Collider signatures of asymptotic safety beyond the SM

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Based on 1702.01727 with G.Hiller, K.Kowalska and D.F.Litim

NExT Meeting, University of Sussex
10th May 2017

Outline

1. Introduction and theory background

2. BSM applications

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Goals

- Have mechanism that allows weakly coupled interacting ultraviolet fixed points
- Want to explore possibilities for UV complete BSM scenarios beyond asymptotic freedom
- How can we test these models at colliders?

Renormalisation group

- Couplings λ_i in QFT run with energy scale — described by renormalisation group equations (RGEs)

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

- Beta functions β_i determined by field content and symmetries
- At weak coupling, β_i may be computed perturbatively

Fixed points

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

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

- If a fixed point is ultraviolet it means we 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

Free parameters of theory determined by UV critical surface

- Space of trajectories coming from directions where we reach fixed point in UV $=$ critical surface.
- Need to make n measurements to determine our theory from an n-dimensional critical surface.
- Important that we have only a finite number of relevant directions — don't know beforehand in general!

Ultraviolet fixed points in perturbation theory

- Two possible fixed point scenarios:
  - Gaussian fixed point $\lambda^* = 0$ — asymptotic freedom
  - Interacting fixed point $\lambda^* \neq 0$ — asymptotic safety
- Perturbation theory $\implies$ need couplings to be small
  - For asymptotic safety need $0 < |\lambda^*| \ll 1$
  - Small corrections to anomalous dimensions — classical mass dimension still governs relevance
- UV critical surface will be finite dimensional — only need to understand marginal interactions

Weakly coupled fixed points in 4d gauge theories

- Only need to worry about marginal interactions — gauge, Yukawa and scalar quartics
- Can achieve an ultraviolet fixed point through cancellation between gauge and Yukawa fluctuations
- Quartics play a subleading role in generating fixed point — need them to attain a valid fixed point for consistency

Structure of beta functions

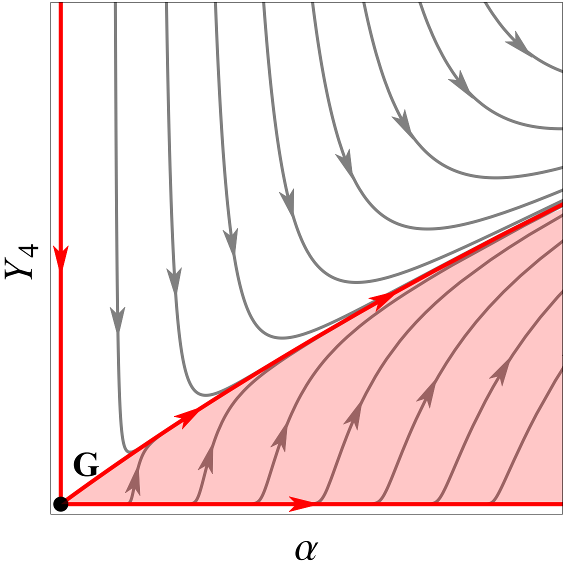
Schematically beta functions are

$$\beta_g = \alpha_g^2(-B + C\alpha_g - D\alpha_y)$$
$$\beta_y = \alpha_y(E\alpha_y - F\alpha_g)$$

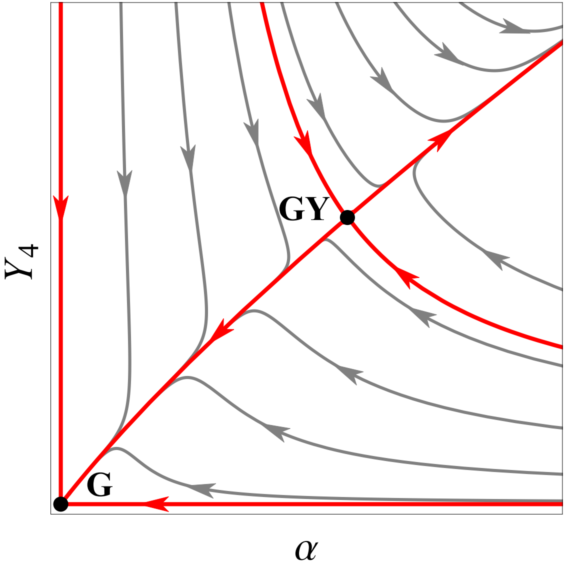
- Sign of B determines whether we have asymptotic freedom: $B > 0$ is AF, $B < 0$ is not
- Fixed point in gauge only $\alpha_g^* = B/C$ is necessarily infrared [1608.00519]
- Combined fixed point can be ultraviolet if $C' < 0$

$$\alpha_g^* = \frac{B}{C'}, \qquad \alpha_y^* = \frac{F}{E}\alpha_g^*$$
$$C' = C - \frac{DF}{E}$$

$B > 0 > C$, only Gaussian fixed point



$B, C' < 0 < C$, Asymptotic safety



Weak asymptotic safety summary

case	gauge group	matter	Yukawa	asymptotic safety
a)	simple	fermions in irreps	No	No
b)	simple or abelian	fermions, any rep	No	No
		scalars, any rep	No	No
		fermions and scalars, any rep	No	No
c)	semi-simple, with or without abelian factors	fermions, any rep	No	No
		scalars, any rep	No	No
		fermions and scalars, any rep	No	No
d)	simple or abelian	fermions and scalars, any rep	Yes	Yes
e)	semi-simple, with or without abelian factors	fermions and scalars, any rep	Yes	Yes

[1608.00519]

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Extending the Standard Model

We take the standard model and add new matter content which respects a new $U(N_F) \times U(N_F)$ flavour symmetry:

- N_F Dirac fermions $\psi(R_3, R_2, Y)$ charged under SM gauge group
- An $N_F \times N_F$ matrix of singlet scalars S

These interact via a new BSM Yukawa interaction

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

[1702.01727]

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

$$\beta_1 \equiv \frac{d\alpha_3}{d\ln\mu} = (-B_3 + C_3\,\alpha_3 + G_3\,\alpha_2 - D_3\,\alpha_y)\,\alpha_3^2\,,$$

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

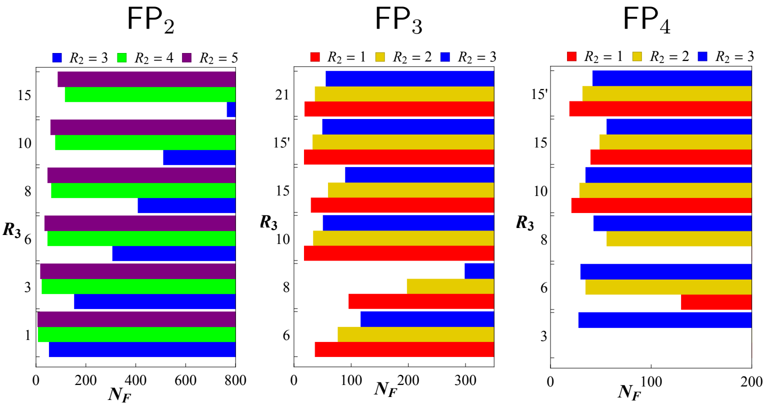
$$\beta_y \equiv \frac{d\alpha_y}{d\ln\mu} = (E\,\alpha_y - F_2\,\alpha_2 - F_3\,\alpha_3)\,\alpha_y\,.$$

Candidate UV fixed points

case	gauge couplings α_3^*	gauge couplings α_2^*	Yukawa coupling α_y^*	type	info
$\mathbf{FP}_1$	0	0	0	$\mathbf{G} \cdot \mathbf{G}$	non-interacting
$\mathbf{FP}_2$	0	$\frac{B_2}{C_2'}$	$\frac{F_2}{E}\,\alpha_2^*$	$\mathbf{G} \cdot \mathbf{GY}$	partially interacting
$\mathbf{FP}_3$	$\frac{B_3}{C_3'}$	0	$\frac{F_3}{E}\,\alpha_3^*$	$\mathbf{GY} \cdot \mathbf{G}$	partially interacting
$\mathbf{FP}_4$	$\frac{C_2' B_3 - B_2 G_3'}{C_2' C_3' - G_2' G_3'}$	$\frac{C_3' B_2 - B_3 G_2'}{C_2' C_3' - G_2' G_3'}$	$\frac{F_3}{E}\,\alpha_3^* + \frac{F_2}{E}\,\alpha_2^*$	$\mathbf{GY} \cdot \mathbf{GY}$	fully interacting

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

Availability of fixed points



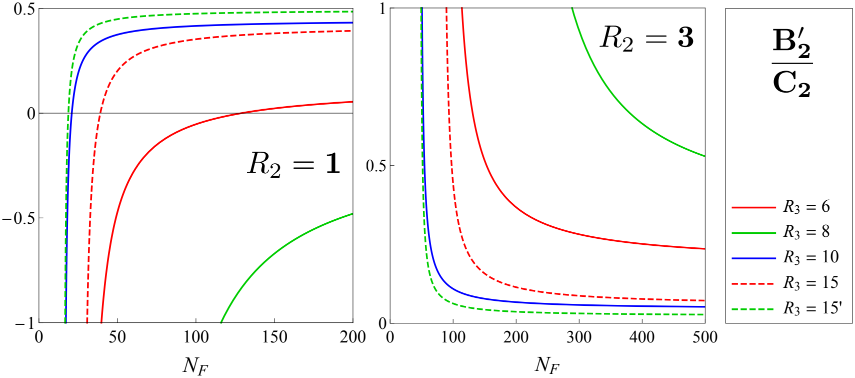
Regaining asymptotic freedom

For partially interacting fixed points, asymptotic freedom governed by effective one-loop term in vicinity of fixed point

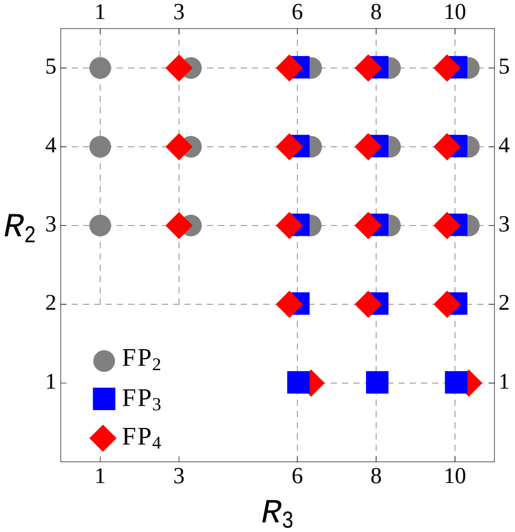
$$B_2' = B_2 - G_2\alpha_3^* + D_2\alpha_y^*$$

- If $B_2' > 0$ then we can reach the fixed point in the UV from this direction
- Can have $B_2' > 0$ even if $B_2 < 0$

Regaining asymptotic freedom — FP_3



Coexistence of fixed points



Lower-lying symbols == larger N_F

Benchmark models

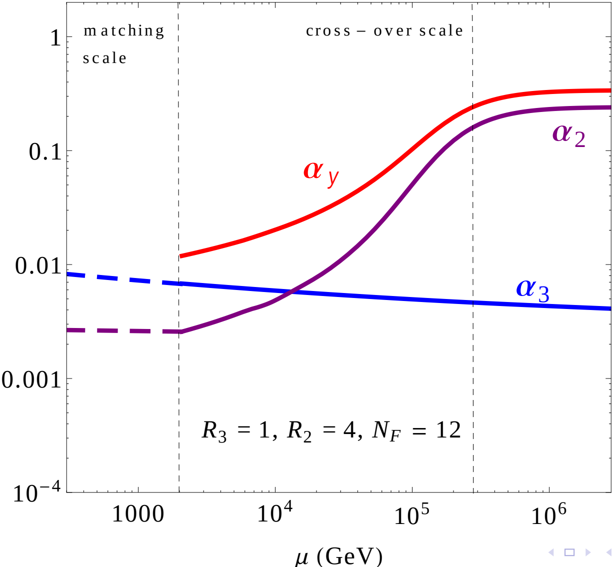
model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	type
A	$(\mathbf{1}, \mathbf{4}, 12)$	0	0.2407	0.3385	$\mathbf{FP_2}$
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	$\mathbf{FP_3}$
		0.1292	0.2769	0.1163	$\mathbf{FP_4}$
C	$(\mathbf{10}, \mathbf{4}, 80)$	0.3317	0	0.0995	$\mathbf{FP_3}$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

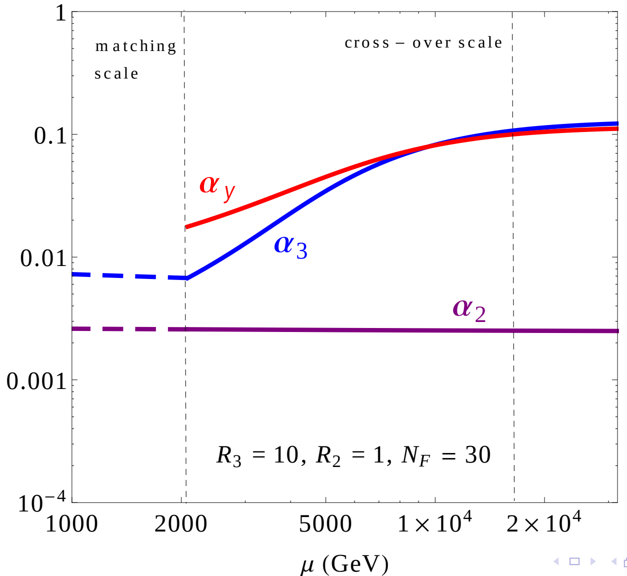
For theory to be viable must match the running of couplings from UV fixed points to SM values at decoupling scale $\sim M_\psi$

- 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, $\delta\alpha_3(\Lambda)$

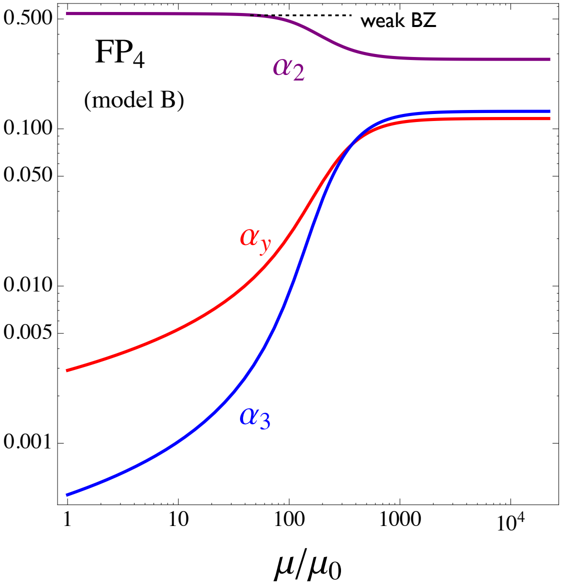
Matching — Model A, FP_2



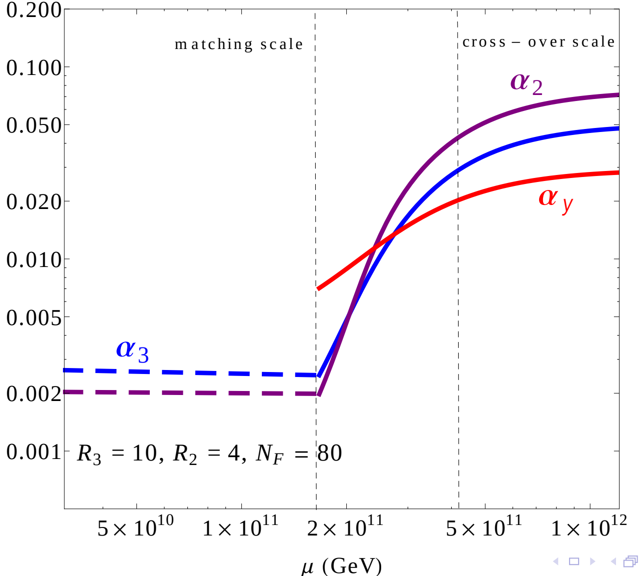
Matching — Model B, FP_3



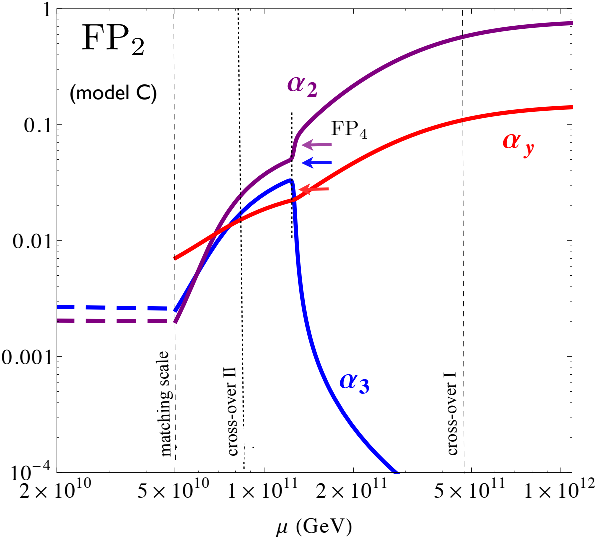
No Matching — Model B, FP_4



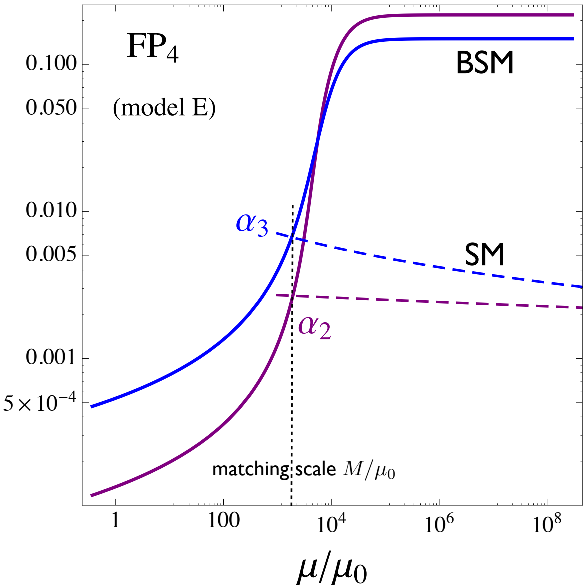
Matching — Model C, FP_4



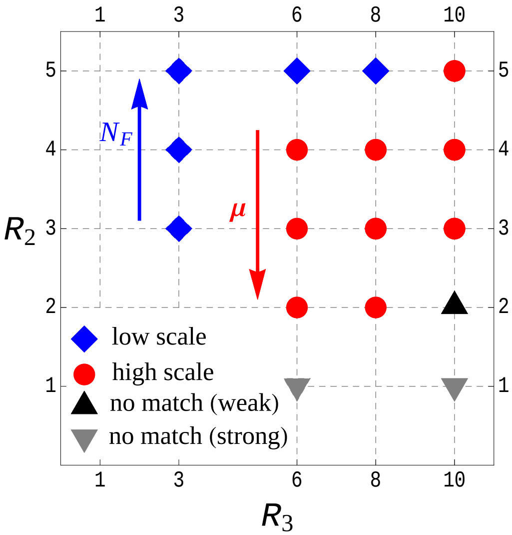
Matching — Model C, FP_2



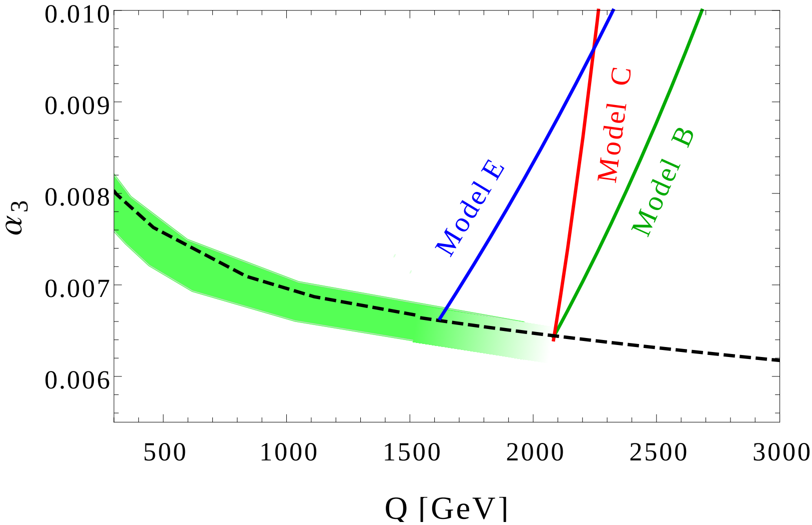
Matching — Model E, FP_4



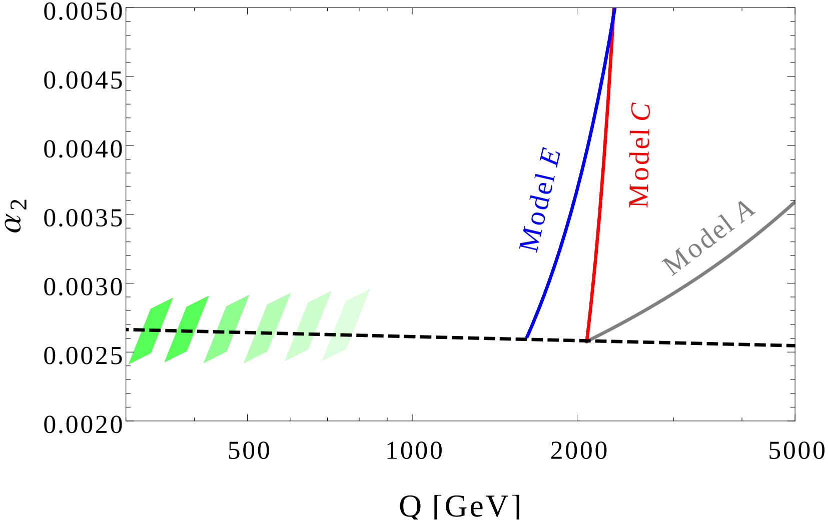
Matching summary



Signatures — running strong coupling



Signatures — running weak coupling



R-hadrons

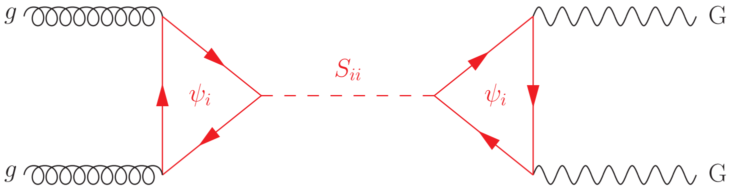
If lightest BSM fermion can be pair-produced $2M_\psi < \sqrt{s}$, can form bound states with SM partons

$\psi(R_3, R_2)$	$R_2 = 1$		$R_2 = 2$		$R_2 = 3$	
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

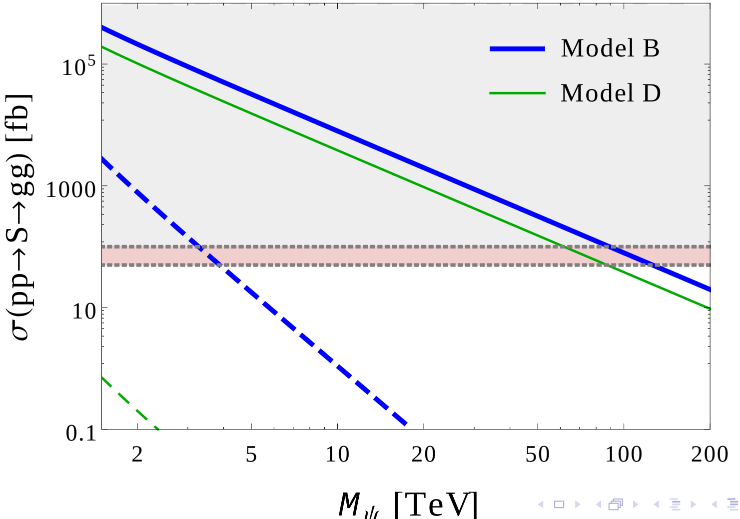


Two extreme cases:

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

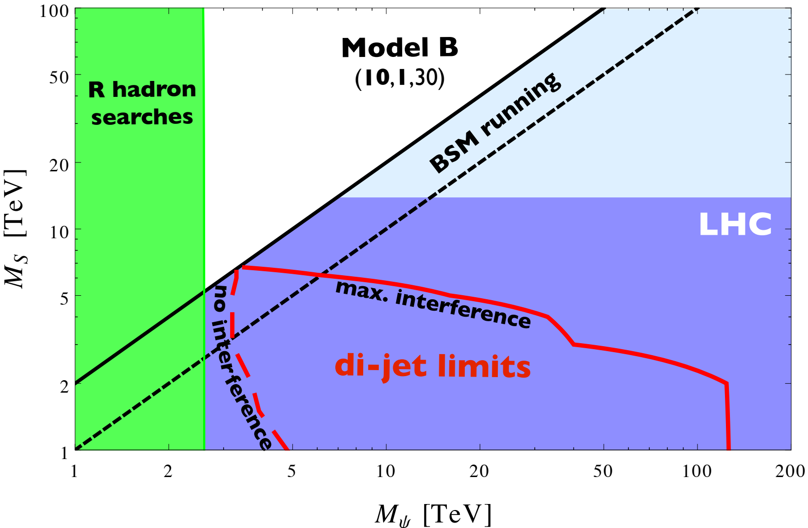
Dijet cross section

(Updated)

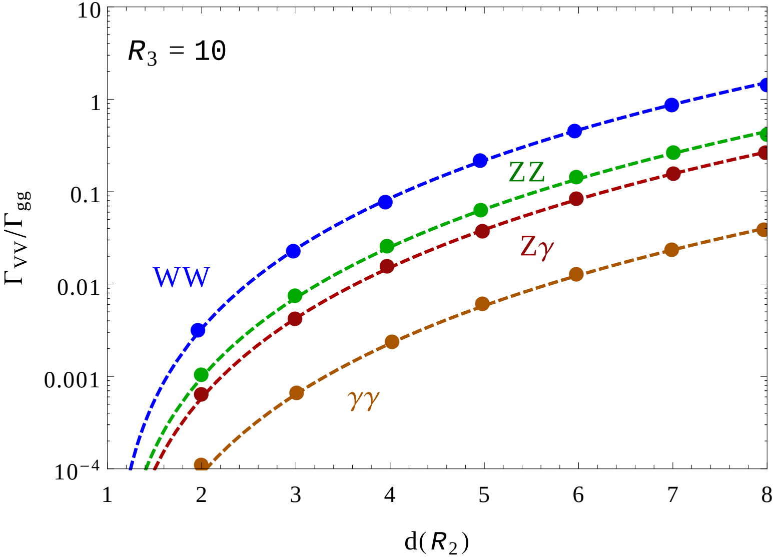


Exclusions — R-hadrons + dijets

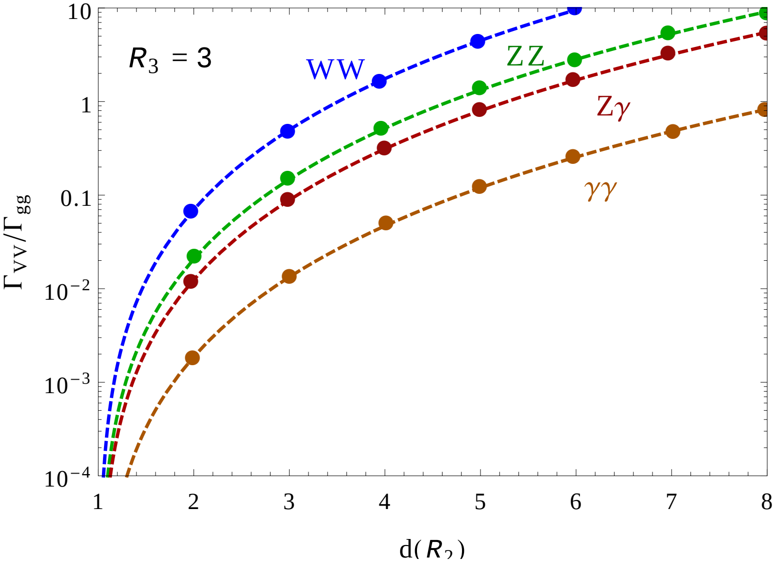
(Updated)



EW dibosons FP_2



EW dibosons FP_2



Summary

- Can construct SM extensions with interacting UV fixed points
- Various scenarios to connect to SM at high or low scales
- Wide variety of experimental signatures — testable at present and future colliders