New Directions for Model Building

… beyond Asymptotic Freedom

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running couplings

quantum fluctuations modify interactions
couplings depend on energy

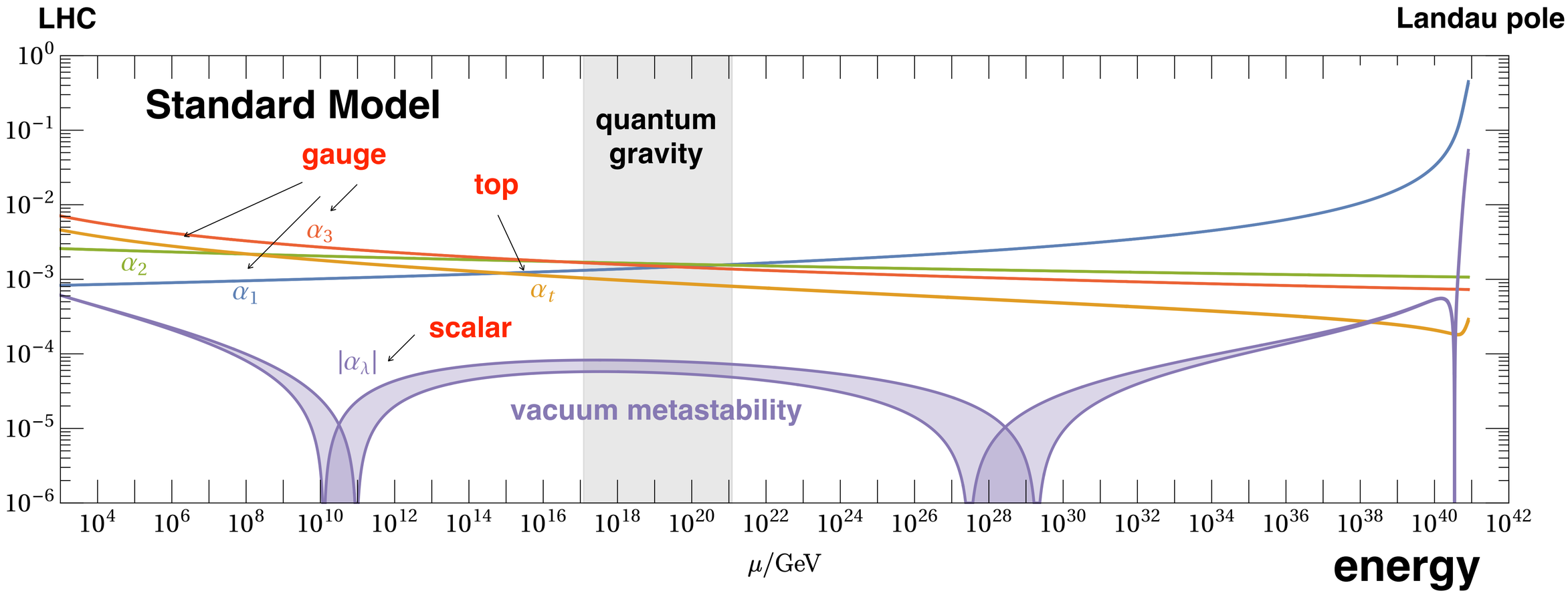
$$\mu \frac{d\alpha}{d\mu} = \beta(\alpha)$$

fluctuations	$\hbar$
energy scale	μ
couplings	$\alpha(\mu)$

QFT provides us with

predictions into regions where we cannot (yet) make measurements

where are we?



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

Higgs quartic

Uncertainty bands:
1-sigma top pole mass

$$m_t = 172.76 \pm 0.30 \text{ GeV}$$

G Hiller, T Hoehne, DF Litim, T Steudtner, **Portals into Higgs Vacuum Stability** 2207.07737

SM vacuum stability

Higgs discovery ’12: **SM vacuum metastability** Buttazzo et al ’13

revisiting vacuum stability ’24: **matching observables to MSbar**

at least 2L + 3L QCD Martin, Patel ‘18

RG running

4L gauge + 5L QCD Davies, Herren, Poole, Steinhauer, Thomsen ’19
Baikov et al ’16, , Herzog et al ’17, Luthe et al ‘17

3L Yukawa + 3L quartic (+4L QCD) Chetyrkin, Zoller ’13-’16
Bednyakov et al ’12-‘14

effective potential

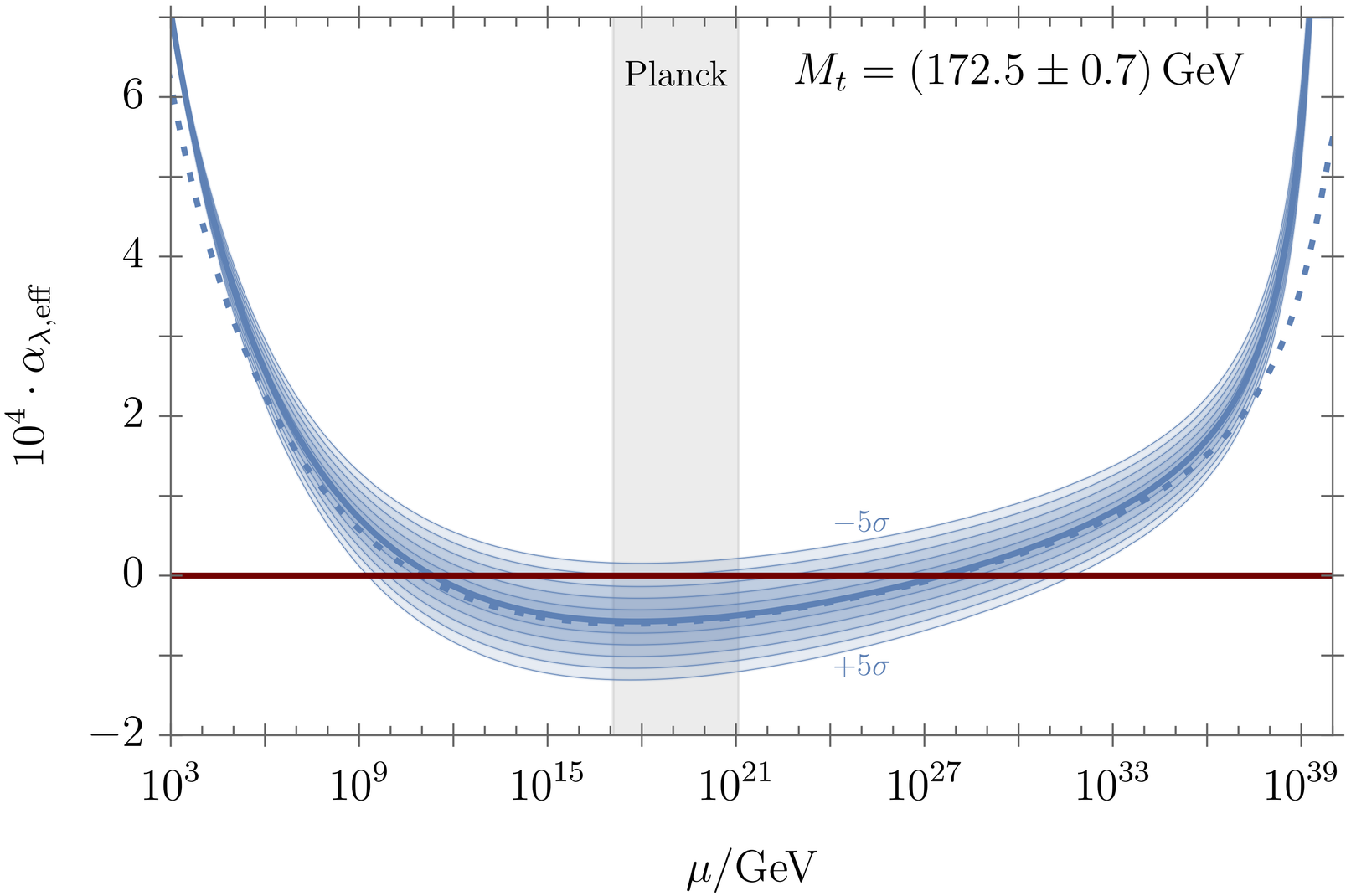
3L (4L QCD) + RG improvement Ford, Jack, Jones ’92, Martin ’13-‘17

PDG 2023 update

Obs.	Value	$\alpha_\lambda > 0$	$\alpha_{\lambda,\text{eff}} > 0$
M_h/GeV	$125.25(17)$	$128.22 \quad +17.5\sigma$	$128.10 \quad +16.7\sigma$
M_t/GeV	$172.5(7)^\ddagger$	$169.62 \quad -4.1\sigma$	$169.74 \quad -3.9\sigma$
	$172.69(30)^\dagger$	-10.3σ	-9.8σ
	$170.5(8)$	$167.85 \quad -3.3\sigma$	$167.97 \quad -3.2\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	$160.0 \quad -1.7\sigma$	$160.1 \quad -1.6\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1180(9)$	$0.1255 \quad +8.3\sigma$	$0.1252 \quad +8.0\sigma$
	$0.1135(^{+21}_{-17})$	$0.1203 \quad +3.2\sigma$	$0.1200 \quad +3.1\sigma$

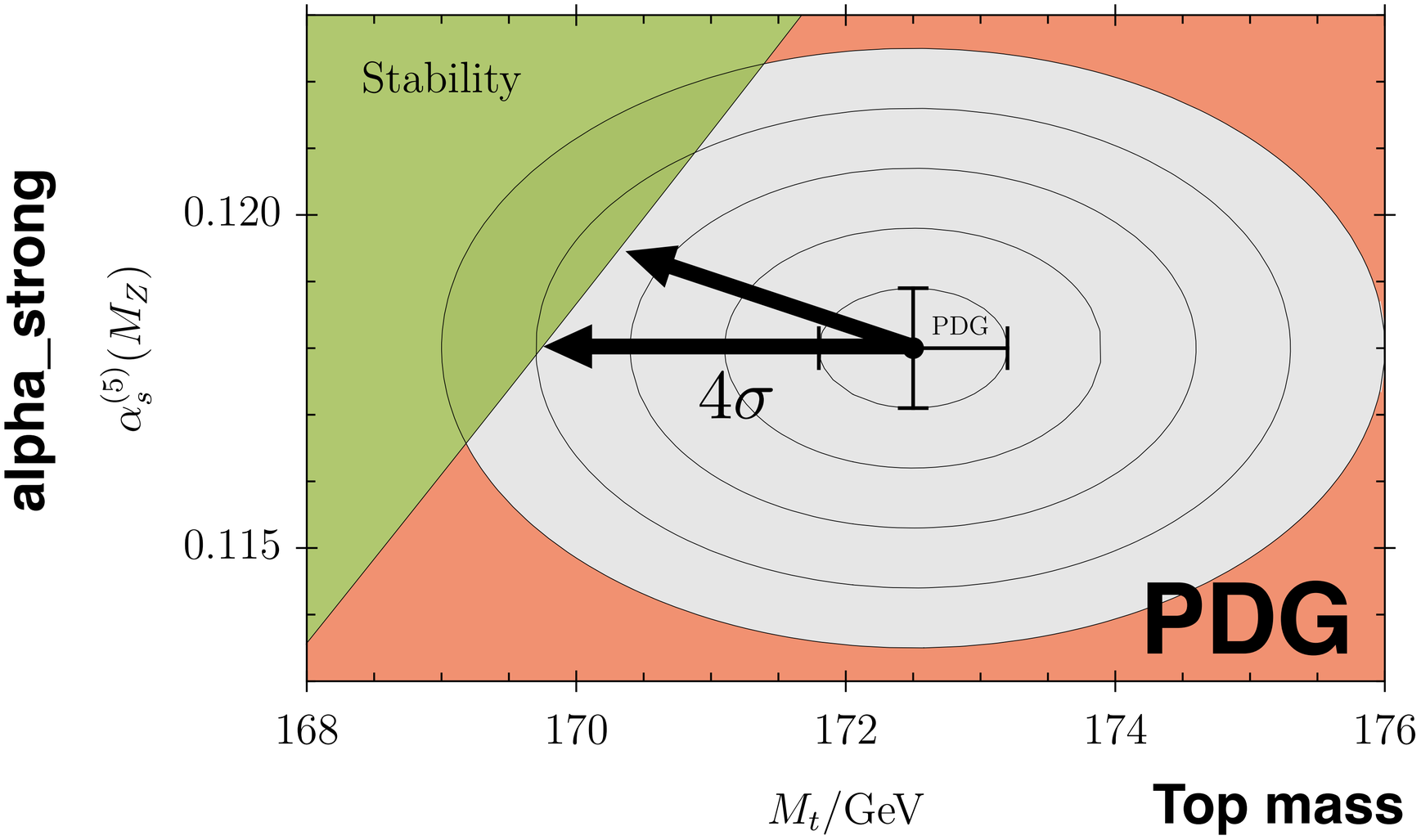
G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

SM vacuum stability



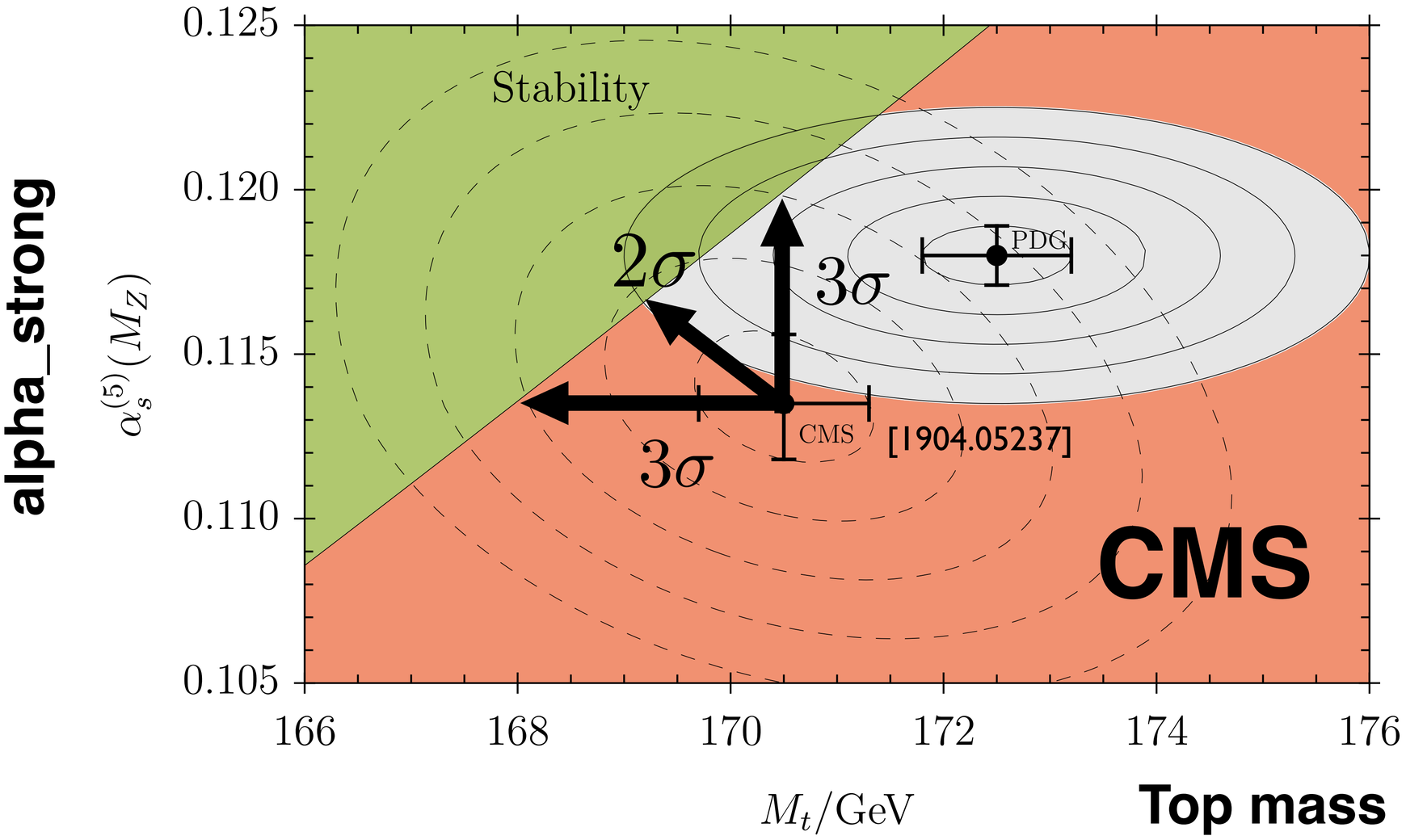
G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

SM vacuum stability



G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

correlations



G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

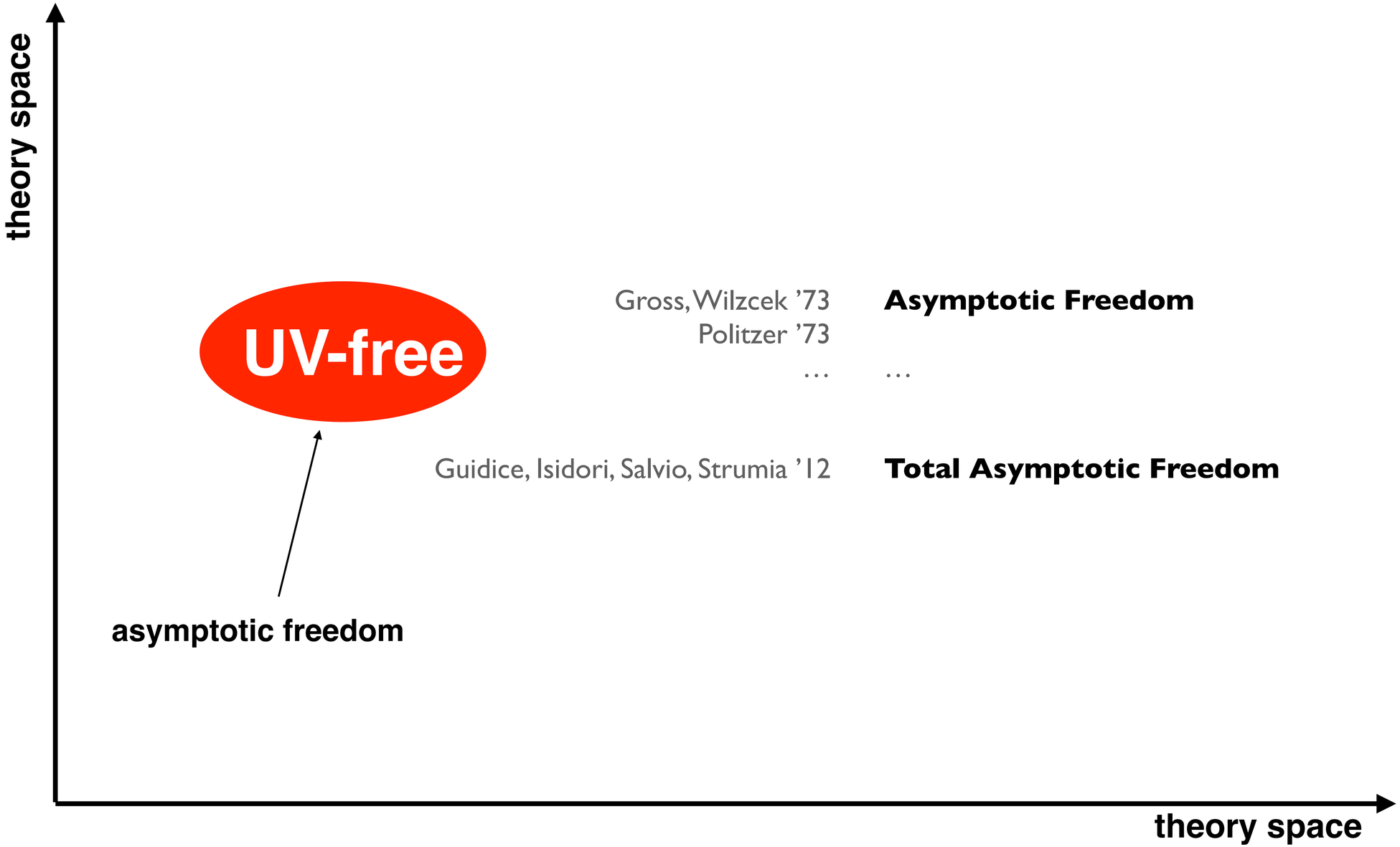
today:

new directions for model building

bottom-up “Planck-safe”

top-down “UV safe”

Top-Down



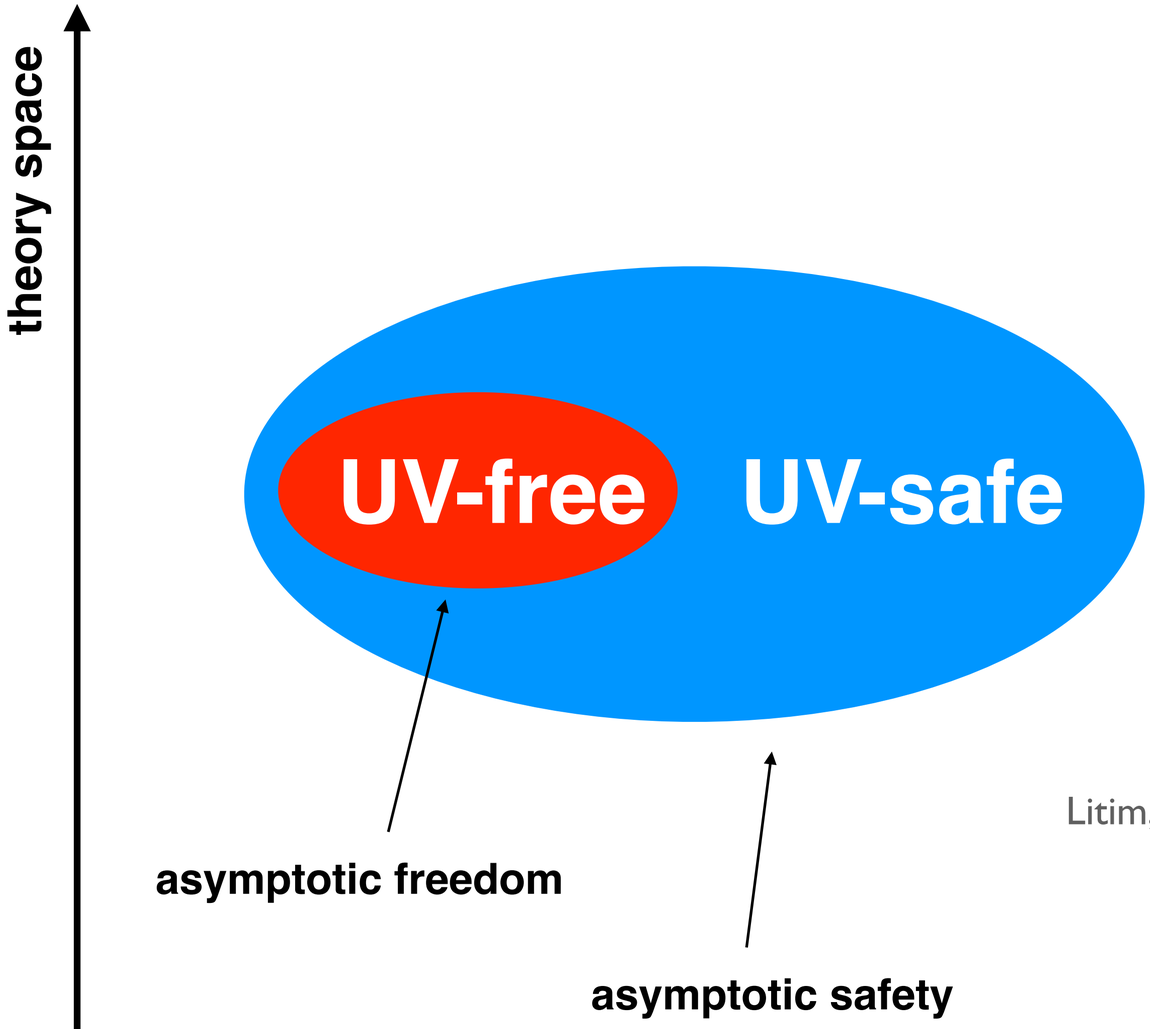
Gross, Wilzcek '73 — **Asymptotic Freedom**

Politzer '73

… …

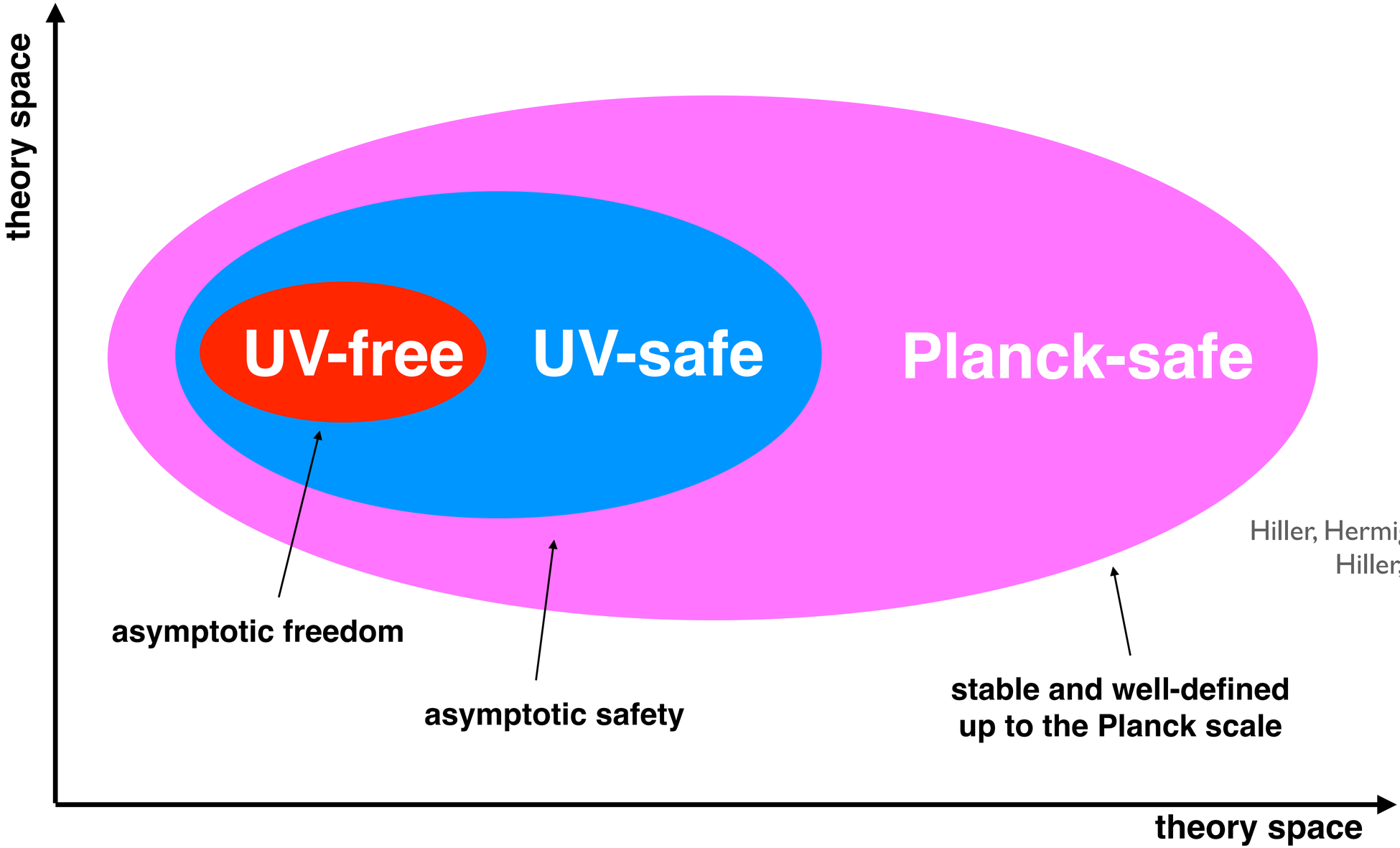
Guidice, Isidori, Salvio, Strumia '12 — **Total Asymptotic Freedom**

Top-Down



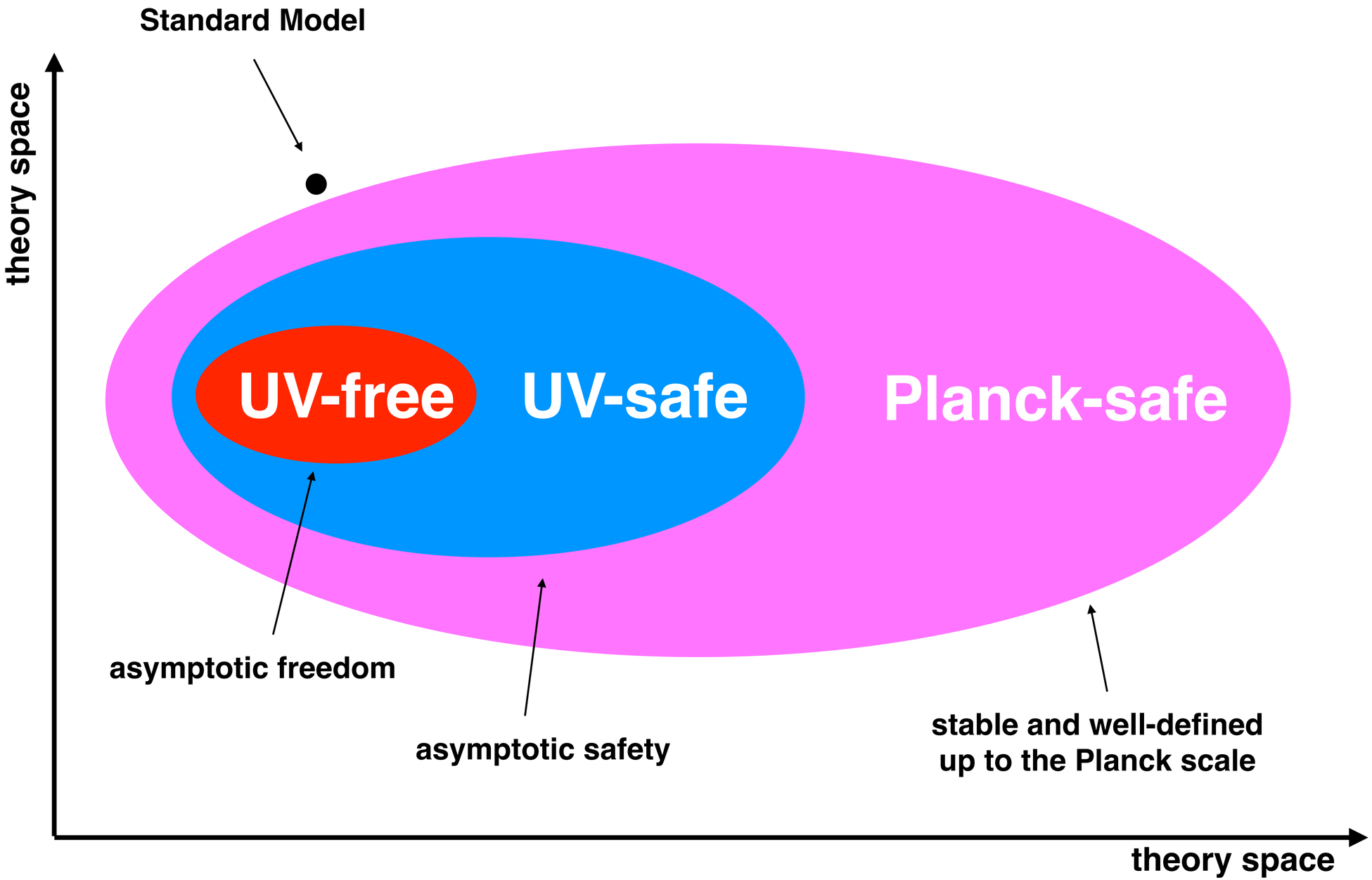
Bailin, Love, '74	**Asymptotic Near-Freedom**
Weinberg '79	**Asymptotic Safety**
Martin, Wells '00	**UV-safe supersymmetry**
Litim, Sannino '14	**interacting UV fixed points in 4d QFTs**
Bond, Litim '16, '17, '18	**general theorems**
Bond, Litim, Steudtner '19	**dualities**
Bond, Litim '20	**supersymmetry**
Litim, Riyaz, Stamou, Steudtner '24	**weakly and strongly coupled FPs**
…	…

Bottom-Up



Hiller, Hermigos-Feliu, Litim, Steudtner ’19, ’20
Hiller, Hoehne, Litim, Steudtner ’22-’24

Bottom-Up


Standard Model
theory space
UV-free
UV-safe
Planck-safe
asymptotic freedom
asymptotic safety
stable and well-defined
up to the Planck scale
theory space

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

→ **modified RG running**

``minimally invasive''

Portals into Stability

Gauge Portals

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

Yukawa Portals

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

Yukawa — κ

VLFs — $\bar{\psi}$

Higgs — H

SM fermion — f_{SM}

→ **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

$$\mathcal{L} \supset \sum_i \delta_i \, (H^\dagger H)(S_i^\intercal S_i)$$

Portals **Higgs** **BSM scalars**

→ **new scalars**

→ **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

$$\mathcal{L} \supset \sum_i \delta_i \, (H^\dagger H)(S_i^\intercal S_i)$$

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** Litim, Steudtner ’21
- **RGBeta** Thomsen ’22
- **Pyr@te3** Sartore, Schienbein ’20
- **Sarah4** Staub ‘13

here: complete 2-loop

Gauge Portals

1-loop running

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

SM BSM

$$\begin{aligned} B_1 &= -\tfrac{41}{3} - \delta B_1, \\ B_2 &= \tfrac{19}{3} - \delta B_2, \\ B_3 &= 14 - \delta B_3\,, \end{aligned}$$

$$\mathcal{L}_{\rm BSM} \supset \bar{\psi}\,(i\not{D} - M_F)\,\psi$$

$$\delta B_1 = \tfrac{8}{3} N_F\, d_2\, d_3\, Y_F^2$$

$$\delta B_{2,3} = \tfrac{8}{3} N_F\, d_{3,2}\, S_2(d_{2,3})$$

Gauge Portals

1-loop running

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

SM BSM

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Three key effects

$\Lambda > \mu_0$

gauge →

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

Gauge Portals

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Three key effects

$\Lambda > \mu_0$

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

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

$$\beta_t \approx \alpha_t \left[9\,\alpha_t - \tfrac{17}{6}\,\alpha_1 - \tfrac{9}{2}\,\alpha_2 - 16\,\alpha_3\right]$$

Gauge Portals

1-loop running

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

SM BSM

$$B_1 = -\tfrac{41}{3} - \delta B_1,$$
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Three key effects

$\Lambda > \mu_0$

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

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

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

$$\beta_\lambda \approx \tfrac{3}{8}\left[\alpha_1^2 + 2\,\alpha_1\alpha_2 + 3\,\alpha_2^2\right] - 6\,\alpha_t^2$$

Why?

Hypercharge

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

Weak

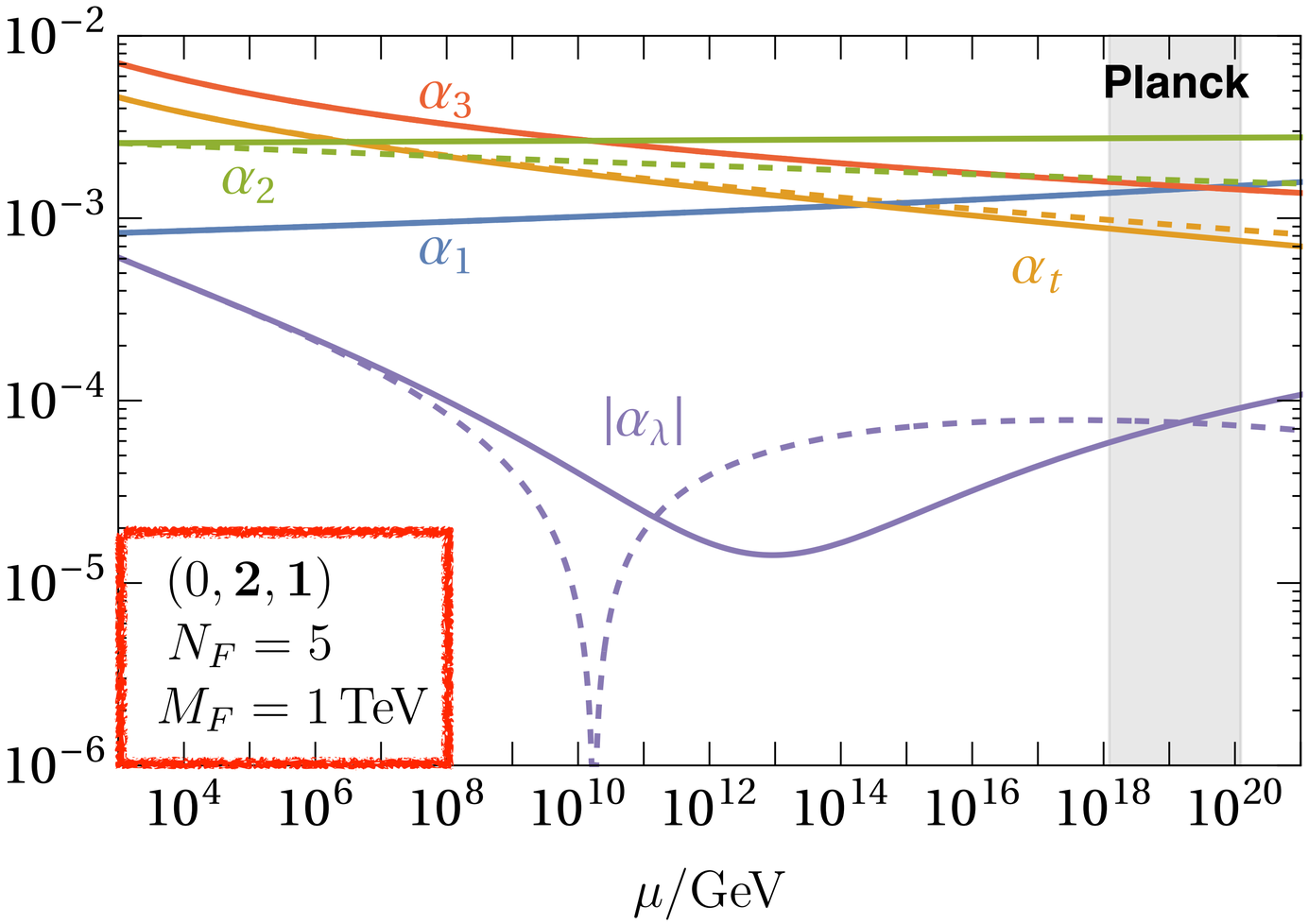
$$+\tfrac{3}{8}\alpha_2^2(\mu_0)\left[\alpha_1(\mu_0)+3\alpha_2(\mu_0)\right]\delta B_2 \ln^2\left(\frac{\Lambda}{\mu_0}\right)$$

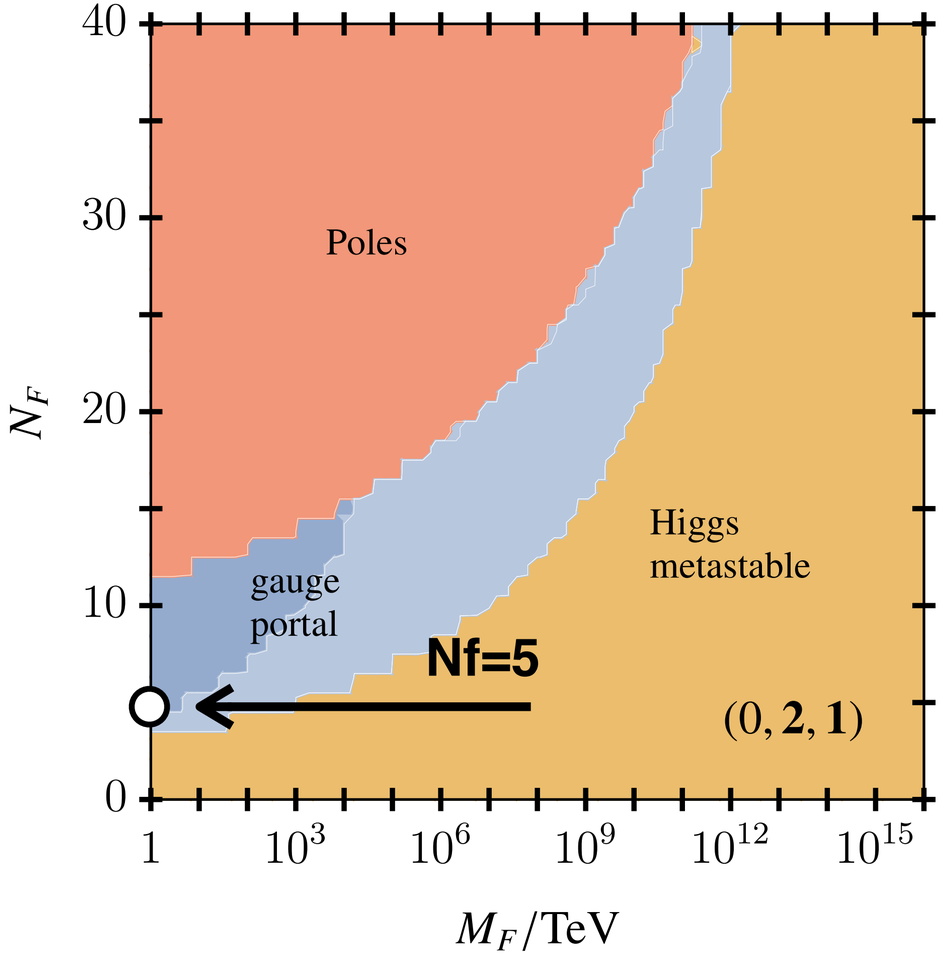
Strong

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

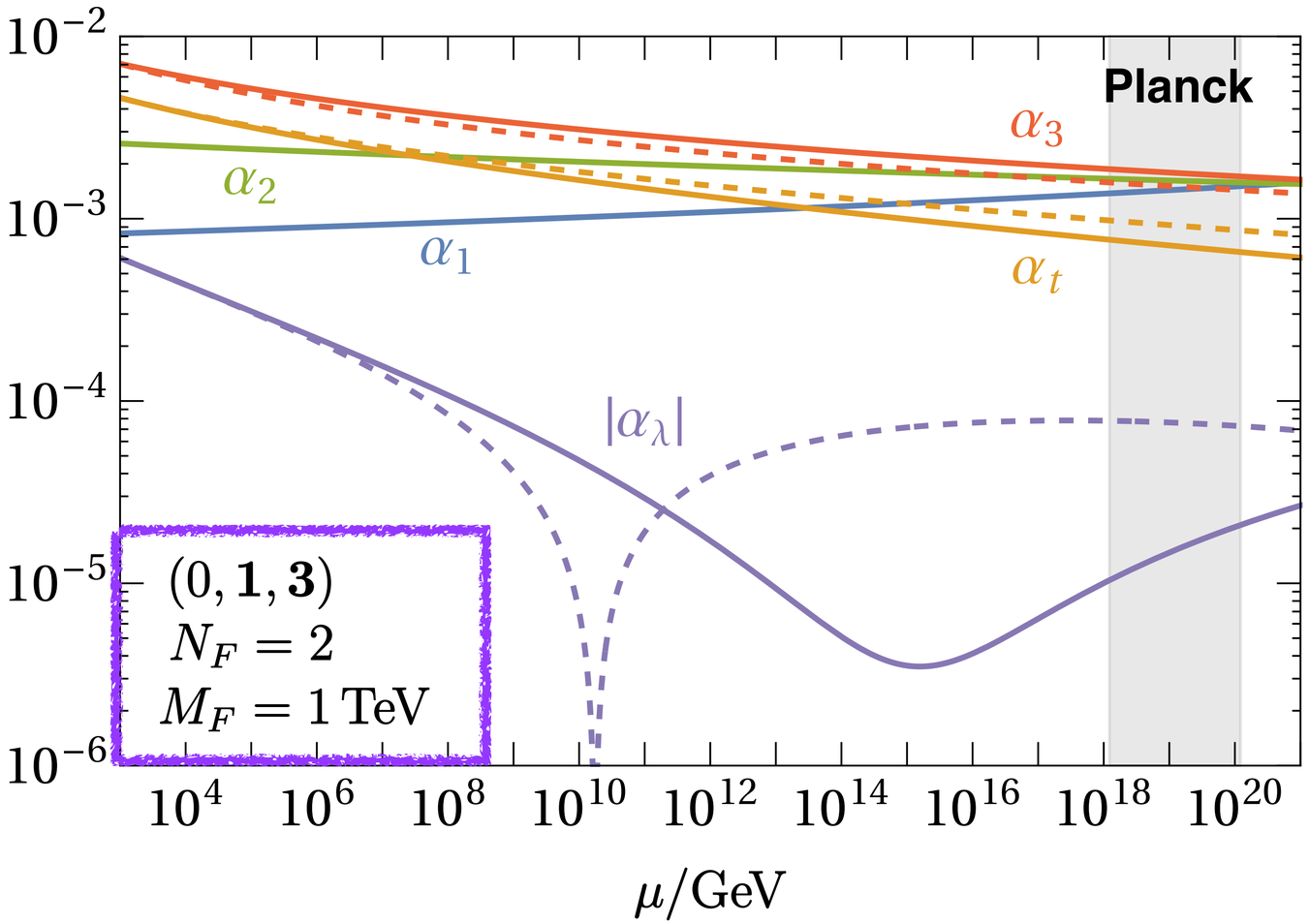
All three gauge portals enhance the quartic

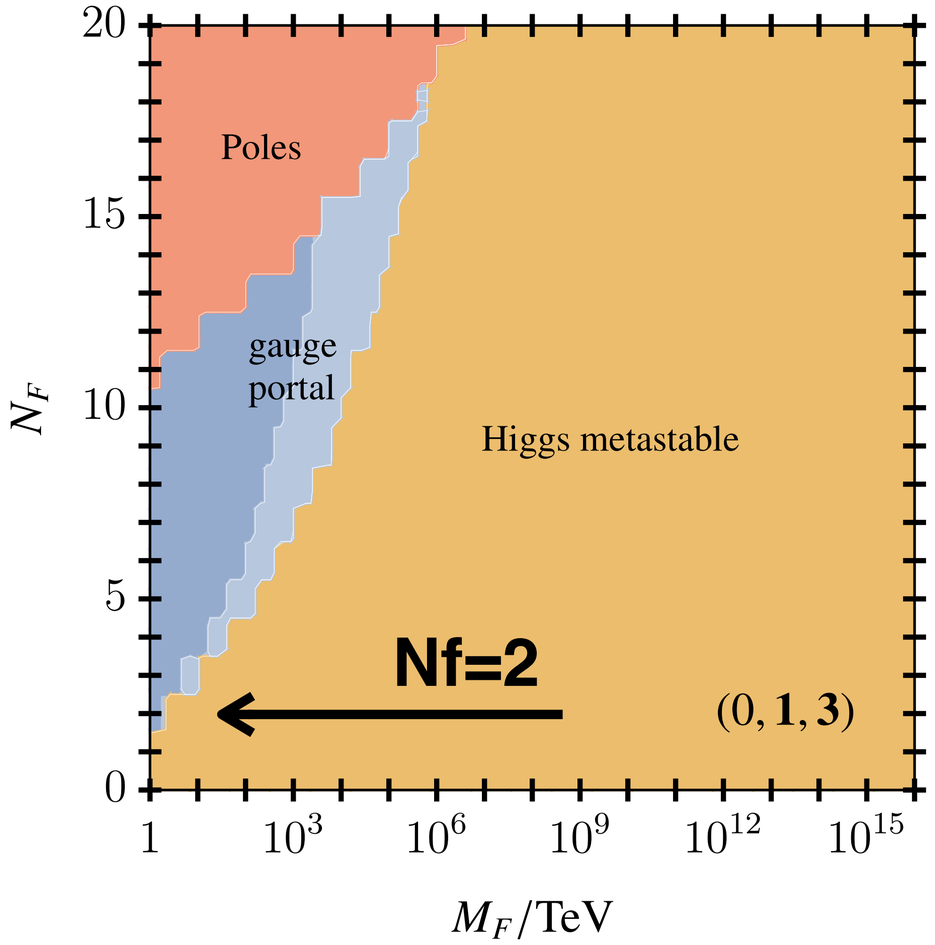
weak portal


Planck
α_3
α_2
α_1
α_t
$|\alpha_\lambda|$
$(0, \mathbf{2}, \mathbf{1})$
$N_F = 5$
$M_F = 1\,\mathrm{TeV}$
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}
μ/GeV

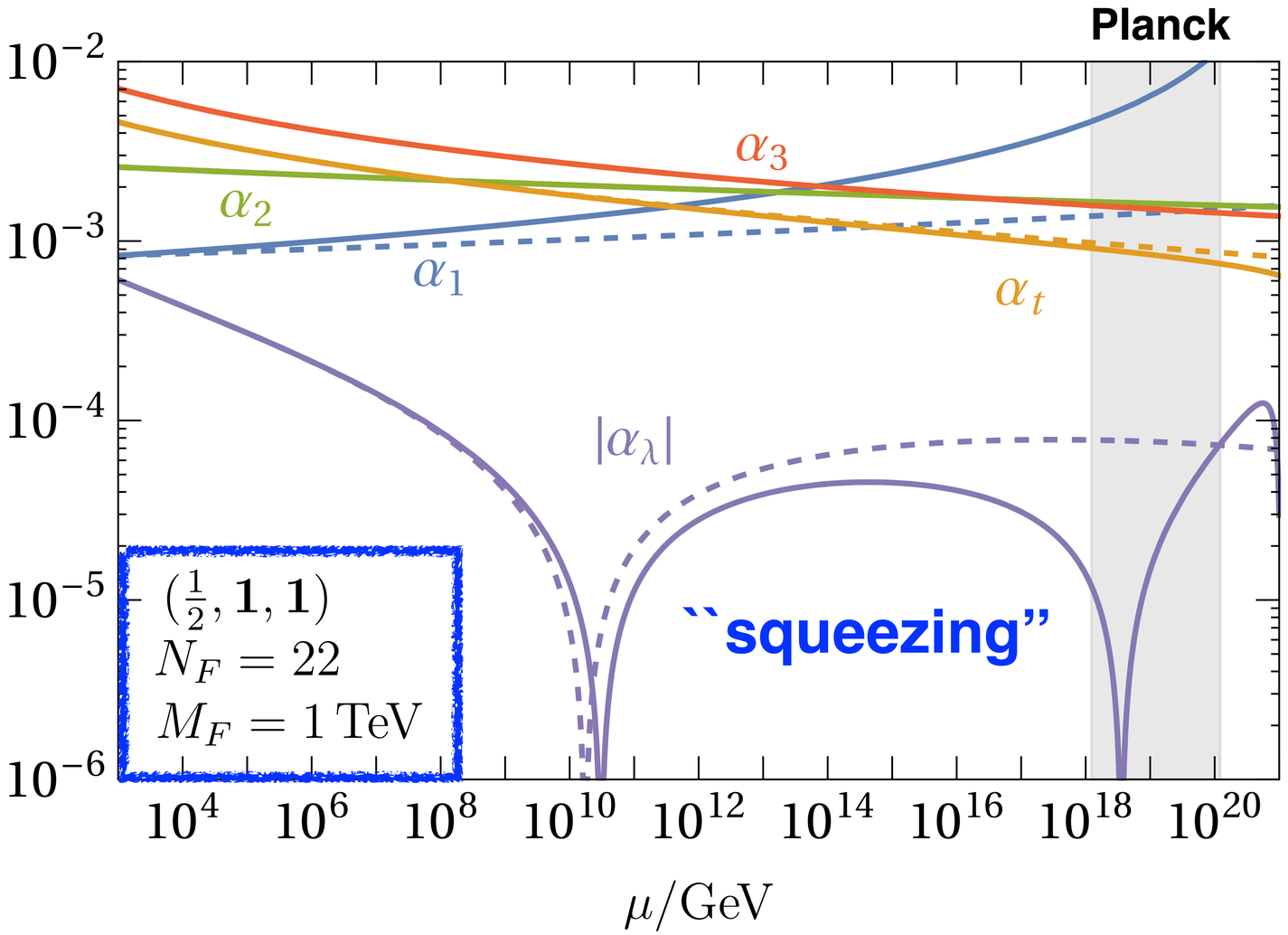

Poles
gauge
portal
Higgs
metastable
Nf=5
$(0, \mathbf{2}, \mathbf{1})$
N_F
40
30
20
10
0
1 10^3 10^6 10^9 10^{12} 10^{15}
M_F/TeV

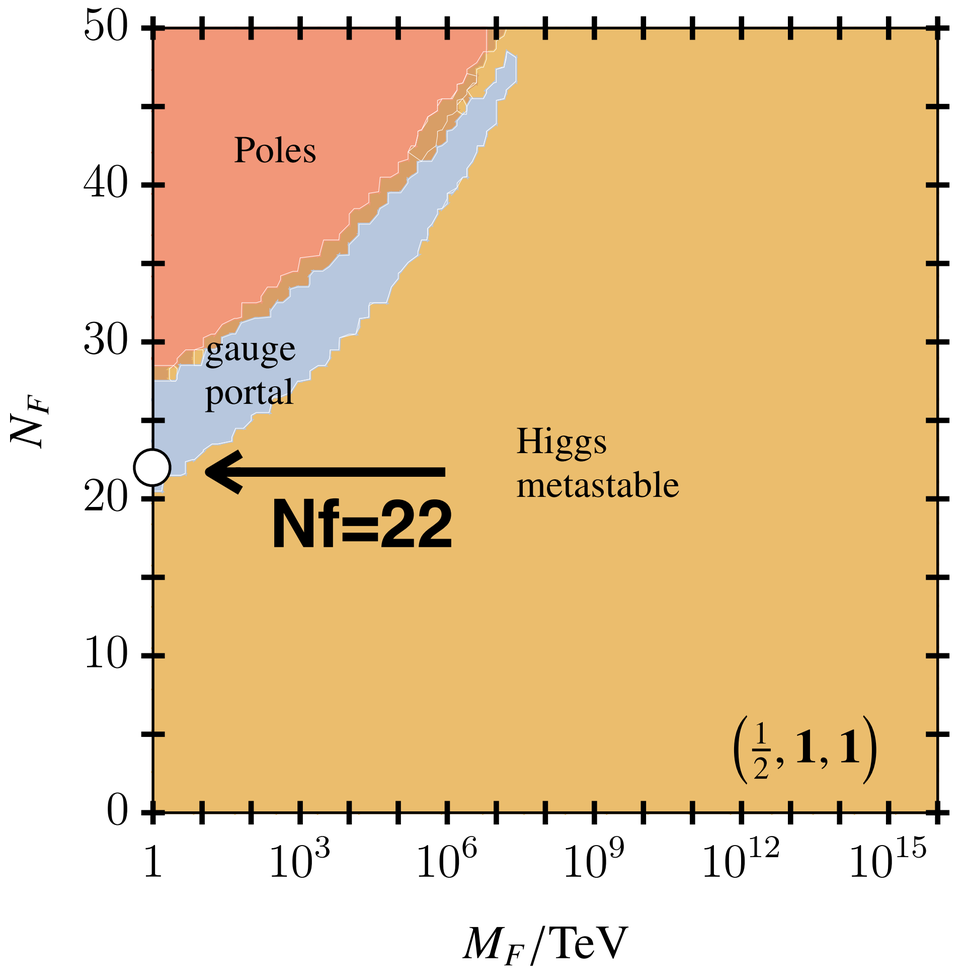
strong portal



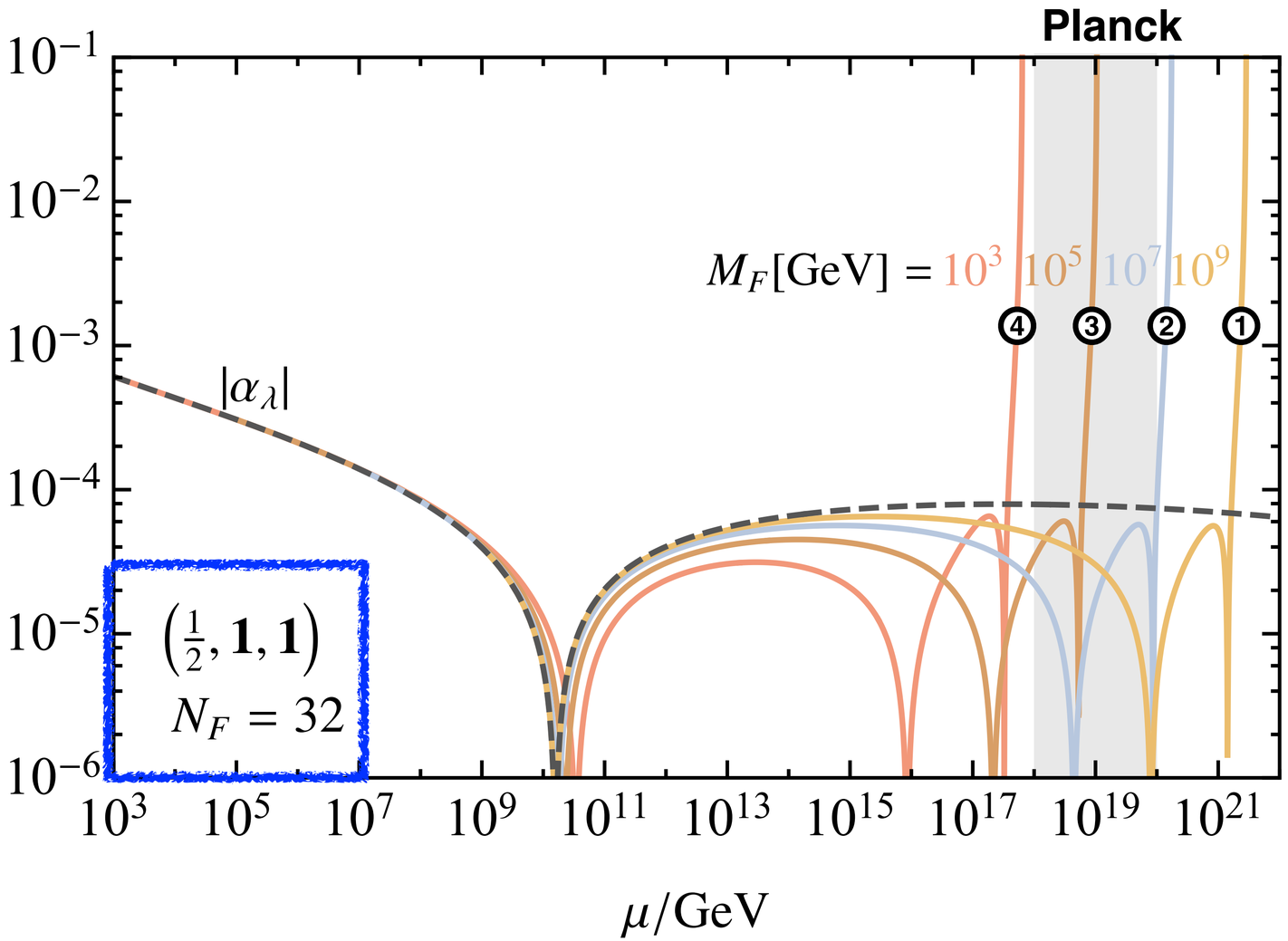


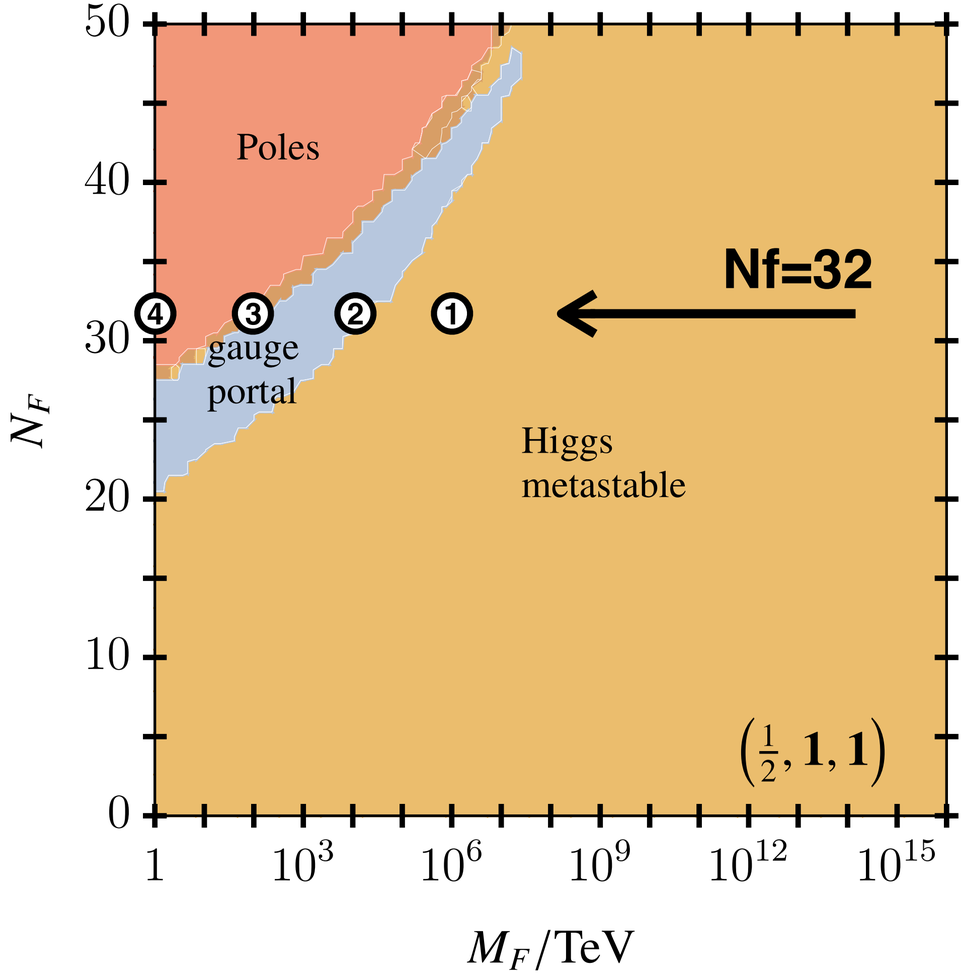
hypercharge portal





hypercharge portal

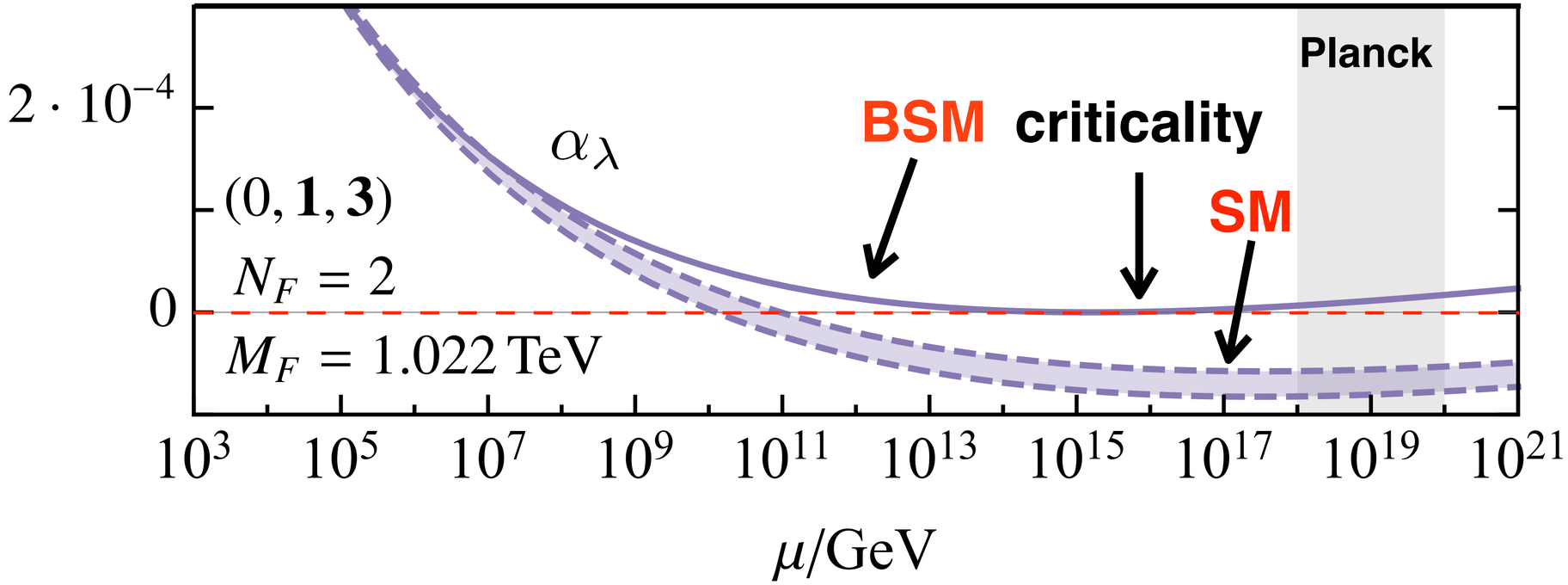




Higgs Criticality

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

Main new RG effect

``good" ``bad"

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

Yukawa

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

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

Competition!

Who wins?

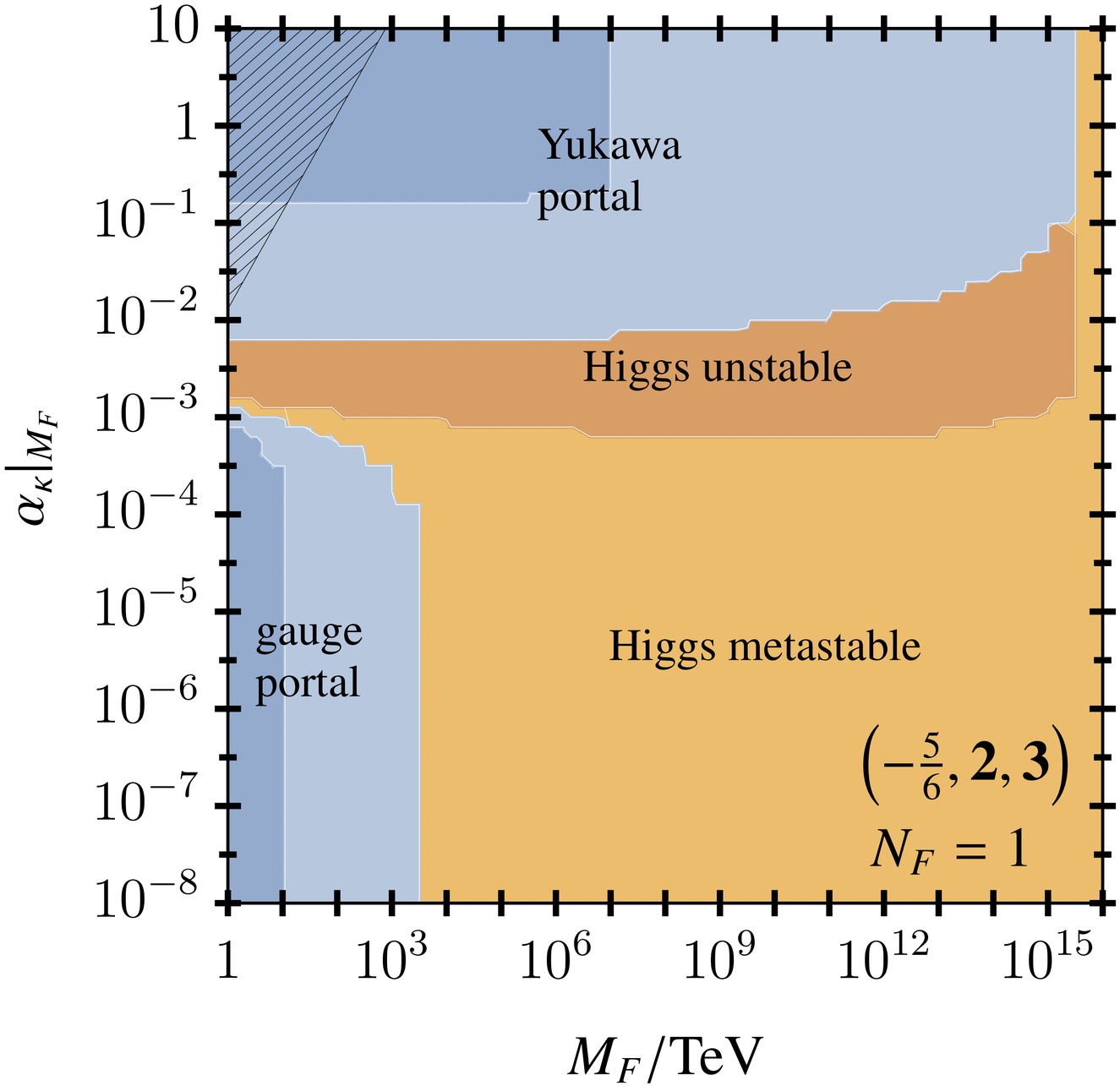
Yukawa Portals

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



Model M

$\kappa\,\overline{\psi}_L H^c D_{\mathbf{3}}$

Higgs Portals

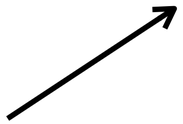
Main new RG effect

$$\mathcal{L} \supset \sum_i \delta_i \, (H^\dagger H)(S_i^\intercal S_i)$$

``good"

$$\beta_\lambda = \beta_\lambda^{\rm SM} + \sum_i 2\, N_i\, \alpha_{\delta_i}^2$$

$$\alpha_\lambda(\Lambda) - \alpha_\lambda^{\rm SM}(\Lambda) \propto \sum_i 2\, N_i\, \alpha_{\delta_i}^2 > 0$$



genuine uplift

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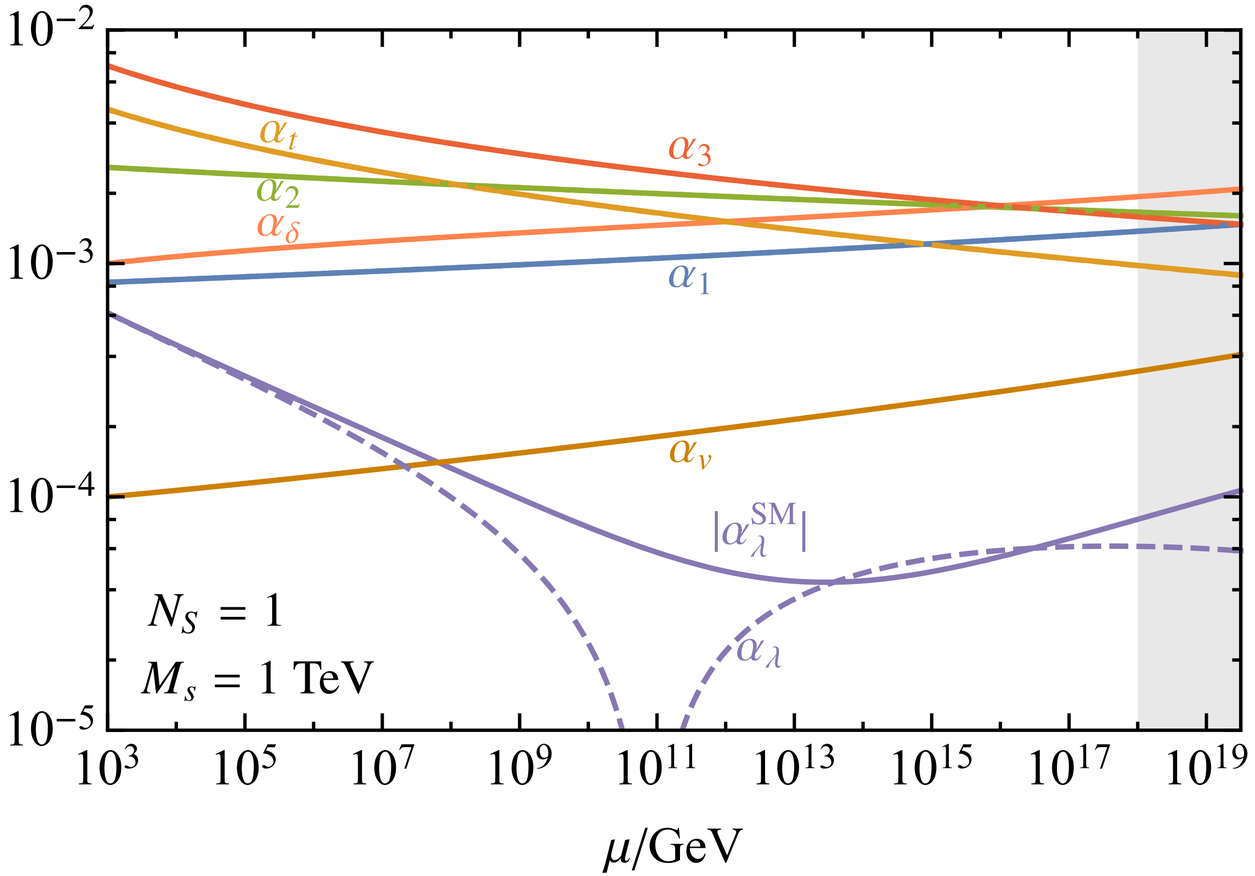
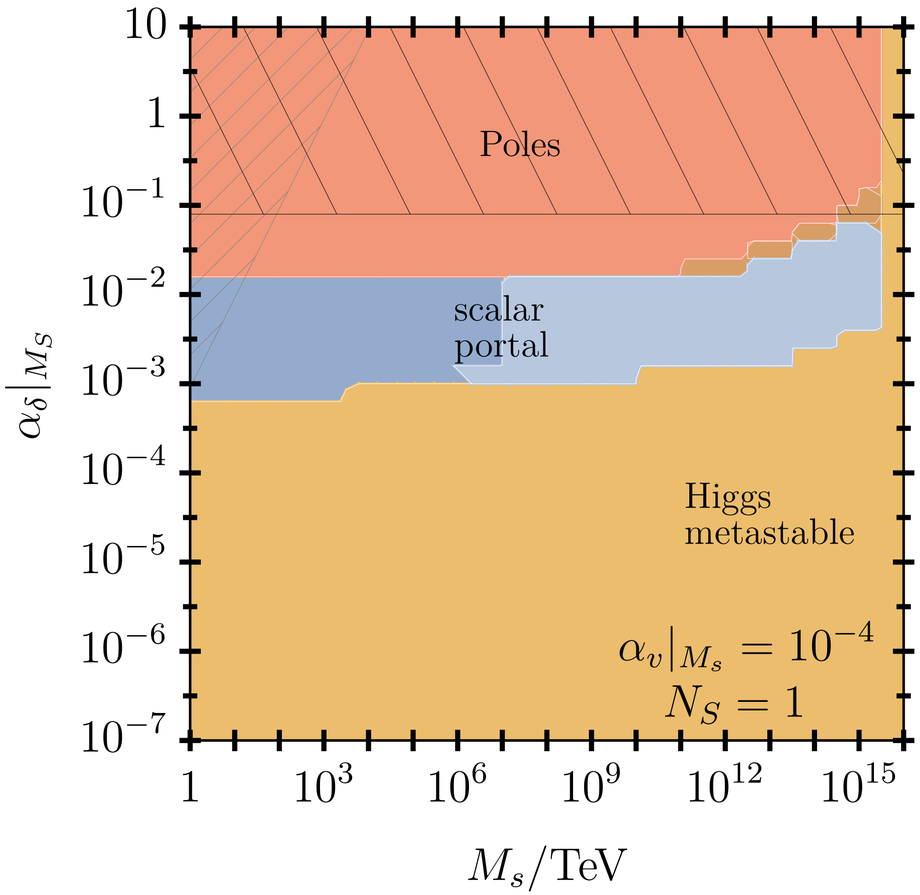
Higgs Portals

single real BSM scalar





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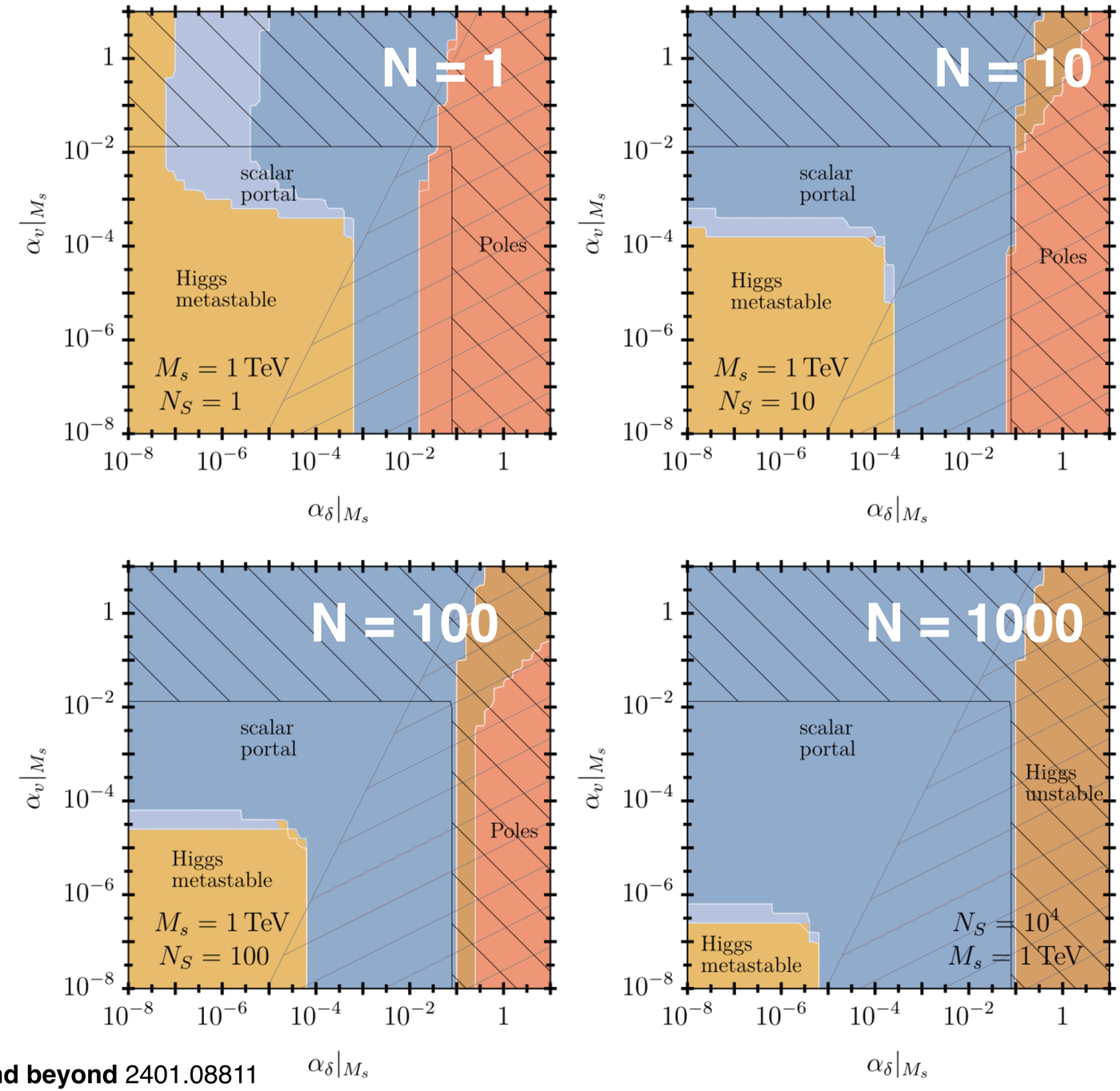
Higgs Portals

O(N) BSM scalars

M = 1 TeV

adding more scalars enhances the range for stability



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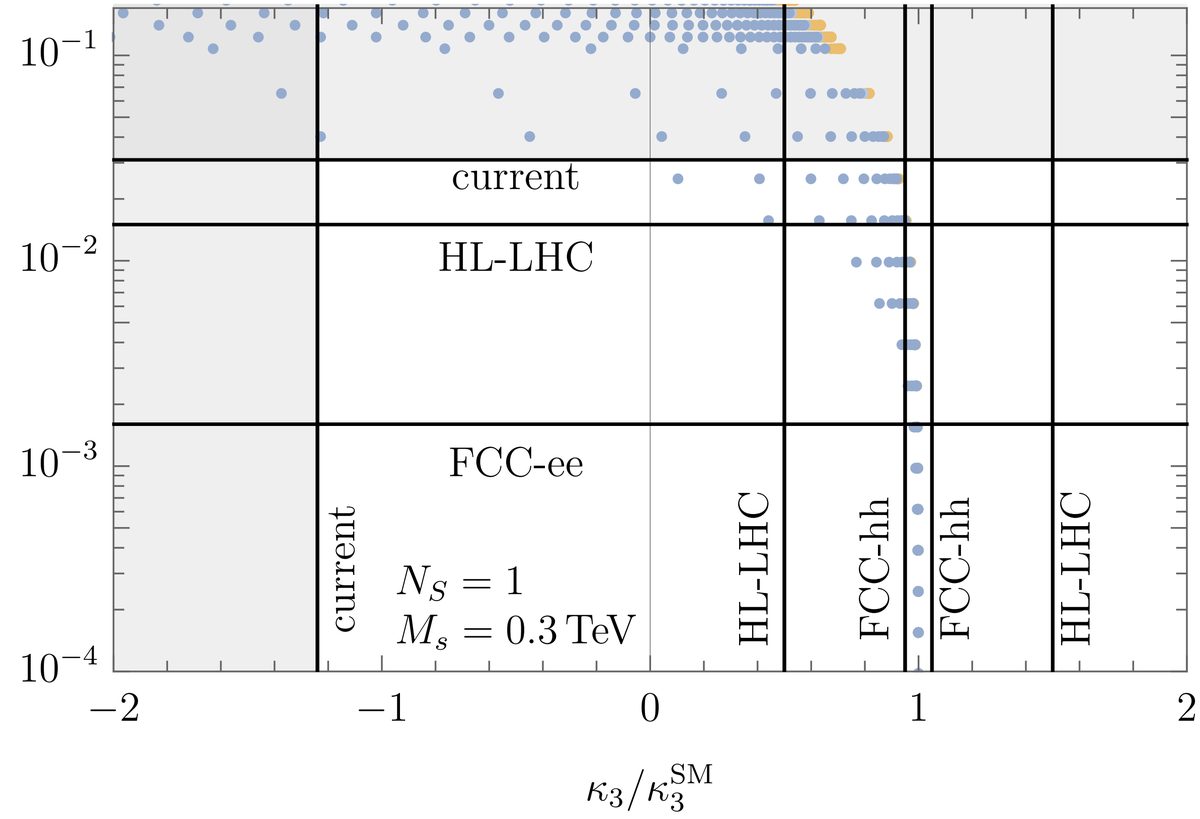
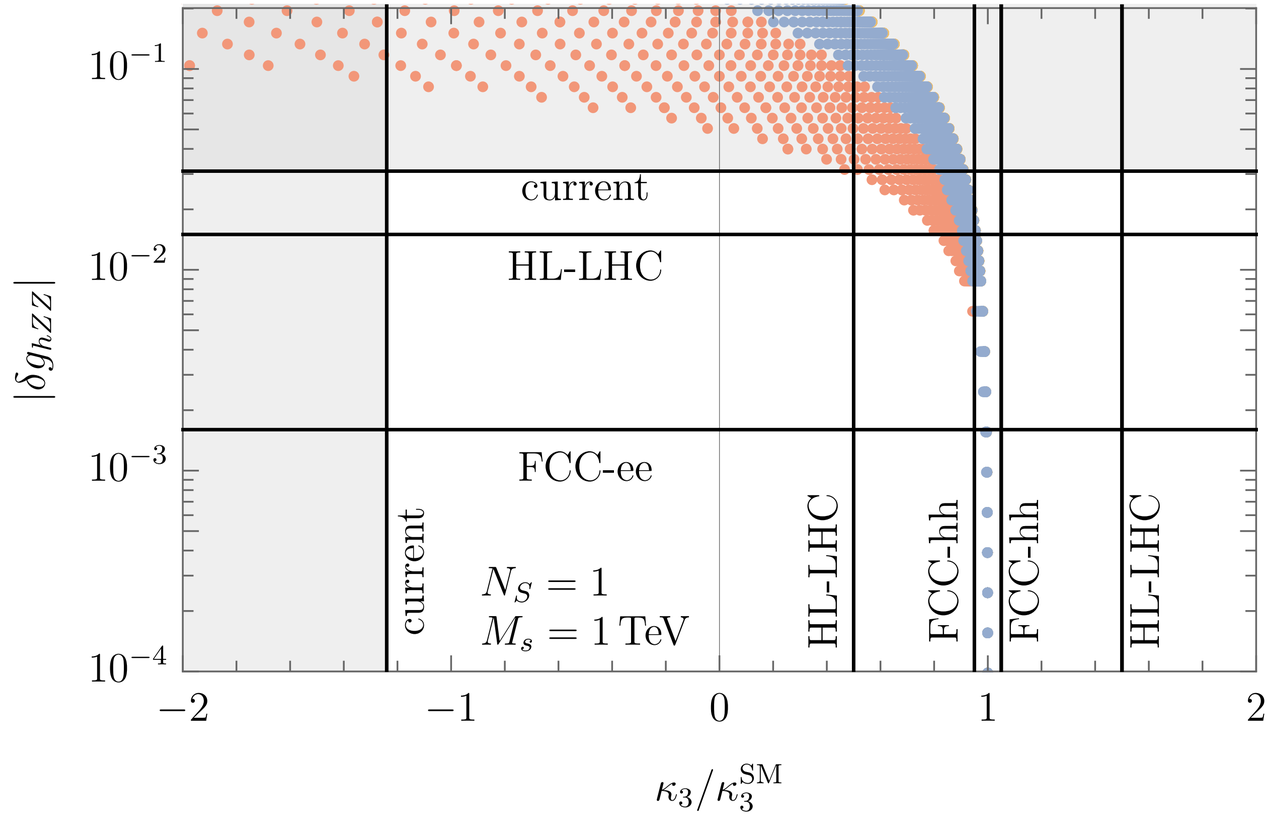
Higgs Portals

Signatures

BSM scalar obtains VEV
modified vertices hZZ, hhh, hhhh





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Top-Down

Q: What does it take to

achieve UV-safe theories

… beyond asymptotic freedom?

Top-Down

rigorous fixed points in 4d:

exist for simple gauge theories with matter

exist for semi-simple gauge theories with matter

compatible with supersymmetry

exist for strongly coupled theories

Top-Down

template UV

Lagrangian

$$L_{\rm YM} = -\frac{1}{2}\,{\rm Tr}\,F^{\mu\nu}F_{\mu\nu} \qquad \text{SU(N)}$$

$$L_F = {\rm Tr}\,\left(\overline{Q}\,i\not{D}\,Q\right)$$

$$L_Y = y\,{\rm Tr}\,\left(\overline{Q}\,H\,Q\right) \qquad \text{fermions}$$

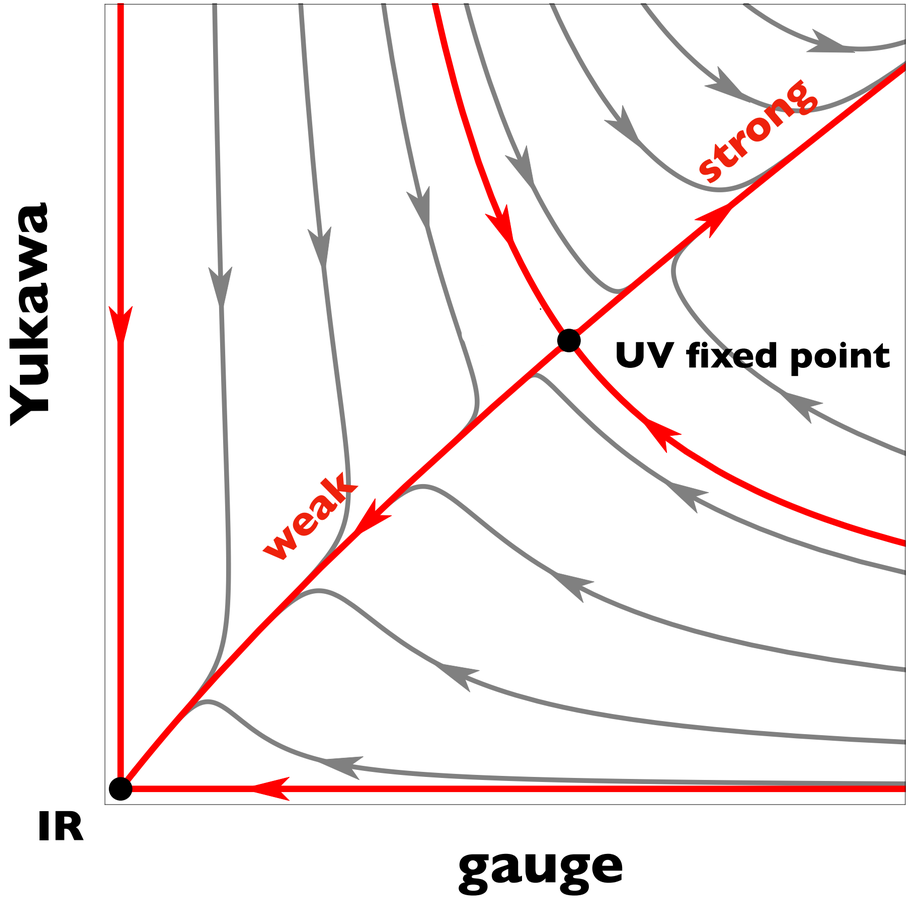
$$L_H = {\rm Tr}\,\left(\partial_\mu H^\dagger\,\partial^\mu H\right)$$

$$L_U = -u\,{\rm Tr}\,\left(H^\dagger H\right)^2 \qquad \text{scalars}$$

$$L_V = -v\,\left({\rm Tr}\,H^\dagger H\right)^2\,.$$

scalars are “meson-like”, H_ij

no asymptotic freedom, yet, stable and predictive
“UV complete”



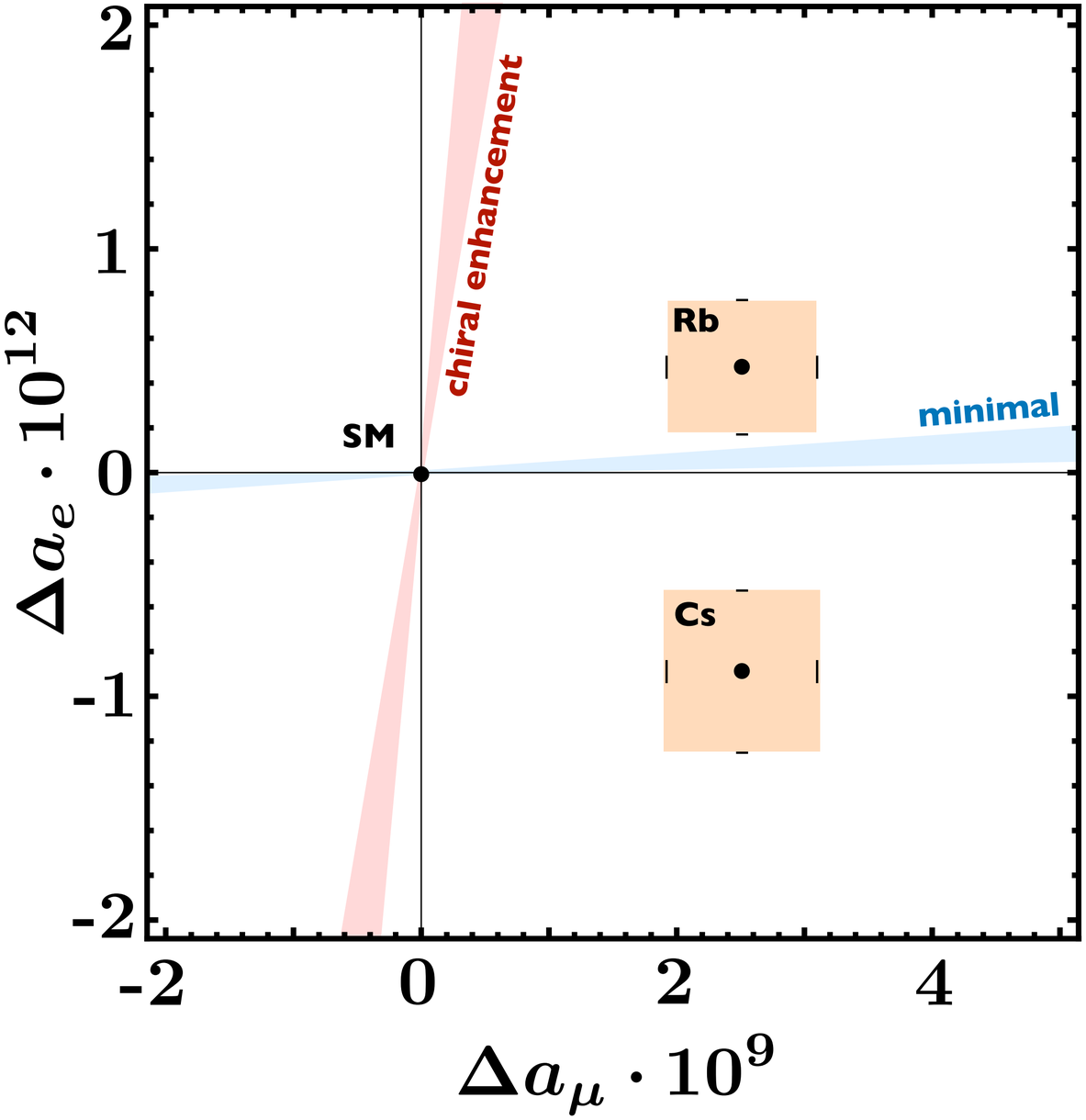
DF Litim, F Sannino, **Asymptotic Safety Guaranteed,** 1406.2337 (JHEP)

electron and muon anomalous magnetic moments

A Bond, G Hiller, K Kowalska, DF Litim,
Directions for model building from asymptotic safety, JHEP1708 (2017) 004

G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner,
Asymptotically safe extensions of the Standard Model and their flavour phenomenology 1905.11020
Anomalous magnetic moments from asymptotic safety 1910.14062
Model building from asymptotic safety with Higgs and flavour portals 2008.08606

AMMs



a puzzle …

what's the new physics?

to date: about < 100 BSM models can explain the muon and electron data simultaneously

All but ONE treat electrons and muons differently
i.e. **break lepton universality manifestly**

AMMs

inspired by UV fixed point:

matrix scalar field S
Nf = 3 vector-like fermions
new Yukawas + portal interactions

$$y\,\mathrm{Tr}\,[\overline{\psi}_L S \psi_R] + \kappa\,\overline{L} H \psi_R + \kappa'\,\mathrm{Tr}[\overline{E} S^\dagger \psi_L]$$

BSM matter

SM matter

feature 1: lepton universality intact

identify SM flavour symmetry
with BSM flavour symmetry

$$\kappa_{ij} = \kappa\,\delta_{ij}$$

AMMs

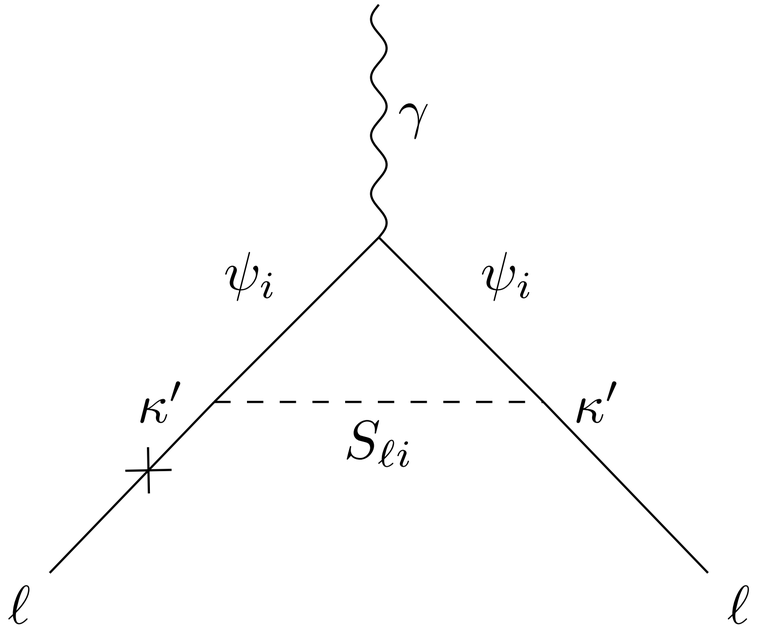
inspired by UV fixed point:

matrix scalar field S
Nf = 3 vector-like fermions
new Yukawas + portal interactions

$$y\,\mathrm{Tr}\,[\overline{\psi}_L S \psi_R] + \kappa\,\overline{L} H \psi_R + \kappa'\,\mathrm{Tr}[\overline{E} S^\dagger \psi_L]$$

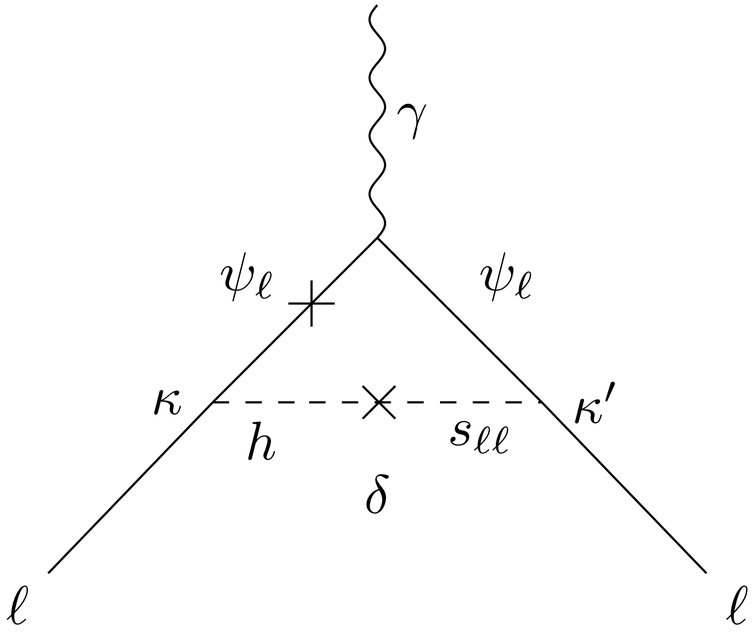
feature 2: **BSM Yukawas can explain anomalous magnetic moments**

AMMs



“minimal”

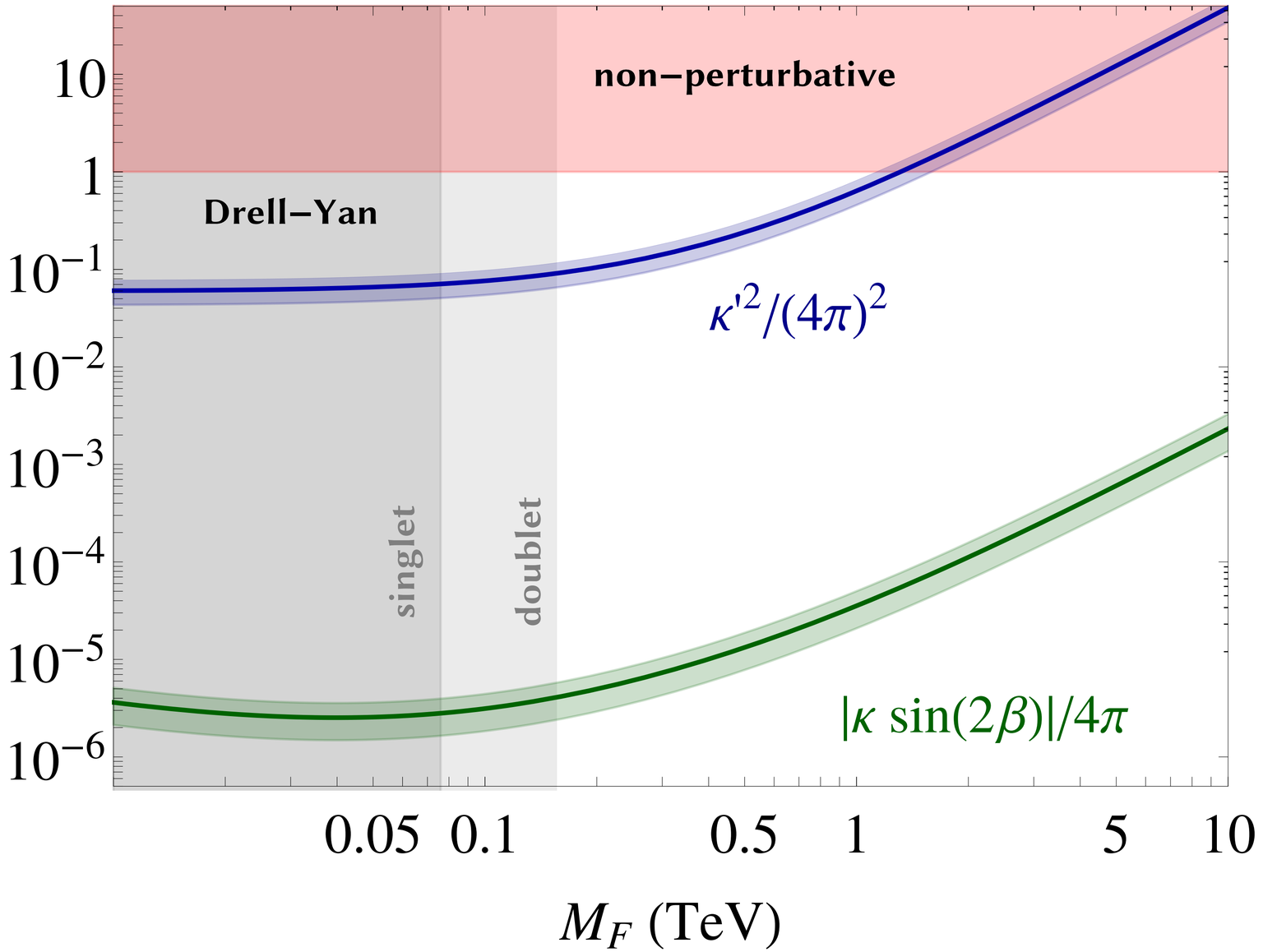
$$\sim (m_e/m_\mu)^2$$



“chirally enhanced”

$$\sim (m_e/m_\mu)$$

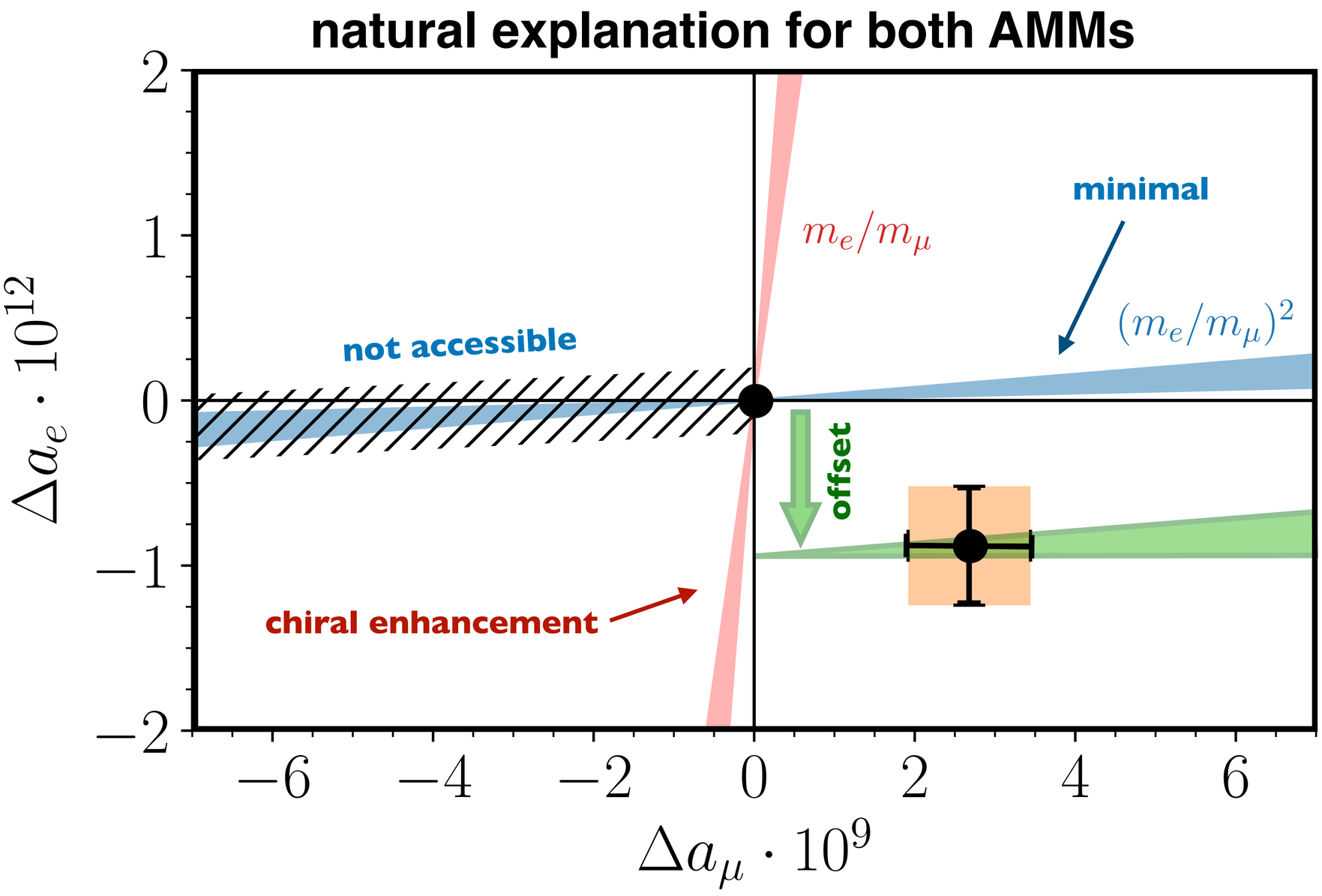
AMMs



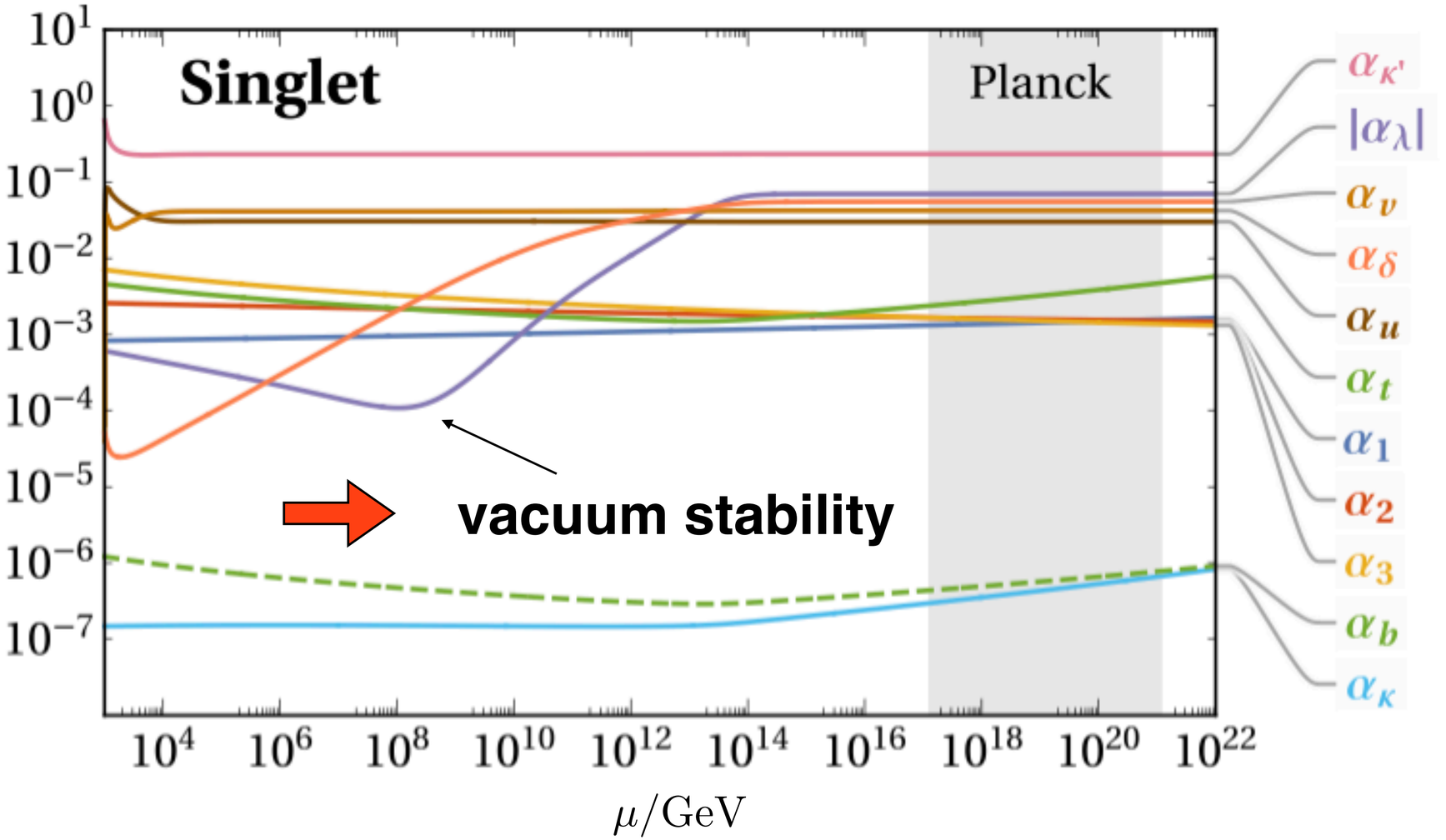
G Hiller, C Hermigos-Feliu, DF Litim, T Steudtner, **Anomalous magnetic moments from asymptotic safety** 1910.14062

Model building from asymptotic safety with Higgs and flavour portals 2008.08606

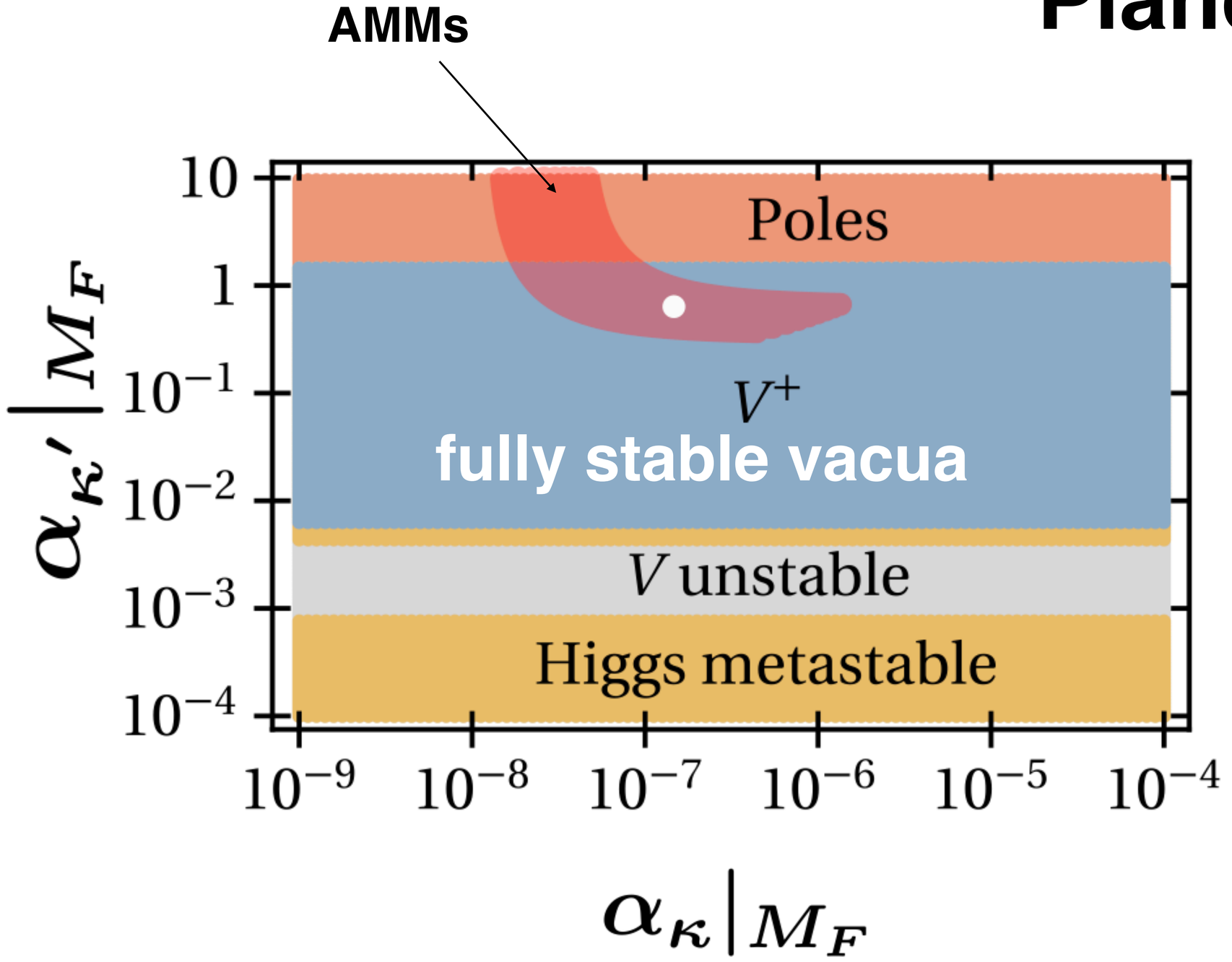
AMMs


natural explanation for both AMMs
$\Delta a_e \cdot 10^{12}$
$\Delta a_\mu \cdot 10^9$
2
1
0
−1
−2
−6
−4
−2
0
2
4
6
not accessible
m_e/m_μ
minimal
$(m_e/m_\mu)^2$
offset
chiral enhancement

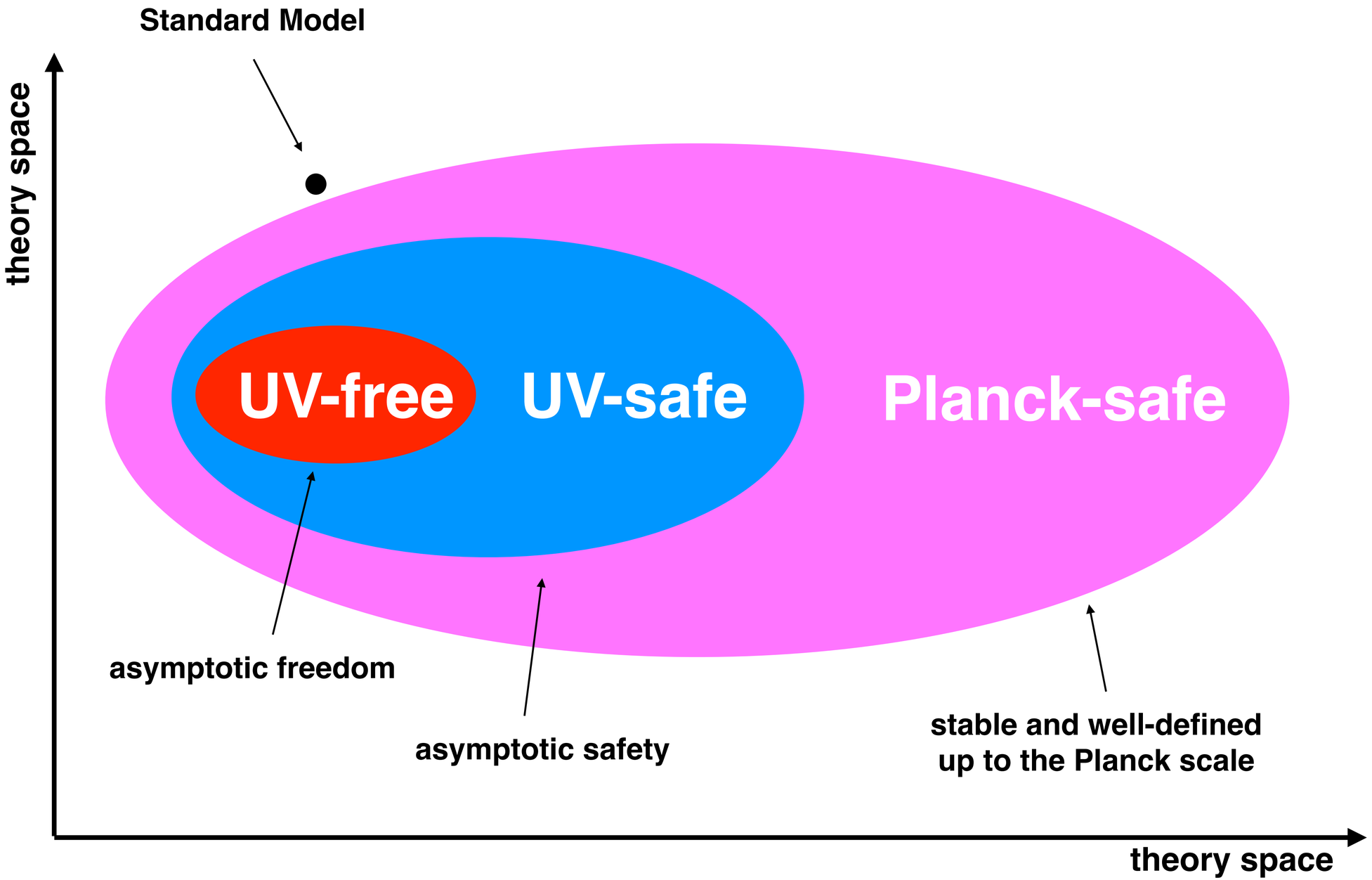
what's more


Singlet
Planck
vacuum stability
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22}
μ/GeV
$\alpha_{\kappa'}$
$|\alpha_\lambda|$
α_v
α_δ
α_u
α_t
α_1
α_2
α_3
α_b
α_κ

“Planck safe”


AMMs
Poles
V^+
fully stable vacua
V unstable
Higgs metastable
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\alpha_{\kappa'}|_{M_F}$
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
$\alpha_{\kappa}|_{M_F}$

Conclusions



Conclusions

Quo vadis model building?

Bottom-Up — **turn SM metastability into BSM task**

various portals, constraining power
new BSM matter as light as TeV
can be searched for at colliders

Top-Down — **new opportunities from UV fixed points**

exploit ideas beyond asymptotic freedom

Outlook — **“quantum gravity connection”**

learn how quantum gravity kicks in
constraining power

Thank you!