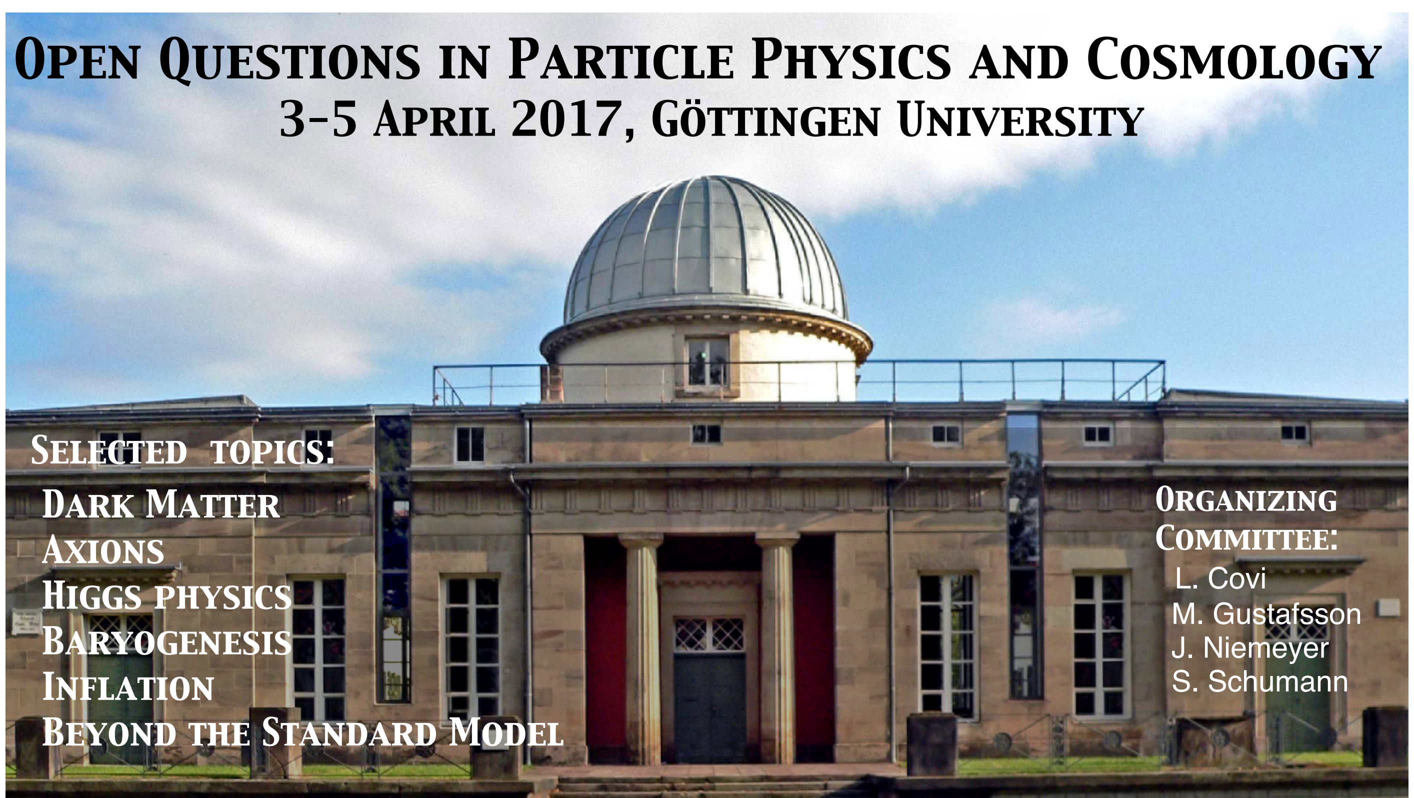
asymptotic safety BSM

Daniel F Litim

University of Sussex



AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727
AD Bond, DF Litim, 1608.00519
DF Litim, F Sannino, 1406.2337

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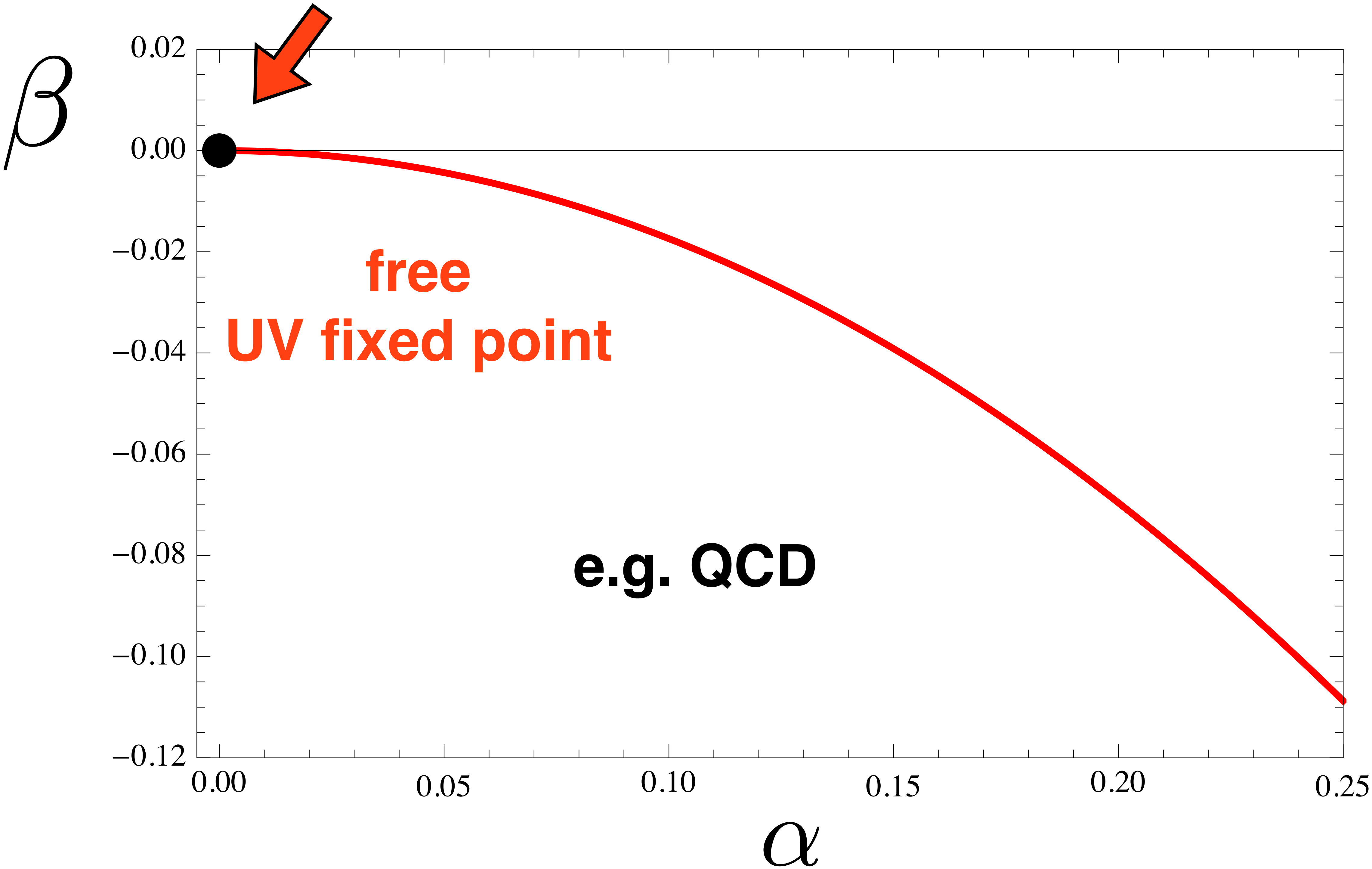
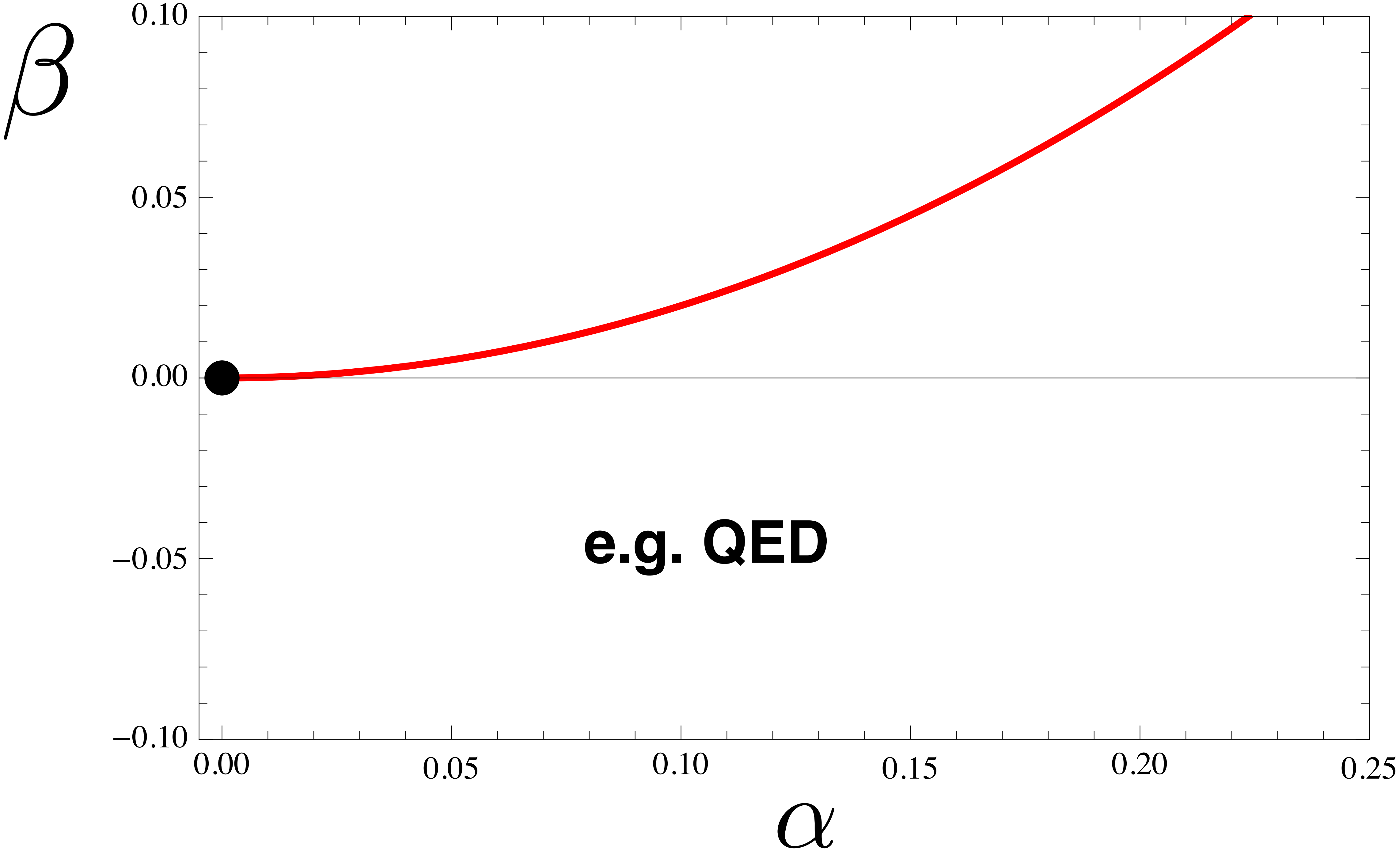
asymptotic freedom



infrared freedom



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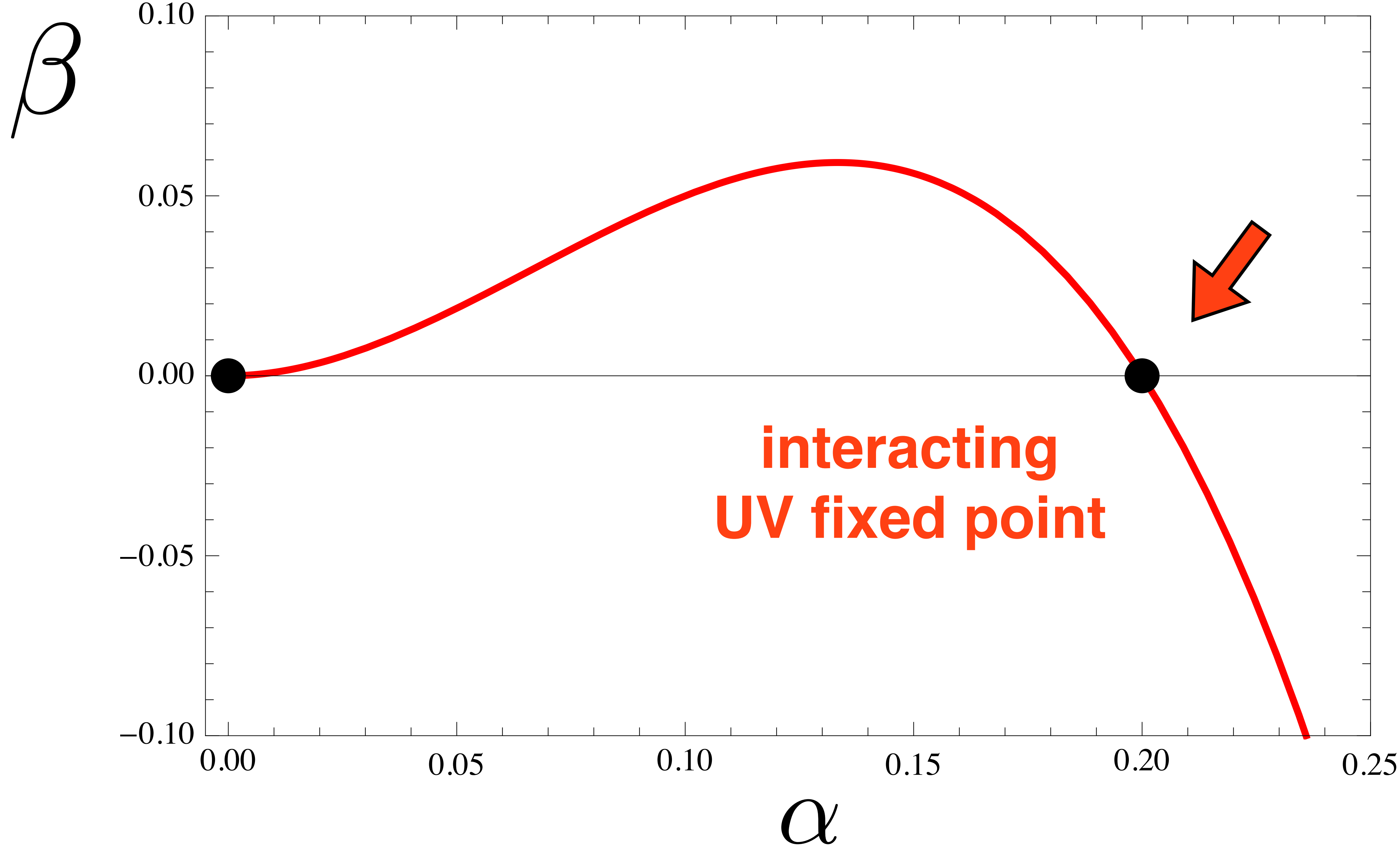
asymptotic safety



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theorems for asymptotic safety

Bond, Litim 1608.00519

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 *)

*) provided certain auxiliary conditions hold true

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fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad\qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

weakly coupled fixed point $\quad 0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad\qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

weakly coupled fixed point

$$0 < \alpha^* = B/C \ll 1$$

competition between matter and gauge fields

$$B = \frac{2}{3}\left(11C_2^G - 2S_2^F - \frac{1}{2}S_2^S\right)$$

$$C = 2\left[\left(\frac{10}{3}C_2^G + 2C_2^F\right)S_2^F + \left(\frac{1}{3}C_2^G + 2C_2^S\right)S_2^S - \frac{34}{3}(C_2^G)^2\right]$$

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fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

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fixed points

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fixed points

gauge theory

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$$\beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

weakly coupled fixed point $0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

$B, C > 0:$

asymptotic freedom

Caswell-Banks-Zaks IR FP

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fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

weakly coupled fixed point $\quad 0 < \alpha^* = B/C \ll 1$

competition between matter and gauge fields

$B, C > 0 :$ asymptotic freedom
Caswell-Banks-Zaks IR FP

$B, C < 0 :$ asymptotic safety UV FP
no known examples !

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fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad\qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

$B, C < 0:$ **UV fixed point ?**

$$C = \frac{2}{11}\left[2S_2^F\left(11C_2^F + 7C_2^G\right) + 2S_2^S\left(11C_2^S - C_2^G\right) - 17B\,C_2^G\right]$$

fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2}$$

$$\beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

$B, C < 0:$ **UV fixed point**

$$C = \frac{2}{11}\Big[\underbrace{2S_2^F\left(11C_2^F + 7C_2^G\right)}_{\text{fermions}} \underbrace{+\,2S_2^S\left(11C_2^S - C_2^G\right)}_{\text{scalars}} \underbrace{-\,17B\,C_2^G}_{\text{1-loop}}\Big]$$

fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

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no go theorem

Caswell '74

fixed points

gauge theory

$$\alpha = \frac{g^2}{(4\pi)^2} \qquad\qquad \beta = -B\,\alpha^2 + C\,\alpha^3 + \mathcal{O}(\alpha^4)$$

$B, C < 0:$ **UV fixed point**

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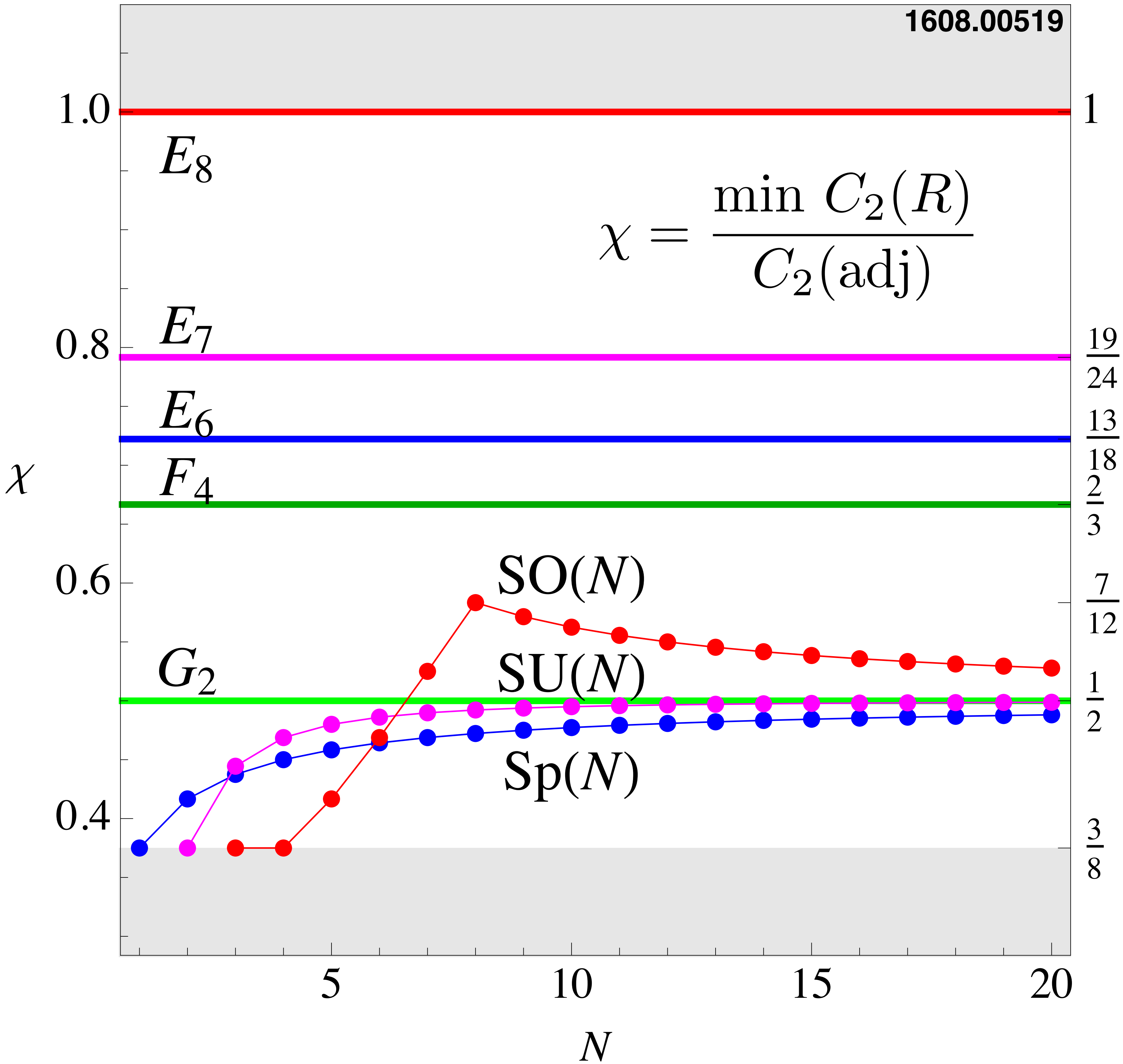
must have $\quad C_2^S < \frac{1}{11}C_2^G$

quadratic Casimirs

result:



asymptotic safety

result

1608.00519

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**
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c)	semi-simple, with or without abelian factors	fermions, any rep	**No**	**No**
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		fermions and scalars, any rep	**No**	**No**

strict no go theorems

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can more couplings help?

more gauge couplings	**No** (same sign)
scalar self-couplings	**No** (start at 3- or 4-loop)
Yukawa couplings	**Yes** (start at 2-loop)

basics of asymptotic safety

gauge Yukawa theory

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y \overset{!}{=} 0 \qquad t = \ln \mu/\Lambda$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y \overset{!}{=} 0 \qquad \alpha_* \ll 1$$

loop coefficients $D, E, F > 0$ in any QFT

Yukawa's **slow down** the running of the gauge

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basics of asymptotic safety

gauge Yukawa theory

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y \qquad t = \ln \mu/\Lambda$$

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y \qquad \alpha_* \ll 1$$

interacting UV fixed point provided that

$$\boxed{D\,F - C\,E > 0}$$

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asymptotic safety

result: necessary and sufficient conditions

1608.00519

case	gauge group	matter	Yukawa	asymptotic safety
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 *)

*) provided certain auxiliary conditions hold true

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asymptotic safety

result:

1608.00519

case	gauge group	matter	**Yukawa**	**asymptotic safety**
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** *)

*) **provided certain auxiliary conditions hold true**

exact proofs of existence (Veneziano limit)

SU(N) + scalars + fermions

DF Litim, F Sannino, 1406.2337

SU(N) x SU(M) + scalars + fermions

AD Bond, DF Litim, @ERG2016 & @BadHonnef2017 (to appear)

asymptotic safety beyond the SM

AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727

minimal framework:

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

N_F flavors of BSM fermions $\psi_i(R_3, R_2, Y)$

BSM singlet scalars S_{ij}

features: vector-like fermions

global flavor symmetry $U(N_F) \times U(N_F)$

single BSM Yukawa coupling

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asymptotic safety beyond the SM

AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727

minimal framework:

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

N_F **flavors of BSM fermions** $\psi_i(R_3, R_2, Y)$

BSM singlet scalars S_{ij}

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

$$L_{\text{BSM, kin.}} = \text{Tr}\left(\overline{\psi}\, i\not{D}\, \psi\right) + \text{Tr}\left(\partial_\mu S^\dagger\, \partial^\mu S\right)$$

UV fixed points

possible fixed points

(two gauge plus BSM Yukawa couplings)

#	gauge couplings		BSM Yukawa	type & info	
$\mathbf{FP_1}$	$\alpha_3^* = 0$	$\alpha_2^* = 0$	$\alpha_y^* = 0$	$\mathbf{G \cdot G}$	non-interacting
$\mathbf{FP_2}$	$\alpha_3^* = 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	$\mathbf{G \cdot GY}$	partially interacting
$\mathbf{FP_3}$	$\alpha_3^* > 0$	$\alpha_2^* = 0$	$\alpha_y^* > 0$	$\mathbf{GY \cdot G}$	partially interacting
$\mathbf{FP_4}$	$\alpha_3^* > 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	$\mathbf{GY \cdot GY}$	fully interacting

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running couplings

gauge couplings

BSM Yukawa

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

BSM RG beta functions

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

BSM fixed points

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$\mathbf{FP_2}$

$\alpha_2^* > 0$ weak becomes strong

$\alpha_3^* = 0$ strong becomes weak

UV critical surface $\delta\alpha_2(\Lambda),\ \delta\alpha_3(\Lambda)$

$\mathbf{FP_3}$

$\alpha_3^* > 0$ strong remains strong

$\alpha_2^* = 0$ weak remains weak

UV critical surface $\delta\alpha_2(\Lambda),\ \delta\alpha_3(\Lambda)$

$\mathbf{FP_4}$

$$\frac{\alpha_2^*}{\alpha_3^*} \to \frac{3}{2}$$

weak becomes the new strong

UV critical surface $\delta\alpha_3(\Lambda)$

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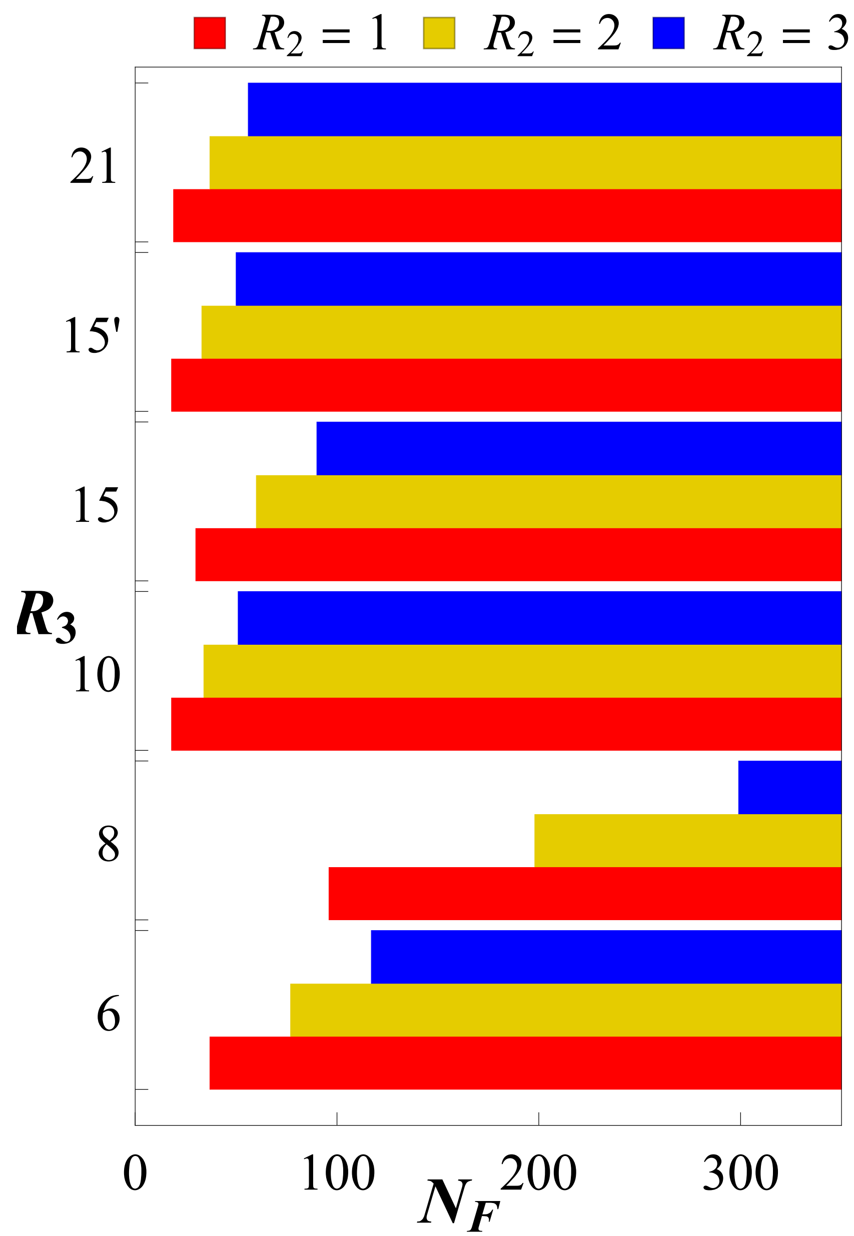
BSM fixed points

$$\mathbf{FP_3}$$

$$\alpha_3^* > 0$$

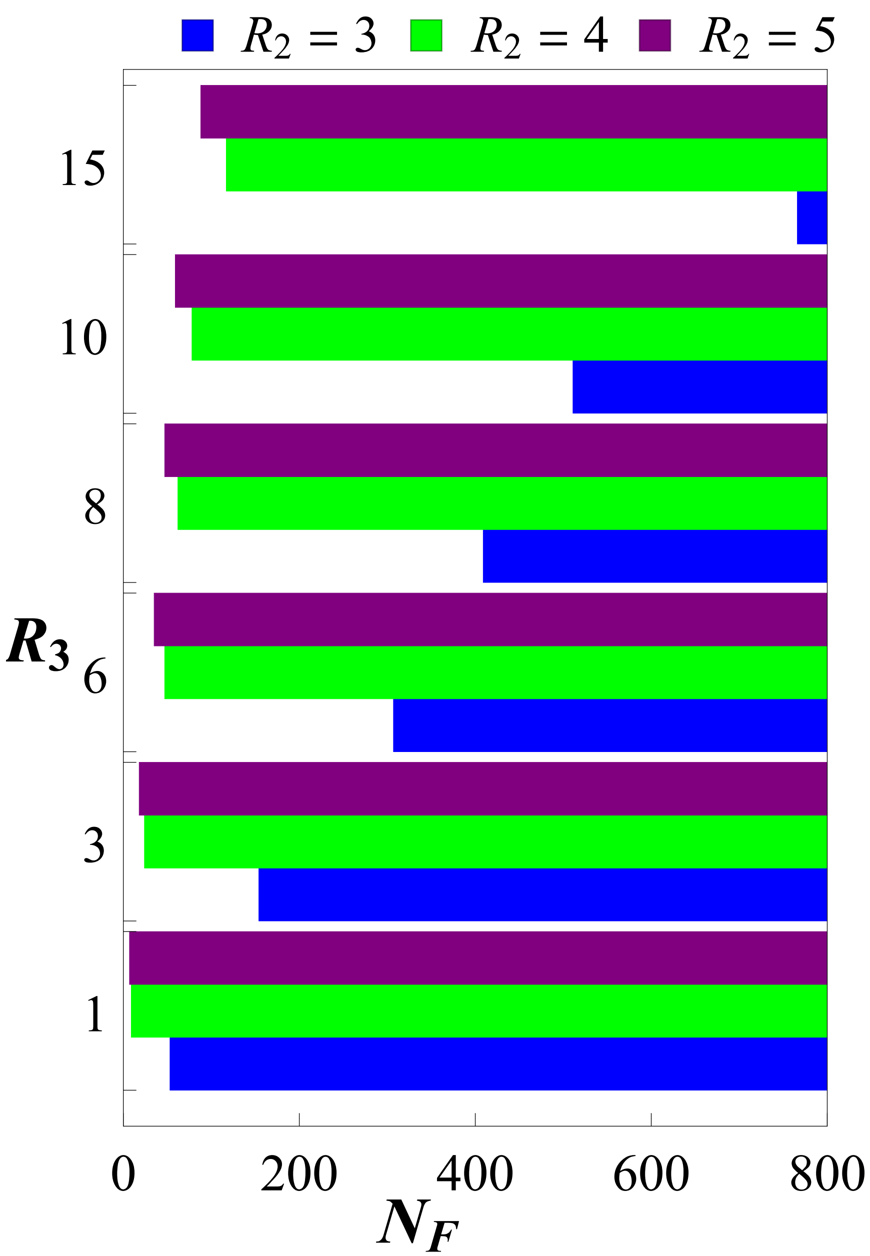
$$\alpha_2^* = 0$$



BSM fixed points

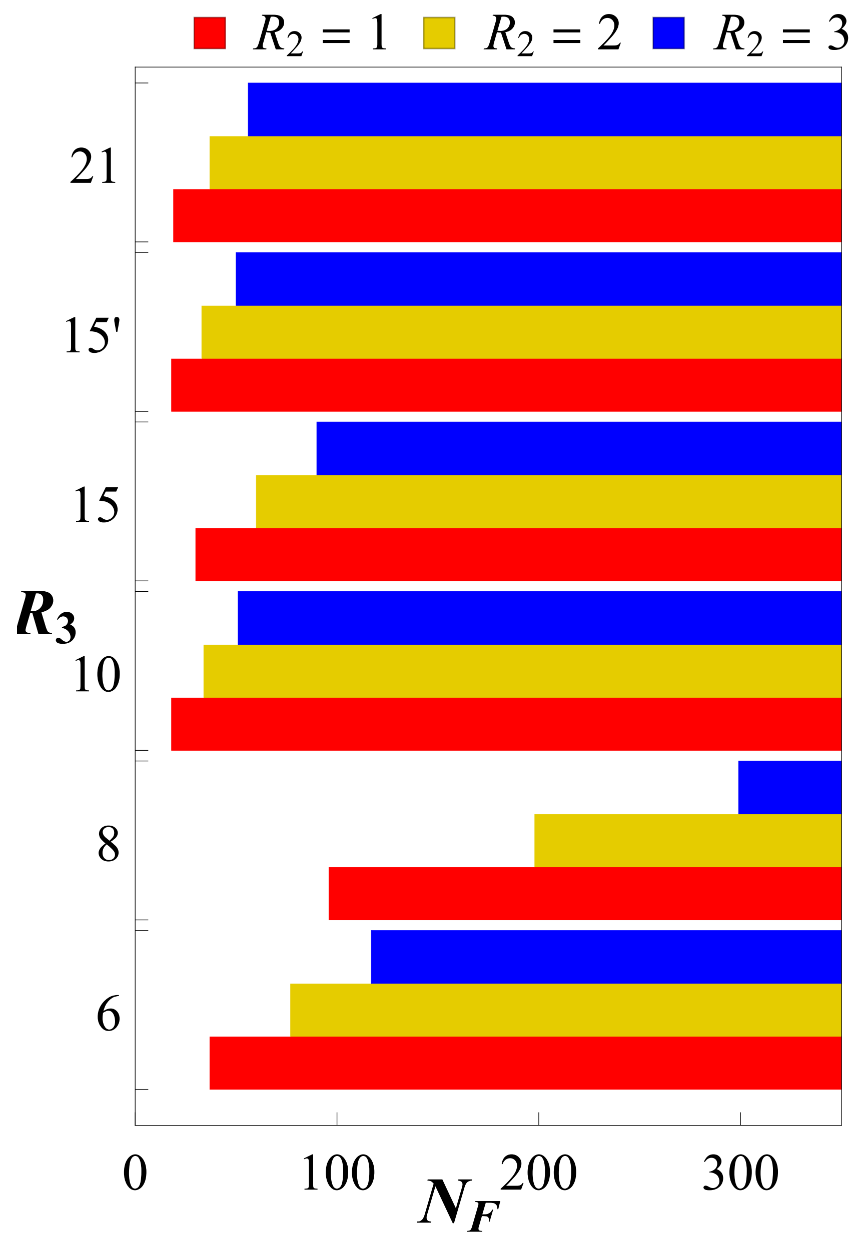
$\mathbf{FP_2}$

$$\alpha_2^* > 0$$
$$\alpha_3^* = 0$$



$\mathbf{FP_3}$

$$\alpha_3^* > 0$$
$$\alpha_2^* = 0$$



BSM fixed points

$\mathbf{FP_2}$

$\alpha_2^* > 0$
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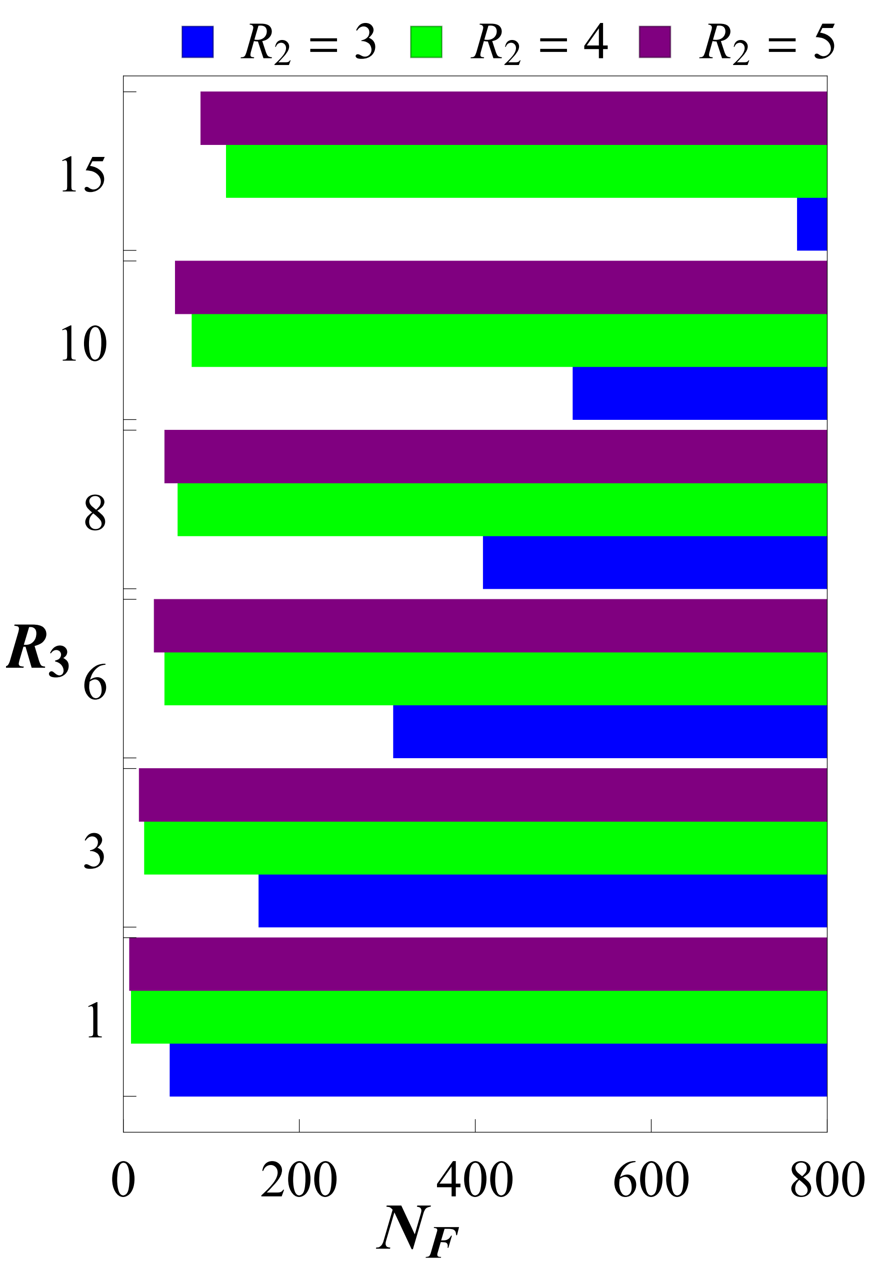
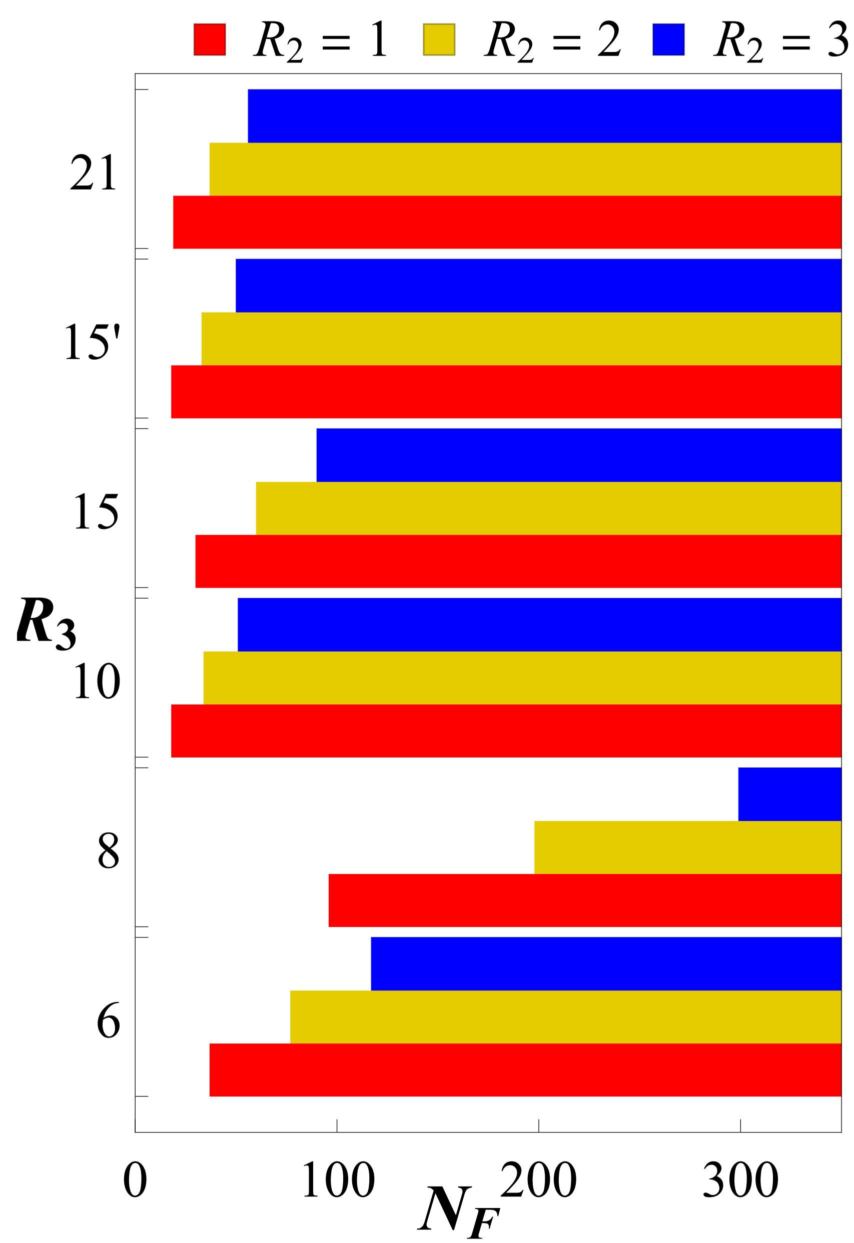


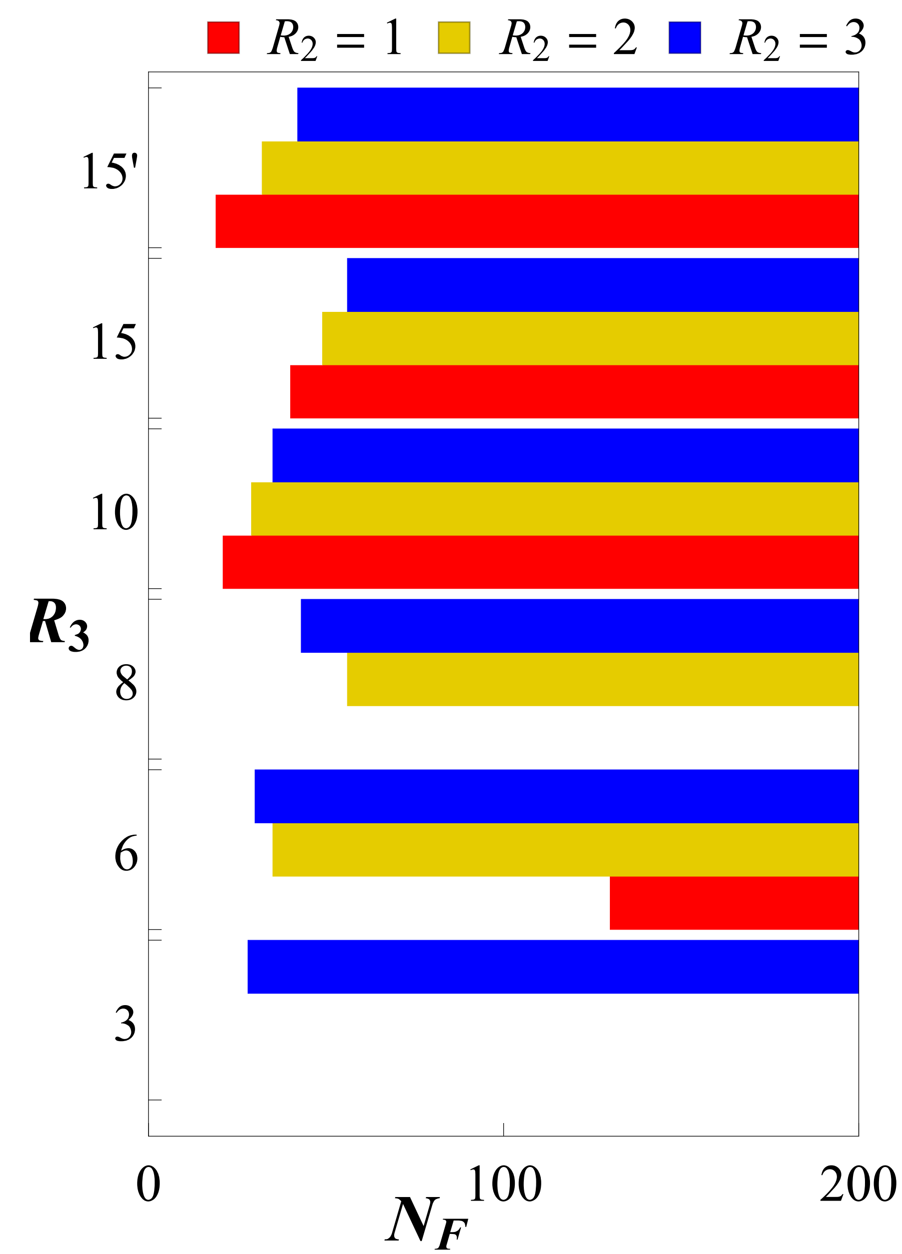
$\mathbf{FP_3}$

$\alpha_3^* > 0$
$\alpha_2^* = 0$

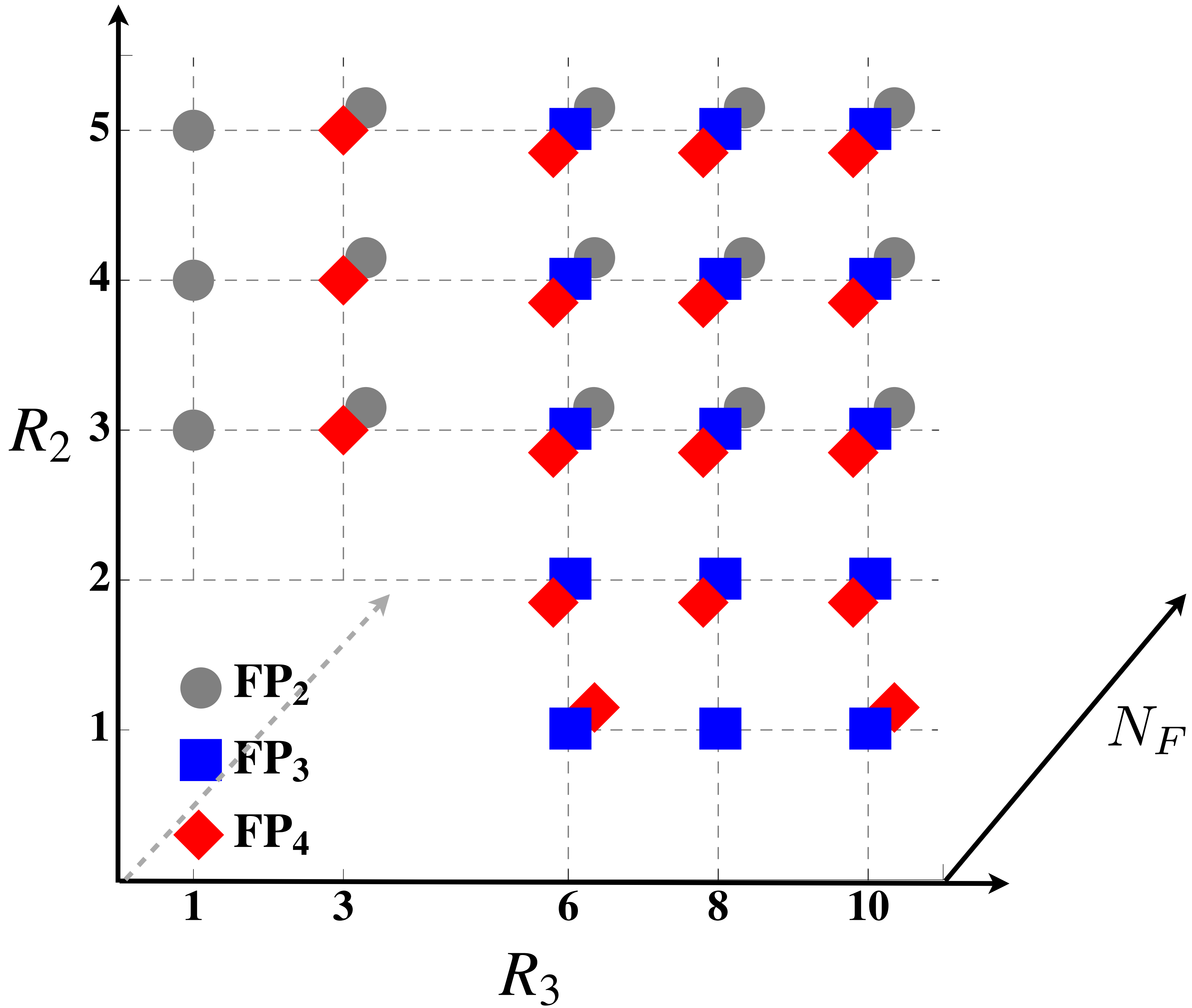


$\mathbf{FP_4}$

$\alpha_2^*, \alpha_3^* > 0$



summary of fixed points



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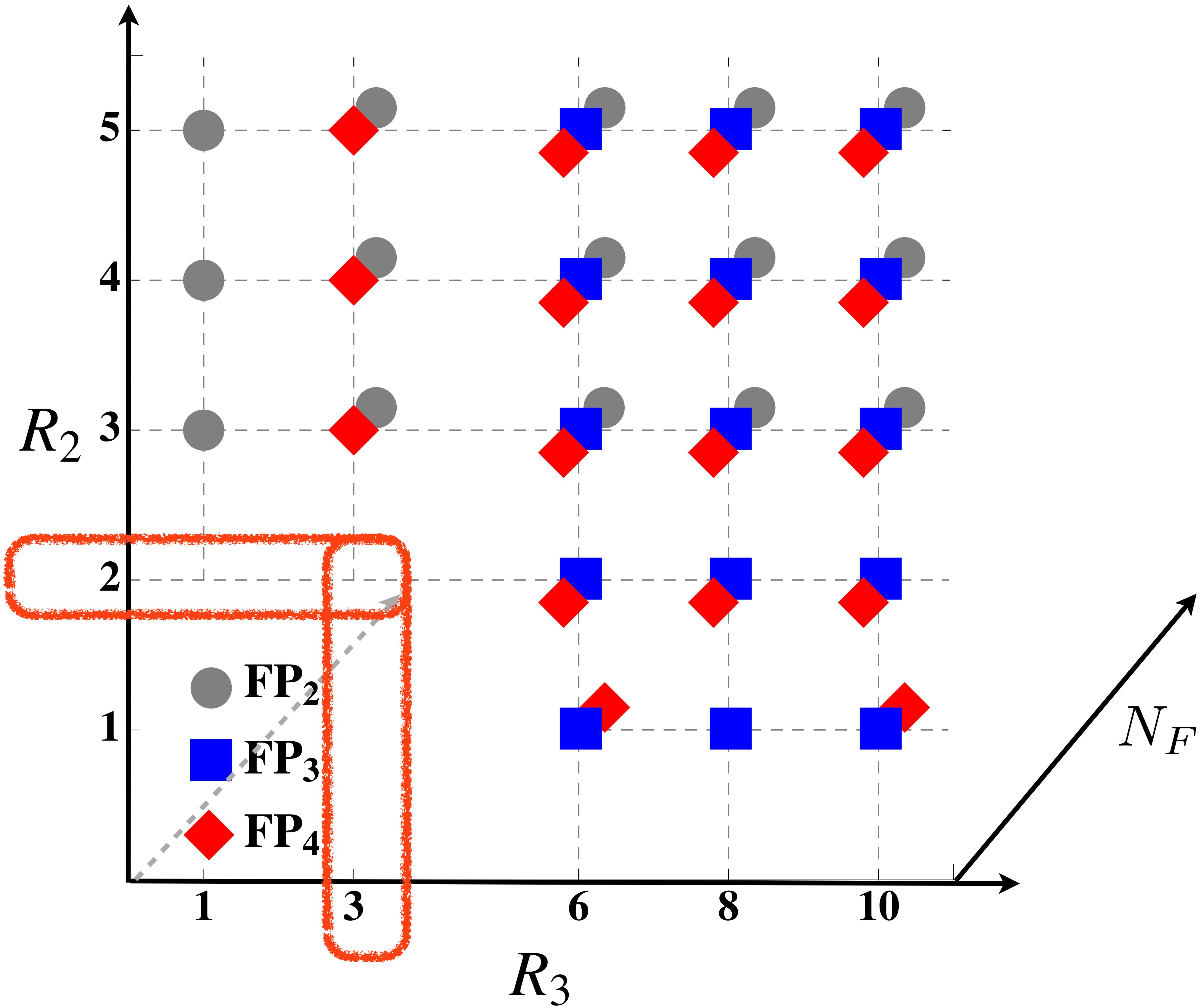

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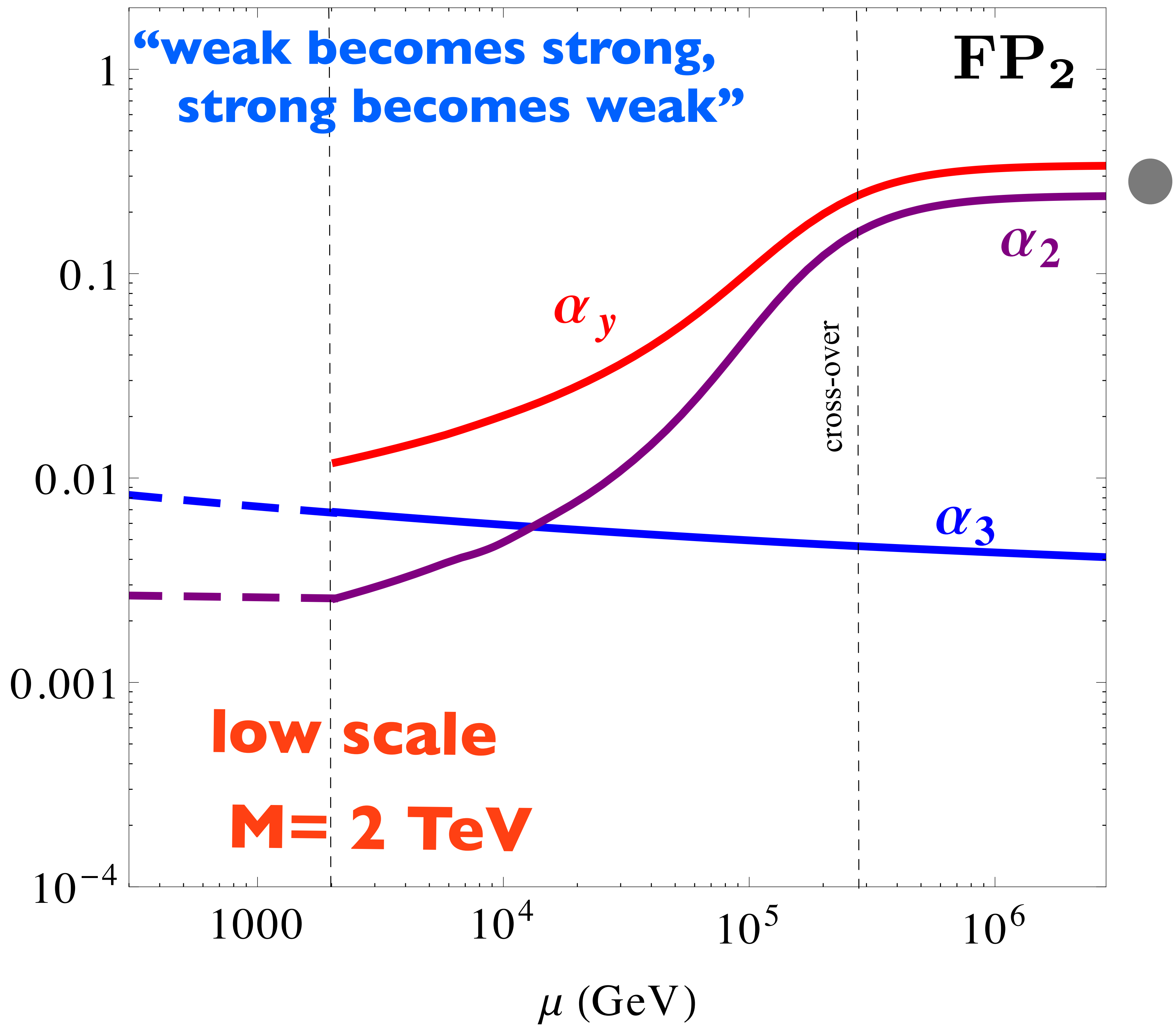
benchmark models

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	$\mathbf{FP_4}$

benchmark models

model A

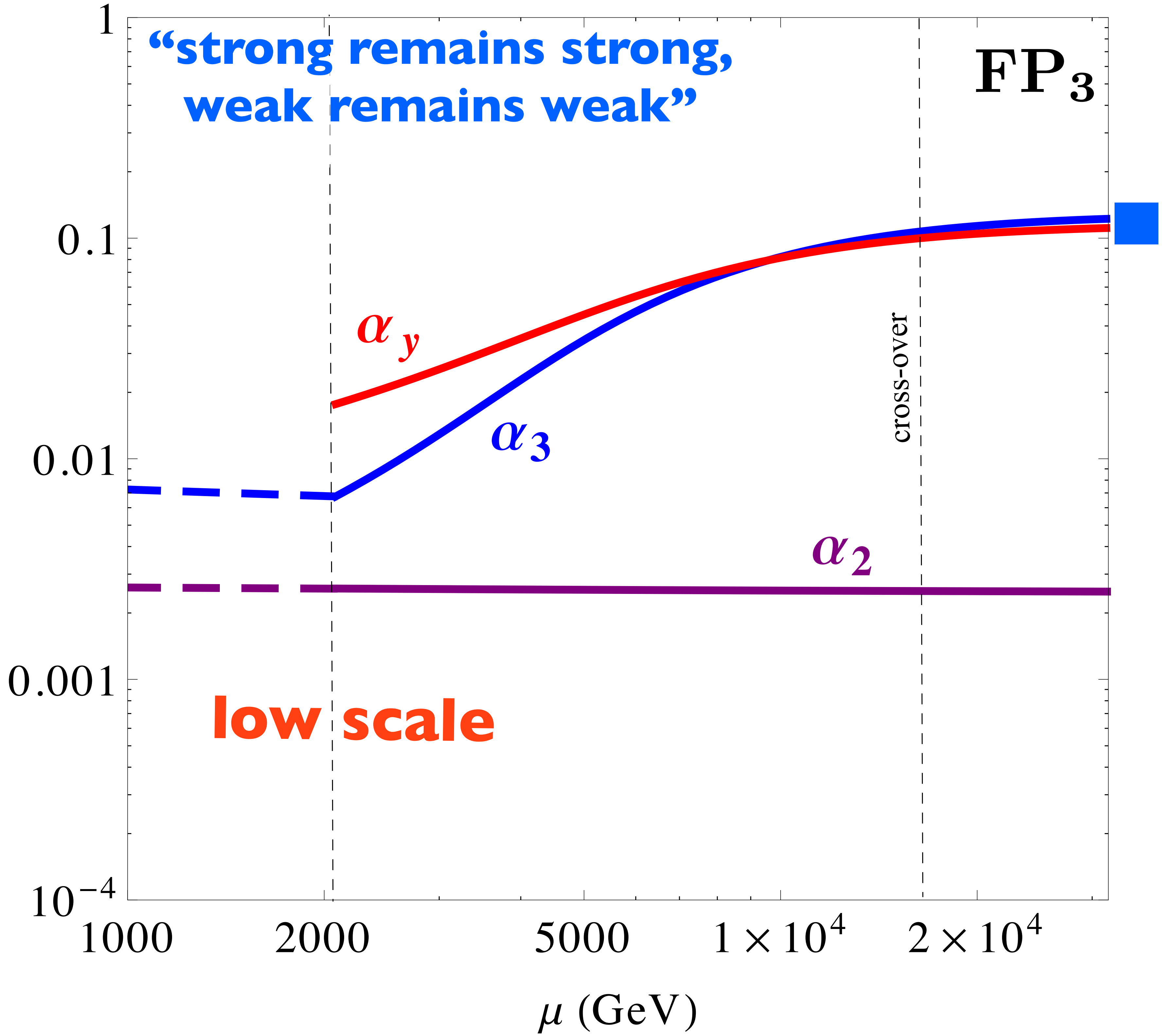
$(R_3, R_2, N_F) =$ $(\mathbf{1},\mathbf{4},12)$



benchmark models

model B

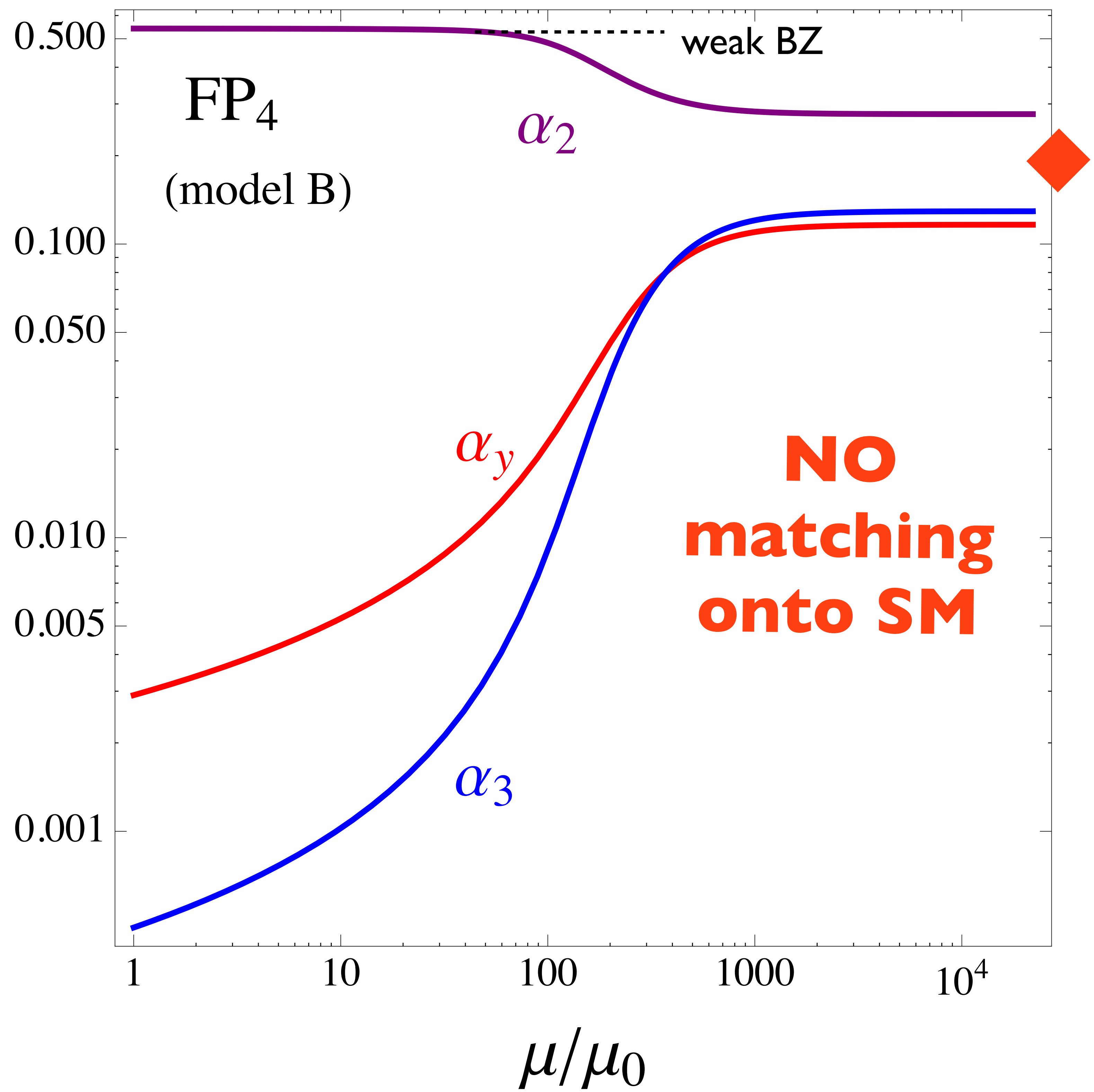
$(R_3, R_2, N_F) = (\mathbf{10},\mathbf{1},30)$



benchmark models

model B

$(R_3, R_2, N_F) =$ **(10,1,**30)



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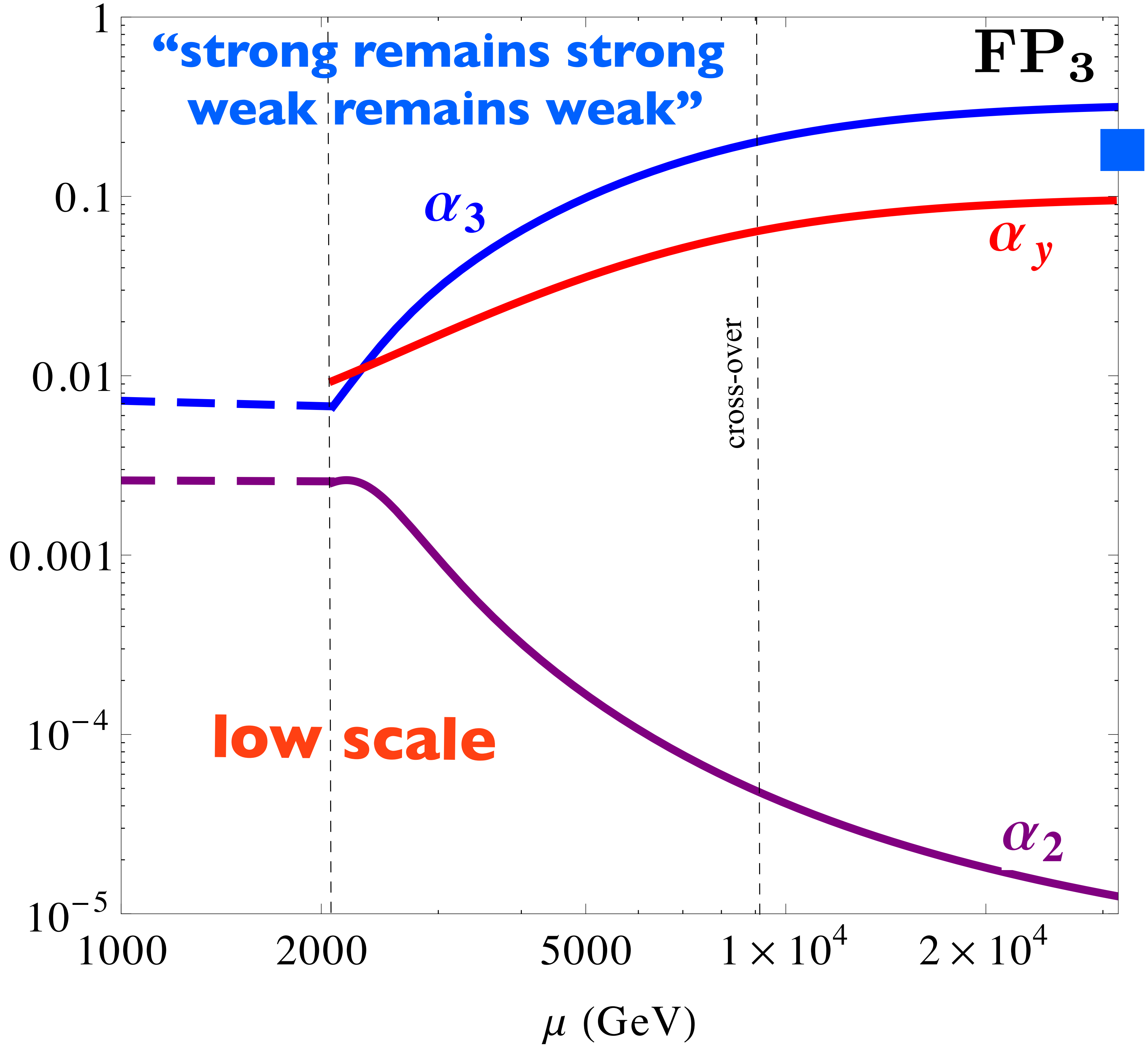
benchmark models

model C

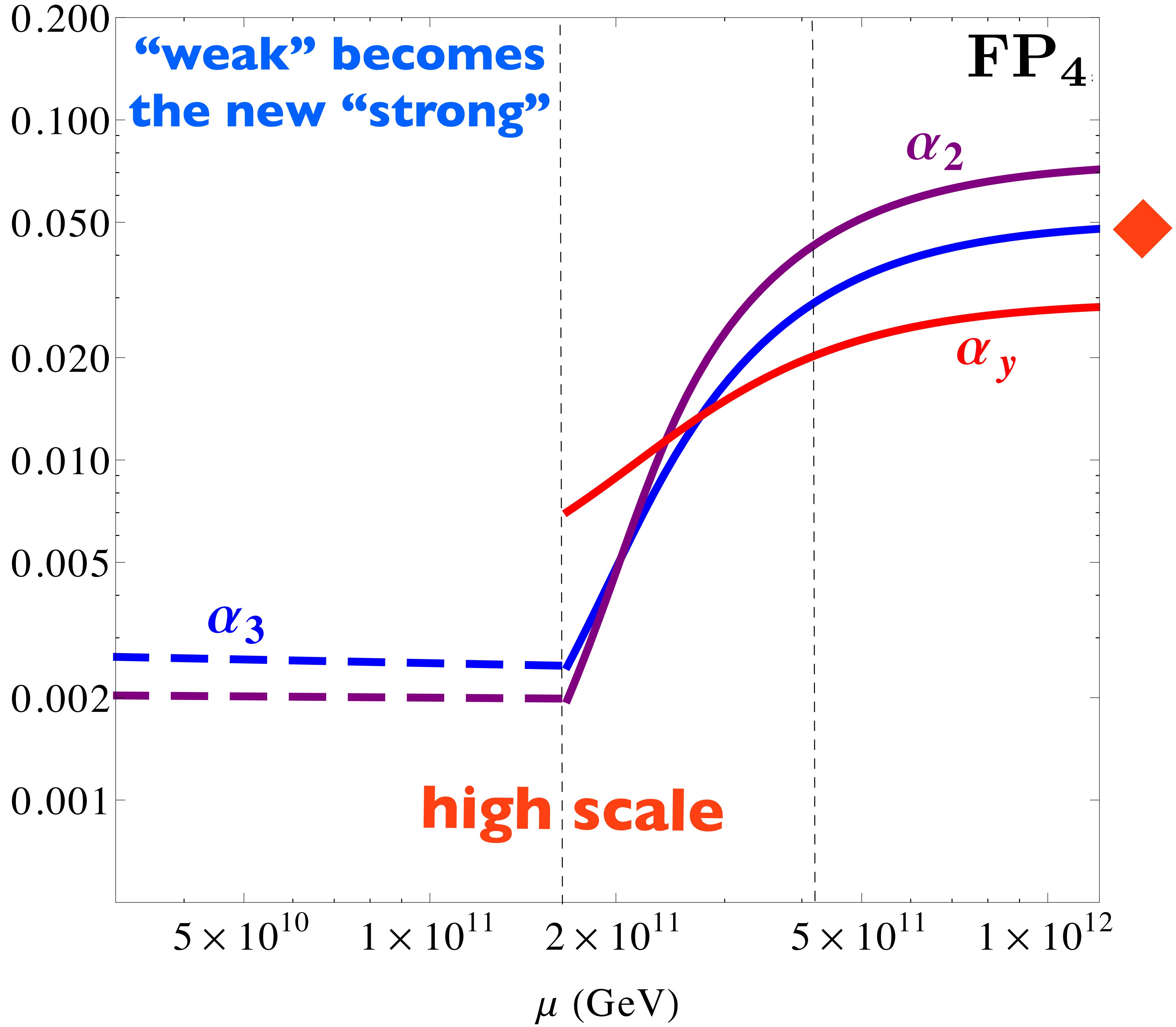
$(R_3, R_2, N_F) =$ $(\mathbf{10},\mathbf{4},80)$



benchmark models

model C

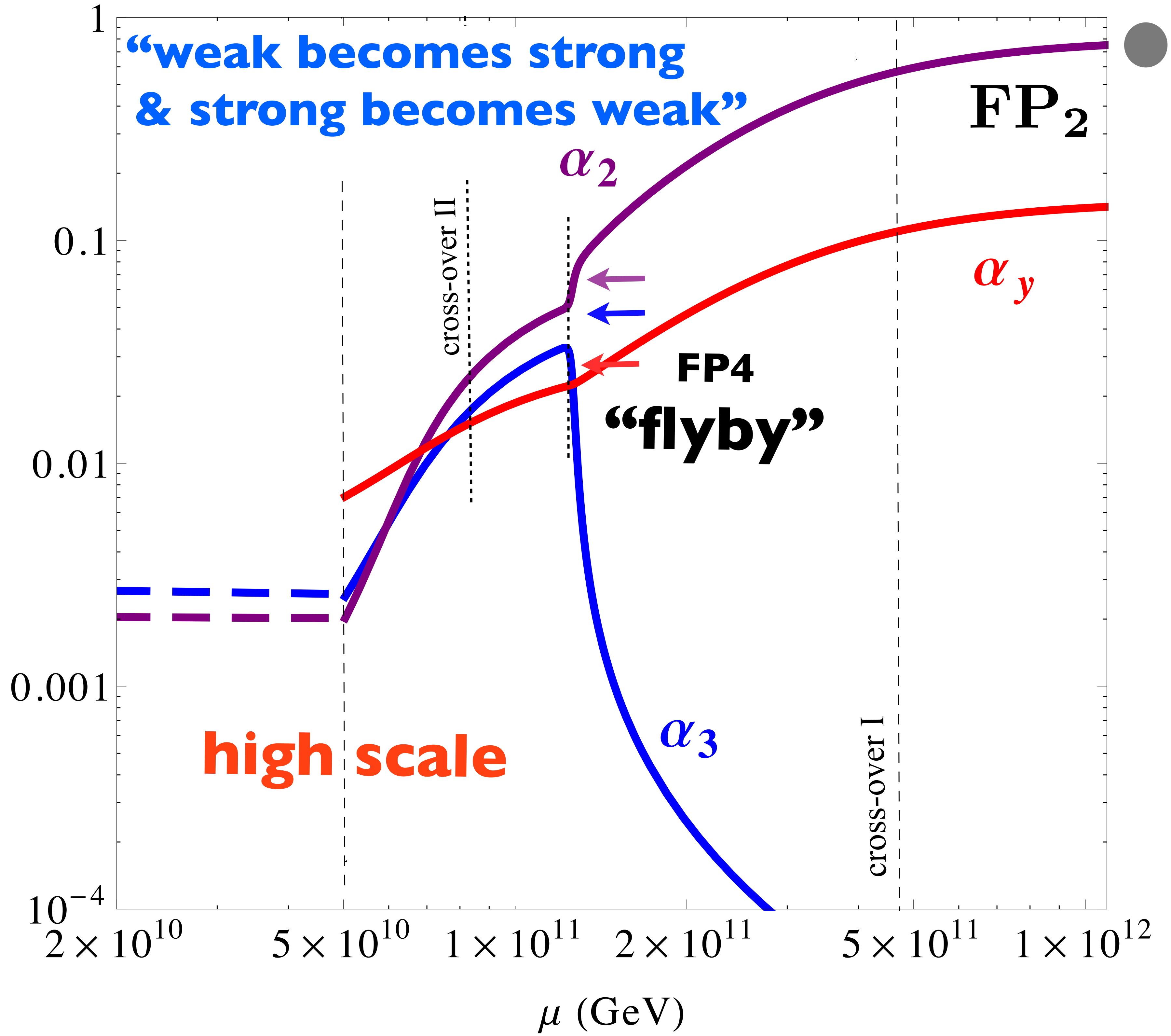
$(R_3, R_2, N_F) =$ (**10**,**4**,80)



benchmark models

model C

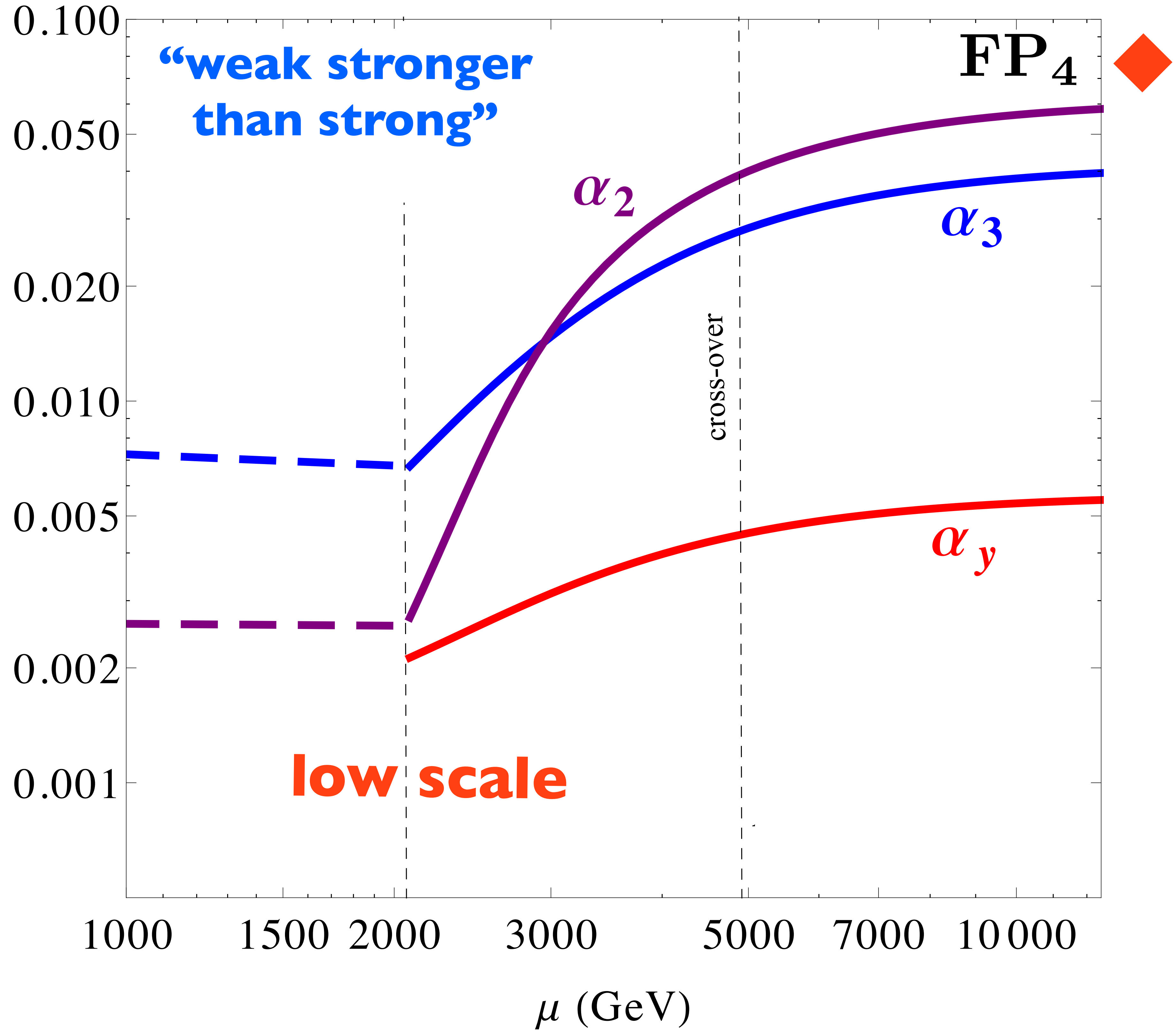
$(R_3, R_2, N_F) = \ (\mathbf{10}, \mathbf{4}, 80)$



benchmark models

model D

$(R_3, R_2, N_F) =$ (**3**,**4**,290)



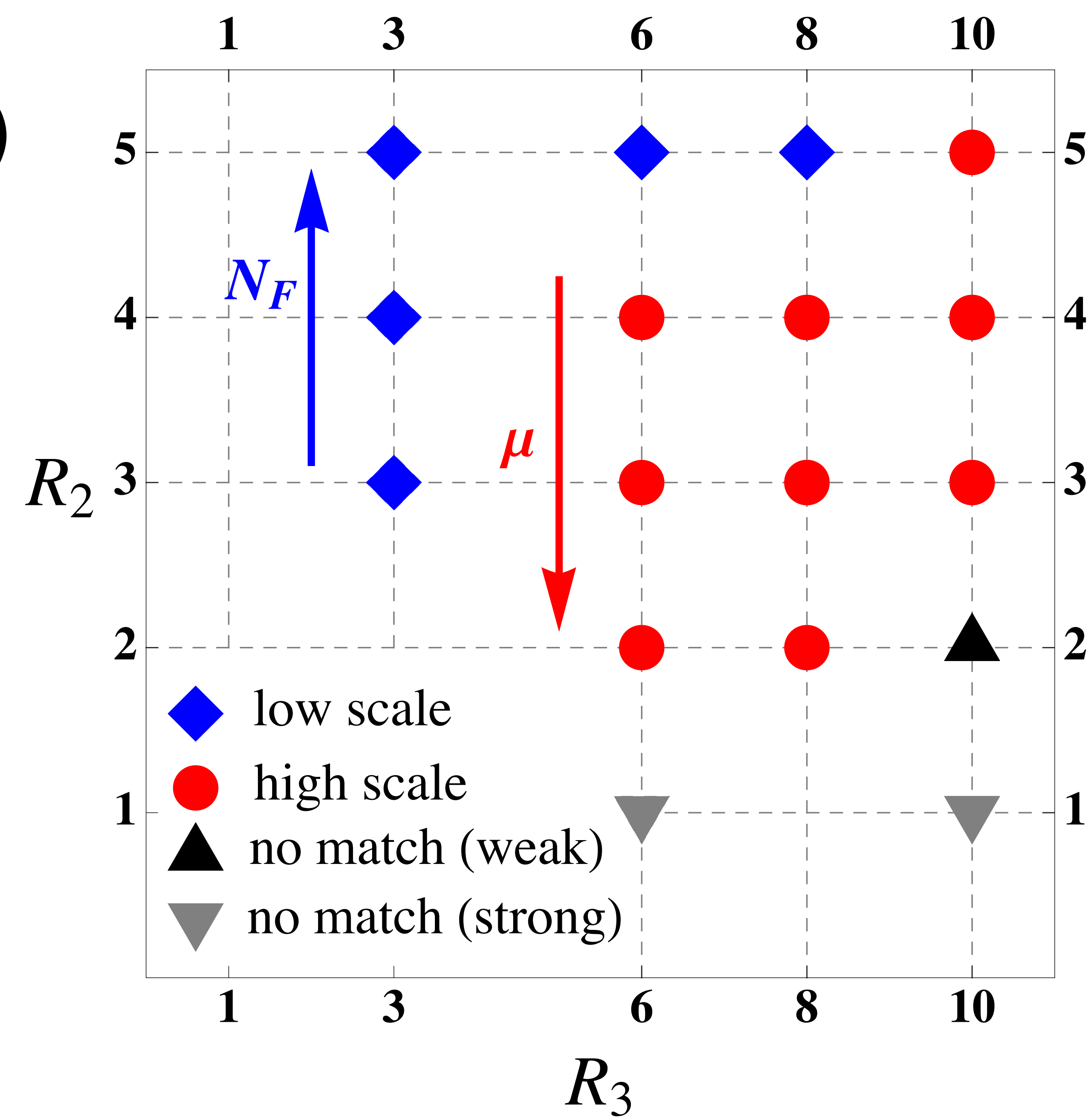
summary of SM matching: when it works

partially interacting FP (one safe, one free)

genuinely, except in very special circumstances

fully interacting FP (both safe)

for most reps - see plot:



asymptotic safety

collider phenomenology

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phenomenology

assume low scale matching

some BSM masses within TeV energy range

assume $R_3 \neq 1$ for LHC

($R_3 = 1$ can be tested at future e^+e^- colliders)

flavor symmetry: stable BSM fermions

broken flavor symmetry: lightest BSM fermion stable

constraints from

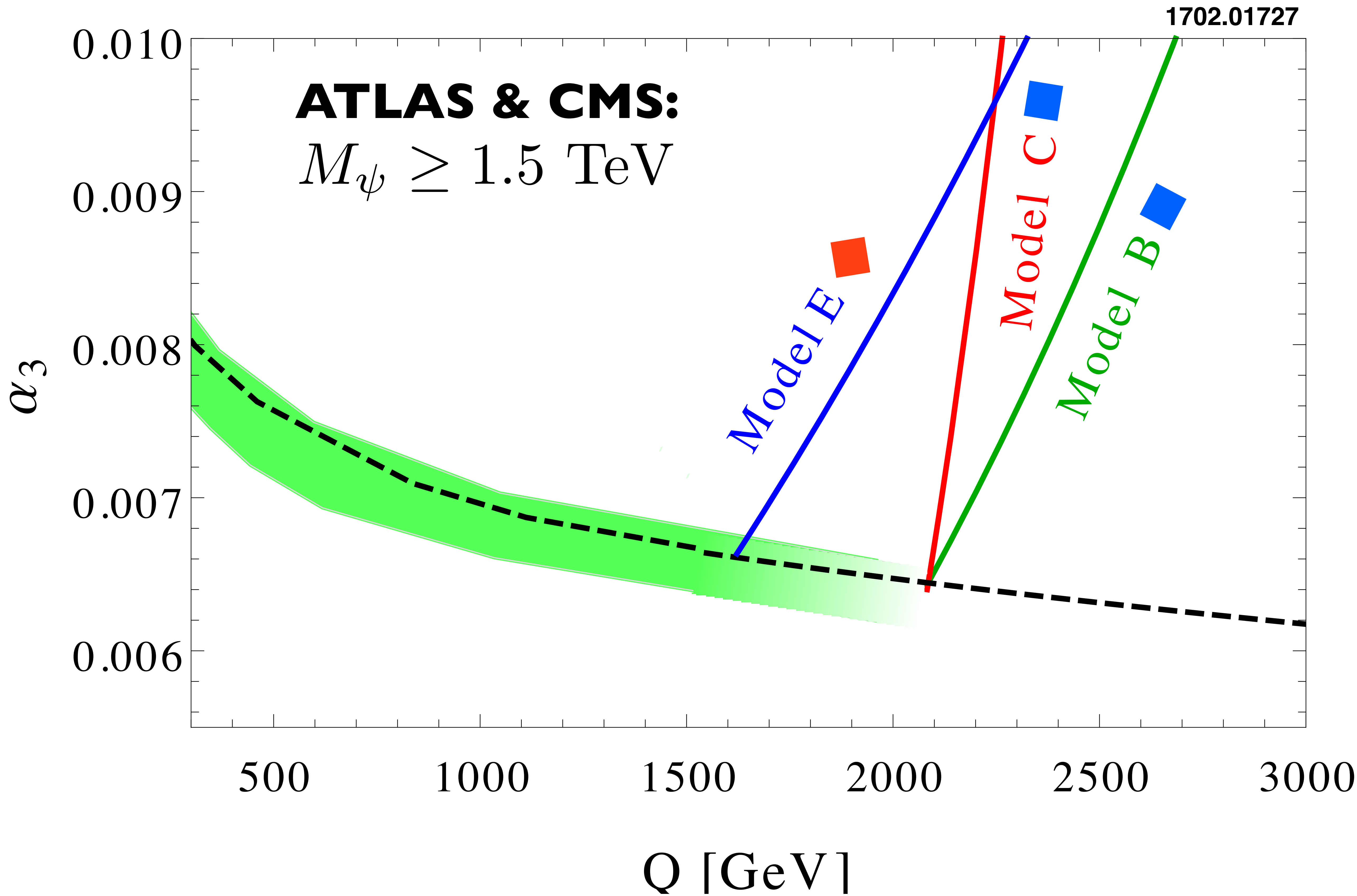
running couplings

the weak sector

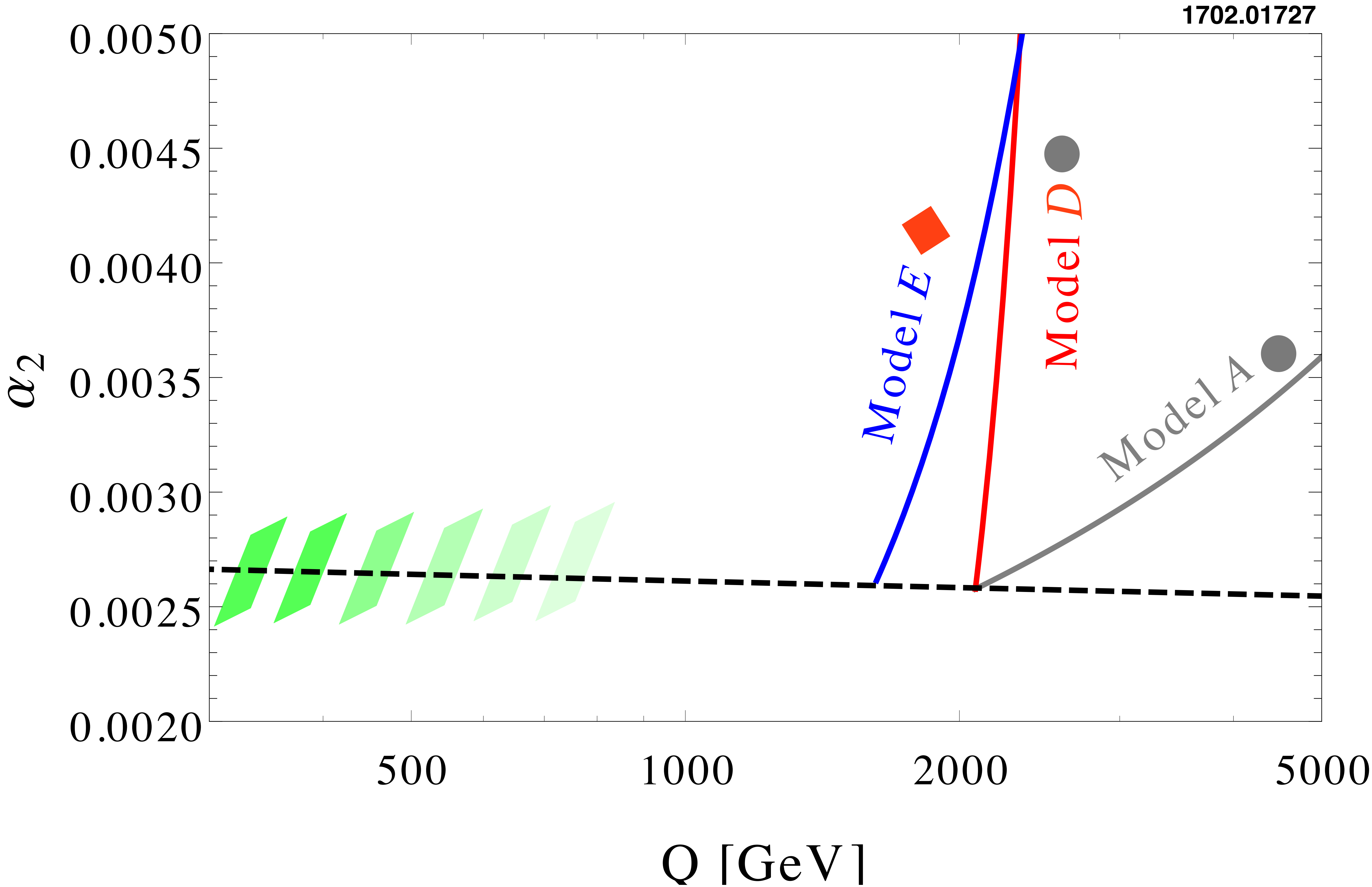
long-lived QCD bound states (R hadrons)

di-boson searches

SU(3) BSM running



SU(2) BSM running



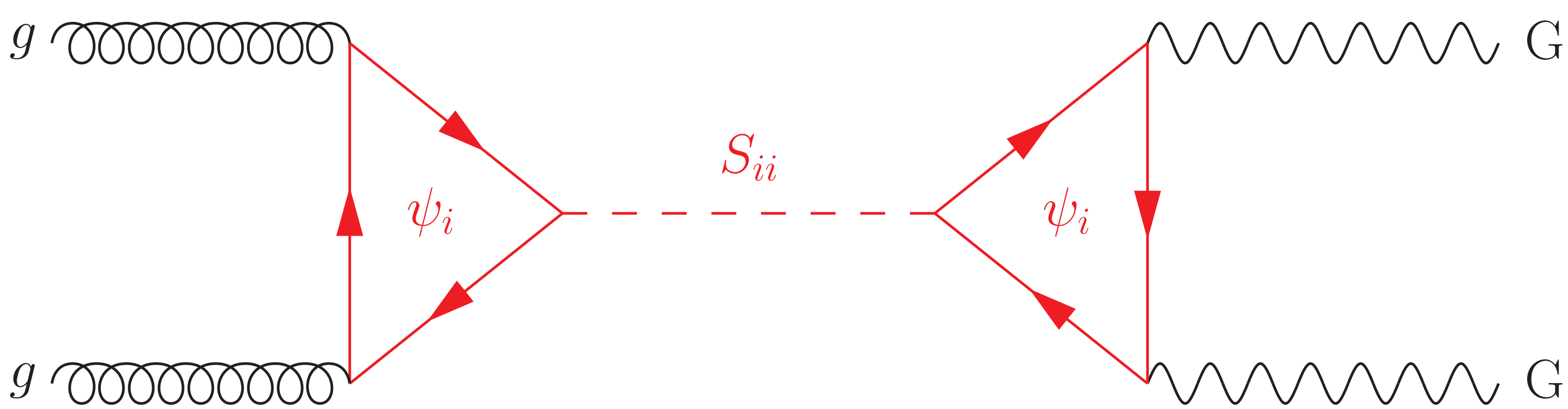
di-boson spectra and resonances

assume **resonant production** of BSM scalars

$$M_S < \sqrt{s} \qquad\qquad M_S < 2M_\psi$$

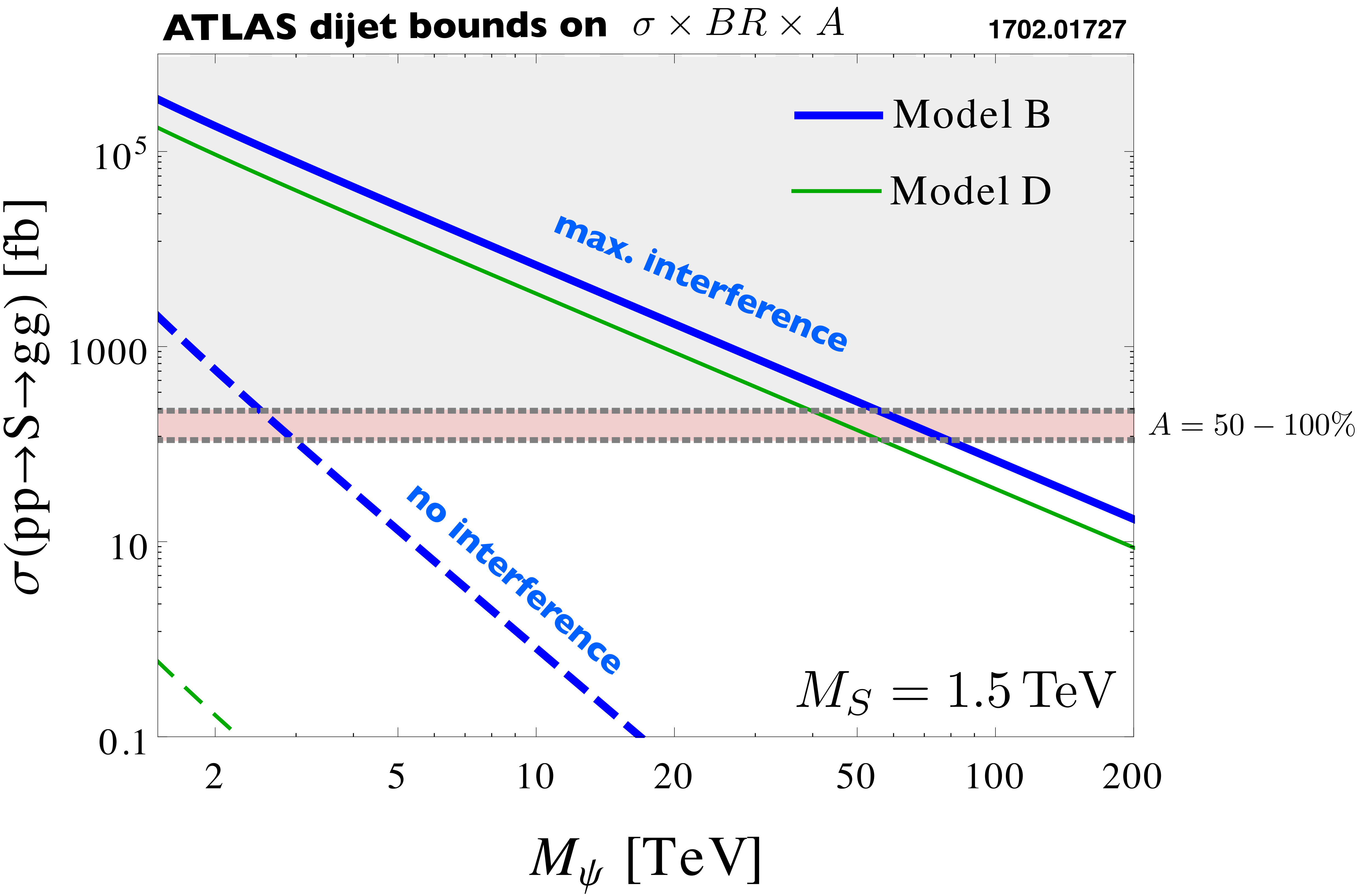
“low Ms” $M_S \lesssim M_\psi$ **“high Ms”** $M_\psi \lesssim M_S < 2M_\psi$

loop-mediated decay into $GG = gg,\ \gamma\gamma,\ ZZ,\ Z\gamma,\ \text{or}\ WW$



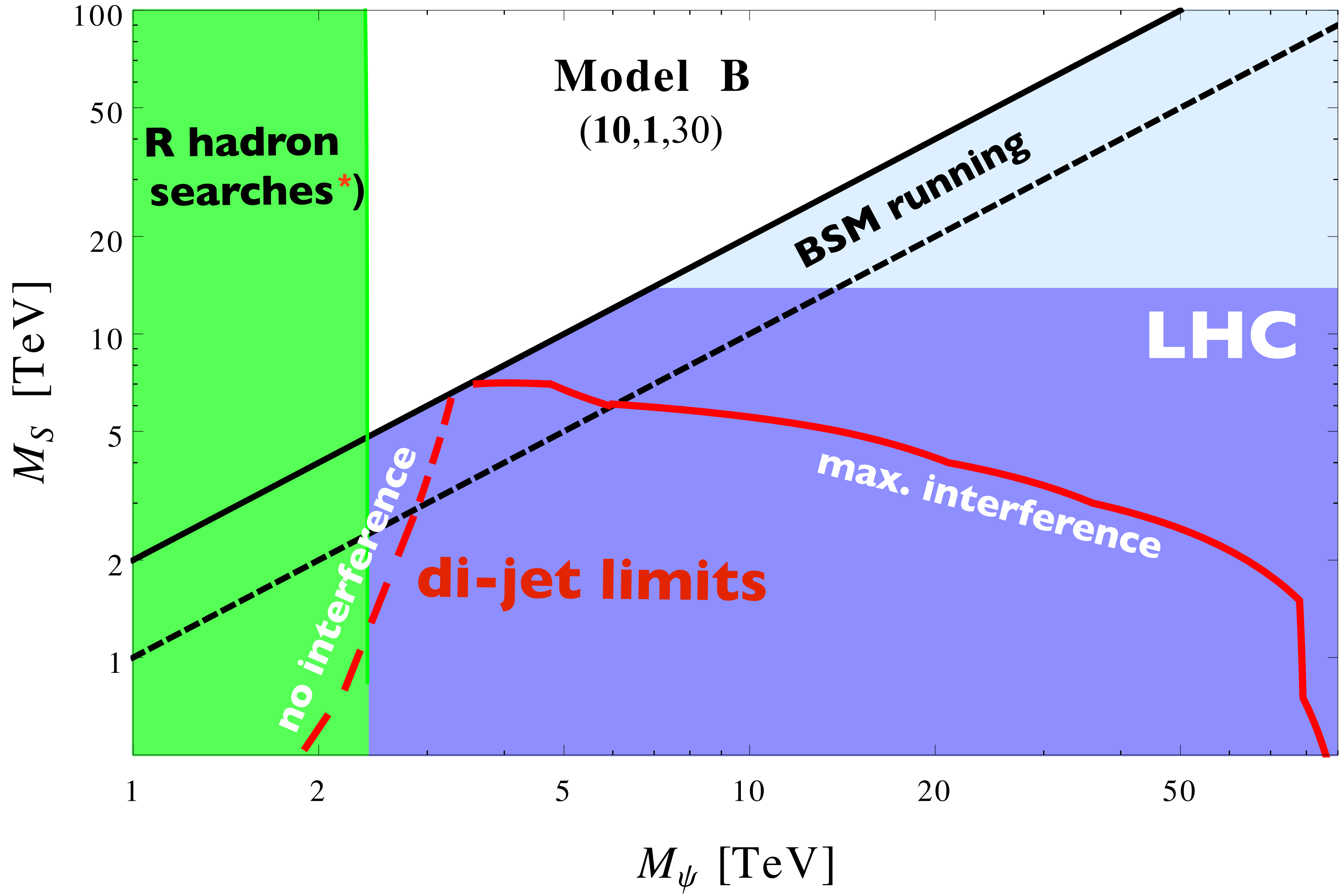
interference effects

dijet cross section



mass exclusion limits

1702.01727



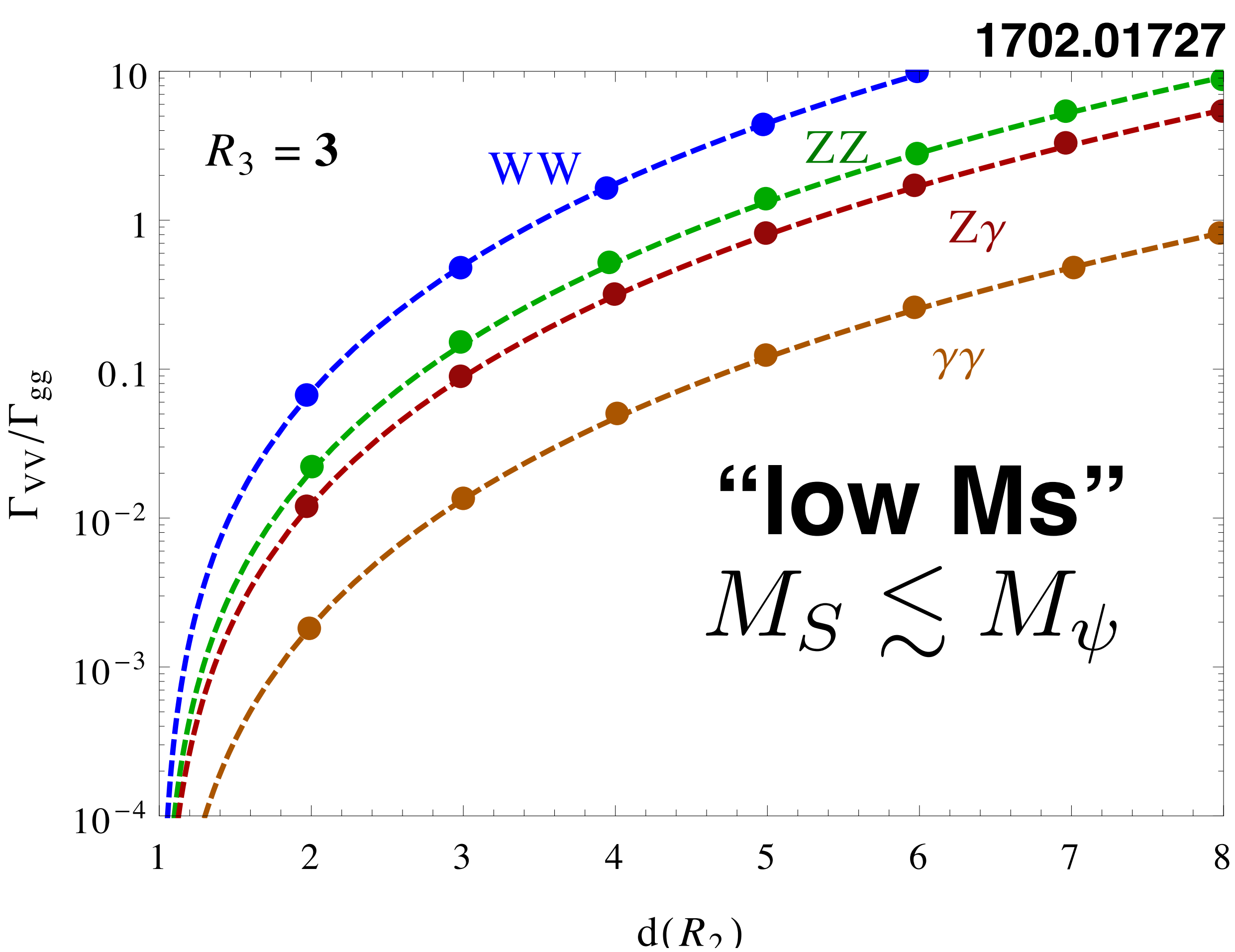
*) **fudged from 13 TeV ATLAS + CMS gluino analysis**

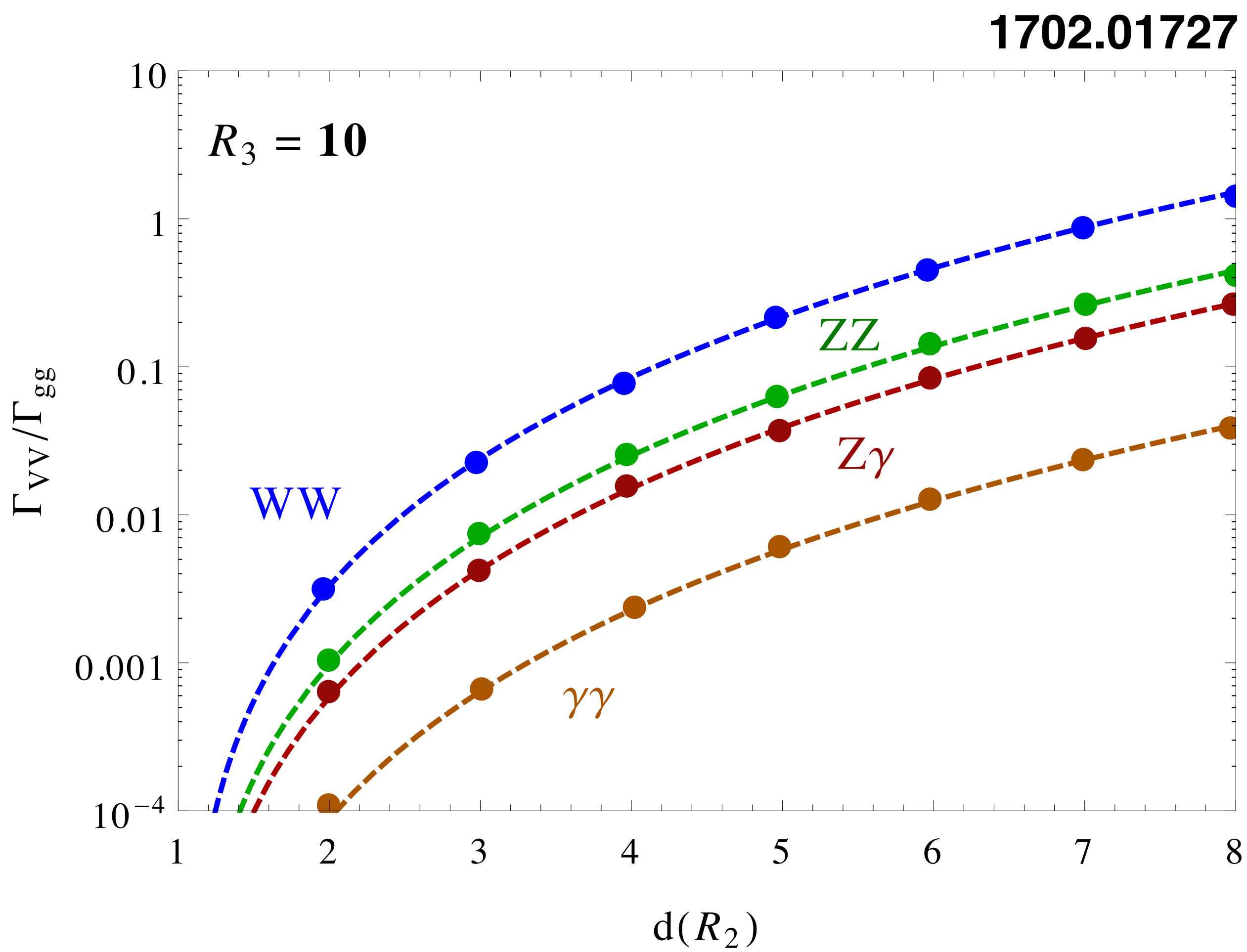
decays into electroweak gauge bosons

further signatures if $d(R_2) \neq 1$

general scalar resonance decaying into $WW, ZZ, Z\gamma, \gamma\gamma$

growth with dim(R2)





decays into electroweak gauge bosons

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“reduced” decay widths

$$\bar{\Gamma}_{VV} = \frac{1}{F}\frac{\Gamma_{VV}}{\Gamma_{gg}}\,, \quad \text{with} \quad F = \left(\frac{4}{3}\frac{C_2(R_2)}{C_2(R_3)}\right)^2$$

for small hypercharge coupling

$$\bar{\Gamma}_{WW} = \frac{\alpha_2^2}{\alpha_3^2}\,, \quad \bar{\Gamma}_{ZZ} \approx \frac{1}{2}\frac{\alpha_2^2}{\alpha_3^2}\,, \quad \bar{\Gamma}_{Z\gamma} \approx \frac{\alpha_1}{\alpha_3}\frac{\alpha_2}{\alpha_3}\,, \quad \bar{\Gamma}_{\gamma\gamma} \approx \frac{1}{2}\frac{\alpha_1^2}{\alpha_3^2}$$

modifications for “high Ms”:

$\mathbf{FP_2}$ $\quad \bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}$ ↗ $\quad \bar{\Gamma}_{\gamma\gamma}$ **?**

$\mathbf{FP_3}$ $\quad \bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}, \bar{\Gamma}_{\gamma\gamma}$ ↘

$\mathbf{FP_4}$ $\quad \bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}$ ↗ $\quad \bar{\Gamma}_{\gamma\gamma}$ ↘ $\quad \bar{\Gamma}_{Z\gamma}$ **?**

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conclusions

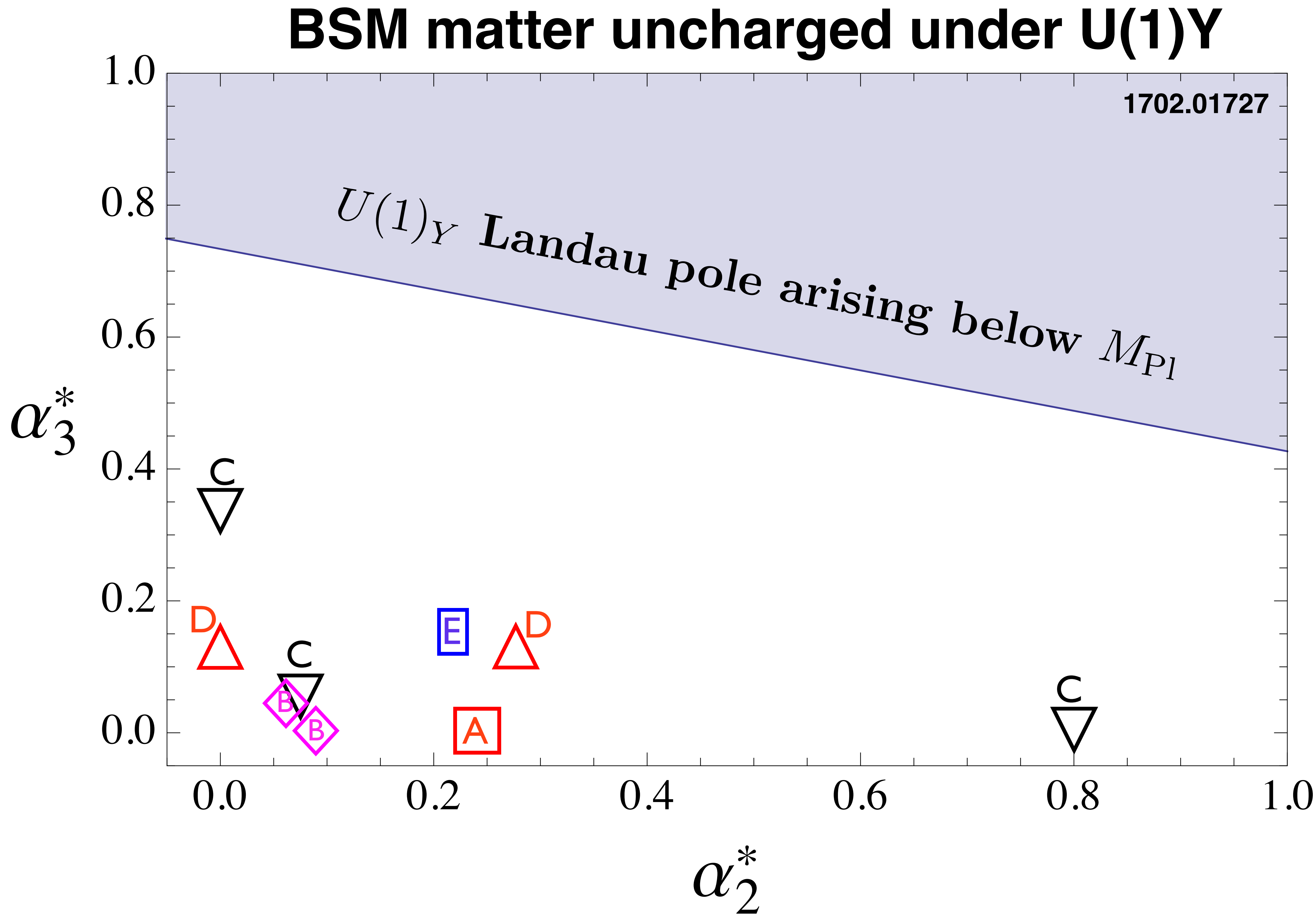
asymptotic safety provides

directions for model building

can be tested at colliders

extra material

U(1)Y BSM


BSM matter uncharged under U(1)Y
1702.01727
$U(1)_Y$ Landau pole arising below $M_{\rm Pl}$
α_3^*
α_2^*
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A
B
B
C
C
C
D
D
E

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U(1)Y BSM

BSM matter charged under U(1)Y

(to appear)

model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	AF for $U(1)_Y$	info
A	$(\mathbf{1}, \mathbf{4}, 12)$	0	0.2407	0.3385	$Y > 0.228$	$\mathbf{FP_2}$ ●
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	$Y > 0.107$	$\mathbf{FP_3}$ ■
		0.1292	0.2769	0.1163	$Y > 0.114$	$\mathbf{FP_4}$ ♦
C	$(\mathbf{10}, \mathbf{4}, 80)$	0.3317	0	0.0995	$Y > 0.024$	$\mathbf{FP_3}$ ■
		0.0503	0.0752	0.0292	$Y > 0.050$	$\mathbf{FP_4}$ ♦
		0	0.8002	0.1500	$Y > 0.018$	$\mathbf{FP_2}$ ●
D	$(\mathbf{3}, \mathbf{4}, 290)$	0	0.0895	0.0066	$Y > 0.042$	$\mathbf{FP_2}$ ●
		0.0416	0.0615	0.0056	$Y > 0.052$	$\mathbf{FP_4}$ ♦
E	$(\mathbf{3}, \mathbf{3}, 72)$	0.1499	0.2181	0.0471	$Y > 0.073$	$\mathbf{FP_4}$ ♦

lower bounds
on hypercharge

SU(2) BSM running