Total Asymptotic Freedom Beyond the Standard Model – Without New Particles

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talk based on: (Gies, LZ '15 and '16)
(Ugolotti, Sondenheimer, Gies, LZ '18 and '19) (Gies, Schmieden, LZ '23)
and work in progress

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Motivations

New Physics Beyond the Standard Model (SM)?

Enhancing the Predictive Power & Understanding Scales

- naturalness
  gauge hierarchy, flavor hierarchy, strong CP, cosmological constant
- effectiveness
  locating new physics, assessing compositeness, questioning locality

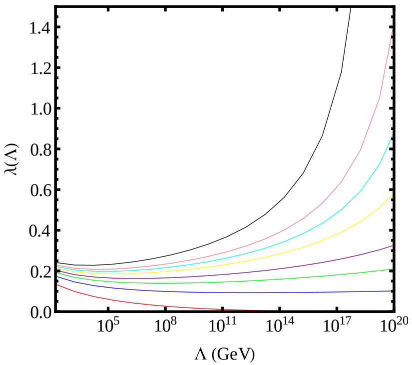
General Understanding of Quantum Field Theories *per se*

(you can see M.Linder's talk as a motivation for my talk)

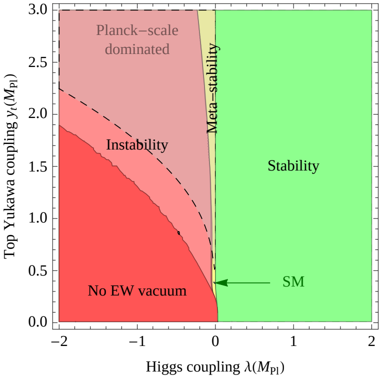
$$\Downarrow$$

RG Methods

RG Flow of λ in the Standard Model



(Holthausen, Lim, Lindner '12)



(Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia '13)

Light Higgs = almost vanishing self-interaction to high scales

Total Asymptotic Freedom (AF): known facts

E.g. one-loop RG of the non-Abelian Higgs model

$$\beta_{g^2} = -b_0 g^4 \ , \quad \beta_{\hat{\lambda}_2} = g^2(A\hat{\lambda}_2^2 + B\hat{\lambda}_2 + C), \quad \hat{\lambda}_2 = \frac{\lambda}{g^2}$$

AF condition: $\Delta = B^2 - 4AC > 0$
then UV asymptotics = RG fixed point $\hat{\lambda}_{2*}$ (Gross, Wilczek '73)

Perturbatively renormalizable AF models have been classified:

(Cheng, Eichten, Li '74) (Chang '74) (Fradkin, Kalashnikov '75)
(Chang, Perez-Mercader '78) (Bais, Weldon '78) (Callaway '88)
(Giudice, Isidori, Salvio, Strumia, '15) (Holdom, Ren, Zhang '15)

strong constraints on matter content and symmetries!

no AF in the SM, guiding principle for BSM

Total Asymptotic Freedom (AF): new results

How close can AF be to the SM?

NEW!

AF is possible already in the generic non-Abelian Higgs model
&
in generic non-Abelian Higgs-Yukawa models

How?

NEW!

AF is realized OUT of the Deep Euclidean Limit ($m^2 \neq 0$)
&
Higher-dimensional operators play some role

The Higgs VEV scales like the RG scale in the UV: $v^2 \sim k^2$

Non-Abelian Higgs Model & Higher-Dimensional Operators

non-Abelian Higgs model with $\phi \in$ fundamental of SU(2)

EFT-like analysis

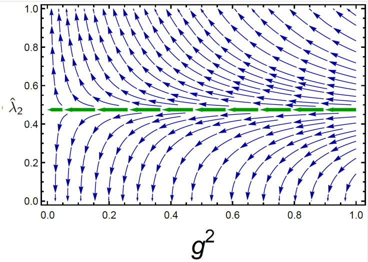
$$u(\phi^\dagger\phi) = \frac{\lambda_2}{2}\left(\phi^\dagger\phi - \kappa\right)^2 + \frac{\lambda_3}{6}\left(\phi^\dagger\phi - \kappa\right)^3 + \dots, \qquad \kappa = \frac{v^2}{2\mu^2}$$

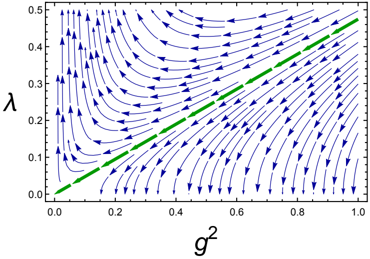
at one-loop in $\overline{\mathrm{MS}}$

$$\partial_t \lambda_2 = \frac{3\lambda_2^2}{4\pi^2} - \frac{9\lambda_2 g^2}{16\pi^2} + \frac{9g^4}{64\pi^2} + \frac{\kappa\lambda_3\lambda_2}{\pi^2} - \frac{9g^4\kappa\lambda_3}{64\pi^2\lambda_2} \tag{1}$$

Fixed points at $\hat{\lambda}_2 = \frac{\lambda_2}{g^2} > 0$ if $\hat{\lambda}_3 = \frac{\lambda_3}{g^{2P_3}}$ is suitably adjusted

Non-Abelian Higgs Model & Higher-Dimensional Operators





Fixed points at $\hat\lambda_2 = \frac{\lambda_2}{g^2} > 0$ if $\hat\lambda_3 = \frac{\lambda_3}{g^{2P_3}}$ is suitably adjusted

A Family of AF Solutions

one-loop RGE of the dim-less effective potential in $\overline{\text{MS}}$: $\rho = \phi^\dagger \phi$

$$\partial_t u(\rho) = -4u(\rho) + (2+\eta_\phi)\rho u'(\rho) + \frac{(u' + 2\rho u'')^2 + 3(u')^2 + 9(g^2\rho)^2/4}{32\pi^2}$$

Ansatz: $\kappa = g^{-2Q}\hat{\kappa}$, $\lambda_n = g^{2P_n}\hat{\lambda}_n$

Solutions: $P_2 = 1,\quad P_{n>2} = (n-2)Q$

$$\hat{\lambda}_{n*} \in \{-\frac{8\pi^2}{\hat{\kappa}}, \frac{26\pi^2}{\hat{\kappa}^2}, -\frac{187\pi^2}{2\hat{\kappa}^3}, \frac{3219\pi^2}{8\hat{\kappa}^4}, \dots\}$$

$\hat{\kappa} > 0$, $Q > 0$ are free

Including the Yukawa(s)

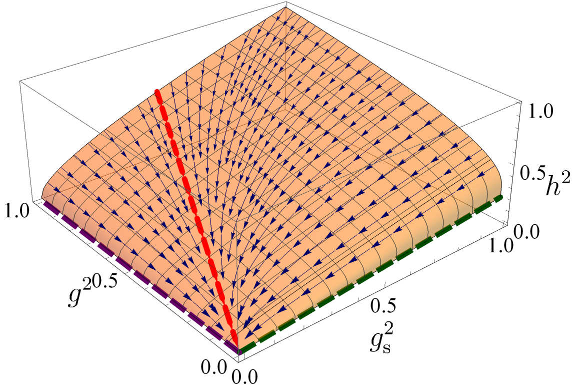
The $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(3)_\mathrm{c}$ sector of the SM

$$
\begin{aligned}
S_{\mathrm{cl}} = \int d^4x \Big[& \frac{1}{4} F_{i\mu\nu} F_i^{\mu\nu} + \frac{1}{4} G_{I\mu\nu} G_I^{\mu\nu} + (D_\mu \phi)^{\dagger a} (D^\mu \phi)^a \\
& + \bar{m}^2 \phi^\dagger \phi + \frac{\bar{\lambda}}{2} \left(\phi^\dagger \phi \right)^2 + \bar{\psi}_{\mathrm{L}}^{aA} \mathrm{i} \not{D}^{abAB} \psi_{\mathrm{L}}^{bB} + \bar{\psi}_{\mathrm{R}}^{A} \mathrm{i} \not{D}^{AB} \psi_{\mathrm{R}}^{B} \\
& + \mathrm{i} \bar{h} (\bar{\psi}_{\mathrm{L}}^{aA} \phi^a \psi_{\mathrm{R}}^{A} + \bar{\psi}_{\mathrm{R}}^{A} \phi^{\dagger a} \psi_{\mathrm{L}}^{aA}) \Big]
\end{aligned}
$$

Non-Abelian Higgs-Yukawa models

The $SU(2)_L \otimes SU(3)_c$ sector of the SM

Phase diagram of the perturbatively renormalizable model



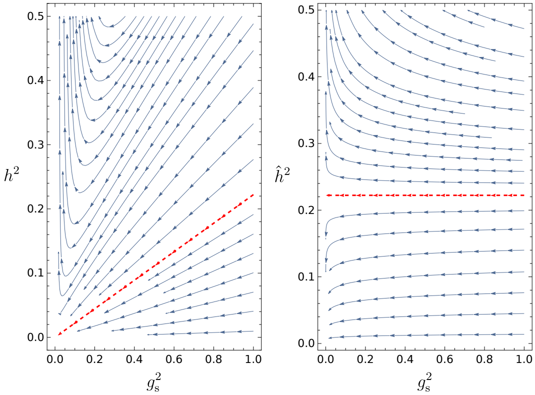
$\mathbb{Z}_2$-Yukawa-QCD (Perturbatively Renormalizable)

Set $g^2 = 0$ and define

$$\hat{h}^2 = \frac{h^2}{g_\mathrm{s}^2}$$

$$\partial_t \hat{h}^2 = \frac{3 + 2N_\mathrm{c}}{16\pi^2} g_\mathrm{s}^2 \hat{h}^2 \left(\hat{h}^2 - \chi_\mathrm{s}^2\right)$$

(Cheng, Eichten, Li '74)



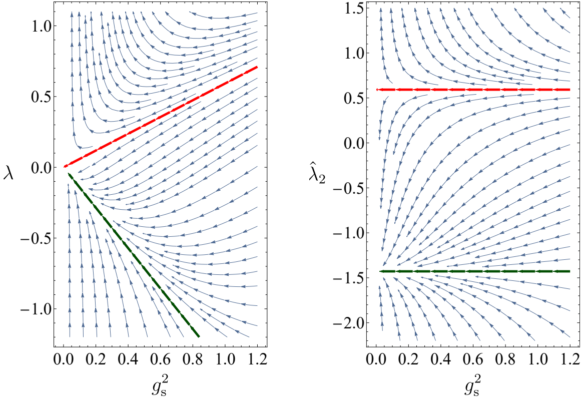
$\mathbb{Z}_2$-Yukawa-QCD (Perturbatively Renormalizable)

Set $g^2 = 0$ and define

$$\hat{\lambda}_2 = \frac{\lambda}{g_s^{4P}}, \quad P = 1/2$$

$$\hat{\lambda}_2^{\pm} = \frac{1}{6}\left(-25 \pm \sqrt{673}\right)$$

(Cheng, Eichten, Li '74)



A Family of AF Solutions

one-loop RGE of the dim-less effective potential in $\overline{\text{MS}}$: $\rho = \phi^\dagger \phi$

$$\partial_t u(\rho) = -4u(\rho) + (2+\eta_\phi)\rho u'(\rho) + \frac{(u' + 2\rho u'')^2 + 3(u')^2 + \frac{9}{4}(g^2\rho)^2 - 12(h^2\rho)^2}{32\pi^2}$$

Rescale: $x = g_{\mathrm{s}}^2 \rho$, $f(x) = u(\rho)$

Weak-g_{s}^2 expansion:

$$f(x) = C_f x^{4/d_x} + \frac{3\,x^2}{256\pi^2 \eta_x}\left(16\hat{h}_*^4 - 3\hat{g}_*^4\right)$$

Fixed-point condition = linear ODE, $C_f < 0$

A Family of AF Solutions

Higher-dimensional operators suppressed by higher powers of g_{s}^2

Weak-g_{s}^2 expansion: Coleman-Weinberg-like FP potential

$$f(x) = C_f x^{4/d_x} + \frac{3\,x^2}{256\pi^2\eta_x}\left(16\hat{h}_*^4 - 3\hat{g}_*^4\right)$$

Fixed-point condition = linear ODE, $C_f < 0$

$$\hat{\lambda}_{2*} = \frac{3(16\hat{h}_*^4 - 3\hat{g}_*^4)}{128\pi^2} > 0, \qquad P_2 = 2$$

$$\hat{\lambda}_{n>2*} = (-1)^{n+1}\frac{(n-3)!}{\hat{\kappa}^{n-2}}\hat{\lambda}_{2*}, \qquad P_{n>2} = (n-2)Q + 2$$

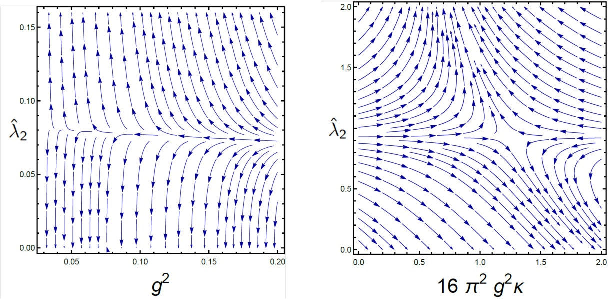
Here $\hat{\kappa} > 0$ and $Q > 0$ are free

Predictive Power

Can perturbatively non-renormalizable theories . . .

. . . be perturbatively renormalizable?

λ_2 marginally irrelevant $\qquad\qquad$ $\kappa = \frac{v^2}{\mu^2}$ relevant



These theories exhibit (almost) Gaussian scaling!

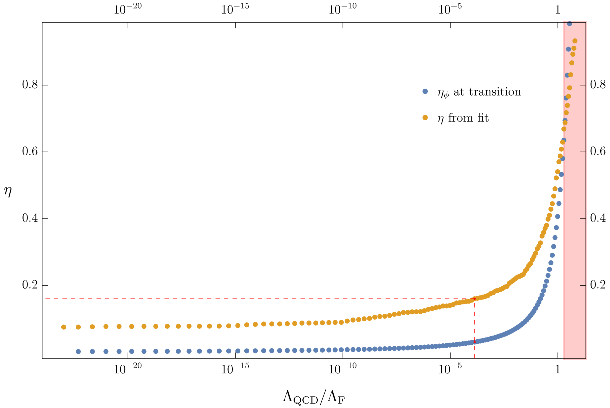
Same number of independent parameters as in perturbation theory.

Summary & Outlook

- Large families of new AF Higgs theories
- Small number of free UV parameters (g^2, v^2, h^2, λ_2, Q)
- Infinitely many higher-dimensional operators predicted
- Compatible with any wanted Higgs/W mass ratio
- We are studying applications to natural scale-invariant models
- Currently working on the inclusion of $\mathrm{U(1)_Y}$

Radiative Breaking of Scale Invariance

Total AF Higgs models feature a subclass of models where ALL SCALES arise from radiative symmetry breaking



Higgs-mass critical exponent $\Theta = 2 - \eta$ at the EW PT (yellow)
η_ϕ in the CEL AF solution of the non-Abelian subsector of the SM (blue)

Asymptotically Free U(1)?

The mechanism that cures λ might cure α?

- Couple the trivial sector to an asymptotically free sector
  $U(1)_Y \times SU(2)_L \times SU(3)_c$ ✓
- Add higher dimensional operators that change the β
  SMEFT, HEFT, ... ✓
- Allow for nonvanishing masses in the UV
  no asymptotic symmetry: $\kappa > 0$ ✓

Asymptotically Free U(1)?

In QED higher dimensional operators, e.g. Pauli-Fierz, can change the running of α (Djukanovic, Gegelia, Meißner '17)

Even induce asymptotic safety (Gies, Ziebell '20 & '22)

Asymptotic freedom: a proof of concept: quarks+photons+gluons

$$S_{\rm cl} = \int d^4x \left[\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{4} G_{I\mu\nu}G_I^{\mu\nu} + \bar{\psi}^A \mathrm{i}\not{D}^{AB}\psi^B + \mathrm{i}n\,\bar{\psi}^A \sigma_{\mu\nu}F^{\mu\nu}\psi^A \right]$$

Treating the coupling n as a free parameter supports fixed-point solutions

$$\hat{\alpha}_* = \frac{\alpha}{g_{\rm s}^{2S}} > 0, \qquad 0 < S \leq 1$$

For a fully consistent picture: Functional analysis of RGEs

(...in preparation)