Title: Some unknown unknowns, and some known unknowns in the Standard Model EFT

Date: Nov 09, 2018 01:00 PM

URL: http://pirsa.org/18110076

Abstract: <p>In recent years the Standard Model Effective Field Theory (SMEFT) has emerged as a well defined and systematically improvable theory to study the constraints on physics beyond the Standard Model. This formalism explains old mysteries in interpreting LEP data and offers a field theory framework to combine such data with LHC measurements of the properties of the Higgs. We discuss the current status of these combined studies. The lack of evidence for new physics resonances at LHC has also encouraged new approaches to explaining the observed value of the electroweak scale, in the presence of physics beyond the Standard Model. One such approach is the Neutrino Option, that generates the electroweak scale from an underlying Majorana scale, when Neutrino masses come about due to a seesaw mechanism. We discuss how this approach is embedded into the SMEFT.</p>

Unknown unknowns and known unknowns in the SMEFT

#SMEFT

M. Trott, Perimeter drive by (the good kind) 2018

VILLUM FONDEN

DET FRIE FORSKNINGSRÅD
DANISH COUNCIL FOR INDEPENDENT RESEARCH

centre for particle physics Discovery

The Niels Bohr International Academy

Michael Trott, Niels Bohr Institute, NBIA, Copenhagen, Denmark

Motivation and theory framework

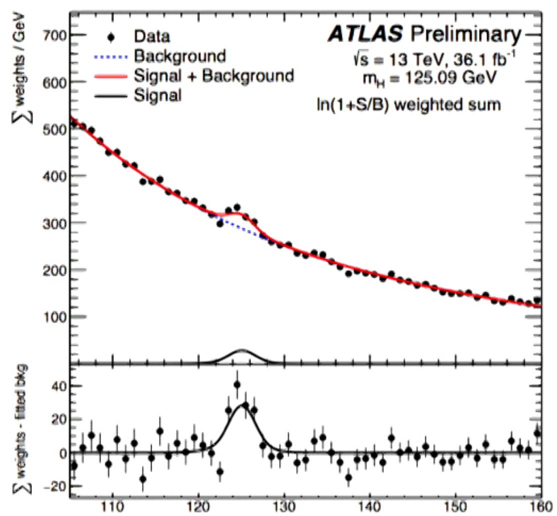
More info: The Standard Model as an Effective Field Theory review
Ilaria Brivio, MT https://arxiv.org/pdf/1706.08945.pdf

SMEFTsim and pole parameter program
Ilaria Brivio, Yun Jiang, MT https://arxiv.org/pdf/1709.06492.pdf,

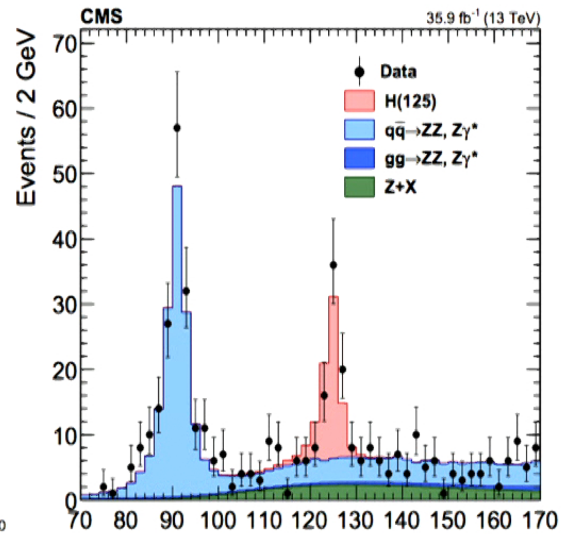
SMEFTsim UFO files http://feynrules.irmp.ucl.ac.be/wiki/SMEFT

The big picture: what was discovered at LHC

- Discovery of a (Higgs like) $J^P \sim 0^+$ particle in 2012



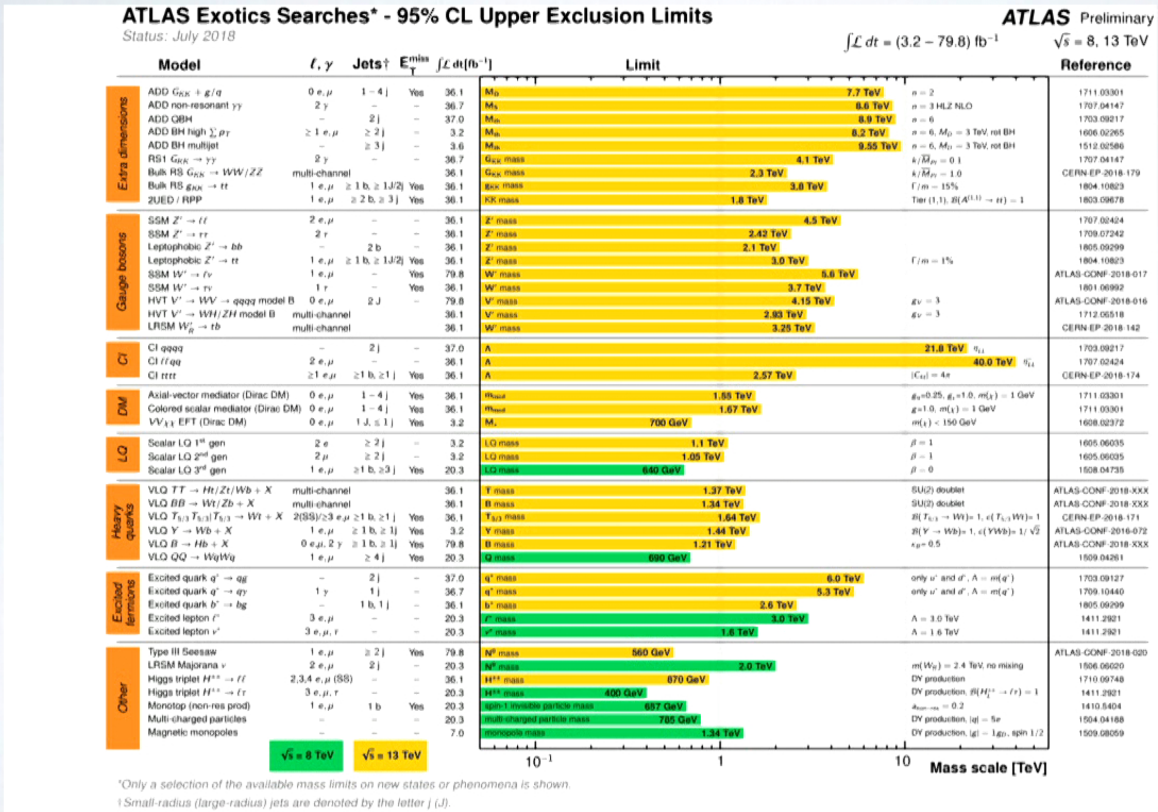
ATLAS-CONF-2017-045 (2017)



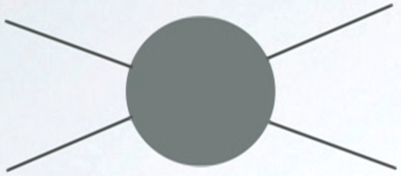
CMS-PAS-HIG-16-041 (2017)

- And what is not discovered as yet…

RunII and beyond: Resonance limits to local operators



When you do measurements below a particle threshold



- Observable is a function of the Lorentz invariants:

$$f(s,t,u)$$

- Generally an analytic function of these invariants, except in special regions of phase space, ex. where an internal state goes on-shell.

$$\sim \frac{1}{s - m^2 + i\Gamma(s)\, m}$$

IF the collision probe does not reach $\sim m^2_{heavy}$
THEN observable's dependence on that scale simplified

EFT approach not a guess.

General approach based on S matrix theory and motivated by experimental situation.

- You can Taylor expand in LOCAL functions (operators)

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

This is the core idea of EFT interpretations of the data.

General "BSM heavy" approach is SMEFT/HEFT

No BSM resonance seen

Decoupling

$v/M < 1$

VERY! Efficient to constrain BSM/interpret the data in EFT

no other (hidden) light states.

SMEFT
observed scalar in doublet

HEFT
observed scalar not in doublet

0704.1505 Grinstein, Trott
(for distinction)

Basics of the SMEFT formulation: IR operator form

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

UV dependent Wilson coefficient and suppression scale

General "BSM heavy" approach is SMEFT/HEFT

No BSM resonance seen

Decoupling

$v/M < 1$

VERY! Efficient to constrain BSM/interpret the data in EFT

no other (hidden) light states.

SMEFT

observed scalar in doublet

HEFT

observed scalar not in doublet

0704.1505 Grinstein, Trott (for distinction)

Basics of the SMEFT formulation: IR operator form

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

UV dependent Wilson coefficient and suppression scale

Michael Trott, Niels Bohr Institute

6

SMEFT:development cycle

SMEFT - built of H doublet + higher D ops

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

- (red) Glashow 1961, Weinberg 1967 (Salam 1967)
- (blue) Weinberg 1979, Wilczek and Zee 1979
- (dark green) Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010
- (cyan) Weinberg 1979, Abbott Wise 1980
- (black) Lehman 1410.4193, Henning et al. 1512.03433
- (light green) Lehman,Martin 1510.00372, Henning et al. 1512.03433

The Lagrangian expansion theory technology is a solved problem Henning et al arXiv:1706.0852.

Complexity is scaling up…

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

$$\frac{1}{\Lambda^2_{\delta B=0}} \mathcal{L}_6$$

Class		$N_{\rm op}$	CP-even n_g	1	3	CP-odd n_g	1	3
	1 g^3X^3	4	2	2	2	2	2	2
	2 H^6	1	1	1	1	0	0	0
	3 H^4D^2	2	2	2	2	0	0	0
	4 $g^2X^2H^2$	8	4	4	4	4	4	4
	5 $y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
	6 $gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
	7 ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
	8 : $(\bar{L}L)(\bar{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
	8 : $(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
ψ^4	8 : $(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
	8 : $(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
	8 : $(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
	8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{4}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{4}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Is the SMEFT too complex to use?

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 non-hermitian flavour dependent operator (neutrino masses and mixing)

- Number of parameters to go after in next SMEFT step at LHC is about 30 as will be shown. This is an achievable challenge.
- Why do we have a significant SMEFT parameter set to simultaneously constrain?

Its because of the Higgs when using $\mathcal{L}^{(d)}$:

$\sqrt{2\langle H^\dagger H\rangle} \sim 246\,\mathrm{GeV}$	$+d \leq 4$	on-shell simplification
	$+d > 4$	local operator degeneracy

SMEFT requires a GLOBAL approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + \ldots, \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

- The operators are defined in a BASIS, fixed by SM field redefinitions.

$$\mathcal{L}_{B'} = -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 \, \mathsf{y}_\psi \, \overline{\psi} \, \not{B}' \, \psi + (D^\mu H)^\dagger (D_\mu H) + \mathcal{C}_B (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu}),$$
$$+ \, \mathcal{C}_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C^{(1)}_{\underset{tt}{Hl}} Q^{(1)}_{\underset{tt}{Hl}} + C_{\underset{tt}{He}} Q_{\underset{tt}{He}} + C^{(1)}_{\underset{tt}{Hq}} Q^{(1)}_{\underset{tt}{Hq}} + C_{\underset{tt}{Hu}} Q_{\underset{tt}{Hu}},$$
$$+ \, C_{\underset{tt}{Hd}} Q_{\underset{tt}{Hd}} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

Over complete set of ops depending on B^μ

1706.08945 I. Brivio, MT

- Perform a field redefinition $B'_\mu \to B_\mu + b_2 \dfrac{H^\dagger i \overleftrightarrow{D}_\mu H}{\Lambda^2}$ then $\mathcal{L}_B{}' - g_1 \, b_2 \Delta B$

<u>The physics is not changed by this choice of path integral variable.</u>

Z,W couplings

$$\mathcal{Q}_{Hl}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hq}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}_{Hq}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$

Top data

$$\mathcal{Q}^{(1)}_{\substack{qq\\prst}} = (\bar{q}_p\gamma^\mu q_r)(\bar{q}_s\gamma_\mu q_t),$$
$$\mathcal{Q}^{(3)}_{\substack{qq\\prst}} = (\bar{q}_p\gamma^\mu\tau^I q_r)(\bar{q}_s\gamma_\mu\tau_I q_t),$$
$$\mathcal{Q}_{\substack{uu\\prst}} = (\bar{u}_p\gamma^\mu u_r)(\bar{u}_s\gamma_\mu u_t),$$
$$\mathcal{Q}^{(1)}_{\substack{ud\\prst}} = (\bar{u}_p\gamma^\mu u_r)(\bar{d}_s\gamma_\mu d_t),$$
$$\mathcal{Q}^{(8)}_{\substack{ud\\prst}} = (\bar{u}_p\gamma^\mu T^A u_r)(\bar{d}_s\gamma_\mu T^A d_t),$$

Bhabha scattering

$$\mathcal{Q}_{ee} = (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{ll} = (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)$$

$$\mathcal{Q}_W = \varepsilon_{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

TGC/multi-boson

Field redefinitions are WHY a global SMEFT is needed

$$\mathcal{Q}_{HD} = (D_\mu H^\dagger H)(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{HWB} = (H^\dagger\sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{Hl}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
$$\mathcal{Q}'_{ll} = (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

input quantities

B anomalies

$$\mathcal{Q}^{(1)}_{\substack{lq\\iisb}} = (\bar{\ell}_i\gamma^\mu\ell_i)(\bar{s}\gamma_\mu b),$$
$$\mathcal{Q}^{(3)}_{\substack{lq\\iisb}} = (\bar{\ell}_i\tau^I\gamma^\mu\ell_i)(\bar{s}\,\tau_I\,\gamma_\mu b).$$

$$\mathcal{Q}_{Hbox} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{Q}_{HG} = (H^\dagger H) G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$$
$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\tilde{H}u)$$
$$\mathcal{Q}_{dH} = (H^\dagger H)(\bar{q}Hd)$$
$$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{q}e)$$
$$\mathcal{Q}_G = \varepsilon_{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$$
$$\mathcal{Q}_{uG} = (\bar{q}\sigma^{\mu\nu} T^a \tilde{H} u) G^a_{\mu\nu}$$

H processes

We are looking for few % to 10's% effects in SMEFT.

Partial image credit: I Brivio.

Automation of this approach

- Need to keep all operators and carefully compute S matrix elements avoiding uncontrolled approximations (and human error)
- Automation of leading order SMEFT in the SMEFTsim package now

https://arxiv.org/abs/1709.06492

feynrules.irmp.ucl.ac.be/wiki/SMEFT

1406.2332.pdf

Wiki | Timeline | View Tickets

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

Ilaria Brivio, Yun Jiang and Michael Trott

ilaria.brivio@nbi.ku.dk, yunjiang@nbi.ku.dk, michael.trott@cern.ch

NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen

SMEFTsim

- 2 input parameter schemes, with all higher dimensional operators included
- 3 symmetry cases: General flavour indicies and phases (2499 parameters!)

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Minimal Flavour Violation SMEFT at LO

Fully flavour symmetric SMEFT at LO

- SMEFTsim designed to take the grind out of these studies, canonical normalization and input relations all done for user.

See: feynrules.irmp.ucl.ac.be/wiki/SMEFT

SMEFTsim paper : https://arxiv.org/abs/1709.06492

This code undergoing validation in new LPCC effort to develop SMEFT results/tools for LHC experiment. Contact Trott/Maltoni for more details on this effort/to contribute.

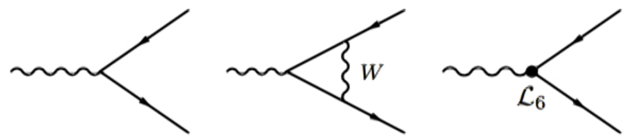
.. are there too many parameters?

- Number of parameters convolution of power counting

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

+ numerical suppression due to interference with SM and resonance domination, or not

- EX - flavour indicies for neutral currents:



$$\mathcal{A}^h_{ik} \simeq \frac{3\bar{v}_T\,\bar{g}_2^3}{16^2\,\pi^2\,\hat{m}_W}\,\bar{\psi}_i\left[y_i\,V^\dagger_{ik}\,V_{kj}\frac{m_k^2}{\hat{m}_W^2}P_L + y_j\,V^\dagger_{kj}\,V_{ik}\frac{m_k^2}{\hat{m}_W^2}P_R\right]\psi_j, + \cdots$$

$$\mathcal{A}^Z_{ik} \simeq -\frac{3\sqrt{\bar{g}_1^2+\bar{g}_2^2}\,\bar{g}_2^2\,V^\star_{jk}\,V_{ji}}{32\,\pi^2}\frac{m_j^2}{m_W^2}\bar{\psi}_k\,\gamma^\mu\,P_L\,\psi_i\,\epsilon^Z_\mu + \cdots,$$

This IR SM physics projects out parameters.

Leading "WHZ pole parameters"

Case	CP even	CP odd	WHZ Pole parameters
General SMEFT ($n_f = 1$)	53 [10]	23 [10]	~ 23
General SMEFT ($n_f = 3$)	1350 [10]	1149 [10]	~ 46
$\mathrm{U}(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

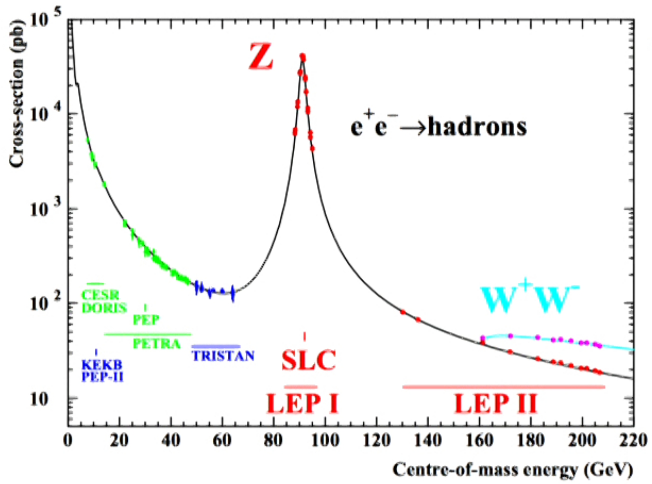
Brivio, Jiang, MT https://arxiv.org/abs/1709.06492

- So long as a measurement is dominated by a near on-shell region of phase space of a narrow boson (like W,Z,H) many other parameters suppressed by

$$\left(\frac{\Gamma_B\, m_B}{\bar{v}_T^2}\right)\frac{\{\mathrm{Re}(C),\mathrm{Im}(C)\}}{g_{SM}\, C_i}, \qquad \left(\frac{\Gamma_B\, m_B}{p_i^2}\right)\frac{\{\mathrm{Re}(C),\mathrm{Im}(C)\}}{g_{SM}\, C_k},$$

Measurement/facility design can DEFINE a subset of SMEFT parameters in a fit

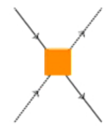
LEP EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

  $\sim 40\,pb^{-1}$ off peak data

  $\sim 155\,pb^{-1}$ on peak data



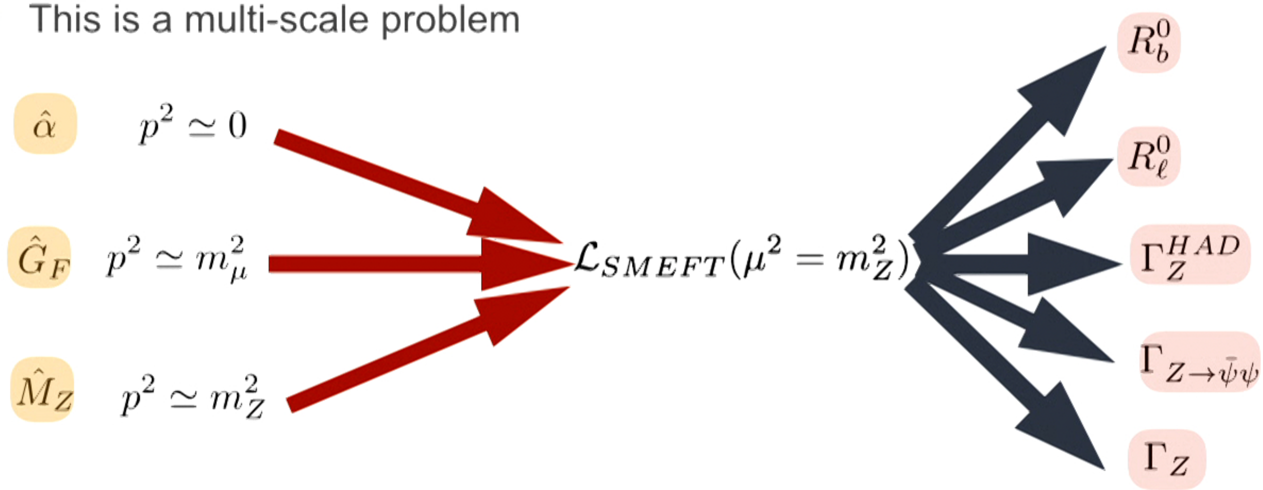
- many more ψ^4 ops suppressed by $\dfrac{m_z\,\Gamma_Z}{v^2}$

Details: arXiv:1502.02570
Berthier, MT

The pseudo-observable LEP data is not subject to large intrinsic measurement bias transitioning from SM to SMEFT.

Recall a prediction is always inputs to outputs

- This is a multi-scale problem



- Measured inputs fix Lagrangian parameters which predict observables
- Can CHOOSE your inputs as you wish, 2 general schemes in use

$\{\hat{\alpha}_{ew}, \hat{m}_Z, \hat{G}_F\}$	$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$
alpha scheme	mw scheme

Global constraints on dim 6.

Global SMEFT analysis on 103 observables (pre LHC data).

arXiv:1502.02570, 1508.05060 Berthier, Trott

Comprehensive global fit of pre-LHC data in SMEFT

- LEP pole data + all these measurements below with clear theory errors

B $2 \to 2$ scattering observables at LEP, Tristan, Pep, Petra.

B.1 $\ell^+ \ell^- \to f \bar{f}$ near and far from the Z pole.

B.1.1 Forward-Backward Asymmetries for u, d, ℓ

B.2 Bhabba scattering, $e^+ e^- \to e^+ e^-$

C Low energy precision measurements

C.1 ν lepton scattering

C.2 ν Nucleon scattering

C.2.1 Neutrino Trident Production

C.3 Atomic Parity Violation

C.4 Parity Violating Asymmetry in eDIS

C.5 Møller scattering

D Universality in β decays

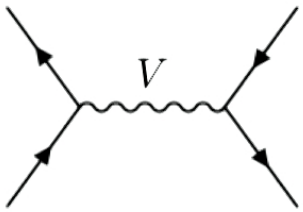
Despite all this, 2 unconstrained directions in wilson coefficient space. (first identified by Han and Skiba)

Now understood as
A reparameterization invariance
arXiv:1701.06424 Ilaria Brivio, MT

- Global data analysis of data from PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II

EWPD flat direction example.

- For measurements of LEPI near Z pole data and W mass at LO:



- Rescaling invariance presence in EWPD:
  Brivio, MT 1701.06424

$$(V, g) \leftrightarrow \left(V' \, (1+\epsilon), g' \, (1-\epsilon)\right),$$

$$\sqrt{2 \, \langle H^\dagger H \rangle} \sim 246 \, \mathrm{GeV}$$

- Effects like this cancel out in subsets of measurements.

- Note the crucial role of the Higgs classical background field here.
- Systematically a reason why the constraints on the C_i in the SMEFT fit space is highly correlated.

SMEFT reparameterization invariance

- At one scale, you can get rid of the effect of the operators

$$H^\dagger H B^{\mu\nu} B_{\mu\nu}, \quad H^\dagger H W^{\mu\nu} W_{\mu\nu}$$

$$\langle y_h\, g_1^2 Q_{HB}\rangle_{S_R} \to \frac{g_1^2\, \bar{v}_T^2}{4\,\Lambda^2} B^{\mu\nu} B_{\mu\nu}, \quad \langle g_2^2 Q_{HW}\rangle_{S_R} \to \frac{g_2^2\, \bar{v}_T^2}{2\,\Lambda^2} W_I^{\mu\nu} W^I_{\mu\nu}.$$

$\bar{\psi}\psi \to \bar{\psi}\psi$

- via $B \to \mathcal{B}(1 + C_{HB} v^2), \qquad g_1 \to \bar{g}_1(1 - C_{HB} v^2)$

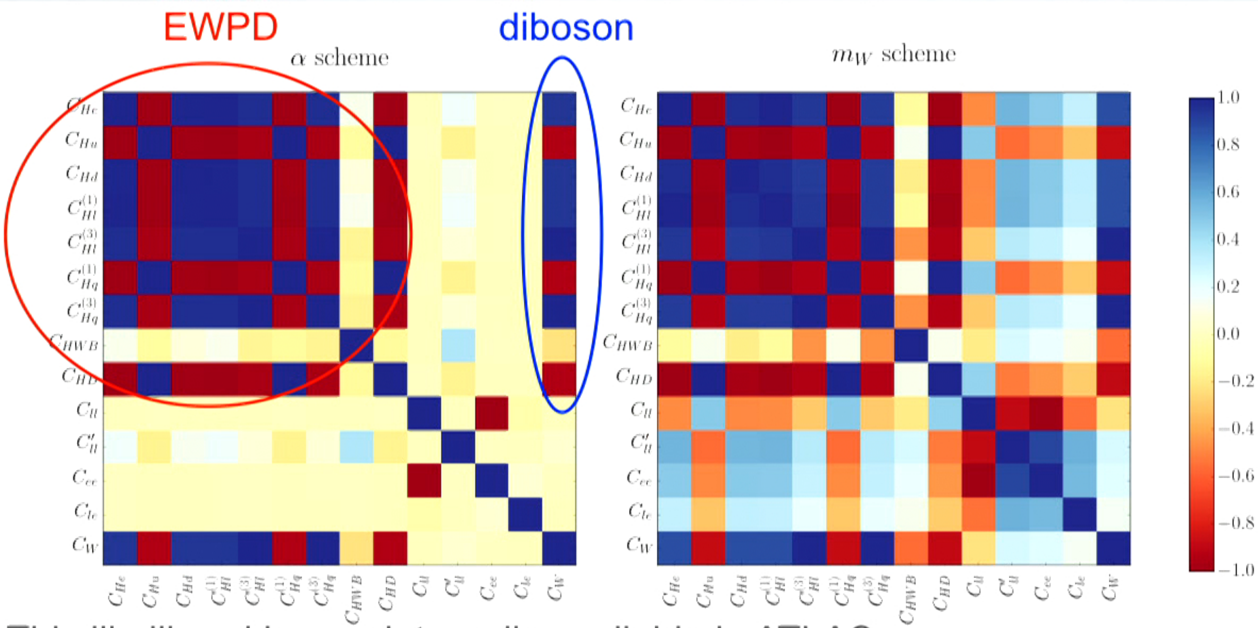
  Which leaves $B\, g_1 \to \mathcal{B}\, \bar{g}_1$ invariant.

- LEP data also can't see what is EOM equivalent to these operators in $\bar{\psi}\psi \to \bar{\psi}\psi$

$$\langle y_h\, g_1^2 Q_{HB}\rangle_{S_R} = \langle \sum_{\substack{\psi_\kappa = u,d,\\ q,e,l}} y_k\, g_1^2\, \bar{\psi}_\kappa\, \gamma_\beta \psi_\kappa\, (H^\dagger\, i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2}\, (Q_{H\Box} + 4 Q_{HD}) - \frac{1}{2} g_1\, g_2\, Q_{HWB}\rangle_{S_R},$$

$$\langle g_2^2 Q_{HW}\rangle_{S_R} = \langle g_2^2\, (\bar{q}\,\tau^I \gamma_\beta q + \bar{l}\,\tau^I \gamma_\beta l)\, (H^\dagger\, i \overleftrightarrow{D}^I_\beta H) + 2\, g_2^2\, Q_{H\Box} - 2\, g_1\, g_2\, y_h\, Q_{HWB}\rangle_{S_R}.$$

Correlations are also key when combining



Corr. matrices

- This likelihood is now internally available in ATLAS
- EWPD Studies that id. correlations in SMEFT as a key issue

Han and Skiba http://arxiv.org/abs/hep-ph/0412166
Berthier, Bjorn, MT 1606.06693
Brivio, MT 1701.06424

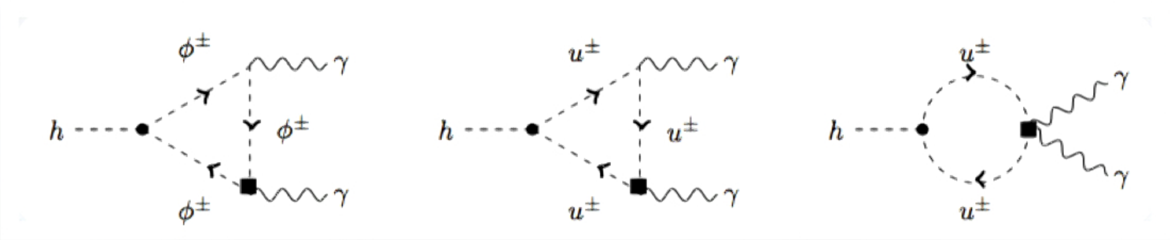
Gauge Fixing In SMEFT space

Recall: SMEFT gauge fixing issues.

- The fields are redefined at each order in the power counting, this leads to the appearance of L6 Wilson coefficients in the gauge fixing term.

$$\mathcal{L}_{FP} = -\bar{u}^\alpha \frac{\delta G^\alpha}{\delta \theta^\beta} u^\beta.$$

Some operators in $\mathcal{L}_6$ then source ghosts!



- This cancels the unusual divergences in $\Gamma_{SMEFT}(h \to \gamma\gamma)$ exactly.
- The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former also results in some interesting local contact operators

$$-\frac{c_w\, s_w}{\xi_B\, \xi_W}(\xi_B - \xi_W)\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu) - \frac{C_{HWB} v^2 (s_w^2 - c_w^2)(s_w^2 \xi_B + c_w^2 \xi_W)}{\xi_B\, \xi_W}\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu)\,.$$

SMEFT reparameterization invariance

- At one scale, you can get rid of the effect of the operators

$$H^\dagger H B^{\mu\nu} B_{\mu\nu}, \quad H^\dagger H W^{\mu\nu} W_{\mu\nu}$$

$$\langle y_h\, g_1^2 Q_{HB}\rangle_{S_R} \to \frac{g_1^2\,\bar{v}_T^2}{4\,\Lambda^2}\, B^{\mu\nu} B_{\mu\nu}, \quad \langle g_2^2 Q_{HW}\rangle_{S_R} \to \frac{g_2^2\,\bar{v}_T^2}{2\,\Lambda^2}\, W_I^{\mu\nu} W^I_{\mu\nu}.$$

$\bar{\psi}\psi \to \bar{\psi}\psi$

- via $B \to \mathcal{B}(1 + C_{HB} v^2), \qquad g_1 \to \bar{g}_1(1 - C_{HB} v^2)$

  Which leaves $B\, g_1 \to \mathcal{B}\, \bar{g}_1$ invariant.

- LEP data also can't see what is EOM equivalent to these operators in $\bar{\psi}\psi \to \bar{\psi}\psi$

$$\langle y_h\, g_1^2 Q_{HB}\rangle_{S_R} = \langle \sum_{\substack{\psi_\kappa = u,d,\\ q,e,l}} y_k\, g_1^2\, \overline{\psi}_\kappa\, \gamma_\beta \psi_\kappa\, (H^\dagger\, i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2}\,(Q_{H\Box} + 4 Q_{HD}) - \frac{1}{2} g_1\, g_2\, Q_{HWB}\rangle_{S_R},$$

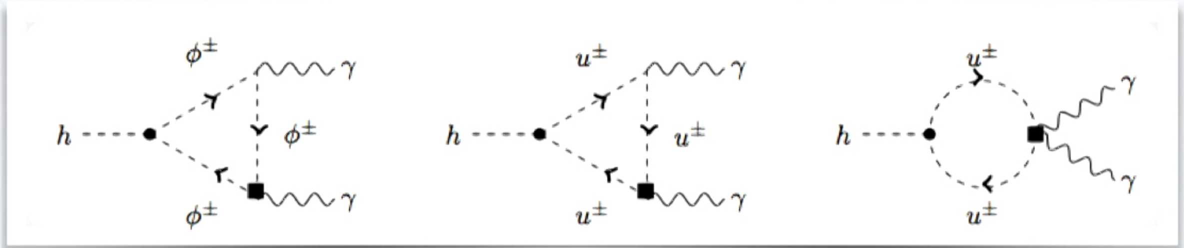
$$\langle g_2^2 Q_{HW}\rangle_{S_R} = \langle g_2^2\,(\overline{q}\,\tau^I \gamma_\beta q + \bar{l}\,\tau^I \gamma_\beta l)\,(H^\dagger\, i \overleftrightarrow{D}^I_\beta H) + 2\, g_2^2\, Q_{H\Box} - 2\, g_1\, g_2\, y_h\, Q_{HWB}\rangle_{S_R}.$$

Recall: SMEFT gauge fixing issues.

- The fields are redefined at each order in the power counting, this leads to the appearance of L6 Wilson coefficients in the gauge fixing term.

$$\mathcal{L}_{FP} = -\bar{u}^\alpha \, \frac{\delta G^\alpha}{\delta \theta^\beta} \, u^\beta .$$

Some operators in $\mathcal{L}_6$ then source ghosts!



- This cancels the unusual divergences in $\Gamma_{SMEFT}(h \to \gamma\gamma)$ exactly.
- The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former also results in some interesting local contact operators

$$-\frac{c_w \, s_w}{\xi_B \, \xi_W}(\xi_B - \xi_W)\,(\partial^\mu A_\mu \, \partial^\nu Z_\nu) - \frac{C_{HWB} v^2 (s_w^2 - c_w^2)(s_w^2 \xi_B + c_w^2 \xi_W)}{\xi_B \, \xi_W}\,(\partial^\mu A_\mu \, \partial^\nu Z_\nu) \, .$$

SMEFT gauge fixing solution!

$$\mathcal{L}_{\text{scalar,kin}} = (D_\mu H)^\dagger (D^\mu H) + C_{H\Box} (H^\dagger H) \Box (H^\dagger H) + C_{HD} (H^\dagger D_\mu H)^* (H^\dagger D^\mu H), \equiv \frac{1}{2} h_{IJ}(\phi) (D_\mu \phi)^I (D^\mu \phi)^J .$$

$$\mathcal{L}_{\text{GF}} = -\frac{\hat{g}_{AB}}{2\,\xi} \mathcal{G}^A \mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{CD} \hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^I \hat{h}_{IK} \tilde{\gamma}^K_{C,J} \hat{\phi}^J .$$

$$\int \mathcal{D}F \det \left[\frac{\Delta \mathcal{G}^A}{\Delta \alpha^B} \right] e^{i \left(S[F+\hat{F}] + \mathcal{L}_{\text{GF}} + \hat{g}_{CD} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J \right)} .$$

SMEFT gauge fixing solution!

$$\mathcal{L}_{\rm scalar,kin} = (D_\mu H)^\dagger (D^\mu H) + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H), \equiv \frac{1}{2} h_{IJ}(\phi)(D_\mu\phi)^I (D^\mu\phi)^J.$$

$$\mathcal{L}_{\rm WB} = -\frac{1}{4}W^a_{\mu\nu}W^{a,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{C_{HB}}{\Lambda^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{C_{HW}}{\Lambda^2}H^\dagger H W^a_{\mu\nu}W^{a,\mu\nu} + \frac{C_{HWB}}{\Lambda^2}H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}, \equiv -\frac{1}{4}g_{AB}(H)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu},$$

$$\mathcal{L}_{\rm GF} = -\frac{\hat{g}_{AB}}{2\,\xi}\mathcal{G}^A\mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu\mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{\ CD}\hat{\mathcal{W}}^C_\mu\mathcal{W}^{D,\mu} + \frac{\xi}{2}\hat{g}^{XC}\phi^I\,\hat{h}_{IK}\,\tilde{\gamma}^K_{C,J}\hat{\phi}^J.$$

$$\int \mathcal{D}F \det\left[\frac{\Delta\mathcal{G}^A}{\Delta\alpha^B}\right] e^{i\left(S[F+\hat{F}]+\mathcal{L}_{\rm GF}+\hat{g}_{CD}J^C_\mu\mathcal{W}^{D,\mu}+\hat{h}_{IJ}J^I_\phi\phi^J\right)}.$$

$$\gamma^I_{1,J} = \begin{bmatrix}0&0&0&-1\\0&0&-1&0\\0&1&0&0\\1&0&0&0\end{bmatrix}, \quad \gamma^I_{2,J} = \begin{bmatrix}0&0&1&0\\0&0&0&-1\\-1&0&0&0\\0&1&0&0\end{bmatrix}, \quad \gamma^I_{3,J} = \begin{bmatrix}0&-1&0&0\\1&0&0&0\\0&0&0&-1\\0&0&1&0\end{bmatrix}, \quad \gamma^I_{4,J} = \begin{bmatrix}0&-1&0&0\\1&0&0&0\\0&0&0&1\\0&0&-1&0\end{bmatrix}$$

Global fit – observables [preliminary]

126 observables included so far

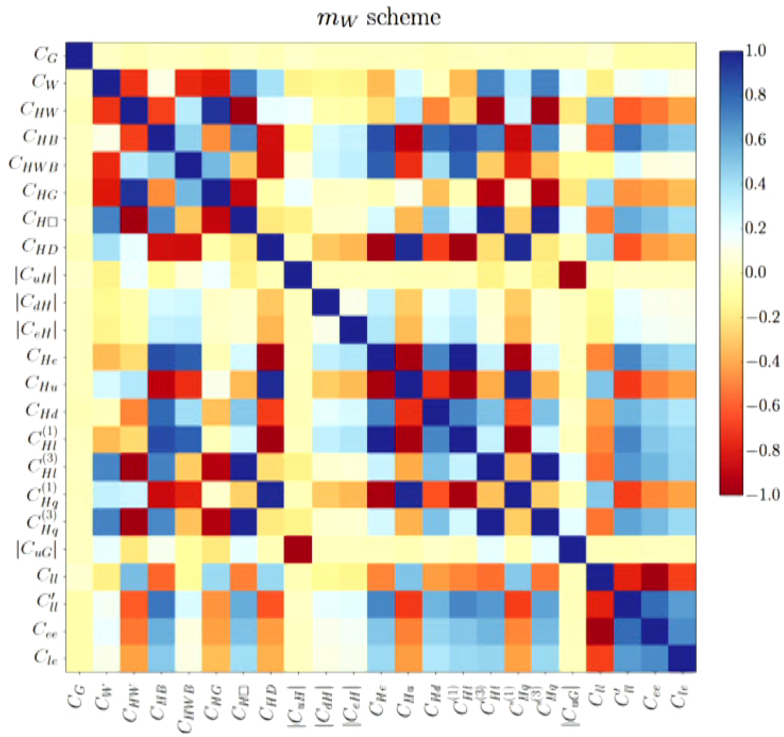
- 10 near-Z-pole EWPO: Γ_Z, $R^0_{\ell,c,b}$, $A^{\ell,c,b,\mu,\tau}_{FB}$, σ^0_h LEPI combination hep-ex/0509008
- 21 distribution bins for bhabha scattering at LEPII LEPII combination 1302.3415
- 74 dist. bins for W^+W^- production at LEPII
  L3: hep-ex/0409016
  OPAL: 0708.1311
  ALEPH: Eur.Phys.J. C38 (2004) 147
  differential combined: 1302.3415
- 21 STXS for Higgs measurements in $H \to \gamma\gamma$ and $H \to 4\ell$ at LHC
  - ATLAS (36 fb^{-1}) ATLAS-CONF-2017-047
  - CMS (36 fb^{-1}) CMS PAS HIG-17-031

Global fit – correlations [preliminary]

Provided by I. Brivio

Best fit (profiled)

$\bar{C}_{HG}$	0.00094 $\pm$ 0.000385784
$\bar{C}'_{ll}$	0.0032 $\pm$ 0.00837061
$\bar{C}^{(1)}_{Hq}$	-0.017 $\pm$ 0.0125669
$\bar{C}_{Hd}$	0.0016 $\pm$ 0.028008
$\bar{C}^{(1)}_{Hl}$	0.050 $\pm$ 0.0374125
$\bar{C}_{HB}$	0.062 $\pm$ 0.0436375
$\bar{C}_{Hu}$	-0.061 $\pm$ 0.0482166
$\bar{C}^{(3)}_{Hl}$	0.042 $\pm$ 0.0536819
$\bar{C}^{(3)}_{Hq}$	0.040 $\pm$ 0.0554775
$\bar{C}_{HWB}$	0.058 $\pm$ 0.0630901
$\bar{C}_{He}$	0.097 $\pm$ 0.0750314
$\bar{C}_{le}$	0.088 $\pm$ 0.0753358



Best fit (profiled)

$\bar{C}_{W}$	0.0084 $\pm$ 0.107913
$\bar{C}_{HD}$	-0.18 $\pm$ 0.13943
$\bar{C}_{HW}$	-0.11 $\pm$ 0.145152
$\bar{C}_{Hbox}$	-0.039 $\pm$ 0.165857
$\lvert\bar{C}_{eH}\rvert$	0.090 $\pm$ 0.171895
$\lvert\bar{C}_{dH}\rvert$	0.10 $\pm$ 0.202495
$\bar{C}_{G}$	0.44 $\pm$ 0.217008
$\lvert\bar{C}_{uG}\rvert$	-0.20 $\pm$ 0.664419
$\lvert\bar{C}_{uH}\rvert$	2.2 $\pm$ 5.05548
$\bar{C}_{ll}$	-8.8 $\pm$ 9.67349
$\bar{C}_{ee}$	9.2 $\pm$ 10.0279

Ongoing fit being developed by : I. Brivio, C. Hays, G. Zemaityte, MT

see also Ellis, Murphy, Sanz, You 1803.03252

23 parameters simultaneously constrained, ~ pole parameter set

The Neutrino Option

Q: "Are any of these damn Wilson coefficients in the SMEFT not 0?"

A: "Yes." — Motivation for this neutrino work.

arXiv:1703.04415 Gitte Elgaard-Clausen, MT **JHEP 1711 (2017) 088**

arXiv:1703.10924 I. Brivio, MT **Phys.Rev.Lett. 119 (2017) no.14, 141801**

arXiv:1809.03450 I. Brivio, MT

Are any Wilson coefficients not 0?

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

- C^5 seems to be non zero.

$$\mathcal{Q}_5^{\beta\,\kappa} = \left(\overline{\ell_L^{c,\beta}}\, \tilde{H}^\star\right)\left(\tilde{H}^\dagger\, \ell_L^\kappa\right).$$

- Working in dirac spinors causes a bit of pain as we define $\psi^c = (-i\gamma_2\,\gamma_0)\,\bar{\psi}^T$
- Introduce singlet right handed fields with majorana mass terms as

$$\overline{N^c_{R,p}}\, M_{pr}\, N_{R,r} + \overline{N_{R,p}}\, M^\star_{pr}\, N^c_{R,r}$$

- Shift phases to couplings defining a field that is not a chiral eigenstate that satisfies Majorana condition (Broncano et al. hep-ph/0406019)

$$N_p = N_p^c \qquad N_p = e^{i\theta_p/2}\, N_{R,p} + e^{-i\theta_p/2}\,(N_{R,p})^c.$$

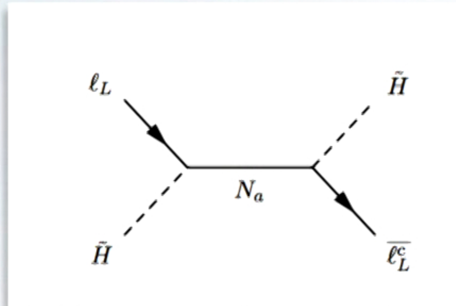
- Obtaining the Standard (type I) seesaw
(Minkowski 77, Gell Mann et al 79, Yanagida 79,Mohapatra at al 79)

$$2\,\mathcal{L}_{N_p} = \overline{N_p}(i\not{\partial} - m_p)N_p - \overline{\ell_L^\beta}\tilde{H}\omega_\beta^{p,\dagger} N_p - \overline{\ell_L^{c\beta}}\,\tilde{H}^*\,\omega_\beta^{p,T} N_p - \overline{N_p}\,\omega_\beta^{p,*}\,\tilde{H}^T\,\ell_L^{c\beta} - \overline{N_p}\,\omega_\beta^p\,\tilde{H}^\dagger\,\ell_L^\beta.$$

Seesaw model to SMEFT.

- Integrating out the seesaw at tree level. Matching now done out to L7

Gitte Elgaard-Clausen, MT



$$(\not{s} + m_p)\frac{-1}{m_p^2}\left(\frac{1}{1 - s^2/m_p^2}\right) = -\frac{1}{m_p} - \frac{\not{s}}{m_p^2} - \frac{s^2}{m_p^3} + \cdots$$

Expand the propagator in the small momentum transfer - MATCH!

- Extremely well known result

$$\mathcal{L}^{(5)} = \frac{c_{\beta\,\kappa}}{2}\, Q_5^{\beta\,\kappa} + h.c. \qquad c_{\beta\,\kappa} = (\omega_\beta^p)^T\, \omega_\kappa^p / m_p$$

p summed over

Here the ω_β^p are complex vectors in flavour space.

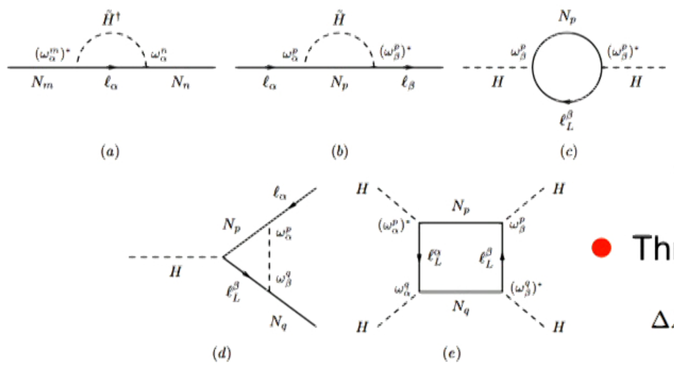
To proceed with further matching we can perform an flavour space expansion

$x, y \in \mathbb{C}^3$.

$$x \cdot y = x_i^\star\, y^i, \quad \|x\| = \sqrt{x \cdot x} \quad x \times y = ((x \times y)_{\mathfrak{R}})^\star$$

Seesaw to SMEFT one loop

- Necessarily one loop results coming with tree level matchings:



Wavefunction

$$V(H^\dagger H) = -\frac{m_0^2\, R_H + \Delta m^2}{2}(H^\dagger H) + (\lambda_0\, R_H^2 + \Delta\lambda)(H^\dagger H)^2 + \cdots .$$

- Threshold matchings:

$$\Delta\lambda = -\frac{5}{32\pi^2}\left[|\omega_1|^4 + |\omega_2|^4 + |\omega_1\omega_2^*|^2\left(1 + \frac{2\,M_1}{M_1 - M_2}\log\frac{M_2^2}{M_1^2}\right)\right],$$
$$+\frac{5}{16\pi^2}\left[\mathrm{Re}(\omega_1\omega_2)^2\frac{M_1\,M_2}{M_1^2 - M_2^2}\log\frac{M_1^2}{M_2^2}\right],$$
$$\Delta m^2 = \frac{1}{8\pi^2}\left[M_1^2|\omega_1|^2 + M_2^2|\omega_2|^2\right].$$

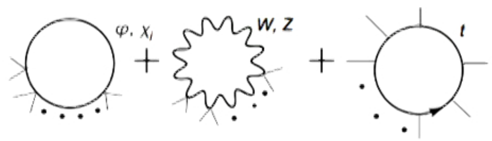
here choose $\mu = M e^{-3/4}$

to be consistent with CW threshold correction
J. A. Casas et al. Phys. Rev. D 62, 053005 (2000), others..

THE SIGN WORKS OUT due to FERMI statistics

- If you assume a seesaw model for neutrino mass generation - this is a “known unknown”.

This threshold matching can be done to CW



- Coleman-Weinberg potential:

$$\Delta V_{CW} = -\frac{1}{32\pi^2}\left[(m_\nu^i(H^\dagger H))^4 \log \frac{m_{\nu_i}^2(H^\dagger H)}{\mu^2}\right]$$

$$m_\nu^i(H^\dagger H) = \frac{1}{2}(M \mp \sqrt{M^2 + 2\,|\omega_p|^2(H^\dagger H)})$$

$$\mu = M e^{-3/4}$$

- If $m_p \gg v_0, \Lambda_{QCD}$ such a threshold matching can dominate the potential and give low scale pheno that is the SM. IR scales are
  - v_0 — Can be small. Doesn't have to be 0.
  - Λ_{QCD} — Known to be smaller than induced vev.
  - μ_{CW} — Exponentially separated due to asy nature of pert theory.
- Such threshold corrections are a direct representation of the Hierarchy problem F. Vissani, Phys. Rev. D 57, 7027 (1998)
- Can one go the full way of dominantly generating the EW scale in this manner? ~~v_0~~ ? arXiv:1703.10924 Neutrino Option Ilaria Brivio, MT

Strangeness of the Higgs potential

- Reminder: Why is the Higgs mechanism and classical potential curious?

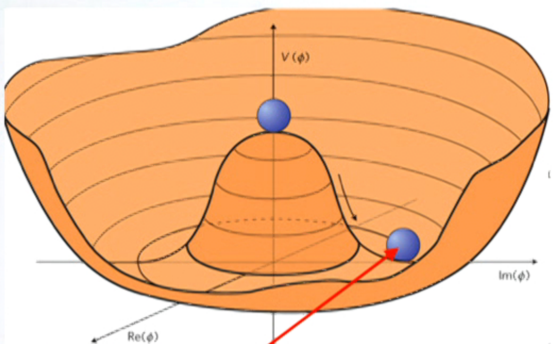
$$S_H = \int d^4x \left(|D_\mu H|^2 - \lambda \left(H^\dagger H - \frac{1}{2} v^2 \right)^2 \right),$$

Partial Higgs action

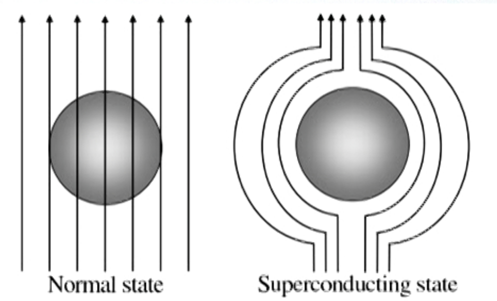
$$LG(s) = \int_{\Re^3} dx^3 \left[\frac{1}{2} |(d - 2\,i\,e\,A)s|^2 + \frac{\gamma}{2} \left(|s|^2 - a^2 \right) \right],$$

Landau-Ginzberg actional, parameterization of Superconductivity

E. Witten, From superconductors and four-manifolds to weak interactions,



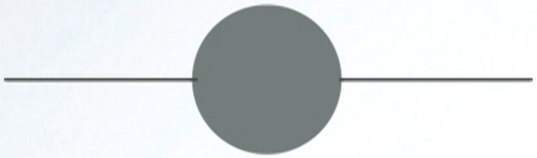
$m_{W/Z} = 0$ field config. energetically excluded (i.e. spon. sym breaking)

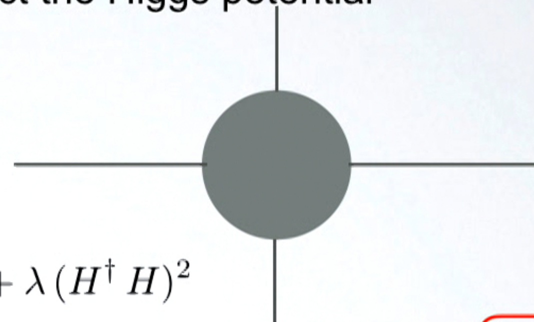


Magnetic field energetically excluded from interior of SC

Challenge of constructing potential

- It would make sense for the Higgs mechanism to just parameterize symmetry breaking. To do better we should construct the Higgs potential





$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- Muon decay: $v = 246\,\mathrm{GeV}$ Higgs mass : $m_h = 125\,\mathrm{GeV}$ → $\lambda = 0.13$

The problem.

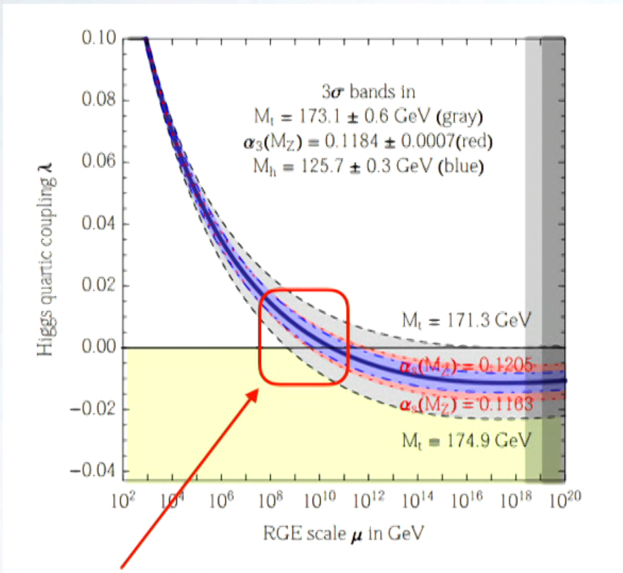
- Composite models (nobly) try to construct the Higgs potential:

$$V(H) \simeq \frac{g_{SM}^2\,\Lambda^2}{16\,\pi^2}\left(-2\,a H^\dagger H + 2b\frac{(H^\dagger H)^2}{f^2}\right)$$ see 1401.2457 Bellazzini et al

- Can get the quartic to work: $\sim 0.1\left(\frac{g_{SM}}{N_c\,y_t}\right)^2\left(\frac{\Lambda}{2\,f}\right)^2$ for $\Lambda/f \ll 4\,\pi$ weak coupling implied, lighter new states

We know more about the potential now

- Due to the improved knowledge of the top and Higgs mass:



An interesting mass scale is 10-100 PeV (or $10^7 - 10^8$ GeV)

1205.6497 Degrassi et al, 1112.3022 Elias-Miro et al..

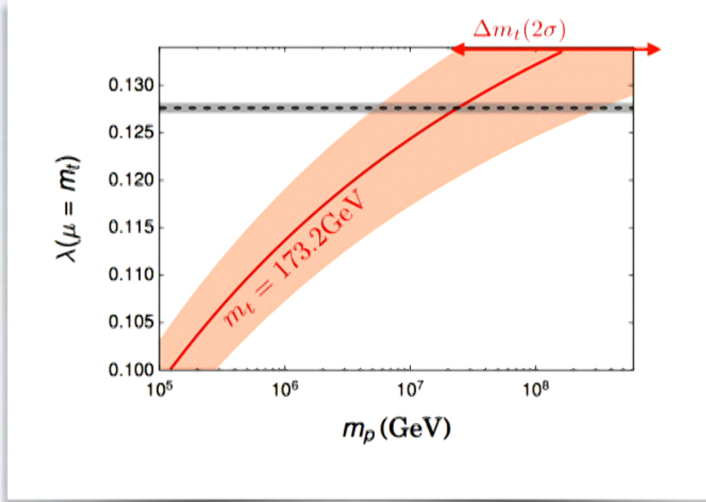
- What does this mean? (if anything)
- For fate of the universe considerations see 1205.6497 Degrassi et al.
  1505.04825 Espinosa et al.
- This might be a different message.
- Build the Higgs potential in the UV, as there $\lambda \sim 0$

Unexplored compared to the fate of the universe issues.

Can the Neutrino Option work?

- Use the RGE (1205.6497 Degrassi et al, 1112.3022 Elias-Miro et al..) to run down the threshold matching corrections

arXiv:1703.10924 Neutrino Option Ilaria Brivio, MT



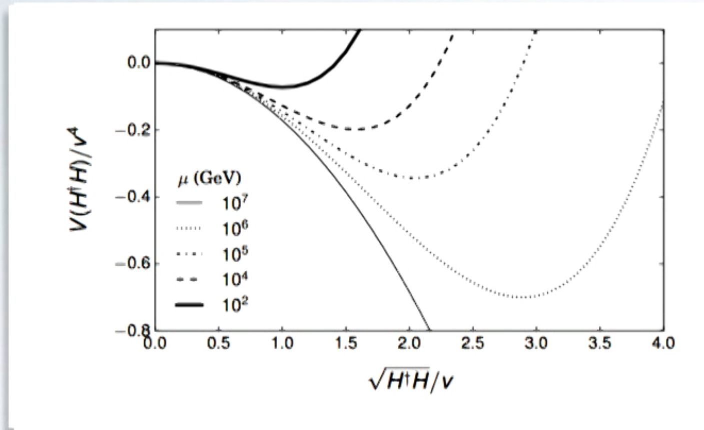
- Can get the troublesome $\lambda \sim 0.13$
- This essentially fixes the mass scale and couplings (large uncertainties)

$$m_p \sim 10^7 \text{GeV}$$

$$|\omega| \sim 10^{-5}$$

- Expand around the classically scaleless limit of the SM. Punch the potential with threshold matching you kick off low scale EW sym. breaking?

Higgs potential. Check. Neutrino mass scale. Check.

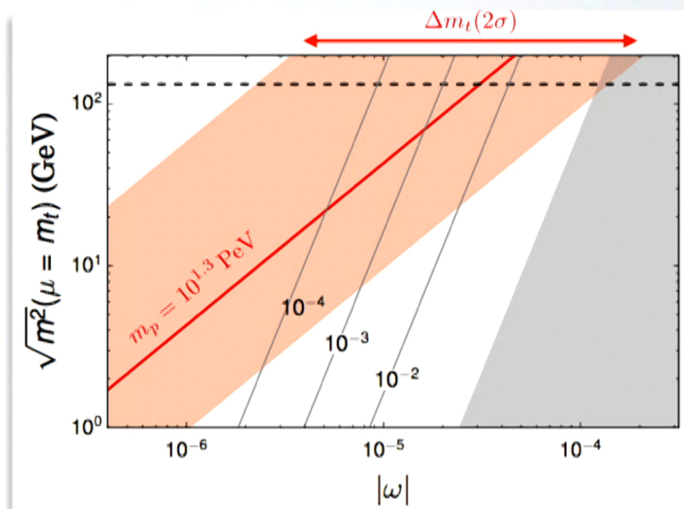


- The EW potential does get constructed correctly running down in a non-trivial manner

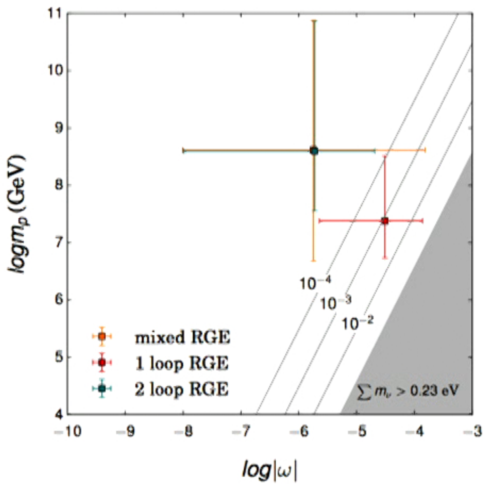
- In a non-trivial manner - and the right neutrino mass scale (diff) can result.

$\Delta m_\nu (\mathrm{eV})$

$$\Delta m^2_{21}/10^{-5}\mathrm{eV}^2 = 6.93 - 7.97,$$
$$\Delta m^2/10^{-3}\mathrm{eV}^2 = 2.37 - 2.63\,(2.33 - 2.60)$$



Neutrino option: the bad



"unburied body" plot

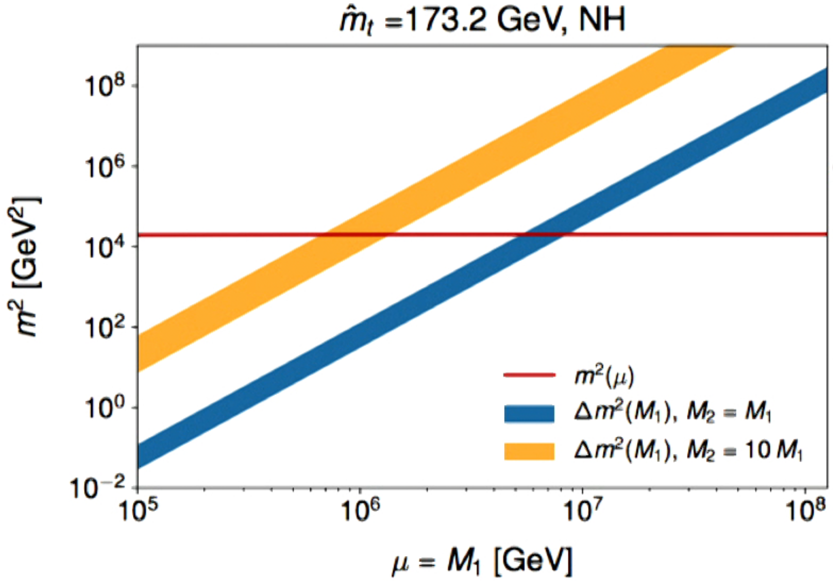
- Very significant numerical uncertainties
  -top quark mass driven
- This is NOT a total solution to the Hierarchy problem. As there is no symmetry protection mechanism against other threshold corrections.
- No non-resonant leptogenesis in this parameter space 1404.6260 Davoudias, Lewis

  Resonant leptogenesis can work here (S. Petcov - private communication)

- No dynamical origin of the Majorana scale supplied. So the IR limit taken is not clearly self consistent.

Improving numerical stability

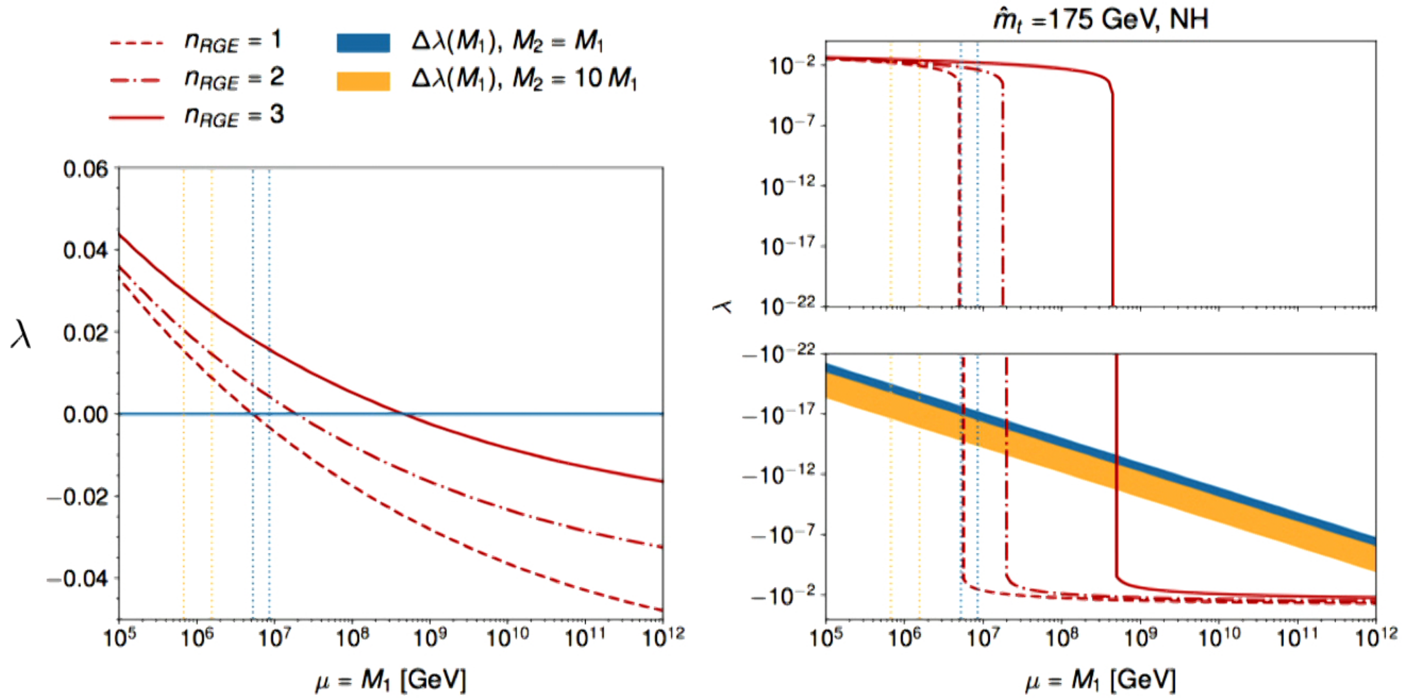
- Severe upgrade in rigor of one loop calc and one loop running of C^5
  1809.03450 Brivio, Trott
- Consistency test reformulated to avoid asymptotic numerical sensitivity to λ



- Scan regions defined by first fitting Neutrino global data Esteban et al. 1611.01514

Minimal case with two heavy neutrino's.

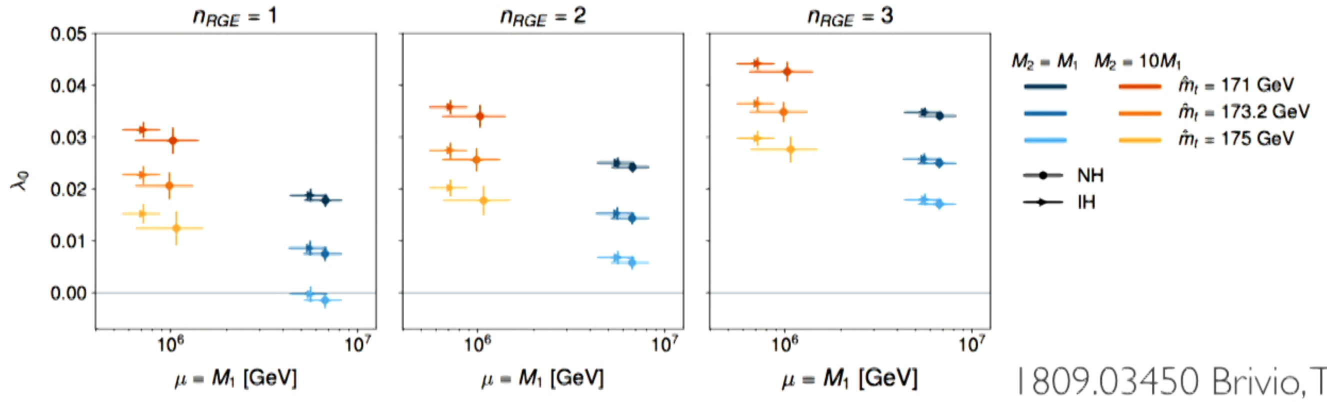
Improving numerical stability



1809.03450 Brivio, Trott

- Beyond one loop need a bare λ OR other threshold corrections

Required bare lambda



1809.03450 Brivio, Trott

- Beyond one loop need a bare λ OR other threshold corrections
- An interpretation:

> ***A consistent treatment of the seesaw model to one loop in SMEFT points to a possible origin for the SM Higgs potential and the EW scale.***

- What "breaks" EW symmetry in the Neutrino Option?

  Fermi statistics + Majorana scale in the UV + SM state spectrum for RGE.

Conclusions/summary

- SMEFT is a theory defined by field redefinitions leading to local operators.
- *Combined global studies are key* to interpretation
- Severe care required in formulating the SMEFT (TH job) and in combining the data (EXP job)
- Reporting SMEFT optimized measurements only starting. Expect legacy LHC data to be in this form.
- Seesaw model supplies an option for low energy pheno of the SM With the Higgs potential having an interesting UV boundary condition

$$m_\nu \sim \frac{\omega^2\,\bar{v}_T^2}{M}, \qquad m_h \sim \frac{\omega M}{4\pi}, \qquad \bar{v}_T \sim \frac{\omega M}{4\,\sqrt{2}\,\pi\,\sqrt{\lambda}}, \qquad m_p \sim 10^7\,\mathrm{GeV} \qquad |\omega| \sim 10^{-5}$$