asymptotic safety beyond the Standard Model

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Frankfurt, 18 May 2017

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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**?
how does **gravity** fit in?

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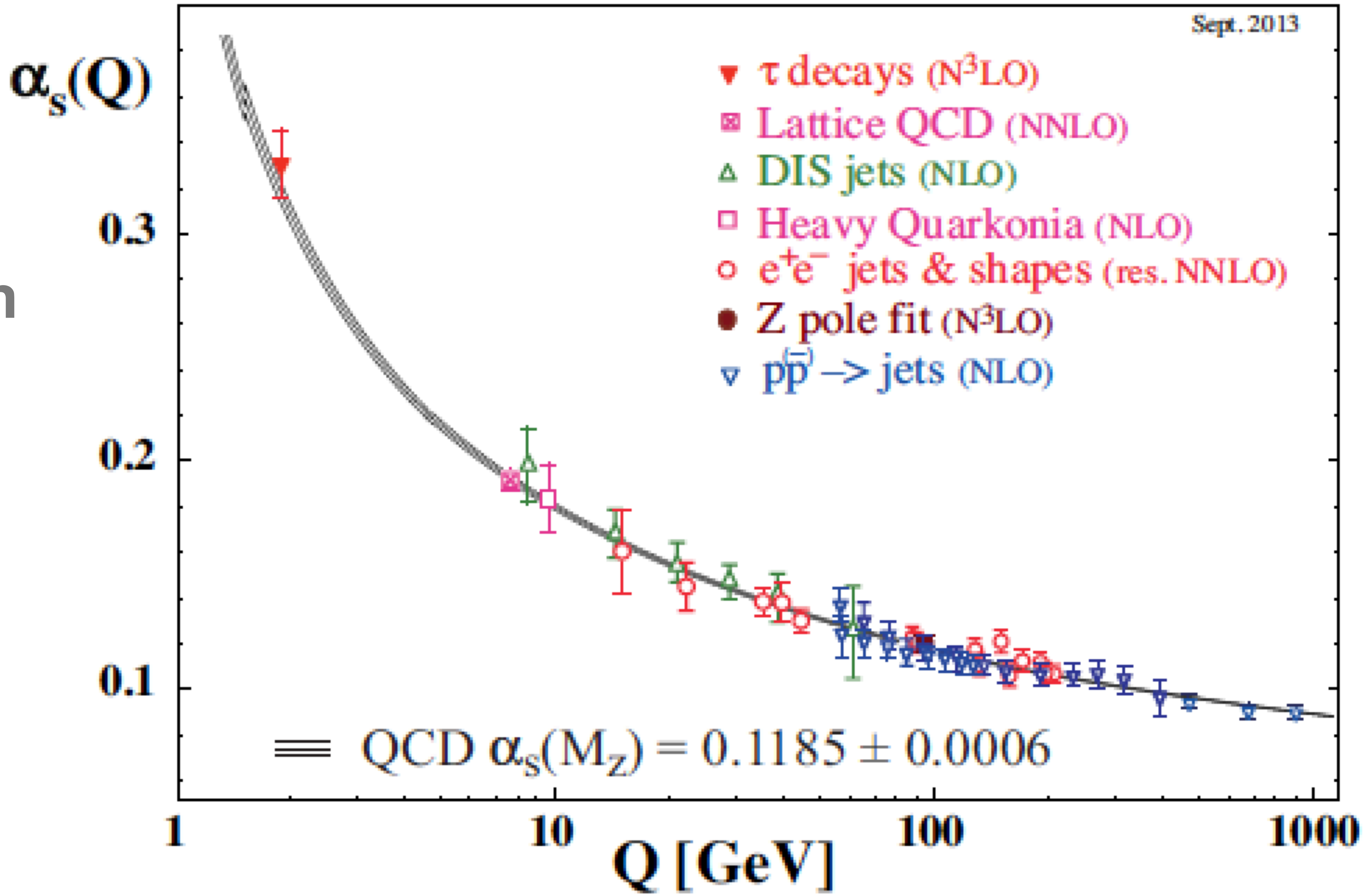
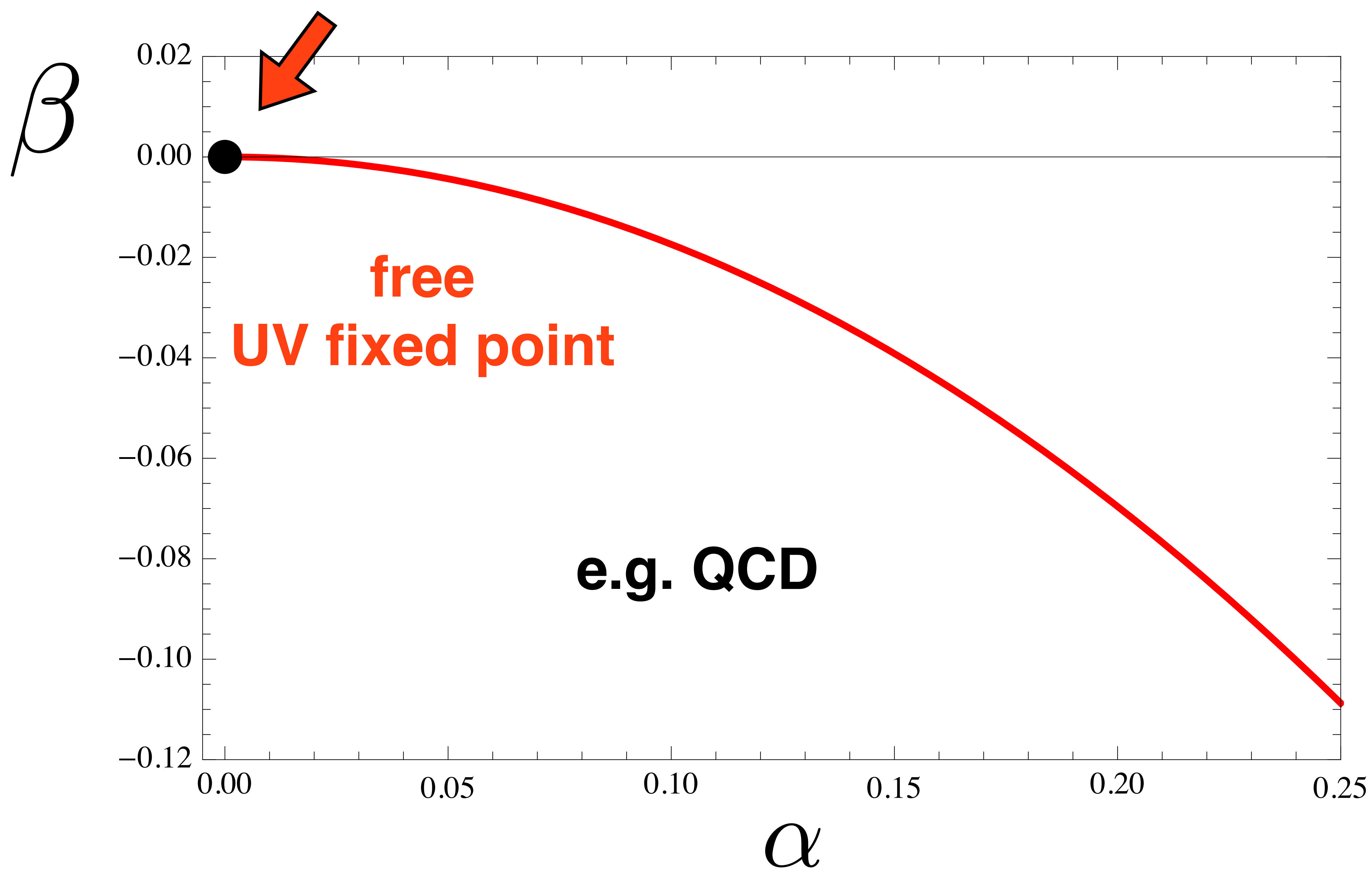
asymptotic freedom

triumph of QFT



asymptotic freedom



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conditions for asymptotic freedom

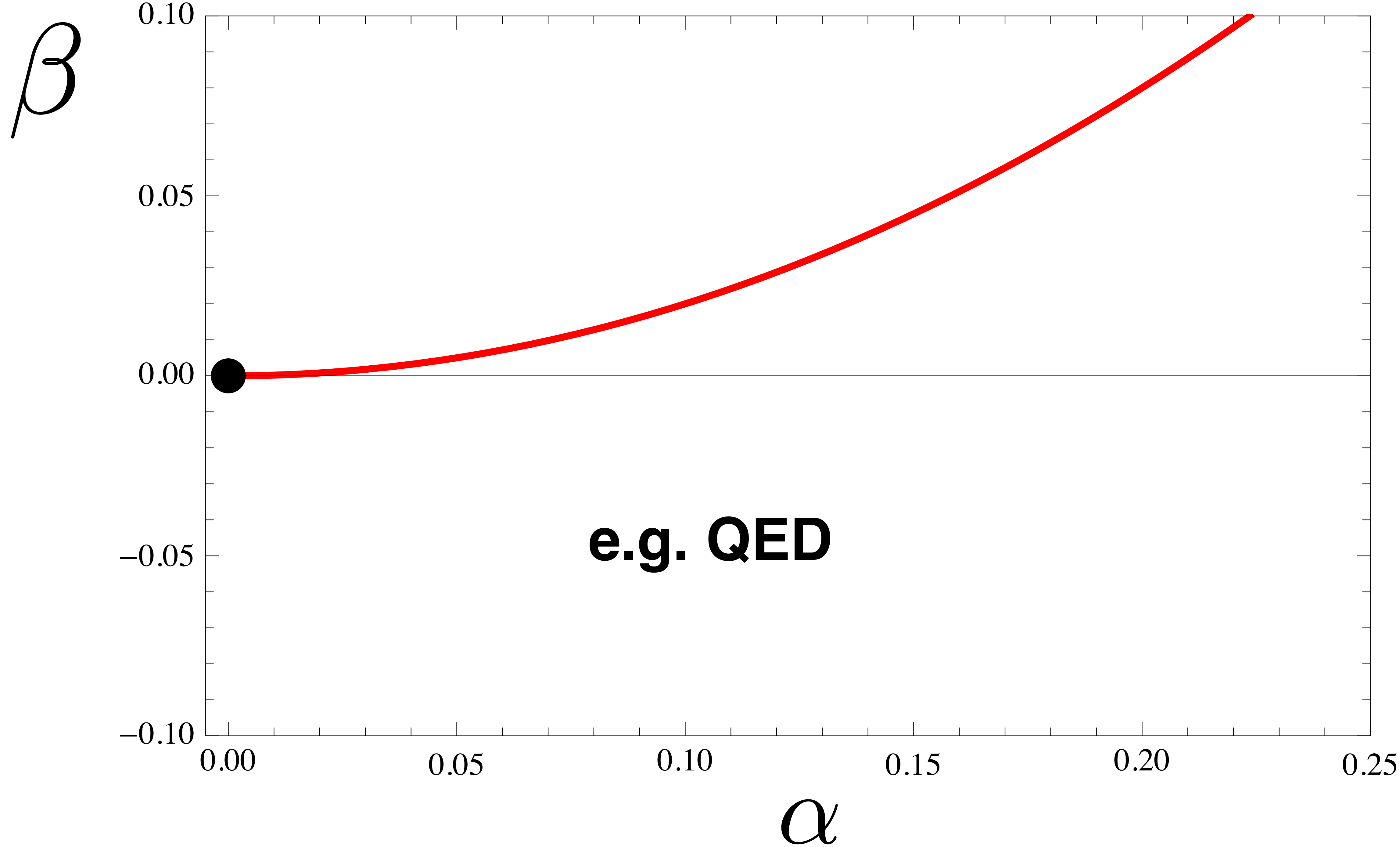
complete asymptotic freedom

couplings achieve non-interacting UV fixed point

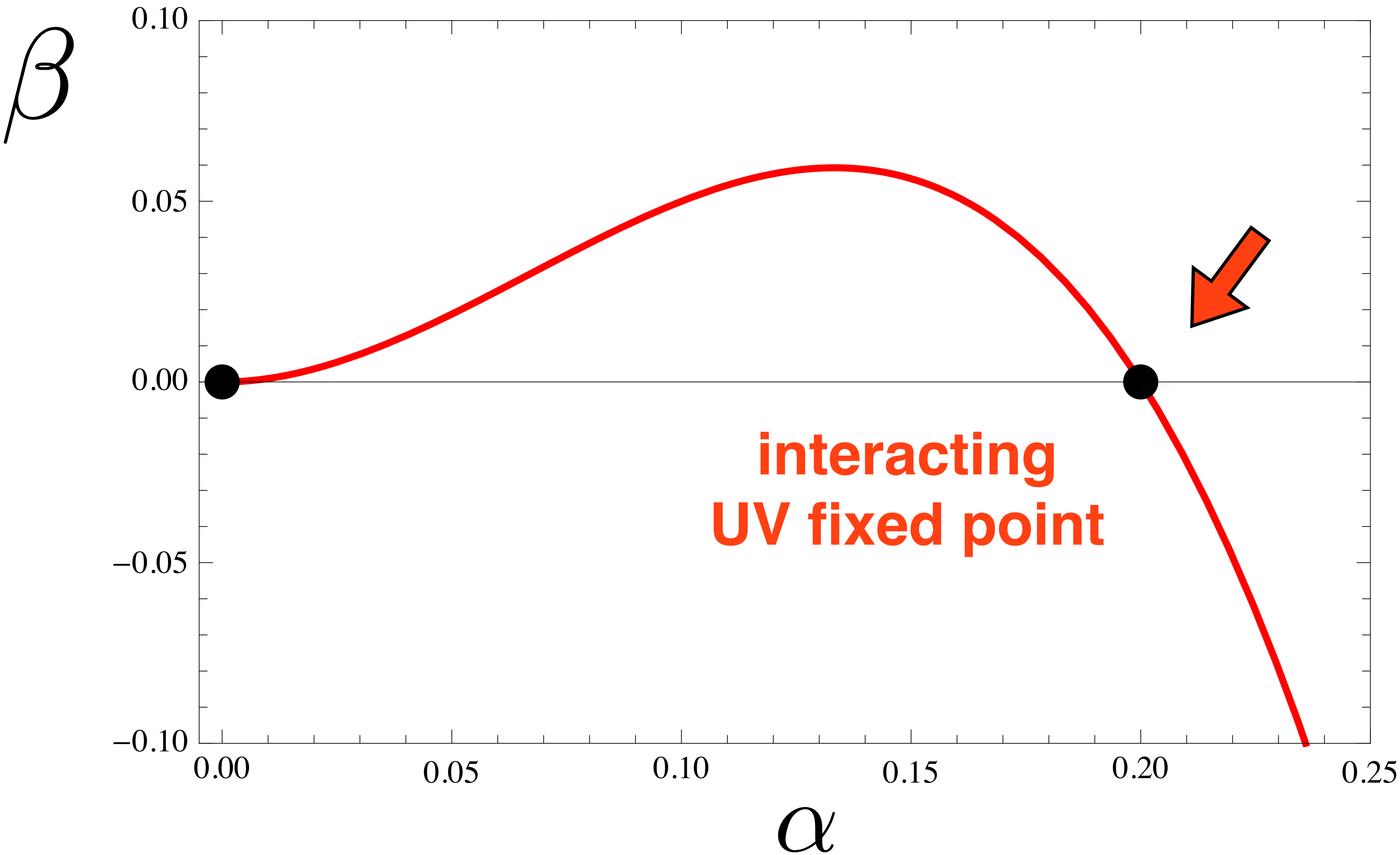
fields	cAF
scalars	no
scalars with fermions	no
U(1) w/o scalars or fermions	no
non-Abelian gauge fields	yes
non-Abelian fields with fermions	yes *)
non-Abelian fields, fermions, scalars	yes *)

*) provided certain auxiliary conditions hold true

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 &, possibly, quantum gravity

proof of existence:

4D gauge-Yukawa theory with
exact asymptotic safety

Litim, Sannino, 1406.2337
Bond, Litim @ERG2016

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asymptotic safety

today:

1. **theorems** for asymptotic safety

Bond, Litim 1608.00519

2. weakly **interacting UV completions** of the Standard Model

3. **constraints** from data (colliders)

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

asymptotic safety

today:

1. **theorems** for asymptotic safety

Bond, Litim 1608.00519

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conditions for asymptotic safety

results

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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basics of asymptotic safety

gauge theory

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

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

loop coefficients

$B > 0$ **asymptotic freedom** $C < 0 \text{ or } C > 0$

in the latter case: $\alpha_g^* = \frac{B}{C}$ **Banks-Zaks** **IR FP**

basics of asymptotic safety

gauge theory

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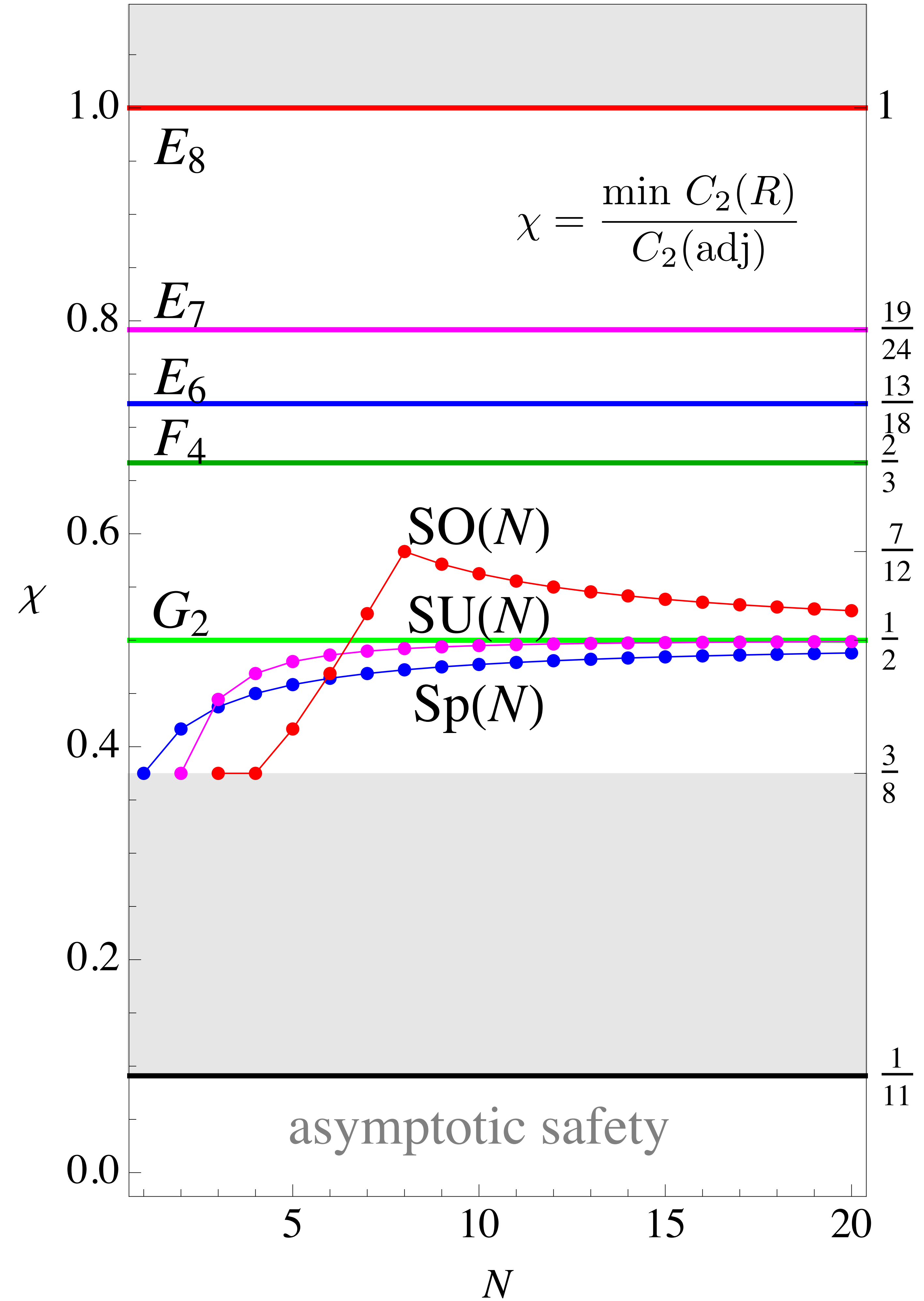
$$0 < \alpha^* = B/C \ll 1 \qquad \alpha_* \ll 1$$

loop coefficients

$B < 0$ **infrared freedom**

for C < 0 we must have $C_2^S < \frac{1}{11} C_2^G$

result:



$\chi = \frac{\min\ C_2(R)}{C_2(\text{adj})}$
E_8
E_7
E_6
F_4
G_2
SO(N)
SU(N)
Sp(N)
asymptotic safety
χ
N
1
$\frac{19}{24}$
$\frac{13}{18}$
$\frac{2}{3}$
$\frac{7}{12}$
$\frac{1}{2}$
$\frac{3}{8}$
$\frac{1}{11}$

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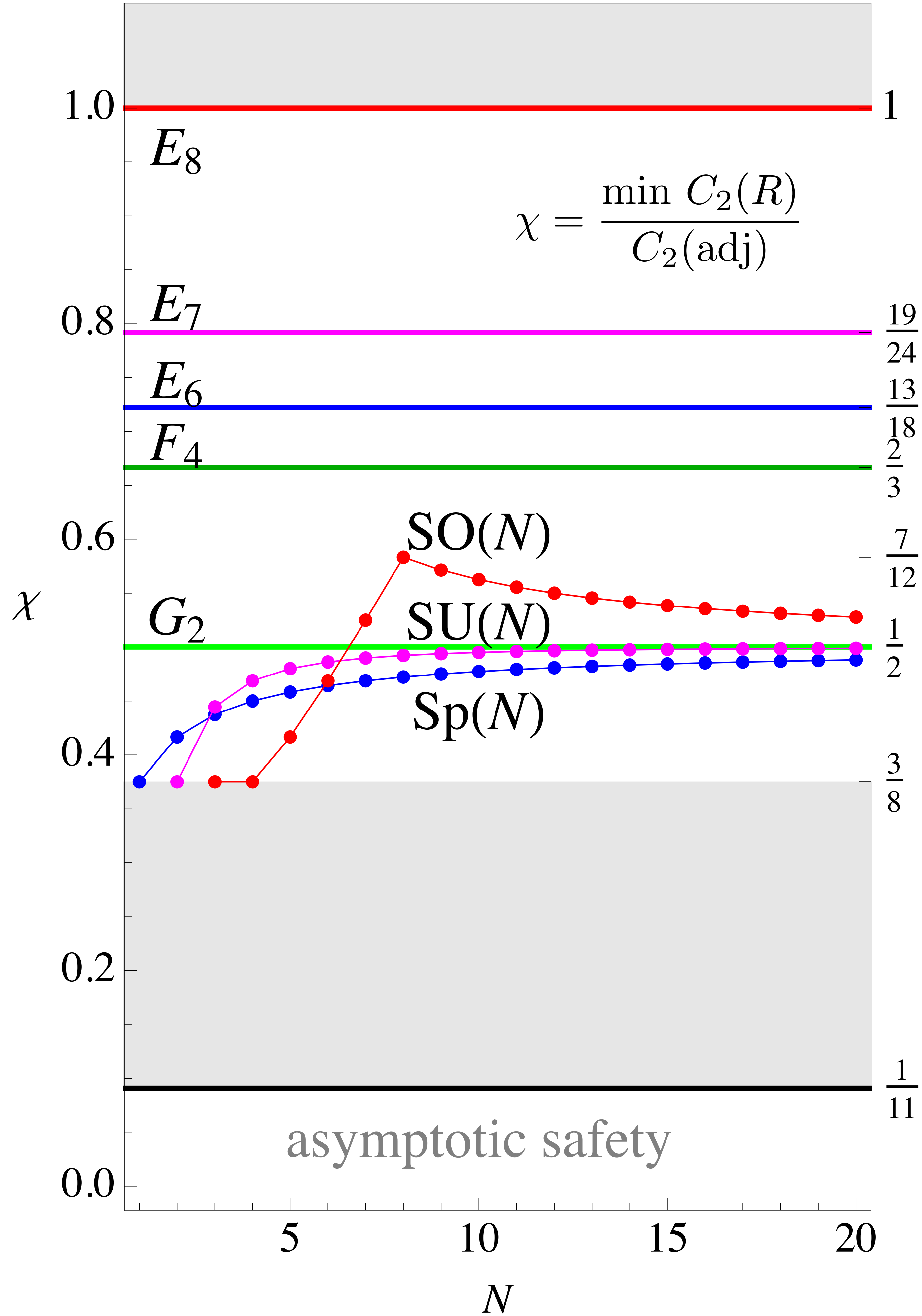
result:



implication:

$$B \leq 0 \quad \Rightarrow \quad C > 0$$

no go theorem

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basics of asymptotic safety

gauge theory

$$\partial_t \alpha_g = -B\,\alpha_g^2 + C\,\alpha_g^3$$

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loop coefficients

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Bond, Litim 1608.00519

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basics of asymptotic safety

gauge theory

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

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

loop coefficients

$B < 0$ **infrared freedom**

$B < 0 \Rightarrow C > 0$

Bond, Litim 1608.00519

can other couplings help?

more gauge: **useless**

scalar quartics: **useless**

→ Yukawas: **unique viable option**

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basics of asymptotic safety

gauge Yukawa theory

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

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

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

basics of asymptotic safety

gauge Yukawa theory

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

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Yukawa nullcline $$\alpha_y^* = \frac{F}{E}\alpha_g^*$$

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basics of asymptotic safety

gauge Yukawa theory

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

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

Yukawa nullcline $\alpha_y^* = \frac{F}{E}\alpha_g^*$

$$\Rightarrow \quad \beta_g| = (-B + C'\,\alpha_g)\,\alpha_g^2$$

shifted two-loop $C \to C' = C - D\frac{F}{E}$

interacting UV fixed point iff $D\,F - C\,E > 0$

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basics of asymptotic safety

gauge Yukawa theory

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

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

Yukawa nullcline $\alpha_y^* = \frac{F}{E}\alpha_g^*$

$$\beta_g\big| = (-B + C'\,\alpha_g)\,\alpha_g^2$$

gauge-Yukawa fixed point

$$\Rightarrow \quad (\alpha_g^*\,,\alpha_y^*) = \left(\frac{B}{C'}\,,\frac{B}{C'}\frac{F}{E}\right)$$

UV or IR

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basics of asymptotic safety

gauge Yukawa theory

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

$$\partial_t \alpha_y = E\,\alpha_y^2 - F\,\alpha_g\,\alpha_y$$

$t = \ln \mu/\Lambda$

$\alpha_* \ll 1$

summary of fixed points

$(\alpha_g^*, \alpha_y^*) = (0, 0)$	Gaussian	UV or IR
$(\alpha_g^*, \alpha_y^*) = \left(\dfrac{B}{C}, 0\right)$	Banks-Zaks	IR
$(\alpha_g^*, \alpha_y^*) = \left(\dfrac{B}{C'}, \dfrac{B}{C'}\dfrac{F}{E}\right)$	gauge-Yukawa	UV or IR

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basics of asymptotic safety

gauge Yukawa theory

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

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

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 (to appear)

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conditions for asymptotic safety

results

Bond, Litim 1608.00519

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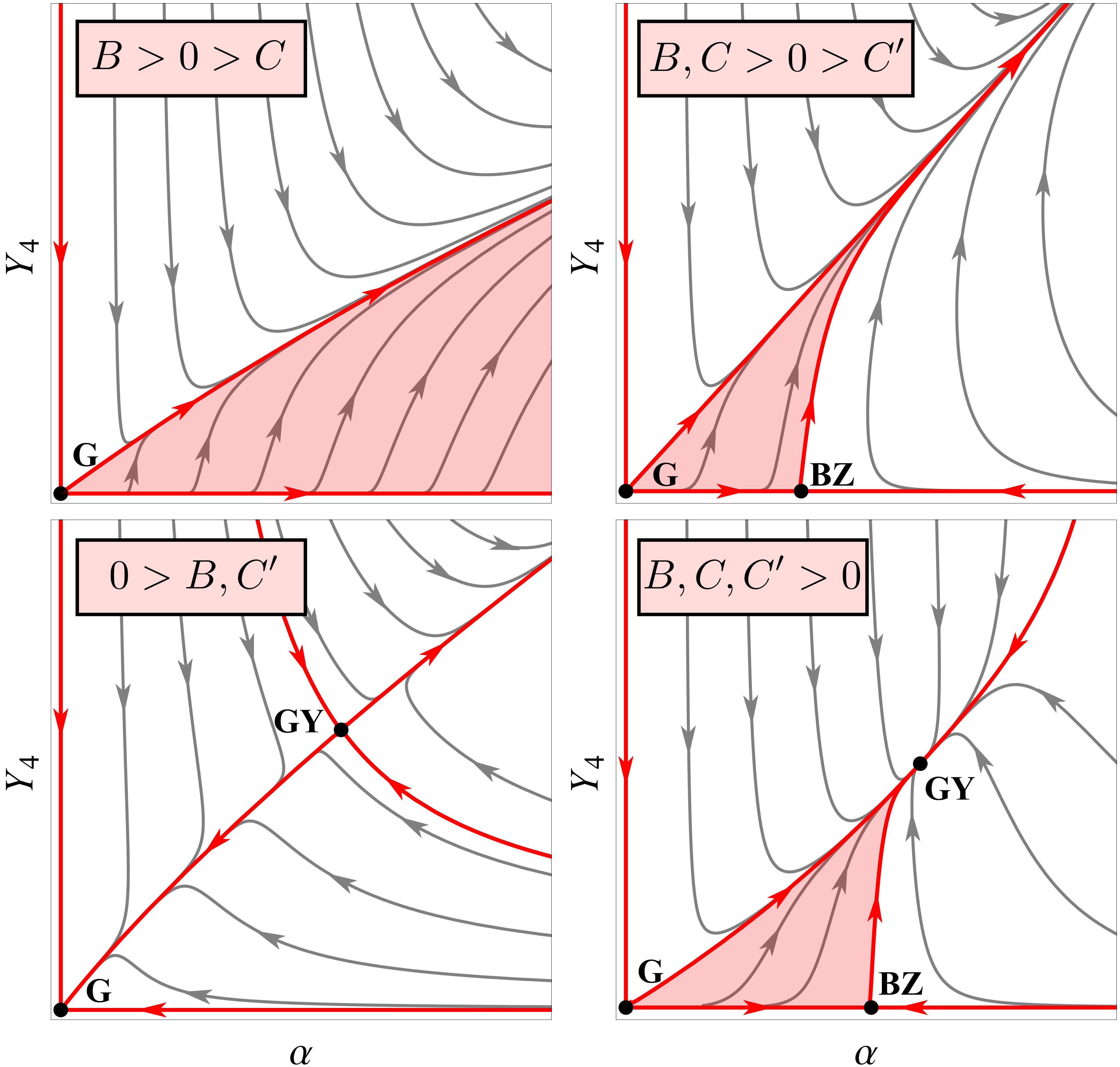
***) provided certain auxiliary conditions hold true**



$B > 0 > C$
$B, C > 0 > C'$
$0 > B, C'$
$B, C, C' > 0$
Y_4
α
G
BZ
GY

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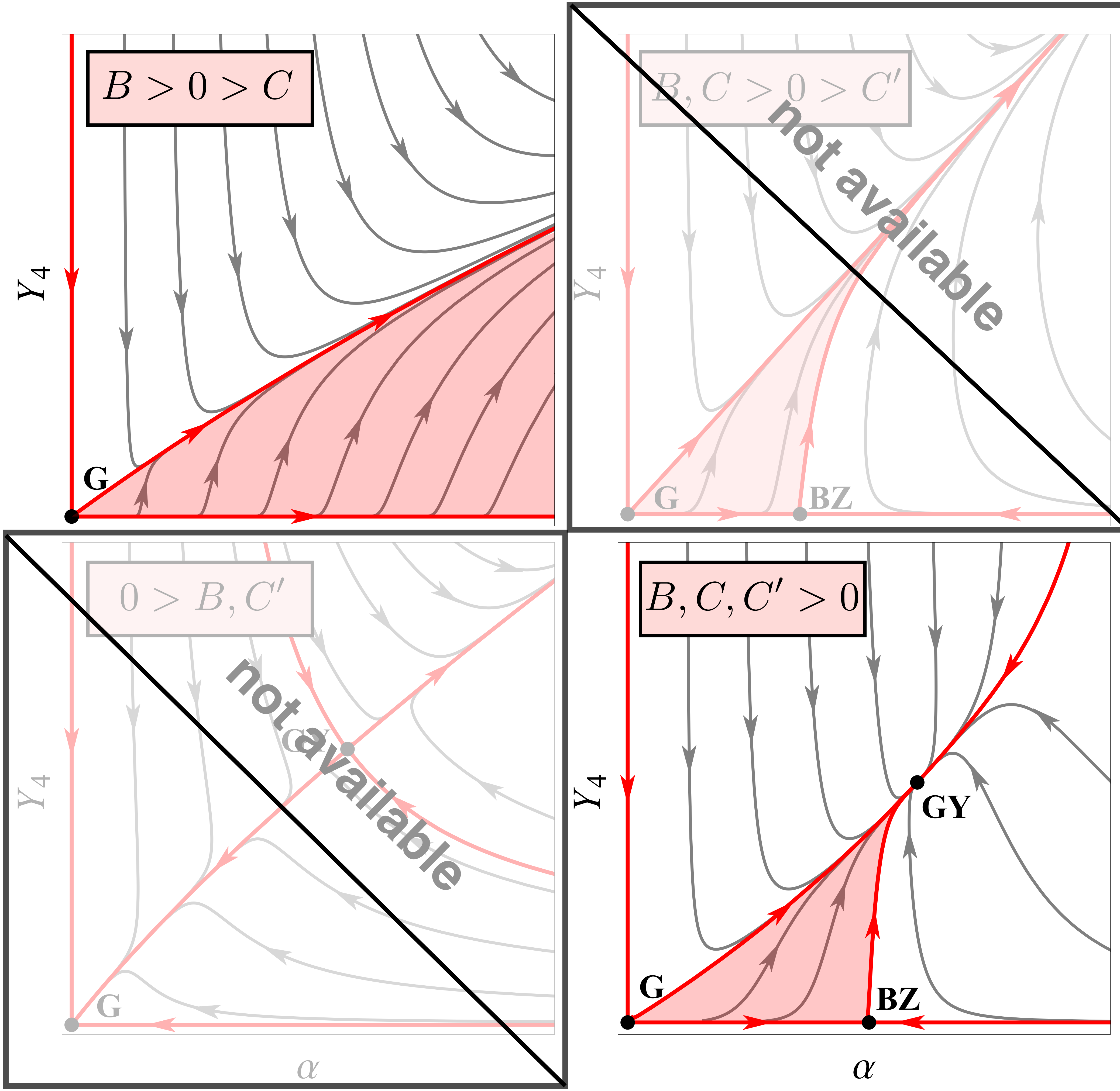
N=1
SUSY



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asymptotic safety

2. weakly **interacting UV completions** of the Standard Model

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

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asymptotic safety beyond the SM

Bond, Hiller, Kowalska, Litim, 1702.01727

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

BSM singlet scalars S_{ij}

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

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

BSM Lagrangean

$$L = L_{\rm SM} + L_{\rm BSM,\,kin.} + L_{\rm BSM,\,pot.} + L_{\rm BSM,\,Yukawa}$$

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UV fixed points

#	gauge couplings		BSM Yukawa	type & info	
FP$_1$	$\alpha_3^* = 0$	$\alpha_2^* = 0$	$\alpha_y^* = 0$	$\mathbf{G \cdot G}$	non-interacting
FP$_2$	$\alpha_3^* = 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	$\mathbf{G \cdot GY}$	partially interacting
FP$_3$	$\alpha_3^* > 0$	$\alpha_2^* = 0$	$\alpha_y^* > 0$	$\mathbf{GY \cdot G}$	partially interacting
FP$_4$	$\alpha_3^* > 0$	$\alpha_2^* > 0$	$\alpha_y^* > 0$	$\mathbf{GY \cdot GY}$	fully interacting

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BSM fixed points

$\mathbf{FP_2}$

$\alpha_2^* > 0$ — 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 $\delta\alpha_2(\Lambda),\ \delta\alpha_3(\Lambda)$

$\mathbf{FP_4}$

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

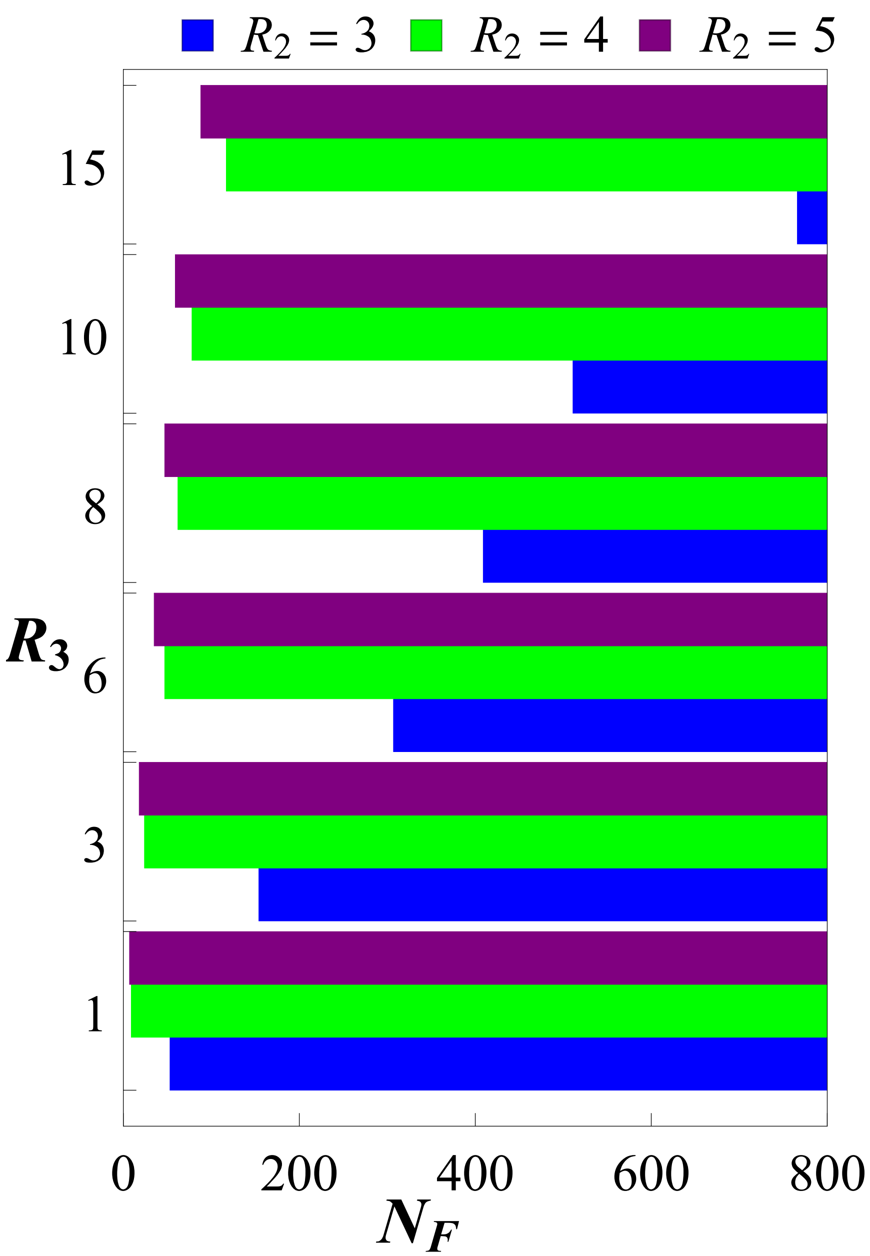
weak becomes the new strong

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

BSM fixed points

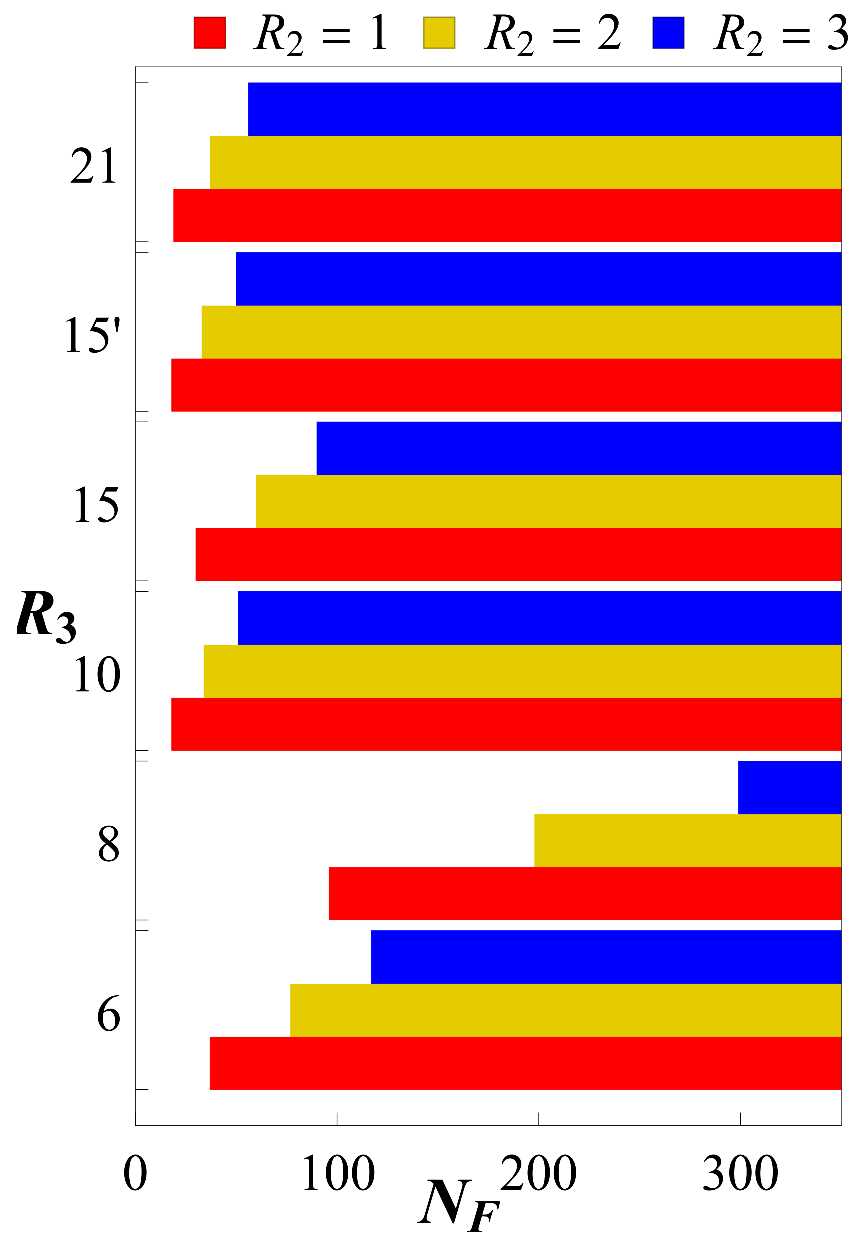
$\mathbf{FP_2}$

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



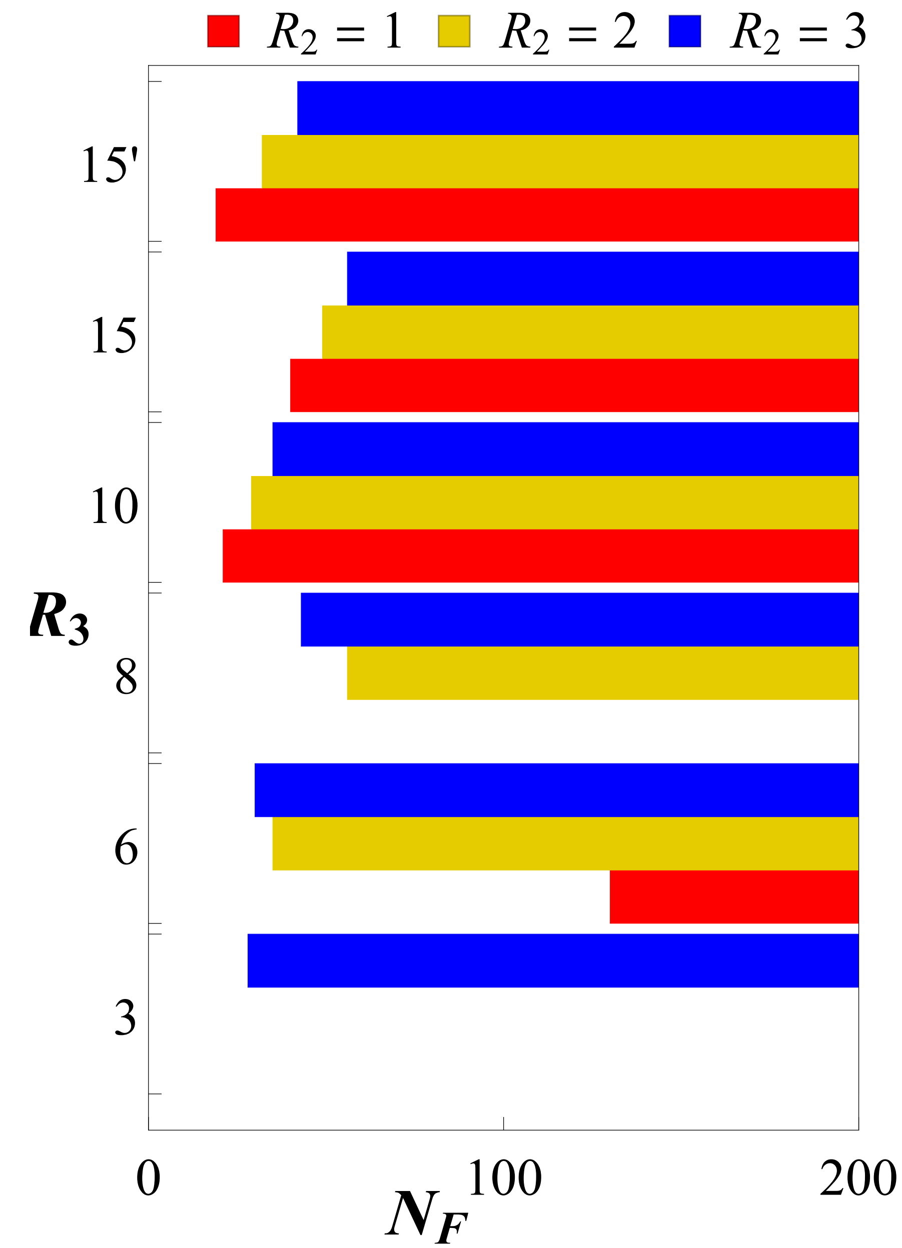
$\mathbf{FP_3}$

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

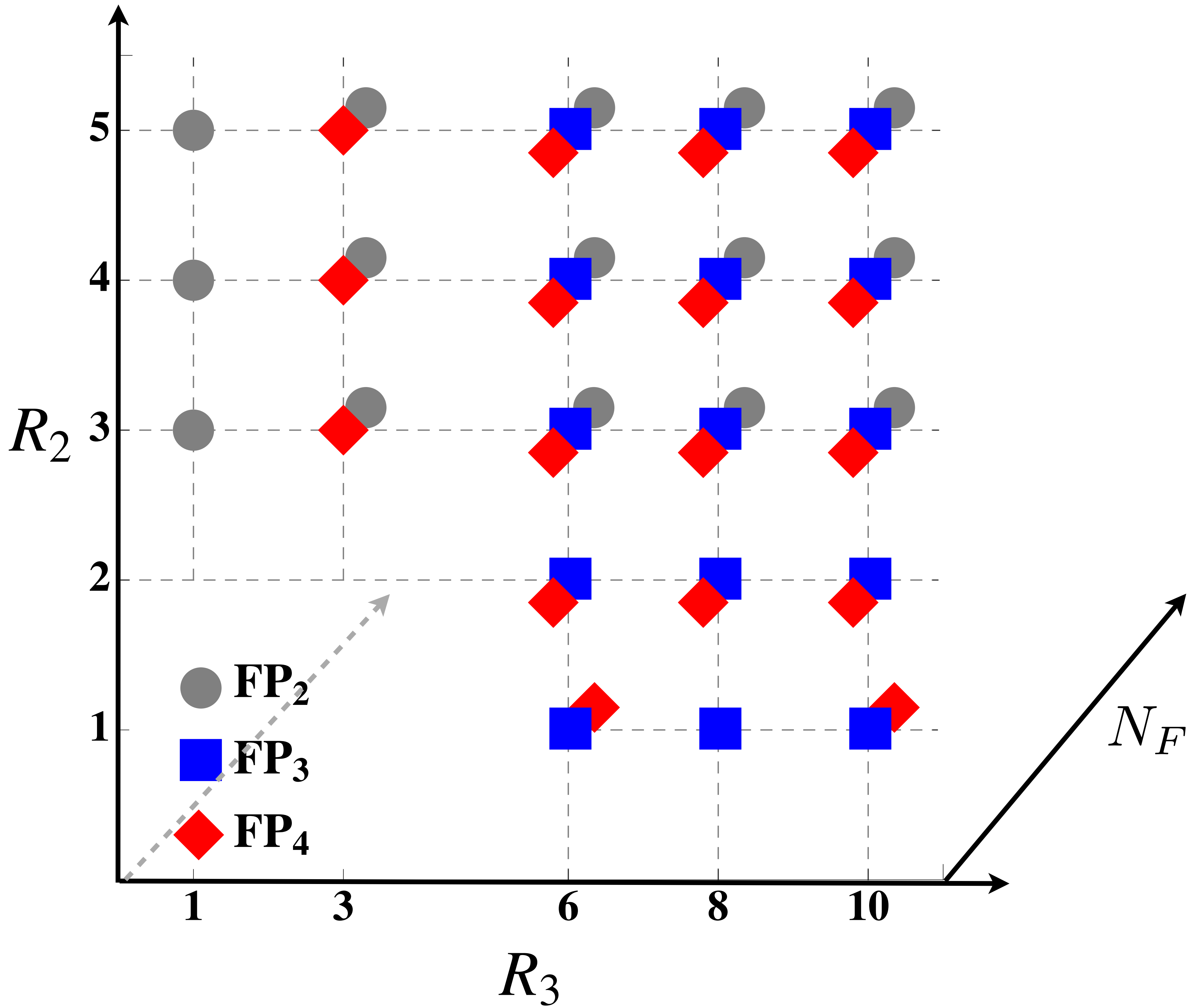


$\mathbf{FP_4}$

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



summary of fixed points



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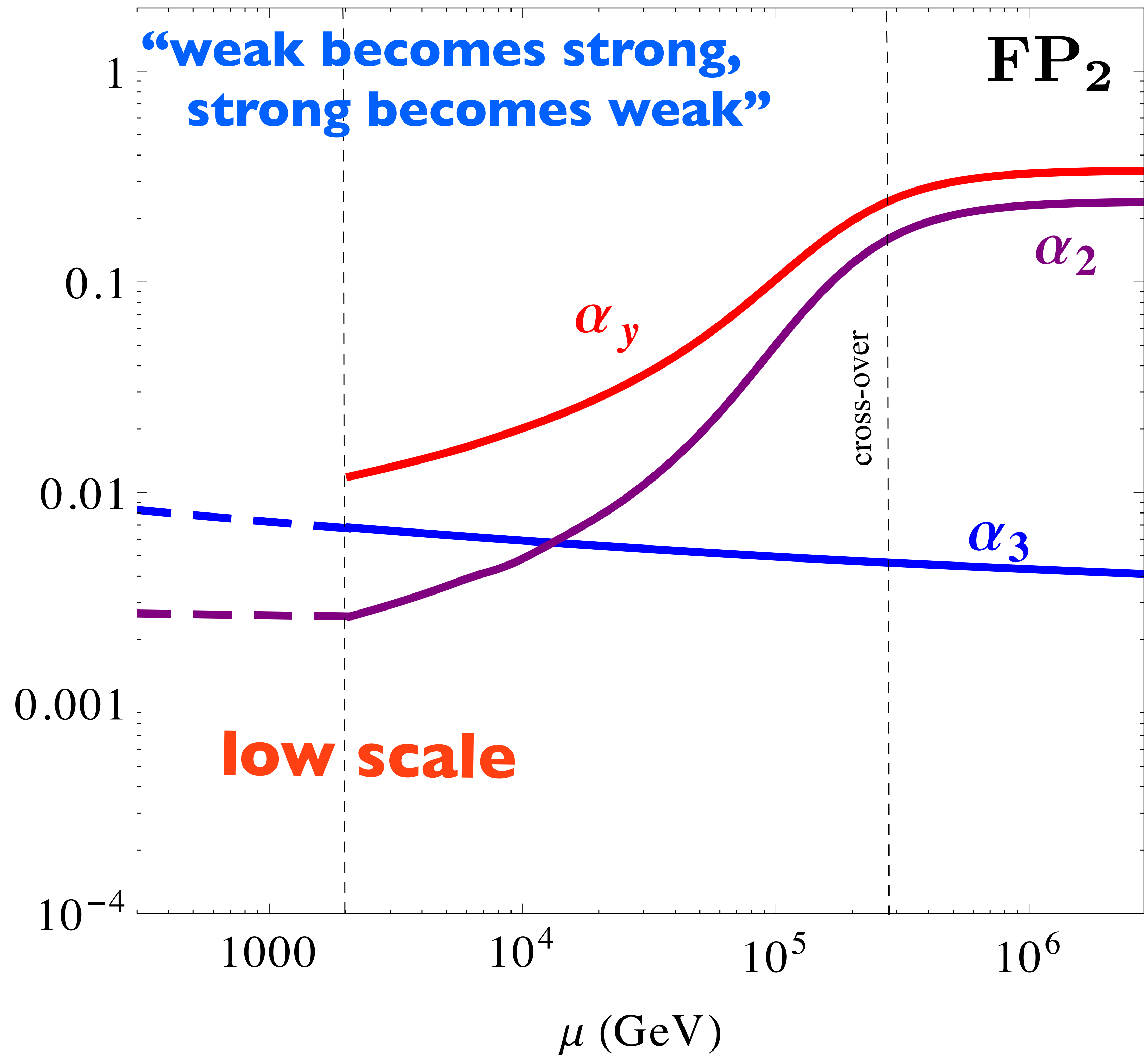
benchmark models

model	parameter (R_3, R_2, N_F)	UV fixed points α_3^*	α_2^*	α_y^*	type
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

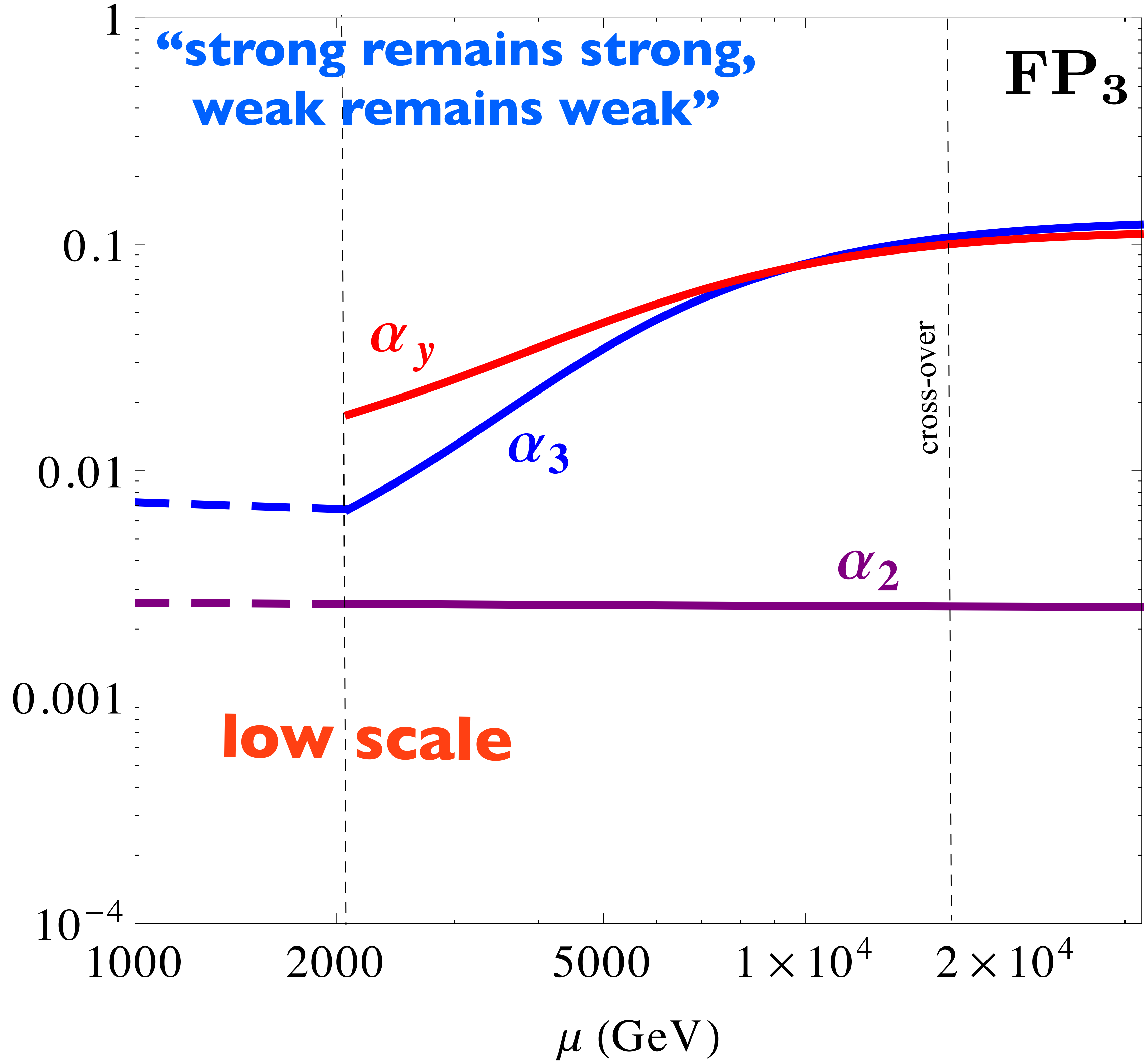
$(R_3, R_2, N_F) = \ (\mathbf{1},\mathbf{4},12)$



benchmark models

model B

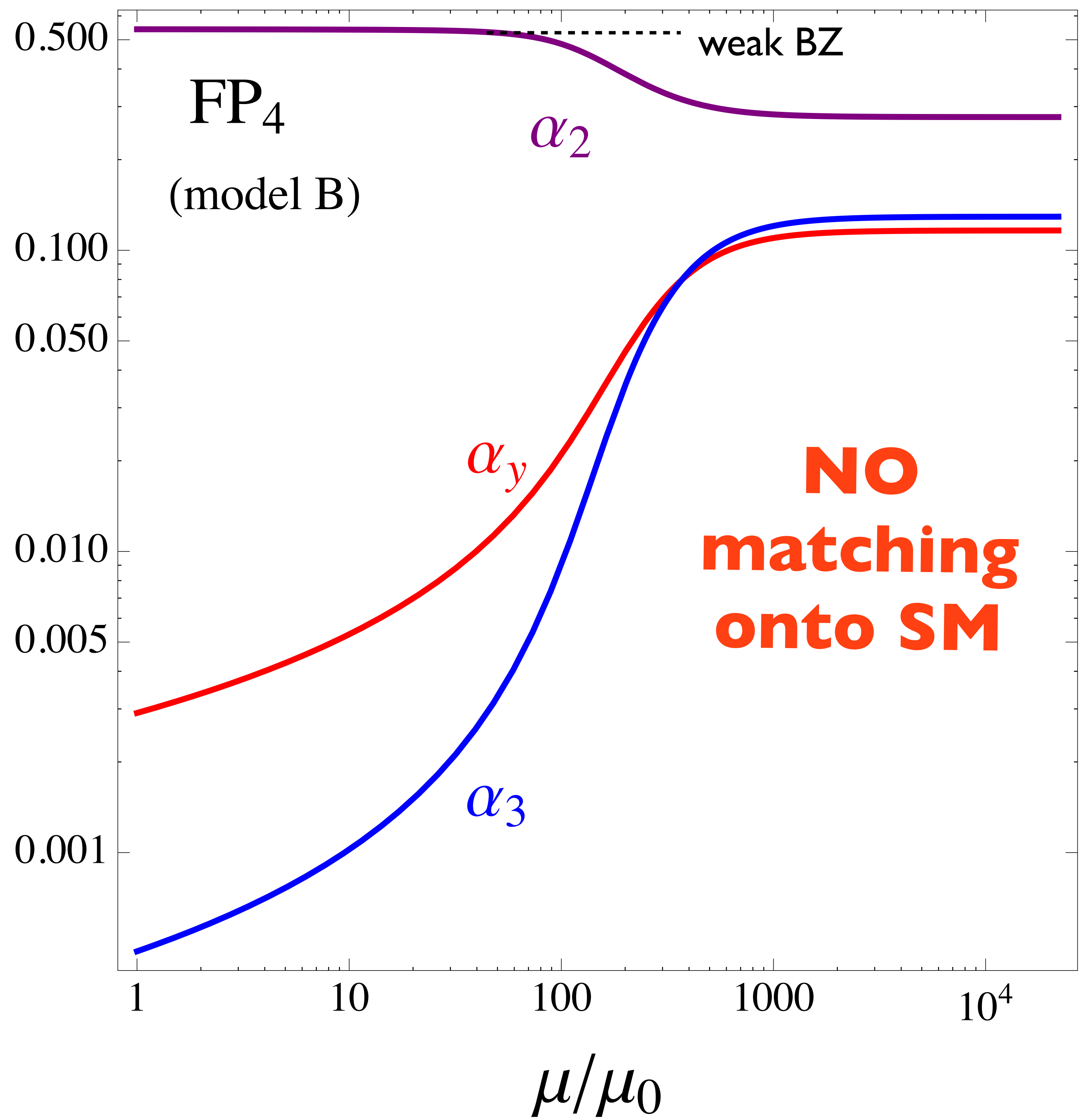
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{1}, 30)$



benchmark models

model B

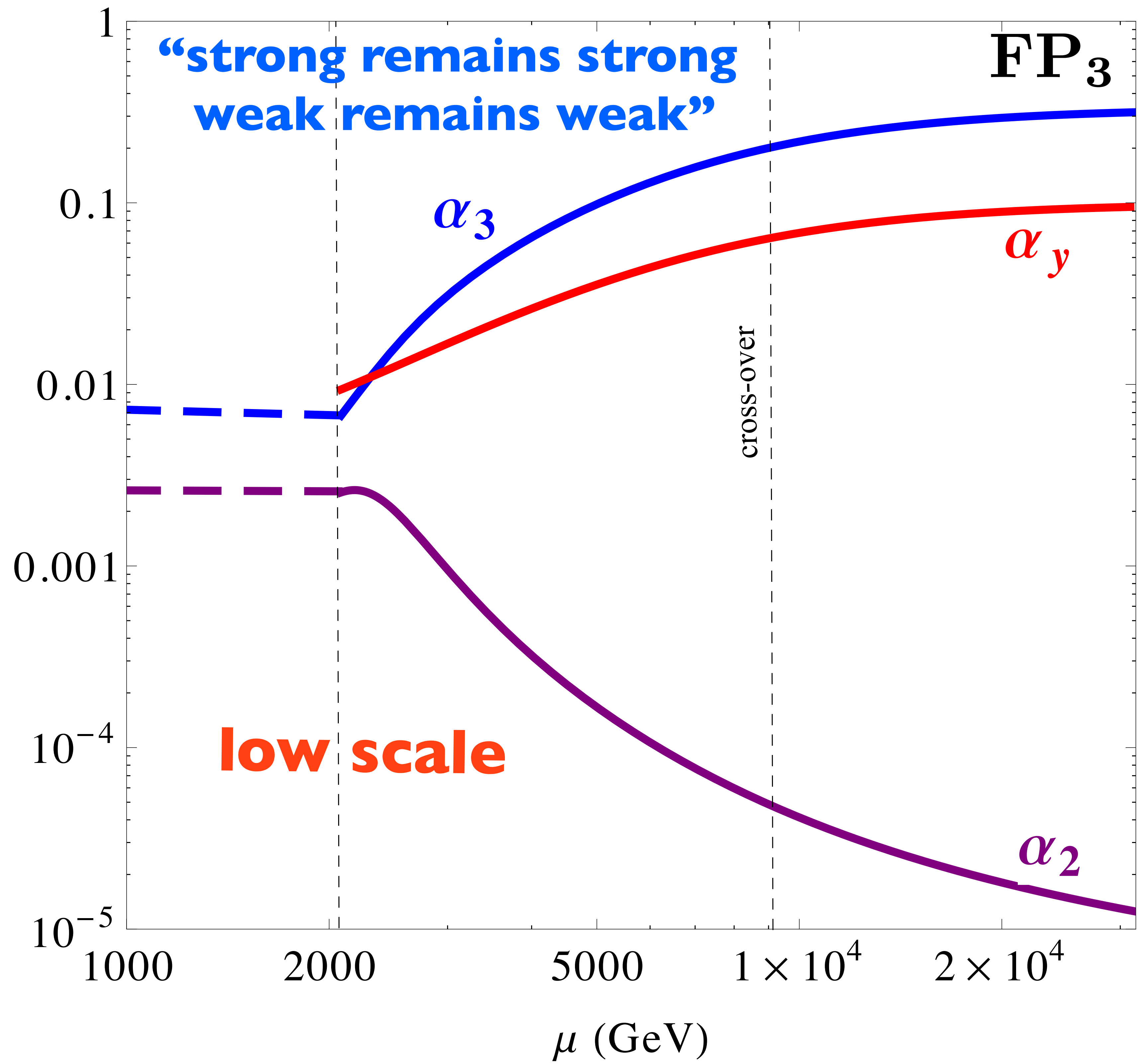
$(R_3, R_2, N_F) =$ **(10,1,30)**



benchmark models

model C

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



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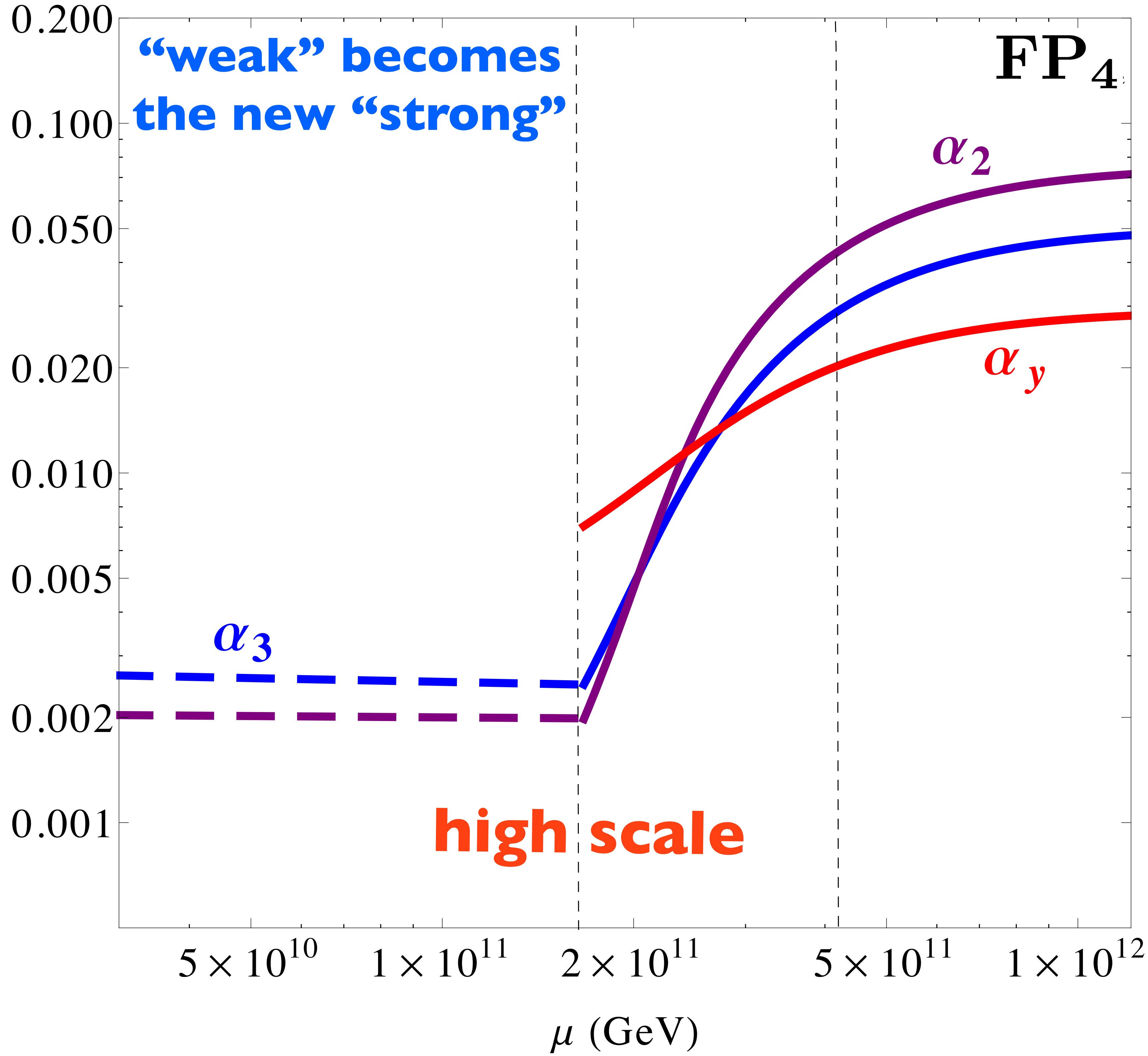
benchmark models

model C

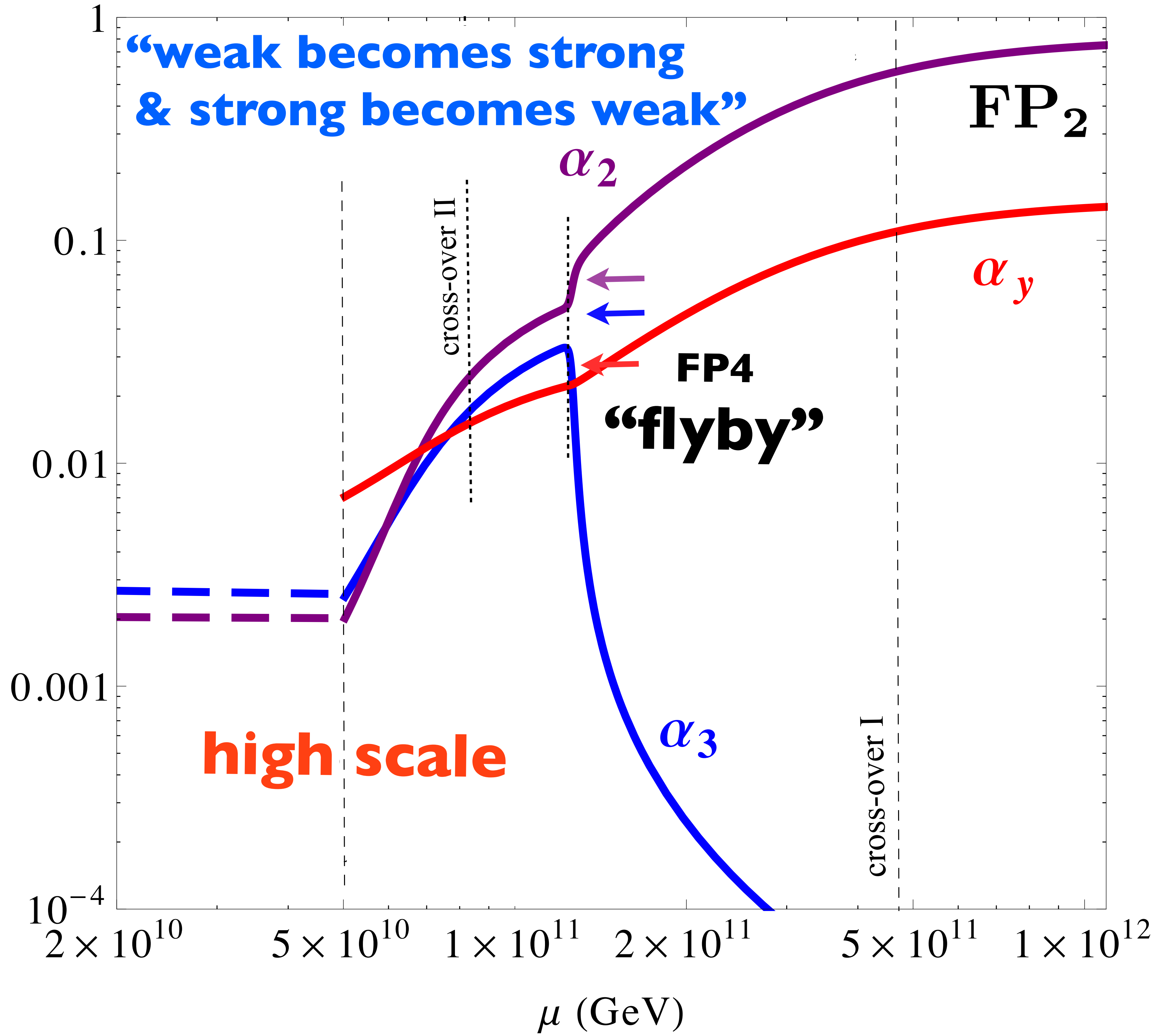
$(R_3, R_2, N_F) =$ $(\mathbf{10},\mathbf{4},80)$



benchmark models

model C

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



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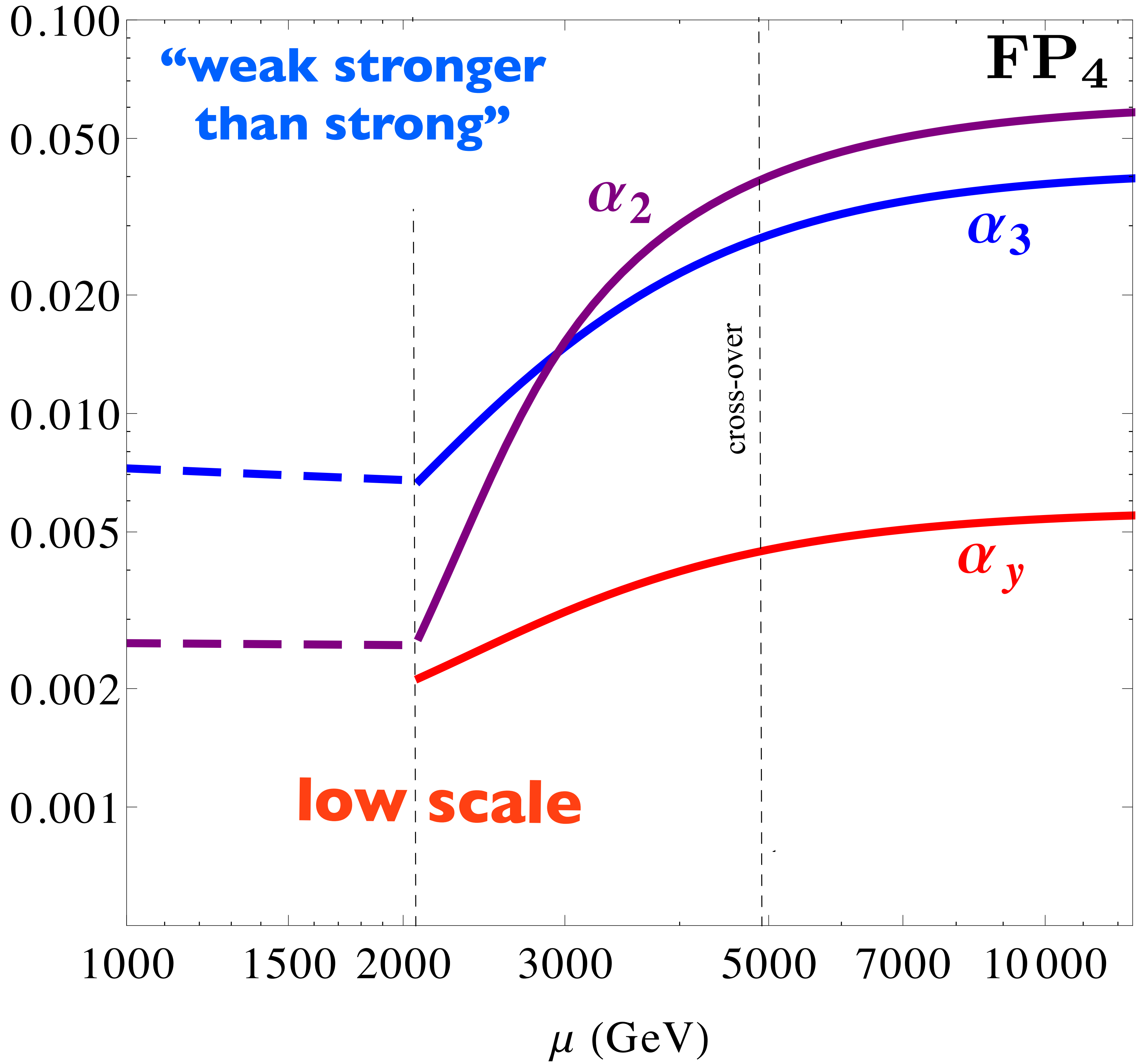
benchmark models

model D

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



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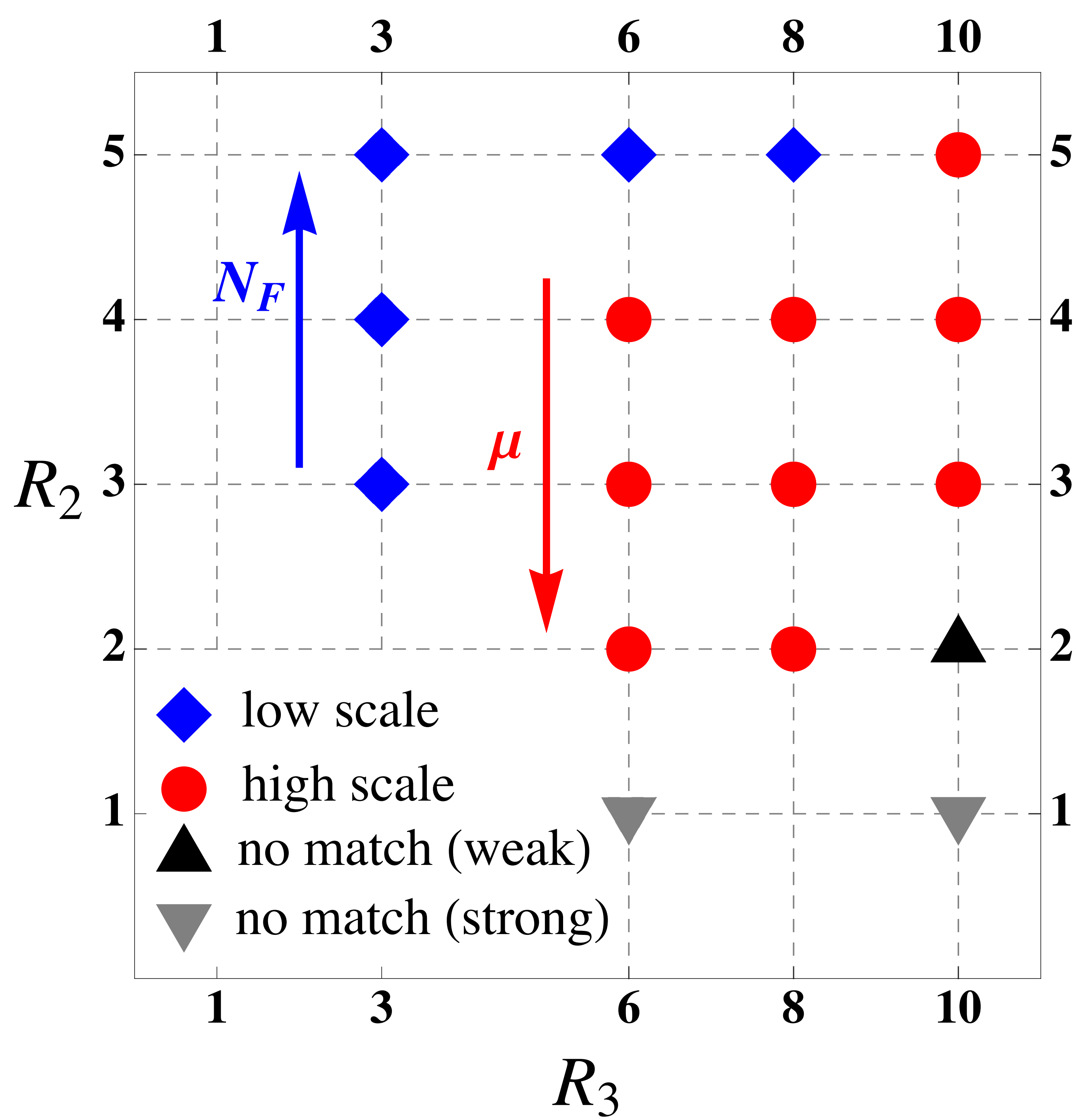
summary of SM matching: when it works

$\mathbf{FP_2}$ **genuinely**, except in special circumstances (competition with other nearby FPs)

$\mathbf{FP_3}$ **genuinely**, except in special circumstances (competition with other nearby FPs)

summary of SM matching: when it works

$\mathbf{FP_4}$



asymptotic safety

3. constraints from data (colliders)

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

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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)

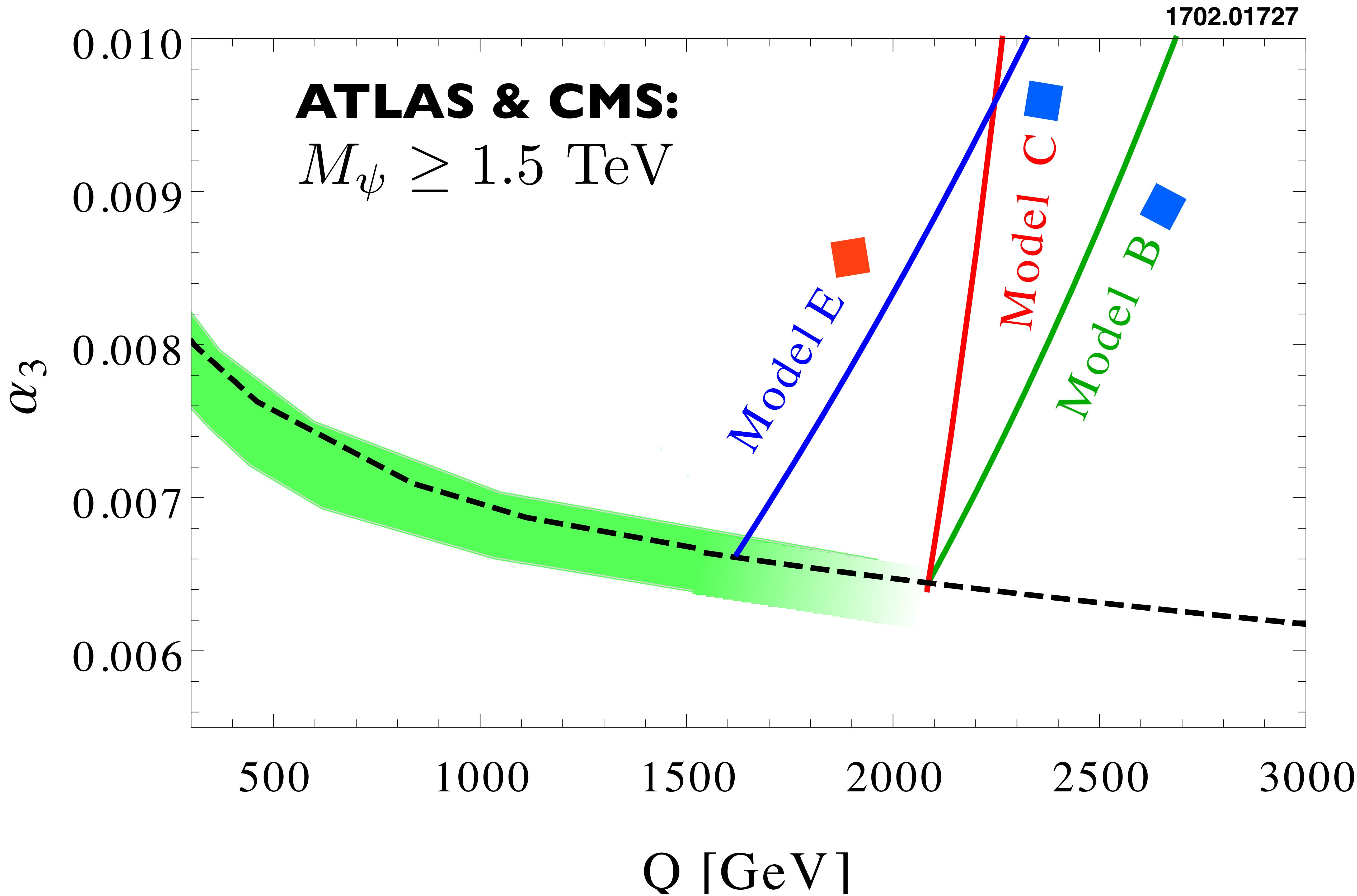
flavor symmetry: stable BSM fermions

broken flavor symmetry: **lightest BSM fermion stable**

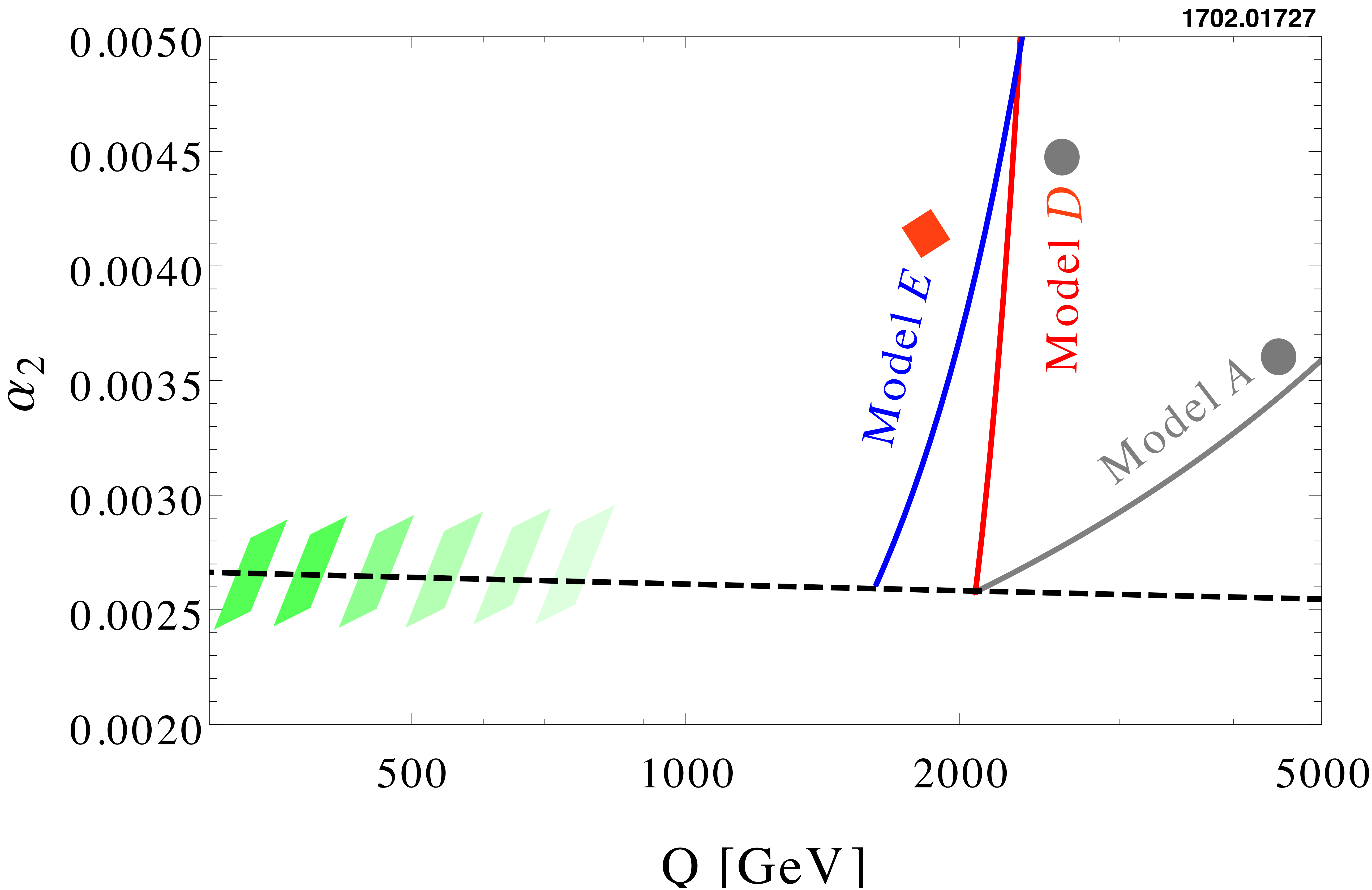
constraints from

- running couplings
- the weak sector
- long-lived QCD bound states
- di-boson searches

SU(3) BSM running



SU(2) BSM running



di-boson spectra and resonances

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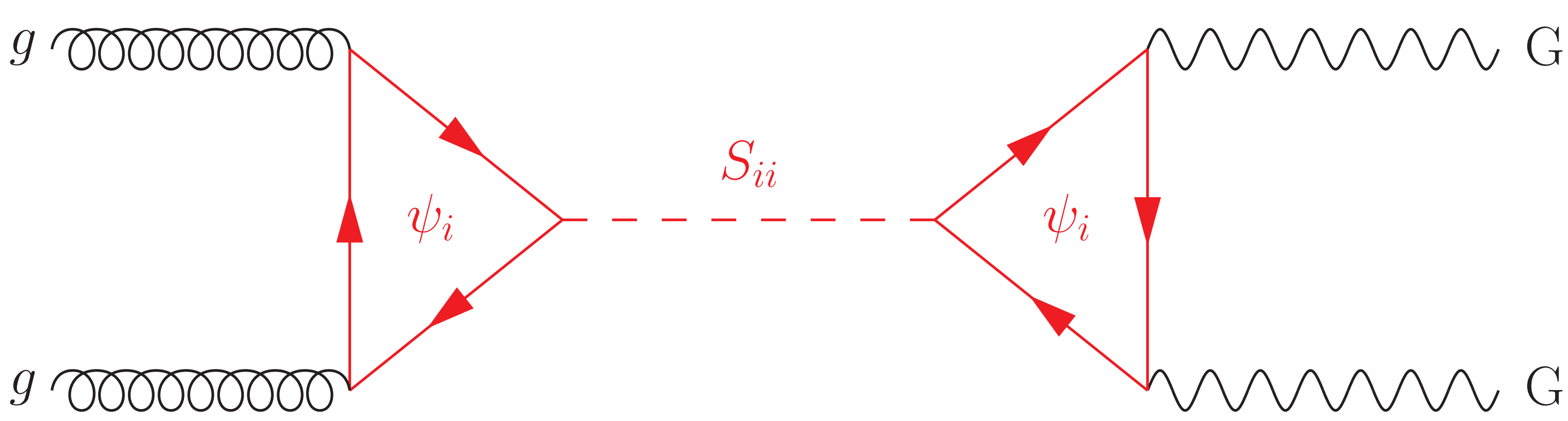
assume resonant production of BSM scalars

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

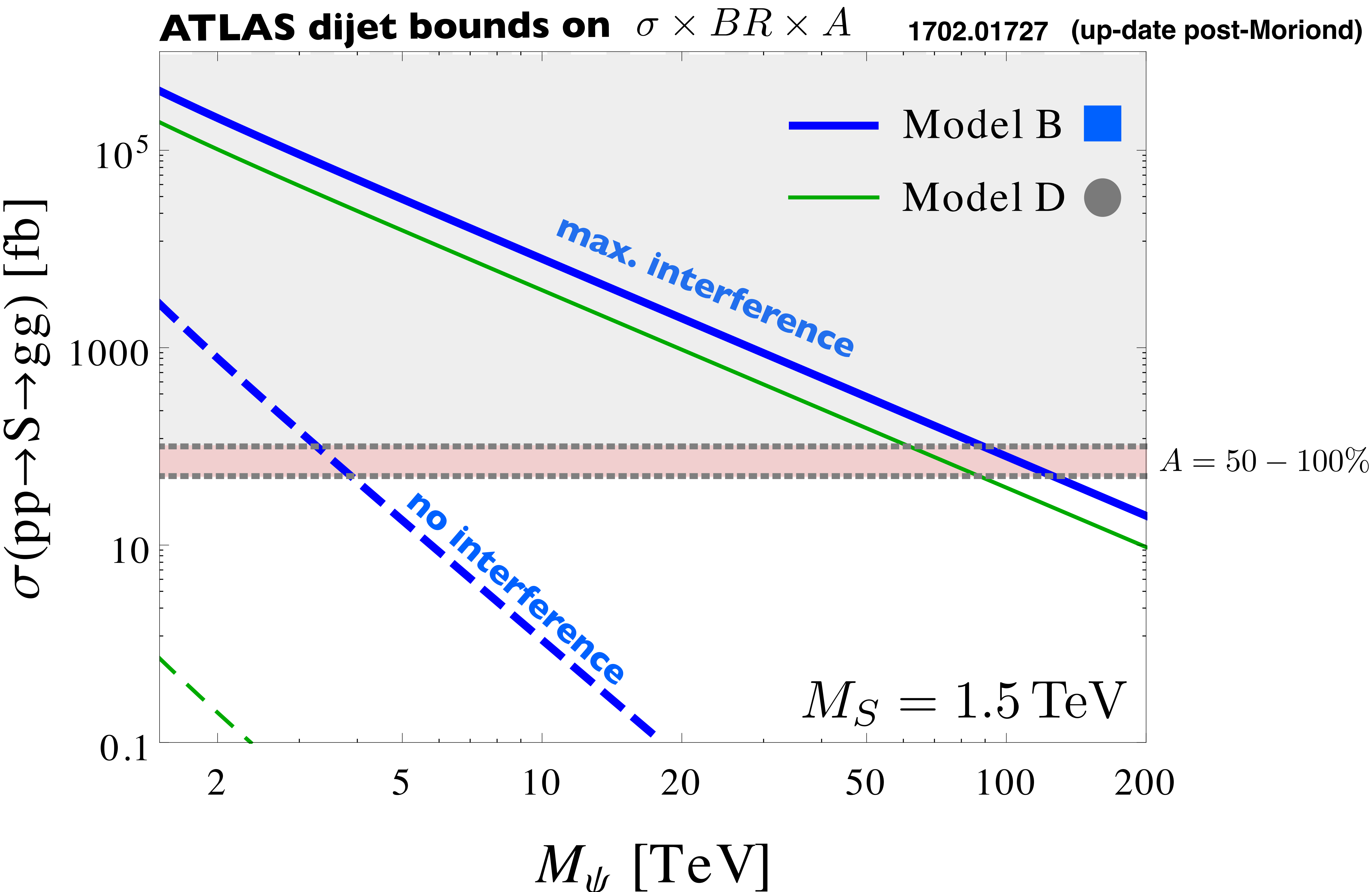
"low Ms" $M_S \lesssim M_\psi$ $\qquad$ **"high Ms"** $M_\psi \lesssim M_S < 2M_\psi$

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

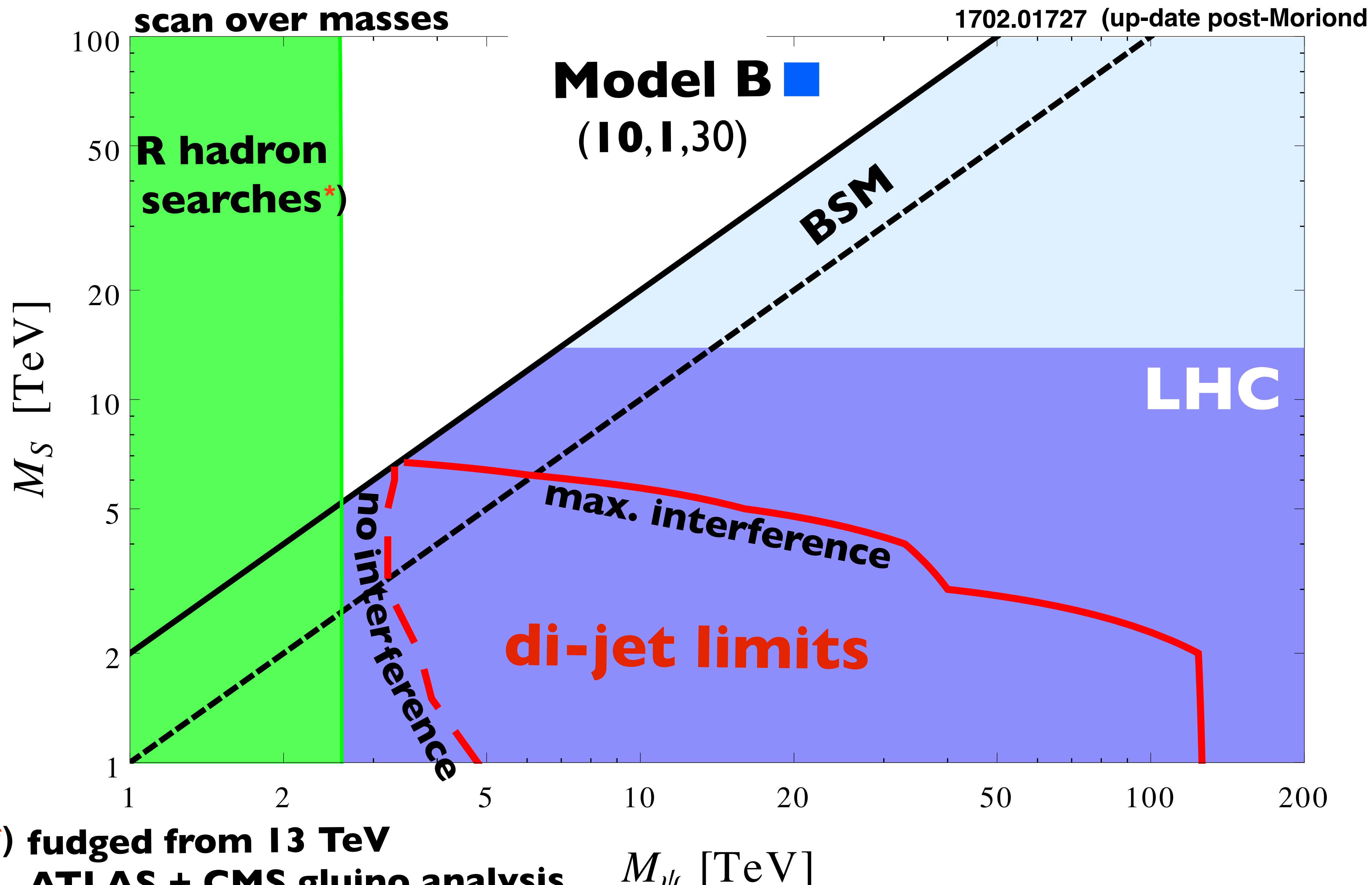


interference effects

dijet cross section



mass exclusion limits



*) fudged from 13 TeV ATLAS + CMS gluino analysis

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conclusions

theorems for fixed points and asymptotic safety

new directions beyond asymptotic freedom

weakly interacting UV completions of the SM

UV FPs can be partially or fully interacting
matching to SM explained, works in many cases

window of opportunities for BSM

new physics can be probed at LHC
constraints from colliders