Asymptotic safety and flavour phenomenology in extensions of the Standard Model

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Motivation

- Asymptotic safety: high-energy behaviour of theory is controlled by UV fixed point
- model parameters, observables remain finite, theory is well defined
- provides powerful paradigm for model building
  - ➔ UV completion, no Landau poles
  - ➔ extends idea of asymptotic freedom
- potential to explain further shortcomings of the SM: $(g-2)_\mu$ ...

Asymptotic safety

- requires fixed point in RG running of all renormalised couplings $\alpha_i(\mu)$

$$\beta_i = \frac{\partial \alpha_i}{\partial \ln \mu} = 0$$

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

- requires N_F new fermions, $N_F \times N_F$ uncharged scalars, Yukawa interaction, $SU(N_C)$ gauge
- SM extensions have already been studied [Bond, Hiller, Kowalska, Litim, JHEP 2017] [Percacci et al., JHEP 2018] (SM + BSM fermions + scalar)

What is new here?

- SM extension that actually connects with the SM flavour symmetry
- mixing with SM fermions/ Higgs via new Yukawa interactions / portal couplings
- fix $N_F = 3$, BSM fermions colorless but with weak isospin, hypercharge
  - ➔ 6 different models

Asymptotic safety

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

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- mixing with SM fermions/ Higg … actions / portal couplings
- fix $N_F = 3$, BSM fermions colo … spin, hypercharge
  - ➔ 6 different models

Renormalisable BSM Interactions

- new Yukawa interactions

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

BSM Yukawa interaction

BSM-SM mixing, (different in each model)

only in model A+C

- extended scalar quartic sector

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

Higgs quartic

Higgs portal

BSM scalar self interactions

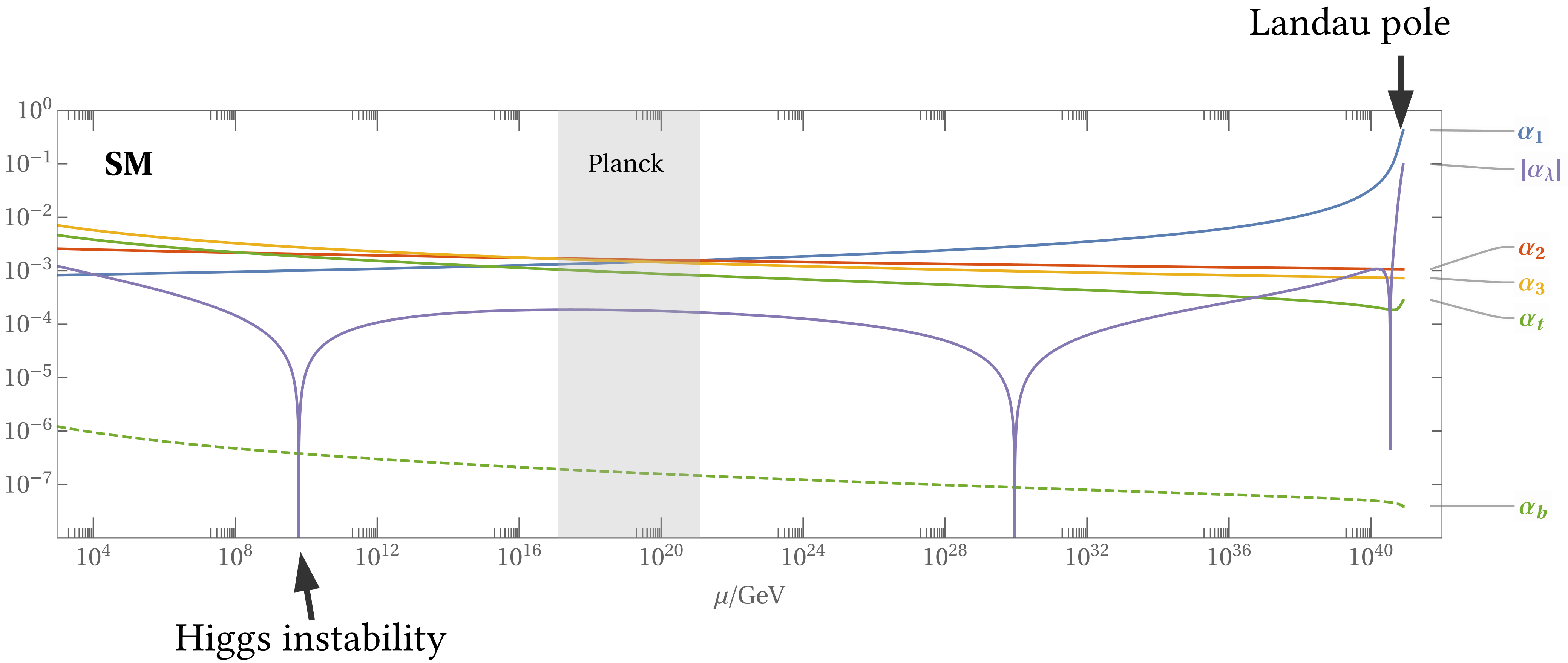
- terms with massive parameters not shown here
- BSM scalar may acquire VEV, scalar and fermion mixing
- RGEs can be computed in perturbation theory [Machacek, Vaughn, NPB 1983-85]

Bottom-Up approach

- matching to SM at BSM fermion mass scale $M_F = 1\,\mathrm{TeV}$
- investigate RG flow up to Planck scale M_{Pl}
  - ➔ more general approach of UV safety: free of instabilities, poles
  - ➔ quantum gravity will change the game

- convenient parametrisation: $\alpha_1 = g_1^2/(4\pi)^2$ $\alpha_y = y^2/(4\pi)^2$ $\alpha_\lambda = \lambda/(4\pi)^2$
- SM fixes $\alpha_{1,2,3,t,b,\lambda}$, need to find matching conditions for BSM Yukawas $\alpha_{y,\kappa,\kappa'}$ and quartics $\alpha_{\delta,u,v}$
- study BSM critical surface of matching conditions from which safe RG trajectories flow towards UV
- complete two-loop analysis – capture non-leading order effects

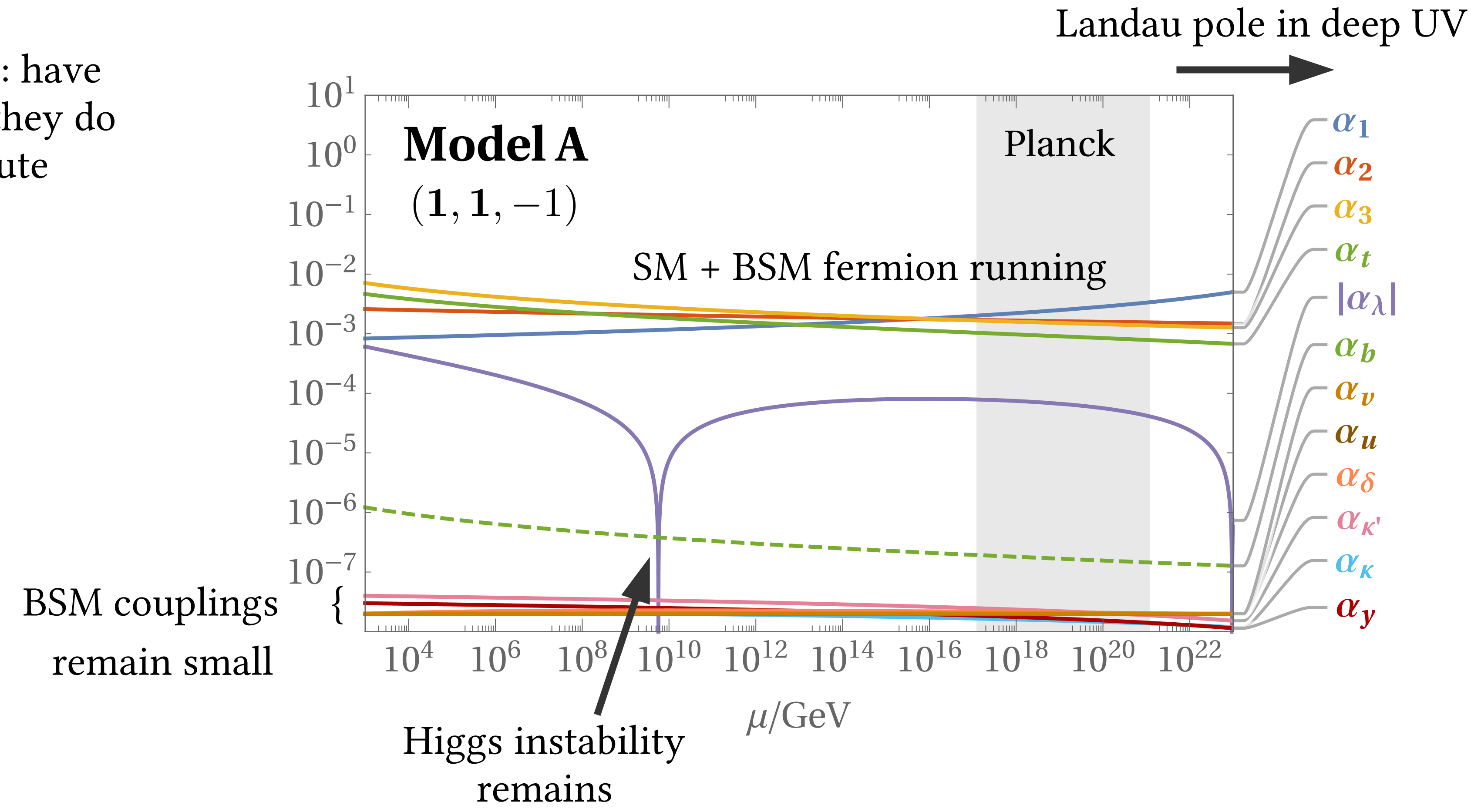
SM flow



Landau pole
SM
Planck
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^4
10^8
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}
10^{32}
10^{36}
10^{40}
μ/GeV
α_1
$|\alpha_\lambda|$
α_2
α_3
α_t
α_b
Higgs instability

Feeble BSM couplings: the good

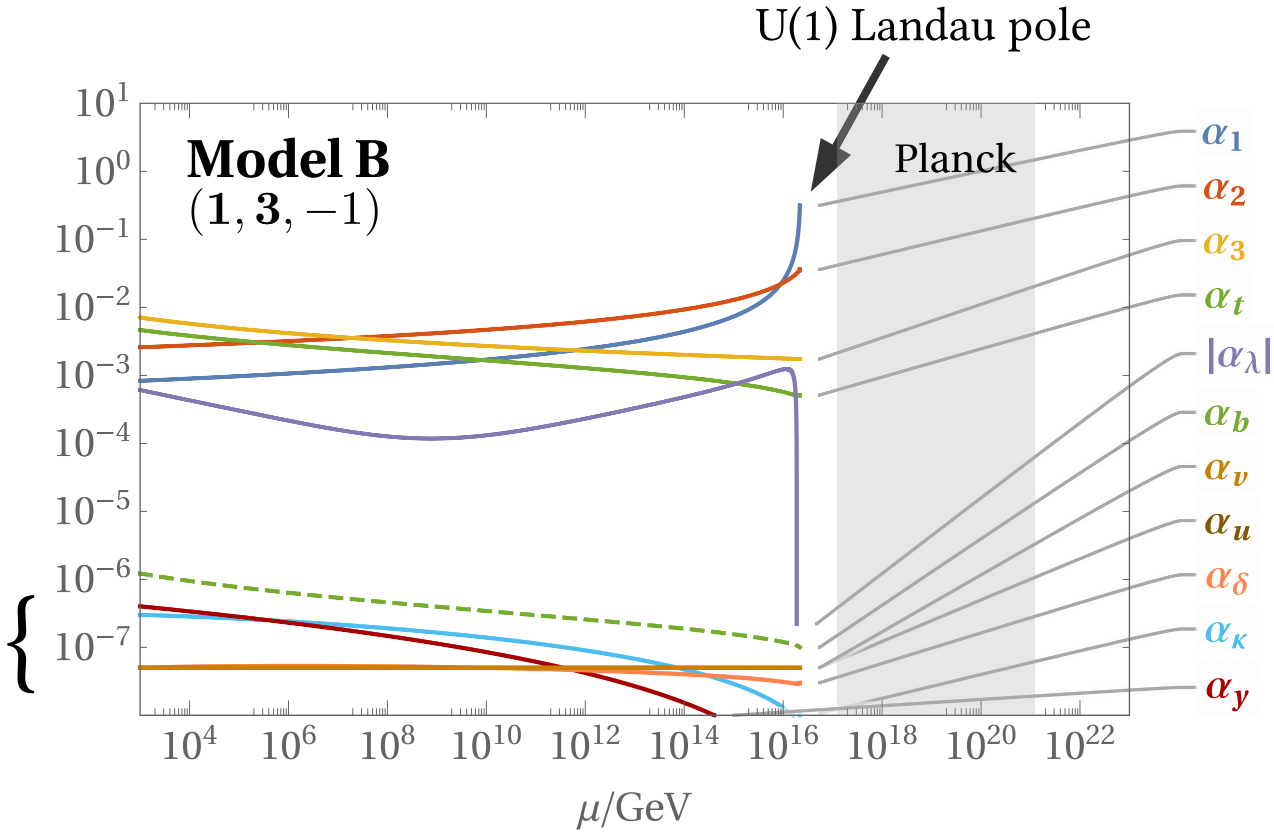
first approach: have BSM so small they do not contribute



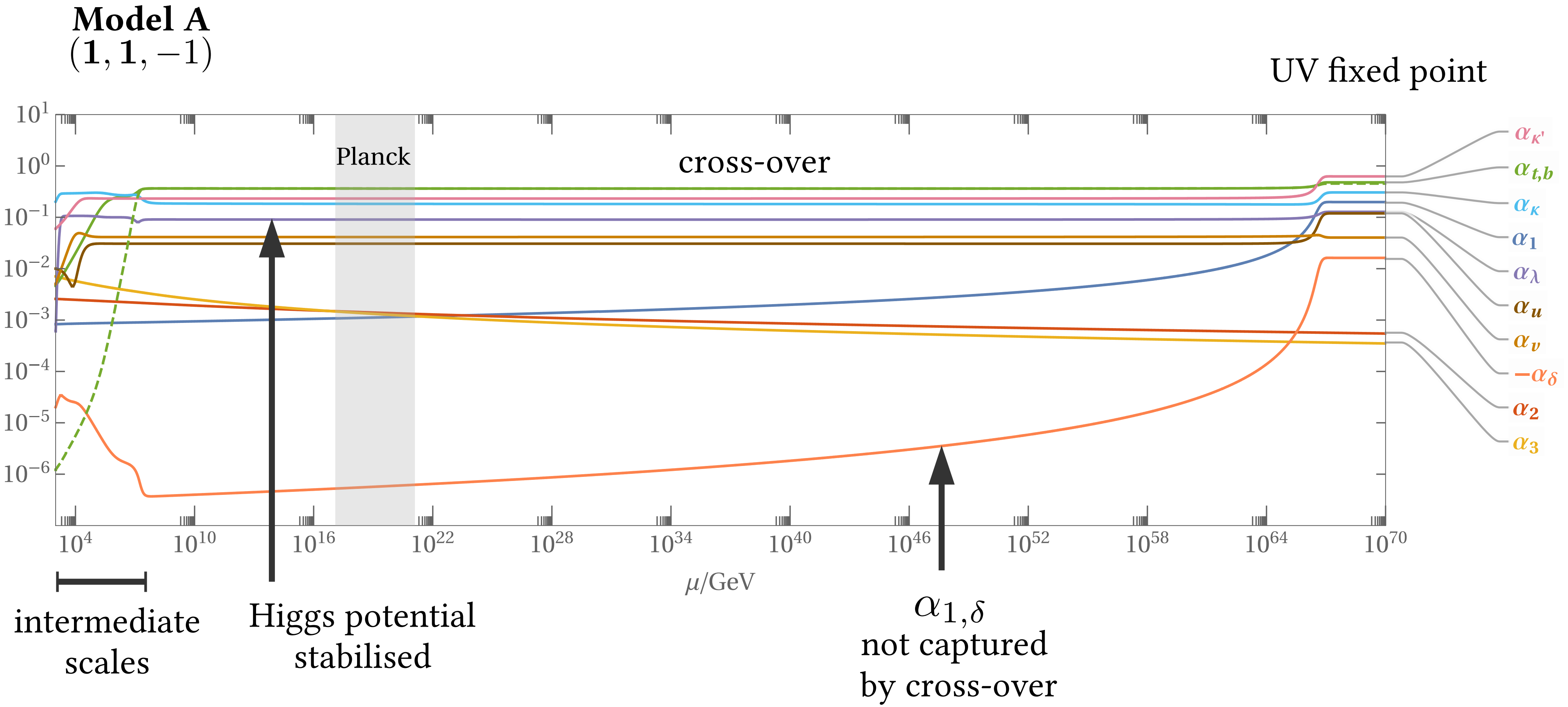
Feeble BSM couplings: the bad

larger BSM coupling are required!

BSM couplings remain small

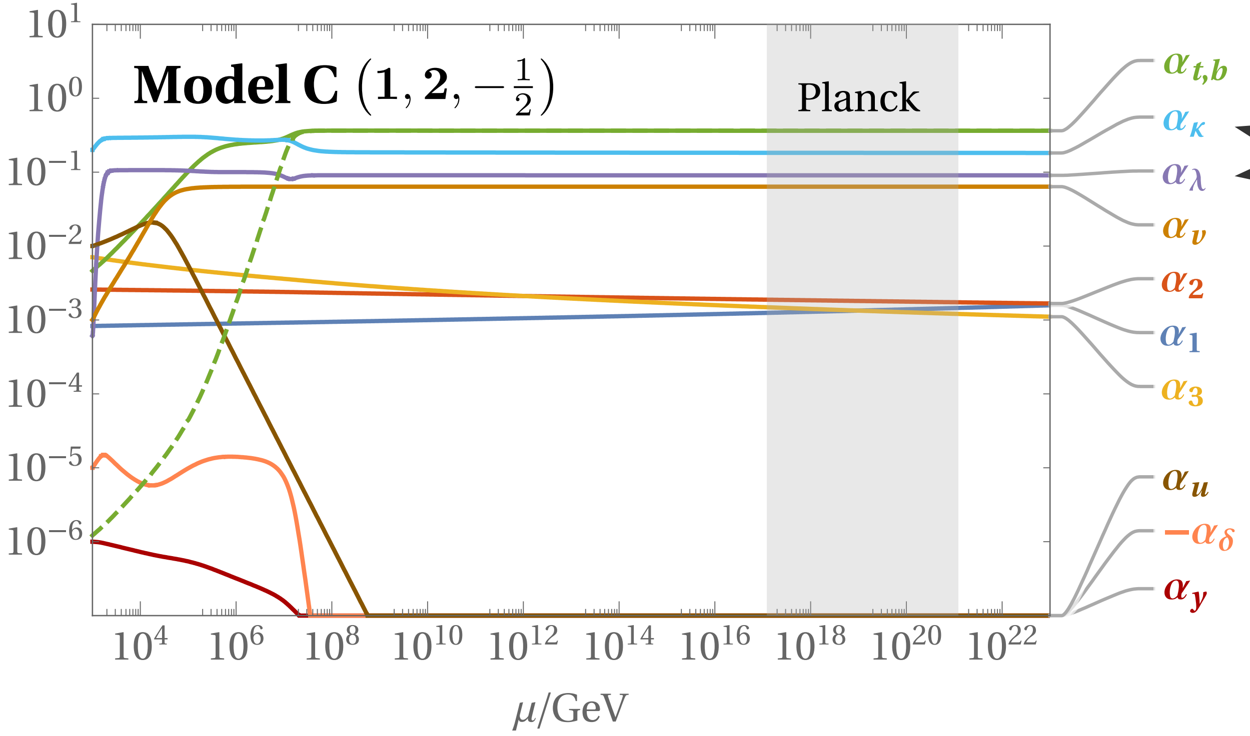


UV fixed points



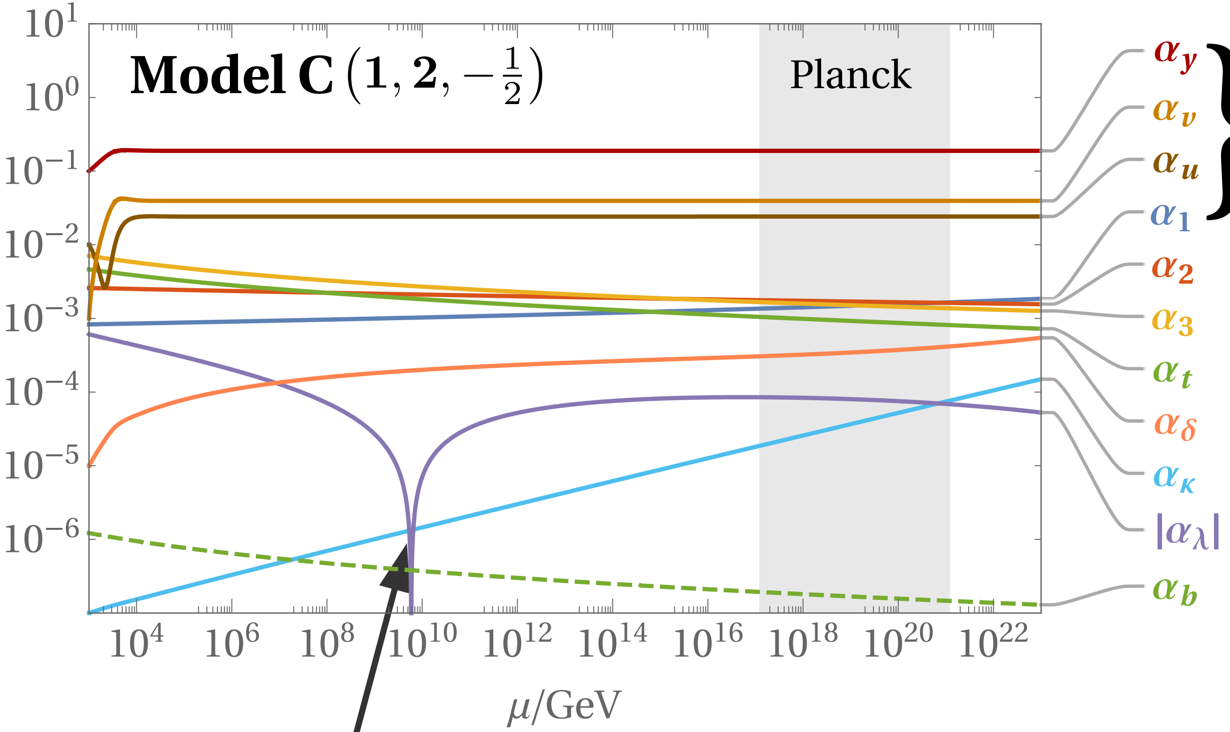
large Yukawas slow down running – different combinations promise more setups

Safety until Planck scale



BSM Yukawa stablilises
Higgs potential

Safety until Planck scale



BSM Yukawa stabilises BSM scalar sector

unstable Higgs potential

Conclusion about UV safety

- some models allow feebly coupled BSM sector
- weakly coupled BSM sector can
  - ➔ stabilise Higgs potential
  - ➔ push Landau poles past M_{Pl}
- BSM Yukawas play crucial role in these tasks

Can we get an experimental handle on BSM fermion and scalar masses $M_{F,S}$?

Are there any bounds from e.g. LHC data?

How can we identify these models in measurements?

Experimental handles

- 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 scalar mixing from Higgs signal strength measurement $|\beta| \lesssim 0.2$
  - ➔ favours heavy scalar [Patrignani et al., CPC 2016]
- charged lepton flavour violation constraints BSM Yukawa sector

- 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 $S \to \psi l,\ \psi\psi$
- Decays and fermion mixing provides insight into BSM charges, Yukawa sector

Application: Anomalous magnetic moments

- measured deviation from SM for muon and electron magnetic moments

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 268(63)(43)\cdot 10^{-11}$$
$$\Rightarrow \ +3.5\,\sigma$$

[Tanabashi et al., PRD 2018]

$$a_e^{\rm exp} - a_e^{\rm SM} = -88(28)(23)\cdot 10^{-14}$$
$$\Rightarrow \ -2.3\,\sigma$$

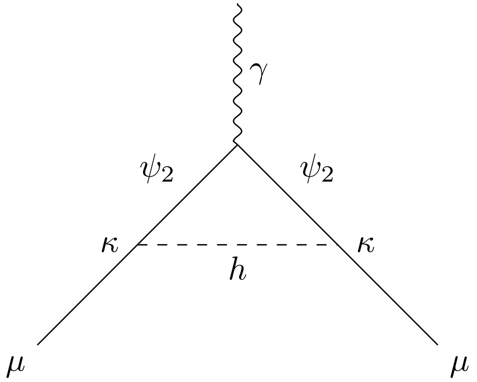
[Hanneke, Fogwell, Gabrielse, PRL 2008]
[Parker et al., Science 2018]

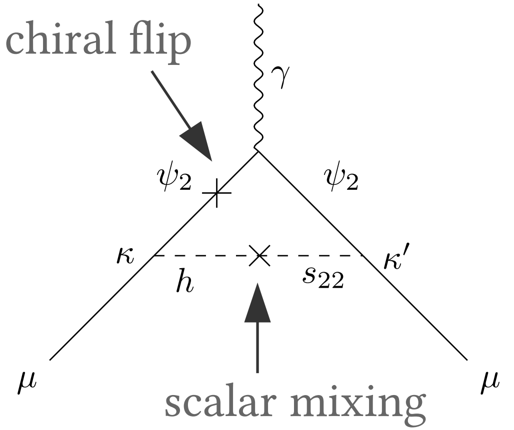
- electron and muon discrepancies have different sign

Can we account for this in our models?

Application: Anomalous magnetic moments

- two new contributions





- different level of supression

$$\delta a_l \sim \alpha_\kappa \, \frac{m_l^2}{M_F^2}$$

can account for muon anomaly with little impact on electron one

$$M_F = 1\,\mathrm{TeV} : \; \alpha_\kappa \sim \mathcal{O}(1)$$

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

can target single generation (BSM vacuum structure)

sign is tunable ⟶ can contribute to either (g-2)

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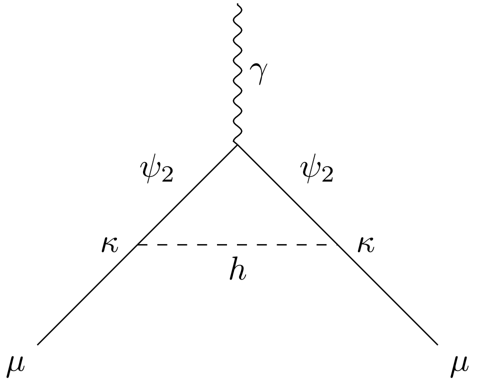

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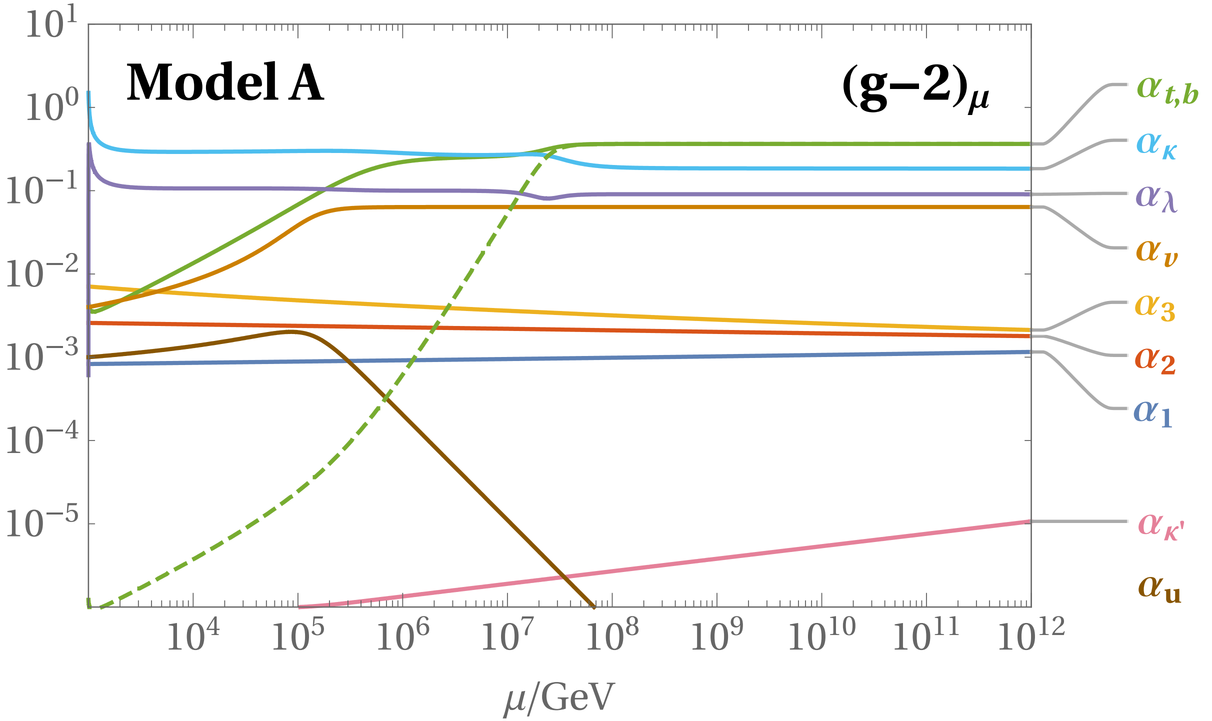

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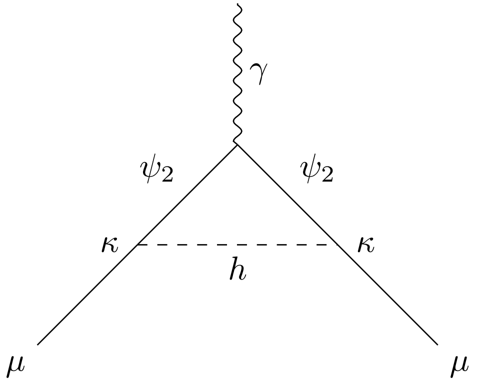

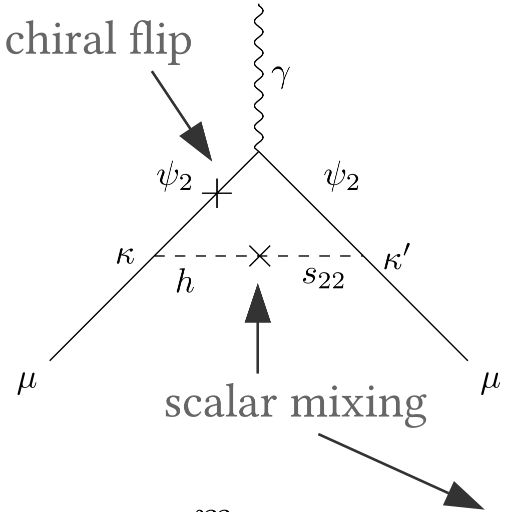

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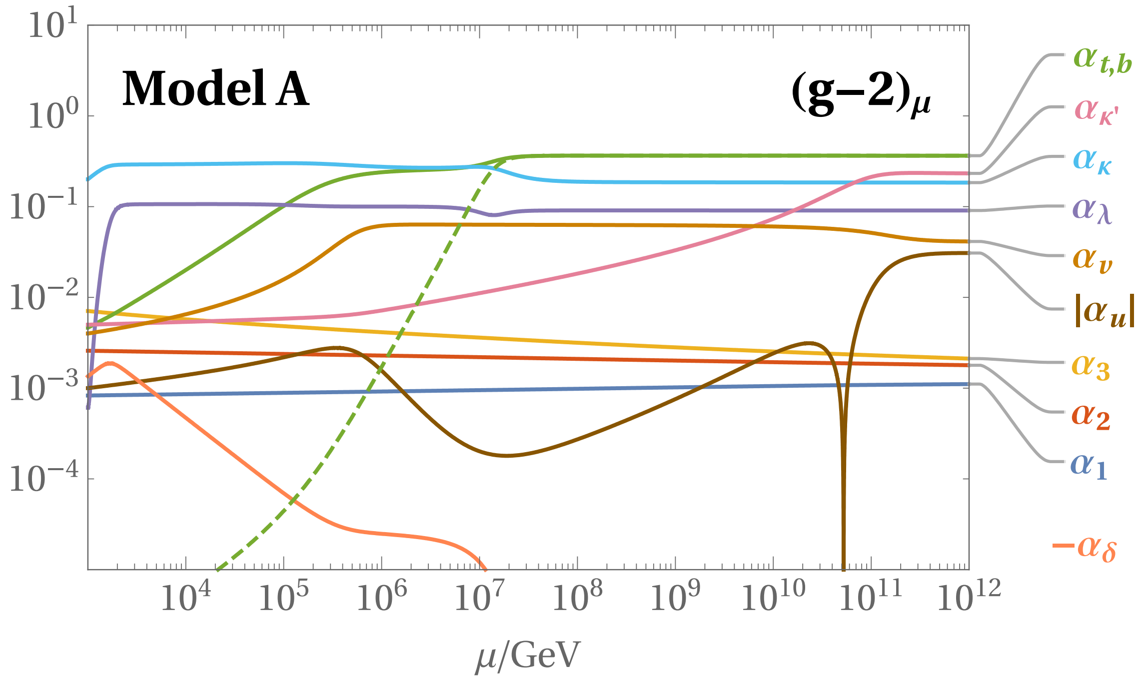

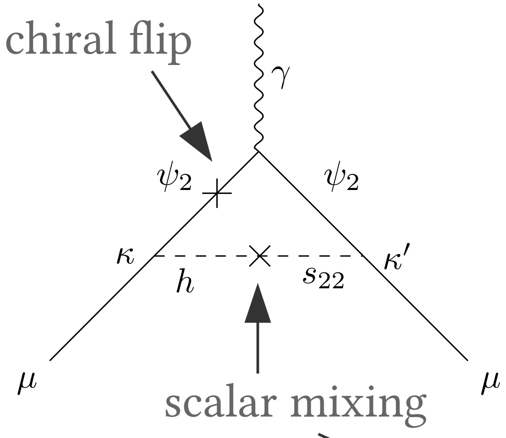

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Conclusion

- explored new set of BSM models, safe until the Planck scale
- discussed some phenomenology
- can stabilise Higgs and BSM scalar sector
- can explain $(g\text{-}2)_{\mu,e}$

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	$(\mathbf{1},\, \mathbf{1},\, -1)$
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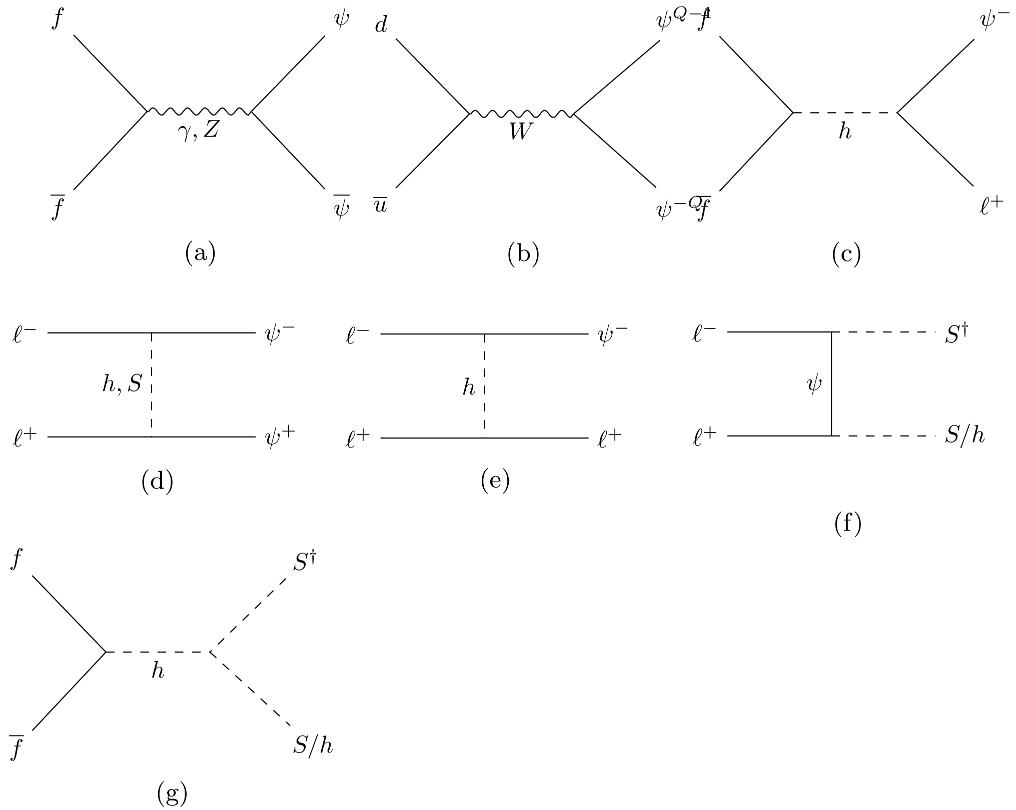
E	$(\mathbf{1},\, \mathbf{1},\, 0)$
F	$(\mathbf{1},\, \mathbf{3},\, 0)$

- 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

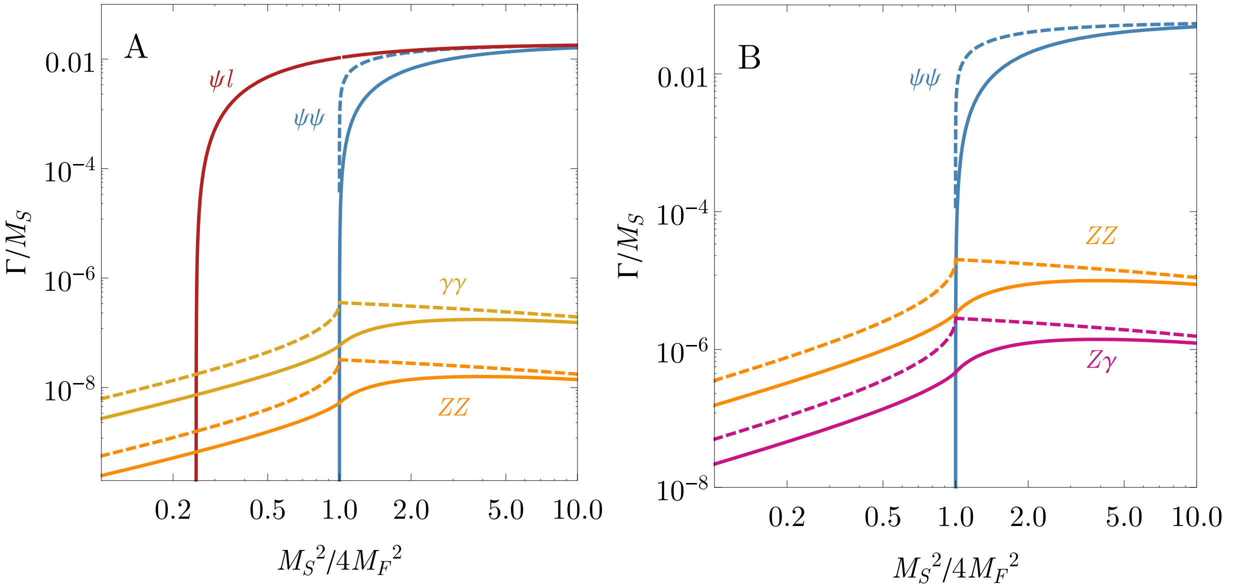
- BSM scalar decays via $y,\ \kappa'$

  or into gauge bosons (ψ-triangle)

- fermion mixing gives additional decays

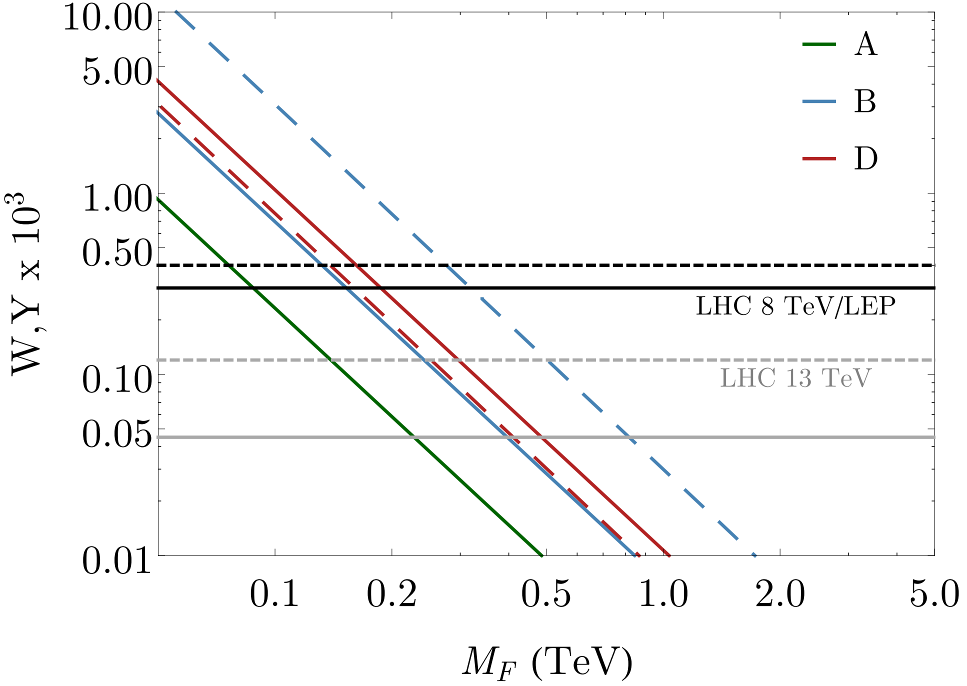
  $S \to ll$

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



Constraints

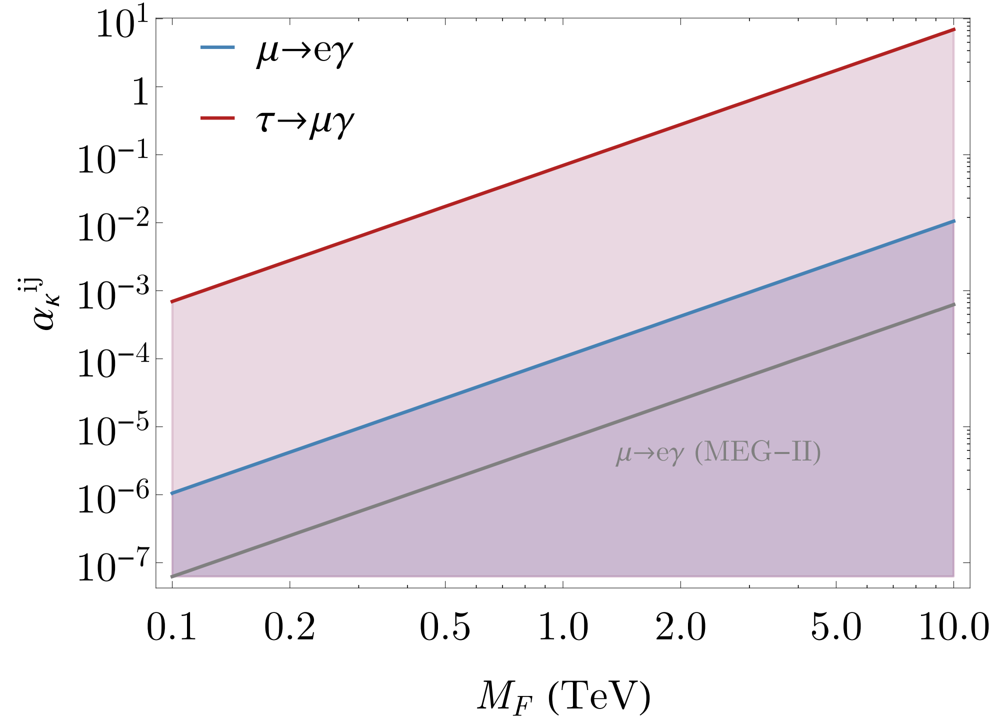
Drell-Yan process



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

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

Charged lepton flavour violation

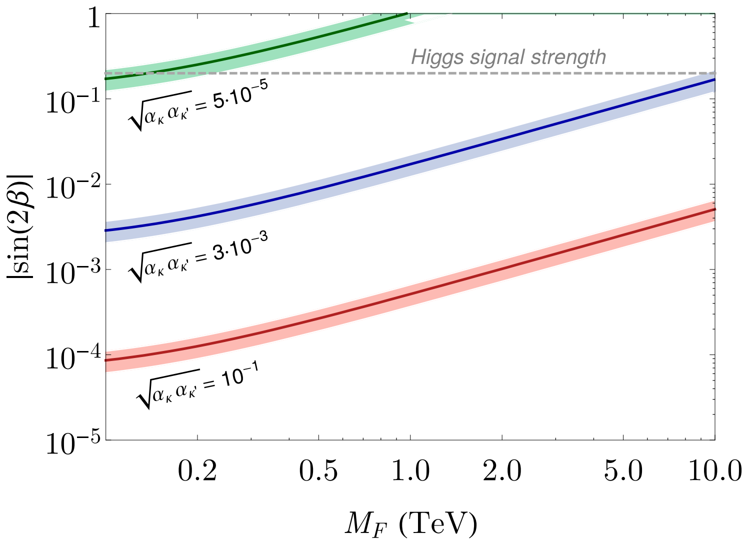


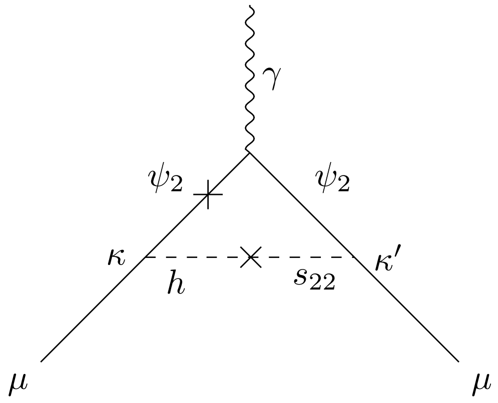
- upper bounds on off-diagonal elements

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

Anomalous magnetic moments

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





Where does the stability come from?

- separation of scalar sectors, two RG subsystems with supressed cross talk as long as

$$\alpha_{1,2,e,y,\delta} \approx 0$$

$$\begin{array}{c|c} H,\, \psi_L,\, L,\, Q,\, U,\, D & S,\, \psi_R,\, E \\ \kappa,\, \lambda & \kappa',\, u,\, v \end{array}$$

- both Higgs quartic and BSM scalar sector stabilised by Yukawas
- requires large values of $\alpha_\kappa \simeq 0.2$ or higher