Neutrino’s in SMEFT and the Neutrino Option

#SMEFT

M. Trott, NuTheories workshop 2018

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

The Standard Model EFT

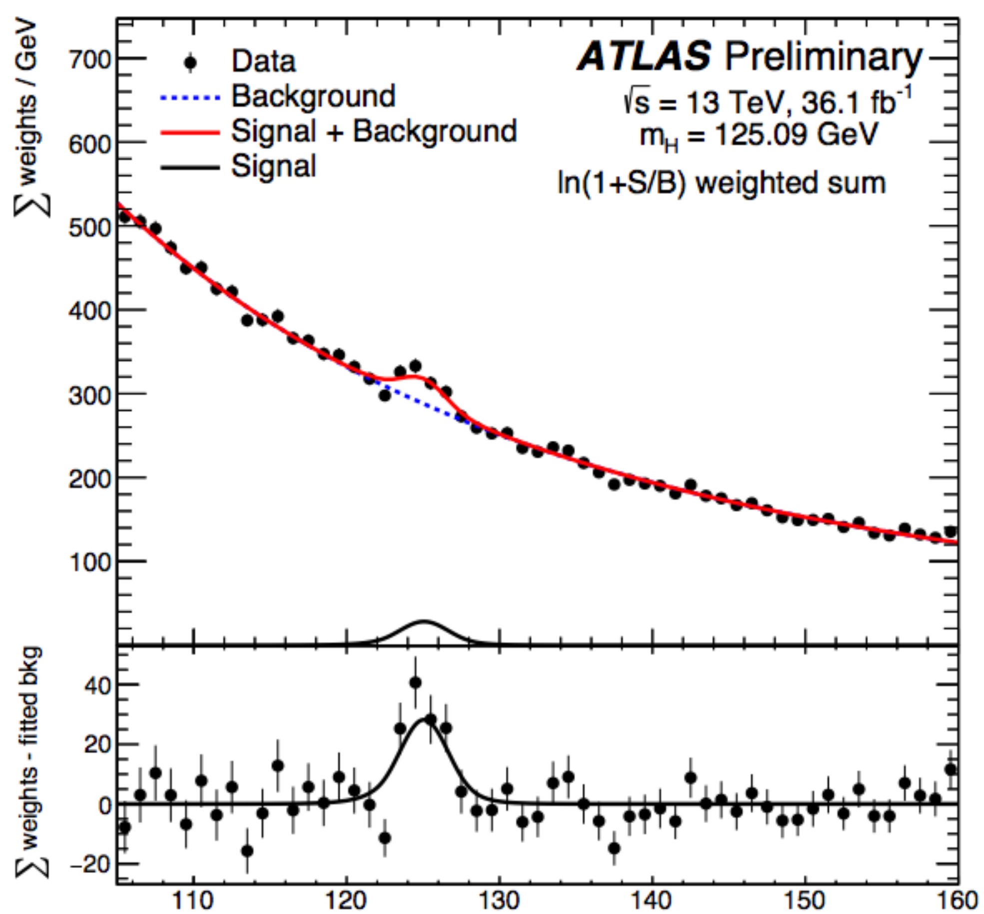
More info: The Standard Model as an Effective Field Theory review
Ilaria Brivio, MT https://arxiv.org/pdf/1706.08945.pdf

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

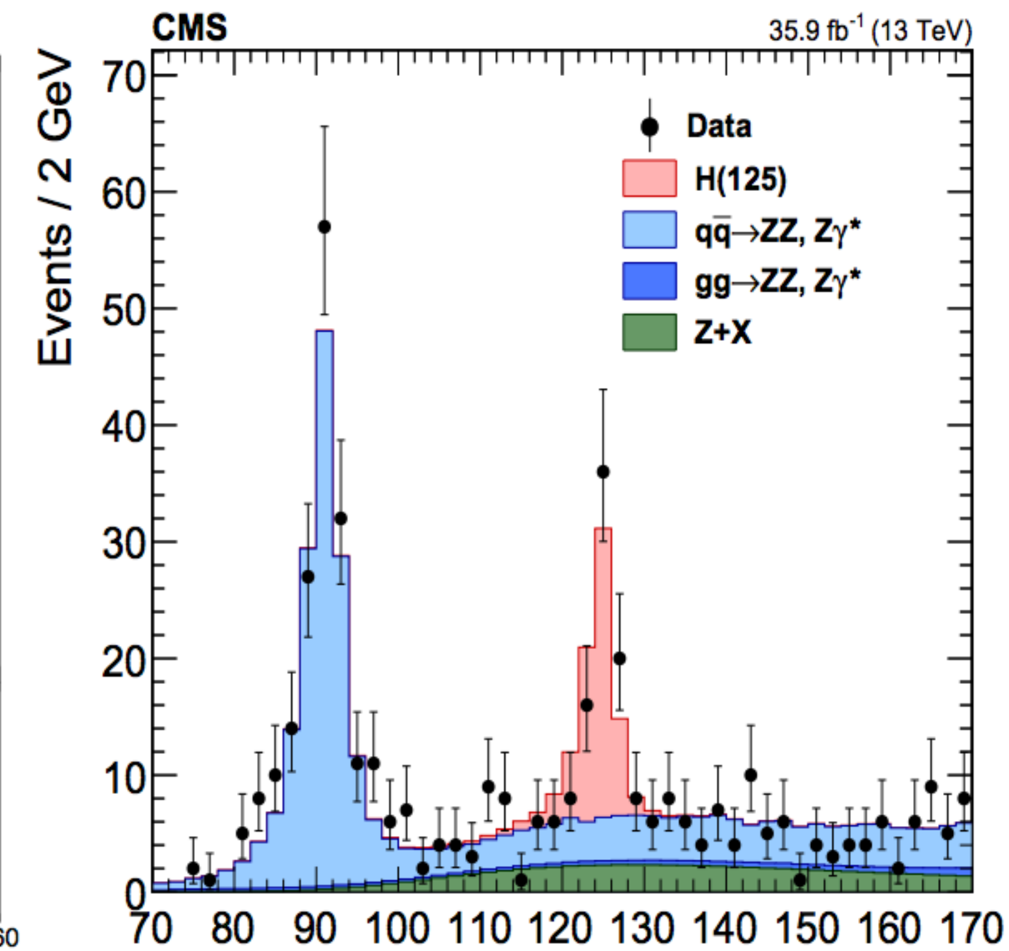
SMEFTsim UFO files http://feynrules.irmp.ucl.ac.be/wiki/SMEFT

The big picture: what was discovered at LHC

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



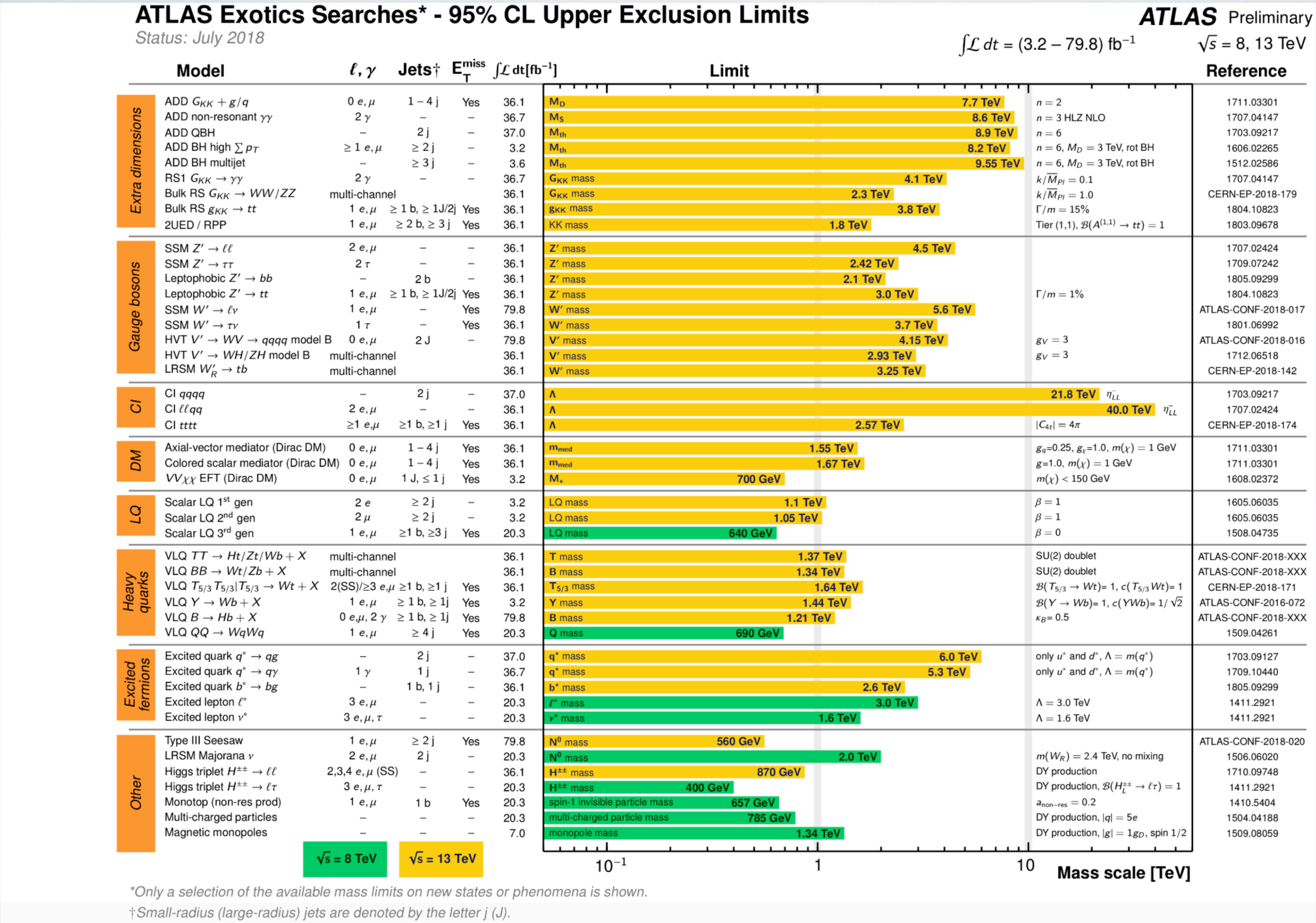
ATLAS-CONF-2017-045 (2017)



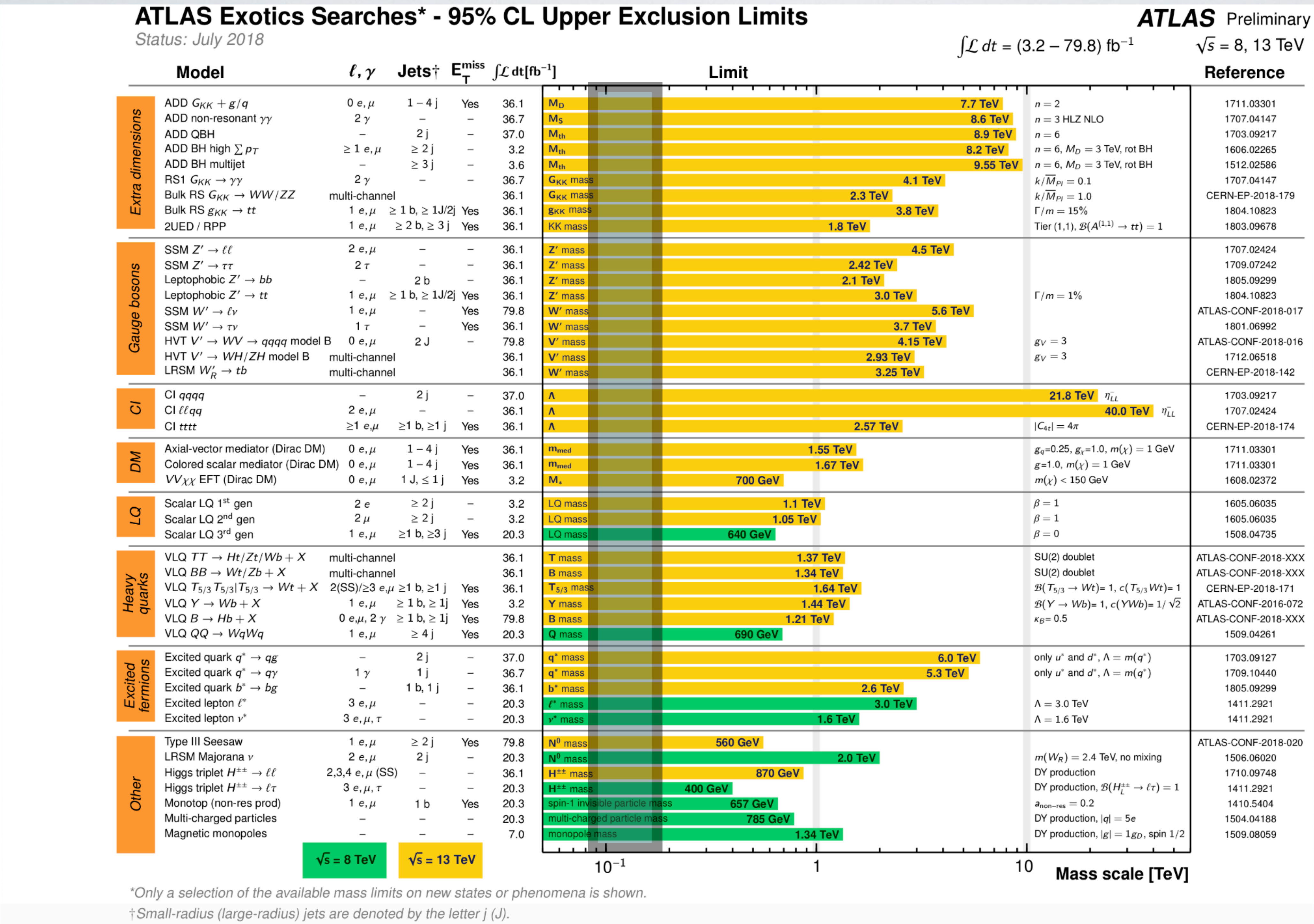
CMS-PAS-HIG-16-041 (2017)

- And what is not discovered as yet…

RunII and beyond: Resonance limits to local operators

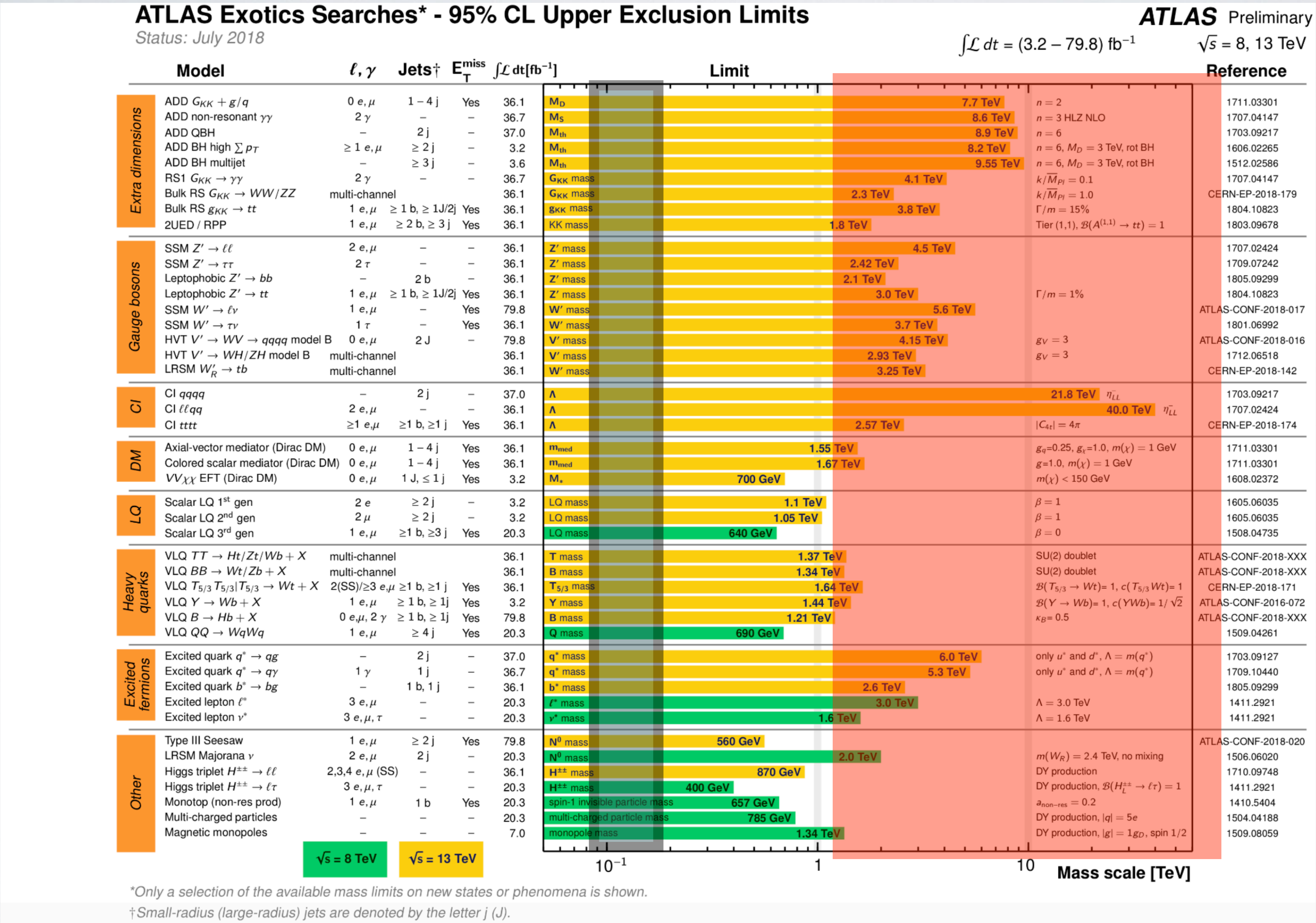


RunII and beyond: Resonance limits to local operators



Masses of EW scale ($\sim g\, v$) states m_W, m_Z, m_t, m_h

RunII and beyond: Resonance limits to local operators



Now that these bounds have been pushed away from v

USE that

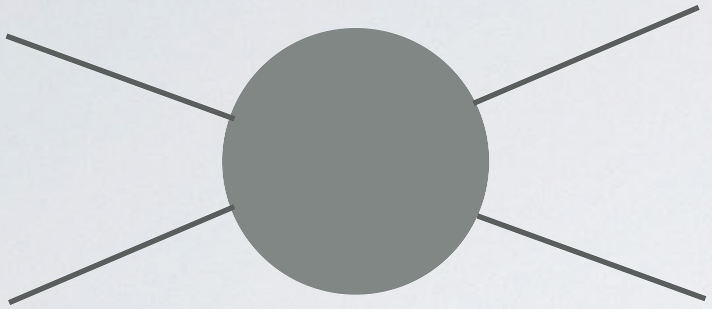
$$v/M < 1$$

to simplify/for more powerful conclusions:

- bound many models at once
- bound multiple resonances at same time

Deviations then look like local contact operator effects in EFT

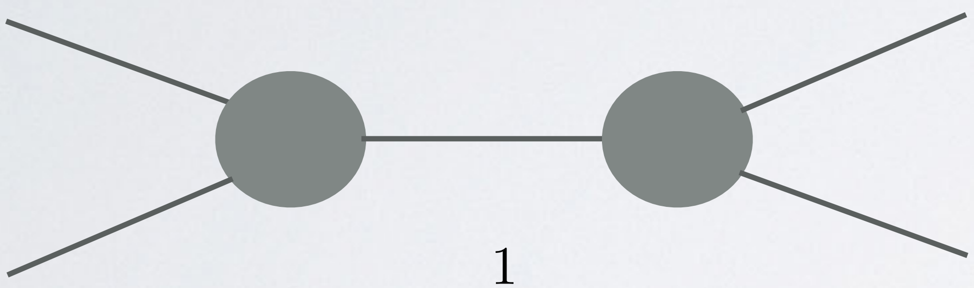
When you do measurements below a particle threshold



- 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

Basics of the SMEFT formulation:

IR operator form

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

UV dependent Wilson coefficient and suppression scale

Using the SMEFT

Is the SMEFT too complex to use?

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

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

(blue) 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

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

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

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

Over complete set of ops depending on B^μ

1706.08945 I. Brivio, MT

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

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

SMEFT requires a GLOBAL approach

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

- CHOOSE $b_2 = \mathcal{C}_B$ THEN

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

Non-redundant set of ops depending on B^μ

1706.08945 I. Brivio, MT

- BUT terms that remain SHIFTED $\mathcal{L}_B - g_1\, b_2 \Delta B$,

$$\Delta B = \mathsf{y}_l Q^{(1)}_{\underset{tt}{Hl}} + \mathsf{y}_e Q_{\underset{tt}{He}} + \mathsf{y}_q Q^{(1)}_{\underset{tt}{Hq}} + \mathsf{y}_u Q_{\underset{tt}{Hu}} + \mathsf{y}_d Q_{\underset{tt}{Hd}}, \quad + \mathsf{y}_H (Q_{H\Box} + 4\, Q_{HD}) + \frac{1}{g_1} B^{\mu\nu} \partial_\mu (H^\dagger i \overleftrightarrow{D}_\nu H).$$

EWPD, diboson, Higgs data all modified globally

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

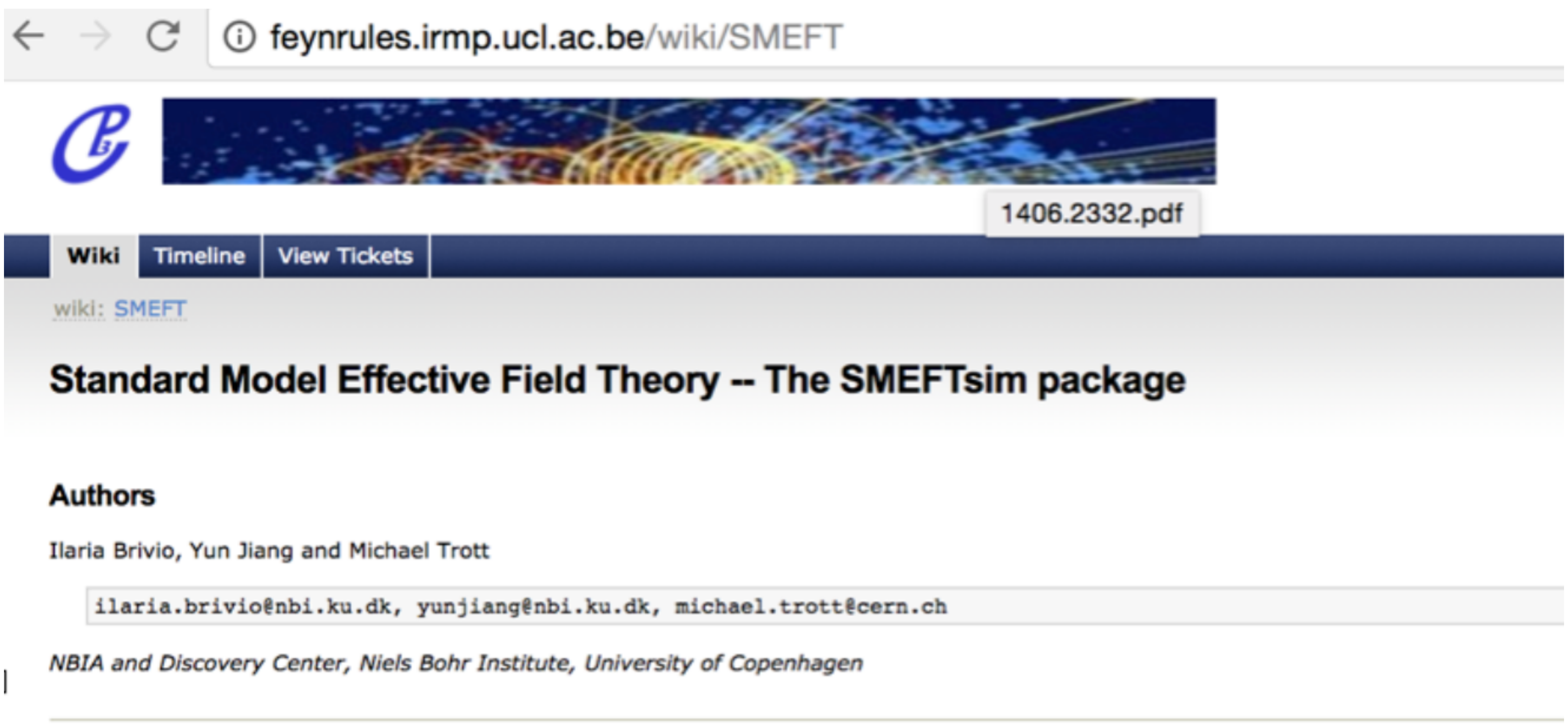
- We are looking for few % to 10’s% effects in SMEFT.

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



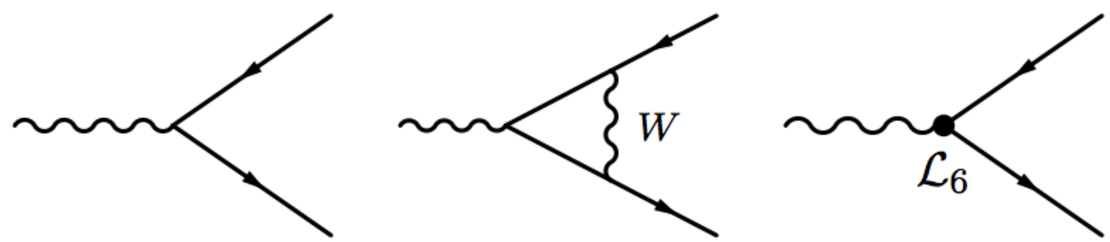
.. are there too many parameters?

- Number of parameters convolution of power counting

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

<u>+ numerical suppression due to interference with SM and resonance domination, or not</u>

- 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
$U(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

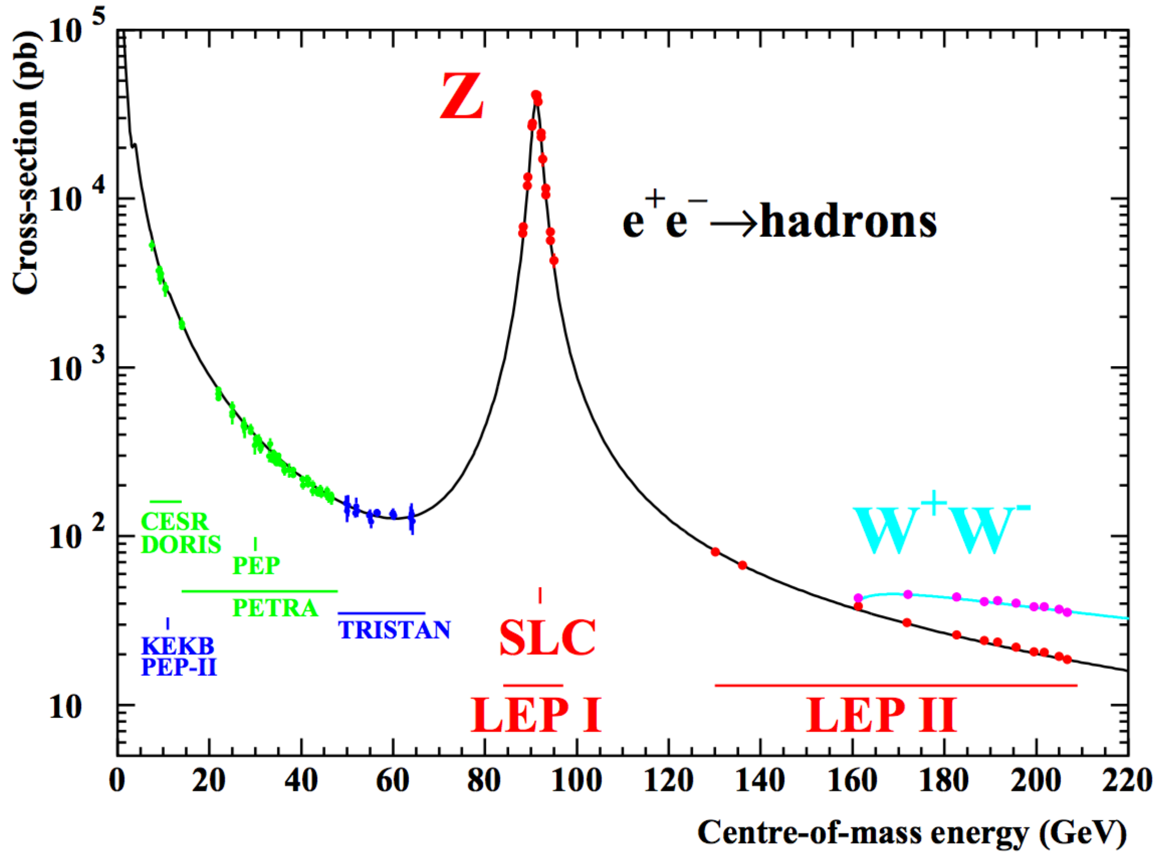
Brivio, Jiang, MT https://arxiv.org/abs/1709.06492

- 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

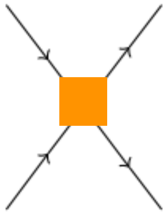
LEP EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

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

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



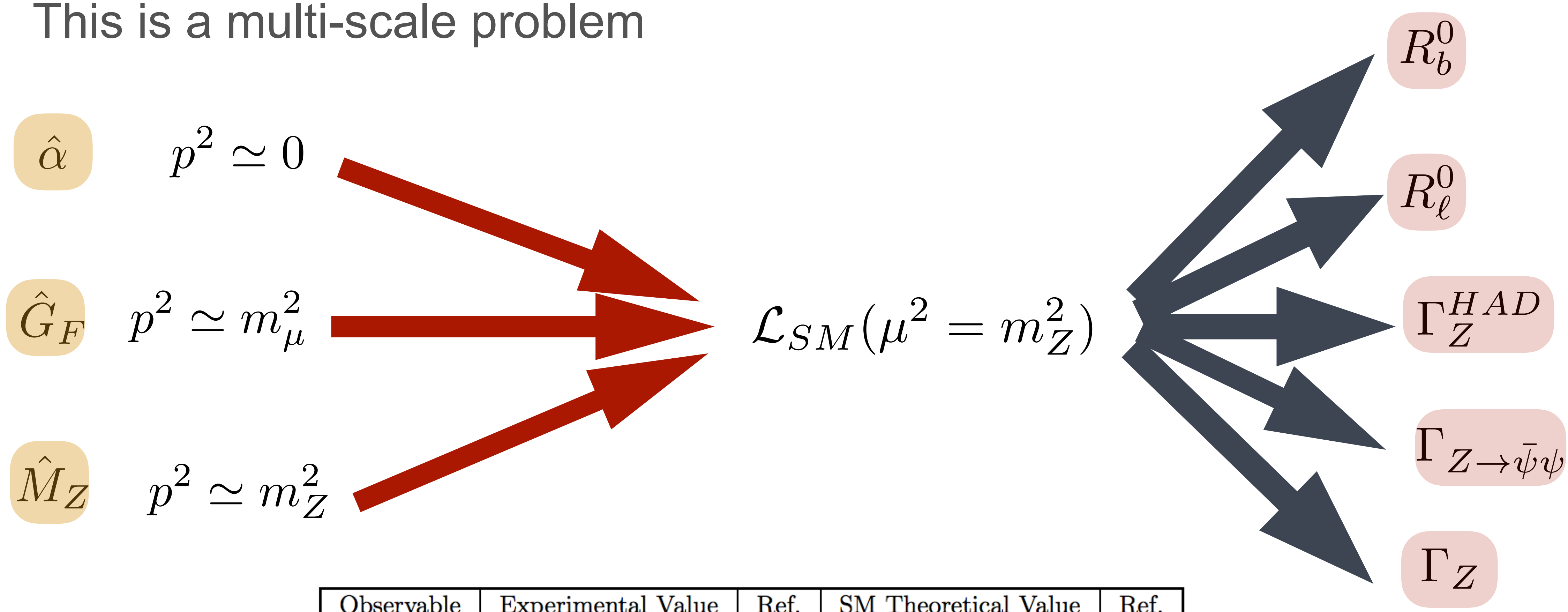
- many more ψ^4 ops suppressed by $\frac{m_z \, \Gamma_Z}{v^2}$

Details: arXiv:1502.02570
Berthier, MT

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

SM, usual approach to EWPD

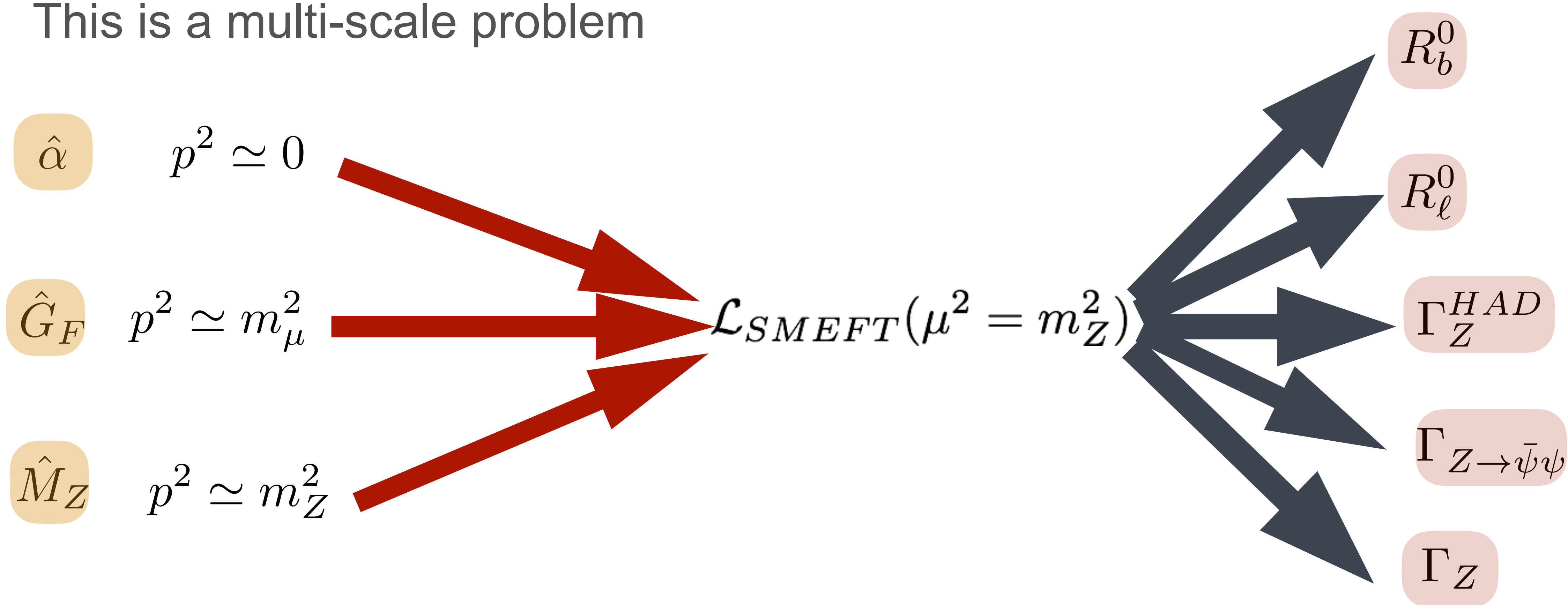
- This is a multi-scale problem



Compare to LEP data:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[19]	-	-
M_W[GeV]	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
Γ_Z[GeV]	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
R_ℓ^0	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
R_c^0	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
R_b^0	0.21629 ± 0.00066	[19]	0.21580 ± 0.00015	[48]
σ_h^0 [nb]	41.540 ± 0.037	[19]	41.488 ± 0.006	[48]
A_{FB}^ℓ	0.0171 ± 0.0010	[19]	0.01616 ± 0.00008	[32]
A_{FB}^c	0.0707 ± 0.0035	[19]	0.0735 ± 0.0002	[32]
A_{FB}^b	0.0992 ± 0.0016	[19]	0.1029 ± 0.0003	[32]

- This is a multi-scale problem



- Lagrangian parameters inferred from inputs now corrected by local contact operators

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

$$\delta\kappa = \bar{\kappa} - \hat{\kappa}$$

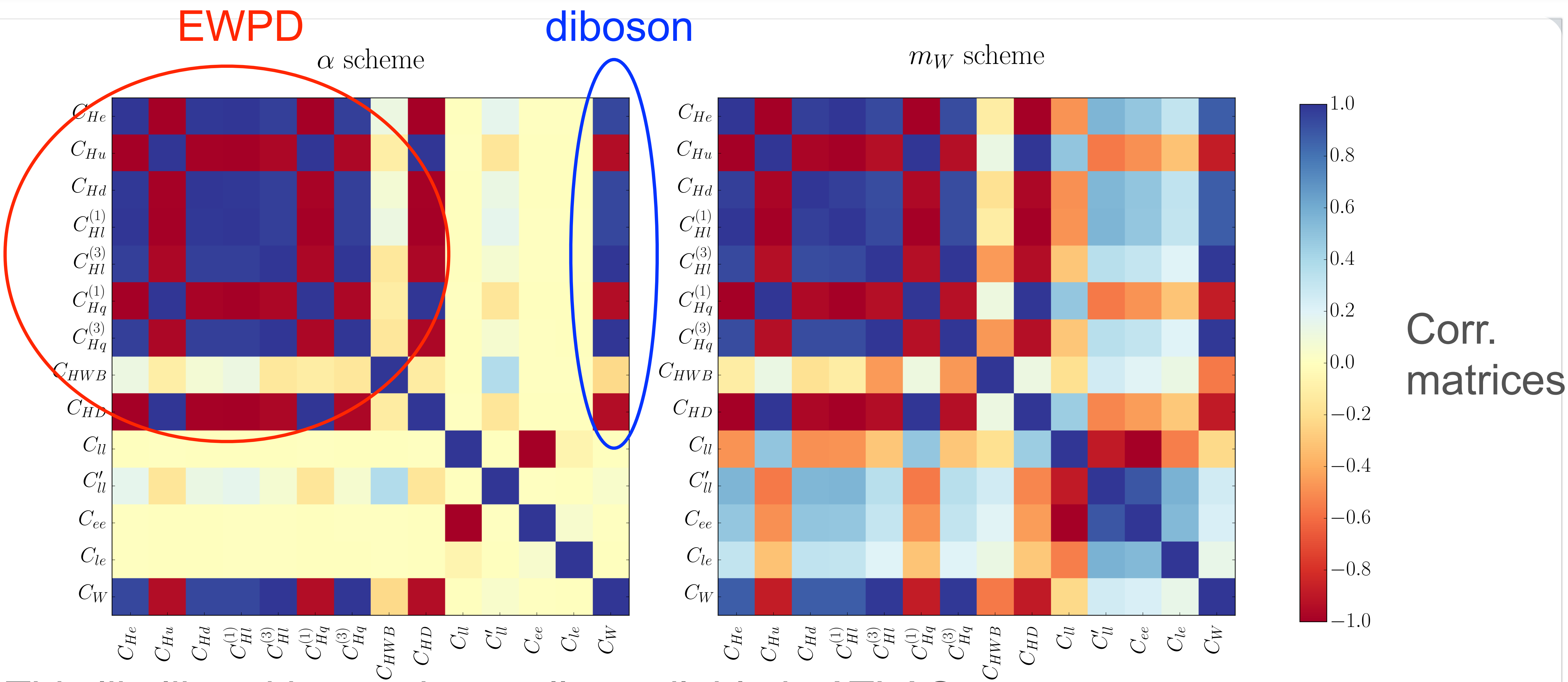
ex:

$$\delta g_1 = \bar{g}_1 - \hat{g}_1 = \frac{\hat{g}_1}{2c_{2\hat{\theta}}}\left[s_{\hat{\theta}}^2\left(\sqrt{2}\delta G_F + \frac{\delta m_Z^2}{\hat{m}_Z^2}\right) + c_{\hat{\theta}}^2\, s_{2\hat{\theta}} \bar{v}_T^2 C_{HWB}\right],$$

$$\delta s_\theta^2 = s_{\bar{\theta}}^2 - s_{\hat{\theta}}^2 = 2c_{\hat{\theta}}^2 s_{\hat{\theta}}^2\left(\frac{\delta g_1}{\hat{g}_1} - \frac{\delta g_2}{\hat{g}_2}\right) + \bar{v}_T^2 \frac{s_{2\hat{\theta}} c_{2\hat{\theta}}}{2} C_{HWB}.$$

The corrections depend on the scheme choice

Correlations are also key when combining



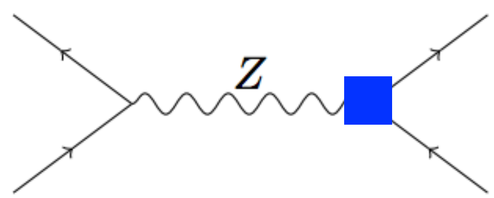
- This likelihood is now internally available in ATLAS
- EWPD Studies that id. correlations in SMEFT as a key issue

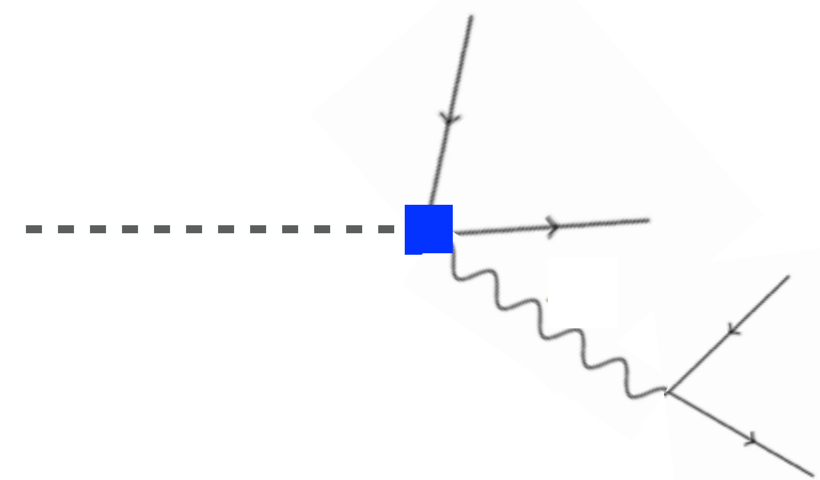
Han and Skiba http://arxiv.org/abs/hep-ph/0412166
Berthier, Bjorn, MT 1606.06693
Brivio, MT 1701.06424

Should Higgs data matter? - YES!

- Higgs data has new parameters but many are also in EWPD (with flat directions)

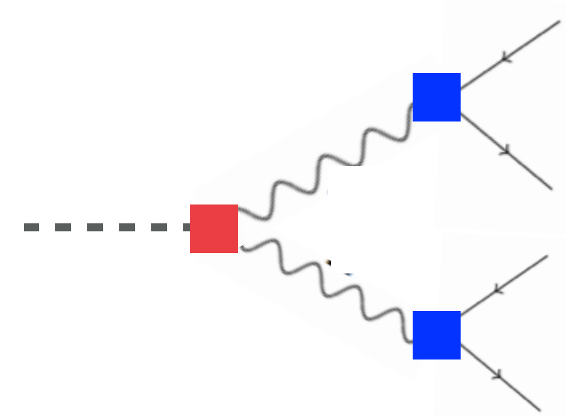
$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$





- Higgs data breaks degeneracies

$$\mathcal{L} = \frac{1}{4}(\bar{g}_2{}^2 + \bar{g}_1{}^2) v_T h(\mathcal{Z}_\mu)^2 \left[1 + c_{H,\text{kin}} + v_T^2 C_{HD}\right] + \frac{1}{2}\bar{g}_1\bar{g}_2 v_T^3 h(\mathcal{Z}_\mu)^2 C_{HWB}$$
$$+ v_T h(\mathcal{Z}_{\mu\nu})^2 \left(\frac{\bar{g}_2{}^2 C_{HW} + \bar{g}_1{}^2 C_{HB} + \bar{g}_1\bar{g}_2 C_{HWB}}{\bar{g}_2{}^2 + \bar{g}_1{}^2}\right)$$
$$c_{H,\text{kin}} \equiv \left(C_{H\Box} - \frac{1}{4}C_{HD}\right) v^2,$$

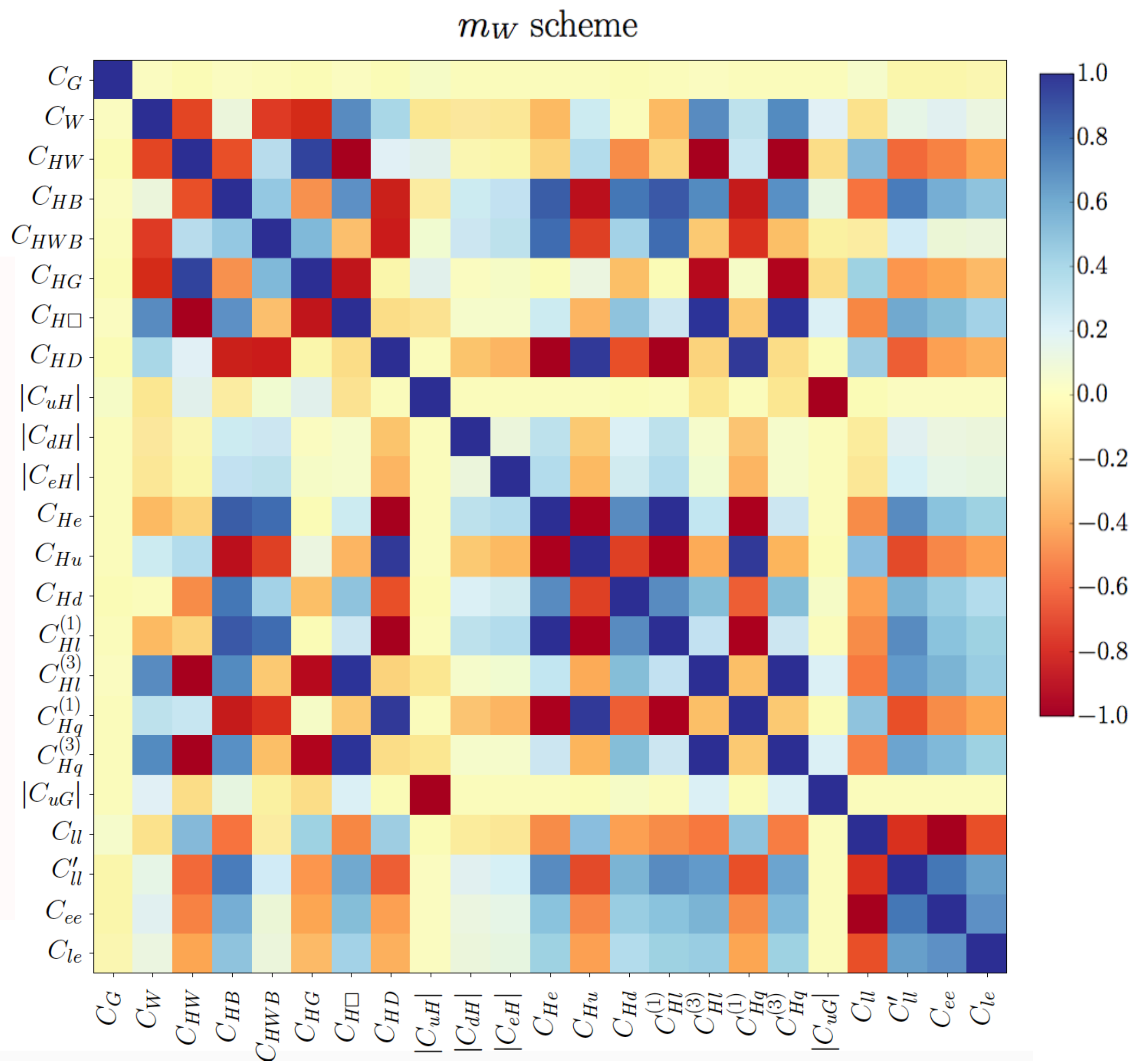


Global fit – correlations [preliminary]

Provided by I. Brivio

Best fit (profiled)

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



Best fit (profiled)

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

Neutrino's in SMEFT and 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

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

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

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

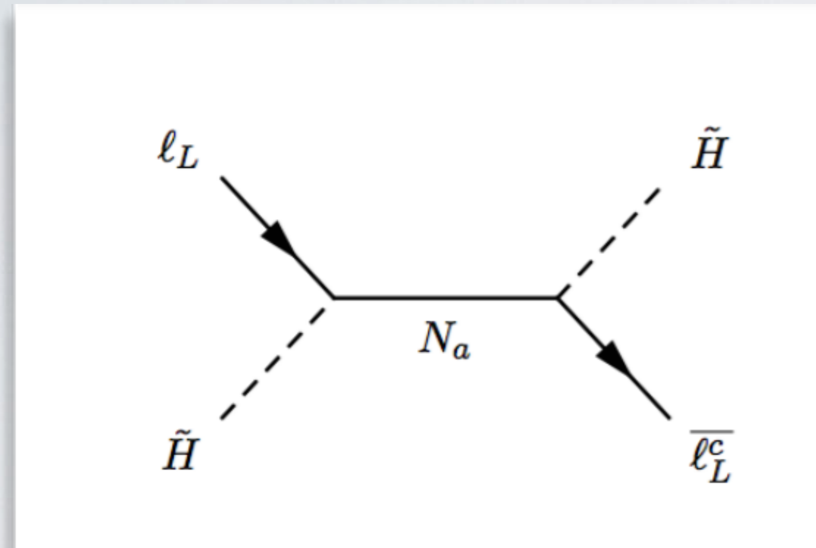
- Obtaining the Standard (type I) seesaw
(Minkowski 77, Gell Mann et al 79, Yanagida 79,Mohapatra at al 79)

$$2\,\mathcal{L}_{N_p} = \overline{N_p}(i\partial\!\!\!/ - m_p)N_p - \overline{\ell_L^\beta}\tilde{H}\omega_\beta^{p,\dagger}N_p - \overline{\ell_L^{c\beta}}\,\tilde{H}^*\,\omega_\beta^{p,T}\,N_p - \overline{N_p}\,\omega_\beta^{p,*}\,\tilde{H}^T\,\ell_L^{c\beta} - \overline{N_p}\,\omega_\beta^p\tilde{H}^\dagger\ell_L^\beta.$$

Seesaw model to SMEFT.

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

arXiv:1703.04415 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 (see back up)

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

$$x \cdot y = x_i^\star\, y^i, \qquad \|x\| = \sqrt{x \cdot x} \qquad x \times y = ((x \times y)_{\Re})^\star$$

L6 SMEFT matching

N_1

N_2

N_3

- At $\mathcal{L}_6$ the fun begins:

$$\mathcal{L}^{(6)} = \frac{(\omega_\beta^p)^\dagger\, \omega_\kappa^p}{2\, m_p^2} \left(\mathcal{Q}^{(1)}_{\substack{H\ell \\ \beta\kappa}} - \mathcal{Q}^{(3)}_{\substack{H\ell \\ \beta\kappa}} \right)$$

$$\mathcal{Q}^{(3)}_{\substack{H\ell \\ \beta\kappa}} = H^\dagger\, i \overleftrightarrow{D}^I_\mu H \ell_\beta \gamma^\mu \tau_I \ell_\kappa$$

$$\mathcal{Q}^{(1)}_{\substack{H\ell \\ \beta\kappa}} = H^\dagger\, i \overleftrightarrow{D}_\mu H \ell_\beta \gamma^\mu \ell_\kappa$$

Can compare to Broncano et al. hep-ph/0406019

- But the N are integrated out in sequence so you also get:

$$\begin{aligned}
\frac{1}{2}\, \mathcal{L}^{(6)}_{N_{2,3}} \supseteq\ & \frac{\mathrm{Re}\left[x_\beta^\dagger\, x^\star \cdot y^\dagger\right]}{4\, m_1^2} \left(\mathcal{Q}^\beta_{N_2} - \mathcal{Q}^{\star,\beta}_{N_2} \right) + \frac{i\,\mathrm{Im}\left[x_\beta^\dagger\, x^\star \cdot y^\dagger\right]}{4\, m_1^2} \left(\mathcal{Q}^\beta_{N_2} + \mathcal{Q}^{\star,\beta}_{N_2} \right) \\
& + \frac{\mathrm{Re}\left[x_\beta^\dagger\, x^\star \cdot z^\dagger\right]}{4\, m_1^2} \left(\mathcal{Q}^\beta_{N_3} - \mathcal{Q}^{\star,\beta}_{N_3} \right) + \frac{i\,\mathrm{Im}\left[x_\beta^\dagger\, x^\star \cdot z^\dagger\right]}{4\, m_1^2} \left(\mathcal{Q}^\beta_{N_3} + \mathcal{Q}^{\star,\beta}_{N_3} \right) \\
& + \frac{\mathrm{Re}\left[y_\beta^\dagger\, y^\star \cdot z^\dagger\right]}{4\, m_2^2} \left(\mathcal{Q}^\beta_{N_3} - \mathcal{Q}^{\star,\beta}_{N_3} \right) + \frac{i\,\mathrm{Im}\left[y_\beta^\dagger\, y^\star \cdot z^\dagger\right]}{4\, m_2^2} \left(\mathcal{Q}^\beta_{N_3} + \mathcal{Q}^{\star,\beta}_{N_3} \right)
\end{aligned}$$

$$\mathcal{Q}^\beta_{N_p} = (H^\dagger H)\, (\overline{\ell^\beta_L} \tilde{H})\, N_p$$

v

L6 SMEFT matching

N_1

N_2

N_3

- At $\mathcal{L}_6$ the fun begins:

$$\mathcal{L}^{(6)} = \frac{(\omega^p_\beta)^\dagger\, \omega^p_\kappa}{2\, m_p^2}\left(\mathcal{Q}^{(1)}_{\substack{H\ell\\ \beta\kappa}} - \mathcal{Q}^{(3)}_{\substack{H\ell\\ \beta\kappa}}\right)$$

$$\mathcal{Q}^{(3)}_{\substack{H\ell\\ \beta\kappa}} = H^\dagger\, i \overleftrightarrow{D}^I_\mu H \ell_\beta \gamma^\mu \tau_I \ell_\kappa$$

$$\mathcal{Q}^{(1)}_{\substack{H\ell\\ \beta\kappa}} = H^\dagger\, i \overleftrightarrow{D}_\mu H \ell_\beta \gamma^\mu \ell_\kappa$$

Can compare to Broncano et al. hep-ph/0406019 (SU(2) diff)

- As a Majorana scale in the EOM:

$$\not{\partial} N_p = -i\left(m_p\, N_p + w^{p,\star}_\beta\, \tilde{H}^T \ell^{c\beta}_L + w^p_\beta \tilde{H}^\dagger \ell^\beta_L\right)$$

which gives the extra matching contributions

$$\frac{1}{2}\, \mathcal{L}^{(6)}_{N_{2,3}} \supseteq \frac{(x_\beta)^T\, x^\star \cdot y^\dagger\, m_2}{4\, m_1^3}\left[\overline{\ell^c_{L\,\beta}}\, \tilde{H}^\star\, N_2\right](H^\dagger\, H) + \frac{(x_\beta)^T\, x^\star \cdot z^\dagger\, m_3}{4\, m_1^3}\left[\overline{\ell^c_{L\,\beta}}\, \tilde{H}^\star\, N_3\right](H^\dagger\, H),$$
$$+ \frac{(y_\beta)^T\, y^\star \cdot z^\dagger\, m_3}{4\, m_2^3}\left[\overline{\ell^c_{L\,\beta}}\, \tilde{H}^\star\, N_3\right](H^\dagger\, H) + h.c.$$

v

Keeping track of all the terms is critical as a set of cancelations occur.

L7 SMEFT matching

- Summary of dim 7 results:

$1: \psi^2 H^4 + \text{h.c.}$

$\mathcal{Q}_{\ell H}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \ell_L^m) H^j H^n (H^\dagger H)$

$2: \psi^2 H^2 D^2 + \text{h.c.}$

$\mathcal{Q}_{\ell HD}^{(1)}$	$\epsilon_{ij}\epsilon_{mn}\ell_L^i C (D^\mu \ell_L^j) H^m (D_\mu H^n)$
$\mathcal{Q}_{\ell HD}^{(2)}$	$\epsilon_{im}\epsilon_{jn}\ell_L^i C (D^\mu \ell_L^j) H^m (D_\mu H^n)$

$3: \psi^2 H^3 D + \text{h.c.}$

$\mathcal{Q}_{\ell HDe}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \gamma_\mu e_R) H^j H^m D^\mu H^n$

$4: \psi^2 H^2 X + \text{h.c.}$

$\mathcal{Q}_{\ell HB}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \sigma_{\mu\nu} \ell_L^m) H^j H^n B^{\mu\nu}$
$\mathcal{Q}_{\ell HW}$	$\epsilon_{ij}(\tau^I \epsilon)_{mn}(\ell_L^i C \sigma_{\mu\nu} \ell_L^m) H^j H^n W^{I\mu\nu}$

$5: \psi^4 D + \text{h.c.}$

$\mathcal{Q}_{\ell\ell\bar{d}uD}^{(1)}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C D^\mu \ell_L^j)$
$\mathcal{Q}_{\ell\ell\bar{d}uD}^{(2)}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C \sigma^{\mu\nu} D_\nu \ell_L^j)$
$\mathcal{Q}_{\bar{\ell}QddD}^{(1)}$	$(Q_L C \gamma_\mu d_R)(\overline{\ell_L} D^\mu d_R)$
$\mathcal{Q}_{\bar{\ell}QddD}^{(2)}$	$(\overline{\ell_L}\gamma_\mu q_L)(d_R C D^\mu d_R)$
$\mathcal{Q}_{ddd\bar{e}D}$	$(\overline{e_R}\gamma_\mu d_R)(d_R C D^\mu d_R)$

$6: \psi^4 H + \text{h.c.}$

$\mathcal{Q}_{\ell\ell\ell\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_R}\ell_L^i)(\ell_L^j C \ell_L^m) H^n$
$\mathcal{Q}_{\ell\ell Q\bar{d}H}^{(1)}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_R}\ell_L^i)(q_L^j C \ell_L^m) H^n$
$\mathcal{Q}_{\ell\ell Q\bar{d}H}^{(2)}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_R}\ell_L^i)(q_L^j C \ell_L^m) H^n$
$\mathcal{Q}_{\ell\ell\bar{Q}uH}$	$\epsilon_{ij}(\overline{q_{L_m}} u_R)(\ell_L^m C \ell_L^i) H^j$
$\mathcal{Q}_{\bar{\ell}QQdH}$	$\epsilon_{ij}(\overline{\ell_{L_m}} d_R)(q_L^m C q_L^i)\tilde{H}^j$
$\mathcal{Q}_{\bar{\ell}dddH}$	$(d_R C d_R)(\overline{\ell_L} d_R) H$
$\mathcal{Q}_{\bar{\ell}uddH}$	$(\overline{\ell_L} d_R)(u_R C d_R)\tilde{H}$
$\mathcal{Q}_{\ell eu\bar{d}H}$	$\epsilon_{ij}(\ell_L^i C \gamma_\mu e_R)(\overline{d_R}\gamma^\mu u_R) H^j$
$\mathcal{Q}_{\bar{e}QddH}$	$\epsilon_{ij}(\overline{e_R} Q_L^i)(d_R C d_R)\tilde{H}^j$

Tree level matching contributions

Basis of Lehman 1410.4193

L7 SMEFT matching

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$1: \psi^2 H^4 + \text{h.c.}$

$Q_{\ell H}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \ell_L^m) H^j H^n (H^\dagger H)$

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$5: \psi^4 D + \text{h.c.}$

$Q^{(1)}_{\ell\ell\bar d uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C D^\mu \ell_L^j)$
$Q^{(2)}_{\ell\ell\bar d uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C\sigma^{\mu\nu} D_\nu \ell_L^j)$
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$Q^{(2)}_{\ell\ell Q\bar d H}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_R}\ell_L^i)(q_L^j C\ell_L^m)H^n$
$Q_{\ell\ell\bar Q uH}$	$\epsilon_{ij}(\overline{q_{L_m}}u_R)(\ell_L^m C\ell_L^i)H^j$
$Q_{\bar\ell QQdH}$	$\epsilon_{ij}(\overline{\ell_{L_m}}d_R)(q_L^m C q_L^i)\tilde H^j$
$Q_{\bar\ell dddH}$	$(d_R C d_R)(\overline{\ell_L}d_R)H$
$Q_{\bar\ell uddH}$	$(\overline{\ell_L}d_R)(u_R C d_R)\tilde H$
$Q_{\ell eu\bar d H}$	$\epsilon_{ij}(\ell_L^i C\gamma_\mu e_R)(\overline{d_R}\gamma^\mu u_R)H^j$
$Q_{\bar e QddH}$	$\epsilon_{ij}(\overline{e_R}Q_L^i)(d_R C d_R)\tilde H^j$

Tree level matching contributions

Tree level matching onto ops with field strengths, from a weakly coupled renormalizable model.

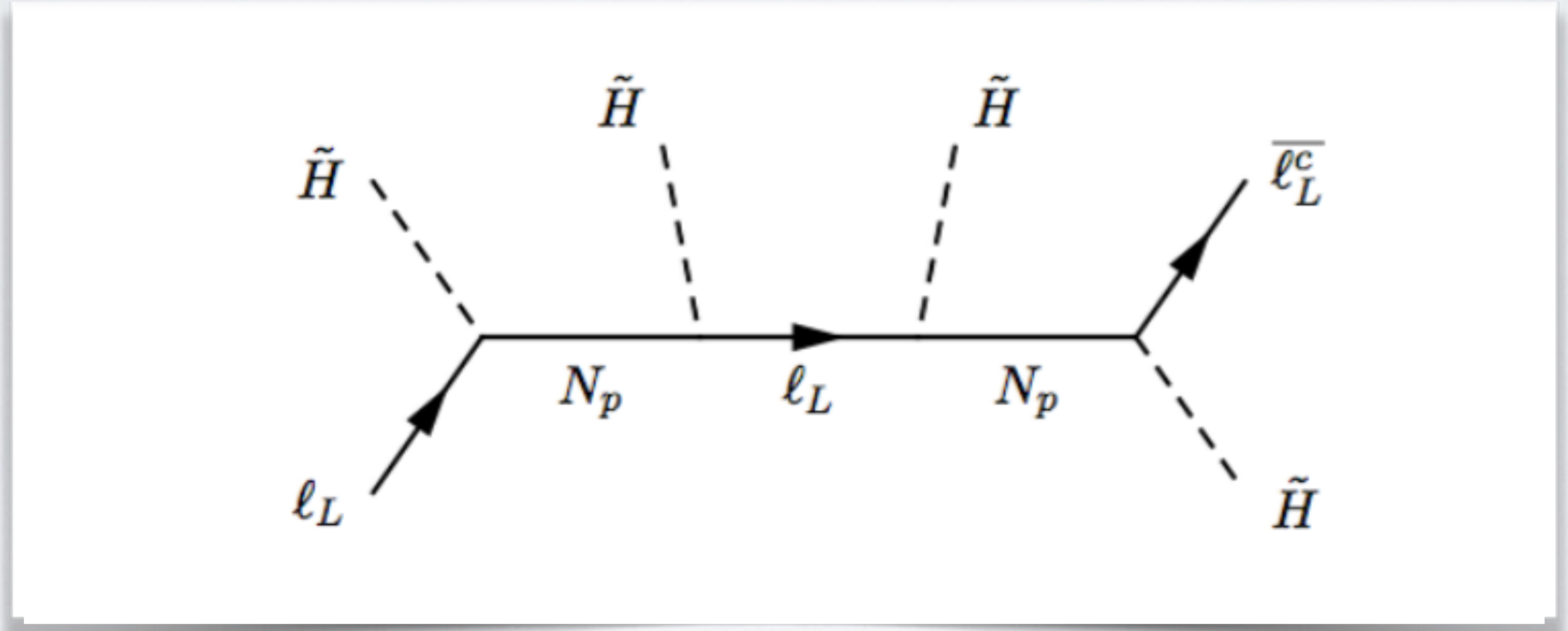
Basis of Lehman 1410.4193

d=7 matching

- Many contributions to $Q_{\ell H}$ cancel out at tree level in a single matching in EW vacuum

$$-\frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\ell_{L\,\kappa}\right)\, H^2 + 2\,\lambda\, \tilde{C}^7_{\beta\,\kappa} Q_{\ell H} + \frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\sigma^I\,\ell_{L\,\kappa}\right)\, H\sigma^I H + h.c$$

When you take the Higgs vev you find this vanishes. As do other matching combinations.



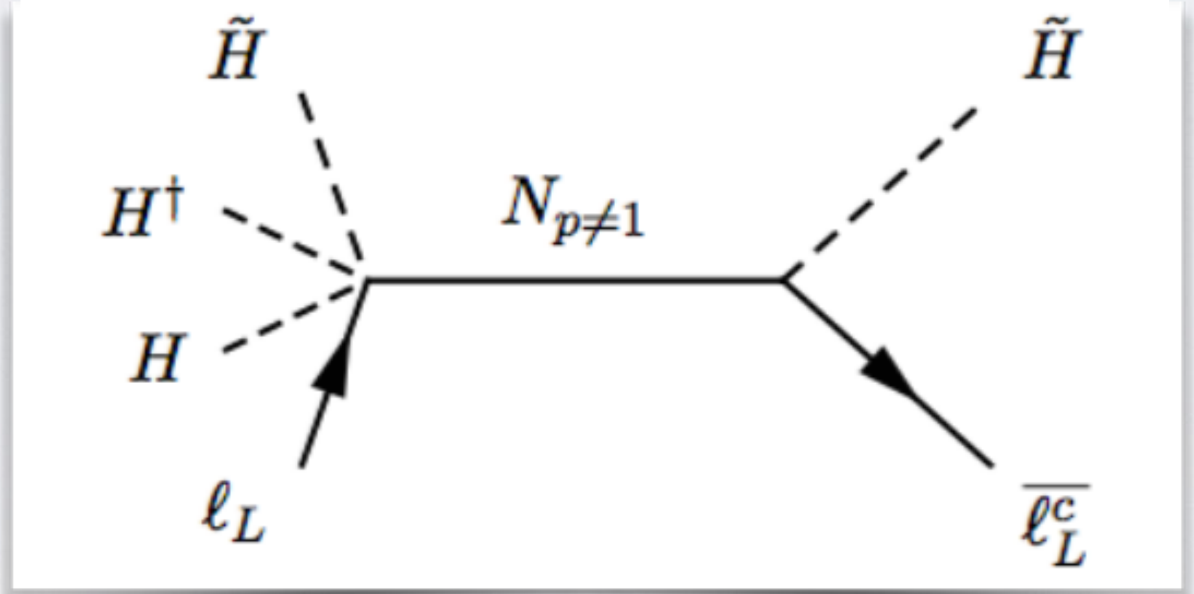
This has to be as extra H fields require another light propagator.

d=7 matching

- Many contributions to $Q_{\ell H}$ cancel out at tree level in a single matching in EW vacuum

$$-\frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\ell_{L\,\kappa}\right)\,H^2 + 2\,\lambda\,\tilde{C}^7_{\beta\,\kappa}\mathcal{Q}_{\ell H} + \frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\sigma^I\,\ell_{L\,\kappa}\right)\,H\sigma^I H + h.c$$

However this argument fails when you integrate things out in sequence



Neutrino mass matrix perturbations only come about at $\mathcal{L}_7$ due to this

$$\frac{1}{2}\mathcal{L}^{(7)} \supseteq -\left(\frac{x^T_\beta\, y_\alpha\, x\cdot y}{4\,m_1^2\,m_2} + \frac{x^T_\beta\, z_\alpha\, x\cdot z}{4\,m_1^2\,m_3} + \frac{y^T_\beta\, z_\alpha\, y\cdot z}{4\,m_2^2\,m_3}\right)\mathcal{Q}^{\beta\,\alpha}_{\ell H} + h.c.$$

d=7 matching

- Many contributions to $Q_{\ell H}$ cancel out at tree level in a single matching in EW vacuum

$$-\frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\ell_{L\,\kappa}\right) H^2 + 2\,\lambda\,\tilde{C}^7_{\beta\,\kappa} Q_{\ell H} + \frac{\lambda\, v^2\, \tilde{C}^7_{\beta\,\kappa}}{2}\left(\overline{\ell^c_{L\,\beta}}\,\sigma^I\,\ell_{L\,\kappa}\right) H\sigma^I H + h.c$$

Other effect is due to redefining the field order by order in the power counting, through EOM shift. Total result

$$\mathcal{L}^{(7)} \supseteq -\left[\frac{x^T_\beta\, x_\kappa\, ||x||}{2m_1^3} + \frac{y^T_\beta\, y_\kappa ||y||}{2m_2^3} + \frac{z^T_\beta\, z_\kappa\, ||z||}{2m_3^3}\right] Q_{\ell H},$$
$$-\left[\frac{y^T_\beta\, x_\kappa y\cdot x}{2m_2^2\, m_1} + \frac{z^T_\beta\, x_\kappa z\cdot x}{2m_3^2\, m_1} + \frac{z^T_\beta\, y_\kappa z\cdot y}{2m_3^2\, m_2}\right] Q_{\ell H} + h.c.$$

Perturbation to neutrino mass matrix in SMEFT. Small effect!

Strangeness of the Higgs potential

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

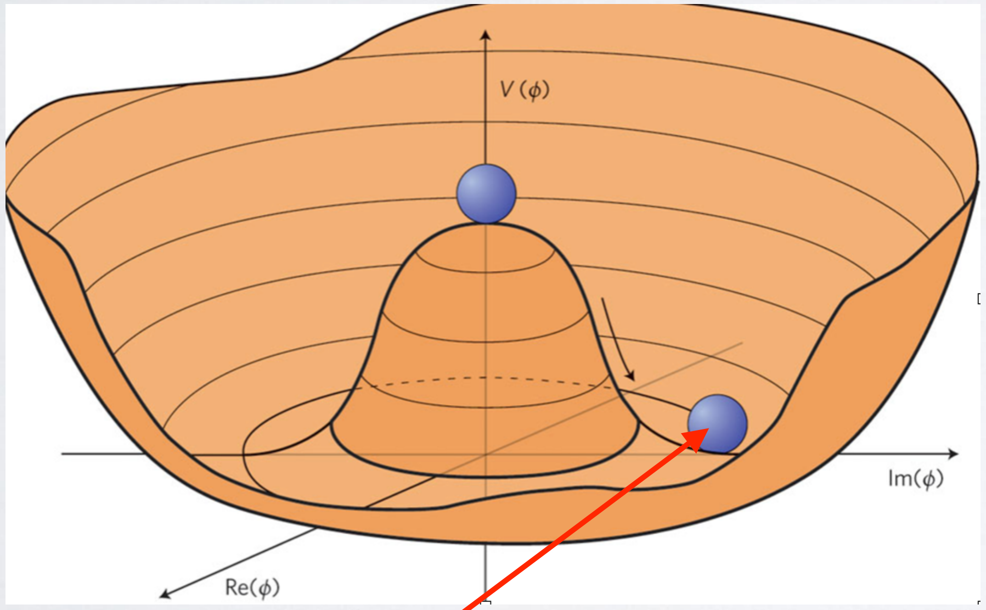
$$S_H = \int d^4x \left(|D_\mu H|^2 - \lambda \left(H^\dagger H - \frac{1}{2} v^2 \right)^2 \right),$$

Partial Higgs action

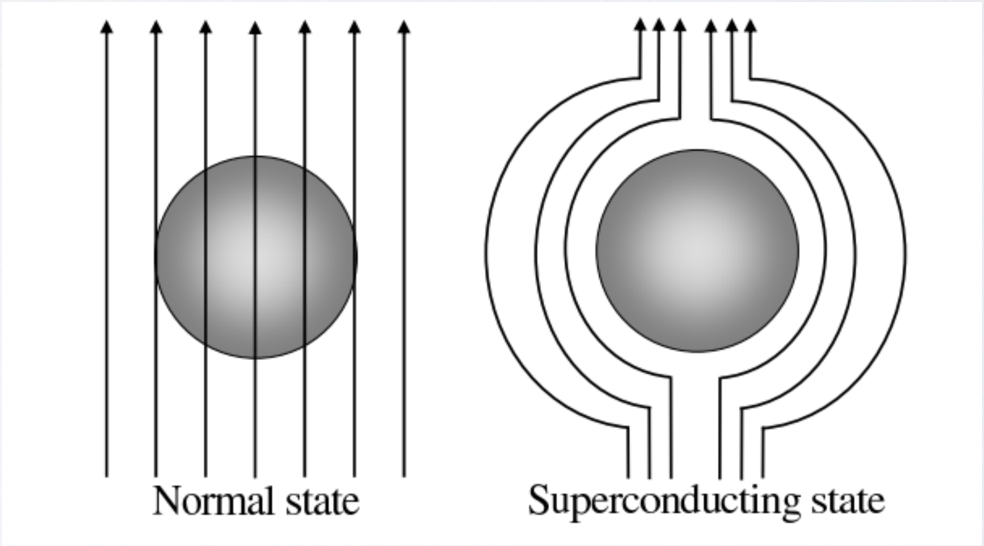
$$LG(s) = \int_{\Re^3} dx^3 \left[\frac{1}{2} |(d - 2\, i\, e\, A) s|^2 + \frac{\gamma}{2} \left(|s|^2 - a^2 \right) \right],$$

Landau-Ginzberg actional, parameterization of Superconductivity

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



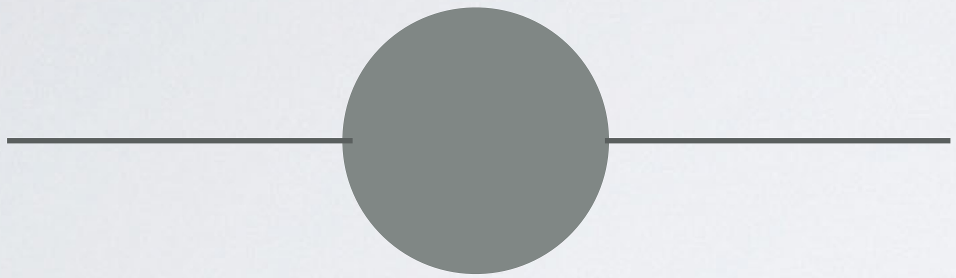
$m_{W/Z} = 0$ field config. energetically excluded (i.e. spon. sym breaking)

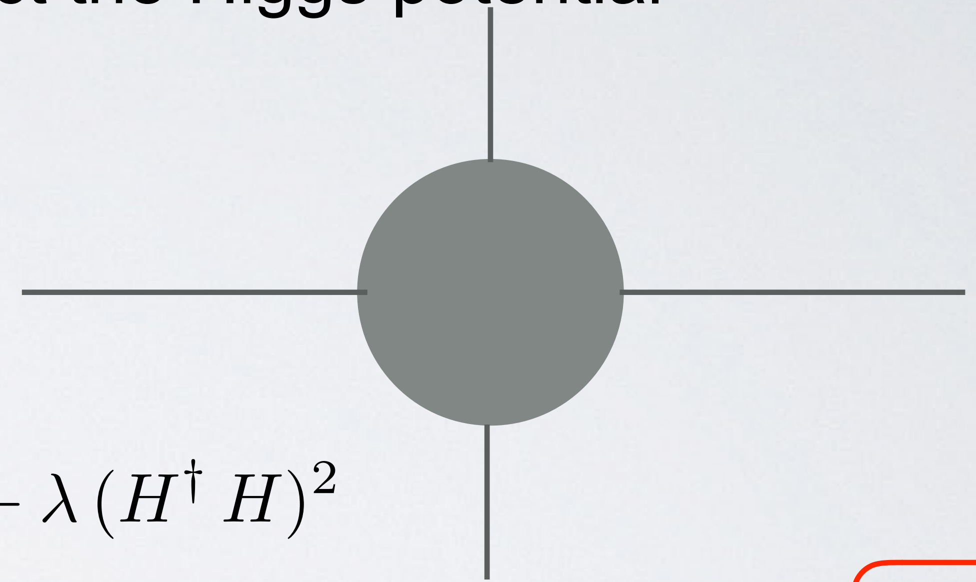


Magnetic field energetically excluded from interior of SC

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.

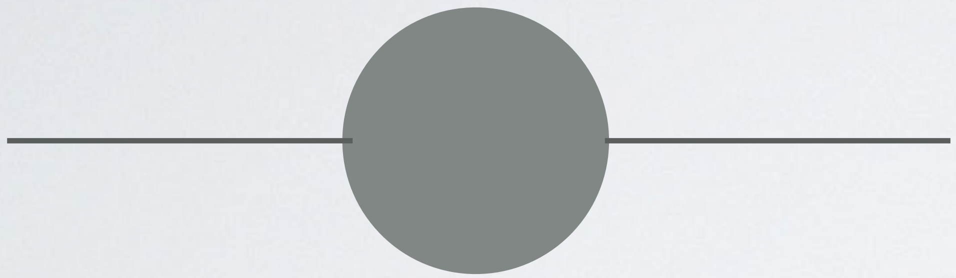
- Composite models (nobly) try to construct the Higgs potential:

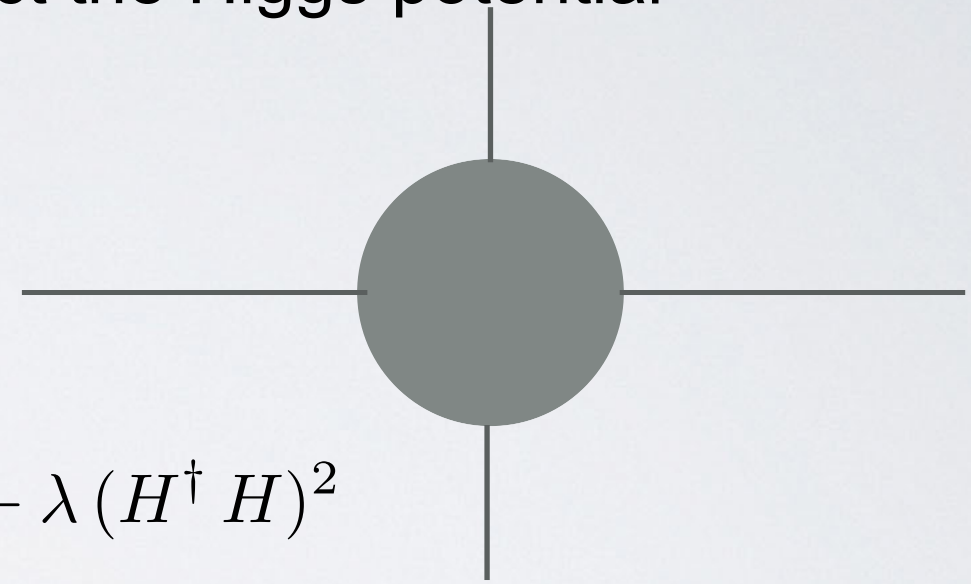
$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{16\,\pi^2}\left(-2\,a H^\dagger H + 2b\frac{(H^\dagger H)^2}{f^2}\right)$$ see 1401.2457 Bellazzini et al

- 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

Challenge of constructing potential.II

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



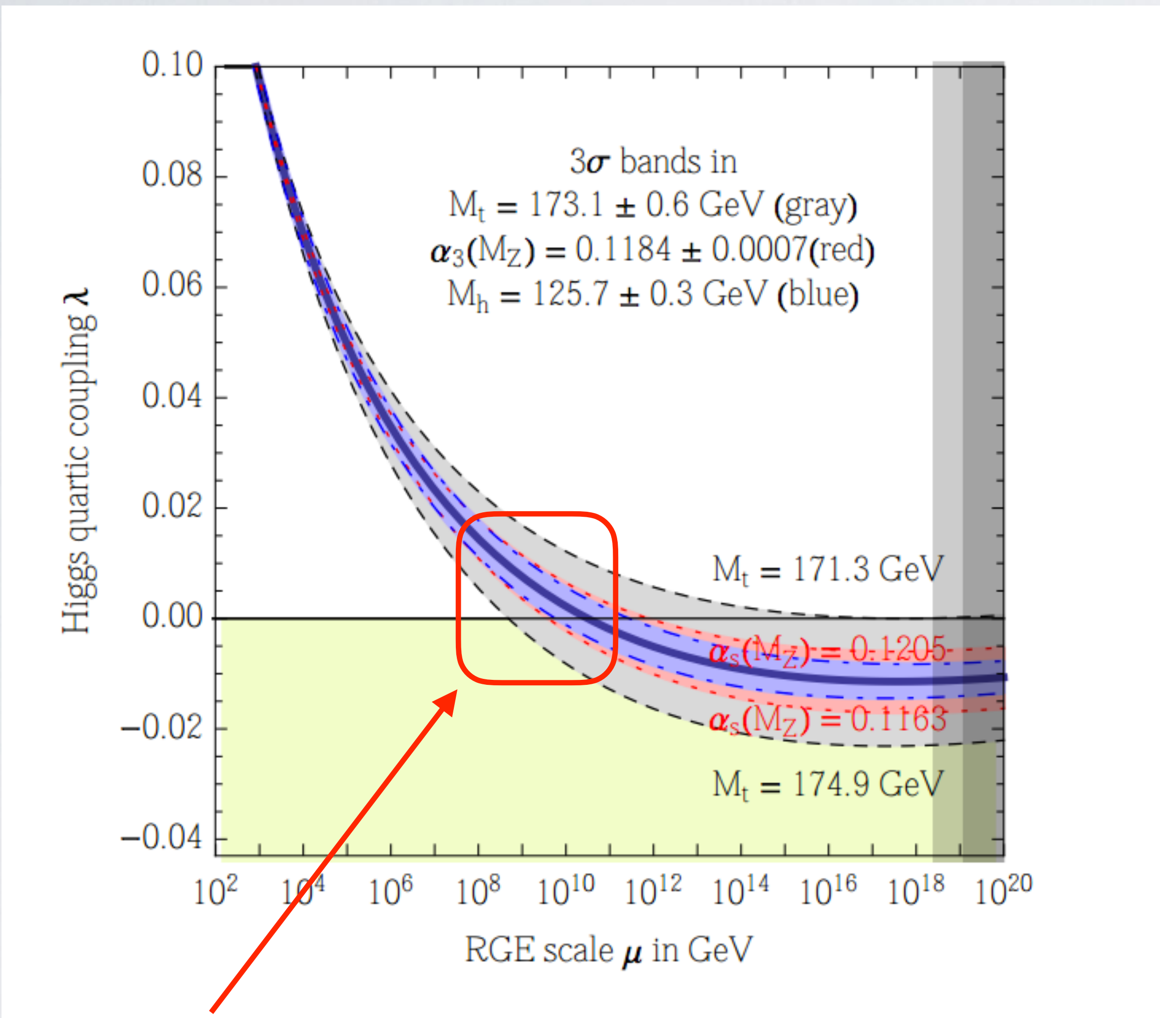


$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- Higgs coupling deviations scale as $\sim 1 - \frac{v^2}{f^2}$ but pheno studies imply $f \gtrsim \mathrm{TeV}$
- Where are the new states at a weakly coupled mass scale below the full cut off?
- Extensive tuning in these models: see 1401.2457 Bellazzini et al,
- This problem killed the initial composite idea initially (Georgi-Kaplan 80's), Modern models introduce tunings and constructed to avoid this. Generic feature - tev or below states to construct potential.

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)

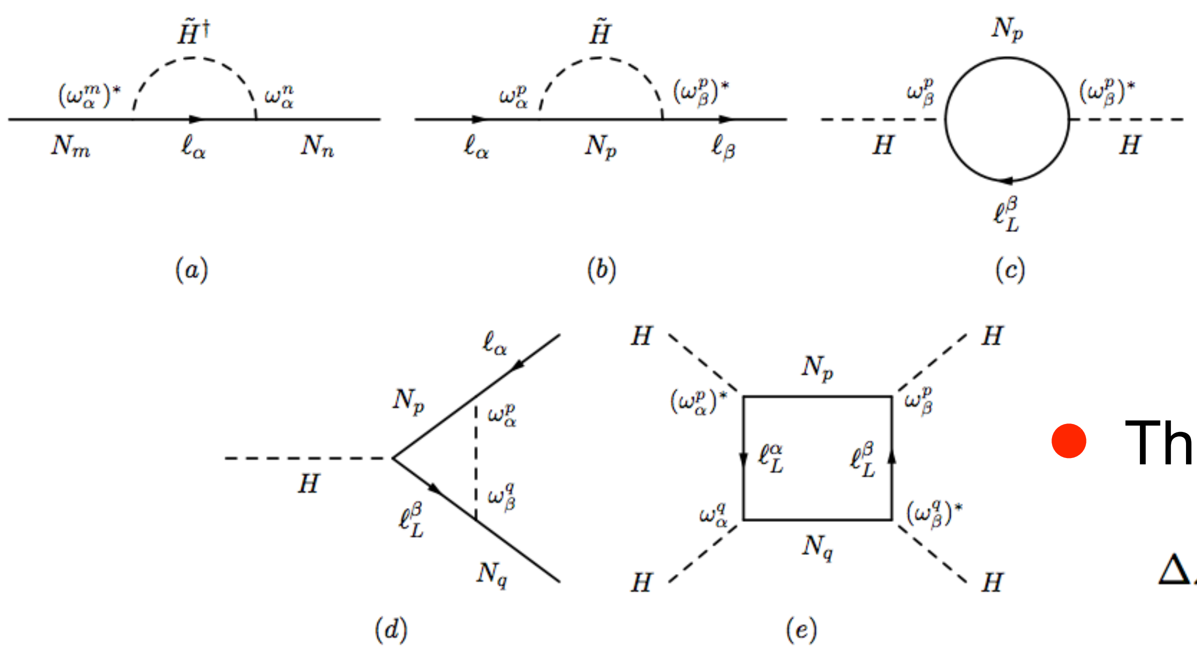
1205.6497 Degrassi et al, 1112.3022 Elias-Miro et al..

- 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.

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:

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

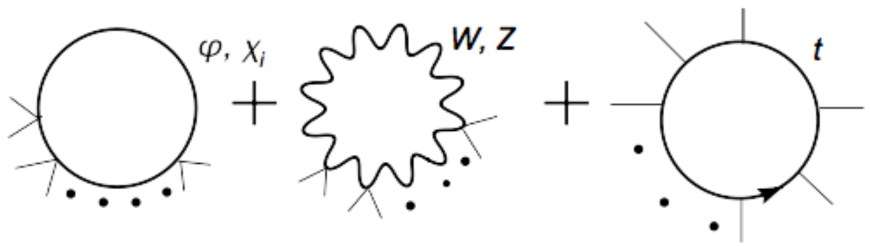
here choose $\mu = M e^{-3/4}$

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:

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

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

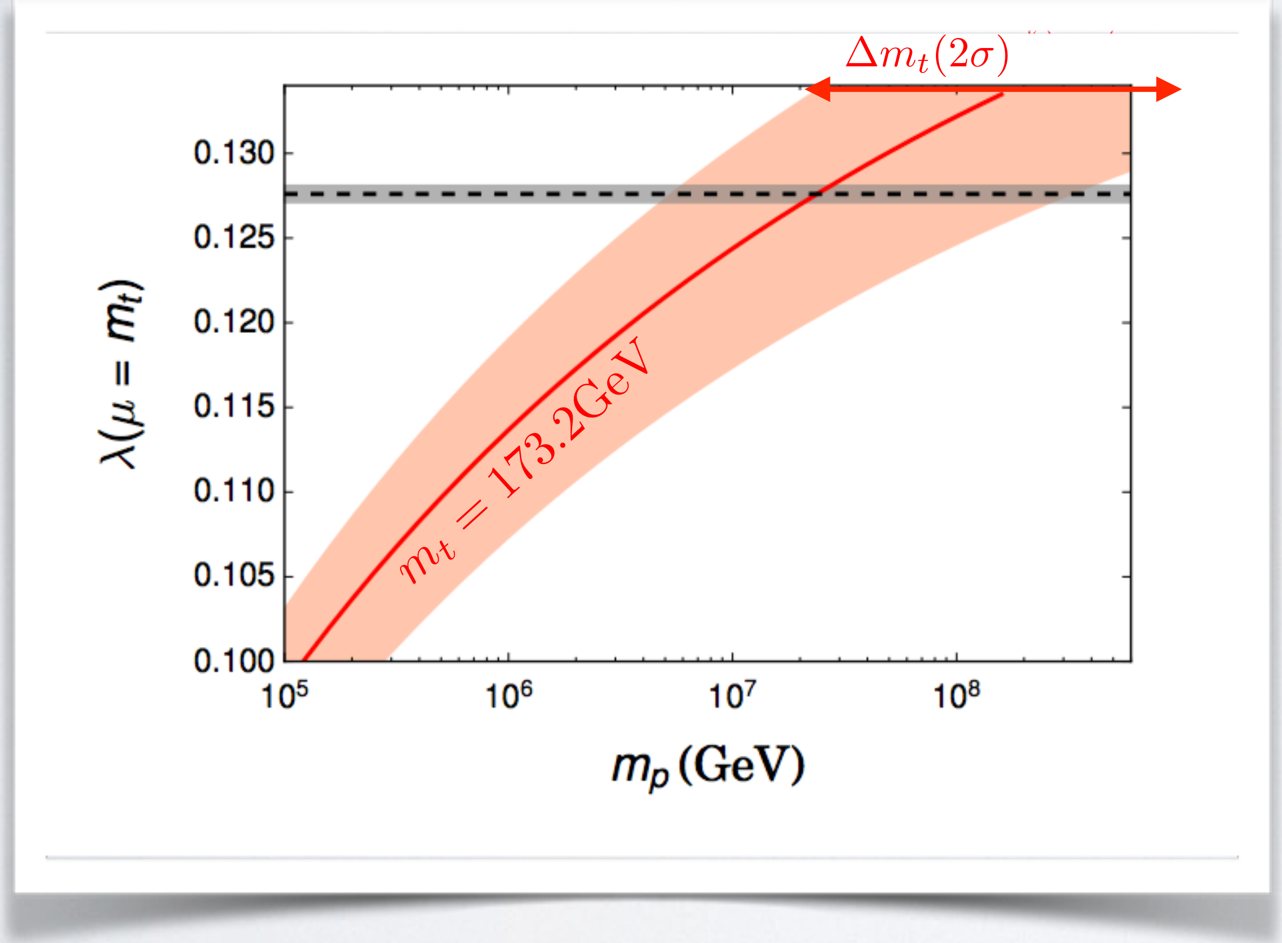
$$\mu = M e^{-3/4}$$

- If $\frac{|\omega_p|^2\, m_p^2}{16\pi^2} \gg v_0, \Lambda_{QCD}$ 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

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 $\lambda \sim 0.13$

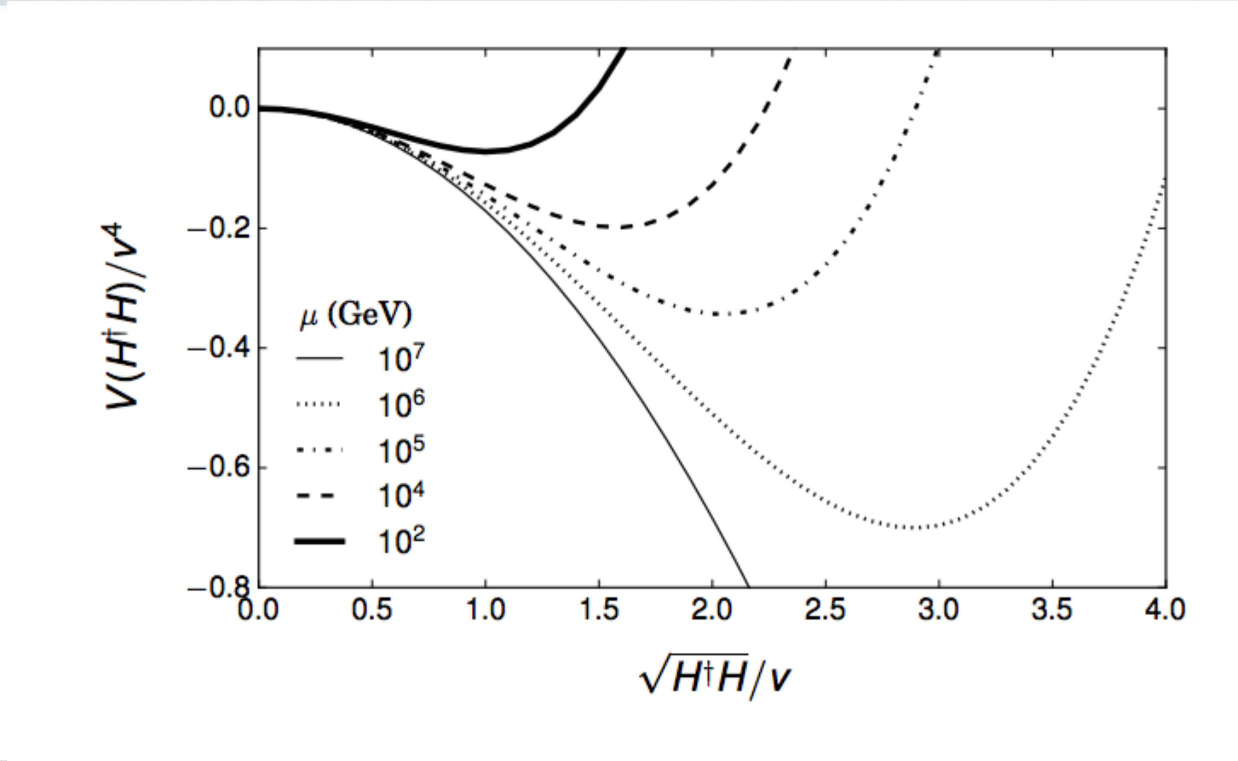
- This essentially fixes the mass scale and couplings (large uncertainties)

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

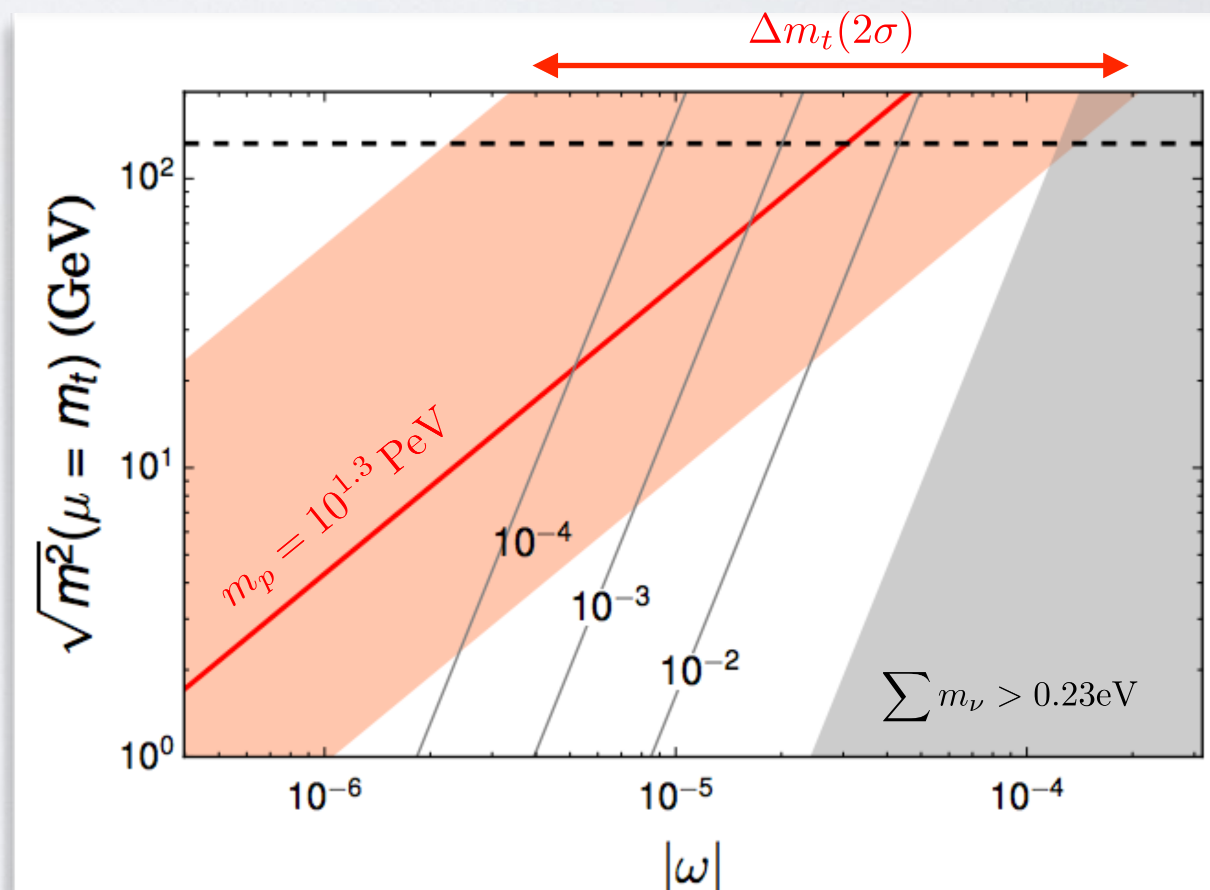
$$|\omega| \sim 10^{-5}$$

- 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

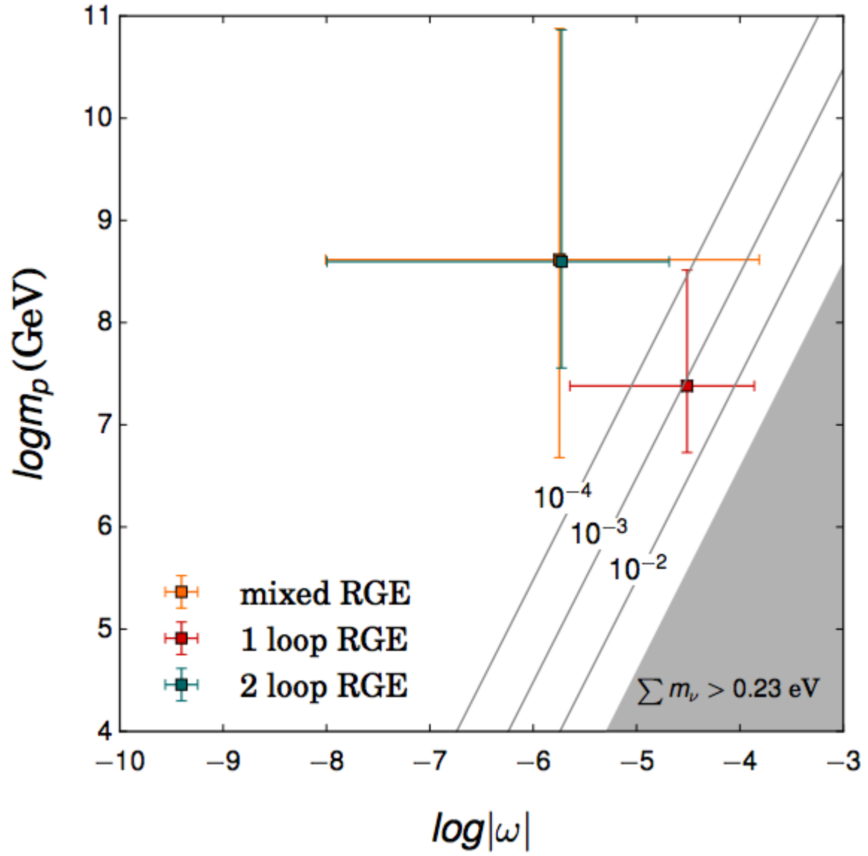


- In a non-trivial manner - and the right neutrino mass scale (diff) can result.

—— $\Delta m_\nu(\mathrm{eV})$

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

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

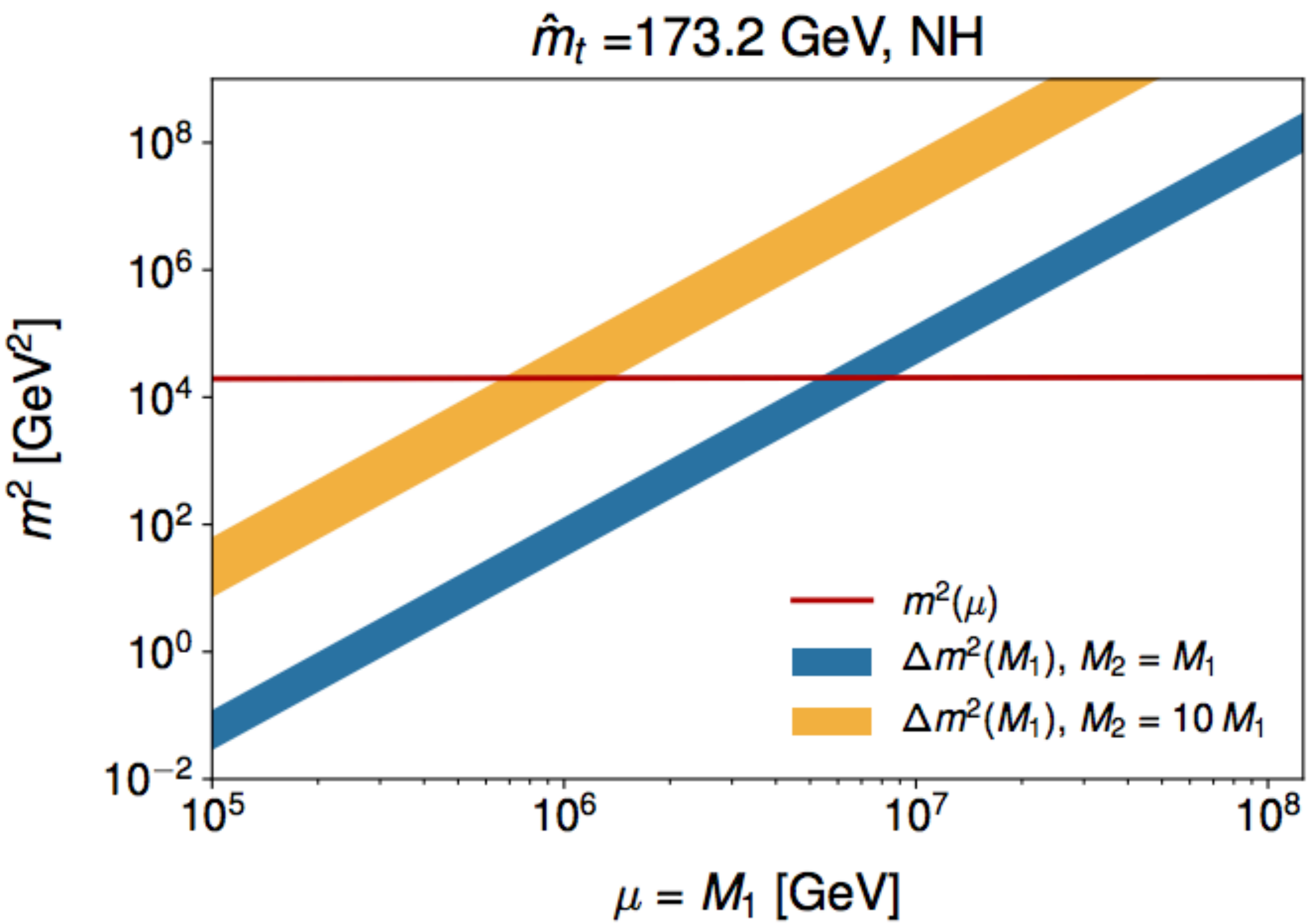
  Resonant leptogenesis can work here (S. Petcov - private communication)

- 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

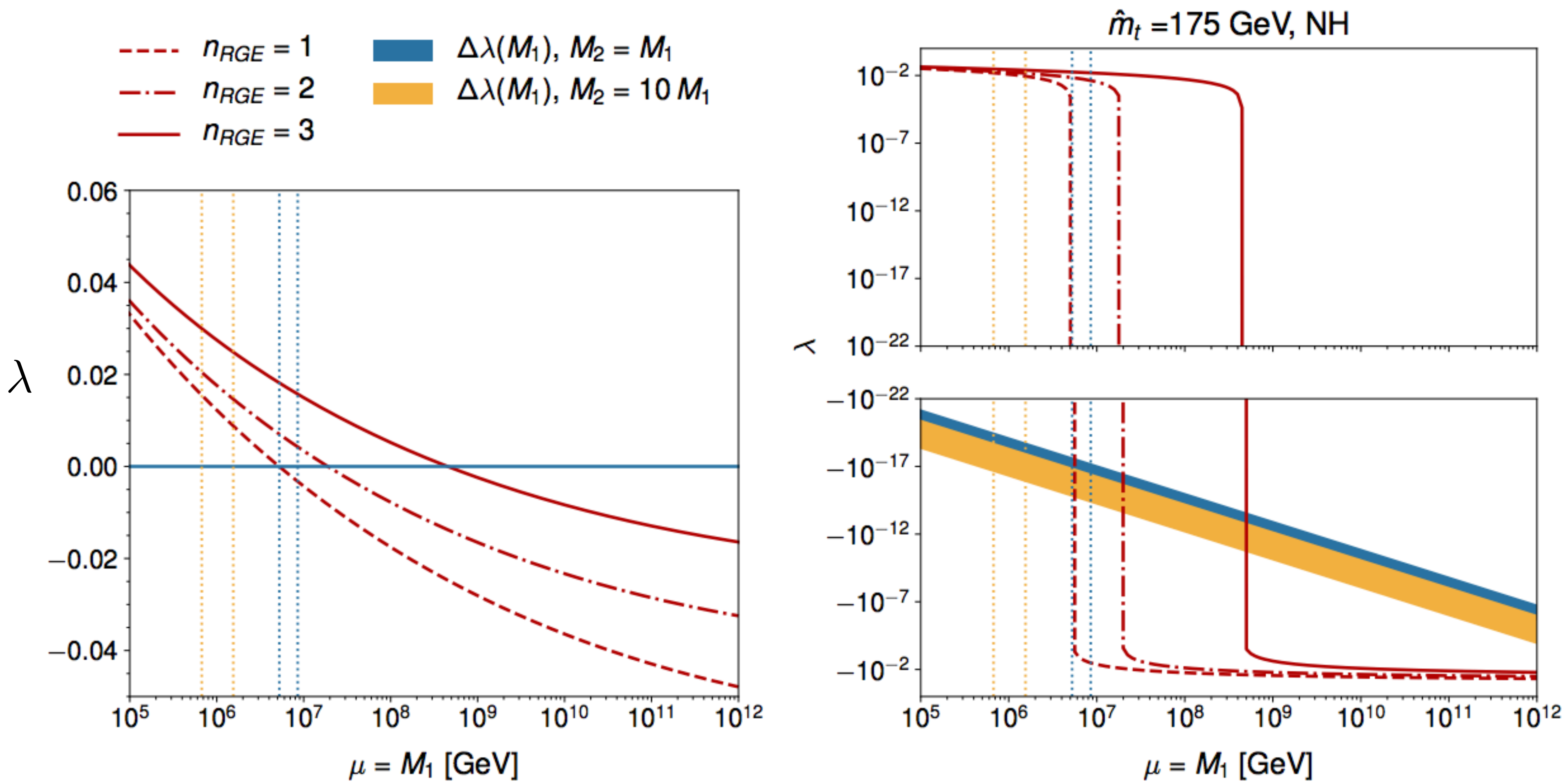
- Consistency test reformulated to avoid asymptotic numerical sensitivity to λ



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

Minimal case with two heavy neutrino's.

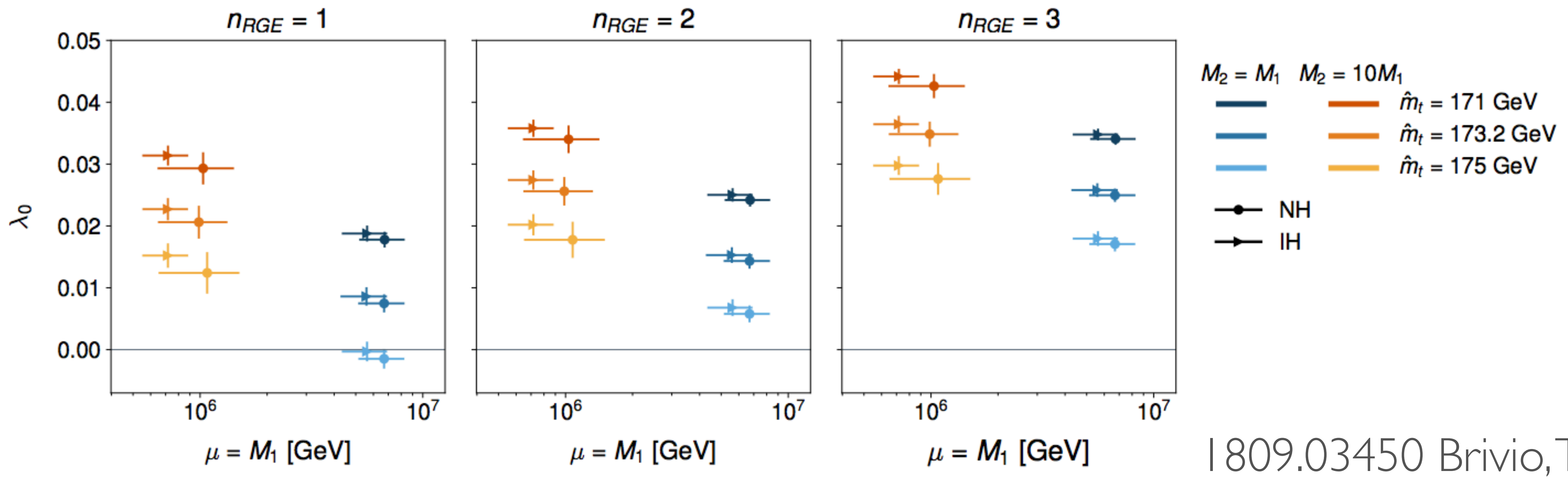
Improving numerical stability



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. Neutrino's with mass embedded.
- <u>*Combined global studies are key*</u> to interpretation
- Severe care required in formulating the SMEFT (TH job) and in combining the data (EXP job)
- Seesaw model supplies an option for low energy pheno of the SM With the Higgs potential having an interesting UV boundary condition

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

- This is a "self seesaw" with only one scale, the EW scale is a loop down from the Majorana scale. We don't see new states at LHC due to a stabilizing symmetry consistent with this.

Open Request

- Can you build a UV completion that generates the majorana scale in a manner that does not induce other threshold corrections?
  - 1807.11490 Brdar et al. Conformal UV completion of Neutrino Option
  - ?
- IF this was true what is the right experimental approach to probe

$$m_p \sim 10^7 \mathrm{GeV} \qquad |\omega| \sim 10^{-5}$$

  - 1810.12306 Brdar et al. Gravitational Waves are potentially significant
  - ?

Backup/Rapid developments

Flavour space expansion

- Summary of dim 7 results its VERY small, down by $\mathcal{O}(v^2/M_p^2)$ and interesting!

- Far bigger effect is how the expansion of

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

is perturbed as the N states are integrated out in sequence.

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

no known quantum numbers

expected to be uniform in interaction eigenbasis, once diagonalized expect

$$||x|| \sim ||y|| \sim ||z||$$

Flavour space expansion

N_1

N_2

N_3

- Lightest singlet state dominates the neutrino mass matrix, heavier singlet states then perturb the mass spectrum and eigenstate spectrum

< 1 by construction

$$M_{\nu\nu}^{\beta\alpha}\,(M_{\nu\nu}^{\kappa\alpha})^\dagger \simeq \frac{||z^\star\cdot z||}{m_3^2}\left[z_\beta^T\,z_\kappa + \frac{z^\star\cdot y^\dagger}{||z^\star\cdot z||}\,\frac{m_3}{m_2}\,z_\beta^T\,y_\kappa^\star + \frac{y^\star\cdot z^\dagger}{||z^\star\cdot z||}\,\frac{m_3}{m_2}\,y_\beta^T\,z_\kappa^\star + \cdots\right].$$

use complex Cauchy-Schwarz

$$a\cdot b = ||a||\,||b||\,\Delta_{ab}$$

< 1 by construction again

- If it is true that

$$\frac{||y||}{||z||}\Delta_{y^\dagger z} < m_2/m_3, \qquad \frac{||y||}{||z||}\Delta_{y z^\dagger} < m_2/m_3.$$

v

another expansion to exploit - a flavour space expansion. 1203.4410 Grinstein, MT

Perturbation theory - OLD SCHOOL!

- Define eigenvectors that correspond to the mass eigenvalues of the C^5 matrix

$$M_{\nu\,\nu}\,\vec{\rho}_p^{\,\star} = m_p\,\vec{\rho}_p,$$

- Construct the orthonormal set as eigenvectors in flavour space

$$\vec{\rho}_a^{\,\star} = \frac{\vec{z}}{\|\vec{z}\|}, \qquad \vec{\rho}_b^{\,\star} = \frac{\vec{z}^{\star} \times (\vec{y} \times \vec{z})}{\|\vec{z}\|\|\vec{z} \times \vec{y}\|}, \qquad \vec{\rho}_c^{\,\star} = \frac{\vec{y}^{\star} \times \vec{z}^{\star}}{\|\vec{z} \times \vec{y}\|}.$$

- Can systematically develop perturbations of the eigenvectors and eigenvalues

$$\delta\vec{\rho}_j = = \sum_{i \neq j} \frac{\langle \vec{\rho}_i | \mathcal{M}\delta\mathcal{M}^\dagger + \delta\mathcal{M}\,\mathcal{M}^\dagger | \vec{\rho}_j \rangle}{m_j^2 - m_i^2}\,\vec{\rho}_i,$$

$$\delta m_i^2 = \langle \vec{\rho}_i | \mathcal{M}\delta\mathcal{M}^\dagger + \delta\mathcal{M}\,\mathcal{M}^\dagger + \delta\mathcal{M}\,\delta\mathcal{M}^\dagger | \vec{\rho}_i \rangle$$

Links perturbations of masses to PMNS

N_1

N_2

N_3

- What is the benefit of this approach?

only matrix involved in neutrino mass spectrum

$$\langle c_{\beta\,\kappa}\,\mathcal{Q}_5^{\beta\,\kappa}\rangle = -\frac{v^2}{2}\,\left[\mathcal{U}^T(\nu,L)^\beta_p\, c_{\beta\,\kappa}\,\mathcal{U}(\nu,L)^\kappa_r\right]\,(\nu_L')^{T p}\,\epsilon\,(\nu_L')^r$$

expansion

measured

Unknown!

$$\mathcal{U}(\nu,L) = \mathcal{U}(e,L)\,\mathcal{U}^{s_{ij}}_{PNMS}$$

$$\mathcal{U}^\dagger(e,L) = (\vec{\sigma}_1^\star,\vec{\sigma}_2^\star,\vec{\sigma}_3^\star)^T$$

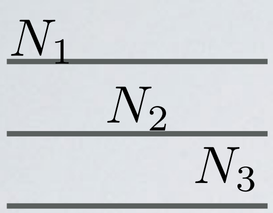
- What is the benefit of this approach?

$$\begin{aligned}
\vec{\rho}_c^{\,\star} &= (s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta})\,\vec{\sigma}_3 + (-s_{12}\,c_{23} - c_{12}s_{23}\,s_{13}e^{i\delta})\,\vec{\sigma}_2 + c_{12}\,c_{13}\,\vec{\sigma}_1,\\
\vec{\rho}_b^{\,\star}\,e^{\frac{-i\alpha_{21}}{2}} &= (-c_{12}\,s_{23} - c_{23}\,s_{12}\,s_{13}\,e^{i\delta})\,\vec{\sigma}_3 + (c_{12}\,c_{23} - s_{23}\,s_{12}\,s_{13}\,e^{i\delta})\,\vec{\sigma}_2 + c_{13}\,s_{12}\,\vec{\sigma}_1,\\
\vec{\rho}_a^{\,\star}\,e^{\frac{-i\alpha_{31}}{2}} &= c_{13}\,c_{23}\,\vec{\sigma}_3 + c_{13}s_{23}\,\vec{\sigma}_2 + e^{-i\delta}\,s_{13}\,\vec{\sigma}_1.
\end{aligned}$$

v

This is where ben and i hit the wall in 1203.4410

Just perturb in the unknown



- Although the σ_i are unknown we do know one thing

$\mathcal{M}_e^\dagger \mathcal{M}_e$ Hermitian positive mass matrix defined over field $\mathbb{C}^3$.

As $\mathcal{U}(e, L)$ diagonalizes a Hermitian positive mass matrix the σ_i for a basis

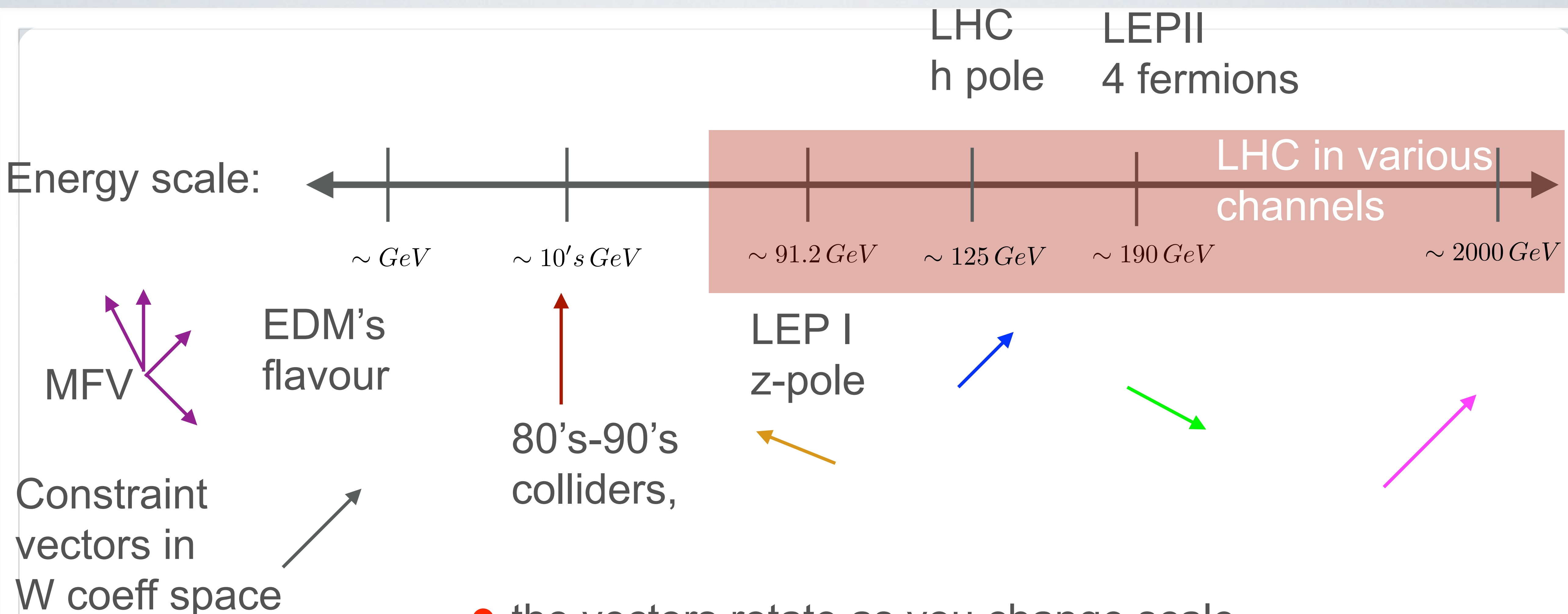
arXiv:1703.04415 Gitte Elgaard-Clausen, MT

- So expand all the complex $\omega_i = A_i \sigma_1 + B_i \sigma_2 + C_i \sigma_3$

- Use the algebra properties $\vec{\sigma}_i \times \vec{\sigma}_j = \epsilon_{ijk} \, \vec{\sigma}_k \quad \vec{\sigma}_i^\star \times \vec{\sigma}_j^\star = \epsilon_{ijk} \, \vec{\sigma}_k^\star$

- This way we have a systematically improvable basis independent link between the neutrino mass spectrum and the PMNS. Might be useful long term.

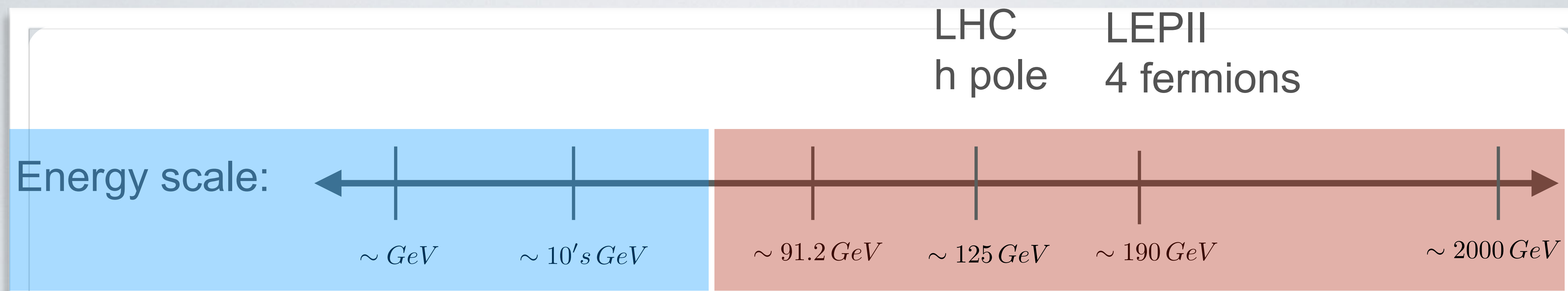
Post Modern Discovery Physics



- the vectors rotate as you change scale..

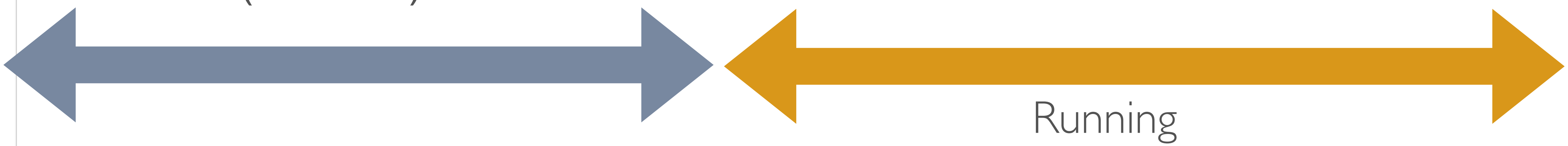
- To combine the various constraints consistently take into account they rotate as you change scale.. or introduce theory error.
- Any future discovery has to be projected back on these constraints to check consistency.

Post Modern Discovery Physics



EFT: WET (or LEFT)

EFT: SMEFT or HEFT



Complete LEFT RGE:

1711.05270 Jenkins, Manohar, Stoffer

HEFT/SMEFT matching LEFT:

1709.04486 Jenkins, Manohar, Stoffer

Complete SMEFT RGE:

arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott
arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott
arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

HEFT RGE:

1710.06848 Alonso, Kanshin Saa
1710.06412 Buchalla, Cata, Celis, Knecht, Krause

One loop results

- Loop results can be numerically significant for interpretations of the data when precision descends below 10% experimentally and when combining data sets which is required going forward.

- Era of NLO SMEFT results has now been kicked off:

Pioneering full calculation $\mu \to e\,\gamma$ Pruna, Signer arXiv:1408.3565

Other processes tacked in 1505.03706 Ghezzi et al. (partial EW precision)

Partial $\Gamma(h \to f\,\bar{f})$ R. Gauld, B. D. Pecjak and D. J. Scott, arXiv:1512.02508

QCD corrections partial SMEFT P. Artoisenet et. al., arXiv:1306.6464

QCD NLO Higgs associated production K. Mimasu. et al. arXiv:1512.02572

QCD NLO single top production C.Zhang, arXiv:1512.02508

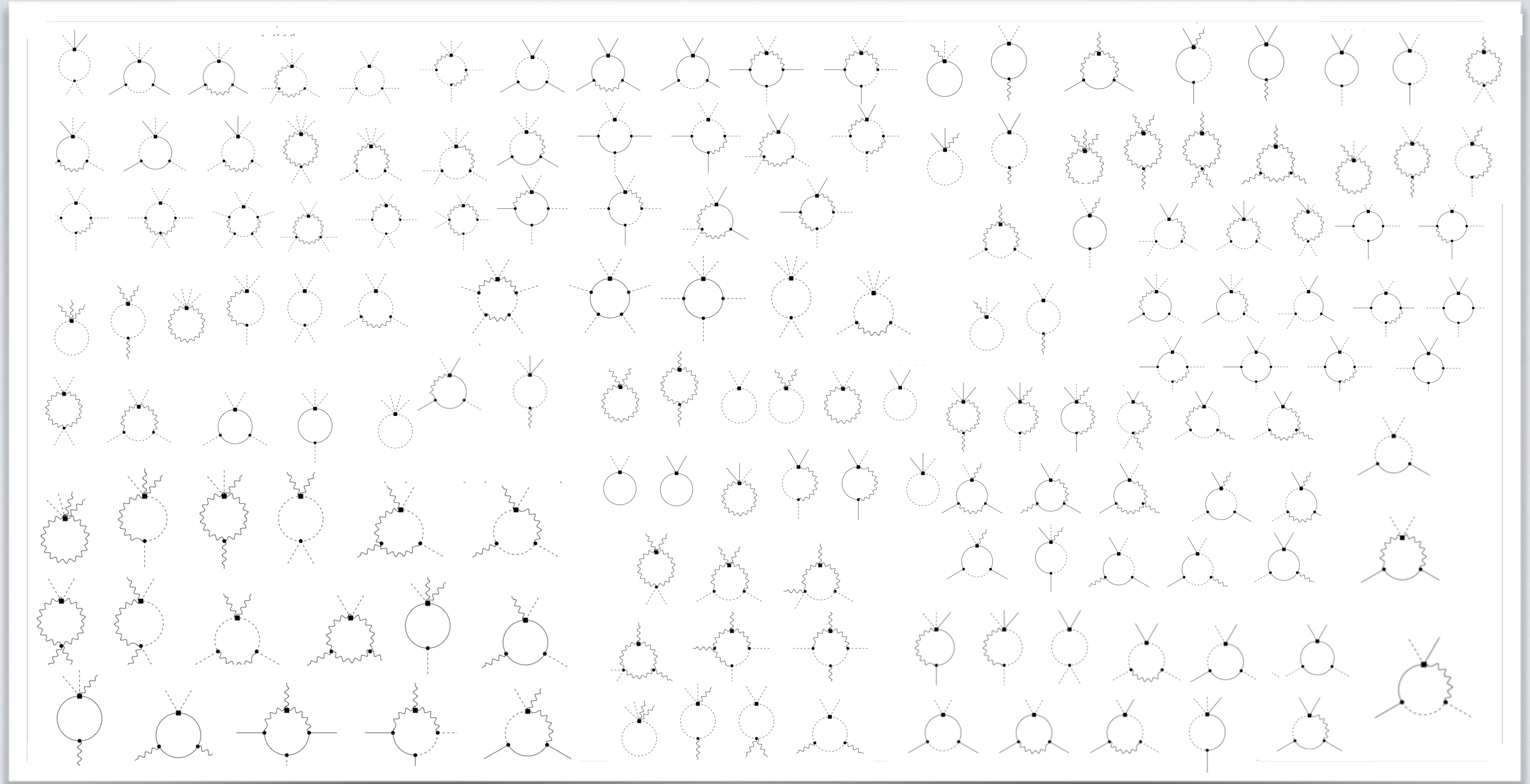
QCD NLO Higgs pair production R. Grober et al. arXiv:1504.0657

(many more works too many to list here)

NLO EW $h \to ZZ, h \to Z\,\gamma$ S. Dawson, P.P. Giardino 1801.01136

2499x2499 RGE

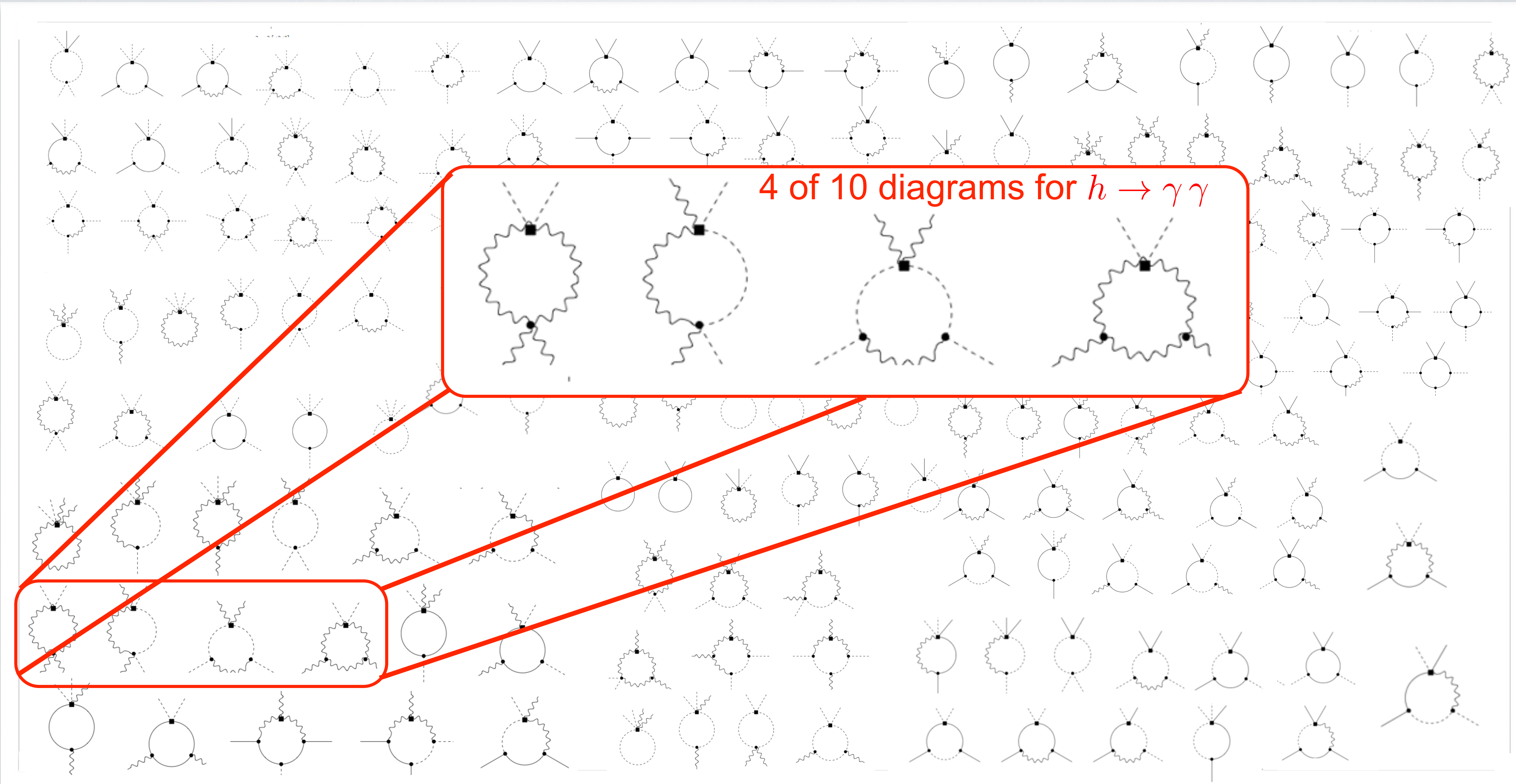
- Full calculation subtle, due to EOM effects.



- Each dot can be 59 types operator

2499x2499 RGE

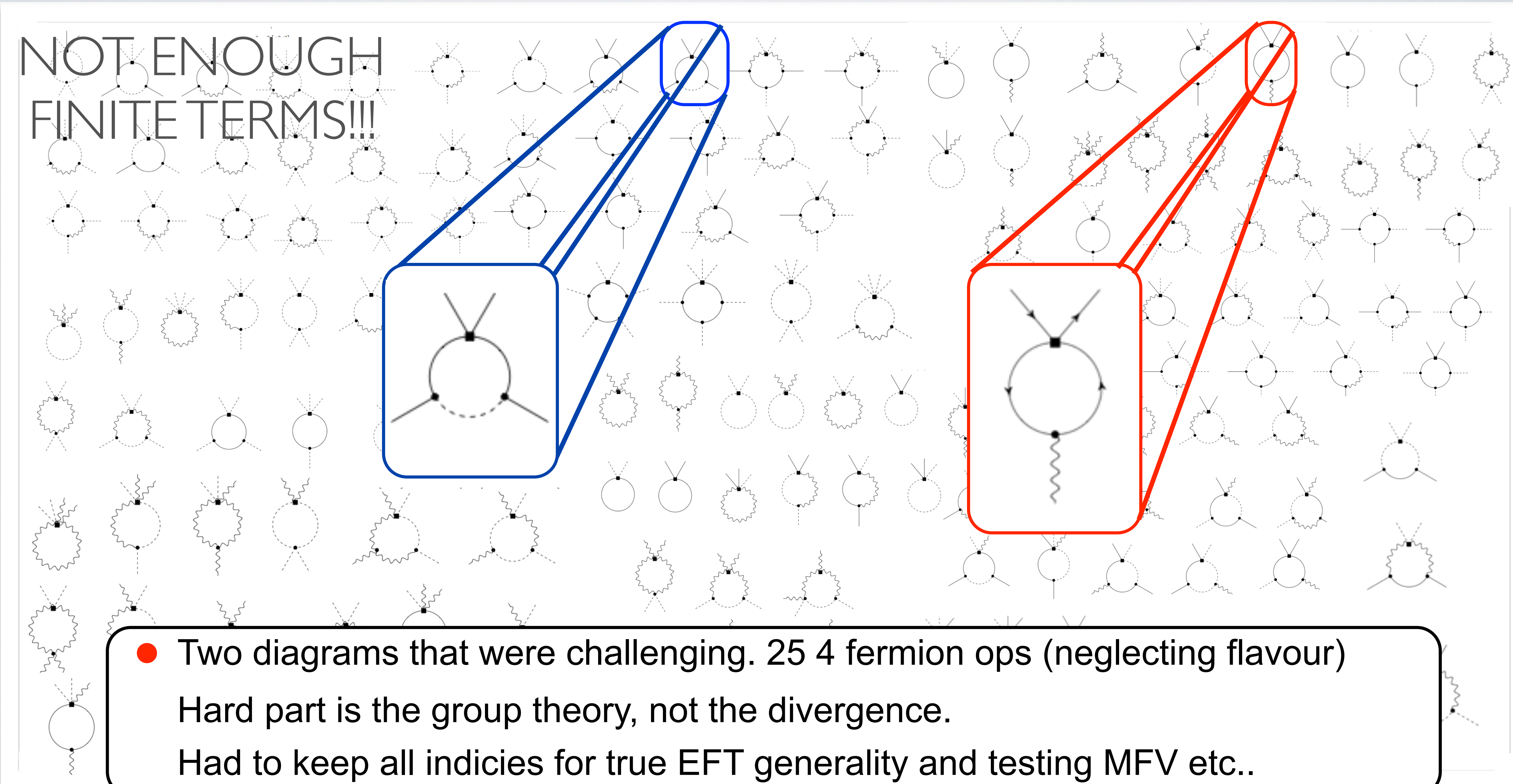
- Full calculation subtle, due to EOM effects.



- Each dot can be 59 types operator

Not a trivial exercise

- Full calculation subtle, due to EOM effects.



- Two diagrams that were challenging. 25 4 fermion ops (neglecting flavour)

  Hard part is the group theory, not the divergence.

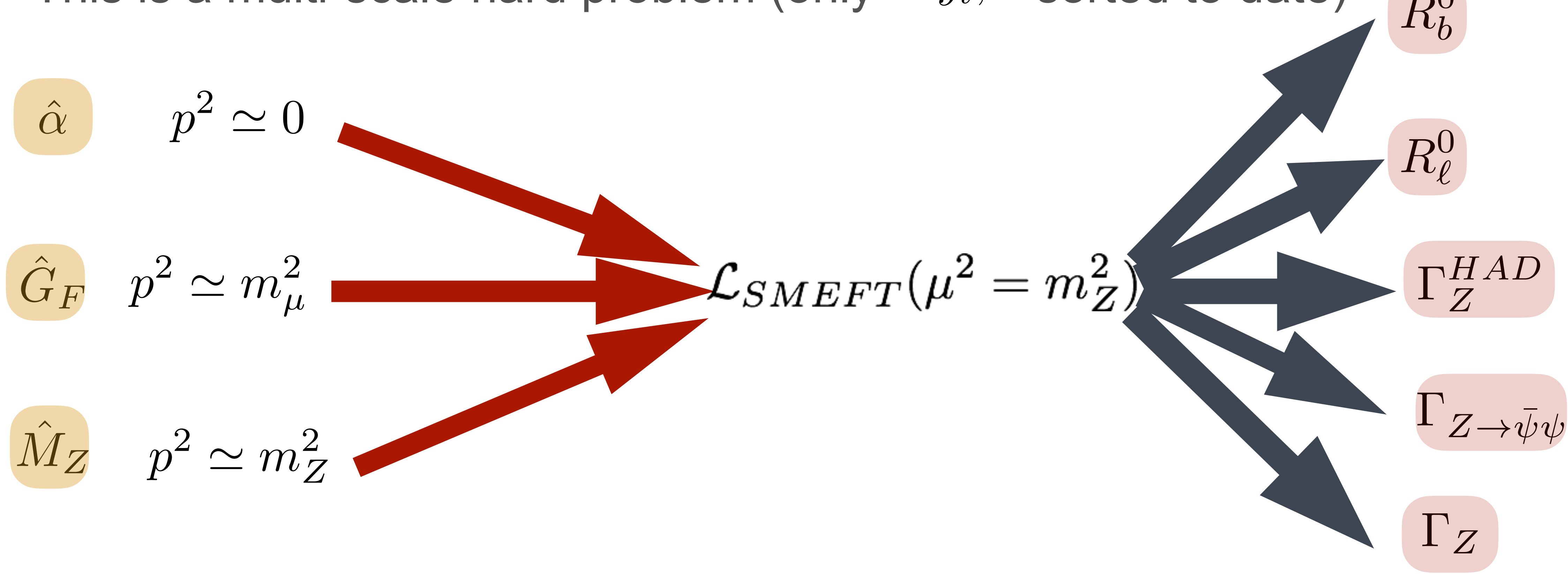
  Had to keep all indicies for true EFT generality and testing MFV etc..

- Each dot can be 59 types operator

SMEFT decay widths of the Z at one loop

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

- This is a multi-scale hard problem (only $\propto y_t, \lambda$ sorted to date)



- LSZ defn: $\langle Z|S|\bar{\psi}_i\,\psi_i\rangle = (1 + \frac{\Delta R_Z}{2})(1 + \Delta R_{\psi_i})\, i\, \mathcal{A}_{Z\bar{\psi}_i\psi_i}.$

- Need to loop improve the extraction of parameters AND the decay process of interest.

input shifts   decay process (wavefunction&process)

see also : Passarino et al arXiv:1607.01236 , arXiv:1505.03706

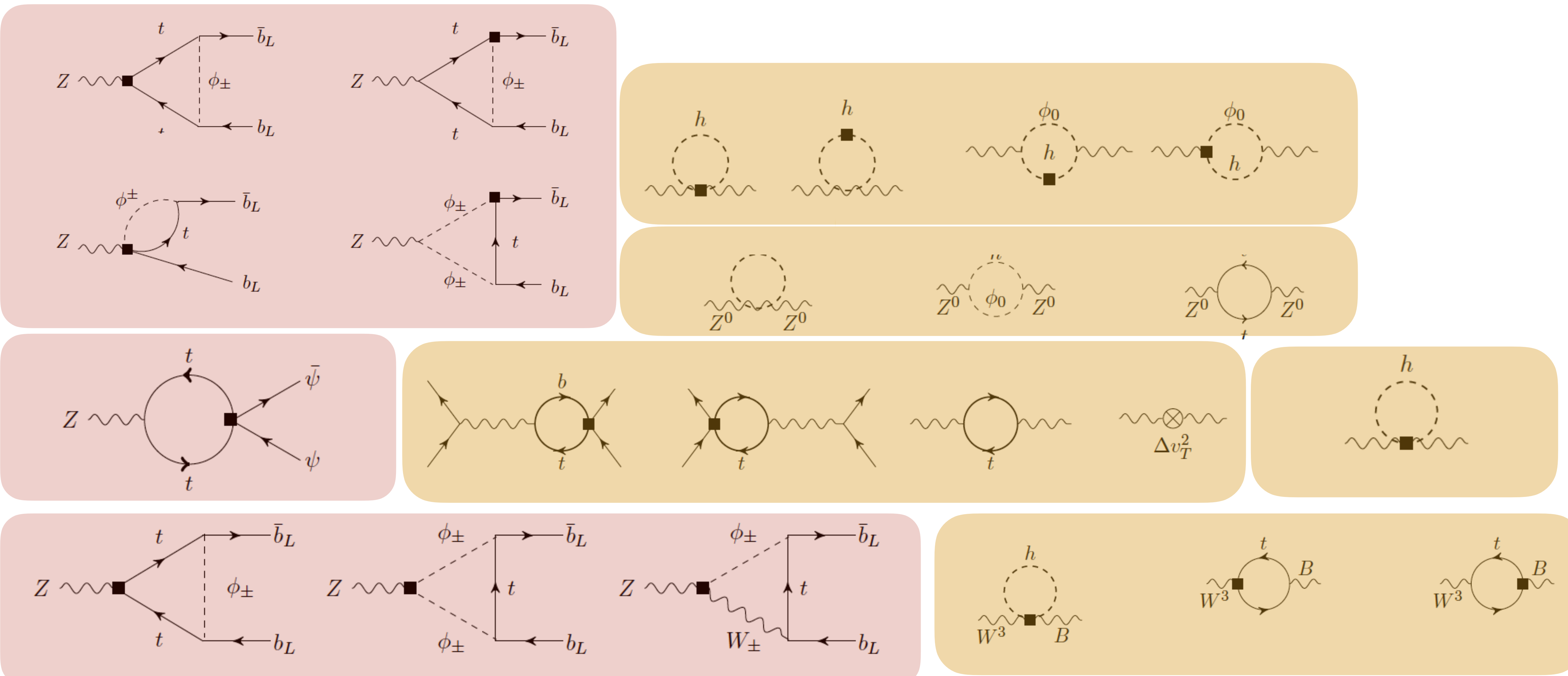
Loops present

- ~ 30 massive loops in addition to the RGE dim reg results of

arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott

arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott

arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

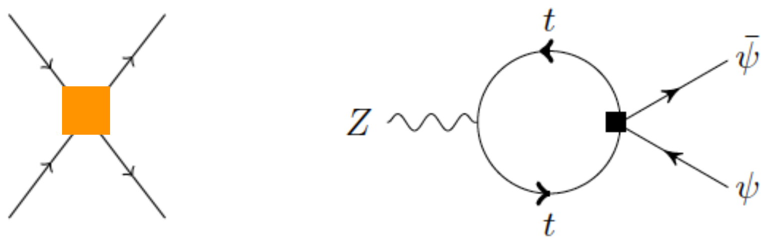


Main conclusions

- ***MORE PARAMETERS*** (At least) the following operators contribute at one loop to EWPD, that are not present at tree level.

$$\{C_{qq}^{(1)}, C_{qq}^{(3)}, C_{qu}^{(1)}, C_{uu}, C_{qd}^{(1)}, C_{ud}^{(1)}, C_{\ell q}^{(1)}, C_{\ell q}^{(3)}, C_{\ell u}, C_{qe}, C_{HB} + C_{HW}, C_{uB}, C_{uW}, C_{uH}\}.$$

- Distinctions between operators made at LO not relevant



- Need to combine data sets carefully due to hierarchies in experimental precision and different scales of measurements

HEFT digression

Two options. Not obvious to choose between them for cut off scale reasons stated.

1) A nonlinear EFT - built of

Idea stumbled upon over and over..
F. Feruglio arXiv:hepph/9301281
Burgess et al. 9912459
Grinstein Trott , arXiv:0704.1505

$$\Sigma = e^{i\sigma_a \pi^a / v} \quad h$$

$$\mathcal{L} = -\frac{1}{4} W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{\psi} i D \psi$$

$$+ \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) - \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$

“Higgs like boson” couplings are given by adding all possibly “h” interactions

$$\mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 - V(h) + \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) \left[1 + 2\, a_{W,Z} \frac{h}{v} + b_{Z,W} \frac{h^2}{v^2} + b_{3,Z,W} \frac{h^3}{v^3} + \cdots \right],$$

$$- \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \left[1 + c_i^{u,d} \frac{h}{v} + c_{2,j}^{u,d} \frac{h^2}{v^2} + \cdots \right] \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c.,$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + \frac{d_3}{6} \left(\frac{3\, m_h^2}{v} \right) h^3 + \frac{d_4}{24} \left(\frac{3 m_h^2}{v^2} \right) h^4 + \cdots .$$

SM mass scales then unrelated to scalar couplings - ***This is used in the “kappa” fits.***

HEFT: Rapid developments

- Used in Higgs data analysis and developed into kappa formalism

  1202.3415 Azatov, Contino galloway , 1202.3697 Espinosa, Grojean, Muhlleitner,, MT

  1209.0040 Higgs XS working group   1504.01707 Buchalla et al.

- Subleading operator basis developed 1212.3305 Alonso et al.

  1203.6510 Buchalla Cata (no h), 1307.5017 Buchalla Cata Krause (+ h)

- Matchings/correlations explored

  1311.1823 Brivio et al.   1405.5412 Brivio et al.   1406.6367 Gavela et al.
  1409.1589 Alonso et al. 1603.05668 Feruglio et al. 1412.6356,1608.03564 Buchalla et al.

- Power counting discussion

  1312.5624 Buchalla et al, 1601.07551 Gavela et al. 1603.03062 Buchalla et al.

- Curvature interpretation (linear/nonlinear distinction = field redef. invariant curvature measure)

  1511.00724 1602.00706, 1605.03602 Alonso et al.

It is the SMEFT not Higgs EFT.

- It does not really make sense to think of just RGE improving a sector like "the Higgs sector". We need the whole RGE evolution. Reality really does not care what basis you choose.

Consider the SM equations of motion:

Higgs:

$$D^2 H_k - \lambda v^2 H_k + 2\lambda (H^\dagger H) H_k + \overline{q}^j\, Y_u^\dagger\, u \epsilon_{jk} + \overline{d}\, Y_d\, q_k + \overline{e}\, Y_e\, l_k = 0$$

Gauge field:

$$i\not{D}\, q_j = Y_u^\dagger\, u\, \widetilde{H}_j + Y_d^\dagger\, d\, H_j\,, \qquad i\not{D}\, d = Y_d\, q_j\, H^{\dagger\, j}\,, \qquad i\not{D}\, u = Y_u\, q_j\, \widetilde{H}^{\dagger\, j}$$

$$i\not{D}\, l_j = Y_e^\dagger\, e H_j\,, \qquad i\not{D}\, e = Y_e\, l_j H^{\dagger\, j}\,,$$

Fermion:

$$[D^\alpha, G_{\alpha\beta}]^A = g_3 j_\beta^A\,, \qquad [D^\alpha, W_{\alpha\beta}]^I = g_2 j_\beta^I, \qquad D^\alpha B_{\alpha\beta} = g_1 j_\beta,$$

$$j_\beta^A = \sum_{\psi=u,d,q} \overline{\psi} T^A \gamma_\beta \psi\,,$$

$$j_\beta^I = \frac{1}{2}\overline{q}\,\tau^I \gamma_\beta q + \frac{1}{2}\overline{l}\,\tau^I \gamma_\beta l + \frac{1}{2} H^\dagger\, i\overleftrightarrow{D}_\beta^I H\,,$$

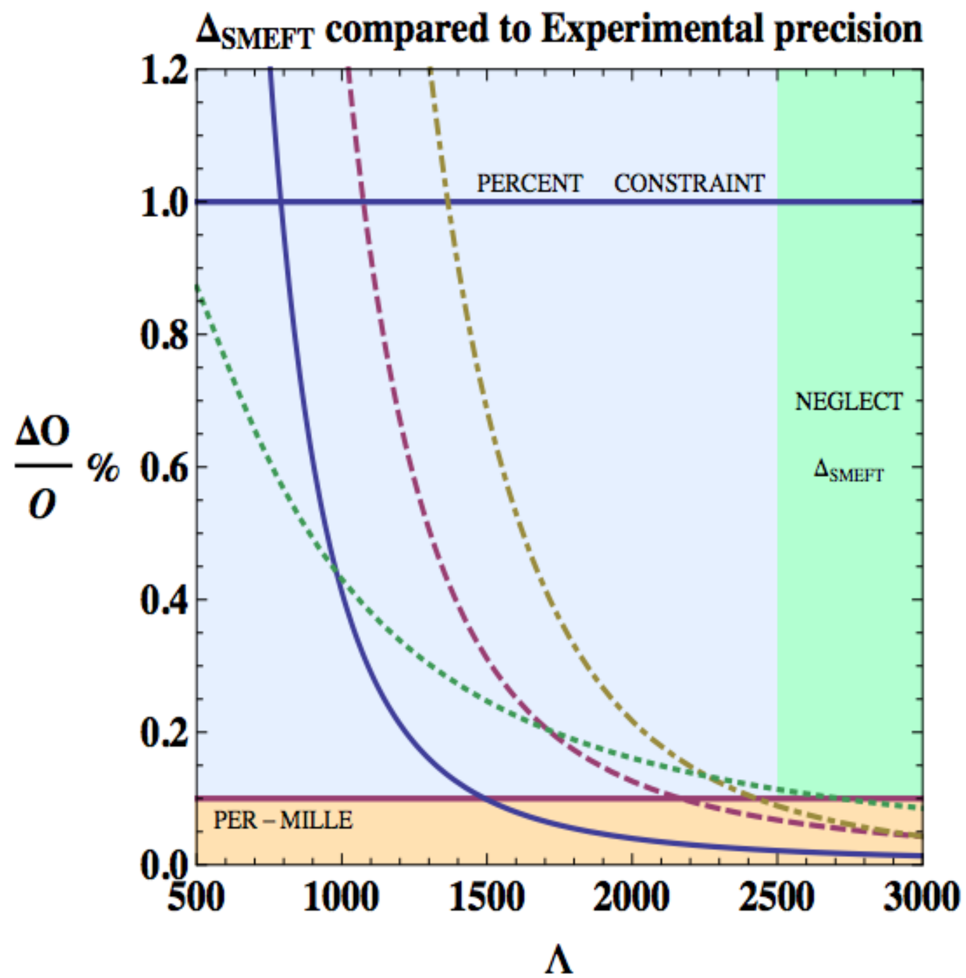
$$j_\beta = \sum_{\psi=u,d,q,e,l} \overline{\psi}\, \mathsf{y}_i \gamma_\beta \psi + \frac{1}{2} H^\dagger\, i\overleftrightarrow{D}_\beta H\,,$$

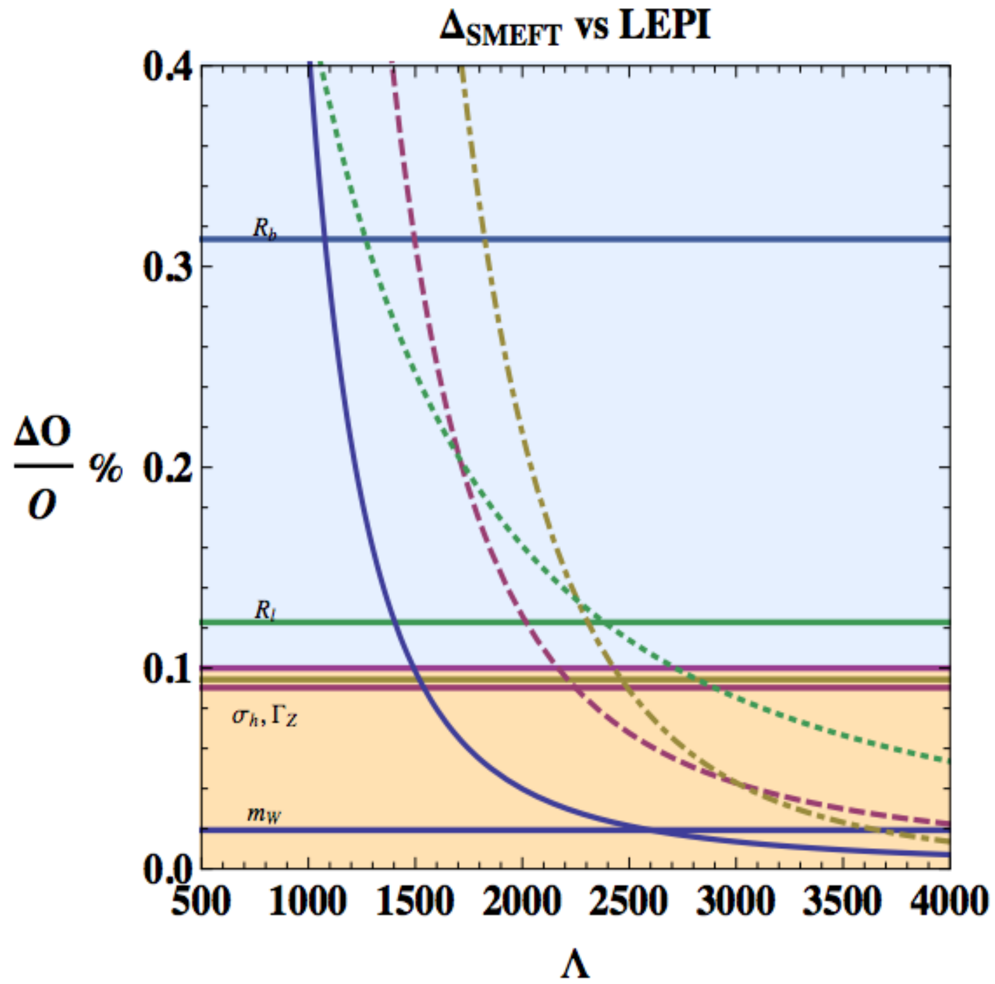
- We need to systematically improve the SMEFT to one loop, due to field redefinitions, do full one loop.
- I used to say Higgs EFT all the time. It is really SMEFT.

Global constraints on dim 6.

For precise observables, we can't ignore error in SMEFT itself:

arXiv:1508.05060 Berthier, Trott





Remember:

$$\frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$ 535+h.c. operators!

$$\Delta^i_{SMEFT}(\Lambda) \simeq \sqrt{N_8}\, x_i \, \frac{\bar{v}_T^4}{\Lambda^4} + \frac{\sqrt{N_6}\, g_2^2}{16\,\pi^2}\, y_i \log\left[\frac{\Lambda^2}{\bar{v}_T^2}\right] \frac{\bar{v}_T^2}{\Lambda^2}.$$

Neutrino Option Numerics

	Normal Hierarchy		Inverted Hierarchy	
	best fit	3σ range	best fit	3σ range
s_1^2	0.441	0.385 – 0.635	0.587	0.393 – 0.640
s_2^2	0.02166	0.01934 – 0.02392	0.02179	0.01953 – 0.02408
s_3^2	0.306	0.271 –0.345	0.306	0.271 – 0.345
$\delta(°)$	261	0 – 360	277	145 – 391
$\Delta m_{21}^2\,(10^{-5}\,\mathrm{eV}^2)$	7.50	7.03 – 8.09	7.50	7.03 – 8.09
$\Delta m_{3l}^2\,(10^{-3}\,\mathrm{eV}^2)$	2.524	2.407 – 2.643	-2.514	(-2.635) – (-2.399)

Table 1: Best fit values of neutrino parameters taken from the global fit in Ref. [35].

SMEFT up to sub-leading order ($\mathcal{L}^{(7)}$ corrections) but we restrict our attention to the matching onto $\mathcal{L}^{(5)}$ in this work.

	best fit	range
$\hat{G}_F$ [GeV^{-2}]	$1.1663787 \cdot 10^{-5}$	
$\hat{\alpha}_s(m_Z)$	0.1185	
$\hat{m}_Z$ [GeV]	91.1875	
$\hat{m}_W$ [GeV]	80.387	
$\hat{m}_h$ [GeV]	125.09	
$\hat{m}_t$ [GeV]	173.2	171 – 175
$\hat{m}_b$ [GeV]	4.18	
$\hat{m}_\tau$ [GeV]	1.776	

	tree	1-loop	2-loop
$\hat{\lambda}$	0.1291	0.1276	0.1258
$\hat{m}$ [GeV]	125.09	132.288	131.431
$\hat{g}_1$	0.451	0.463	0.461
$\hat{g}_2$	0.653	0.6435	0.644
$\hat{g}_3$	——	1.22029	——
$\hat{y}_t$	0.995	0.946	0.933
$\hat{y}_b$	0.024	-	-
$\hat{y}_\tau$	0.0102	-	-

Table 2: Left table: best fit values of the quantities used as inputs in the numerical analysis, while m_t is varied in the range specified. Right table: matching values for the SM parameters at $\mu = m_t$ obtained from the expressions in Appendix A in Ref. [42] with the inputs on the left when $m_t = 173.2\,\mathrm{GeV}$.

STXS data set

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$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
$t\bar{t}H$+tH leptonic (two tHX and one $t\bar{t}H$ categories)	$t\bar{t}H$
$t\bar{t}H$+tH hadronic (two tHX and four BDT $t\bar{t}H$ categories)	VH leptonic
VH dilepton	2-jet VH
VH one-lepton, $p_T^{\ell+\mathrm{MET}} \geq 150$ GeV	2-jet VBF, $p_T^{j1} \geq 200$ GeV
VH one-lepton, $p_T^{\ell+\mathrm{MET}} < 150$ GeV	2-jet VBF, $p_T^{j1} < 200$ GeV
VH E_T^{miss}, $E_T^{\mathrm{miss}} \geq 150$ GeV	1-jet ggF, $p_T^{4\ell} \geq 120$ GeV
VH E_T^{miss}, $E_T^{\mathrm{miss}} < 150$ GeV	1-jet ggF, 60 GeV$< p_T^{4\ell} <$120 GeV
VH+VBF$p_T^{j1} \geq 200$ GeV	1-jet ggF, $p_T^{4\ell} < 60$ GeV
VH hadronic (BDT tight and loose categories)	0-jet ggF
VBF, $p_T^{\gamma\gamma jj} \geq 25$ GeV(BDT tight and loose categories)	
VBF, $p_T^{\gamma\gamma jj} < 25$ GeV(BDT tight and loose categories)	
ggF 2-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	
ggF 2-jet, 120 GeV$\leq p_T^{\gamma\gamma} <$200 GeV	
ggF 2-jet, 60 GeV$\leq p_T^{\gamma\gamma} <$120 GeV	
ggF 2-jet, $p_T^{\gamma\gamma} < 60$ GeV	
ggF 1-jet, $p_T^{\gamma\gamma} \geq 200$ GeV	
ggF 1-jet, 120 GeV$\leq p_T^{\gamma\gamma} <$200 GeV	
ggF 1-jet, 60 GeV$\leq p_T^{\gamma\gamma} <$120 GeV	
ggF 1-jet, $p_T^{\gamma\gamma} < 60$ GeV	
ggF 0-jet (central and forward categories)	

Intermediate fit:

$$y_j = \sum_i A_{ji} \cdot r_i \cdot (\sigma_i \cdot \mathrm{B}_{4\ell})_{\mathrm{SM}} \cdot r_f \cdot \left(\frac{\mathrm{B}_f}{\mathrm{B}_{4\ell}}\right)_{\mathrm{SM}} \cdot \mathcal{L},$$

STXS data set

Measurement region	Result	Uncertainty Total	Stat.	Syst.		SM prediction
$B_{\gamma\gamma}/B_{4\ell}$	12.5	$^{+2.8}_{-2.3}$	$\left(^{+2.6}_{-2.2}\right.$	$\left.^{+0.8}_{-0.6}\right)$		18.1 ± 0.2
$gg \to H$ (0-jet)	29.7	$^{+7.3}_{-6.4}$	$\left(^{+6.6}_{-6.0}\right.$	$\left.^{+3.1}_{-2.4}\right)$	pb	27.6 ± 1.9 pb
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	4.4	$^{+4.8}_{-4.5}$	$\left(^{+4.4}_{-4.1}\right.$	$\left.^{+1.7}_{-1.8}\right)$	pb	6.6 ± 0.9 pb
$gg \to H$ (1-jet, $60 \leq p_T^H < 120$ GeV)	4.6	$^{+2.8}_{-2.4}$	$\left(^{+2.7}_{-2.4}\right.$	$\left.^{+0.7}_{-0.5}\right)$	pb	4.6 ± 0.7 pb
$gg \to H$ (1-jet, $120 \leq p_T^H < 200$ GeV)	1.6	$^{+1.1}_{-0.9}$	$\left(^{+1.0}_{-0.9}\right.$	$\left.^{+0.3}_{-0.2}\right)$	pb	0.75 ± 0.15 pb
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 200$ GeV or VBF-like)	10.6	$^{+4.7}_{-4.2}$	$\left(^{+4.3}_{-3.9}\right.$	$\left.^{+1.9}_{-1.4}\right)$	pb	4.8 ± 1.0 pb
$gg \to H$ ($\geq$ 1-jet, $p_T^H \geq 200$ GeV) + $qq \to Hqq$ ($p_T^j \geq 200$ GeV)	1.9	$^{+0.9}_{-0.7}$	$\left(^{+0.8}_{-0.7}\right.$	$\left.^{+0.3}_{-0.2}\right)$	pb	0.81 ± 0.16 pb
$qq \to Hqq$ ($p_T^j < 200$ GeV)	9.8	$^{+4.3}_{-3.5}$	$\left(^{+4.0}_{-3.2}\right.$	$\left.^{+1.5}_{-1.4}\right)$	pb	$4.58^{+0.15}_{-0.18}$ pb
$gg/qq \to H\ell\ell/H\ell\nu$	0.2	$^{+0.9}_{-0.7}$	$\left(^{+0.8}_{-0.7}\right.$	$\left.\pm 0.2\right)$	pb	$0.63^{+0.03}_{-0.06}$ pb
$q\bar{q}/gg \to t\bar{t}H$	0.3	$^{+0.5}_{-0.4}$	$\left(^{+0.5}_{-0.4}\right.$	$\left.\pm 0.1\right)$	pb	$0.59^{+0.04}_{-0.05}$ pb

Intermediate fit: $$y_j = \sum_i A_{ji} \cdot r_i \cdot (\sigma_i \cdot B_{4\ell})_{SM} \cdot r_f \cdot \left(\frac{B_f}{B_{4\ell}}\right)_{SM} \cdot \mathcal{L},$$