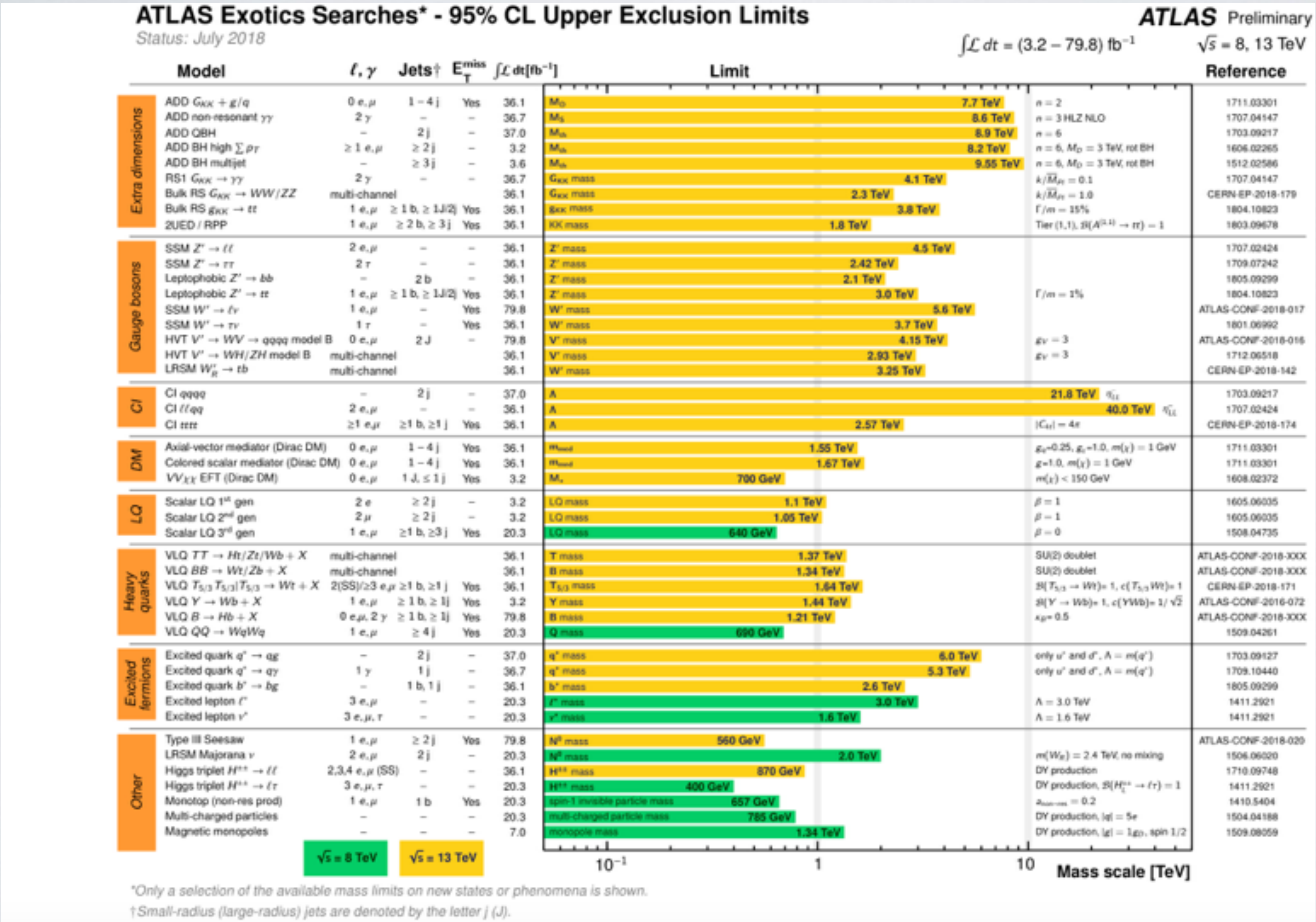
Don’t be a tool, do the SMEFT right. (And use a tool to check)

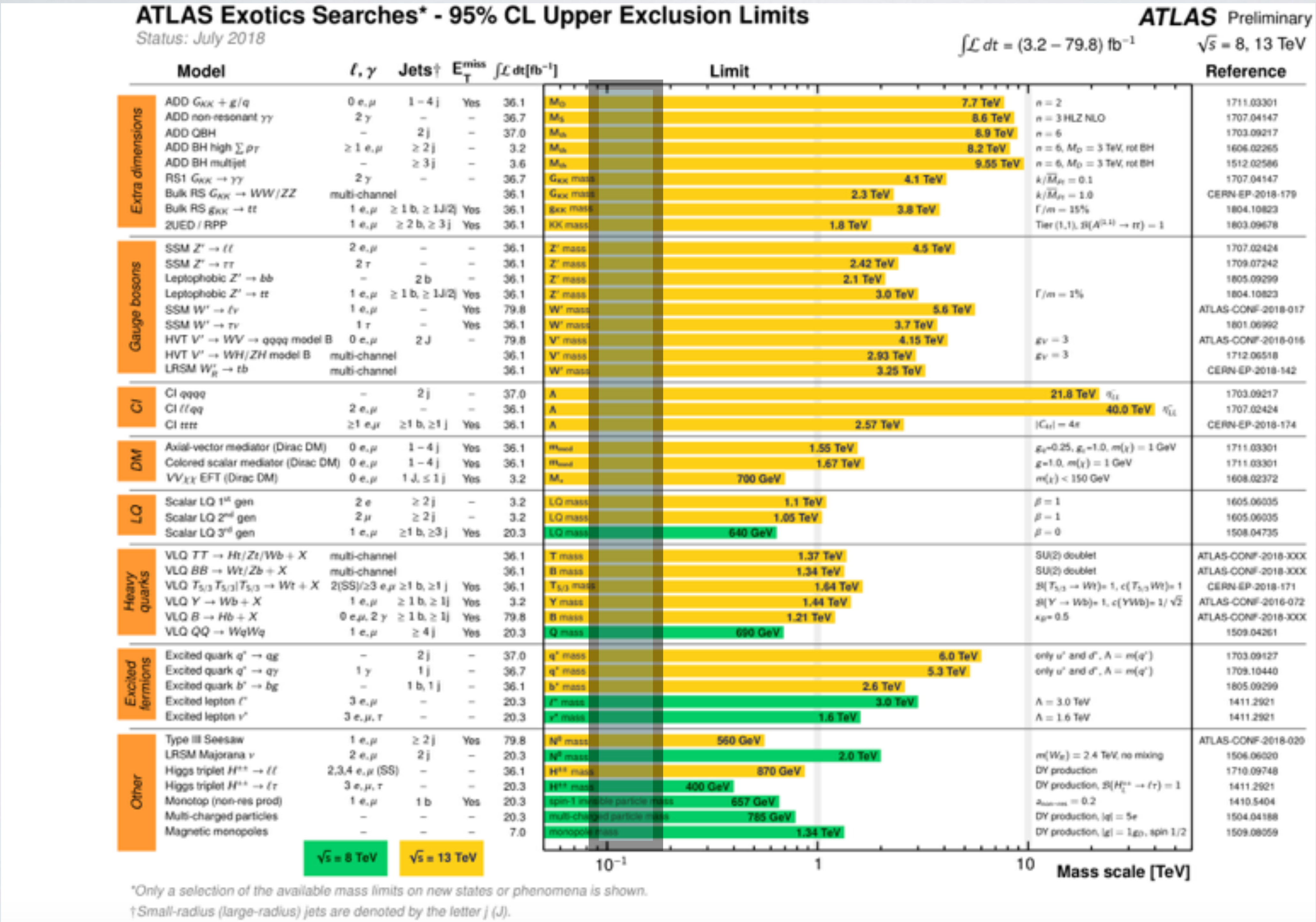
((first talk dibs on the punning))

M. Trott, SMEFTtools 2019

Why develop the SMEFT?

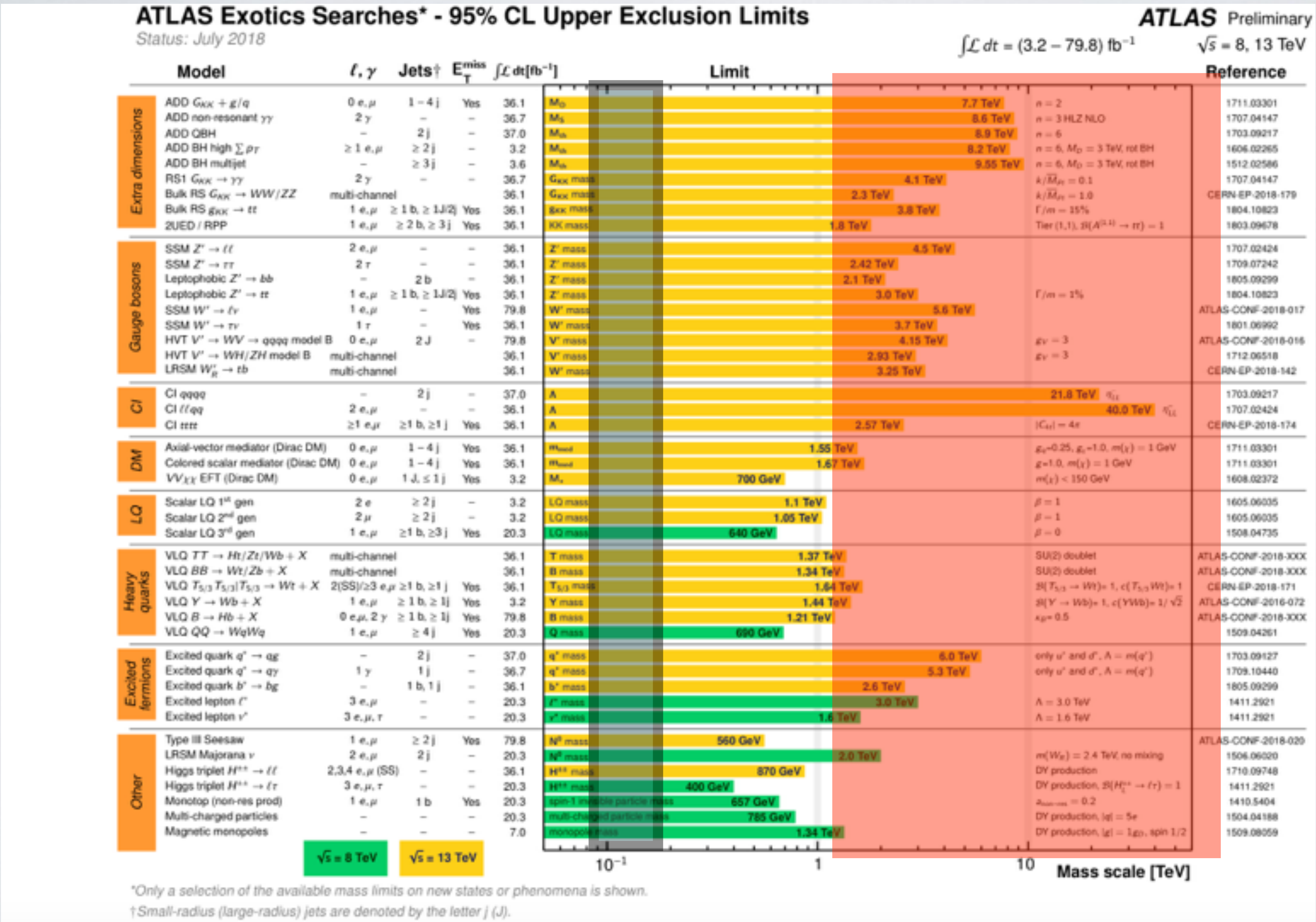


What wasn’t discovered at LHC



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

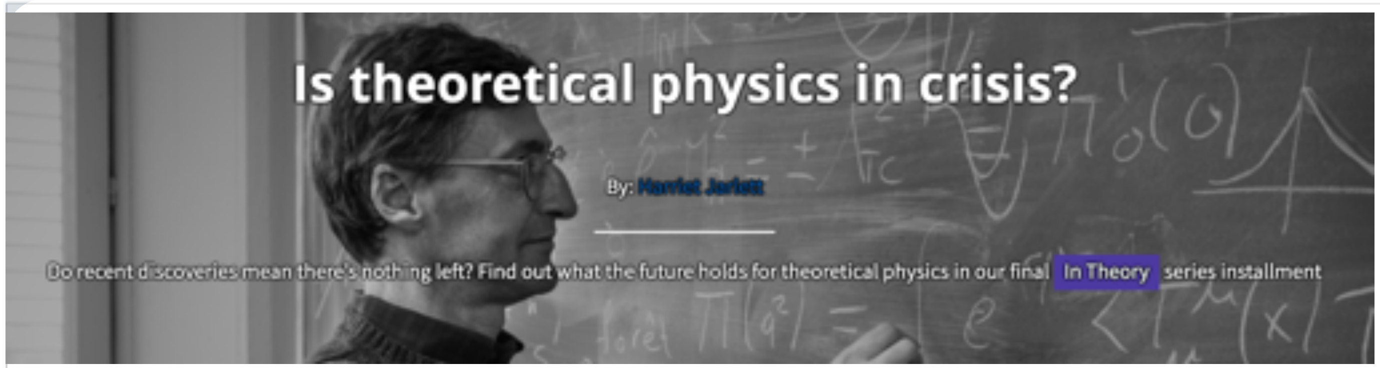
What wasn't discovered at LHC (yet)



These bounds have been pushed away from

$$v \sim m_h$$

What does this mean?



Not a crisis, an opportunity!
Now we know what to do.

BOOKS AND ARTS · 12 JUNE 2018

How the belief in beauty has triggered a crisis in physics

Anil Ananthaswamy parses Sabine Hossenfelder's analysis of why the field is at an impasse.

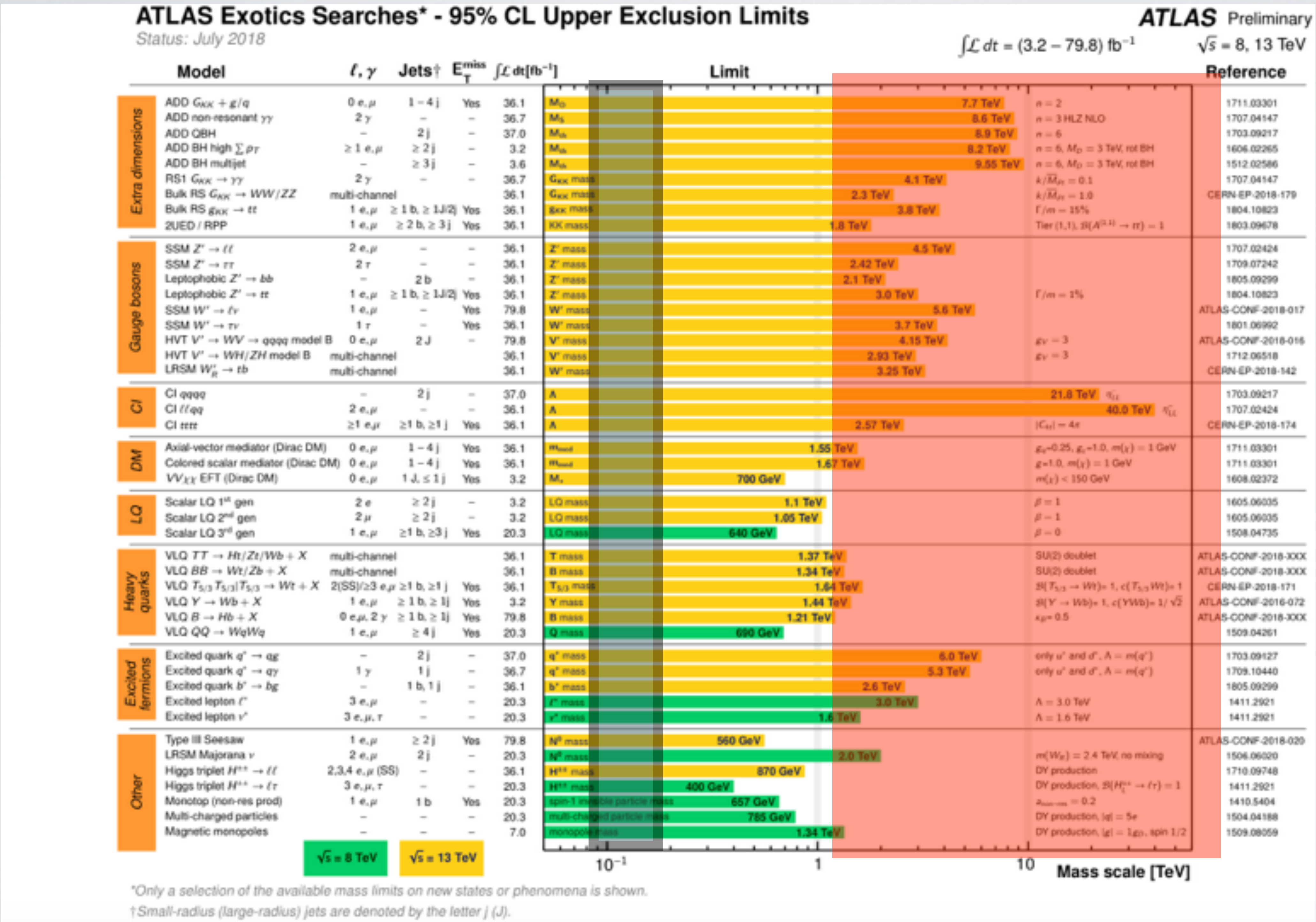
'We'll die before we find the answer': Crisis at the heart of physics

Ambitious new theories dreamed up to explain reality have led us nowhere. Meet the hardcore physicists trying to think their way out of this black hole

The Higgs hunter has just turned 10. Why is nobody celebrating?

The Large Hadron Collider unleashed unprecedented euphoria when it switched on, but the search for the true nature of reality has proved harder than we thought

RunII and beyond: Resonance limits to local operators



Now that these bounds have been pushed away from v

USE that

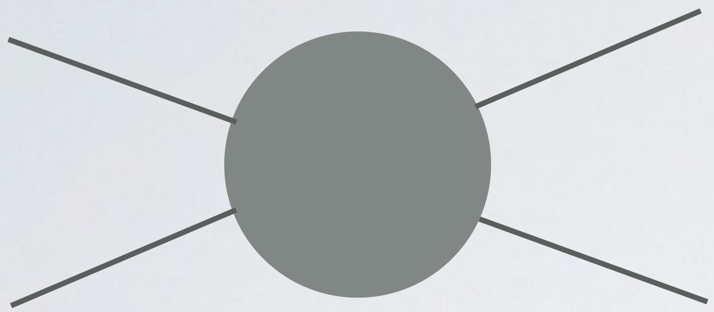
$$v/M < 1$$

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

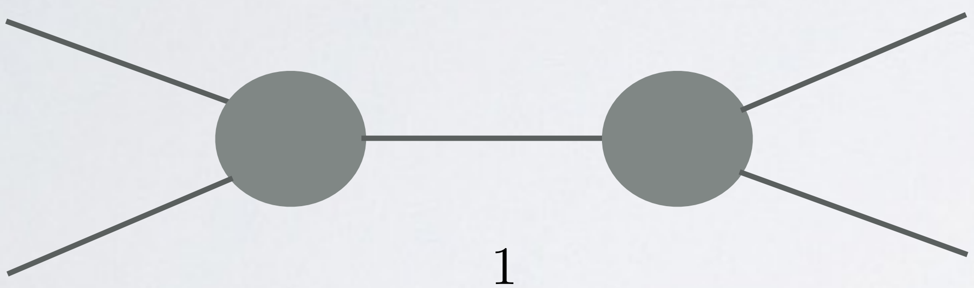
When you do measurements below a particle threshold



- 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

- 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.

EFT approach not a guess.

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

A "BSM is 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

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

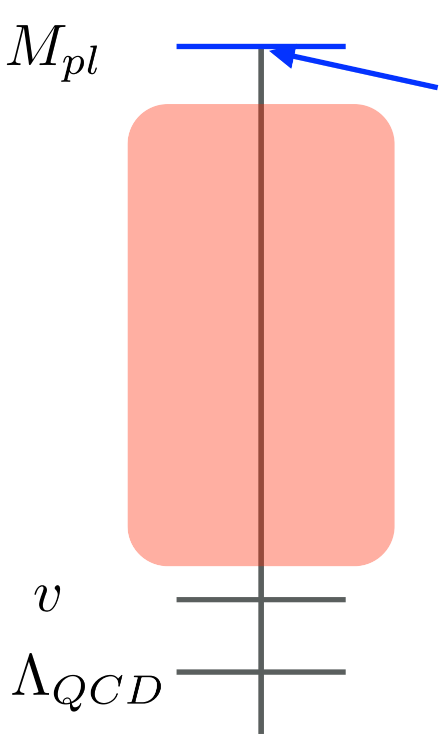
UV dependent Wilson coefficient and suppression scale

The Cut Off scale(s)

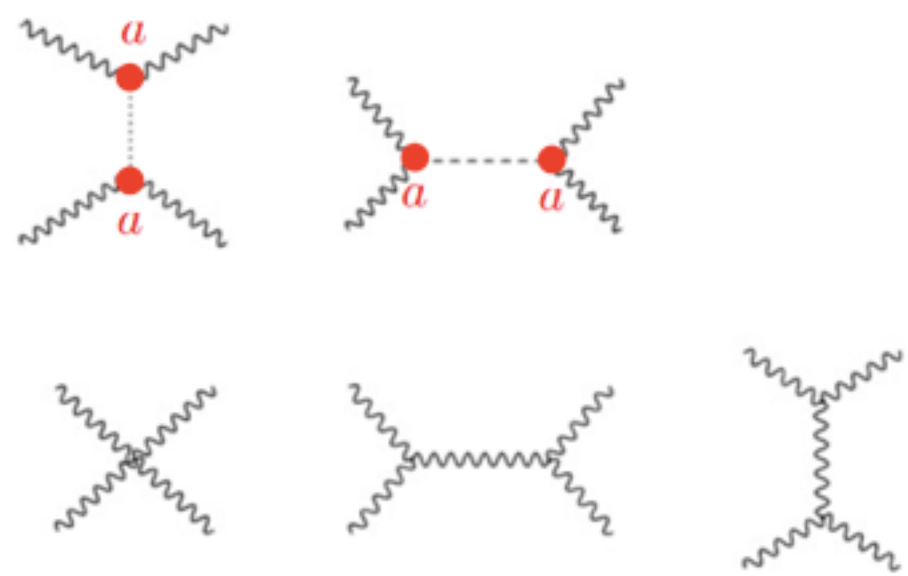
- What do we know? Without a doubt a very Higgs like boson.

<u>1. SM is of course consistent with the data.</u>

The observed Higgs LIKE boson pushed the unitarity implied cut off scale away from the EW scale.



Exactly the SM Higgs.
Nothing else coupled to the SM.



"Higgs like scalar" cut off set by new mass scales

Relevant questions are - how far is the cut off scale?
What is the right EFT to capture the IR limit of the unknown UV.
This question is not trivially about assuming the Higgs mechanism or not.

What is the EFT: 1)Nonlinear EFT

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

Idea stumbled upon over and over..
F. Feruglio arXiv:hepph/9301281
Burgess et al. 9912459
(understood non-linear possible)
Grinstein Trott , arXiv:0704.1505
(clearly articulated distinction)

1) Nonlinear EFT - built of

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

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

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

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

$$\begin{aligned}
\mathcal{L} &= \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4} \mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma) \left[1 + 2\, a_{W,Z} \frac{h}{v} + b_{Z,W} \frac{h^2}{v^2} + b_{3,Z,W} \frac{h^3}{v^3} + \cdots \right], \\
& - \frac{v}{\sqrt{2}} (\bar{u}_L^i \bar{d}_L^i) \Sigma \left[1 + c_i^{u,d} \frac{h}{v} + c_{2,j}^{u,d} \frac{h^2}{v^2} + \cdots \right] \begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c., \\
V(h) &= \frac{1}{2} m_h^2 h^2 + \frac{d_3}{6} \left(\frac{3\, m_h^2}{v}\right) h^3 + \frac{d_4}{24} \left(\frac{3 m_h^2}{v^2}\right) h^4 + \cdots .
\end{aligned}$$

SM mass scales then unrelated to scalar couplings - ***this is used in the "kappa" fits.***

Nonlinear EFT: important developments

- Used in Higgs data analysis and developed into kappa formalism

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

  1209.0040 Higgs XS working group 1504.01707 Buchalla et al.

- Subleading operator basis developed 1212.3305 Alonso et al.

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

- Matchings/correlations explored

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

- Power counting discussion

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

- Curvature interpretation (linear/nonlinear distinction = field redef. invariant curvature measure) 1511.00724 1602.00706 Alonso et al.

Higgs Inflation - but as an EFT..

- The basic idea: $\mathcal{L}_{HI} = \mathcal{L}_{SM} - \sqrt{-g}\left[\frac{m_p^2}{2} + \xi\, H^\dagger H\right] R + \cdots$

Spokoiny Phys Lett B 147B 39 (1984)
Salopek, Bond, Bardeen Phys Rev D 40 1753 (1989)
Bezrukov, Shaposhnikov Phys Lett B 659, 703 (2008) arXiv:0710.3755

- Further interesting lesson:

THIS TERM EXISTS. (unless some unknown symmetry forces it to be 0)

Higgs Inflation: $\xi \simeq 5 \times 10^4 \left(\frac{m_h}{\sqrt{2}\, v}\right)$ Conformal symmetry: $\xi = -\frac{1}{6}$

(in the absence of a Higgs vev)

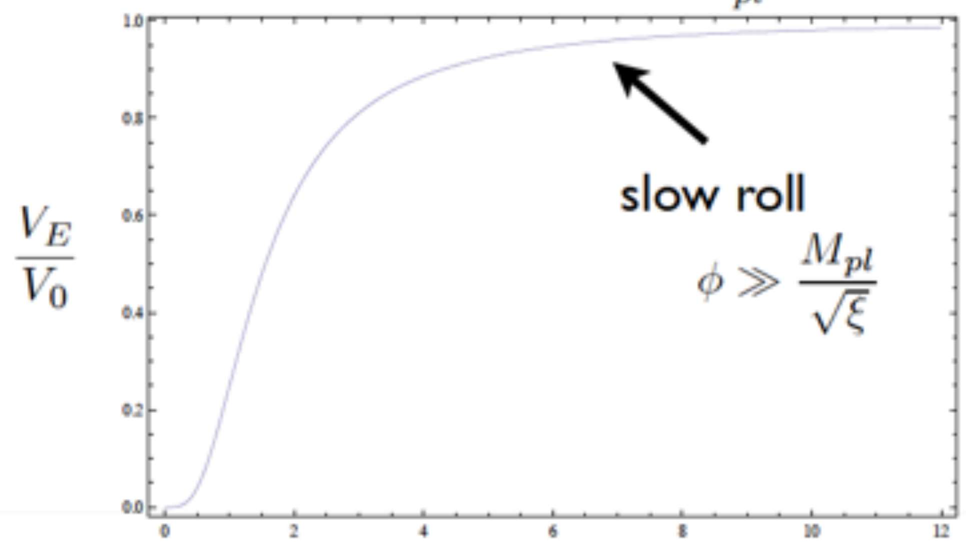
Higgs Inflation - but as an EFT..

- The basic idea: $\mathcal{L}_{HI} = \mathcal{L}_{SM} - \sqrt{-g}\left[\frac{m_p^2}{2} + \xi\, H^\dagger H\right] R + \cdots$

  Spokoiny Phys Lett B 147B 39 (1984)
  Salopek, Bond, Bardeen Phys Rev D 40 1753 (1989)
  Bezrukov, Shaposhnikov Phys Lett B 659, 703 (2008) arXiv:0710.3755

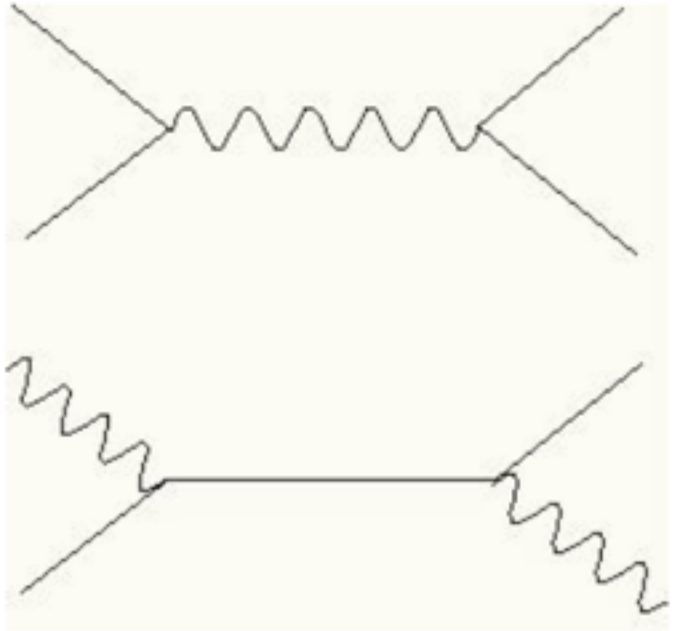
- Flatten the SM potential with a large non-minimal coupling.
  Weyl rescaling to the Einstein frame:

$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$ where $\Omega^2 = 1 + \frac{\xi\,\phi^2}{M_{pl}^2}$ and $V_E(\phi) = \frac{V(\phi)}{(1+\frac{\xi\,\phi^2}{M_{pl}^2})^2}$



Higgs Inflation - but as an EFT..

- As $\xi \simeq 5 \times 10^4 \left(\frac{m_h}{\sqrt{2}\,v}\right)$ largest dependence on ξ origin of the scattering that violates unitarity.



$h\,h \to h\,h$

$g\,h \to g\,h$

$$A_4(E) \simeq \left(\frac{\xi E}{M_{pl}}\right)^2 \left(\frac{\xi E}{4\pi M_{pl}}\right)^{2L}$$

Insisting on unitarity ie $\sigma \propto 1/E^2$ we find

$$E < E_{max} \simeq \frac{M_{pl}}{\xi} \qquad M < \frac{M_{pl}}{\xi}$$

In the EW vacuum this is the case - old news. arXiv:0902.4465,arXiv:1002.2730
Burgess,Lee,Trott

See also arXiv:0903.0355 Barbon, Espinosa

Higgs Inflation - an important lesson.

- Cut off scales easy to understand (goldstone scattering)

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \left(1-(a_{sm}+\delta a)^2\right)\frac{s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}}{\bar{\chi}^2},$$
$$= \frac{2\,\xi^2}{M_{pl}^2}\left(s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right),\ \text{small field}$$

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \frac{\xi}{M_p^2}\left[s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right],\quad \text{large field}$$

- Between the scales the cut off scale rises as $\Lambda \sim 4\,\pi\bar{\chi}$

  As in a theory with un-higgs massive vectors.

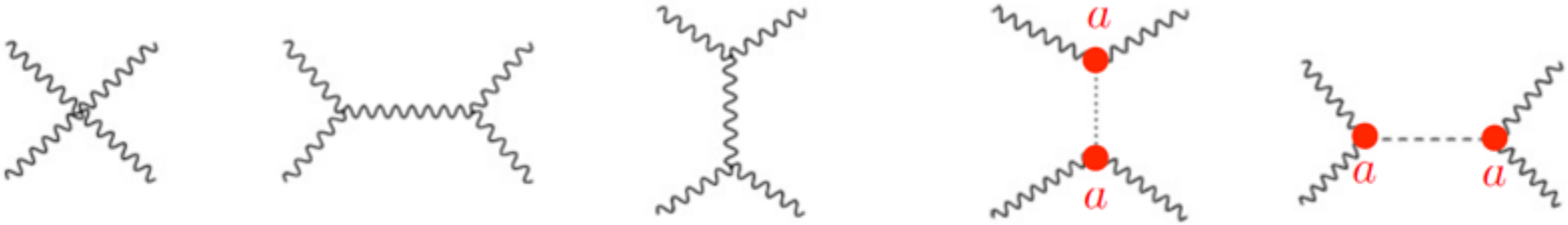
Higgs Inflation - an important lesson.

- Cut off scales easy to understand (goldstone scattering)

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \left(1-(a_{sm}+\delta a)^2\right)\frac{s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}}{\bar{\chi}^2},$$

$$= \frac{2\,\xi^2}{M_{pl}^2}\left(s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right), \text{ small field}$$

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \frac{\xi}{M_p^2}\left[s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right], \quad \text{large field}$$



- Exactly the scattering physics of the nonlinear realization Higgs EFT.

The fundamental Higgs EFT is...

- NONLINEAR. Even when the Higgs mechanism and doublet is present.

- The right EFT has to reproduce the IR of the UV theory, and gravity introduces nonlinearities due to the singlet higgs field mixing with a scalar gravity component proportional to

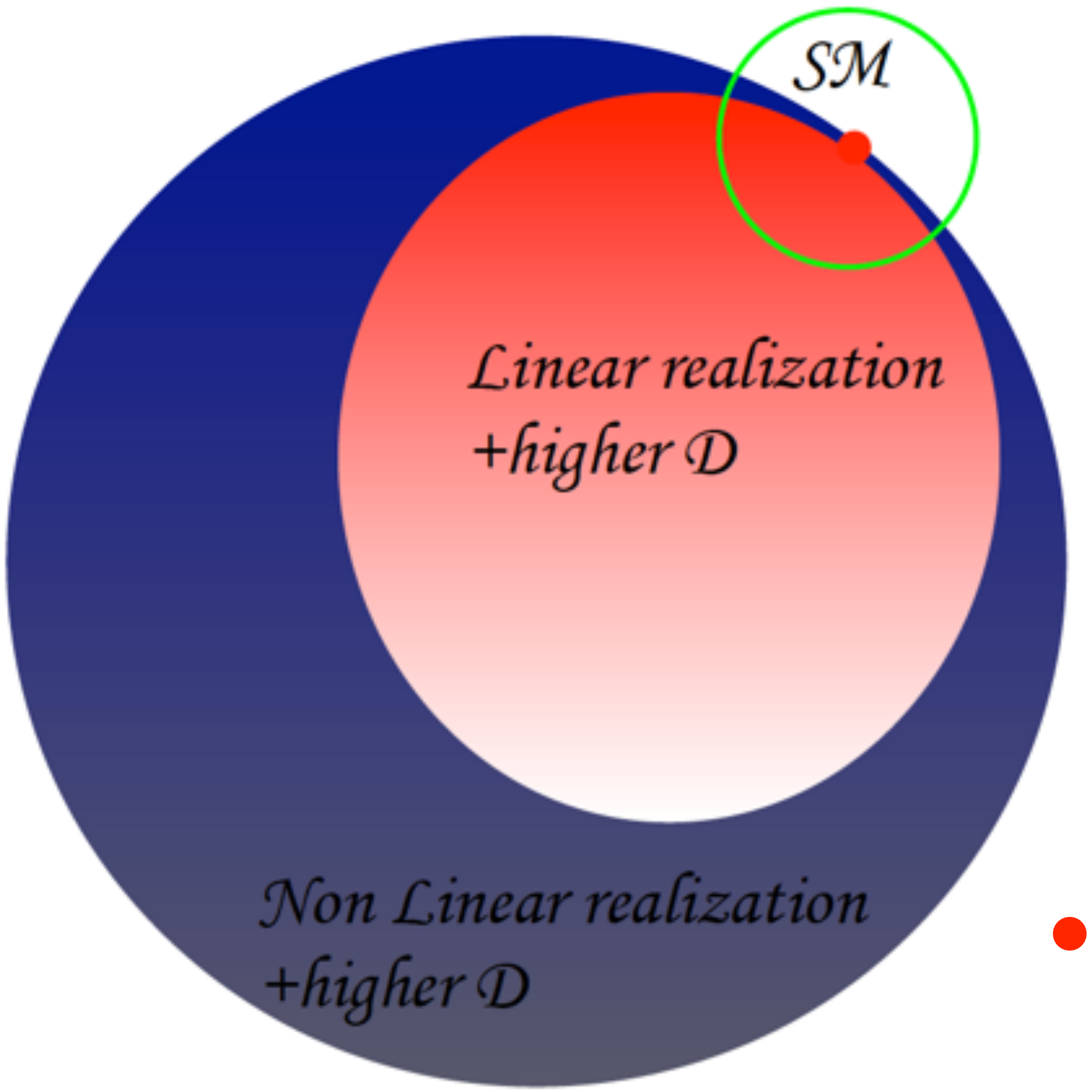
$$\xi \frac{\bar{X}}{M_{pl}}$$

- The question is not is the Higgs doublet or mechanism present.
The question is “do we have interactions in the UV that force us to use a nonlinear formalism to reproduce the IR”.

- Note that convergence on SM values of couplings implies the cut off scale is parametrically separated from the ew vev scale, not a linear EFT.

Consistency in bounding the SMEFT

- We need to bound the SMEFT consistently and precisely and look at patterns of deviations (if any found) and relations between observables to even know the right EFT formalism.



- Linear EFT $H \supset h$ and relations between measurements that follow from this hold
- Non-Linear EFT, singlet h. Broader range of relations between measurements.
- Non-Linear EFT not equivalent and more general
- So why SMEFT? Its more minimal and simpler, thats basically it.

Requests.

- Please develop your tools with an eye to relaxing constraints due to linearly realized symmetry in design. This has 2 advantages.

  1) can allow reinterpretations to the HEFT - if we need it

  2) allows relaxation of constraints due to L6 relations, when we start getting serious about dim 8 theory errors interpreting things

Care required in linear realized sym relations

- Example. It is frequently asserted that "gauge invariance" by which linearly realized symmetry in EW sector is meant, impose relations between couplings shifts in:

$$\frac{\mathcal{L}_{WWV,eff}}{-i\,\hat{g}_{WWV}} = g_1^V \left(W^+_{\mu\nu} W^{-\mu} V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{i\lambda_V}{\hat{m}_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu},$$

With $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$.

Frequently asserted that for L6 SMEFT corrections: $\delta\kappa_Z = \delta g_1^Z - t_\theta^2\, \delta\kappa_\gamma$

Initial paper mentioning this, Zeppenfeld et al careful, they are aware that L8 can change this in statement made.

Care required in linear realized sym relations

- Question: If its gauge invariance how can it be violated at sub-leading order in the SMEFT expansion respecting the global symmetries too?

$$\frac{\mathcal{L}_{WWV,eff}}{-i\,\hat{g}_{WWV}} = g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{i\lambda_V}{\hat{m}_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu},$$

Really a $\{\alpha, \hat{m}_Z, \hat{G}_F\}$ scheme dependent accidental relationship.

$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme:

$$\delta g_1^\gamma = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD}\frac{\hat{m}_W^2}{\hat{m}_W^2 - \hat{m}_Z^2} - 4C^{(3)}_{H\ell} + 2C_{ll} - C_{HWB}\frac{4\hat{m}_W}{\sqrt{\hat{m}_Z^2 - \hat{m}_W^2}}\right),$$

$$\delta g_1^Z = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD} - 4C^{(3)}_{H\ell} + 2C_{ll} + 4\frac{\hat{m}_Z}{\hat{m}_W}\sqrt{1 - \frac{\hat{m}_W^2}{\hat{m}_Z^2}}C_{HWB}\right),$$

$$\delta\kappa_\gamma = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD}\frac{\hat{m}_W^2}{\hat{m}_W^2 - \hat{m}_Z^2} - 4C^{(3)}_{H\ell} + 2C_{ll}\right),$$

$$\delta\kappa_Z = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD} - 4C^{(3)}_{H\ell} + 2C_{ll}\right),$$

$$\delta\lambda_\gamma = 6\, s_{\hat{\theta}}\frac{\hat{m}_W^2}{\hat{g}_{WWA}}C_W,$$

$$\delta\lambda_Z = 6\, c_{\hat{\theta}}\frac{\hat{m}_W^2}{\hat{g}_{WWZ}}C_W.$$

General L6 relationship is: $\delta\kappa_Z - \delta g_1^Z = -t_{\hat{\theta}}^2(\delta\kappa_\gamma - \delta g_1^\gamma),$ Brivio, MT 1701.06424

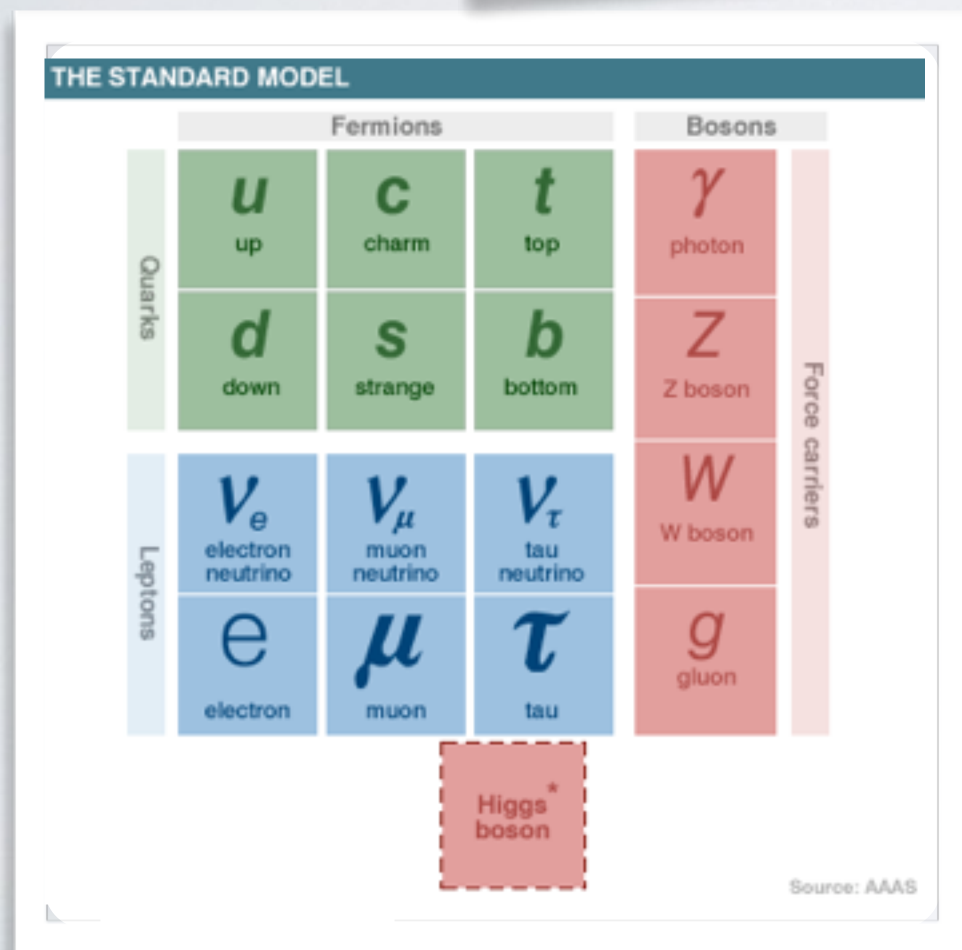
More requests.

- Use more than one scheme in fits and analysis.
- If you see the EWPD SM prediction guys (Erler, Freitas…), please ask them to report the LEP pseudo-observables completely to highest accuracy in the MW scheme.

The Standard Model EFT

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

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



- A fundamental scalar Higgs is a NEW type of particle.

- The interaction strengths of the Higgs with the other SM particles are *not fixed in magnitude by a gauge symmetry.*

The Standard Model EFT

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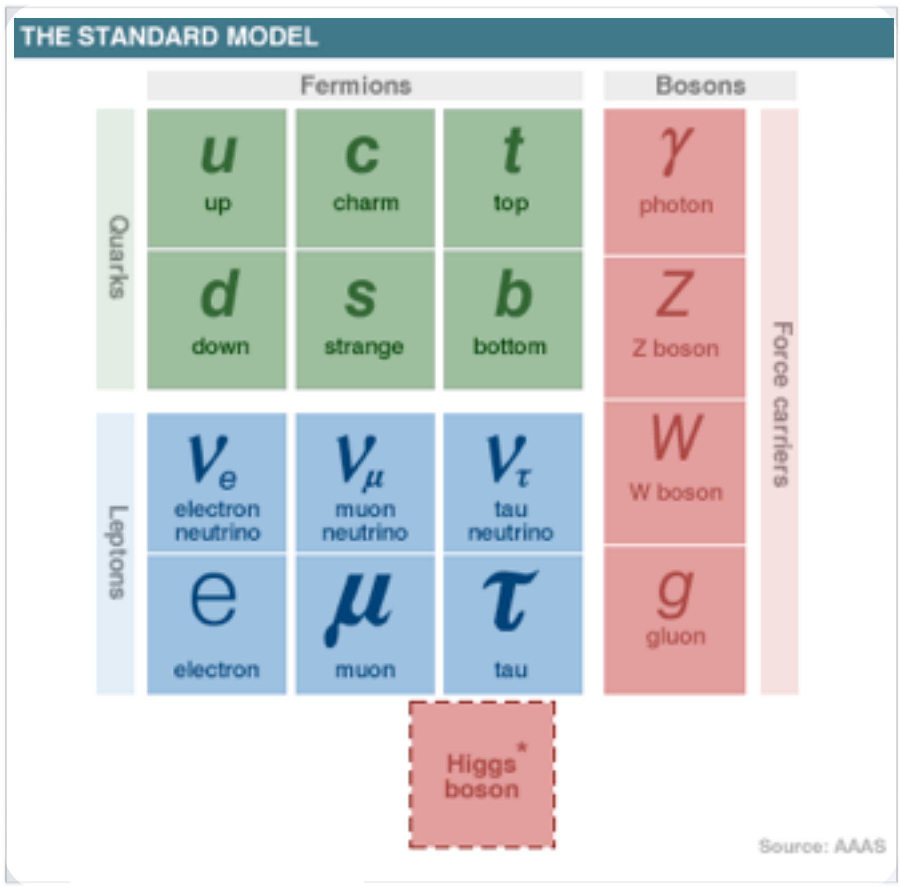
$$\mathcal{L}_{\rm SM} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i \not{D}\, \psi$$
$$- \lambda \left(H^\dagger H - \frac{1}{2} v^2 \right)^2 - \left[H^{\dagger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



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

- (red) Glashow 1961, Weinberg 1967 (Salam 1967)
- (blue) Weinberg 1979, Wilczek and Zee 1979
- (green) Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

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

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

1 operator, and 7 extra parameters (mass, mixing, CP phase) 9 with majorana phases rather hard to measure

Complexity is scaling up…

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

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

Class	N_{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
ψ^4 8 : $(\bar{L}L)(\bar{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 : $(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 : $(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 : $(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	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 $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, MT

SMEFT requires a GLOBAL approach: matching

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

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

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

Over complete set of ops depending on B^μ

1706.08945 I. Brivio, MT

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

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

SMEFT requires a GLOBAL approach: matching

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

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

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

Non-redundant set of ops depending on B^μ

1706.08945 I. Brivio, MT

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

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

EWPD, diboson, Higgs data all modified globally

Z,W couplings

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

Top data

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

Bhabha scattering

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

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

TGC /multi-boson

Field redefinitions are WHY a global SMEFT is needed

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

input quantities

B anomalies

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

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

H processes

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

Partial image credit I. Brivio

Why few percent corrections of interest?

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

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

- We now have a scalar with mass $m_h \sim 125\,\mathrm{GeV}$
  reasonable to expect $g_i\, M_j \sim few\, \mathrm{TeV}$

- LHC reach limited $\lesssim 14/6 \sim 2\,\mathrm{TeV}$ (rule of thumb due to PDF suppression)

- Corrections expected on the order of

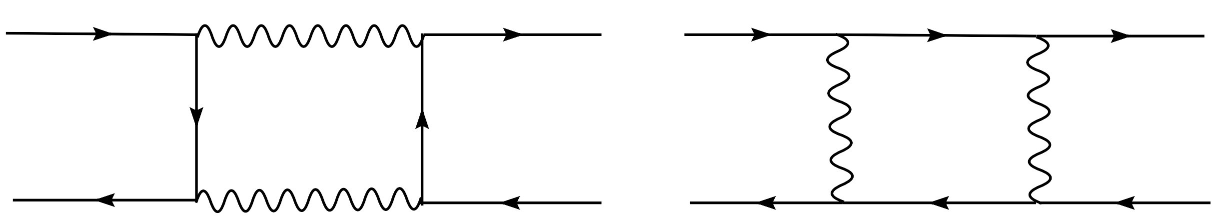
$\langle H|\mathcal{L}_{SM}|H\rangle$ → $\frac{v^2}{\Lambda^2} \sim few\,\%$ $\qquad \frac{E^2}{\Lambda^2} \sim few - tens\%$

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

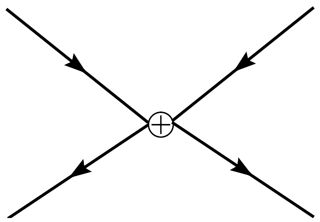
(LEP data few % to 0.1 % precise)

Is this already ruled out by flavour?

Flavour and CP assumptions



VS



Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^\star\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

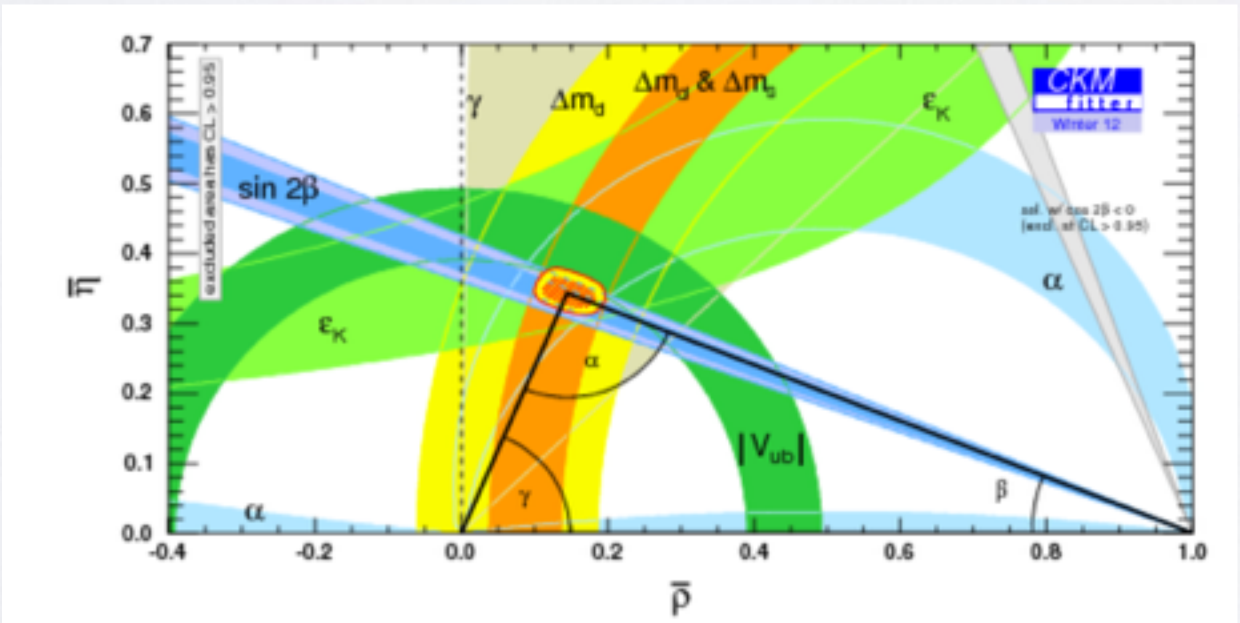
SM PATTERN has GIM suppression, CKM suppression , and loop suppression

$\lambda \sim 0.2$ so $\lambda^8 \sim 10^{-6}$ $\lambda^4 \sim 10^{-3}$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$

We assume MFV for TeV new physics to be robust (for now).



- SM flavour violating pattern validated

Flavour and CP assumptions

Operator	Bounds on Λ in TeV ($c_{NP}=1$)		Bounds on c_{NP} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

- CP violating effects strongest constraints

$$\Lambda < \frac{3.4\ \text{TeV}}{|V_{3i}^* V_{3j}|/|c_{ij}|^{1/2}} < \begin{cases} 9\times10^3\ \text{TeV}\times|c_{21}|^{1/2} & \text{from}\quad K^0-\bar{K}^0 \\ 4\times10^2\ \text{TeV}\times|c_{31}|^{1/2} & \text{from}\quad B_d-\bar{B}_d \\ 7\times10^1\ \text{TeV}\times|c_{32}|^{1/2} & \text{from}\quad B_s-\bar{B}_s \end{cases}$$

- Wilson coefficient that carry the CKM factors (MFV) can resolve

Operator	Bound on Λ	Observables
$\phi^\dagger\left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B\to X_s\gamma$, $B\to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$\phi^\dagger\left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B\to X_s\gamma$, $B\to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(\overline{E}_R\gamma_\mu E_R)$	5.7 TeV	$B_s\to\mu^+\mu^-$, $B\to K^*\mu^+\mu^-$
$i\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)\phi^\dagger D_\mu\phi$	4.1 TeV	$B_s\to\mu^+\mu^-$, $B\to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(\overline{L}_L\gamma_\mu L_L)$	5.7 TeV	$B_s\to\mu^+\mu^-$, $B\to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.7 TeV	$B\to K^*\mu^+\mu^-$

- In the MFV case, still flavour violation, but TeV sectors viable

Charts all from Isidori 1302.0661

Flavour and CP assumptions

https://arxiv.org/pdf/1603.03049.pdf V. Cirigliano, I W. Dekens, J. de Vries, and E. Mereghetti

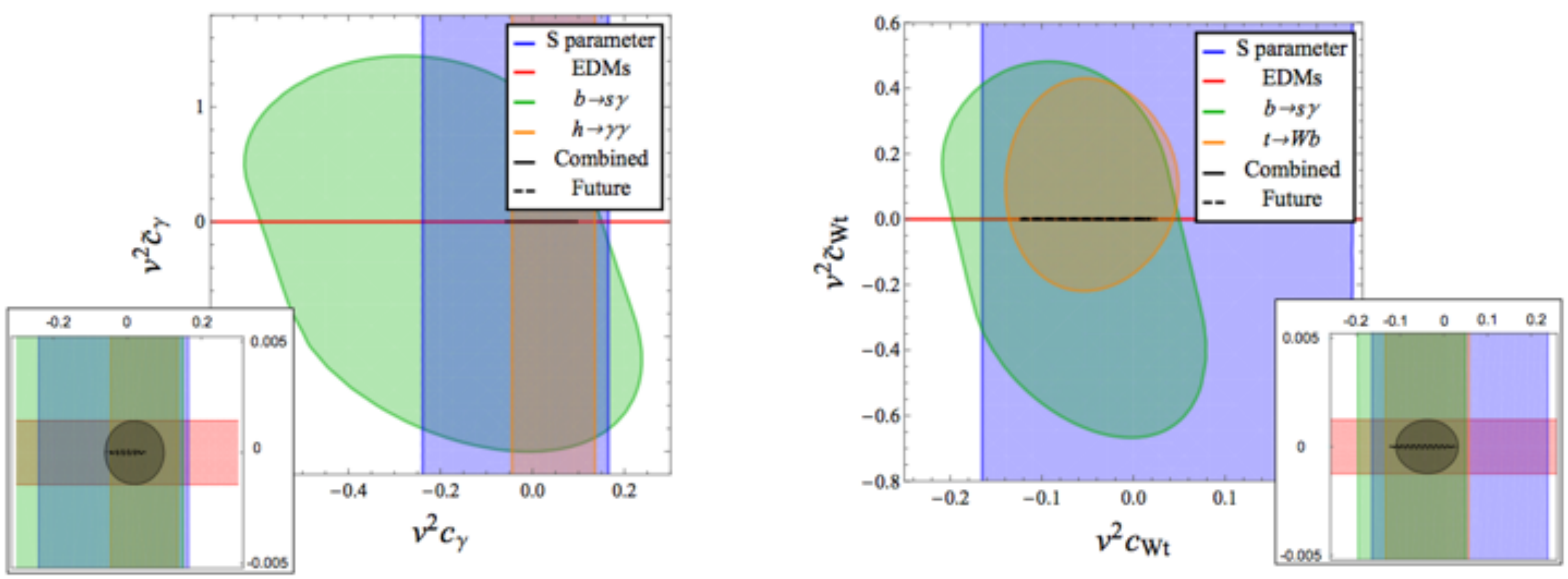


FIG. 2: 90% CL allowed regions in the $v^2c_\gamma - v^2\tilde{c}_\gamma$ (left panel) and $v^2c_{Wt} - v^2\tilde{c}_{Wt}$ planes (right panel), with couplings evaluated at $\Lambda = 1$ TeV. In both cases, the inset zooms into the current combined allowed region and shows projected future sensitivities. Future EDM searches will probe $v^2\tilde{c}_\gamma \sim 8 \cdot 10^{-5}$ and $v^2\tilde{c}_{Wt} \sim 7 \cdot 10^{-5}$.

- "The overarching message emerging from our single-operator analysis is that the CPV couplings (top-higgs) are very tightly constrained, and out of reach of direct collider searches."
- One operator at a time. But symmetry violation constraint leads to symmetry conclusions.

SMEFT parameters that violate SM symmetries

- Beyond the general SMEFT, if is of interest to examine the following cases

Respect the SM flavour symmetry that exists in the $Y_U, Y_D \to 0$ limit in a new sector.

$$\mathrm{G_F} = \mathrm{U}(3)^5 = \mathrm{S_Q} \otimes \mathrm{S_L} \otimes \mathrm{U}(1)^5$$

where $S_Q = \mathrm{SU}(3)_{\mathrm{Q_L}} \otimes \mathrm{SU}(3)_{\mathrm{U_R}} \otimes \mathrm{SU}(3)_{\mathrm{D_R}}$ $\quad S_L = \mathrm{SU}(3)_{\mathrm{L_L}} \otimes \mathrm{SU}(3)_{\mathrm{E_R}}$

Technically the Yukawas act as spurions: $Y_U \sim (\bar{3}, 3, 1)\,, Y_D \sim (\bar{3}, 1, 3)$

- U(3)^5 SMEFT with possible CP violating phases beyond the SM
- MFV SMEFT with NO possible CP violating phases beyond the SM

One operator at a time analysis does not matter so much for SYMMETRY violation tests

.. are there too many parameters?

- Number of parameters convolution of power counting

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

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

- EX - flavour indicies for neutral currents:

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

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

This IR SM physics projects out parameters.

On the poles things are do-able

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

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

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

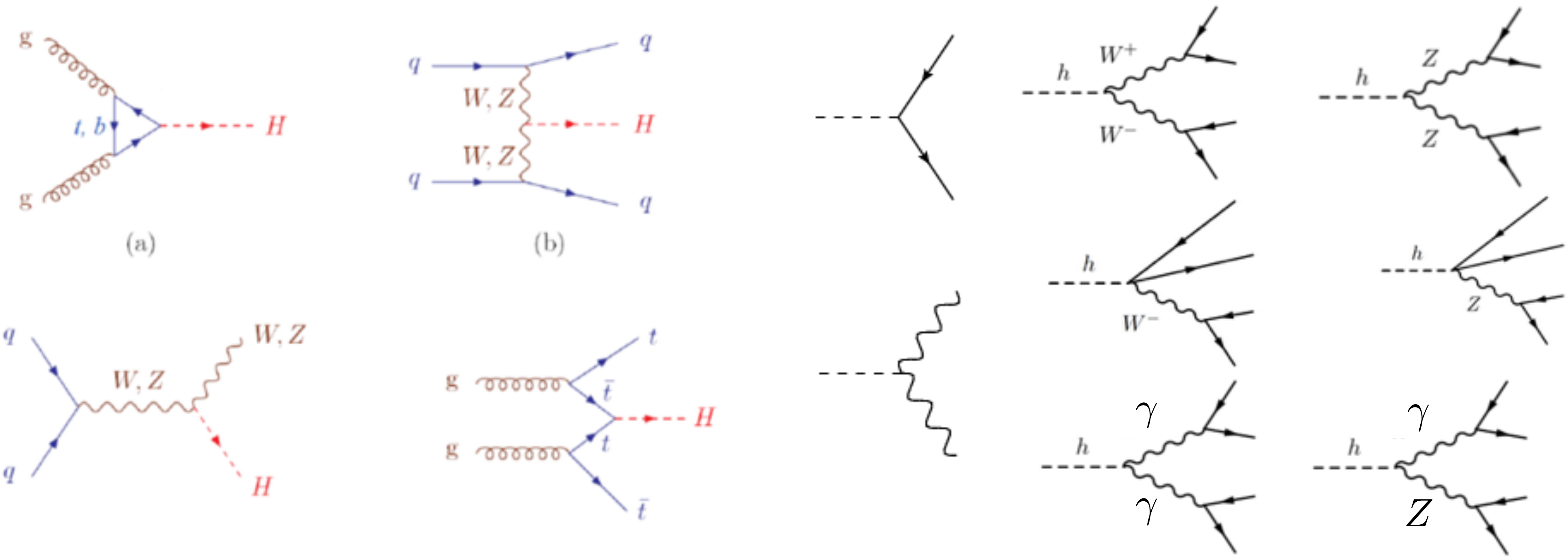
$$\left(\frac{\Gamma_B \, m_B}{\bar{v}_T^2}\right) \frac{\{\mathrm{Re}(C), \mathrm{Im}(C)\}}{g_{SM} \, C_i}, \qquad \left(\frac{\Gamma_B \, m_B}{p_i^2}\right) \frac{\{\mathrm{Re}(C), \mathrm{Im}(C)\}}{g_{SM} \, C_k},$$

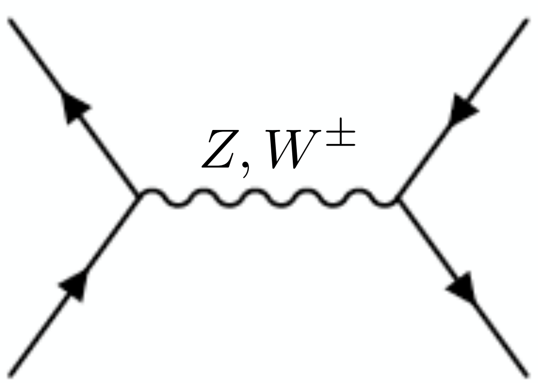
Measurement/facility design can DEFINE a subset of SMEFT parameters in a fit

- Suggested strategy of https://arxiv.org/abs/1709.06492 use this, do a dedicated pole parameter constraint program, then expand to tackle tails

Key processes to focus on

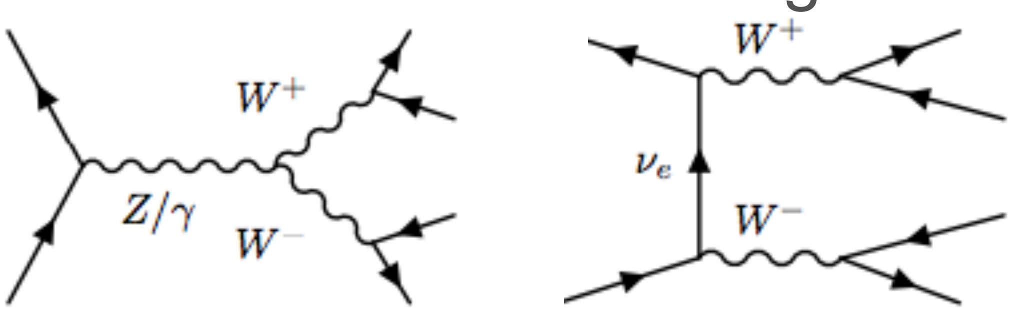
Higgs σ/Br (narrow higgs)



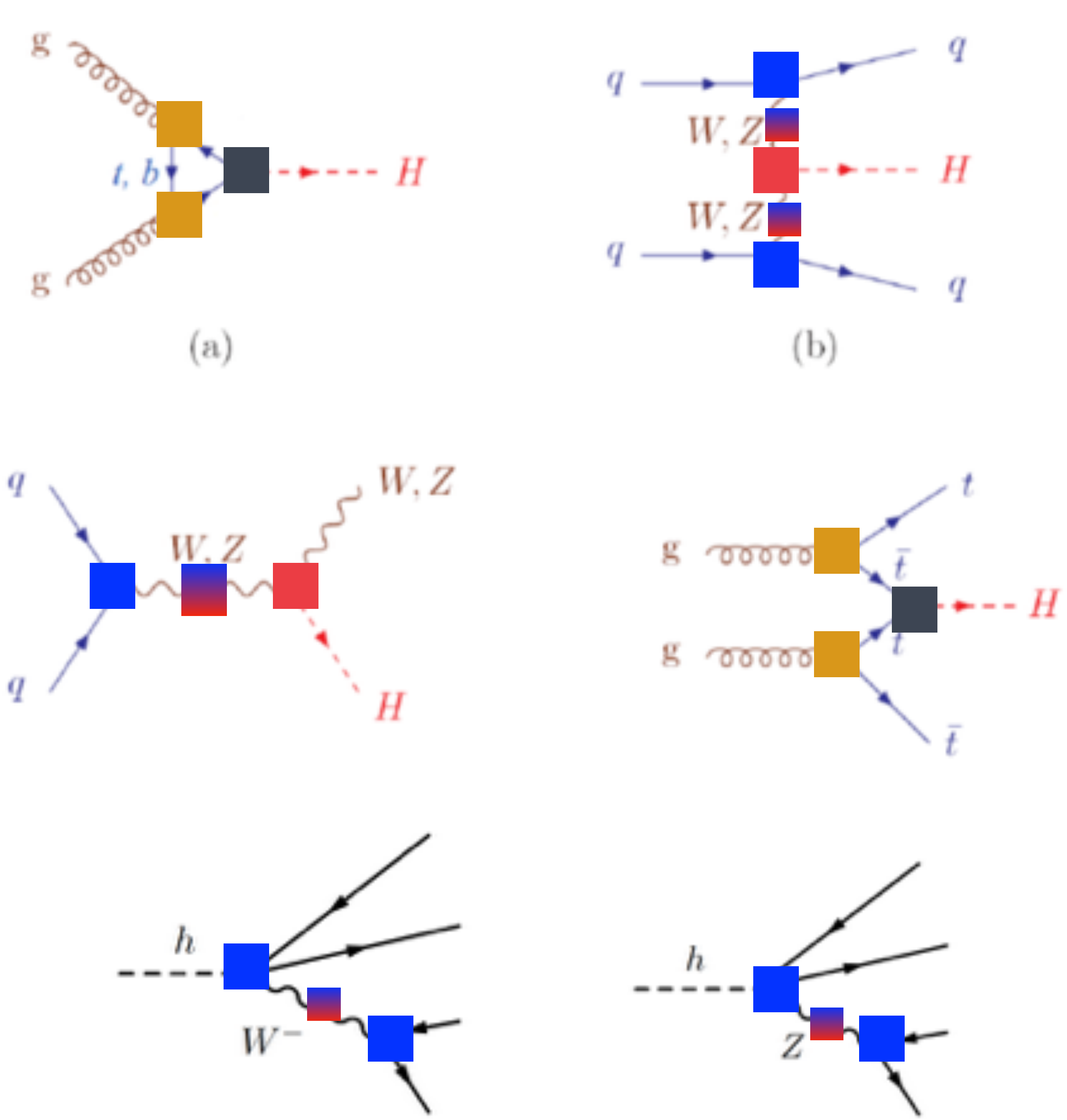


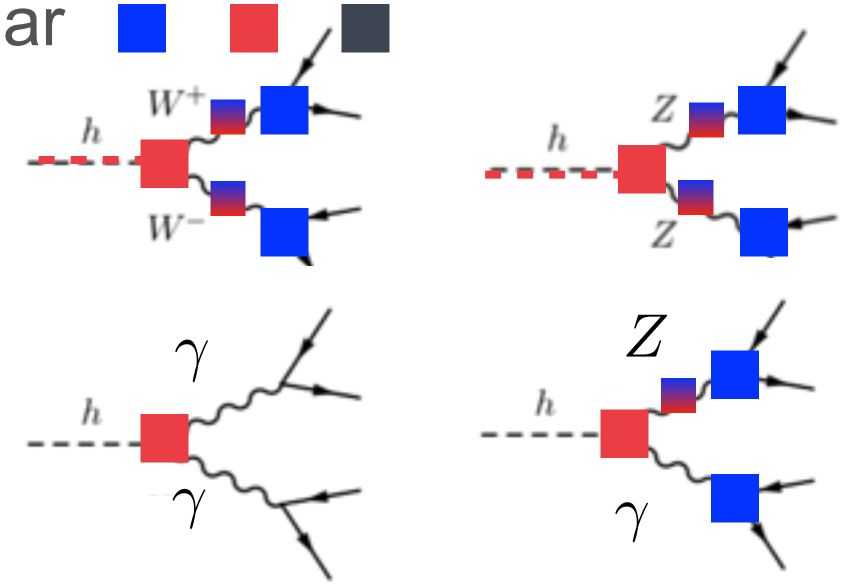
LEP/Tevatron pole scans

Vector current scattering



- Various operator based perturbations can appear





X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Soon to appear - the SMEFT Higgs width

Brivio, Corbett, MT https://arxiv.org/abs/this.week.damn.it

- These analyses look overwhelming. If you stick near the SM poles and interfering with the SM at LO, its a small subset of parameters we can consistently bound even now. We find the inclusive higgs width (*preliminary*)

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} = 1 - 1.50\tilde{C}_{HB} - 1.21\tilde{C}_{HW} + 1.21\tilde{C}_{HWB} + 50.6\tilde{C}_{HG} + 1.83\tilde{C}_{H\Box} - 0.43\tilde{C}_{HD}$$

$$+1.17\tilde{C}'_{\ell\ell} - 8.19 y_c \mid \tilde{C}_{uH} \mid -48.0 y_b \mid \tilde{C}_{dH} \mid -13.3 y_\tau \mid \tilde{C}_{eH} \mid +0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq}$$

$$+0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd} - 0.0009\,\tilde{C}^{(1)}_{Hl} - 2.32\,\tilde{C}^{(3)}_{Hl} - 0.0006\,\tilde{C}_{He}$$

- To be used for all Higgs BR based measurements. NOT 2499 parameters! See ilaria’s talk for more details.

Narrow width approx of W,Z in this calc failed rather badly.

EFT Corrections to EOM

Recall the SM EOM

- Principle of least action to EOM

$$S^{SM} = \int \mathcal{L}^{SM}(\chi, \partial\chi) d^{4-2\epsilon}x. \qquad 0 = \delta S^{SM} = \int d^{4-2\epsilon}x \left[\frac{\partial \mathcal{L}^{SM}}{\partial \chi}\delta\chi - \partial_\mu\left(\frac{\partial \mathcal{L}^{SM}}{\partial(\partial_\mu \chi)}\right)\delta\chi\right],$$

Higgs:

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

Fermion:

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

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

Gauge field:

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

SM currents:

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

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

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

Notation:

$$H^\dagger\, i\overleftrightarrow{D}_\mu H = iH^\dagger (D_\mu H) - i(D_\mu H)^\dagger H,$$

$$H^\dagger\, i\overleftrightarrow{D}_\mu^I H = iH^\dagger \tau^I (D_\mu H) - i(D_\mu H)^\dagger \tau^I H,$$

$$[D^\mu, Q]^I = \partial^\mu Q^I - g_2\, \epsilon^{JKI}\, W_J^\mu Q_K,$$

$$[D^\mu, Q]^A = \partial^\mu Q^A - g_3\, f^{BCA}\, A_B^\mu Q_C.$$

Recall the SM EOM

- Principle of least action to EOM

$$S^{SMEFT} = \int \mathcal{L}^{SMEFT}(\chi, \partial\chi) d^{4-2\epsilon}x.$$

$$0 = \delta S^{SMEFT} = \int d^{4-2\epsilon}x \left[\frac{\partial \mathcal{L}^{SMEFT}}{\partial \chi}\delta\chi - \partial_\mu \left(\frac{\partial \mathcal{L}^{SMEFT}}{\partial(\partial_\mu \chi)}\right)\delta\chi\right],$$

arXiv:1806.06354 Barzinji, MT, Vasudevan

This leads to a tower of corrections to the SMEFT EOM:

$$i\not{D}\, q^j_m = u^n\,[Y_u]^\star_{nm}\,\widetilde{H}^j + d^n\,[Y_d]^\star_{nm}\,H^j + \sum_{d=5}^{\infty}\frac{\Delta^{j,(d)}_{q,m}}{\Lambda^{d-4}}$$

$$i\not{D}\, \ell^j_m = [Y_e]^\star_{nm}\,e^n H^j + \sum_{d=5}^{\infty}\frac{\Delta^{j,(d)}_{\ell,m}}{\Lambda^{d-4}},$$

$$i\not{D}\, d_m = [Y_d]_{mn}\,q^j_n\,H^\dagger_j + \sum_{d=5}^{\infty}\frac{\Delta^{(d)}_{d,m}}{\Lambda^{d-4}},$$

$$i\not{D}\, u_m = [Y_u]_{mn}\,q^n_j\,\widetilde{H}^{\dagger j} + \sum_{d=5}^{\infty}\frac{\Delta^{(d)}_{u,m}}{\Lambda^{d-4}},$$

$$i\not{D}\, e_m = [Y_e]_{mn}\,\ell^n_j H^{\dagger j} + \sum_{d=5}^{\infty}\frac{\Delta^{(d)}_{e,\kappa}}{\Lambda^{d-4}}.$$

$$[D^\mu, G_{\mu\nu}]^A = g_3\,j^A_\nu + g_3\sum_{d=5}^{\infty}\frac{\Delta^{A,(d)}_{G,\nu}}{\Lambda^{d-4}},$$

$$[D^\mu, W_{\mu\nu}]^I = g_2 j^I_\nu + g_2\sum_{d=5}^{\infty}\frac{\Delta^{I,(d)}_{W,\nu}}{\Lambda^{d-4}},$$

$$D^\mu B_{\mu\nu} = g_1 j_\nu + g_1\sum_{d=5}^{\infty}\frac{\Delta^{(d)}_{B,\nu}}{\Lambda^{d-4}}.$$

$$D^2 H^j = \lambda v^2 H^j - 2\lambda(H^\dagger H)H^j - \overline{q}^n_k\,[Y_u]^\star_{mn}\,u^m\epsilon^{kj}, - \overline{d}^n[Y_d]_{nm}q^j_m - \overline{e}^n[Y_e]_{nm}\ell^{m,j} + \sum_{d=5}^{\infty}\frac{\Delta^{j,(d)}_{H}}{\Lambda^{d-4}}$$

SM → SMEFT EOM

- Example

$$Q_5^{\beta\,\kappa} = \left(\overline{\ell_L^{c,\beta}}\,\tilde{H}^\star\right)\left(\tilde{H}^\dagger\,\ell_L^\kappa\right).$$

arXiv:1806.06354 Barzinji, MT, Vasudevan

$$i\not{D}\,\ell_m^j = [Y_e]^\star_{nm}\,e^n H^j + \sum_{d=5}^{\infty}\frac{\Delta_{\ell,m}^{j,(d)}}{\Lambda^{d-4}},$$

$$D^2 H^j = \lambda v^2 H^j - 2\lambda(H^\dagger H)H^j - \overline{q}_k^n\,[Y_u]^\star_{mn}\,u^m\epsilon^{kj},$$
$$- \overline{d}^n[Y_d]_{nm}q_m^j - \overline{e}^n[Y_e]_{nm}\ell^{m,j} + \sum_{d=5}^{\infty}\frac{\Delta_H^{j,(d)}}{\Lambda^{d-4}}$$

$$\Delta_{\ell,m}^{j,(5)} = -2\,C_{nm}^{(5)\star}\,\tilde{H}^j\left(\tilde{H}^T\ell_n^c\right),$$
$$\Delta_H^{j,(5)} = -C_{nm}^{(5)\star}\,\epsilon^{jk}\left[\overline{\ell_k^m}\,(\tilde{H}^T\,\ell_n^c) + (\overline{\ell^m}\,\tilde{H})\,\ell_n^{c,k}\right]$$

This is an example of "higher order compensation" in the language of Passarino's talk.

- Leads to matching corrections as in the Seesaw model case.

arXiv:1703.04415 Gitte Elgaard-Clausen, MT

SM → SMEFT EOM

arXiv:1806.06354 Barzinji, MT, Vasudevan

- Example

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

$$D^\mu B_{\mu\nu} = g_1 j_\nu + g_1 \sum_{\mathrm{d}=5}^{\infty} \frac{\Delta^{(\mathrm{d})}_{B,\nu}}{\Lambda^{\mathrm{d}-4}}.$$

Notation: $(\mathbf{g},\mathbf{G}) = \{(\,,\mathbb{I}),(I,\tau^I),(A,T^A)\}$

$$J^{\psi\,\mu}_{pr} = \overline{\psi}_p\gamma^\mu\psi_r, \qquad J^{\psi,I,\mu}_{pr} = \overline{\psi}_p\gamma^\mu\,\tau^I\,\psi_r,$$

$$C^{\mu\nu}_{\substack{\psi_1\psi_2 F\\ pr,\mathbf{g}}} = C_{\substack{\psi_1 F\\ pr}}\,\overline{\psi_{2,p}}\sigma_{\mu\nu}\mathbf{G}\,\psi_{1,r}H + \text{h.c.}, \qquad \tilde{C}^{\mu\nu}_{\substack{\psi_1\psi_2 F\\ pr,\mathbf{g}}} = C_{\substack{\psi_1 F\\ pr}}\,\overline{\psi_{2,p}}\sigma_{\mu\nu}\mathbf{G}\psi_{1,r}\tilde{H} + \text{h.c.},$$

$$J^{\psi,A,\mu}_{pr} = \overline{\psi}_p\gamma^\mu\,T^A\,\psi_r,$$

$$\begin{aligned}
\Delta^{(6)}_{B,\mu} = {} & 2\mathsf{y}_H(H^\dagger H)\left[\sum_{\psi=\ell,q} C^{(1)}_{\substack{H\psi\\ pr}}\,J^{\psi\,\mu}_{pr} + \sum_{\psi=e,u,d} C_{\substack{H\psi\\ pr}}\,J^{\psi\,\mu}_{pr} + \frac{C_{HD}}{2}\,H^\dagger i\overleftrightarrow{D}_\mu H\right] + 2\mathsf{y}_H(H^\dagger\,\tau_I\,H)\sum_{\psi=\ell,q} C^{(3)}_{\substack{H\psi\\ pr}} J^{\psi\,I\,\mu}_{pr}, \\
& + \frac{4\,C_{HB}}{g_1}\partial^\nu(H^\dagger H)B_{\nu\,\mu} + \frac{2\,C_{HWB}}{g_1}[D^\nu, H^\dagger\tau H]_I W^I_{\nu\,\mu} + 4\,C_{HB}\,H^\dagger H\,j_\mu + \frac{2\,g_2}{g_1}\,C_{HWB}\,(H^\dagger\,\tau_I\,H)J^I_\mu, \\
& + \frac{4\,C_{H\tilde{B}}}{g_1}\partial^\nu\left(H^\dagger H\tilde{B}_{\nu\,\mu}\right) + \frac{2\,C_{H\tilde{W}B}}{g_1}[D^\nu, H^\dagger\tau H]_I\tilde{W}^I_{\nu\,\mu} + \frac{2\,C_{H\tilde{W}B}}{g_1}[D^\nu,\tilde{W}_{\nu\,\mu}]_I\,H^\dagger\tau^I H, \\
& + \frac{2}{g_1}\left(\partial_\nu C^{\nu\mu}_{\substack{e\ell B\\ pr}} + \partial_\nu\tilde{C}^{\nu\mu}_{\substack{uqB\\ pr}} + \partial_\nu C^{\nu\mu}_{\substack{dqB\\ pr}}\right),
\end{aligned}$$

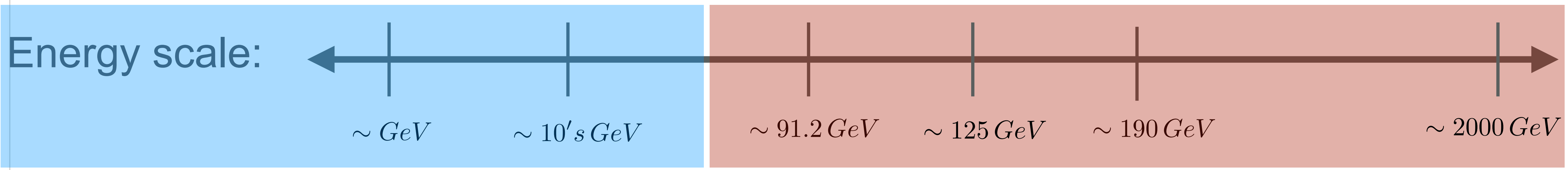
- These matching contributions are EOM effects so there is no trivial 1PI diagram.

LEFT, symmetry currents and gauss's law

Post Modern Discovery Physics

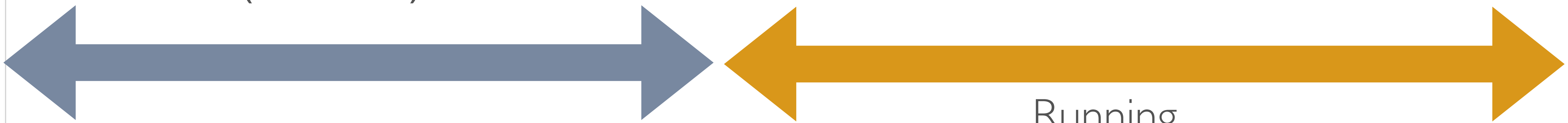
LHC
h pole

LEPII
4 fermions



EFT: WET (or LEFT)

EFT: SMEFT or HEFT



Running

Complete LEFT RGE:

1711.05270 Jenkins, Manohar, Stoffer

HEFT/SMEFT matching LEFT:

1709.04486 Jenkins, Manohar, Stoffer

LEFT EOM:

arXiv:1812.02991 Helset, MT

Complete SMEFT RGE:

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

HEFT RGE:

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

SMEFT EOM: arXiv:1806.06354 Barzinji, MT, Vasudevan

LEFT and LEFT EOM

- LEFT notation:

$$L_{\text{LEFT}} = L_{\text{LEFT}}^{\text{SM}} + L^{(5)} + L^{(6)} + L^{(7)} + \dots$$
$$L^{(d)} = \sum_i \frac{C_i}{\bar{v}_T^{d-4}} \mathcal{P}_i^{(d)} \text{ for } d > 4,$$

LEFT defined integrating out the W,Z,h,t SM states. This means parts of linear multiplets are integrated out, other states retained.

SM contributions:

$$L_{\text{LEFT}}^{\text{SM}} = -\frac{1}{4}\left[F_{\mu\nu}F^{\mu\nu} + G_{\mu\nu}^A G^{A\mu\nu}\right] + \frac{\theta_{\text{QCD}}}{32\pi^2} G_{\mu\nu}^A \tilde{G}^{A\mu\nu} + \frac{\theta_{\text{QED}}}{32\pi^2} F_{\mu\nu}^A \tilde{F}^{A\mu\nu} + \sum_\psi \bar{\psi} i \not{D} \psi + \bar{\nu}_L i \not{D} \nu_L + L_{\text{LEFT}}^{(3)}.$$

$$-L_{\text{LEFT}}^{(3)} = \sum_\psi \bar{\psi}_{R\,r} [M_\psi]_{rs} \psi_{L\,s} + \bar{v}_T\, C_{\nu\,rs}\, \bar{\nu}^c_{L\,r} \nu_{L\,s} + \text{h.c.}$$

- Higher dimensional operators in LEFT come about due to possible higher d ops in SMEFT, in LEFT's UV, and also integrating out SM states.

Symmetry currents

- Recall a symmetry of the action is such that when an infinitesimal change to a field is made

$$\chi(x) \to \chi'(x) = \chi(x) + \alpha\nabla\chi(x),$$

- Action is unchanged $S \to S'$ up to a possible surface term $\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \chi)} \nabla\chi \right),$

  Then the Lagrangian is unchanged up to a possible total derivative

$$\mathcal{L} \to \mathcal{L} + \alpha\partial_\mu\mathcal{K}^\mu,$$

For each such change we can define a corresponding current

$$J^\mu = \frac{\partial \mathcal{L}}{\partial\left(\partial_\mu \chi\right)}\nabla\chi - \mathcal{K}^\mu.$$

And if the theory preserves the symmetry then $\partial_\mu J^\mu = 0.$ ⇦ EOM correction feeds in

Lepton number example

- Consider a simple symmetry example, lepton number, perform rephrasing

$$\underset{p}{e_L} \to e^{i\alpha} \underset{p}{e_L}, \qquad \underset{p}{e_R} \to e^{i\alpha} \underset{p}{e_R}, \qquad \text{current} \quad \underset{rr}{J^\mu_e} \equiv \underset{rr}{J^\mu_{e,L}} + \underset{rr}{J^\mu_{e,R}} \equiv \underset{r}{\bar e_L} \gamma^\mu \underset{r}{e_L} + \underset{r}{\bar e_R} \gamma^\mu \underset{r}{e_R} + \dots$$

Is this current conserved?

$$\begin{aligned} i\partial_\mu \underset{rr}{J^\mu_{e,L}} &= i\left(\partial_\mu \underset{r}{\bar e_L}\right)\gamma^\mu \underset{r}{e_L} + i\underset{p}{\bar e_L}\gamma^\mu\left(\partial_\mu \underset{p}{e_L}\right) \\ &= \left(-\underset{p}{\bar e_R} \underset{pr}{M_e} + \Delta^{(6)}_{\underset{r}{\bar e_L}}\right)\underset{r}{e_L} + \underset{p}{\bar e_L}\left(\underset{rp}{M_e}\underset{r}{e_R} - \Delta^{(6)}_{\underset{p}{e_L}}\right), \end{aligned}$$

Higher dimensional operator contributions to current, an effect not individually Invariant under charged lepton rephrasing

$$\begin{aligned} \Delta^{(6,L)}_{\underset{r}{\bar e_L}} \underset{r}{e_L} - \underset{p}{\bar e_L}\Delta^{(6,L)}_{\underset{p}{e_L}} + \Delta^{(6,L)}_{\underset{r}{\bar e_R}}\underset{r}{e_R} - \underset{p}{\bar e_R}\Delta^{(6,L)}_{\underset{p}{e_R}} &= \left(\underset{prst}{C^{V,LL}_{\nu edu}} \underset{pr}{J^\mu_{\nu e,L}} \underset{st}{J^\nu_{du,L}} - \underset{rpts}{C^{V,LL*}_{\nu edu}} \underset{pr}{J^\mu_{e\nu,L}} \underset{st}{J^\nu_{ud,L}}\right)\eta_{\mu\nu} \\ &+ \left(\underset{prst}{C^{V,LR}_{\nu edu}} \underset{pr}{J^\mu_{\nu e,L}} \underset{st}{J^\nu_{du,R}} - \underset{rpts}{C^{V,LR*}_{\nu edu}} \underset{pr}{J^\mu_{e\nu,L}} \underset{st}{J^\nu_{ud,R}}\right)\eta_{\mu\nu} + \underset{prst}{C^{S,RR}_{\nu edu}} \underset{pr}{S_{\nu e,L}} \underset{st}{S_{du,L}} - \underset{rpts}{C^{S,RR*}_{\nu edu}} \underset{pr}{S_{e\nu,R}} \underset{st}{S_{ud,R}} \\ &+ \left(\underset{prst}{C^{T,RR}_{\nu edu}} \underset{pr}{T^{\mu\nu}_{\nu e,L}} \underset{st}{T^{\alpha\beta}_{du,L}} - \underset{rpts}{C^{T,RR*}_{\nu edu}} \underset{pr}{T^{\mu\nu}_{e\nu,R}} \underset{st}{T^{\alpha\beta}_{ud,R}}\right)\eta_{\alpha\mu}\eta_{\beta\nu} + \underset{prst}{C^{S,RL}_{\nu edu}} \underset{pr}{S_{\nu e,L}} \underset{st}{S_{du,R}} - \underset{rpts}{C^{S,RL*}_{\nu edu}} \underset{pr}{S_{e\nu,R}} \underset{st}{S_{ud,L}}. \end{aligned}$$

Corresponding corrections to the neutrino current $\underset{rr}{J^\mu_\nu} \equiv \underset{r}{\bar\nu_L}\gamma^\mu \underset{r}{\nu_L} + \dots$

$$\Delta^{(6,L)}_{\underset{r}{\bar e_L}} \underset{r}{e_L} - \underset{p}{\bar e_L}\Delta^{(6,L)}_{\underset{p}{e_L}} + \Delta^{(6,L)}_{\underset{r}{\bar e_R}}\underset{r}{e_R} - \underset{p}{\bar e_R}\Delta^{(6,L)}_{\underset{p}{e_R}} + \Delta^{(6,L)}_{\underset{r}{\bar\nu_L}}\underset{r}{\nu_L} - \underset{p}{\bar\nu_L}\Delta^{(6,L)}_{\underset{p}{\nu_L}} = 0.$$

Current conserved $\partial_\mu J^{(L)\mu}_\ell = 0,$

Lepton number example

- Consider a simple symmetry example, lepton number, perform rephrasing

$$\underset{p}{e_L} \to e^{i\alpha} \underset{p}{e_L}, \qquad \underset{p}{e_R} \to e^{i\alpha} \underset{p}{e_R}, \qquad \text{current} \quad \underset{rr}{J^\mu_e} \equiv \underset{rr}{J^\mu_{e,L}} + \underset{rr}{J^\mu_{e,R}} \equiv \underset{r}{\bar{e}_L} \gamma^\mu \underset{r}{e_L} + \underset{r}{\bar{e}_R} \gamma^\mu \underset{r}{e_R} + \cdots$$

KEEP ALL THE OPERATORS AS THIS CAN HAPPEN WITH UV SYMMETRIES

Is this current conserved?

$$i\partial_\mu \underset{rr}{J^\mu_{e,L}} = i\left(\partial_\mu \underset{r}{\bar{e}_L}\right)\gamma^\mu \underset{r}{e_L} + i\underset{p}{\bar{e}_L}\gamma^\mu\left(\partial_\mu \underset{p}{e_L}\right)$$
$$= \left(-\underset{p}{\bar{e}_R} \underset{pr}{M_e} + \Delta^{(6)}_{\underset{r}{\bar{e}_L}}\right) \underset{r}{e_L} + \underset{p}{\bar{e}_L}\left(\underset{rp}{M_e}\underset{r}{e_R} - \Delta^{(6)}_{\underset{p}{e_L}}\right),$$

Higher dimensional operator contributions to current, an effect not individually Invariant under charged lepton rephrasing

$$\Delta^{(6,L)}_{\underset{r}{\bar{e}_L}} \underset{r}{e_L} - \underset{p}{\bar{e}_L} \Delta^{(6,L)}_{\underset{p}{e_L}} + \Delta^{(6,L)}_{\underset{r}{\bar{e}_R}} \underset{r}{e_R} - \underset{p}{\bar{e}_R} \Delta^{(6,L)}_{\underset{p}{e_R}} = \left(\underset{prst}{C^{V,LL}_{\nu edu}} \underset{pr}{J^\mu_{\nu e,L}} \underset{st}{J^\nu_{du,L}} - \underset{rpts}{C^{V,LL*}_{\nu edu}} \underset{pr}{J^\mu_{e\nu,L}} \underset{st}{J^\nu_{ud,L}}\right)\eta_{\mu\nu}$$
$$+ \left(\underset{prst}{C^{V,LR}_{\nu edu}} \underset{pr}{J^\mu_{\nu e,L}} \underset{st}{J^\nu_{du,R}} - \underset{rpts}{C^{V,LR*}_{\nu edu}} \underset{pr}{J^\mu_{e\nu,L}} \underset{st}{J^\nu_{ud,R}}\right)\eta_{\mu\nu} + \underset{prst}{C^{S,RR}_{\nu edu}} \underset{pr}{S_{\nu e,L}} \underset{st}{S_{du,L}} - \underset{rpts}{C^{S,RR*}_{\nu edu}} \underset{pr}{S_{e\nu,R}} \underset{st}{S_{ud,R}}$$
$$+ \left(\underset{prst}{C^{T,RR}_{\nu edu}} \underset{pr}{T^{\mu\nu}_{\nu e,L}} \underset{st}{T^{\alpha\beta}_{du,L}} - \underset{rpts}{C^{T,RR*}_{\nu edu}} \underset{pr}{T^{\mu\nu}_{e\nu,R}} \underset{st}{T^{\alpha\beta}_{ud,R}}\right)\eta_{\alpha\mu}\eta_{\beta\nu} + \underset{prst}{C^{S,RL}_{\nu edu}} \underset{pr}{S_{\nu e,L}} \underset{st}{S_{du,R}} - \underset{rpts}{C^{S,RL*}_{\nu edu}} \underset{pr}{S_{e\nu,R}} \underset{st}{S_{ud,L}}.$$

Corresponding corrections to the neutrino current $\underset{rr}{J^\mu_\nu} \equiv \underset{r}{\bar{\nu}_L}\gamma^\mu \underset{r}{\nu_L} + \ldots$

$$\Delta^{(6,L)}_{\underset{r}{\bar{e}_L}} \underset{r}{e_L} - \underset{p}{\bar{e}_L} \Delta^{(6,L)}_{\underset{p}{e_L}} + \Delta^{(6,L)}_{\underset{r}{\bar{e}_R}} \underset{r}{e_R} - \underset{p}{\bar{e}_R} \Delta^{(6,L)}_{\underset{p}{e_R}} + \Delta^{(6,L)}_{\underset{r}{\bar{\nu}_L}} \underset{r}{\nu_L} - \underset{p}{\bar{\nu}_L} \Delta^{(6,L)}_{\underset{p}{\nu_L}} = 0.$$

Current conserved $\partial_\mu J^{(L)\mu}_\ell = 0,$

Hypercharge example

- SM hyper-charge current $J^{\mu}_{\Psi \mathsf{y},\mathrm{SM}} = \sum_{\substack{\Psi = e_R, u_R, d_R,\\ \ell_L, q_L}} \mathsf{y}_\Psi \overline{\Psi}\gamma^\mu \Psi$, $\mathsf{y}_\Psi = \{-1, 2/3, -1/3, -1/2, 1/6\}$.

Not manifest in LEFT. (includes states integrated out)

Defining a current of the states retained $J^{\mu}_{\Upsilon \mathsf{y}} = \sum_{\Upsilon} \mathsf{y}_\Upsilon \overline{\Upsilon}\gamma^\mu \Upsilon$. $\Upsilon = \{\psi_R, \psi_L, \nu_L\}$

Is this conserved? (impose matching to SMEFT and SM)

$$
\begin{aligned}
i\partial_\mu J^\mu_{\Upsilon \mathsf{y}}\Big|_{\mathrm{match}} = {} & \frac{(\mathsf{y}_{u_R} - \mathsf{y}_{d_R})}{\bar{v}_T^2} \left(C^{V,LR}_{\substack{\nu edu\\ prst}} J^\mu_{\substack{\nu e,L\\ pr}} J^\nu_{\substack{du,R\\ st}} - C^{V,LR\star}_{\substack{\nu edu\\ rpts}} J^\mu_{\substack{e\nu,L\\ pr}} J^\nu_{\substack{ud,R\\ st}} + C^{V1,LR}_{\substack{uddu\\ prst}} J^\mu_{\substack{ud,L\\ pr}} J^\nu_{\substack{du,R\\ st}} - C^{V1,LR\star}_{\substack{uddu\\ rpts}} J^\mu_{\substack{du,L\\ pr}} J^\nu_{\substack{du,R\\ st}} \right) \eta_{\mu\nu} \\
& + (\mathsf{y}_{\psi_R} - \mathsf{y}_{\psi_L}) \left(\overline{\psi}_{\substack{R\\ p}} \left[M_\psi\right]_{pr} \psi_{\substack{L\\ r}} - \overline{\psi}_{\substack{L\\ p}} \left[M^\dagger_\psi\right]_{pr} \psi_{\substack{R\\ r}} \right) + 2\, \bar{v}_T \mathsf{y}_{\nu_L} \left[\overline{\nu}_{\substack{L\\ p}} C^\star_{\substack{\nu\\ pr}} \nu^c_{\substack{L\\ r}} - \overline{\nu}^c_{\substack{L\\ p}} C^T_{\substack{\nu\\ pr}} \nu_{\substack{L\\ r}} \right] \\
& + \frac{(\mathsf{y}_{\psi_L} - \mathsf{y}_{\psi_R})}{\bar{v}_T} \sum_{\psi \neq e} \left[\overline{\psi}_{\substack{R\\ p}} \sigma^{\alpha\beta} T^A \psi_{\substack{L\\ r}} C^\star_{\substack{\psi G\\ rp}} - \overline{\psi}_{\substack{L\\ p}} \sigma^{\alpha\beta} T^A \psi_{\substack{R\\ r}} C^T_{\substack{\psi G\\ rp}} \right] G^{\alpha\beta}_A \\
& + \frac{(\mathsf{y}_{\psi_L} - \mathsf{y}_{\psi_R})}{\bar{v}_T} \left[\overline{\psi}_{\substack{R\\ p}} \sigma^{\alpha\beta} \psi_{\substack{L\\ r}} C^\star_{\substack{\psi\gamma\\ rp}} - \overline{\psi}_{\substack{L\\ p}} \sigma^{\alpha\beta} \psi_{\substack{R\\ r}} C^T_{\substack{\psi\gamma\\ rp}} \right] F_{\alpha\beta} + \ldots
\end{aligned}
$$

No. Even the contributions coming from the SM are such that $\partial_\mu J^\mu_{\Psi \mathsf{y},\mathrm{SM}} \neq 0$.

Hypercharge example

- What is going wrong is some states missing from spectrum that carry hypercharge

$$J^{\mu}_{\mathrm{y,full}} = J^{\mu}_{\Psi \mathrm{y}} + \mathrm{y}_H H^\dagger i \overleftrightarrow{D}^{\mu} H,$$

- How do we find the conserved current? Define a current with the spurion:

$$J^{\mu}_{\mathrm{y,LEFT}} = J^{\mu}_{\Upsilon \mathrm{y}} + J^{\mu}_{\mathrm{y,S}},$$

$$\mathcal{L}^{kin}_{\mathrm{S}} = \sum_{\tilde{C}} \left(D^{\mu}\tilde{C}\right)^\dagger \left(D_{\mu}\tilde{C}\right).$$

$$J^{\mu}_{\mathrm{y,S}} = \sum_{\tilde{C}} \mathrm{y}_{\tilde{C}} \tilde{C}^\dagger i \overleftrightarrow{D}^{\mu} \tilde{C}.$$

Using the EOM contribution of the spurion field $D^2\tilde{C} = \delta L_{\mathrm{LEFT}}/\delta\tilde{C}^\star$.

Assigned charges:

$$\begin{aligned} \mathrm{y}_{\tilde{C}} &= \mathrm{y}_{d_R} - \mathrm{y}_{u_R} && \text{for } \tilde{C}^{V,LR}_{\nu edu},\ \tilde{C}^{V1,LR}_{uddu}, \\ \mathrm{y}_{\tilde{C}} &= -\mathrm{y}_{\nu} && \text{for } \tilde{C}_{\nu}, \\ \mathrm{y}_{\tilde{C}} &= \mathrm{y}_{\psi_R} - \mathrm{y}_{\psi_L} && \text{for } \tilde{C}_{\psi\gamma}, \tilde{C}_{\psi G}, \\ \mathrm{y}_{\tilde{C}} &= \mathrm{y}_{\psi_L} - \mathrm{y}_{\psi_R} && \text{for } \tilde{C}_{\psi}. \end{aligned}$$

One recovers the conserved current: $i\partial_{\mu} J^{\mu}_{\mathrm{y,LEFT}} = 0.$

Hypercharge example

- What is going wrong is some states missing from spectrum that carry hypercharge

$$J^{\mu}_{\mathrm{y,full}} = J^{\mu}_{\Psi \mathrm{y}} + \mathrm{y}_H H^\dagger i \overleftrightarrow{D}^\mu H,$$

- How do we find the conserved current? Define a current with the spurion.

KEEP ALL THE OPERATORS AS THIS CAN HAPPEN WITH UV SYMMETRIES

$$J^{\mu}_{\mathrm{y,LEFT}} = J^{\mu}_{\Upsilon \mathrm{y}} + J^{\mu}_{\mathrm{y,S}},$$

$$\mathcal{L}^{kin}_{\mathrm{S}} = \sum_{\tilde{C}} \left(D^\mu \tilde{C}\right)^\dagger \left(D_\mu \tilde{C}\right).$$

$$J^{\mu}_{\mathrm{y,S}} = \sum_{\tilde{C}} \mathrm{y}_{\tilde{C}} \, \tilde{C}^\dagger i \overleftrightarrow{D}^\mu \tilde{C}.$$

Assigned charges:

$$\begin{aligned}
\mathrm{y}_{\tilde{C}} &= \mathrm{y}_{d_R} - \mathrm{y}_{u_R} && \text{for } \tilde{C}^{V,LR}_{\nu edu}, \ \tilde{C}^{V1,LR}_{uddu}, \\
\mathrm{y}_{\tilde{C}} &= -\mathrm{y}_{\nu} && \text{for } \tilde{C}_{\nu}, \\
\mathrm{y}_{\tilde{C}} &= \mathrm{y}_{\psi_R} - \mathrm{y}_{\psi_L} && \text{for } \tilde{C}_{\psi\gamma}, \tilde{C}_{\psi G}, \\
\mathrm{y}_{\tilde{C}} &= \mathrm{y}_{\psi_L} - \mathrm{y}_{\psi_R} && \text{for } \tilde{C}_{\psi}.
\end{aligned}$$

Using the EOM contribution of the spurion field $D^2 \tilde{C} = \delta L_{\mathrm{LEFT}} / \delta \tilde{C}^\star$.

One recovers the conserved current: $i\partial_\mu J^{\mu}_{\mathrm{y,LEFT}} = 0.$

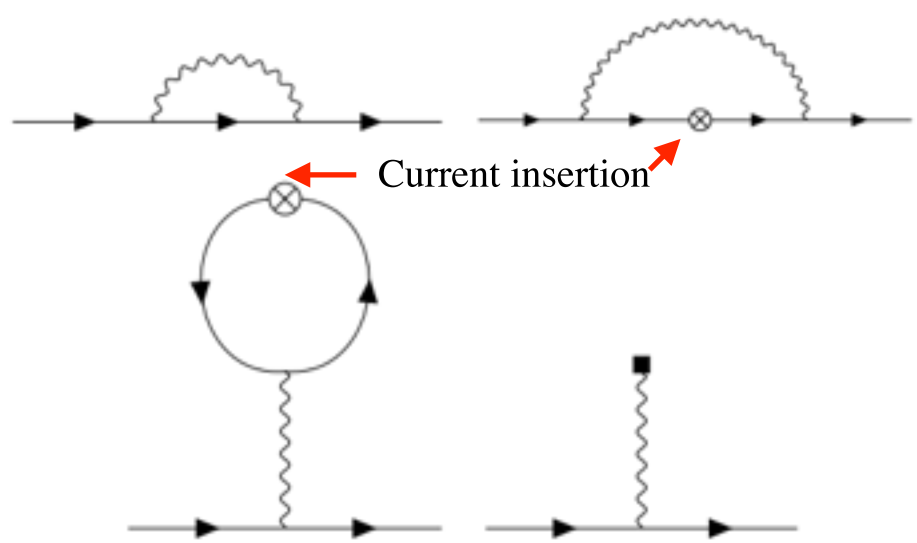
Current redefinition and gauss's law

- Gauss's law (1845), see also Lagrange (1773!) relates time component of EM current $J^\mu = \overline{\psi}_e \gamma^\mu \psi_e$ to

$$J^0 = \frac{\nabla \cdot \mathbf{E}}{-e_{phys}}.$$

Its a good thing if the EM current is conserved: $\partial_\mu J^\mu = 0,$

There is a subtlety. Sorted out in Collins, Manohar, Wise arXiv:hep-th/0512187 [hep-th].
See also Lurie 1968



Cancel!

There is mixing with a surface term

Gupta-Bleuler condition

$$0 = \frac{\delta S_{\rm LEFT}}{\delta A_\mu(x)} = e\mu^\epsilon J^\mu_N + Z_3 \partial_\nu F^{\nu\mu} + \frac{1}{\xi}\partial^\mu \partial \cdot A.$$

Current redefinition and gauss's law

- Counterintuitively, a naive definition of the current runs

$$\mu\frac{d}{d\mu}J^{\mu}_{\overline{\mathrm{MS}}} = 2\gamma_A \frac{1}{e_0 Z_3}\partial_\nu F^{(0),\nu\mu}.$$

Just redefine the current to cancel the log
Collins, Manohar, Wise arXiv:hep-th/0512187 [hep-th].

$$J^{\mu}_{\mathrm{LEFTphys}} = J^{\mu}_{\overline{\mathrm{MS}}} - \frac{\Pi(0)}{e\mu^{\epsilon}}\partial_\nu F^{\nu\mu},$$

$$\Pi(0) = -\frac{e^2}{12\pi^2}\log\frac{m_e^2}{\mu^2}$$

$$F^{\nu\mu}_{\mathrm{LEFT,phys}} = \left[1+\Pi(0)\right]^{1/2} F^{\nu\mu},$$

$$e_{\mathrm{LEFT,phys}} = \left[1+\Pi(0)\right]^{-1/2} e\mu^{\epsilon}.$$

- Left has a natural generalisation of this

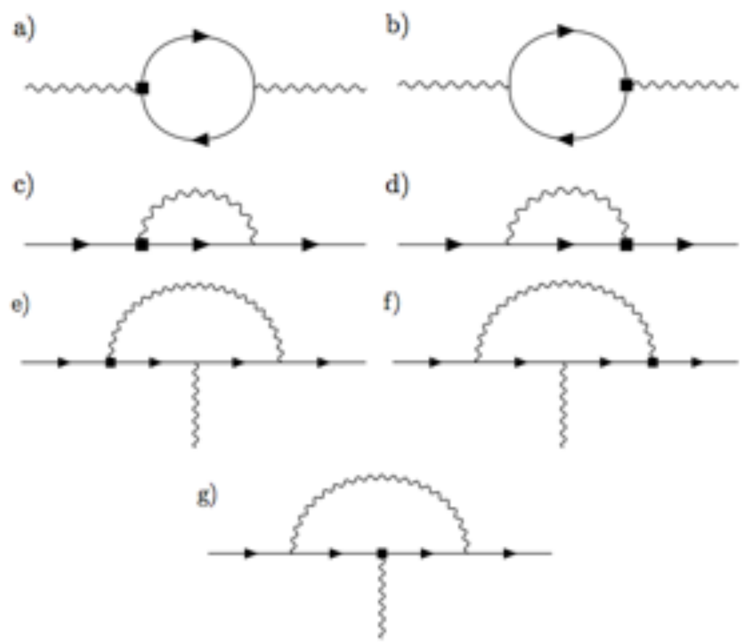
$$J^{\mu}_{\overline{\mathrm{MS}}} = J^{\mu}_{N} + \frac{Z_3 - 1}{e\mu^{\epsilon}}\partial_\nu F^{\nu\mu}$$

$$+\frac{\sqrt{Z_3}Z_2}{e\mu^{\epsilon}}\partial_\nu\left(Z_C C_{e\gamma}\left(\bar{e}_L\sigma^{\nu\mu}e_R\right) + Z_C^{*}C_{e\gamma}^{*}\left(\bar{e}_R\sigma^{\nu\mu}e_L\right)\right) + \dots$$

← Dipole

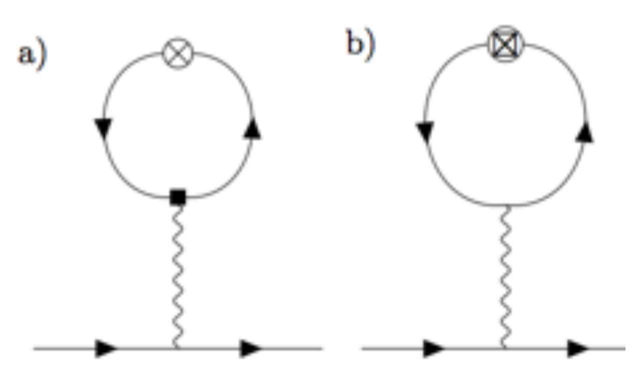
Current redefinition and gauss's law

- Left has a natural generalisation of this



Calculated in 1711.05270 Jenkins, Manohar, Stoffer

$$J^{\mu}_{\overline{\mathrm{MS}}} = J^{\mu}_{N} + \frac{Z_3 - 1}{e\mu^{\epsilon}}\partial_\nu F^{\nu\mu}$$
$$+ \frac{\sqrt{Z_3}Z_2}{e\mu^{\epsilon}}\partial_\nu \left(Z_C C_{e\gamma}\left(\bar{e}_L\sigma^{\nu\mu}e_R\right) + Z_C^* C_{e\gamma}^*\left(\bar{e}_R\sigma^{\nu\mu}e_L\right)\right) + \ldots$$



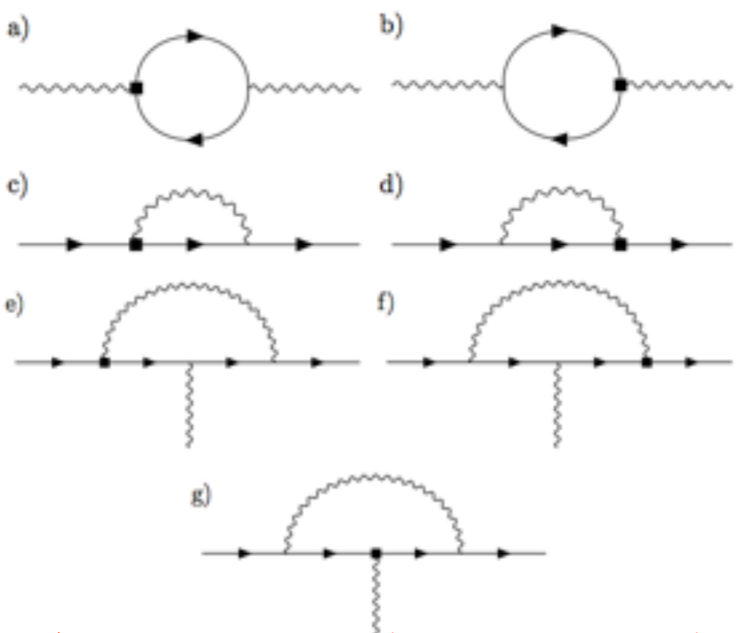
Corresponding surface diagrams with current insertions.

Have to redefine the current with higher D ops (multipole expansion) to have the divergence cancel

$$J^{\mu}_{\mathrm{LEFTphys}} = J^{\mu}_{\overline{\mathrm{MS}}} - \frac{\Pi(0)}{e\mu^{\epsilon}}\partial_\nu F^{\nu\mu}, \qquad \Pi(0) = -\frac{e^2}{12\pi^2}\log\frac{m_e^2}{\mu^2}$$
$$+ \frac{e\,q_e}{2\,\pi^2}\left(C_{\substack{e\gamma\\11}}[M_e]_{11} + C^{\star}_{\substack{e\gamma\\11}}[M_e^{\dagger}]_{11}\right)\log\frac{m_e^2}{\mu^2} + \ldots$$

Current redefinition and gauss's law

- Left has a natural generalisation of this



Calculated in 1711.05270 Jenkins, Manohar, Stoffer

$$J^\mu_{\overline{\mathrm{MS}}} = J^\mu_N + \frac{Z_3 - 1}{e\mu^\epsilon}\partial_\nu F^{\nu\mu}$$
$$+ \frac{\sqrt{Z_3}Z_2}{e\mu^\epsilon}\partial_\nu \left(Z_C C_{e\gamma}\left(\bar{e}_L \sigma^{\nu\mu} e_R\right) + Z_C^* C_{e\gamma}^*\left(\bar{e}_R \sigma^{\nu\mu} e_L\right)\right) + \dots$$

"In summary, the manuscript is very technical, difficult to read, and lacks <u>any</u> novel results that could be of interest to the particle physics community."

— anonymous (no doubt unbiased) Phys Rev D reviewer

(The "don't be a tool" title of the talk seems to apply here as well.)

Thx, and have a nice workshop!