Applications of Effective Field Theory to LHC Data
(Work in Progress)

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Higgs: Only Elementary Scalar

What lies beyond?

- More elementary scalars?
  - Sfermions? Other Higgses?
- Other new particles?
- Supersymmetry?
- Desert?

More and more Precise Measurements
Figure of Merit? Implications?

EQFT: Model Independent Analysis

Fermi Theory of Beta Decay

$$n \rightarrow p \ e^- \ \overline{\nu}_e$$

$$G_F(\bar{p}\,\gamma_\mu\,n)(\bar{e}\,\gamma^\mu\,\nu)$$

$$G_F = \frac{1}{v^2}$$

$$v \approx 250 \ GeV$$

Electroweak Theory

Standard Model
SU(3) x SU(2) x U(1)

If BSM physics
weakly coupled
lies at a higher mass scale

Then corrections describable by operators of higher dimension with coefficients like

$$f\,(1/\Lambda)^n\,.$$

Higher Dimensional Operators

One dim-5; rest dim-6.

Operators composed of $\{W^I_\mu, B_\mu, \varphi, D_\mu\}$

Even if only 1 Family (u, d, $\nu_{e,}$ e), 100's.

Buchmuller & Wyler (1986), reduced to 80, assuming B, L.

Equivalence theorem:

S-matrix unchanged if $\mathcal{O} - \mathcal{O}' = 0$ when EOM satisfied.

$$\mathcal{L}_0 = \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4}\phi^4$$

$$\Box\phi + \lambda\phi^3 = 0$$

Discrete Symmetry: $\phi \to -\phi$.

$$\mathcal{L}' = \frac{1}{\Lambda^2}\Big(a\phi^6 + b\phi^2(\partial\phi)^2 + c(\Box\phi)^2\Big)$$

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EOM: $\Box\phi + \lambda\phi^3 = 0$ $\quad \{\phi^6, \phi^2(\partial\phi)^2, (\Box\phi)^2\}$ X X

$$\mathcal{L}' = \frac{a}{\Lambda^2}\phi^6$$

Which one to choose?

B&W (1986) $\longrightarrow$ 80

Grzadkowski *et. al.* (2010) $\longrightarrow$ 59 (next two slides)

Arzt, ME,Wudka (1994) Patterns of Deviation from SM

Given any extension of SM, calculate coefficients of these operators. Some operators arise from Tree Graphs (TG); others from Loop Graphs (LG). Considered possible vertices in *any* BSM Lagrangian consistent with gauge symmetries.

Scalars, Vectors, & Fermions

X^3 LG		PTG φ^6 and $\varphi^4 D^2$		PTG $\psi^2\varphi^3$	
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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$ LG		$\psi^2 X\varphi$ LG		$\psi^2\varphi^2 D$ PTG	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Four-Fermions

All PTG

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$Q_{ledq}^{(2)}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)(2)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)(2)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)(2)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)(2)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Trees in the Forest

Instead of $\frac{a}{\Lambda^2}$, one-loop down by $\frac{a}{16\pi^2\Lambda^2}$.

$$\frac{1}{16\pi^2} \approx 0.6 \times 10^{-2}$$

Some operators cannot arise from trees in ANY extension of the SM! (Table 1)

e.g., Triple Vector Boson interactions.

Instead of, say, 5% correction, 0.03%.

If greater, then different kind of physics, e.g.,

- Non-decoupling (large Yukawa),
- Strong forces

Caveats

- Are some bases better than others?
  - A LG operator **can** be equivalent to a PTG.
  - Some LG operators **not** equivalent to PTG. (TGB couplings, certain Higgs couplings.)
- S-matrix **independent** of choice of basis. Green's functions are not. Neglecting certain vertices may overconstrain fits.
- Are there too many operators?

Initial Conclusions

- Determined all the equivalence classes for SM dim-6 operators.
  - Some bases are better than others.
  - None of the LG ops in Grzadkowski *et. al.* basis is equivalent to a PTG. (Minimizing # of derivatives a good strategy.)
- Probably not too many operators, (but too many incorrect papers!)
  - custodial SU(2) symmetry well-tested at LEP
  - FCNC operators severely constrained
  - couplings of VB to fermions constrained

Prospects for LHC

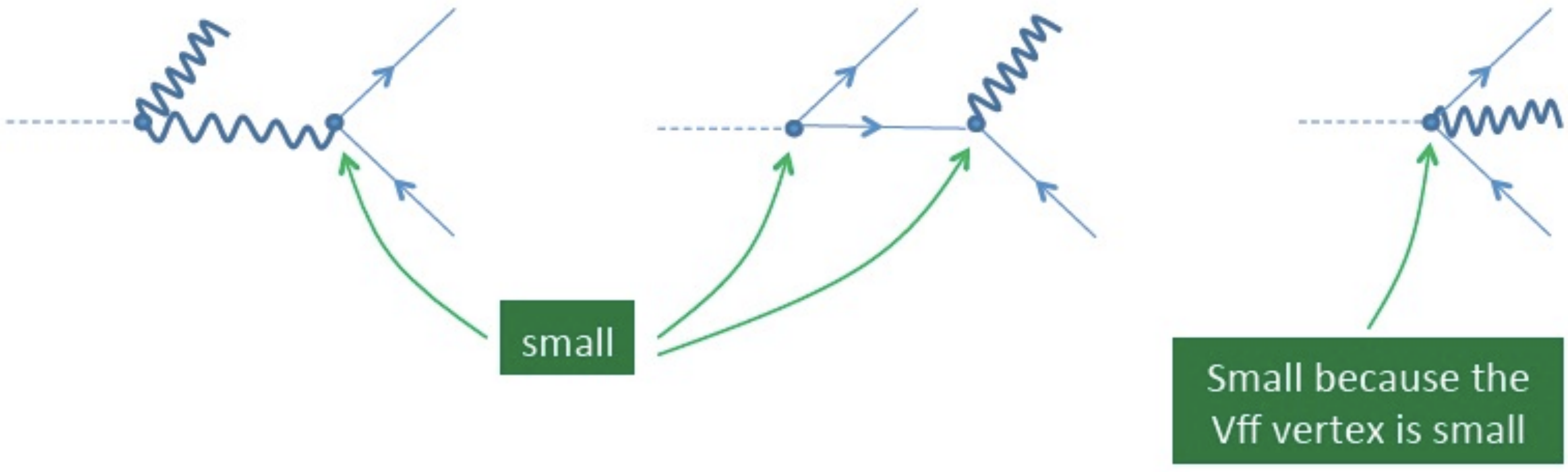
- With more precise data on Higgs production and decays, LHC can constrain BSM physics.
  - Higgs production dominated by gluon fusion (LG in SM). Deviations limited.
  - Higgs decay to 2 photons. (LG in SM.)

Example: $H \to \gamma\gamma$

- W loop: small effects
- Top loop: effective Htt coupling
- Heavy loops: H$\gamma\gamma$ contact term
- H rescaling (small)

$$\Gamma(H \to \gamma\gamma) = \kappa_\gamma^2 \Gamma_{SM}(H \to \gamma\gamma)\,; \qquad \kappa_\gamma^2 = 1 - b_{\partial\phi}\epsilon + 0.31\tilde{b}_\gamma\epsilon + 1.28\frac{\sqrt{2}\,v}{m_t}b_t\epsilon$$

Example: $H \to V f \bar{f} \quad (H \to VV^*)$



$$\mathcal{O}_{\partial\varphi} \equiv (\partial_\mu |\varphi|^2)^2$$

$$\Gamma(H \to VV^*) = \kappa_V^2 \Gamma_{SM}(H \to VV^*), \quad \kappa_V^2 = 1 - b_{\partial\varphi}\epsilon, \quad \left(\epsilon = \frac{v^2}{\Lambda^2}\right)$$

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