Vacuum Stability as a Guide for Model Building

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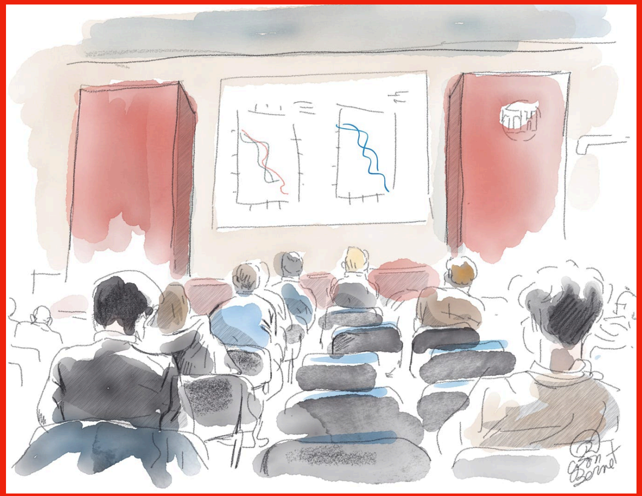
based on 2207.07737 [PRD 106 (2022)115004)]



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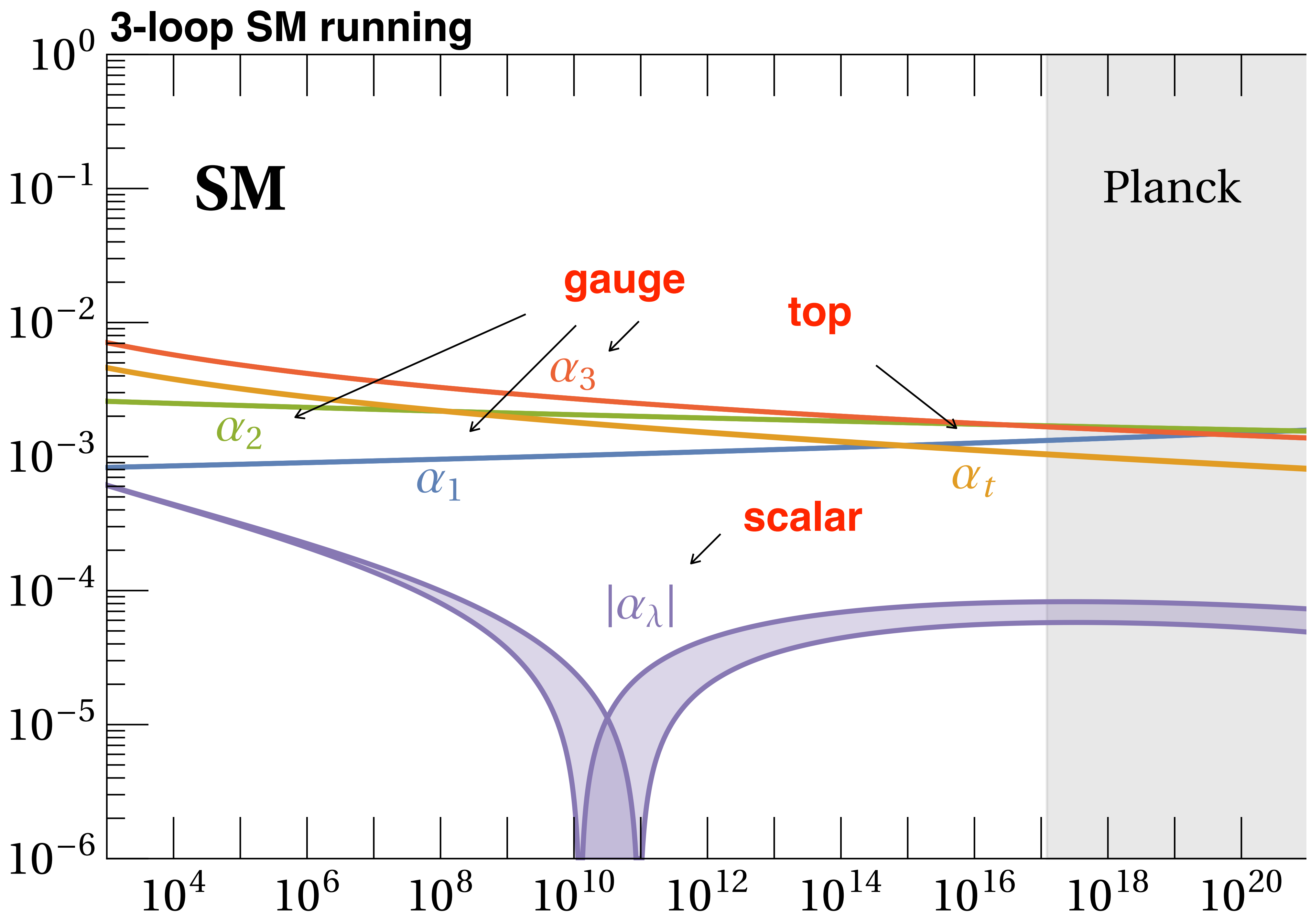
Vacuum Stability

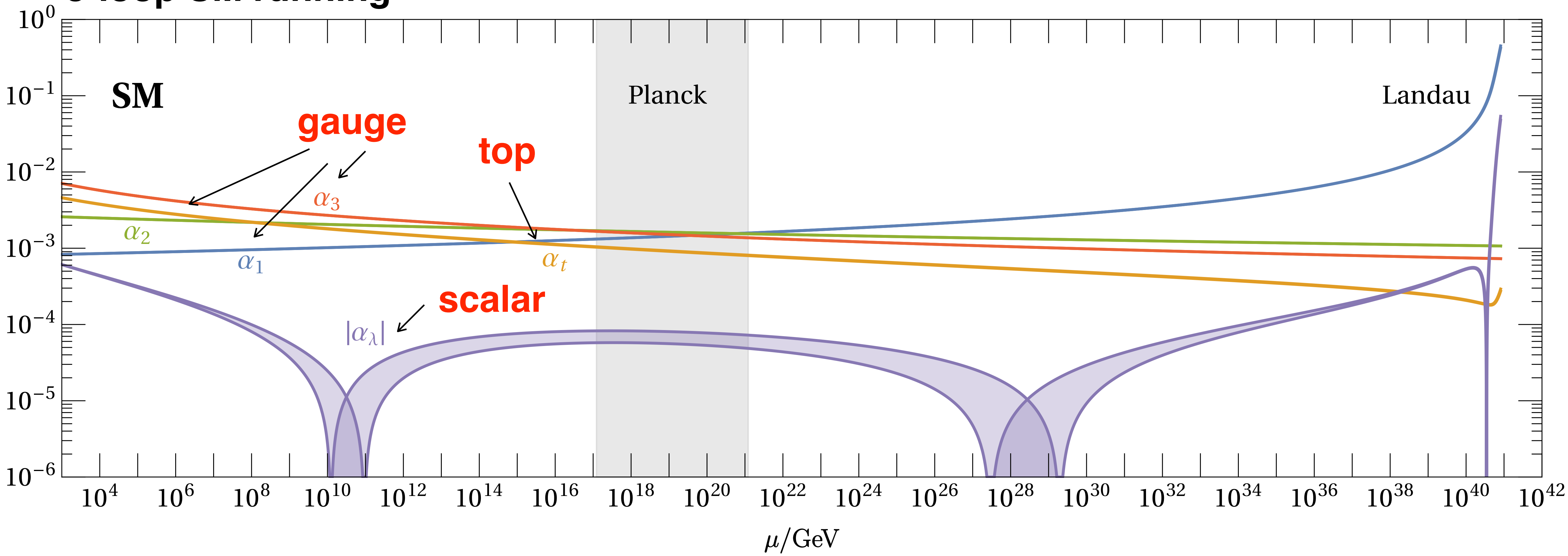


$$\alpha_\lambda = \frac{\lambda}{(4\pi)^2}$$ ⟵ **Higgs quartic**

Uncertainty bands:
1-sigma top pole mass
$m_t = 172.76 \pm 0.30\ \text{GeV}$

Vacuum Stability

3-loop SM running



Higgs quartic

$$\alpha_\lambda = \frac{\lambda}{(4\pi)^2}$$

Bottom-Up

Q: What does it take to

achieve vacuum stability?

… and make it safely up to the Planck scale?

Portals into Stability

Gauge Portals

Portals into Stability

Gauge Portals

$$\mathcal{L} \supset \bar{\psi} i \not{D} \psi$$

Vectorlike Fermions (VLFs)

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

charges (Y_F, d_2, d_3)

mass M_F

multiplicity N_F

$\longrightarrow$ modified RG running

``minimally invasive''

Portals into Stability

Gauge Portals

$$\mathcal{L} \supset \bar{\psi} i \not{D} \psi$$

Yukawa Portals

$$\mathcal{L} \supset -\kappa\, \bar{\psi}\, H\, f_{\rm SM}$$

- κ: Yukawa
- $\bar{\psi}$: VLFs
- H: Higgs
- $f_{\rm SM}$: SM fermion

⟶ new interactions

⟶ new RG beta functions
modified RG running

Portals into Stability

Gauge Portals

$$\mathcal{L} \supset \bar{\psi} i \not{D} \psi$$

Yukawa Portals

$$\mathcal{L} \supset -\kappa \, \bar{\psi} \, H \, f_{\mathrm{SM}}$$

Higgs Portals (and more)

...

How do they work?

Study RG running of couplings

Matching: $$\alpha^{\mathrm{BSM}}_{1,2,3,t,b,\lambda}(\mu_0) = \alpha^{\mathrm{SM}}_{1,2,3,t,b,\lambda}(\mu_0)$$

scale of new physics

Tools: **ARGES**
RGBeta
Pyr@te

Here: complete 2-loop

Gauge Portals

1-loop running

$$\beta_i \approx -B_i\,\alpha_i^2$$

SM | BSM

$$B_1 = -\frac{41}{3} - \delta B_1\,,$$
$$B_2 = \frac{19}{3} - \delta B_2\,,$$
$$B_3 = 14 - \delta B_3\,,$$

$$\delta B_1 = \tfrac{8}{3} N_F\, d_2\, d_3\, Y_F^2$$
$$\delta B_{2,3} = \tfrac{8}{3} N_F\, d_{3,2}\, S_2(d_{2,3})$$

Three key effects

gauge $\longrightarrow$ $$\alpha_i(\Lambda) - \alpha_i^{\rm SM}(\Lambda) \geq 0$$

top $\longrightarrow$ $$\alpha_t(\Lambda) - \alpha_t^{\rm SM}(\Lambda) < 0$$

Higgs $\longrightarrow$ $$\alpha_\lambda(\Lambda) - \alpha_\lambda^{\rm SM}(\Lambda) > 0$$

$\Lambda > \mu_0$

Why?

Hypercharge

Weak

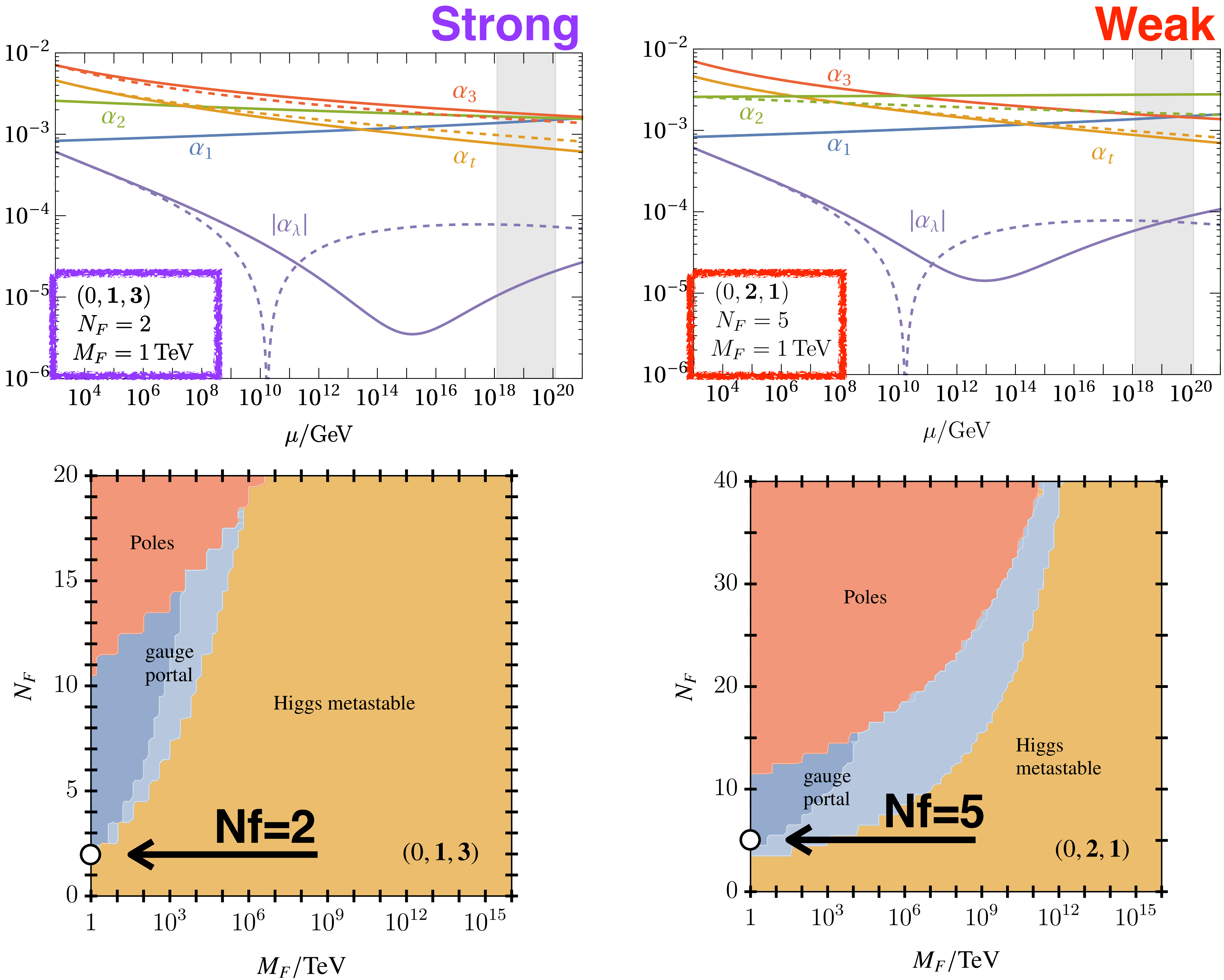
Strong

$$\alpha_\lambda(\Lambda) - \alpha_\lambda^{\rm SM}(\Lambda) \approx +\tfrac{3}{8}\alpha_1^2(\mu_0)\left[\alpha_1(\mu_0) + \alpha_2(\mu_0)\right]\boxed{\delta B_1}\ln^2\left(\frac{\Lambda}{\mu_0}\right)$$

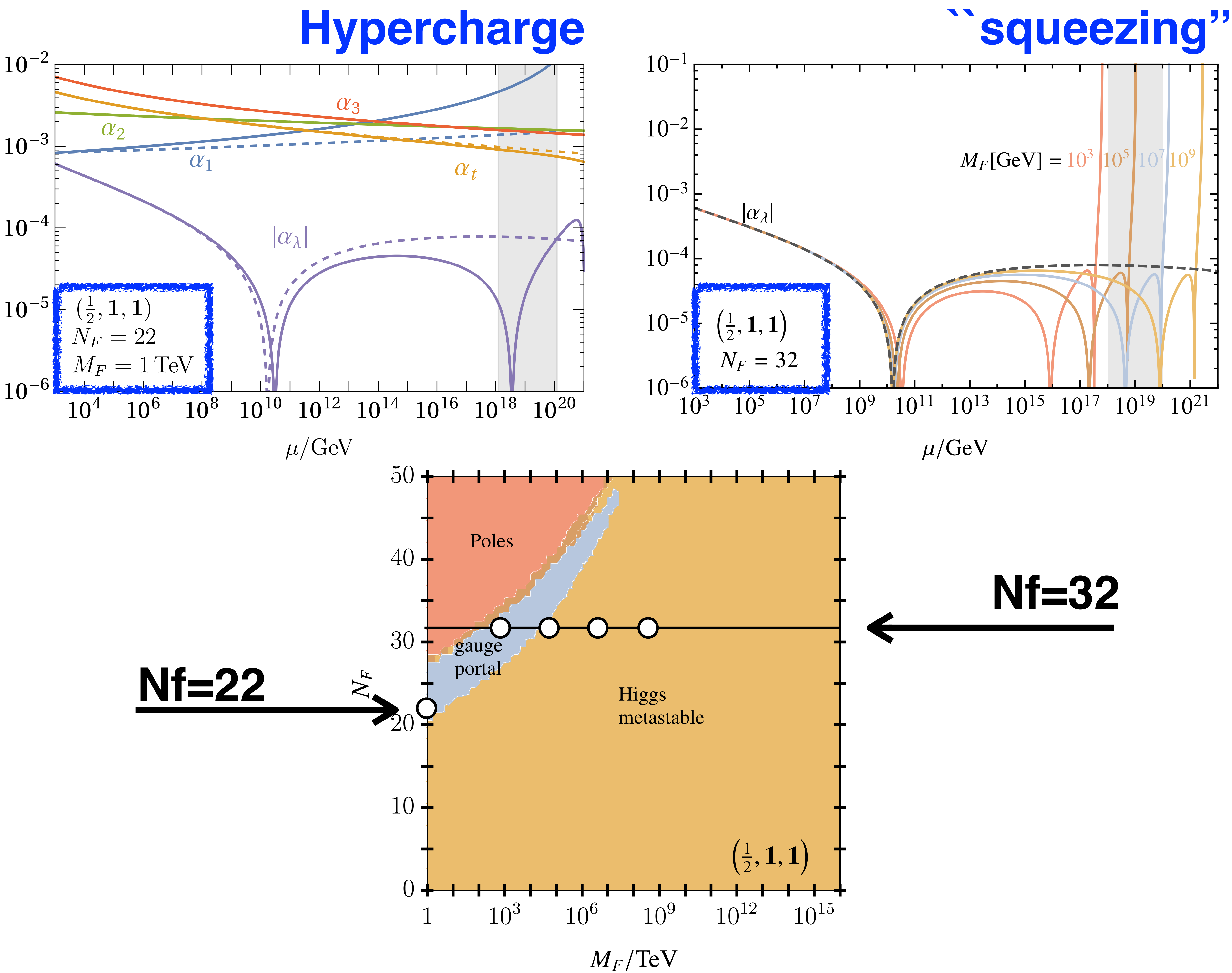
$$+\tfrac{3}{8}\alpha_2^2(\mu_0)\left[\alpha_1(\mu_0) + 3\alpha_2(\mu_0)\right]\boxed{\delta B_2}\ln^2\left(\frac{\Lambda}{\mu_0}\right)$$

$$+32\,\alpha_t^2(\mu_0)\,\alpha_3^2(\mu_0)\boxed{\delta B_3}\ln^3\left(\frac{\Lambda}{\mu_0}\right)$$

All three gauge portals enhance the quartic!



Strong
Weak
α_3
α_2
α_1
α_t
$|\alpha_\lambda|$
$(0, \mathbf{1}, \mathbf{3})$
$N_F = 2$
$M_F = 1$ TeV
$(0, \mathbf{2}, \mathbf{1})$
$N_F = 5$
$M_F = 1$ TeV
μ/GeV
Poles
gauge portal
Higgs metastable
Nf=2
Nf=5
N_F
M_F/TeV



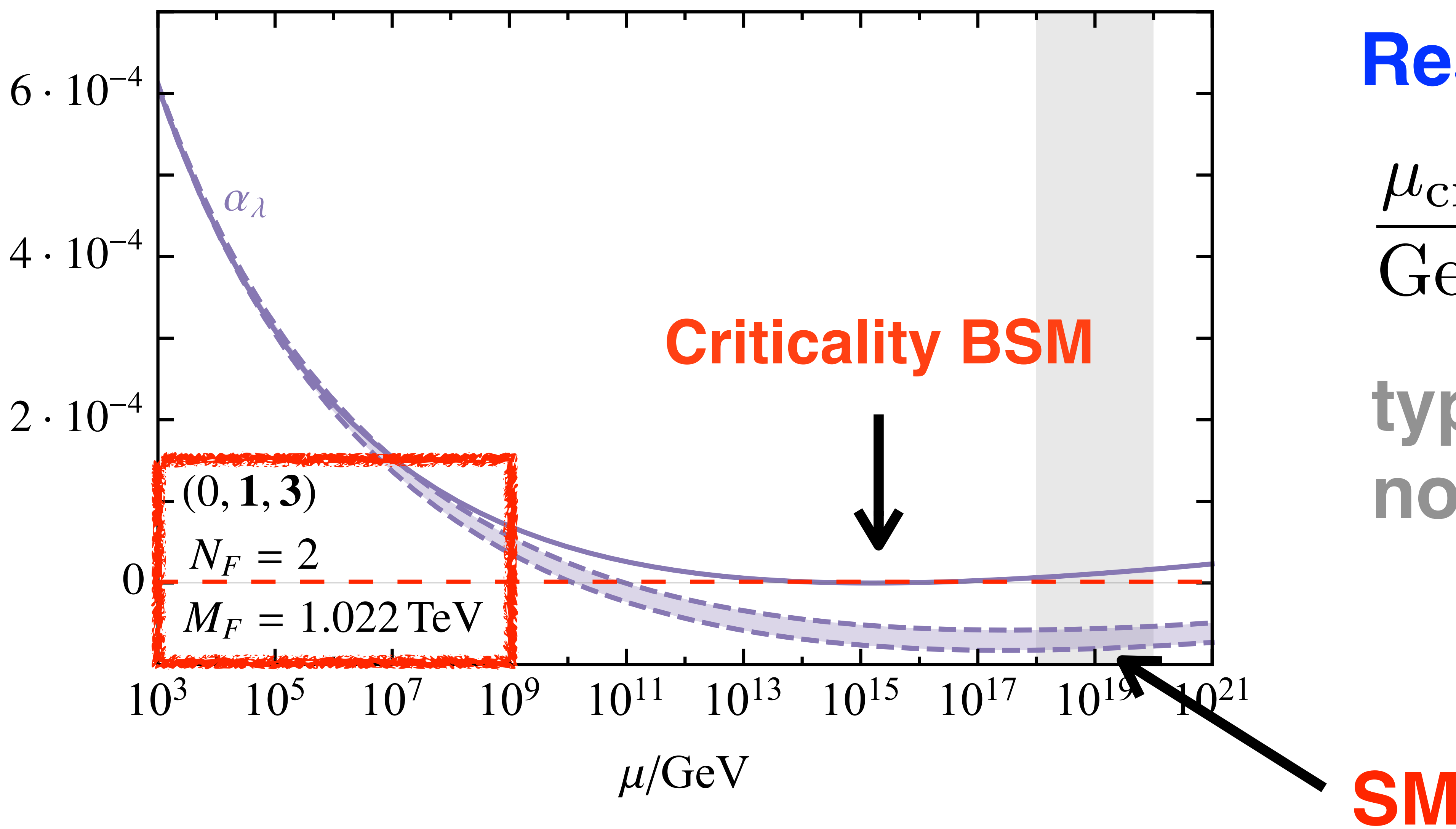
Hypercharge
``squeezing"
α_3
α_2
α_1
α_t
$|\alpha_\lambda|$
$(\frac{1}{2}, \mathbf{1}, \mathbf{1})$
$N_F = 22$
$M_F = 1$ TeV
μ/GeV
M_F[GeV] = 10^3 10^5 10^7 10^9
$(\frac{1}{2}, \mathbf{1}, \mathbf{1})$
$N_F = 32$
μ/GeV
Poles
gauge portal
Higgs metastable
$(\frac{1}{2}, \mathbf{1}, \mathbf{1})$
N_F
M_F/TeV
Nf=32
Nf=22

Higgs Criticality

Criticality: $\lambda|_{\mu_{\rm crit}} = 0 \quad \text{and} \quad \beta_\lambda|_{\mu_{\rm crit}} = 0$

(**SM** $\beta_\lambda|_{\mu=M_{\rm Pl}} \approx 0 \quad \text{and} \quad \lambda|_{\mu=M_{\rm Pl}} \approx 0 \quad \text{within} \quad \mathcal{O}(10^{-4})$)

[Buttazzo et al '13]



Result:

$$\frac{\mu_{\rm crit}}{\rm GeV} \approx 10^{11} - 10^{15}$$

typical GUT scale
not Planck scale

Yukawa Portals

all 13 possibilities

TABLE I. Complete list of vectorlike fermion extensions of the SM with Yukawa portals to the Higgs and SM fermions, also showing the respective gauge charges and interactions; $H^c = i\sigma_2 H^*$. Note that model K offers two Yukawa portals.

Model	(Y_F, d_2, d_3)	Yukawa interactions
A	$(-1, \mathbf{1}, \mathbf{1})$	$\kappa_{ij}\bar{L}_i H \psi_{Rj} + \text{h.c.}$
B	$(-1, \mathbf{3}, \mathbf{1})$	$\kappa_{ij}\bar{L}_i \psi_{Rj} H + \text{h.c.}$
C	$\left(-\frac{1}{2}, \mathbf{2}, \mathbf{1}\right)$	$\kappa_{ij}\bar{\Psi}_{Li} H E_j + \text{h.c.}$
D	$\left(-\frac{3}{2}, \mathbf{2}, \mathbf{1}\right)$	$\kappa_{ij}\bar{\Psi}_{Li} H^c E_j + \text{h.c.}$
E	$(0, \mathbf{1}, \mathbf{1})$	$\kappa_{ij}\bar{L}_i H^c \psi_{Rj} + \text{h.c.}$
F	$(0, \mathbf{3}, \mathbf{1})$	$\kappa_{ij}\bar{L}_i \psi_{Rj} H^c + \text{h.c.}$
G	$\left(-\frac{1}{3}, \mathbf{1}, \mathbf{3}\right)$	$\kappa_{ij}\bar{Q}_i H \psi_{Rj} + \text{h.c.}$
H	$\left(+\frac{2}{3}, \mathbf{1}, \mathbf{3}\right)$	$\kappa_{ij}\bar{Q}_i H^c \psi_{Rj} + \text{h.c.}$
I	$\left(-\frac{1}{3}, \mathbf{3}, \mathbf{3}\right)$	$\kappa_{ij}\bar{Q}_i \psi_{Rj} H + \text{h.c.}$
J	$\left(+\frac{2}{3}, \mathbf{3}, \mathbf{3}\right)$	$\kappa_{ij}\bar{Q}_i \psi_{Rj} H^c + \text{h.c.}$
K	$\left(+\frac{1}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa^u_{ij}\bar{\Psi}_{Li} H^c U_j + \kappa^d_{ij}\bar{\Psi}_{Li} H D_j + \text{h.c.}$
L	$\left(+\frac{7}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa_{ij}\bar{\Psi}_{Li} H U_j + \text{h.c.}$
M	$\left(-\frac{5}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa_{ij}\bar{\Psi}_{Li} H^c D_j + \text{h.c.}$

Yukawa Portals

Main new RG effect

``good''  ``bad''

$$\beta_\lambda = \beta_\lambda^{\rm SM} + I_{\kappa\lambda}\,\alpha_\kappa\,\alpha_\lambda - I_{\kappa\kappa}\,\alpha_\kappa^2 + \mathcal{O}(2\text{-loop})$$

Yukawa

$$\alpha_\lambda = \frac{\lambda}{(4\pi)^2}$$

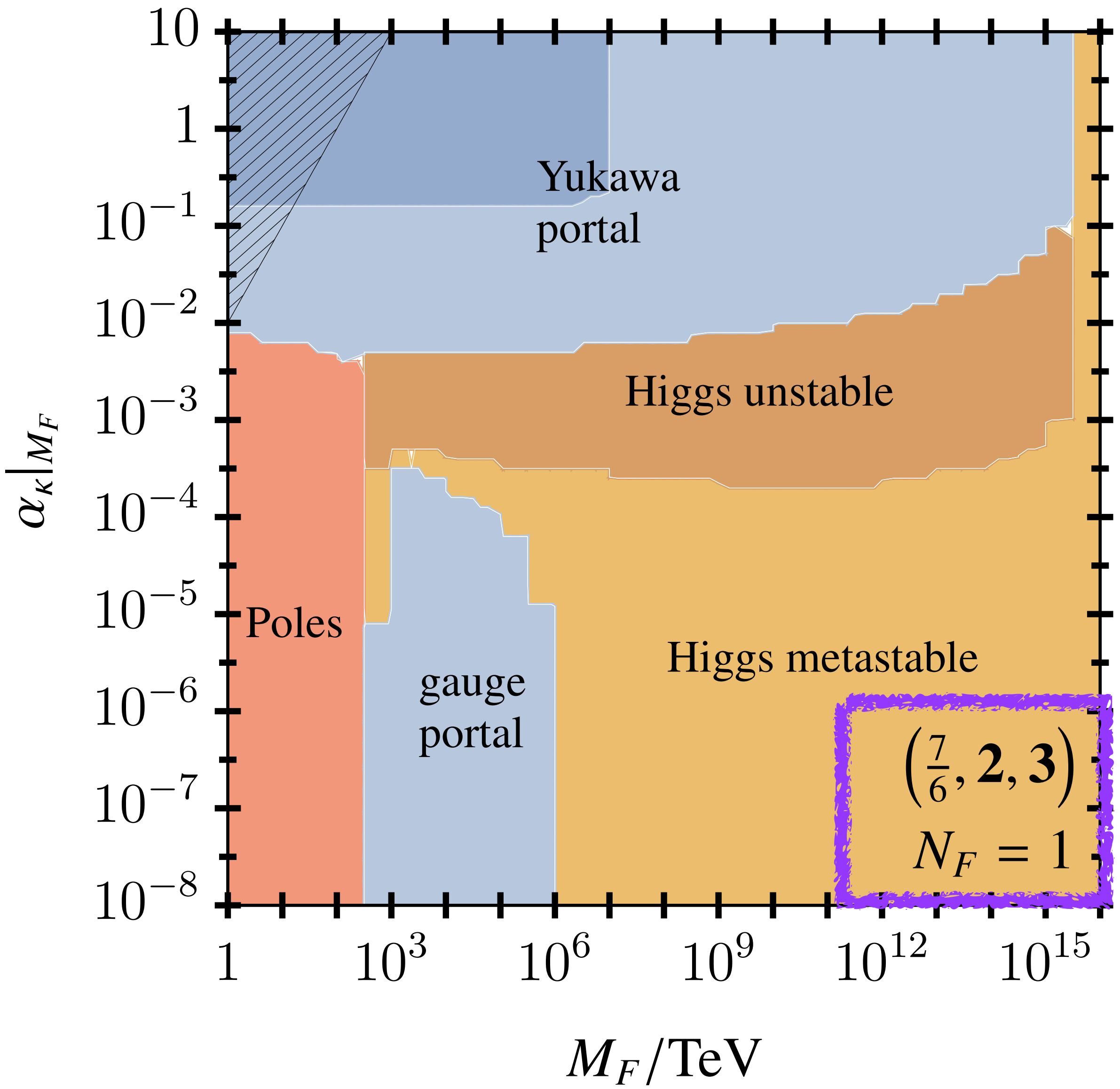
$$\alpha_\kappa = \frac{\kappa^2}{(4\pi)^2}$$

Competition!

Who wins?

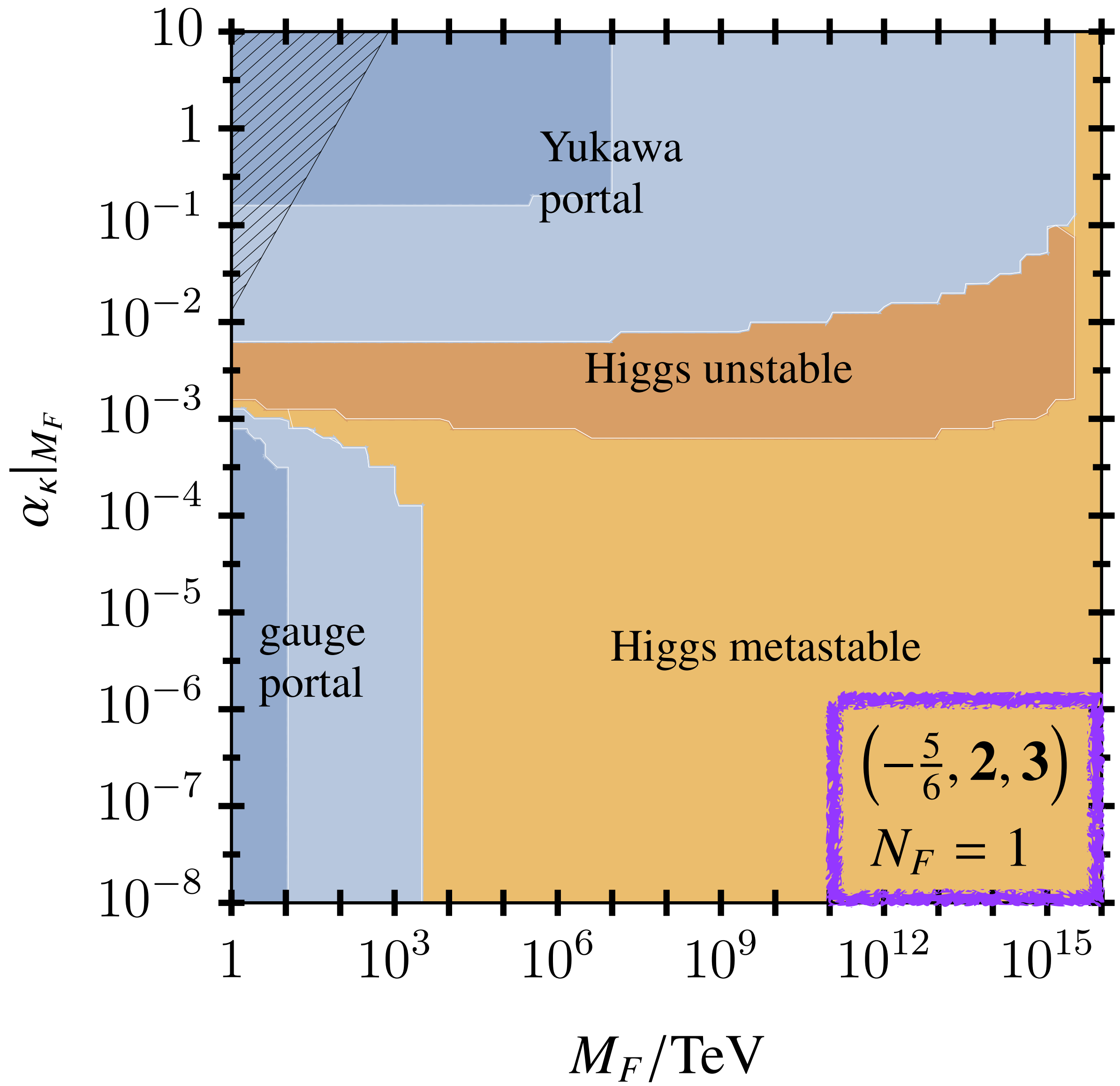
Yukawa Portals

Model L



$$\kappa\,\overline{\psi}_L H^c U$$

Model M



$$\kappa\,\overline{\psi}_L H^c D$$

Yukawa Portals

TABLE III. Vacuum stability at the Planck scale for SM extensions with a single vectorlike fermion of mass $M_F = 1$ TeV and Yukawa couplings to the Higgs and third-generation SM fermions. Shown are the parameter ranges of Yukawa couplings at the matching scale ($\mu_0 = M_F$) which ensure stability via either the gauge or the Yukawa portal. Values without (with) brackets refer to settings where $\alpha_\lambda \geq 0$ ($\alpha_\lambda|_{M_{\rm Pl}} \geq 0$). For small $\alpha_\kappa(\mu_0)$, we observe that a few models offer stability via a gauge portal. For moderate or large $\alpha_\kappa(\mu_0)$, stability is provided by the Yukawa portal and a strongly coupled walking regime. For vanishing Yukawas, the results of Table II are recovered.

Model	(Y_F, d_2, d_3)	Interactions	Gauge portal	Yukawa portal
A	$(-1, \mathbf{1}, \mathbf{1})$	$\kappa \bar{L}_3 H \psi_R$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (6\times 10^{-3})$
B	$(-1, \mathbf{3}, \mathbf{1})$	$\kappa \bar{L}_3 \psi_R H$	$\alpha_\kappa\|_{1\text{ TeV}} \lesssim 2\times 10^{-4} (1.6\times 10^{-3})$	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.4 (1.6\times 10^{-2})$
C	$\left(-\frac{1}{2}, \mathbf{2}, \mathbf{1}\right)$	$\kappa \bar{\psi}_L H E_3$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (6\times 10^{-3})$
D	$\left(-\frac{3}{2}, \mathbf{2}, \mathbf{1}\right)$	$\kappa \bar{\psi}_L H^c E_3$	$(\alpha_\kappa\|_{1\text{ TeV}} \lesssim 3\times 10^{-5})$	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (8\times 10^{-3})$
E	$(0, \mathbf{1}, \mathbf{1})$	$\kappa \bar{L}_3 H^c \psi_R$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (5\times 10^{-3})$
F	$(0, \mathbf{3}, \mathbf{1})$	$\kappa \bar{L}_3 \psi_R H^c$	$(\alpha_\kappa\|_{1\text{ TeV}} \lesssim 10^{-3})$	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.4 (1.6\times 10^{-2})$
G	$\left(-\frac{1}{3}, \mathbf{1}, \mathbf{3}\right)$	$\kappa \bar{Q}_3 H \psi_R$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (1\times 10^{-2})$
H	$\left(+\frac{2}{3}, \mathbf{1}, \mathbf{3}\right)$	$\kappa \bar{Q}_3 H^c \psi_R$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (6\times 10^{-3})$
I	$\left(-\frac{1}{3}, \mathbf{3}, \mathbf{3}\right)$	$\kappa \bar{Q}_3 \psi_R H$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.6 (0.3)$
J	$\left(+\frac{2}{3}, \mathbf{3}, \mathbf{3}\right)$	$\kappa \bar{Q}_3 \psi_R H^c$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.6 (0.3)$
K	$\left(+\frac{1}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa_t \bar{\psi}_L H^c U_3 + \kappa_b \bar{\psi}_L H D_3$	$\alpha_{\kappa_t,\kappa_b(\kappa_t)}\|_{1\text{ TeV}} \lesssim 10^{-5} (10^{-4})$	$\alpha_{\kappa_t,\kappa_b}\|_{1\text{ TeV}} \gtrsim 0.25 (0.13)$
L	$\left(+\frac{7}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa \bar{\psi}_L H U_3$	X	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.20 (10^{-2})$
M	$\left(-\frac{5}{6}, \mathbf{2}, \mathbf{3}\right)$	$\kappa \bar{\psi}_L H^c D_3$	$\alpha_\kappa\|_{1\text{ TeV}} \lesssim 8\times 10^{-4} (1.4\times 10^{-3})$	$\alpha_\kappa\|_{1\text{ TeV}} \gtrsim 0.2 (8\times 10^{-3})$

Conclusions

Vectorlike quarks and vectorlike leptons are very well motivated BSM particles

They enable various portals to vacuum stability
New: electroweak gauge portals

VLFs can be as light as a TeV
can be pair-produced at colliders

VLFs without Yukawa can be long-lived
Flavorful VLFs decay promptly in SM matter