asymptotic safety beyond the Standard Model

Daniel F Litim

University of Sussex

Colloquium SFB-676
"Particles, strings, and the early universe"
DESY, 28 June 2017

standard model

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local QFT for fundamental interactions

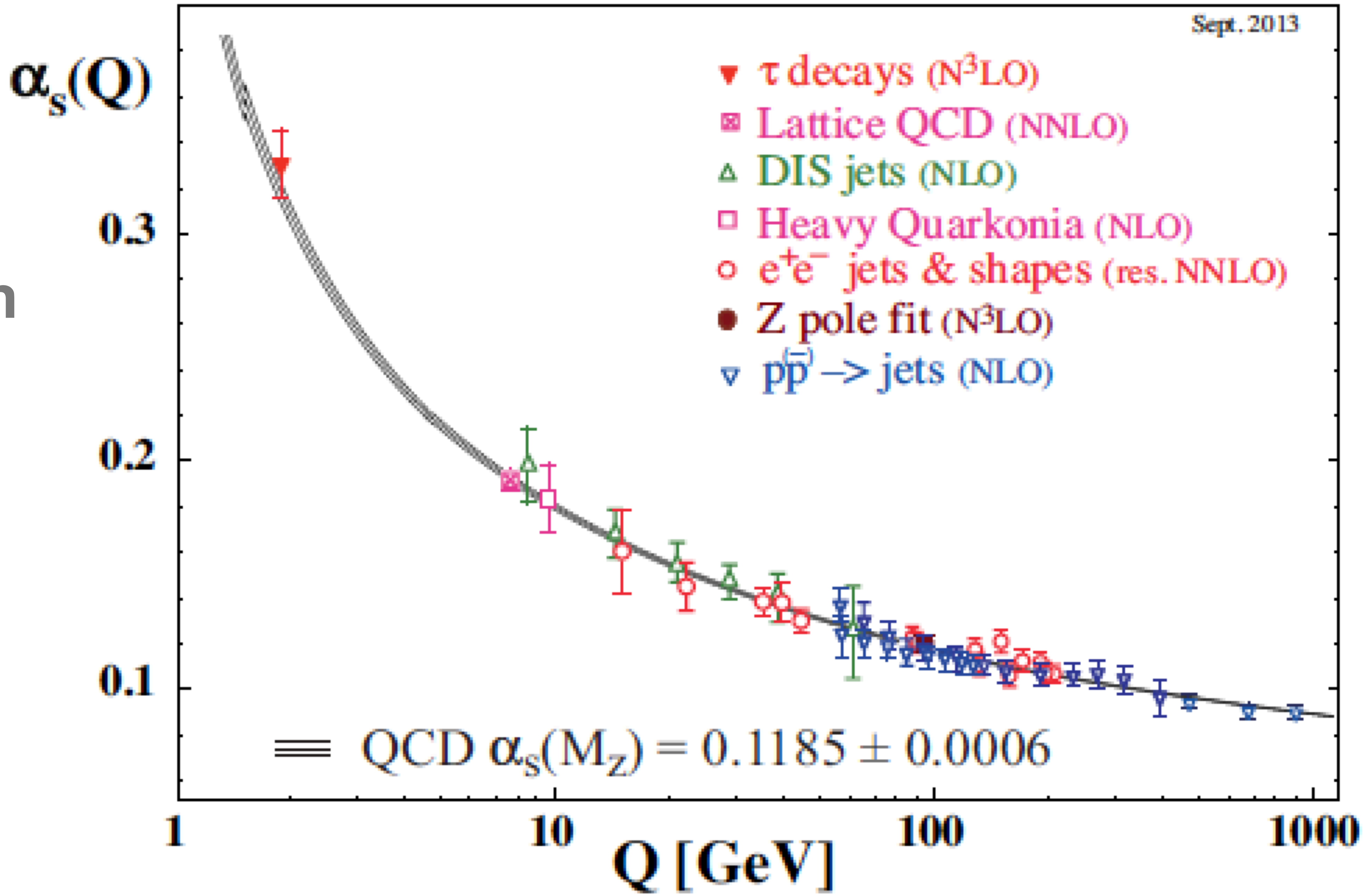
strong nuclear force
weak force
electromagnetic force

open challenges

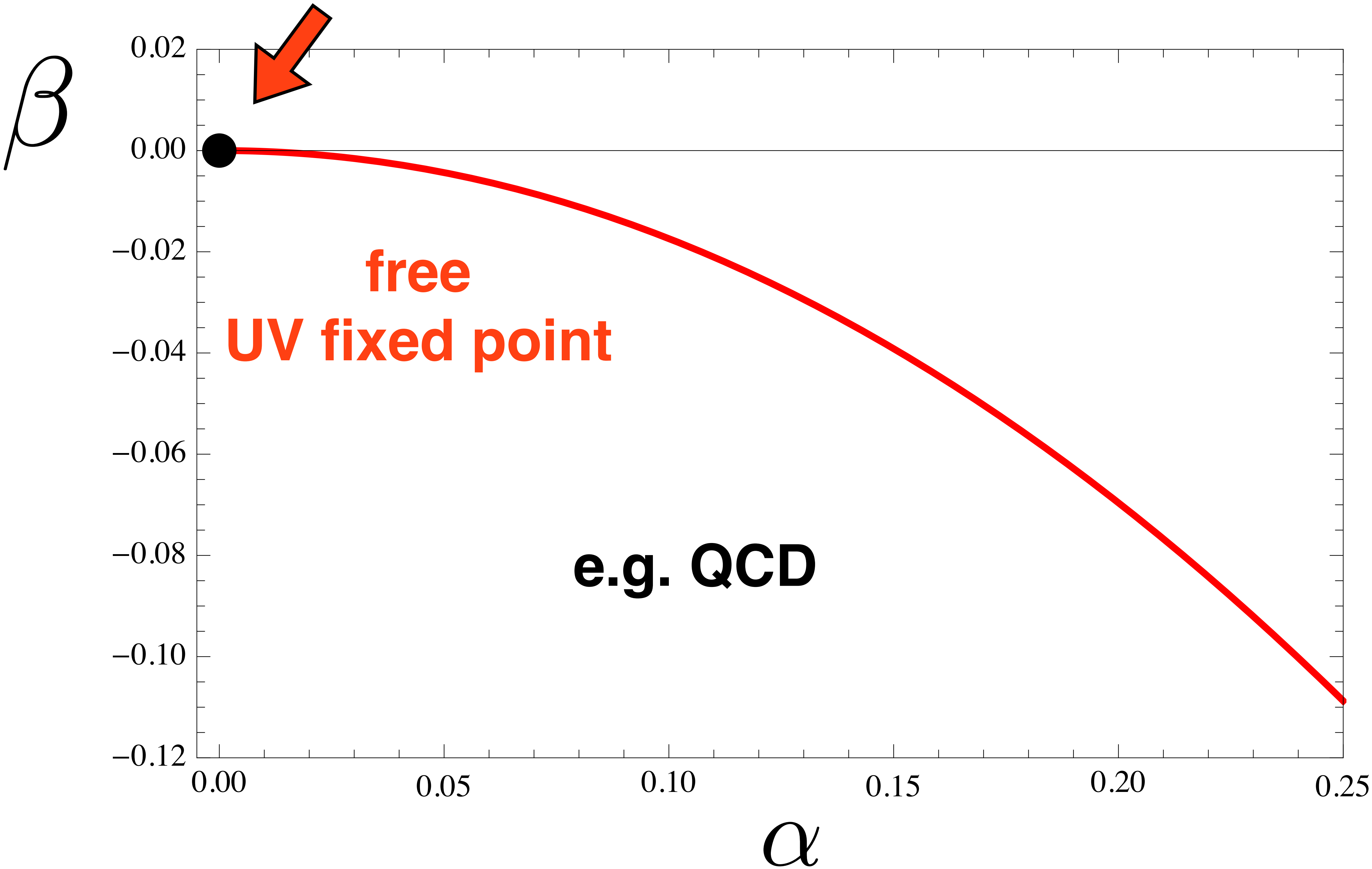
what comes beyond the SM?
(and how does gravity fit in?)

asymptotic freedom

triumph
of QFT



asymptotic freedom



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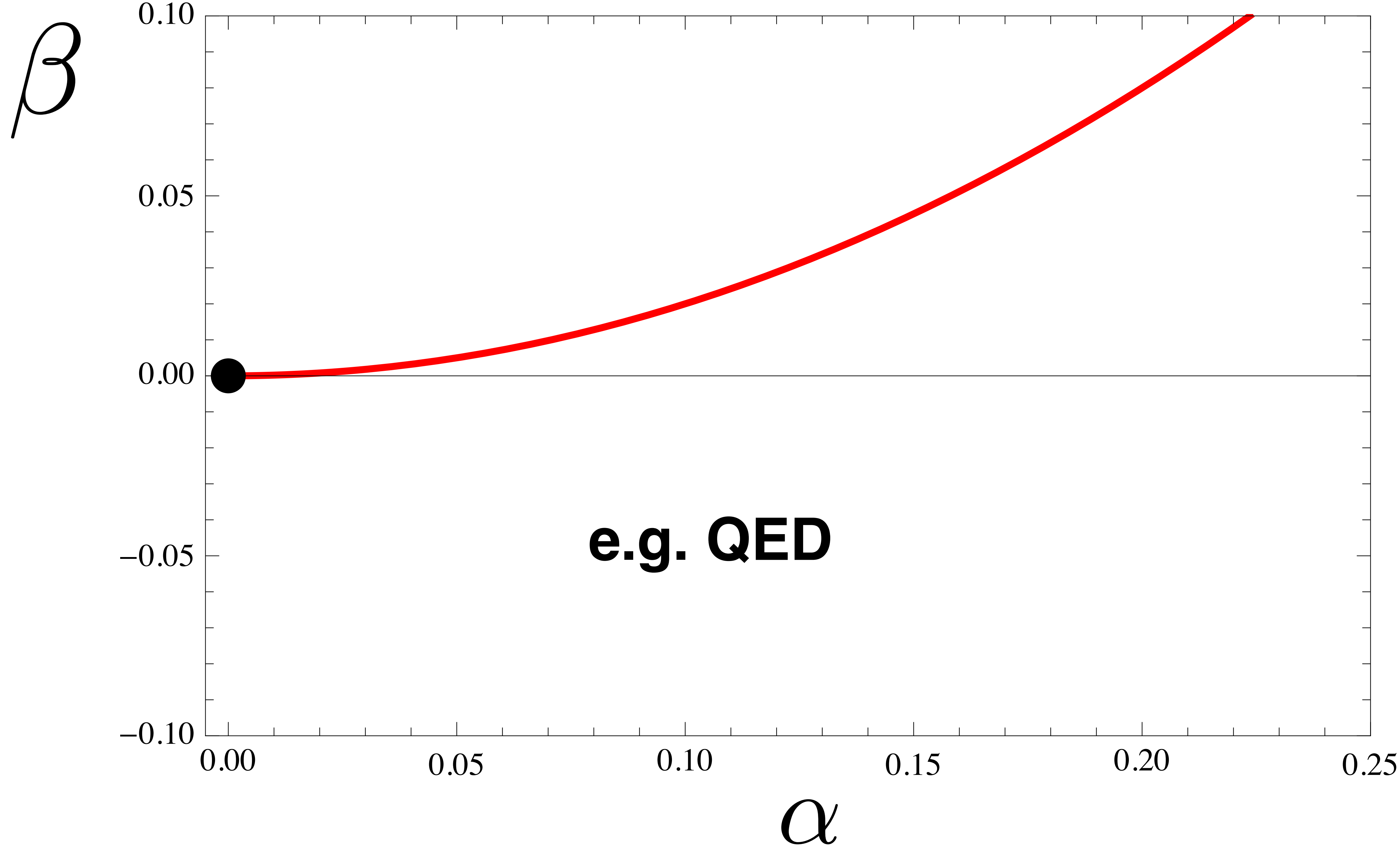
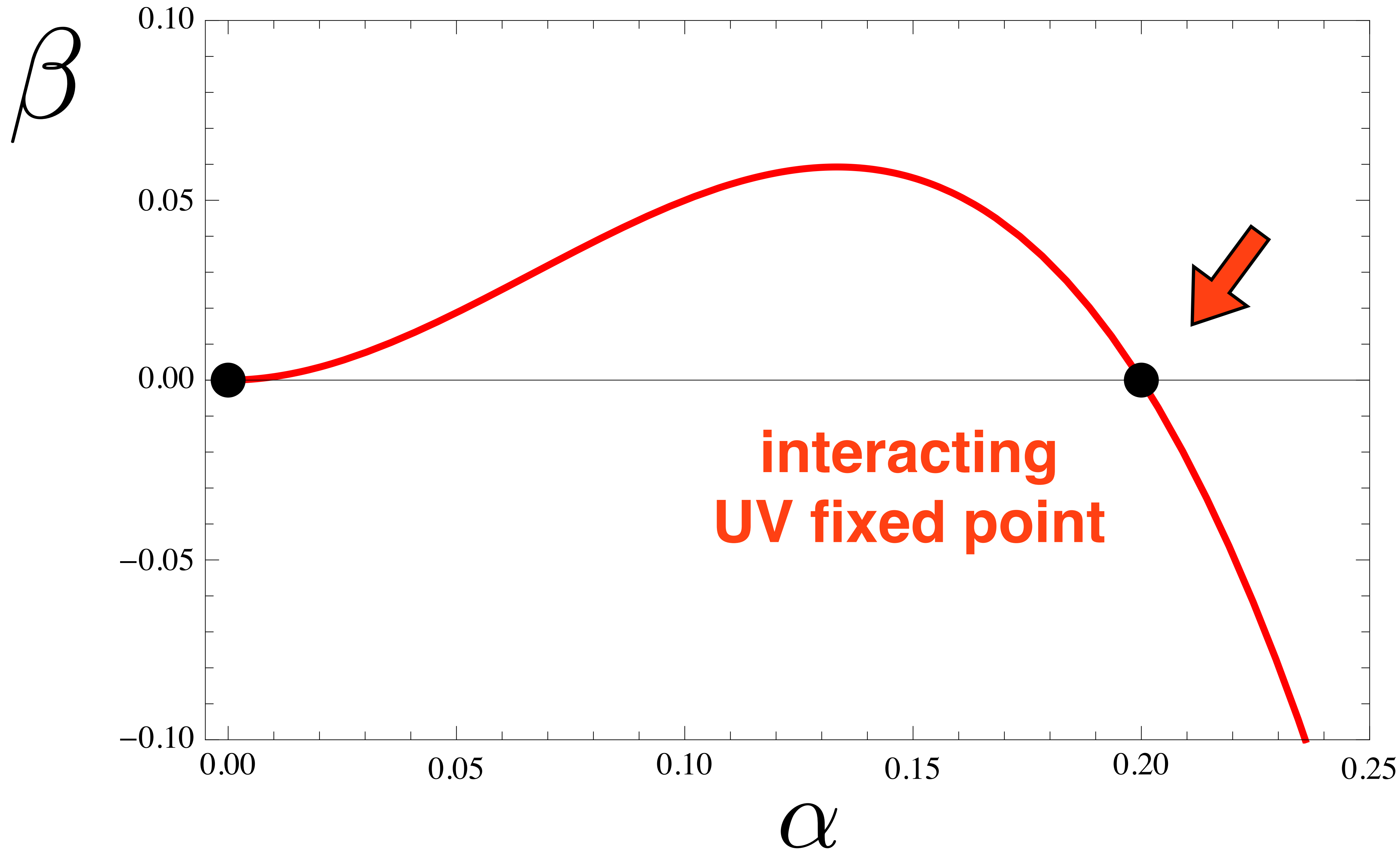
infrared freedom



asymptotic safety



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asymptotic safety

idea:

some or all couplings achieve
interacting UV fixed point

Wilson '71
Weinberg '79

if so, **new directions** for
BSM physics (and, possibly, quantum gravity)

basics of asymptotic safety

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theorems for asymptotic safety

AD Bond, DF Litim 1608.00519/EPJC

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

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

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

weakly coupled fixed point

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

competition between matter and gauge fields

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

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

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

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

weakly coupled fixed point

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

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fixed points

gauge theory

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fixed points

gauge theory

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

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

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

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

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 !

fixed points

gauge theory

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

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

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

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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 ?**

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fermions **scalars** **1-loop**

fixed points

gauge theory

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

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

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

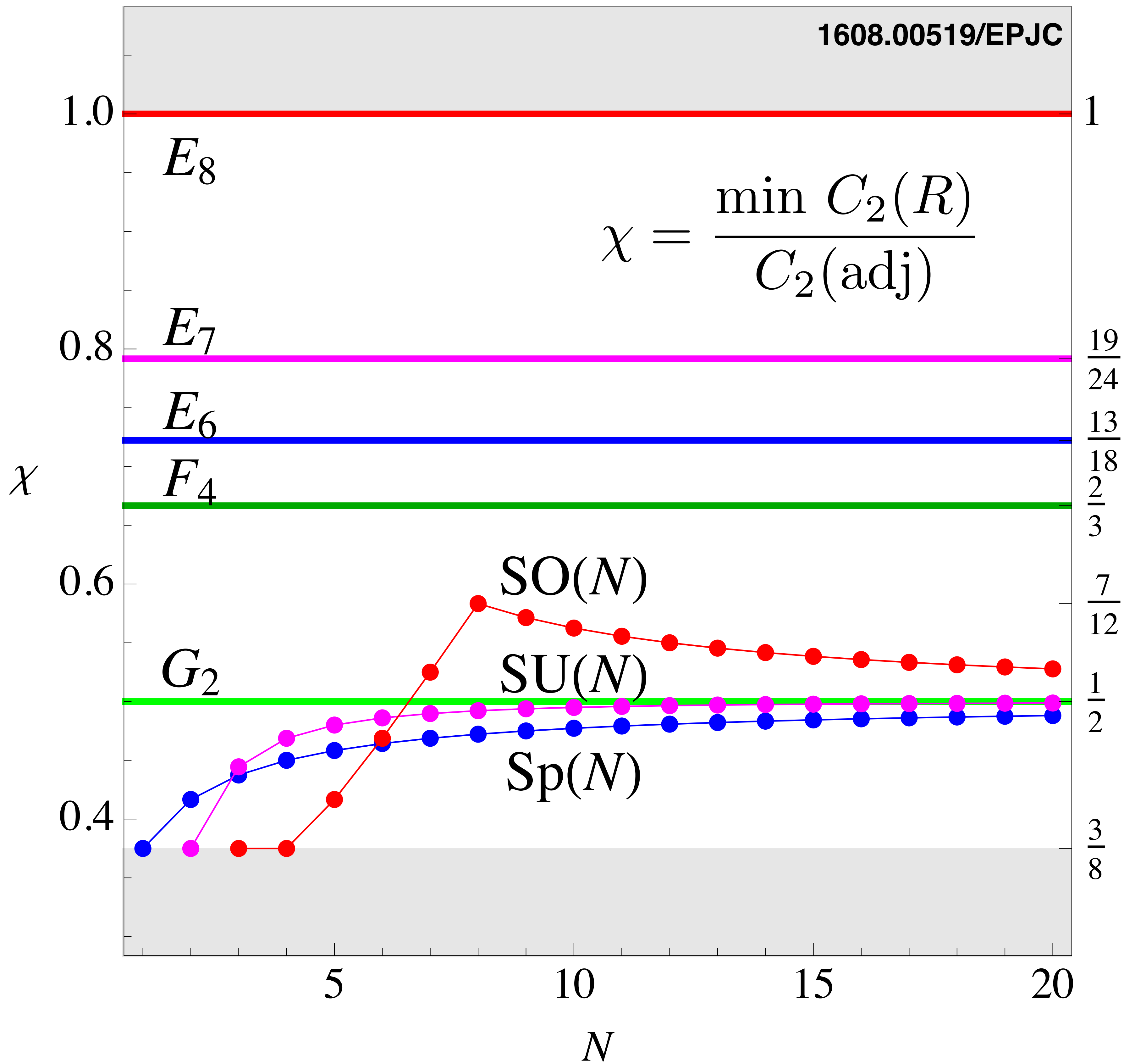
fermions — scalars — 1-loop

scalars ⇒ **must have**

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

quadratic Casimirs

result:



asymptotic safety

result

1608.00519/EPJC

case	gauge group	matter	Yukawa	asymptotic safety
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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)

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basics of asymptotic safety

gauge Yukawa theory

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

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

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

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3 - D\,\alpha_g^2\,\alpha_y$$
$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

→ **interacting UV fixed point** provided that

$$D\,F - C\,E > 0$$

$$B < 0$$

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asymptotic safety

result: necessary and sufficient conditions

1608.00519/EPJC

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/EPJC

case	gauge group	matter	Yukawa	asymptotic safety
d)	simple or abelian	fermions and scalars, any rep	Yes	Yes *)
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*) provided certain auxiliary conditions hold true

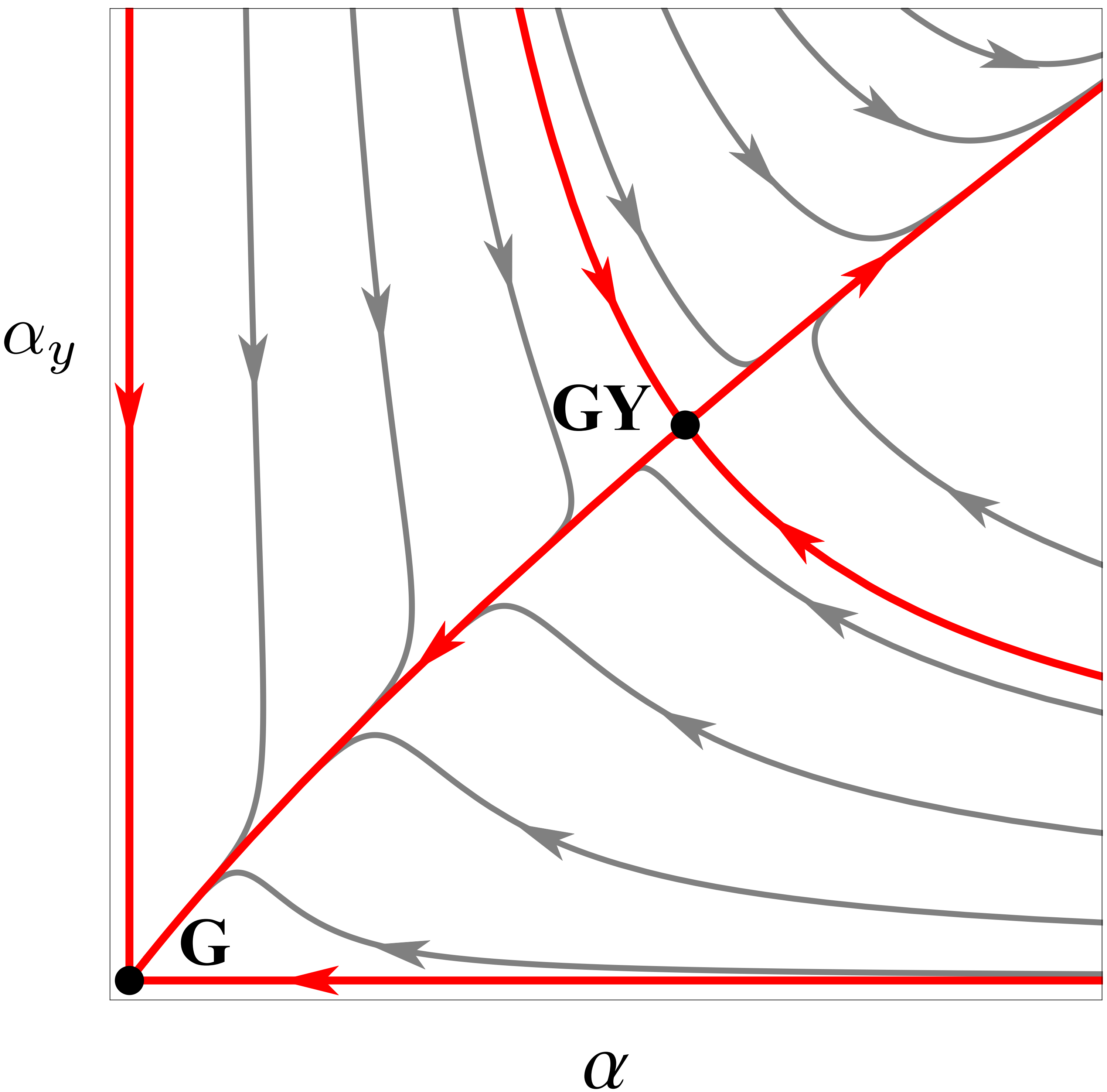
exact proofs of existence

d) SU(N) + scalars + fermions DF Litim, F Sannino, 1406.2337/JHEP

e) SU(N) x SU(M) + scalars + fermions AD Bond, DF Litim, @ERG2016

basics of asymptotic safety

UV fixed point in gauge Yukawa theory



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asymptotic safety beyond the SM

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

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asymptotic safety beyond the SM

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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UV fixed points

$$\psi_i(R_3, R_2)$$

#	gauge couplings		BSM Yukawa	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

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BSM fixed points

FP$_2$

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

weak becomes strong
strong becomes weak

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

FP$_3$

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

strong remains strong
weak remains weak

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

FP$_4$

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

weak becomes the new strong

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

BSM fixed points

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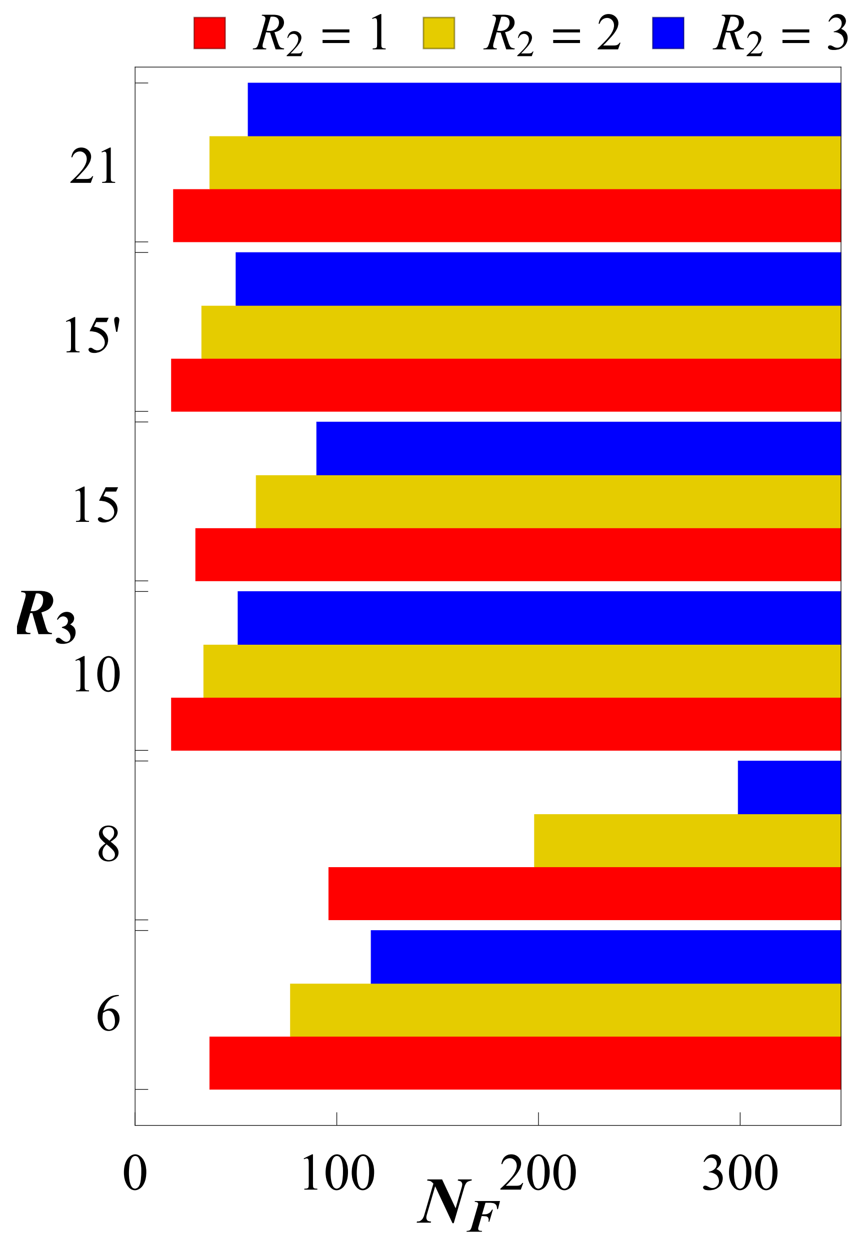
$\mathbf{FP_3}$

$$\alpha_3^* > 0$$

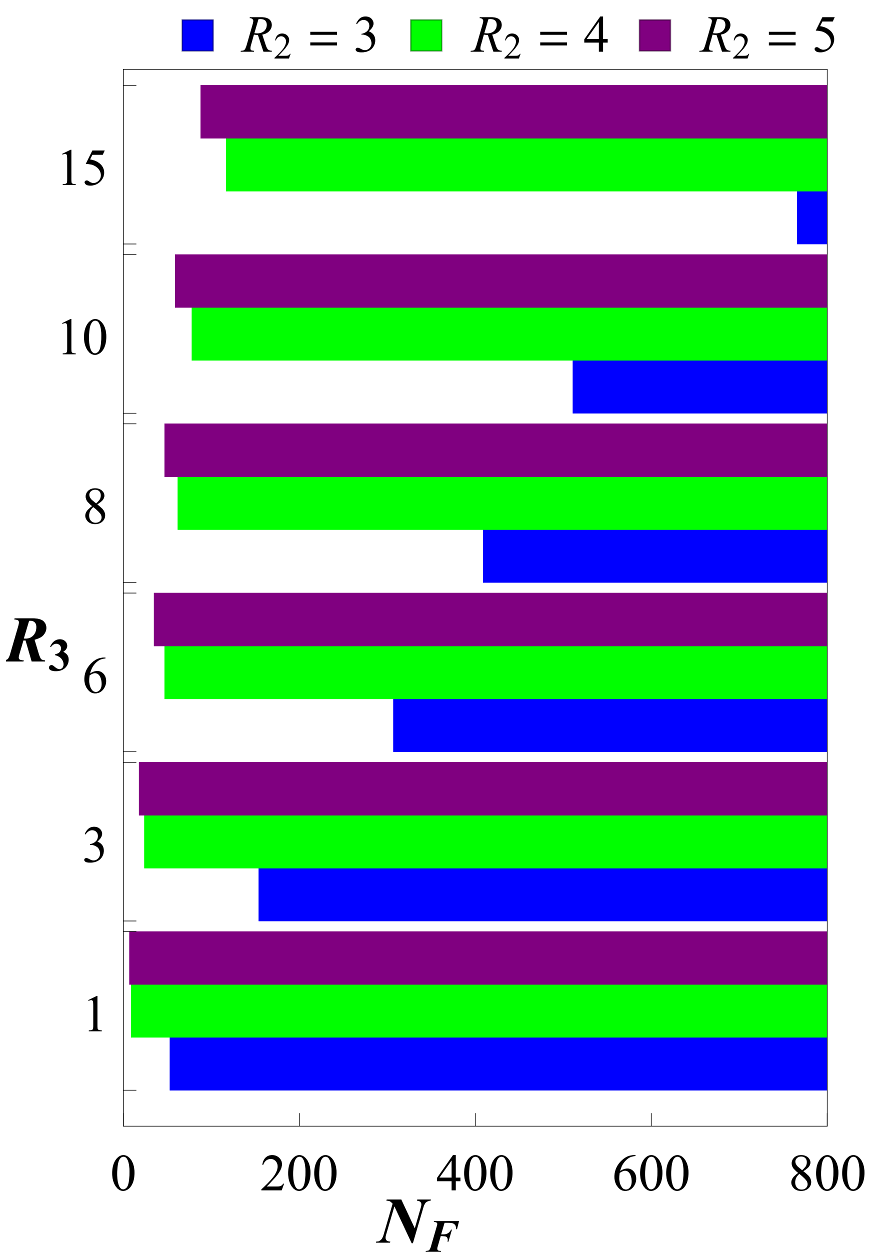
$$\alpha_2^* = 0$$



BSM fixed points

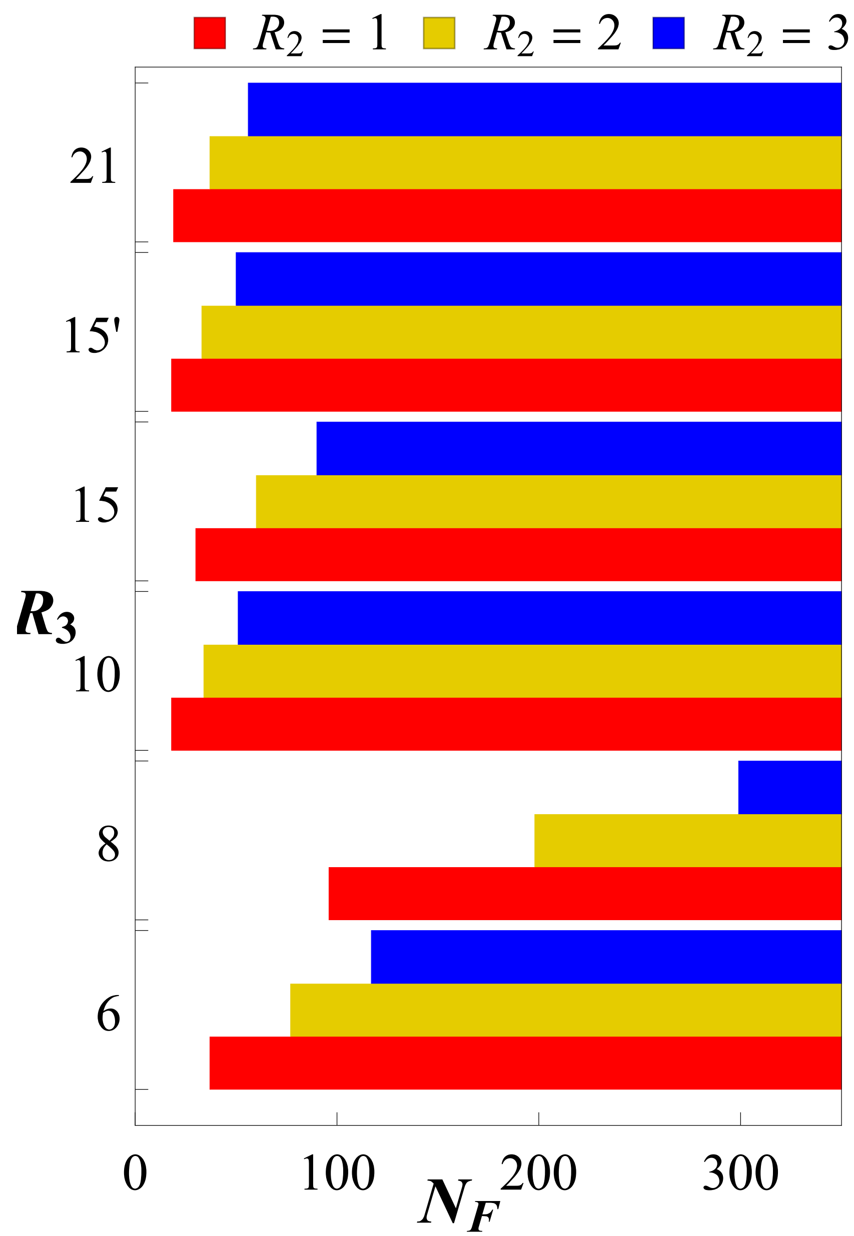
FP_2

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



FP_3

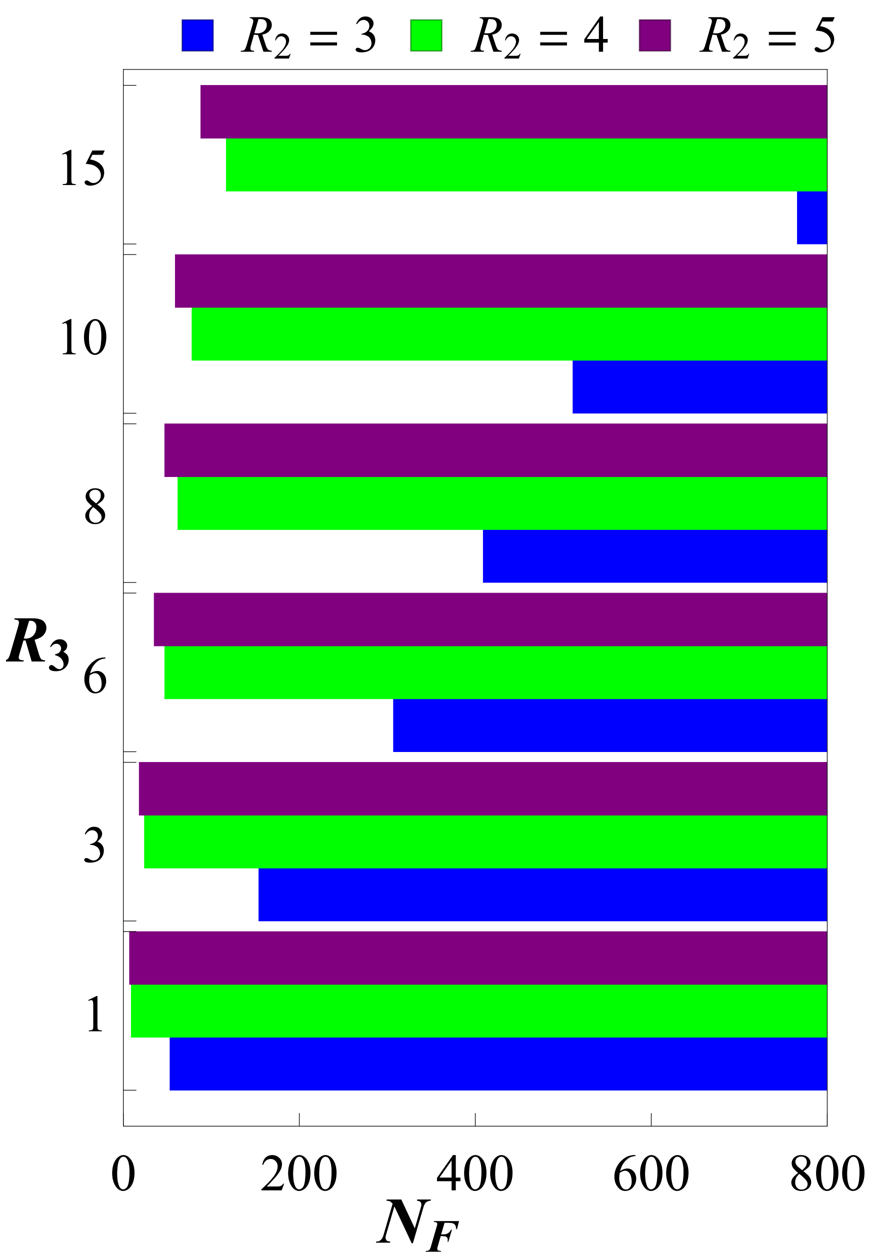
$\alpha_3^* > 0$
$\alpha_2^* = 0$



BSM fixed points

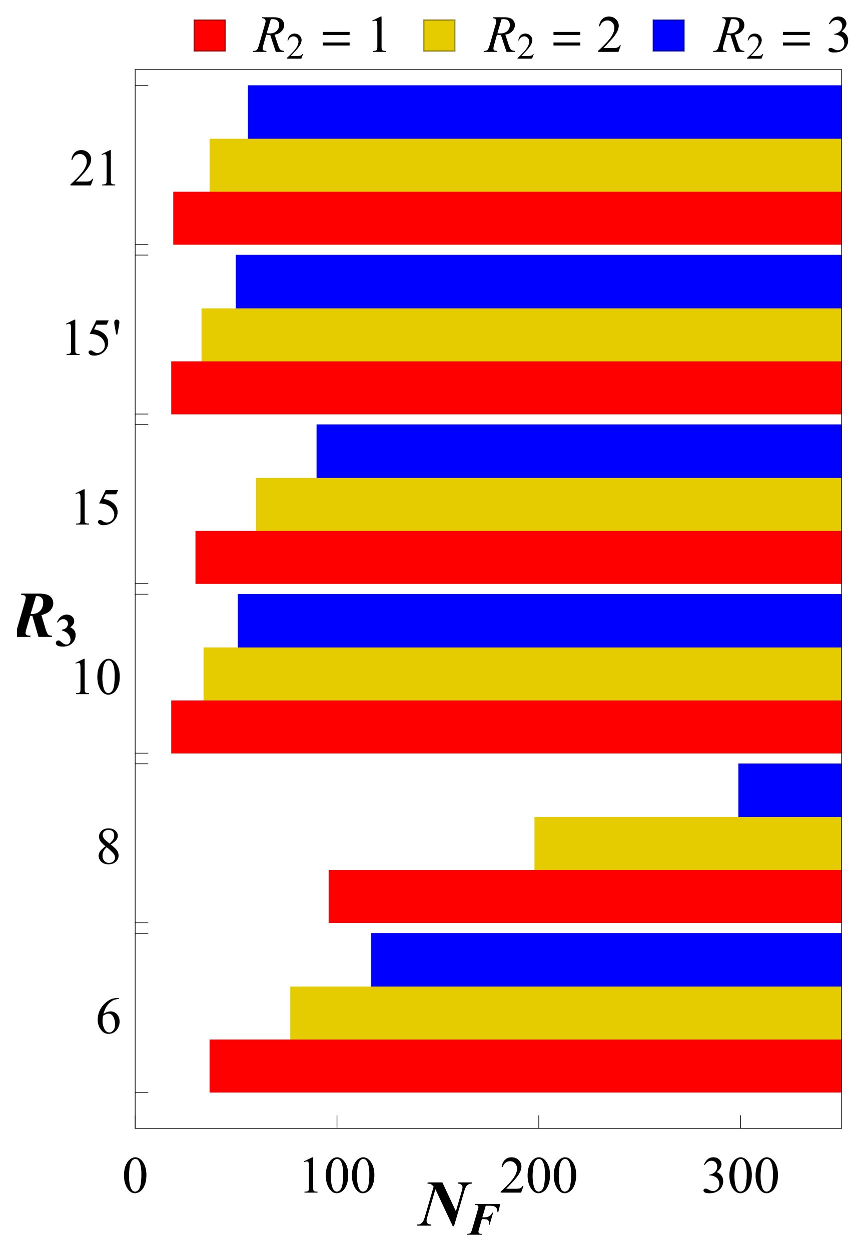
$\mathbf{FP_2}$

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



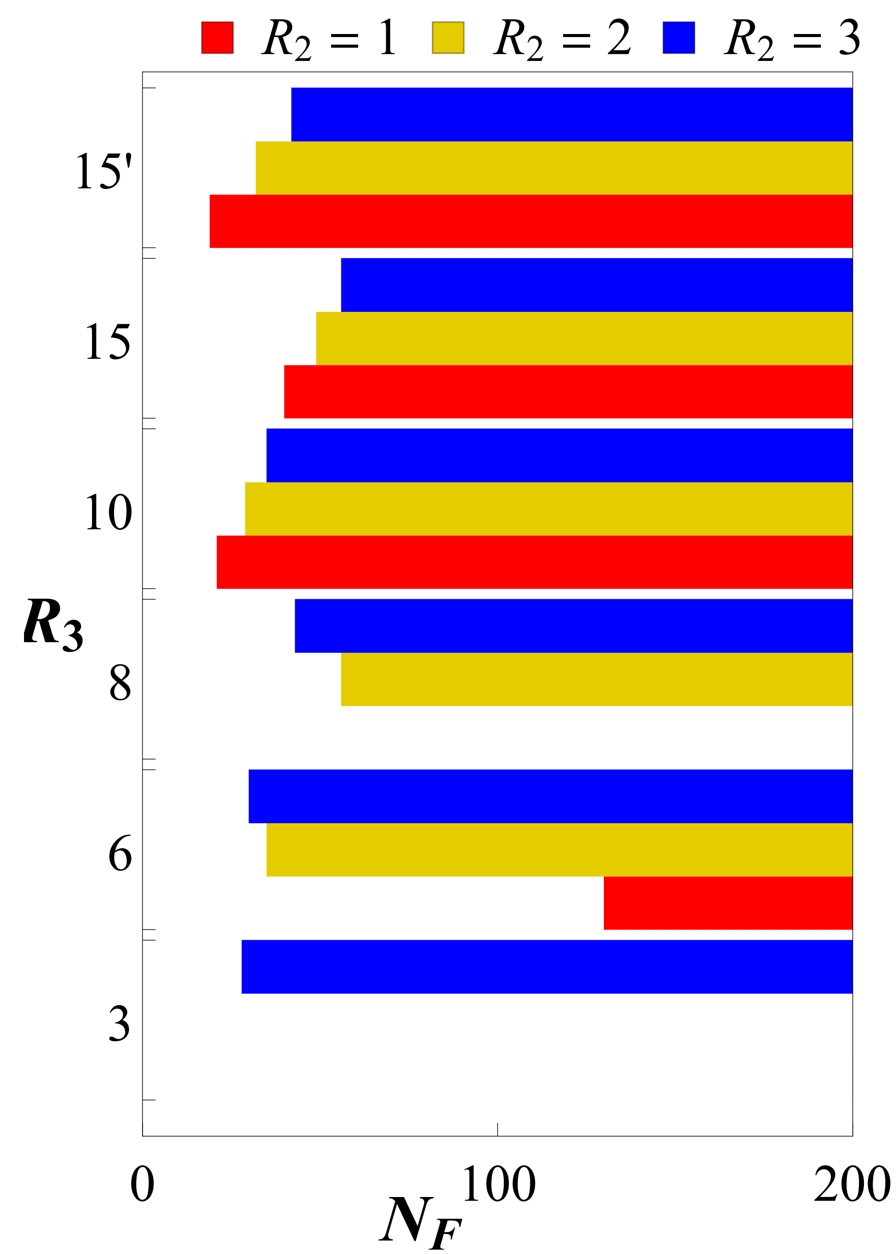
$\mathbf{FP_3}$

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



$\mathbf{FP_4}$

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



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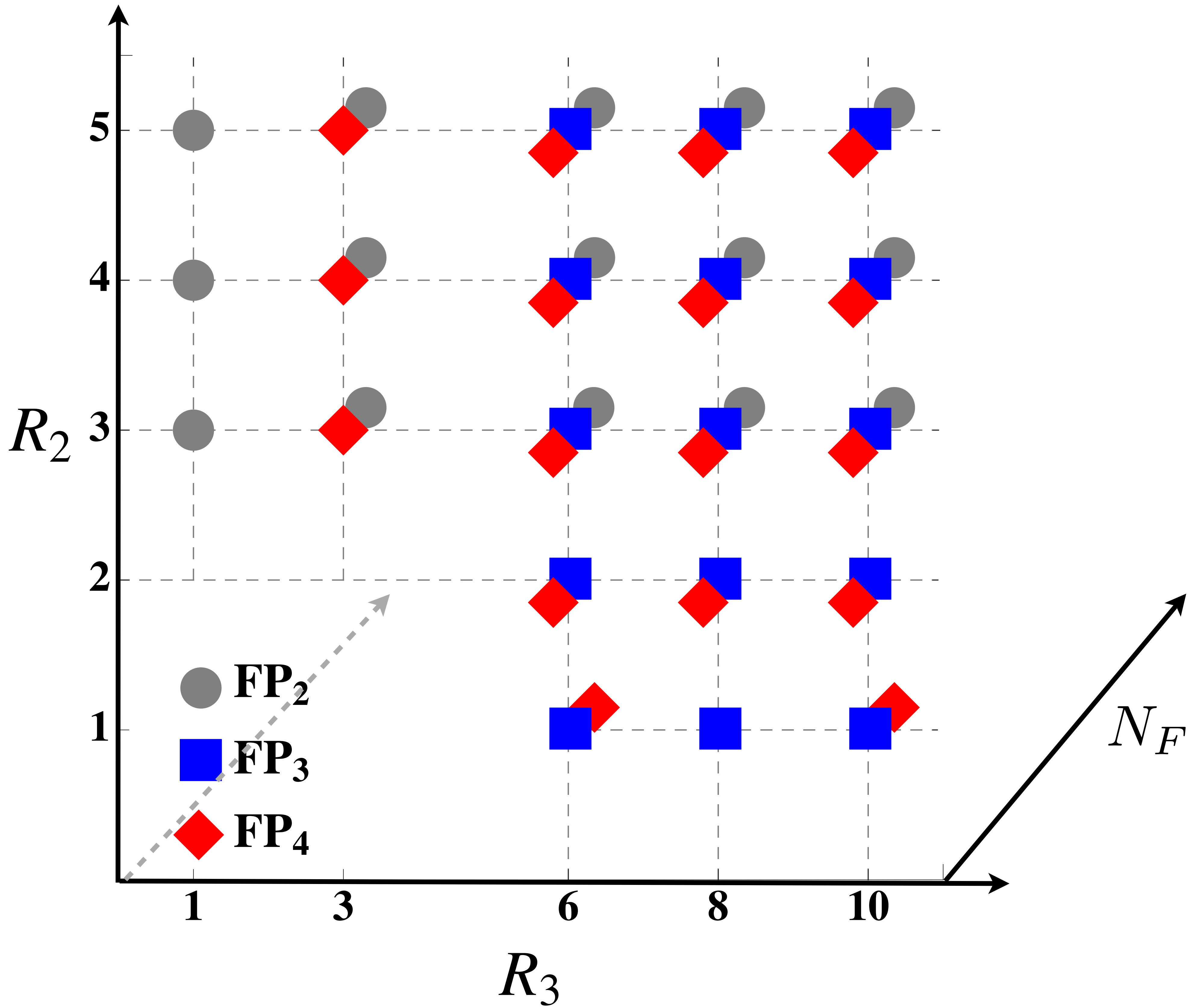
summary of fixed points



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benchmark models

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	$\mathbf{FP_2}$ ●	low scale*
B	$(\mathbf{10}, \mathbf{1}, 30)$	0.1287	0	0.1158	$\mathbf{FP_3}$ ■	low scale*
		0.1292	0.2769	0.1163	$\mathbf{FP_4}$ ◆	no match
C	$(\mathbf{10}, \mathbf{4}, 80)$	0.3317	0	0.0995	$\mathbf{FP_3}$ ■	low scale*
		0.0503	0.0752	0.0292	$\mathbf{FP_4}$ ◆	high scale
		0	0.8002	0.1500	$\mathbf{FP_2}$ ●	high scale
D	$(\mathbf{3}, \mathbf{4}, 290)$	0	0.0895	0.0066	$\mathbf{FP_2}$ ●	low scale*
		0.0416	0.0615	0.0056	$\mathbf{FP_4}$ ◆	low scale
E	$(\mathbf{3}, \mathbf{3}, 72)$	0.1499	0.2181	0.0471	$\mathbf{FP_4}$ ◆	low scale

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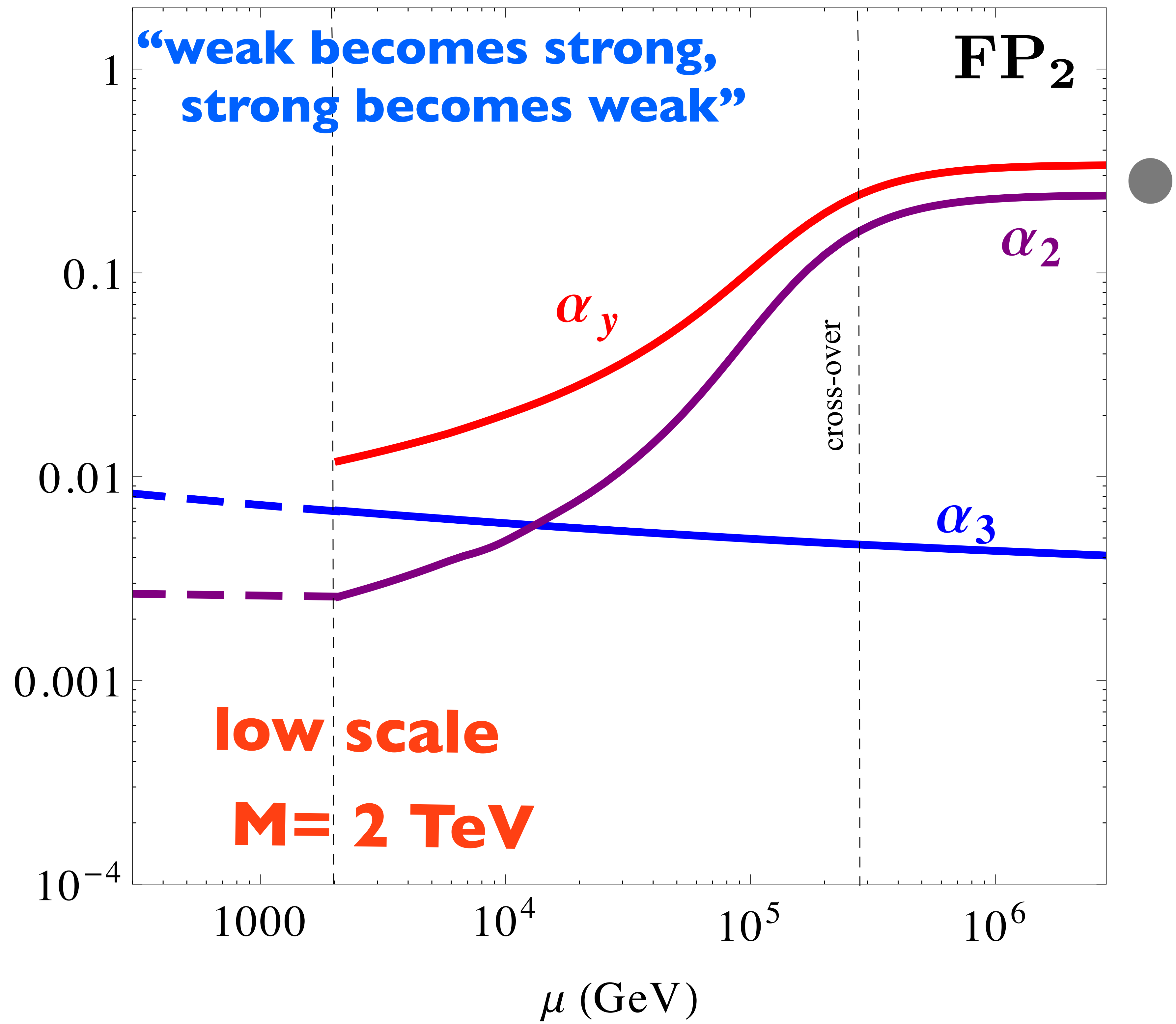
benchmark models

model A

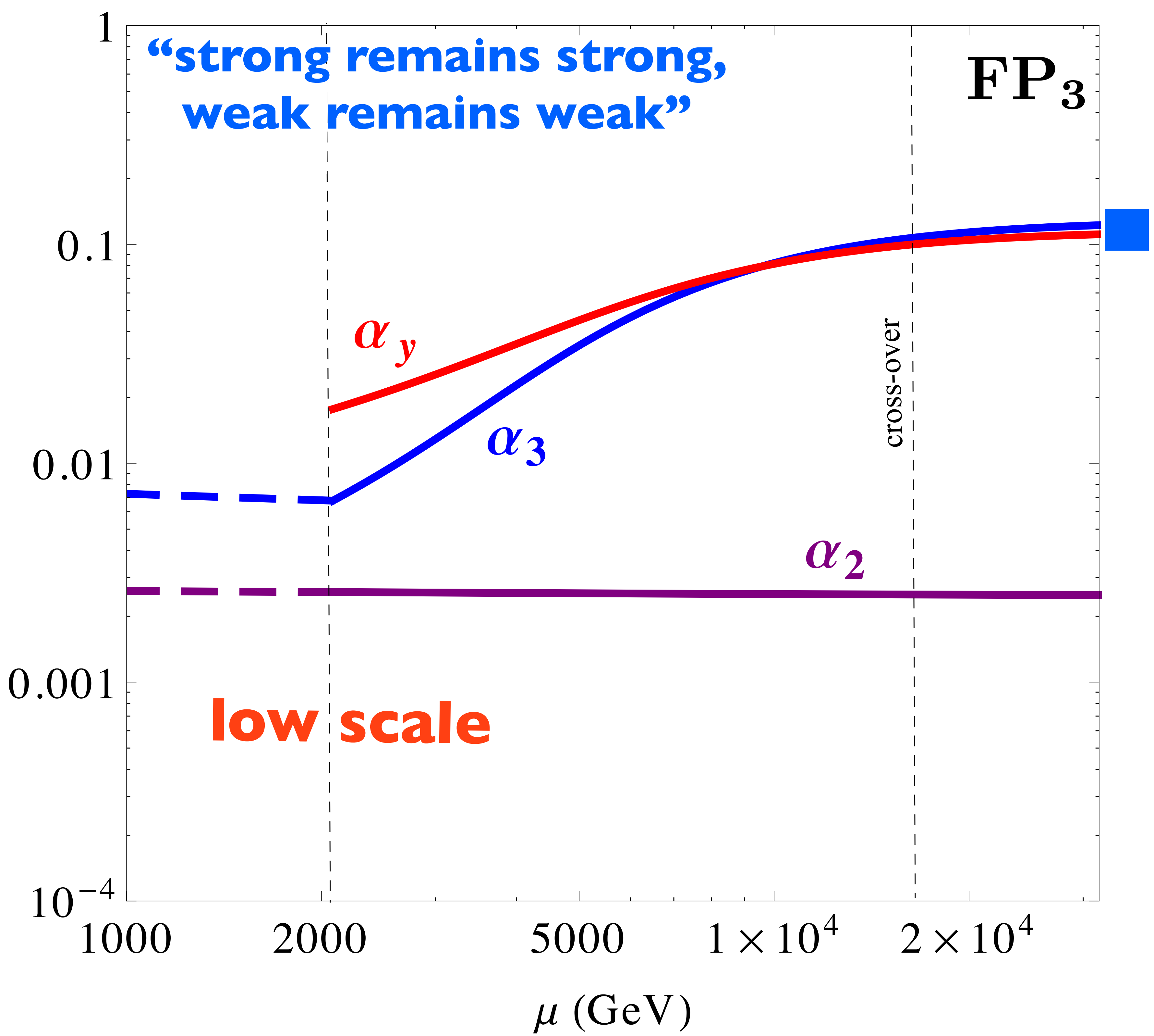
$(R_3, R_2, N_F) =$ (**1**,**4**,12)



benchmark models

model B

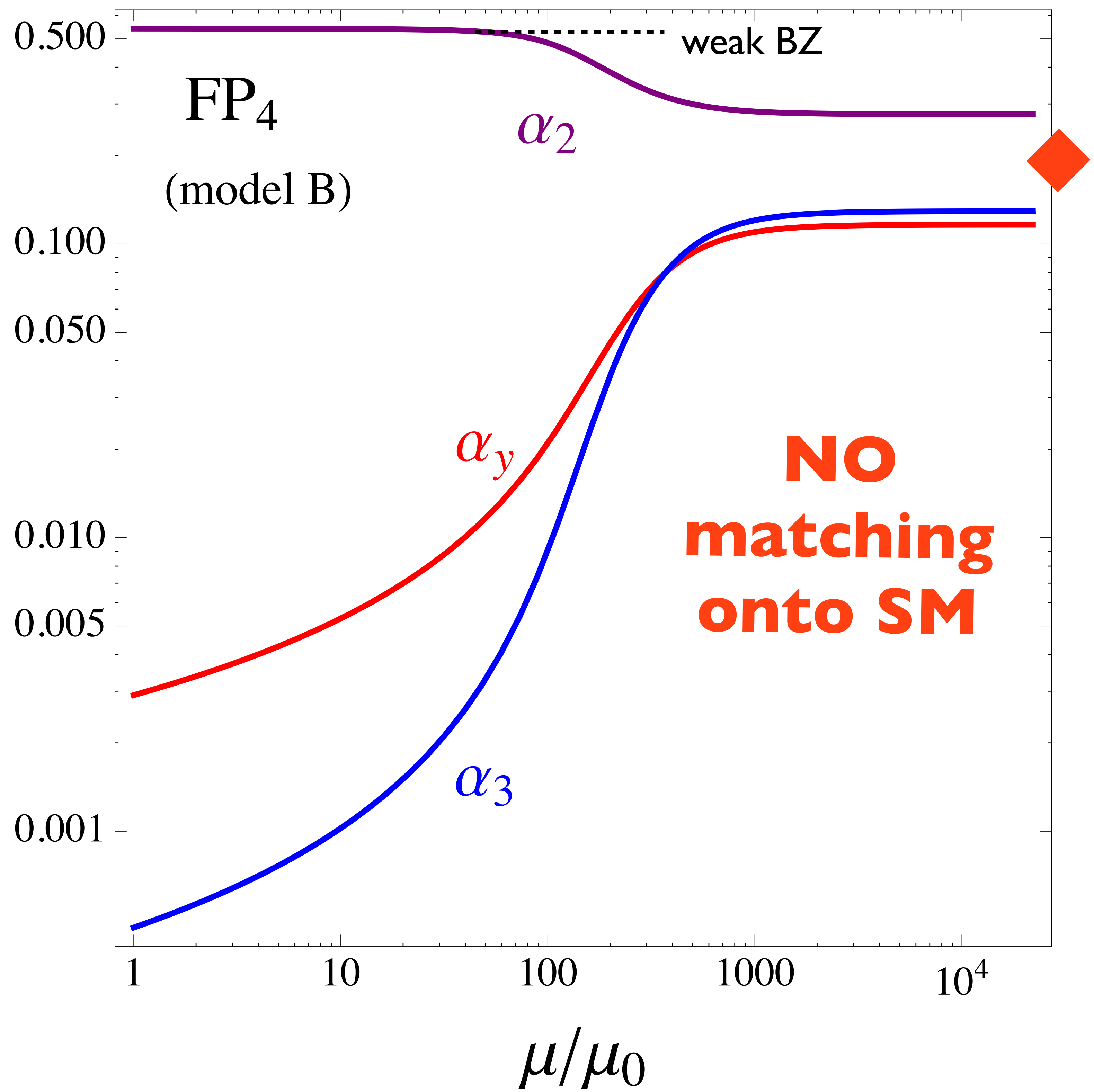
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{1}, 30)$



benchmark models

model B

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



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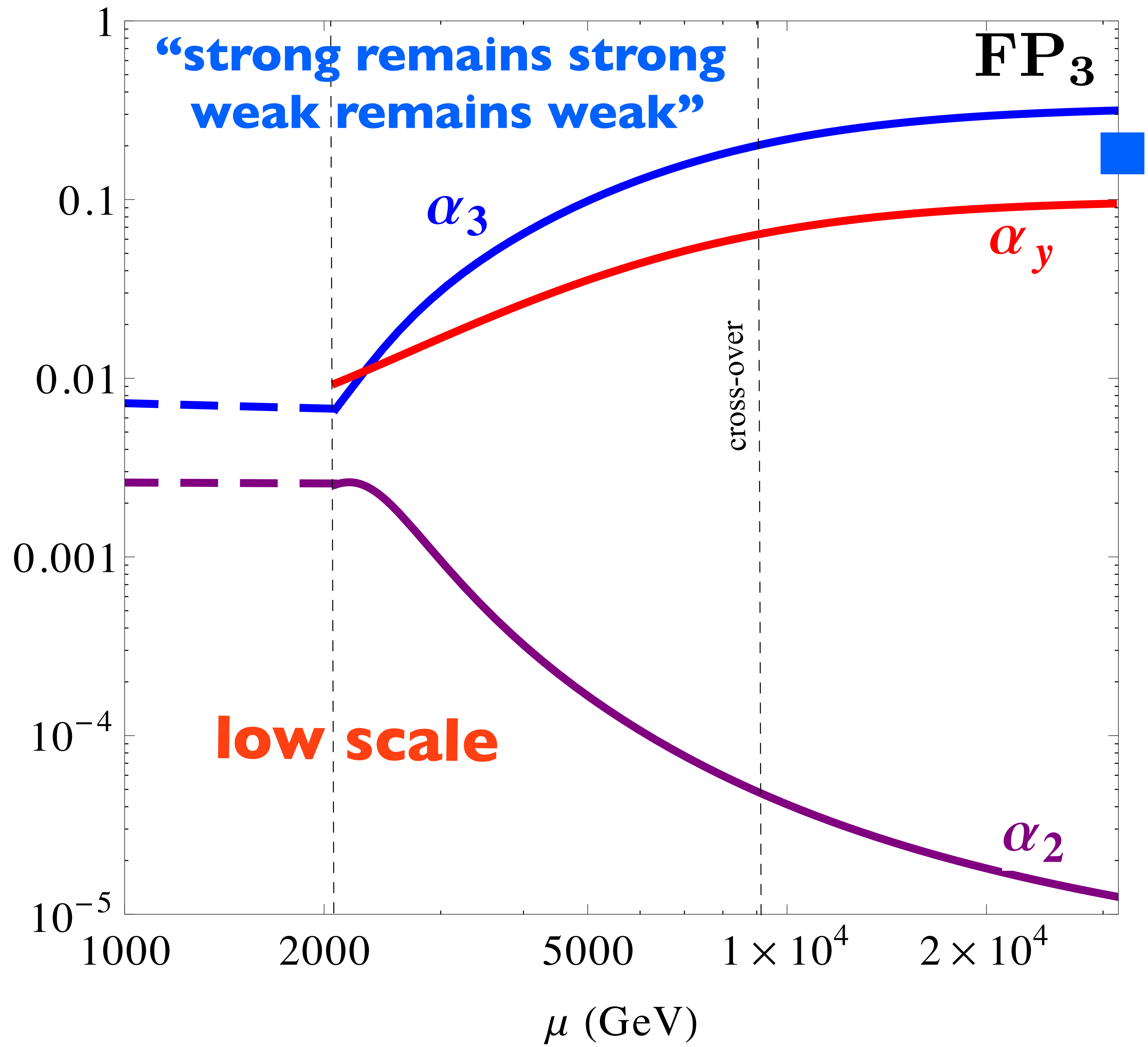
benchmark models

model C

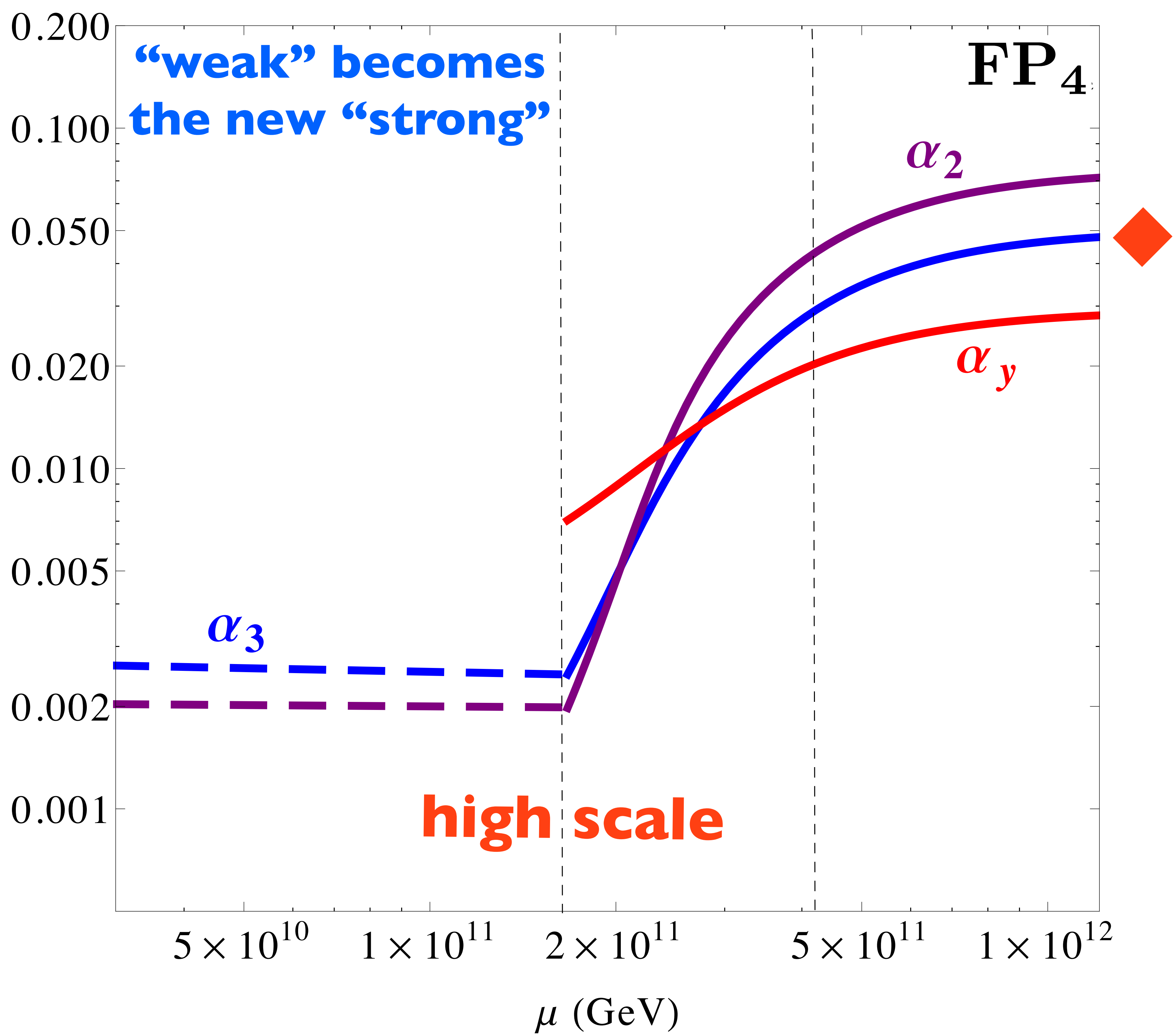
$(R_3, R_2, N_F) =$ $(\mathbf{10},\mathbf{4},80)$



benchmark models

model C

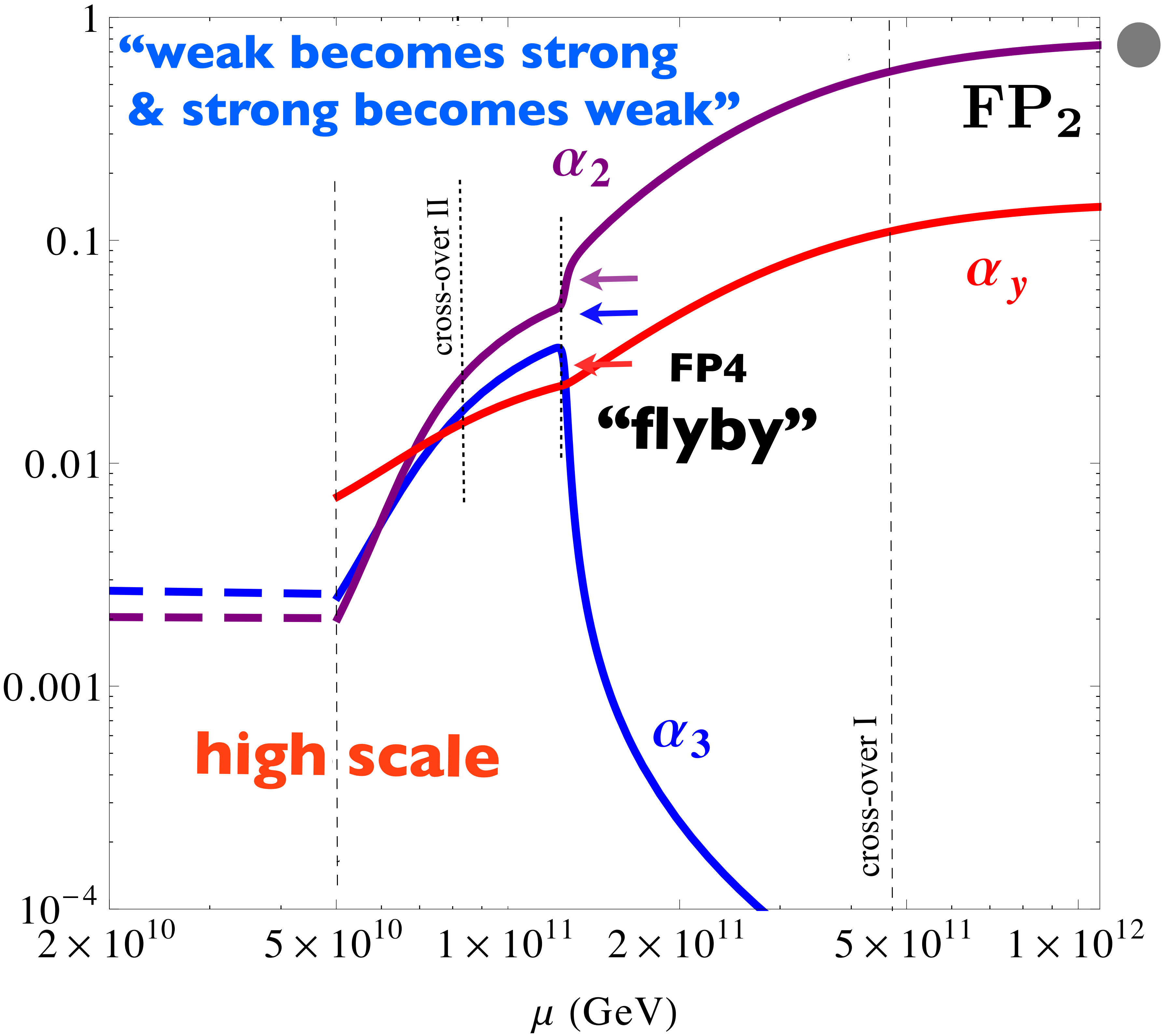
$(R_3, R_2, N_F) =$ (**10**,**4**,80)



benchmark models

model C

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



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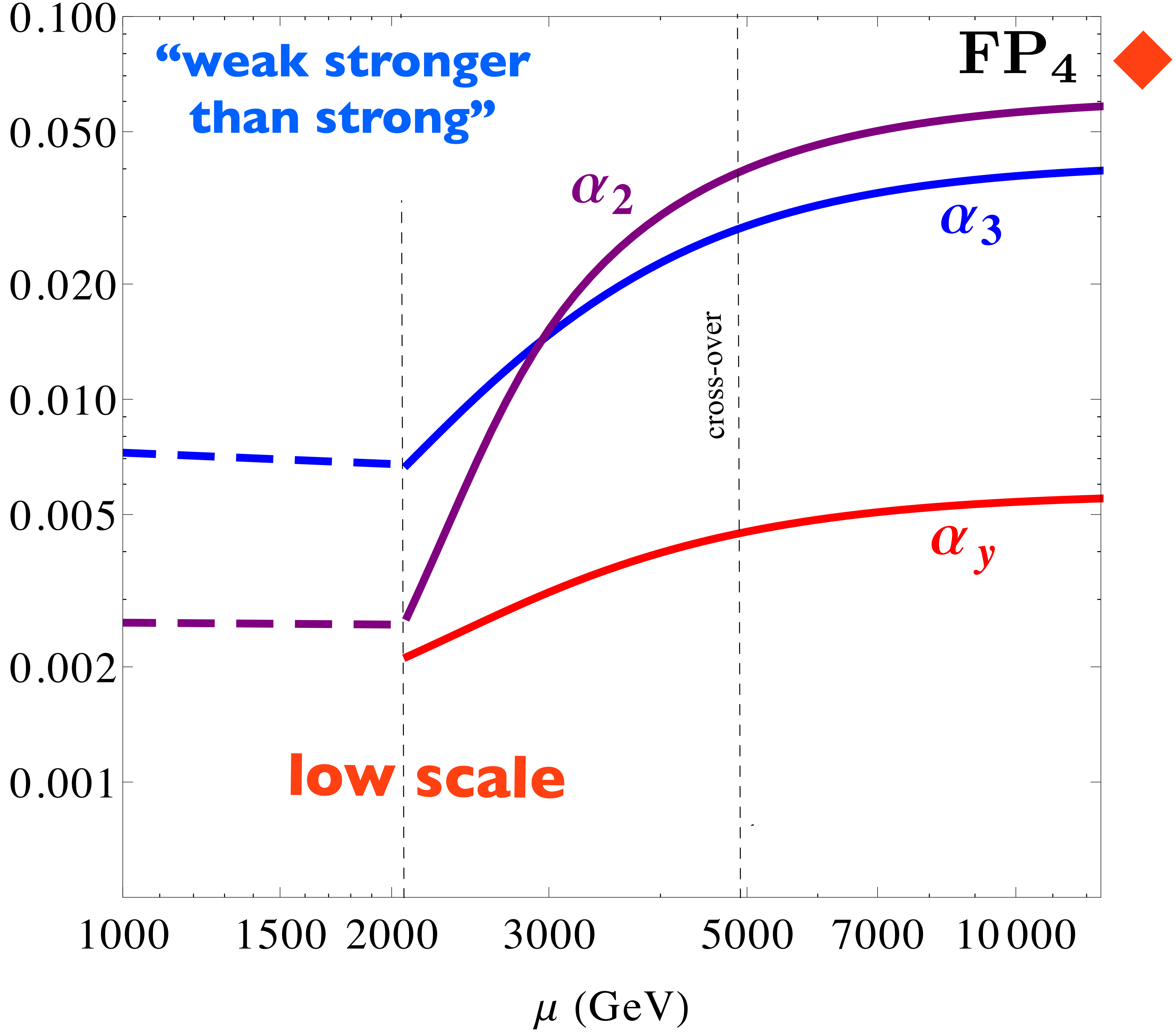
benchmark models

model D

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



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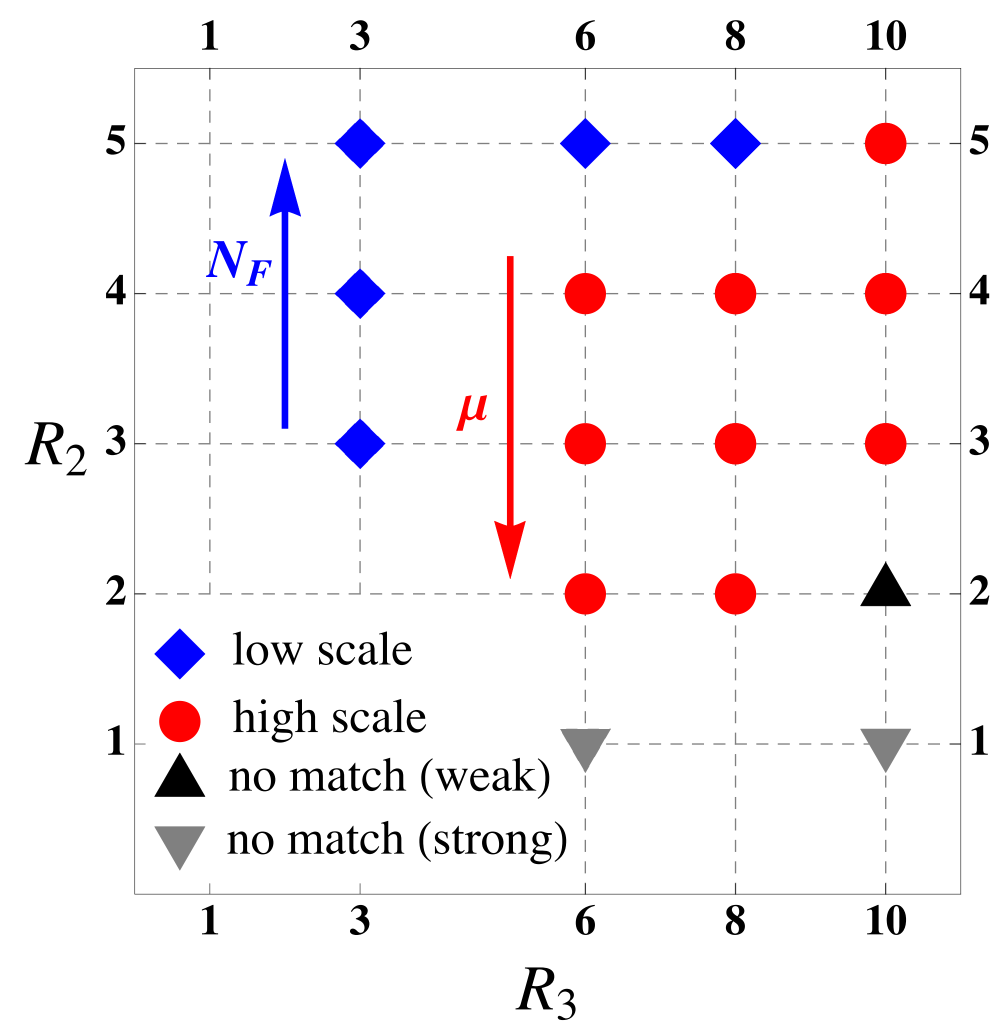
summary: when it works

partially interacting FPs (one “safe”, one “free”)

genuinely, except in very special circumstances

fully interacting FPs (both “safe”)

for most reps - see plot:



collider phenomenology

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

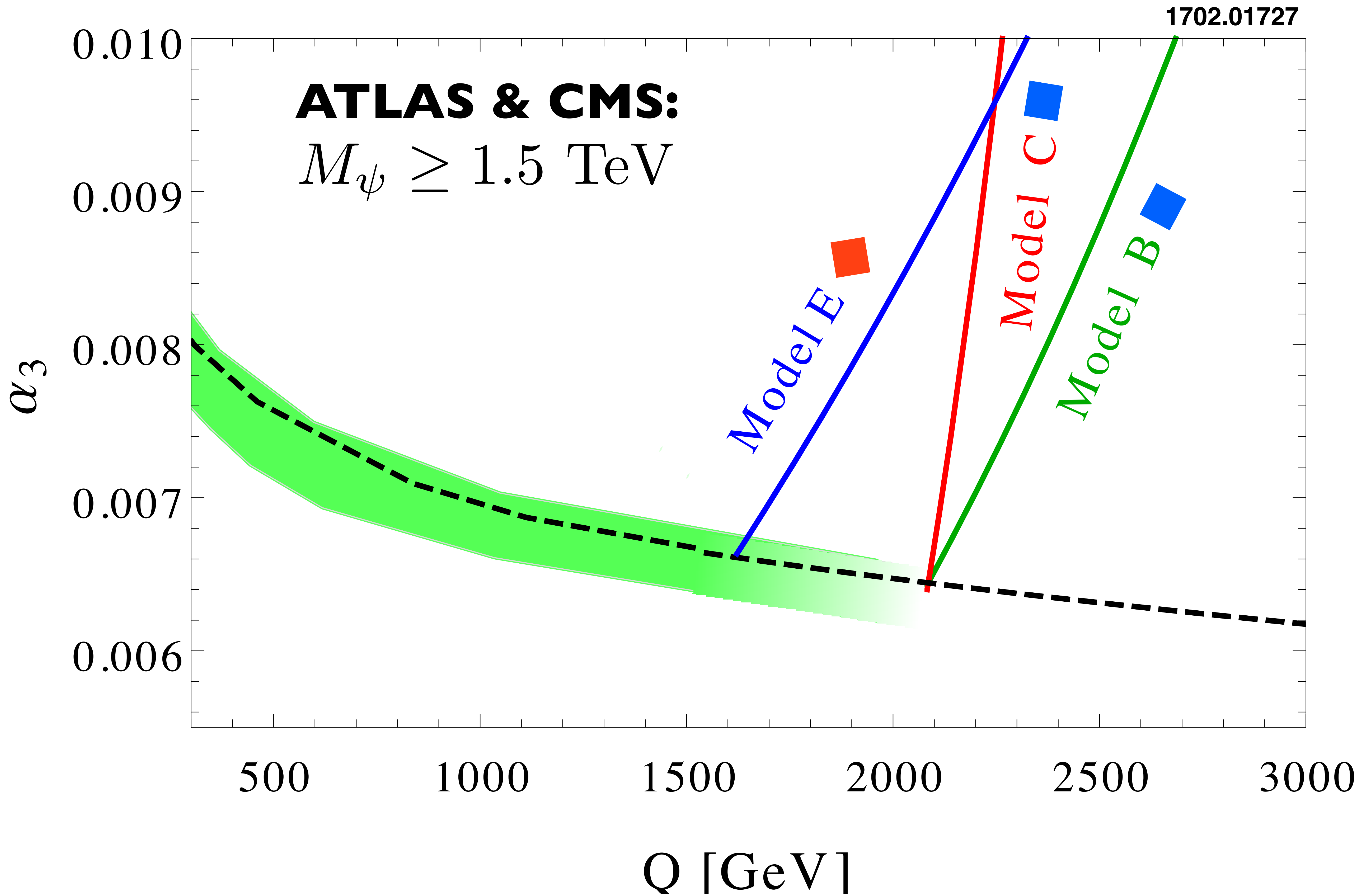
running couplings

the weak sector

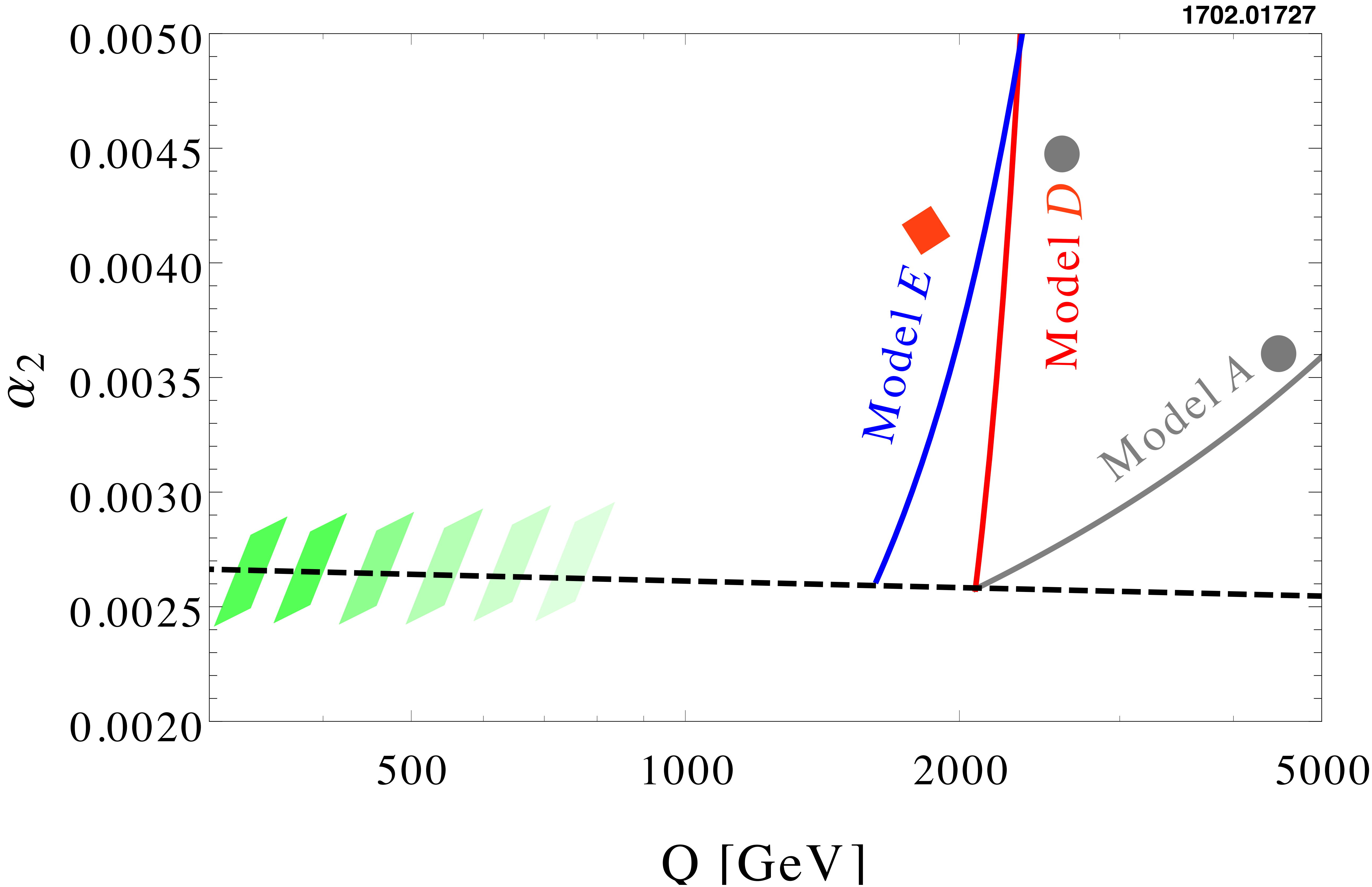
long-lived QCD bound states (R hadrons)

di-boson searches

SU(3) BSM running



SU(2) BSM running



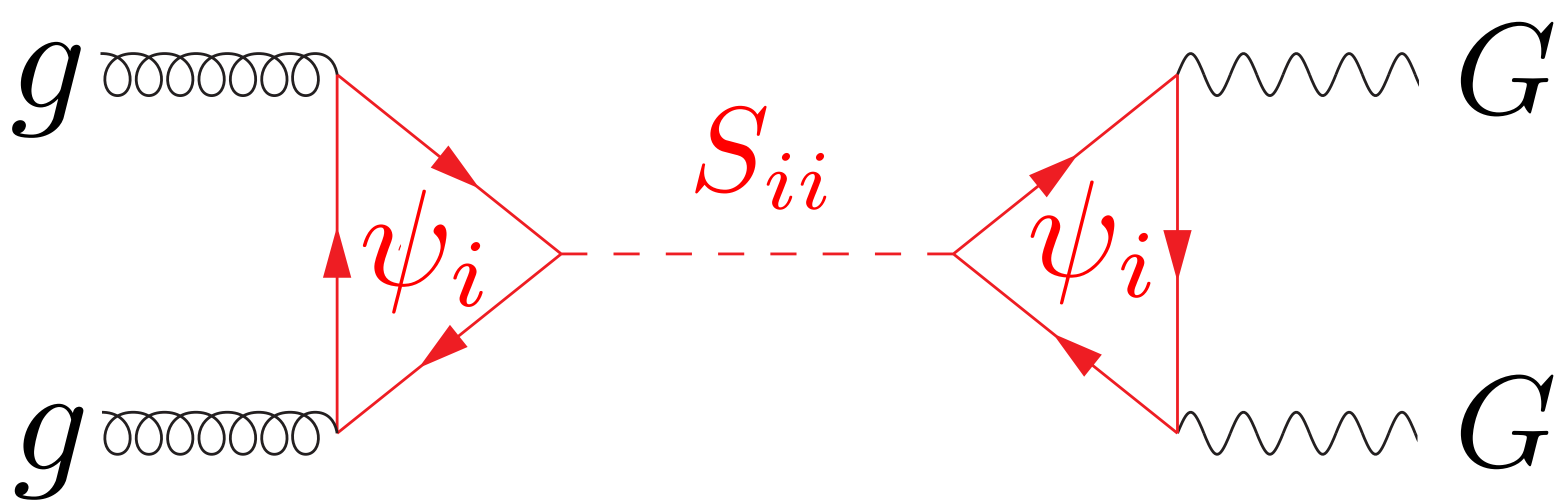
di-boson spectra and resonances

assume **resonant production** of BSM scalars

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

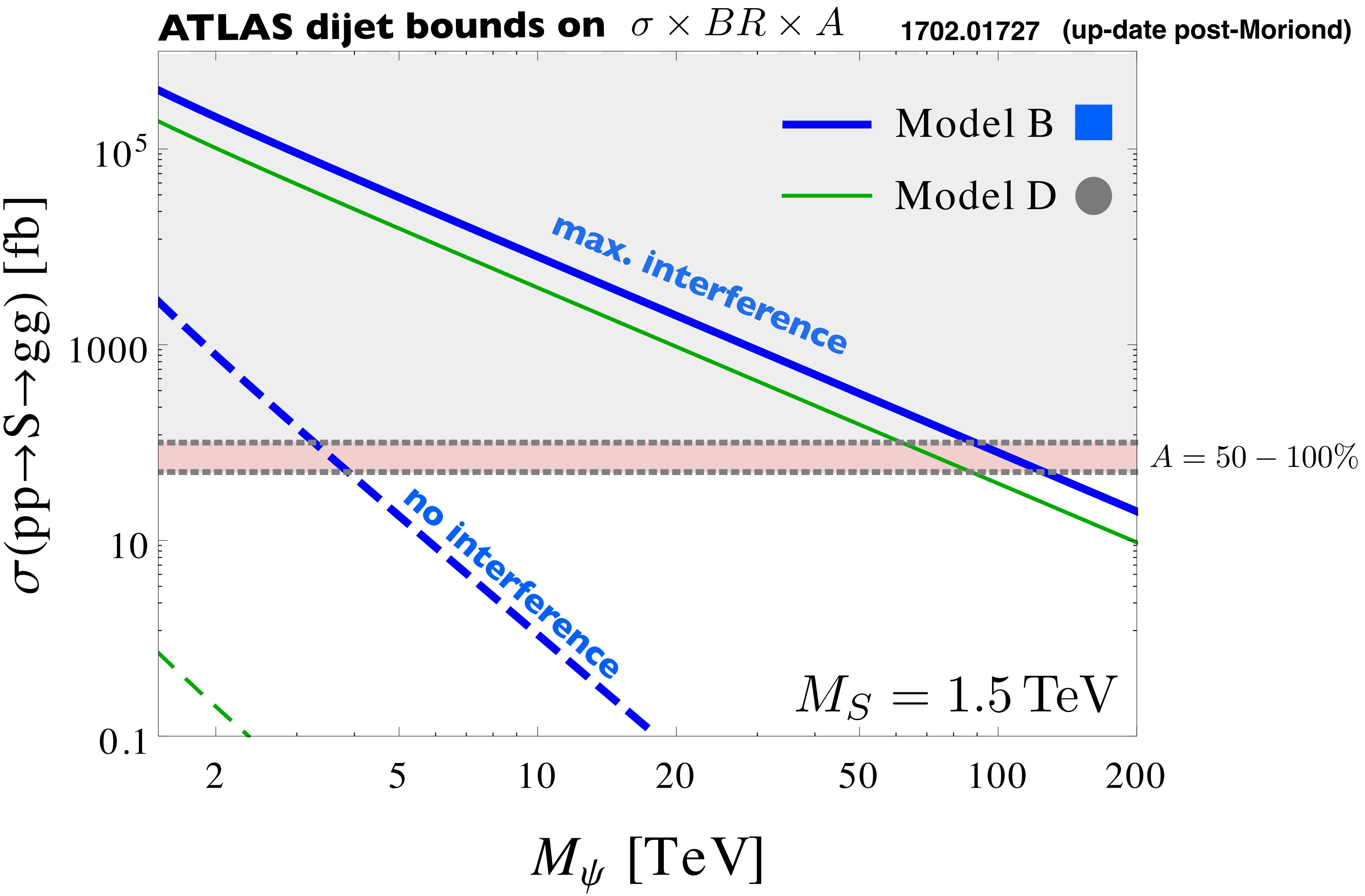
"low Ms" $M_S \lesssim M_\psi$ $\quad$ **"high Ms"** $M_\psi \lesssim M_S < 2M_\psi$

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

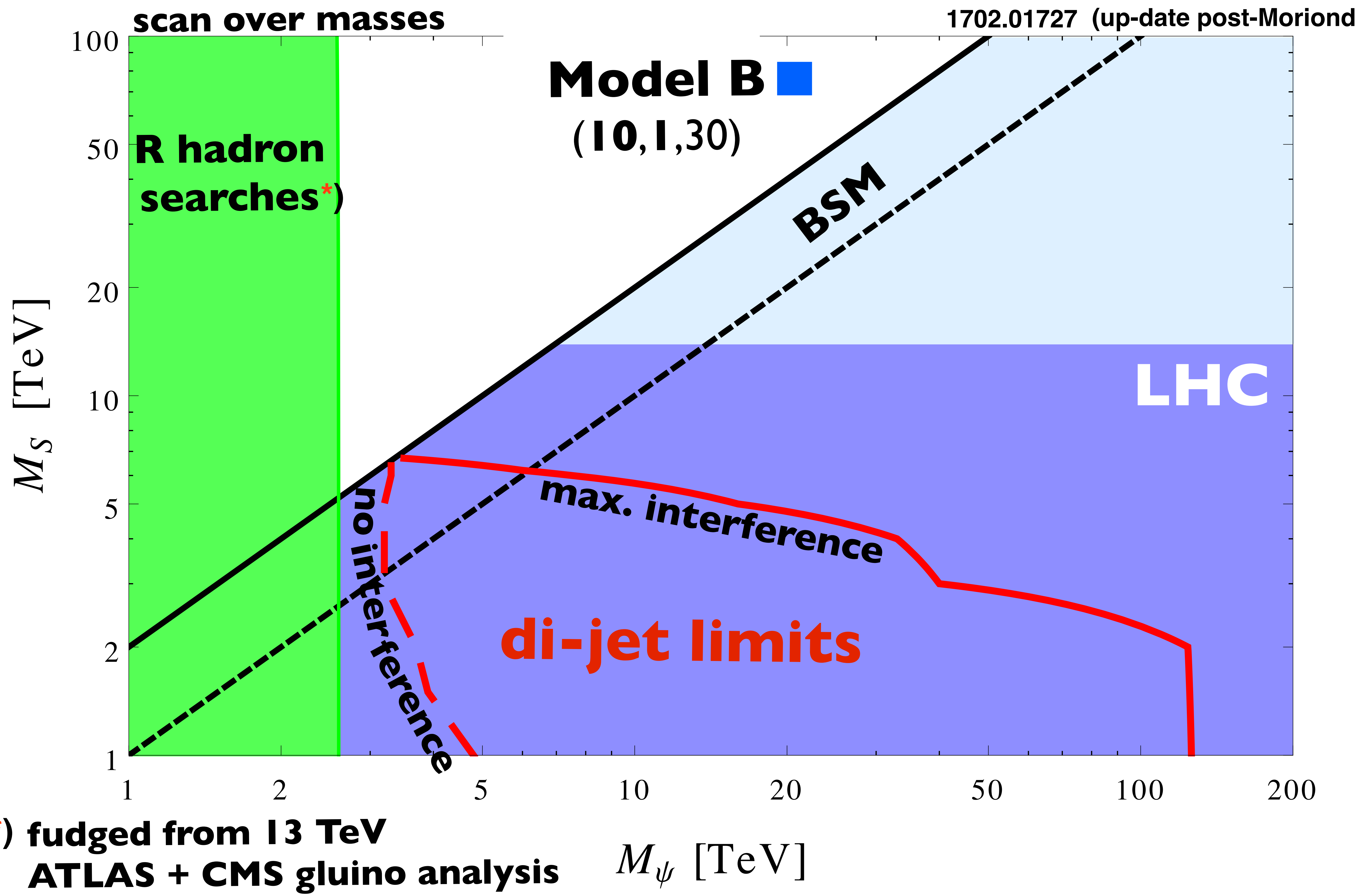


interference effects

dijet cross section



mass exclusion limits



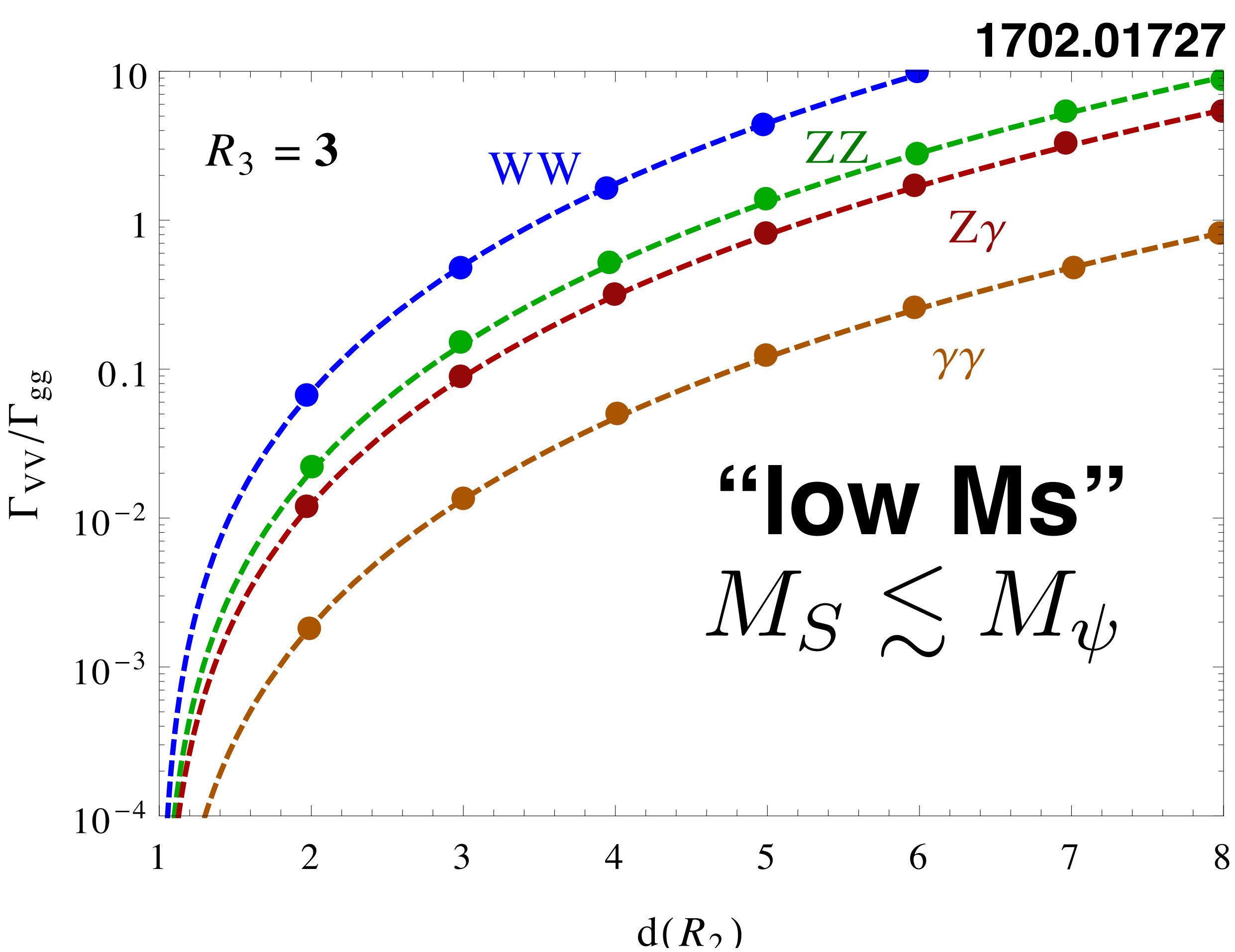
*) fudged from 13 TeV ATLAS + CMS gluino analysis

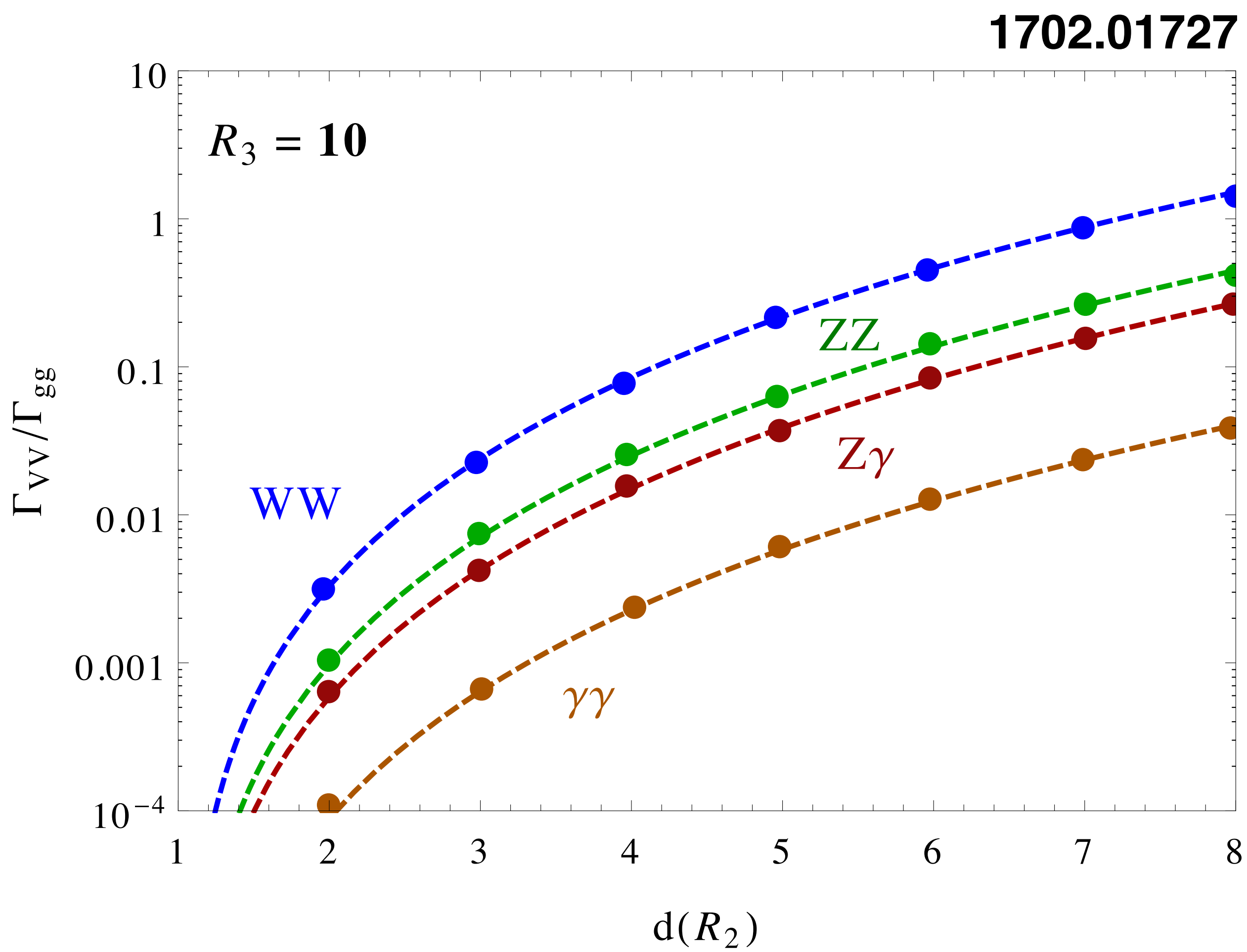
decays into electroweak gauge bosons

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

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

growth with dim(R2)





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decays into electroweak gauge bosons

"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":

FP₂ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}$ ↗ $\bar{\Gamma}_{\gamma\gamma}$?

FP₃ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}, \bar{\Gamma}_{\gamma\gamma}$ ↘

FP₄ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}$ ↗ $\bar{\Gamma}_{\gamma\gamma}$ ↘ $\bar{\Gamma}_{Z\gamma}$?

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conclusions

theorems for asymptotic safety

new directions beyond asymptotic freedom

weakly interacting UV completions of the SM

UV FPs can be partially or fully interacting

new physics can be probed at LHC

window of opportunities for BSM

what's next?

more BSM, DM, flavour, ...

strong coupling, susy, quantum gravity, ...

extra material

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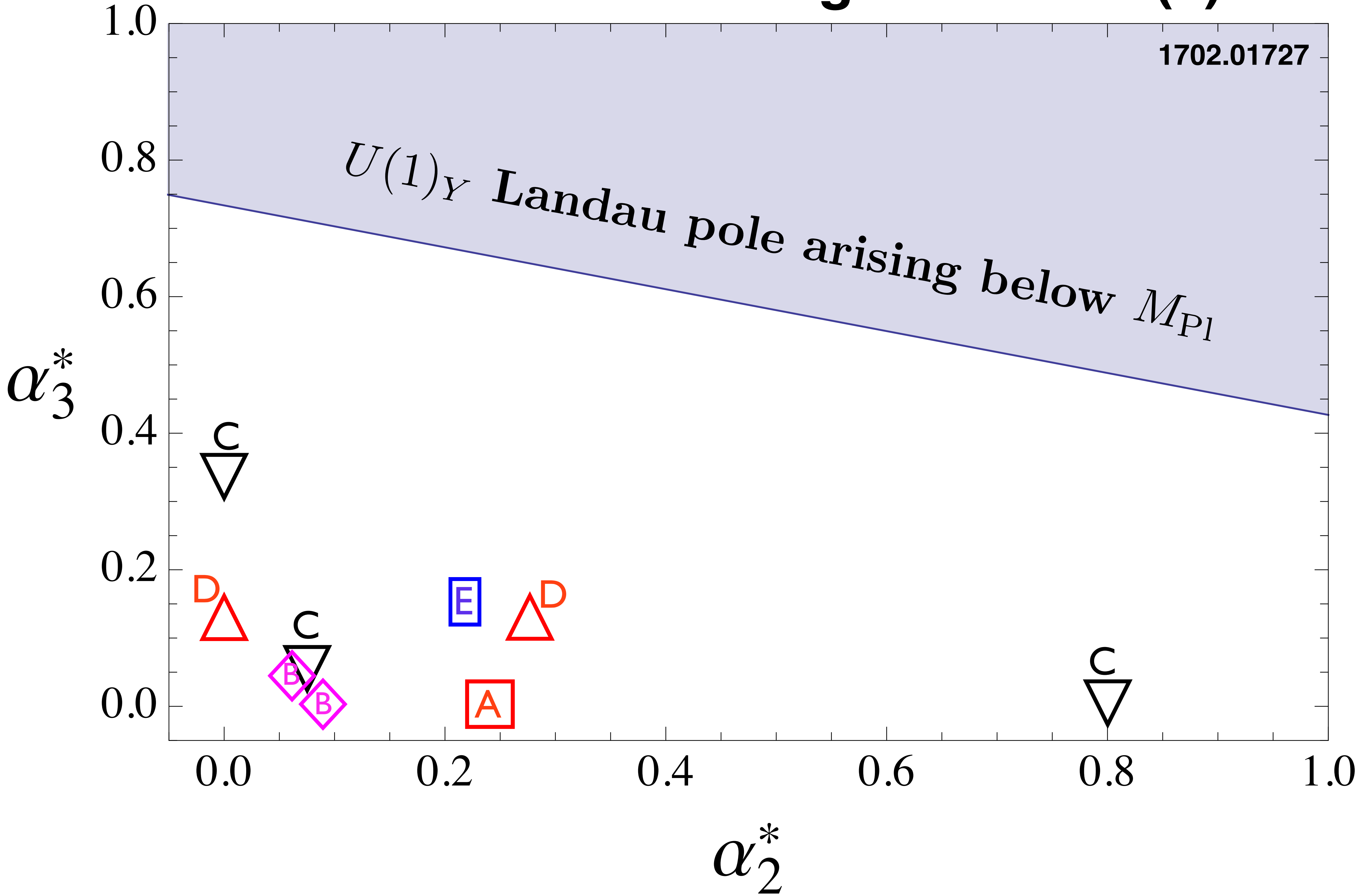
U(1)Y BSM

BSM matter uncharged under U(1)Y



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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