Higgs beyond the Standard Model - an EFT approach

– "Strong Interactions in the LHC Era", Bad Honnef 2014 –

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Ludwig-Maximilians-Universität München

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"Complete Electroweak Chiral Lagrangian with a Light Higgs at NLO",
by G. Buchalla, O. Catà & C.K., [hep-ph/1307.5017; Nucl. Phys. B]

"On the Power Counting in Effective Field Theories", by G. Buchalla, O. Catà & C.K., [hep-ph/1312.5624; Phys. Lett. B]

"A Systematic Approach to the SILH Lagrangian", by G. Buchalla, O. Catà & C.K., in preparation

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- Standard Model is confirmed to good accuracy
- Scalar particle found by
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Is it the/a Higgs or something else?

- Experimental precision of Higgs-couplings is $\sim 20\%$

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non-linear realization

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- scalar h and Goldstones form Higgs-doublet ϕ
- theory becomes renormalizable
- NLO is given by dimension 6 terms

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non-linear realization

- include h as scalar singlet
- theory stays non-renormalizable for arbitrary couplings
- NLO will be discussed now

$\rightarrow$ more general ansatz

The non-linear realization

The Goldstone bosons φ are described by:

$$\mathcal{L} = \frac{v^2}{4} \langle \partial_\mu U^\dagger \partial^\mu U \rangle,$$

where

$$U = \exp\left\{ 2i \frac{T_a \varphi_a}{v} \right\}.$$

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This was used in Chiral Perturbation Theory (χPT)

$$U \rightarrow lUr^\dagger, \qquad \text{where } l, r \in SU(2)_{L,R}$$

Effective Lagrangian at leading order

- In the SM we have $SU(2)_L \times U(1)_Y \to U(1)_{em}$.
- The Higgs sector exhibits an additional (custodial) symmetry that enlarges the symmetry to $SU(2)_L \times SU(2)_R \to SU(2)_{V=L+R}$.

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Effective Lagrangian at next-to-leading order

- $\mathcal{L}_{\text{LO}}$ is not renormalizable in the traditional sense.
- It is renormalizable in the modern sense – order by order in an effective expansion:
- The LO counterterms are included at NLO.

$\rightarrow$ The basis of NLO-operators is at least given by the counterterms of the one loop divergences.

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→ The basis of NLO-operators is at least given by the counterterms of the one loop divergences.

- We identify $\frac{f^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$.
- The scale of new physics $f \approx v$
  $\xi = \frac{v^2}{f^2} \approx 1$

Power-counting

$$\mathcal{L}_{\mathrm{LO}} =\frac{1}{2}(\partial_\mu h)(\partial^\mu h) - \mathcal{V}\left(\tfrac{h}{v}\right) + \frac{v^2}{4}\langle (D_\mu U)(D^\mu U^\dagger)\rangle \; a_n\left(\tfrac{h}{v}\right)^n$$
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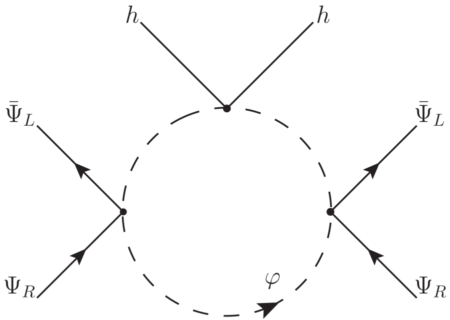

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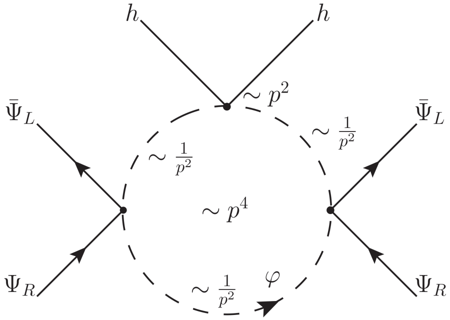

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$$\mathcal{D} \sim p^{2L+2-X-\frac{1}{2}(F_L+F_R)-N_V} \left(\frac{\varphi}{v}\right)^B \left(\frac{h}{v}\right)^H \bar{\Psi}_L^{F_L^1} \Psi_L^{F_L^2} \bar{\Psi}_R^{F_R^1} \Psi_R^{F_R^2} \left(\frac{\mathcal{X}_{\mu\nu}}{v}\right)^X$$

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define chiral dimensions with

$$2L+2 = d_p + X + \tfrac{1}{2}(F_L + F_R) + N_V \equiv \chi$$

$$[\partial_\mu]_\chi = [D_\mu]_\chi = 1 \qquad [g]_\chi = [g']_\chi = 1 \qquad [y]_\chi = 1$$

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Naive dimensional analysis - NDA:

(Georgi, Manohar ['84 Nucl. Phys. B]; Georgi [hep-ph/9207278; Phys. Lett. B])

- Overall factor $f^2\Lambda^2$, f^{-1} for each strongly interacting field, Λ^{-1} to reach dimension 4
- Is consistent with our counting only if internal gauge lines and Yukawa interactions are neglected.
- Gives wrong scaling in some cases, e.g. $F_{\mu\nu}F^{\mu\nu}$.

Application of chiral dimensions

- Classify the NLO ($\chi = 4$) operators
- Control the explicit breaking of symmetries (e.g. custodial or CP):
  If they are broken by weak perturbations (like gauge or Yukawa), their spurions come with chiral dimensions as well.
- Gain additional informations about dimension 6 operators:
  $[g^3 \langle W_\mu^\nu W_\nu^\rho W_\rho^\mu \rangle]_\chi = 6 \rightarrow$ arises at 2 loops

Expansion in ξ

- Reintroduce $\xi = \frac{v^2}{f^2}$ in the operators - link to linear model
- Procedure:
  1. Take an operator of the linear EFT with the dimension d
  2. Translate it to the non-linear EFT with $\phi = \frac{(v+h)}{\sqrt{2}}\ U\binom{0}{1}$
  3. The power of ξ is then given by: $\frac{d-4}{2}$

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- Non-linear EFT gives a more general approach.
- LO and NLO terms linear in ξ give a subset of the dimension 6 operators.
- The doublet structure of ϕ gives well-defined correlations between the NLO coefficients.
- Depending on the size of ξ, $\mathcal{O}(\xi^2)$-effects might be more important than $\mathcal{O}(\frac{\xi}{16\pi^2})$.

Conclusions

- A full set of next-to-leading order operators, including also the CP-odd terms was constructed to all orders in $\xi = \frac{v^2}{f^2}$.
- It was explained in detail what systematics defines next-to-leading order of the effective expansion with the use of a power-counting formula.
- The relation of the power-counting to the concept of chiral dimensions was explained.
- In the limit $\xi \ll 1$ the dimensional counting is recovered and the doublet structure induces correlations among the coefficients.
- Some processes have been analyzed within this framework, e.g. $e^+e^- \to W^+W^-$ [hep-ph/1302.6481; EPJC] and $h \to Z\ell^+\ell^-$ [hep-ph/1310.2574; EPJC].
- Further aspects and applications are currently investigated.

Backup

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Vertex	Contribution to diagram	Number of vertices
h^m	v^{4-m}	ν_m
$\varphi^{2i}h^n$	$p^2 v^{2-2i-n}$	μ_{in}
$\varphi^q \mathcal{X}^2 h^r$	$g^2 v^{2-q-r}$	δ_{qr}
$\varphi^s \mathcal{X} h^t$	pgv^{2-t-s}	τ_{st}
$\bar{\Psi}_{L/R}\Psi_{L/R}\mathcal{X}$	g	$\gamma_{L/R}$
$\bar{\Psi}_{L/R}\Psi_{R/L}h^l\varphi^j$	yv^{1-j-l}	ρ_{jl}
$\mathcal{X}^3$	gp	α
$\mathcal{X}^4$	g^2	ϑ

Table: Vertices of the theory and their contribution to a given Feynman diagram.

$$d_p = 2L + 2 - X - \tfrac{1}{2}(F_L + F_R) - \rho - 2\delta - \tau - 2\nu - \alpha - 2\vartheta - \gamma$$

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Table: Vertices of the theory and their contribution to a given Feynman diagram.

$$d_p = 2L + 2 - X - \tfrac{1}{2}(F_L + F_R) - \rho - 2\delta - \tau - 2\nu - \alpha - 2\vartheta - \gamma$$

The electroweak chiral Lagrangian for $\xi \ll 1$ - the Strongly-Interacting Light Higgs

$$\lim_{\xi \to 0} \mathcal{L}_{\chi EW} \equiv \mathcal{L}_{SM} + \xi \bar{\mathcal{L}}_{SILH} + \mathcal{O}(\xi^2)$$

$$\begin{aligned}\mathcal{L}_{SM} = & \, i\bar{q}\not{D}q + i\bar{l}\not{D}l + i\bar{u}\not{D}u + i\bar{d}\not{D}d + i\bar{e}\not{D}e + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - V_0(h) \\ & - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle + \frac{v^2}{4}\langle L_\mu L^\mu\rangle \left(1 + \frac{h}{v}\right)^2 \\ & - \left[\bar{l}Y_e^{(0)}UP_-\eta + \bar{q}Y_u^{(0)}UP_+r + \bar{q}Y_d^{(0)}UP_-r + \text{h.c.}\right](v+h)\end{aligned}$$

with

$$V_0(h) = -m^2\frac{(v+h)^2}{2} + \lambda\frac{(v+h)^4}{8} = -\frac{\lambda v^4}{4}\left[\left(1+\frac{h}{v}\right)^2 - \frac{1}{2}\left(1+\frac{h}{v}\right)^4\right]$$

The electroweak chiral Lagrangian for $\xi \ll 1$ - the Strongly-Interacting Light Higgs II

$$
\begin{aligned}
\mathcal{L}_{SILH} = {} & V_1(h) + \frac{v^2}{4}\langle L_\mu L^\mu \rangle F_U(h) - \beta_1 v^2 \langle L_\mu \tau_L \rangle^2 \left(1+\frac{h}{v}\right)^2 - \frac{c_{Xh1}}{4} B_{\mu\nu} B^{\mu\nu} \left[1 - \left(1+\frac{h}{v}\right)^2\right] \\
& - \frac{c_{Xh2}}{2}\langle W_{\mu\nu} W^{\mu\nu}\rangle \left[1 - \left(1+\frac{h}{v}\right)^2\right] - \frac{c_{Xh3}}{2}\langle G_{\mu\nu} G^{\mu\nu}\rangle \left[1 - \left(1+\frac{h}{v}\right)^2\right] \\
& - v\left[\bar{l}\mathcal{F}_{Ye}(h, Y_e) U P_- \eta + \bar{q}\mathcal{F}_{Yu}(h, Y_u) U P_+ r + \bar{q}\mathcal{F}_{Yd}(h, Y_d) U P_- r + \text{h.c.}\right] \\
& + c_{XU1} g g' \langle W_{\mu\nu}\tau_L\rangle B^{\mu\nu}\left(1+\frac{h}{v}\right)^2 + c_{\psi V7}(\bar{l}\gamma^\mu l)\langle L_\mu \tau_L\rangle \left(1+\frac{h}{v}\right)^2 + c_{\psi V1}(\bar{q}\gamma^\mu q)\langle L_\mu \tau_L\rangle \left(1+\frac{h}{v}\right)^2 \\
& + c_{\psi V10}(\bar{e}\gamma^\mu e)\langle L_\mu \tau_L\rangle \left(1+\frac{h}{v}\right)^2 + c_{\psi V4}(\bar{u}\gamma^\mu u)\langle L_\mu \tau_L\rangle \left(1+\frac{h}{v}\right)^2 + c_{\psi V5}(\bar{d}\gamma^\mu d)\langle L_\mu \tau_L\rangle \left(1+\frac{h}{v}\right)^2 \\
& + c_{\psi V6}(\bar{u}\gamma^\mu d)\langle P_{21} U^\dagger L_\mu U\rangle \left(1+\frac{h}{v}\right)^2 + \text{h.c.} + c_{\psi Vq}\mathcal{O}_q \left(1+\frac{h}{v}\right)^2 + c_{\psi Vl}\mathcal{O}_l \left(1+\frac{h}{v}\right)^2 + \mathcal{L}_{\Psi^4}
\end{aligned}
$$

The electroweak chiral Lagrangian for $\xi \ll 1$ - the Strongly-Interacting Light Higgs III

where we used

$$\mathcal{O}_q = 2(\bar{q}\tau_L\gamma^\mu q)\langle L_\mu \tau_L\rangle + (\bar{q}UP_{12}U^\dagger\gamma^\mu q)\langle P_{21}U^\dagger L_\mu U\rangle + (\bar{q}UP_{21}U^\dagger\gamma^\mu q)\langle P_{12}U^\dagger L_\mu U\rangle$$
$$\mathcal{O}_l = 2(\bar{l}\tau_L\gamma^\mu l)\langle L_\mu \tau_L\rangle + (\bar{l}UP_{12}U^\dagger\gamma^\mu l)\langle P_{21}U^\dagger L_\mu U\rangle + (\bar{l}UP_{21}U^\dagger\gamma^\mu l)\langle P_{12}U^\dagger L_\mu U\rangle$$

$$V_1(h) = \frac{\lambda v^4}{2}\left[a_1\left(\frac{h}{v}\right)^2 + a_2\left(\frac{h}{v}\right)^3 + \left(\frac{13a_1}{12} + \frac{a_2}{2}\right)\left(\frac{h}{v}\right)^4 + a_1\left(\frac{h}{v}\right)^5 + \frac{a_1}{6}\left(\frac{h}{v}\right)^6\right]$$
$$F_U(h) = -a_1\left(\frac{h}{v}\right) + \frac{6a_2 - 19a_1}{2}\left(\frac{h}{v}\right)^2 + \frac{12a_2 - 34a_1}{3}\left(\frac{h}{v}\right)^3 + \frac{6a_2 - 17a_1}{6}\left(\frac{h}{v}\right)^4$$
$$\mathcal{F}_{Y\Psi}(h, Y_\Psi) = -\left[\frac{a_1}{2}Y_\Psi^{(0)} + 2Y_\Psi^{(1)}\right]\left(\frac{h}{v}\right) - \left[\frac{17a_1 - 6a_2}{4}Y_\Psi^{(0)} + 3Y_\Psi^{(1)}\right]\left(\frac{h}{v}\right)^2 - \left[\frac{17a_1 - 6a_2}{12}Y_\Psi^{(0)} + Y_\Psi^{(1)}\right]\left(\frac{h}{v}\right)^3$$

Operators without fermions

$g^2 UD^2 H$

$\mathcal{O}_{\beta_1} = (g' v)^2 \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \mathcal{F}$

$UD^4 H$

$$\mathcal{O}_{D0,1} = \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \mathcal{F} \qquad \mathcal{O}_{D0,2} = \langle L_\mu L_\nu \rangle \langle L^\mu L^\nu \rangle \mathcal{F}$$

$$\mathcal{O}_{D0,3} = \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \langle \tau_L L^\nu \rangle \mathcal{F} \qquad \mathcal{O}_{D0,4} = \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \langle L_\nu L^\nu \rangle \mathcal{F}$$

$$\mathcal{O}_{D0,5} = \langle \tau_L L_\mu \rangle \langle \tau_L L_\nu \rangle \langle L^\mu L^\nu \rangle \mathcal{F}$$

$$\mathcal{O}_{D1,1} = \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \langle \tau_L L_\nu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F} \qquad \mathcal{O}_{D1,2} = \langle L_\mu L^\mu \rangle \langle \tau_L L_\nu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F}$$

$$\mathcal{O}_{D1,3} = \langle \tau_L L_\mu L_\nu \rangle \langle \tau_L L^\mu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F} \qquad \mathcal{O}_{D1,4} = \langle L_\mu L_\nu \rangle \langle \tau_L L^\mu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F}$$

$$\mathcal{O}_{D2,1} = \langle \tau_L L_\mu \rangle \langle \tau_L L_\nu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \left(\partial^\mu \tfrac{h}{v}\right) \mathcal{F} \qquad \mathcal{O}_{D2,3} = \langle L_\mu L_\nu \rangle \left(\partial^\nu \tfrac{h}{v}\right) \left(\partial^\mu \tfrac{h}{v}\right) \mathcal{F}$$

$$\mathcal{O}_{D2,2} = \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \left(\partial_\nu \tfrac{h}{v}\right) \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F} \qquad \mathcal{O}_{D2,4} = \langle L_\mu L^\mu \rangle \left(\partial_\nu \tfrac{h}{v}\right) \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F}$$

$$\mathcal{O}_{D3,1} = \langle \tau_L L_\mu \rangle \left(\partial^\mu \tfrac{h}{v}\right) \left(\partial_\nu \tfrac{h}{v}\right) \left(\partial^\nu \tfrac{h}{v}\right) \mathcal{F} \qquad \mathcal{O}_{D4,1} = \left(\partial^\mu \tfrac{h}{v}\right) \left(\partial^\nu \tfrac{h}{v}\right) \left(\partial_\mu \tfrac{h}{v}\right) \left(\partial_\nu \tfrac{h}{v}\right) \mathcal{F}$$

$$\mathcal{F}\left(\tfrac{h}{v}\right) = 1 + a_1 \left(\tfrac{h}{v}\right) + a_2 \left(\tfrac{h}{v}\right)^2 + \ldots$$

Operators without fermions II

$gUHXD^2$

$$\mathcal{O}_{XUD1} = g'\langle\tau_L L_\mu L_\nu\rangle B^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD2} = g'\langle\tau_L L_\mu L_\nu\rangle \widetilde{B}^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD3} = g\langle\tau_L L_\mu L_\nu\rangle\langle\tau_L W^{\mu\nu}\rangle\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD4} = g\langle\tau_L L_\mu L_\nu\rangle\langle\tau_L \widetilde{W}^{\mu\nu}\rangle\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD5} = g\langle L_\mu L_\nu W^{\mu\nu}\rangle\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD6} = g\langle L_\mu L_\nu \widetilde{W}^{\mu\nu}\rangle\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XUD7} = g\langle\tau_L L_\mu\rangle\langle L_\nu W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{XUD8} = g\langle\tau_L L_\mu\rangle\langle L_\nu \widetilde{W}^{\mu\nu}\rangle\,\mathcal{F}$$

$g^2 UHX^2$

$$\mathcal{O}_{XU1} = g'^2 B_{\mu\nu} B^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU2} = g'^2 B_{\mu\nu} \widetilde{B}^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU3} = g^2 W_{\mu\nu} W^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU4} = g^2 W_{\mu\nu} \widetilde{W}^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU5} = g_s^2 G_{\mu\nu} G^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU6} = g_s^2 G_{\mu\nu} \widetilde{G}^{\mu\nu}\,\widetilde{\mathcal{F}}$$
$$\mathcal{O}_{XU7} = g^2\langle\tau_L W_{\mu\nu}\rangle\langle\tau_L W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{XU8} = g^2\langle\tau_L W_{\mu\nu}\rangle\langle\tau_L \widetilde{W}^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{XU9} = gg' B_{\mu\nu}\langle\tau_L W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{XU10} = gg' B_{\mu\nu}\langle\tau_L \widetilde{W}^{\mu\nu}\rangle\,\mathcal{F}$$

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \dots$$

$$\widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1\left(\frac{h}{v}\right) + \widetilde{a}_2\left(\frac{h}{v}\right)^2 + \dots$$

Operators with two fermions I

$y^2 UHD\Psi^2$

$$\mathcal{O}_{\Psi V1} = y^2(\bar{q}\gamma^\mu q)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V2} = y^2(\bar{q}\gamma^\mu \tau_L q)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V3} = y^2(\bar{q}\gamma^\mu UP_{12}U^\dagger q)\langle UP_{21}U^\dagger L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V4} = y^2(\bar{u}\gamma^\mu u)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V5} = y^2(\bar{d}\gamma^\mu d)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V6} = y^2(\bar{u}\gamma^\mu d)\langle UP_{21}U^\dagger L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V7} = y^2(\bar{l}\gamma^\mu l)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V8} = y^2(\bar{l}\gamma^\mu \tau_L l)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V9} = y^2(\bar{l}\gamma^\mu UP_{12}U^\dagger l)\langle UP_{21}U^\dagger L_\mu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi V10} = y^2(\bar{e}\gamma^\mu e)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$

$\mathcal{O}_{\Psi V3^\dagger}, \mathcal{O}_{\Psi V6^\dagger}, \mathcal{O}_{\Psi V9^\dagger}$

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \ldots$$

$ygUH\Psi^2 X$

$$\mathcal{O}_{\Psi X1} = yg'\bar{q}\sigma_{\mu\nu}UP_+ rB^{\mu\nu}\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X2} = yg'\bar{q}\sigma_{\mu\nu}UP_- rB^{\mu\nu}\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X3} = yg\bar{q}\sigma_{\mu\nu}UP_+ r\langle\tau_L W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X4} = yg\bar{q}\sigma_{\mu\nu}UP_- r\langle\tau_L W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X5} = yg\bar{q}\sigma_{\mu\nu}UP_{12} r\langle UP_{21}U^\dagger W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X6} = yg\bar{q}\sigma_{\mu\nu}UP_{21} r\langle UP_{12}U^\dagger W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X7} = yg_s\bar{q}\sigma_{\mu\nu}G^{\mu\nu}UP_+ r\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X8} = yg_s\bar{q}\sigma_{\mu\nu}G^{\mu\nu}UP_- r\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X9} = yg'\bar{l}\sigma_{\mu\nu}UP_-\eta B^{\mu\nu}\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X10} = yg\bar{l}\sigma_{\mu\nu}UP_-\eta\langle\tau_L W^{\mu\nu}\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi X11} = yg\bar{l}\sigma_{\mu\nu}UP_{12}\eta\langle UP_{21}U^\dagger W^{\mu\nu}\rangle\,\mathcal{F}$$

Operators with two fermions II

$yUHD^2\Psi^2$ scalar currents

$$\mathcal{O}_{\Psi S1} = y\bar{q}UP_+ r\langle L_\mu L^\mu\rangle\,\mathcal{F} \qquad \mathcal{O}_{\Psi S2} = y\bar{q}UP_- r\langle L_\mu L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S3} = y\bar{q}UP_+ r\langle \tau_L L_\mu\rangle\langle \tau_L L^\mu\rangle\,\mathcal{F} \qquad \mathcal{O}_{\Psi S4} = y\bar{q}UP_- r\langle \tau_L L_\mu\rangle\langle \tau_L L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S5} = y\bar{q}UP_{12} r\langle \tau_L L_\mu\rangle\langle UP_{21}U^\dagger L^\mu\rangle\,\mathcal{F} \qquad y\mathcal{O}_{\Psi S6} = \bar{q}UP_{21} r\langle \tau_L L_\mu\rangle\langle UP_{12}U^\dagger L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S7} = y\bar{l}UP_-\eta\langle L_\mu L^\mu\rangle\,\mathcal{F} \qquad \mathcal{O}_{\Psi S8} = y\bar{l}UP_-\eta\langle \tau_L L_\mu\rangle\langle \tau_L L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S9} = y\bar{l}UP_{12}\eta\langle \tau_L L_\mu\rangle\langle UP_{21}U^\dagger L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S10} = y\bar{q}UP_+ r\langle \tau_L L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F} \qquad \mathcal{O}_{\Psi S11} = y\bar{q}UP_- r\langle \tau_L L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S12} = y\bar{q}UP_{12} r\langle UP_{21}U^\dagger L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F} \qquad \mathcal{O}_{\Psi S13} = y\bar{q}UP_{21} r\langle UP_{12}U^\dagger L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S14} = y\bar{l}UP_-\eta\langle \tau_L L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F} \qquad \mathcal{O}_{\Psi S15} = y\bar{l}UP_{12}\eta\langle UP_{21}U^\dagger L_\mu\rangle\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S16} = y\bar{q}UP_+ r\left(\partial_\mu \tfrac{h}{v}\right)\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F} \qquad \mathcal{O}_{\Psi S17} = y\bar{q}UP_- r\left(\partial_\mu \tfrac{h}{v}\right)\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{O}_{\Psi S18} = y\bar{l}UP_-\eta\left(\partial_\mu \tfrac{h}{v}\right)\left(\partial^\mu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{F}\left(\tfrac{h}{v}\right) = 1 + a_1\left(\tfrac{h}{v}\right) + a_2\left(\tfrac{h}{v}\right)^2 + \ldots$$

Operators with two fermions III

$yUHD^2\Psi^2$ tensor currents

$$\mathcal{O}_{\Psi T1} = y\bar{q}\sigma_{\mu\nu}UP_{+}r\langle\tau_L L_\mu L_\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T2} = y\bar{q}\sigma_{\mu\nu}UP_{-}r\langle\tau_L L_\mu L_\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T3} = y\bar{q}\sigma_{\mu\nu}UP_{12}r\langle\tau_L L^\mu\rangle\langle UP_{21}U^\dagger L^\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T4} = y\bar{q}\sigma_{\mu\nu}UP_{21}r\langle\tau_L L^\mu\rangle\langle UP_{12}U^\dagger L^\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T5} = y\bar{l}\sigma_{\mu\nu}UP_{12}\eta\langle\tau_L L^\mu\rangle\langle UP_{21}U^\dagger L^\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T6} = y\bar{l}\sigma_{\mu\nu}UP_{-}\eta\langle\tau_L L_\mu L_\nu\rangle\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T7} = y\bar{q}\sigma_{\mu\nu}UP_{+}r\langle\tau_L L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T8} = y\bar{q}\sigma_{\mu\nu}UP_{-}r\langle\tau_L L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T9} = y\bar{q}\sigma_{\mu\nu}UP_{21}r\langle UP_{12}U^\dagger L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T10} = y\bar{q}\sigma_{\mu\nu}UP_{12}r\langle UP_{21}U^\dagger L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T11} = y\bar{l}\sigma_{\mu\nu}UP_{-}\eta\langle\tau_L L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$
$$\mathcal{O}_{\Psi T12} = y\bar{l}\sigma_{\mu\nu}UP_{12}\eta\langle UP_{21}U^\dagger L^\mu\rangle\left(\partial^\nu \tfrac{h}{v}\right)\,\mathcal{F}$$

$$\mathcal{F}\left(\tfrac{h}{v}\right) = 1 + a_1\left(\tfrac{h}{v}\right) + a_2\left(\tfrac{h}{v}\right)^2 + \dots$$

Operators with four fermions

$y^2\Psi^4 UH : \bar{L}L\bar{L}L$

$$\begin{aligned}
\mathcal{O}_{LL1} &= y^2(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)\,\mathcal{F}\\
\mathcal{O}_{LL2} &= y^2(\bar{q}\gamma^\mu T^a q)(\bar{q}\gamma_\mu T^a q)\,\mathcal{F}\\
\mathcal{O}_{LL3} &= y^2(\bar{q}\gamma^\mu q)(\bar{l}\gamma_\mu l)\,\mathcal{F}\\
\mathcal{O}_{LL4} &= y^2(\bar{q}\gamma^\mu T^a q)(\bar{l}\gamma_\mu T^a l)\,\mathcal{F}\\
\mathcal{O}_{LL5} &= y^2(\bar{l}\gamma^\mu l)(\bar{l}\gamma_\mu l)\,\mathcal{F}\\
\mathcal{O}_{LL6} &= y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{q}\gamma_\mu \tau_L q)\,\mathcal{F}\\
\mathcal{O}_{LL7} &= y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{q}\gamma_\mu q)\,\mathcal{F}\\
\mathcal{O}_{LL8} &= y^2(\bar{q}_\alpha\gamma^\mu \tau_L q_\beta)(\bar{q}_\beta\gamma_\mu \tau_L q_\alpha)\,\mathcal{F}\\
\mathcal{O}_{LL9} &= y^2(\bar{q}_\alpha\gamma^\mu \tau_L q_\beta)(\bar{q}_\beta\gamma_\mu q_\alpha)\,\mathcal{F}\\
\mathcal{O}_{LL10} &= y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{l}\gamma_\mu \tau_L l)\,\mathcal{F}\\
\mathcal{O}_{LL11} &= y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{l}\gamma_\mu l)\,\mathcal{F}\\
\mathcal{O}_{LL12} &= y^2(\bar{q}\gamma^\mu q)(\bar{l}\gamma_\mu \tau_L l)\,\mathcal{F}\\
\mathcal{O}_{LL13} &= y^2(\bar{q}\gamma^\mu \tau_L l)(\bar{l}\gamma_\mu \tau_L q)\,\mathcal{F}\\
\mathcal{O}_{LL14} &= y^2(\bar{q}\gamma^\mu \tau_L l)(\bar{l}\gamma_\mu q)\,\mathcal{F}\\
\mathcal{O}_{LL15} &= y^2(\bar{l}\gamma^\mu \tau_L l)(\bar{l}\gamma_\mu \tau_L l)\,\mathcal{F}\\
\mathcal{O}_{LL16} &= y^2(\bar{l}\gamma^\mu \tau_L l)(\bar{l}\gamma_\mu l)\,\mathcal{F}
\end{aligned}$$

$y^2\Psi^4 UH : \bar{R}R\bar{R}R$

$$\begin{aligned}
\mathcal{O}_{RR1} &= y^2(\bar{u}\gamma^\mu u)(\bar{u}\gamma_\mu u)\,\mathcal{F}\\
\mathcal{O}_{RR2} &= y^2(\bar{d}\gamma^\mu d)(\bar{d}\gamma_\mu d)\,\mathcal{F}\\
\mathcal{O}_{RR3} &= y^2(\bar{u}\gamma^\mu u)(\bar{d}\gamma_\mu d)\,\mathcal{F}\\
\mathcal{O}_{RR4} &= y^2(\bar{u}\gamma^\mu T^A u)(\bar{d}\gamma_\mu T^A d)\,\mathcal{F}\\
\mathcal{O}_{RR5} &= y^2(\bar{u}\gamma^\mu u)(\bar{e}\gamma_\mu e)\,\mathcal{F}\\
\mathcal{O}_{RR6} &= y^2(\bar{d}\gamma^\mu d)(\bar{e}\gamma_\mu e)\,\mathcal{F}\\
\mathcal{O}_{RR7} &= y^2(\bar{e}\gamma^\mu e)(\bar{e}\gamma_\mu e)\,\mathcal{F}
\end{aligned}$$

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \dots$$

Operators with four fermions II

$y^2\Psi^4 UH : \bar{L}L\bar{R}R$

$$\mathcal{O}_{LR1} = y^2(\bar{q}\gamma^\mu q)(\bar{u}\gamma_\mu u)\,\mathcal{F}$$
$$\mathcal{O}_{LR2} = y^2(\bar{q}\gamma^\mu T^A q)(\bar{u}\gamma_\mu T^A u)\,\mathcal{F}$$
$$\mathcal{O}_{LR3} = y^2(\bar{q}\gamma^\mu q)(\bar{d}\gamma_\mu d)\,\mathcal{F}$$
$$\mathcal{O}_{LR4} = y^2(\bar{q}\gamma^\mu T^A q)(\bar{d}\gamma_\mu T^A d)\,\mathcal{F}$$
$$\mathcal{O}_{LR5} = y^2(\bar{u}\gamma^\mu u)(\bar{l}\gamma_\mu l)\,\mathcal{F}$$
$$\mathcal{O}_{LR6} = y^2(\bar{d}\gamma^\mu d)(\bar{l}\gamma_\mu l)\,\mathcal{F}$$
$$\mathcal{O}_{LR7} = y^2(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)\,\mathcal{F}$$
$$\mathcal{O}_{LR8} = y^2(\bar{l}\gamma^\mu l)(\bar{e}\gamma_\mu e)\,\mathcal{F}$$
$$\mathcal{O}_{LR9} = y^2(\bar{q}\gamma^\mu l)(\bar{e}\gamma_\mu d)\,\mathcal{F}$$
$$\mathcal{O}_{LR10} = y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{u}\gamma_\mu u)\,\mathcal{F}$$
$$\mathcal{O}_{LR11} = y^2(\bar{q}\gamma^\mu T^A \tau_L q)(\bar{u}\gamma_\mu T^A u)\,\mathcal{F}$$
$$\mathcal{O}_{LR12} = y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{d}\gamma_\mu d)\,\mathcal{F}$$
$$\mathcal{O}_{LR13} = y^2(\bar{q}\gamma^\mu T^A \tau_L q)(\bar{d}\gamma_\mu T^A d)\,\mathcal{F}$$
$$\mathcal{O}_{LR14} = y^2(\bar{l}\gamma^\mu \tau_L l)(\bar{u}\gamma_\mu u)\,\mathcal{F}$$
$$\mathcal{O}_{LR15} = y^2(\bar{l}\gamma^\mu \tau_L l)(\bar{d}\gamma_\mu d)\,\mathcal{F}$$
$$\mathcal{O}_{LR16} = y^2(\bar{q}\gamma^\mu \tau_L q)(\bar{e}\gamma_\mu e)\,\mathcal{F}$$
$$\mathcal{O}_{LR17} = y^2(\bar{l}\gamma^\mu \tau_L l)(\bar{e}\gamma_\mu e)\,\mathcal{F}$$
$$\mathcal{O}_{LR18} = y^2(\bar{q}\gamma^\mu \tau_L l)(\bar{e}\gamma_\mu d)\,\mathcal{F}$$

$y^2\Psi^4 UH : \bar{L}R\bar{L}R$

$$\mathcal{O}_{ST1} = y^2\epsilon_{ij}(\bar{q}^i u)(\bar{q}^j d)\,\mathcal{F}$$
$$\mathcal{O}_{ST2} = y^2\epsilon_{ij}(\bar{q}^i T^A u)(\bar{q}^j T^A d)\,\mathcal{F}$$
$$\mathcal{O}_{ST3} = y^2\epsilon_{ij}(\bar{q}^i u)(\bar{l}^j e)\,\mathcal{F}$$
$$\mathcal{O}_{ST4} = y^2\epsilon_{ij}(\bar{q}^i \sigma^{\mu\nu} u)(\bar{l}^j \sigma_{\mu\nu} e)\,\mathcal{F}$$
$$\mathcal{O}_{ST5} = y^2(\bar{q}UP_+ r)(\bar{q}UP_- r)\,\mathcal{F}$$
$$\mathcal{O}_{ST6} = y^2(\bar{q}UP_{21} r)(\bar{q}UP_{12} r)\,\mathcal{F}$$
$$\mathcal{O}_{ST7} = y^2(\bar{q}UP_+ T^A r)(\bar{q}UP_- T^A r)\,\mathcal{F}$$
$$\mathcal{O}_{ST8} = y^2(\bar{q}UP_{21} T^A r)(\bar{q}UP_{12} T^A r)\,\mathcal{F}$$
$$\mathcal{O}_{ST9} = y^2(\bar{q}UP_+ r)(\bar{l}UP_- \eta)\,\mathcal{F}$$
$$\mathcal{O}_{ST10} = y^2(\bar{q}UP_{21} r)(\bar{l}UP_{12} \eta)\,\mathcal{F}$$
$$\mathcal{O}_{ST11} = y^2(\bar{q}\sigma^{\mu\nu} UP_+ r)(\bar{l}\sigma_{\mu\nu} UP_- \eta)\,\mathcal{F}$$
$$\mathcal{O}_{ST12} = y^2(\bar{q}\sigma^{\mu\nu} UP_{21} r)(\bar{l}\sigma_{\mu\nu} UP_{12} \eta)\,\mathcal{F}$$

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \ldots$$

Operators with four fermions III

$y^2\Psi^4 UH : \bar{L}R\bar{L}R$

$$
\begin{aligned}
\mathcal{O}_{FY1} &= y^2(\bar{q}UP_+ r)(\bar{q}UP_+ r)\,\mathcal{F} \\
\mathcal{O}_{FY2} &= y^2(\bar{q}UP_+ T^A r)(\bar{q}UP_+ T^A r)\,\mathcal{F} \\
\mathcal{O}_{FY3} &= y^2(\bar{q}UP_- r)(\bar{q}UP_- r)\,\mathcal{F} \\
\mathcal{O}_{FY4} &= y^2(\bar{q}UP_- T^A r)(\bar{q}UP_- T^A r)\,\mathcal{F} \\
\mathcal{O}_{FY5} &= y^2(\bar{q}UP_- r)(\bar{r}P_+ U^\dagger q)\,\mathcal{F} \\
\mathcal{O}_{FY6} &= y^2(\bar{q}UP_- T^A r)(\bar{r}P_+ U^\dagger T^A q)\,\mathcal{F} \\
\mathcal{O}_{FY7} &= y^2(\bar{q}UP_- r)(\bar{l}UP_- \eta)\,\mathcal{F} \\
\mathcal{O}_{FY8} &= y^2(\bar{q}\sigma^{\mu\nu} UP_- r)(\bar{l}\sigma_{\mu\nu} UP_- \eta)\,\mathcal{F} \\
\mathcal{O}_{FY9} &= y^2(\bar{l}UP_- \eta)(\bar{r}P_+ U^\dagger q)\,\mathcal{F} \\
\mathcal{O}_{FY10} &= y^2(\bar{l}UP_- \eta)(\bar{l}UP_- \eta)\,\mathcal{F} \\
\mathcal{O}_{FY11} &= y^2(\bar{l}UP_- r)(\bar{r}P_+ U^\dagger l)\,\mathcal{F}
\end{aligned}
$$

$$
\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \ldots
$$

The covariant derivative of U reads:

$$
D_\mu U = \partial_\mu U + igW_\mu U - ig' B_\mu U T_3
$$