Developments in Treating the Standard Model as an EFT

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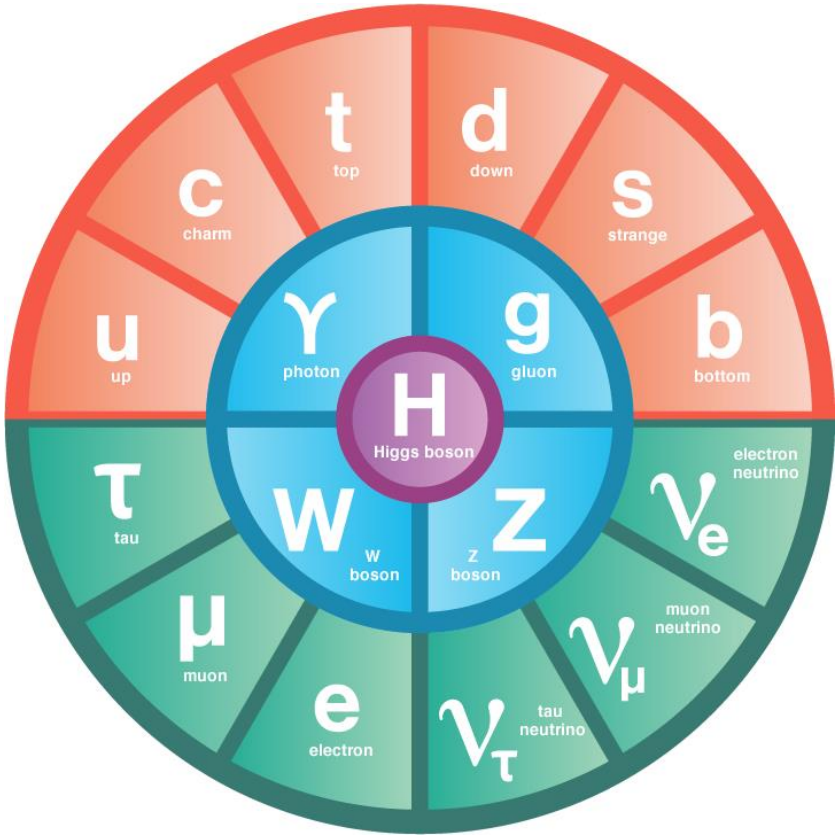
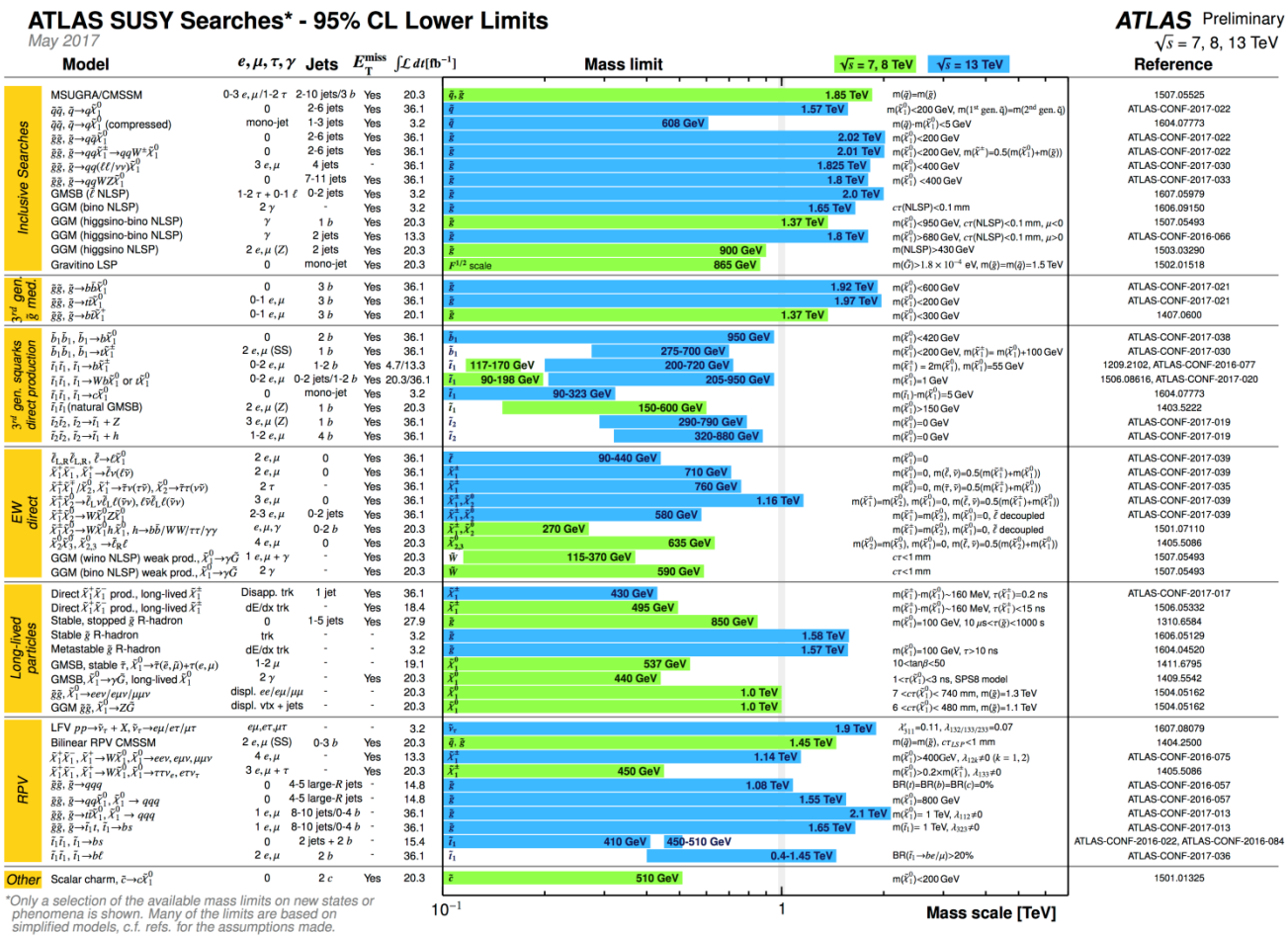
With woefully inadequate citations throughout; my apologies

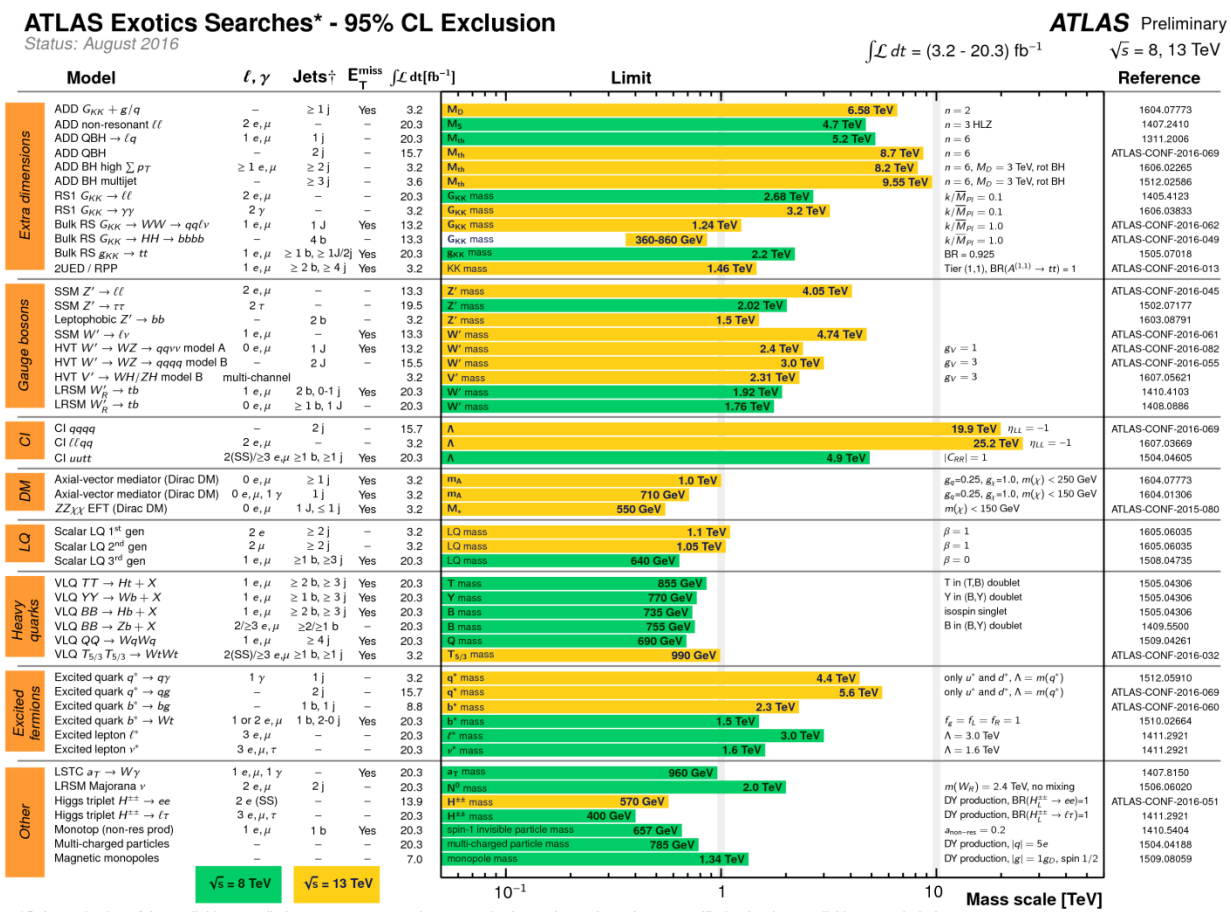
Particle physics today



Why EFT and not SUSY?

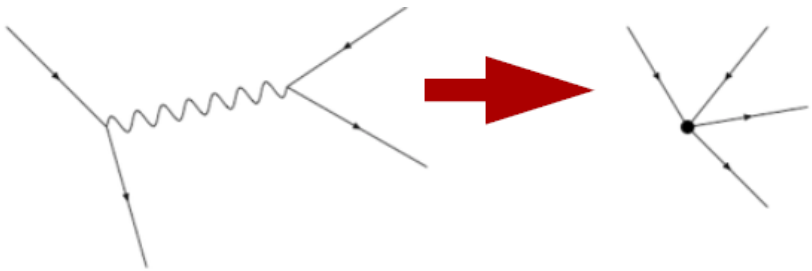


Why EFT and not <my favorite model>?

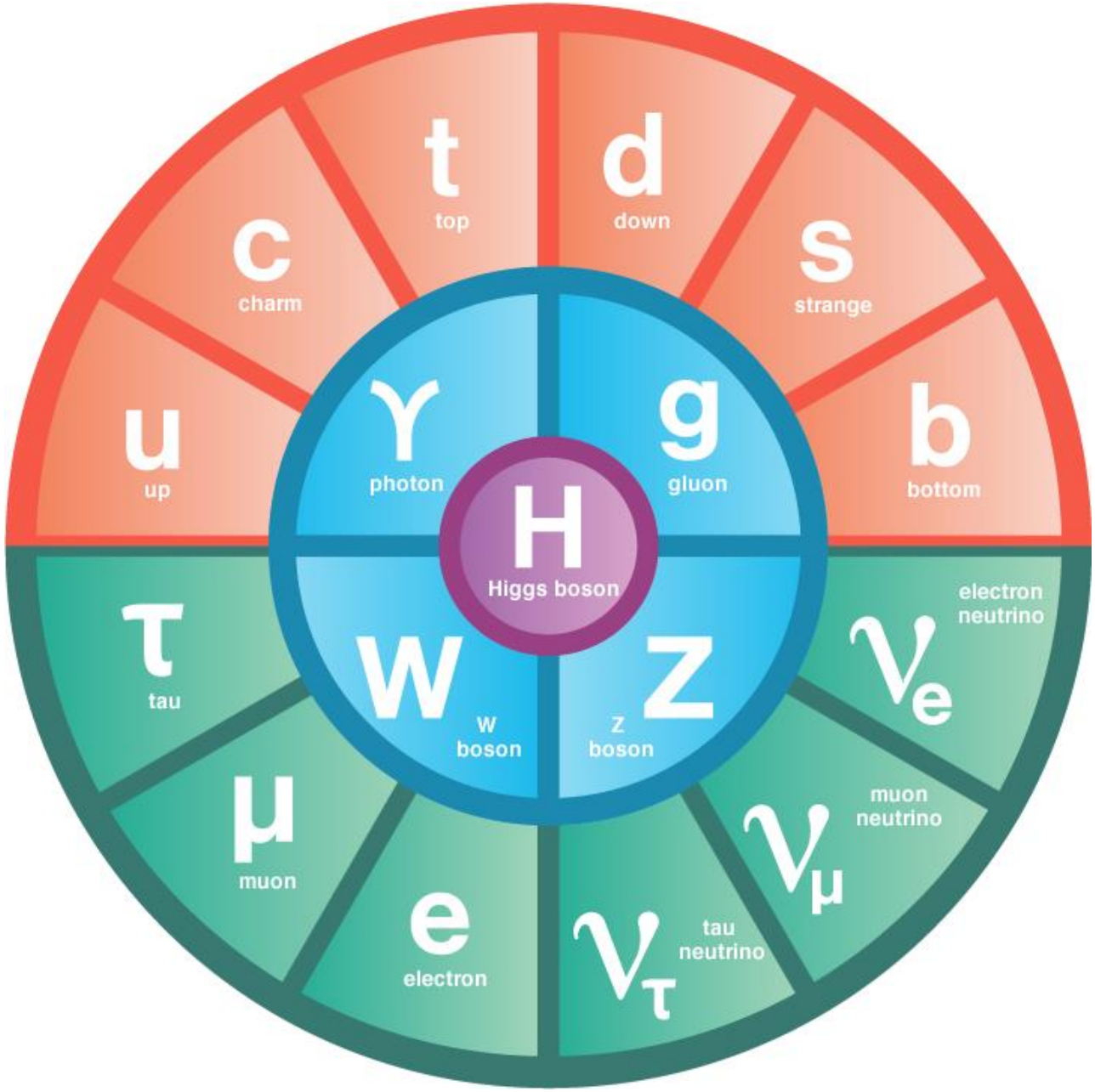


Effective Field Theory

- The canonical example of an EFT is Fermi's theory of weak decay
  - A real limit of the SM



- We still use this today!
- Captures physics in a particular energy regime
  - Able to be improved in precision systematically
- Ability to systematically improve theory predictions is the key virtue of EFTs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What isn’t an EFT?

What isn't an EFT?

- Anything where some operators are turned off or neglected by hand
  - More generally, any setup which doesn't close under field redefinitions or renormalization
- These "phenomenological Lagrangian" studies can be well-motivated in various UV assumptions, and have value, but they aren't proper EFT treatments, where the UV dependence is properly suppressed by separation of scales

Two Candidate Theories

Higgs EFT

- That's some "Higgs-like scalar"
- If that's not THE Higgs then something else breaks EWS
- Expand EW sector a la χPT
- Scalar contributions may be suppressed by a lower scale, include them to higher orders

Standard Model EFT

- That's the Higgs
- We can insist on full EW symmetry at the weak scale
- Any new physics appears suppressed by a large scale
- Expand straightforwardly in operator dimension

HEFT History

- The general approach of treating WBGBs using χPT has been around for a long time
- Recently been systematized to allow proper power counting
  - Distinct choices possible for defining orders
- Contains 148 parameters at leading order in flavor-blind NP contributions (1307.5017, 1604.06801)
- Allows h and WBGBs to couple independently to fields
  - Breaks SU(2) relations expected for h in doublet
- Basis of κ-formalism for varied scalar couplings
  - This formalism is nonetheless not an EFT treatment

HEFT Developments

- Fits to Higgs and LEP data have been performed with great detail
- Investigations of matchings to various UV theories have been done
  - Higgs inflation
  - Dilaton-Higgs
  - Composite Higgs
- Investigation of differences in predictions ongoing, generally absent in pole measurements

SMEFT History

- Enumeration of operators took some time:
  - Leung, Love, Rao 1984, Buchmuller Wyler 1986
  - Hagiwara, Ishihara, Szalapski, Zeppenfeld 1993
  - 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek
- Final answer: 2499 flavorful parameters, 76 flavor-blind
- We now have full RG description at 1-loop
  - 1312.2014 Alonso, Jenkins, Manohar, Trott

Distinction between HEFT and SMEFT

- Looks naively like one can send SMEFT -> HEFT with a field redefinition on h but not WBGBs
  - Spawned many arguments about which is correct/general
- This is not actually true, as different basis sizes (now that we agree on them) make manifest
- The real difference is in the topology of the metric in field space (1511.00724, 1605.03602)
  - SM has a flat scalar metric
  - SMEFT has curvature from H^4 D^2 terms
  - HEFT has curvature and no $O(4)$-preserving fixed point

Warsaw Basis

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Warsaw Basis: 4-fermion

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

SMEFT Developments

- Fits to LEP and Higgs data
- Development of multiple bases and translation tools
- Revitalization of matching techniques
  - Automating Feynman 1-loop matching
  - CDE techniques in functional matching
- Loop corrections to precise observables

Why Loops?

- Electroweak observables have been measured with amazing precision
  - Theory calculations have to match this precision to get full value out of the data

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]

Why Loops?

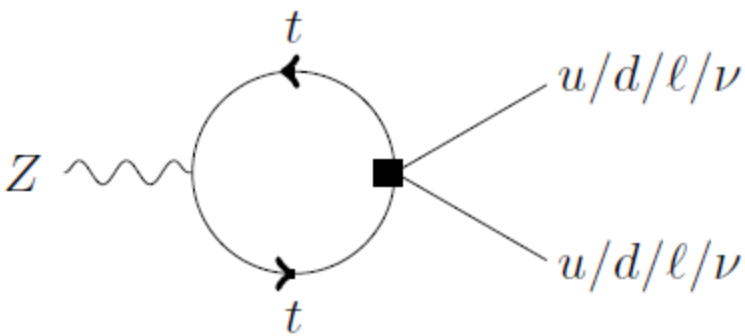
- What is the theory error on a tree-level prediction for EFT effects?
  - Standard loop factor is $\frac{1}{16\pi^2} \sim 1\%$
  - $\frac{v^2}{\Lambda^2} \sim 1\%$ as well
  - Numerical coefficients not known a priori
- SMEFT renormalization known, RG improvement will capture logs
  - For LHC-scale physics logs aren't so large
  - Pure-finite effects can be of comparable size

SMEFT 1-loop calculations

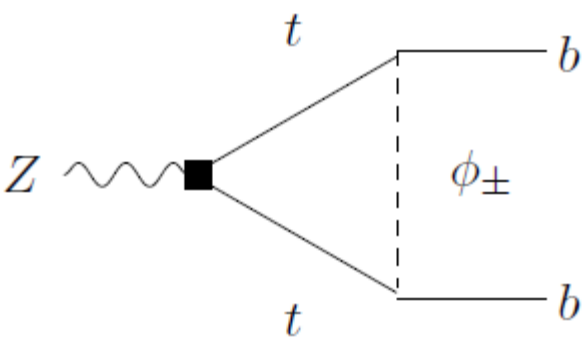
- $H \to \gamma\gamma$ Hartmann and Trott 1505.02646
- $H \to \bar{f} f$
  - 4ψ effects Gauld, Pecjak, Scott 1512.02508
  - QCD radiative Gauld, Pecjak, Scott 1607.06354
- $pp \to \bar{t} t H$ Maltoni, Vryonidou, Zhang 1607.05330
- $Z \to \bar{f} f$ Hartmann, WS, Trott 1611.09879

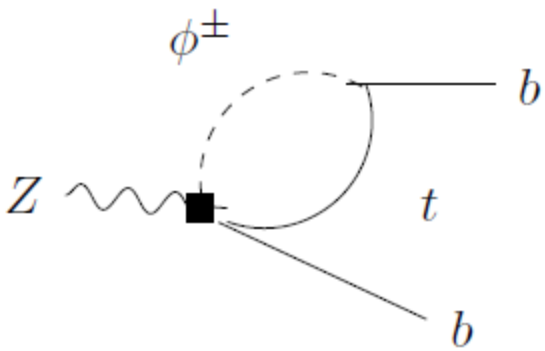
Contributing Operators

- 4-fermion operators:



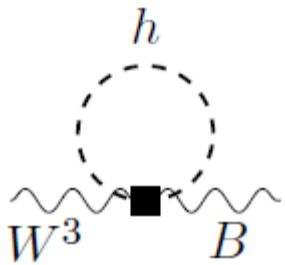
- Scalar-fermionic current operators:



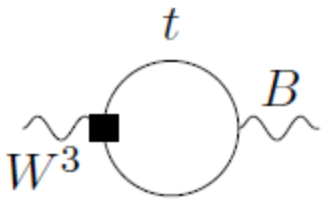


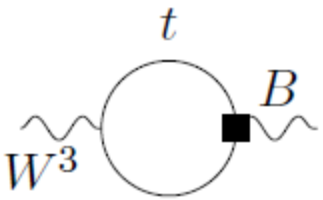
Contributing Operators

- Gauge-Higgs operators:



- Dipole operators:





Input Parameters

- Any calculation depends on the inputs used to set the theory parameters
- We use a canonical set of inputs for the SM
  - $\alpha_{EM}, G_F, M_Z, M_t, M_h$
- EFT gives corrections to the extraction of each
- We treat the Wilson coefficients in $\overline{MS}$ at the NP scale as EFT input parameters to be measured and/or constrained

Sample Results

$$
\begin{aligned}
\Delta(g_L^d)_{rr} = {} & \Delta\bar{g}_Z (g_L^d)_{rr}^{SM} + \frac{N_c \hat{m}_t^2}{16\pi^2} \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right] \left[C^{(1)}_{\substack{qq\\33rr}} + C^{(1)}_{\substack{qq\\rr33}} - C^{(3)}_{\substack{qq\\33rr}} - C^{(3)}_{\substack{qq\\rr33}} - C^{(1)}_{\substack{qu\\rr33}}\right], \\
& - \frac{1}{2}\left(\frac{\Delta G_F}{\hat{G}_F} + \Delta V^2\right)\left(C^{(1)}_{\substack{Hq\\rr}} + C^{(3)}_{\substack{Hq\\rr}}\right) + \delta_{br} \frac{\hat{m}_t^2}{4\pi^2}\left[C^{(3)}_{\substack{qq\\3333}}\left(-1 + \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right)\right] - \frac{1}{3}\Delta s_\theta^2, \\
& - \delta_{br} \frac{\hat{m}_t^2}{16\pi^2}\left[\left(\frac{1}{4} - \frac{1}{2}\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right) C_{Hu} + C^{(1)}_{Hq}\right] - \delta_{br}\, \Delta R_b^L \left((g_L^d)_{rr}^{SM} + \delta(g_L^d)_{rr}\right), \\
& - \delta_{br} \frac{\hat{m}_t^2}{16\pi^2} C^{(3)}_{Hq}\left[\frac{1}{2} - \mathcal{Q}_b\, s_{\hat{\theta}}^2 + (3 - 2\,\mathcal{Q}_b\, s_{\hat{\theta}}^2)\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right], \\
& - \delta_{br} \frac{\hat{m}_t^2}{4\pi} \tilde{\alpha}\,(c_{\hat{\theta}}^2 - s_{\hat{\theta}}^2)\, C_{HWB}\,(\mathcal{Q}_u - 1)\left[\frac{3}{2} + \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\right],
\end{aligned}
$$

$$
\begin{aligned}
\Delta\Gamma_{Z\to Had} &= 2\,\Delta\Gamma_{Z\bar{u}u} + 2\,\Delta\Gamma_{Z\bar{d}d} + \Delta\Gamma_{Z\bar{b}b}, \\
&= \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\,\pi}\left[4\,(g_R^u + \delta g_R^u)\,\Delta g_R^u + 4\,(g_L^u + \delta g_L^u)\,\Delta g_L^u + 4\,(g_R^d + \delta g_R^d)\,\Delta g_R^d\right] \\
&+ \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\,\pi}\left[4\,(g_L^d + \delta g_L^d)\,\Delta g_L^d + 2\,(g_R^b + \delta g_R^b)\,\Delta g_R^b + 2\,(g_L^b + \delta g_L^b)\,\Delta g_L^b\right]
\end{aligned}
$$

Phenomenology

- Counting is all that's needed for the most important point
- Tree amplitude depends on:
  - 1 Higgs-gauge WC
  - 1 Higgs-derivative WC
  - 7 Higgs-fermion WCs
  - 1 four-fermion WC
- NLO corrections have introduced additional dependence on:
  - 2 Higgs-gauge WCs
  - 1 Yukawa-correcting WC
  - 2 Dipole WCs
  - 11 four-fermion WCs
- At this level of precision, we can measure only 5 Z pole observables (A_{FB} goes beyond NWA)

Phenomenology

- Recall that at tree level there were flat directions in Z pole observables
  - Lifted by TGC measurements
- With this increase in relevant parameters, all of EWPD not enough to constrain the EFT
- The lesson: loop corrections cannot be constrained by EWPD alone, thus EWPD bounds (at tree level) can never be more precise than a loop factor on WCs

Numerics

The δ correction to $\bar{\Gamma}_{Z\to\bar{d}d}$ (where $d = \{d, s, b\}$) is given by

$$\frac{\delta\bar{\Gamma}_{Z\to\bar{d}d}}{10^{-2}} = -0.939\, C_{Hd} - 1.58\, C_{HD} - 6.31\, C_{H\ell}^{(3)} + 5.10\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right) - 0.510\, C_{HWB} + 3.15\, C_{\ell\ell}. \tag{7.21}$$

The $\delta\,\Delta$ correction to $\bar{\Gamma}_{Z\to\bar{d}d}$ (where $d = \{d, s\}$) has the contributions

$$\begin{aligned}\frac{\delta\Delta\bar{\Gamma}_{Z\to\bar{d}d}}{10^{-3}} = \Big[&(0.071\,\Delta\bar{v}_T + 0.201)\, C_{Hd} - (0.115\,\Delta\bar{v}_T + 0.144)\, C_{HD}, - (1.45\,\Delta\bar{v}_T + 1.08)\, C_{H\ell}^{(3)} \\ &+ (0.316\,\Delta\bar{v}_T - 0.206)\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right) - (0.024\,\Delta\bar{v}_T + 0.064)\, C_{HWB} + 4.23\,\Delta\bar{v}_T, \\ &+ (0.727\,\Delta\bar{v}_T + 0.541)\, C_{\ell\ell} + 0.593\, C_{\ell q}^{(3)} + 0.072\,(C_{HB} + C_{HW})\Big],\end{aligned} \tag{7.22}$$

and the $\delta\,\Delta$ corrections to $\bar{\Gamma}_{Z\to\bar{d}d}$ (where $d = \{d, s\}$) also has the logarithmic terms

$$\begin{aligned}\frac{\delta\Delta\bar{\Gamma}_{Z\to\bar{d}d}}{10^{-3}} = \Big[&0.342\, C_{Hd} - 0.266\, C_{HD} - 0.995\, C_{H\ell}^{(3)} - 0.225\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right) - 0.110\, C_{HWB}, \\ &+1.09\, C_{\ell\ell} - 1.19\, C_{\ell q}^{(3)} + 0.176\left(C_{qd}^{(1)} - C_{ud}^{(1)}\right) + 1.92\left(C_{qq}^{(3)} - C_{qq}^{(1)}\right) + 0.958\, C_{qu}^{(1)}, \\ &-0.091\, C_{uW} - 0.055\, C_{uB}\Big]\, \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right] + \Big[(2.43\times 10^{-5}\, C_{HD} + 0.015\, C_{Hd}, \\ &+0.103\, C_{Hl}^{(3)} - 0.083\left(C_{hq}^{(1)} + C_{hq}^{(3)}\right) - 0.005\, C_{HWB} - 0.052\, C_{\ell\ell}\Big]\, \log\left[\frac{\Lambda^2}{\hat{m}_h^2}\right]\end{aligned} \tag{7.23}$$

Numerics

The δ correction to $\bar{R}_\ell^b$ is given by

$$\frac{\delta R_b^0}{10^{-2}} = -0.192\, C_{Hd} + 0.039\, C_{HD} + 0.158\, C_{H\ell}^{(3)} + 2.13\, C_{Hq}^{(1)} - 0.055\, C_{Hq}^{(3)}, \\ -0.494\, C_{Hu} + 0.043\, C_{HWB} - 0.079\, C_{\ell\ell}. \tag{7.35}$$

Similarly, the $\delta\,\Delta$ correction to $\bar{R}_b^0$ has the contributions

$$\begin{aligned}\frac{\delta\Delta R_b^0}{10^{-3}} = \Big[&(0.036\,\Delta\bar{v}_T + 0.083)\, C_{Hd} + (0.011\,\Delta\bar{v}_T + 0.013)\, C_{HD} + (0.084\,\Delta\bar{v}_T - 0.014)\, C_{H\ell}^{(3)}, \\ &- (0.085\,\Delta\bar{v}_T + 0.152)\, C_{Hq}^{(1)} - (0.016\,\Delta\bar{v}_T + 0.019)\, C_{Hq}^{(3)} + (0.099\,\Delta\bar{v}_T + 0.208)\, C_{Hu}, \\ &- (0.042\,\Delta\bar{v}_T - 0.007)\, C_{\ell\ell} + (0.013\,\Delta\bar{v}_T + 0.009)\, C_{HWB} - 0.015\, C_{\ell q}^{(3)}, \\ &+0.597\, C_{qq}^{(3)} + 0.047\, C_{uH} - 0.006\,(C_{HB} + C_{HW}) - 0.106\,\Delta v\Big],\end{aligned} \tag{7.36}$$

and the $\delta\,\Delta$ correction to R_b^0 also has the logarithmic terms

$$\begin{aligned}\frac{\delta\Delta R_b^0}{10^{-3}} = \Big[&0.129\, C_{Hd} + 0.025\, C_{HD} + 0.067\, C_{H\ell}^{(3)} - 0.559\, C_{Hq}^{(1)} + 0.383\, C_{Hq}^{(3)} + 0.240\, C_{Hu}, \\ &+0.023\, C_{HWB} - 0.049\, C_{\ell\ell} + 0.030\, C_{\ell q}^{(3)} + 0.036\left(C_{qd}^{(1)} - C_{ud}^{(1)}\right) - 0.618\, C_{qq}^{(3)}, \\ &-0.803\, C_{qq}^{(1)} + 0.494\, C_{qu}^{(1)} - 0.002\, C_{uB} + 0.032\, C_{uH} - 0.004\, C_{uW} - 0.186\, C_{uu}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right] \\ &+ \Big[-8.94\times 10^{-7}\, C_{HD} + \Big(0.313\, C_{Hd} - 3.49\, C_{Hq}^{(1)} + 0.090\, C_{Hq}^{(3)} - 0.258\, C_{H\ell}^{(3)}, \\ &+0.808\, C_{Hu} + 0.129\, C_{\ell\ell} - 0.020\, C_{HWB}\Big)10^{-2}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_h^2}\right].\end{aligned} \tag{7.37}$$

Conclusions

- We have excellent data available, and must have enough respect for that to understand our predictions at comparable precision
- In the case of LEP data at the Z pole, this requires NLO
- In a model-independent formulation of heavy new physics, the NLO predictions are under-constrained by low energy data
  - Setting shifts in EW observables to zero for further searches does not give model-independent results, is not EFT
- A truly global analysis will be needed to properly constrain the EFT without UV assumptions
- Thank goodness we have the LHC with its unprecedented data set to constrain new physics at higher energies!

Outlook

- Tools are coming online for EFT analyses to more easily make contact with UV theories
- These model-independent tools have the potential to become very useful to future model builders
- In the increasingly likely scenario where the LHC doesn't discover new physics on shell, EFTs are the best bet for parametrizing the results for future utility
- Continuing efforts to further our understanding of EFTs in the LHC context will hopefully allow a complete and consistent exploration of their parameter space

Thank You!