Towards an asymptotically safe completion of the Standard Model

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based on 1702.01727 and work in progress
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PLANCK 2017

Warsaw, 25 May 2017

technische universität
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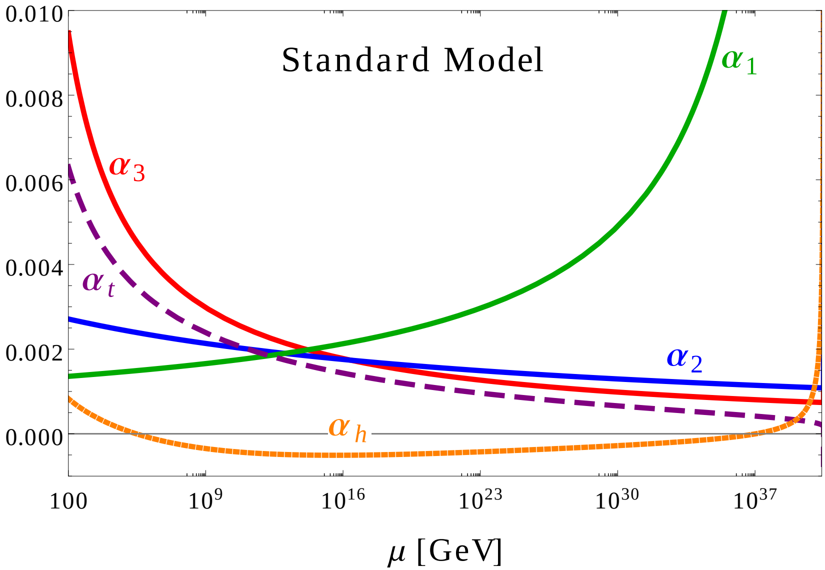
Motivation



Standard Model
0.010
0.008
0.006
0.004
0.002
0.000
α_1
α_2
α_3
α_t
α_h
100
10^9
10^{16}
10^{23}
10^{30}
10^{37}
μ [GeV]

Basics of asymptotic safety

The set of RGEs for gauge ($SU(N_c)$) and Yukawa couplings:

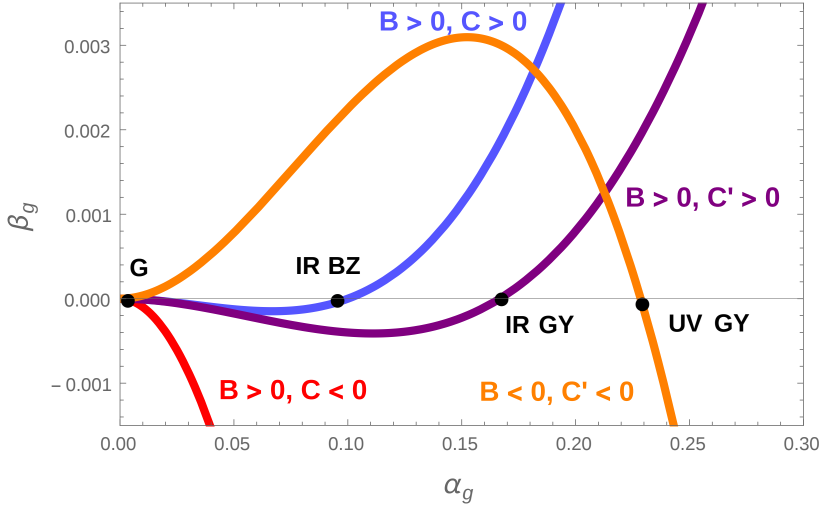
$$\beta_g = \frac{d\alpha_g}{d\ln\mu} = \alpha_g^2(-B + C\alpha_g - D\alpha_y),$$
$$\beta_y = \frac{d\alpha_y}{d\ln\mu} = \alpha_y(E\alpha_y - F\alpha_g)$$

(where $\alpha_g = \frac{g^2}{(4\pi)^2}$, $\alpha_y = \frac{y^2}{(4\pi)^2}$)

- $B > 0$ (asymptotic freedom) or $B < 0$ (asymptotic safety)
- $C > 0$ if $B < 0$ in any QFT (proof in *Bond, Litim, arXiv:1608.00519)*
- $D, E, F > 0$ for any quantum field theory
- $C' = C - \frac{DF}{E} \to \beta_g = \alpha_g^2(-B + C'\alpha_g)$

Basics of asymptotic safety

Different types of fixed points possible:



The setting:

(following *Litim, Sannino, JHEP 1412 (2014) 178, arXiv:1406.2337)*

N_F flavors of VL BSM fermions ψ_i

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\psi_i(R_3, R_2, Y)$$

$N_F \times N_F$ scalar singlets S_{ij}

$$\mathcal{L} \sim -y(\bar{\psi}_{Li} S_{ij} \psi_{Rj} + \bar{\psi}_{Ri} S^{\dagger}_{ij} \psi_{Lj})$$

In this talk: we neglect the effects from the scalar potential (three loop effect) and SM Yukawas

Case 1: $\mathbf{R_3 \neq 0,\ R_2 \neq 0,\ Y = 0}$

Renormalization group equations

$$
\begin{aligned}
\beta_3 &\equiv \frac{d\alpha_3}{d\ln\mu} = \left(-B_3 + C_3\,\alpha_3 + G_3\,\alpha_2 - D_3\,\alpha_y\right)\alpha_3^2\,,\\
\beta_2 &\equiv \frac{d\alpha_2}{d\ln\mu} = \left(-B_2 + C_2\,\alpha_2 + G_2\,\alpha_3 - D_2\,\alpha_y\right)\alpha_2^2\,,\\
\beta_y &\equiv \frac{d\alpha_y}{d\ln\mu} = \left(E\,\alpha_y - F_2\,\alpha_2 - F_3\,\alpha_3\right)\alpha_y\,.
\end{aligned}
$$

where we define

$$
\alpha_2 = \frac{g_2^2}{(4\pi)^2}\,, \qquad \alpha_3 = \frac{g_3^2}{(4\pi)^2}\,, \qquad \alpha_y = \frac{y^2}{(4\pi)^2}
$$

UV fixed points

Possible types of fixed points:

case	gauge couplings		BSM Yuk	type	info
FP₁	$\alpha_3^* = 0$	$\alpha_2^* = 0$	$\alpha_y^* = 0$	**G · G**	non-interacting
FP₂	$\alpha_3^* = 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	**G · GY**	partially interacting
FP₃	$\alpha_3^* > 0$	$\alpha_2^* = 0$	$\alpha_y^* > 0$	**GY · G**	partially interacting
FP₄	$\alpha_3^* > 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	**GY · GY**	fully interacting

The existence of a UV fixed point depends on transformation properties under $SU(3)_C \times SU(2)_L$ and N_F.

UV fixed points

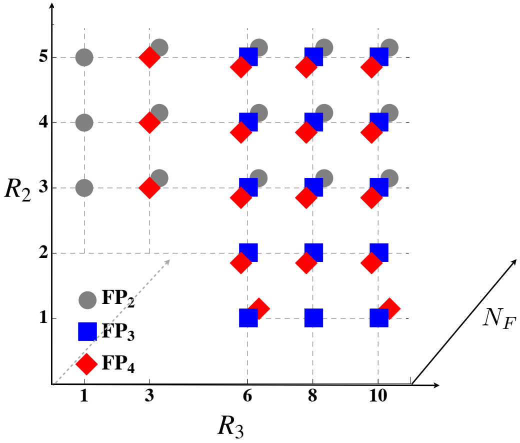
An example: $\mathbf{FP_3}$ ($\alpha_3^* > 0$, $\alpha_2^* = 0$)

	$\mathbf{R_2 = 1}$		$\mathbf{R_2 = 2}$		$\mathbf{R_2 = 3}$	
$\mathbf{R_3}$	N_{AF}	N_{AS}	N_{AF}	N_{AS}	N_{AF}	N_{AS}
3	10	–	6	–	3	–
6	2	37	1	77	–	116
8	1	95	–	198	–	299
10	–	17	–	34	–	51
15	–	30	–	60	–	90
$\mathbf{15'}$	–	17	–	33	–	50

- AF is lost if $B_3 < 0$
- physicality condition $D_3 F_3 - E C_3 > 0$

UV fixed points

Summary of fixed points:



Conclusions

- no partially-intracting UV fixed points with BSM fermions in fundamental reps. only
- large number of N_F needed for AS
- $\alpha_3^* \sim \frac{1}{2C_2(R_3)+3C_2(R_2)-5}$, $\alpha_y^* \sim \frac{1}{N_F}$

Matching onto the SM

UV fixed point should be connected through a RG trajectory with the SM

- partially interacting UV fixed point: one relevant, one irrelevant, one marginal eigendirection $\rightarrow$ 2D critical surface given by $\alpha_y(\alpha_{AS})$.

- fully interacting UV fixed point: 1 relevant, 2 irrelevant eigendirection $\rightarrow$ 1D critical surface with $\alpha_y(\alpha_3)$ and $\alpha_2(\alpha_3)$

Matching onto the SM

Benchmark scenarios

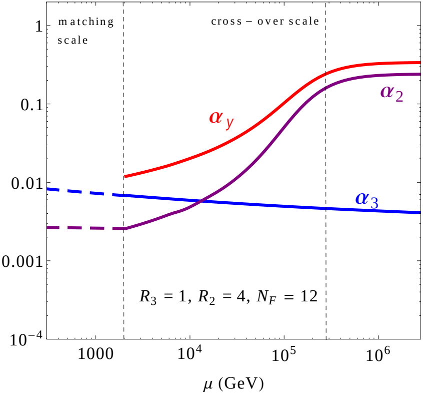
model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	type	info
A	$(\mathbf{1}, \mathbf{4}, 12)$	0	0.2407	0.3385	**FP$_2$**	low scale*
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	**FP$_3$**	low scale*
		0.1292	0.2769	0.1163	**FP$_4$**	no match
C	$(\mathbf{10}, \mathbf{4}, 80)$	0.3317	0	0.0995	**FP$_3$**	low scale*
		0.0503	0.0752	0.0292	**FP$_4$**	high scale
		0	0.8002	0.1500	**FP$_2$**	high scale
D	$(\mathbf{3}, \mathbf{4}, 290)$	0	0.0895	0.0066	**FP$_2$**	low scale*
		0.0416	0.0615	0.0056	**FP$_4$**	low scale
E	$(\mathbf{3}, \mathbf{3}, 72)$	0.1499	0.2181	0.0471	**FP$_4$**	low scale

* matching at any scale including low (TeV)

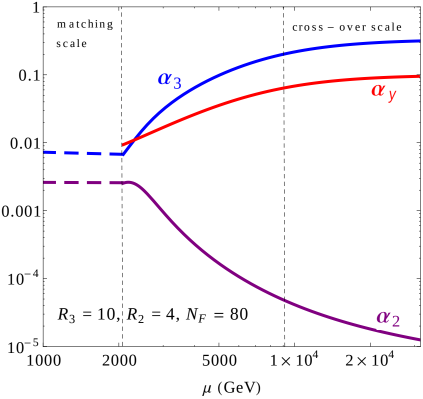
Matching onto the SM

Matching at any scale: partially interacting fixed points

$\mathbf{FP_2}$
model A
$(R_3, R_2, N_F) = (\mathbf{1}, \mathbf{4}, 12)$



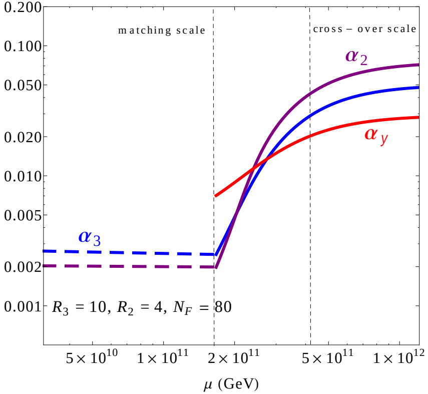
$\mathbf{FP_3}$
model C
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{4}, 80)$



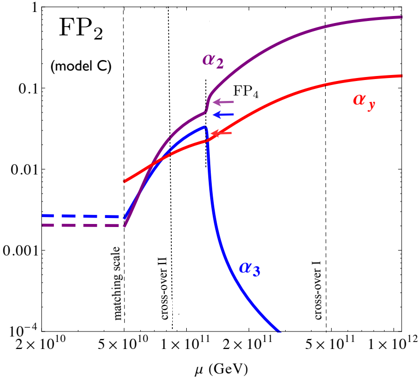
Matching onto the SM

High scale matching:

FP_4
model C
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{4}, 80)$

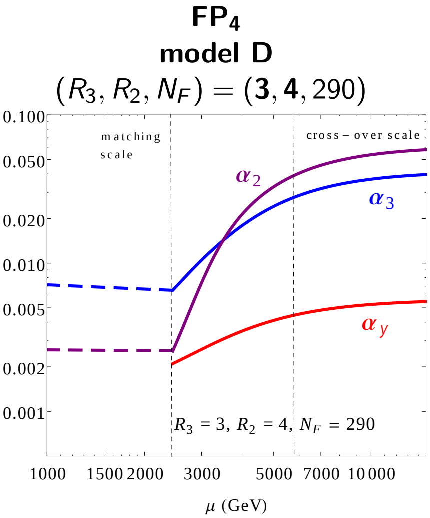


FP_2
model C
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{4}, 80)$



Matching onto the SM

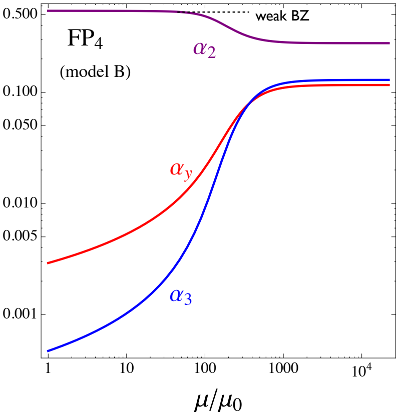
Low scale matching at fixed scale: fully interacting fixed point



Matching onto the SM

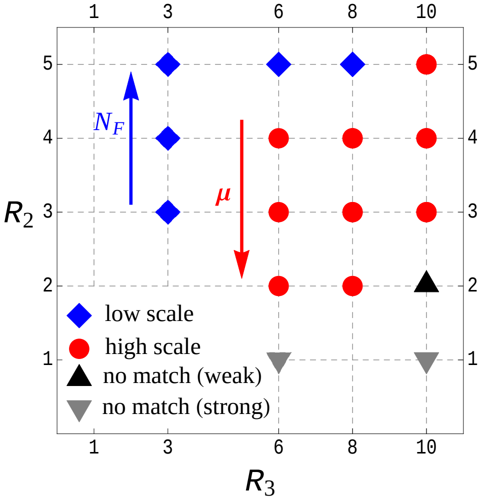
No matching (all models with $R_2 = 1$)

$\mathbf{FP_4}$
model B
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{1}, 30)$



Matching onto the SM

Summary of matching conditions:



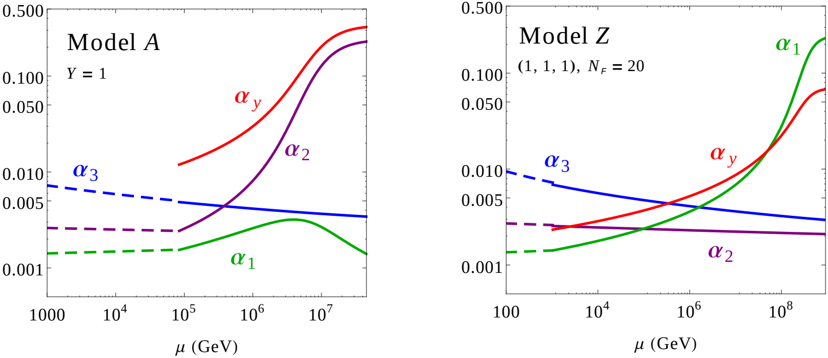
Conclusions

- partially interacting UV FP can be connected with the SM at any energy ...
- unless a nearby fully interacting FP affects the UV-safe trajectory (high scale)
- fully interacting FP more difficult the match, however ...
- AS predicts a relation between the gauge couplings

Case 2: we add $\mathbf{Y \neq 0}$

There is always a lower bound on the hypercharge, above which α_1 becomes asymptotically free.

It is also possible to make α_1 asymptotically safe.



Summary

- Yukawa couplings offer the **ONLY** dynamical mechanism to obtain interacting fixed points in gauge theories.
- To make the SM asymptotically safe new fermions in reps. higher then fundamental are required.
- Matching with the SM possible for certain types of FP and matter content.
- There are experimental signatures to test at the colliders (running of the couplings, precision observables, R-hadrons, diboson searches).

Extra slides

Asymptotic Safety in Gauge-Yukawa theory

Three types of fixed points possible:

- $(\alpha_g^*, \alpha_y^*) = (0, 0)$

  Gaussian fixed point, always exists, UV ($B > 0$) or IR ($B < 0$).

- $(\alpha_g^*, \alpha_y^*) = (B/C, 0)$

  Caswell-Banks-Zaks fixed point, ALWAYS IR fixed point.

  Interacting UV fixed point ONLY with Yukawas.

- $(\alpha_g^*, \alpha_y^*) = \left(\frac{B}{C'}, \frac{BF}{C'E}\right)$, where $C' = C - D\frac{F}{E}$

  Fully interacting gauge-Yukawa fixed point:

  - IR ($B > 0$ and $C^{'} > 0$)
  - UV ($B < 0$ and $C^{'} < 0$)

  Asymptotic Safety: $B < 0$ and $CE - DF < 0$.

Asymptotic Safety in Gauge-Yukawa theory

Critical exponents:

linearization of the RG flow in vicinity of the FP:

$$\beta_i = \sum_j M_{ij}(\alpha_j - \alpha_j^*) + \mathcal{O}(\alpha_j^2)$$

where stability matrix is defined as $M_{ij} = \partial\beta_i/\partial\alpha_j|_*$.

Properties of the FP (scaling of the couplings near the FP) determined by eigenvalues λ_k of M:

- $Re(\lambda_k) > 0$ irrelevant direction $\rightarrow \delta\alpha_i \sim \mu^{\lambda_k}$ increasing with μ
- $Re(\lambda_k) < 0$ relevant direction $\rightarrow \delta\alpha_i \sim \mu^{\lambda_k}$ decreasing with μ
- $Re(\lambda_k) = 0$ marginal direction $\rightarrow \delta\alpha_i \sim \log(\mu)$

Asymptotic Safety in Gauge-Yukawa theory

Critical surface:

In the vicinity of the UV fixed point:

$$\alpha_g(\mu) = \alpha_g^* + \sum_n c_n V_g^n \left(\frac{\mu}{\Lambda}\right)^{\lambda_n}$$

$$\alpha_y(\mu) = \alpha_y^* + \sum_n c_n V_y^n \left(\frac{\mu}{\Lambda}\right)^{\lambda_n}$$

and V_i - eigenvectors of M.

So for the relevant eigendirection one gets:

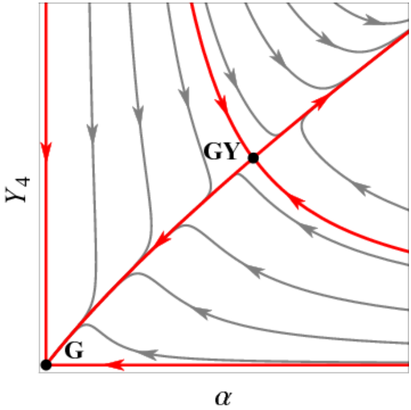
$$\alpha_y(\alpha_g) = \alpha_y^* + (V_y^1)^{-1}(\alpha_g - \alpha_g^*)$$

The UV fixed point can be reached only along a critical direction

Phase diagrams

Asymptotic safety ($B < 0$ and $C' < 0$):

Bond, Litim, arXiv:1608.00519

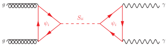


$\lambda_1 = \frac{B^2}{C'}$, $\lambda_2 = \frac{BF}{C'}$ $\rightarrow$ one relevant and one irrelevant direction

NO Landau Poles!

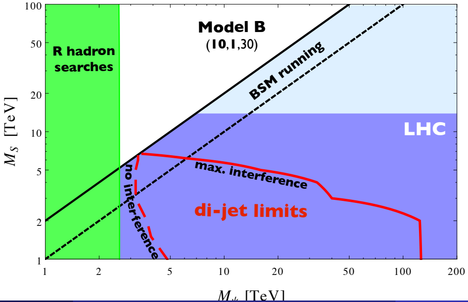
Diboson spectra

if $m_S \leq m_\psi$ than loop decays $S \to gg, \gamma\gamma, ZZ, Z\gamma, WW$



Strong limits from the dijet search, ex. 13 TeV ATLAS $\sigma_{jj} \times A \times BR < 1.3\,\mathrm{pb}$

$$\Gamma_{gg} = \frac{\alpha_s^2 m_S^3}{32\pi^3} \left| \sum_{i=1}^{n_f} \frac{y S_2(R_3)}{M_\psi} A_{1/2}(x) \right|^2$$



Experimental signatures

R-hadron searches

if $m_S \geq m_\psi$ and $Y_\psi = 0$ than ψ can be stable $\rightarrow$ R-hadrons can be formed

$$\psi\bar{\psi},\ \psi_6 qq,\ \psi_8 q\bar{q},\ \psi_{10} qqq, \ldots.$$