from exact asymptotic safety to physics beyond the Standard Model

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Heidelberg, 9 Mar 2017

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DF Litim 1102.4624
DF Litim, F Sannino, 1406.2337
AD Bond, DF Litim, 1608.00519
AD Bond, G Hiller, K Kowalska, DF Litim, 1702.01727

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 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

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asymptotic safety

today:

1. **theorems** for asymptotic safety

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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** $C < 0$ or $C > 0$

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

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basics of asymptotic safety

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

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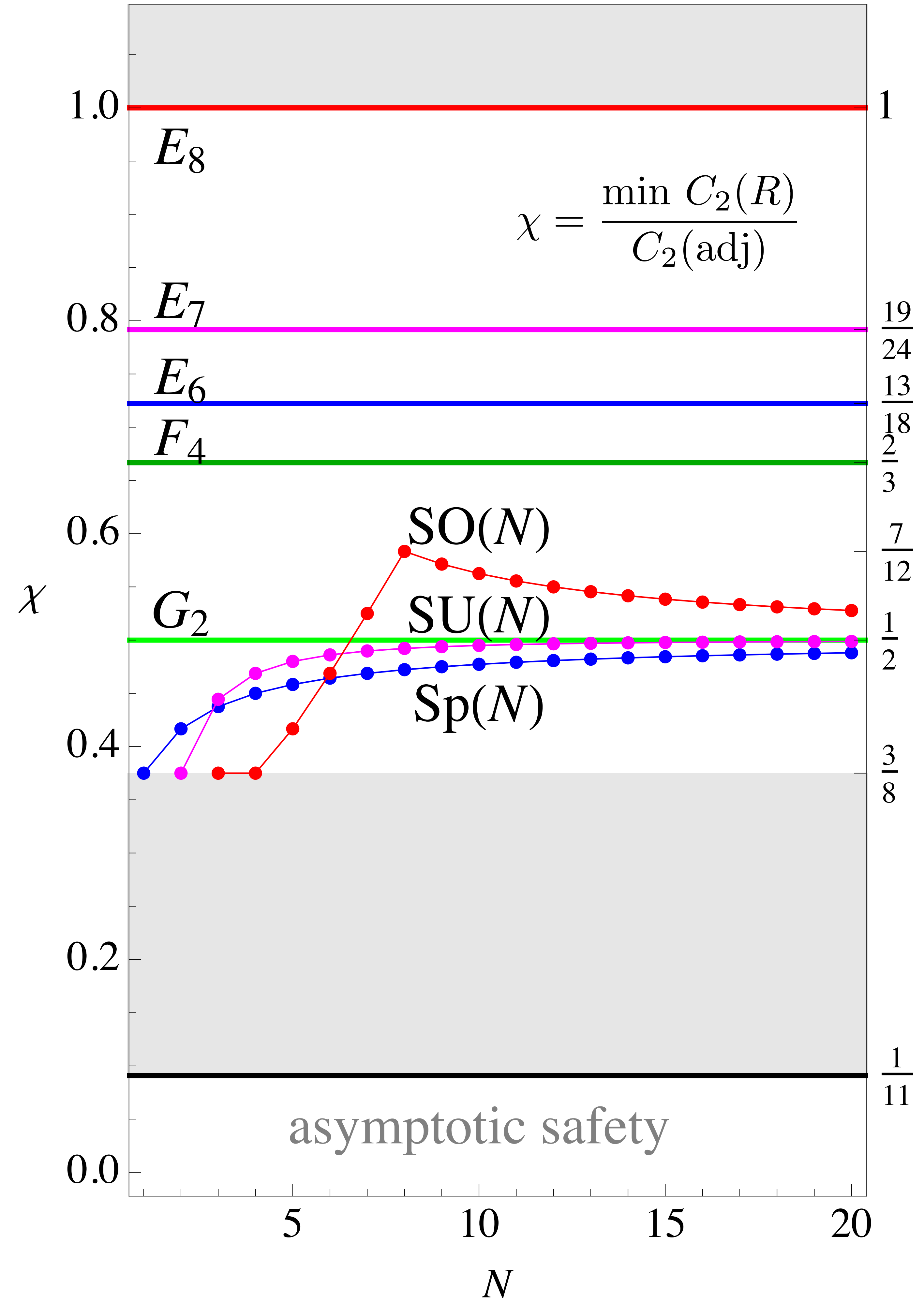
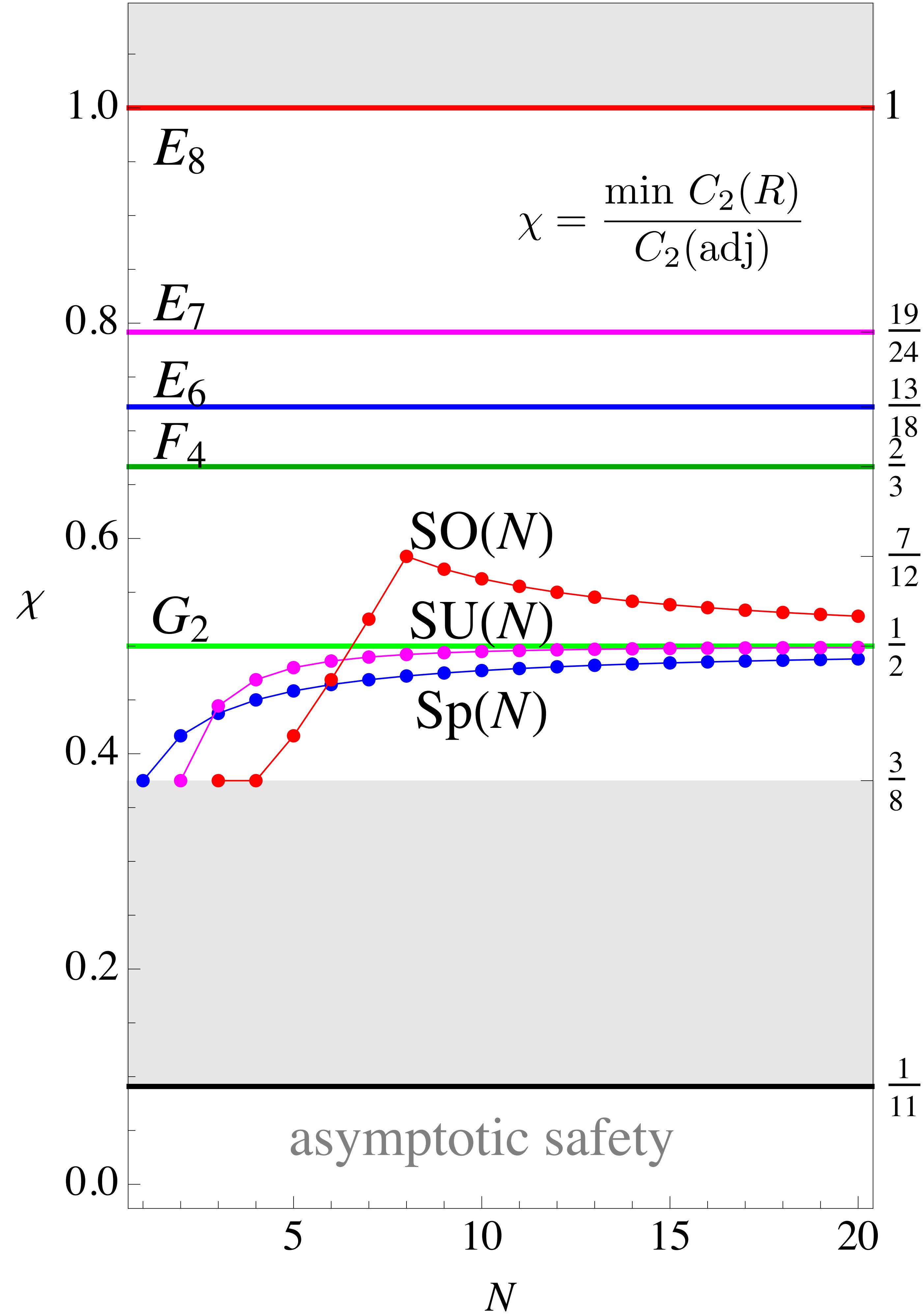
result:



result:



implication:

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

no go theorem

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basics of asymptotic safety

gauge theory

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basics of asymptotic safety

gauge theory

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loop coefficients

$B < 0$ **infrared freedom**

$B < 0 \Rightarrow C > 0$

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can other couplings help?

more gauge: **useless**
scalar quartics: **useless**
Yukawas: **unique viable option**

basics of asymptotic safety

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gauge Yukawa theory

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

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

$t = \ln \mu / \Lambda$

$\alpha_* \ll 1$

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

basics of asymptotic safety

gauge Yukawa theory

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

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

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

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

→

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

UV or IR

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basics of asymptotic safety

gauge Yukawa theory

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

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

summary of fixed points

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

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conditions for asymptotic safety

results

Bond, Litim 1608.00519

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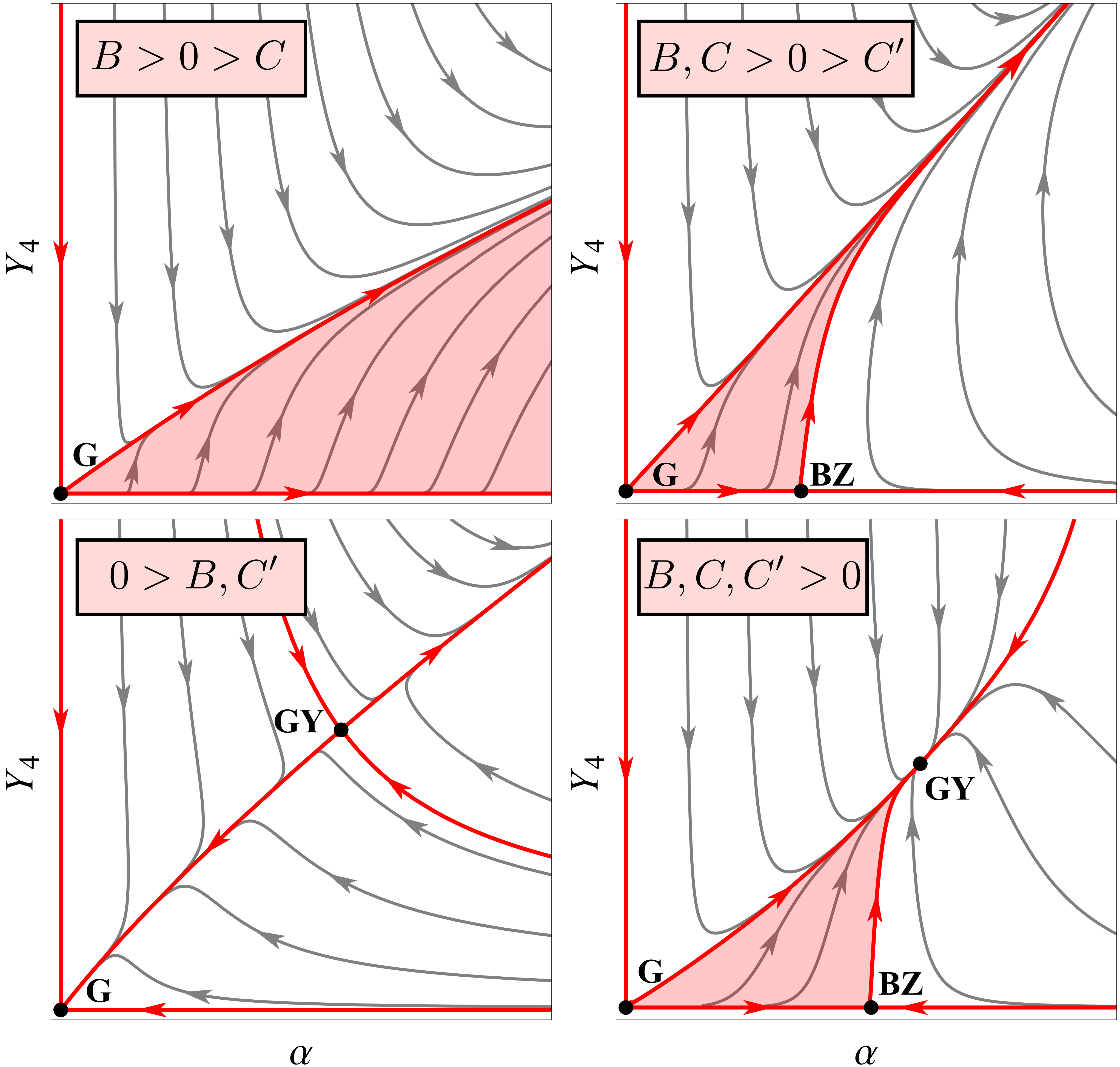

$B > 0 > C$
$B, C > 0 > C'$
$0 > B, C'$
$B, C, C' > 0$
G
BZ
GY
Y_4
α

asymptotic safety

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

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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 $U(N_F) \times U(N_F)$

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

BSM Lagrangean

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

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UV fixed points

#	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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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 $\delta\alpha_3(\Lambda)$

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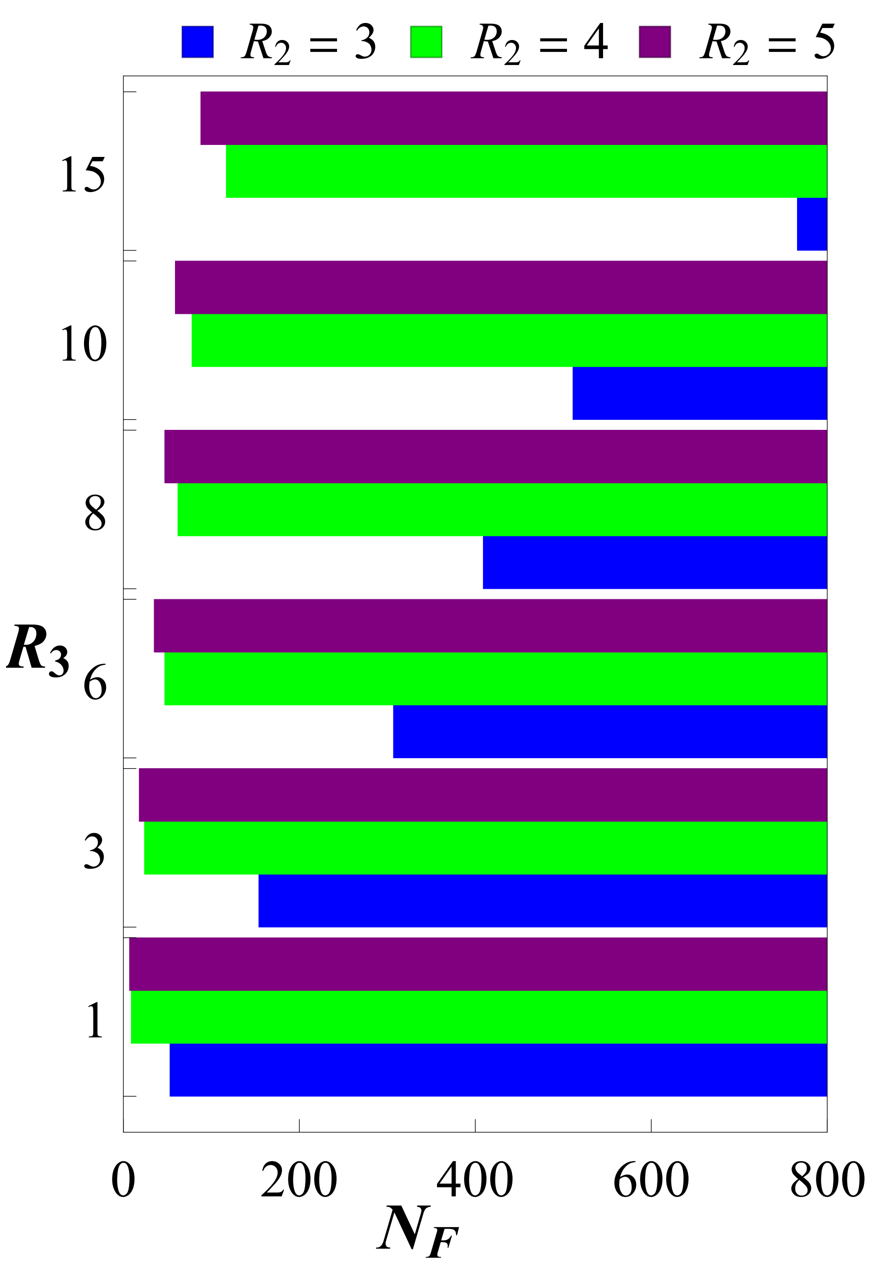
BSM fixed points

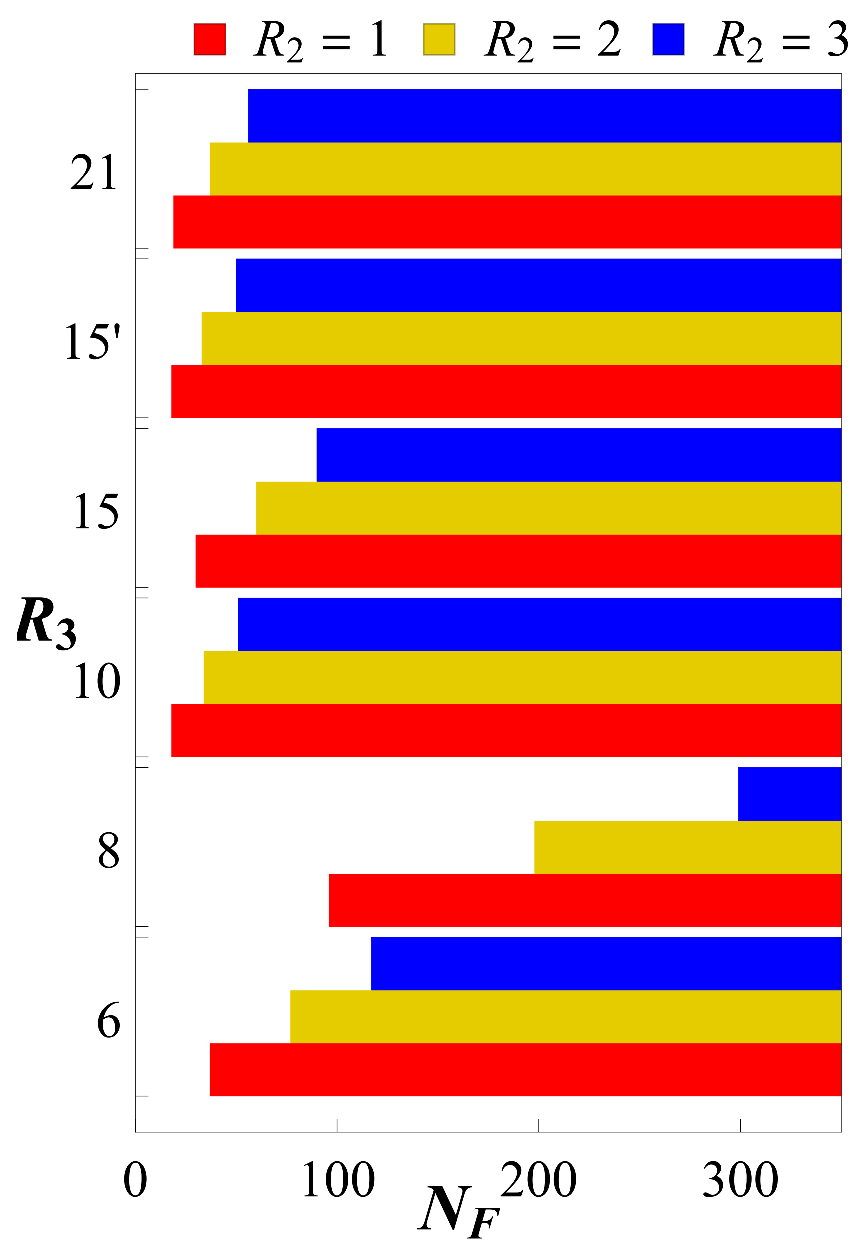
$\mathbf{FP_2}$

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



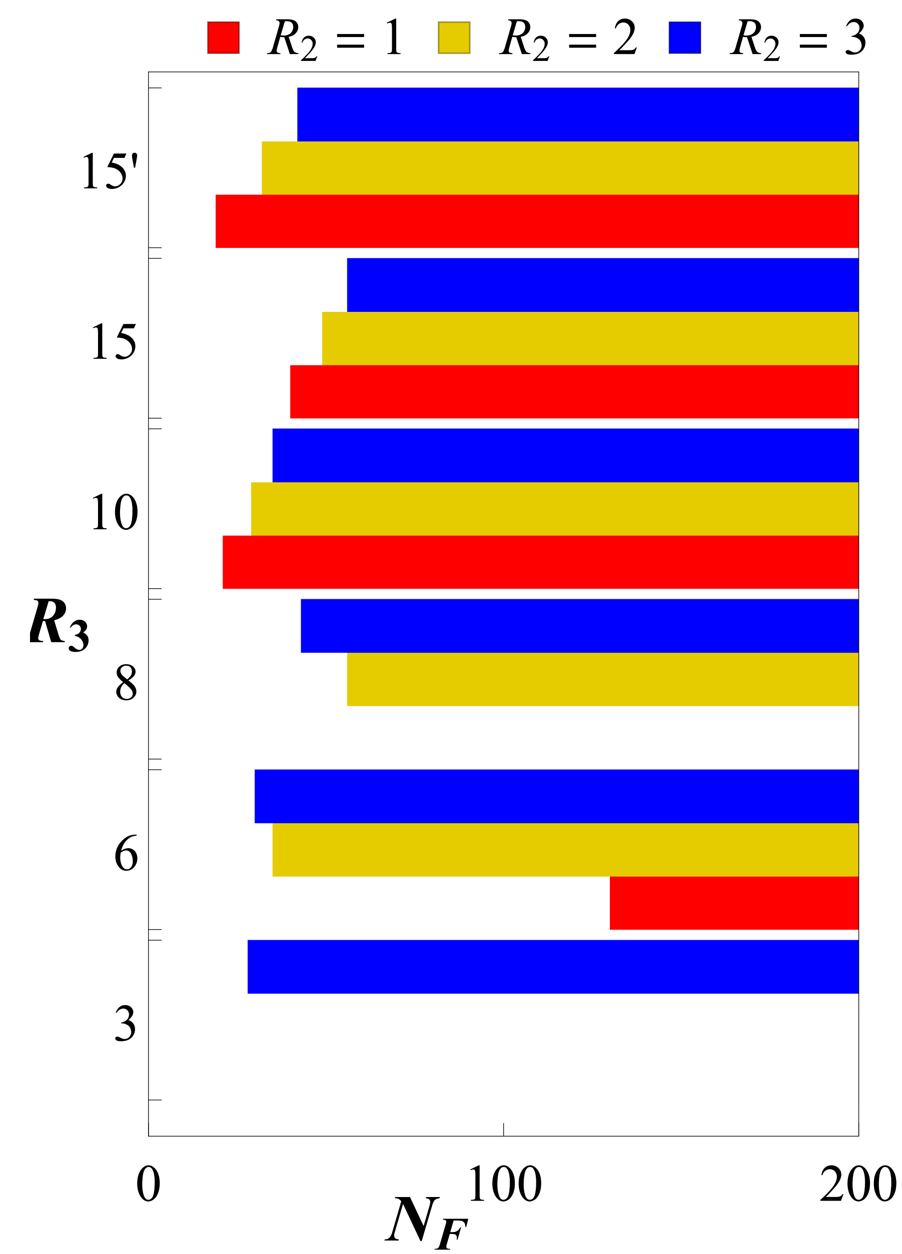
$\mathbf{FP_3}$

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

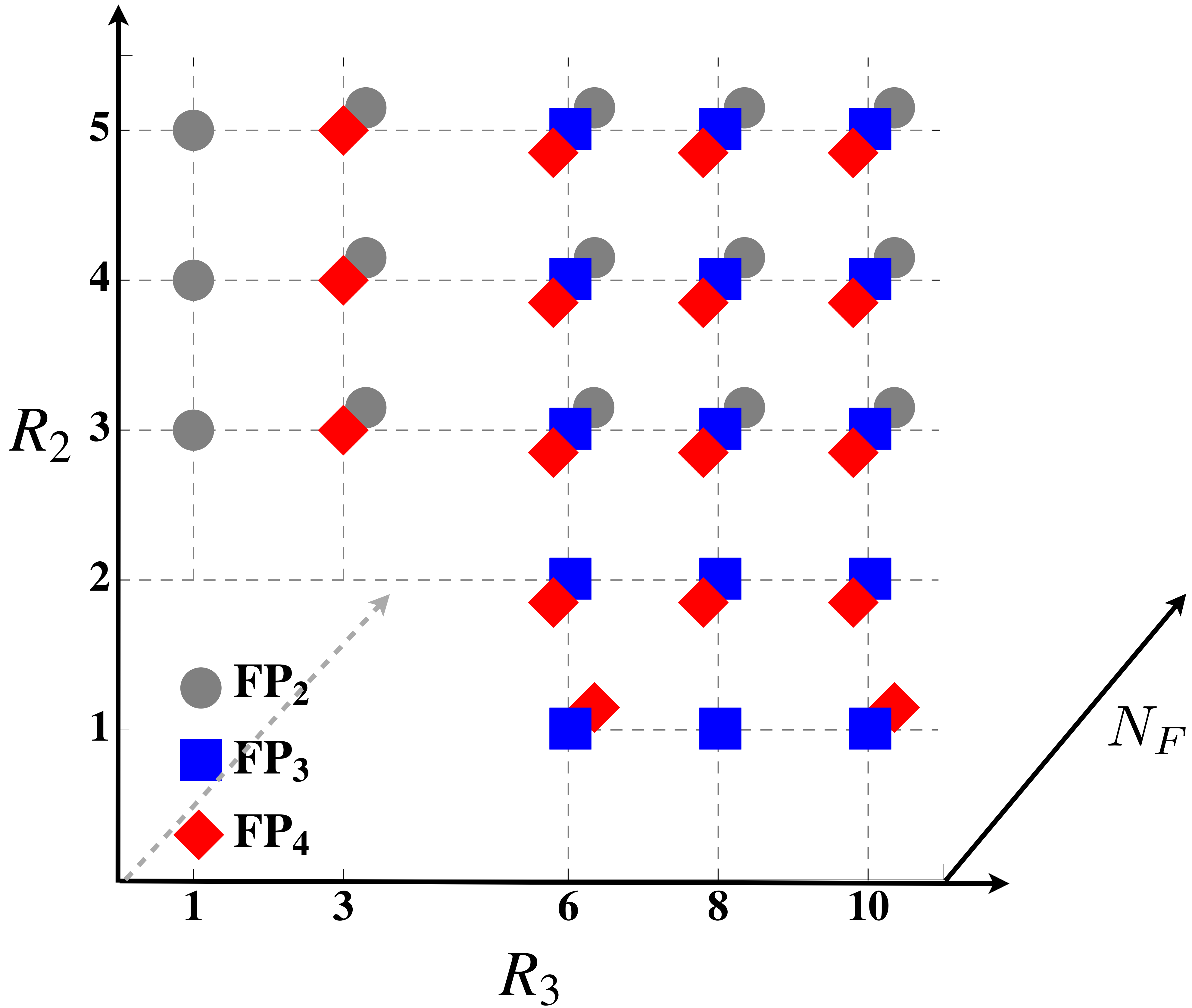


$\mathbf{FP_4}$

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



summary of fixed points



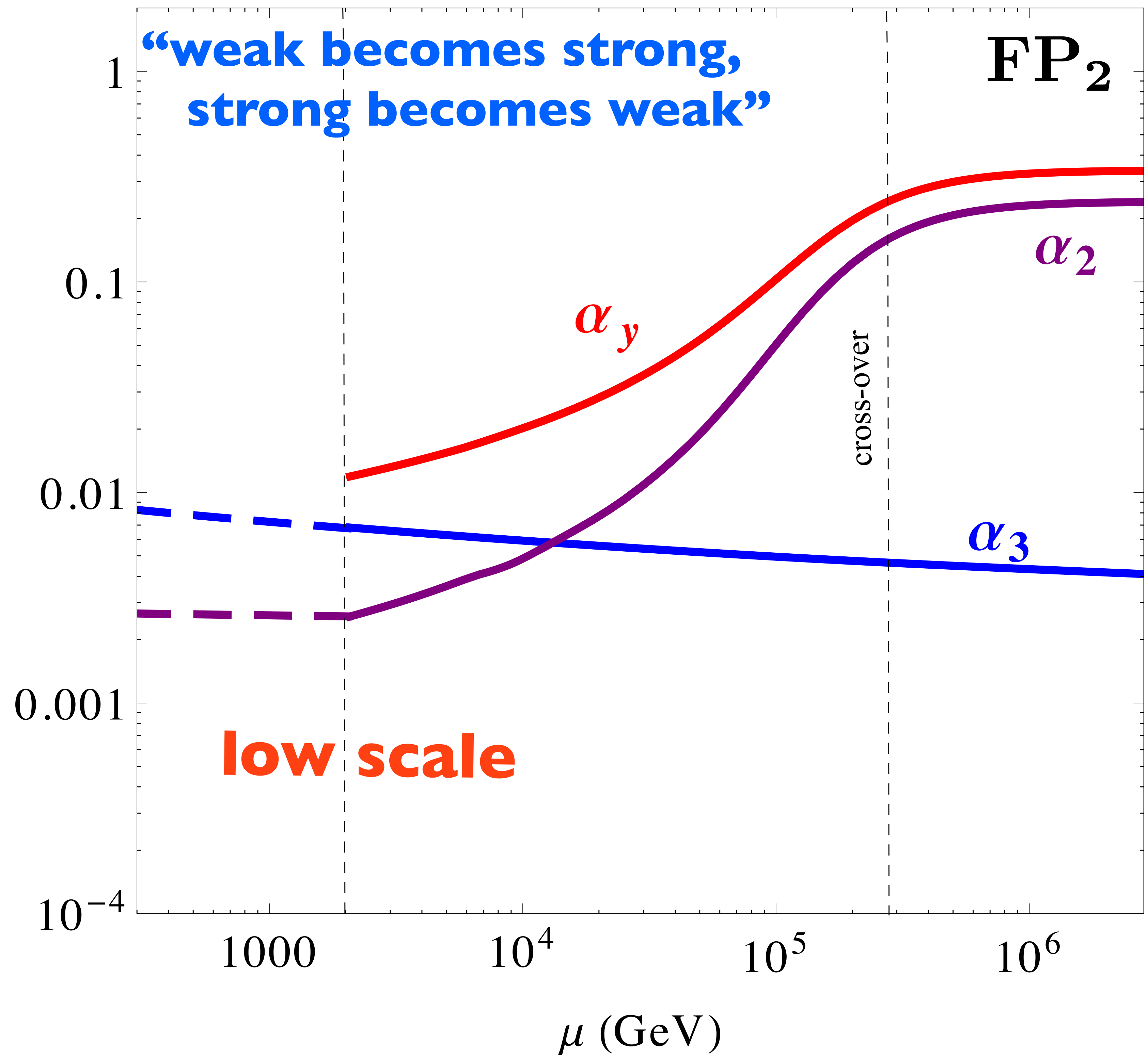
benchmark models

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

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



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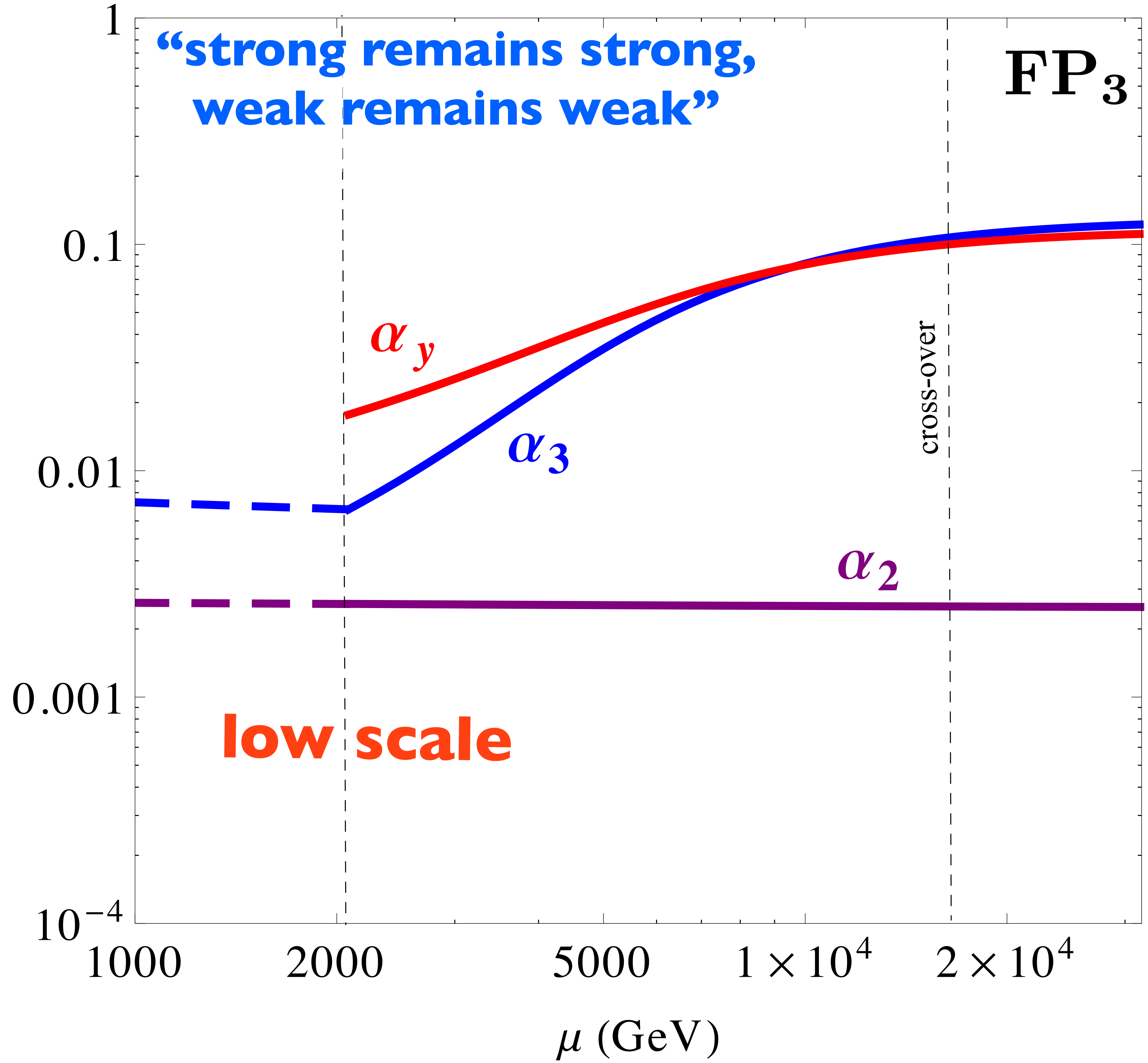
benchmark models

model B

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



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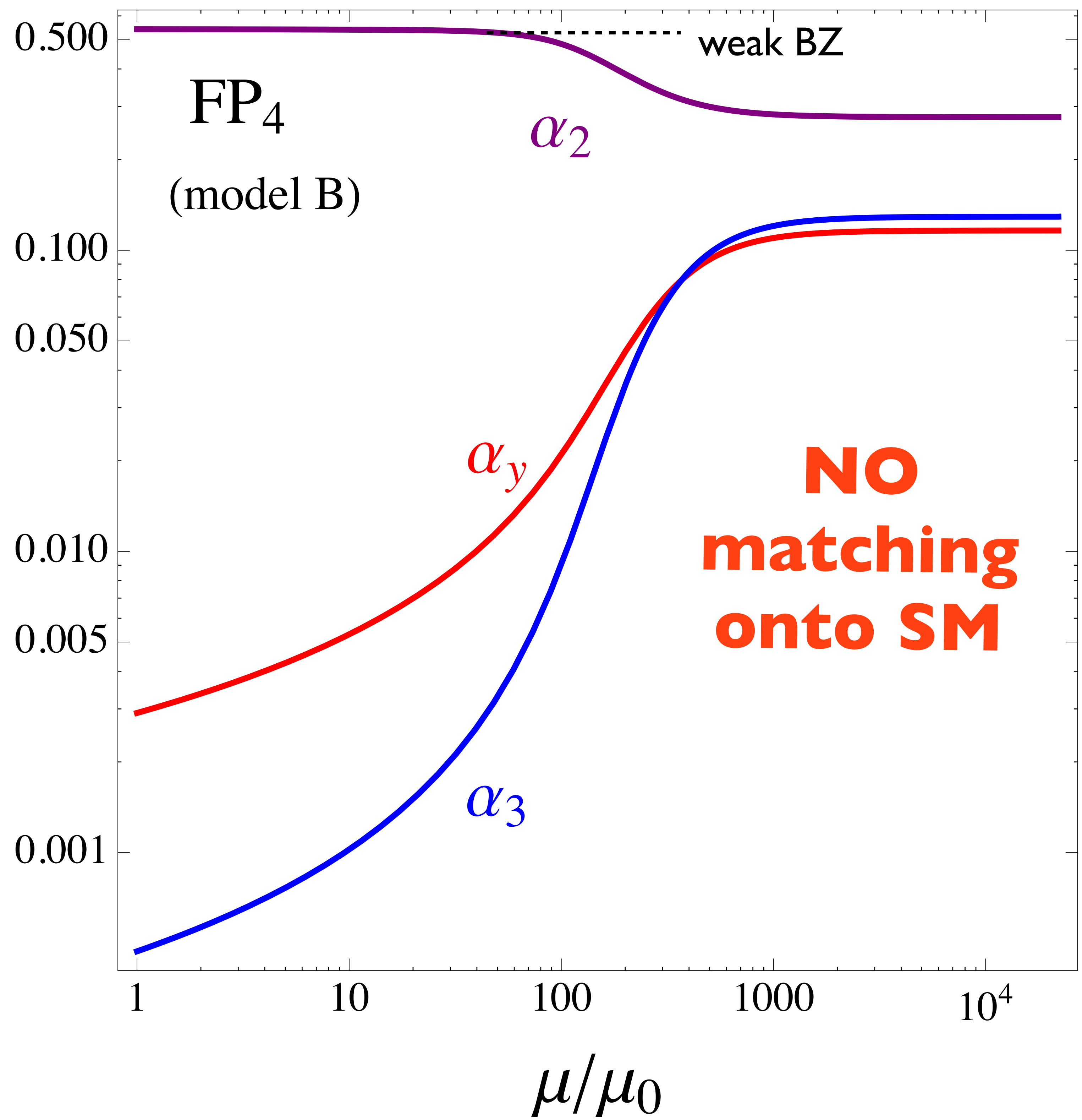
benchmark models

model B

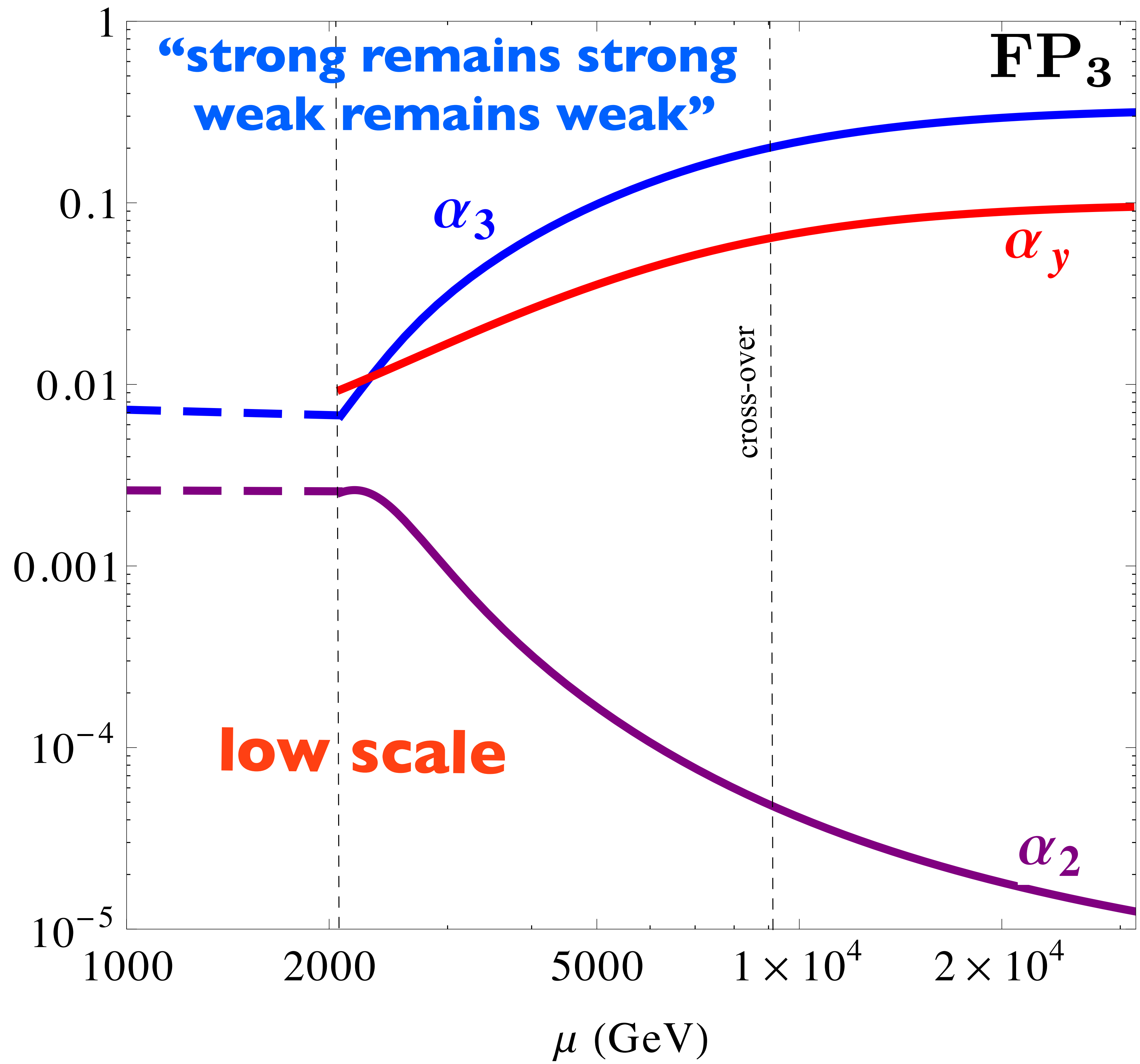
$(R_3, R_2, N_F) =$ (**10**,**1**,30)



benchmark models

model C

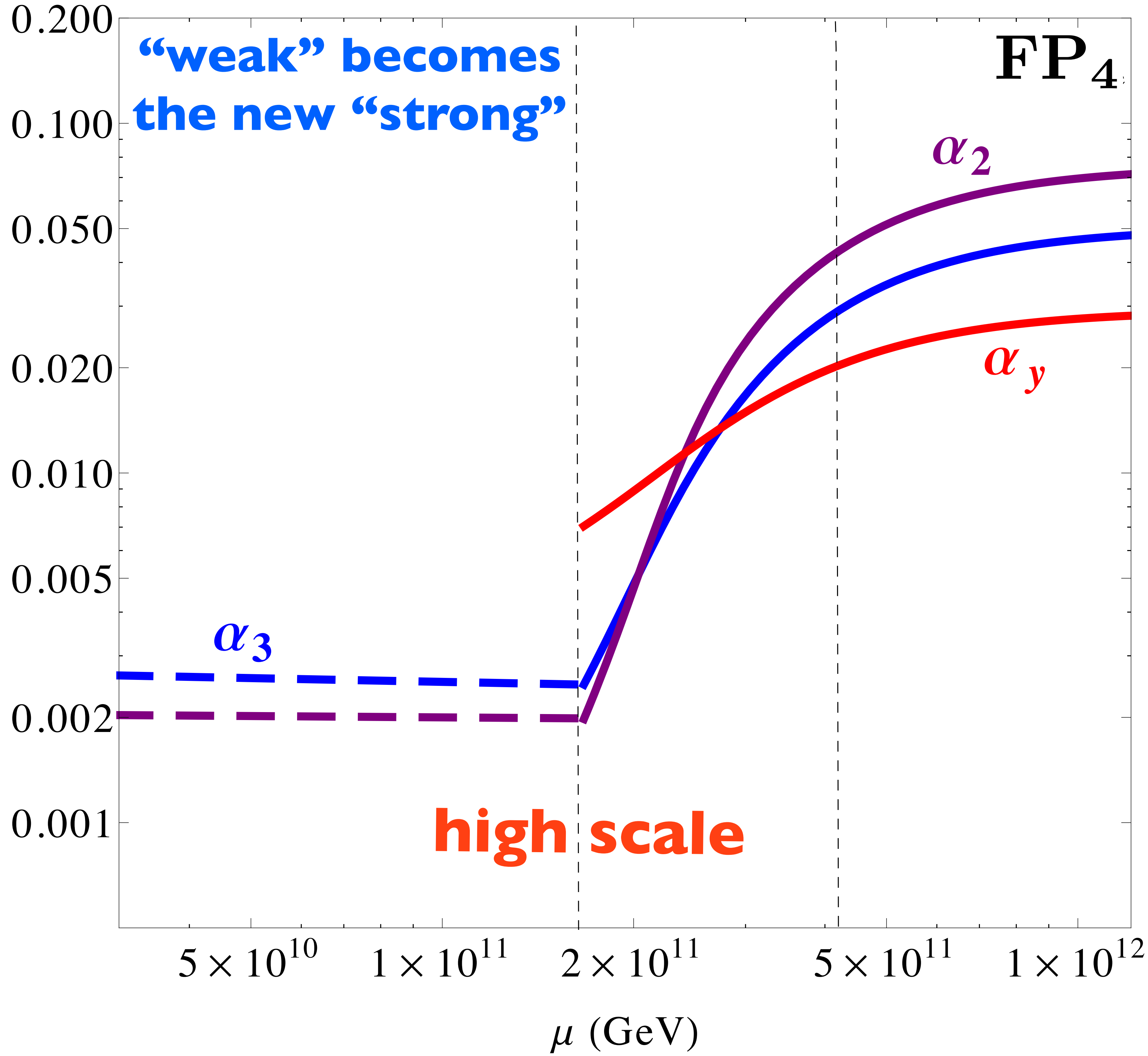
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{4}, 80)$



benchmark models

model C

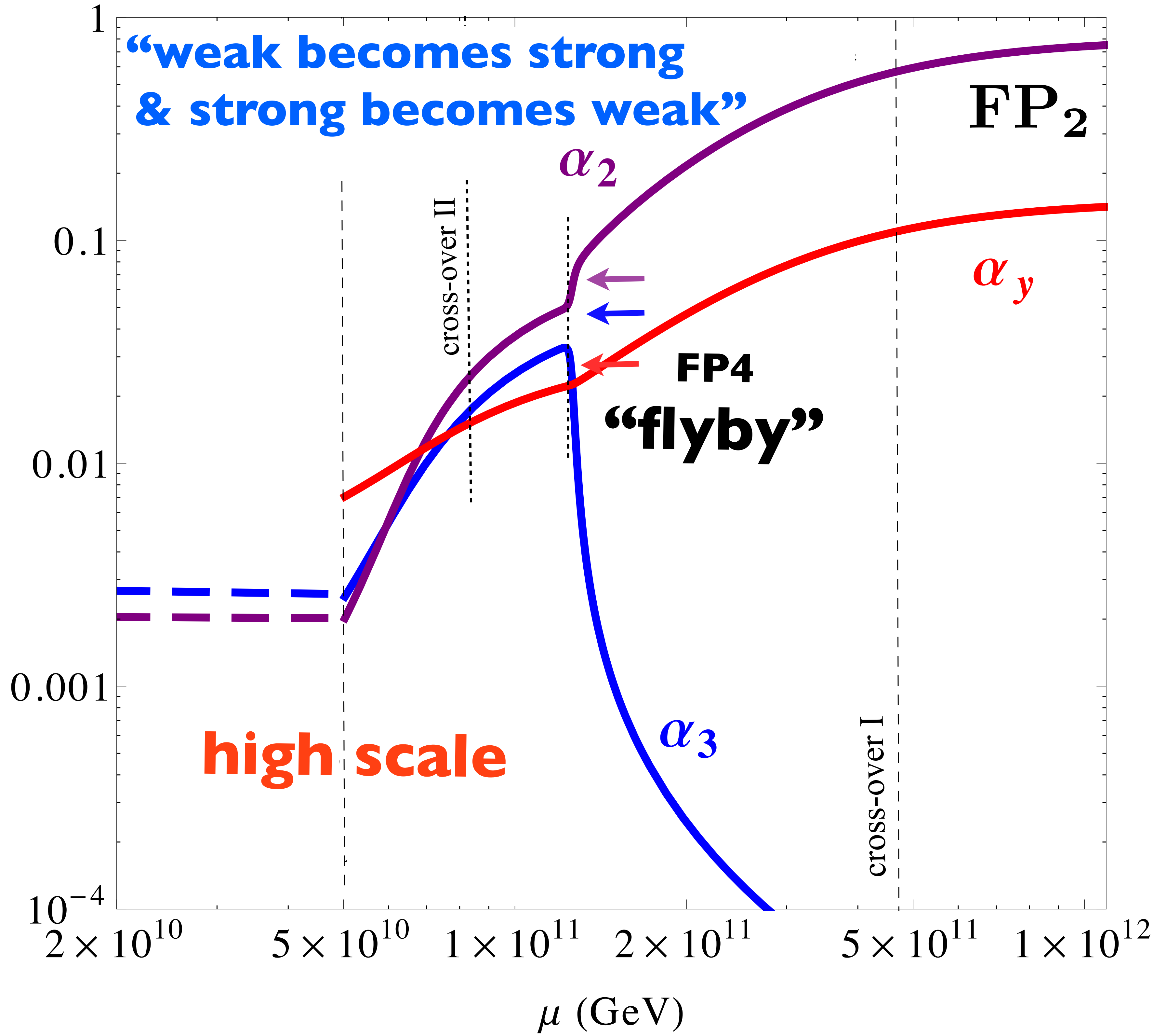
$(R_3, R_2, N_F) = (\mathbf{10}, \mathbf{4}, 80)$



benchmark models

model C

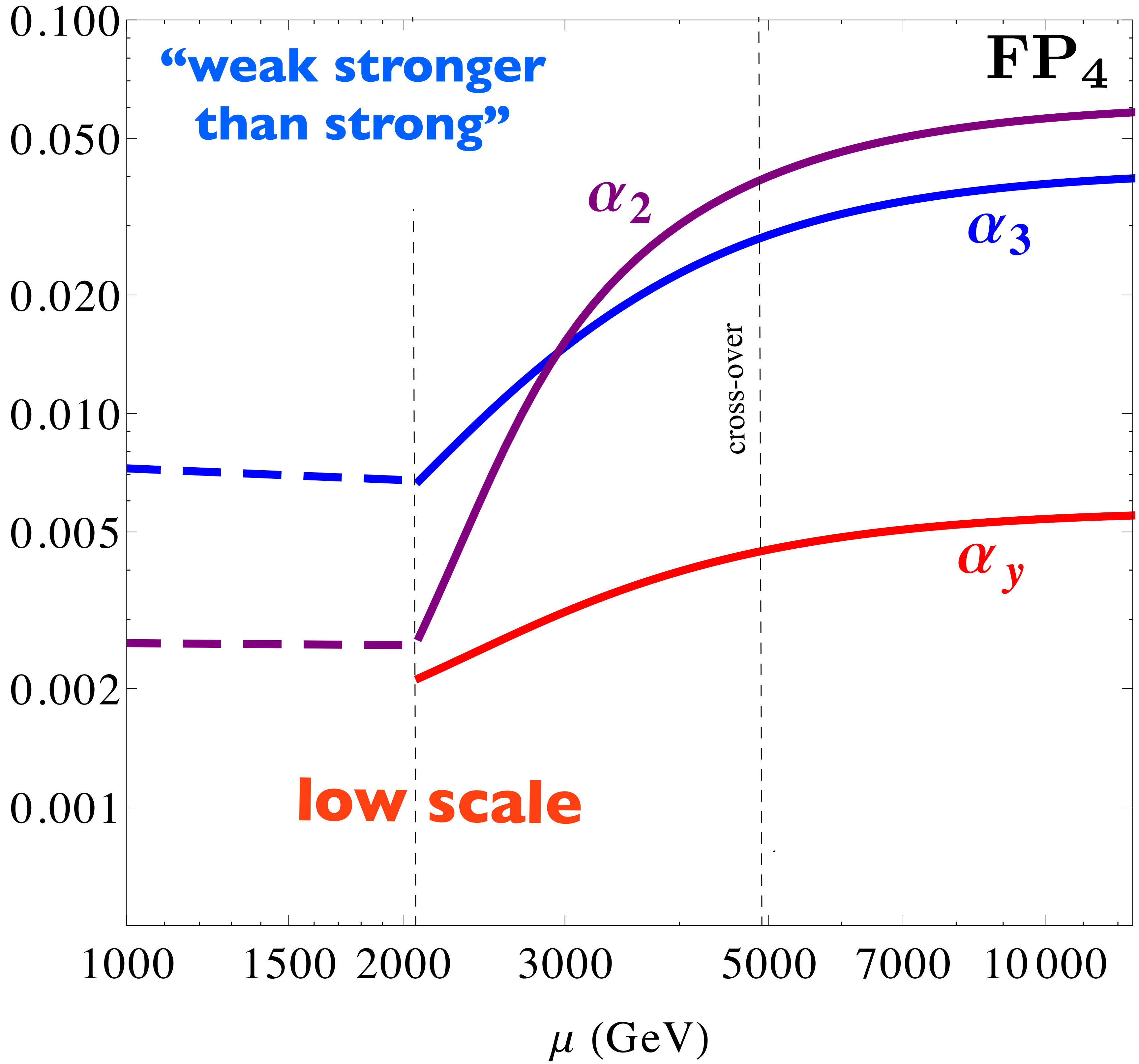
$(R_3, R_2, N_F) =$ $(\mathbf{10},\mathbf{4},80)$



benchmark models

model D

$(R_3, R_2, N_F) =$ $(\mathbf{3},\mathbf{4},290)$



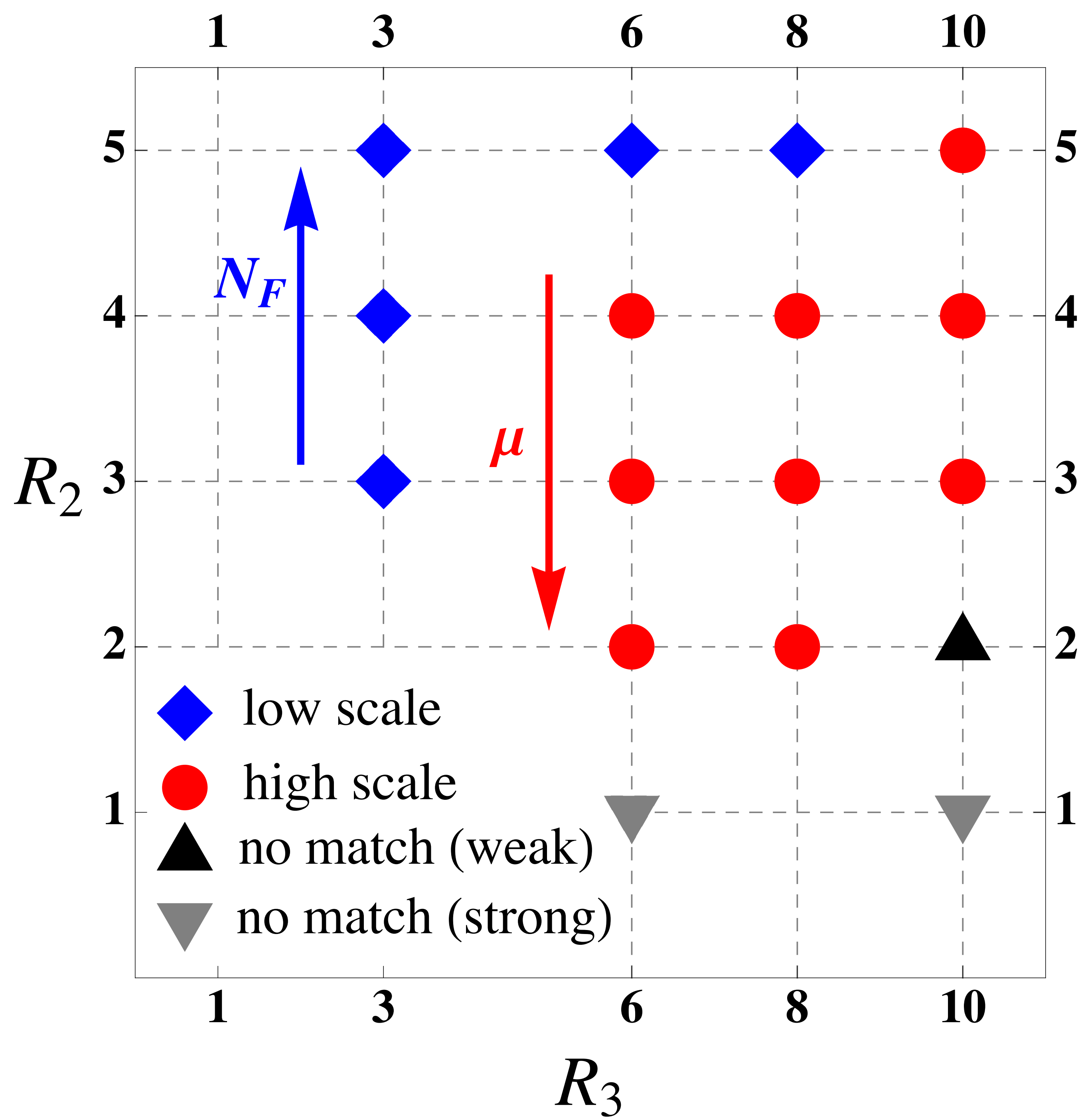
summary of SM matching: when it works

$\mathbf{FP_2}$ 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

$\mathbf{FP}_4$



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asymptotic safety

3. constraints from data (colliders)

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

phenomenology

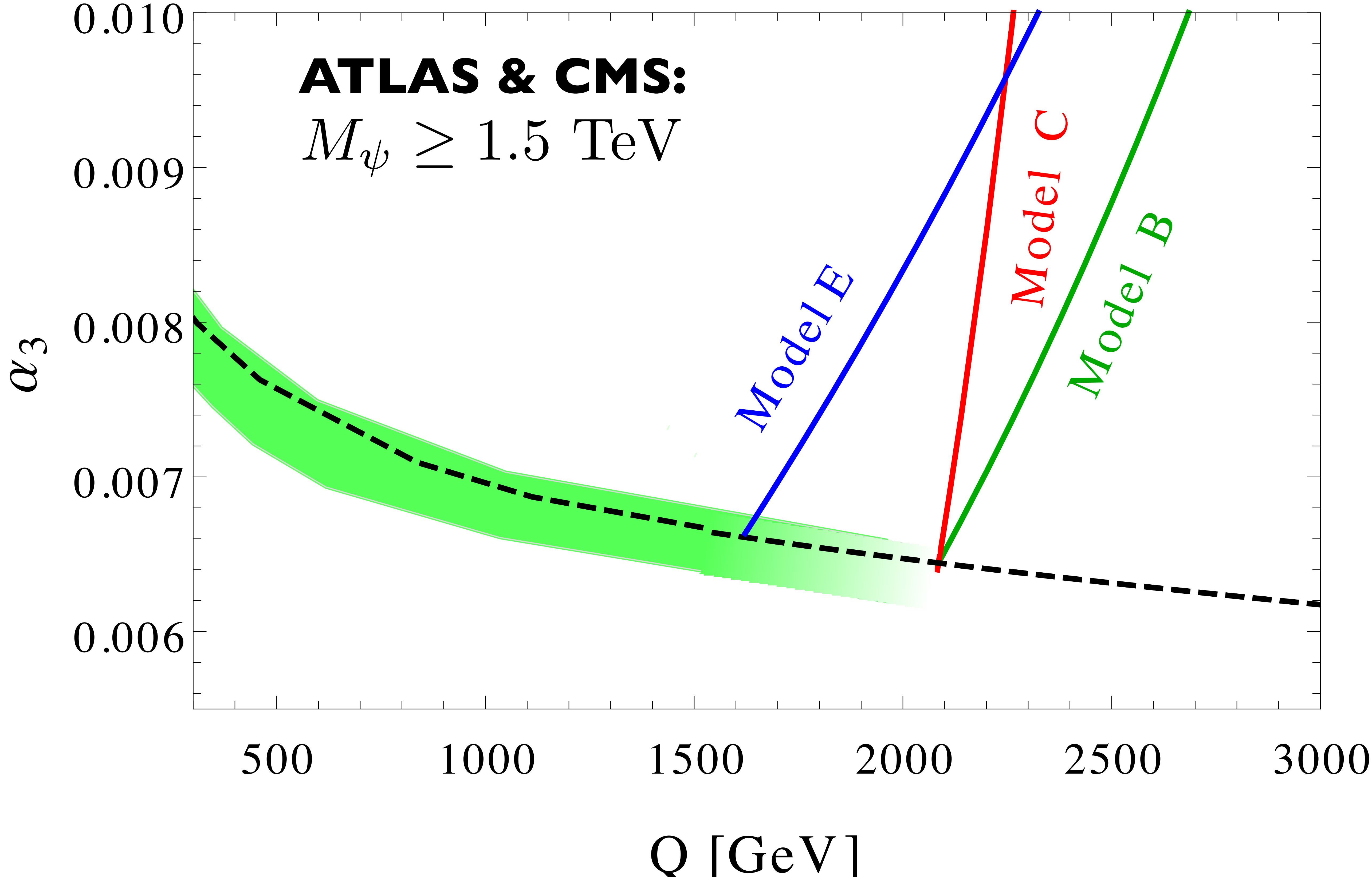
assume low scale matching
some BSM masses within TeV energy range

assume $R_3 \neq 1$ for LHC
($R_3 = 1$ can be tested at future e^+e^- colliders)

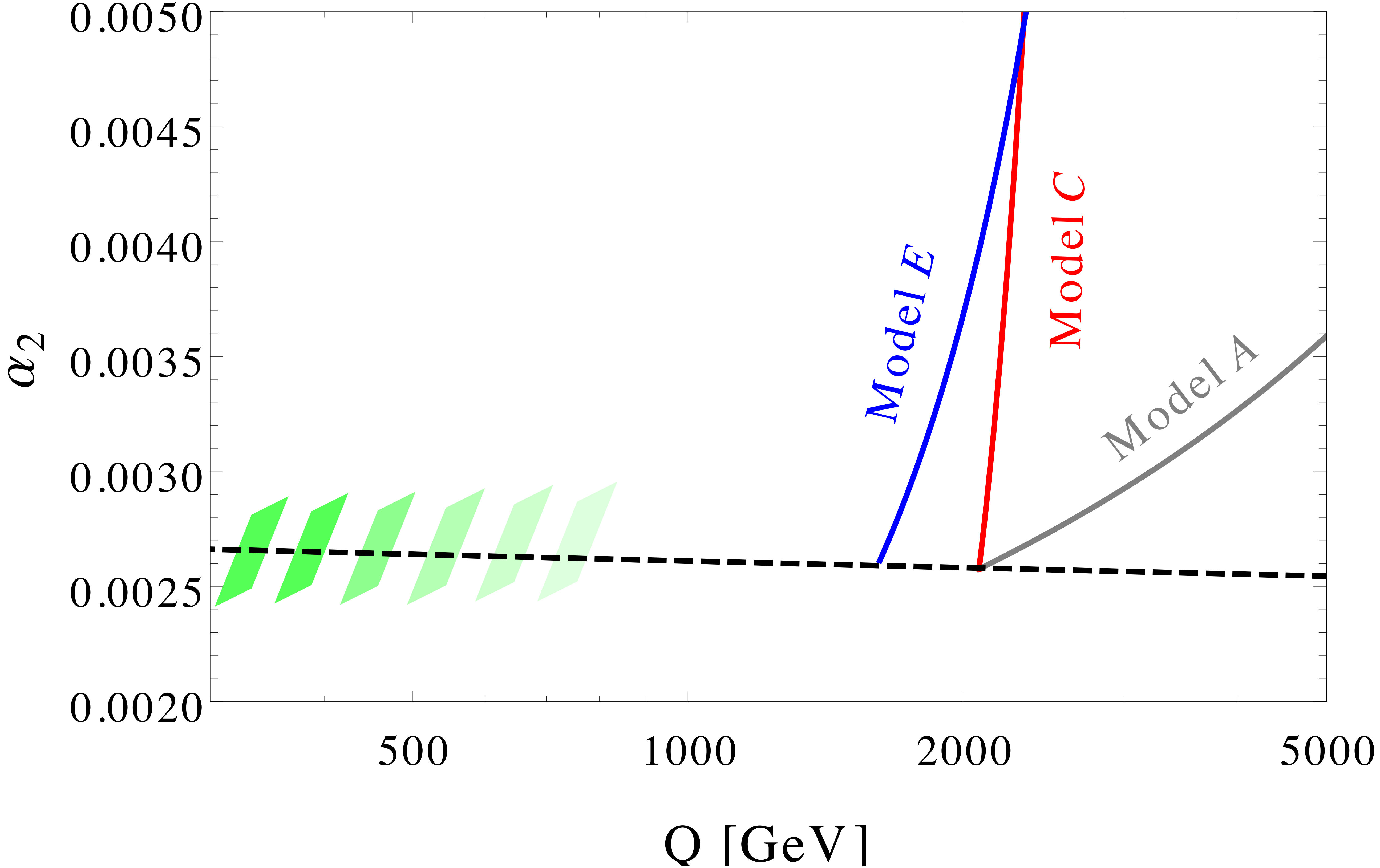
flavor symmetry: stable BSM fermions
broken flavor symmetry: lightest BSM fermion stable

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

SU(3) BSM running



SU(2) BSM running



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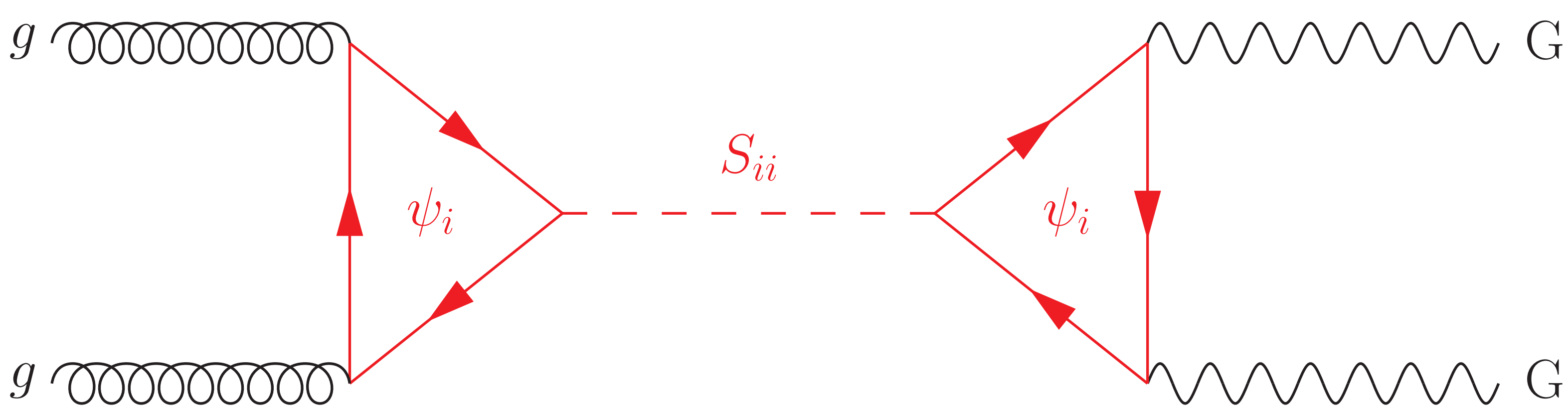
di-boson spectra and resonances

assume **resonant production** of BSM scalars

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

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

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



interference effects

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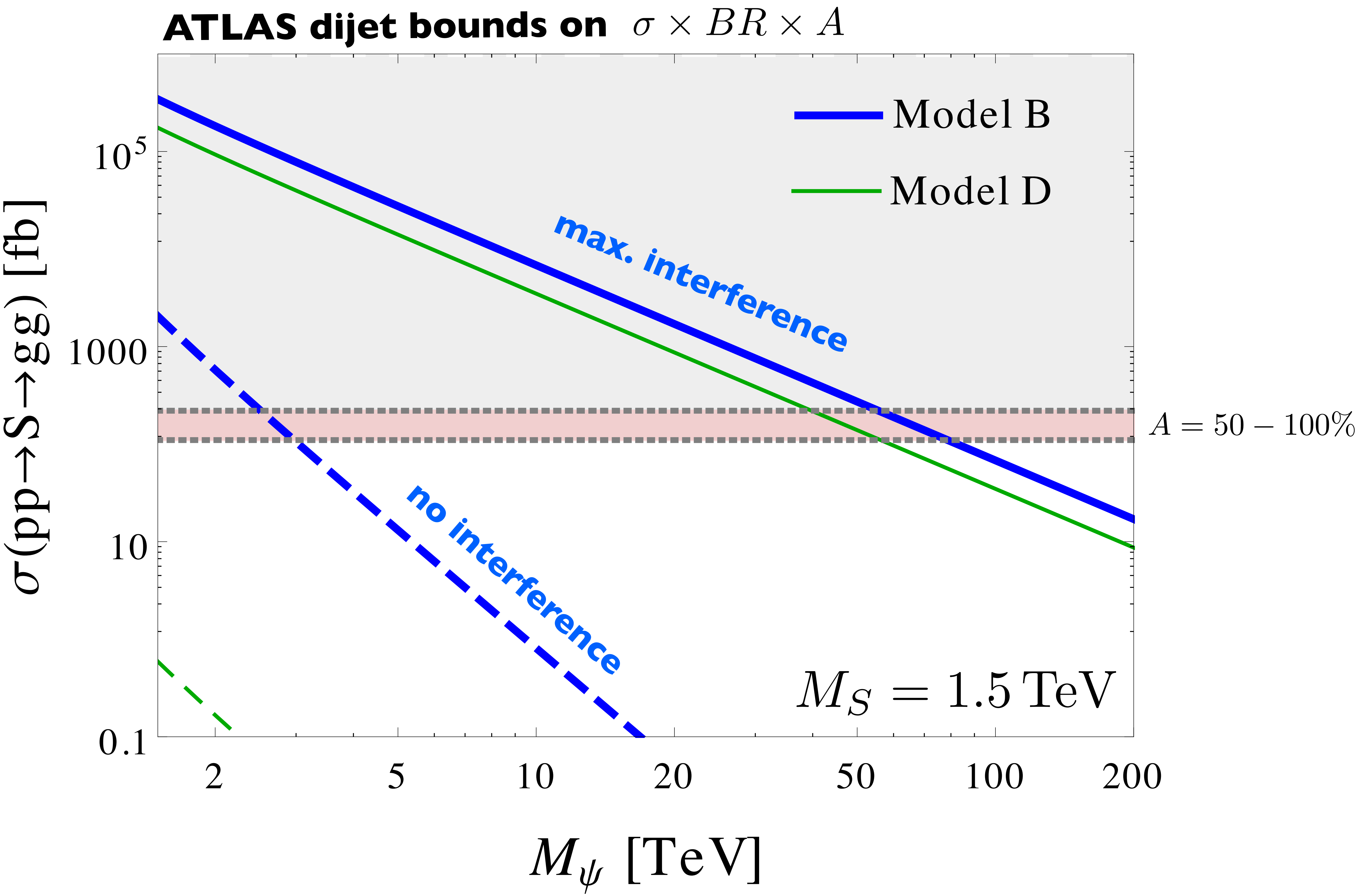
dijet cross section



mass exclusion limits

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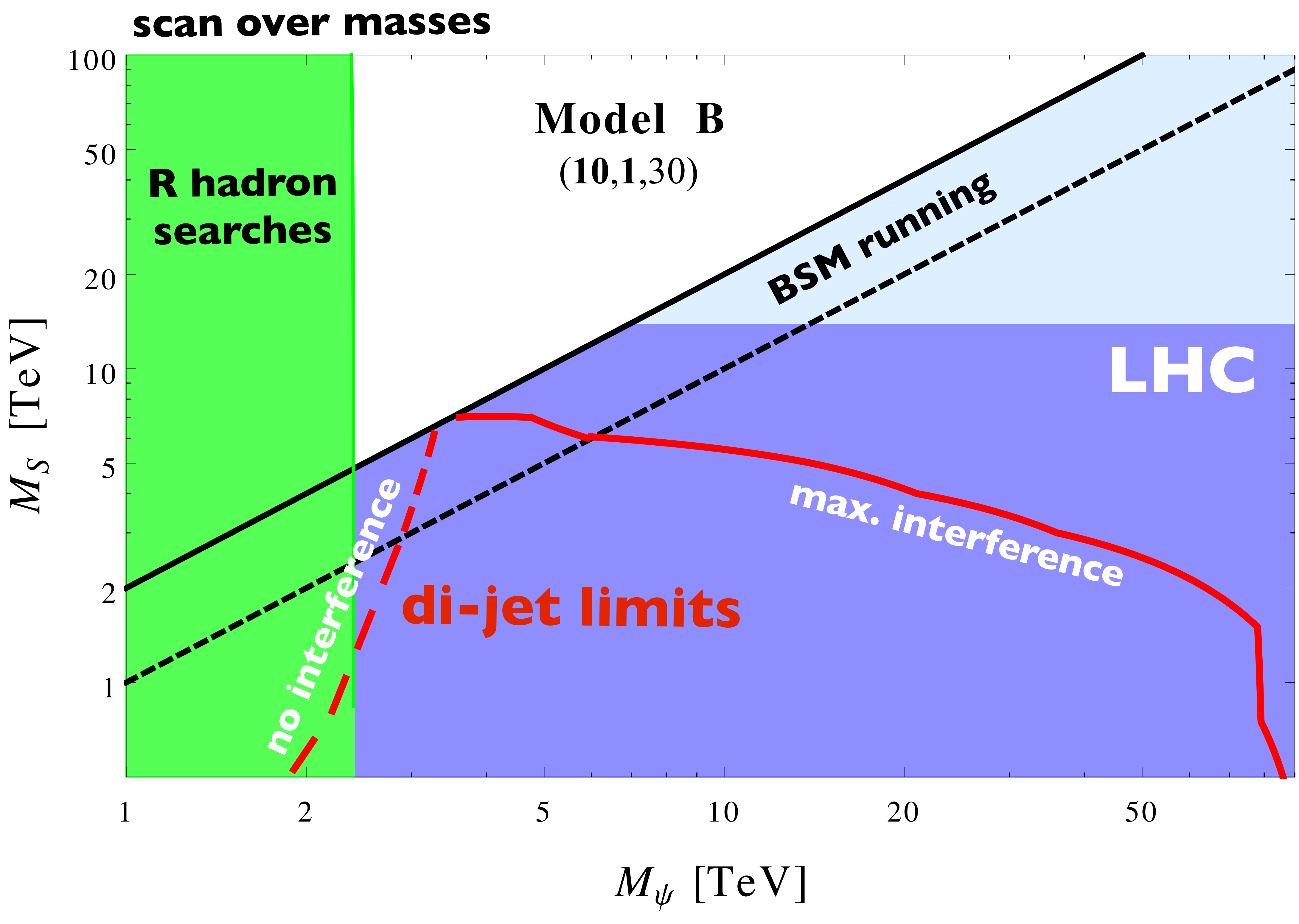


conclusions

theorems for fixed points and asymptotic safety

systematics

weakly interacting **UV completions** of the SM

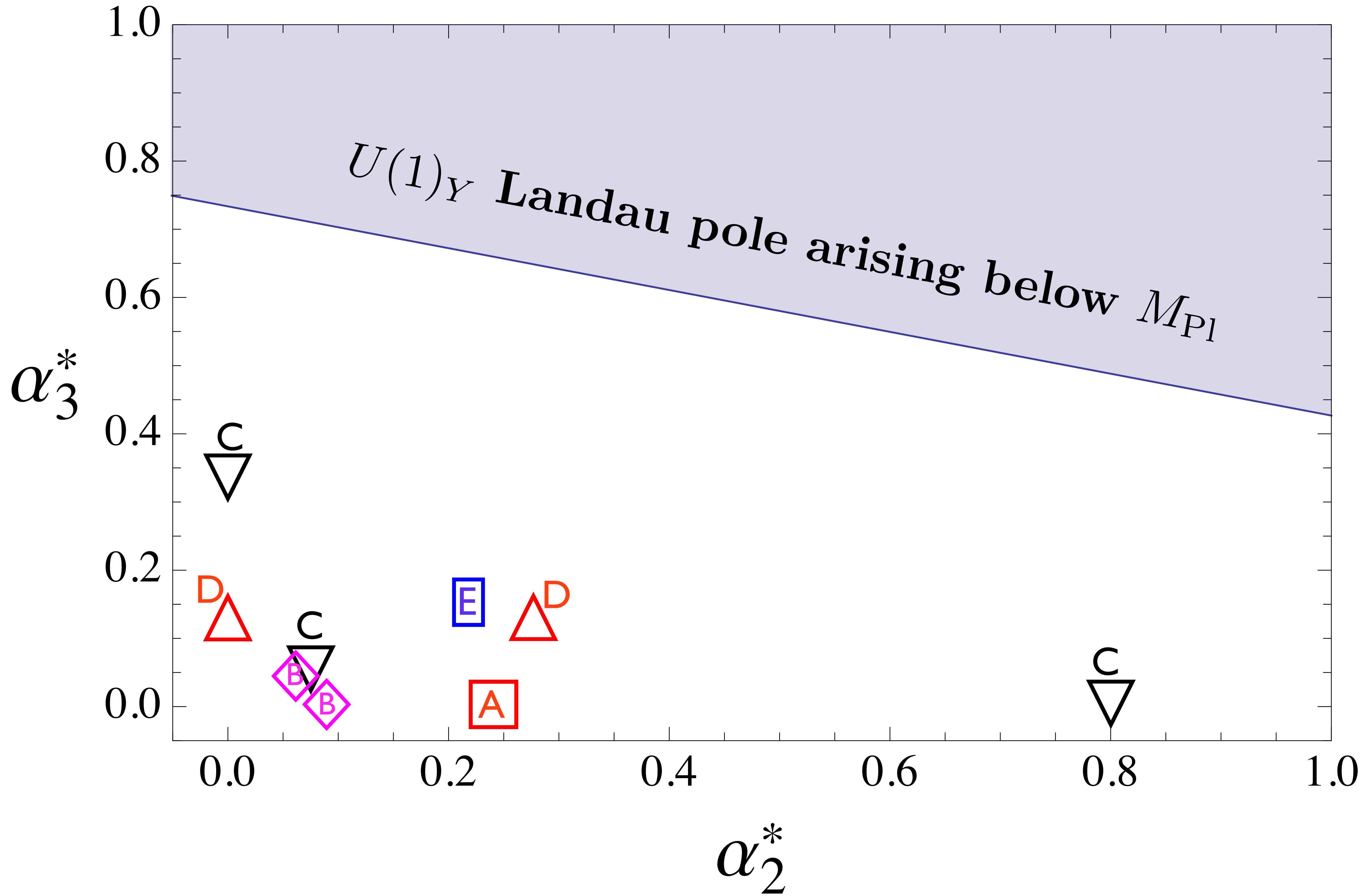
UV FPs can be partially or fully interacting
matching to SM explained, works in many cases

window of opportunities for BSM

new physics, can be probed at LHC
constraints from colliders

extra material

U(1)Y BSM


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

phase diagrams

phase diagrams of simple gauge theories

parameters

B, C matter content

C' Yukawa structure

c)	simple	**Yes**	$B > 0$ and $C > 0 > C'$	Banks-Zaks	**IR**
	simple	**Yes**	$B > 0$ and $C > C' > 0$	BZ and GYs	**IR**
	simple or abelian	**Yes**	$B < 0$ and $C' < 0$	gauge-Yukawas	**UV/IR**

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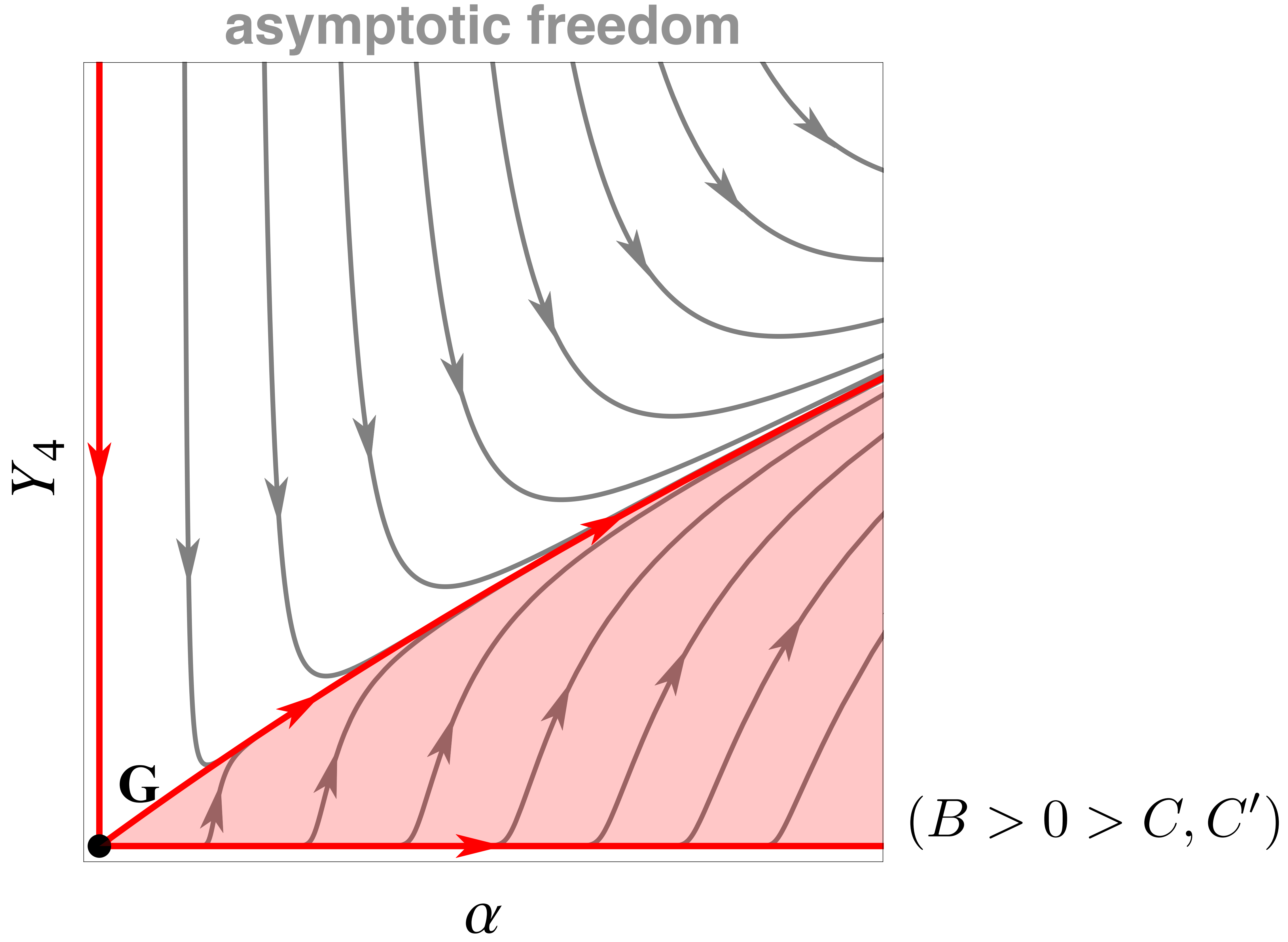
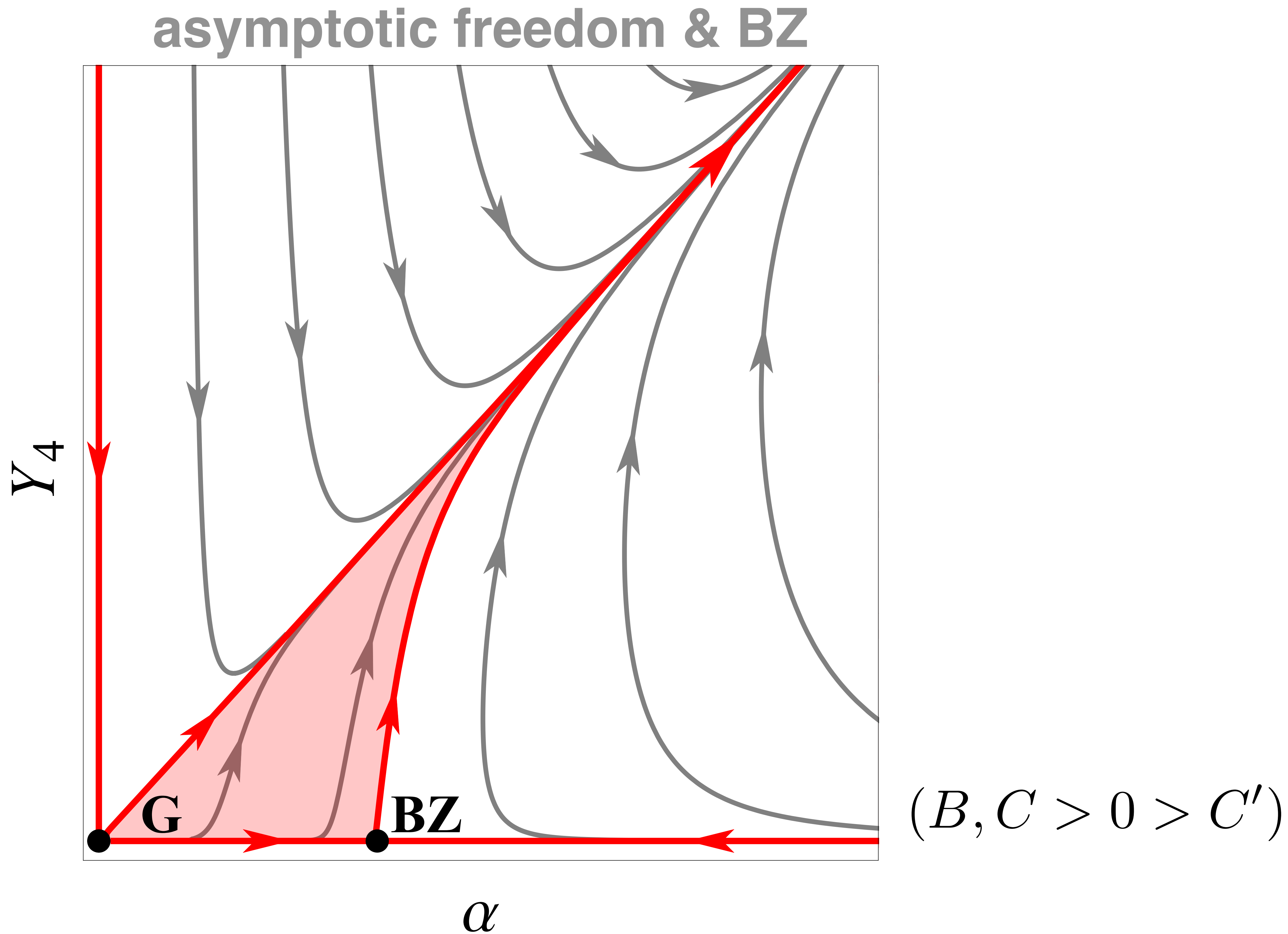
phase diagrams

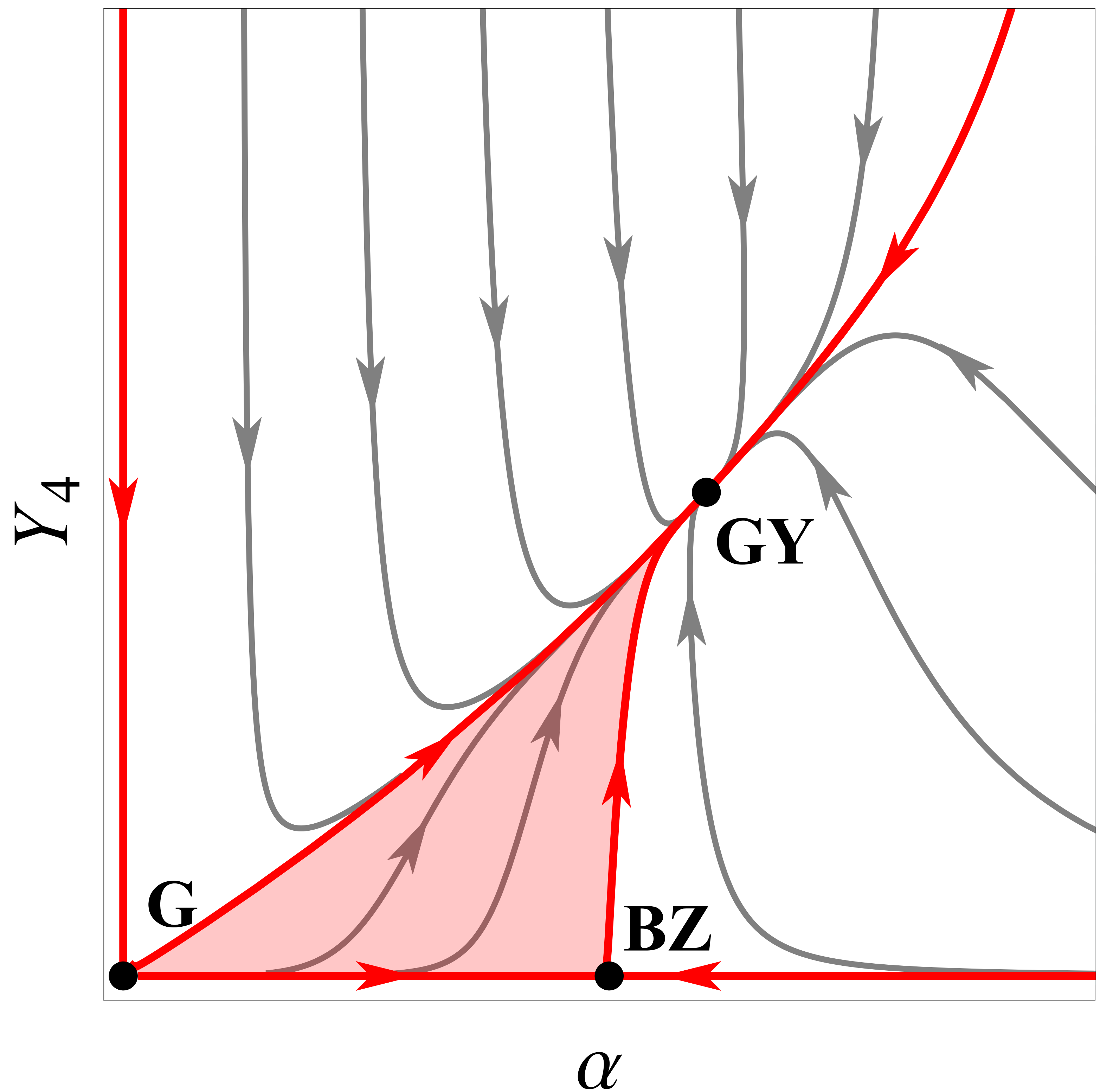


phase diagrams



phase diagrams

asymptotic freedom, BZ & GY



$(B, C, C' > 0)$

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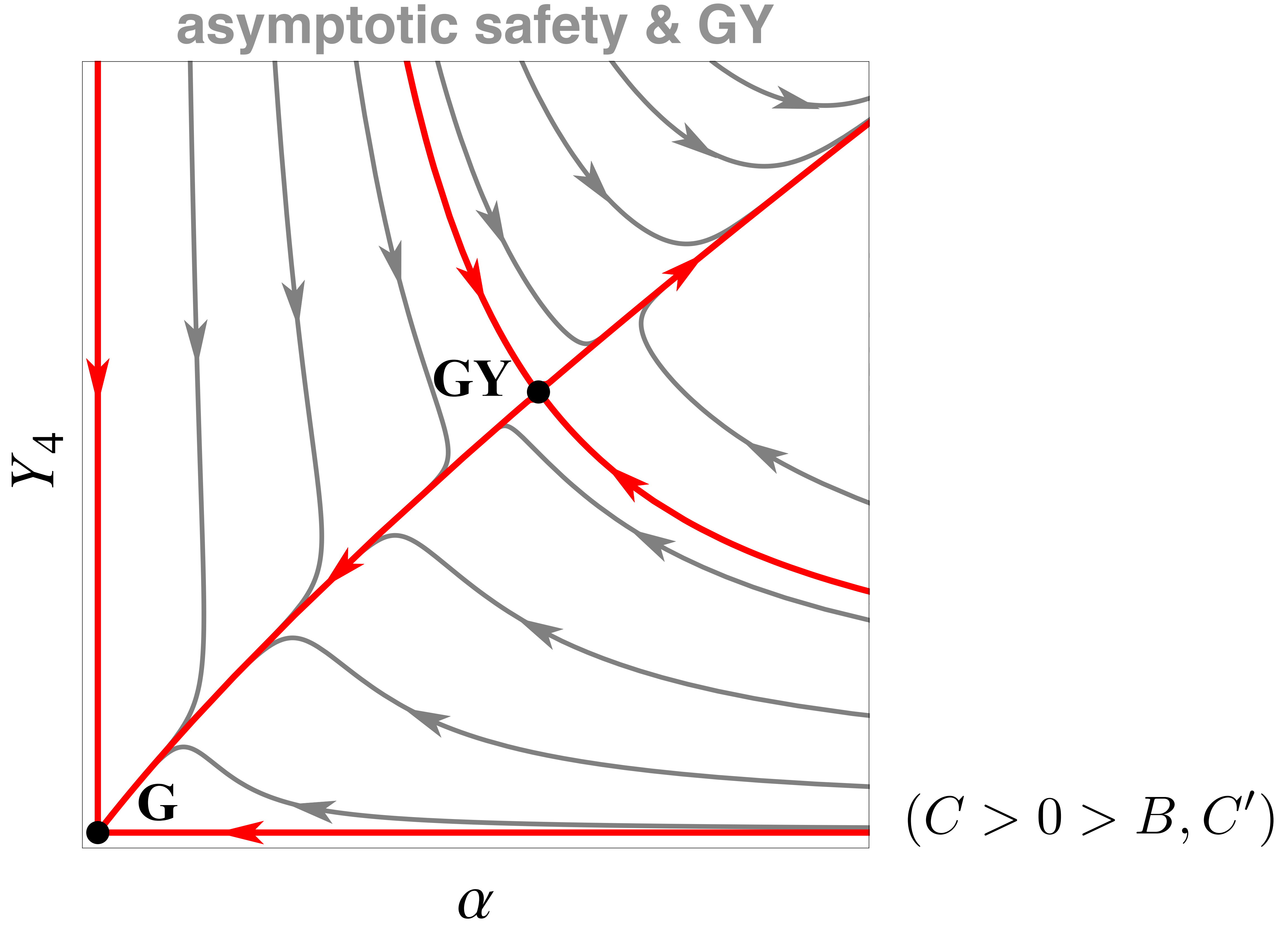
phase diagrams



extensions I

interacting UV FPs with exact asymptotic safety exist for simple gauge theories

Litim, Sannino, 1406.2337

but: do interacting UV FPs with exact asymptotic safety exist for semi-simple gauge theories?

Yes!

Bond @ ERG 2016 and @ this meeting

→ space of UV FP solutions is non-empty

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extensions II

what is the impact of couplings with non-vanishing canonical mass dimension?

results:

fixed point persists
effective potential remains stable

extensions II

Lagrangean

$$L_{\rm YM} = -\frac{1}{2}\,{\rm Tr}\, F^{\mu\nu} F_{\mu\nu}$$
$$L_F = {\rm Tr}\left(\overline{Q}\, i\not{D}\, Q\right)$$
$$L_Y = y\,{\rm Tr}\left(\overline{Q}\, H\, Q\right)$$
$$L_H = {\rm Tr}\left(\partial_\mu H^\dagger\, \partial^\mu H\right)$$
$$L_U = -u\,{\rm Tr}\,(H^\dagger H)^2$$
$$L_V = -v\,({\rm Tr}\, H^\dagger H)^2\,.$$

Litim, Sannino, 1406.2337

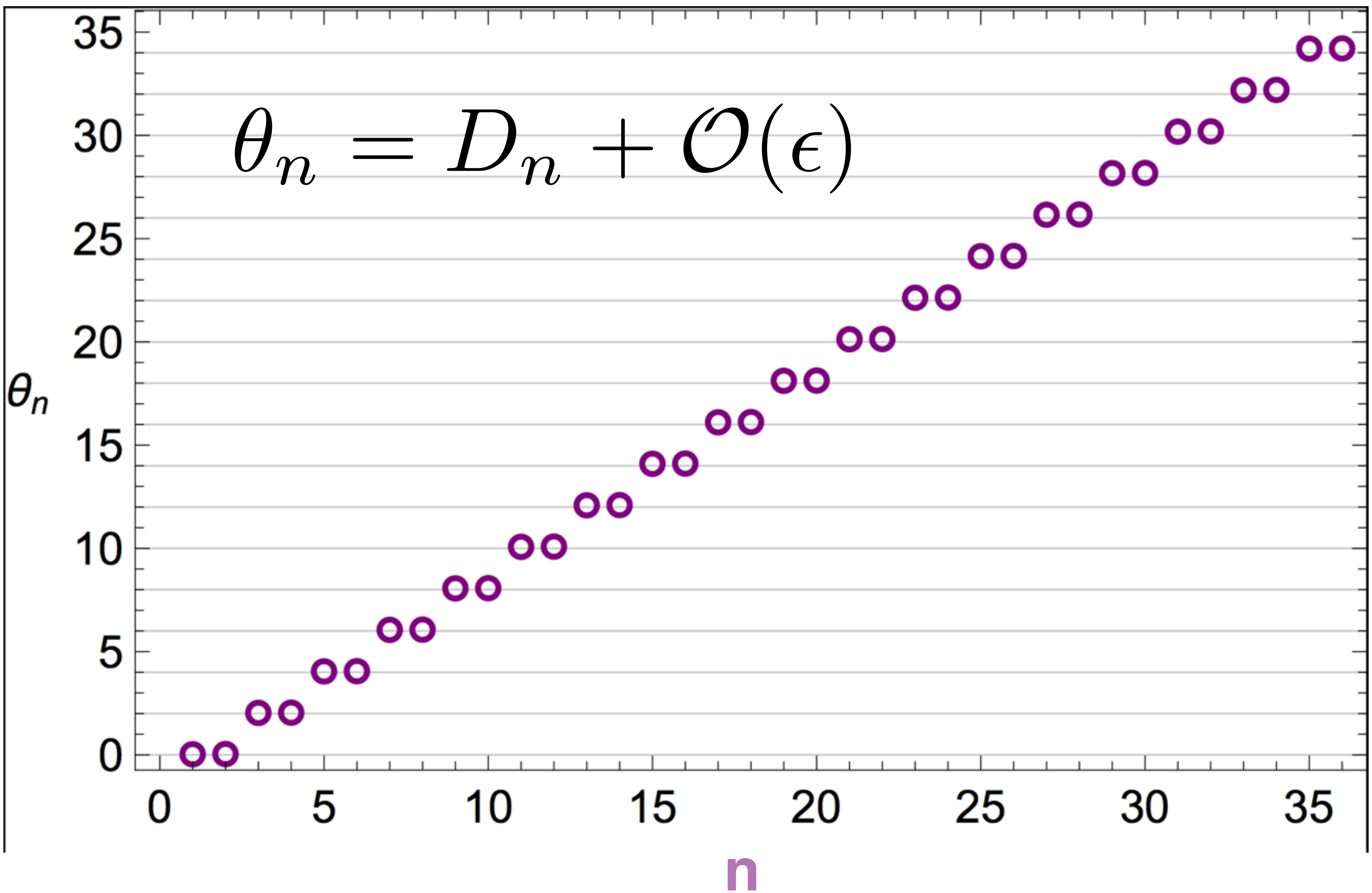
further scalar invariants

$$v_k(i_1, i_2) = u_k(i_1) + i_2 c_k(i_1)$$
$$u_k(i_1) = \sum_{j=2}^{N_i} \frac{(4\pi)^{2j-2}\, i_1^j\, \lambda_{2j-2}}{N_f^{2j-2}}$$
$$c_k(i_1) = \sum_{i=0}^{N_i} \frac{(4\pi)^{2j+2}\, i_1^j\, \lambda_{2j+1}}{N_f^{2j+1}}$$
$$i_1 = {\rm Tr}(h^\dagger h)$$
$$i_2 = {\rm Tr}\left((h^\dagger h)^2 - \frac{1}{N_f}({\rm Tr} h^\dagger h)^2\right)$$

Buyukbese, Litim @ Lattice2016 (in prep.)

extensions II

results: **exact eigenvalue spectrum**



more weak sector

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contributions to **muon anomalous magnetic moment** together with $\Delta a_\mu^{\rm exp} \sim (2-3)\cdot 10^{-9}$ leads to **constraint**

$$d(R_3)\,S(R_2)\,N_F\,\left(\frac{\rm TeV}{M_\psi}\right)^2 \lesssim 10^4$$

obeyed by all benchmark models.

contributions to the **rho parameter** arise if fermion multiplets encounter mass splitting $\delta M \ll M_\psi$ due to SU(2) breaking

$$N_F\,d(R_3)\,S(R_2)\,\delta M^2 \lesssim (40\,{\rm GeV})^2$$

sub-percent splitting for TeV or higher BSM masses

R-hadron searches

assume **pair-production** of BSM fermions $2M_\psi < \sqrt{s}$

at least the lightest has a long life ($> \tau_{\text{hadron}}$) and forms colorless **QCD bound states** with SM matter

$pp \to \psi\bar{\psi}$ via *t*-channel gluon fusion

$\sigma_{\psi\bar{\psi}} \sim N_F\, \mathcal{C}_3$ with $\mathcal{C}_3 = [C_2(R_3)]^2\, d(R_3)\, d(R_2)$

lower limits $M_\psi^{\min}$ from ATLAS and CMS gluino searches

$\psi(R_3, R_2)$	$R_2 = 1$		$R_2 = 2$		$R_2 = 3$	
R_3	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)	$\mathcal{C}_3$	$M_\psi^{\min}$ (TeV)
3	$5\frac{1}{3}$	(1.2)	$10\frac{2}{3}$	(1.3)	16	1.3
6	$66\frac{2}{3}$	1.5	$133\frac{1}{3}$	1.6	200	1.7
8	72	1.5	144	1.6	216	1.7
10	360	1.8	720	1.8	1080	1.9
15	$426\frac{2}{3}$	1.8	$853\frac{1}{3}$	1.9	1280	2.0
15′	$1306\frac{2}{3}$	2.0	$2313\frac{1}{3}$	2.1	3920	2.1

model *B, C, D, E*: 2.3, >2.4, 2.2, 2.0 TeV

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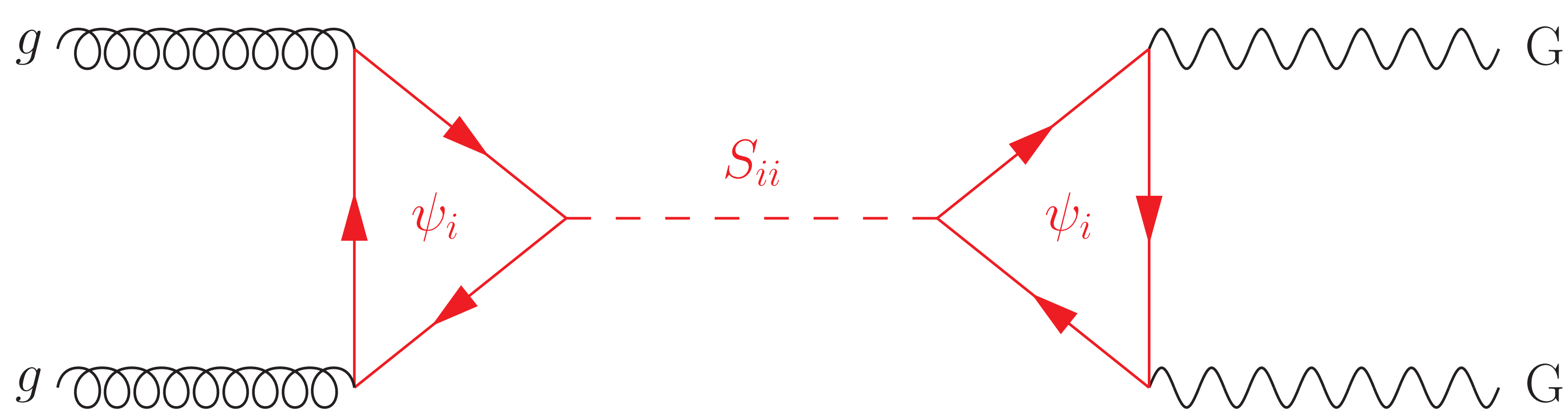
di-boson spectra and resonances

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

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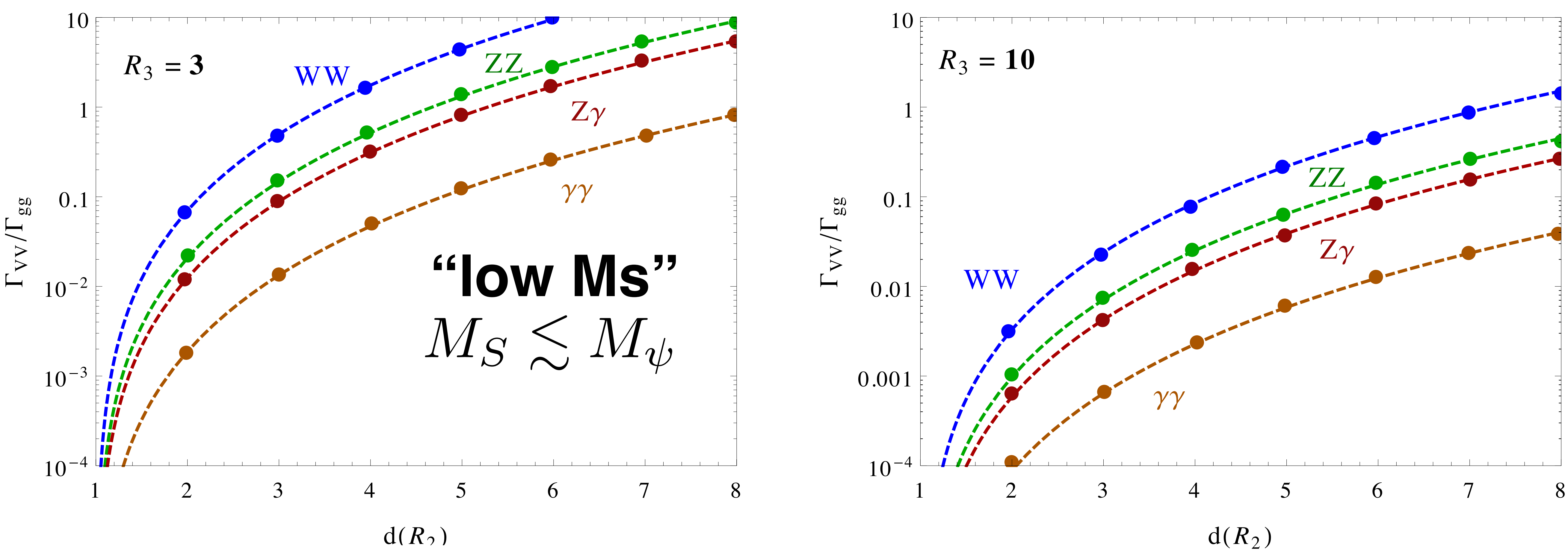
decays into electroweak gauge bosons

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

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

modification of widths for "high Ms"

FP$_4$ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}$ ↗ $\bar{\Gamma}_{\gamma\gamma}$ ↘ $\bar{\Gamma}_{Z\gamma}$?

FP$_2$ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}, \bar{\Gamma}_{\gamma\gamma}$ ↗

FP$_3$ $\bar{\Gamma}_{WW}, \bar{\Gamma}_{ZZ}, \bar{\Gamma}_{Z\gamma}, \bar{\Gamma}_{\gamma\gamma}$ ↘