technische universität
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Stabilizing the SM with Vector-like Fermions

soon on arxiv

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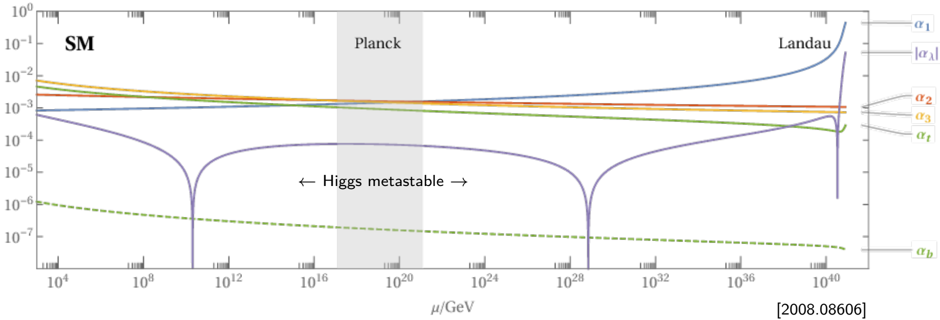
Motivation

Standard Model RG Flow (3-loop)

gauge: $\alpha_i = \frac{g_i^2}{16\pi^2}$, Yukawas: $\alpha_{t,b} = \frac{y_{t,b}^2}{16\pi^2}$, quartics: $\alpha_\lambda = \frac{\lambda}{16\pi^2}$



[2008.08606]

- Higgs potential metastable ($\alpha_\lambda < 0$) at 10^{10} - 10^{29} GeV [1307.3536]
- Hypercharge Landau pole at 10^{41} GeV

Planck Safety

'Well-behaved' RG Running of couplings up to $M_{\mathrm{Pl}} \sim 10^{19}$ GeV without

- Landau poles
- Vacuum instabilities (Higgs)

  $\Rightarrow$Soft PS: scalar potential stable at $M_{\mathrm{Pl.}}$:

  $$\lambda(M_{\mathrm{Pl.}}) > 0$$

  $\Rightarrow$Strict PS: scalar potential stable up to $M_{\mathrm{Pl.}}$:

  $$\lambda(\mu) > 0,\ \forall\mu \in [\mu_0,\ M_{\mathrm{Pl.}}]$$

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$\Rightarrow$Constraints on model parameters *independent* from experimental data

very promising concept for BSM model building!

[1702.0172, 1910.14062, 2008.08606, 2011.12964, 2109.06201]

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How to make the SM Planck-safe in a minimally invasive way?

Setup

Model

- Extend SM with vector-like fermions ψ
  $\Rightarrow$Avoids gauge anomalies
  $\Rightarrow$Explicit Dirac mass term

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  $\Rightarrow$Avoids gauge anomalies
  $\Rightarrow$Explicit Dirac mass term
- Free parameters
  $\Rightarrow$Representation (Y_F, d_2, d_3) under $U(1)_Y \times SU(2)_L \times SU(3)_C$
  $\Rightarrow$Multiplicity N_F
  $\Rightarrow$Mass $M_F \gtrsim 1$ TeV
  $\Rightarrow$some rep.: Yukawa portal coupling κ to SM fields

Gauge Portal

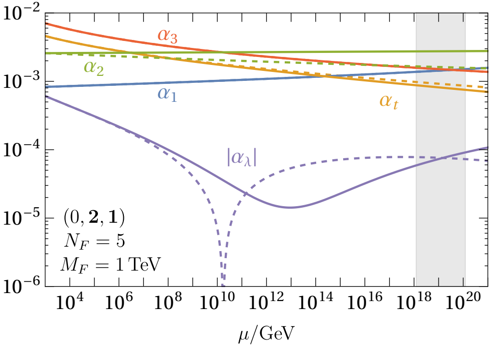
Effects

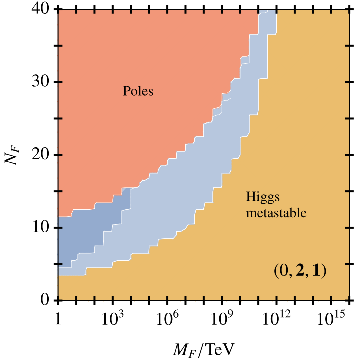
Focus on representations without Yukawa portal to SM

- VLFs generically enhance running of gauge couplings
  ⇒Landau poles for high representations or large N_F
  ⇒Upper limit $N_F < N_F^{\text{pole}}$ for fixed (Y_F, d_2, d_3) and M_F
- Stabilization of Higgs potential possible
  ⇒Requires minimal $N_F > N_F^{\text{min}}$ depending on rep.
  ⇒Possible Planck safety window $N_F^{\text{min}} < N_F < N_F^{\text{pole}}$ for fixed M_F!

Electroweak Portal

'Pure VLLs': (0, **2**, **1**)

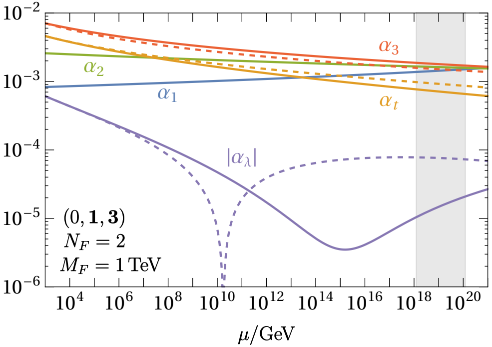


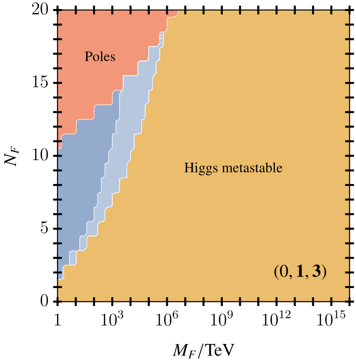


Electroweak portal (2-loop): $\alpha_{1,2}(\mu) \uparrow \Rightarrow \ \alpha_\lambda(\mu) \uparrow$

Strong Portal

'Pure VLQs': (0, **1**, **3**)





Strong portal (3-loop): $\alpha_3(\mu) \uparrow \Rightarrow \alpha_t(\mu) \downarrow \Rightarrow \alpha_\lambda(\mu) \uparrow$

Yukawa Portal

Models ($N_F = 1$)

Model	(Y_F, d_2, d_3)	$-\mathcal{L}^Y_{\text{portal}}$	RG fate for $\kappa = 0$, $M_F = 1\,\text{TeV}$
A	$(-1, \mathbf{1}, \mathbf{1})$	$\kappa_i\,\overline{L}_i H \psi_R$	Higgs metastable
B	$(-1, \mathbf{3}, \mathbf{1})$	$\kappa_i\,\overline{L}_i \psi_R H$	strict Planck safety
C	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$	$\kappa_i\,\overline{\psi}_L H E_i$	Higgs metastable
D	$(-\frac{3}{2}, \mathbf{2}, \mathbf{1})$	$\kappa_i\,\overline{\psi}_L H^c E_i$	soft Planck safety
E	$(\ 0,\ \mathbf{1}, \mathbf{1})$	$\kappa_i\,\overline{L}_i H^c \psi_R$	Higgs metastable
F	$(\ 0,\ \mathbf{3}, \mathbf{1})$	$\kappa_i\,\overline{L}_i \psi_R H^c$	soft Planck safety
G	$(-\frac{1}{3}, \mathbf{1}, \mathbf{3})$	$\kappa_i\,\overline{Q}_i H \psi_R$	Higgs metastable
H	$(+\frac{2}{3}, \mathbf{1}, \mathbf{3})$	$\kappa_i\,\overline{Q}_i H^c \psi_R$	Higgs metastable
I	$(-\frac{1}{3}, \mathbf{3}, \mathbf{3})$	$\kappa_i\,\overline{Q}_i \psi_R H$	α_2-pole at 10^{16} GeV
J	$(+\frac{2}{3}, \mathbf{3}, \mathbf{3})$	$\kappa_i\,\overline{Q}_i \psi_R H^c$	α_2-pole at 10^{16} GeV
K	$(+\frac{1}{6}, \mathbf{2}, \mathbf{3})$	$\kappa_i^{(u)}\,\overline{\psi}_L H^c U_i + \kappa_i^{(d)}\,\overline{\psi}_L H D_i$	strict Planck safety
L	$(+\frac{7}{6}, \mathbf{2}, \mathbf{3})$	$\kappa_i\,\overline{\psi}_L H U_3$	α_1-pole at 10^{17} GeV
M	$(-\frac{5}{6}, \mathbf{2}, \mathbf{3})$	$\kappa_i\,\overline{\psi}_L H^c D_3$	strict Planck safety

Yukawa portals κ generically tame growth of gauge couplings
BUT: tend to destabilize the Higgs

Models ($N_F = 1$)

Model	(Y_F, d_2, d_3)	$-\mathcal{L}^Y_{\text{portal}}$	RG fate for $\kappa_i = 0$, $M_F = 1$ TeV
A	$(-1, \mathbf{1}, \mathbf{1})$	$\kappa_i \overline{L}_i H \psi_R$	Higgs metastable
B	$(-1, \mathbf{3}, \mathbf{1})$	$\kappa_i \overline{L}_i \psi_R H$	strict Planck safety
C	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$	$\kappa_i \overline{\psi}_L H E_i$	Higgs metastable
D	$(-\frac{3}{2}, \mathbf{2}, \mathbf{1})$	$\kappa_i \overline{\psi}_L H^c E_i$	soft Planck safety
E	$(0, \mathbf{1}, \mathbf{1})$	$\kappa_i \overline{L}_i H^c \psi_R$	Higgs metastable
F	$(0, \mathbf{3}, \mathbf{1})$	$\kappa_i \overline{L}_i \psi_R H^c$	soft Planck safety
G	$(-\frac{1}{3}, \mathbf{1}, \mathbf{3})$	$\kappa_i \overline{Q}_i H \psi_R$	Higgs metastable
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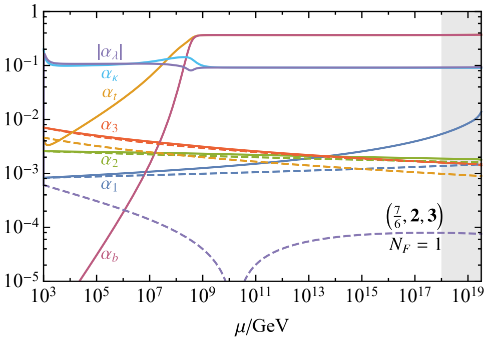
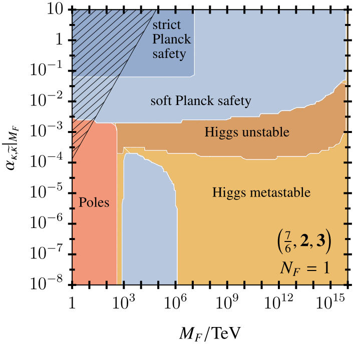
Some models: Planck safety window for feeble $\alpha_\kappa(\mu_0) \simeq 0$
$\Rightarrow$Gauge portal mechanisms (constructive interference)

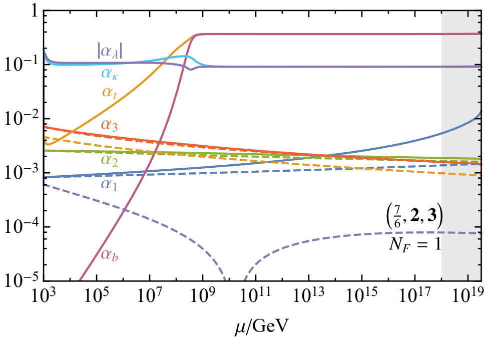
Yukawa Portal

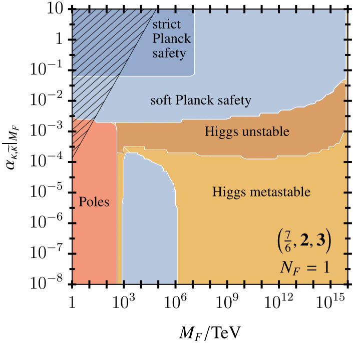




- All models: strict PS window for large $\alpha_\kappa(\mu_0) \gtrsim \mathcal{O}(0.1)$
  $\Rightarrow$Strongly coupled walking regimes
- Phenomenological constraints from fermionic mixing α_κ / M_F^2

Yukawa Portal





- universal κ_i: Strong FCNC constraints on $\alpha_\kappa^{(2)}/M_F^2$

$\Rightarrow$Here: 1-loop D-mixing from $\mathcal{L}_{\text{eff}} = -\frac{(\kappa_i \kappa_j^*)^2}{128\pi^2 M_F^2}\left(\bar{U}_i \gamma_\mu U_j\right)\left(\bar{U}_j \gamma^\mu U_i\right)$

$\Rightarrow$Lower mass bounds for strict PS $M_F \gtrsim 500$ TeV

Conclusion

Conclusion

- Extending the SM with VLFs can stabilize the Higgs
  ⇒Possible for VLQs and VLLs, with and without Yukawa portals
- Without Yukawa portals
  ⇒Strong and weak gauge portal mechanisms
  ⇒Upper limits on Y_F, d_2, d_3, N_F due to Landau poles
- With Yukawa portals
  ⇒Stabilization possible for **all** suitable representations
  ⇒Large $\alpha_\kappa(M_F)$ induces strongly coupled walking regime
  ⇒Strong FCNC constraints for universal κ_i
  ⇒Combined lower mass bounds of up to few 100 TeV

BACKUP

Gauge Portal mechanisms

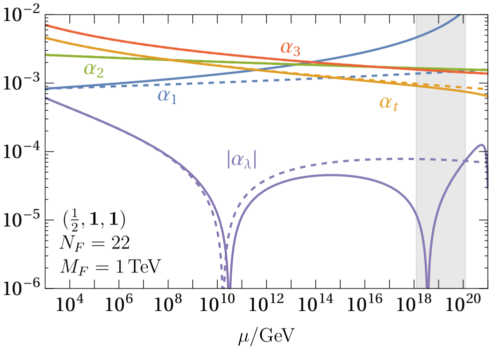
Derive gauge portal mechanism: leading-loop, leading-log, linear in δB_i

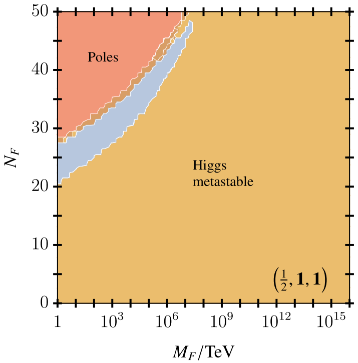
- Running of gauge couplings: $\beta_i^{\text{1-loop}} = -B_i\alpha_i^2, \quad B_i = B_i^{\text{SM}} - \delta B_i$
  $\Rightarrow$VLFs: $\delta B_1 = \frac{8}{3}N_F d_2 d_3 Y_F^2 \geq 0, \quad \delta B_{2,3} = \frac{8}{3}N_F d_{3,2} S_2(d_{2,3}) \geq 0$
  $\Rightarrow$Presence of VLFs generically enhances running $\alpha_i(\mu)$
- Induced decrease in running of $\alpha_t(\mu)$ from $\beta_t^{\text{1-loop}}$
  $\Rightarrow\alpha_t(\Lambda) - \alpha_t^{\text{SM}}(\Lambda) \approx -\alpha_t(\mu_0)\Delta_t(\mu_0)\,\ln^2\left(\frac{\Lambda}{\mu_0}\right),$
  $\Delta_t = \frac{17}{12}\delta B_1\,\alpha_1^2 + \frac{9}{4}\delta B_2\,\alpha_2^2 + 8\,\delta B_3\,\alpha_3^2 > 0$
- Increase in running of $\alpha_\lambda(\mu)$ from $\beta_\lambda^{\text{1-loop}}$

$$\begin{aligned}\Rightarrow\alpha_\lambda(\Lambda) - \alpha_\lambda^{\text{SM}}(\Lambda) \approx &+ \tfrac{3}{8}\alpha_1^2(\mu_0)\left[\alpha_1(\mu_0) + \alpha_2(\mu_0)\right]\delta B_1\,\ln^2(\Lambda/\mu_0)\\ &+ \tfrac{3}{8}\alpha_2^2(\mu_0)\left[\alpha_1(\mu_0) + 3\alpha_2(\mu_0)\right]\delta B_2\,\ln^2(\Lambda/\mu_0)\\ &+ 32\,\alpha_t^2(\mu_0)\,\alpha_3^2(\mu_0)\,\delta B_3\,\ln^3(\Lambda/\mu_0)\end{aligned}$$

Hypercharge Portal

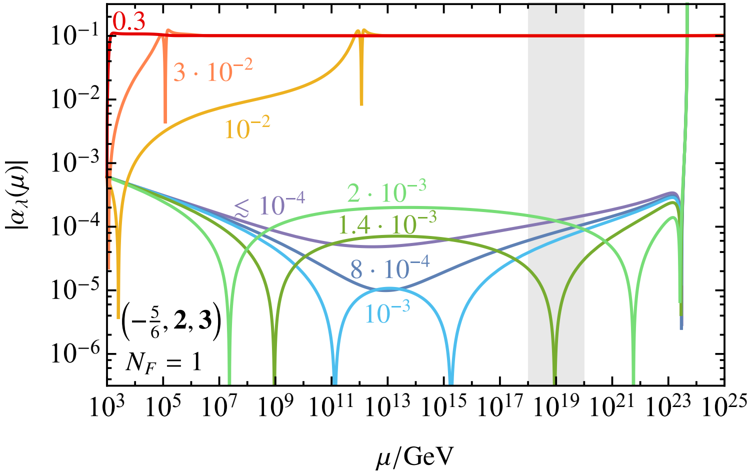
'Pure Hypercharge VLLs': $(\frac{1}{2}, \mathbf{1}, \mathbf{1})$



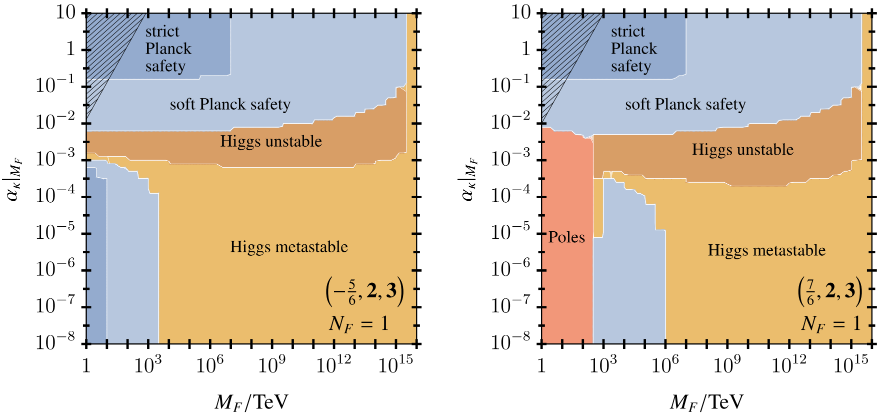


Hypercharge portal (2-loop): $\alpha_1(\mu) \uparrow \Rightarrow \ \alpha_\lambda(\mu) \uparrow$

Planck Safety Windows



BSM Crititcal Surface 3rd gen. Yukawa Portal



Mass bounds

Lower VLF mass bounds in the flavor universal benchmark

Model	(Y_F, d_2, d_3)	soft PS	strict PS
A	$(-1, \mathbf{1}, \mathbf{1})$	170 TeV	870 TeV
C	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$	170 TeV	870 TeV
D	$(-\frac{3}{2}, \mathbf{2}, \mathbf{1})$	-	870 TeV
G	$(-\frac{1}{3}, \mathbf{1}, \mathbf{3})$	56 TeV	420 TeV
H	$(+\frac{2}{3}, \mathbf{1}, \mathbf{3})$	13 TeV	420 TeV
I	$(-\frac{1}{3}, \mathbf{3}, \mathbf{3})$	29 TeV	29 TeV
J	$(+\frac{2}{3}, \mathbf{3}, \mathbf{3})$	30 TeV	30 TeV
L	$(+\frac{7}{6}, \mathbf{2}, \mathbf{3})$	19 TeV	480 TeV