Neutrino's in SMEFT and the Neutrino Option

#SMEFT

M. Trott, Prospects in Neutrino Physics 2019

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Talk summary

- Two key ideas to transmit:

Small neutrino mass can be linked to the smallness of the Higgs mass. (Small here compared to UV scales linked to Lepton number violation)

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.

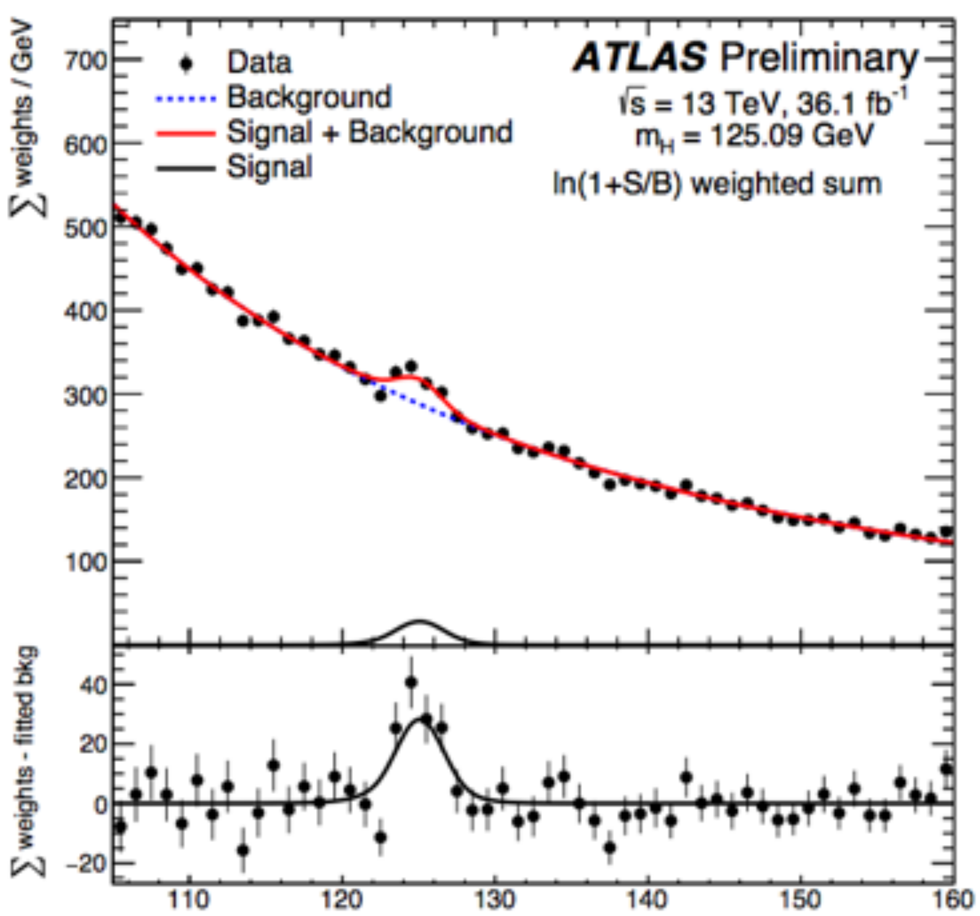
- This idea is embedded in several overlapping expansions:

    1) The SMEFT operator expansion.
    2) A flavour space expansion for L5 operator due to seesaw.
    3) The perturbative matching expansion of the seesaw model to the SMEFT.

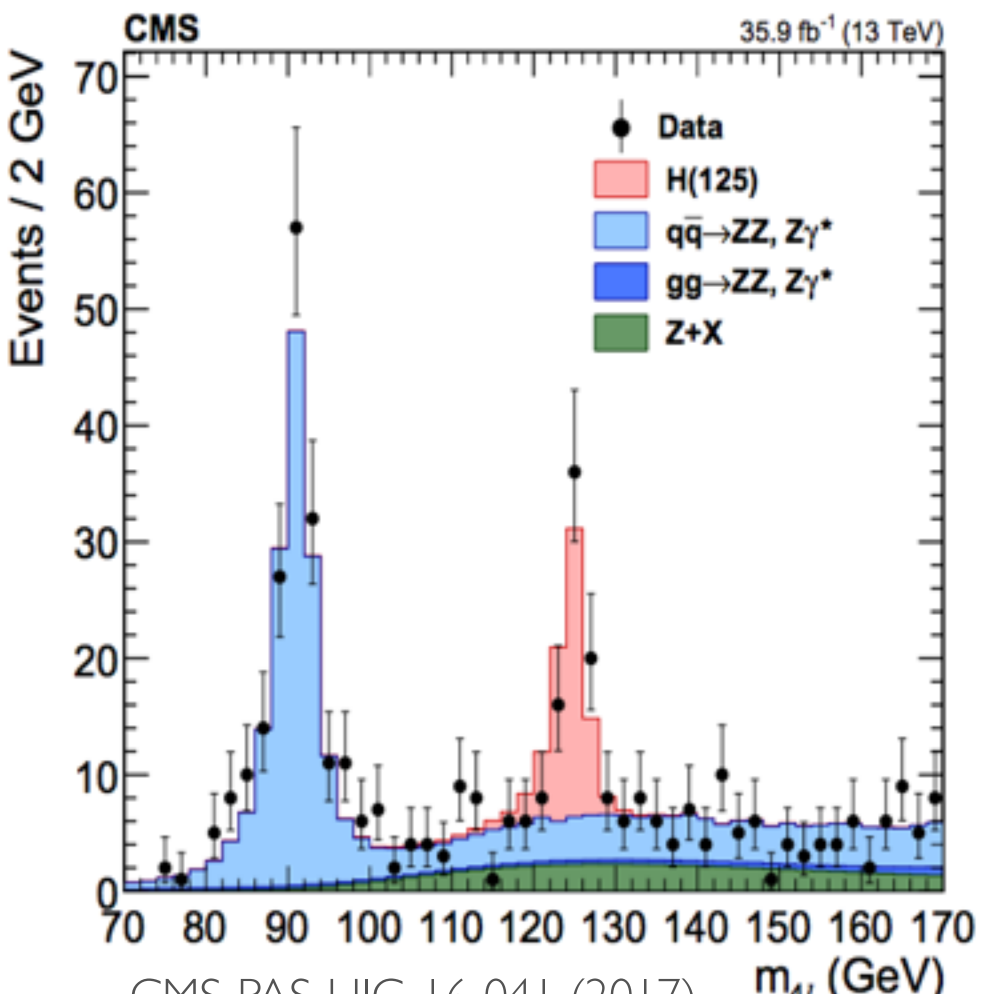
The SMEFT expansion

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)

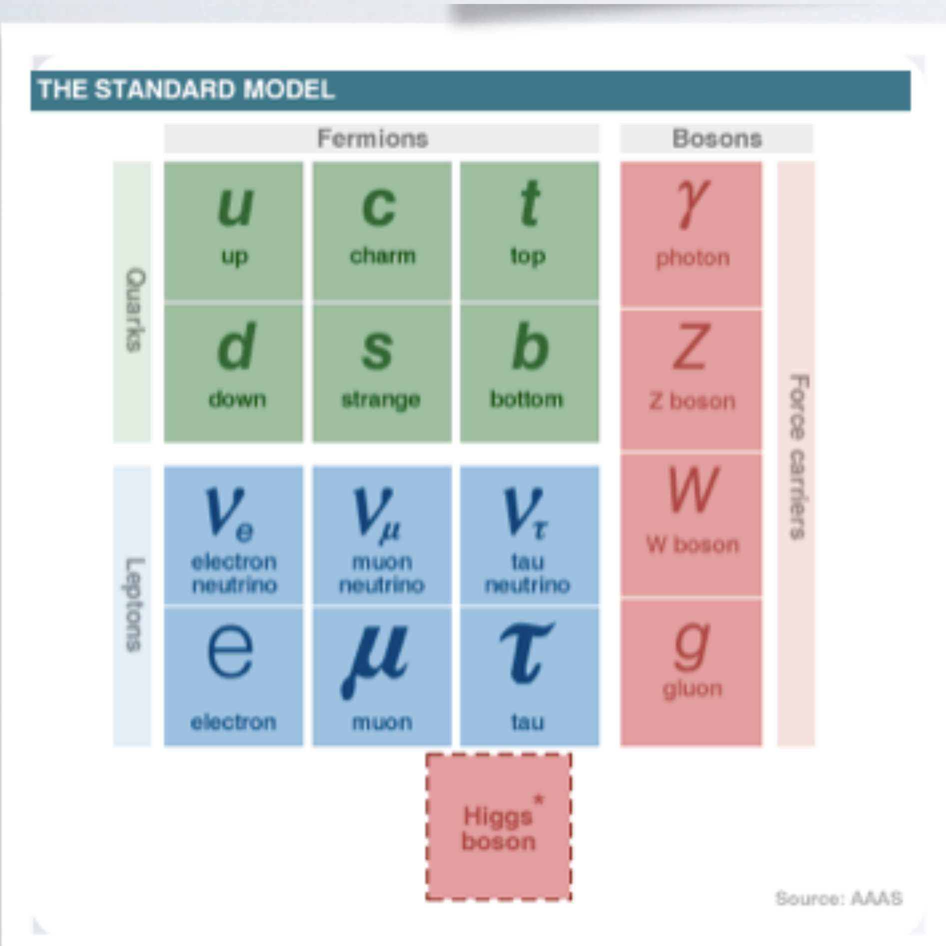


CMS-PAS-HIG-16-041 (2017)

and a theory…the Standard Model EFT

- The SM, an SU(3) xSU(2)xU(1) gauge theory:

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



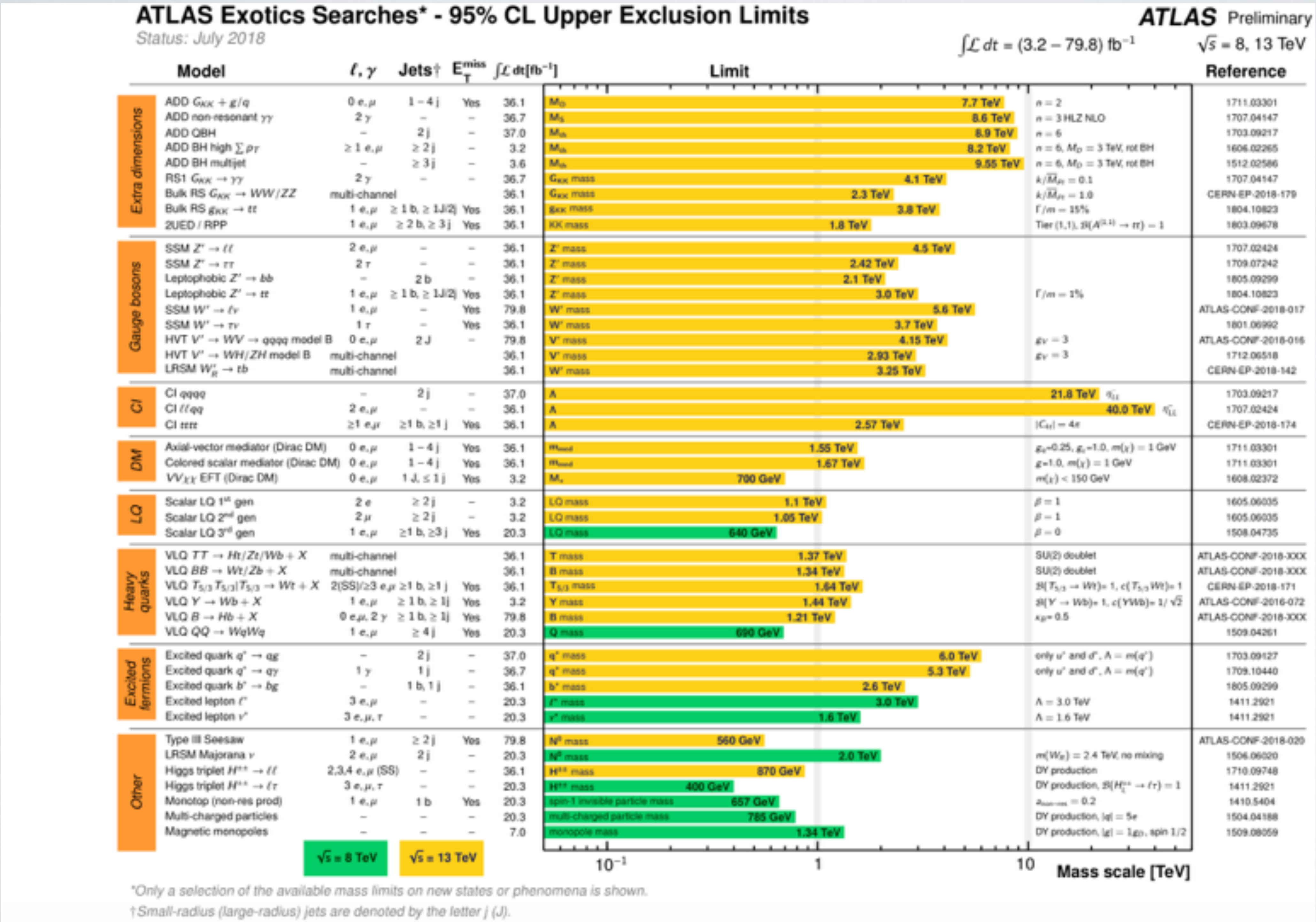
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

Glashow 1961, Weinberg 1967 (Salam 1967)

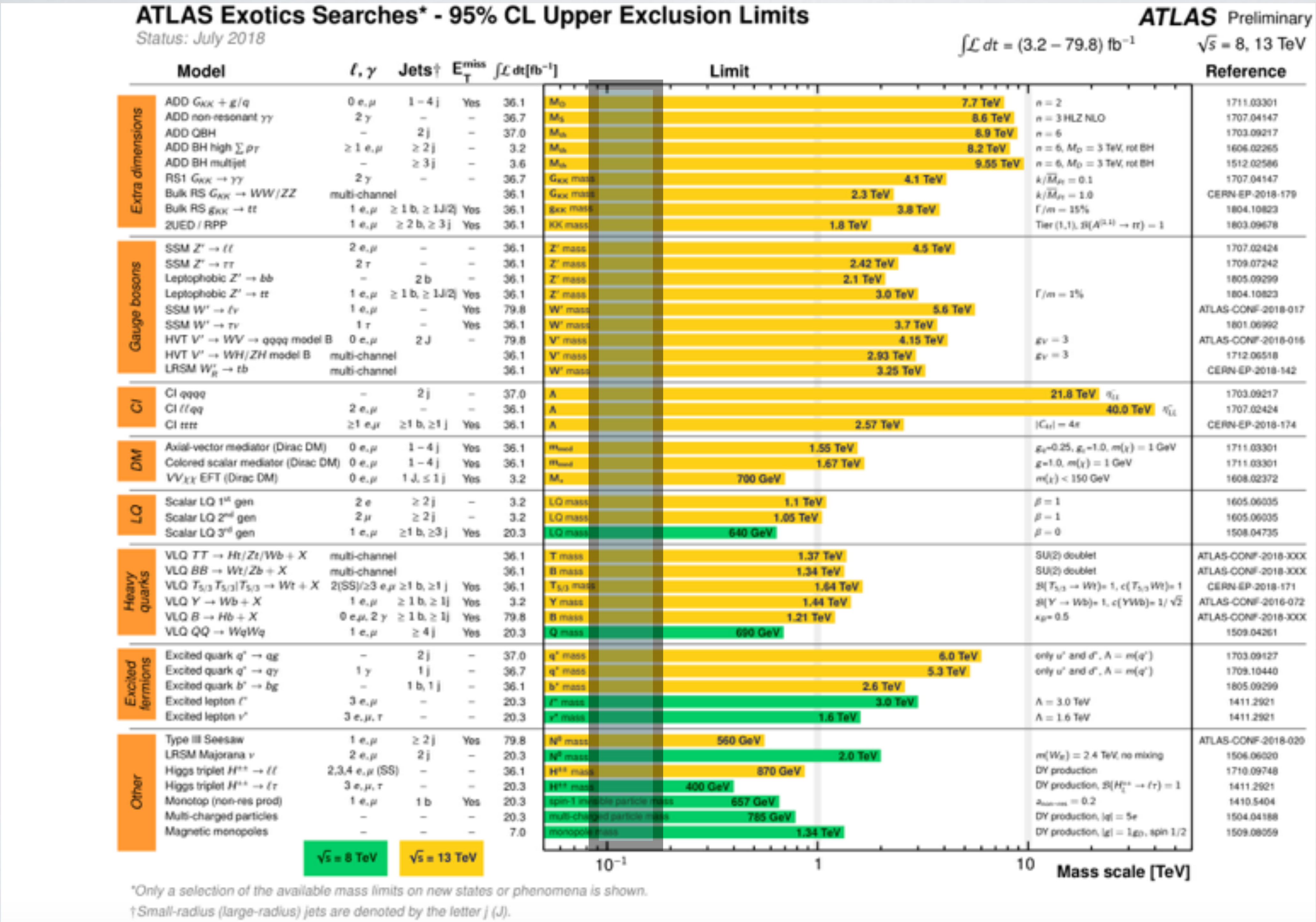
Weinberg 1979, Wilczek and Zee 1979

Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

RunII and beyond: Resonance limits to local operators

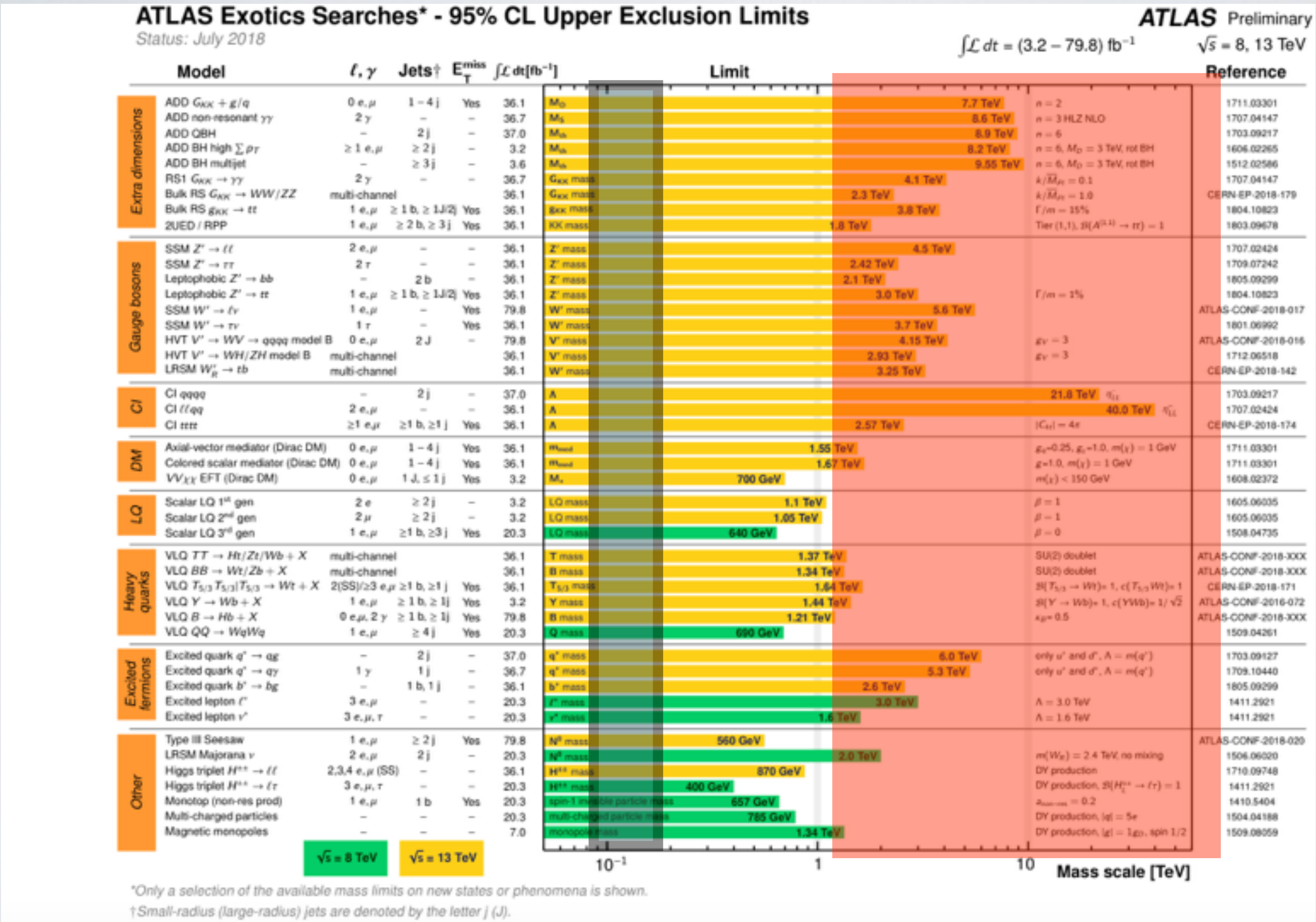


RunII and beyond: Resonance limits to local operators



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

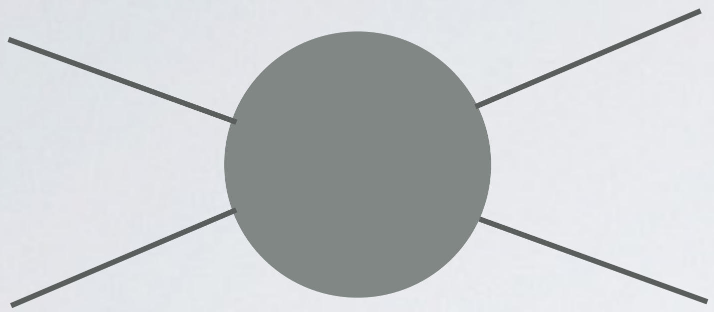
$$v/M < 1$$

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

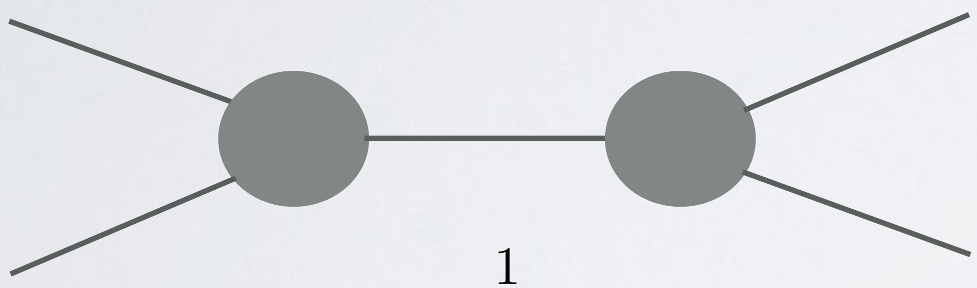
When you do measurements below a particle threshold



- 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

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

UV dependent Wilson coefficient and suppression scale

SMEFT:development cycle

SMEFT - built of H doublet + higher D ops

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

Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1979, Wilczek and Zee 1979

Leung, Love, Rao 1984, Buchmuller Wyler 1986,
Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Weinberg 1979, Abbott Wise 1980

Lehman 1410.4193, Henning et al. 1512.03433

Lehman,Martin 1510.00372, Henning et al. 1512.03433

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

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 JHEP 1711 (2017) 088 Gitte Elgaard-Clausen, MT

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

arXiv:1809.03450 JHEP 1902 (2019) 107 I. Brivio, MT

Are any Wilson coefficients not 0?

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

- C^5 seems to be non zero.

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

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

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

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

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

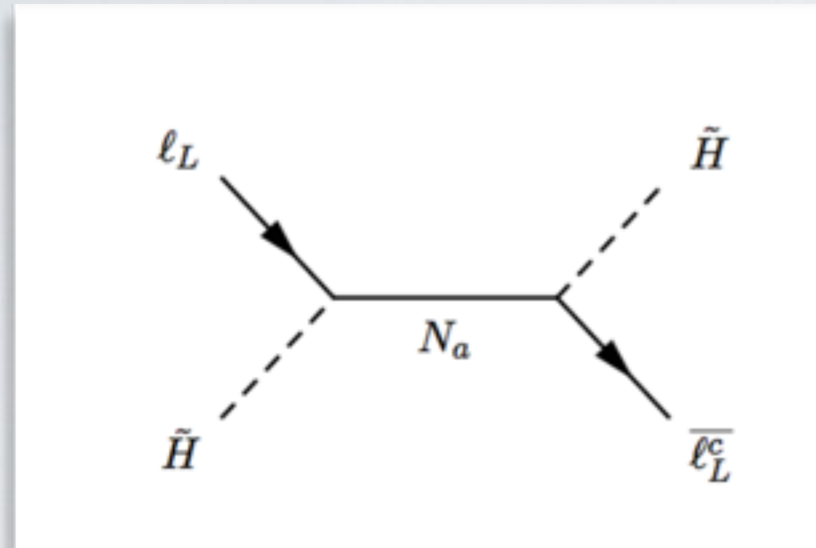
- Obtaining the Standard (type I) seesaw
(Minkowski 77, Gell Mann et al 79, Yanagida 79,Mohapatra at al 79…)

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

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 a flavour space expansion

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

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

L6 SMEFT matching

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

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

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

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

N_1

N_2

N_3

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

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

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

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

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

N_1

N_2

N_3

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

- As a Majorana scale in the EOM:

$$\partial\!\!\!/ N_p = -i\Big(m_p\, N_p + w^{p,*}_\beta\, \tilde{H}^T \ell^{c\beta}_L + w^p_\beta \tilde{H}^\dagger \ell^\beta_L \Big)$$

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:

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

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

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

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

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

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

Tree level matching contributions

Basis of Lehman 1410.4193

L7 SMEFT matching

- Summary of dim 7 results: arXiv:1703.04415 Gitte Elgaard-Clausen, MT

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

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

$3:\psi^2H^3D+\mathrm{h.c.}$	
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$4:\psi^2H^2X+\mathrm{h.c.}$	
$\mathcal{Q}_{\ell HB}$	$\epsilon_{ij}\epsilon_{mn}(\ell^i_L C\sigma_{\mu\nu}\ell^m_L)H^j H^n B^{\mu\nu}$
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$5:\psi^4D+\mathrm{h.c.}$	
$\mathcal{Q}^{(1)}_{\ell\ell\bar{d}uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell^i_L C D^\mu \ell^j_L)$
$\mathcal{Q}^{(2)}_{\ell\ell\bar{d}uD}$	$\epsilon_{ij}(\overline{d_R}\gamma_\mu u_R)(\ell^i_L C\sigma^{\mu\nu} D_\nu \ell^j_L)$
$\mathcal{Q}^{(1)}_{\bar{\ell}QddD}$	$(Q_L C\gamma_\mu d_R)(\overline{\ell_L} D^\mu d_R)$
$\mathcal{Q}^{(2)}_{\bar{\ell}QddD}$	$(\overline{\ell_L}\gamma_\mu q_L)(d_R C D^\mu d_R)$
$\mathcal{Q}_{ddd\bar{e}D}$	$(\overline{e_R}\gamma_\mu d_R)(d_R C D^\mu d_R)$

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

Tree level matching contributions

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

Basis of Lehman 1410.4193

Linking the Higgs potential with Neutrino mass generation.

Strangeness of the Higgs potential

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

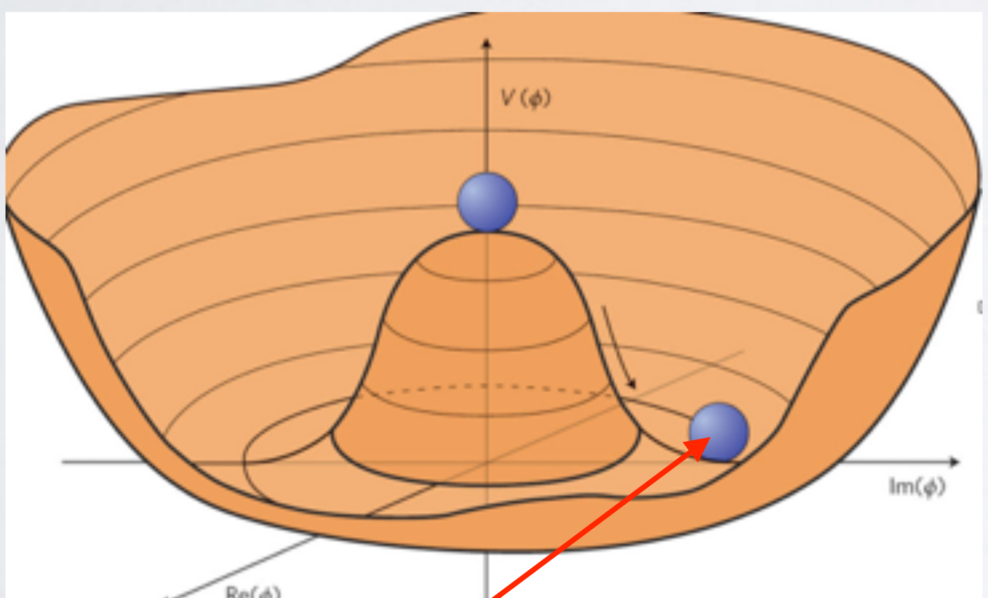
$$S_H = \int d^4x \left(|D_\mu H|^2 - \lambda \left(H^\dagger H - \frac{1}{2}v^2 \right)^2 \right),$$

Partial Higgs action

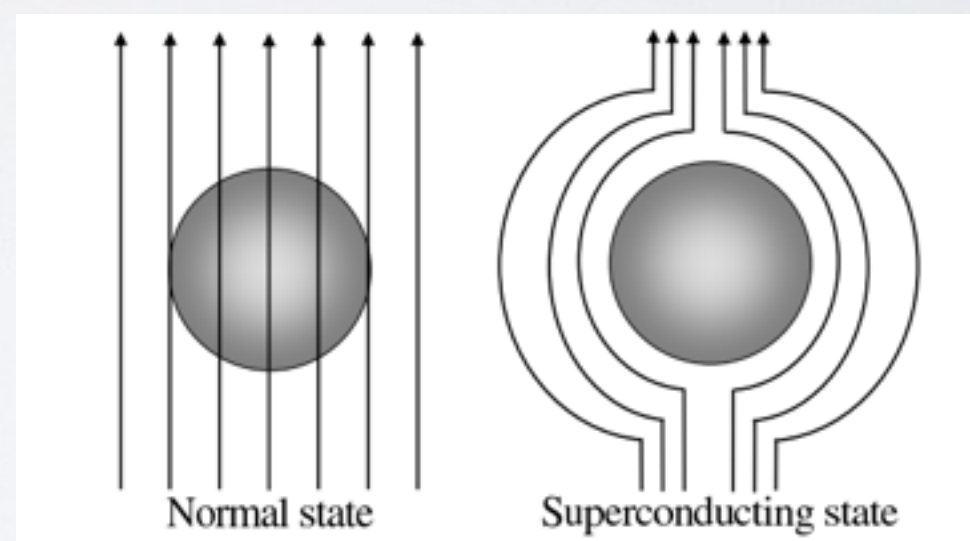
$$LG(s) = \int_{\Re^3} dx^3 \left[\frac{1}{2}|(d - 2\,i\,e\,A)s|^2 + \frac{\gamma}{2}\left(|s|^2 - a^2\right) \right],$$

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 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

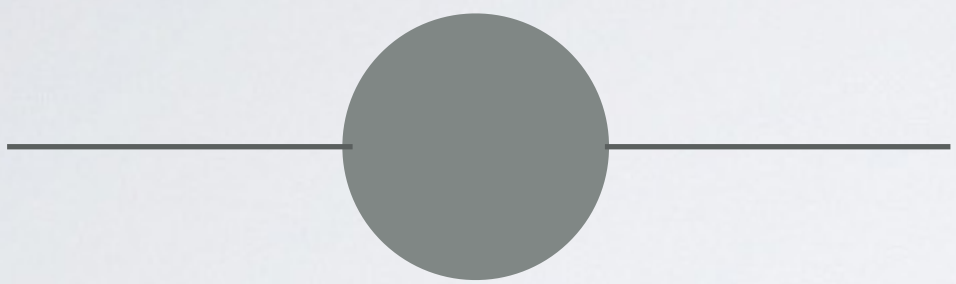
- Initial efforts studied the induced potential of a scalar and used vacuum misalignment to get $SU(2)_L \times U(1)_Y \to U(1)_Q$

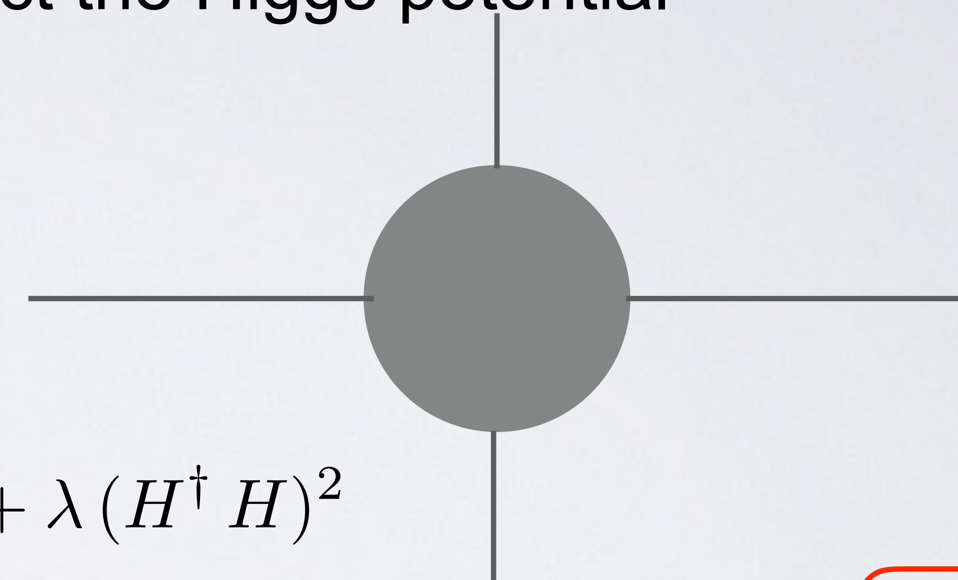
$$\Sigma(x) = e^{i\Pi_a T^a/f}\, U\, e^{i\Pi_a T^a/f} \qquad \mathcal{L} = \frac{f^2}{4}(D_\mu\Sigma)(D^\mu\Sigma)^T + \Lambda^4 \mathrm{Tr}\left[T^a\Sigma(T^a)^T\Sigma^\dagger\right] + \cdots$$

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

Challenge of constructing potential

- 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 : $m_h = 125\,\mathrm{GeV}$ $\Longrightarrow$ $\boxed{\lambda = 0.13}$

The problem.

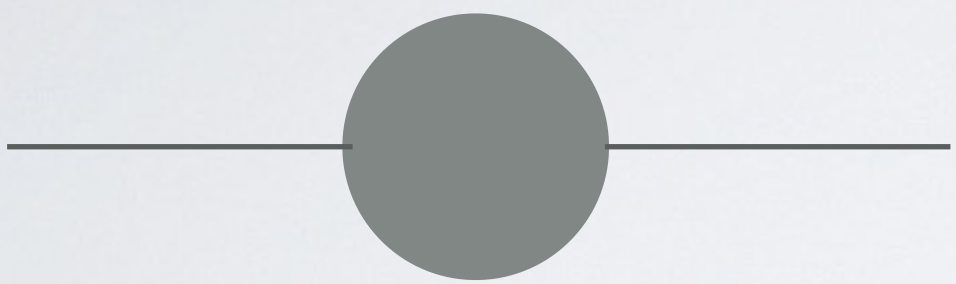
- Composite models (nobly) try to construct the Higgs potential:

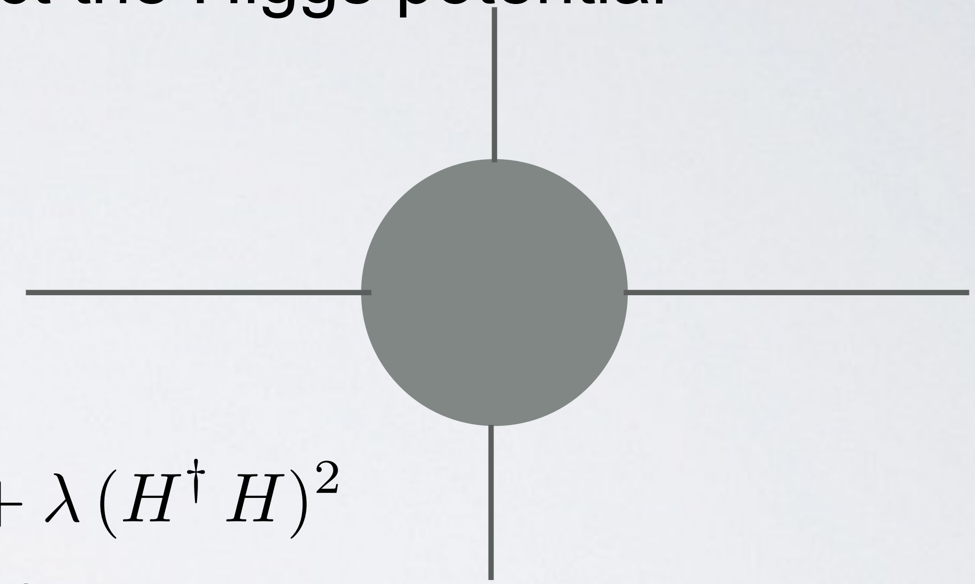
$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{16\,\pi^2}\left(-2\,aH^\dagger H + 2b\frac{(H^\dagger H)^2}{f^2}\right)$$ see 1401.2457 Bellazzini et al

- 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



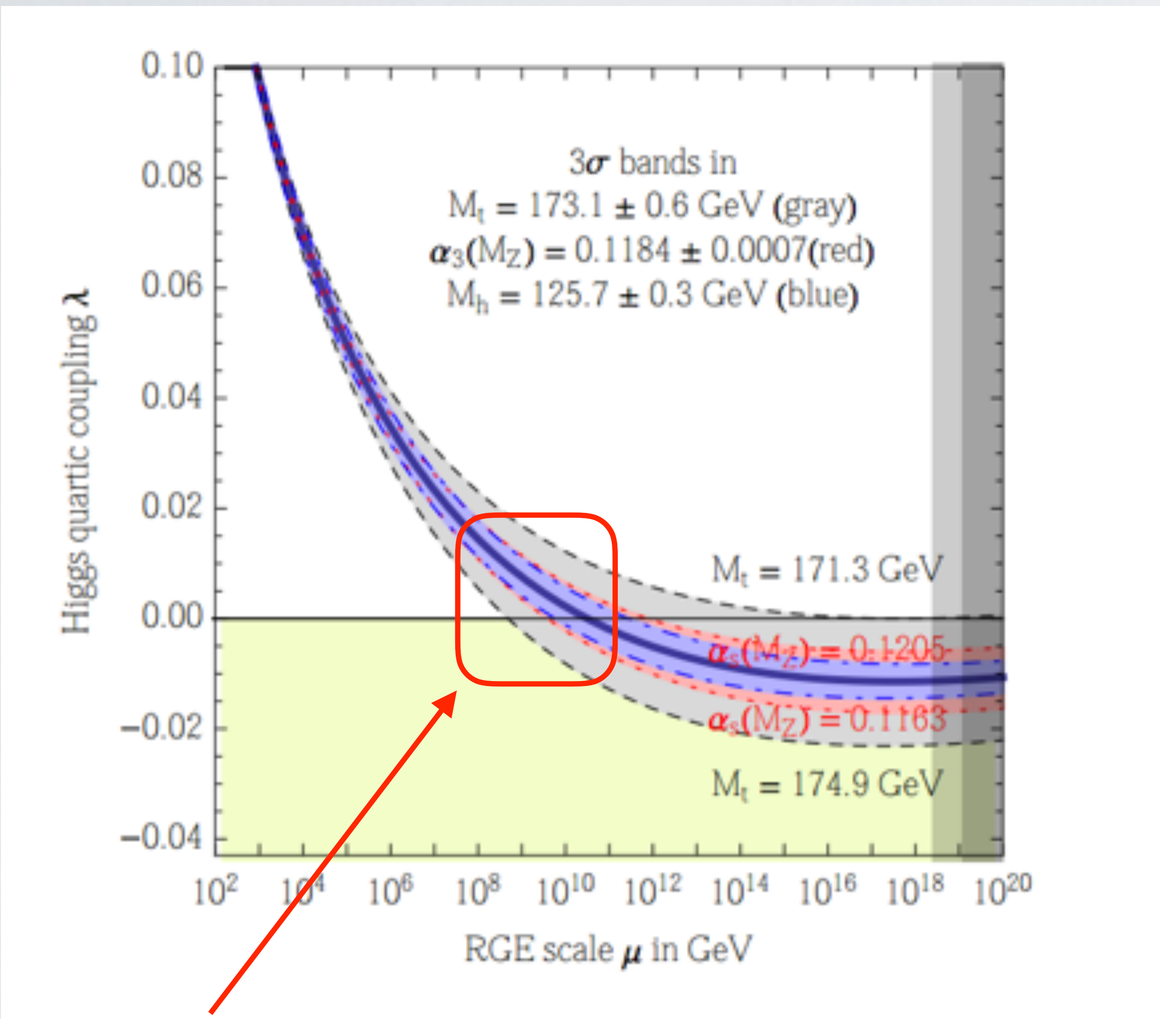


$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- 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)

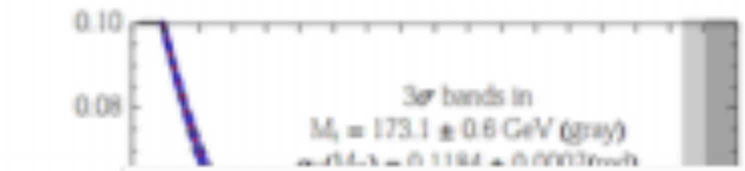
1205.6497 Degrassi et al, 1112.3022 Elias-Miro et al..

- What does this mean?
- 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.

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

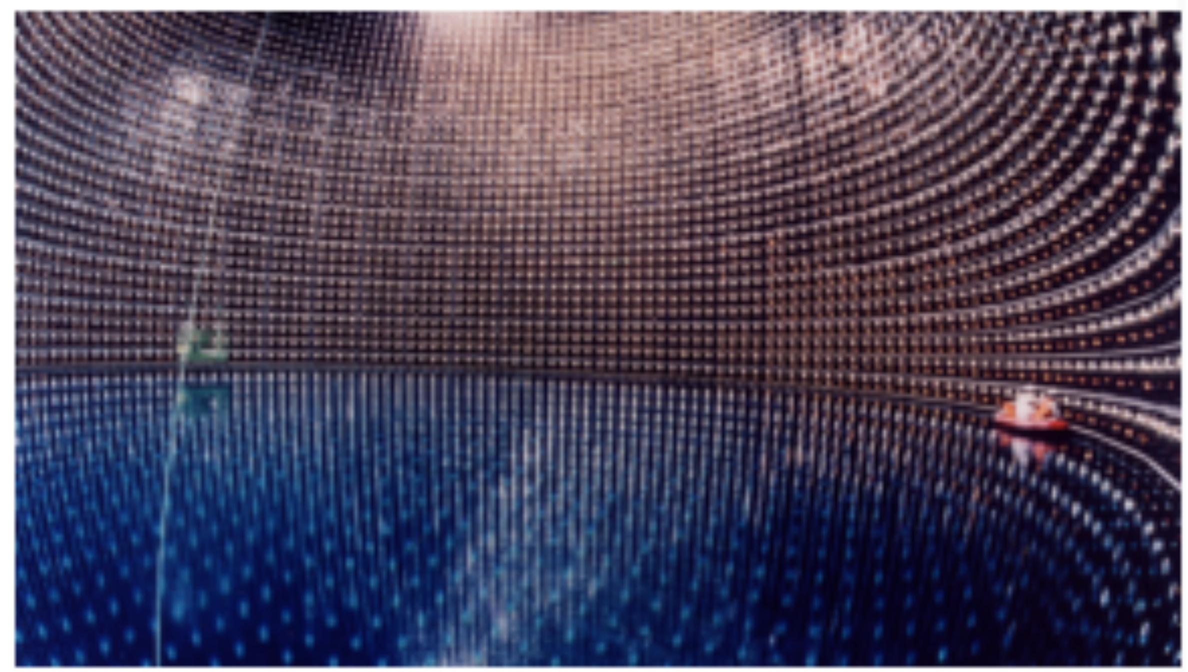
- Neutrino's have mass

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

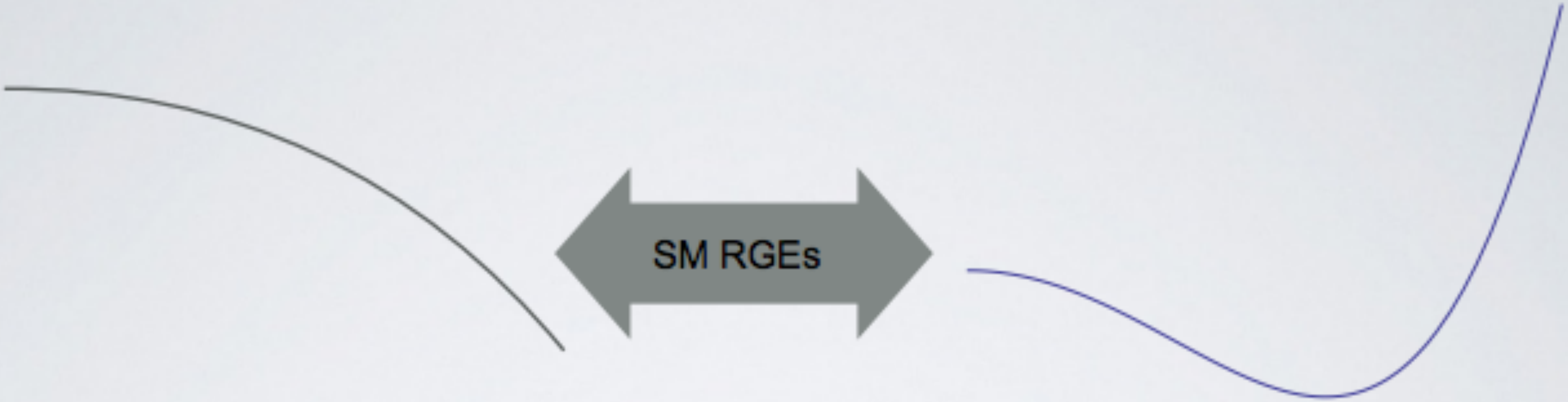
Photo: A. Mahmoud
Arthur B. McDonald

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"*

4.4057



Idea is use the non trivial spectrum we have

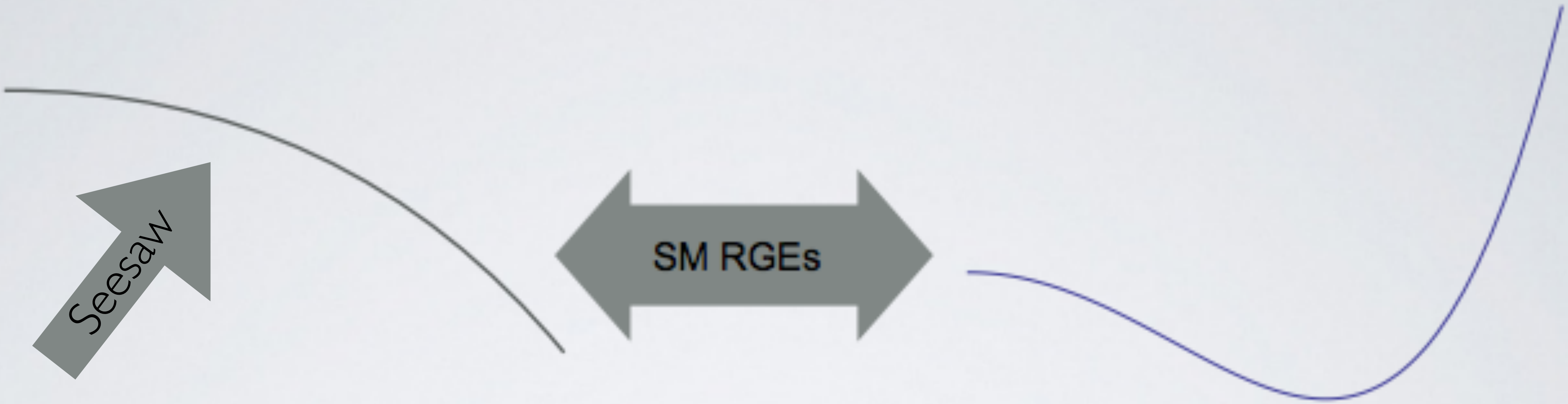


- Still need a non trivial spectrum with lots of interactions (and some weird couplings) to generate a non trivial potential. But lets use the weird spectrum we have.

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

Field	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$	$SO^+(3,1)$
$q_i = (u^i_L, d^i_L)^T$	**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.

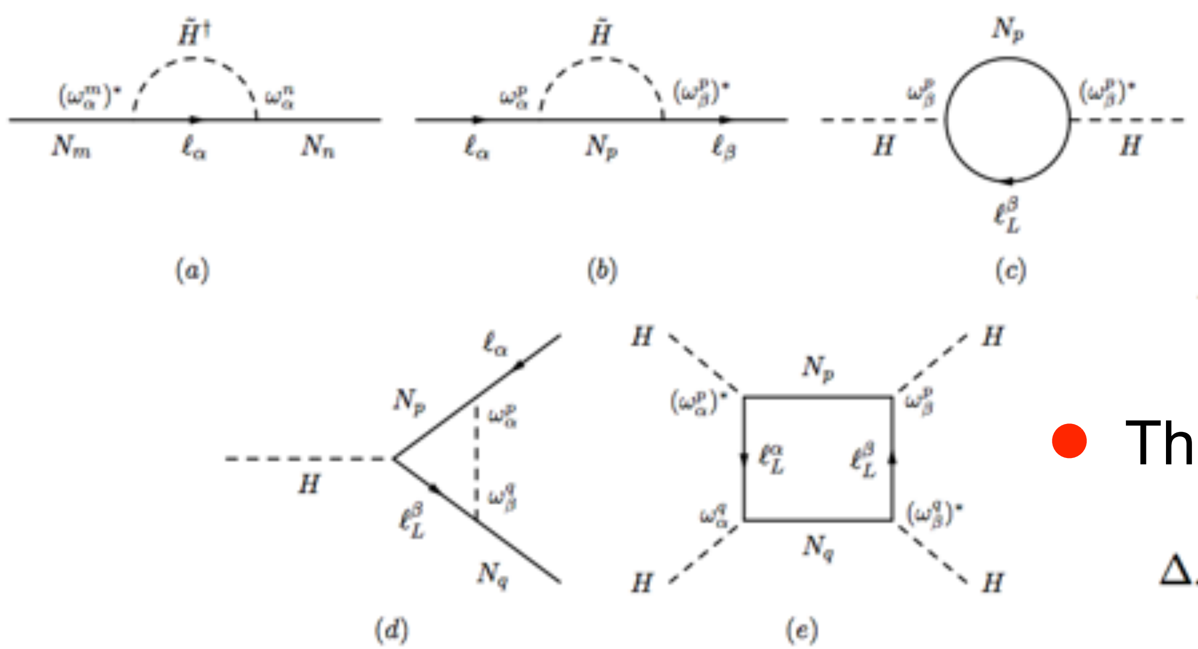


- Lets use the weird spectrum we have expressed through the SM RGE's

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

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:

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

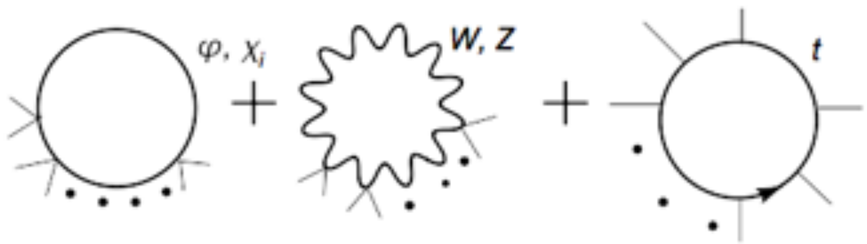
THE SIGN WORKS OUT due to FERMI statistics

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..

- 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:

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

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

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

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

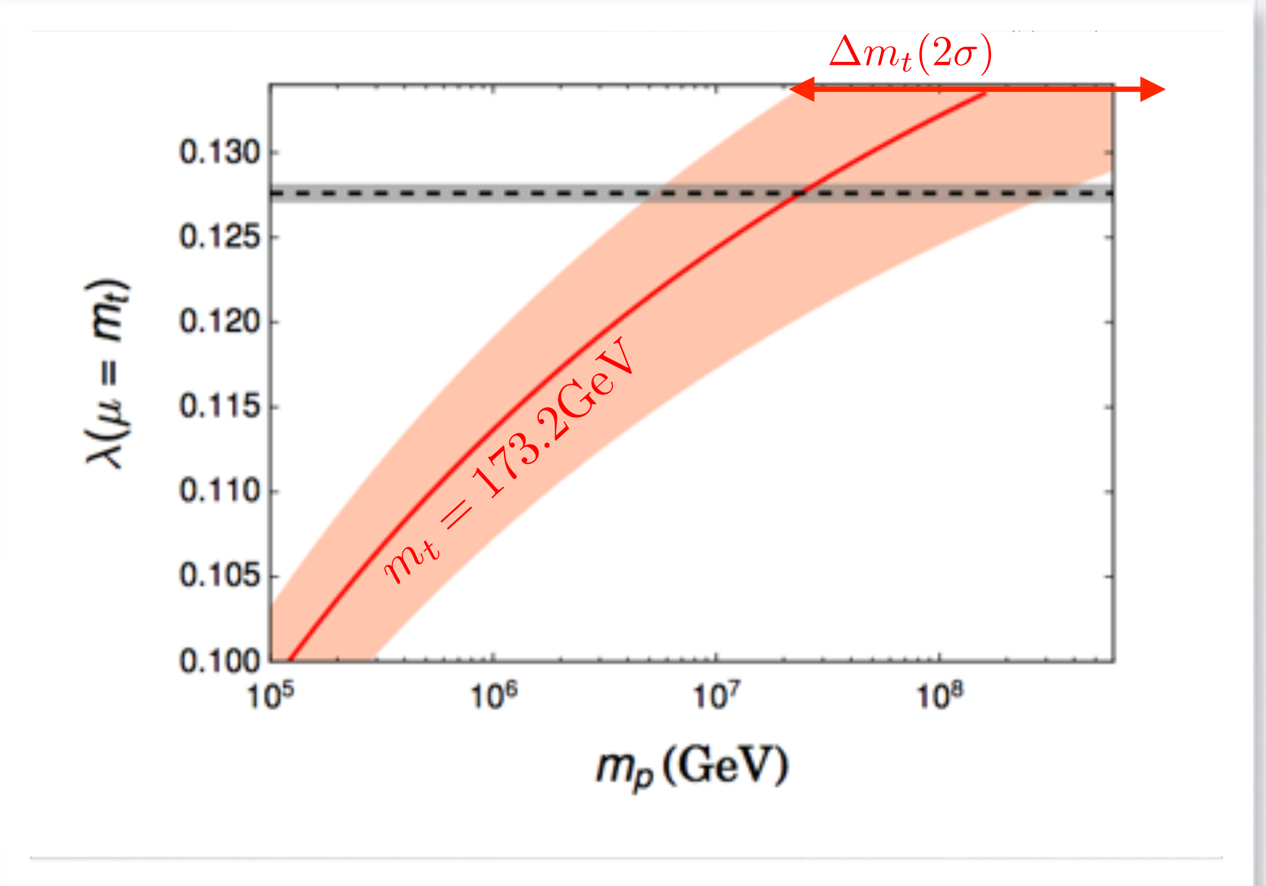
- Such threshold corrections are a direct representation of the Hierarchy problem F. Vissani, Phys. Rev. D 57, 7027 (1998)

- Can one go the full way of dominantly generating the EW scale in this manner? $\cancel{v_0}$? 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



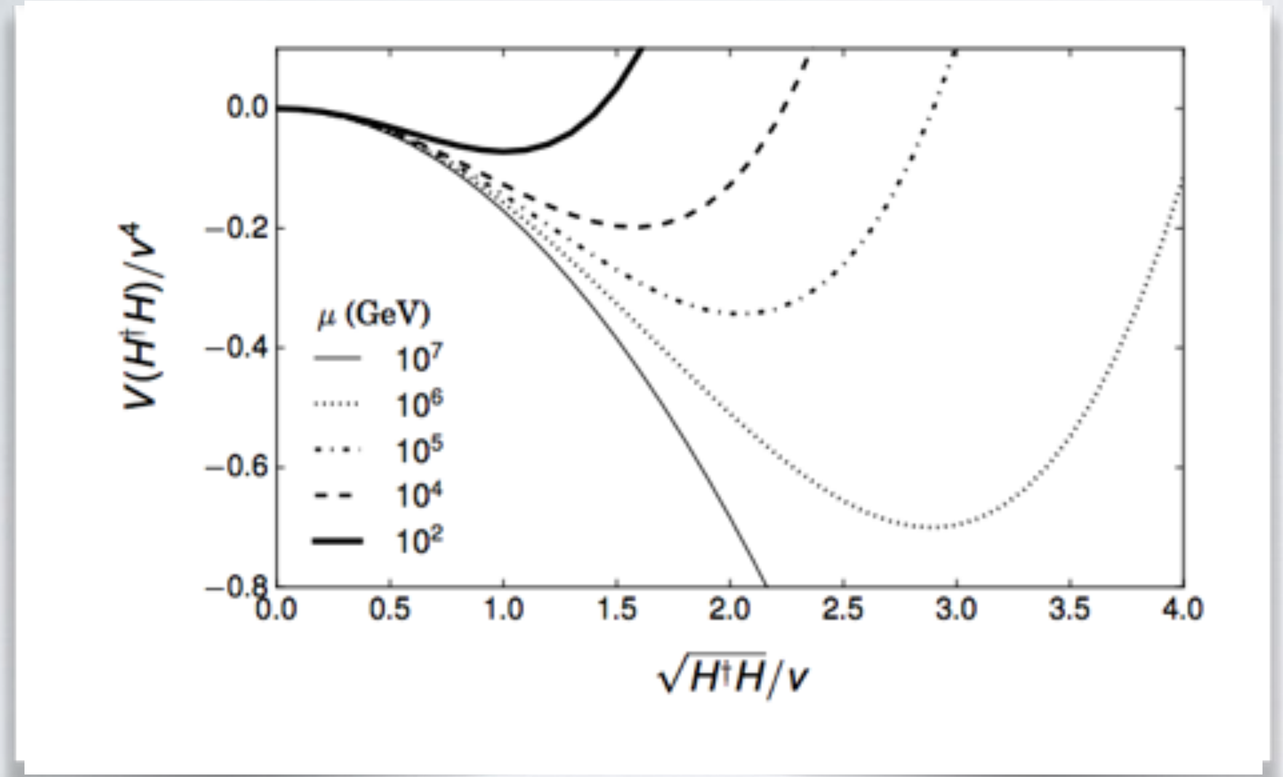
- Can get the troublesome $\lambda \sim 0.13$

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

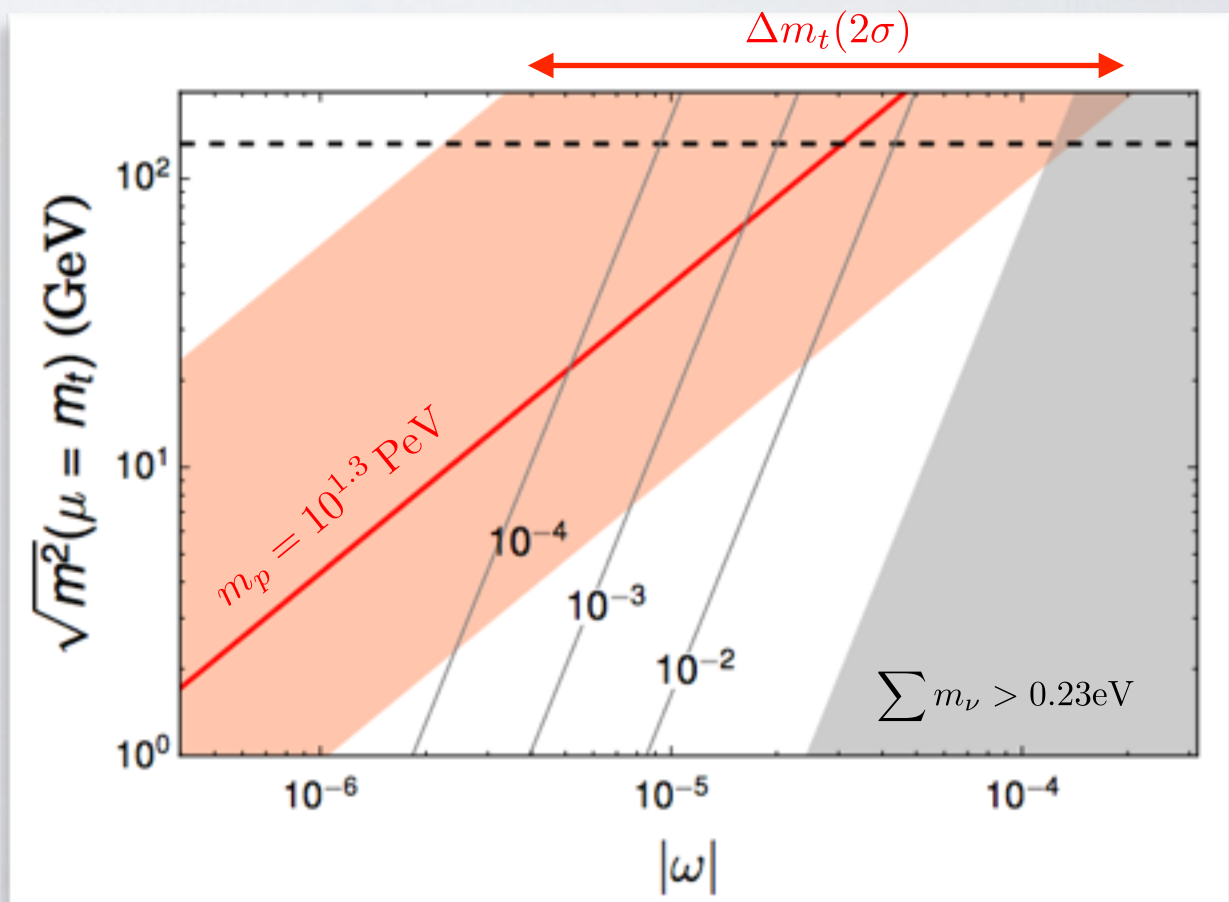
$$\boxed{\begin{array}{c} m_p \sim 10^7 \mathrm{GeV} \\ |\omega| \sim 10^{-5} \end{array}}$$

- 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

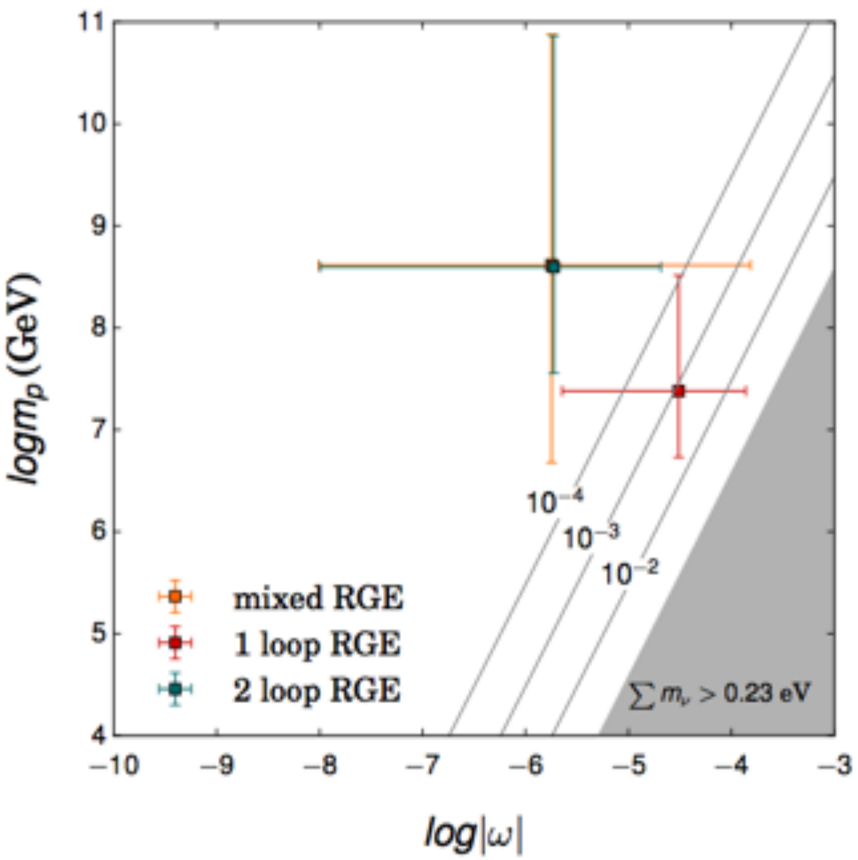


- In a non-trivial manner - and the right neutrino mass scale (diff) can result.

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

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

Neutrino option: the bad



"unburied body" plot

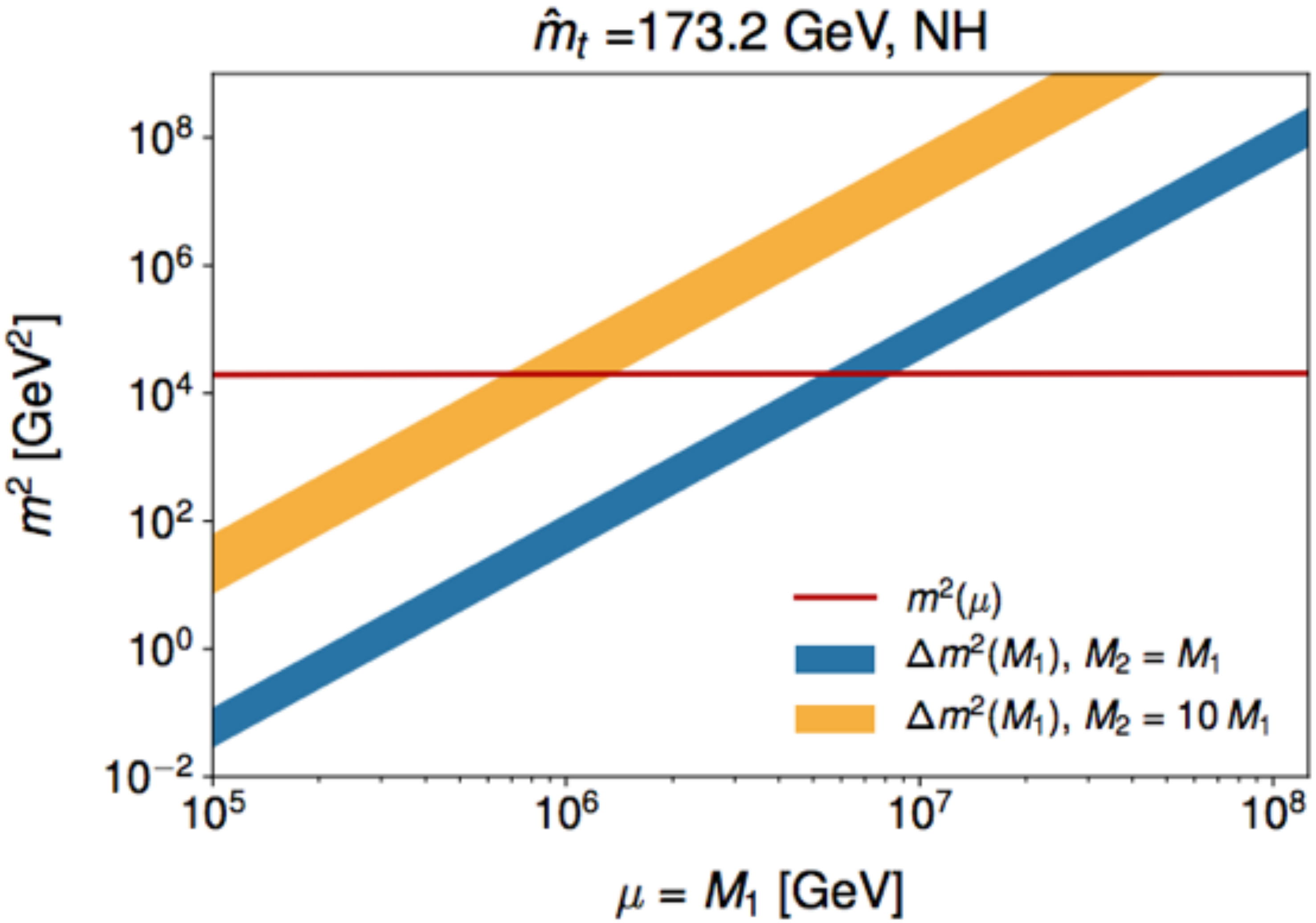
- Very significant numerical uncertainties
  -top quark mass driven
- This is NOT a total solution to the Hierarchy problem. As there is no symmetry protection mechanism against other threshold corrections.
- No non-resonant leptogenesis in this parameter space 1404.6260 Davoudias, Lewis

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

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

Improving numerical stability

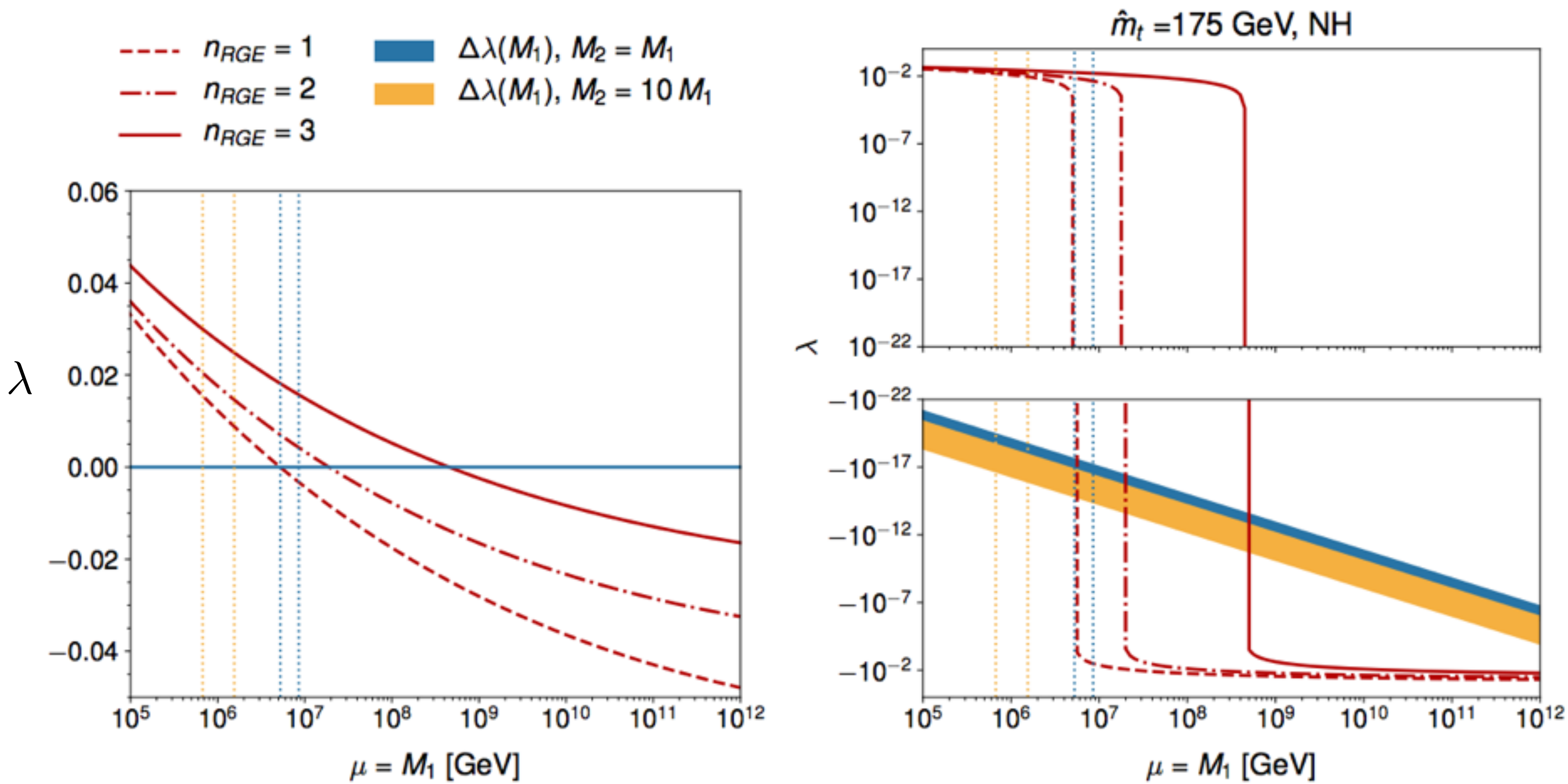
- Severe upgrade in rigor of one loop calc and one loop running of C^5
  1809.03450 Brivio, Trott
- Consistency test reformulated to avoid asymptotic numerical sensitivity to λ



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

Minimal case with two heavy neutrino's.

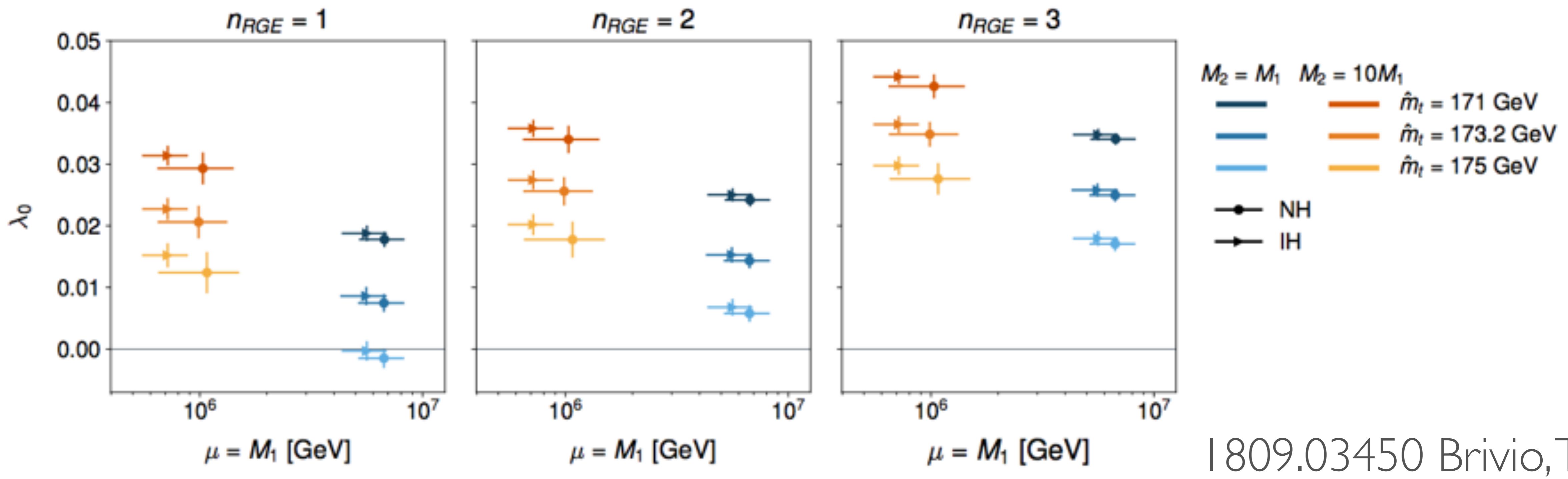
Improving numerical stability



1809.03450 Brivio, Trott

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

Required bare lambda



1809.03450 Brivio, Trott

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

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

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

<u>Fermi statistics + Majorana scale in the UV + SM state spectrum for RGE.</u>

Conclusions/summary

- SMEFT is a theory defined by field redefinitions leading to local operators. Neutrino's with mass embedded.
- *Combined global studies are key* 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

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

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

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

$$\overline{N_{R,p}^c}\, M_{pr}\, N_{R,r} + \overline{N_{R,p}}\, M_{pr}^\star\, N_{R,r}^c$$

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

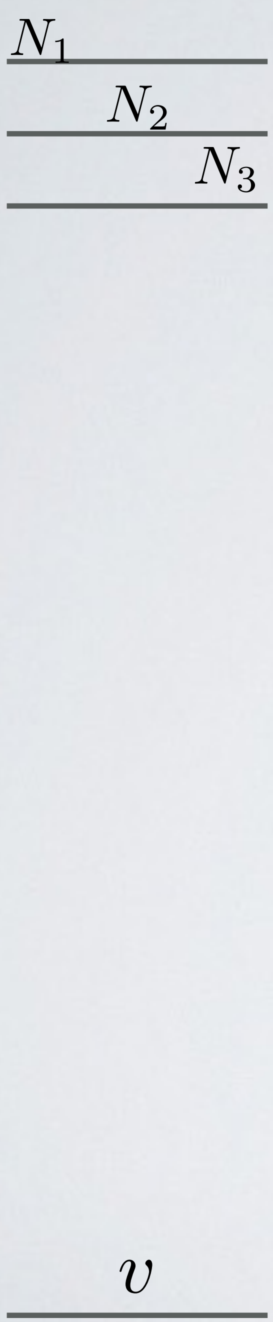
$$a\cdot b = ||a||\,||b||\underbrace{\Delta_{ab}}_{<\,1 \text{ by construction again}}$$

- 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

Old school Perturbation theory



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

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

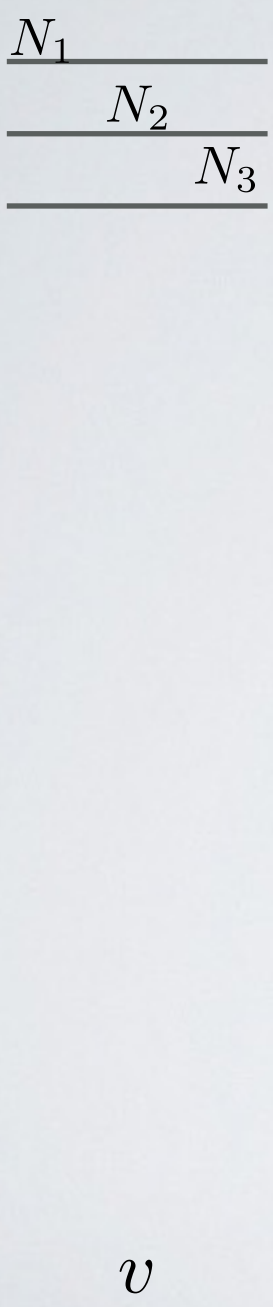
- Construct the orthonormal set as eigenvectors in flavour space

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

- Can systematically develop perturbations of the eigenvectors and eigenvalues

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

Links perturbations of masses to PMNS



- What is the benefit of this approach?

only matrix involved in neutrino mass spectrum

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

expansion

measured

Unknown!

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

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

- What is the benefit of this approach?

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

This is where ben and i hit the wall in 1203.4410

Just perturb in the unknown

N_1

N_2

N_3

- 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 form 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.

v

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
$\delta(^\circ)$	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 $m_t = 173.2\,\mathrm{GeV}$.