Model building with asymptotic safety

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Based on 1702.01727 and work in progress
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SUSY 17
TIFR, Mumbai
14th December 2017

Goals

- Interested in field theories that are predictive up to highest energies
- Have examples of theories with reliable weakly coupled ultraviolet fixed point
- How can we begin to apply these ideas to physics beyond the standard model?

Renormalisation group

- Renormalisation group equations (RGEs) describe running of couplings λ_i with scale μ

$$\frac{\partial \lambda_i}{\partial \log \mu} = \beta_i(\{\lambda\})$$

- Beta functions β_i determined by field content and symmetries
- Perturbation theory $\rightarrow$ expand β_i in powers of coupling

Fixed points

- Fixed points λ_i^* are points in coupling space that satisfy

$$\beta_i(\{\lambda^*\}) = 0$$

- Infrared means have solutions to RGEs which satisfy $\lim_{\mu\to 0^+} \lambda(\mu) = \lambda^*$
- Ultraviolet means have solutions to RGEs which satisfy $\lim_{\mu\to\infty} \lambda(\mu) = \lambda^*$
- Ultraviolet fixed points allow us to define QFTs up to arbitrarily large energies

UV critical surface

- Space of trajectories reaching fixed point in UV $=$ critical surface.
- For a fixed choice of RG scale, all points on critical surface are valid UV theories. Need to make n measurements to determine our theory from an n-dimensional critical surface.
- Critical surface finite-dimensional $\rightarrow$ asymptotic safety

Weak fixed points in gauge theories

[AB, D Litim, 1608.00519]

- Can write simple gauge beta function as

$$\beta = \alpha(-B + C\alpha + \dots)$$

- Interacting fixed points are of the form

$$\alpha^* = B/C$$

- Only gauge interactions mean $C > 0$ when $B \leq 0 \implies$ fixed points are IR
- Encode effect of Yukawas as shift in effective two-loop $C \to C' \leq C$, can have $C' < 0 \implies$ UV

Partially interacting fixed points

- For semisimple gauge groups have multiple independent gauge couplings α_a
- Partially interacting fixed points (some $\alpha_a^* = 0$) give marginal directions
- Relevancy determined by effective one-loop coefficient

$$\begin{aligned}\beta_a &= \alpha_a^2(-B_a + C_{ab}\alpha_b^* - D_a\alpha_y^*) \\ &\equiv -B'_a\alpha_a^2\end{aligned}$$

- Sign of B' can be different from $B \to$ couplings can change between being IR or UV free

Extending the Standard Model

- Start with the standard model
- Add new matter content:
  - N_F Dirac fermions $\psi(R_3, R_2, Y)$ charged under SM gauge group
  - An $N_F \times N_F$ matrix of scalars $S(1,1,0)$ uncharged under SM gauge group
- Furnish with a new BSM Yukawa interaction

$$L_{\text{BSM, Yukawa}} = -y \, \text{Tr}(\overline{\psi}_L \, S \, \psi_R + \overline{\psi}_R \, S^\dagger \, \psi_L) \, .$$

RGEs

Running of the rescaled couplings

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

is governed be the renormalisation group equations

$$\beta_3 \equiv \frac{d\alpha_3}{d\ln\mu} = (-B_3 + C_3\,\alpha_3 + G_3\,\alpha_2 - D_3\,\alpha_y)\,\alpha_3^2\,,$$

$$\beta_2 \equiv \frac{d\alpha_2}{d\ln\mu} = (-B_2 + C_2\,\alpha_2 + G_2\,\alpha_3 - D_2\,\alpha_y)\,\alpha_2^2\,,$$

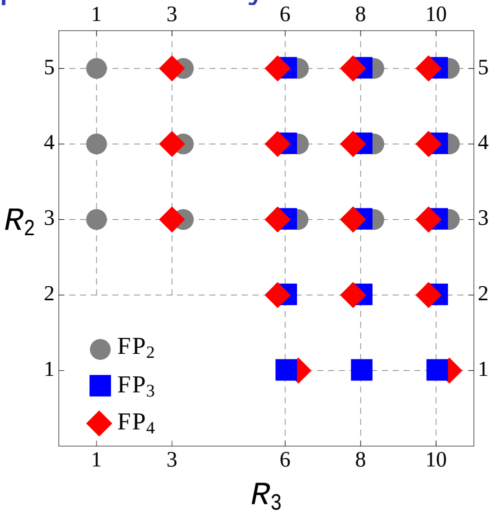
$$\beta_y \equiv \frac{d\alpha_y}{d\ln\mu} = (E\,\alpha_y - F_2\,\alpha_2 - F_3\,\alpha_3)\,\alpha_y\,.$$

Candidate UV fixed points

case	gauge couplings α_3^*	α_2^*	Yukawa coupling α_y^*	type	info
$\mathbf{FP_1}$	0	0	0	$\mathbf{G \cdot G}$	non-interacting
$\mathbf{FP_2}$	0	$\dfrac{B_2}{C_2'}$	$\dfrac{F_2}{E}\,\alpha_2^*$	$\mathbf{G \cdot GY}$	partially interacting
$\mathbf{FP_3}$	$\dfrac{B_3}{C_3'}$	0	$\dfrac{F_3}{E}\,\alpha_3^*$	$\mathbf{GY \cdot G}$	partially interacting
$\mathbf{FP_4}$	$\dfrac{C_2'B_3 - B_2G_3'}{C_2'C_3' - G_2'G_3'}$	$\dfrac{C_3'B_2 - B_3G_2'}{C_2'C_3' - G_2'G_3'}$	$\dfrac{F_3}{E}\,\alpha_3^* + \dfrac{F_2}{E}\,\alpha_2^*$	$\mathbf{GY \cdot GY}$	fully interacting

Physicality and UV relevance of each governed by values of (R_3, R_2, N_F) — various scenarios available

Fixed point summary



Lower-lying symbols == larger N_F

Benchmark models

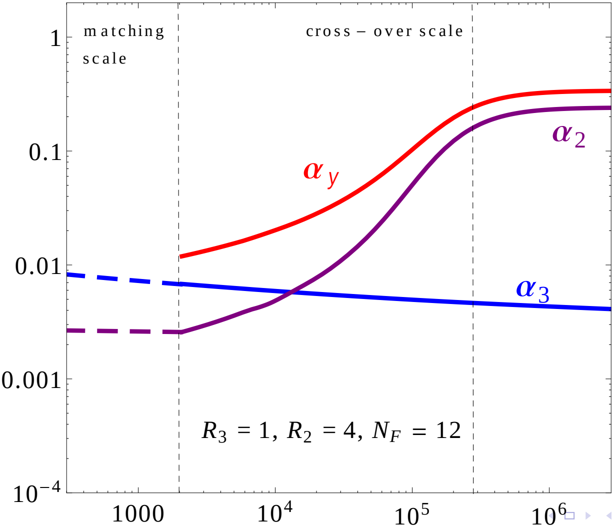
model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	type
A	$(\mathbf{1}, 4, 12)$	0	0.2407	0.3385	$\mathbf{FP_2}$
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	$\mathbf{FP_3}$
		0.1292	0.2769	0.1163	$\mathbf{FP_4}$
C	$(\mathbf{10}, 4, 80)$	0.3317	0	0.0995	$\mathbf{FP_3}$
		0.0503	0.0752	0.0292	$\mathbf{FP_4}$
		0	0.8002	0.1500	$\mathbf{FP_2}$
D	$(\mathbf{3}, 4, 290)$	0	0.0895	0.0066	$\mathbf{FP_2}$
		0.0416	0.0615	0.0056	$\mathbf{FP_4}$
E	$(\mathbf{3}, \mathbf{3}, 72)$	0.1499	0.2181	0.0471	$\mathbf{FP_4}$

Matching to SM

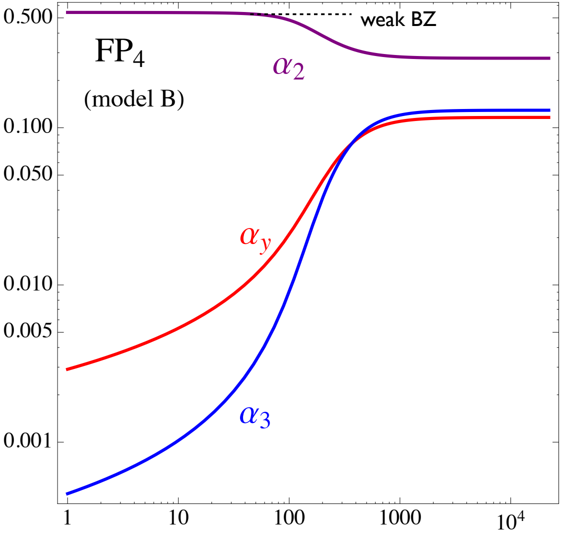
For theory to be viable must match the running of couplings from UV fixed points to SM values at decoupling scale $\sim M_\psi$

- FP_2 — weak strong and strong weak — have 2 parameters, $\delta\alpha_3(\Lambda), \delta\alpha_2(\Lambda)$
- FP_3 — strong strong and weak weak — have 2 parameters, $\delta\alpha_3(\Lambda), \delta\alpha_2(\Lambda)$
- FP_4 — fully interacting — have only 1 parameter, $\delta\alpha_3(\Lambda)$ $\implies$ matching scale fixed

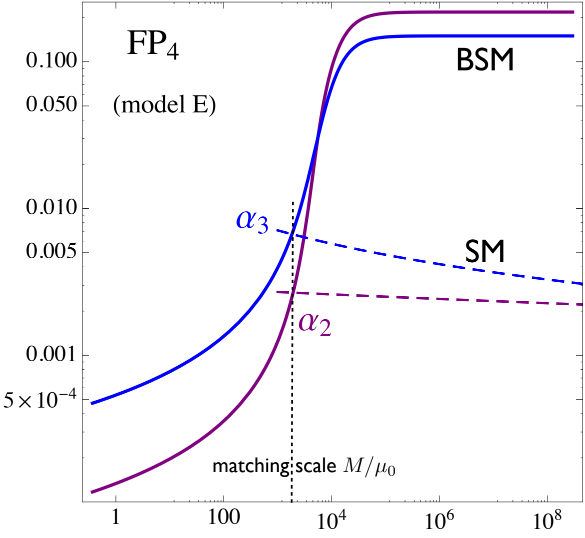
Matching — Model A, FP_2



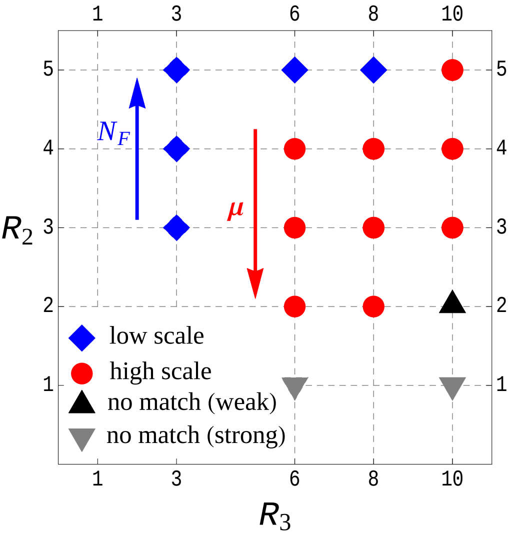
No matching — Model B, FP_4



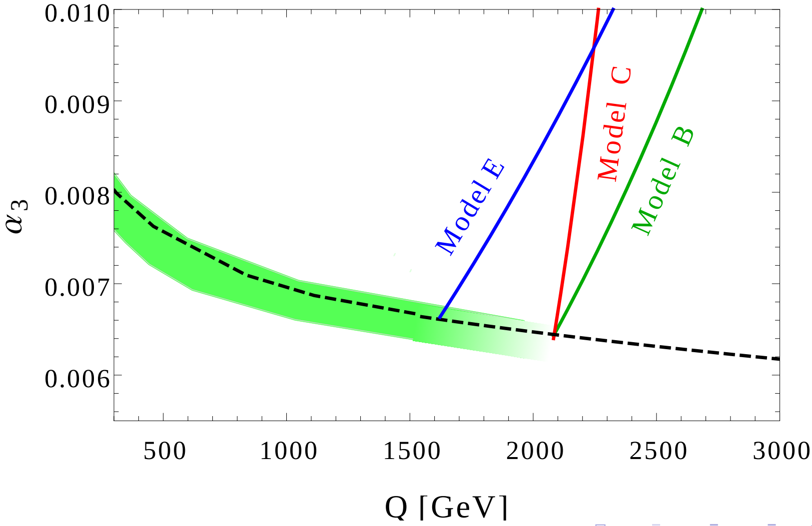
Matching — Model E, FP_4



Matching summary



Signatures — running strong coupling



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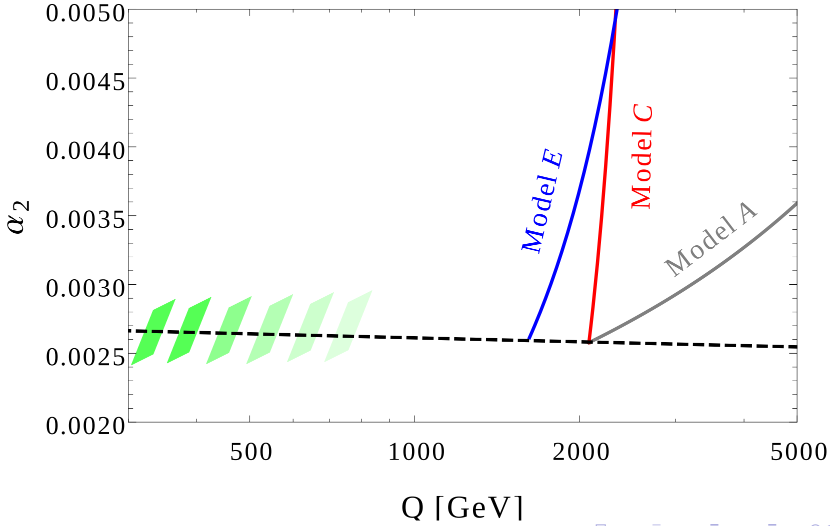


R-hadrons

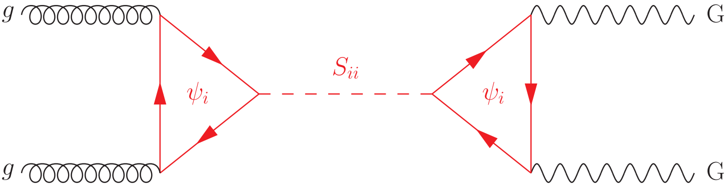
If lightest BSM fermion can be pair-produced $2M_\psi < \sqrt{s}$, can form bound states with SM partons

$\psi(R_3, R_2)$	$R_2 = 1$		$R_2 = 2$		$R_2 = 3$	
R_3	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)
3	$5\frac{1}{3}$	(1.3)	$10\frac{2}{3}$	(1.4)	16	1.5
6	$66\frac{2}{3}$	1.7	$133\frac{1}{3}$	1.8	200	1.9
8	72	1.7	144	1.8	216	1.9
10	360	2.0	720	2.1	1080	2.2
15	$426\frac{2}{3}$	2.0	$853\frac{1}{3}$	2.1	1280	2.2
15′	$1306\frac{2}{3}$	2.2	$2313\frac{1}{3}$	2.3	3920	2.4

Mass bound increases with N_F

Signatures — dibosons

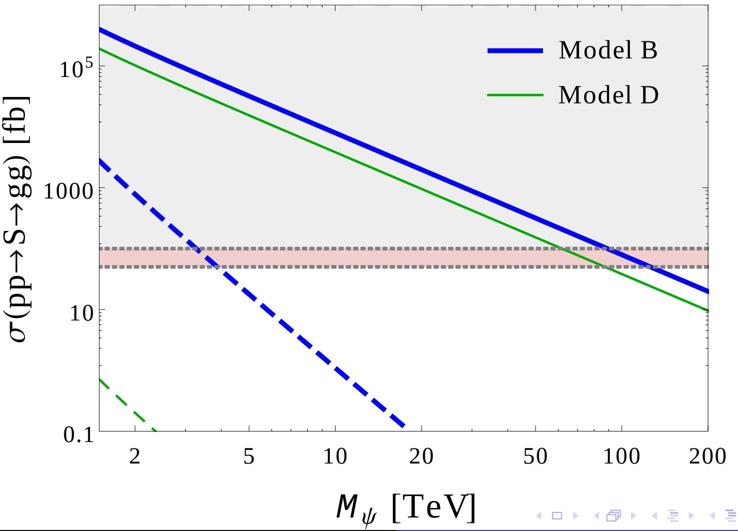
If scalars not heavy enough to decay to fermions $M_S < 2M_\psi$, may decay to dibosons via loops



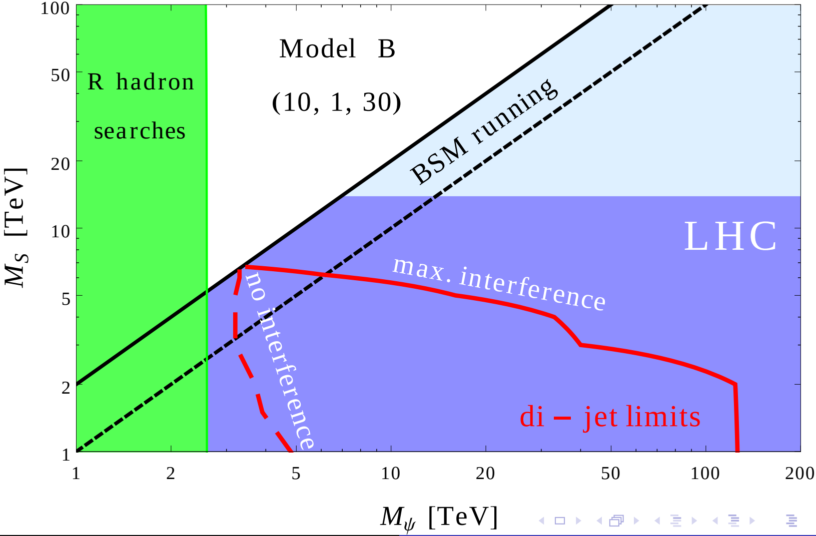
Two extreme cases:

- Maximum interference — all masses equal $\sigma \sim N_F^2$
- No interference — mass spacings small, widths non-overlapping $\sigma \sim N_F$

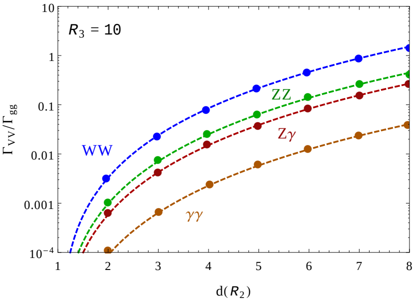
Dijet cross section

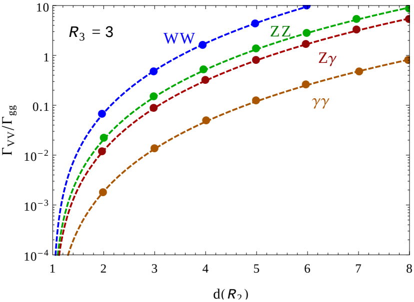


Exclusions — R-hadrons + dijets



EW dibosons — FP_2





Summary

- New matter content may allow SM to be interacting but controlled in the UV
- Fermions and scalars crucial to generate UV fixed point
- Fully interacting fixed points enhance predictivity
- Many interesting experimental signatures testable at colliders