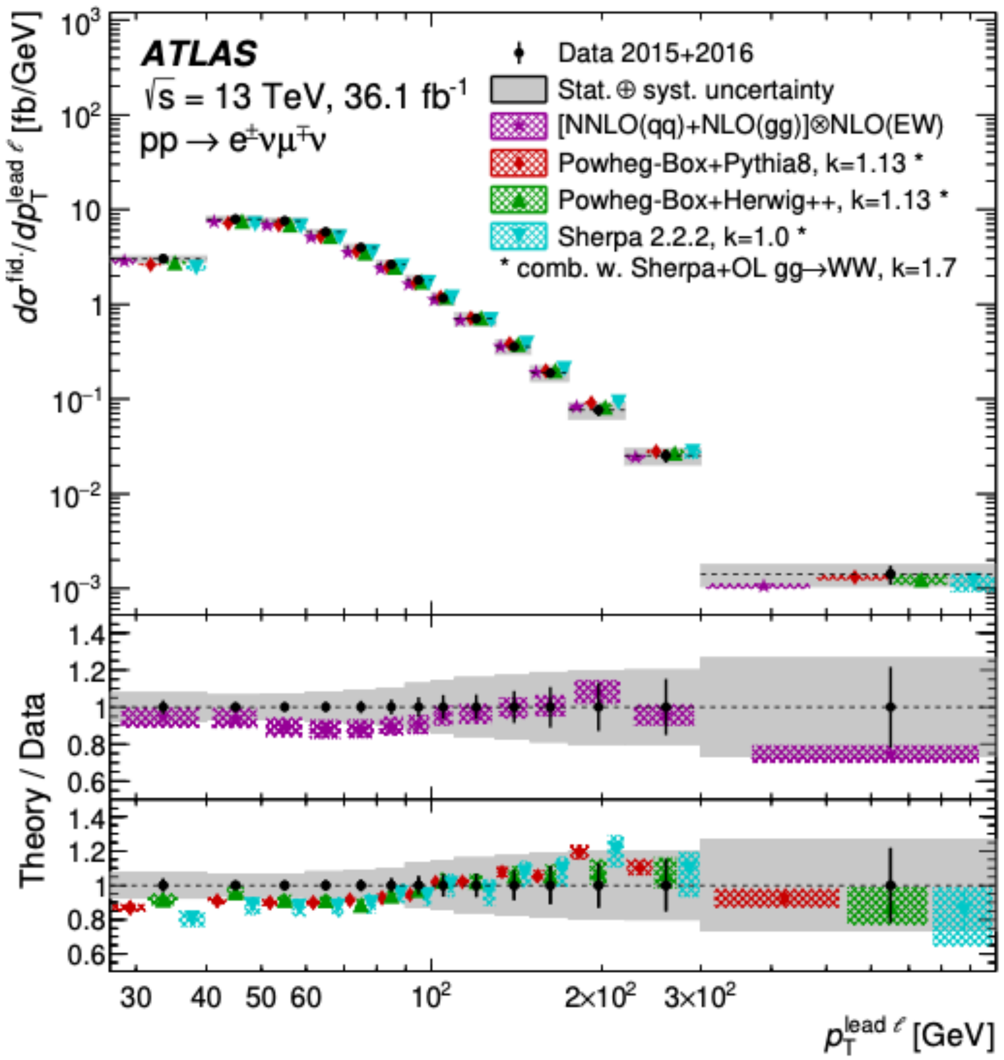
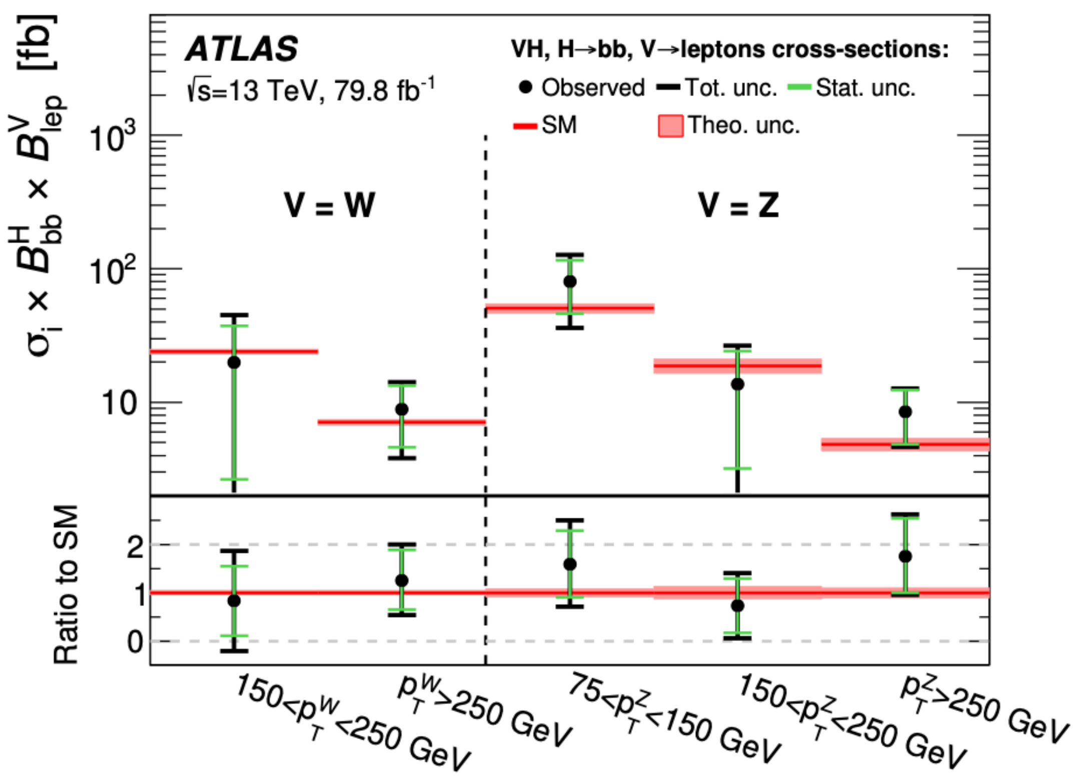
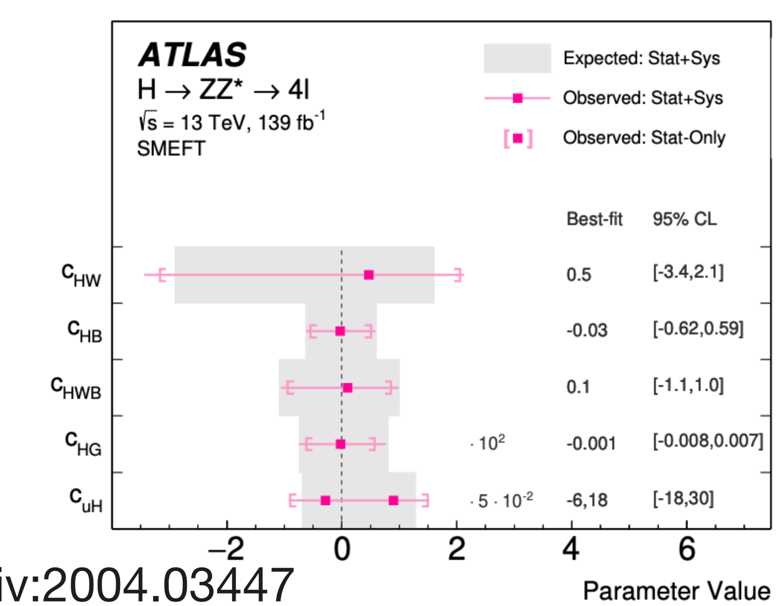
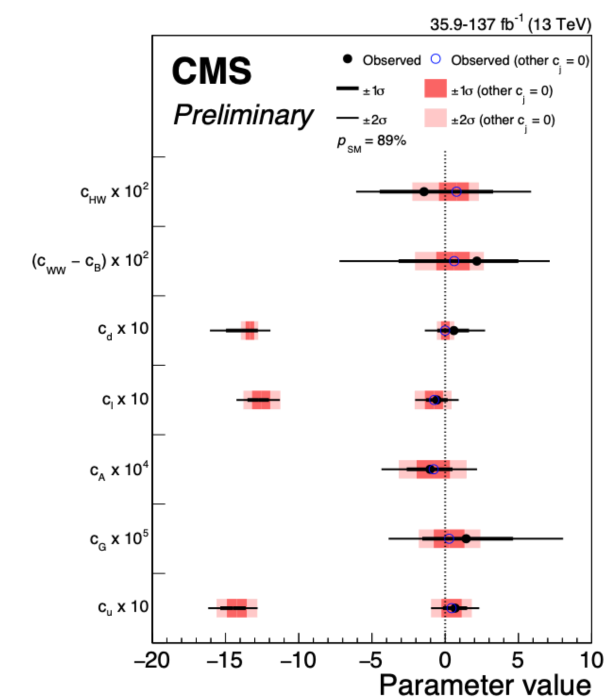






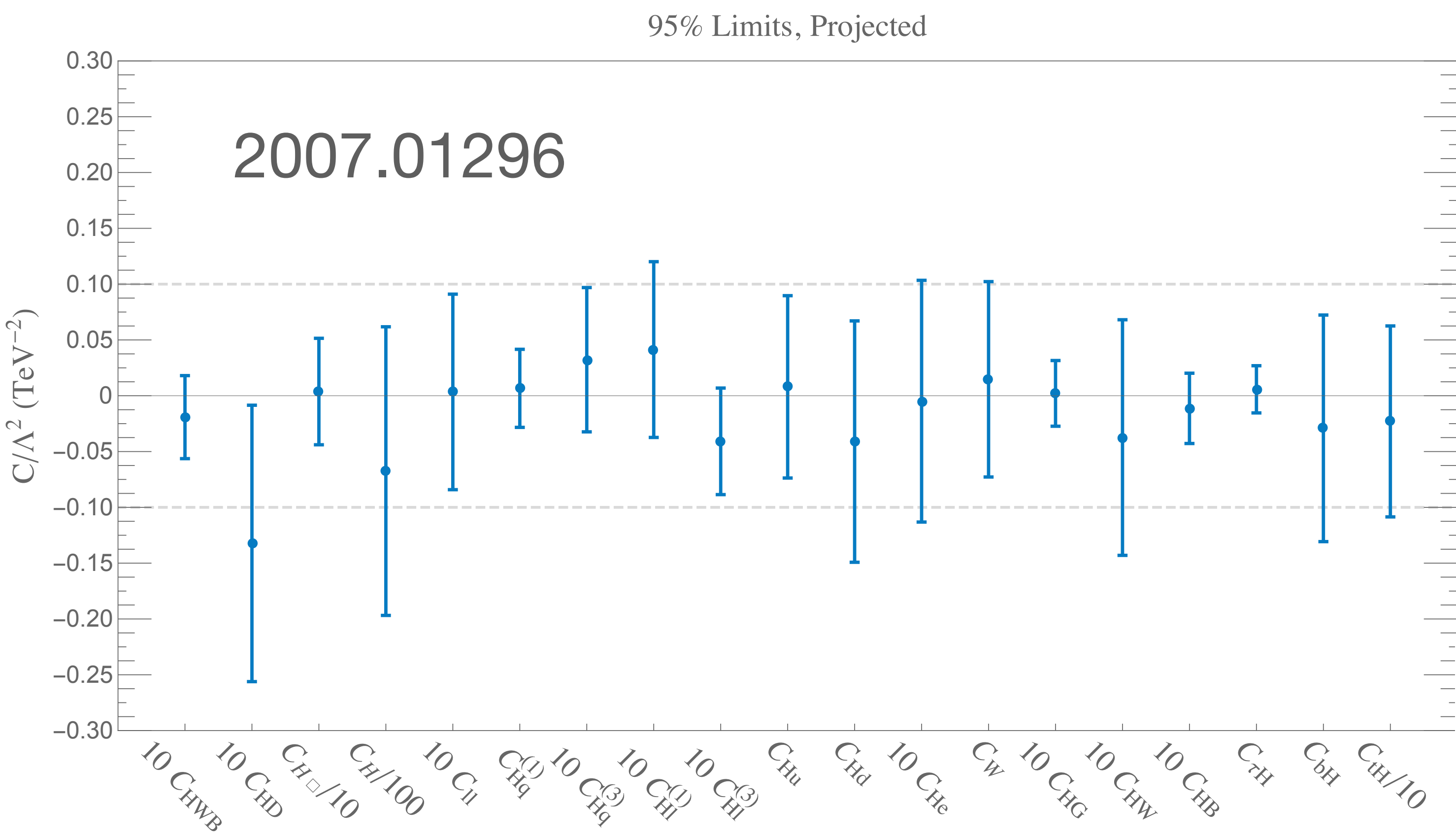


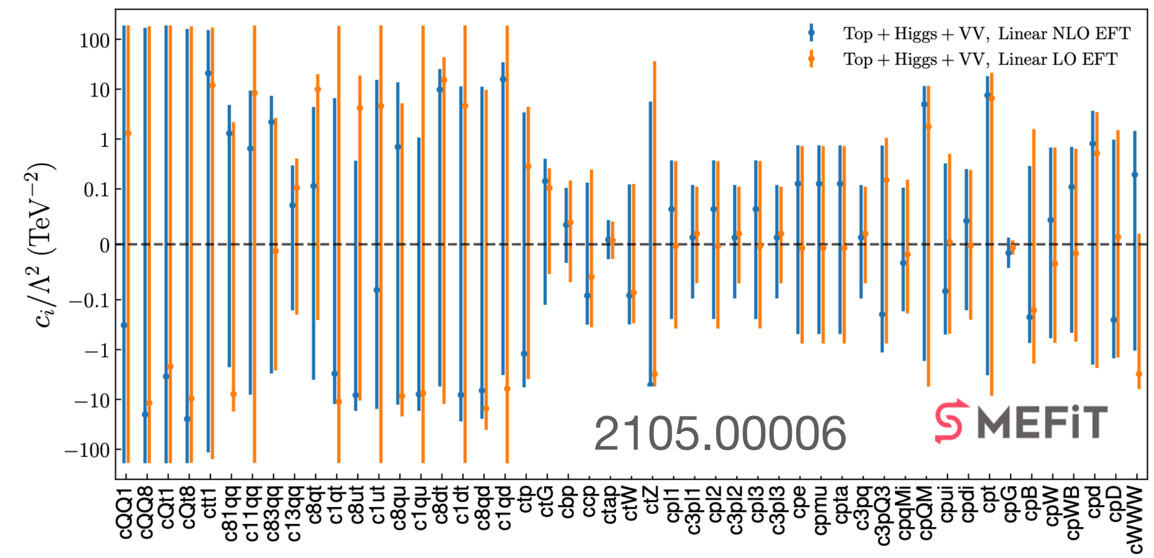
Experiments starting to present limits in this framework:

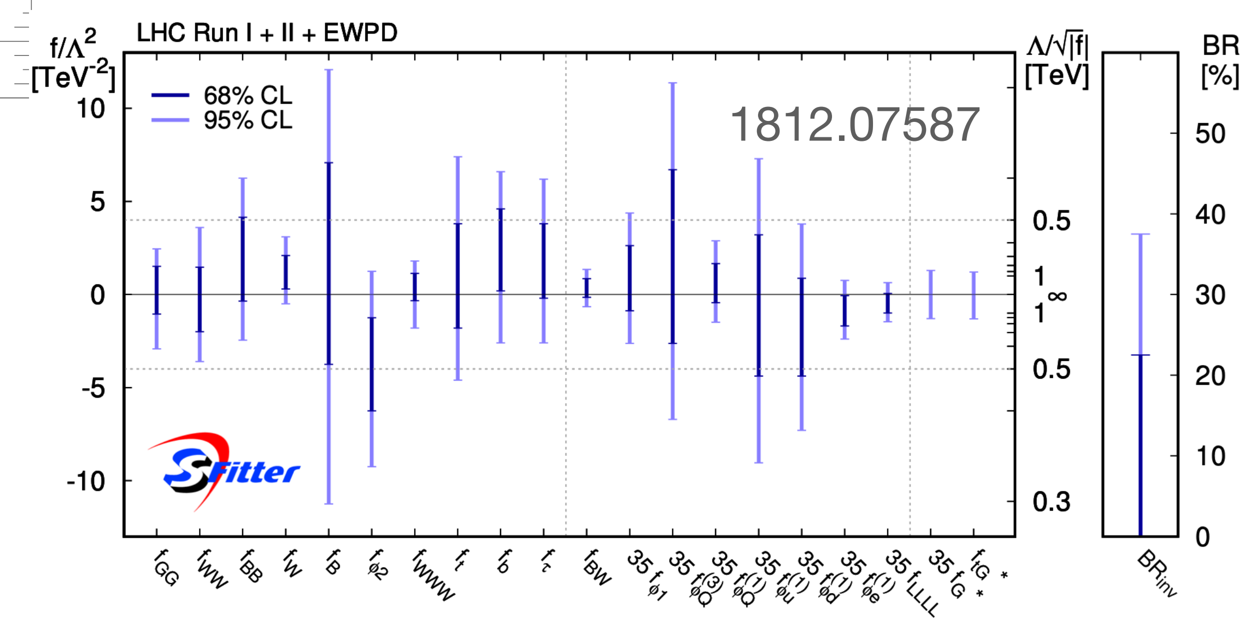
arXiv:2004.03447

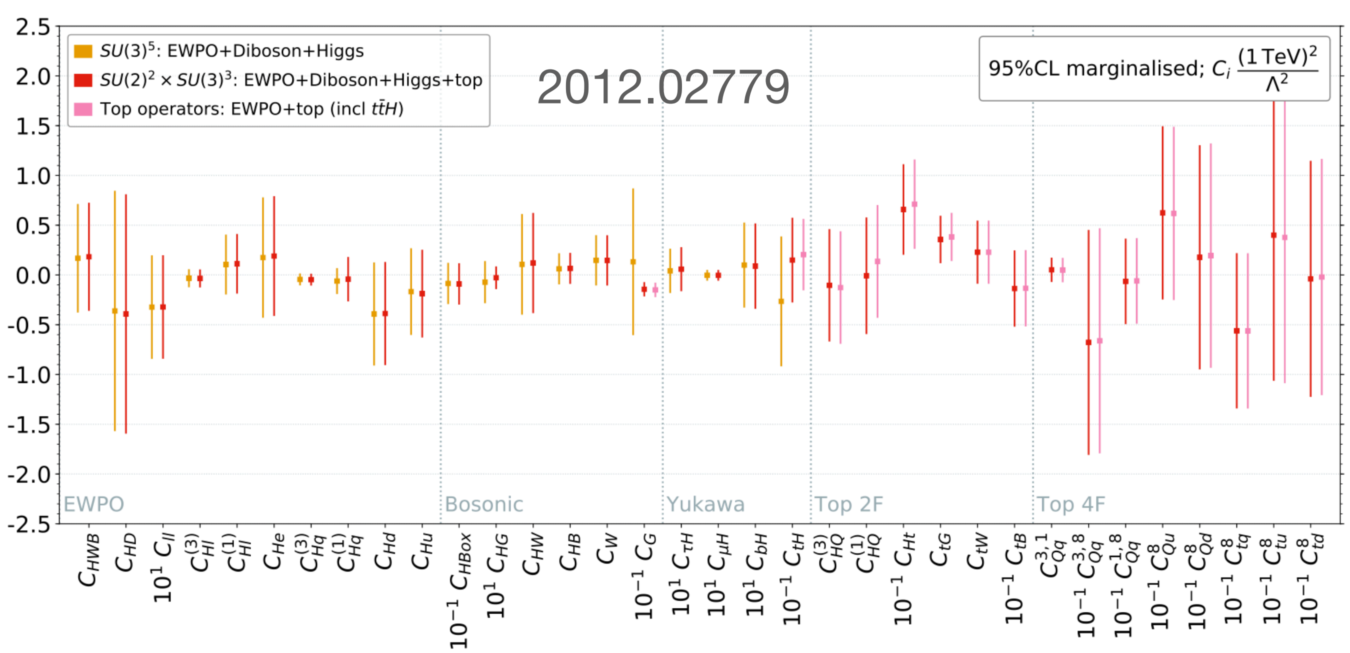
CMS-PAS-HIG-19-005

Lots of effort on SMEFT Global Fits:



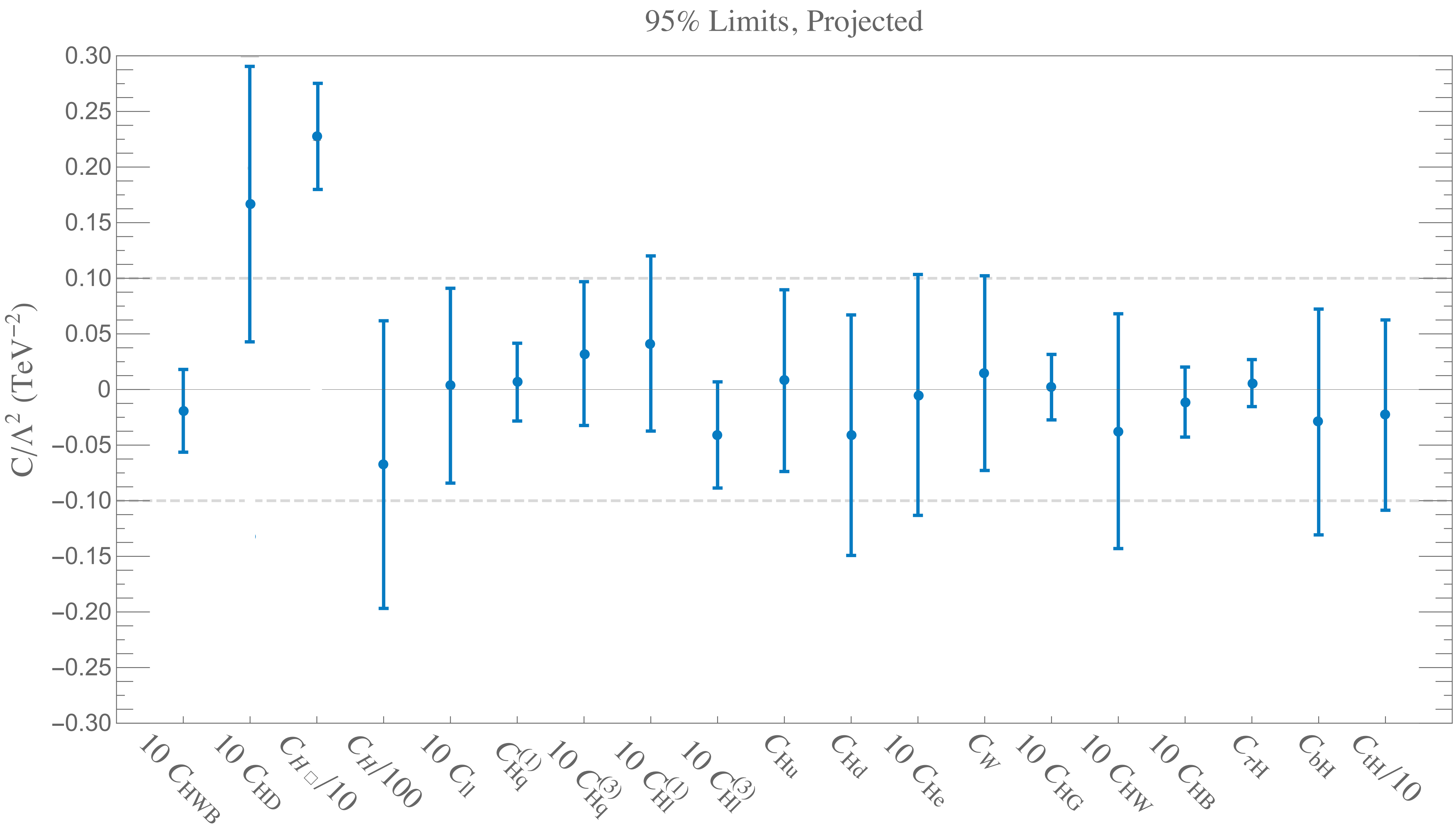






See also 1803.03252, 1812.01009, 1910.14012, 1911.07866, …

The Dream:



95% Limits, Projected
C/Λ^2 (TeV^{-2})
0.30
0.25
0.20
0.15
0.10
0.05
0
−0.05
−0.10
−0.15
−0.20
−0.25
−0.30
$10\ C_{HWB}$
$10\ C_{HD}$
$C_{H\Box}/10$
$C_H/100$
$10\ C_{ll}$
$C_{Hq}^{(1)}$
$10\ C_{Hq}^{(3)}$
$10\ C_{Hl}^{(1)}$
$10\ C_{Hl}^{(3)}$
C_{Hu}
C_{Hd}
$10\ C_{He}$
C_W
$10\ C_{HG}$
$10\ C_{HW}$
$10\ C_{HB}$
$C_{\tau H}$
C_{bH}
$C_{tH}/10$

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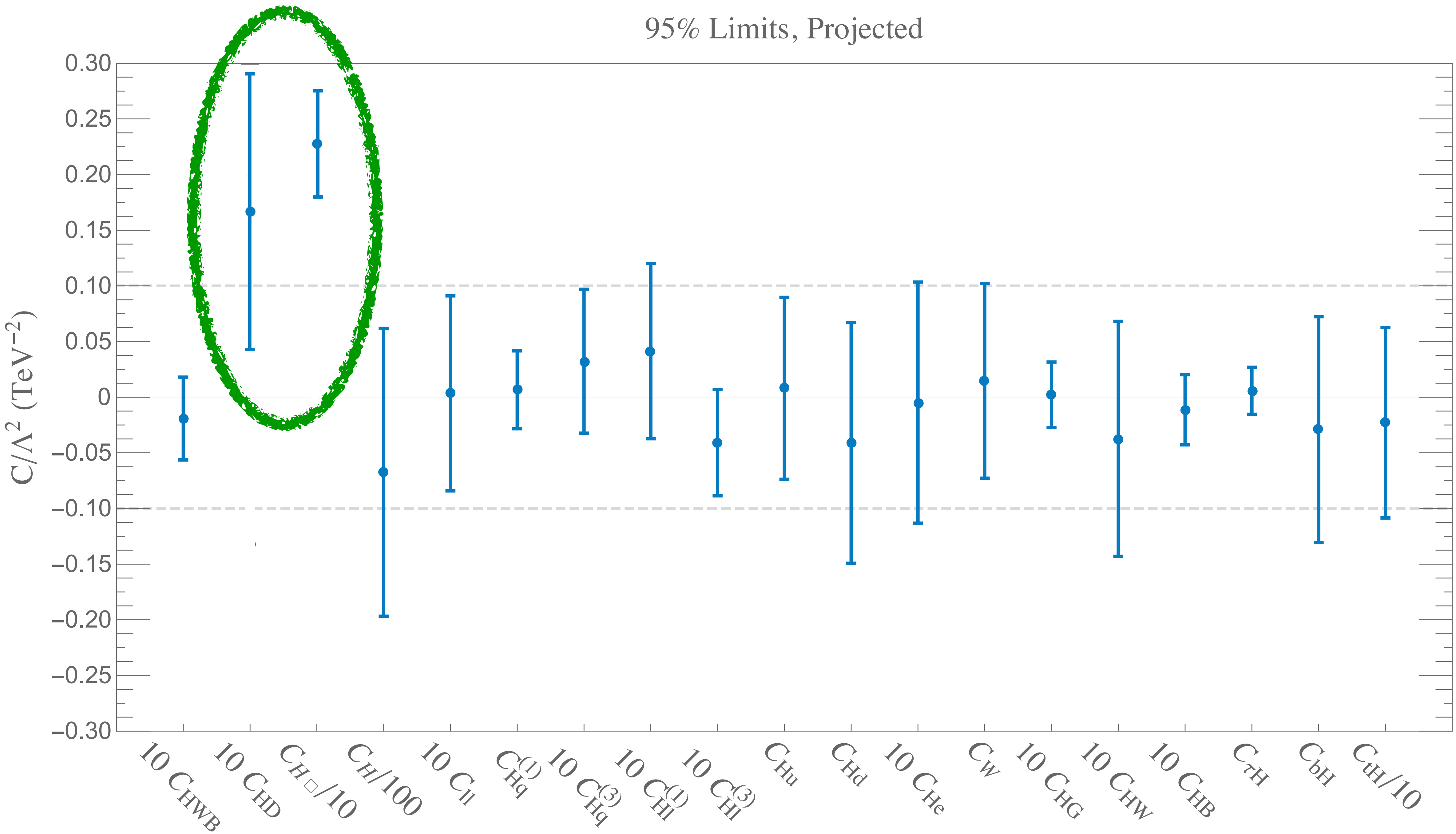
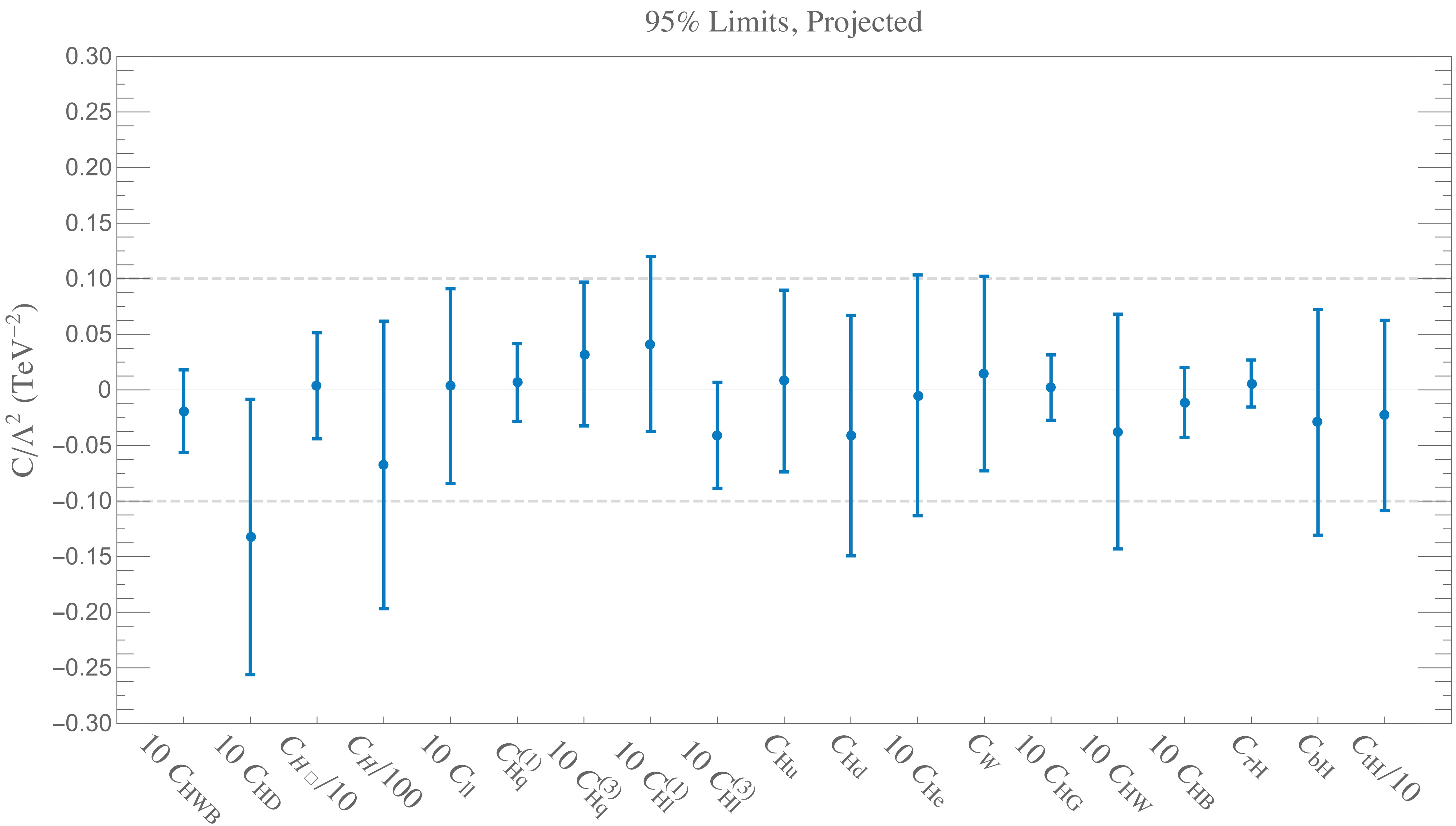


$\Longrightarrow$ Start model building! Focussed searches, make sure we understand the SM, …

Alas…

(Though CDF may have different ideas…)



We are still learning a lot about the Standard Model!

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,
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One way to assess the importance of these effects is by evaluating them in the contest of *concrete models*.

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SMEFT program at the LHC allows for robust, precision program, but ultimately operators are parameterizing *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?
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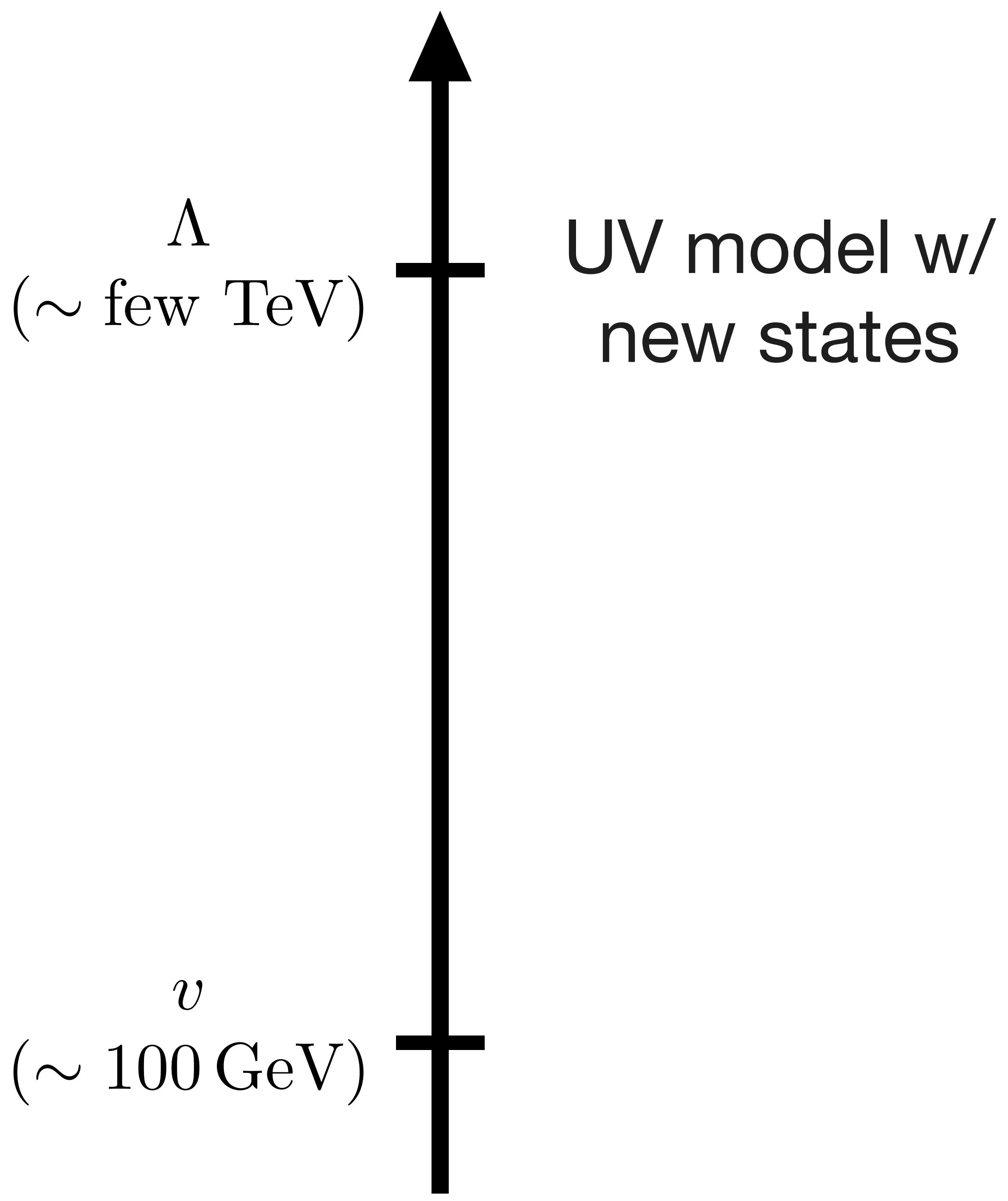
No completely "model independent" answer to some of these questions… but they are easy to investigate in examples!

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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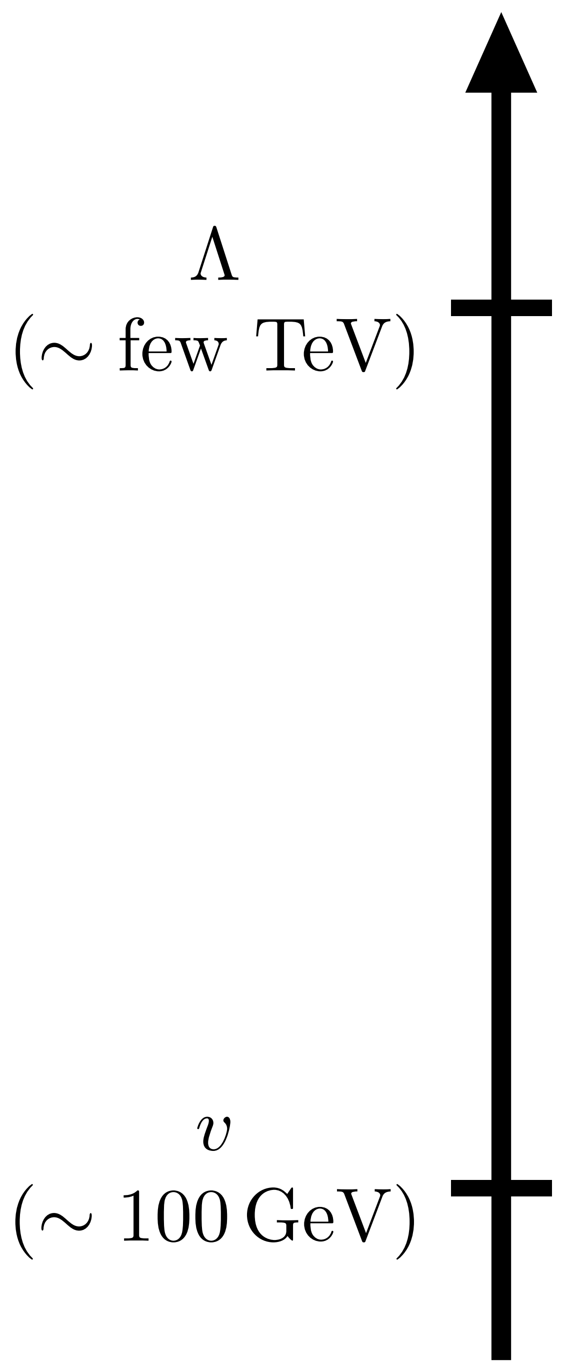

UV model w/ new states → Subset of EFT coefficients $C_i(\Lambda)$

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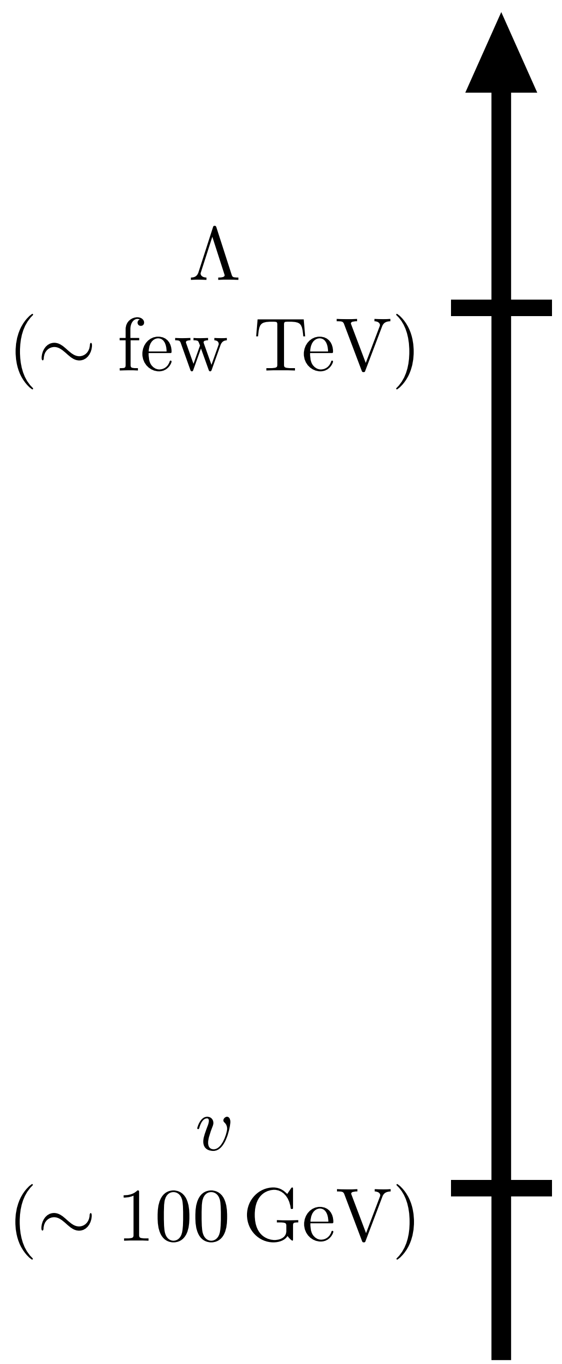

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RG Evolution to EW scale
(using anomalous dimensions given in Trott et. Al, 1308.2627+)

↓

$C_j(m_W)$

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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, …)

Example 1: the T VLQ Model

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

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Denoting the SM third generation as:

$$\psi_L = \begin{pmatrix} \mathcal{T}_L^1 \\ b_L \end{pmatrix}, \quad \mathcal{T}_R^1, \quad b_R$$

The most general Lagrangian can be written:

$$-\mathcal{L} = \lambda_b \bar{\psi}_L H b_R + \lambda_t \bar{\psi} H^c \mathcal{T}_R^1 + m_{12} \bar{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_T \bar{\psi}_L H^c \mathcal{T}_R^2 + m_T \bar{\mathcal{T}}_L^2 \mathcal{T}_R^2 + \text{h.c.}$$

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Heavy Dirac mass

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Can be rotated away by redefinition of $T_R^{1,2}$

New Yukawa coupling (leads to mixing w/ SM top)

Example 1: the T VLQ Model

Diagonalize the left- and right-handed tops to find physical eigenstates with masses m_t $(= 173\,\mathrm{GeV})$, 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, λ_t, λ_T, $m_{\mathcal{T}}$)

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

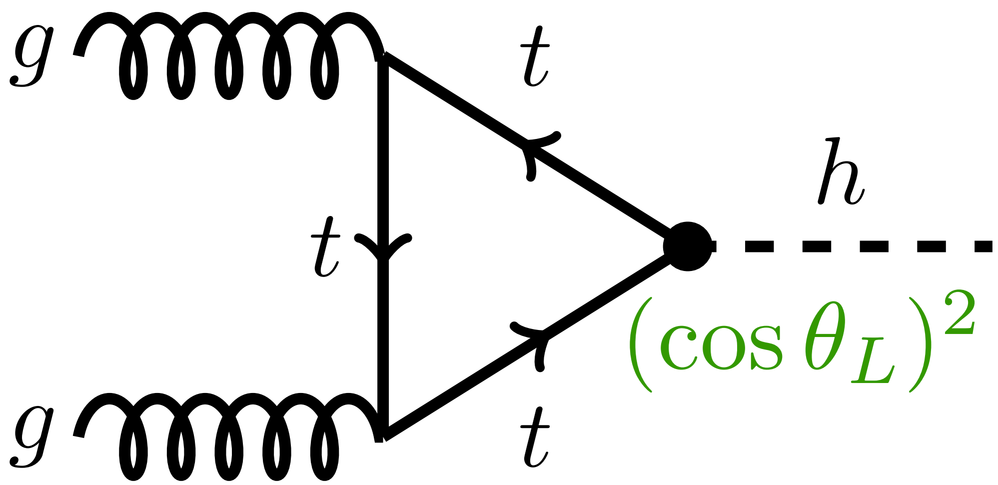
Note: expansions in M_T and $m_{\mathcal{T}}$ have different counting in inverse mass dimension for fixed $\sin\theta_L$

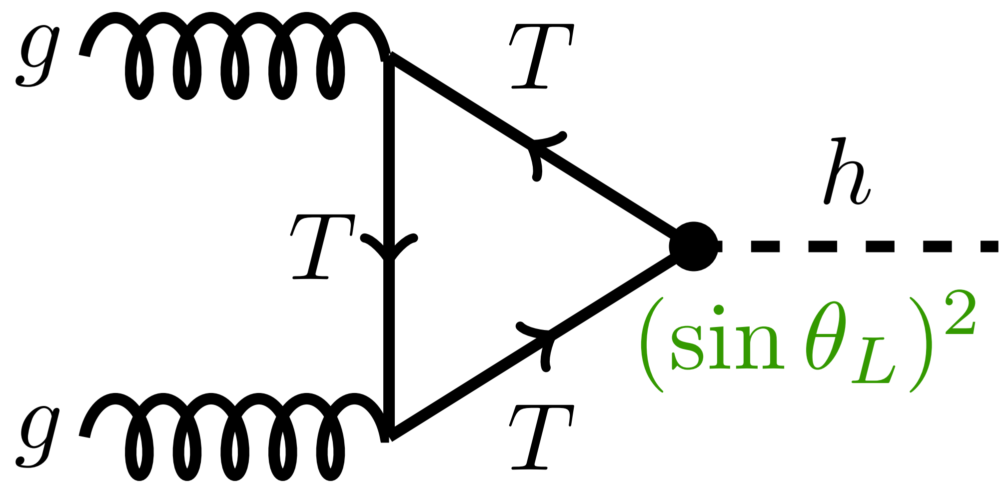
$$\frac{1}{m_{\mathcal{T}}^2} = \frac{1}{M_T^2} + \frac{s_L^2}{M_T^2}\left(1 - \frac{m_t^2}{M_T^2}\right)$$

We match at $m_{\mathcal{T}}$, see however Brehmer, Freitas, Lopez-Val, Plehn [1510.03443]

T VLQ Pheno: Higgs Production

Chiral fourth generation is completely excluded by Higgs production, but what about vector-like pairs?

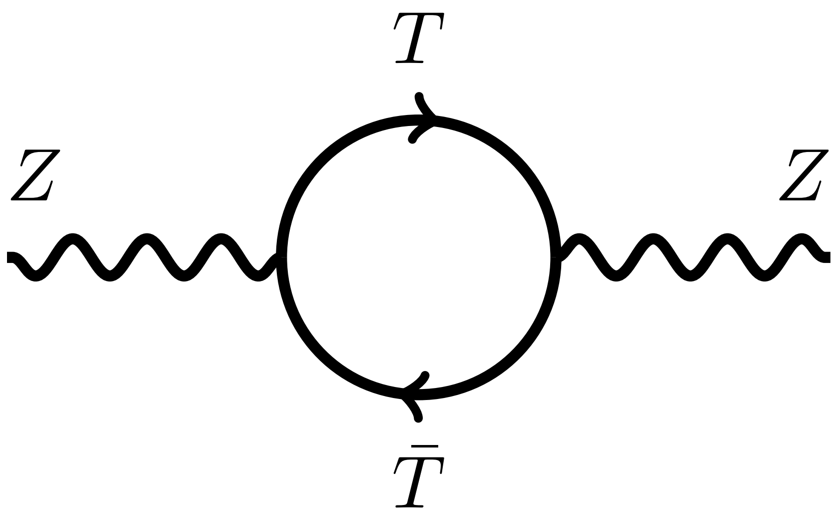




In the limit $m_H \ll m_t, M_T$ the ggh amplitude is unchanged!

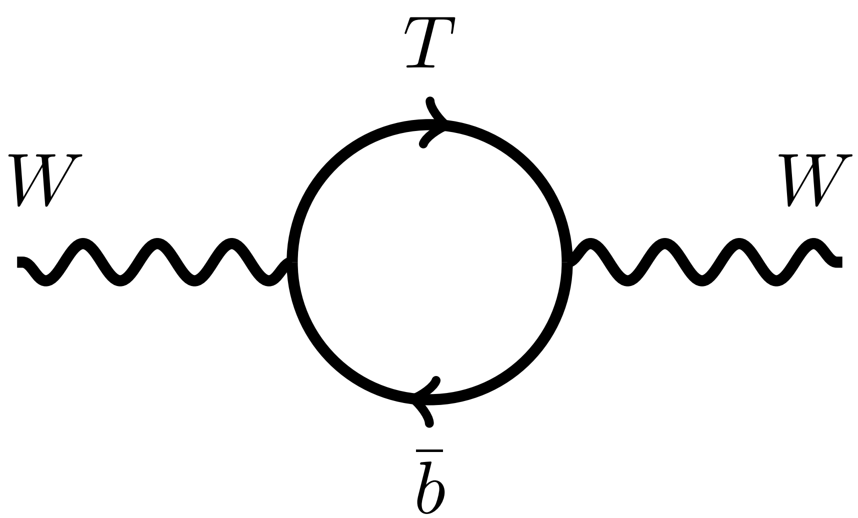
(this is a reasonably good approximation, compare to e.g., $m_t \to \infty$ limit for Higgs production…)

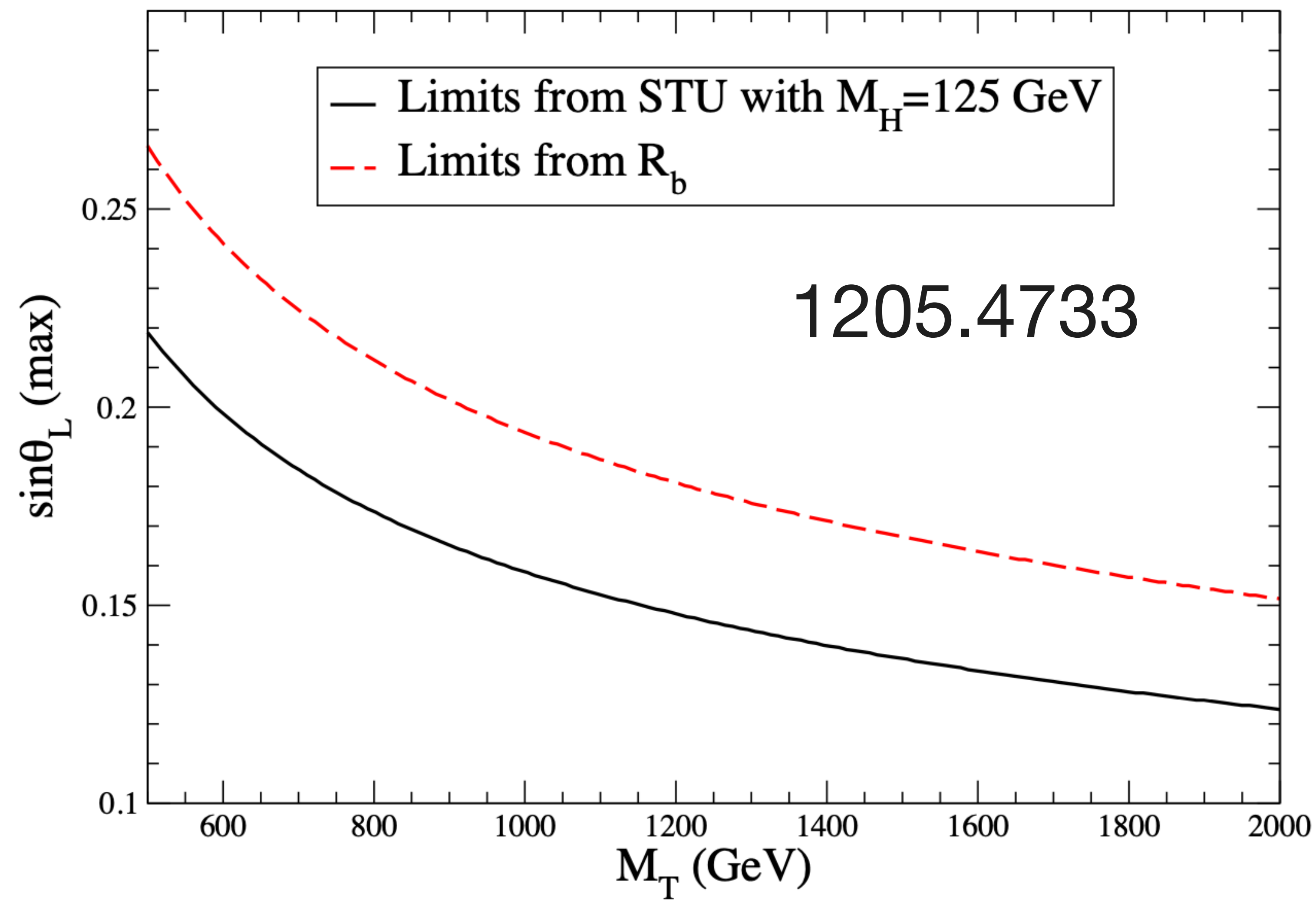
T VLQ Pheno: EW Precision



$$\Delta T = s_L^2\left[-(1+c_L^2) + s_L^2\frac{M_T^2}{m_t^2} + 2c_L^2\log\left(\frac{M_T^2}{m_t^2}\right)\right]T_{\rm SM}$$

$$\Delta S = -\frac{s_L^2}{6\pi}\left[5c_L^2 + (1-3c_L^2)\log\left(\frac{M_T^2}{m_t^2}\right)\right]S_{\rm SM}$$



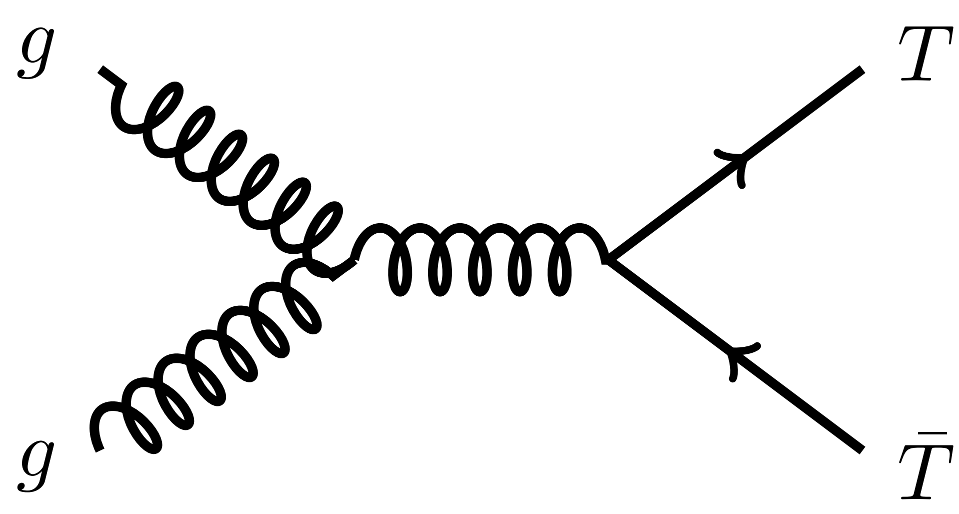


Also limits from unitarity, perturbativity of λ_T

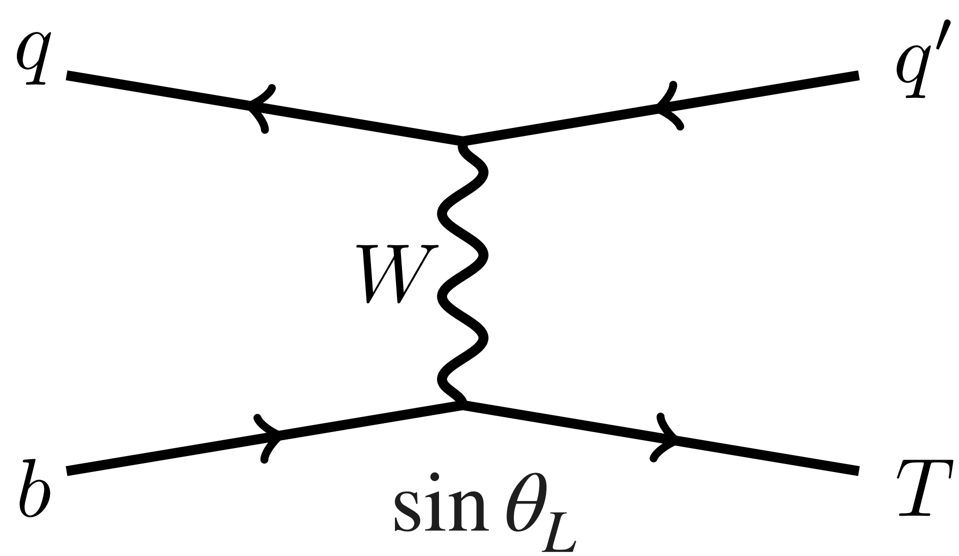
see e.g., Dawson, Furlan [1205.4733], Dawson, Furlan, Chen [1703.06134]

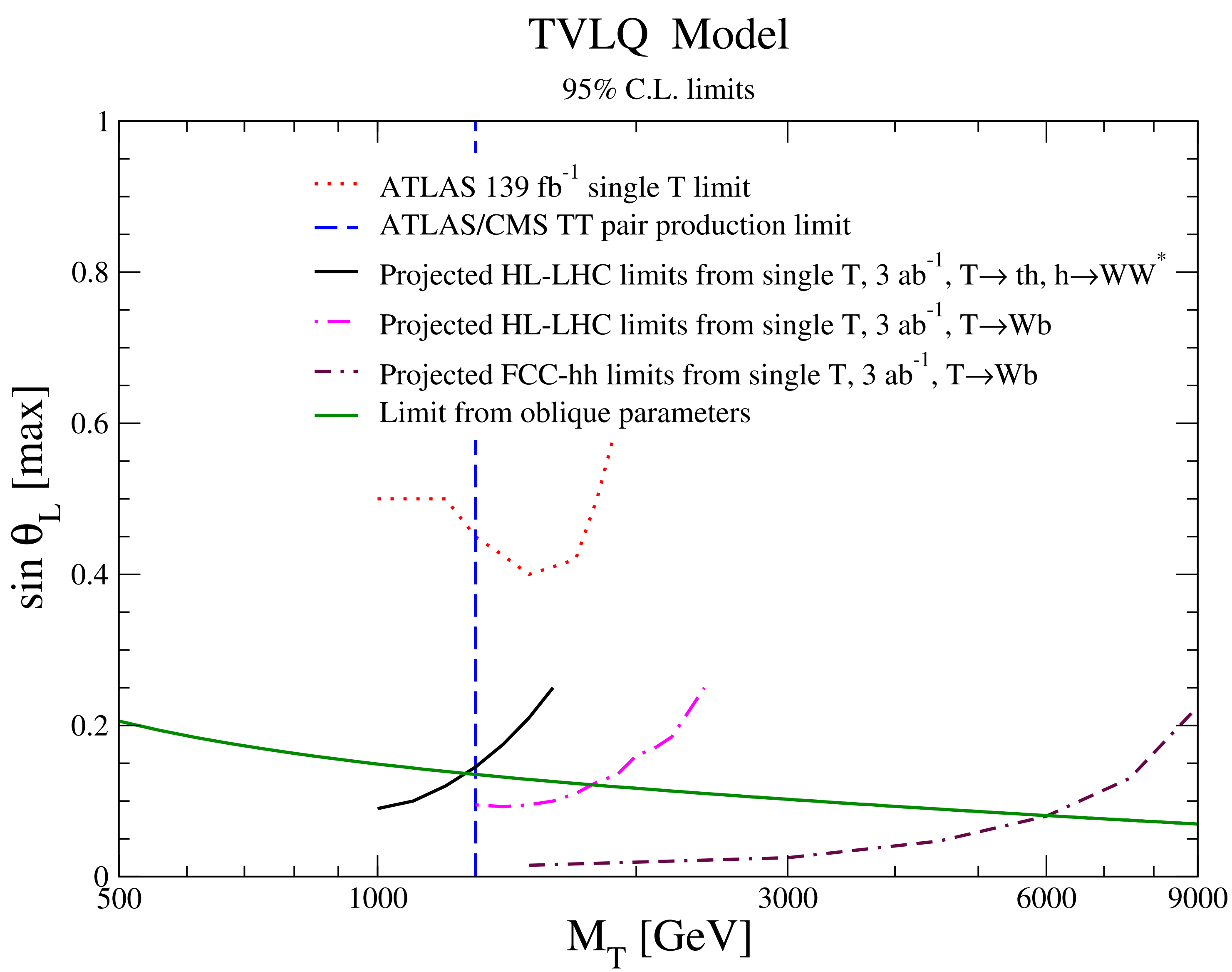
T VLQ Pheno: Direct Searches

Pair production:



Single-production:





VLQs must be heavier than ~1.7 TeV, independent of mixing angle!

$\Longrightarrow$ Ideal candidate for SMEFT!

T VLQ in the SMEFT

Dimension-6 Matching

Using Eqns. of motion (CDE) to integrate out the heavy Top, we have at dimension-6:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{i}{2}\frac{\lambda_T^2}{m_T^2}\bar{\psi}_L H^c \not{D}\left(H^{c\dagger}\psi_L\right) + \text{h.c.} + \ldots$$

New interactions + non-canonical kinetic term

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

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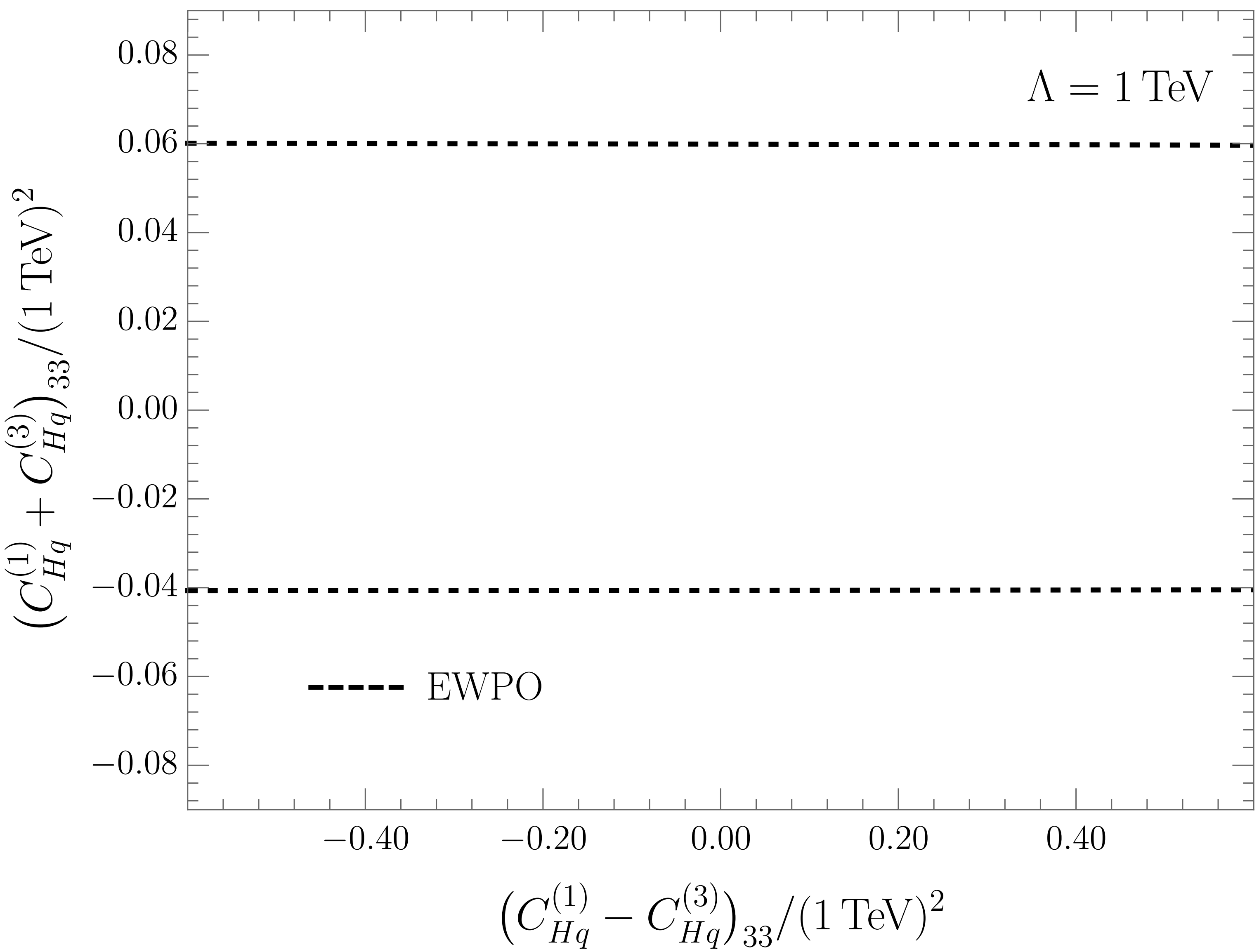
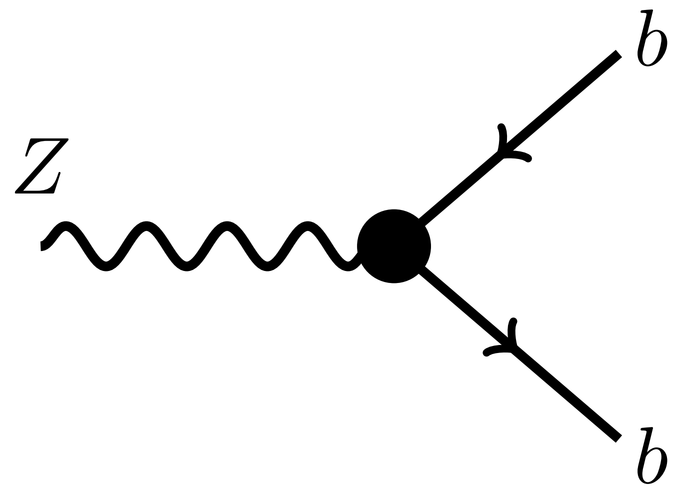
Note: all dim-6 corrections scale like $(\lambda_T/m_T)^2$!

T VLQ in the SMEFT

LEP Constraints: Tree Level



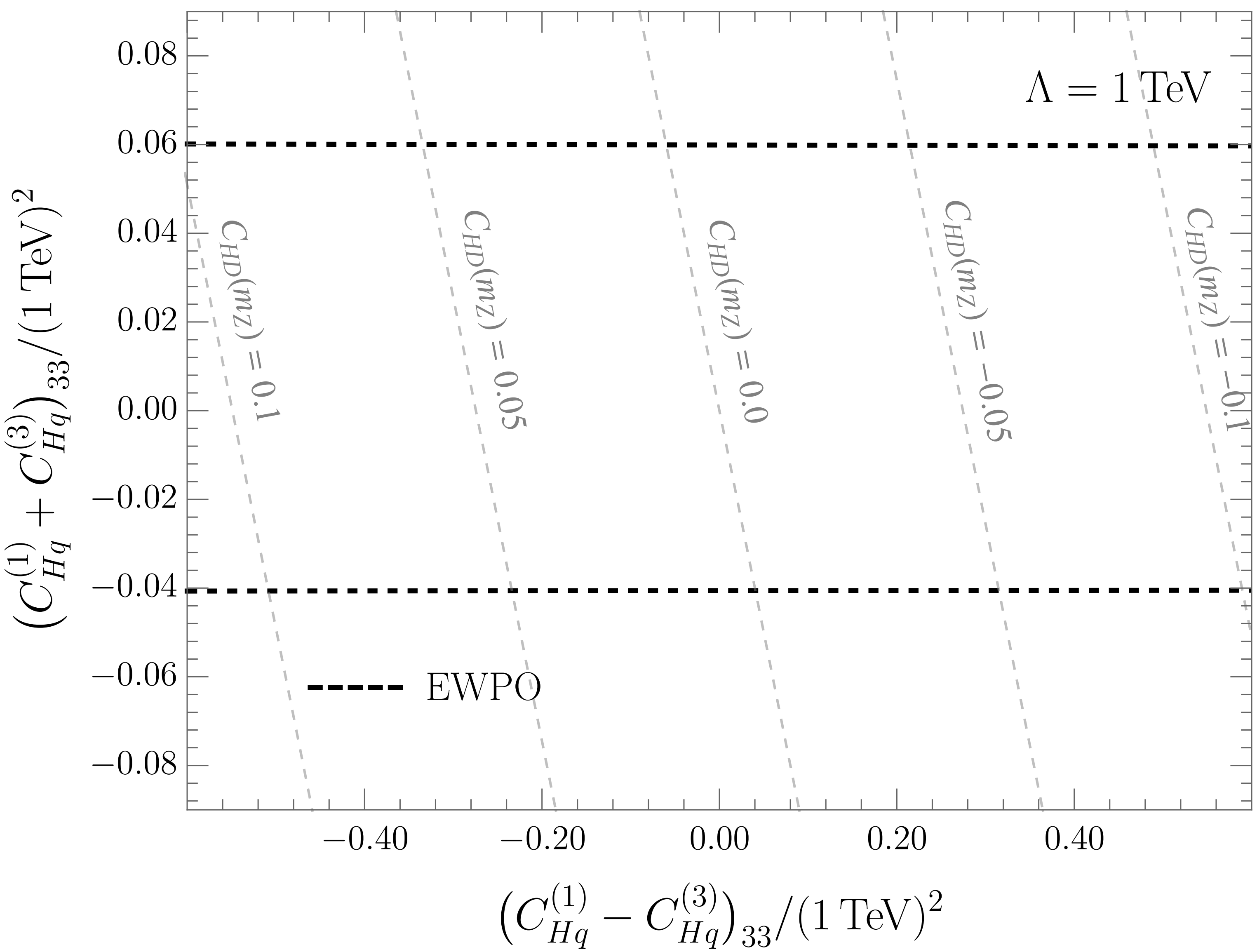
At tree level, only one way to measure operators $C^{(1)}_{Hq,33}$, $C^{(3)}_{Hq,33}$:



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

T VLQ in the SMEFT

LEP Constraints: RGE-Induced



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

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

T VLQ in the SMEFT

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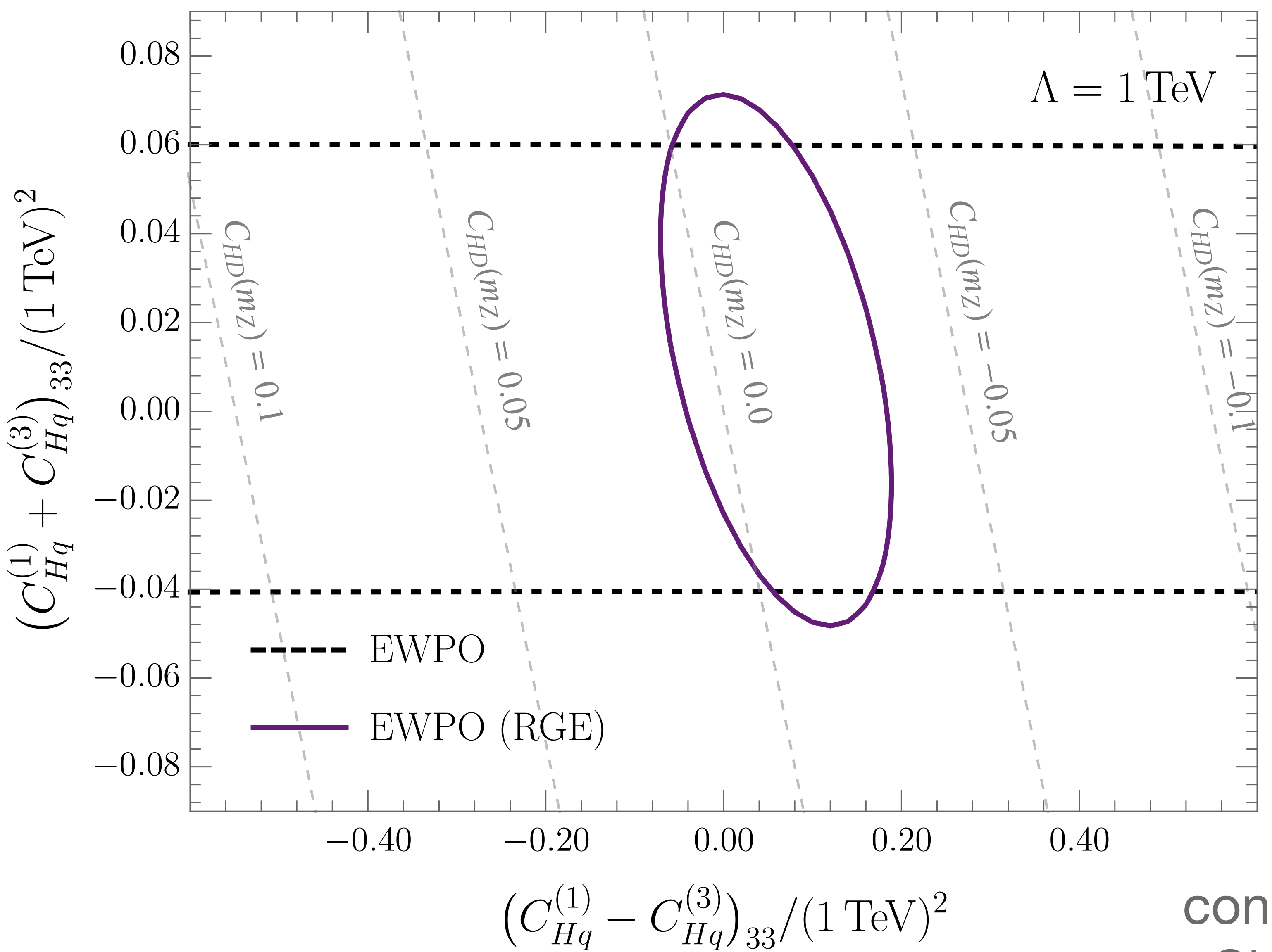

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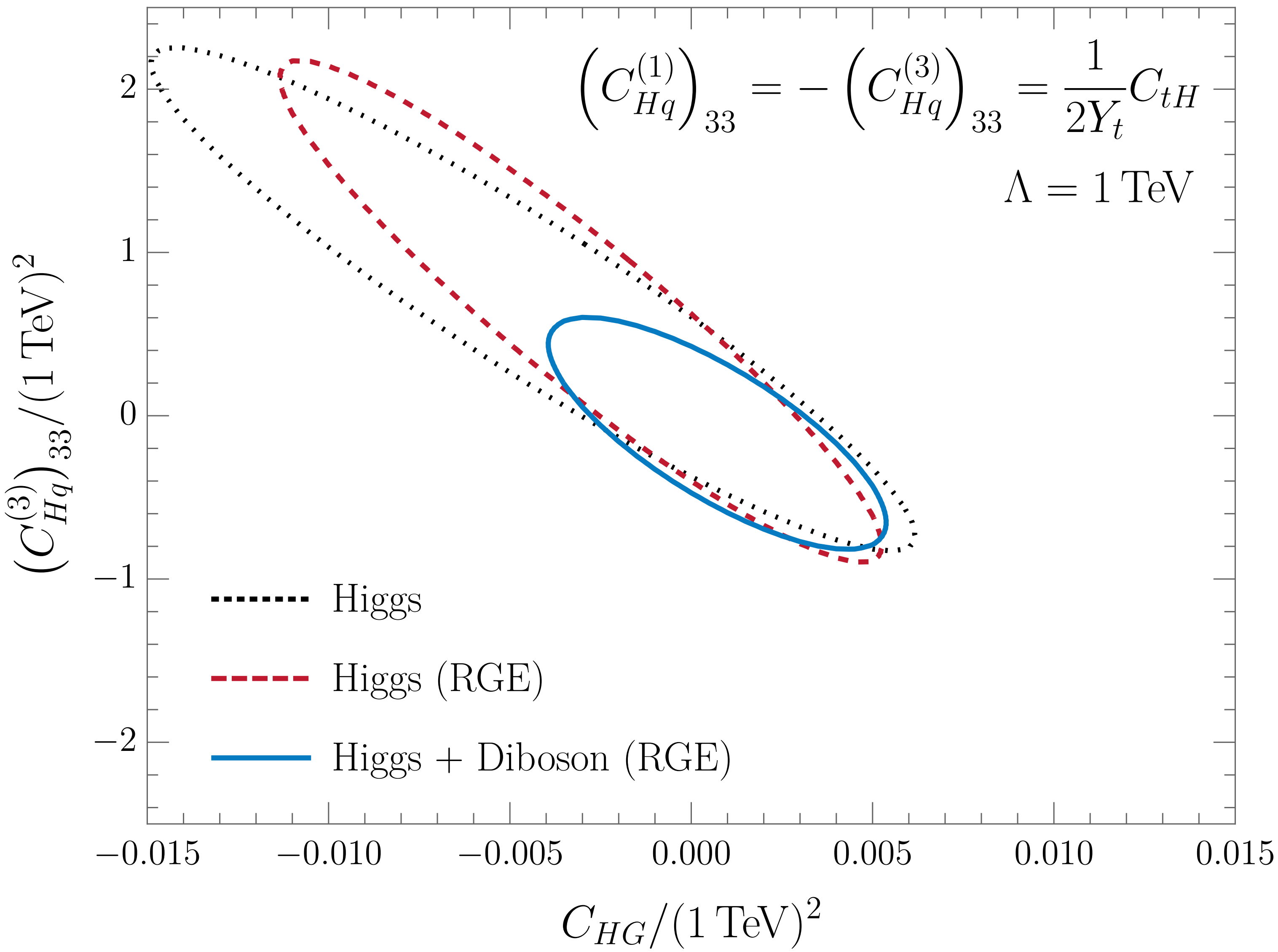
(Well understood in UV theory — constraints from oblique parameters, e.g., Chen, Dawson, Furlan, arXiv:1406.3349

T VLQ in the SMEFT

LHC Constraints: Tree-Level + RGEs

Similar lessons apply to LHC bounds:



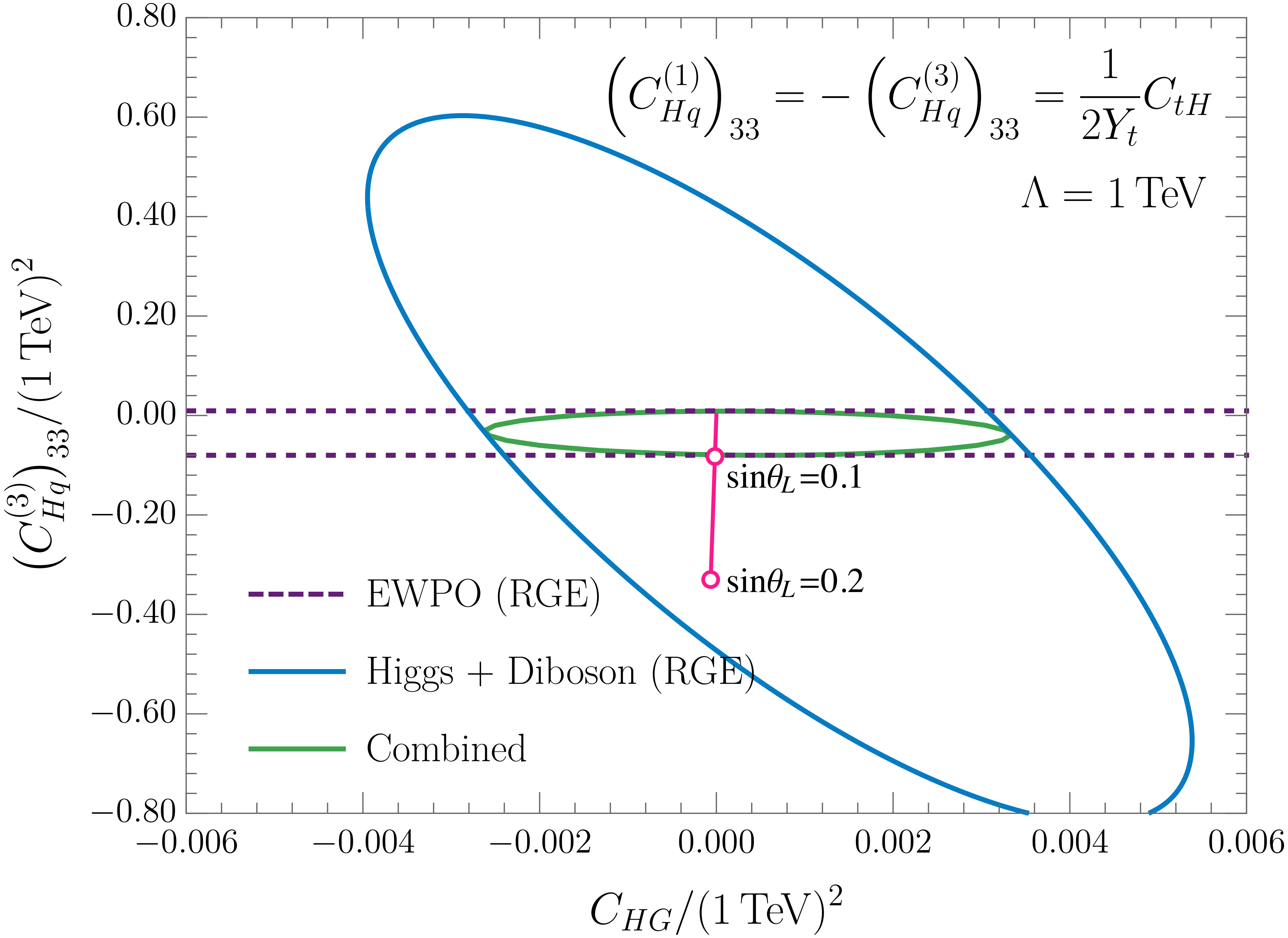
But RG evolution also generates *new* operators measured at the LHC in *WW*, *WZ*, *WH*, *ZH* production!

Strongest LHC constraint from RGEs!

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

T VLQ in the SMEFT

Combined Constraints: a Constrained SMEFT Fit



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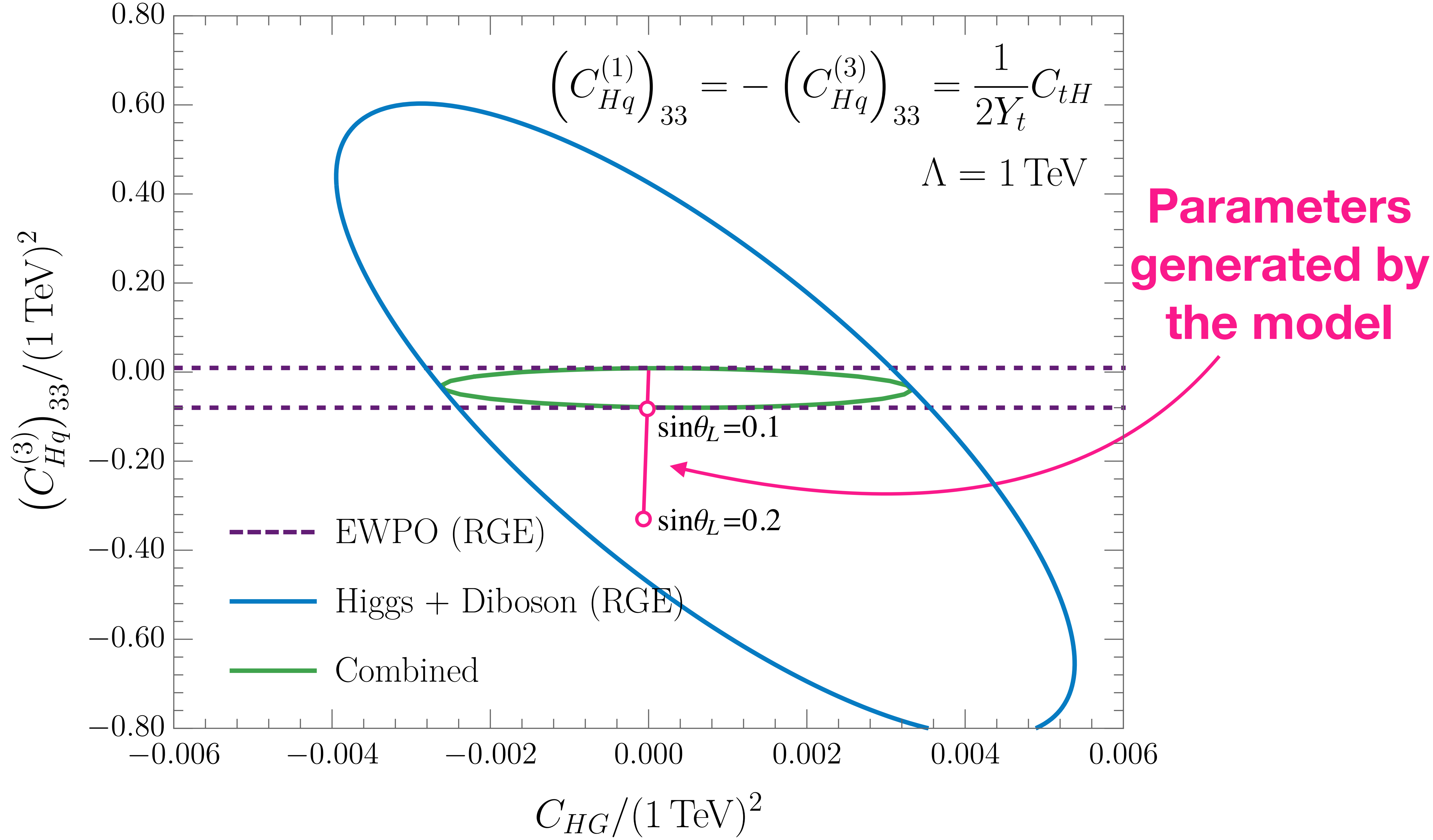
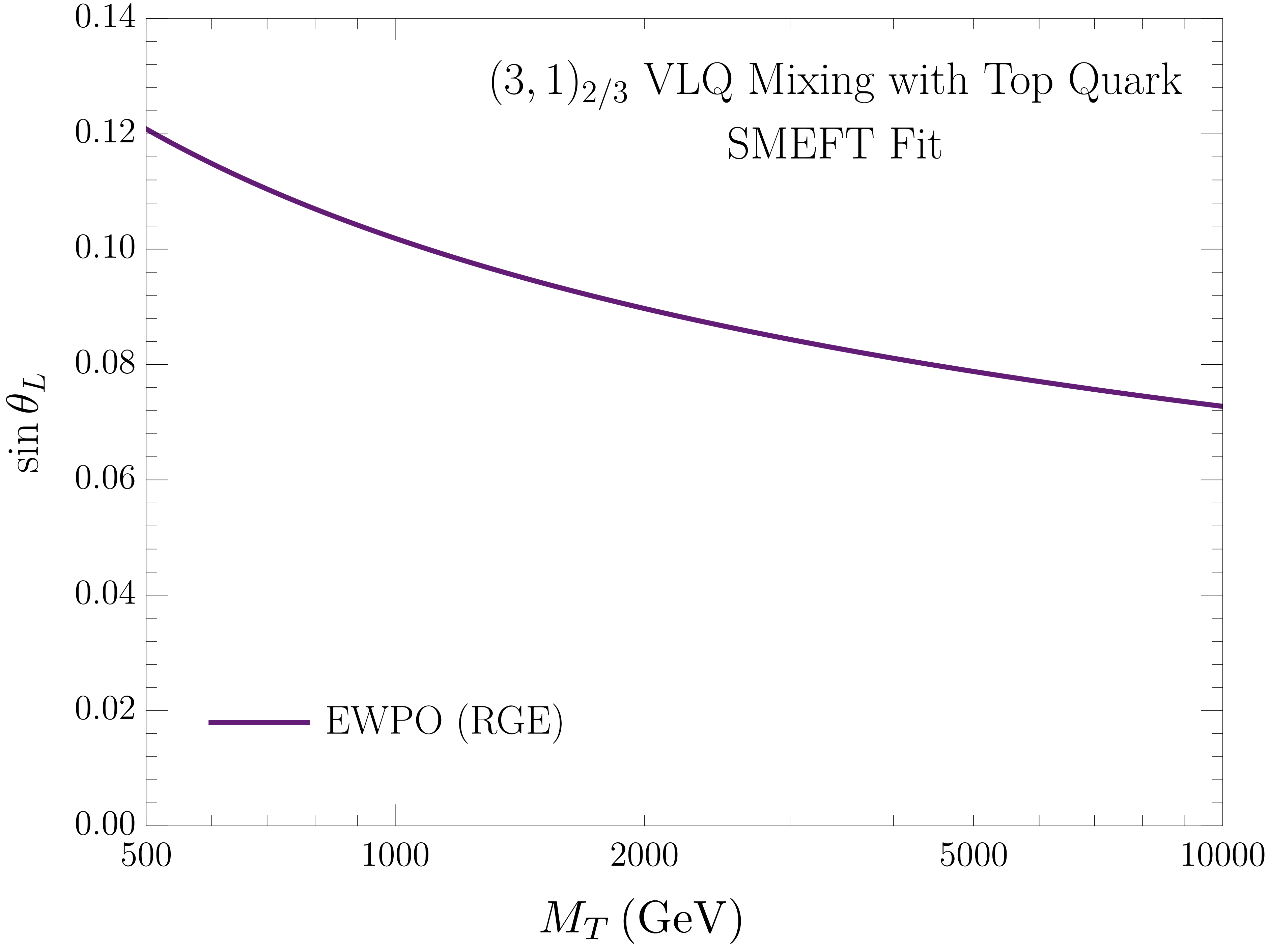


T VLQ in the SMEFT

Re-Interpretation in terms of model parameters



Is Dimension-6 Fit Sufficient?

Expanding an arbitrary observable in powers of $1/\Lambda^2$:

$$\mathrm{d}\sigma \sim \left|\mathcal{A}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\mathcal{A}_6 + \frac{1}{\Lambda^4}\mathcal{A}_8 + \ldots\right|^2$$

$$\sim \left|\mathcal{A}_{\mathrm{SM}}\right|^2 + \frac{2}{\Lambda^2}\mathrm{Re}\left|\mathcal{A}_{\mathrm{SM}}^*\mathcal{A}_6\right| + \frac{1}{\Lambda^4}\left|\mathcal{A}_6\right|^2 + \frac{2}{\Lambda^4}\mathrm{Re}\left|\mathcal{A}_{\mathrm{SM}}^*\mathcal{A}_8\right| + \ldots$$

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But if we keep the dim-6 squared terms, linear terms at dim-8 are of the same order….

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But if we keep the dim-6 squared terms, linear terms at dim-8 are of the same order….

Several pheno studies including dim-8 terms, finding sometimes significant effects:

- Hays, Martin, Sanz, Setford (WH production) [1808.00442]
- Grazzini et al, Battaglia et al, ($H+\mathrm{jet}$ production) [1612.00283, 2109.02987]
- Corbett, Helset, Martin, Trott (EWPO) [2102.02819]

T VLQ Matched to Dimension-8

arXiv:2110.06948, Dawson, SH, Sullivan

Perform the matching by continuing the CDE:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\frac{\lambda_T^2}{m_T^2}\bar{\psi}_L H^c \not{D}\left(H^{c\dagger}\psi_L\right) + \text{h.c.} + \dots$$

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The necessary field redefinition is unchanged,

$$\psi_{L,i} \to \psi_{L,i} - \frac{\lambda_T^2}{2m_T^2}\left(H_i^c H_j^{c\dagger}\right)\psi_{L,j} + \ldots$$

… but now must be included in the dim-6 operators as well.

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After repeated use of the EOMs:

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

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Note: different scaling than at dim-6!

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Also additional momentum-dependent interactions, and interactions with gluons:

$$+ \; i\frac{\lambda_T^2}{m_T^4}(\bar{\psi}_L D^\mu H^c)\gamma_\mu(D^\nu H^{c\dagger} D_\nu \psi_L) + i\frac{\lambda_T^2}{m_T^4}(\bar{\psi}_L H^c)\gamma_\mu(D^\mu D^\nu H^{c\dagger} D_\nu \psi_L)$$

$$- \, i\frac{\lambda_T^2}{m_T^4}(\bar{\psi}_L H^c)\gamma_\mu(D^\nu D^\mu H^{c\dagger} D_\nu \psi_L) - \frac{\lambda_t \lambda_T^2}{m_T^4}(H^\dagger H)\bar{t}_R(D^\mu H^{c\dagger} D_\mu \psi_L) + \text{h.c.} + \ldots$$

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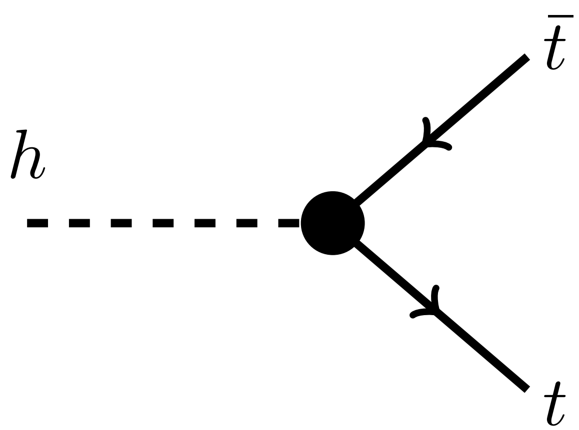
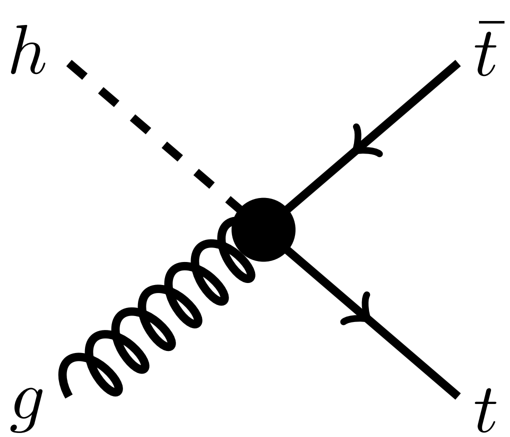
New, momentum-dependent interactions:



$$= -i\frac{Y_t^{(8)}}{\sqrt{2}} + i\frac{\lambda_T^2 v m_t}{4m_T^4}(p_t - p_{\bar{t}}) \cdot p_h (P_L - P_R)$$



$$= i g_s T^A \frac{\lambda_T^2 v m_t}{2m_T^4} p_h^\mu (P_L - P_R)$$

Also new tbW, $tbWh$, interactions, and interactions with more Higgses…

Complete set of interactions implemented in FeynRules model.

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Clearest effect at dim-8 is the change in the top Yukawa:

$$Y_t^{(8)} = \frac{m_t\sqrt{2}}{v}\left(1 - \frac{\lambda_T^2 v^2}{2m_T^2} - \frac{m_t^2 v^2 \lambda_T^2}{m_T^4} + \frac{\lambda_T^4 v^4}{4m_T^4}\right)$$

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Again see the difference in counting in λ_T/m_T

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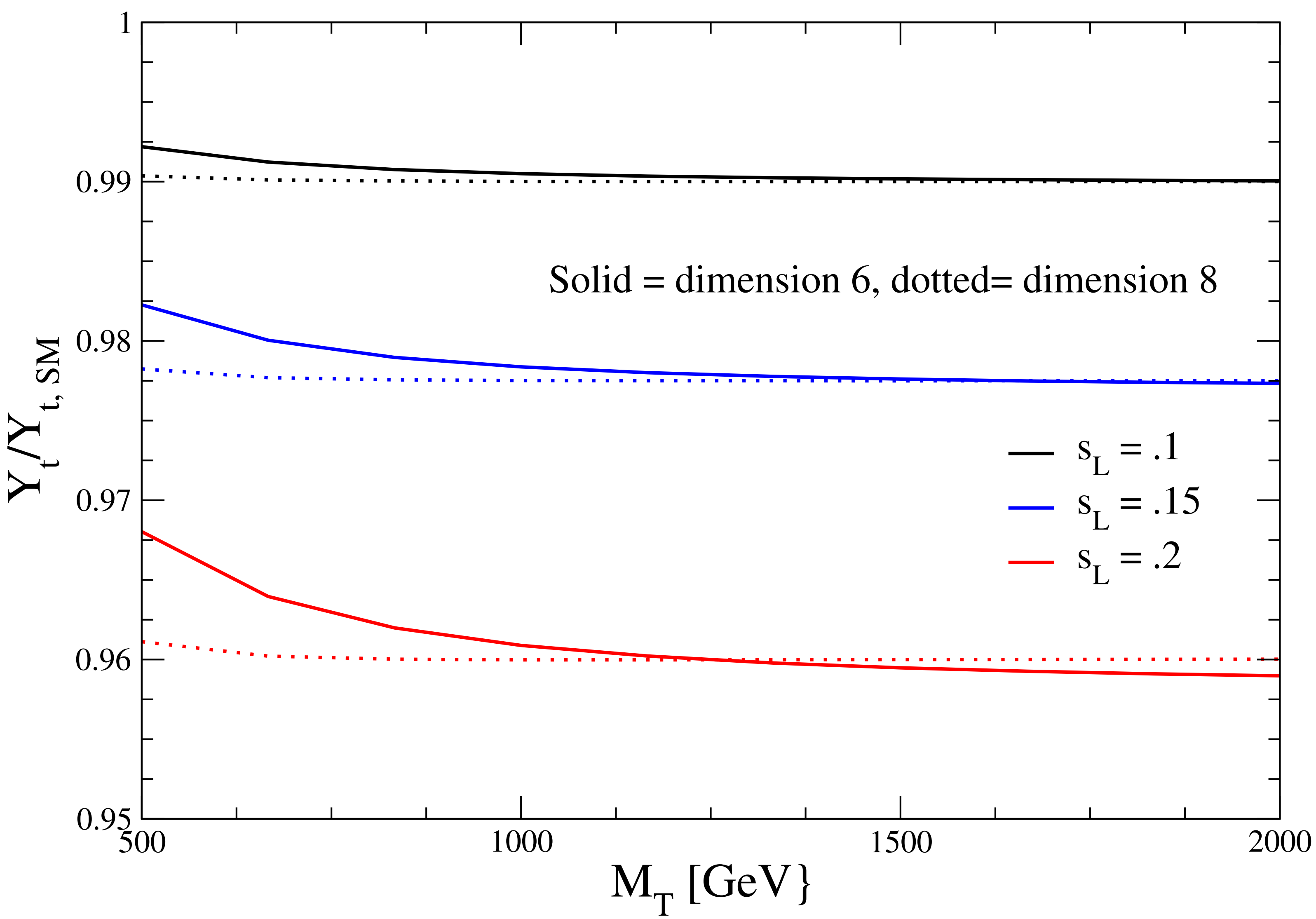

Again see the difference in counting in $\lambda_T/m_{\mathcal{T}}$

Impact of Dim-8 Terms: $t\bar{t}h$ Production

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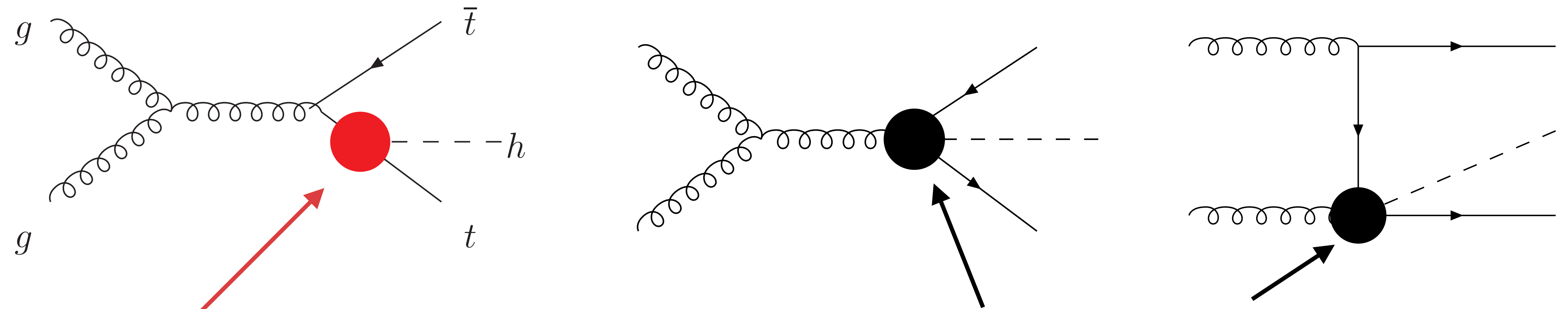
Implement full set of interactions in FeynRules, simulate $t\bar{t}h$ production in MadGraph:



Insertion of dim-6 or dim-8

Appear only at dim-8 — s-enhanced!

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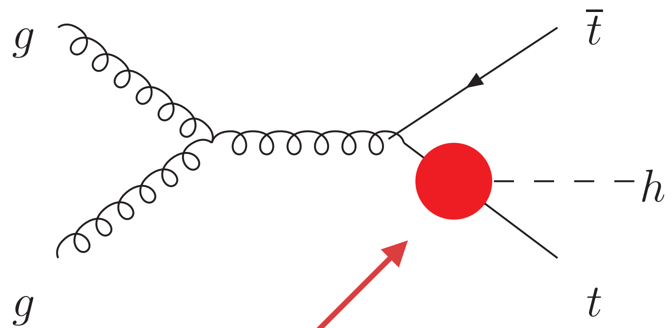

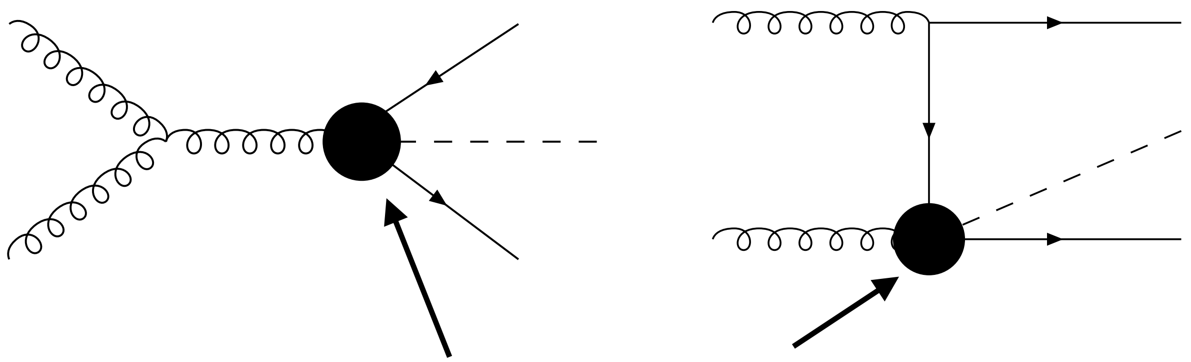

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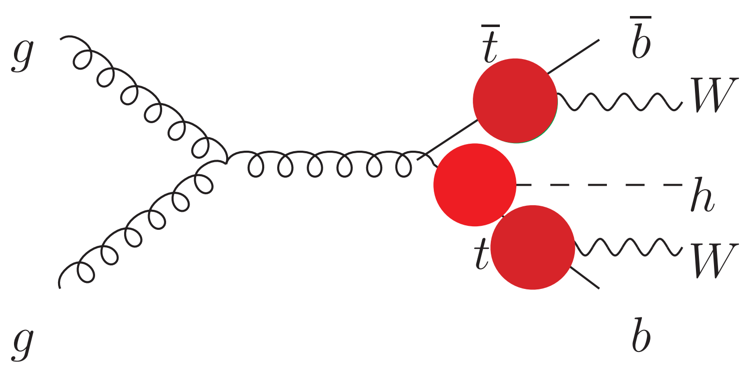
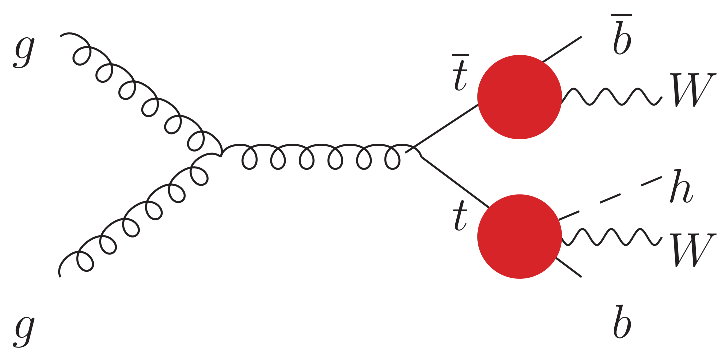
Important to also include decays, including corrections to $tbWh$ vertex:





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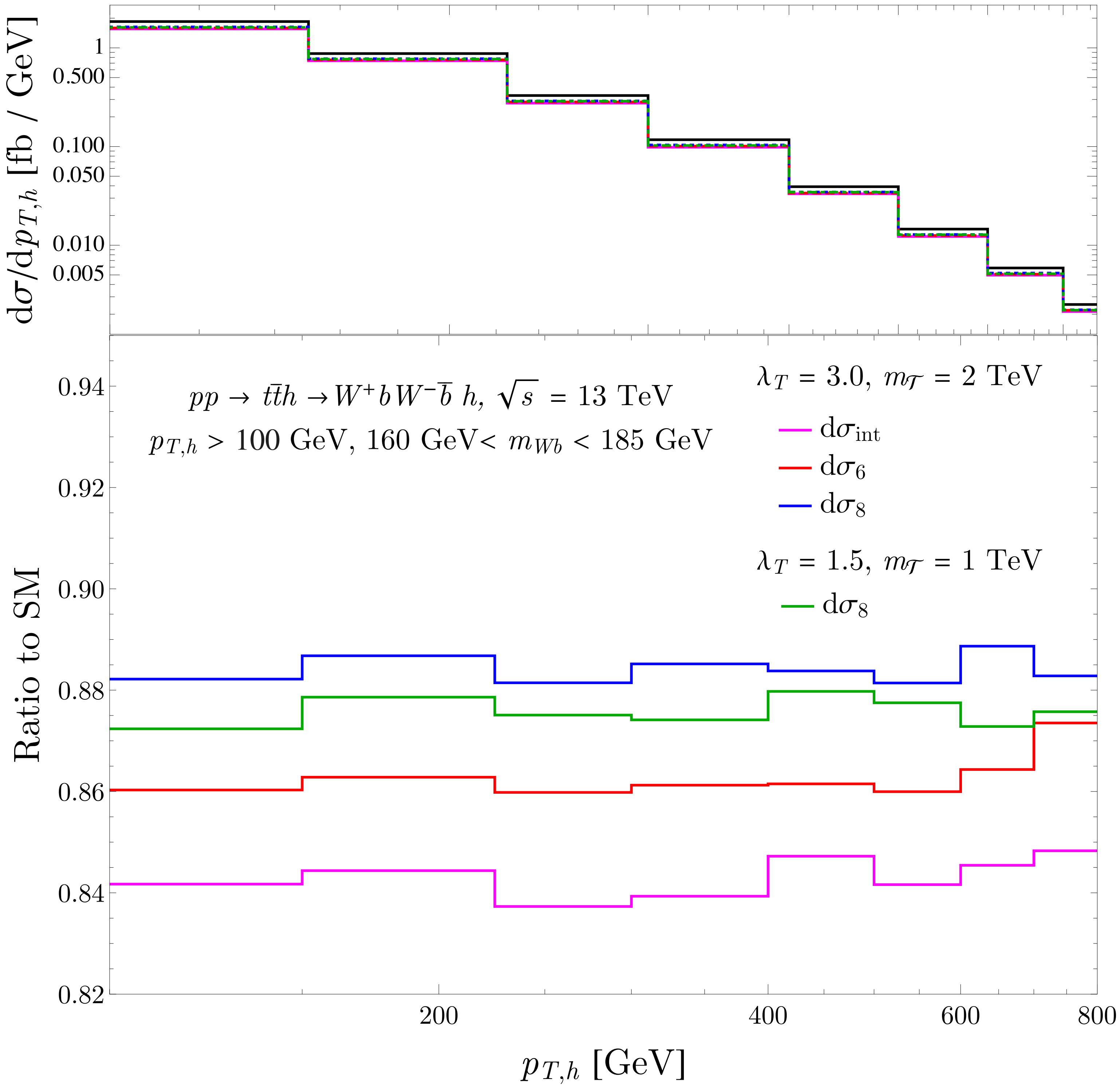

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(but *not* a universal effect!)

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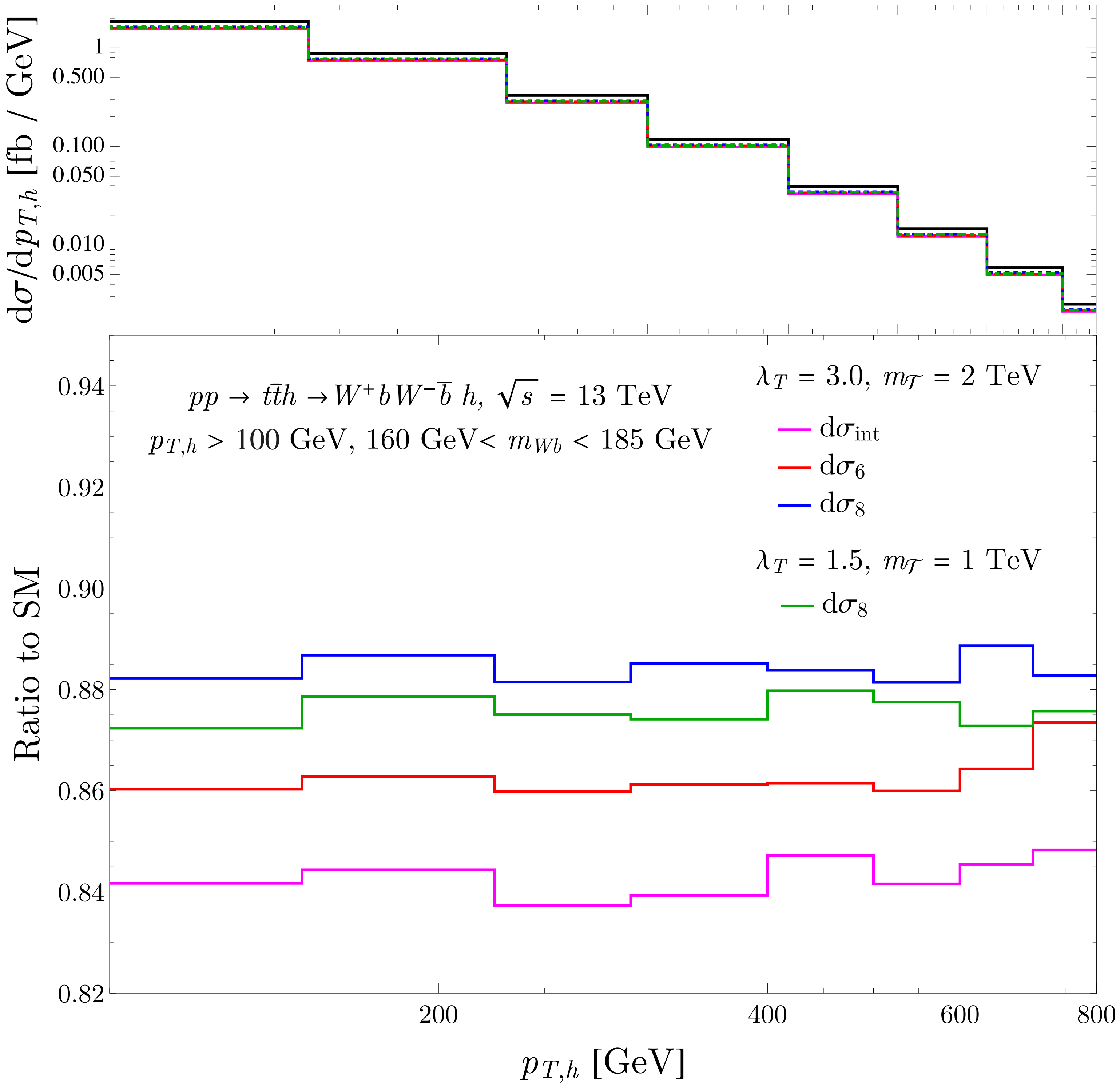

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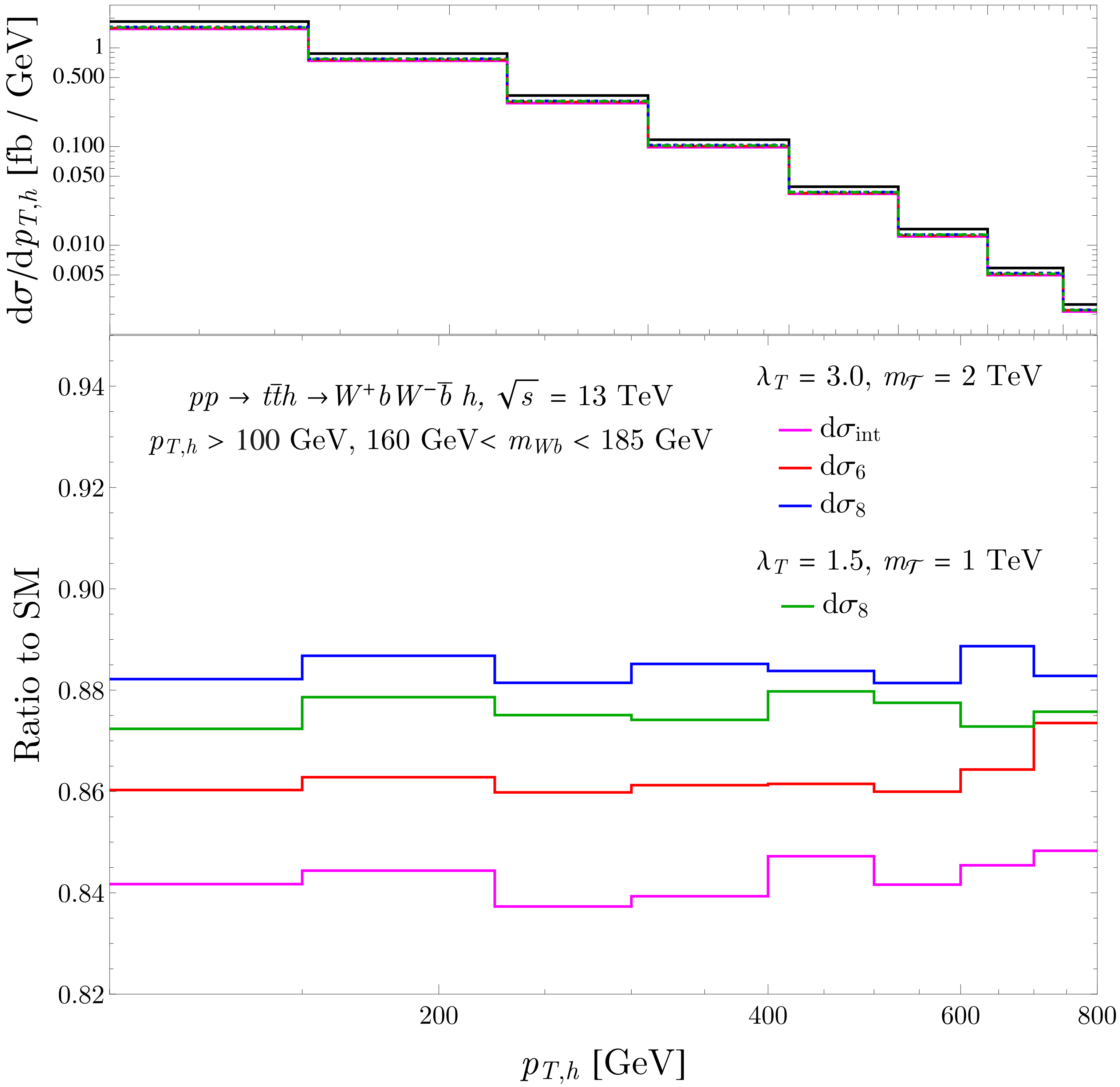

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Dim-8 Effects sensitive to mass, independently of coupling (mixing angle)!

Dim-8 Terms in $t\bar{t}h$ production: Summary

arXiv:2110.06948, Dawson, SH, Sullivan

Several apparent effects from matching up to dimension-8 in this model:

- Higher order terms can have different scalings in coupling/ mass — interesting interplay with decoupling limit
- New vertices with different particles, momentum structure that didn't exist at dimension-6 — can lead to kinematic effects
- Effects are *small* — $\mathcal{O}(1\%)$ for allowed parameters — but this model is too simple!

More complicated models may lead to larger effects, particularly if there is interplay with the EW input parameters?

(see e.g., 2102.02819 in context of EWPO)

Example 2: The 2HDM

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

Assume two scalar doublets, Φ_1, Φ_2 distinguished by a softly broken Z_2 symmetry, $\Phi_2 \to -\Phi_2$.

Extend to fermions to avoid FCNCs, leads four types of 2HDMs (I, II, L, and F)

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Useful to work in the *Higgs basis*, denoted H_1, H_2 defined by $\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

A second mixing angle α, puts h_{125} into H_1

Example 2: The 2HDM

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

For each type, 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

The matching at dimension-6 is well known. Ignoring light flavor, there are four operators generated:

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

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

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

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

	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

Matching to Dimension-6

The matching at dimension-6 is well known. Ignoring light flavor, there are four operators generated:

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

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

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

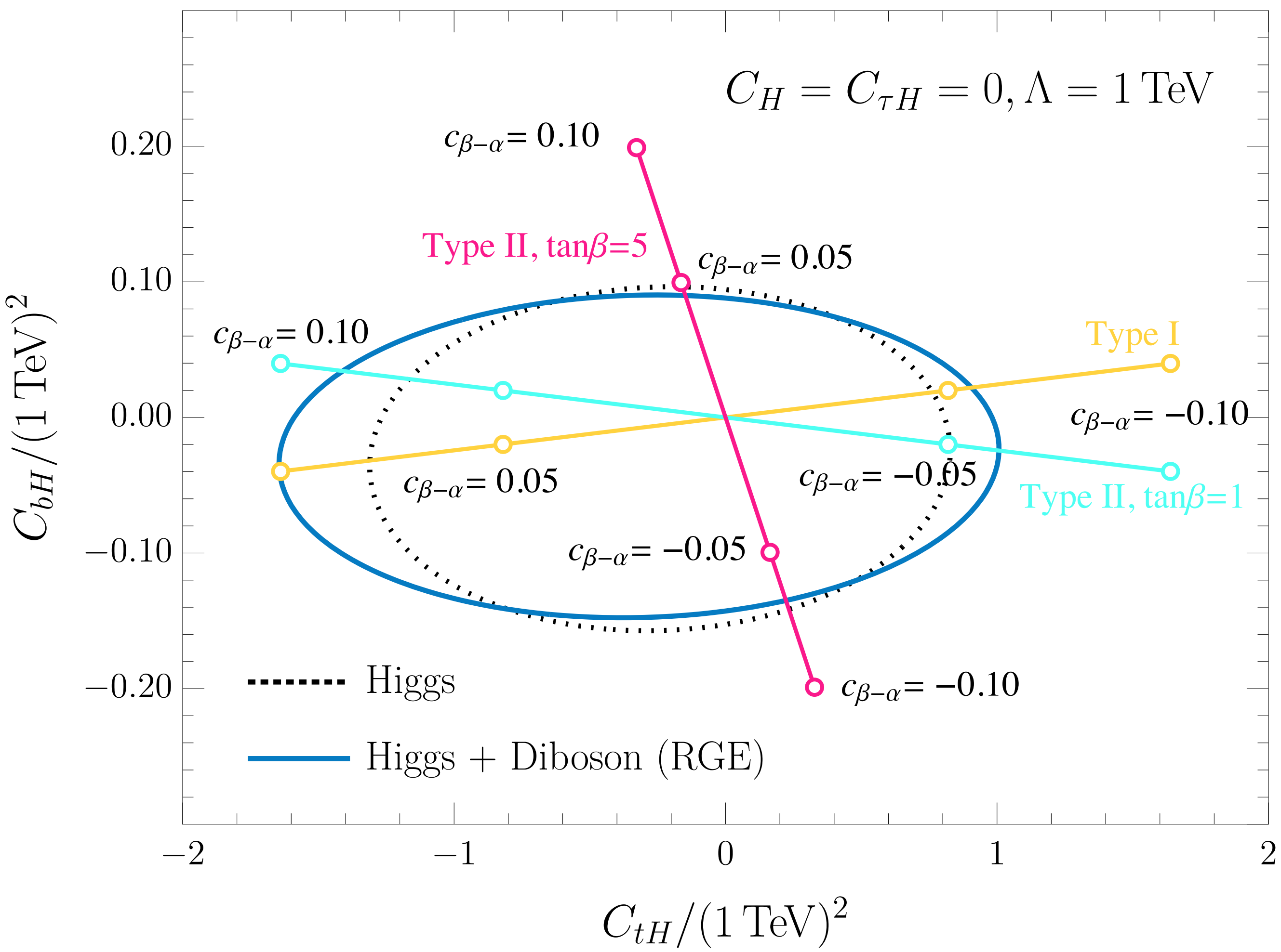
$$\mathcal{O}_{\tau H} = (H^\dagger H)(\bar{L}_3 \tau_R \tilde{H}), \quad \frac{v^2}{\Lambda^2} C_{\tau H} = -y_\tau \eta_\tau \frac{\cos(\beta - \alpha)}{\tan\beta}$$

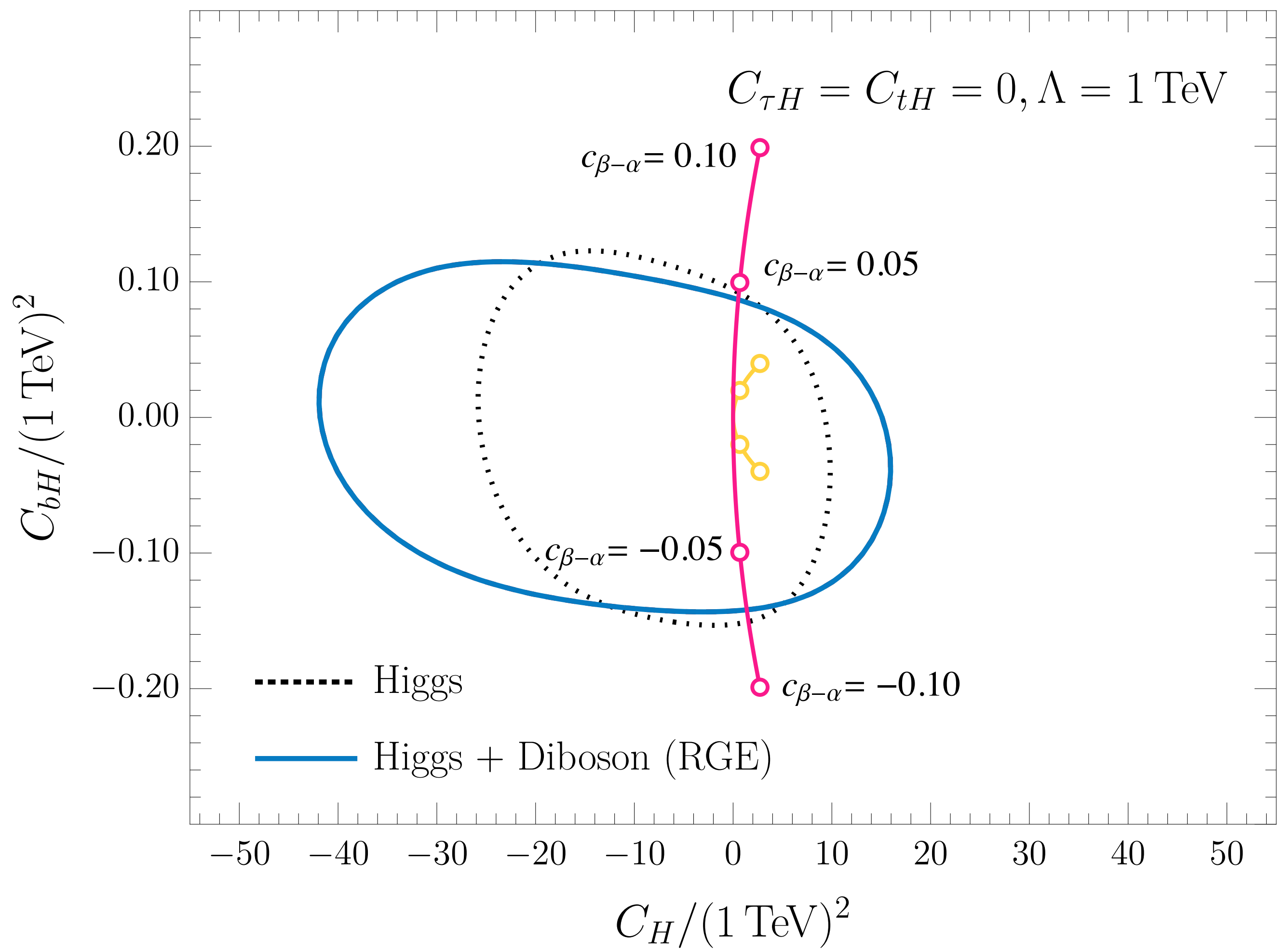
	η_t	η_b	η_τ
Type-I	1	1	1
Type-II	1	$-\tan^2\beta$	$-\tan^2\beta$
Lepton-specific	1	1	$-\tan^2\beta$
Flipped	1	$-\tan^2\beta$	1

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

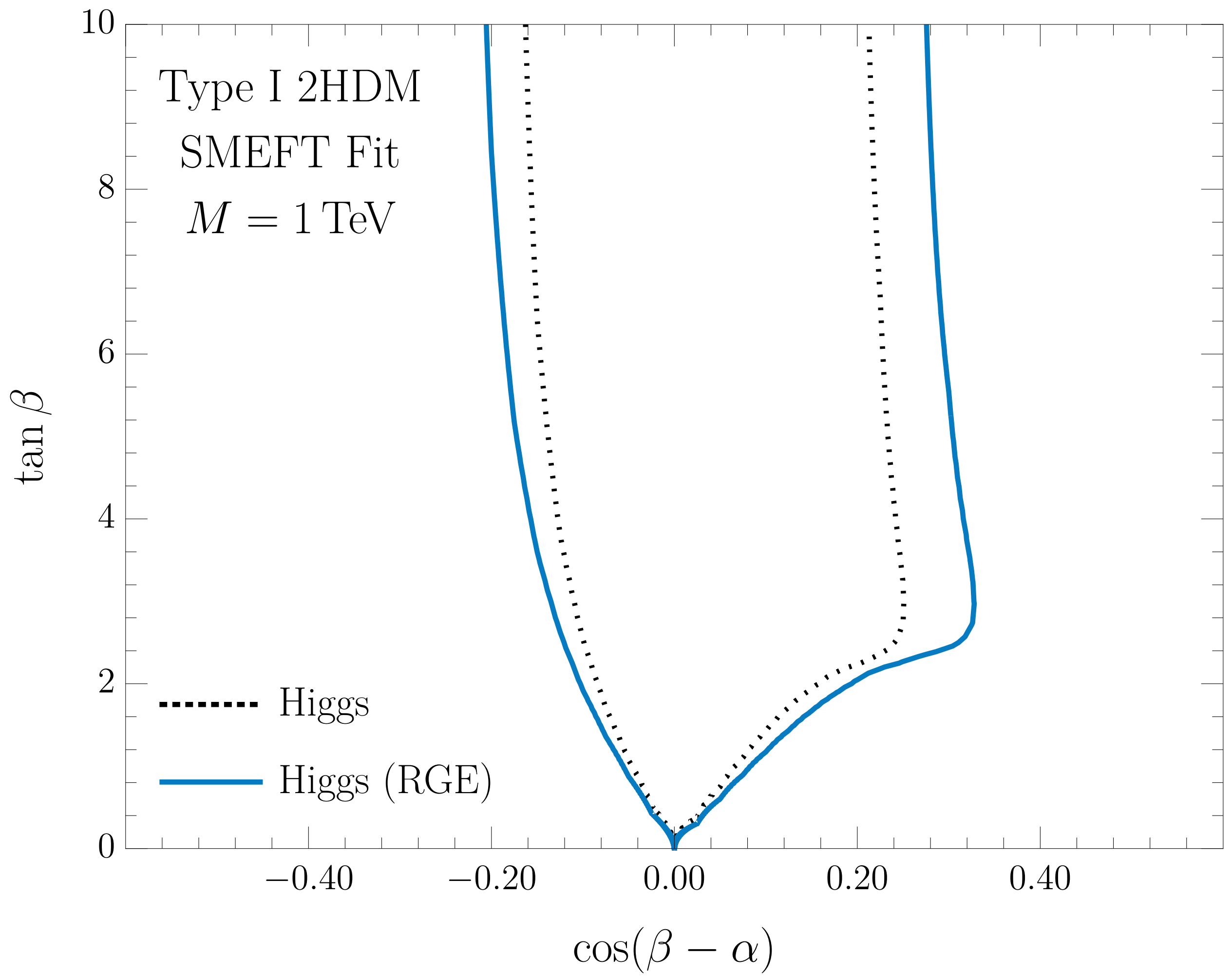


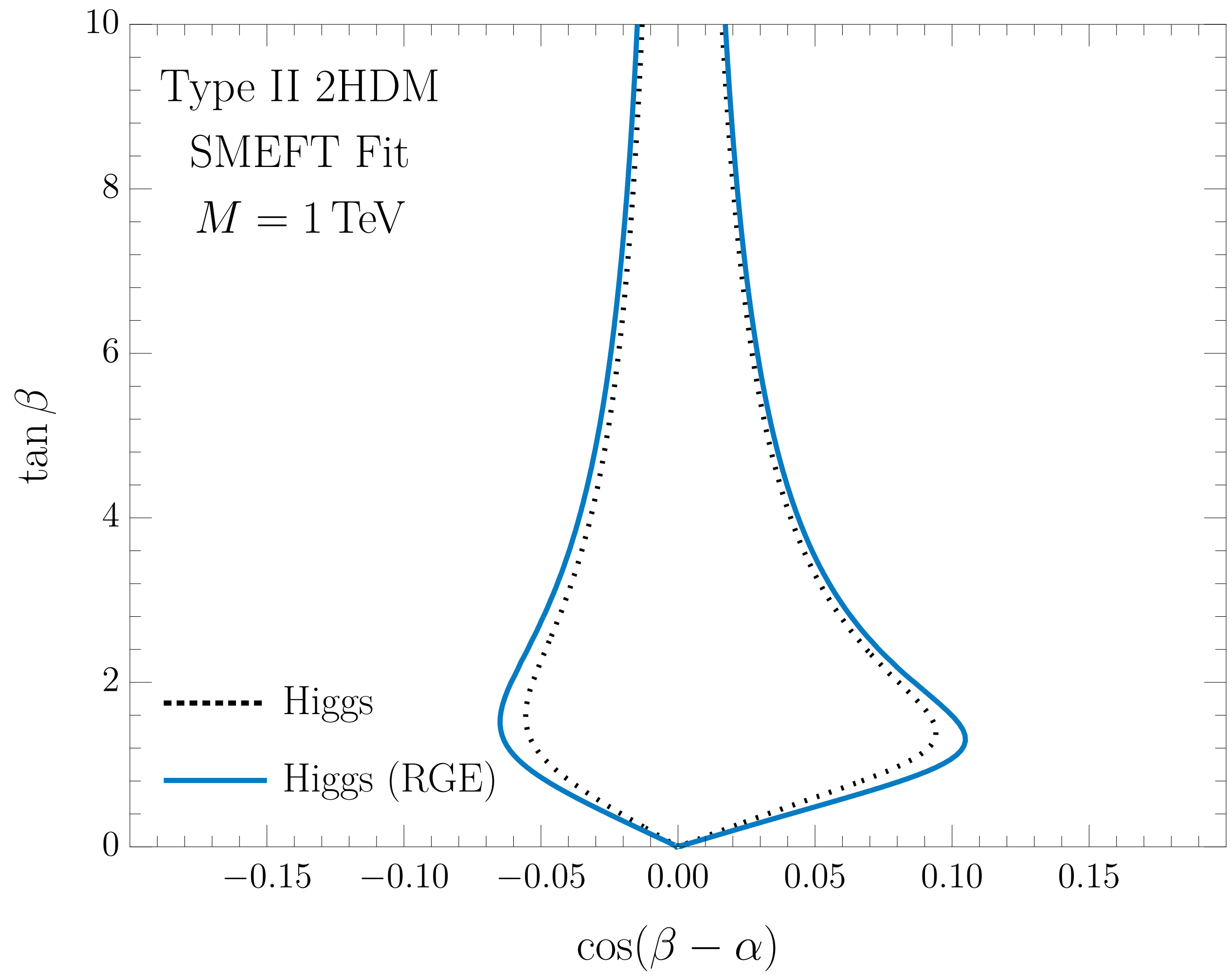


Different types of 2HDM sweep out different ranges of allowed coefficients

Matching to Dimension-6

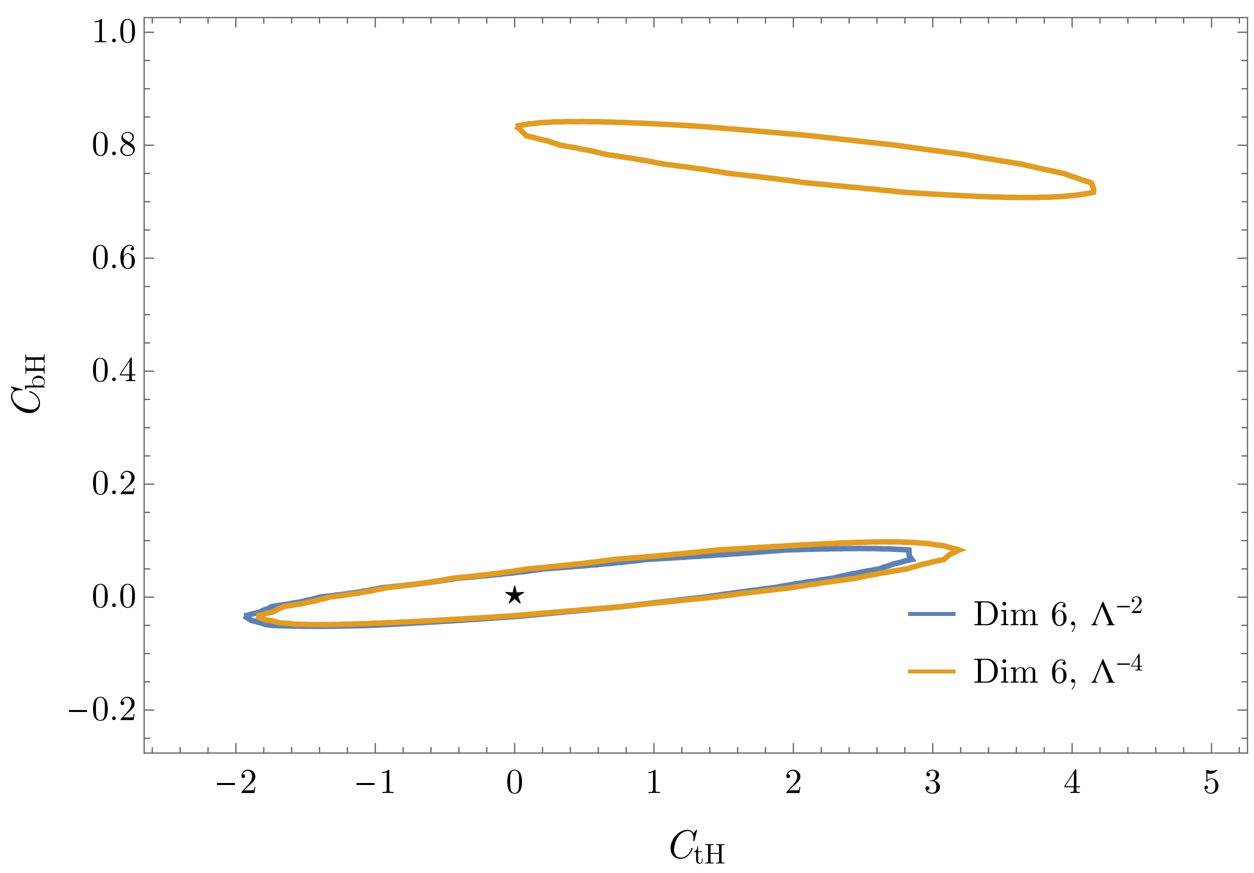
For a given type of 2HDM, easy to translate into the $\tan\beta, \cos(\beta-\alpha)$ plane





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

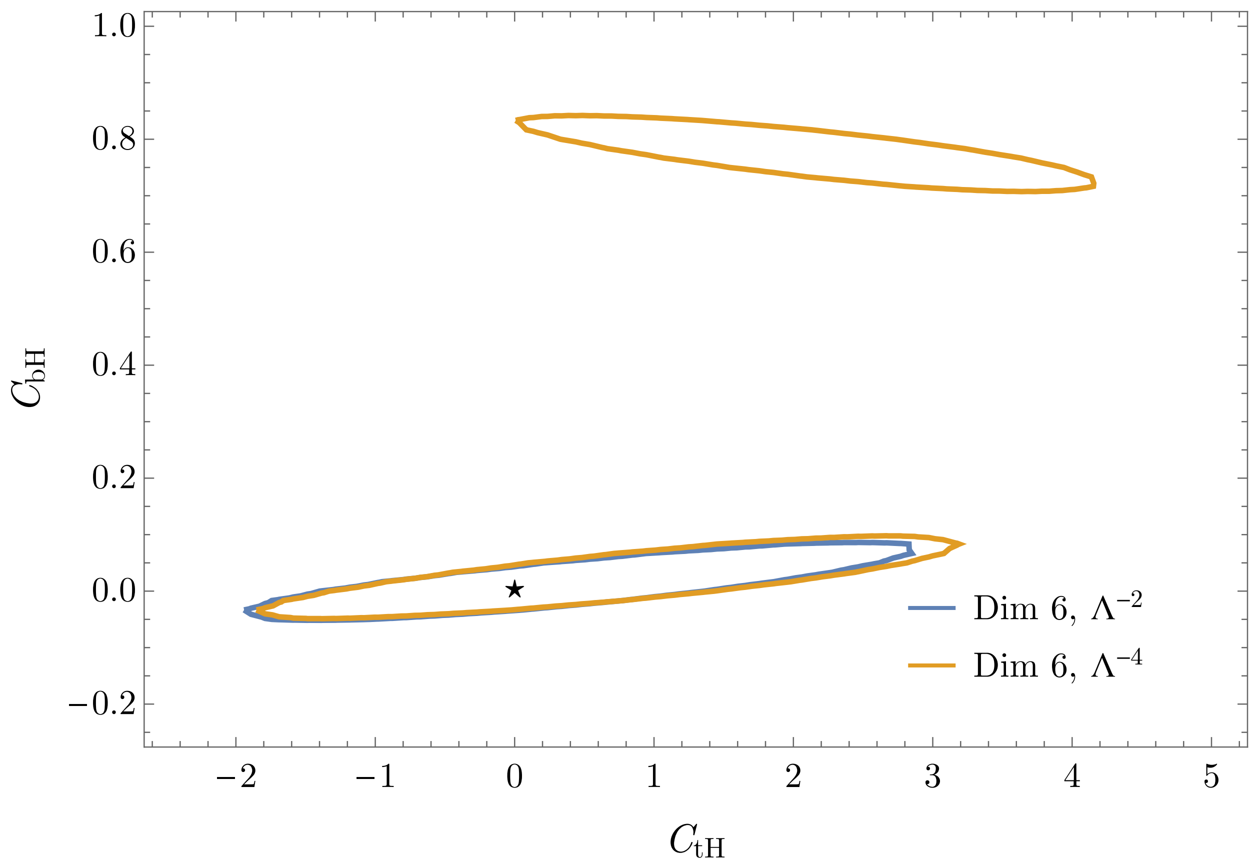
Effects at Large $\tan\beta$



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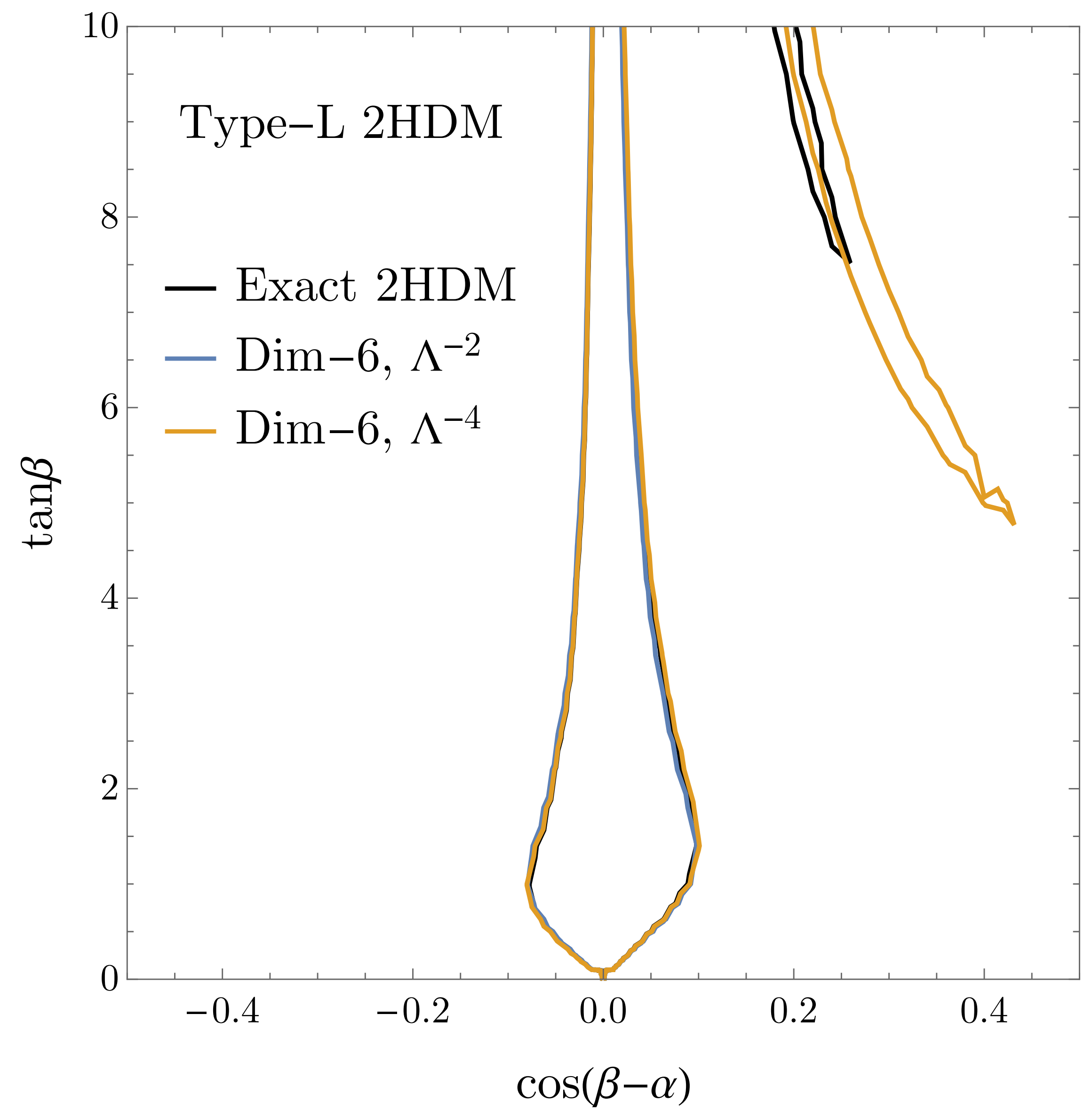
The well-known “wrong-sign” region of the Type-II 2HDM

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!



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

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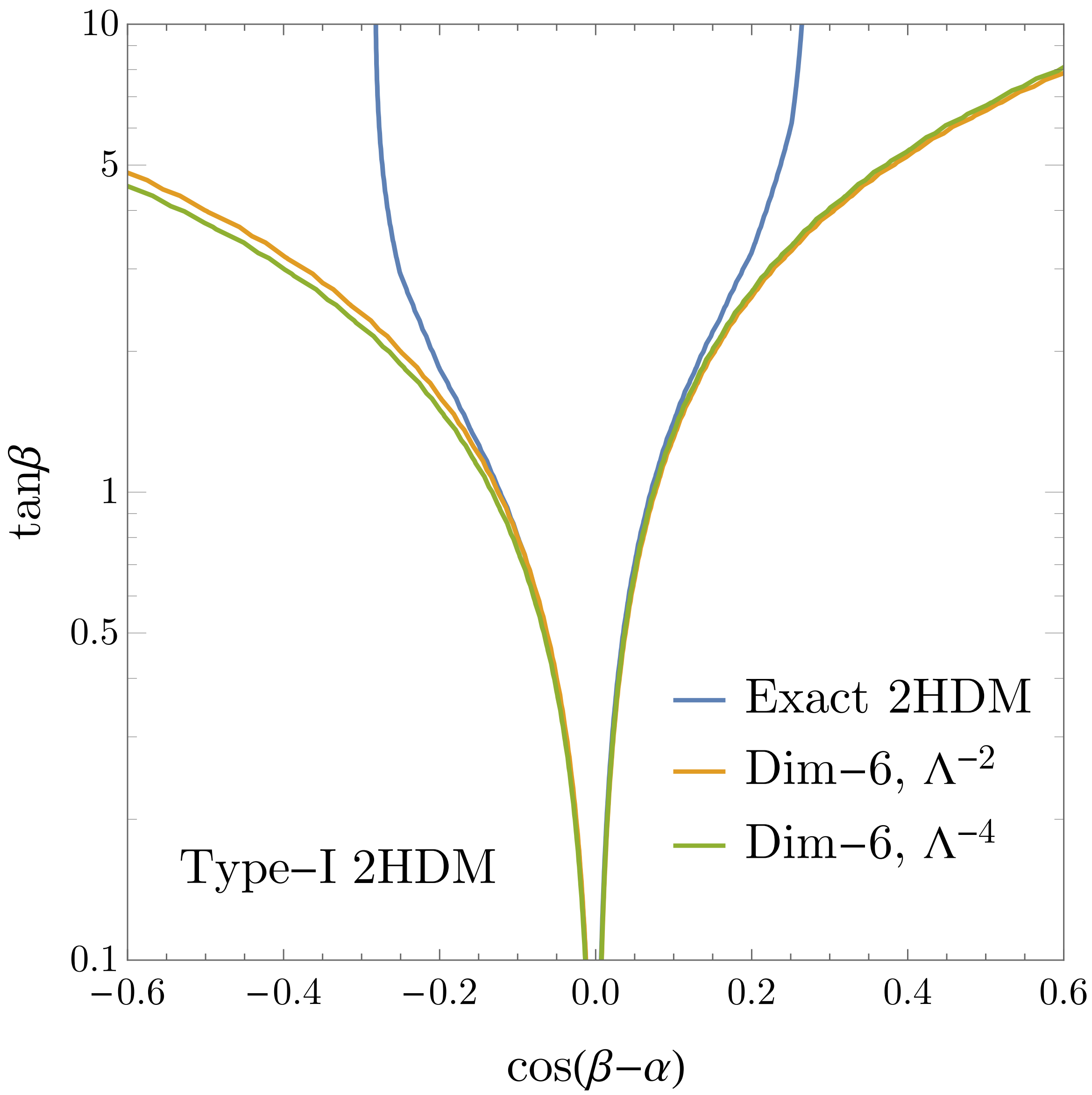
Ignoring the constraints on C_H, we see the dimension-6 description fails (see e.g., [1611.01112])

$\Longrightarrow$ 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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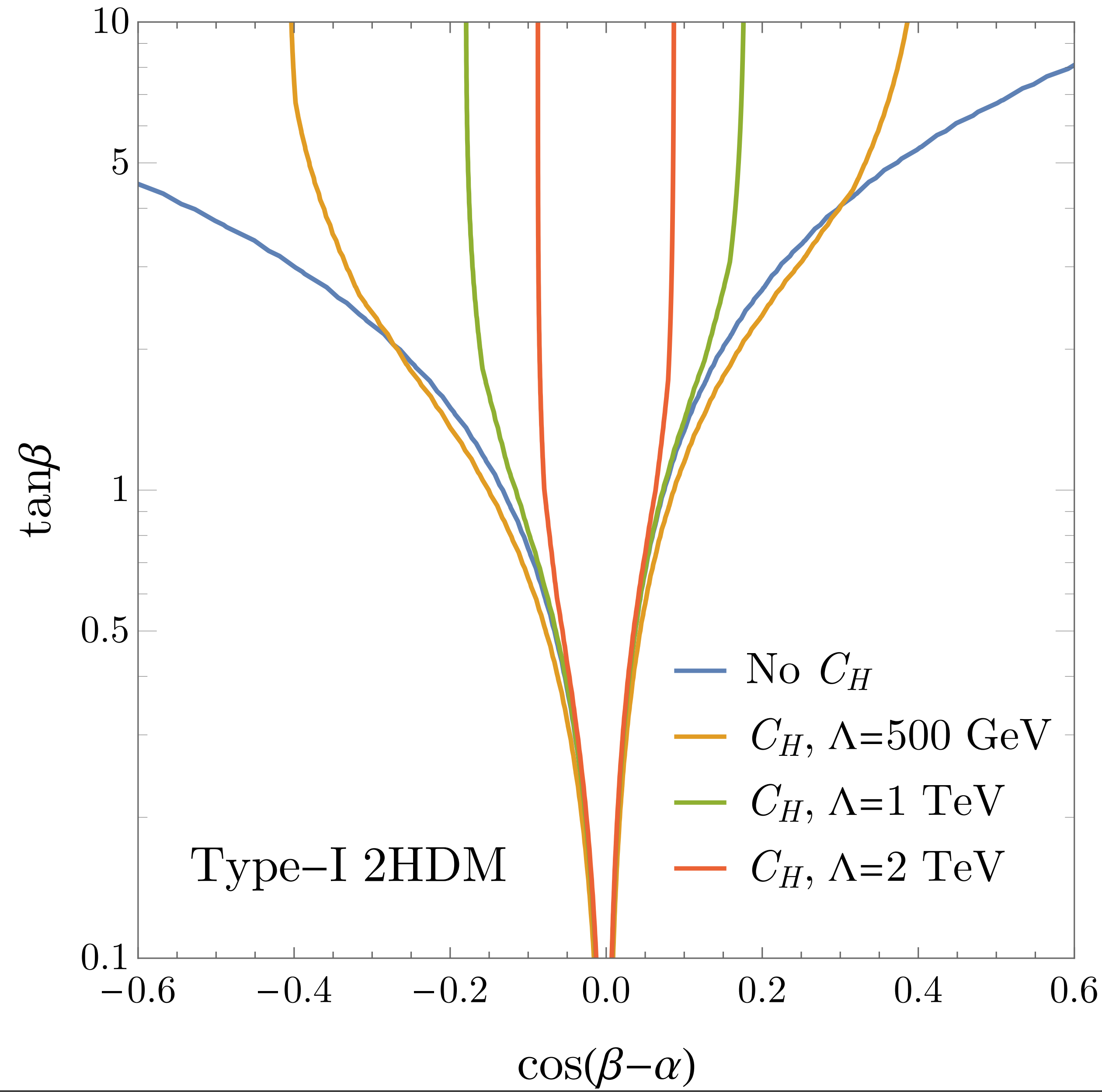

Matching the 2HDM to Dimension-8

arXiv:2205.01561, Dawson, Fontes, SH, Sullivan

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

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

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

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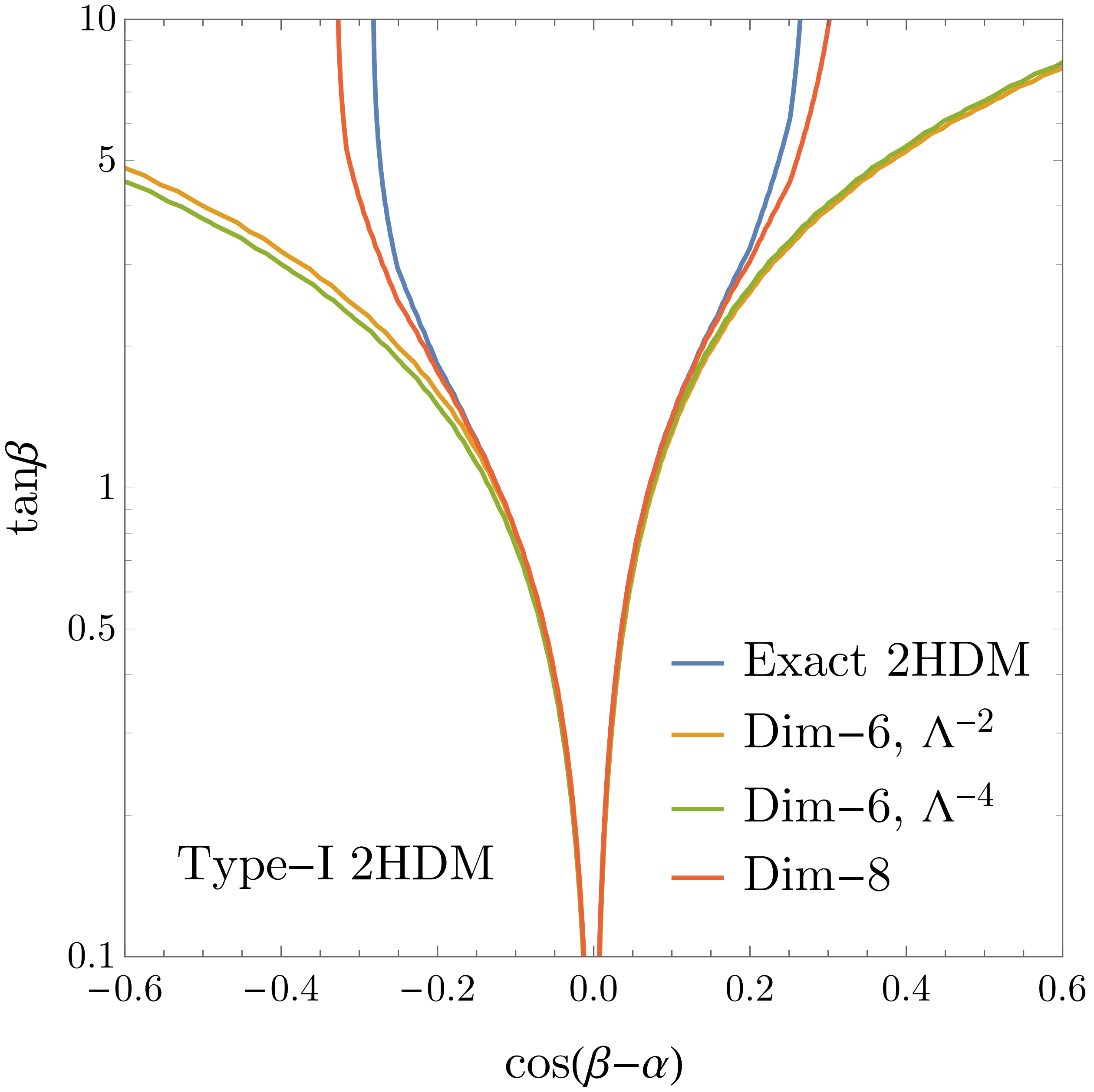
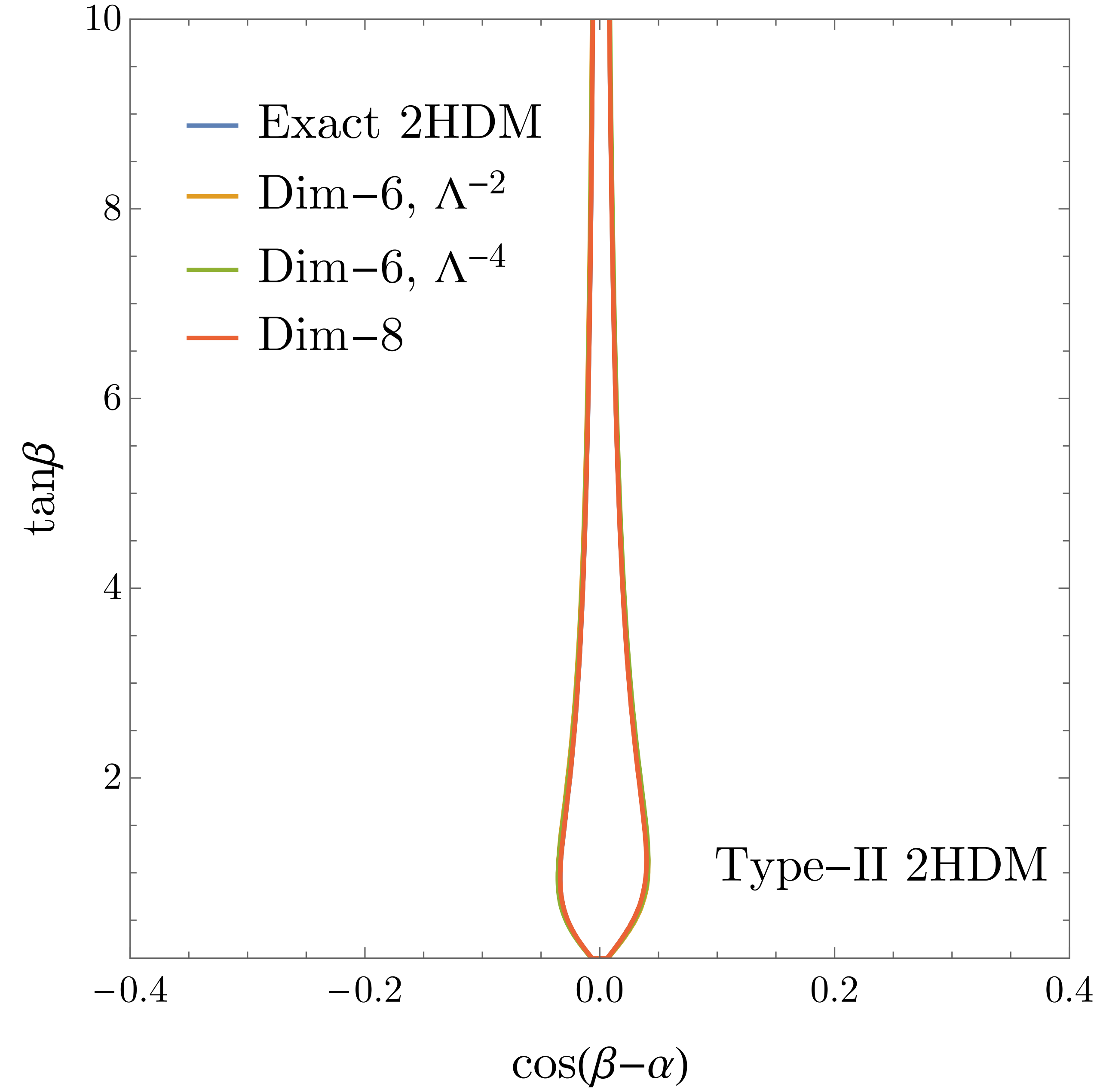
$$\mathcal{O}_{H^6}^{(1)} = (H^\dagger H)^2 (D_\mu H)^\dagger (D^\mu H), \quad C_{H^6}^{(1)} = -\frac{\Lambda^4}{v^4}\cos(\beta-\alpha)^2$$

Fit Results Including Dimension-8





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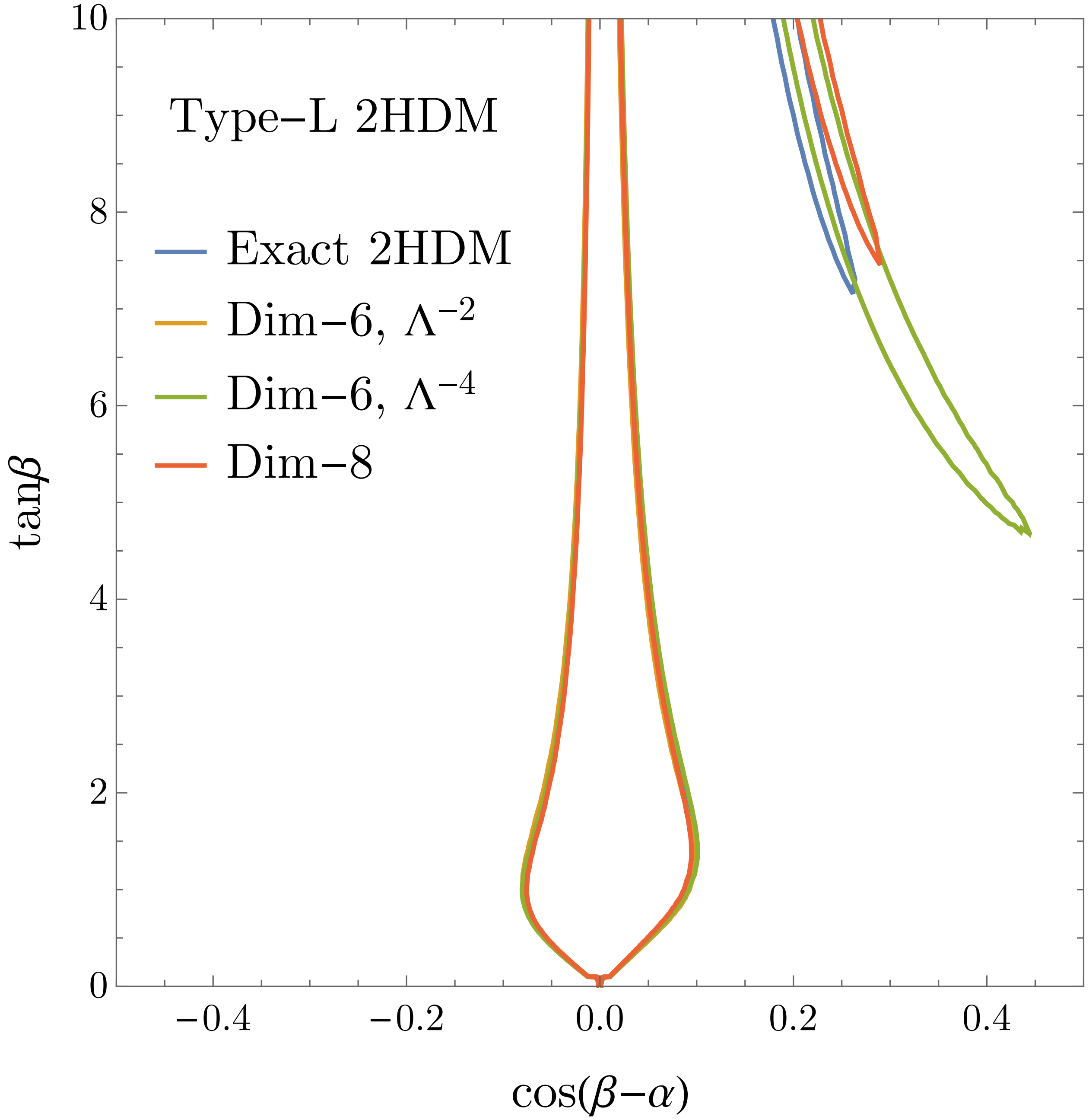

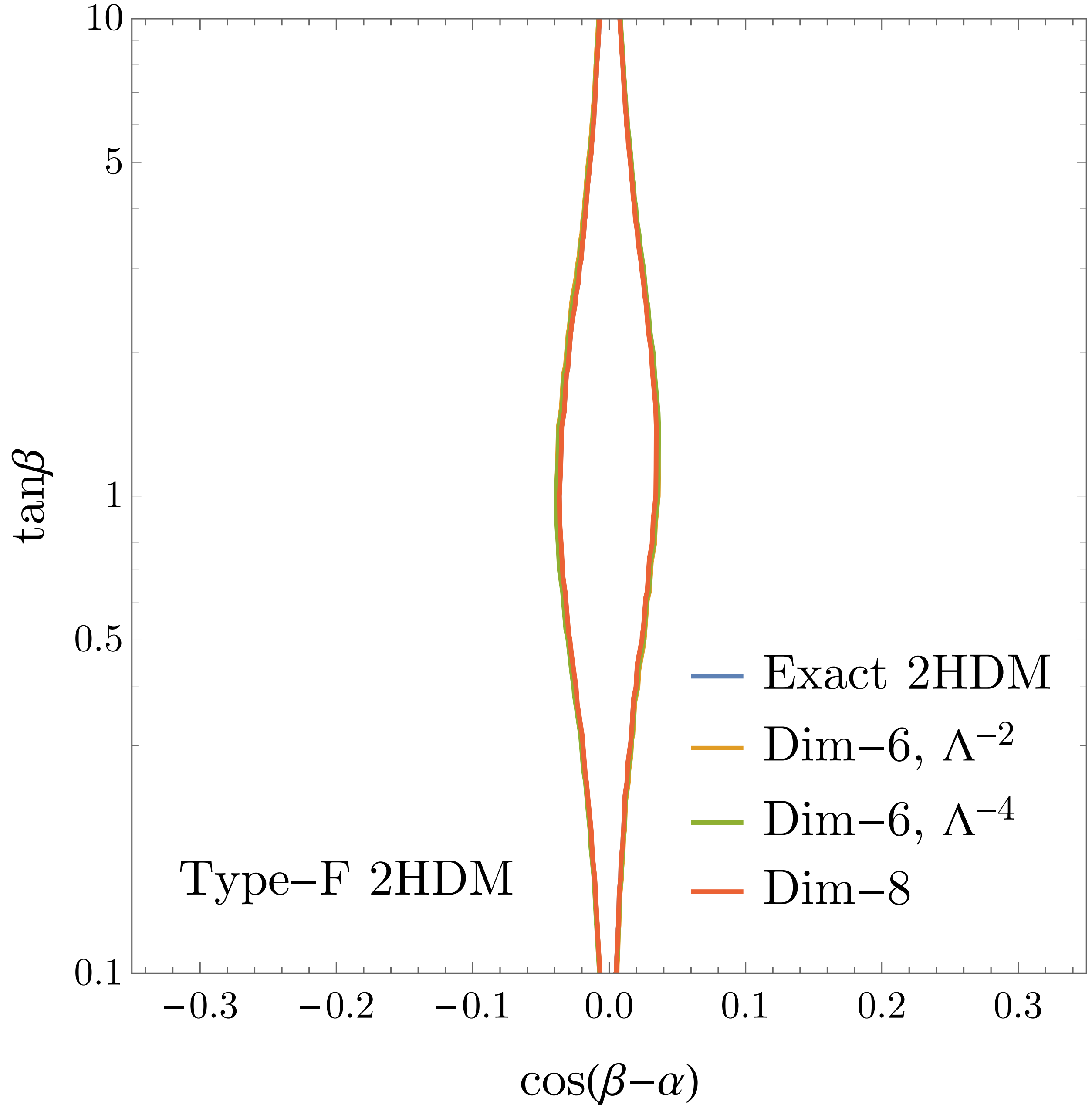

EFT of the 2HDM Summary

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

Example 3: 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
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  (Jiang et al., 1811.08878, Haisch et al., 2003.05936)

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

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 $v_S \to 0$

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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:

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

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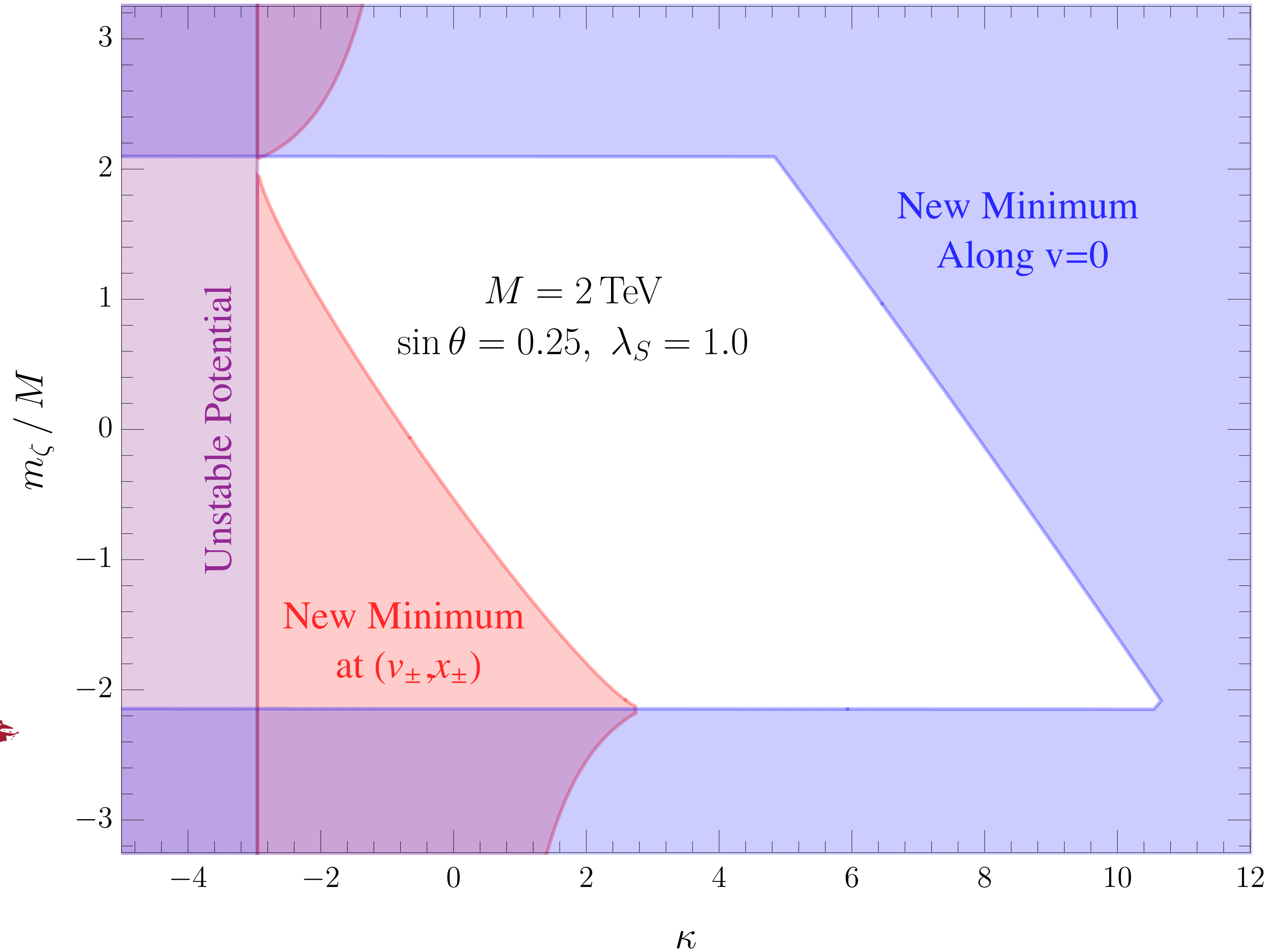
Furthermore, have to demand that the EWSB minimum be the global minimum of the potential



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

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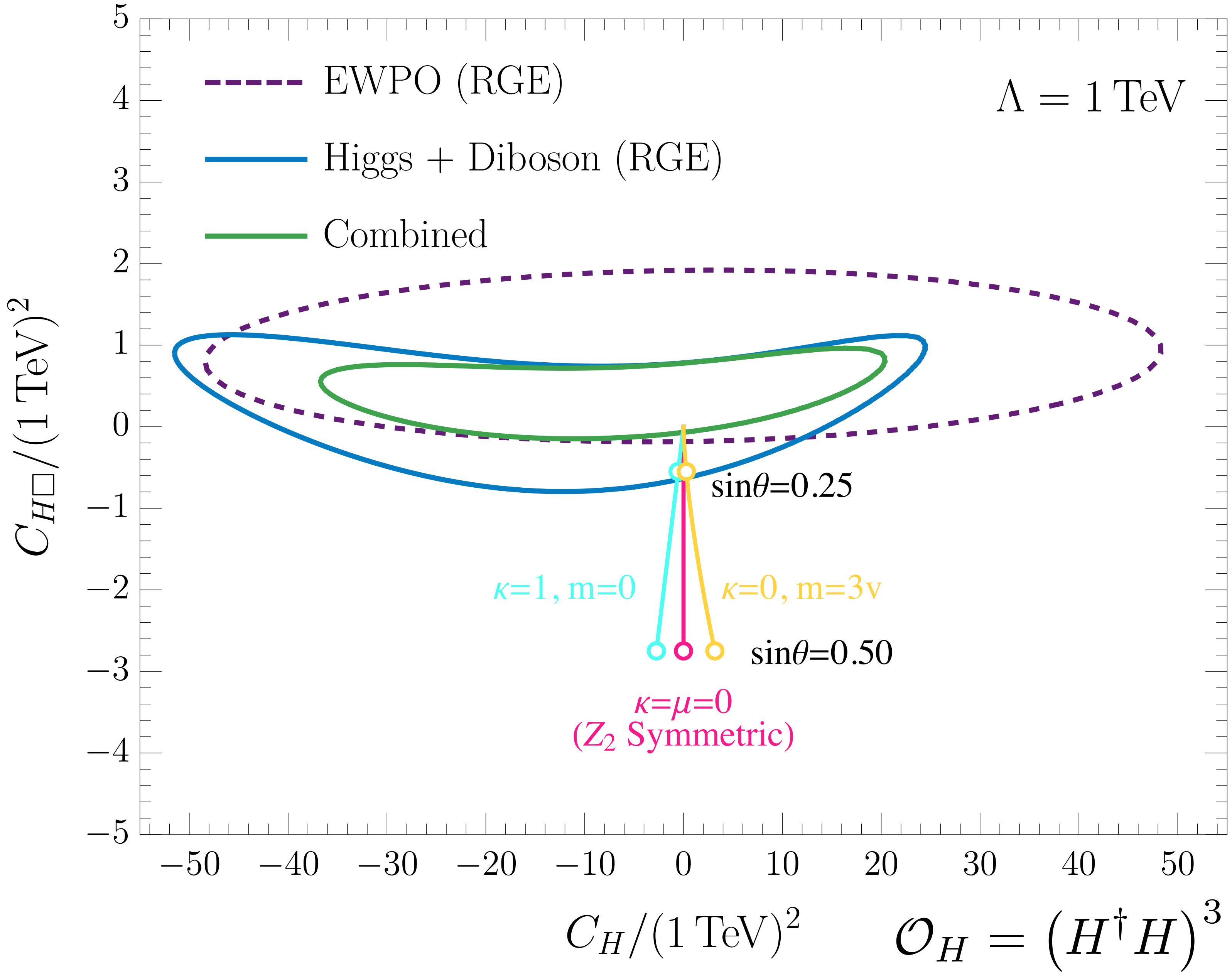
These operators introduce

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

at the weak scale from RG running

Tree Level (+RGE) Results



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

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

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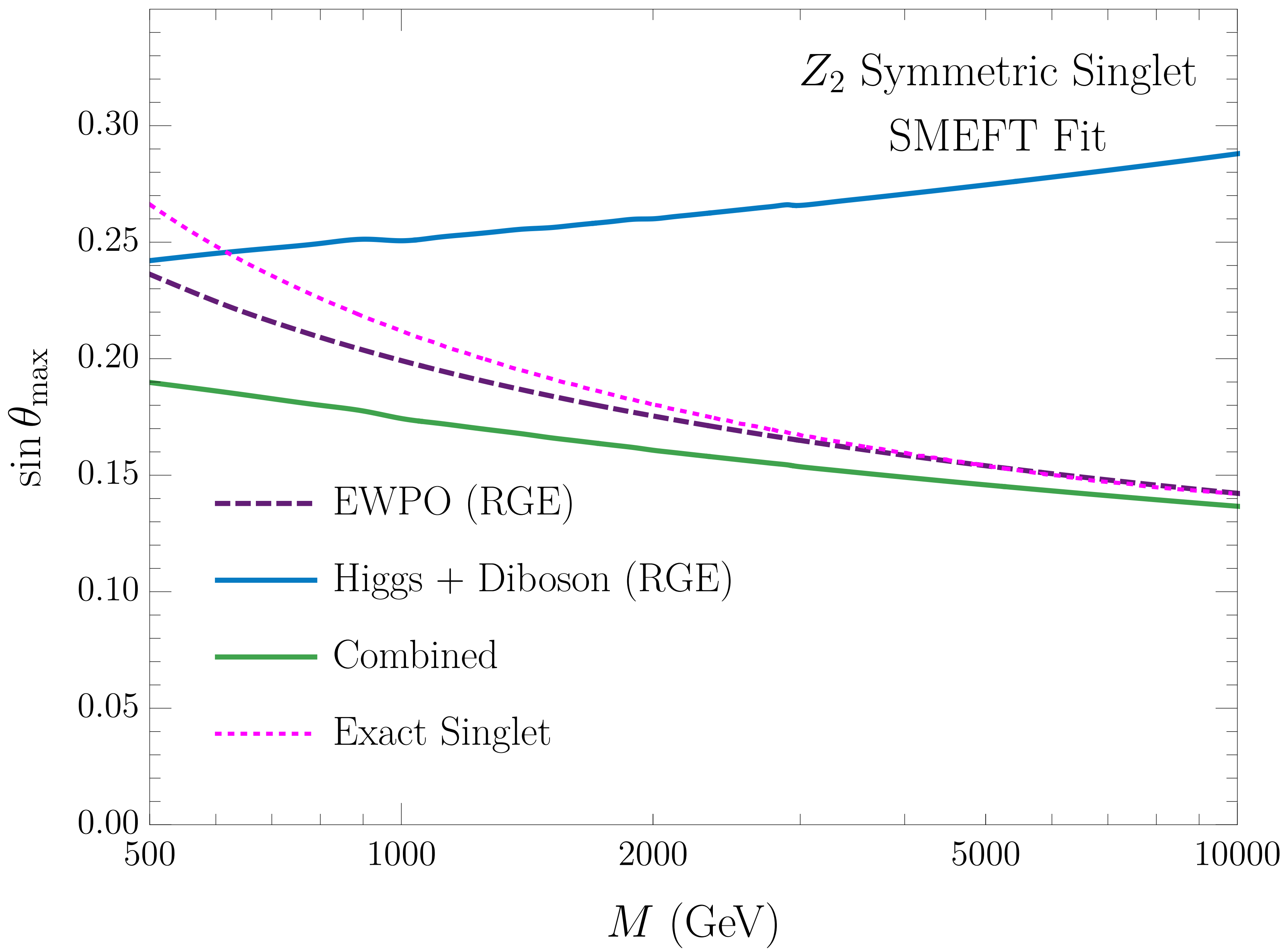

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One-Loop Matching

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…

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

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

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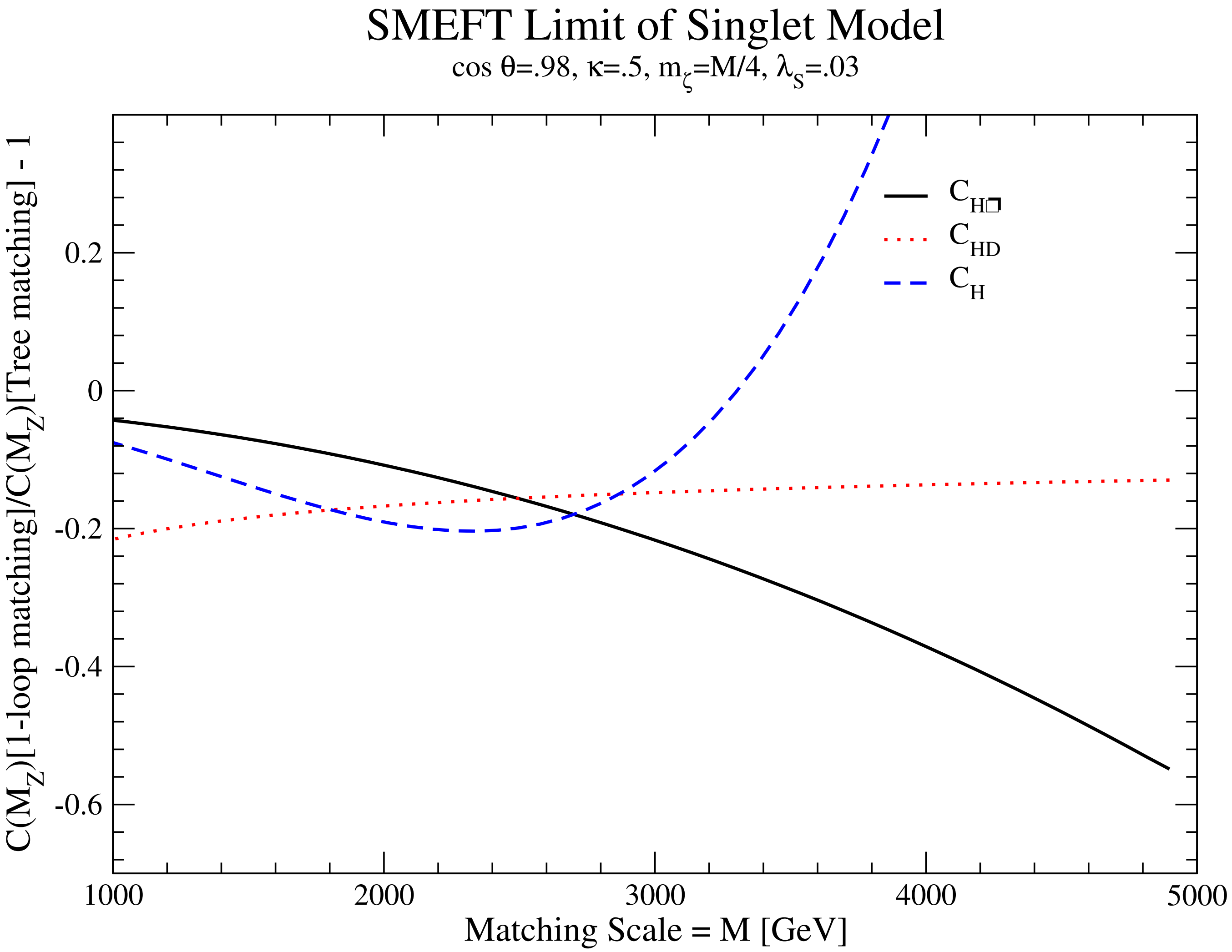
…as well as many operators that don't appear at tree-level

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

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

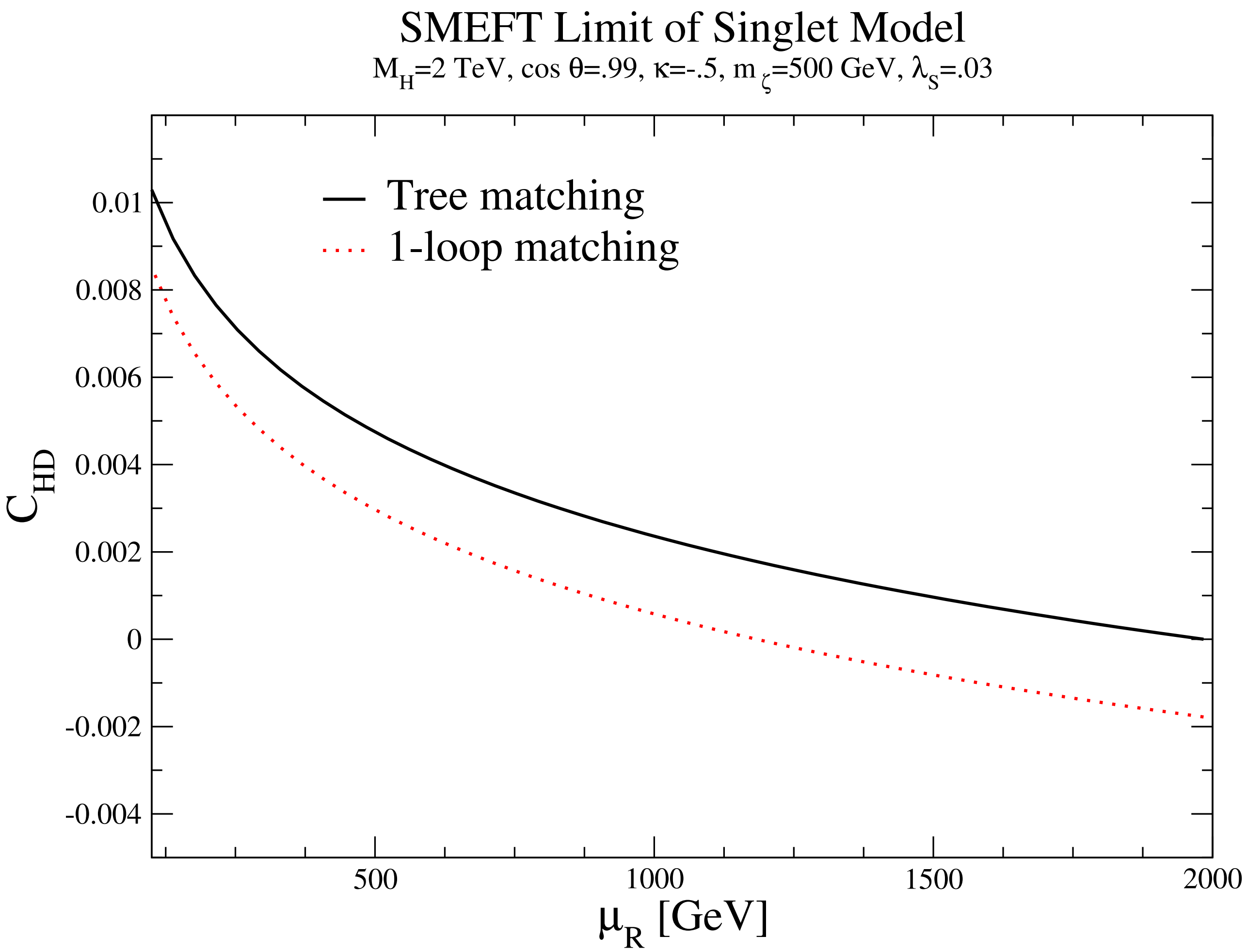
In principle of comparable size to RGE-induced contribution!

One-Loop Matching



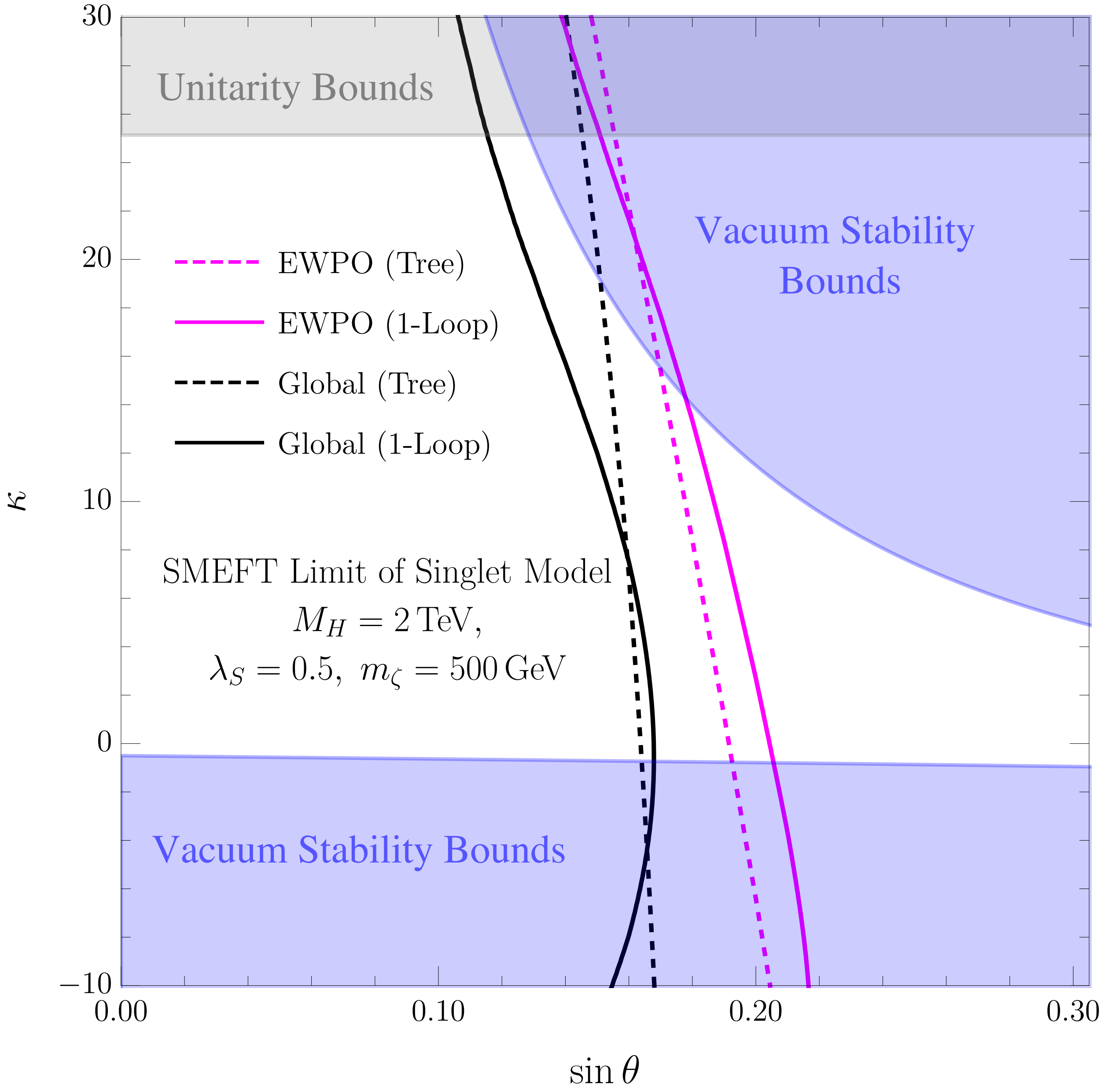
Include only one-loop RGEs

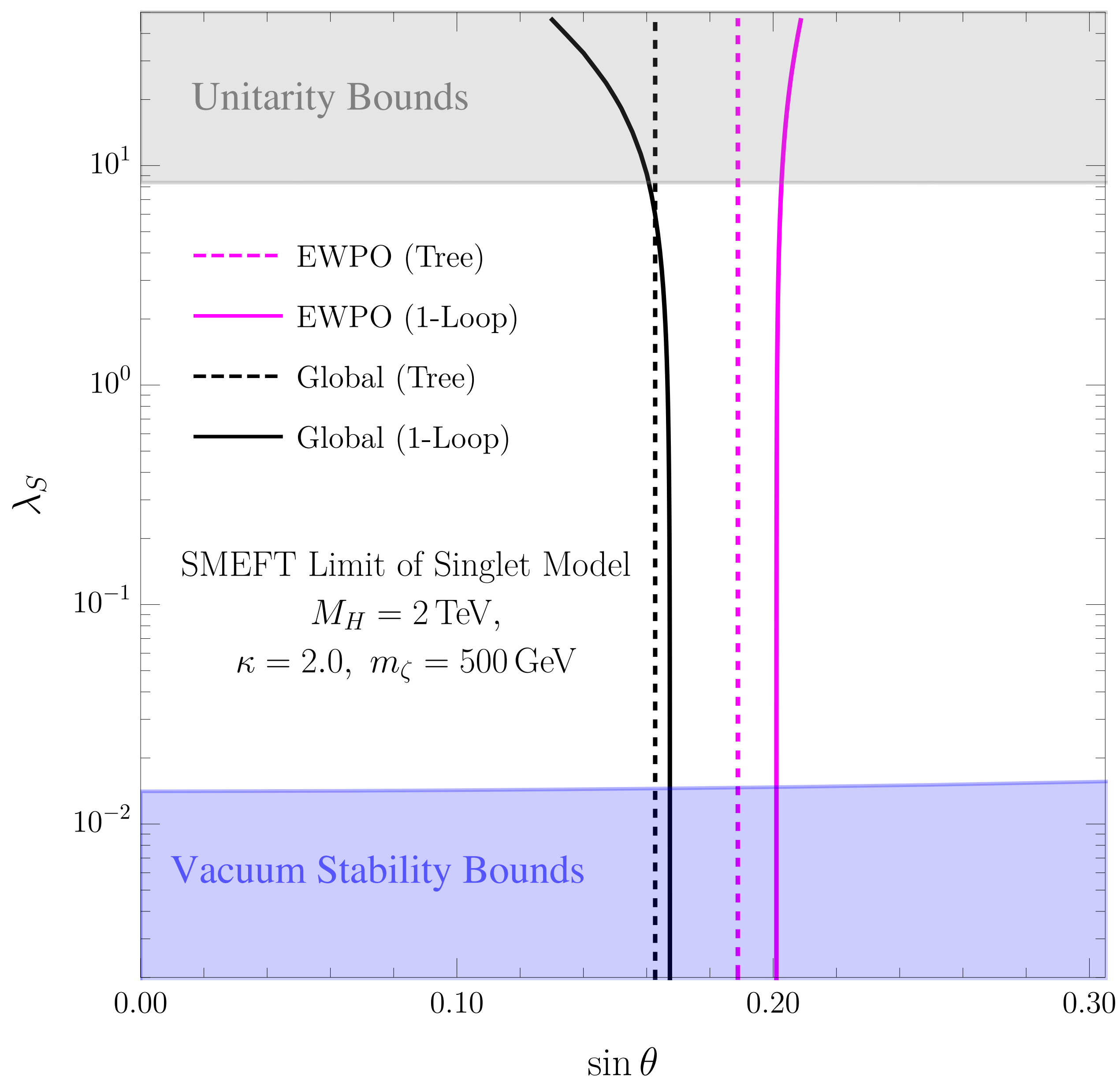
(two loops unavailable, but necessary to run one-loop induced operators)



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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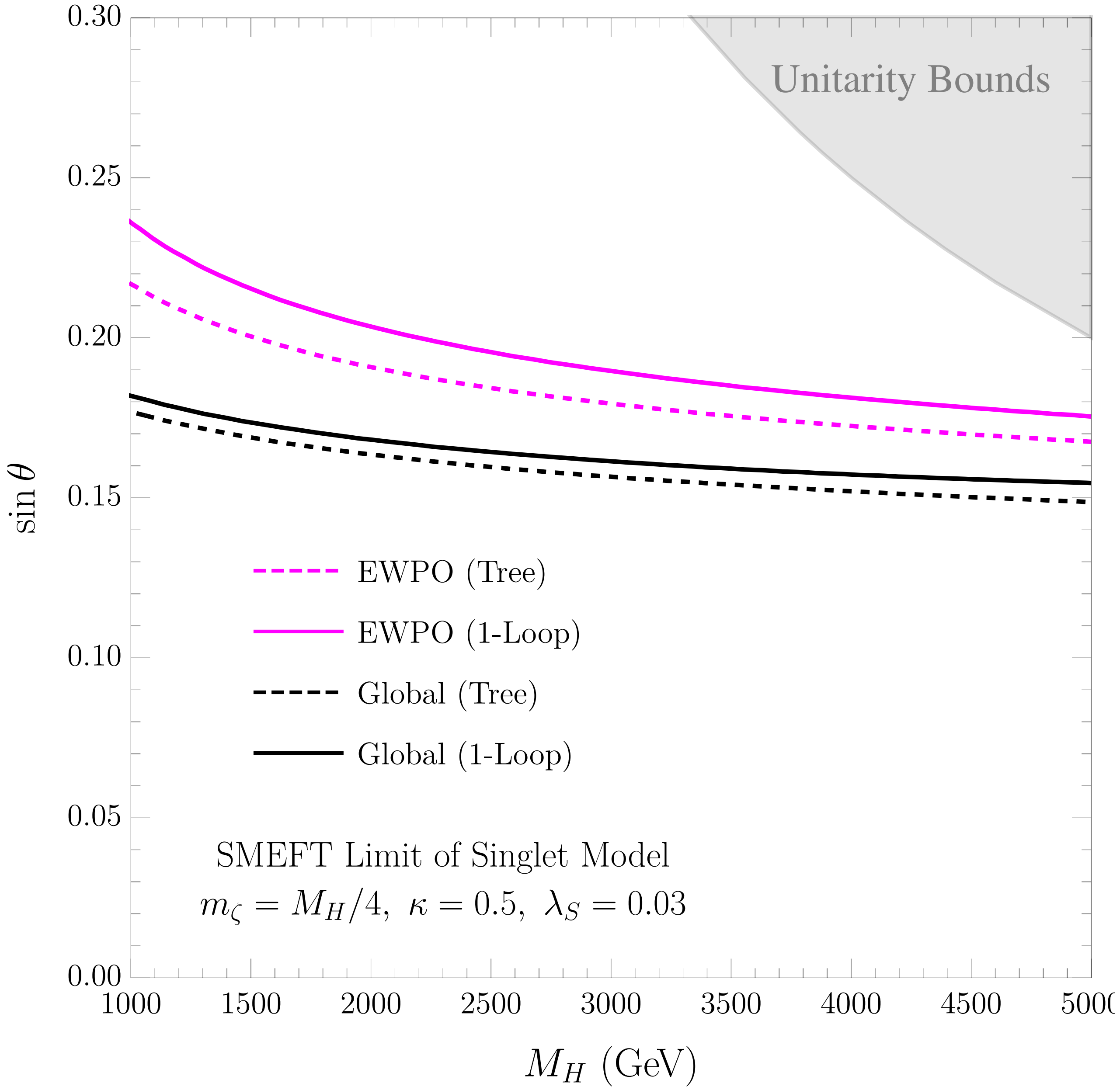

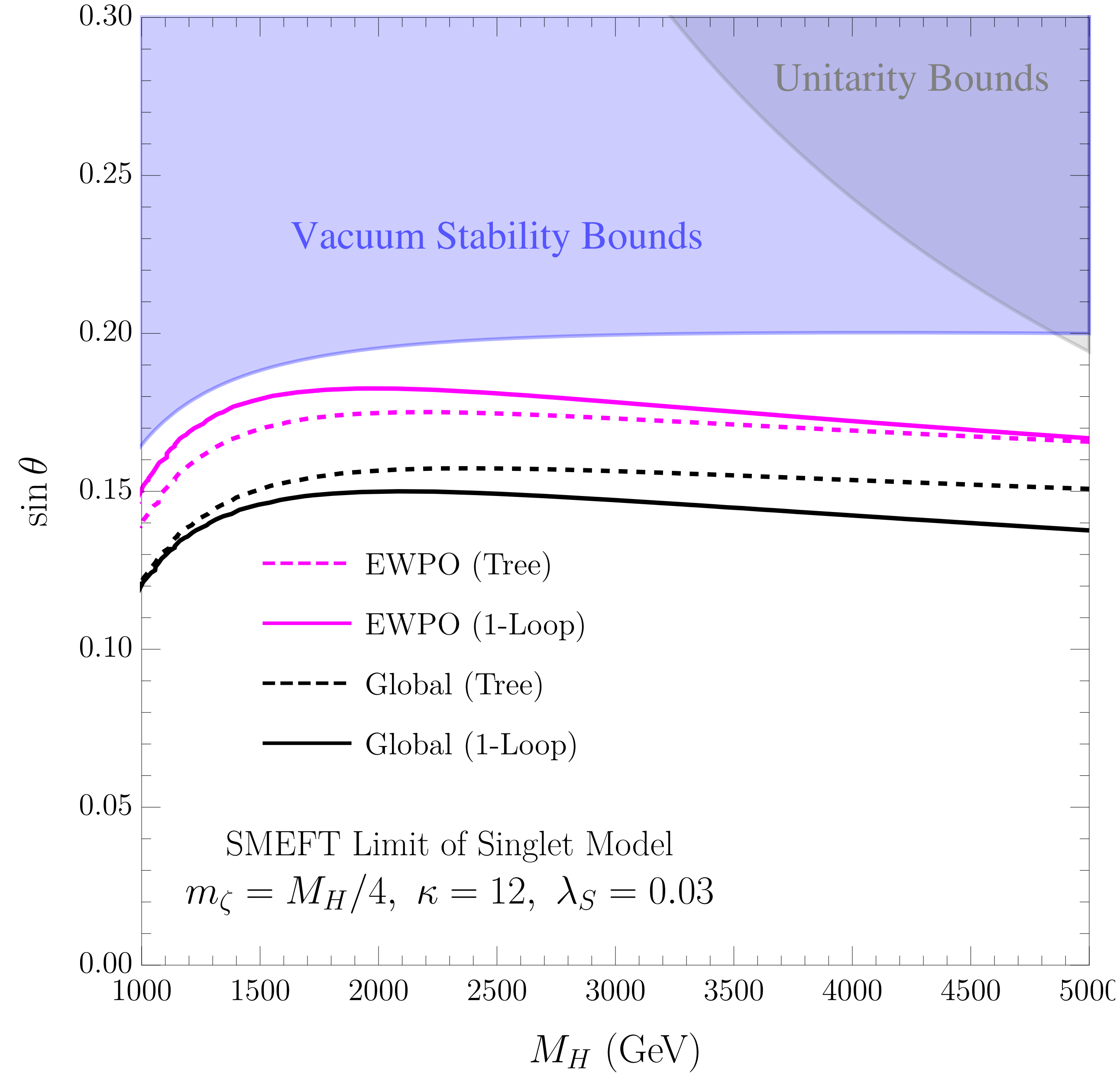

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Conclusions

- 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]
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Thanks for your attention!