A series of fortunate EFT events

- M. Trott

HEFT 2017

NBI, NBIA, Copenhagen

EFT for LHC?

"Fate is like a strange, unpopular restaurant filled with odd little waiters who bring you things you never asked for and don't always like."
— Lemony Snicket

Mentions from papers:

arXiv:1705.soon SMEFT, HEFT etc (review) Ilaria Brivio, MT

arXiv:1703.10924 Neutrino Option Ilaria Brivio, MT

arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT

arXiv:1606.06693 EWPD series L. Berthier, M. Bjorn, MT

arXiv:1606.06502 SMEFT W mass, M. Bjorn, MT

SM $\neq$ SMEFT $\neq$ "an extra operator"

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

UV model $\longrightarrow$ SMEFT* $\longrightarrow$ SM

$$\frac{C_i\, v^2}{\Lambda^2}, \frac{C_i\, p^2}{\Lambda^2} < 1 \qquad \Lambda \to \infty$$

* Assuming no large "nonlinearities/scalar manifold curvatures" (HEFT vs SMEFT as the IR limit assumption.)

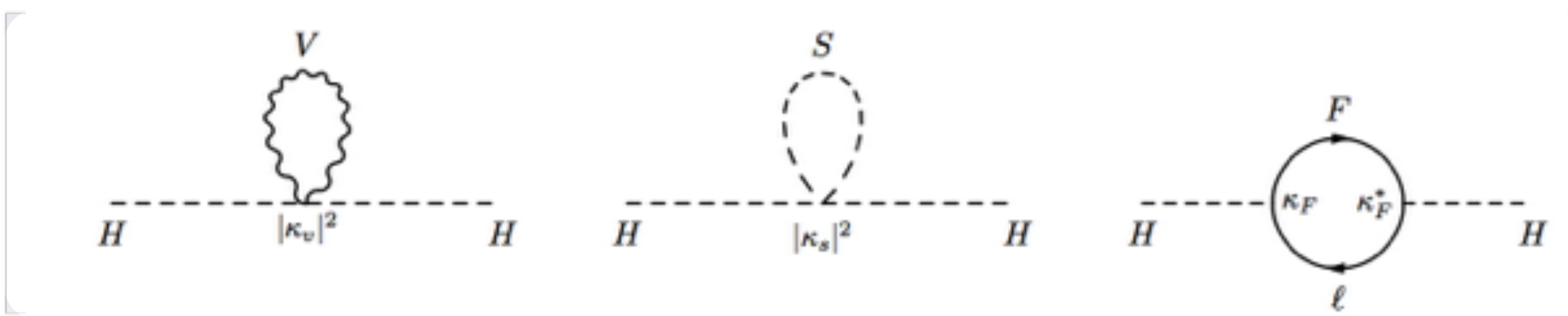
- All IR assumptions on the EFT limit, not a UV assumption.

- EFT prime directive, separate the scales in the problem and calculate with the long distance propagating states consistently. In SMEFT these are still the SM states. Calculate IN the EFT.

Typical size of effects to search for

- When you don’t rely on a resonance discovery the SM interactions are perturbed by local interactions

Unknown UV: M_i , g_j → $\sum_{i,j} \frac{g_i^2 M_j^2}{16\,\pi^2}\, h^2$



$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{|\kappa_v|^2\, m_v^2\, N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\, m_s^2\, N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\, m_F^2\, N_F}{16\,\pi^2} \right).$$

$$\frac{\sigma_{SM+i}}{\sigma_{SM}} \simeq \frac{1}{16\,\pi^2} \left(\frac{N_i^2\, |\kappa_i|^2 \kappa'}{g_{SM}\, \lambda} \right).$$

- LHC reach $\lesssim 14/6 \sim 2\,\mathrm{TeV}$ (rule of thumb due to PDF suppression)
- Corrections expected on the order of $\frac{v^2}{\Lambda^2} \sim few\,\%$ $\quad \frac{E^2}{\Lambda^2} \sim few - tens\%$

  (LEP data few % to 0.1 % precise)

$\Lambda \sim M/\sqrt{g}$ in this talk

Parameter breakdown

- Dim 6 counting is a bit non trivial.

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

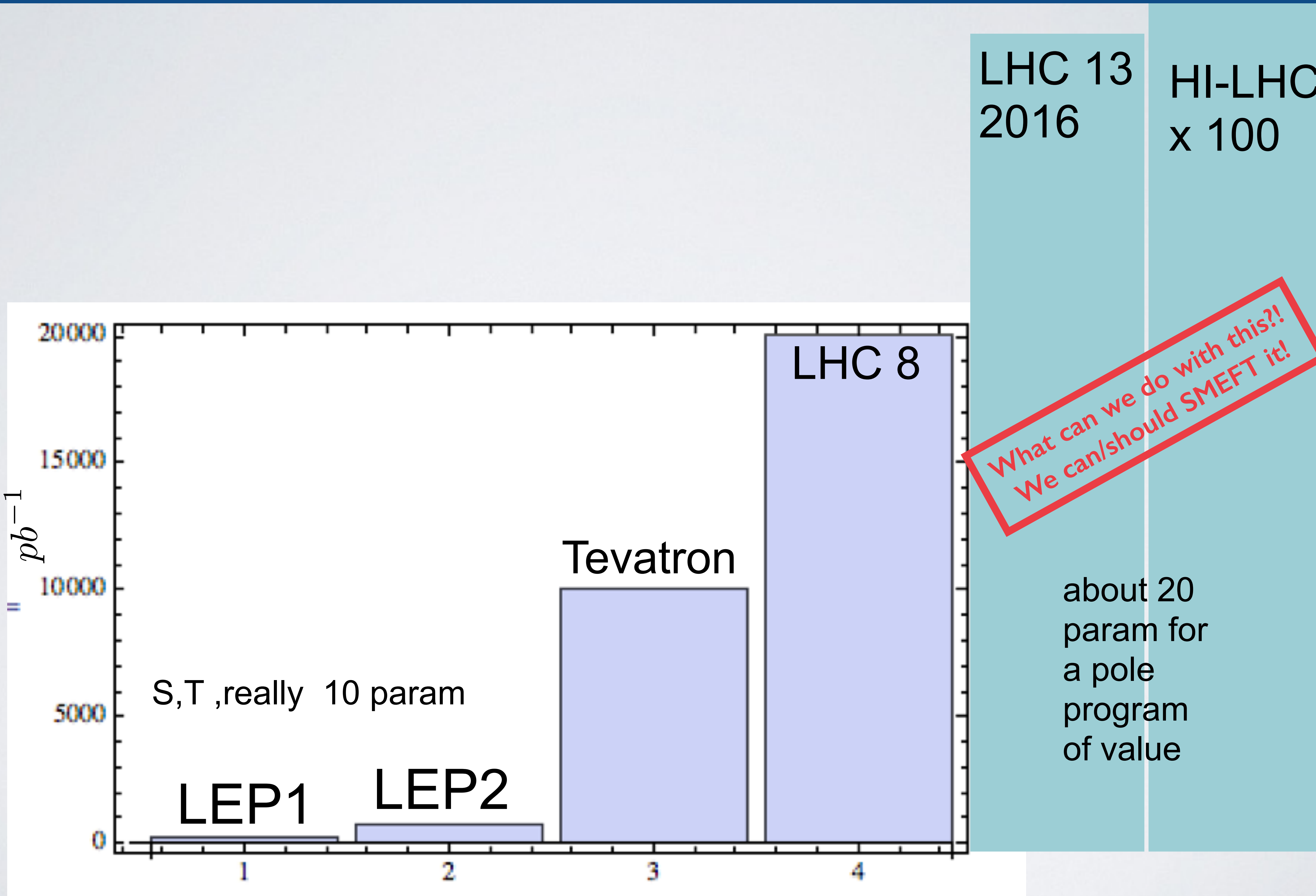
Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

Lots of ways to count…for ex at LO:

76	-	9	-	23	-	24	=	20
		flavour		CP		ψ^4		

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

More parameters, but MUCH more data



What does EWPD mean in the SMEFT?

- Do we have a factor of 10 problem?
- Corrections expected on the order of $\frac{v^2}{\Lambda^2} \sim few\,\%$ $\qquad \frac{E^2}{\Lambda^2} \sim few - tens\%$

  (LEP data few % to 0.1 % precise)

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[38]	-	-
$\hat{m}_W$[GeV]	80.385 ± 0.015	[39]	80.365 ± 0.004	[40]
σ_h^0 [nb]	41.540 ± 0.037	[38]	41.488 ± 0.006	[41]
Γ_Z[GeV]	2.4952 ± 0.0023	[38]	2.4942 ± 0.0005	[41]
R_ℓ^0	20.767 ± 0.025	[38]	20.751 ± 0.005	[41]
R_b^0	0.21629 ± 0.00066	[38]	0.21580 ± 0.00015	[41]
R_c^0	0.1721 ± 0.0030	[38]	0.17223 ± 0.00005	[41]
A_{FB}^ℓ	0.0171 ± 0.0010	[38]	0.01616 ± 0.00008	[42]
A_{FB}^c	0.0707 ± 0.0035	[38]	0.0735 ± 0.0002	[42]
A_{FB}^b	0.0992 ± 0.0016	[38]	0.1029 ± 0.0003	[42]

per-mill

percent!

- How worried should we be about the need to get a factor of 10 or so by cancelations?

Worries that we should/are sorting out:

- Can we use the measurements without a significant extra bias introduced due to transition from SM to the SMEFT? Ex given next.

- What are the one loop corrections on the most precise observables (see Will's talk)

- How correlated is the fit space? (very) Should we work harder on statistical measures of cancelations? (yes)

- Remember that LEP PO highly experimentally correlated:

  Simultaneous PO extraction of: $\{\hat{m}_Z, \Gamma_Z, \sigma^0_{had}, R^0_e, R^0_\mu, R^0_\tau\}$

  Also the calibration of the calorimeter in extraction of $\hat{m}_W$ means that it is really an extraction of $\hat{m}_W/\hat{m}_Z$

- Theoretically can't get just one operator at a time, so probably also theoretically correlated (see Yun's talk).

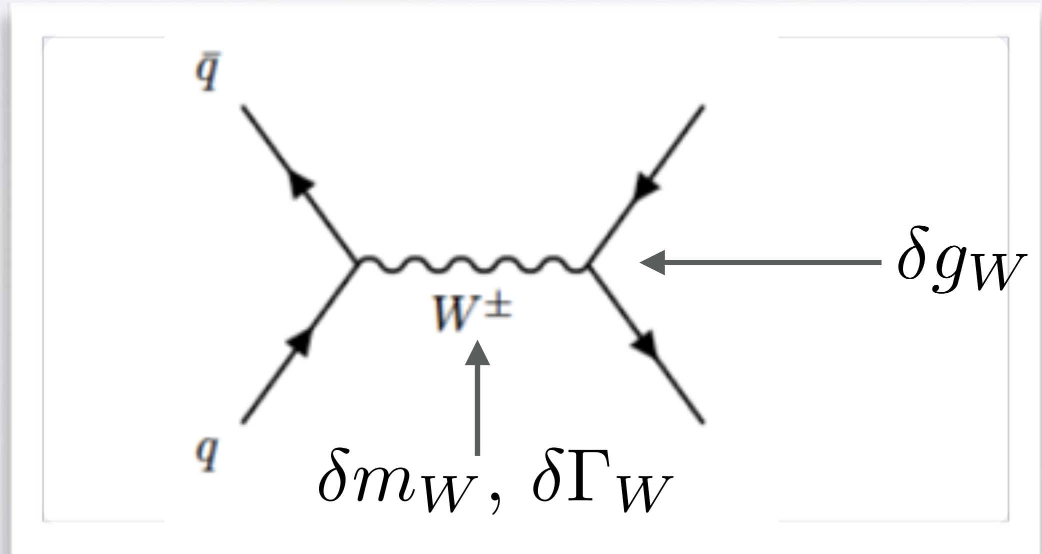
Ex of measurement bias check

- To use a measurement of M_W to constrain the SMEFT: $\{\hat{\alpha}, \hat{G}_F, \hat{m}_Z\}$ inputs

$$\frac{\delta m_W^2}{\hat{m}_W^2} = \frac{c_{\hat{\theta}}\, s_{\hat{\theta}}}{(c^2_{\hat{\theta}} - s^2_{\hat{\theta}}) 2\sqrt{2}\,\hat{G}_F} \left[4C_{HWB} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} C_{HD} + 4\,\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C^{(3)}_{H\ell} - 2\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{\ell\,\ell} \right]$$

This is how you want the constraint to act.

BUT measurement via transverse variables actually measures a process:

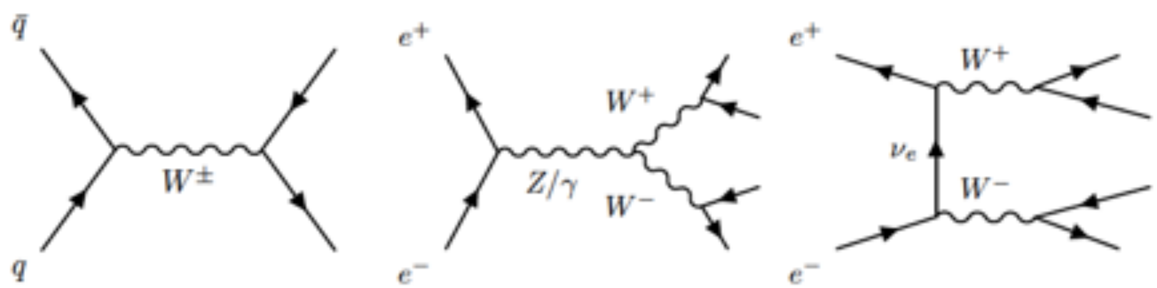


- How wrong is it to just apply the constraint pretending the other shifts not there?

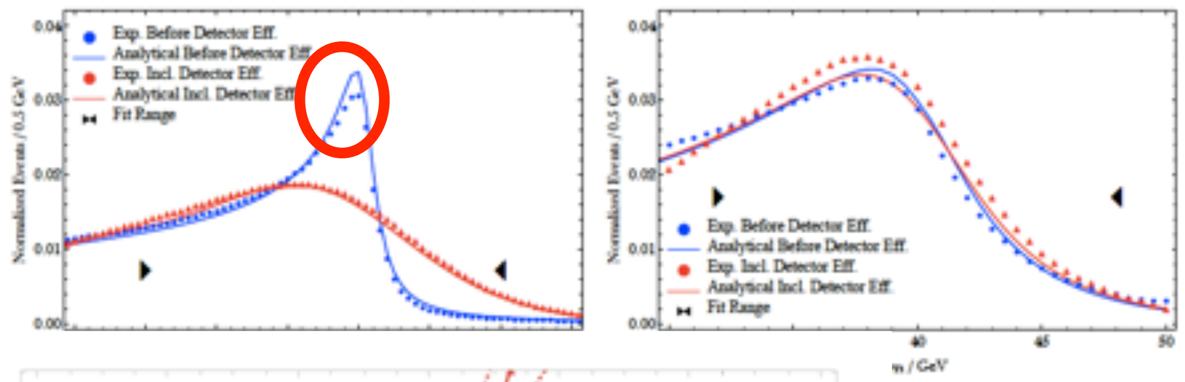
Mw measurements in SMEFT

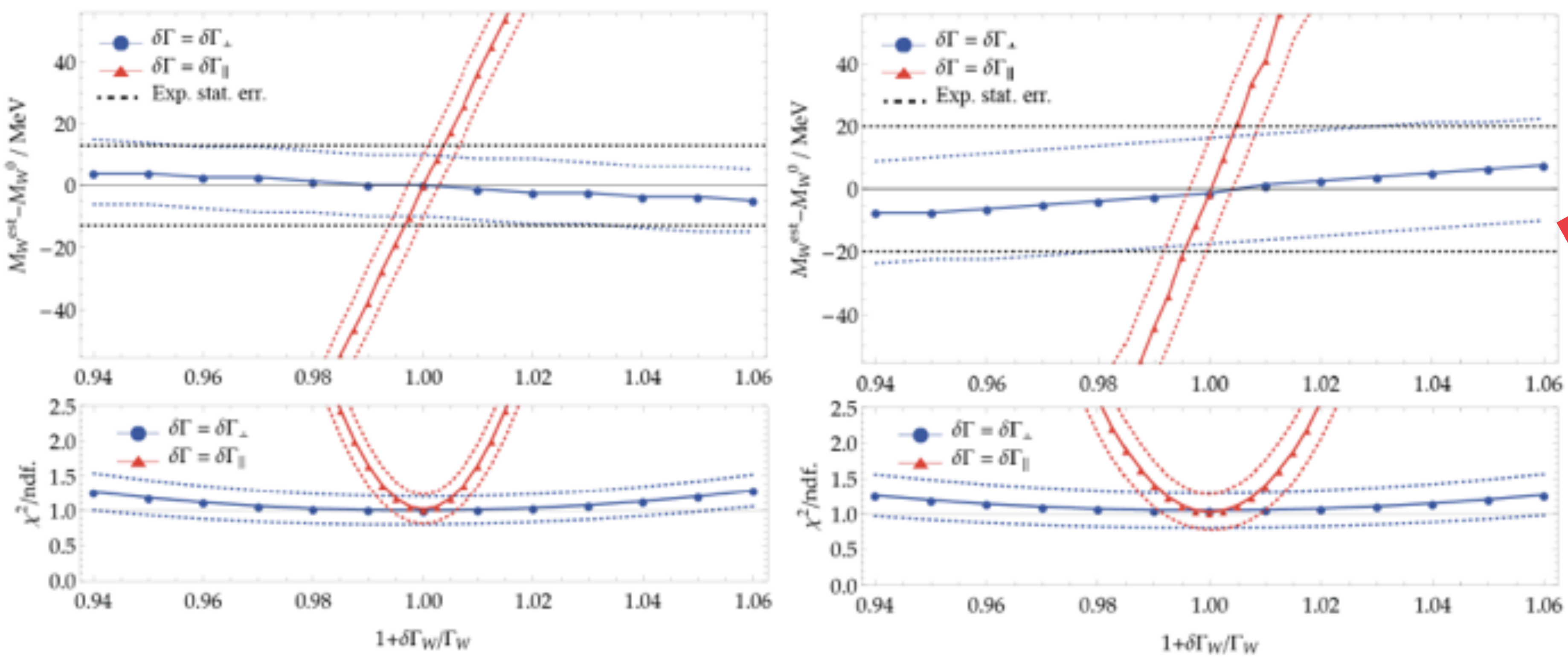
- Mw is a template fit at LEP and at the Tevatron.

1606.06502 Bjorn, Trott



Transverse mass Jacobian peak

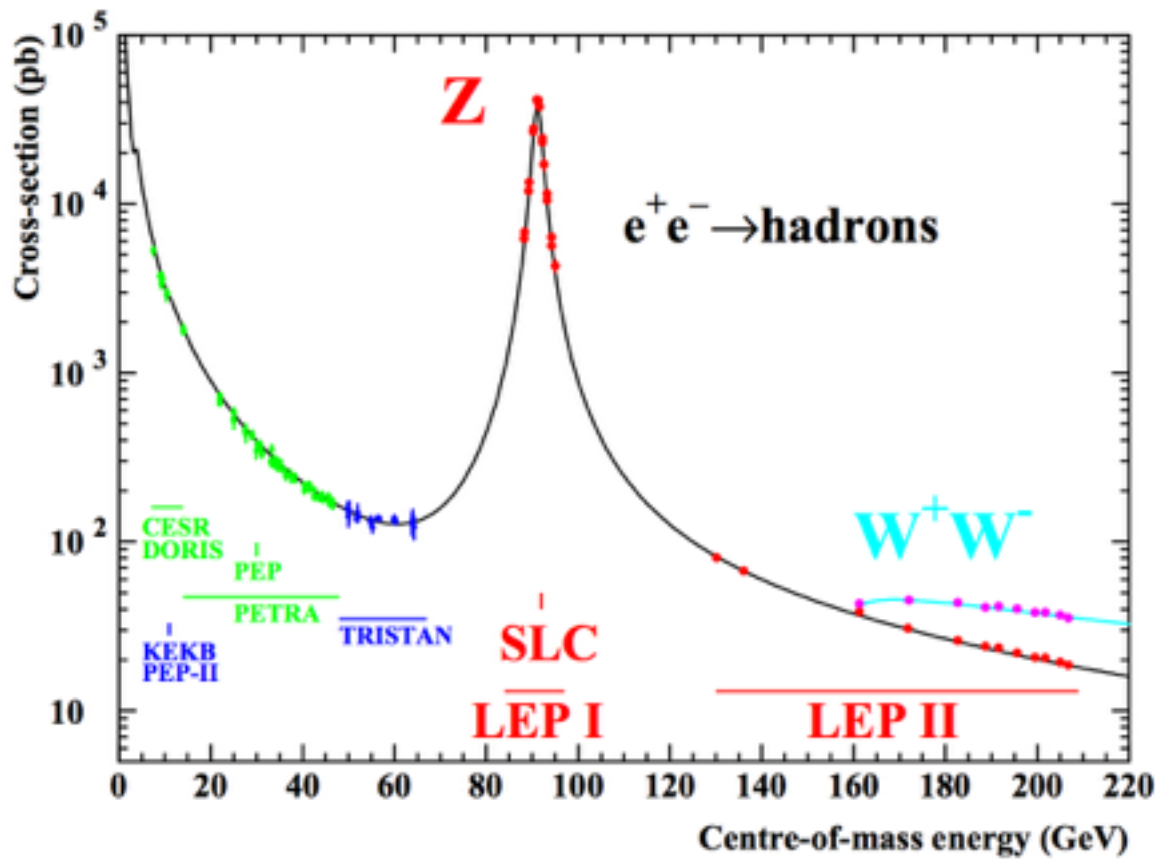




Below percent measurements in SMEFT at colliders possible

- Error quoted on the extraction for the Tevatron is OK in the SMEFT!

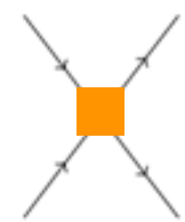
EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

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

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



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

arXiv:1502.02570 Berthier, MT

- The pseudo-observable LEP data is not subject to large intrinsic measurement bias transitioning from SM to SMEFT, so loops a go!

How many parameters in EWPD?

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

$$\boxed{Q_{HWB}, Q_{HD}}, \boxed{Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}}, \boxed{Q_{\ell\ell}}$$

- Relevant four fermion operator at LO is introduced due to $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ (used to extract G_F)
- Some basis dependence in this, but $\mathcal{O}(10) \ll 76$ as $\Gamma_{W,Z}/M_{W,Z} \ll 1$

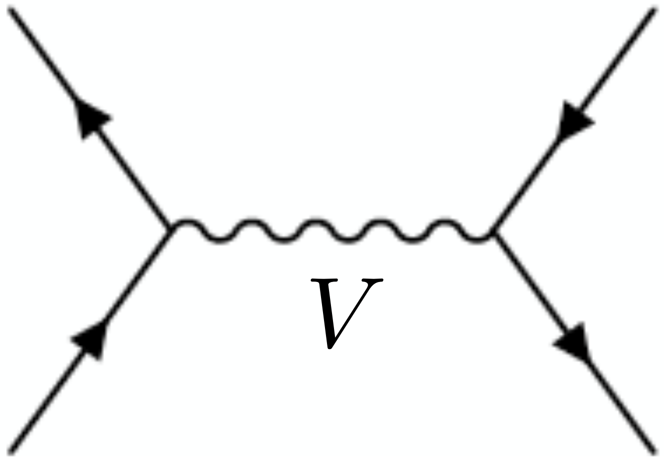
Two core issues:

- What is going on with the different claims and flat directions?
- How do neglected higher order terms effect EWPD?

The reparameterization invariance

- Recently we have been able to understand the origin of weak constraints when using the Warsaw basis in LEP data. Not a bug - its a physics feature!

arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT



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

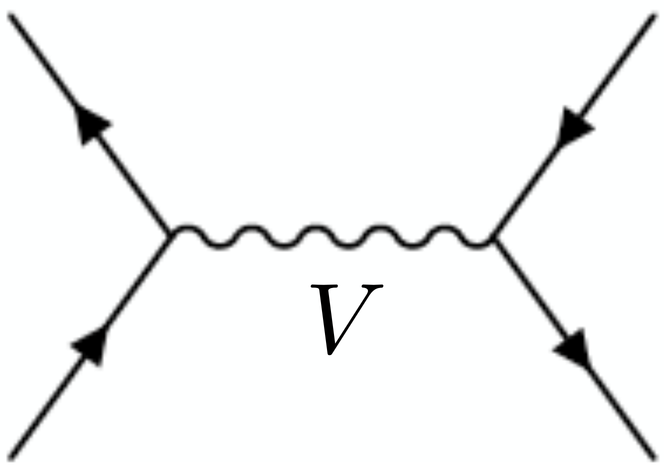
$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance (RI)

$$\mathcal{L}_{V\psi_i} = \frac{1}{2} m_V^2\, V^\mu\, V_\mu - \frac{1}{4} V^{\mu\nu} V_{\mu\nu} - g\,\bar{\psi}_i \gamma^\mu \psi_j V_\mu - g\,\kappa\,\bar{\psi}_k \gamma^\mu \psi_l V_\mu + \cdots .$$

The reparameterization invariance

- Recently we have been able to understand the origin of weak constraints when using the Warsaw basis in LEP data. Not a bug - its a physics feature!

arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT



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

$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance (RI)

$$\mathcal{L}_{V\psi_i} = \underline{\frac{1}{2} m_V^2 \, V^\mu \, V_\mu} - \boxed{\frac{1}{4} V^{\mu\nu} V_{\mu\nu}} - \underline{g\,\bar{\psi}_i \gamma^\mu \psi_j V_\mu - g\,\kappa\,\bar{\psi}_k \gamma^\mu \psi_l V_\mu} + \cdots .$$

These terms invariant under shift

This term changes!

- BUT! The LSZ formula corrects out the non-normalized kinetic terms, so no physical effect.

The reparameterization invariance

- This is why at one scale, you can get rid of the effect of the operators

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

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

$\bar\psi\psi \to \bar\psi\psi$

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

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

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

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

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

The reparameterization invariance

- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

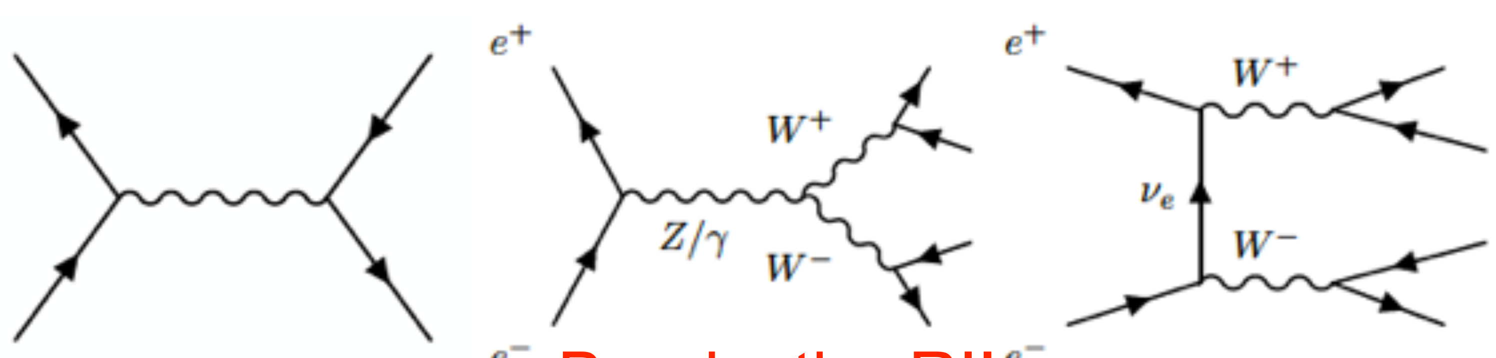
$$w_1^\alpha = -\boxed{w_B} - 2.59\boxed{w_W} \qquad w_2^\alpha = -\boxed{w_B} + 4.31\boxed{w_W}.$$

- We have also confirmed that this is scheme independent.

- The message is not “ there are too many parameters” but combine data sets in a well defined SMEFT, as no matter what operator basis you choose you get consistent results

Not as precisely measured.

So weaker constraints

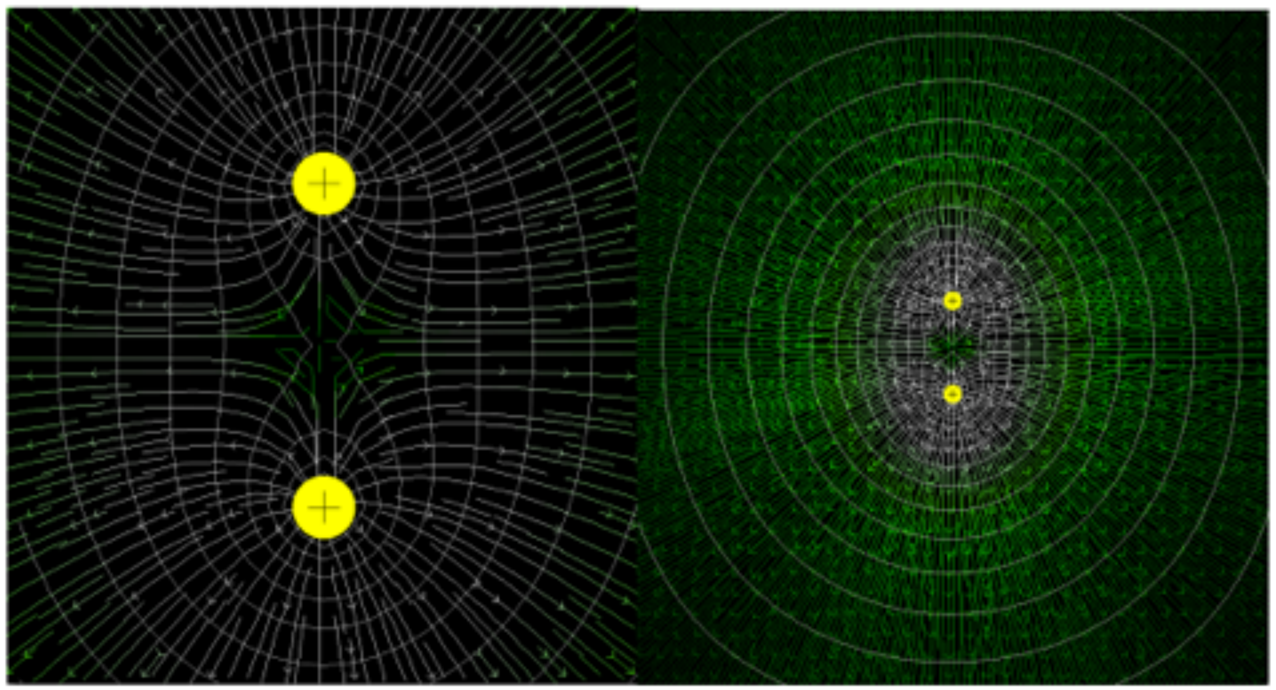


RI not broken | Breaks the RI! | RI not broken

- Can compare to operator basis choice arguments in Grojean et al [hep-ph/0602154]. Contino et al arXiv:1303.3876].

More scales, more possible signals

- What are we probing? Just for indirect mass scales of new states?



The field far away looks just like a point charge.

Consider the electrostatics multipole expansion

$$V(r) = \frac{1}{r} \sum c_{lm} Y_{lm}(\Omega) \left(\frac{a}{r}\right)^l$$

- By adding a series of terms (operators) like the dipole quadraple etc one approx the field

- “Non-minimal” coupling effects can be there, there is more than UV states to matching.

1305.0017 Jenkins,Manohar,Trott, Seminars at: - NBI Winter School lec 2015, MTCP Higgs 2015
also 1603.03064 Liu, Pomarol, Rattazzi, Riva

More on scales

- We want to probe the multipole scales of the (fundamental?) scalar to determine if its effectively point-like

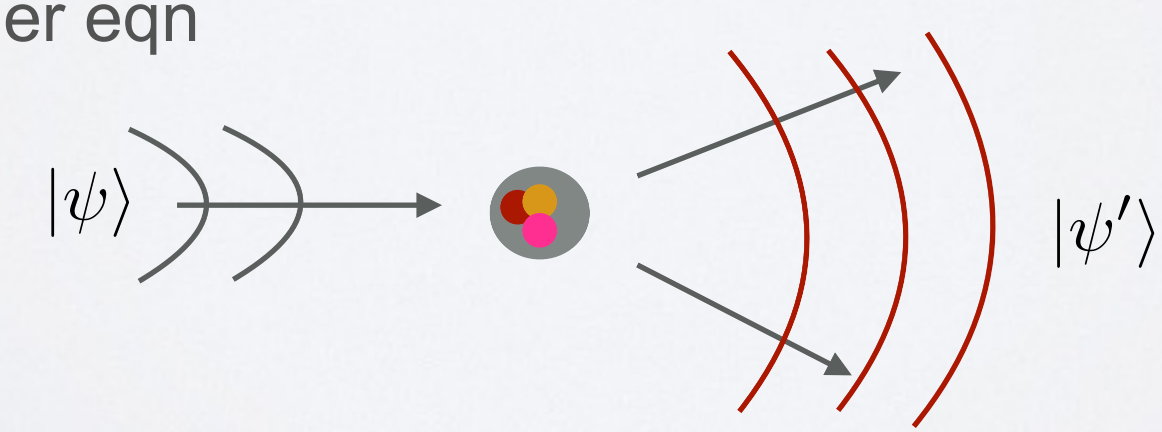
$$\lambda^2_{Mul} \simeq \{\frac{C_{H\Box}}{\Lambda^2}, \frac{C_{HD}}{\Lambda^2}, \frac{C_{HWB}}{\Lambda^2}, \frac{C_{HW}}{\Lambda^2}, \frac{C_{HB}}{\Lambda^2}\}.$$

Are these substructure coefficients:

$$\lambda_{mul} \ll \hbar/m_h c$$

Scattering lengths (i.e characteristic scales) can be larger than Compton wavelength), we are interested in a bit smaller but not vanishingly small.

- How can you think about the multipole expansion in SMEFT? Think of quantum mechanical scattering off of a non-local potential. With boundary conditions Lippman-Schwinger eqn



The multipole expansion

- We want to probe the multipole scales of the (fundamental?) scalar to determine if its effectively point-like

$$\lambda^2_{Mul} \simeq \{\frac{C_{H\square}}{\Lambda^2}, \frac{C_{HD}}{\Lambda^2}, \frac{C_{HWB}}{\Lambda^2}, \frac{C_{HW}}{\Lambda^2}, \frac{C_{HB}}{\Lambda^2}\}.$$

Are these substructure coefficients:

$$\lambda_{mul} \ll \hbar/m_h c$$

- Described as:

$$T_\ell(\mathbf{k},\mathbf{k}';E) = V_\ell(\mathbf{k},\mathbf{k}') + \frac{2}{\pi}\int_0^\infty d|\mathbf{q}|\, q^2 \frac{V_\ell(\mathbf{k}',\mathbf{q})T_\ell(\mathbf{q},\mathbf{k};E)}{E - q^2/\mu + i\epsilon}.$$

Transition matrix for non-local potential for Wavefunctions

- S matrix for partial wave scattering: $S_\ell(k) = e^{2i\delta_\ell(k)}$

(first introduced by wheeler)

More scales

- This is the effective range expansion:

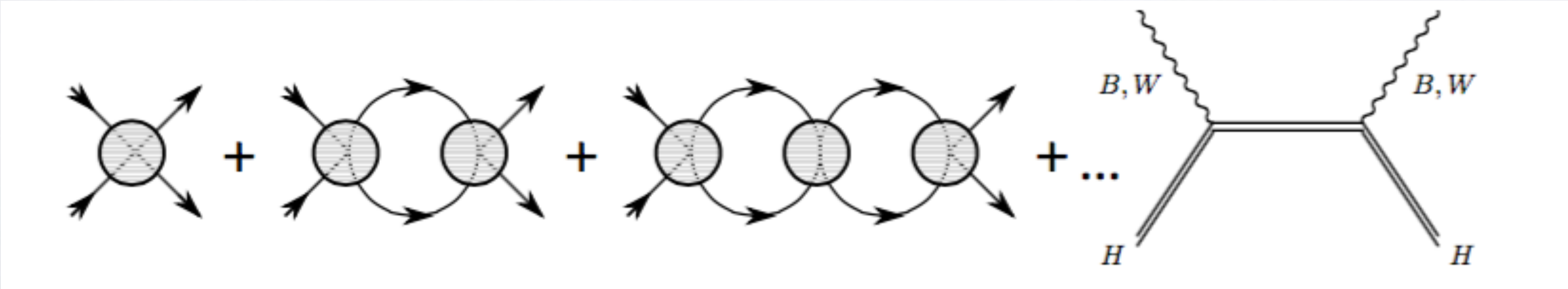
$$k \cot \delta_0(k) = -\frac{1}{a_0} + \frac{1}{2} r_0 k^2 - C_2 r_0^3 k^4 + \cdots$$

These are distinct scales to consider. We should think harder about them.

- How does it work in field theory? For NR bound states (see Kaplan et al 9605002, 9802075, manohar and luke 9610534, etc..)

$$i\mathcal{A} = -i\langle p|\hat{V} + \hat{V}G_E^0\hat{V} + \hat{V}(G_E^0\hat{V})^2 + \cdots |p'\rangle \;\Rightarrow\; i\mathcal{A} = -i\langle p|(G_E^0)^{-1}\, G_E\, (G_E^0)^{-1}|p'\rangle$$

free g.f. full g.f.



More on scales

- This is the effective range expansion:

$$k\cot\delta_0(k) = -\frac{1}{a_0} + \frac{1}{2}r_0\,k^2 - C_2 r_0^3\,k^4 + \cdots$$

These are distinct scales to consider. We should think harder about them.

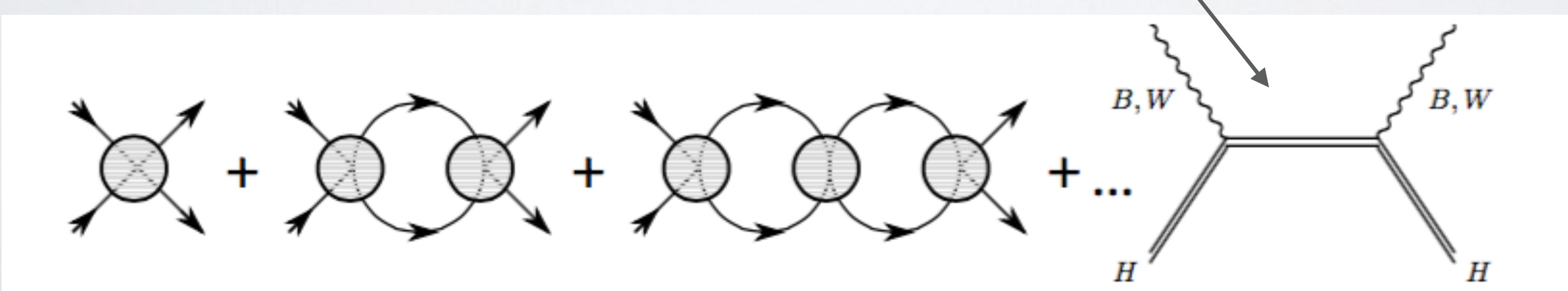
- How does it work in field theory? For NR bound states (see Kaplan et al 9605002, 9802075, manohar and luke 9610534, etc..)

$$i\mathcal{A} = -i\langle p|\hat{V} + \hat{V}G^0_E\hat{V} + \hat{V}(G^0_E\hat{V})^2 + \cdots|p'\rangle \;\Rightarrow\; i\mathcal{A} = -i\langle p|(G^0_E)^{-1}\boxed{G_E\,(G^0_E)^{-1}|p'\rangle}$$

free g.f.

satisfies sch. eqn

- In the end $|\mathbf{p}|\cot\delta(\mathbf{p}) = i|\mathbf{p}| + \frac{4\pi}{M}\frac{1}{\mathcal{A}}$ Problem is this is NOT NR



More on scales

- This is the effective range expansion:

$$k \cot \delta_0(k) = -\frac{1}{a_0} + \frac{1}{2} r_0 k^2 - C_2 r_0^3 k^4 + \cdots$$

These are distinct scales to consider. We should think harder about them.

- How does it work in field theory? For NR bound states (see Kaplan et al 9605002, 9802075, manohar and luke 9610534, etc..)

$$i\mathcal{A} = -i\langle p|\hat{V} + \hat{V} G_E^0 \hat{V} + \hat{V}(G_E^0 \hat{V})^2 + \cdots |p'\rangle \rightarrow i\mathcal{A} = -i\langle p|(G_E^0)^{-1} \boxed{G_E\,(G_E^0)^{-1}|p'\rangle}$$

free g.f.

satisfies sch. eqn

- In the end $|\mathbf{p}| \cot \delta(\mathbf{p}) = i|\mathbf{p}| + \frac{4\pi}{M}\frac{1}{\mathcal{A}}$
- We know, expansion of Higgs as a bound state in SMEFT case projects onto ops. Just because we have trouble calculating this physics does not make it 0.

$$\lambda^2_{Mul} \simeq \{\frac{C_{H\Box}}{\Lambda^2}, \frac{C_{HD}}{\Lambda^2}, \frac{C_{HWB}}{\Lambda^2}, \frac{C_{HW}}{\Lambda^2}, \frac{C_{HB}}{\Lambda^2}\}.$$

Test this without prejudice!

If a series of unfortunate events happens…

Look away
look away
Look away
look away
This show will reck your evening
Your whole life and your day
Every single episode is nothing but dismay …
but horror and inconvenience on the way
Ask any stable person "should I watch?" and they will say
Look away
look away,
look away
Look away
look away
look away
Look away
look away
look away

Neutrino option

It would be extremely curious.

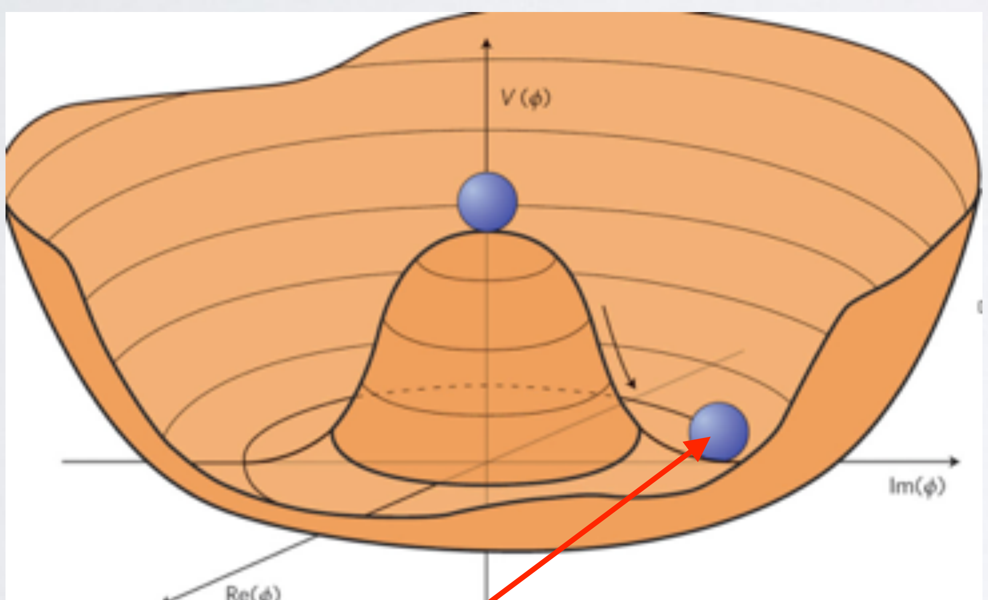
- Reminder: Why is the Higgs mechanism and classical potential curious?

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

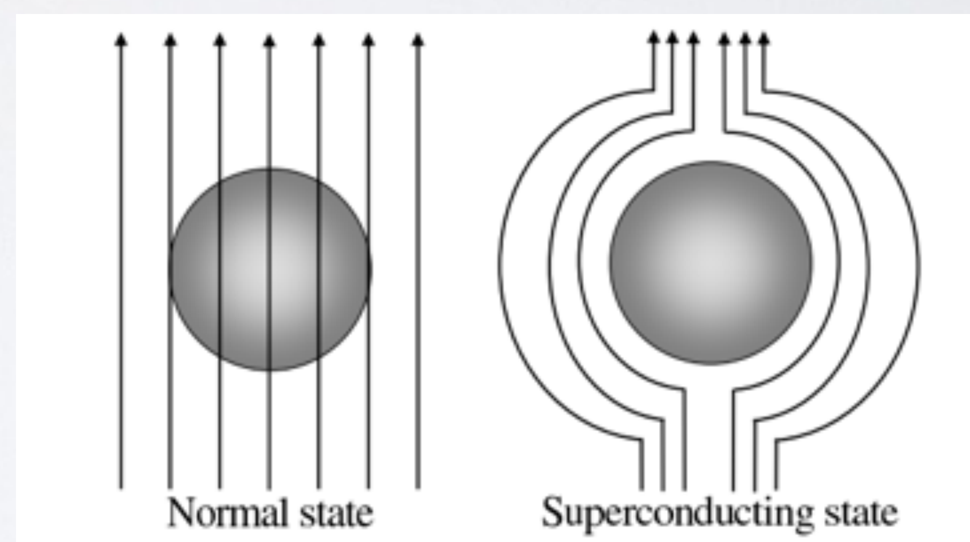
Partial Higgs action

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

Landau-Ginzberg actional, parameterization of Superconductivity



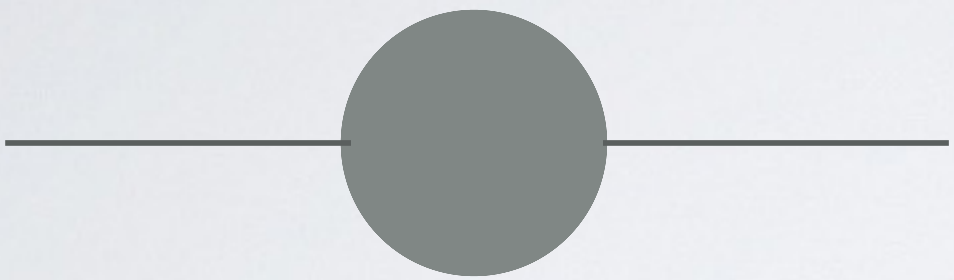
$m_{W/Z} = 0$ field config. energetically excluded (i.e. spon. sym breaking)

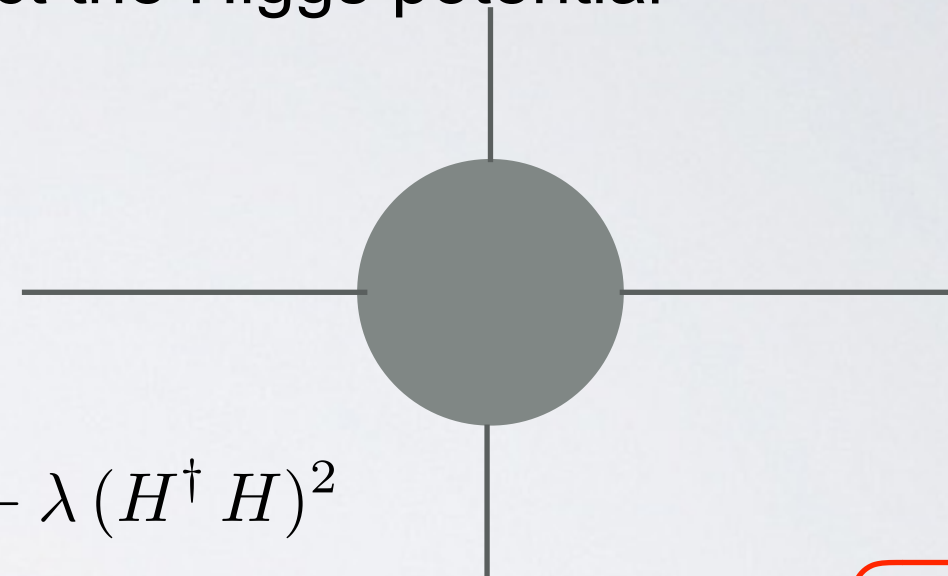


Magnetic field energetically excluded from interior of SC

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

The problem.

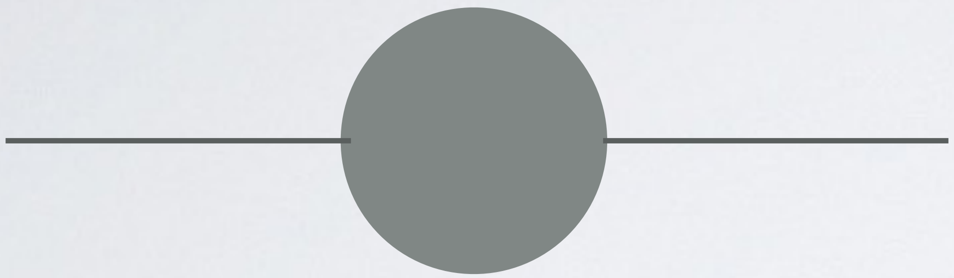
- Composite models (nobly) try to construct the Higgs potential:

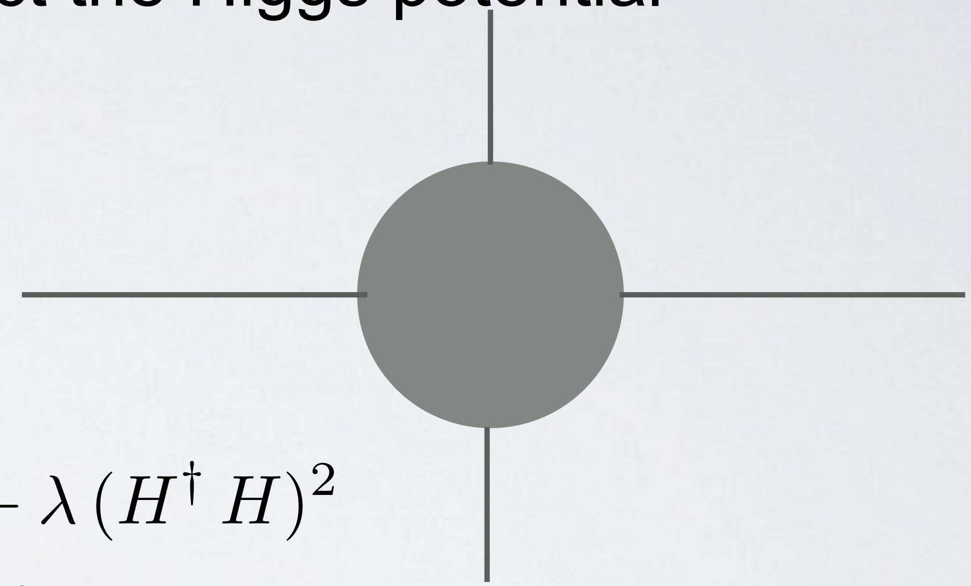
$$V(H) \simeq \frac{g_{SM}^2\,\Lambda^2}{16\,\pi^2}\left(-2\,aH^\dagger H + 2b\frac{(H^\dagger H)^2}{f^2}\right)$$ see 1401.2457 Bellazzini et al

- 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



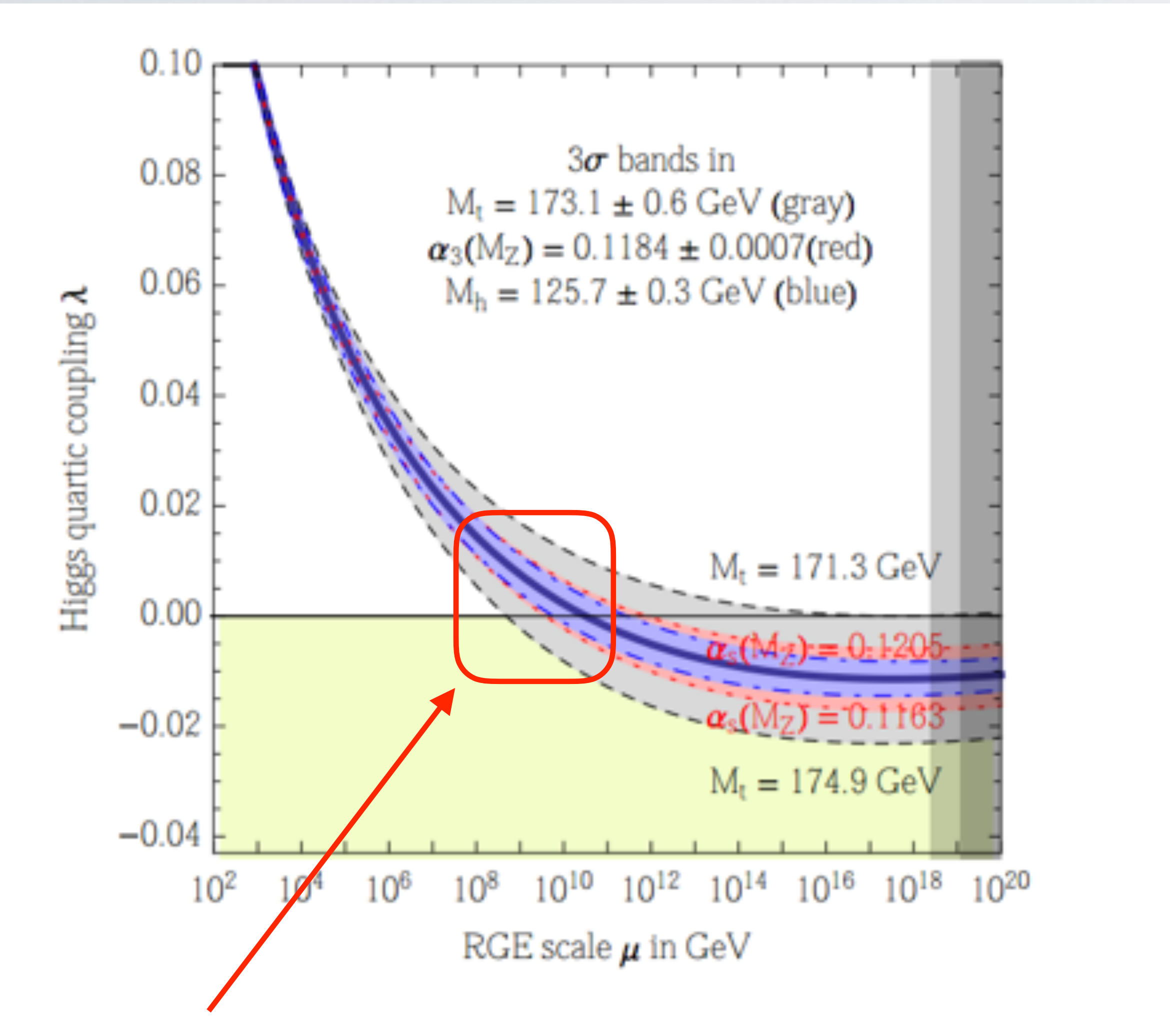


$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- Higgs coupling deviations scale as $\sim 1 - \dfrac{v^2}{f^2}$ 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.

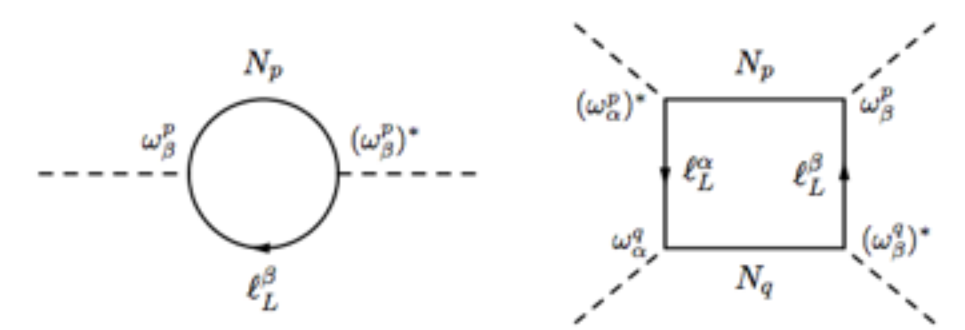
Simplest example of building the potential

- 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 $d \leq 4$

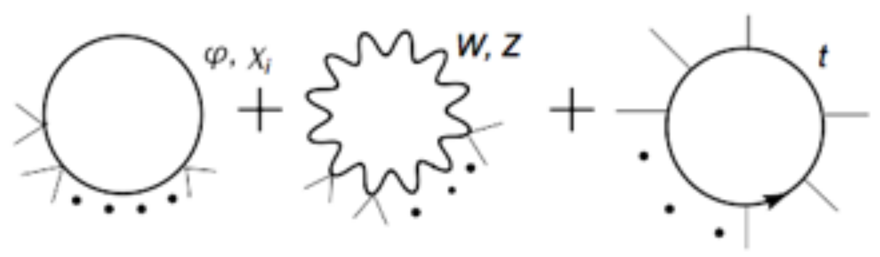


- Direct threshold matching onto $\mathcal{L}_{SM}$

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

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

This threshold matching should be done to CW



- Construct quantum corrections:

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

- If $m_p \gg v, \Lambda_i$ such a threshold matching can dominate the potential and give low scale pheno that is the SM

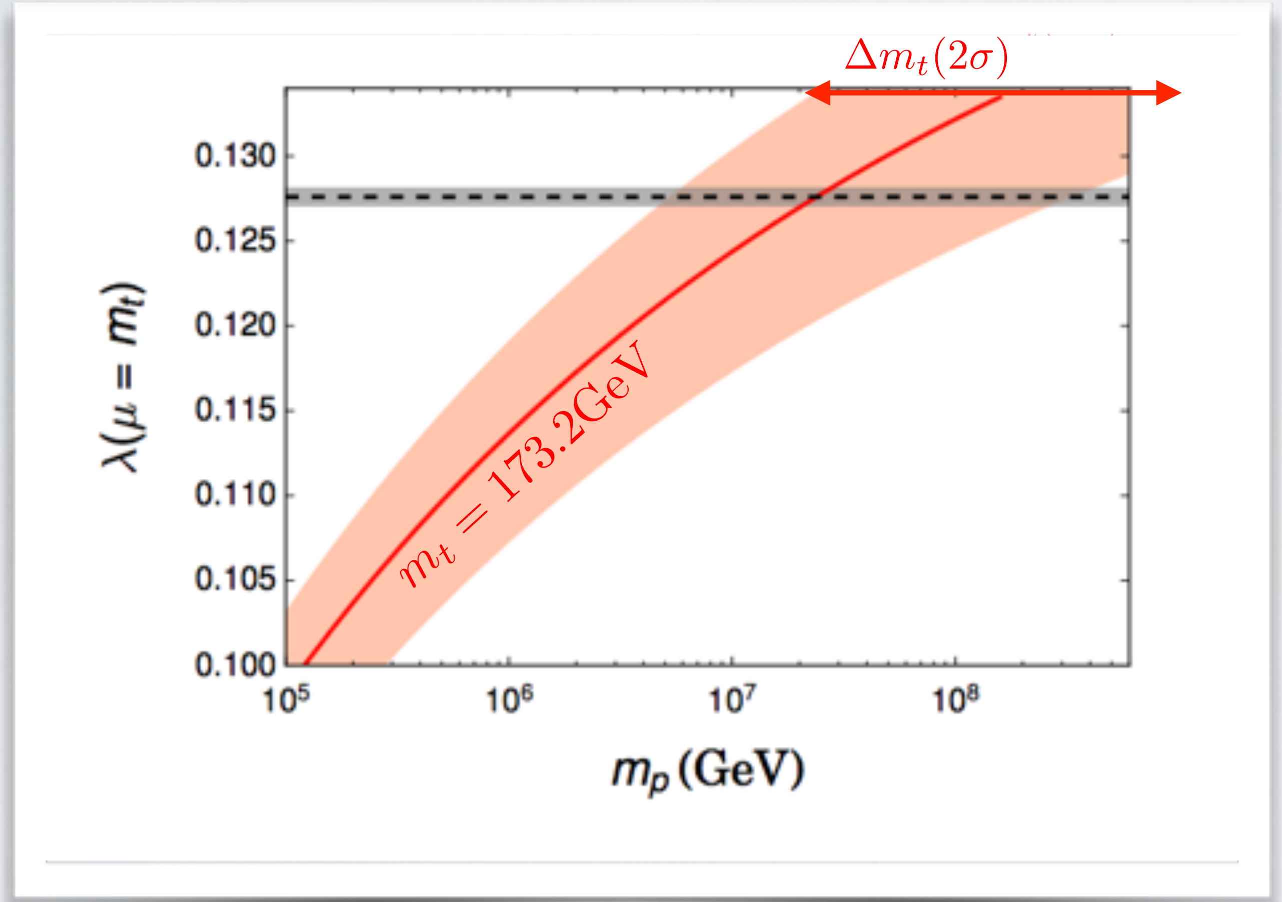
- It has long been known that such threshold corrections are a direct representation of the Hierarchy problem F. Vissani, Phys. Rev. D 57, 7027 (1998)

- Can one go the full way of generating the EW scale 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 $\lambda \sim 0.13$

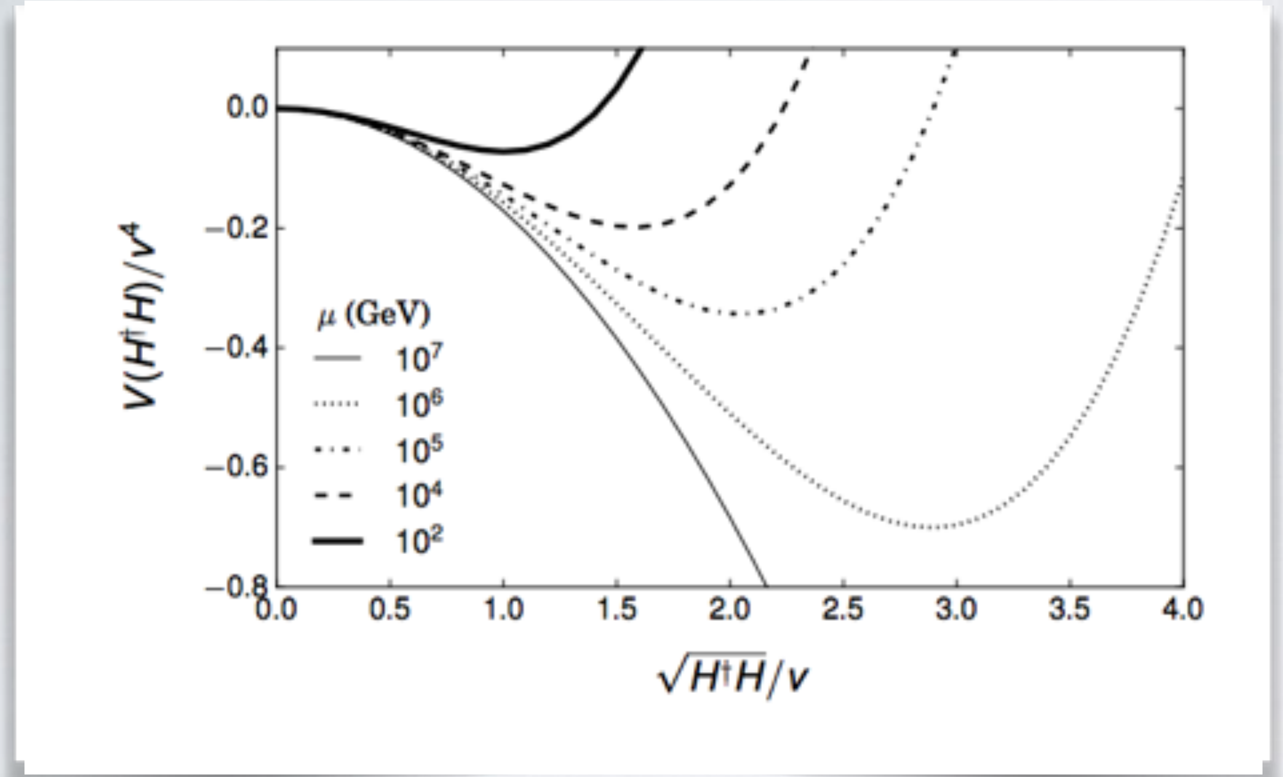
- This essentially fixes the mass scale and couplings

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

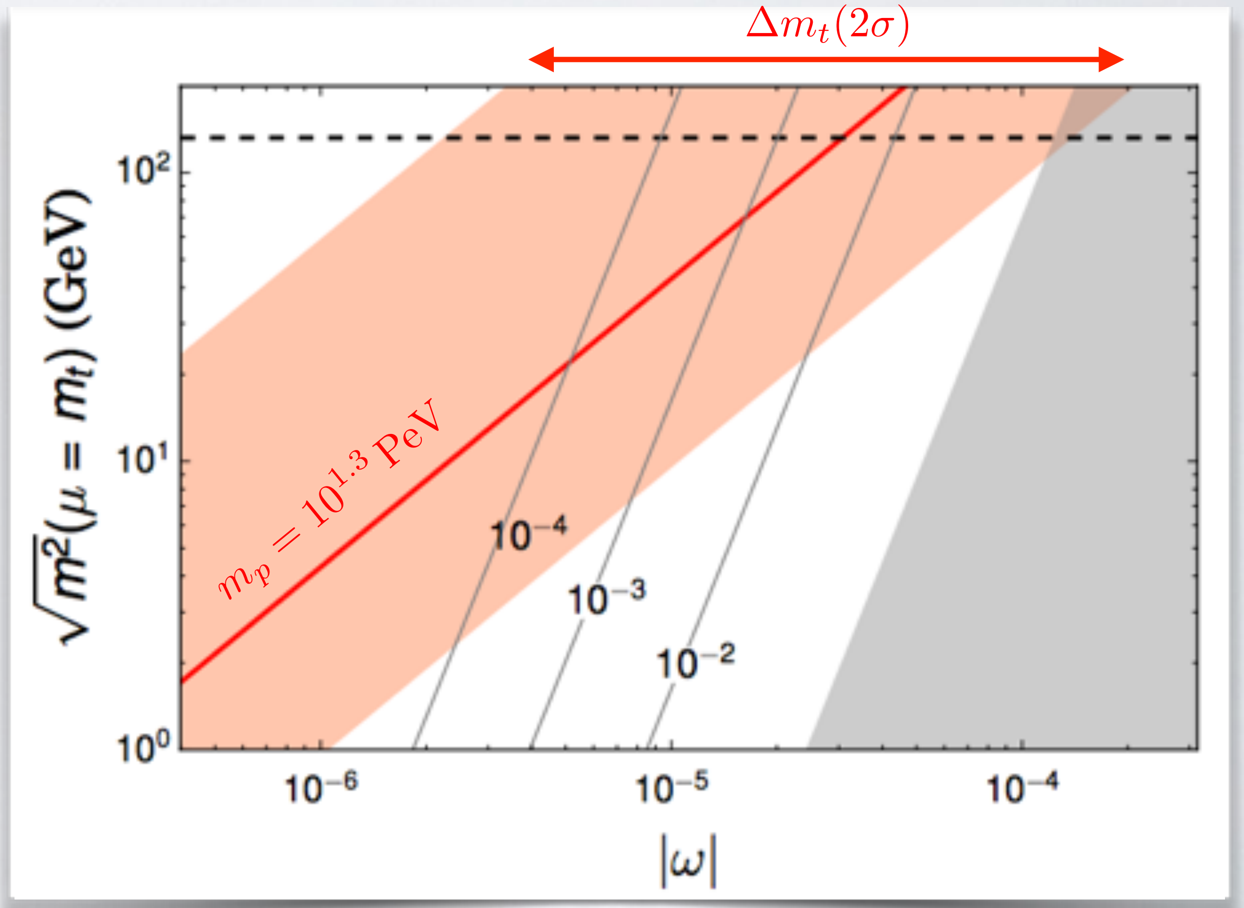
$$|\omega| \sim 10^{-5}$$

- 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.



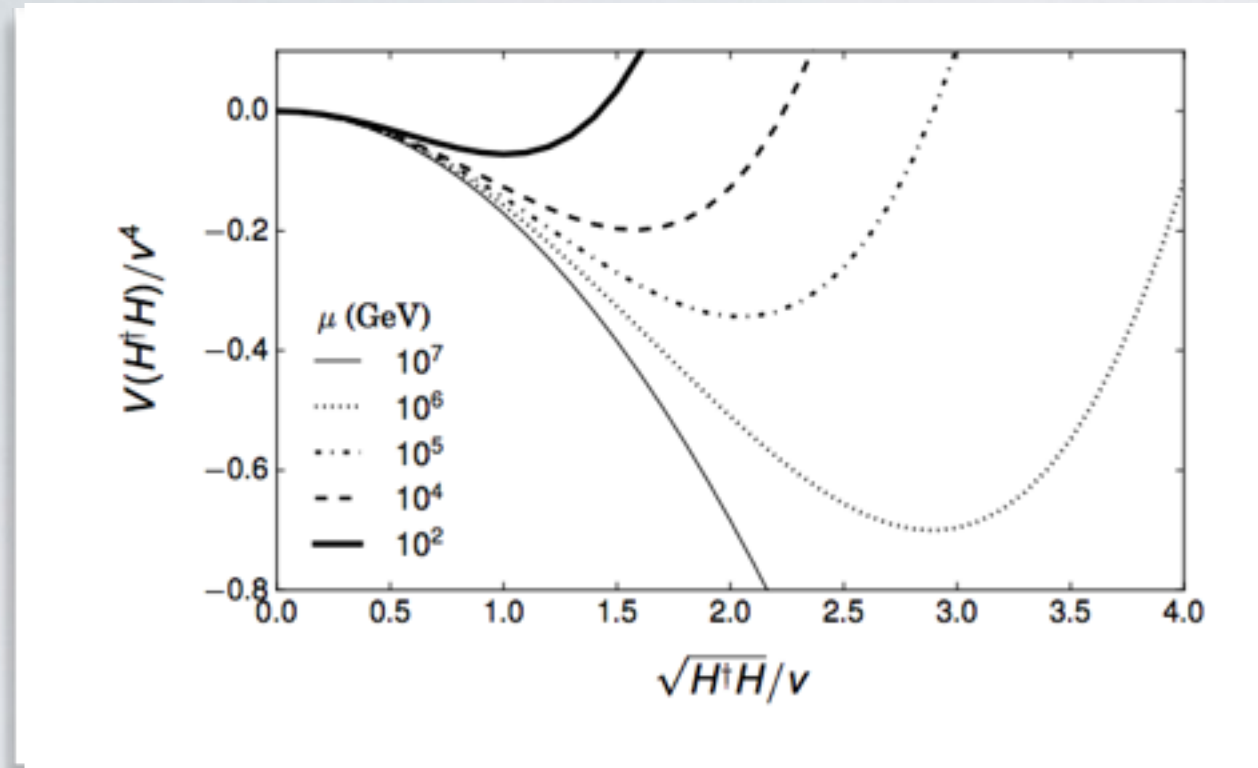
- The EW potential does get constructed correctly running down in a non-trivial manner



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

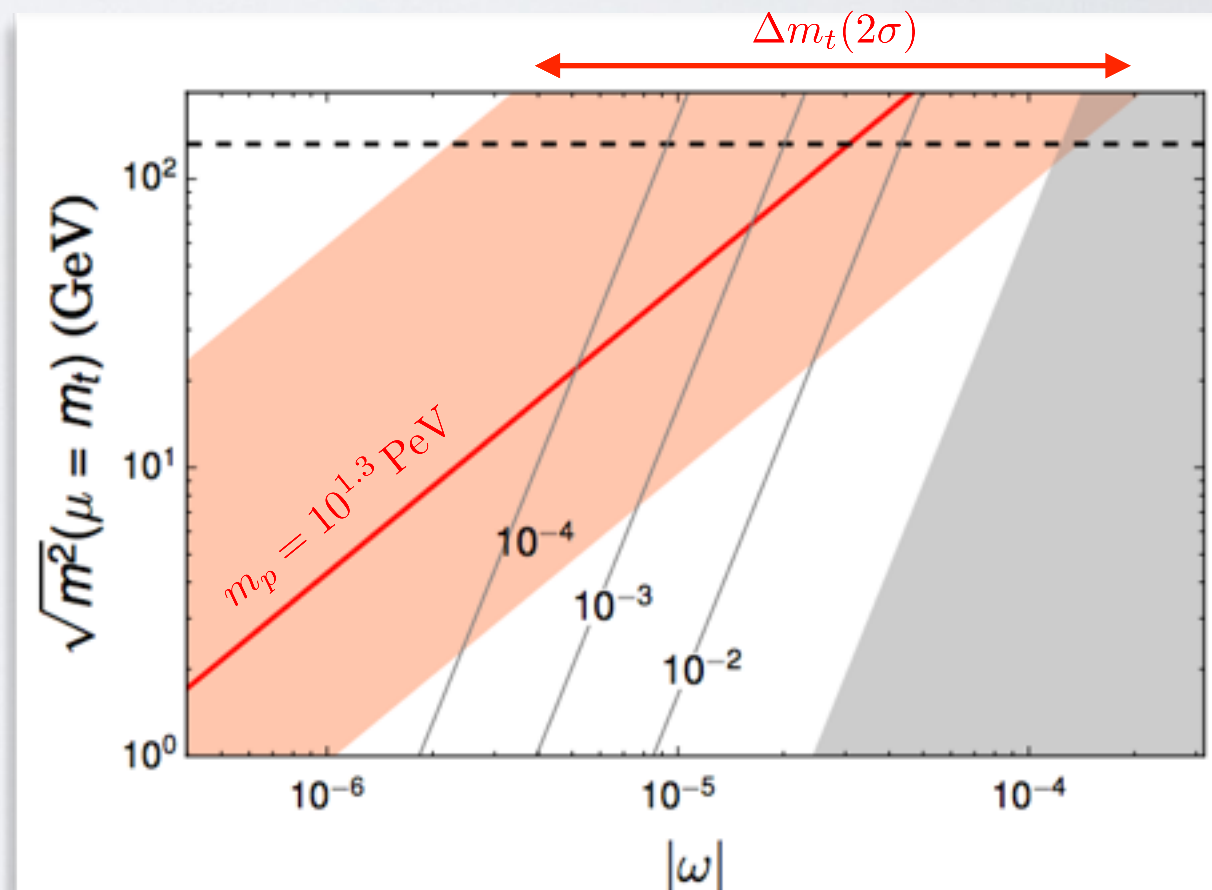
$\Delta m_\nu(\mathrm{eV})$

The mass scales of neutrinos also works.



- you were warned…

Look away
look away
Look away
look away



- The right neutrino mass scale (diff) can result.

Δm_ν(eV)

Neutrino option summary:

- Radiative EW symmetry breaking due to see-saw model field content extending the SM + SM RGE's.

- ~~Expectation of TeV scale new states~~

- Expectation of PeV scale mass generation mechanism associated with lepton number violating neutrino masses.

- Protection mechanism of the SM: Accidental L number global symmetry

Scale invariant limit with CW breaking and threshold matching hard breaking.

Leading way that L number violating effects feed in is loop level $H^\dagger H$, $(H^\dagger H)^2$

- Build the Higgs potential in the far UV and run it down!

Conclusions:

- Massive pessimism before the greatest data set ever recored in collider particle physics history is delivered is perhaps misplaced.
- We expected resonances, but the waiter seems to have brought EFT.
- Fortunate events 1: We are talking factor of 10 cancelations between out naive expectation of effects, and flavour symmetric tests (EWPD). (sym test different)
- Highly correlated fit space in EWPD due to experiment, and the RI.
  If we break that by hand - much stronger constraints. This is a multiple orders of magnitude effect. Things are not as dire if you take this seriously.
- Fortunate events 2: We are probing MORE than just for states in SMEFT, we are probing for substructure too. More opportunity for discovery.
- Unfortunate event : Neutrino option disturbingly compelling and simple, but also unexplored!

Back up:

If you insist - that HB thing.

- Basis is defined by first writing down a full set of $\mathrm{SU}(3) \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{Y}}$ ops

- Then small field redefinitions are used to fix the meaning of the SM fields in the power counting expansion

$$SM \to SM + dim3/\Lambda^2$$

Dim 3 bit is gauge independent structure with same transformation properties as the field shifted. For example

$$H_j' \to H_j + h_1 \frac{D^2 H_j}{\Lambda^2} + h_2 \frac{\bar{e}\,\ell_j\,Y_e}{\Lambda^2} + h_3 \frac{\bar{d}\,q_j\,Y_d}{\Lambda^2} + h_4 \frac{(\bar{u}\epsilon\,q_j)^\star\,Y_u^\star}{\Lambda^2} + h_5 \frac{H^\dagger H\,H_j}{\Lambda^2},$$

$$B_\mu' \to B_\mu + b_1 \frac{\bar{\psi}\gamma_\mu\psi}{\Lambda^2} + b_2 \frac{H^\dagger\,i\overleftrightarrow{D}_\mu H}{\Lambda^2} + b_3 \frac{D^\alpha B_{\alpha\mu}}{\Lambda^2} + b_4 \frac{H^\dagger H\,B_\mu}{\Lambda^2},$$

- Consequence is dim 6 op relations

If you insist - that HB thing.

- For example

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

Use field redefinition:
$$B'_\mu \to B_\mu + b_2\frac{H^\dagger\, i\overleftrightarrow{D}_\mu H}{\Lambda^2},$$

- Shift that results is $\mathcal{L}'_B \to \mathcal{L}_B - g_1 b_2 \Delta B$

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

If you insist - that HB thing.

- This is justified as the EOM difference you can then use to choose to cancel an op out projects out of the external states - it is vanishing in the on shell projection defining the S matrix element

$$\langle SM | S | SM \rangle$$

$$\Delta B = 0 \qquad\qquad \Delta B = 0$$

- Another way to say it is in the path integral formulation you are just changing interpolating variables without violating a symmetry, no physical effect.

- The field redefinition has to be gauge invariant as the observables do not carry gauge dependence. Ie. Unitary gauge is not some "gauge of reality"

- Following the rules protects you from insisting the Lagrangian is put into a gauge dependent form with gauge dependent field redefintions.

If you insist - that HB thing.

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

- You fix the lagrangian parameters at the cost of shifting the remaining parameters retained in the theory. This is why the wilson coefficients are not physical, but contextual as to the fully defined basis.
- Consequence 1: You should retain all operators that are present in the theory to be consistent (see 1409.7605)
- Consequence 2: This is why the RGE dim six ops have to run down and change the scale dependence of the dim 4 terms
- Consequence 3: Scalar manifolds are tricky

If you insist - that HB thing.

- Parameterize the H field as $H = \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$

- You can work out the derivative terms

$$\mathcal{L}_{derv} = \frac{1}{2}(\partial_\mu \vec{\phi}) \cdot (\partial^\mu \vec{\phi}) + \frac{C_{H\Box}}{\Lambda^2} \vec{\phi}^2 \Box \vec{\phi}^2 + \frac{C_{HD}}{\Lambda^2} (\vec{\phi} \cdot (\partial^\mu \vec{\phi}))^2 + \cdots$$

- This defines a tensor for the scalar manifold $\partial^\mu \phi_i \partial_\mu \phi_j / 2$

$$R_{ij} = \delta_{ij} + 2\frac{\phi_i \, \phi_j}{\Lambda^2}(C_{HD} - 4C_{H\Box}) + \cdots$$

You find $R^i_{jkl} \neq 0$

Burgess, Lee, Trott arXiv:1002.2730].

- The same point is made observing that $D^2 H \neq \Box H$ but $D^2 h = \Box h$
  This is why in unitary gauge you can do this field redefinition to put in canonical form

$$h \to h\left(1 + (C_{H\Box} - \frac{1}{4} C_{HD}) \bar{v}_T^2 \left(1 + \frac{h}{\bar{v}_T} + \frac{h^2}{3\bar{v}_T^2}\right)\right).$$

See the review upcoming and …

R. E. Kallosh and I. V. Tyutin, *The Equivalence theorem and gauge invariance in renormalizable theories*, *Yad. Fiz.* **17** (1973) 190–209. [Sov. J. Nucl. Phys.17,98(1973)].

S. Kamefuchi, L. O'Raifeartaigh, and A. Salam, *Change of variables and equivalence theorems in quantum field theories*, *Nucl. Phys.* **28** (1961) 529–549.

G. 't Hooft and M. J. G. Veltman, *Combinatorics of gauge fields*, *Nucl. Phys.* **B50** (1972) 318–353.

M. C. Bergere and Y.-M. P. Lam, *Equivalence Theorem and Faddeev-Popov Ghosts*, *Phys. Rev.* **D13** (1976) 3247–3255.

H. D. Politzer, *Power Corrections at Short Distances*, *Nucl. Phys.* **B172** (1980) 349–382.

G. Passarino and M. Trott, *The Standard Model Effective Field Theory and Next to Leading Order*, arXiv:1610.08356.

G. Passarino, *Field reparametrization in effective field theories*, *Eur. Phys. J. Plus* **132** (2017),

C. P. Burgess, H. M. Lee, and M. Trott, *Comment on Higgs Inflation and Naturalness*, *JHEP* **07** (2010) 007, [arXiv:1002.2730].

R. Alonso, E. E. Jenkins, and A. V. Manohar, *A Geometric Formulation of Higgs Effective Field Theory: Measuring the Curvature of Scalar Field Space*, *Phys. Lett.* **B754** (2016) 335–342, [arXiv:1511.00724].

R. Alonso, E. E. Jenkins, and A. V. Manohar, *Geometry of the Scalar Sector*, *JHEP* **08** (2016) 101, [arXiv:1605.03602].