A Neutrino Option for the Higgs Potential.

Michael Trott

Affiliations: NBIA & Discovery Center, Copenhagen University.

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

This conversation was the initial motivation for this work:

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

A: "Yes."

SCALAR~~S~~ 2017

Just one potential

But, perhaps, a good option for that.

The Higgs potential is weird

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

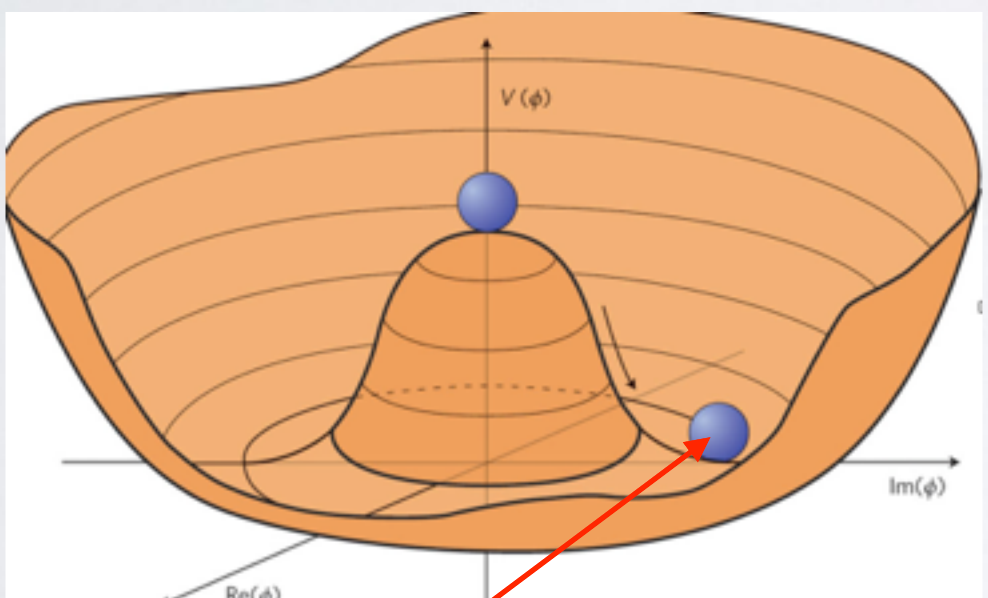
$$S_H = \int d^4x \left(|D_\mu H|^2 - \lambda\left(H^\dagger H - \frac{1}{2}v^2\right)^2\right),$$

Partial Higgs action

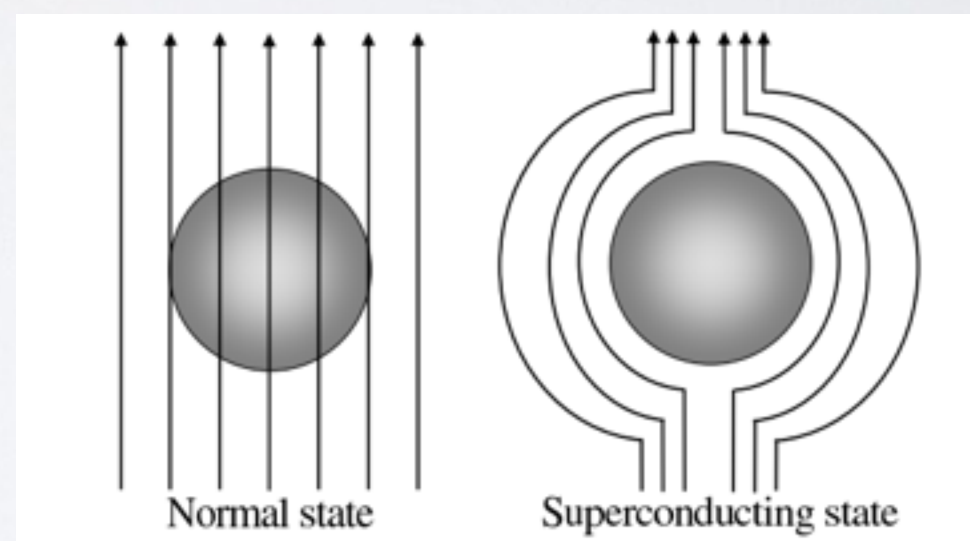
$$LG(s) = \int_{\Re^3} dx^3 \left[\frac{1}{2}|(d - 2\,i\,e\,A)s|^2 + \frac{\gamma}{2}\left(|s|^2 - a^2\right)\right],$$

Landau-Ginzberg actional, parameterization of Superconductivity

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



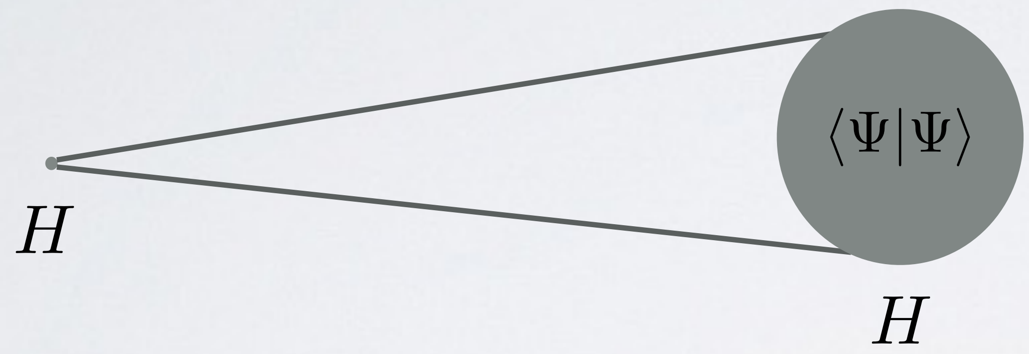
$m_{W/Z} = 0$ field config. energetically excluded
(i.e. Higgs'd $SU(2)_L \times U(1)_Y \to U(1)_Q$)



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 can try and construct the Higgs potential with QFT



- Naturally leads to the idea of composite Higgs field due to some new strong interaction

Kaplan, Georgi, Dimopoulos, Dugan 84-85

- Initial efforts studied the induced potential of a scalar and used vacuum misalignment to get $SU(2)_L \times U(1)_Y \to U(1)_Q$

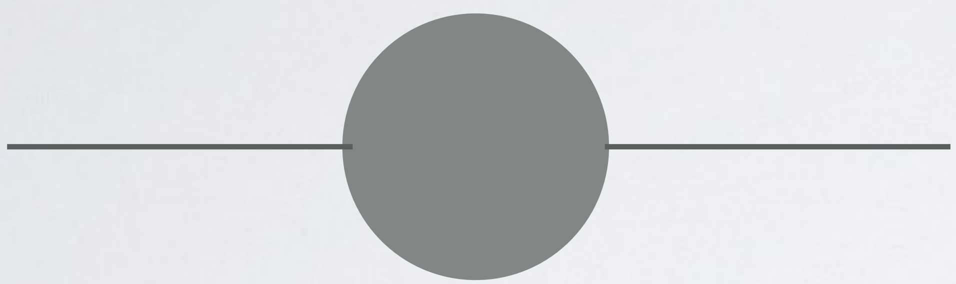
$$\Sigma(x) = e^{i\Pi_a T^a/f}\, U\, e^{i\Pi_a T^a/f} \qquad \mathcal{L} = \frac{f^2}{4}(D_\mu \Sigma)(D^\mu \Sigma)^T + \Lambda^4 \mathrm{Tr}\left[T^a \Sigma (T^a)^T \Sigma^\dagger\right] + \cdots$$

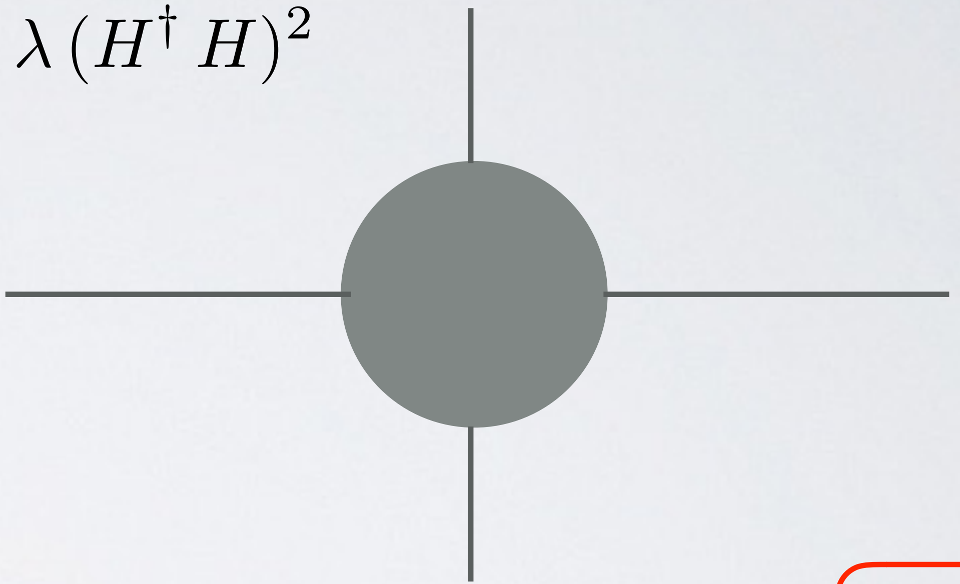
- Group theory embedding of SM into larger global sym groups exhaustively studied

Challenge of constructing potential

- As we have measured a Higgs (like) mass, what can we infer ?

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





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

The problem.

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

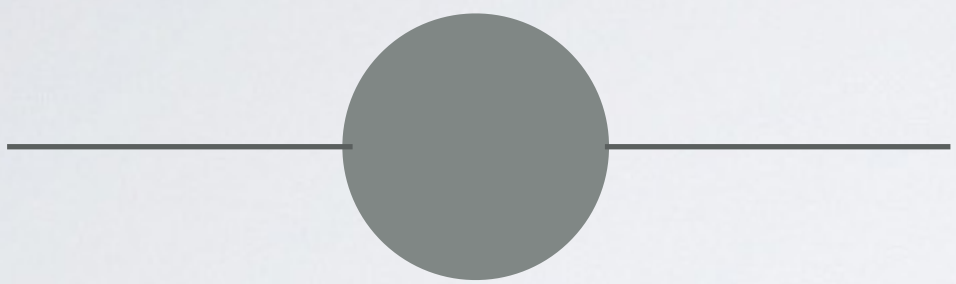
$$V(H) \simeq \frac{g_{SM}^2 \, \Lambda^2}{16\,\pi^2} \left(-2\,a H^\dagger H + 2b \frac{(H^\dagger H)^2}{f^2} \right)$$ see 1401.2457 Bellazzini et al

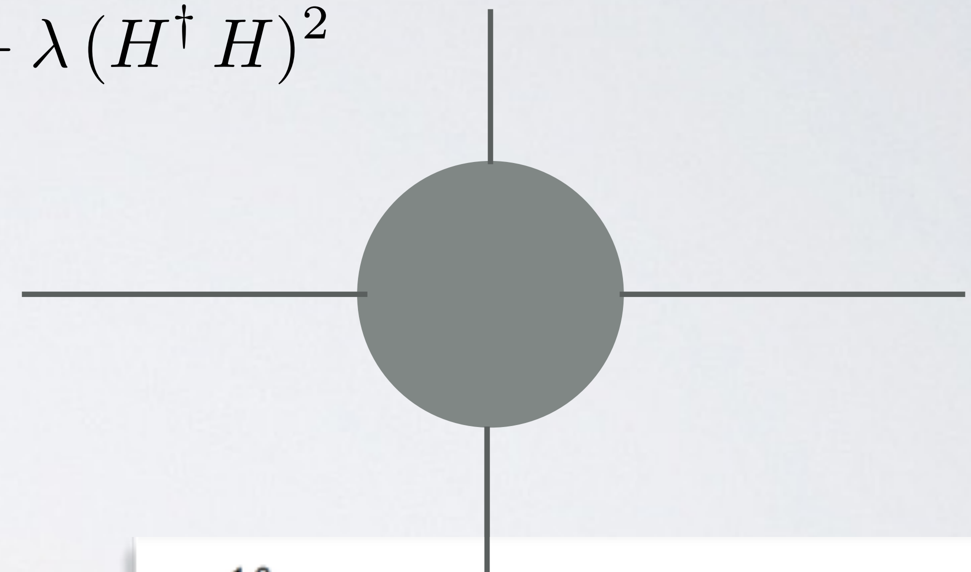
- Can get the quartic to work: $\sim 0.1 \left(\frac{g_{SM}}{N_c \, y_t} \right)^2 \left(\frac{\Lambda}{2\,f} \right)^2$ for $\Lambda / f \ll 4\,\pi$ weak coupling implied, lighter new states

Challenge of constructing potential.II

- As we have measured a Higgs (like) mass, what can we infer ?

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



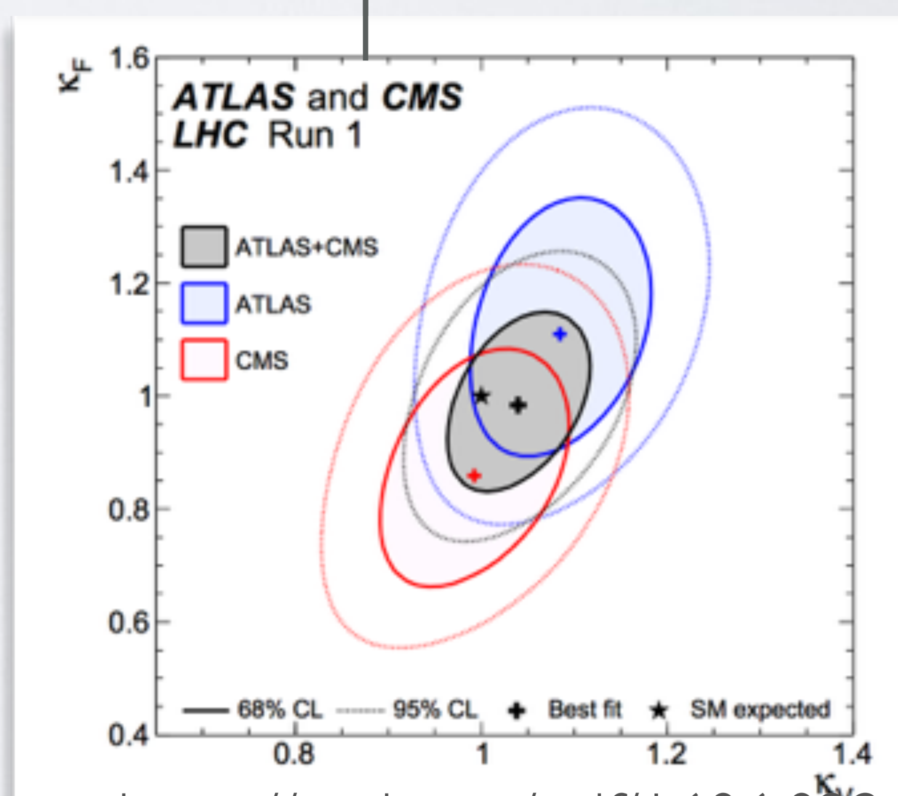


- Higgs coupling deviations scale as

$$\sim 1 - \frac{v^2}{f^2}$$

but pheno studies imply $f \gtrsim \mathrm{TeV}$

And global results show the shifts going in the wrong direction.

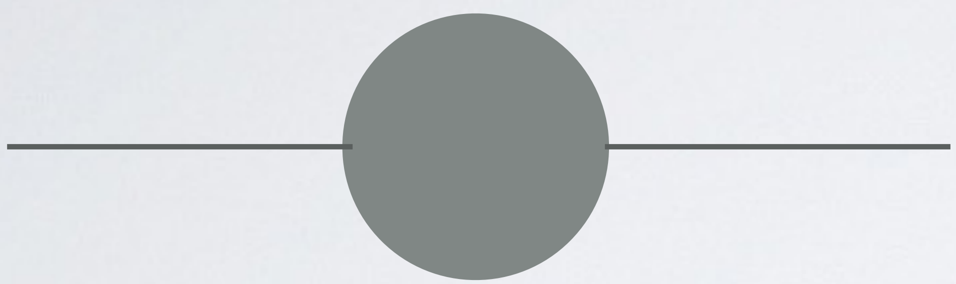


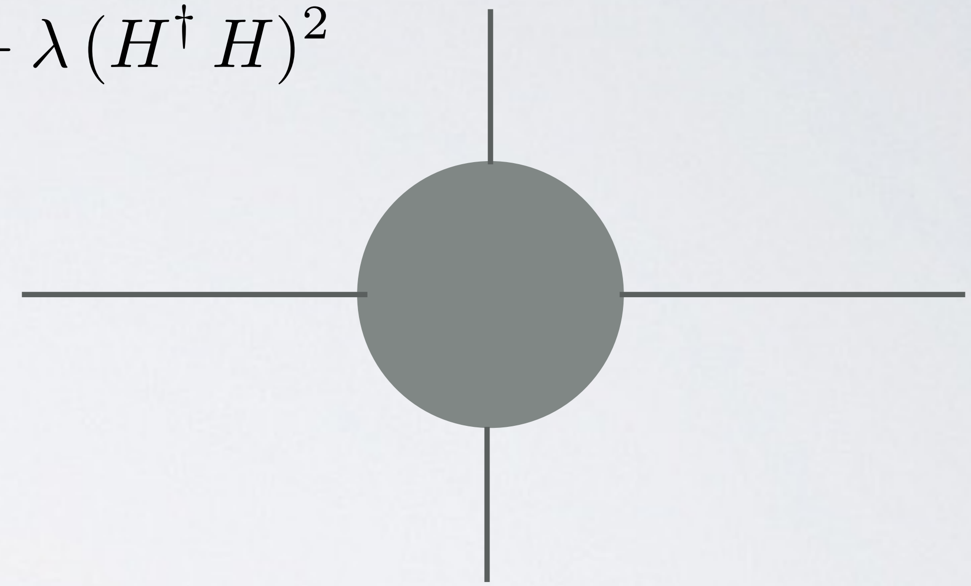
https://arxiv.org/pdf/1606.02266.pdf

Challenge of constructing potential.II

- As we have measured a Higgs (like) mass, what can we infer ?

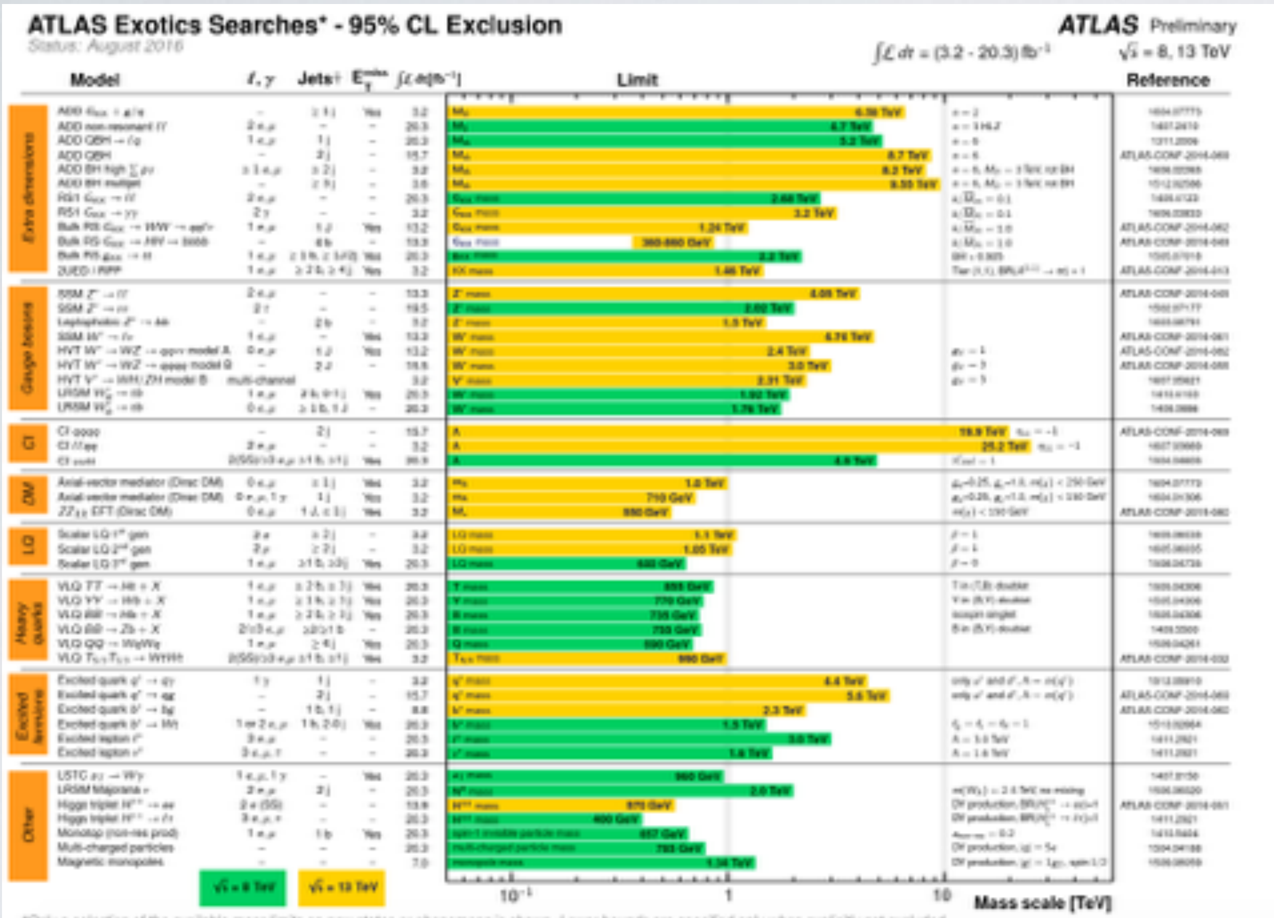
$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$



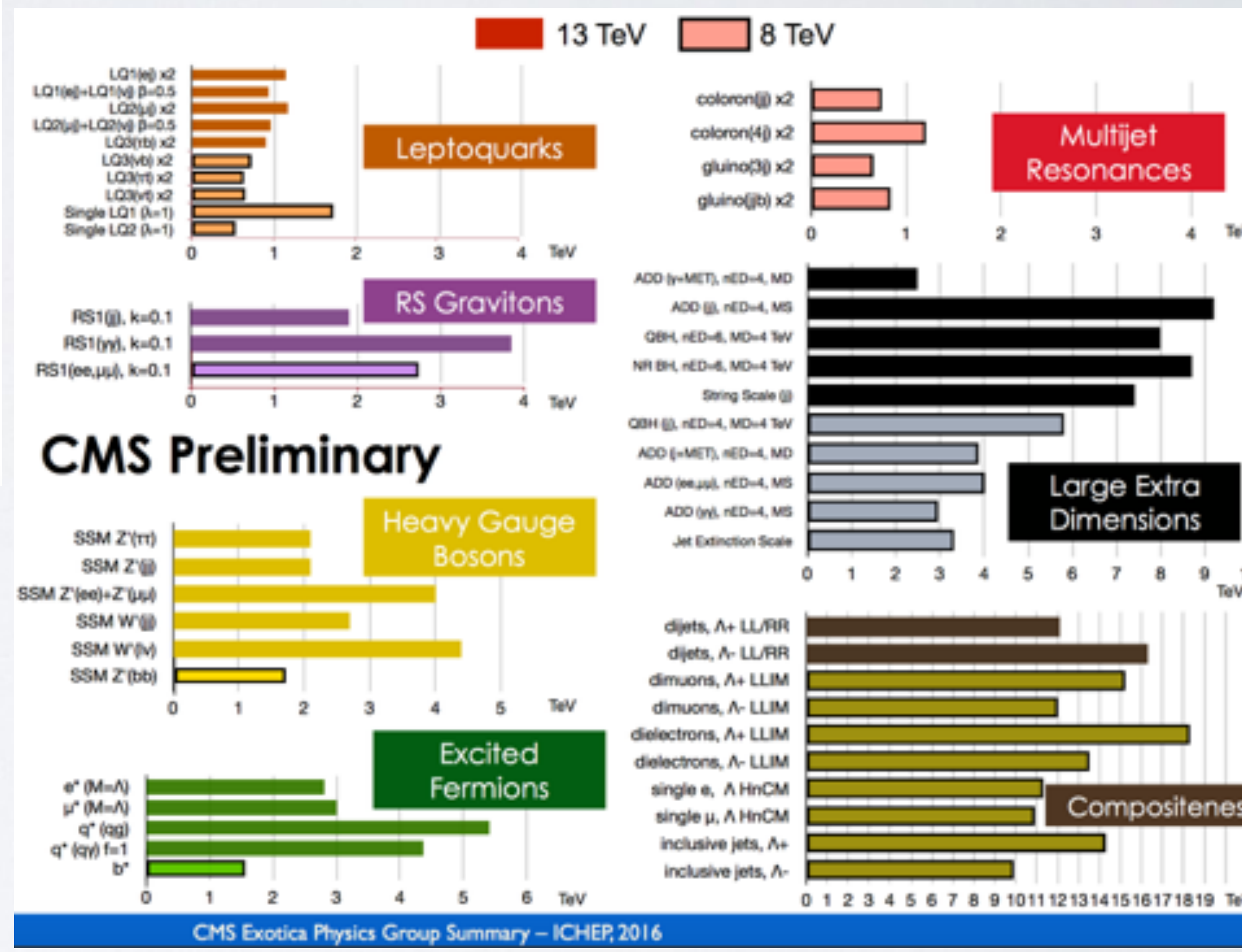


- Where are the new states at a weakly coupled mass scale below the full cut off?
- Extensive tuning in these models: see 1401.2457 Bellazzini et al,
- A basic reason, quantum contributions to the 2 point and 4 point functions linked until model building to break the link
- This problem challenged the composite idea initially. Modern models introduce tunings and are constructed to avoid this. Generic feature - tev or below states to construct potential.

Even weirder.



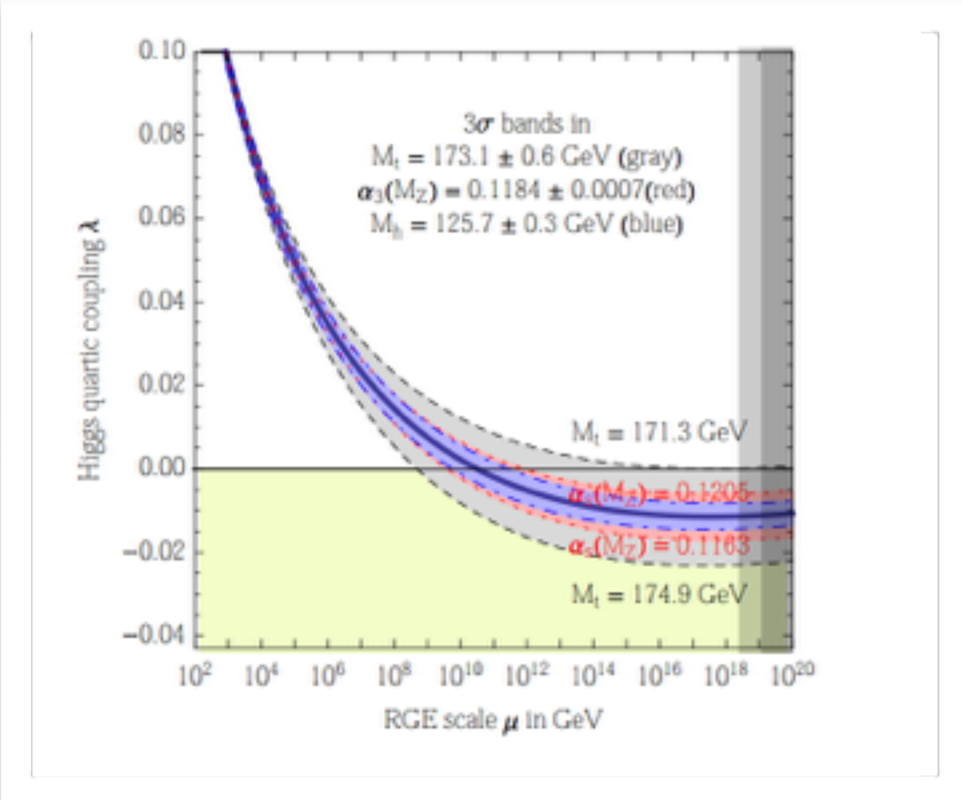
- Despite well motivated hopes, resonance searches currently not giving new states.



- Partners should have shown, or should soon show.

A set of clues?

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



- Observed mass spectrum is such that the running of the quartic does something interesting

  tied to $y_t(m_h) \simeq 1!$

- Fields of the SMEFT, and charges are such that operator dimension (d) in SMEFT has non trivial relation to global symmetries

  Kobach arXiv:1604.05726, de Gouvea, Herrero-Garcia, Kobach rXiv:1404.4057

$$d = (\Delta B - \Delta L)/2 \bmod 2$$

Even dimension operators $\Delta B = \Delta L$

Odd dimension violate Baryon or Lepton number

- Proof essentially follows from $U(1)_Y$ conservation + Lorentz invariance. From Kobach:

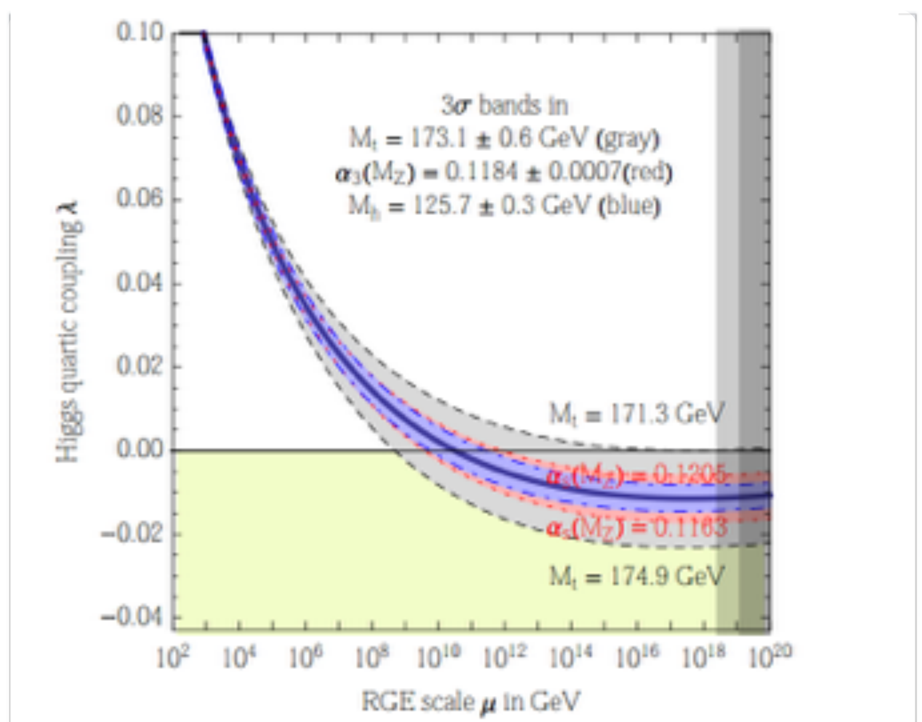
$$0 = \frac{1}{3}(N_Q - N_{Q^\dagger}) - \frac{4}{3}(N_u - N_{u^\dagger}) + \frac{2}{3}(N_d - N_{d^\dagger}) - (N_L - N_{L^\dagger}) + 2(N_e - N_{e^\dagger}) + (N_H - N_{H^*})$$

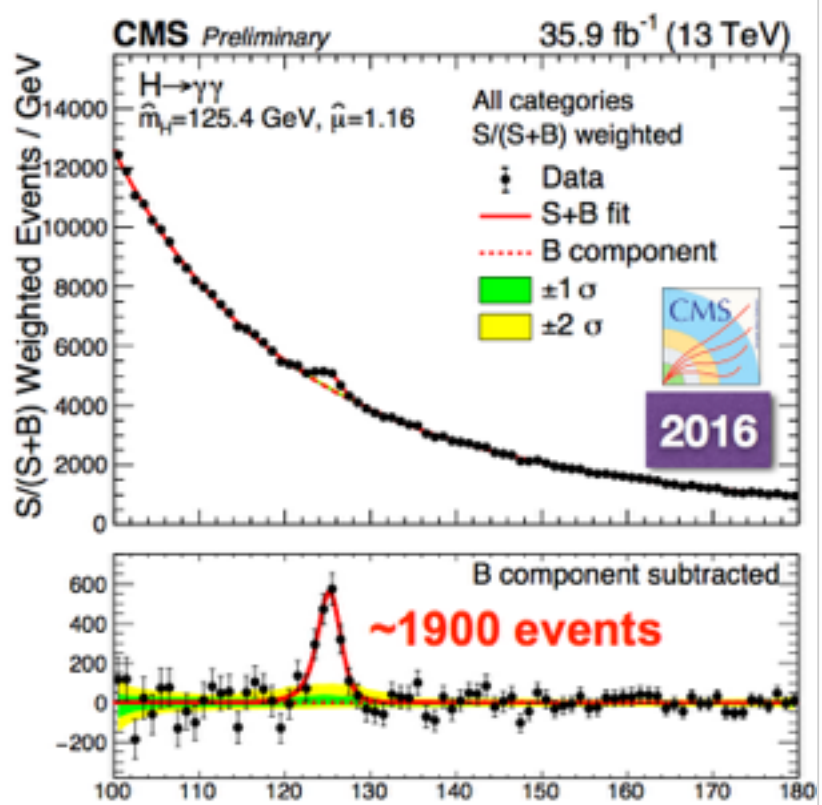
if N_D is even (odd), then $(N_{Q^\dagger} + N_{u^\dagger} + N_{d^\dagger} + N_{L^\dagger} + N_{e^\dagger} + N_{\nu^\dagger})$ is even (odd).

if N_D is even (odd), then $(N_Q + N_u + N_d + N_L + N_e + N_\nu)$ is even (odd),

A set of clues?

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





LANDSBERG's talk Thursday

- Observed mass spectrum is such that the running of the quartic does something interesting

  tied to $y_t(m_h) \simeq 1!$

- Fields of the SMEFT, and charges are such that operator dimension (d) in SMEFT has non trivial relation to global symmetries

  Kobach arXiv:1604.05726, de Gouvea, Herrero-Garcia, Kobach rXiv:1404.4057

$$d = (\Delta B - \Delta L)/2 \mod 2$$

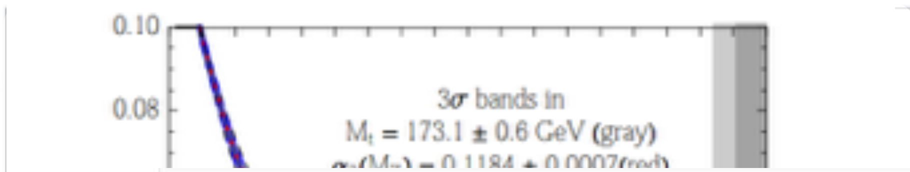
Even dimension operators $\Delta B = \Delta L$

Odd dimension violate Baryon or Lepton number

- We seem to have a d=2 operator related to this bump, and massive W,Z

A set of clues?

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



LANDSBERG's talk Thursday

- Observed mass spectrum is such that the running of the quartic does something interesting

r

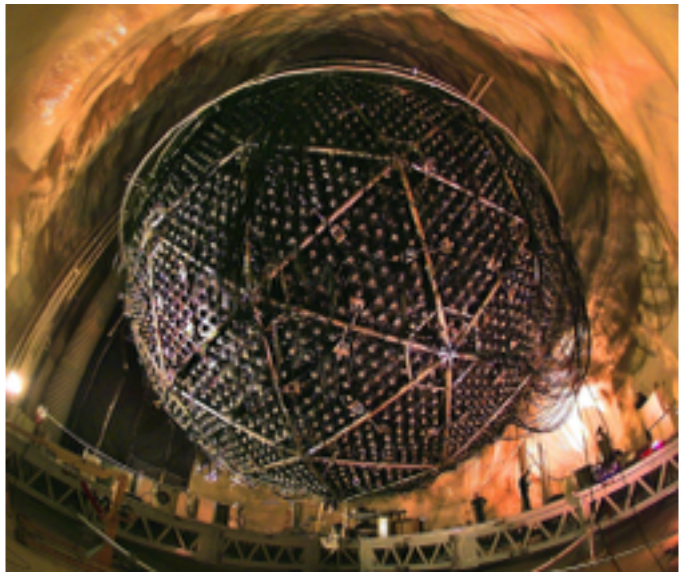
)4.4057

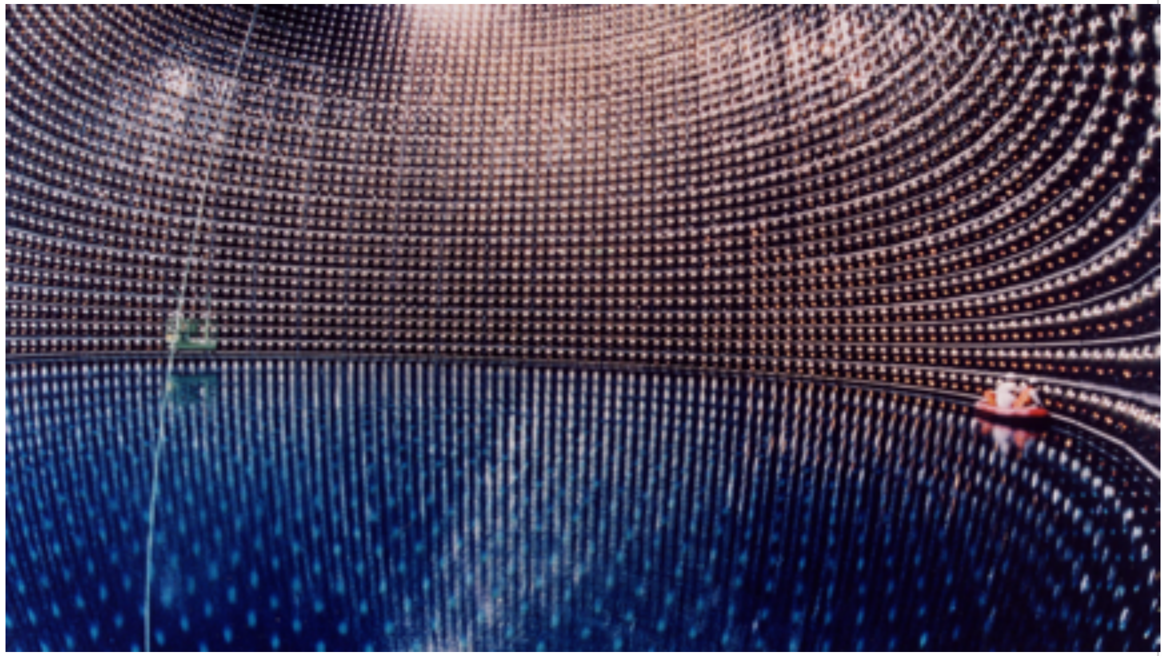
- Neutrino's have mass

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

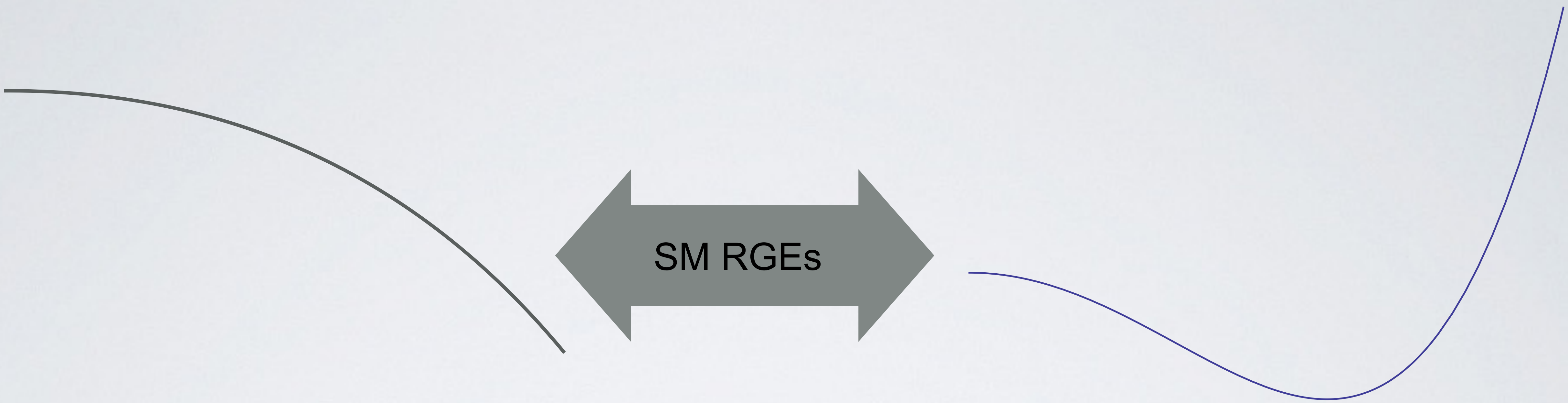
Photo: A. Mahmoud
Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*





Idea is use the non trivial spectrum we have

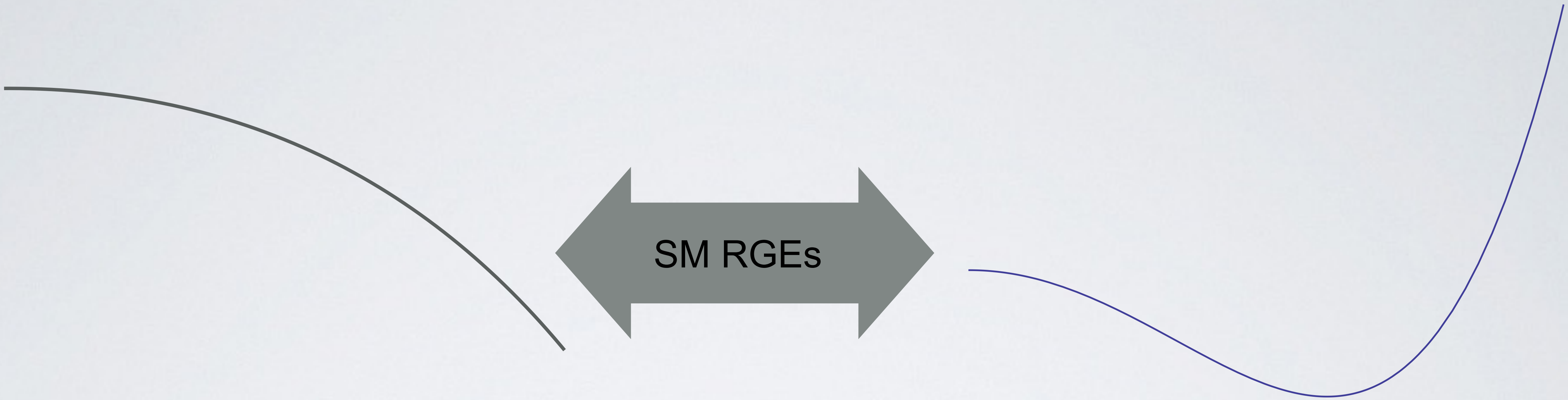


- Still need a non trivial spectrum with lots of interactions (and some weird couplings) to generate a non trivial potential. But lets use the weird spectrum we have.

$$
\begin{aligned}
\mathcal{L}_{\rm SM} = & -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q,u,d,\ell,e} \bar{\psi}\, i \not{D}\, \psi \\
& + (D_\mu H)^\dagger (D^\mu H) - \lambda \left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\bar{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\bar{u}\, Y_u\, q_j + H^{\dagger j}\bar{e}\, Y_e\, \ell_j + \text{h.c.}\right],
\end{aligned}
$$

Field	$\mathrm{SU_c(3)}$	$\mathrm{SU_L(2)}$	$\mathrm{U_Y(1)}$	$\mathrm{SO^+(3,1)}$
$q_i = (u^i_L, d^i_L)^T$	**3**	**2**	$1/6$	$(1/2, 0)$
$u_i = \{u_R, c_R, t_R\}$	**3**	**1**	$2/3$	$(0, 1/2)$
$d_i = \{d_R, s_R, b_R\}$	**3**	**1**	$-1/3$	$(0, 1/2)$
$\ell_i = (\nu^i_L, e^i_L)^T$	**1**	**2**	$-1/2$	$(1/2, 0)$
$e_i = \{e_R, \mu_R, \tau_R\}$	**1**	**1**	-1	$(0, 1/2)$
H	**1**	**2**	$1/2$	$(0, 0)$

Turns out the SM can do it.

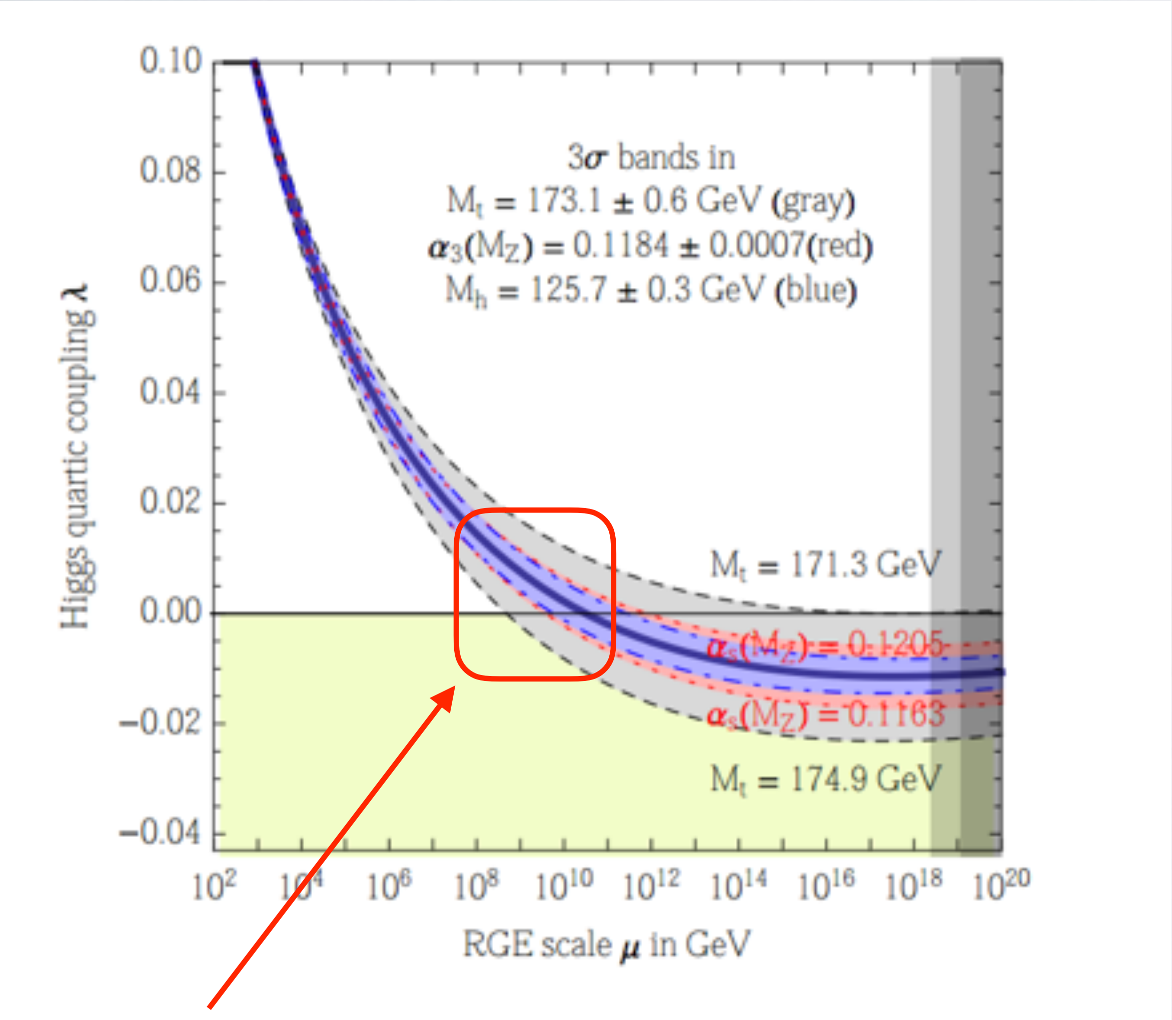


- Lets use the weird spectrum we have expressed through the SM RGE's

$$
\begin{aligned}
\beta(g_Y^2) &= g_Y^4 \frac{41}{6}, \; \beta(g_2^2) = g_2^4 \left(-\frac{19}{6}\right), \; \beta(g_3^2) = g_3^4(-7), \\
\beta(\lambda) &= \left[\lambda \left(12\lambda + 6Y_t^2 - \frac{9}{10}(5g_2^2 + \frac{5\,g_Y^2}{3})\right)\right. \\
&\quad \left. - \; 3Y_t^4 + \frac{9}{16}g_2^4 + \frac{3}{16}g_Y^4 + \frac{3}{8}g_Y^2 g_2^2\right], \\
\beta(m^2) &= m^2 \left[6\lambda + 3Y_t^2 - \frac{9}{20}(5g_2^2 + \frac{5\,g_Y^2}{3})\right], \\
\beta(Y_t^2) &= Y_t^2 \left[\frac{9}{2}Y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_Y^2\right].
\end{aligned}
$$

Different interpretation of famous result

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



Interesting mass scales are 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 $\lambda \sim 0$

Rather unexplored till now.

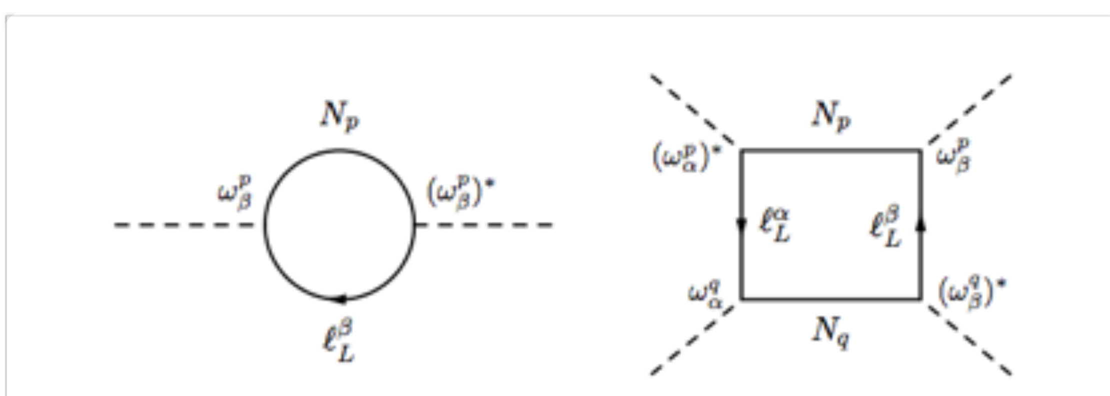
Simplest example of building the potential

- Add the simplest thing we can, a singlet fermion with a heavy mass scale to the SM

- $\tilde{H} L$ only thing we can then couple to to make a Lorentz and gauge singlet

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

- How such a fermion talks to the SM at $d \leq 4$



- Direct threshold matching onto $\mathcal{L}_{SM}$

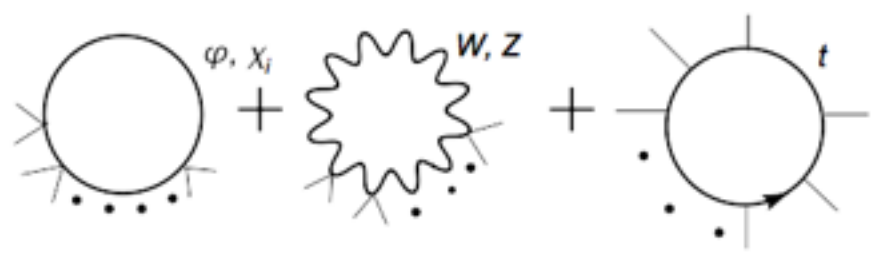
$$
\Delta m^2 = m_p^2\frac{|\omega_p|^2}{8\,\pi^2}, \quad \Delta\lambda = -5\,\frac{(\omega_q\cdot\omega^{p,\star})(\omega_p\cdot\omega^{q,\star})}{64\,\pi^2}.
$$

In agreement with J. A. Casas et al.
Phys. Rev. D 62, 053005 (2000) others..

- λ still has to be small, but at high scales, that is fine!

- Consistent with decoupling approach to eff potential of 9809275 Casas, Clemente, Quiros

This threshold matching should be done to CW



- Construct quantum corrections:

$$V_{CW} = \frac{m_h^4(\phi)}{64\pi^2}\left[\log\frac{m_h(\phi)^2}{\mu^2} - \frac{3}{2}\right] + \cdots$$

General point of view present in Bardeen 95, Lindner et al (many works), 1404.6260 Davoudiasl, Lewis

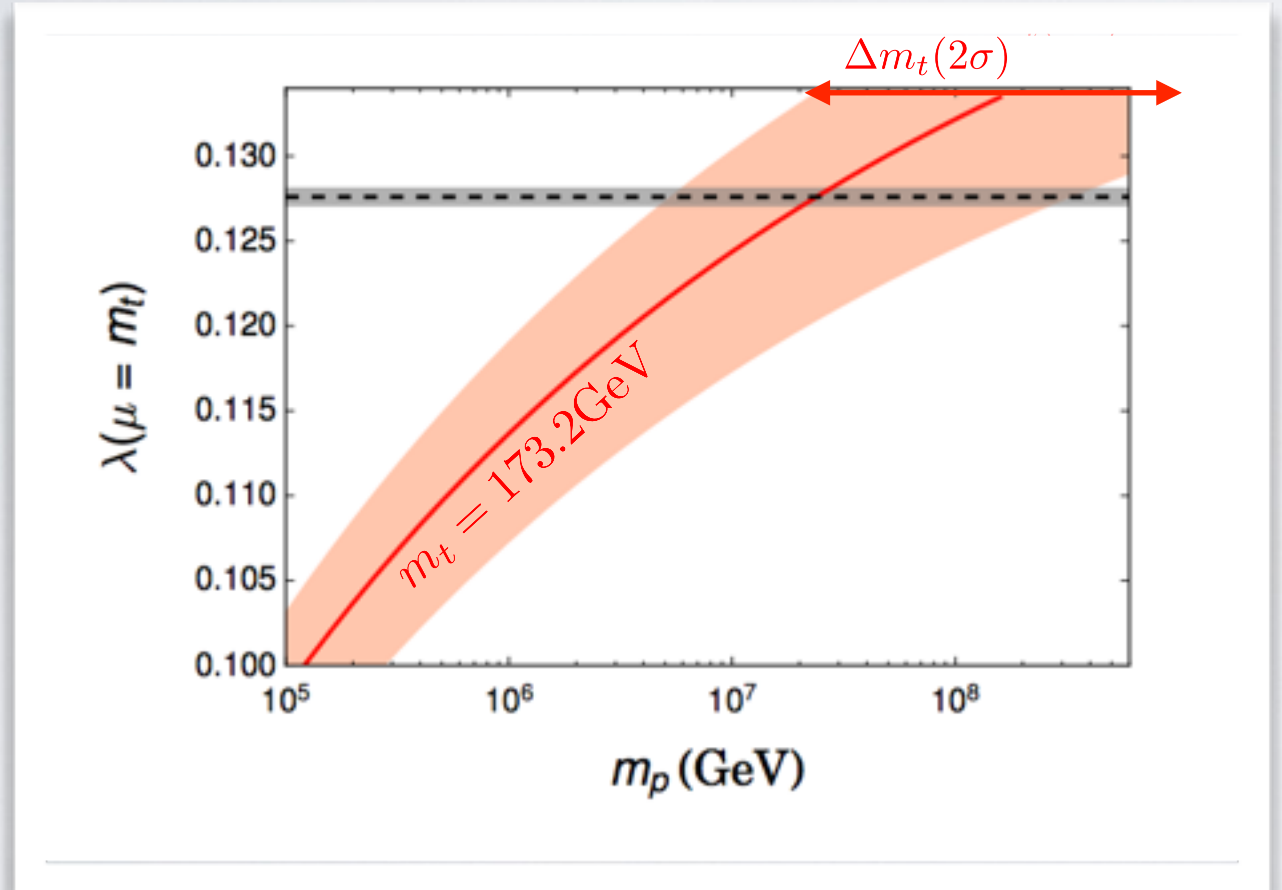
- If $m_p \gg v, \Lambda_i$ such a threshold matching can dominate the potential and give low scale pheno that is the SM. IR scales are
  - v_0 Can be small Doesn't have to be 0.
  - Λ_{QCD} Known to be smaller than induced vev.
  - μ_{CW} Exponentially separated due to asy nature of pert theory.

- It has long been known that such threshold corrections are a direct representation of the Hierarchy problem F. Vissani, Phys. Rev. D 57, 7027 (1998)

- Neutrino Option: Can one go the full way of dominantly generating the EW scale and Higgs potential in this manner ?

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



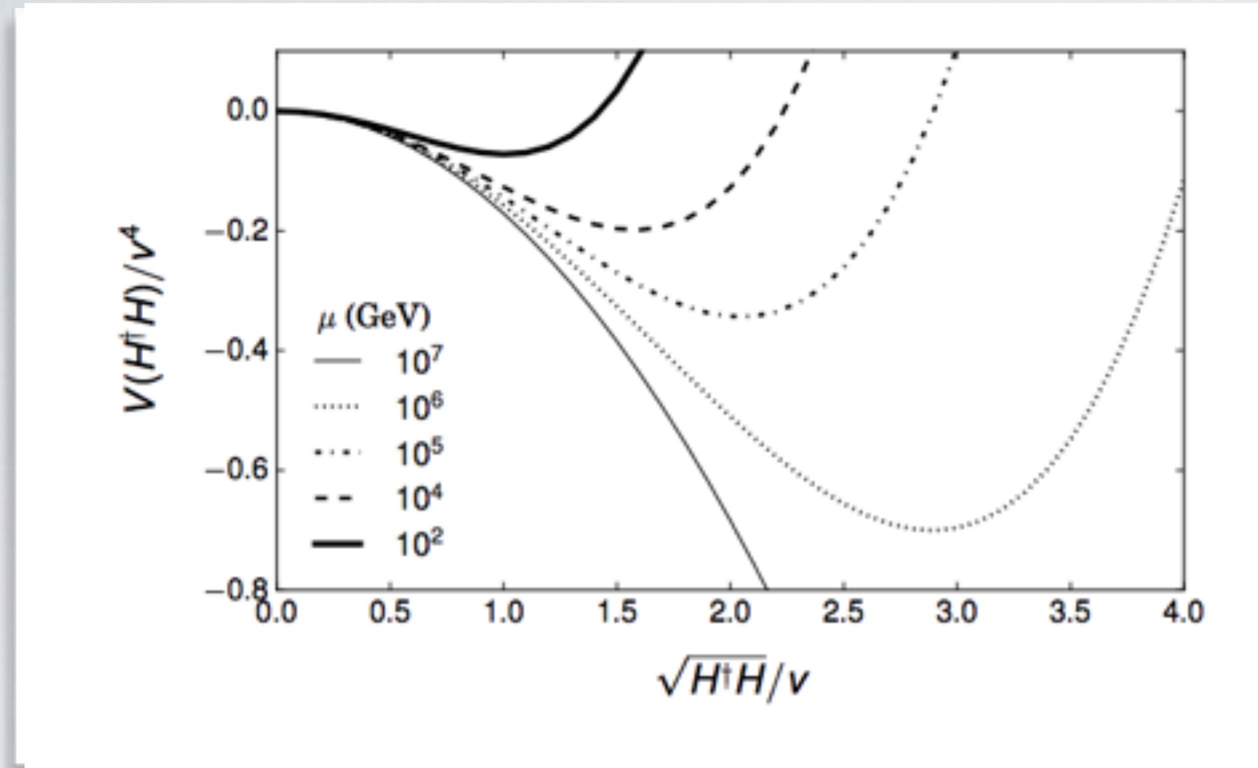
- Can get the troublesome $\lambda \sim 0.13$
- Parameter space chosen to fix the mass scale and couplings (large uncertainties) and get Higgs potential

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

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

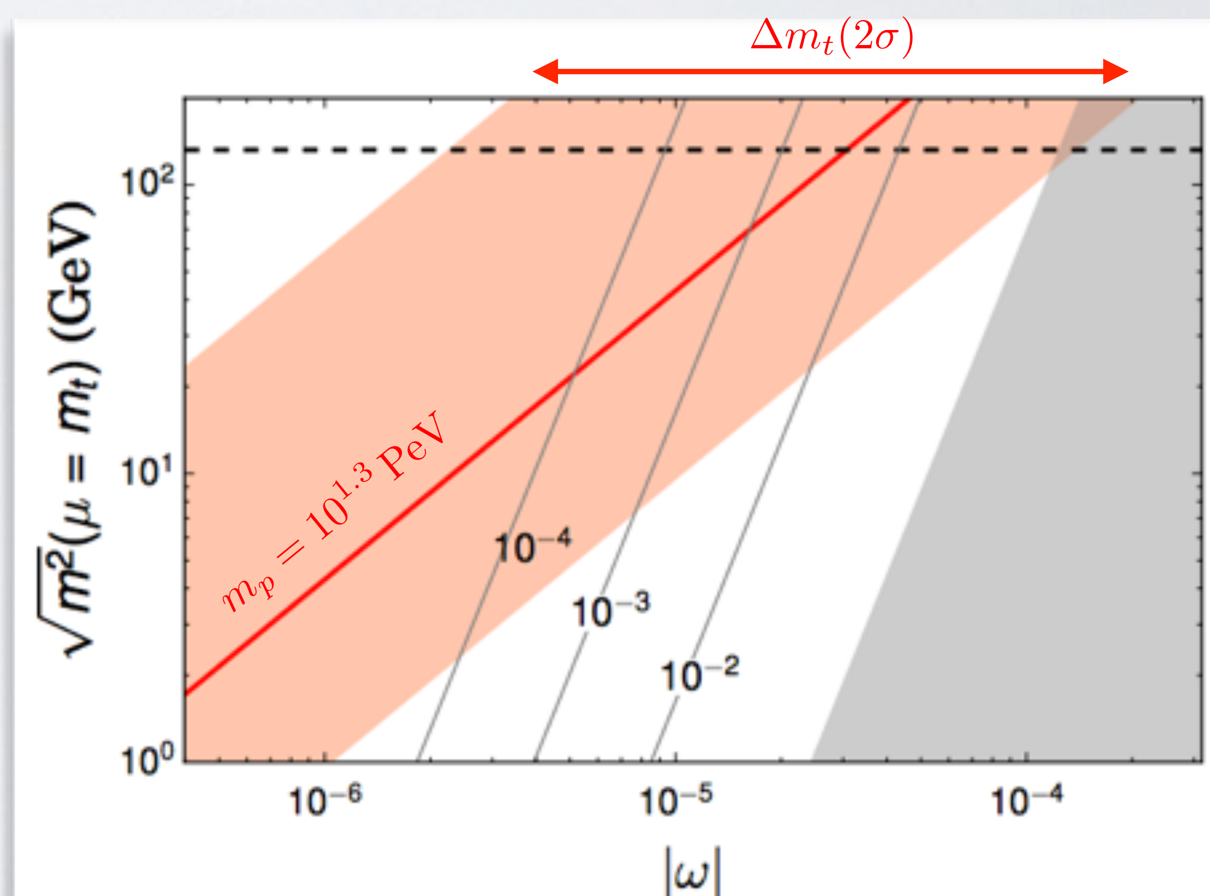
- Expand around the classically scaleless limit of the SM. Punch the potential with threshold matching you kick off lower scale $SU(2)_L \times U(1)_Y \to U(1)_Q$?

Higgs potential. Check. Neutrino mass scale. ~Check.



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

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

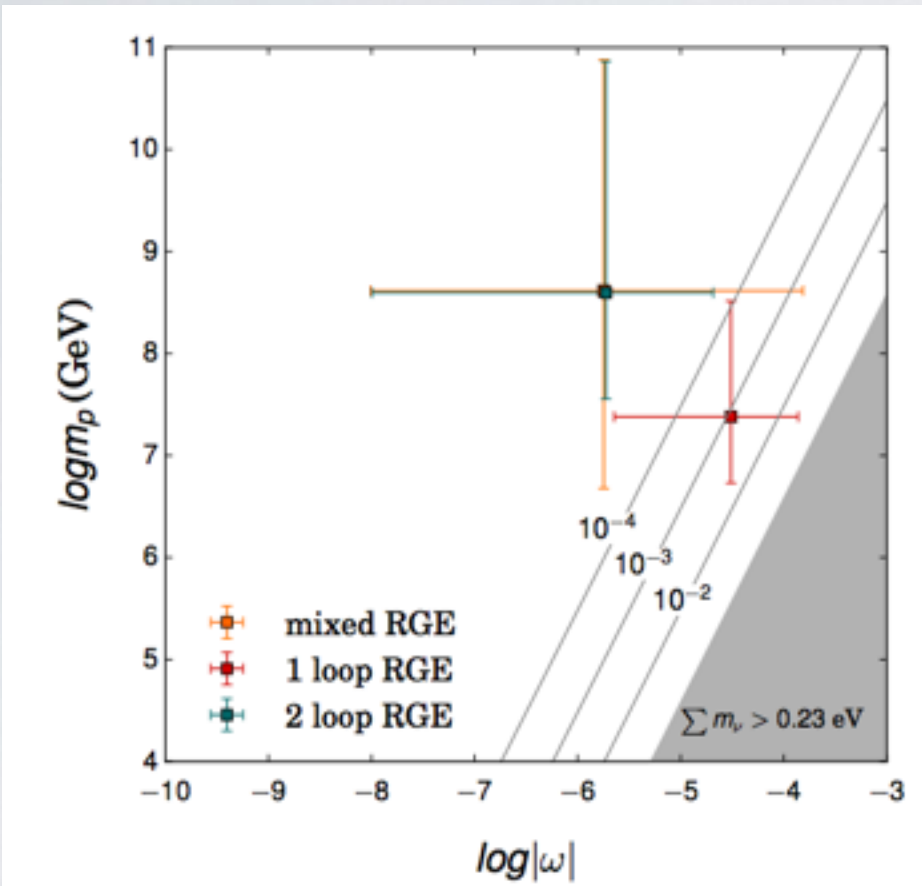


- In a non-trivial manner as well - the right neutrino mass scale (diff) can result.

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

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

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. Minor symmetry protection mechanism against other threshold corrections global: $d = (\Delta B - \Delta L)/2 \bmod 2$

- No leptogenesis in this parameter space
  1404.6260 Davoudiasl, Lewis

- We can't seem to find a way to rule it out as yet/confirm it. We can get the mass spectrum at one and 2 loop running despite plot.

- No dynamical origin of the Majorana scale supplied. So the IR limit taken is not clearly self consistent. Needs more UV model building

Neutrino option: What else do you get?

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

C^5 seems to be non-zero (answer to the motivating question)

- What is the pattern of other effects that is encoded in the SMEFT Lagrangian?

IF a source of L number violation and a fermion:

L number violation protection

Tree level matching
L violation

Tree level matching
L protection

Tree level matching
L violation

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

Follows from Kobach arXiv:1604.05726, de Gouvea, Herrero-Garcia, Kobach rXiv:1404.4057

Seesaw model to SMEFT.

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

- What is the pattern of other effects that is encoded in the SMEFT Lagrangian?

IF a source of L number violation and a fermion:

L number violation protection

one loop matching

Tree level matching
L violation

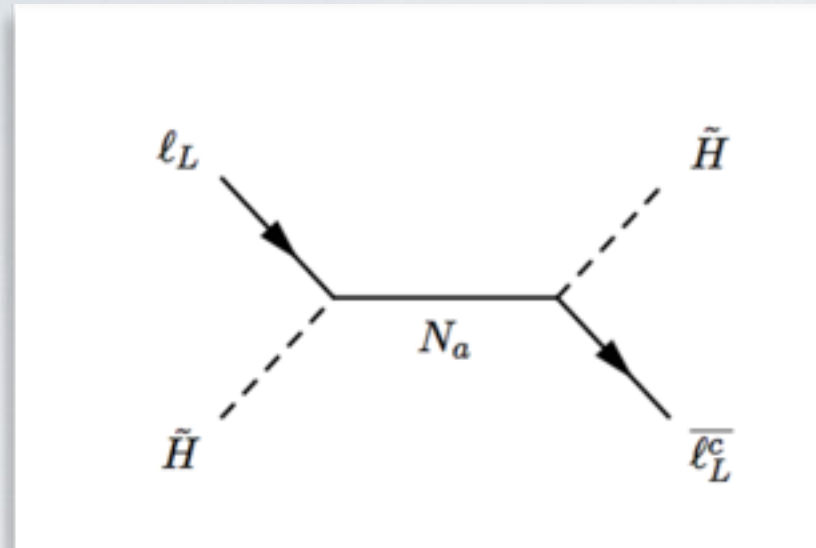
Tree level matching
L protection

Tree level matching
L violation

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

Seesaw model to SMEFT.

- Integrating out the seesaw at tree level



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

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 need some complex math, inner and outer products on $x, y \in \mathbb{C}^3$.

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

From Cayley

d=6 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)

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

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

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

v

d=6 matching

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

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

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

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

N_1

N_2

N_3

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

- As a Majorana scale in the EOM:

$$\not{\partial} N_p = -i \left(m_p \, N_p + w_\beta^{p,\star} \tilde{H}^T \ell_L^{c\beta} + w_\beta^p \tilde{H}^\dagger \ell_L^\beta \right)$$

which also gives the extra matching contributions

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

v

Keeping track of all the terms is critical it turns out, as a set of cancelations occur.

d=7 matching

- Summary of dim 7 results:

$1: \psi^2 H^4 + \text{h.c.}$	
$\mathcal{Q}_{\ell H}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \ell_L^m) H^j H^n (H^\dagger H)$

$2: \psi^2 H^2 D^2 + \text{h.c.}$	
$\mathcal{Q}^{(1)}_{\ell HD}$	$\epsilon_{ij}\epsilon_{mn}\ell_L^i C (D^\mu \ell_L^j) H^m (D_\mu H^n)$
$\boxed{\mathcal{Q}^{(2)}_{\ell HD}}$	$\epsilon_{im}\epsilon_{jn}\ell_L^i C (D^\mu \ell_L^j) H^m (D_\mu H^n)$

$3: \psi^2 H^3 D + \text{h.c.}$	
$\boxed{\mathcal{Q}_{\ell HDe}}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \gamma_\mu e_R) H^j H^m D^\mu H^n$

$4: \psi^2 H^2 X + \text{h.c.}$	
$\boxed{\mathcal{Q}_{\ell HB}}$	$\epsilon_{ij}\epsilon_{mn}(\ell_L^i C \sigma_{\mu\nu} \ell_L^m) H^j H^n B^{\mu\nu}$
$\boxed{\mathcal{Q}_{\ell HW}}$	$\epsilon_{ij}(\tau^I \epsilon)_{mn}(\ell_L^i C \sigma_{\mu\nu} \ell_L^m) H^j H^n W^{I\mu\nu}$

$5: \psi^4 D + \text{h.c.}$	
$\mathcal{Q}^{(1)}_{\ell\ell\bar{d}uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C D^\mu \ell_L^j)$
$\mathcal{Q}^{(2)}_{\ell\ell\bar{d}uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell_L^i C \sigma^{\mu\nu} D_\nu \ell_L^j)$
$\mathcal{Q}^{(1)}_{\bar{\ell}QddD}$	$(Q_L C \gamma_\mu d_R)(\overline{\ell_L} D^\mu d_R)$
$\mathcal{Q}^{(2)}_{\bar{\ell}QddD}$	$(\overline{\ell_L}\gamma_\mu q_L)(d_R C D^\mu d_R)$
$\mathcal{Q}_{ddd\bar{e}D}$	$(\overline{e_R}\gamma_\mu d_R)(d_R C D^\mu d_R)$

$6: \psi^4 H + \text{h.c.}$	
$\boxed{\mathcal{Q}_{\ell\ell\bar{e}H}}$	$\epsilon_{ij}\epsilon_{mn}(\overline{e_R}\ell_L^i)(\ell_L^j C \ell_L^m) H^n$
$\boxed{\mathcal{Q}^{(1)}_{\ell\ell Q\bar{d}H}}$	$\epsilon_{ij}\epsilon_{mn}(\overline{d_R}\ell_L^i)(q_L^j C \ell_L^m) H^n$
$\boxed{\mathcal{Q}^{(2)}_{\ell\ell Q\bar{d}H}}$	$\epsilon_{im}\epsilon_{jn}(\overline{d_R}\ell_L^i)(q_L^j C \ell_L^m) H^n$
$\boxed{\mathcal{Q}_{\ell\ell\bar{Q}uH}}$	$\epsilon_{ij}(\overline{q_{L_m}} u_R)(\ell_L^m C \ell_L^i) H^j$
$\mathcal{Q}_{\bar{\ell}QQdH}$	$\epsilon_{ij}(\overline{\ell_{L_m}} d_R)(q_L^m C q_L^i)\tilde{H}^j$
$\mathcal{Q}_{\bar{\ell}dddH}$	$(d_R C d_R)(\overline{\ell_L} d_R) H$
$\mathcal{Q}_{\bar{\ell}uddH}$	$(\overline{\ell_L} d_R)(u_R C d_R)\tilde{H}$
$\mathcal{Q}_{\ell eu\bar{d}H}$	$\epsilon_{ij}(\ell_L^i C \gamma_\mu e_R)(\overline{d_R}\gamma^\mu u_R) H^j$
$\mathcal{Q}_{\bar{e}QddH}$	$\epsilon_{ij}(\overline{e_R} Q_L^i)(d_R C d_R)\tilde{H}^j$

$\boxed{\text{Tree level matching contributions}}$

Basis of Lehman 1410.4193

d=7 matching

- Summary of dim 7 results:

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

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

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

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

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

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

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

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

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

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

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

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

Tree level matching contributions

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

Basis of Lehman 1410.4193

d=7 matching

- Summary of dim 7 nice result:

$$
\begin{aligned}
\mathcal{L}^{(7)} \supseteq & -\tilde{C}^7_{\beta\kappa} Y_u^\dagger Q^{\kappa\beta}_{\ell\ell\bar{Q}uH} - (\tilde{C}^7_{\kappa\beta} - \tilde{C}^7_{\beta\kappa})\, Y_d\, Q^{(1)\,\beta\kappa}_{\ell\ell Q\bar{d}H} - \tilde{C}^7_{\beta\kappa}\, Y_d\, Q^{(2)\,\beta\kappa}_{\ell\ell Q\bar{d}H} + \tilde{C}^7_{\beta\kappa}\, Y_e\, Q^{\kappa\beta}_{\ell\ell\ell\bar{e}H}, \\
& + g_1\, \mathsf{y}_\ell\, \tilde{C}^7_{\beta\kappa}\, Q^{\beta\kappa}_{\ell HB} + \frac{g_2\, \tilde{C}^7_{\beta\kappa}}{2}\, Q^{\beta\kappa}_{\ell HW} - i\, \tilde{C}^7_{\beta\kappa}\, (Y_e^\dagger)^\alpha_\kappa\, Q^{\beta}_{\ell HDe_\alpha} + \frac{(x_\beta)^T\, x^\star \cdot y^\dagger\, y_\delta}{4\, m_1^3}\, Q^{\beta\delta}_{\ell H}, \\
& + \frac{(x_\beta)^T\, x^\star \cdot z^\dagger\, z_\delta}{4\, m_1^3}\, Q^{\beta\delta}_{\ell H} + \frac{(y_\beta)^T\, y^\star \cdot z^\dagger\, z_\delta}{4\, m_2^3}\, Q^{\beta\delta}_{\ell H} - 2\, \tilde{C}^7_{\beta\kappa}\, Q^{(2)}_{\ell HD} + h.c.
\end{aligned}
$$

$$
\tilde{C}^7_{\beta\kappa} = \sum_p \frac{(\omega^p_\beta)^T\, \omega^p_\kappa}{2\, m_p^3}.
$$

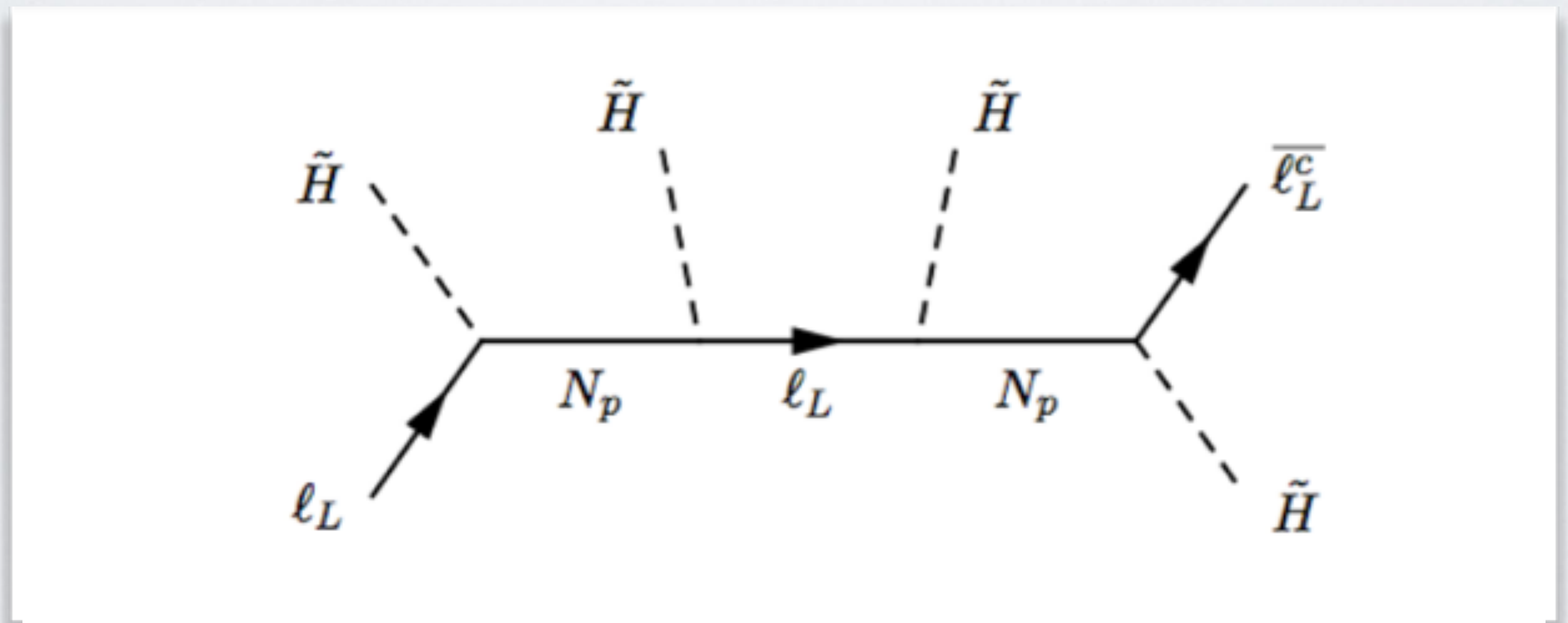
arXiv:1703.04415 **Gitte Elgaard-Clausen,** MT JHEP 1711 (2017) 088

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 can find this vanishes. As do other combinations.



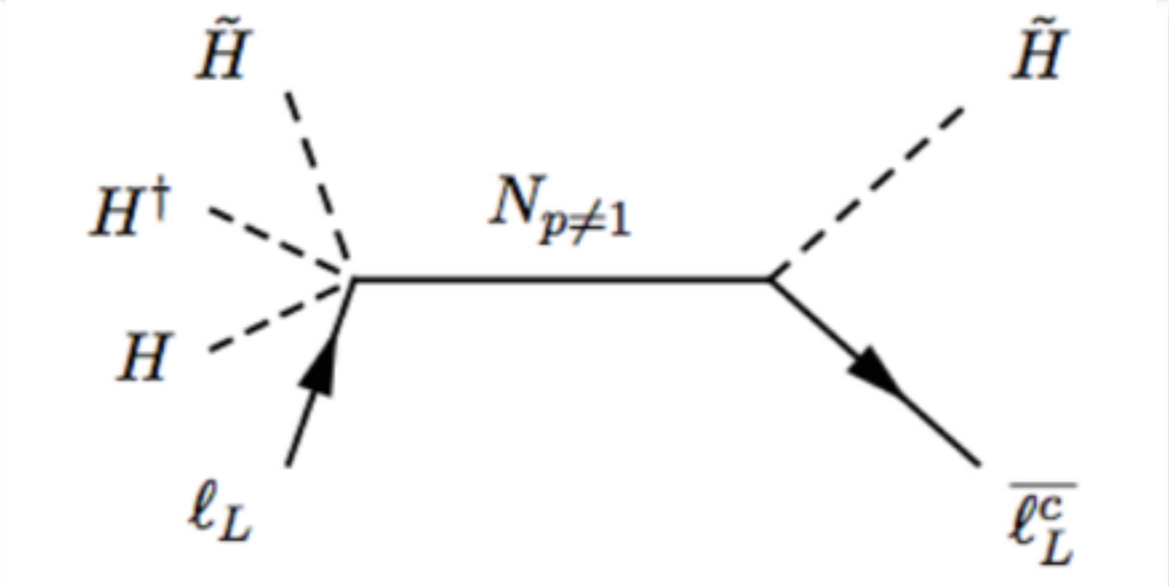
WHY? :This has to be as extra H fields require another light propagator. Would mess up the cancelations key to this by keeping only some of the operators in a chosen basis. Yet ANOTHER example of keep all ops at an order to be well defined in SMEFT.

d=7 matching

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

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

However this argument fails when you integrate things out in sequence or use EOM

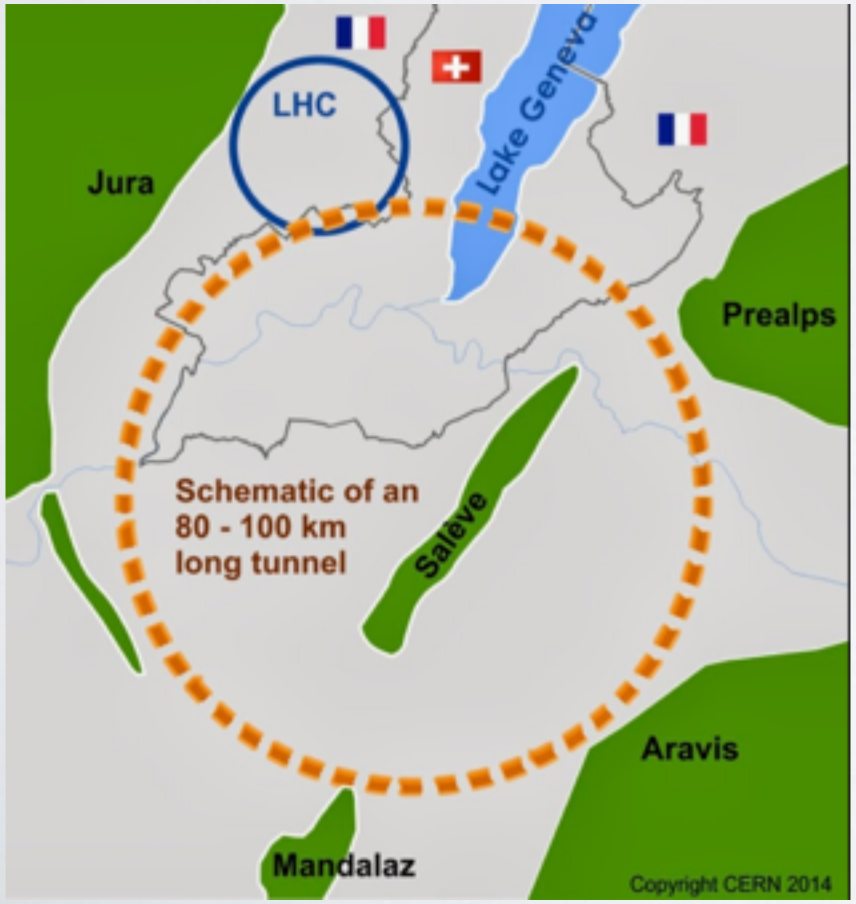


Neutrino mass matrix perturbations come about at $\mathcal{L}_7$ due to this

$$\begin{aligned}\mathcal{L}^{(7)} \supseteq & -\left[\frac{x^T_\beta\, x_\kappa\, ||x||}{4 m_1^3} + \frac{y^T_\beta\, y_\kappa ||y||}{4 m_2^3} + \frac{z^T_\beta\, z_\kappa\, ||z||}{4 m_3^3}\right] Q_{\ell H}, \\ & -\left[\frac{x^T_\beta\, y_\kappa y \cdot x}{4 m_2^2\, m_1} + \frac{x^T_\beta\, z_\kappa z \cdot x}{4 m_3^2\, m_1} + \frac{y^T_\beta\, z_\kappa z \cdot y}{4 m_3^2\, m_2}\right] Q_{\ell H} + h.c.\end{aligned}$$

Conclusions

- If this was true a trivial UV boundary condition for the Higgs potential combined with the non-trivial nature of the SM SPECTRUM leads to $SU(2)_L \times U(1)_Y \to U(1)_Q$ we see. Really an amazing example of self-consistency in field theory.
- If true, the observed EW scale is a quantum shadow of the Majorana scale indicated by the Seesaw. It's a "self seesaw" and massive neutrino's were the clue. Flavour makes sense. Other signals very,very small.
- Matching is known up to Dimension 7 for the minimal seesaw now.



- There is a lot of discussion recently about a 100 TeV machine, which might seem like a guarantee to find something.

Conclusions

- If this was true a trivial UV boundary condition for the Higgs potential combined with the non-trivial nature of the SM SPECTRUM leads to $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$ we see. Really an amazing example of self-consistency in field theory.

- If true, the observed EW scale is a quantum shadow of the Majorana scale indicated by the Seesaw. Its a “self seesaw” and massive neutrino’s were the clue. Flavour makes sense. Other signals very,very small.

- Matching is known up to Dimension 7 for the minimal seesaw now.

- There is a lot of discussion recently about a 100 TeV machine, which might seem like a guarantee to find something.

- However, unfortunately $10\,\mathrm{PeV} > 100\,\mathrm{TeV}$