The renormalisation of Higgs effective field theory

Rodrigo Alonso

In collaboration with Kirill Kanshin y Sara Saa

CERN

Universität Zürich Oct 17/2017

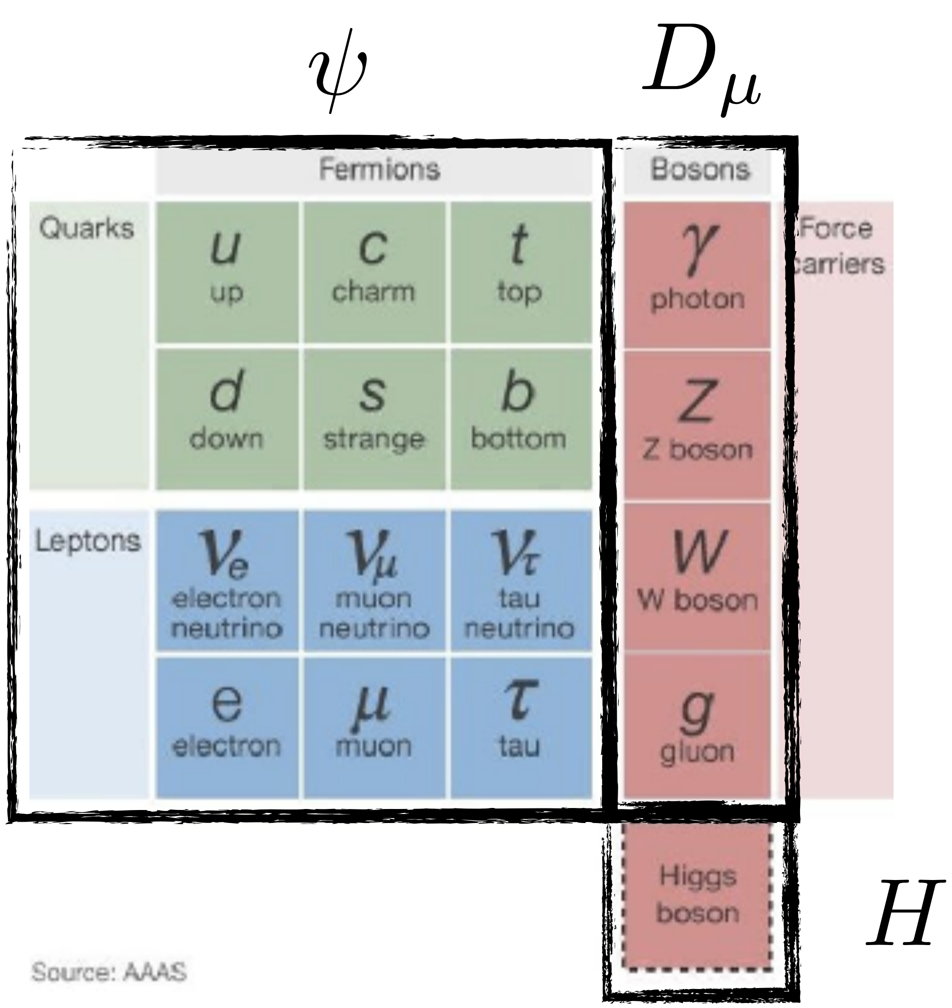
Outline

- The song of praise for effective field theory
- Relevance today; the Standard Model generalized
- Progress in EFT
- Application; Higgs effective field theory

Song of praise for EFT

- Embodies the stepwise approach of physics
- Computationally convenient even if we know the UV
- The UV could be known but non-perturbative and the degrees of freedom different
- If UV is not known it help us keep an ‘open mind’

Relevance today: the Standard Model



$$i\bar{\psi}(\not{D} - \mathcal{M}(H)\psi + D_\mu H^\dagger D^\mu H$$
$$- \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - V(H^\dagger H)$$

$$\mathcal{M} = Y H P_R + \mathrm{h.c.}$$

$$A_{\mu\nu} = [D_\mu, D_\nu]$$

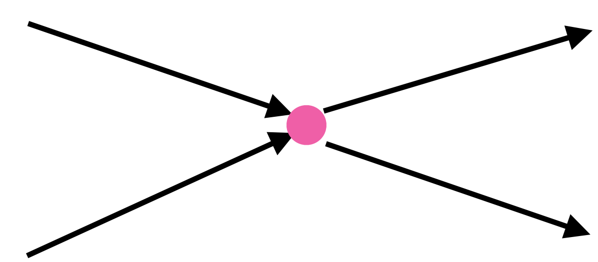
(perturbative) Unitarity

the Standard Model generalized

$$i\bar{\psi}(\not{D} - \mathcal{M}(H)\psi + D_\mu H^\dagger D^\mu H$$
$$- \frac{1}{4}A_{\mu\nu}A^{\mu\nu} - V(H^\dagger H)$$

$$+ \sum \frac{C}{\Lambda^2}\mathcal{O} + \text{h.c.}$$

$$\mathcal{O}_{\text{e.g.}} = \bar{q}\gamma_\rho q\,\bar{\mu}\gamma^\rho\mu$$



$$A^3_{\mu\nu}\,,\ A^2_{\mu\nu}H^2\,,\ A_{\mu\nu}\psi^2 H\,,\ H^3\psi^2\,,\ H^6\,,\ H^4D^2\,,\ DH^2\psi^2\,,\ \psi^4$$

The EFT Times

- Functional Methods
- Helicity sum rules and Holomorphy
- Operator counting
- Scalar field space geometry

Functional methods

Based on the path integral formulation

$$Z[J] \equiv e^{iW[J]} = \int D\Phi \, \exp\left[i \left(S[\Phi] + \int dx \; J\Phi \right) \right] .$$

$$\Gamma[\Phi_0] = W[J] - \Phi_0 J, \qquad \Phi_0 \equiv \frac{\delta W}{\delta J} \,,$$

$$\frac{\delta S[\Phi_0]}{\delta \Phi} = J \,.$$

Functional methods

$$\int \mathcal{D}\Phi e^{iS[\Phi_0]+i\Phi^2\delta^2 S[\Phi_0]/2+\mathcal{O}(\Phi^3)} = \frac{\mathcal{N}e^{iS[\Phi_0]}}{\sqrt{\det(-\delta^2 S[\Phi_0])}}$$

$$S_{1-\mathrm{loop}} = S_0 + \frac{i}{2}\log\left[\det\left(-\frac{\delta^2 S[\Phi_0]}{\delta^2\Phi}\right)\right]$$

$$= S_0 + \frac{i}{2}\mathrm{Tr}\left[\log\left(-\frac{\delta^2 S[\Phi_0]}{\delta^2\Phi}\right)\right]$$

Functional Methods: 1st Quantum Correction

$$S = \mathrm{Tr}(\mathcal{L})$$

$$\mathrm{Tr}[\mathcal{O}(\mathbf{x},\,\mathbf{p})] = \int \frac{d^4p}{(2\pi)^4} \langle p|\mathcal{O}(\mathbf{x},\,\mathbf{p})|p\rangle$$

$$= \int \frac{d^4p}{(2\pi)^4} \int d^4x \langle p|x\rangle\langle x|\mathcal{O}(\mathbf{x},\,\mathbf{p})|p\rangle$$

$$= \int d^4x \int \frac{d^4p}{(2\pi)^4} e^{ipx}\mathcal{O}(x,\,i\partial_x)e^{-ipx}$$

Covariant Derivative Expansion

[Gaillard '85, Cheyette,86] [Henning, Lu & Murayama; '15]

$$e^{ipx}\mathcal{O}(x, i\partial_x)e^{-ipx} = \mathcal{O}(x, i\partial_x + p)$$

$$e^{ipx}\mathcal{O}(x, iD)e^{-ipx} = \mathcal{O}(x, iD + p)$$

For example a scalar with gauge interaction and a potential

$$\int d^4x \int \frac{d^4p}{(2\pi)^4} \log((D - ip)^2 + m^2 + \partial^2 V)$$

$$\int d^4x \int \frac{d^4p}{(2\pi)^4} \log\left((m^2 - p^2)\left(1 - \frac{D^2 - 2ipD + \partial^2 V}{p^2 - m^2}\right)\right)$$

Calculate once and for all

[Henning, Lu & Murayama; '15]

$$
\begin{aligned}
\Delta\mathcal{L}_{\text{eff,1-loop}} = \frac{c_s}{(4\pi)^2}\,\text{tr}\Bigg\{ \\
&+ m^4\left[-\frac{1}{2}\left(\log\frac{m^2}{\mu^2}-\frac{3}{2}\right)\right] \\
&+ m^2\left[-\left(\log\frac{m^2}{\mu^2}-1\right)U\right] \\
&+ m^0\left[-\frac{1}{12}\left(\log\frac{m^2}{\mu^2}-1\right)G'^2_{\mu\nu}-\frac{1}{2}\log\frac{m^2}{\mu^2}U^2\right] \\
&+ \frac{1}{m^2}\left[-\frac{1}{60}(P_\mu G'_{\mu\nu})^2-\frac{1}{90}G'_{\mu\nu}G'_{\nu\sigma}G'_{\sigma\mu}-\frac{1}{12}(P_\mu U)^2-\frac{1}{6}U^3-\frac{1}{12}UG'_{\mu\nu}G'_{\mu\nu}\right] \\
&+ \frac{1}{m^4}\left[\frac{1}{24}U^4+\frac{1}{12}U(P_\mu U)^2+\frac{1}{120}(P^2U)^2+\frac{1}{24}\left(U^2G'_{\mu\nu}G'_{\mu\nu}\right)\right. \\
&\qquad \left.-\frac{1}{120}[(P_\mu U),(P_\nu U)]G'_{\mu\nu}-\frac{1}{120}[U[U,G'_{\mu\nu}]]G'_{\mu\nu}\right] \\
&+ \frac{1}{m^6}\left[-\frac{1}{60}U^5-\frac{1}{20}U^2(P_\mu U)^2-\frac{1}{30}(UP_\mu U)^2\right] \\
&+ \frac{1}{m^8}\left[\frac{1}{120}U^6\right]\Bigg\}.
\end{aligned}
\tag{2.54}
$$

Holomorphy and helicity

	helicity
$F^{+}_{\mu\nu} = \frac{1}{2}\left(F_{\mu\nu} - iF_{\mu\nu}\right)$	$+1$
$F^{-}_{\mu\nu} = \frac{1}{2}\left(F_{\mu\nu} + iF_{\mu\nu}\right)$	-1
$\psi_L\,(L),\ \bar{\psi}_R\,(\bar{R})$	$-1/2$
$\psi_R\,(R),\ \bar{\psi}_L\,(\bar{L})$	$+1/2$

Holomorphy and helicity

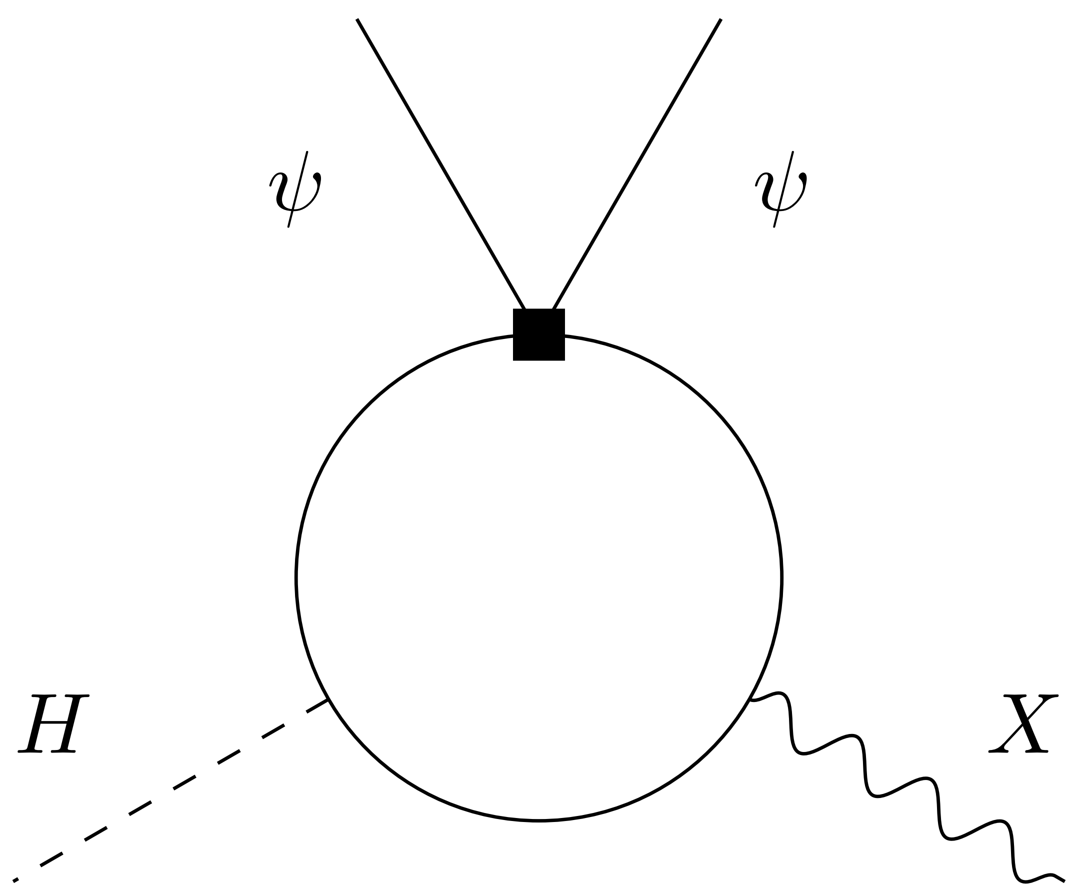
	helicity
$F^{+}_{\mu\nu} = \frac{1}{2}\left(F_{\mu\nu} - i F_{\mu\nu}\right)$	$+1$
$F^{-}_{\mu\nu} = \frac{1}{2}\left(F_{\mu\nu} + i F_{\mu\nu}\right)$	-1
$\psi_L\,(L),\ \bar{\psi}_R\,(\bar{R})$	$-1/2$
$\psi_R\,(R),\ \bar{\psi}_L\,(\bar{L})$	$+1/2$

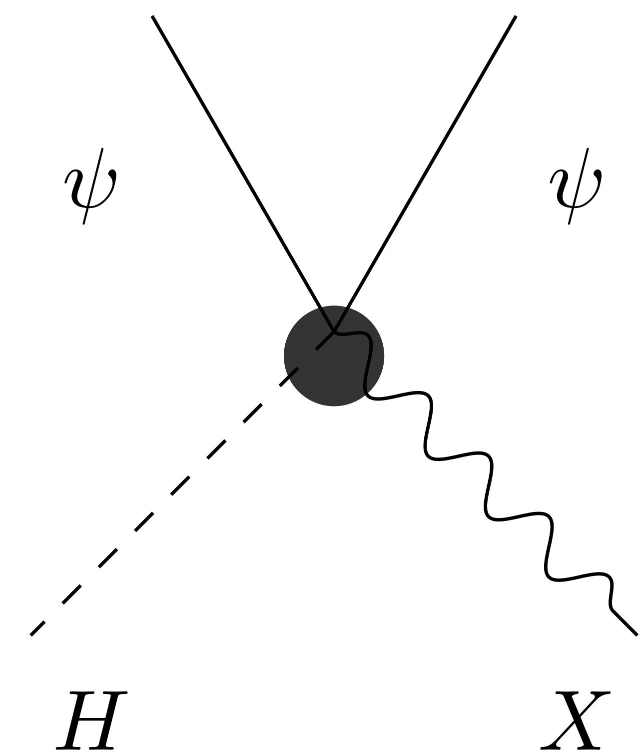
IN SM EFT:

$$\mathcal{O}_{\rm hol} \subset \left\{ {F^{+}_{\mu\nu}}^{3},\ {F^{+}_{\mu\nu}}^{2} H^2,\ \left(\overline{L}\sigma^{\mu\nu}R\right) F^{+} H,\ (\overline{L}R)(\overline{L}R) \right\}$$

$$\mathcal{O}_{\rm h\not{o}l} \subset \left\{ H^6,\ H^4 D^2,\ \psi^2 H^2 D,\ (\overline{L}R)(\overline{R}L),\ JJ \right\} \qquad \psi^2 H^3,$$

RGE in SM EFT





$$C_{\psi^2 XH}^{1-loop} = C_{\psi^2 XH}^{tree} + \frac{1}{16\pi^2} C_{\psi^4}$$

Holomorphy ~respected by RGE

[RA, Manohar, Jenkins; '14]

$$\frac{dC_{\rm hol}}{d\mu} = \frac{1}{16\pi^2} C_{\rm hol}$$

$$\frac{dC_{\rm h\not{o}l}}{d\mu} = \frac{1}{16\pi^2} C_{\rm h\not{o}l}$$

But not

$C_{\rm h\not{o}l} \quad C^\dagger_{\rm hol}$

which would 'break' holomorphy

Helicity sum rules and holomorphy

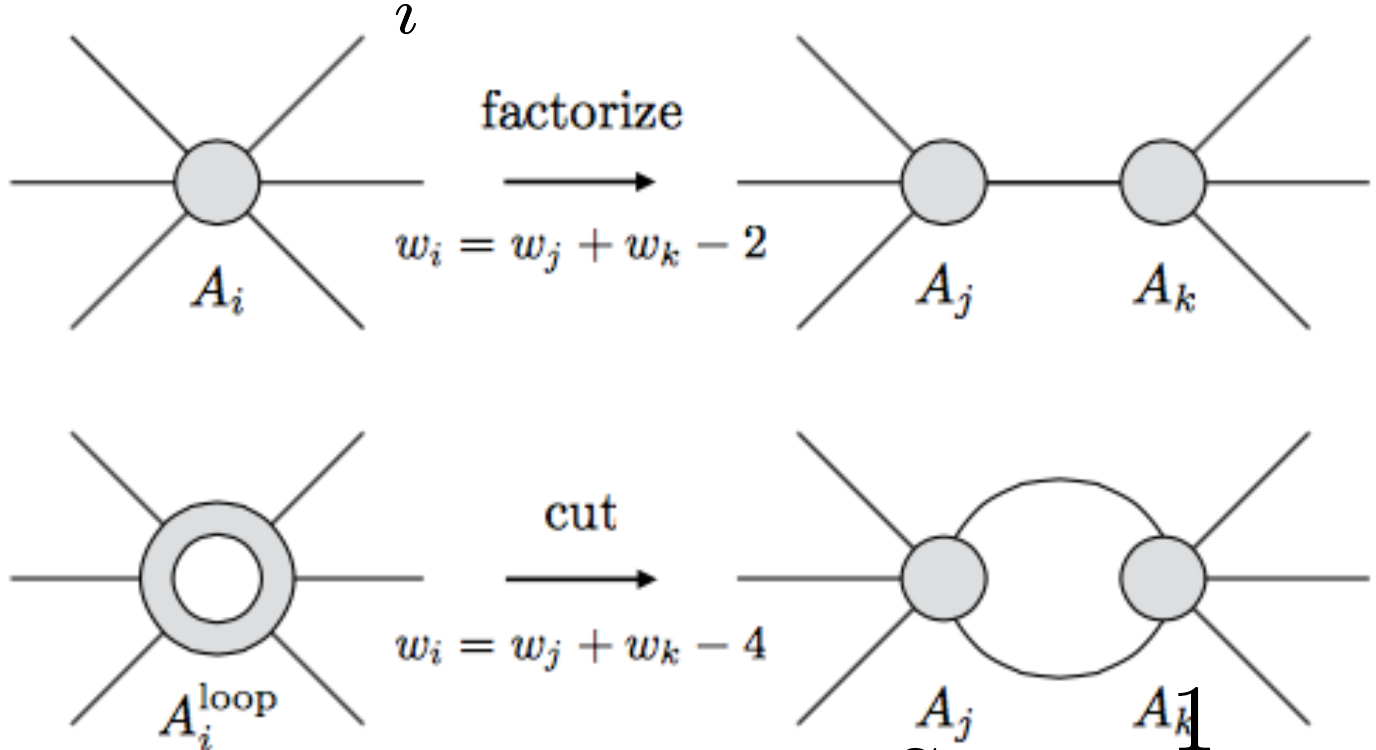
	$(X^+)^3$	$(X^+)^2H^2$	ψ^2X^+H	$(\bar{L}R)(\bar{L}R)$	$(\bar{L}R)(\bar{R}L)$	JJ	ψ^2H^3	H^6	H^4D^2	ψ^2H^2D
$(X^+)^3$	$\to \mathfrak{h}$	$\to 0$	0	0	0	0	0	0	0	0
$(X^+)^2H^2$	$\to \mathfrak{h}$	$\to \mathfrak{h}$	$\to \mathfrak{h}$	0	0	$\nexists$	0	0	$\to 0$	$\to 0$
ψ^2X^+H	$\to \mathfrak{h}$	$\to \mathfrak{h}$	$\to \mathfrak{h}$	$\mathfrak{h}_F$	$\to 0$	$\to 0$	$\to 0$	0	$\nexists$	$\to 0$
$(\bar{L}R)(\bar{L}R)$	$\to 0$	$\nexists$	$\mathfrak{h}_F$	$\mathfrak{h}_F$	$Y_u^\dagger Y_{e,d}^\dagger$	$Y_u^\dagger Y_{e,d}^\dagger$	$\nexists$	$\nexists$	$\nexists$	$\to 0$
$(\bar{L}R)(\bar{R}L)$	$\to 0$	$\nexists$	$\to 0$	$Y_uY_d,\ Y_u^\dagger Y_e^\dagger$	$\mathfrak{h}_F$	$*$	$\nexists$	$\nexists$	$\nexists$	$\to 0$
JJ	$\to 0$	$\nexists$	$\to 0$	$Y_uY_{e,d}$	$*$	$*$	$\nexists$	$\nexists$	$\nexists$	$*$
ψ^2H^3	$\to 0$	$\to \mathfrak{h}$	$\to \mathfrak{h}$	$\to \mathfrak{h}$	$*$	$*$	$*$	$\nexists$	$*$	$*$
H^6	$\to 0$	$\boxed{\star}$	$\nexists$	$\nexists$	$\nexists$	$\nexists$	$*$	$*$	$*$	$*$
H^4D^2	$\to 0$	$\to 0$	$\to 0$	$\nexists$	$\nexists$	$\nexists$	$\to 0$	$\nexists$	$*$	$*$
ψ^2H^2D	$\to 0$	$\to 0$	$\to 0$	$\to 0$	$\to 0$	$*$	$\to 0$	$\nexists$	$*$	$*$

[RA, Manohar, Jenkins; '14]

Helicity sum rules

[Cheung & Shen; '15]

$$w(\mathcal{O}) = n - \sum_i^n h_i\,, \qquad \bar{w}(\mathcal{O}) = n + \sum_i^n h_i$$



SM $\qquad \dfrac{1}{\Lambda^2}$

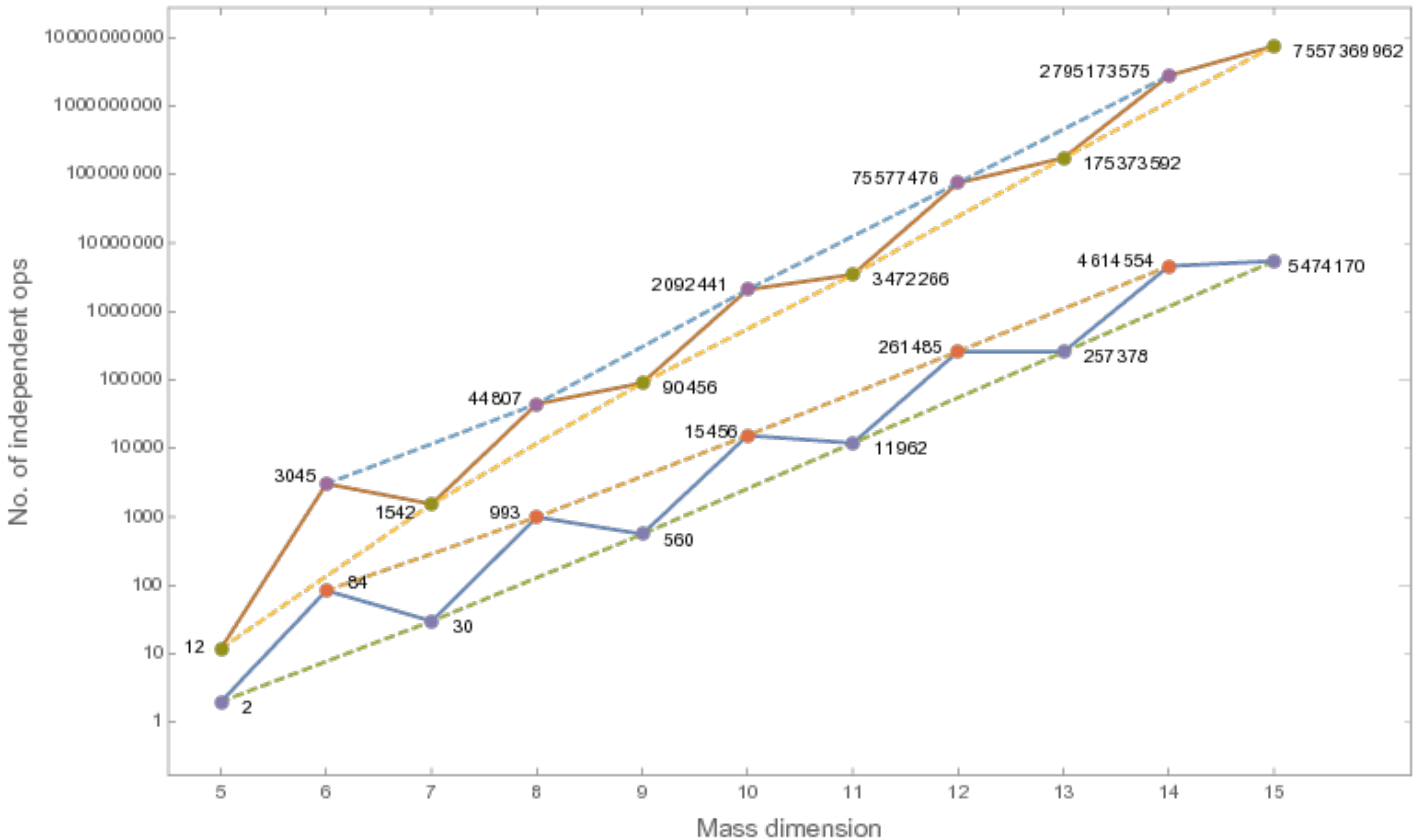
$w_{\text{SM}} \geq 4$ *

$$w_i^{(6)} = w_{\text{SM}} + w_j^{(6)} - 4$$

At one loop helicity weight can only grow

Operator counting

Based on conformal group and Hilbert series

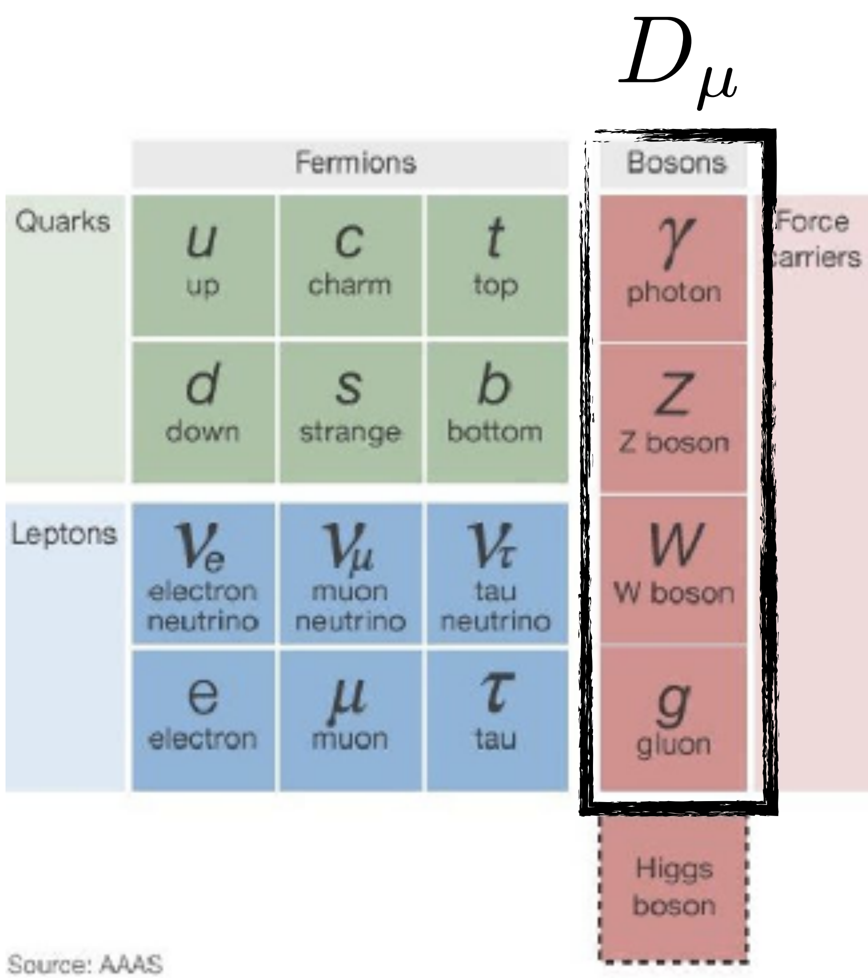


[Henning, Lu, Melia & Murayama; ’15]

Geometry for scalars

Pions live in

$$\text{Manifold} = SU(2)_L \times SU(2)_R / SU(2)_V$$



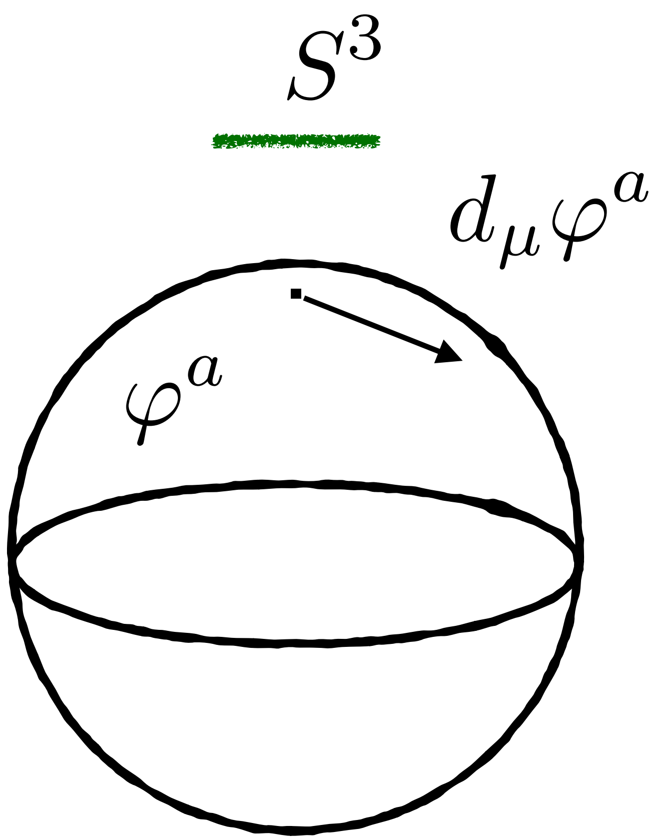
SM Goldstones live in

$$\text{Manifold} =$$
$$SU(2)_L \times U(1)_Y / U(1)_{\text{em}}$$

If we impose custodial

$$\text{Manifold} =$$
$$SO(4)/SU(2)$$

The Goldstone bosons of the SM



Metric

$$G_{ab}$$

Custodial

$$\text{Manifold} = $$
$$SO(4)/SU(2) \quad \sim S^3$$

Symmetries are the given by the killing vectors

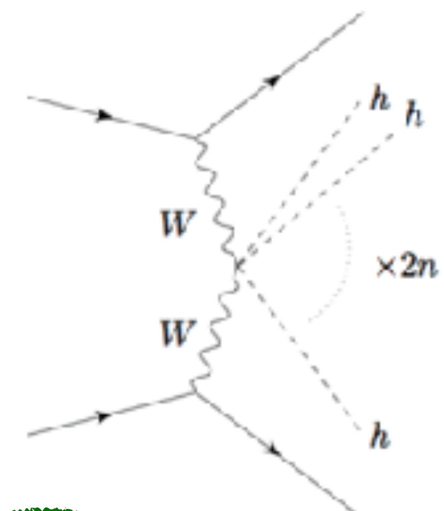
$$t_A^k \frac{\partial G_{ij}}{\partial \phi^k} + G_{kj} \frac{\partial t_A^k}{\partial \phi^i} + G_{ik} \frac{\partial t_A^k}{\partial \phi^j} = 0\,.$$

$$d_\mu \varphi^a = \partial_\mu \varphi^a + A_\mu^B t_B^a(\varphi)$$

Factoring in the Higgs

$$\frac{1}{2} g_{ab}(\varphi) d_\mu \varphi^a d^\mu \varphi^b - \frac{1}{4} A_{\mu\nu} A^{\mu\nu}$$
$$+ \bar{\psi} \left(i \not{D} - \mathcal{U}(\varphi)\, v Y P_R - Y^\dagger v \mathcal{U}^\dagger(\varphi) P_L \right) \psi$$

h, a singlet under $SU(2)_L \times U(1)_Y$



$$\frac{1}{2} \partial_\mu h \partial^\mu h + \frac{1}{2} F(h)^2 d\varphi^2 - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - V(h)$$
$$+ \bar{\psi} \left(i \not{D} - \mathcal{U}(\varphi)\, \mathcal{Y}(h) P_R - \mathcal{Y}^\dagger(h) \mathcal{U}^\dagger(\varphi) P_L \right) \psi$$

$$[F_{\rm SM}(h) = v + h\,,\ \mathcal{Y}_{\rm SM} = (v+h) Y]$$

The Curvature and Physical Observables

Ricci scalar

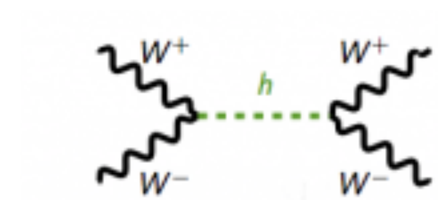
$$R(h) = \left[1 - (F'(h))^2\right] \frac{6}{F(h)^2} - \frac{6F''(h)}{F(h)}.$$

[RA, Manohar, Jenkins; '15]

E.g. in an HEFT longitudinal boson scattering is not fully unitarized:

[Barbieri, Bellazzini, Rychkov & Varagnolo; '07]

$$\mathcal{A}(W_L W_L \to W_L W_L) = \frac{s+t}{v^2}\mathfrak{R}(0)\,,$$



Which means new resonances are required at (NDA):

$$4\pi v/\sqrt{\mathfrak{R}}$$

Geometry of scalars @ 1-loop

What are the peculiarities of living in a curved space?

[Honerkamp; ’72]
[Tataru; ’72]

Higgsless

[Appelquist & Bernard; ’80]

With the Higgs singlet

[Gavela, Kanshin, Machado, Saa; ’15]

Appearance of non-invariant terms!!!
that vanish on shell

HEFT @ 1 loop

The reason is not treating the action covariantly

[Honerkamp; '72]

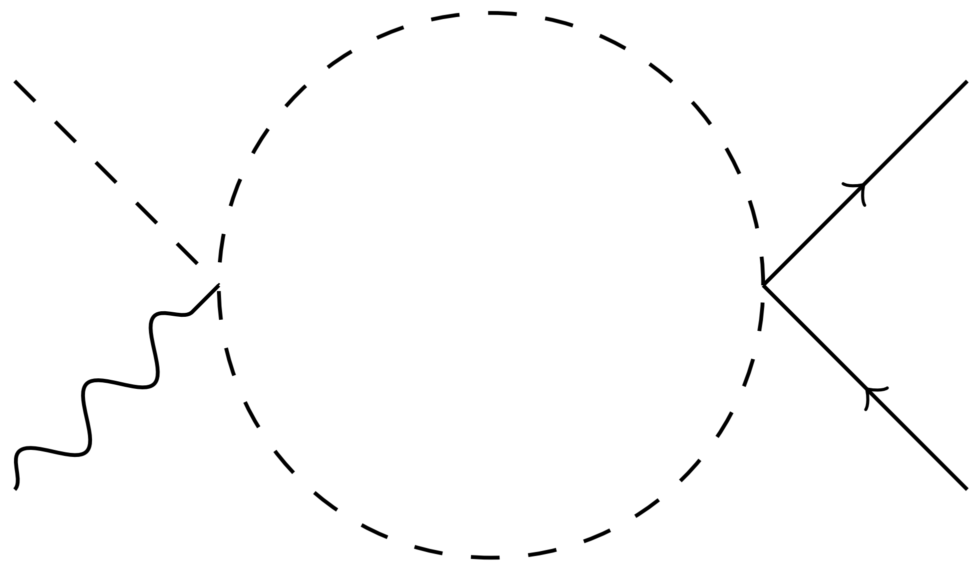
$$\nabla_b \nabla_a S = \frac{\delta^2 S}{\delta\phi^b \delta\phi^a} - \Gamma^c_{ab} \frac{\delta S}{\delta\phi^c} \,.$$

If we drop the connection:

$$\delta\mathcal{L} = \frac{1}{32\pi^2\epsilon}\left(X^{ij}\Gamma^k_{ij}\frac{\delta S}{\delta\phi^k} + \frac{1}{2}\Gamma^k_{ij}\frac{\delta S}{\delta\phi^k}\Gamma^{lij}\frac{\delta S}{\delta\phi^l}\right)$$

[RA, Jenkins, Manohar; '15]

The complete RGE

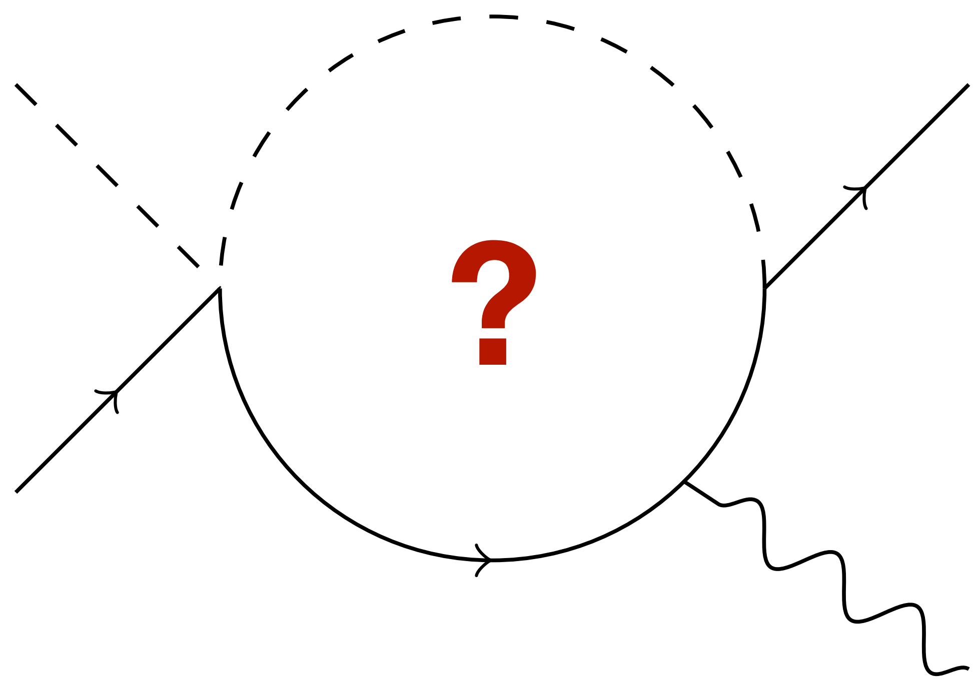


[Gavela, Kanshin, Machado & Saa; '15]

[Guo,Ruiz-Femenia & Sanz-Cillero;'15]

[RA, Jenkins, Manohar; '15]

How about the full RGE?
It would imply computing:



Completing squares

[Henning, Lu & Murayama; '16]

$$\delta^2 S = -\frac{1}{2}\delta\phi\left\{D_\mu D^\mu + R d\phi^2 + \dots\right\}\delta\phi + \delta\bar{\psi}\left\{i\not{D} - \mathcal{Y}\right\}\delta\psi$$

$$-\delta\bar{\psi}(\nabla_{\delta\phi}\mathcal{Y} + \delta\not{A})\psi$$

$$\delta\psi \to \delta\psi + \frac{1}{i\not{D} - \mathcal{Y}}\left(\nabla_{\delta\phi}\mathcal{Y} + g\delta\not{A}\right)\psi$$

$$\delta^2 S = -\frac{1}{2}\delta\phi\left\{\Pi_\phi + \bar{\psi}\nabla\mathcal{Y}\frac{1}{i\not{D} - \mathcal{Y}}\nabla\mathcal{Y}\psi + h.c.\right\}\delta\phi + \dots$$

From tree level

$$
\begin{aligned}
\mathcal{L} =& \frac{G_{ij}}{2} d^\mu \phi^i d_\mu \phi^j - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(\phi) \\
&+ \bar{\psi} \left(i \not{D} - \mathcal{M}(\phi) \right) \psi
\end{aligned}
$$

To the 1-loop UV sensitive

$$\int d^4x \frac{\mathcal{O}}{16\pi^2(4-\mathrm{d})}$$

$$\mathcal{O} = \bar{\psi}T\left(2i\not{D} - 8\mathcal{M}\right)T\psi + \frac{11}{12}\mathbb{C}_{\mathcal{G}}F_{\mu\nu}F^{\mu\nu}$$

$$+ \frac{1}{2}\mathrm{Tr}\Big[\left(Rd\phi^2 + \nabla^2(V + \bar{\psi}\mathcal{M}\psi) - t\cdot t\right)^2 + \frac{1}{6}[D,D]^2 + 2(t\cdot t)^2\Big]$$

$$+ \bar{\psi}\nabla\mathcal{M}\left(i\not{D} + 2\mathcal{M}^\dagger\right)\nabla\mathcal{M}\psi - \left(i2\bar{\psi}t\nabla\mathcal{M}T\psi + h.c.\right)$$

$$- 2d_\mu\phi\nabla_i t d^\mu\phi\nabla^i t - \frac{1}{2}\mathrm{Tr}\left\{\left(\mathcal{M}^\dagger\mathcal{M} - i(\not{D}\mathcal{M})\right)^2 - \frac{1}{6}[D,D]^2\right\}$$

Higgs-dependent renormalisation

$$h \to h - \frac{1_\epsilon}{32\pi^2} \int dh \left[\frac{(g')^2 + 3g^2}{4} \left(F'' F - 2(F')^2 \right) + 2\mathrm{Tr}(\mathcal{Y}' \mathcal{Y}^{\dagger\prime}) - 3 \frac{V' F'' F'}{F^2} \right]$$

$$\psi_L \to \psi_L - \frac{1_\epsilon}{32\pi^2} \left(\mathbb{C}^{\mathcal{G}}_{\psi_L} + \frac{\mathcal{U}}{2} \left(\mathcal{Y}' \mathcal{Y}'^\dagger - \frac{\mathcal{Y}\mathcal{Y}^\dagger}{F^2} \right) \mathcal{U}^\dagger + \frac{\mathcal{Y}\mathcal{Y}^\dagger + \tilde{\mathcal{Y}}\tilde{\mathcal{Y}}^\dagger}{F^2} \right) \psi_L$$

LO Renormalization Group Evolution

$$\mu\frac{\partial F(h,\mu)^2}{\partial\mu} - \frac{FF'}{16\pi^2}\int\left[\frac{g_Y^2+3g^2}{2}\left(F''F-2(F')^2\right)+4\mathrm{Tr}(\mathcal{Y}'\mathcal{Y}'^\dagger)-6\frac{V'F''F'}{F^2}\right]dh$$
$$+\frac{2}{16\pi^2}\left[2\mathrm{Tr}(\mathcal{Y}\mathcal{Y}^\dagger)-\frac{g_Y^2+3g^2}{2}F^2+F^2(F'^2-1)\left(\frac{g_Y^2}{4}-2\frac{V'F'}{F^3}\right)-FF''V''\right]=0$$

$$\mu\frac{\partial V(h,\mu)}{\partial\mu} - \frac{V'}{32\pi^2}\int\left[\frac{g_Y^2+3g^2}{2}\left(F''F-2(F')^2\right)+4\mathrm{Tr}(\mathcal{Y}'\mathcal{Y}'^\dagger)-6\frac{V'F''F'}{F^2}\right]dh$$
$$-\frac{1}{16\pi^2}\left[\frac{1}{2}(V'')^2+\frac{3}{2}\frac{(V'F')^2}{F^2}-2\mathrm{Tr}\left(\mathcal{Y}^\dagger\mathcal{Y}\right)^2-\frac{g_Y^2+3g^2}{4}FF'V'+\frac{3}{2}F^4\frac{g_Y^4+2g_Y^2g^2+3g^4}{16}\right]=0$$

$$-\mu\frac{\partial\mathcal{Y}(h,\mu)}{\partial\mu}+\frac{1}{16\pi^2}\left[g_Y^2\left(Q_{\psi_L}^2\mathcal{Y}+\mathcal{Y}Q_{\psi_R}^2-8Q_{\psi_L}\mathcal{Y}Q_{\psi_R}-\frac{\mathcal{Y}}{4}+\mathcal{Y}'\left(\int\frac{F''F-2F'^2}{4}dh-\frac{F'F}{4}\right)\right)\right.$$
$$-6\mathcal{Y}\mathbb{C}_\psi^{SU(3)_c}+3g^2\mathcal{Y}'\left(\int\frac{F''F-2F'^2}{4}dh-\frac{F'F}{4}\right)+\frac{1}{2}\left(\mathcal{Y}'\mathcal{Y}'^\dagger\mathcal{Y}+\mathcal{Y}\mathcal{Y}'^\dagger\mathcal{Y}'\right)+2\mathcal{Y}'\mathcal{Y}^\dagger\mathcal{Y}'$$
$$\left.-3\frac{\tilde{\mathcal{Y}}\tilde{\mathcal{Y}}^\dagger}{F^2}\mathcal{Y}+\mathcal{Y}'\int\left(2\mathrm{Tr}\left(\mathcal{Y}'\mathcal{Y}'^\dagger\right)-3\frac{V'F'F''}{F^2}\right)dh+V''\mathcal{Y}''+3\frac{V'F'}{F^3}(\mathcal{Y}'F'F-\mathcal{Y})\right]=0$$

One operator is naively LO

$$\mathcal{O}_{\not{C}} \equiv (d_\mu \varphi t_Y)^2 \sim g_{\mathrm{Y}}^2 Z_\mu^2$$

$$\mu \frac{\partial C_{\not{C}}}{\partial \mu} - 3F^2(F'^2 - 1) = 0$$

$$\alpha\, \delta T = -\frac{3g_{\mathrm{Y}}^2}{32\pi^2}(F'^2(0) - 1)\log\left(\frac{v}{\Lambda}\right)$$

NLO operators that run

4 Derivatives Scalar

$$\mathcal{O} = (\partial_\mu h)^4/F^4 \qquad \mathcal{O} = (d_\mu\varphi \cdot d_\nu\varphi)^2$$

$$\mathcal{O} = \left((d_\mu\varphi)^2\right)^2 \qquad \mathcal{O} = (\partial_\nu h)^2 d_\mu\varphi^2/F^2$$

$$\mathcal{O} = (d_\mu\varphi\partial^\mu h)^2/F^2 \qquad \mathcal{O} = d_\mu\varphi^a d_\nu\varphi_b \nabla_a t^b_B A^B_{\mu\nu}$$

$$\mathcal{O} = \partial^\mu h d^\nu\varphi \cdot t_B A^B_{\mu\nu}/F \qquad \mathcal{O} = t_A t_B A^B_{\mu\nu} A^{C,\mu\nu}$$

Yukawa 2 Derivates

$$\bar{\mathcal{O}} = (\partial_\mu h/F)^2 (\bar{\psi}_L \mathcal{U})^I \psi^I_R \qquad \bar{\mathcal{O}} = (d_\mu\varphi)^2 (\bar{\psi}_L \mathcal{U})^I \psi^I_R$$

$$\bar{\mathcal{O}} = \partial^\mu h d_\mu \varphi^a \partial_a (\bar{\psi}\mathcal{U})^I \psi^I_R/F$$

Fermion Current Scalar current

$$\mathcal{O}^* = \partial_\mu h \bar{\psi}^I \gamma_\mu \psi^I_R/F$$

$$\mathcal{O}^* = \partial_\mu h (\bar{\psi}\mathcal{U})^I \gamma^\mu (\mathcal{U}^\dagger \psi_L)^I/F$$

$$\mathcal{O} = i d_\mu\varphi^a \bar{\psi}^I \gamma^\mu \left(\mathcal{U}^\dagger \partial_a \mathcal{U}\right)_{IJ} \psi^J_R$$

$$\mathcal{O} = i d_\mu\varphi^a (\bar{\psi}\mathcal{U})^I \gamma^\mu \overleftrightarrow{\partial}_a (\mathcal{U}^\dagger \psi_L)^I/2$$

$$\mathcal{O}^* = d_\mu\varphi^a \partial_a (\bar{\psi}\mathcal{U})^I \gamma^\mu (\mathcal{U}^\dagger \psi_L)^I/2$$

$$\mathcal{O} = (\bar{\psi}_L\mathcal{U})^I \psi^I_R \bar{\psi}^J_R (\mathcal{U}^\dagger \psi_L)^J \qquad \bar{\mathcal{O}} = (\bar{\psi}_L\mathcal{U})^I \psi^I_R (\bar{\psi}_L \mathcal{U})^J \psi^J_R$$

$$\mathcal{O} = \bar{\psi}^I_R (\psi_L \bar{\psi}_L \otimes 1)^{IJ} \psi^J_R \qquad \bar{\mathcal{O}} = (\bar{\psi}\varepsilon[\psi^I_R]\bar{\psi}_L \otimes \epsilon)^{IJ} \psi^J_R$$

4-Fermion

[31/32]

Conclusions

- EFT continues to surprise
- Search for new higgs coupling and see how the ones we know run to characterize the boson

[Fin]