LOOPFEST XXI

Uncertainties in SMEFT predictions: The Role of Flavor

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June, 2023

Based on work:

- Flavor
  - ***The Importance of Flavor in SMEFT Electroweak Precision Fits*** (Bellafronte, Dawson, Giardino), 2304.00029
  - ***Flavorful Electroweak Precision Observables in the SMEFT*** (Dawson and Giardino), 2201.09887
- Double Insertions
  - ***Double Insertions of SMEFT Operators in Gluon Fusion Higgs Boson Production*** (Asteriadis, Dawson, and Fontes), 2212.03258

SMEFT (Also Known As): *Is it the SM?*

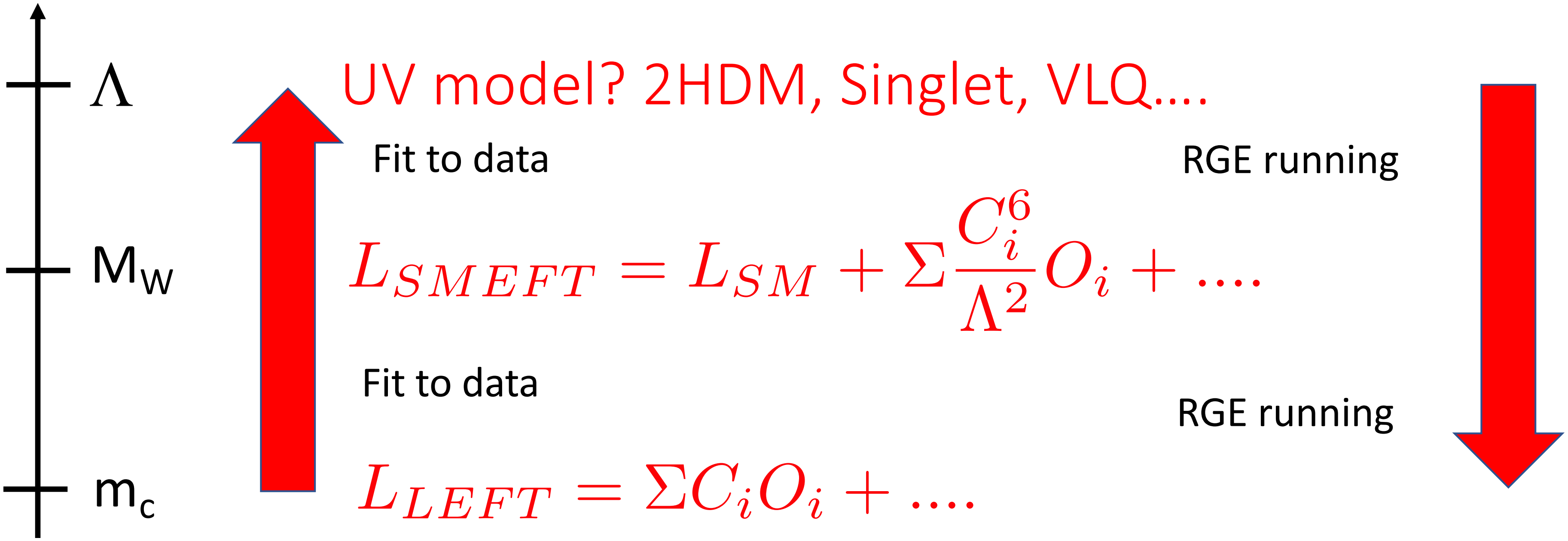
- If there are *no new light particles* discovered, EFTs can help
- SMEFT predicts observables as a power series in a high scale
- SMEFT assumes the Higgs is in an SU(2) doublet and constructs SU(3) x SU(2) x U(1) gauge invariant operators

$$L = L_{SM} + \Sigma C_i^6 \frac{O_i^6}{\Lambda^2} + \ldots$$

- *SMEFT is model independent, but….*
- In general, too many operators to be practical
  - Power is connection between Higgs, di-boson, EWPO, top data
  - Hidden assumptions

From far away, SMEFT is model independent

- Relies on large separation of scales



UV model? 2HDM, Singlet, VLQ….

Fit to data

RGE running

$$L_{SMEFT} = L_{SM} + \Sigma \frac{C_i^6}{\Lambda^2} O_i + \ldots.$$

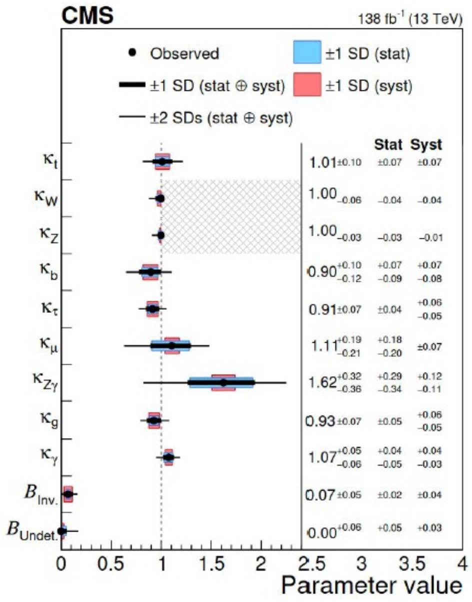
Fit to data

RGE running

$$L_{LEFT} = \Sigma C_i O_i + \ldots.$$

Top-down vs Bottoms-up

- Bottoms-up: Fit to multiple observables at EW scale and try to figure out the UV model from patterns of coefficients

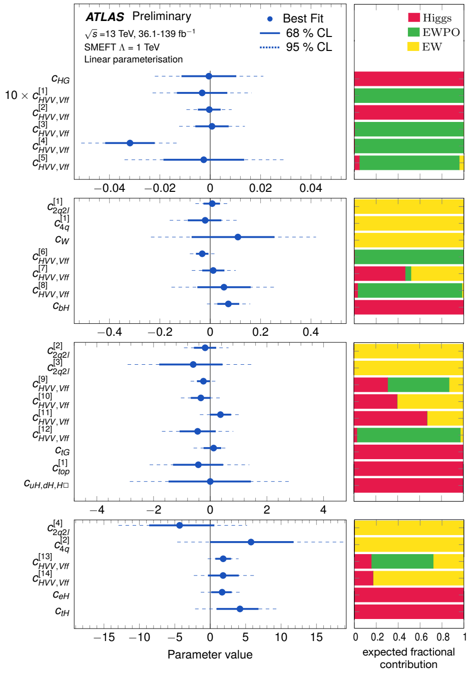


CMS, Nature, 2022

Higgs only

What are theory uncertainties?

Higgs, di-boson, EWPO at quadratic order

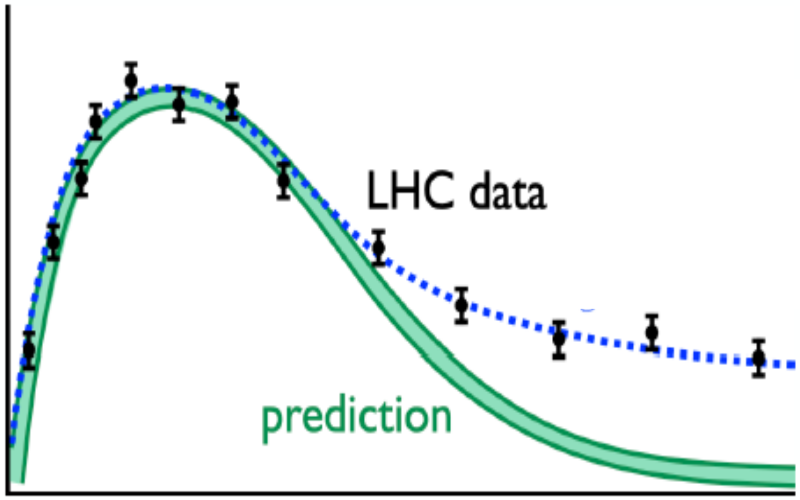


ATLAS, 2301.03212

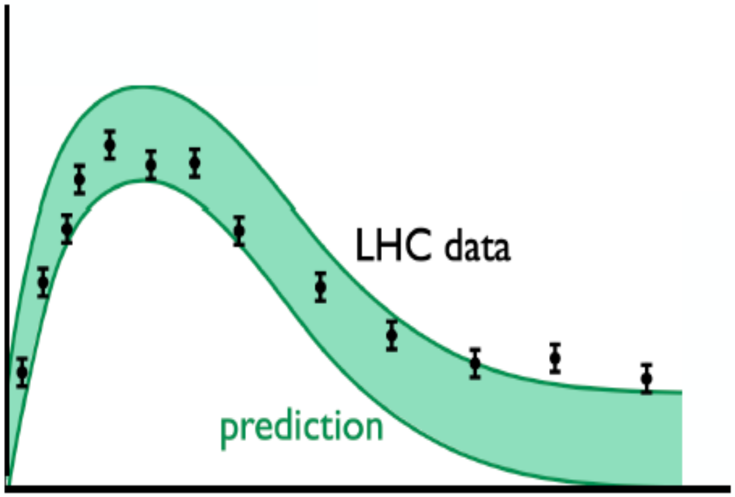
Using the SMEFT

- Need accurate SM and EFT predictions
- EFTs give shape changes in tails (need theory precision!)

Want this



Not this

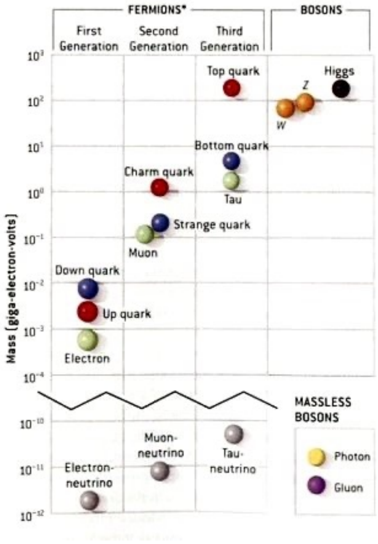


Zanderhigi Higgs2022

Flavor and the SMEFT

- Flavor is poorly understood in the SM

$$L_{YUK} = -\bar{q}_L V^\dagger Y_u \tilde{H} u_R - \bar{q}_L Y_d H d_R - \bar{l}_L Y_e H e_R + h.c$$



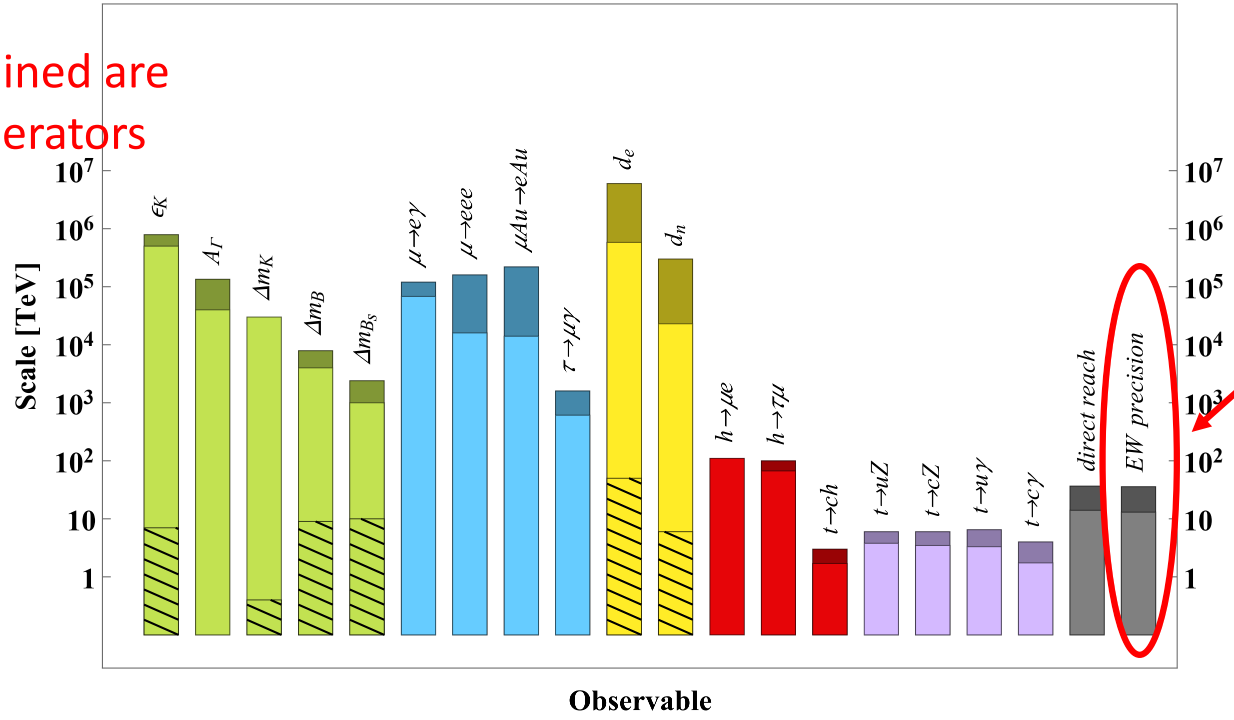
- Large hierarchy of masses: Y_u, Y_d, Y_e
- Approximate alignment of CKM matrix:

$$V_{CKM} \sim \begin{pmatrix} 1 & .2 & (.2)^3 \\ .2 & 1 & (.2)^2 \\ (.2)^3 & (.2)^2 & 1 \end{pmatrix}$$

- Do SMEFT operators follow a similar flavor pattern?
- Imposing global flavor symmetries reduces number of operators

Strong constraints on flavor violation in SMEFT from low energy measurements

Most constrained are 4-fermion operators

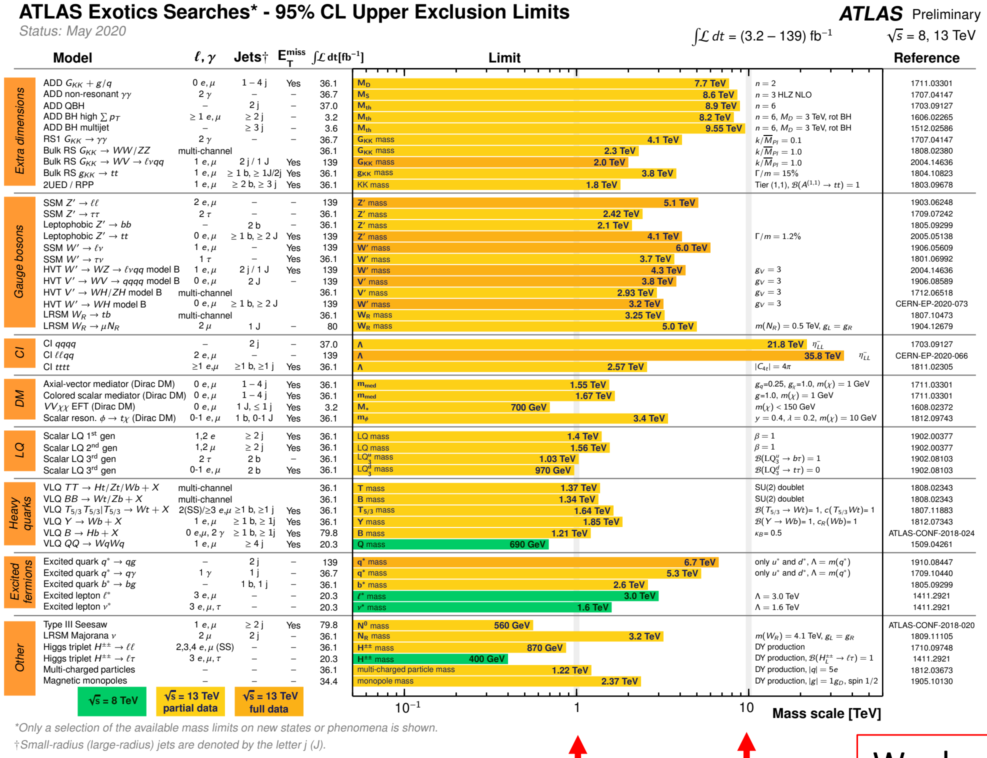


What are assumptions?

Interpreting measurements in terms of scale implies assuming SMEFT coefficients C=1

European Strategy, 1910.11775

Is SMEFT flavor violation at the TeV scale allowed?



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	CERN-EP-2020-066
	CI $tttt$	≥ 1 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

Strong limits on new physics at 1 TeV; mostly from 1st and 2nd generation

Weaker limits on new physics at multi-TeV scales

No evidence for new physics in EWPOs

- Electroweak precision observables (EWPOs) provide strong evidence for SM at EW scale
- Comparison between EWPOs and SMEFT theory predictions strongly constrains new physics
- At NLO SMEFT, new 2-fermion and 4-fermion contributions to EWPOs from operators that do not arise at LO

Measurement	Experiment	"Best" theory
Γ_Z(GeV)	2.4955 ± 0.0023	2.4943 ± 0.0006 [62–64]
R_e	20.804 ± 0.05	20.732 ± 0.009 [62–64]
R_μ	20.784 ± 0.034	20.732 ± 0.009 [62–64]
R_τ	20.764 ± 0.045	20.779 ± 0.009 [62–64]
R_b	0.21629 ± 0.00066	0.2159 ± 0.0001[62–64]
R_c	0.1721 ± 0.0030	0.1722 ± 0.00005[62–64]
σ_h	41.481 ± 0.033	41.492 ± 0.008[62–64]
A_e(from A_{LR} had	0.15138 ± 0.00216	0.1469 ± 0.0004 [64, 65]
A_e(from A_{LR} lep)	0.1544 ± 0.0060	0.1469 ± 0.0004 [64, 65]
A_e(from Bhabba pol)	0.1498 ± 0.0049	0.1469 ± 0.0004 [64, 65]
A_μ	0.142 ± 0.015	0.1469 ± 0.0004 [64, 65]
A_τ(from SLD)	0.136 ± 0.015	0.1469 ± 0.0004 [64, 65]
A_τ(τ pol)	0.1439 ± 0.0043	0.1469 ± 0.0004 [64, 65]
A_c	0.670 ± 0.027	0.66773 ± 0.0002[64, 65]
A_b	0.923 ± 0.020	0.92694 ± 0.00006[64–66]
A_s	0.895 ± 0.091	0.93563 ± 0.00004[64, 65]
$A_{e,FB}$	0.0145 ± 0.0025	0.0162 ± 0.0001 [64, 65]
$A_{\mu,FB}$	0.0169 ± 0.0013	0.0162 ± 0.0001 [64, 65]
$A_{\tau,FB}$	0.0188 ± 0.0017	0.0162 ± 0.0001 [64, 65]
$A_{b,FB}$	0.0996 ± 0.0016	0.1021 ± 0.0003 [64–66]
$A_{c,FB}$	0.0707 ± 0.0035	0.0736 ± 0.0003 [64, 65]
$A_{s,FB}$	0.0976 ± 0.0114	0.10308 ± 0.0003 [64, 65]
M_W(GeV) PDG World Ave	80.377 ± 0.012	80.357 ± 0.006[67, 68]
Γ_W(GeV)	2.085 ± 0.042	2.0903 ± 0.0003[69]

https://doi.org/10.1007/JHEP05(2023)208

W and Z pole observables

- Fit to 24 data points—inputs are G_μ, M_Z, α

$$M_W, \Gamma_W, \Gamma_Z, \sigma_h, A_{l,FB}, A_{b,FB}, A_{c,FB}, A_b, A_c, A_l, R_l, R_b, R_c$$

- Tree level expressions depend on (in Warsaw basis)

$$C_{ll}, C_{HWB}, C_{Hu}, C_{Hq}^{(3)}, C_{Hq}^{(1)}, C_{Hl}^{(3)}, C_{Hl}^{(1)}, C_{He}, C_{HD}, C_{Hd}$$

- Tree level observables depend on 8 combinations of operators parameterized as:

$$M_W, \delta g_L^{Zu}, \delta g_L^{Zd}, \delta g_L^{Z\nu}, \delta g_L^{Ze}, \delta g_R^{Zu}, \delta g_R^{Zd}, \delta g_R^{Ze}$$

⇒ 2 blind directions (resolved by other measurements)

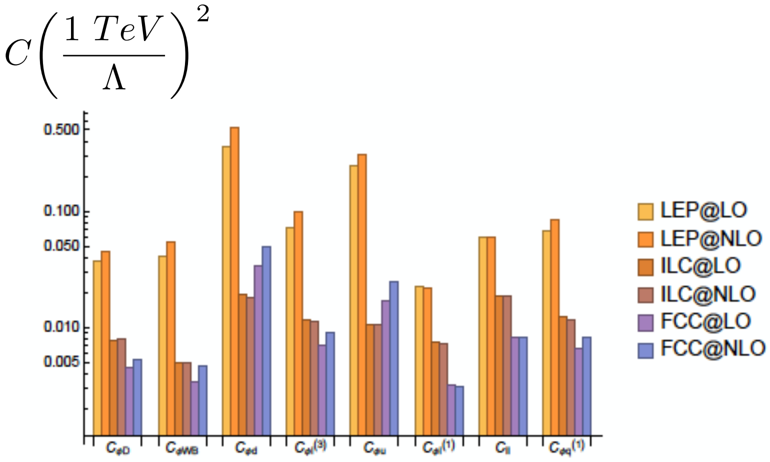
Fits are straightforward

- Compute observables in SMEFT including all NLO QCD and EW contributions:

$$O_i = O_{i,SM} + \delta O_{i,SMEFT}$$

- Use most accurate SM theory
- Do χ^2 fit to data
- Operators contributing to EWPOs at tree level strongly restricted
- At NLO, many new operators contribute

Previous study assumed no flavor structure in 4-fermion operators



Coefficients constrained at tree level

Dawson, Giardino 2201.09887

Include Flavor Structure

- Consider CKM diagonal, which implies specific flavor structures
- In Warsaw basis:
  - 4-fermion operators

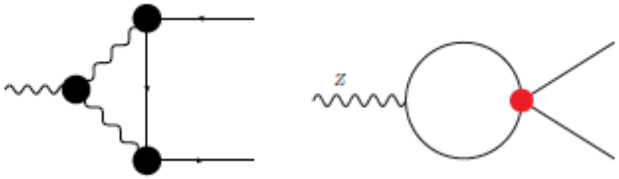
$$(\overline{f}_i\gamma^\mu f_j)(\overline{f}_k\gamma_\mu f_l)$$

Not all combinations of flavor indices arise in EWPOs

  - 2-fermion operators

$$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{q}_i\gamma^\mu q_j)\rightarrow C_X[ij]=E_X\delta_{ij}$$

  - Bosonic operators
- Most general case: NLO EWPO calculation involves 178 independent coefficients (6 from bosonic, 23 from 2-fermion, 149 from 4-fermion)



Enhancement of diagrams with internal top quarks

What about flavor assumptions?

- Global fits often done assuming flavor universality
- SM has $U(3)^5$ global symmetry that is broken only by Yukawas

$$(q_L)^T = (u_L, d_L),\ (l_L)^T = (\nu_L, e_L),\ u_R,\ d_R,\ e_R$$

- 3rd generation is different
  - Do fits with $U(2)^5$ global symmetry
- MFV assumption assumes top Yukawa is only source breaking $U(3)^5$ symmetry (since we assume all other fermions are massless)
- Do fits assuming new physics only couples to 3rd generation
- Do fits assuming new physics doesn't couple to 3rd generation

Do flavor assumptions make significant differences to SMEFT fits?

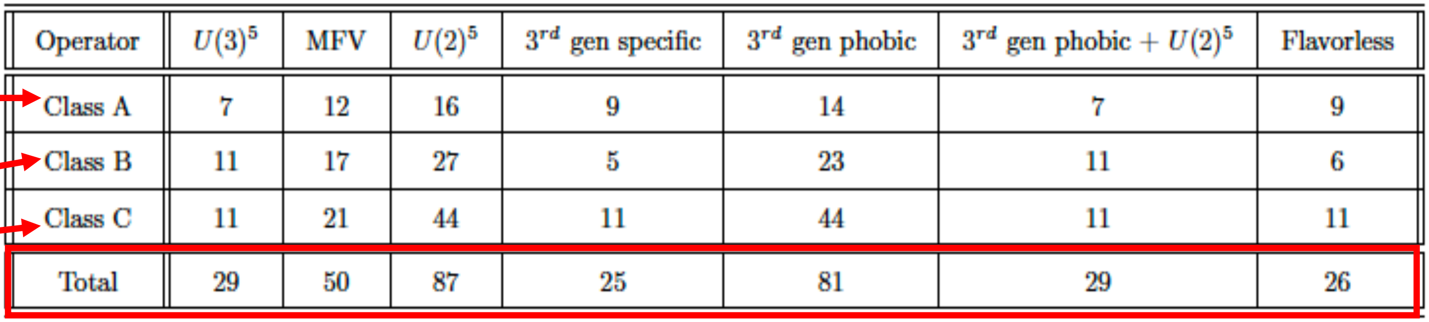
Flavor assumptions reduce possibilities

Operators that contribute to EWPO at NLO

2-fermion

4-fermion with identical representations

Remaining 4-fermion



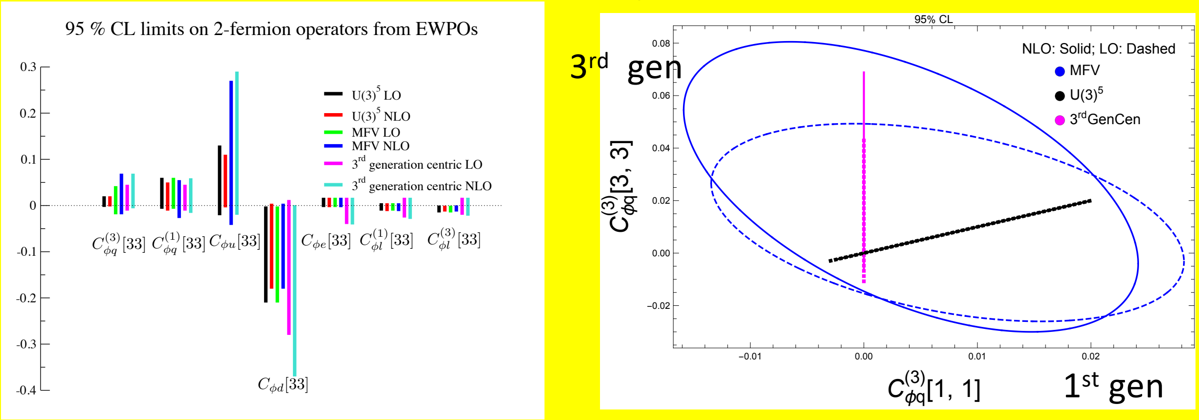
Operator	$U(3)^5$	MFV	$U(2)^5$	3^{rd} gen specific	3^{rd} gen phobic	3^{rd} gen phobic + $U(2)^5$	Flavorless
Class A	7	12	16	9	14	7	9
Class B	11	17	27	5	23	11	6
Class C	11	21	44	11	44	11	11
Total	29	50	87	25	81	29	26

- NLO SMEFT EW fits done with coefficients evaluated at M_Z
- Input parameter dependence? Results use G_F, M_Z, α
- After separating out dominant scheme independent contributions, residual scheme dependent contributions similar in commonly used schemes [Biekotter, Pecjak, Scott, Smith, 2305.03763]

Flavor matters!

- Take-away: Neglecting flavor gives overly aggressive limits
- Strong correlations in flavor space
- NLO can have large effects

2-fermion operators



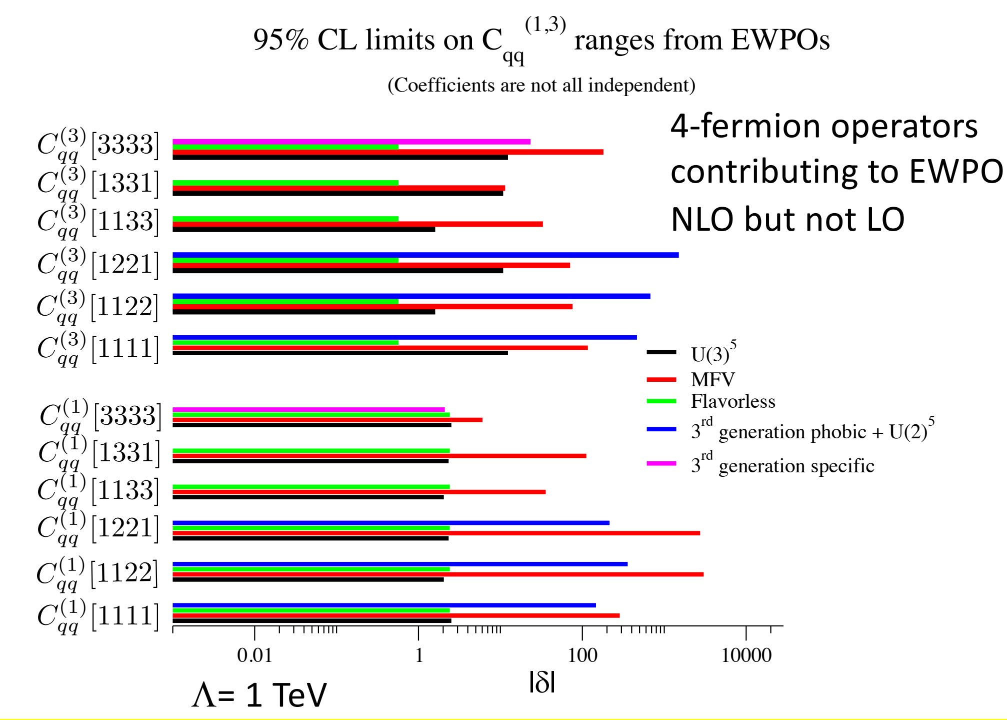
Note difference in NLO/LO shapes in MFV scenario

* Coefficients are related by flavor assumptions

Flavor matters

Flavorless assumption yields more stringent bounds than flavor scenarios

Can also limit these coefficients with fits to LHC dijets. More stringent limits for gens 1 and 2 from dijets (tree level process) [Bruggisser, Westhoff: 2212.02532]

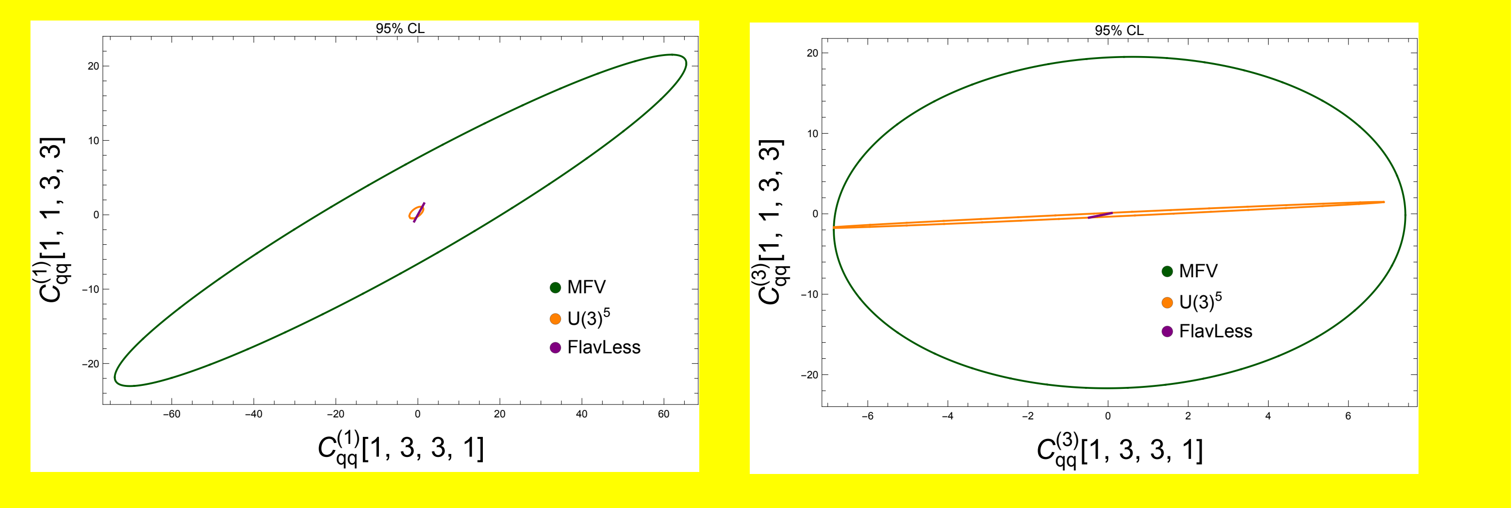


4-fermion operators contributing to EWPO at NLO but not LO

Λ= 1 TeV

$U(3)^5$ results more constrained than MFV

Flavor matters!



Consider 1 operator type at a time and marginalize over flavor structures not shown

How to tame the SMEFT expansion?

- Various terminations of the expansion possible

$$A \sim A_{SM} + C_i^6 \frac{A_i^6}{\Lambda^2} + C_i^6 C_j^6 \frac{A_{ij}}{\Lambda^4} + C_i^8 \frac{A_i^8}{\Lambda^4}$$

- Linear: (Not guaranteed to be positive definite!)

$$\sigma_{lin} = \mid A_{SM} \mid^2 + \frac{C_i^6}{\Lambda^2} A_{SM} A_i^6$$

- Quadratic: (Why does it make sense to neglect dim-8 and double insertions?)

$$\sigma_{quad} = \mid A_{SM} + \frac{C_i^6}{\Lambda^2} A_i^6 \mid^2$$

- Dimension-8 + double insertions

$$\sigma_8 \sim \mid A_{SM} + \frac{C_i^6}{\Lambda^2} A_i^6 \mid^2 + \frac{A_{SM}}{\Lambda^4} \left(C_i^6 C_j^6 A_{ij} + C_8 A^8 \right)$$

Flavor results
obtained in
linear scenario

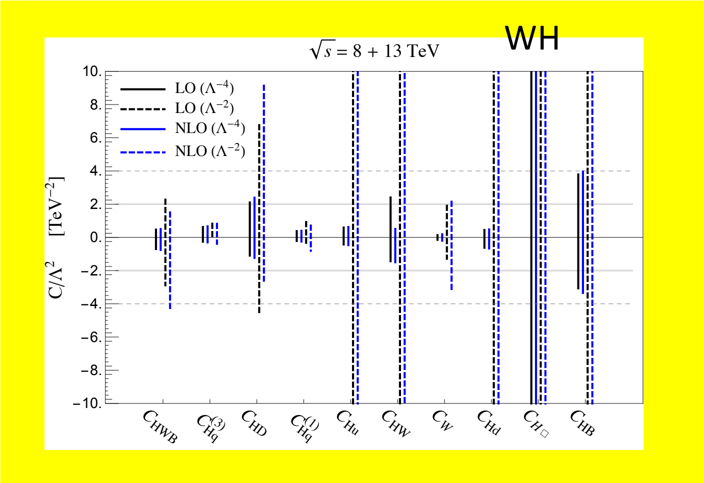
- Proliferation of operators is a problem for studies of the impact of dimension-8
- Ignoring flavor, but including CP violation: 84 dim-6 ops and 993 dim-8 ops

Bottom up approach: Double Insertions

- For tree level processes, it is straightforward to include as many insertions of SMEFT operators as you like (included in standard SMEFT codes)

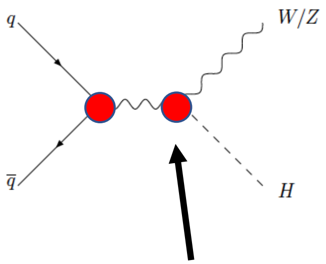
$$\sigma_{quad'} = | A_{SM} + \frac{C_i^6}{\Lambda^2} A_i^6 |^2 + \frac{A_{SM}}{\Lambda^4}\left(C_i^6 C_j^6 \right)$$

This is only NLO QCD



Baglio et al, [2003.07862](2003.07862)

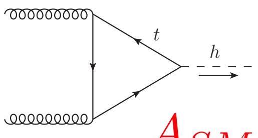
Small effects for well constrained coefficients



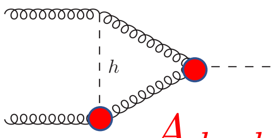
SM+dim-6 operator

Double Insertions for loop processes

- gg→ H $L \sim \frac{C_{Hg}}{\Lambda^2}(H^\dagger H)G^A_{\mu\nu}G^{\mu\nu,A}$



A_{SM}



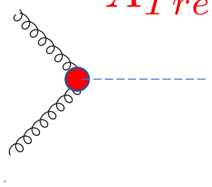
A_{double}

$$\Longrightarrow \quad A_{double}A_{SM} \sim \frac{C^2_{HG}}{\Lambda^4(16\pi^2)^2}$$

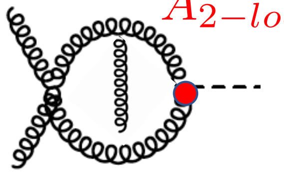
- C_{Hg} contribution starts at tree level

Need both for double insertions

A_{Tree}



A_{2-loop}

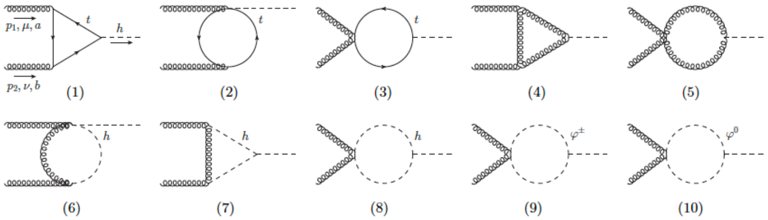


$$\Longrightarrow \quad A_{tree}A_{2-loop} \sim \frac{C^2_{HG}}{\Lambda^4(16\pi^2)^2}$$

*A_{Tree} and A_{SM} are same order in loop expansion in M_t →∞ limit

Double Insertions without C_{Hg}

- C_{Hg} not generated at tree level by new color singlet scalars or gauge bosons
- Simplest model to generate C_{Hg} is colored vector-like quark, but this arises at 1-loop
- Ignore C_{Hg}: remaining dim-6 operators contribute at one-loop and SMEFT amplitudes can be expanded around SM top loop result
- Compute amplitude consistently to $1/(16\pi^2\Lambda^4)$
- Compute SMEFT relations between Lagrangian parameters and physical parameters to $O(1/\Lambda^4)$
- UV divergences absorbed bv renormalization of dim-8 term:

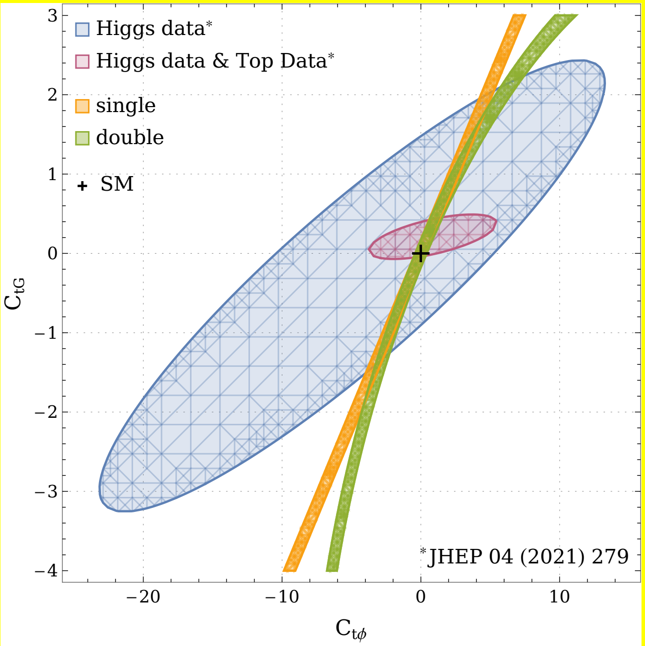


$$L \sim \frac{C^8}{\Lambda^4}(H^\dagger H)^2 G^A_{\mu\nu} G^{\mu\nu,A}$$

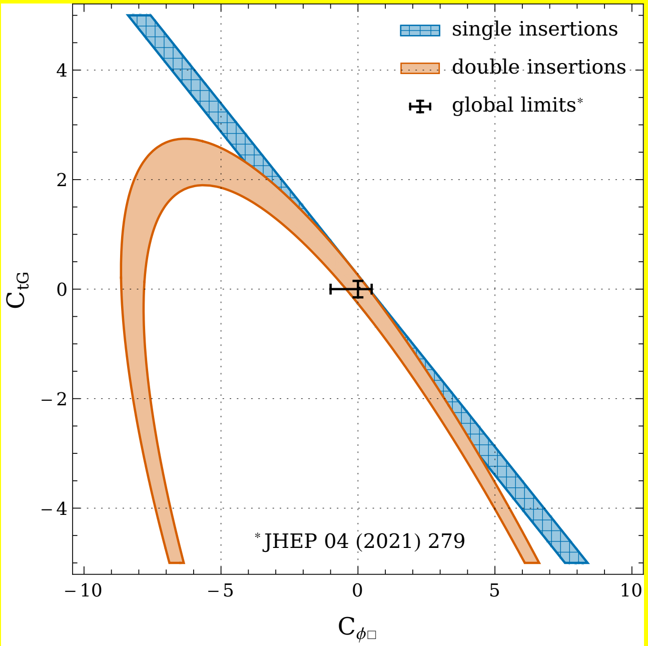
Double insertions

- Effects irrelevant when compared to global fit limits!
- Plot regions where μ_{ggH} is within 5% of measured value

Top dipole operator



Changes top Yukawa



Changes Higgs kinetic energy

Conclusions

- SMEFT fits have many uncertainities baked in
- Studies of flavor effects in EWPOs show that neglecting the flavor structure of 4-fermion operators leads to overly optimistic results
- Preliminary study of double insertions of dimension-6 operators to gluon fusion demonstrates that for the operators studied, these effects can be ignored

LOOPFEST XXI

Thanks to the loopfest organizers!