Asymptotic safety and phenomenology in extensions of the Standard Model

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Motivation

SM is complete (as a theory) – but this is not the end of the story:

- does not address e.g. gravity
- cannot explain some observations e.g. $(g-2)_\mu$

Extension required, but is there a paradigm?

➔ UV completion

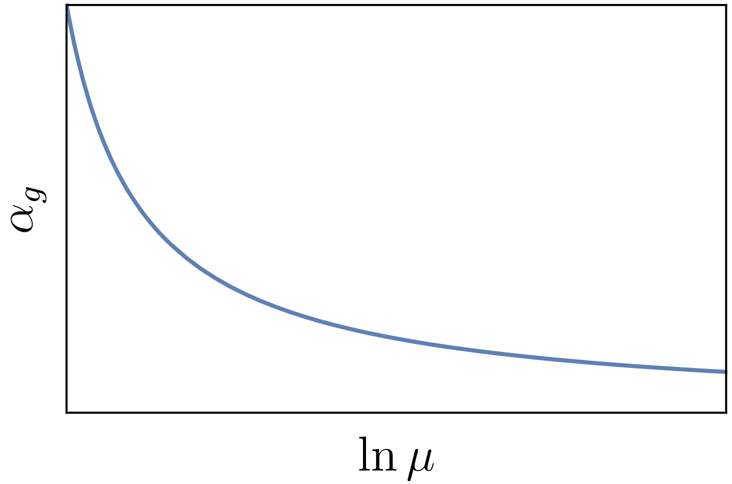
Motivation

Historic approach: asymptotic freedom [Gross, Wilczek, Politzer (1973)]

- theory becomes non-interacting at high energies
- viable for non-abelian gauge groups $U(1)_Y \times SU(2)_L \times SU(3)_C$

$$\beta_g = \frac{\partial \alpha_g}{\partial \ln \mu} = \underbrace{-B}_{<0}\, \alpha_g^2 + \mathcal{O}\left(\alpha^3\right)$$

asymptotic freedom



Total AF for model building:

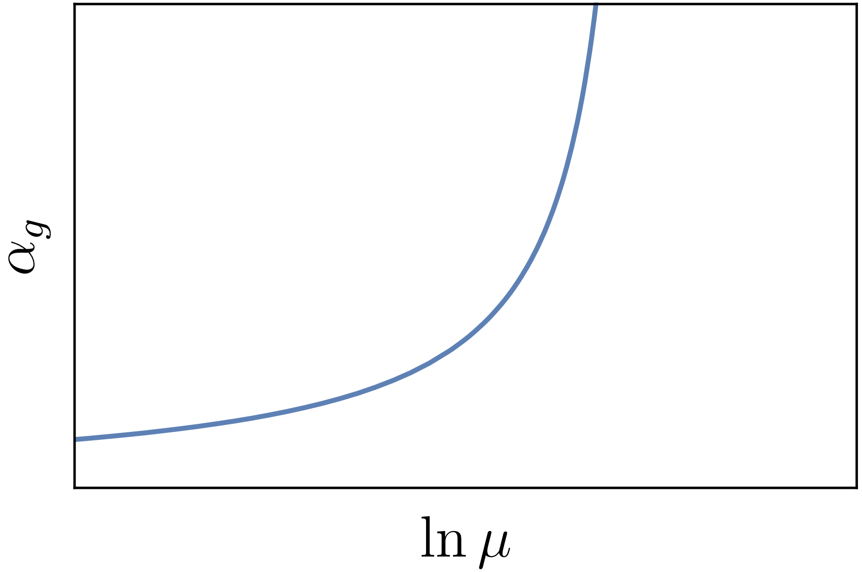
- ➔ embed U(1) groups
- ➔ avoid too much matter

$$B \sim [\text{Gauge Bosons}] - [\text{Matter}]$$

Beyond asymptotic freedom?

Landau poles endanger UV completion

$$\beta_g = \frac{\partial \alpha_g}{\partial \ln \mu} = \underbrace{-B}_{>0}\, \alpha_g^2 + \mathcal{O}\left(\alpha^3\right)$$



Is there a mechanism to cure poles?

- ➔ Asymptotic safety

Asymptotic safety

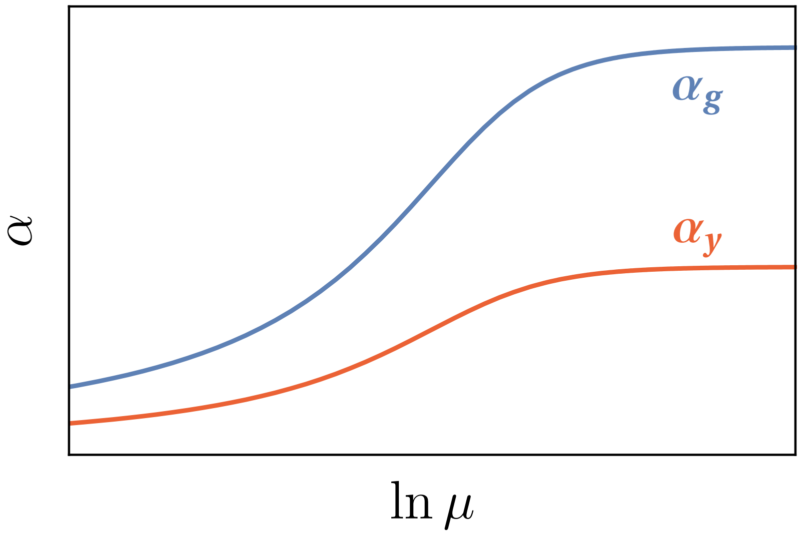
- interacting UV fixed point

$$\beta_g = \underbrace{-B}_{>0}\,\alpha_g^2 \;\; \underbrace{+C}_{>0}\,\alpha_g^3 \;\; \underbrace{-D}_{<0}\,\alpha_y\alpha_g^2 + \mathcal{O}\left(\alpha^4\right)$$

[Bond, Litim, (EPJ 2017)]

$$\beta_y = \underbrace{E}_{>0}\,\alpha_y^2 - \underbrace{F}_{>0}\,\alpha_g\alpha_y + \mathcal{O}\left(\alpha^3\right)$$

$$\alpha_y^* = \frac{F}{E}\alpha_g^* \qquad\qquad \alpha_g^* = \frac{BE}{CE - DF}$$



- running of gauge coupling towards Landau pole is controlled by Yukawa interaction

- fundamental building block is a gauge-Yukawa theory
  [Litim, Sannino, JHEP 2014][Litim, Sannino, Mojaza, JHEP 2016]

  ➔ new opportunities for model building

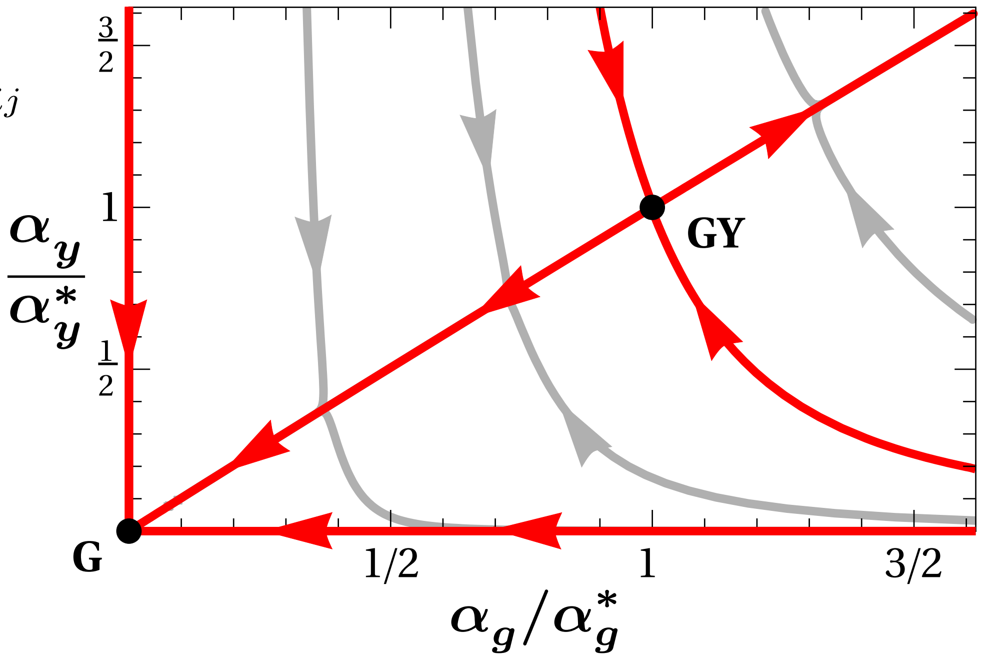
Asymptotic safety: template model

- $SU(N_c)$ gauge sector
- N_f quark-like fermions ψ_i
- N_f^2 uncharged, meson-like scalar matrix S_{ij}
- Yukawa interaction

$$-\mathcal{L}_{yuk} = y\,\overline{\psi}_{Li}\,S_{ij}\,\psi_{Rj} + \text{h.c.}$$

- scalar quartic sector

$$-\mathcal{L}_{qrt} = u\,\mathrm{tr}\left(S^\dagger S\right)^2 + v\left(\mathrm{tr}\,S^\dagger S\right)^2$$



Asymptotic safety: template model

- asymptotic safety is guaranteed in Veneziano limit

$$N_{c,f} \to \infty \,, \qquad \epsilon = \frac{N_f}{N_c} - \frac{11}{2}$$

$\epsilon \ll 1$ expansion parameter for UV fixed point, critical exponents

- RGEs up to 3-loop gauge, 2-loop Yukawa, 2-loop quartics
  [Bond, Litim, Medina, TS (PRD 2018)]

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[Bond, Litim, Medina, TS (PRD 2018)]

$$\begin{aligned}
\beta_g^{(1)} &= \frac{4}{3}\epsilon\,\alpha_g^2 \\
\beta_g^{(2)} &= \left(25 + \tfrac{26}{3}\epsilon\right)\alpha_g^3 - 2\left(\tfrac{11}{2} + \epsilon\right)^2 \alpha_y \alpha_g^2 \\
\beta_g^{(3)} &= \left(\tfrac{701}{6} + \tfrac{53}{3}\epsilon - \tfrac{112}{27}\epsilon^2\right)\alpha_g^4 \\
&\quad -\tfrac{27}{8}(11+2\epsilon)^2\alpha_g^3\alpha_y \\
&\quad +\tfrac{1}{4}(11+2\epsilon)^2(20+3\epsilon)\alpha_y^2\alpha_g^2
\end{aligned}$$

$$\begin{aligned}
\beta_y^{(1)} &= (13+2\epsilon)\,\alpha_y^2 - 6\,\alpha_y\,\alpha_g \\
\beta_y^{(2)} &= \tfrac{20\epsilon-93}{6}\alpha_g^2\,\alpha_y + (49+8\epsilon)\alpha_g\alpha_y^2 \\
&\quad -4\big[(11+2\epsilon)\alpha_y - \alpha_u\big]\,\alpha_u\alpha_y \\
&\quad -\left(\tfrac{385}{8} + \tfrac{23}{2} + \tfrac{\epsilon^2}{2}\right)\alpha_y^3
\end{aligned}$$

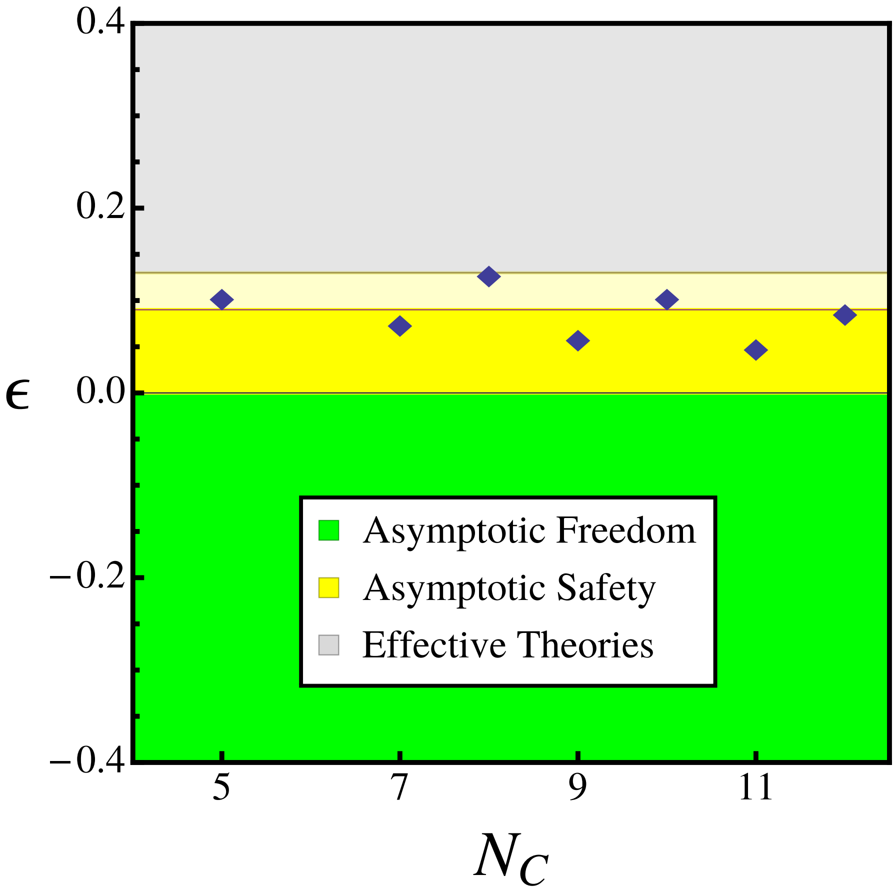
$$\begin{aligned}
\beta_u^{(1)} &= -(11+2)\,\alpha_y^2 + 4\alpha_u(\alpha_y + 2\alpha_u) \\
\beta_u^{(2)} &= \alpha_u\alpha_y\big[10\alpha_g - 16\alpha_u - 3(11+2\epsilon)\alpha_y\big] \\
&\quad +(11+2\epsilon)\big[(11+2\epsilon)\alpha_y - 2\alpha_g\big]\alpha_y^2 \\
&\quad -24\alpha_u^3
\end{aligned}$$

$$\begin{aligned}
\beta_v^{(1)} &= 12\alpha_u^2 + 4\alpha_v\left(\alpha_v + 4\alpha_u + \alpha_y\right) \\
\beta_v^{(2)} &= 8\alpha_v\alpha_y\big[\tfrac{5}{4}\alpha_g - 4\alpha_u - \alpha_v \\
&\qquad -(\tfrac{33}{8} + 34\epsilon)\alpha_y\big] + \\
&\quad (11+2\epsilon)\big[(11+2\epsilon)\alpha_y + 4\alpha_u\big]\alpha_y^2 \\
&\quad -8\alpha_u^2\big[12\alpha_u + 5\alpha_v + 3\alpha_y\big]
\end{aligned}$$

Asymptotic safety: template model

- RGEs imply constraints $\epsilon < \epsilon_{max}$ from vacuum stability, fixed point mergers, …

- allows for finite values $N_C \geq 5$



Can it actually be used in SM extensions ?

SM + template model

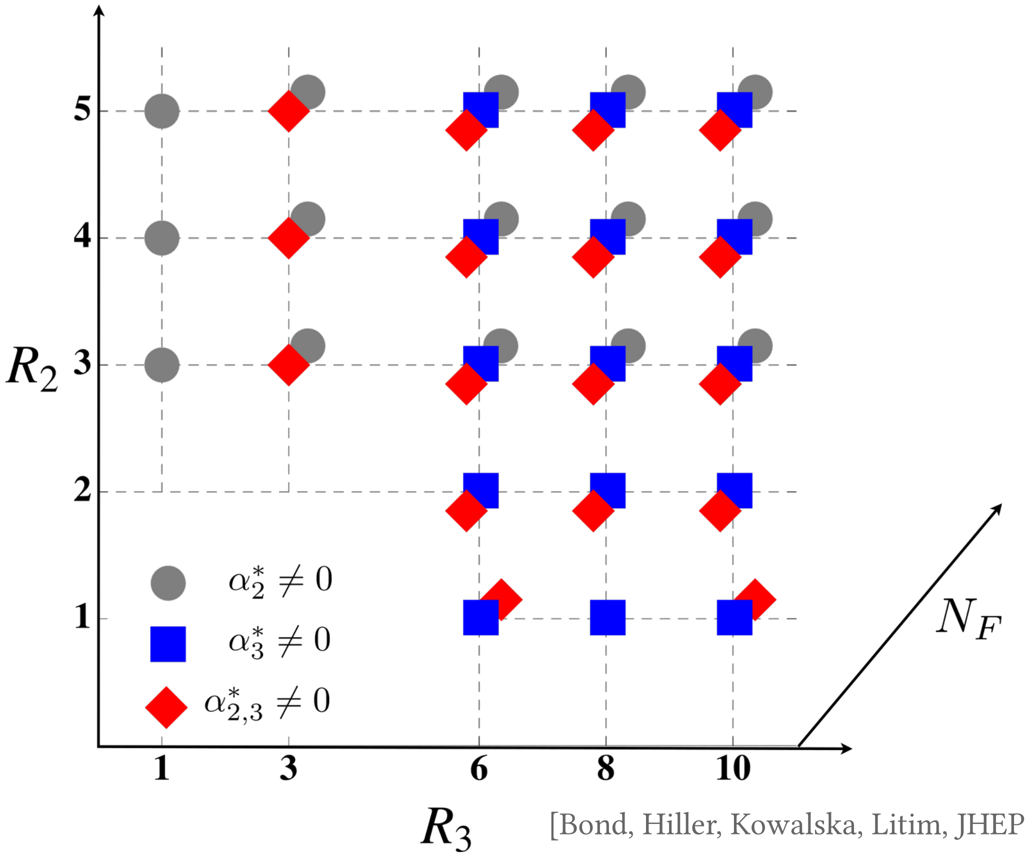
- SM particle content, gauge group
- N_f BSM fermions ψ_i, various reps of $SU(2)_L \times SU(3)_C$ [Bond, Hiller, Kowalska, Litim, JHEP 2017]
  - ➔ no large N_c
- uncharged BSM scalar S_{ij}
- Yukawa interactions

$$-\mathcal{L}_{yuk} = \underbrace{y\,\overline{\psi}_{Li}\,S_{ij}\,\psi_{Rj}}_{\text{BSM Yukawa interaction}} + \text{h.c.}$$

- scalar quartic sector

$$-\mathcal{L}_{qrt} = \underbrace{u\,\mathrm{tr}\left(S^\dagger S\right)^2 + v\left(\mathrm{tr}\,S^\dagger S\right)^2}_{\text{BSM scalar self interactions}} + \underbrace{\lambda\left(H^\dagger H\right)^2}_{\text{Higgs quartic}} + \underbrace{\delta\left(H^\dagger H\right)\left(\mathrm{tr}\,S^\dagger S\right)}_{\text{Higgs portal}}$$

SM + template model



[Bond, Hiller, Kowalska, Litim, JHEP 2017]

- further study with full SM gauge group
  [Percacci et al., JHEP 2018]

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

  - → no fixed points under perturbative control
  - → stronger couplings required

New idea

- connect SM and BSM flavour symmetries
- Yukawa interaction of Higgs with BSM fermions ψ_i
- fixes $N_f = 3$
- for now, consider ψ_i only with hypercharge and weak isospin, but no color
  - ➔ 6 different models

$$-\mathcal{L}_{yuk} = y\,\overline{\psi}_{Li}\, S_{ij}\, \psi_{Rj} + \kappa_{ij}\, \overline{L}_i\, H\, \psi_{Rj} + \kappa'\, \overline{E}_i\, S^\dagger_{ij} \psi_{Lj} + \text{h.c.}$$

BSM Yukawa interaction

Higgs-BSM mixing

BSM scalar + SM leptons

$$-\mathcal{L}_{qrt} = u\,\text{tr}\left(S^\dagger S\right)^2 + v\left(\text{tr}\,S^\dagger S\right)^2 + \lambda\left(H^\dagger H\right)^2 + \delta\left(H^\dagger H\right)\left(\text{tr}\,S^\dagger S\right)$$

BSM scalar self interactions

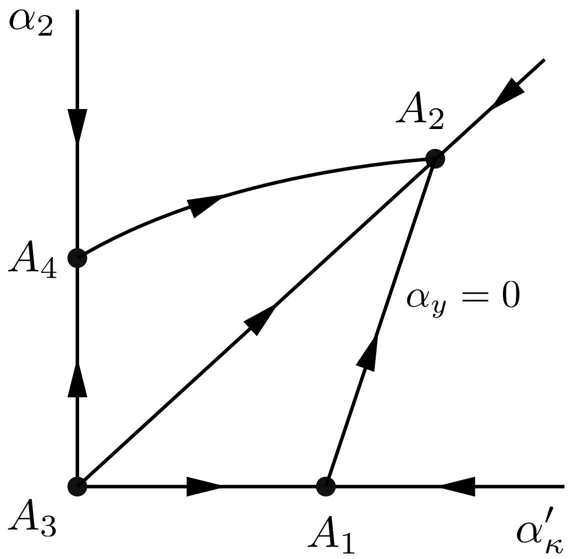
Higgs quartic

Higgs portal

RG study

- RGEs can be computed in perturbation theory [Machacek, Vaughn, NPB 1983-85]
- leading order analysis:

FP	α_1^*	α_2^*	α_κ^*	$\alpha_{\kappa'}^*$	α_y^*
A_1	1.063	0	0.886	1.594	0
A_2	1.105	0.569	1.205	1.657	0
A_3	2.151	0	0.782	0	3.032
A_4	2.267	0.200	0.933	0	3.165



- ➔ fixed points are boarderline perturbative
- ➔ require higher loop-order analysis, but complexity grows...

$$
\begin{aligned}
\beta_\delta^{(2)} =& -4\alpha_\delta^2\alpha_{\kappa'} - 9\alpha_\delta\alpha_{\kappa'}^2 + 10\alpha_1\alpha_\delta\alpha_{\kappa'} - 72\alpha_\delta\alpha_\kappa\alpha_\lambda - 12\alpha_\delta^2\alpha_\kappa - \frac{27}{2}\alpha_\delta\alpha_\kappa^2 + \frac{75}{4}\alpha_1\alpha_\delta\alpha_\kappa \\
&+ \frac{45}{4}\alpha_2\alpha_\delta\alpha_\kappa - 72\alpha_\delta^2\alpha_\lambda - 60\alpha_\delta\alpha_\lambda^2 + 24\alpha_1\alpha_\delta\alpha_\lambda + 72\alpha_2\alpha_\delta\alpha_\lambda - 19\alpha_\delta^3 \\
&+ \alpha_1\alpha_\delta^2 + 3\alpha_2\alpha_\delta^2 + \frac{797}{48}\alpha_1^2\alpha_\delta - \frac{145}{16}\alpha_2^2\alpha_\delta + \frac{15}{8}\alpha_1\alpha_2\alpha_\delta - 12\alpha_1^2\alpha_{\kappa'} + 40\alpha_3\alpha_\delta\alpha_b \\
&- 72\alpha_\delta\alpha_\lambda\alpha_b - 12\alpha_\delta^2\alpha_b - \frac{27}{2}\alpha_\delta\alpha_b^2 + \frac{25}{12}\alpha_1\alpha_\delta\alpha_b + \frac{45}{4}\alpha_2\alpha_\delta\alpha_b - 21\alpha_\delta\alpha_b\alpha_t \\
&+ 40\alpha 3\alpha_\delta\alpha_t - 72\alpha_\delta\alpha_\lambda\alpha_t - 12\alpha_\delta^2\alpha_t - \frac{27}{2}\alpha_\delta\alpha_t^2 + \frac{85}{12}\alpha_1\alpha_\delta\alpha_t + \frac{45}{4}\alpha_2\alpha_\delta\alpha_t - 48\alpha_\delta\alpha_u\alpha_{\kappa'} \\
&- 144\alpha_\delta^2\alpha_u - 200\alpha_\delta\alpha_u^2 - 240\alpha_\delta\alpha_u\alpha_v - 48\alpha_\delta\alpha_u\alpha_y - 80\alpha_\delta\alpha_v\alpha_{\kappa'} - 240\alpha_\delta^2\alpha_v - 200\alpha_\delta\alpha_v^2 \\
&- 80\alpha_\delta\alpha_v\alpha_y - 18\alpha_\delta\alpha_y\alpha_{\kappa'} + \frac{47}{2}\alpha_\delta\alpha_\kappa\alpha_y - 4\alpha_\delta^2\alpha_y - 9\alpha_\delta\alpha_y^2 + 10\alpha_1\alpha_\delta\alpha_y \\
&+ 30\alpha_\kappa\alpha_y\alpha_{\kappa'} + 14\alpha_\kappa^2\alpha_y + 30\alpha_\kappa\alpha_y^2 - 12\alpha_1\alpha_\kappa\alpha_y - 12\alpha_1^2\alpha_y
\end{aligned}
$$

➔ need a different search strategy

Search for UV trajectories

- start from SM and run IR $\longrightarrow$ UV, 2-loop
- BSM fermions all have mass $M_F \approx 1$ TeV, which is the matching scale

6 SM parameters,
fixed by matching

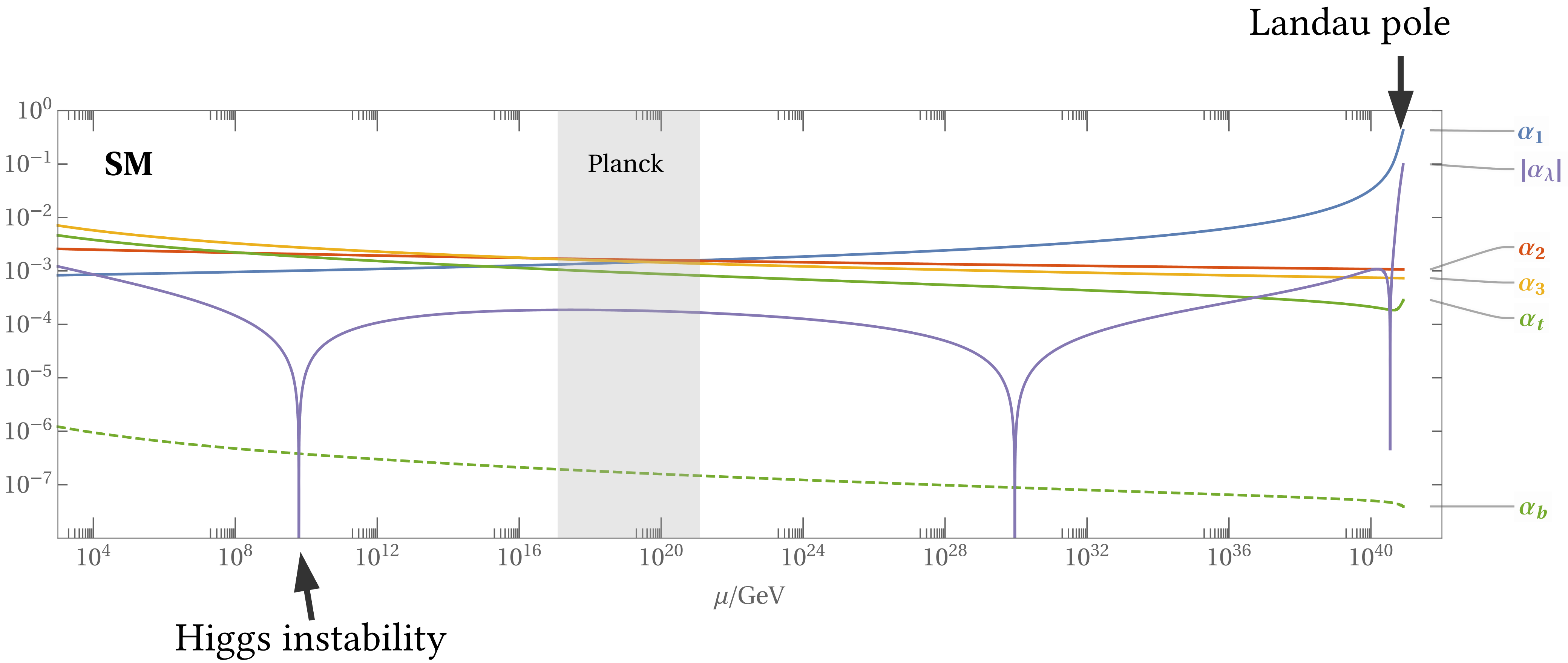
α_1	hypercharge gauge
α_2	weak gauge
α_3	strong gauge
α_t	top Yukawa
α_b	bottom Yukawa
α_λ	Higgs quartic

6 open BSM parameters

α_κ	Higgs + BSM fermion Yukawa
$\alpha_{\kappa'}$	BSM scalar + SM lepton Yukawa
α_y	BSM-only Yukawa
α_δ	Higgs + BSM scalar portal quartic
α_u, α_v	BSM quartics

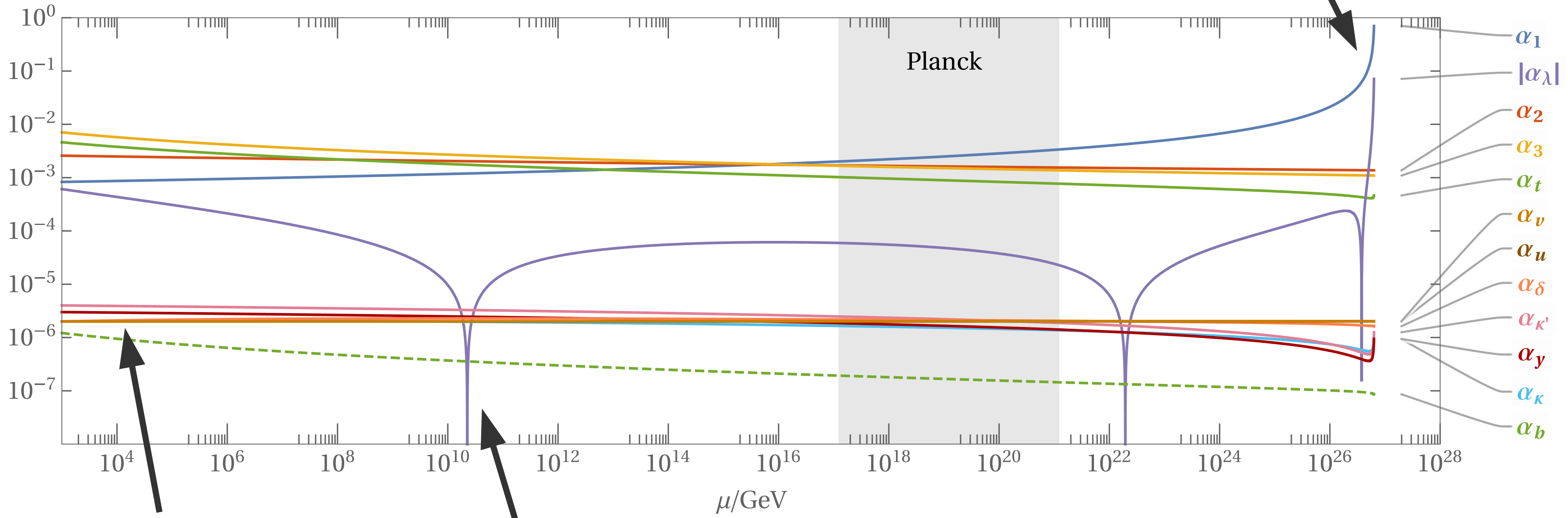
What to expect in the SM …

Standard Model flow



SM + BSM fermions

Landau pole
at lower scale

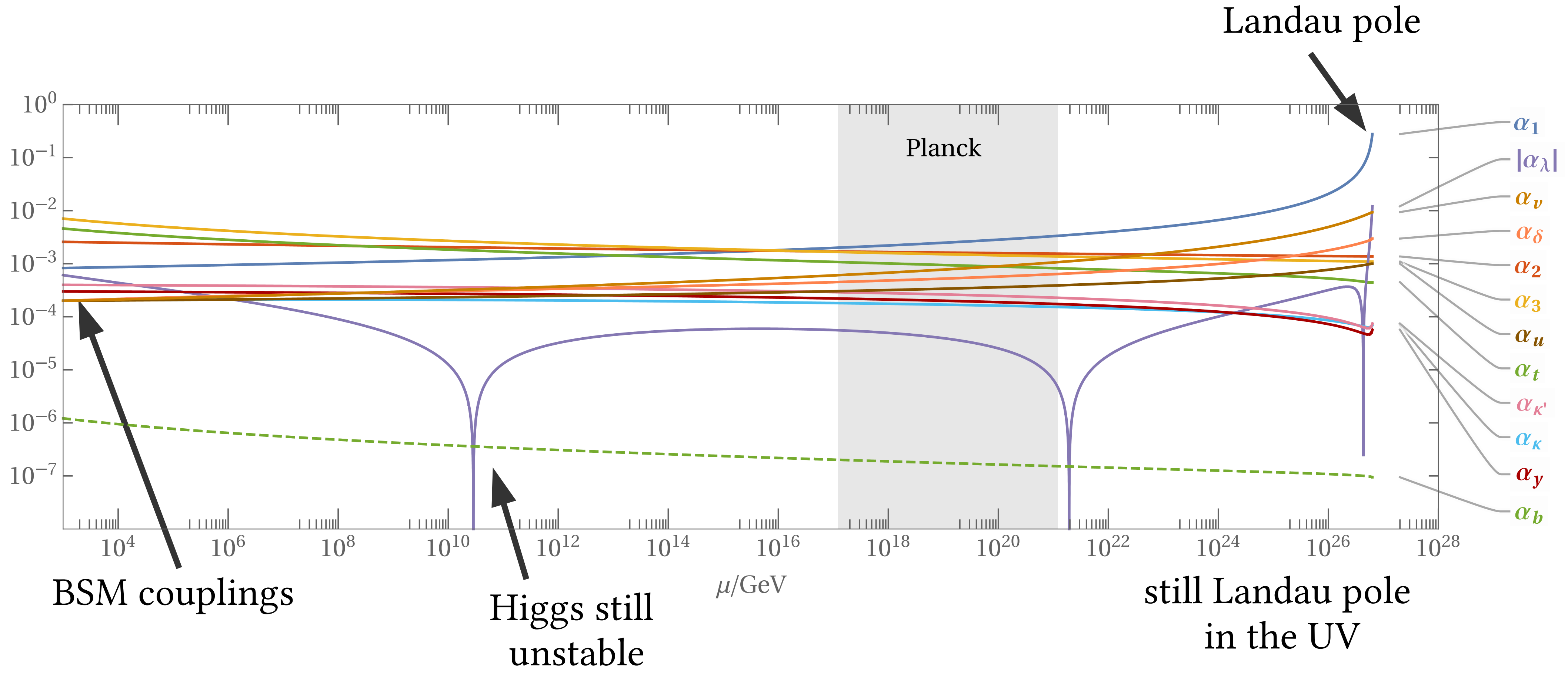


BSM couplings
remain feeble

Higgs still
unstable

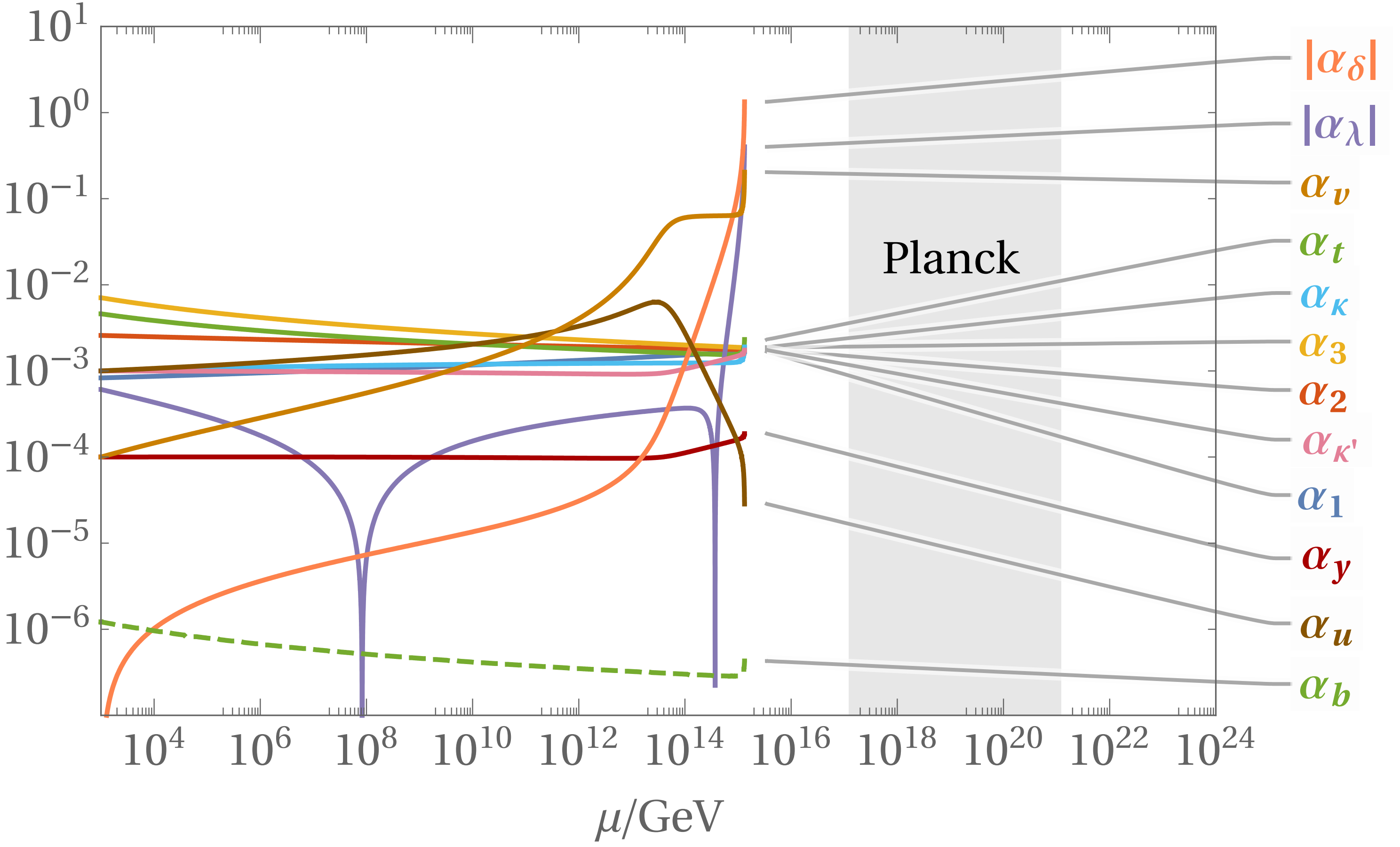
What happens if we increase
initial values of BSM couplings?

Weak BSM sector



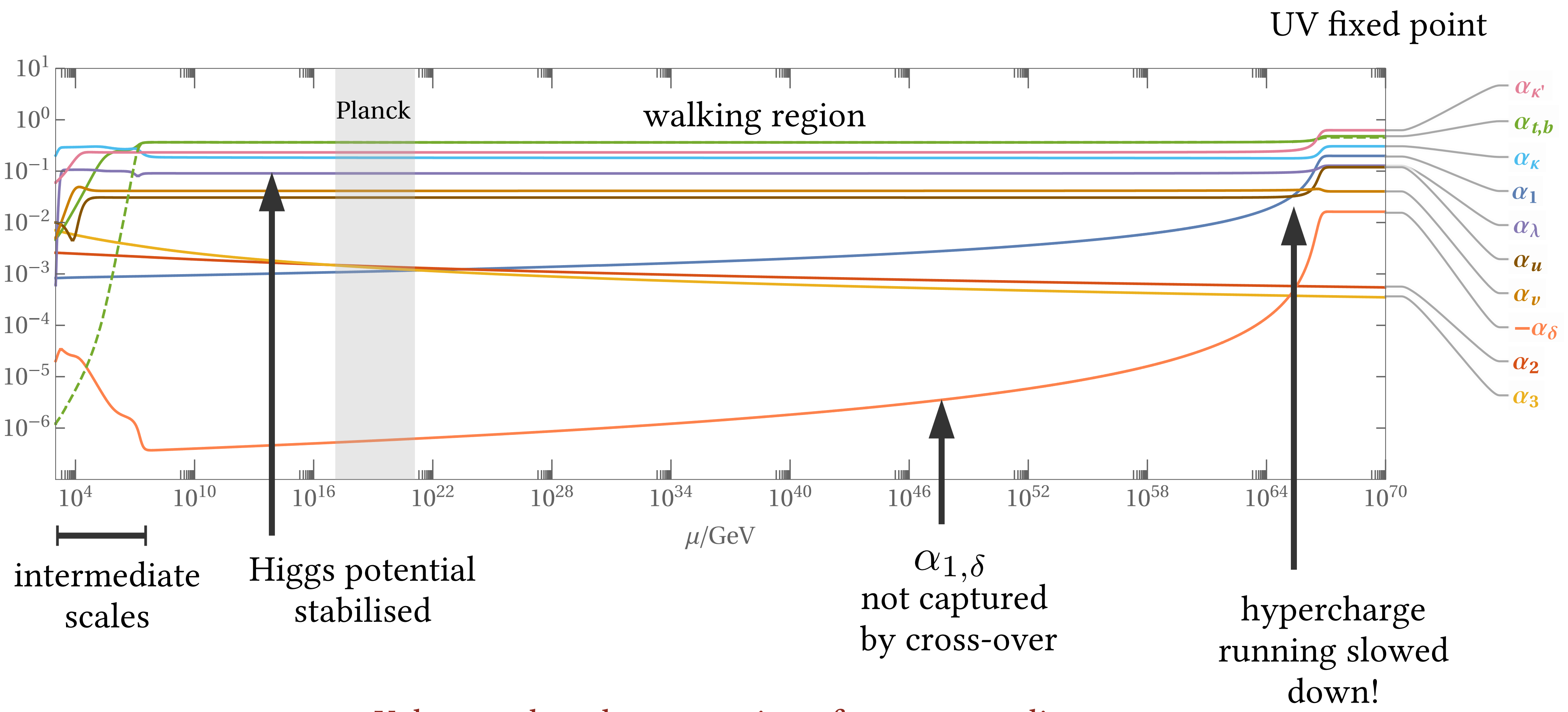
still Landau pole in the UV

→ stronger BSM couplings required



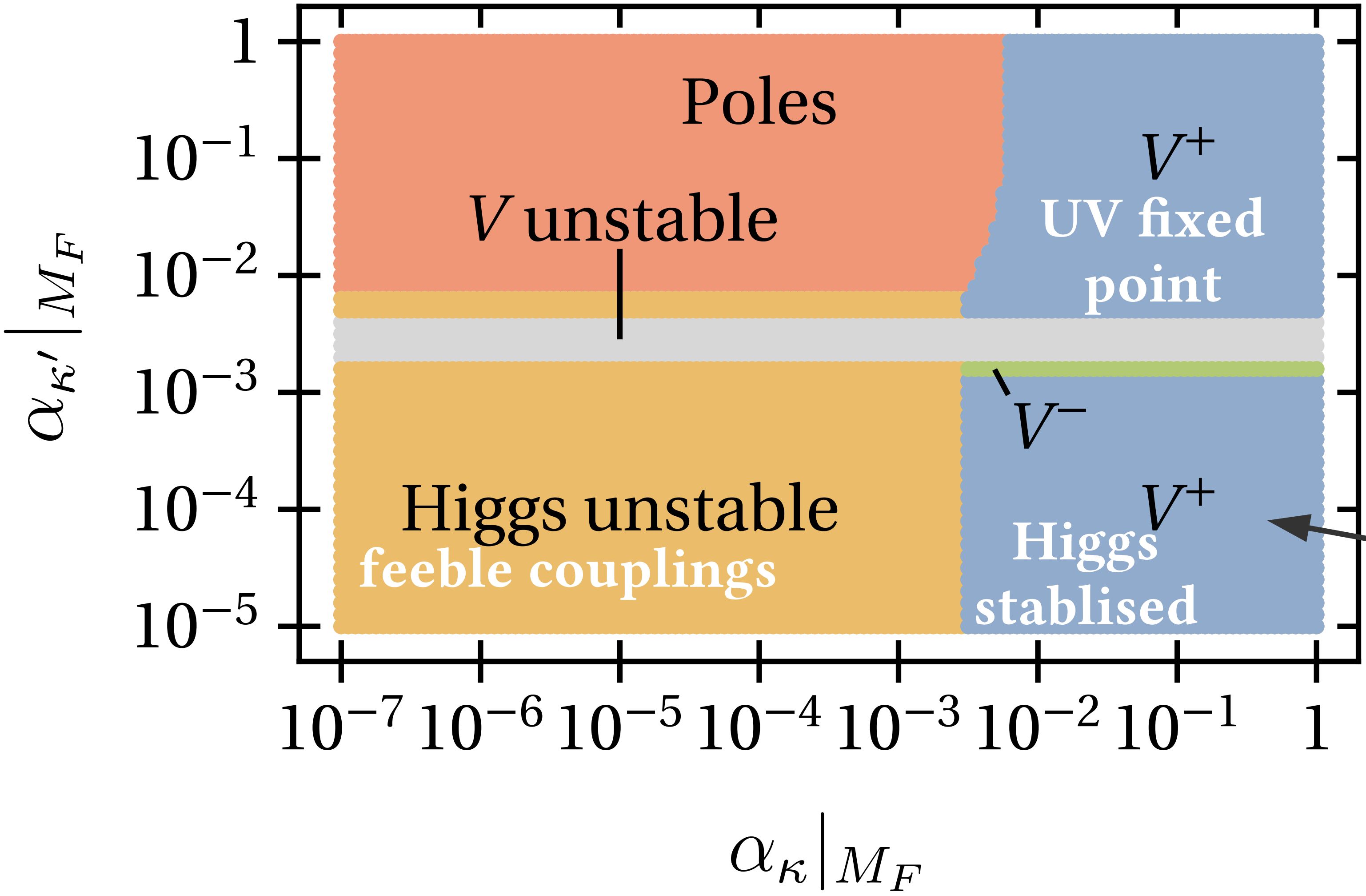
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22} 10^{24}
μ/GeV
Planck
$|\alpha_\delta|$
$|\alpha_\lambda|$
α_v
α_t
α_κ
α_3
α_2
$\alpha_{\kappa'}$
α_1
α_y
α_u
α_b

UV fixed points



Yukawas slow down running of gauge couplings

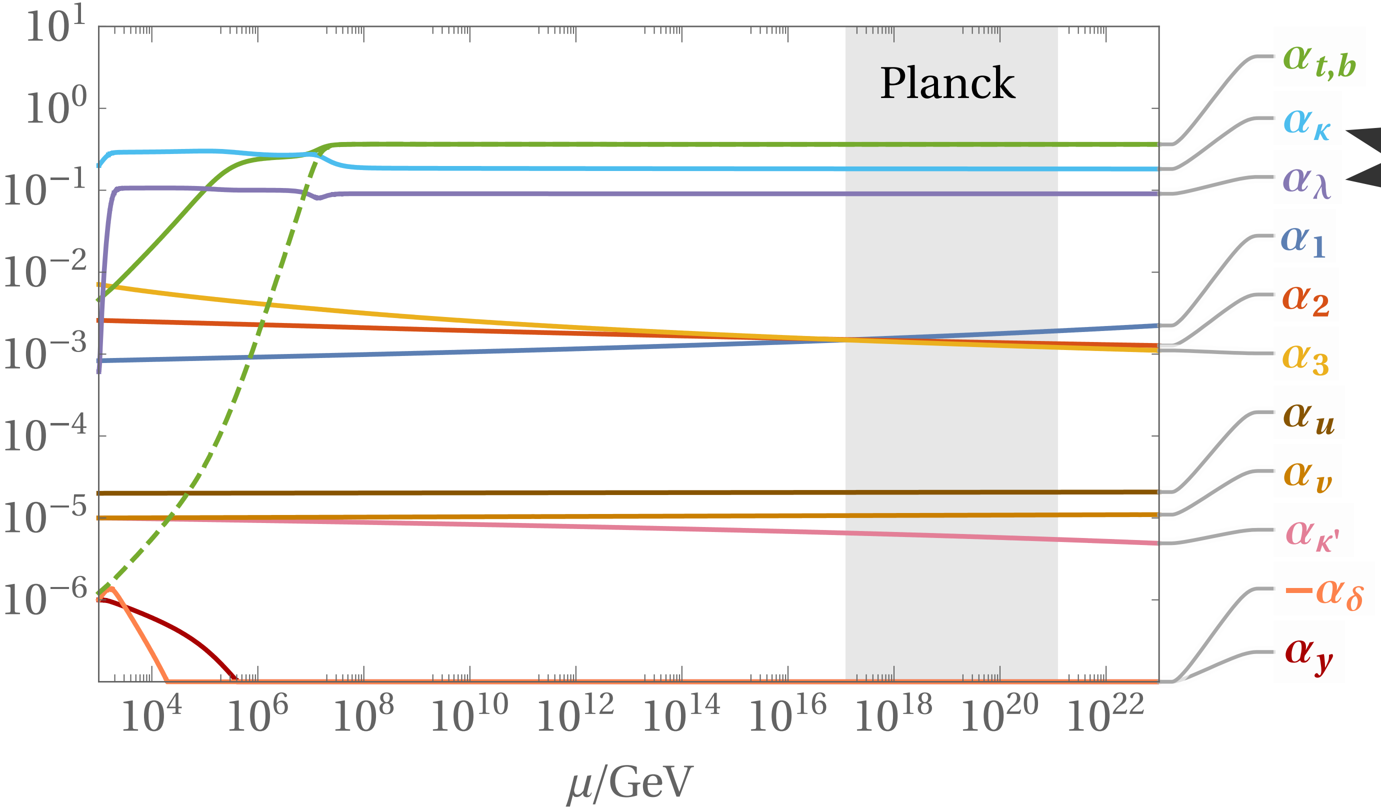
UV critical surface



couplings at M_{Pl} , depending on initial BSM Yukawas at M_F

More configurations allow for safety until M_{Pl}

Safety until Planck scale



BSM Yukawa stablilises
Higgs potential

Conclusion about UV safety

- some models allow feebly coupled BSM sector
- BSM sector can
  - stabilise Higgs potential
  - push Landau poles towards UV
- BSM Yukawas play crucial role in these tasks

Are there experimantally verifiable predictions?

Some experimental predictions / constraints

- lower bound on BSM fermion mass M_F from e.g. Drell-Yan process [Farina et al., PRB 2017]

  $M_F \gtrsim \mathcal{O}\left(10^2\right)$ GeV 1 TeV is reasonable choice

- bound on mixing between Higgs and BSM scalar $|\beta| \lesssim 0.2$ [Patrignani et al., CPC 2016]
  - ➔ favours heavy scalar

- Production at pp/ll colliders via BSM Yukawa and gauge interactions
  - ➔ sensitive on model, representations
- BSM fermion decays promptly $\Gamma\left(\psi \to h\,l\right) \sim \alpha_\kappa\, M_F \left(1 - \frac{m_h^2}{M_F^2}\right)^2$
- $M_{F,S}$ mass hierarchy observable via scalar decay $S \to \psi l,\, \psi\psi$

Application: Anomalous magnetic moments

- measured deviation from SM for muon and electron magnetic moments

Muon:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 268(63)(43) \cdot 10^{-11}$$

$$\Rightarrow \; +3.5\,\sigma$$

[Tanabashi et al., PRD 2018]

Electron:

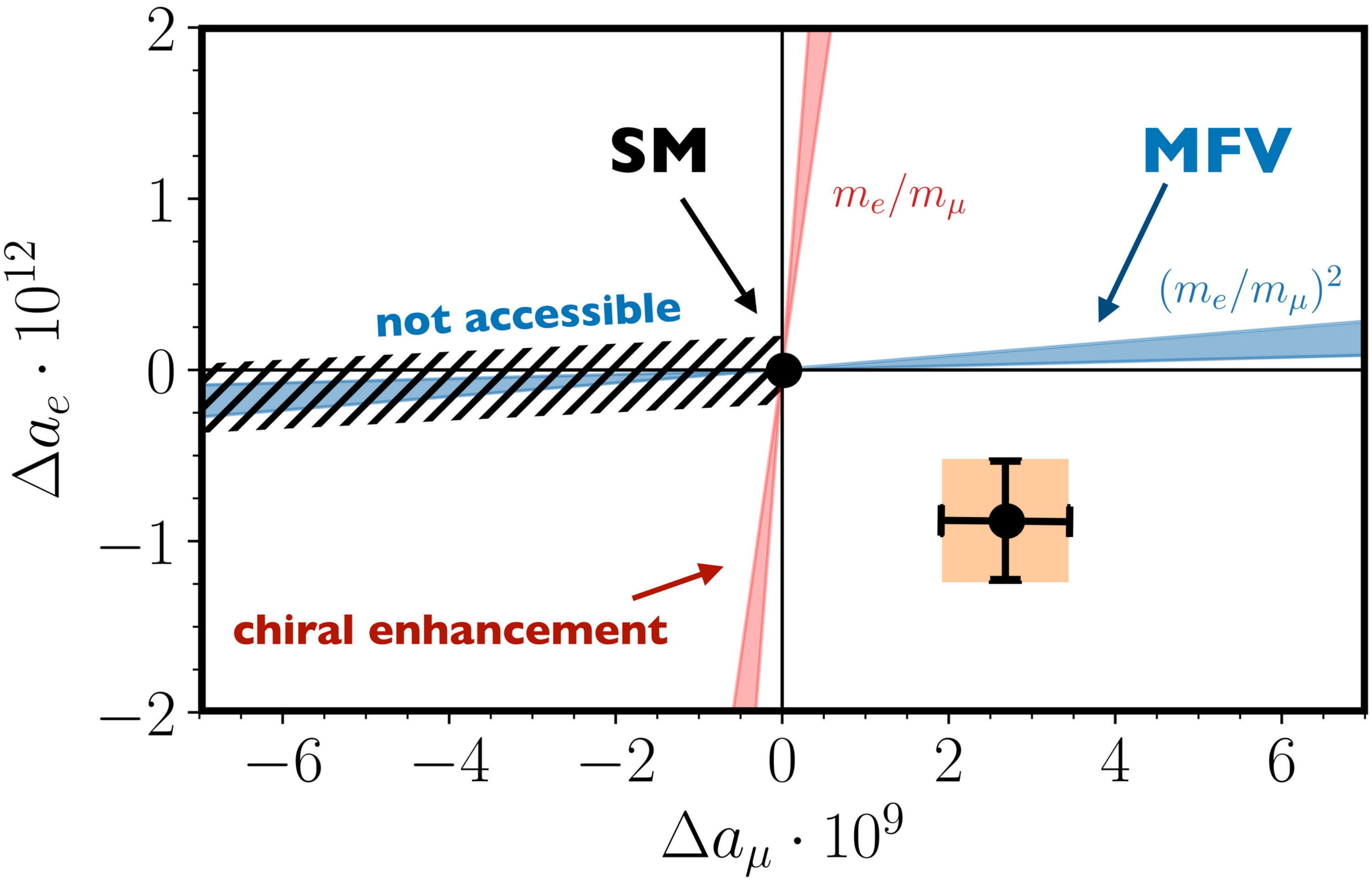
$$a_e^{\text{exp}} - a_e^{\text{SM}} = -88(28)(23) \cdot 10^{-14}$$

$$\Rightarrow \; -2.4\,\sigma$$

[Hanneke, Fogwell, Gabrielse, PRL 2008]
[Parker et al., Science 2018]

- electron and muon discrepancies have different sign, difficult to explain both together without breaking flavour universality

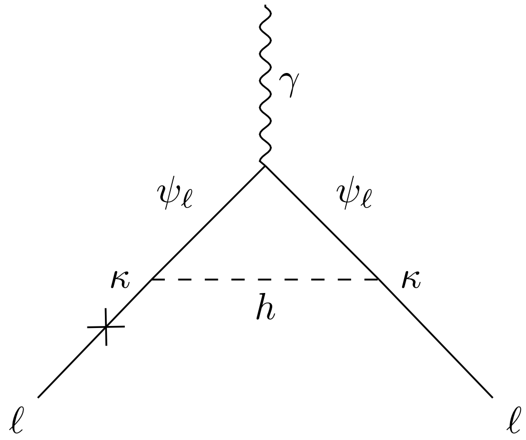
Application: Anomalous magnetic moments



Application: Anomalous magnetic moments

$$-\mathcal{L}_{yuk} = y\,\overline{\psi}_{Li}\,S_{ij}\,\psi_{Rj} + \kappa_{ij}\,\overline{L}_i\,H\,\psi_{Rj} + \kappa'\,\overline{E}_i\,S^\dagger_{ij}\psi_{Lj} + \text{h.c.}$$

„MFV“



universal for all flavours,
always positive

$$\delta a_l \sim \frac{\kappa^2}{(4\pi)^2}\,\frac{m_l^2}{M_F^2}$$

Application: Anomalous magnetic moments

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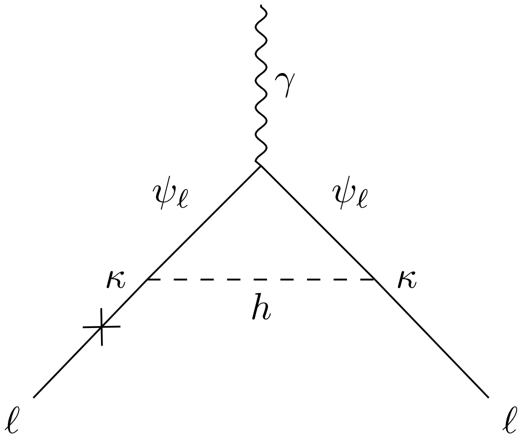
„MFV“

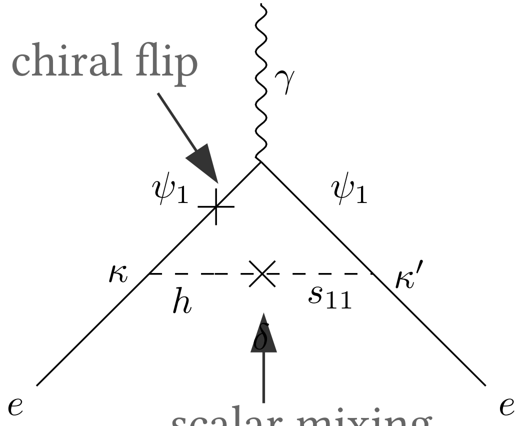


universal for all flavours,
always positive

$$\delta a_l \sim \frac{\kappa^2}{(4\pi)^2}\,\frac{m_l^2}{M_F^2}$$

„chiral enhancement“

chiral flip



scalar mixing

$$\delta a_e = -\frac{m_e}{2M_F}\,\frac{\kappa\kappa'}{(4\pi)^2}\,\sin 2\beta$$

sign is tunable

Summary

- explored new set of BSM models
- hints of safety until the Planck scale
- can stabilise Higgs and BSM scalar sector
- potential to explain both $(g\text{-}2)_{\mu,e}$

Thank you for your attention

Backup

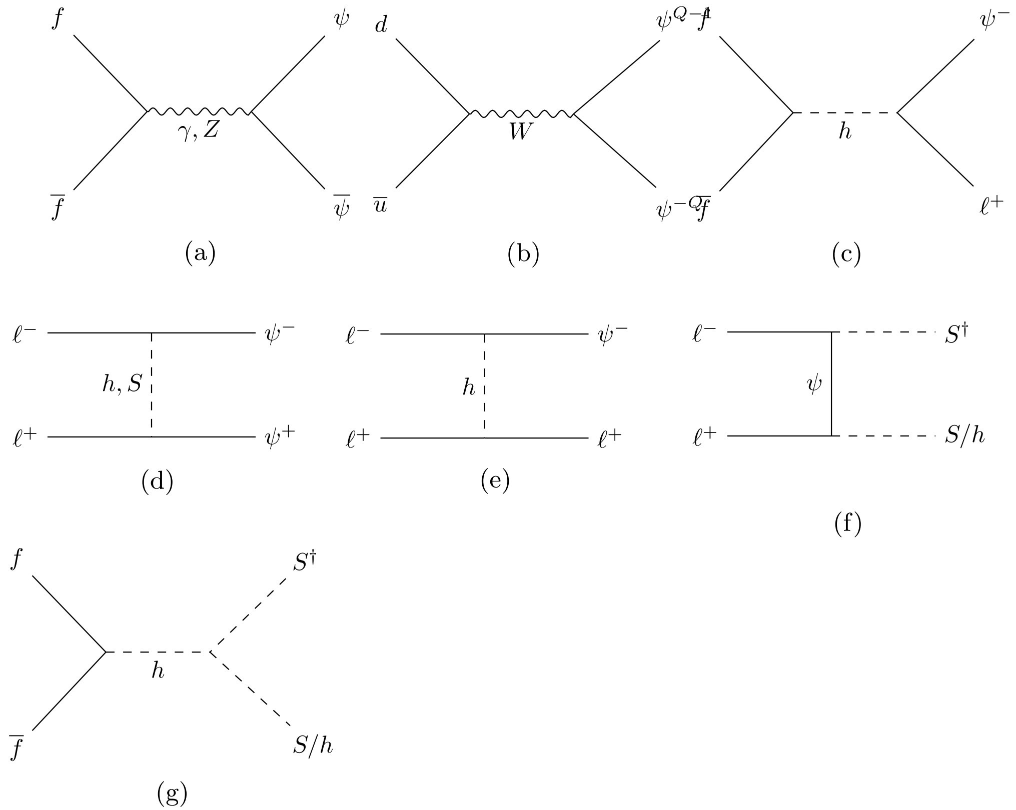
Field content

- SM gauge interactions, fermions, and Higgs H
- 3 Vector-like BSM fermions $\psi_{L,R}$ with mass M_F, carrying electroweak charge, interaction with SM Higgs + leptons

Model	$(R_3,\, R_2,\, Y_F)$
A	$(\mathbf{1},\, \mathbf{1},\, -1)$
B	$(\mathbf{1},\, \mathbf{3},\, -1)$
C	$\left(\mathbf{1},\, \mathbf{2},\, -\frac{1}{2}\right)$
D	$\left(\mathbf{1},\, \mathbf{2},\, -\frac{3}{2}\right)$
E	$(\mathbf{1},\, \mathbf{1},\, 0)$
F	$(\mathbf{1},\, \mathbf{3},\, 0)$

- Meson-like BSM scalar S_{ij}, (3 x 3) flavour matrix

Production channels



Decay

- Decay hierachies depend on BSM fermion/scalar mass $M_{F,S}$ and model
- BSM fermions undergo prompt decay $\Gamma\left(\psi \to h\,l\right) \sim \alpha_\kappa\, M_F \left(1 - \frac{m_h^2}{M_F^2}\right)^2$

$$M_F = 1\,\text{TeV},\ \alpha_\kappa = 3\cdot 10^{-3}\ :\quad \Gamma^{-1} \sim \mathcal{O}\left(10^{-25}\right)\ \text{s}$$

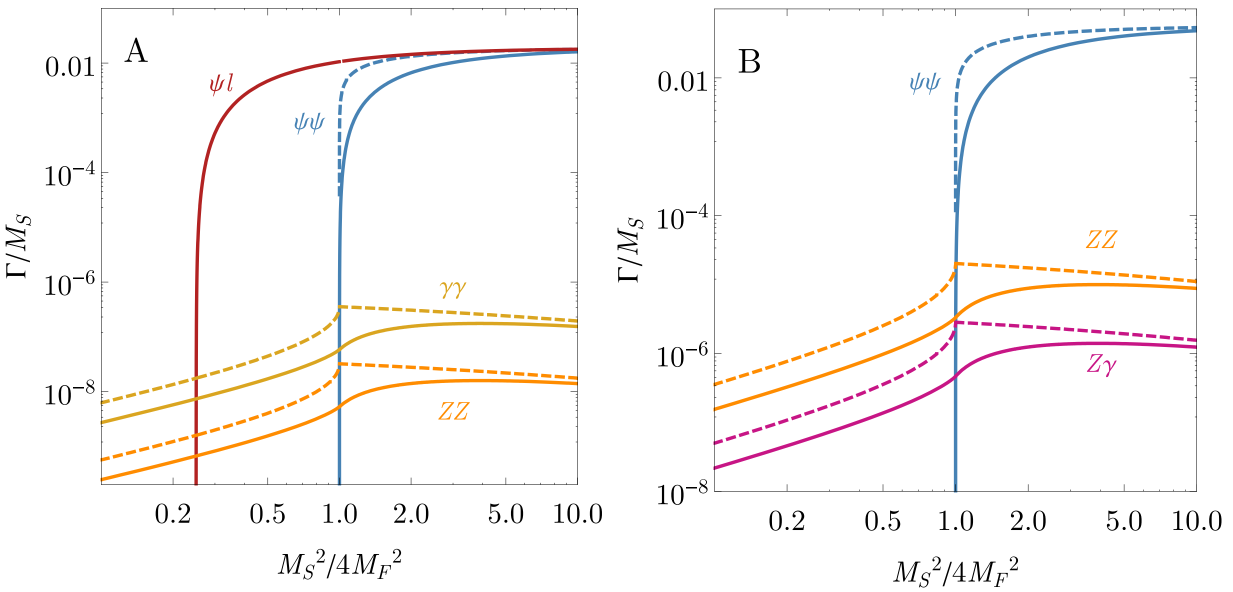
  higher charged ones live longer

- BSM scalar decays via $y,\ \kappa'$

  or into gauge bosons (ψ-triangle)

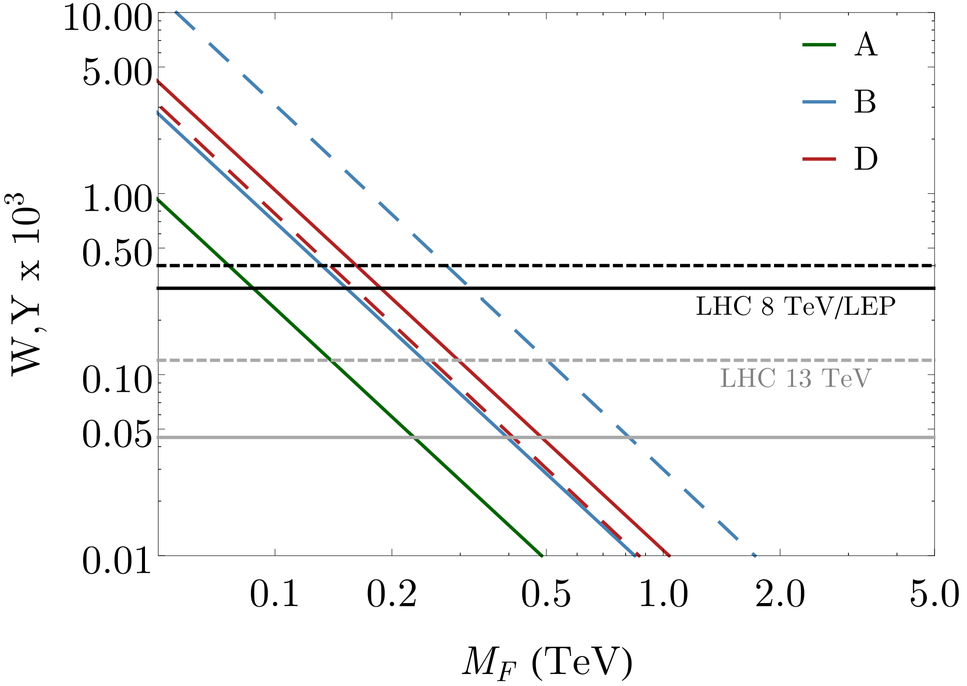
- fermion mixing gives additional decays $S \to ll$

$$\alpha_{\kappa,\kappa',y} = 3\cdot 10^{-3},\quad M_F = 1\,\text{TeV}$$



Constraints

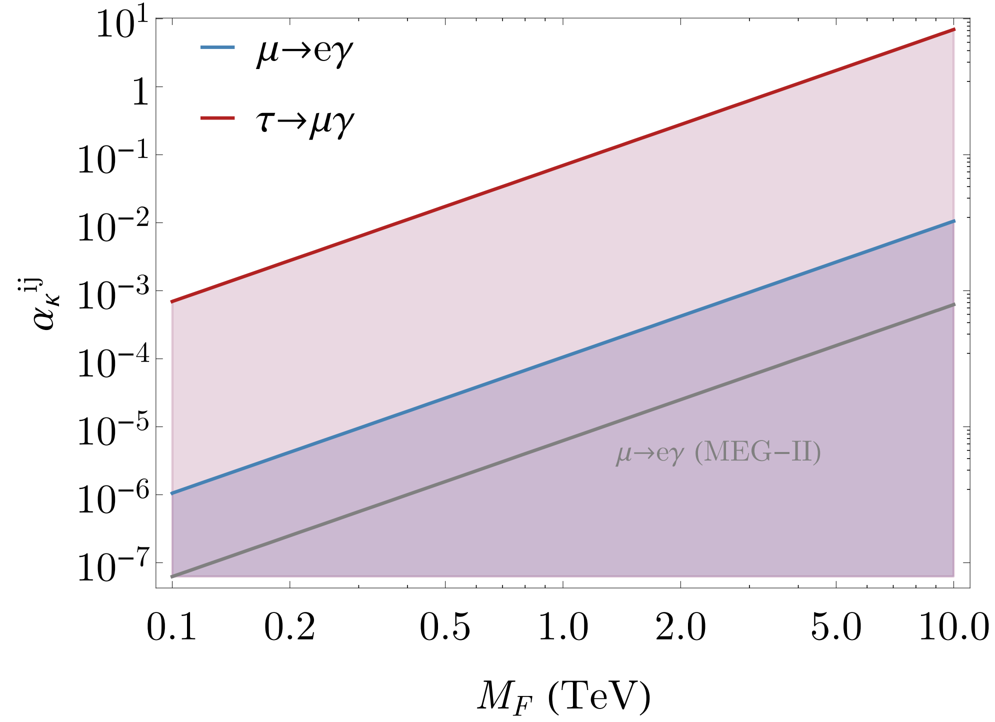
Drell-Yan process



$$Y,\, W \sim \left(\frac{M_W}{M_F}\right)^2 \left(\beta_{1,2}^{1\mathrm{L}} - \beta_{1,2}^{1\mathrm{L}\,\mathrm{SM}}\right)/\alpha_{1,2}$$

- lower bound on fermion mass M_F, 1 TeV is fine

Charged lepton flavour violation

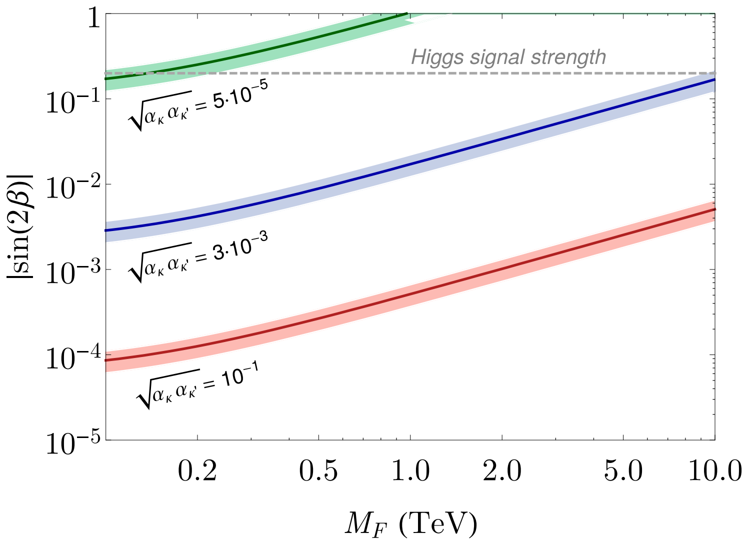


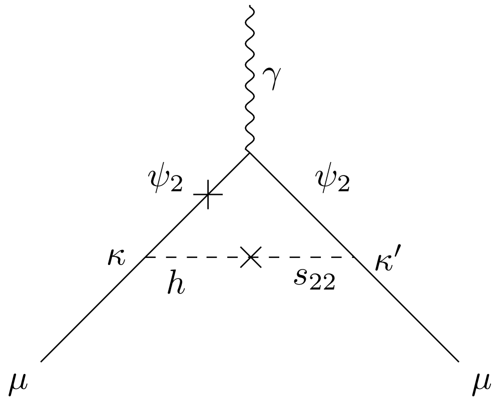
- upper bounds on off-diagonal elements

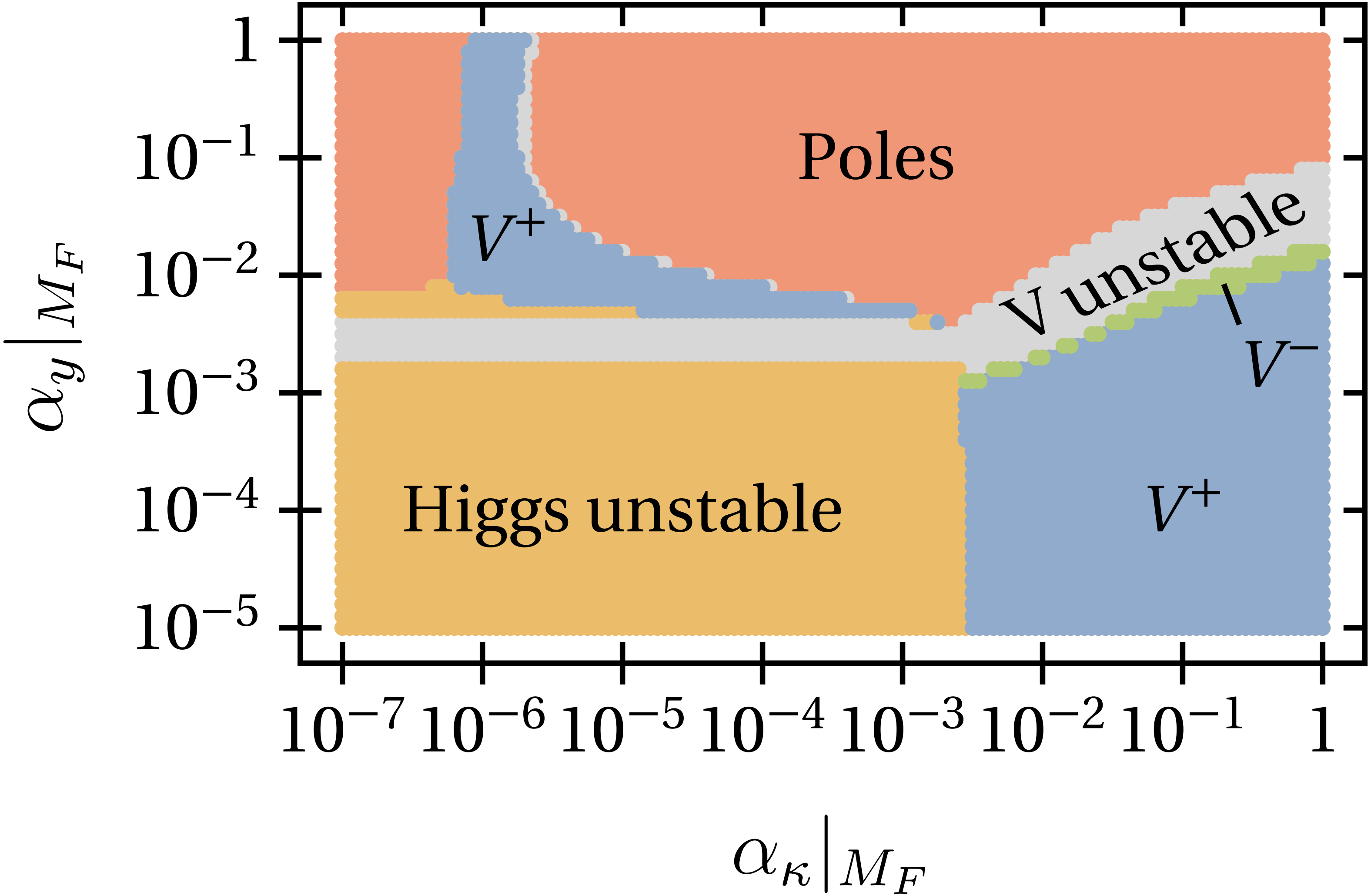
$$\alpha_\kappa^{ij} = (4\pi)^{-2} \sum_m \kappa_{mi}\kappa_{mj}$$

Anomalous magnetic moments

$$\delta a_l = -\frac{m_l}{2M_F}\sqrt{\alpha_\kappa \alpha_{\kappa'}}\,\sin 2\beta$$






Poles
V unstable
V^+
V^-
V^+
Higgs unstable
$\alpha_y\big|_{M_F}$
$\alpha_\kappa\big|_{M_F}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1