BSM from vacuum stability

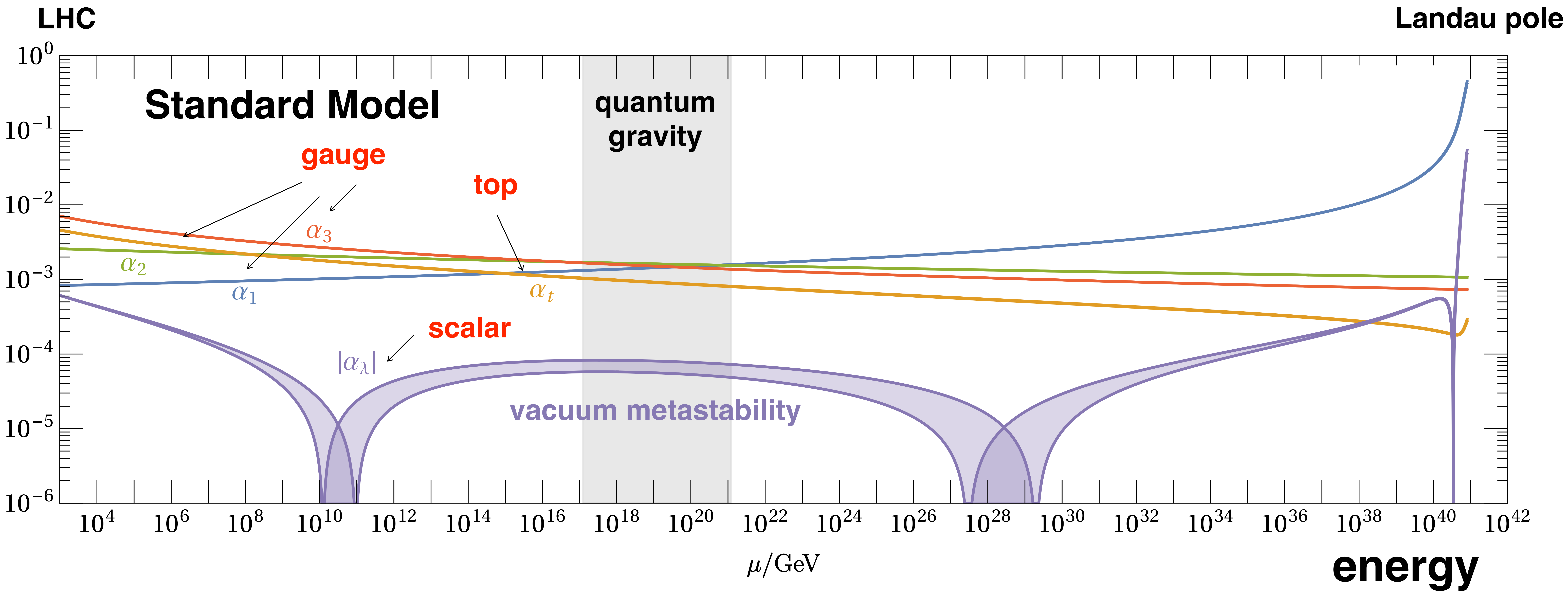
Daniel Litim

University of Sussex

based on works with Gudrun Hiller, Tim Hoehne, and Tom Steudtner

Moriond EW
27 Mar 25

where are we?



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

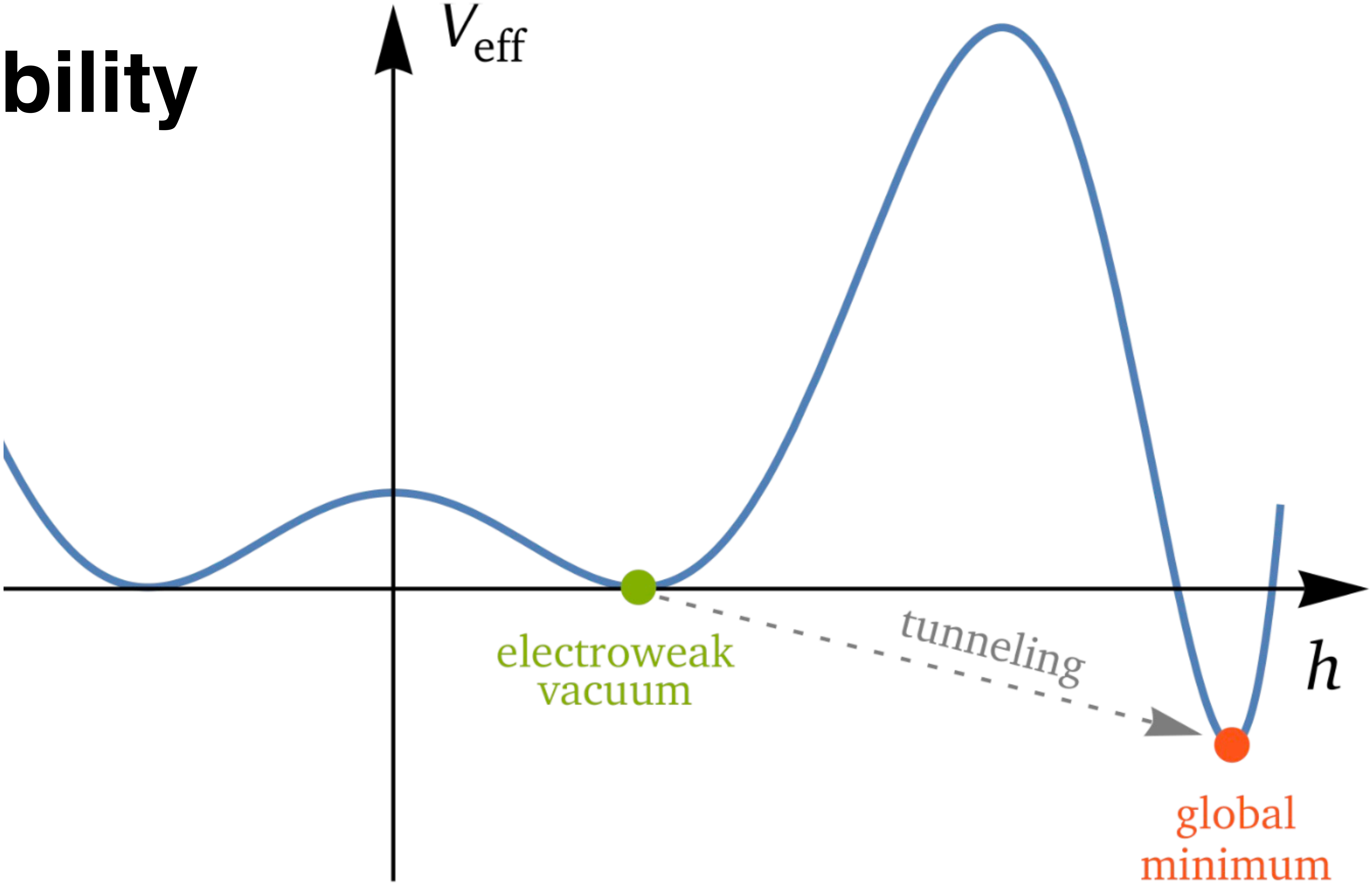
Higgs quartic

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

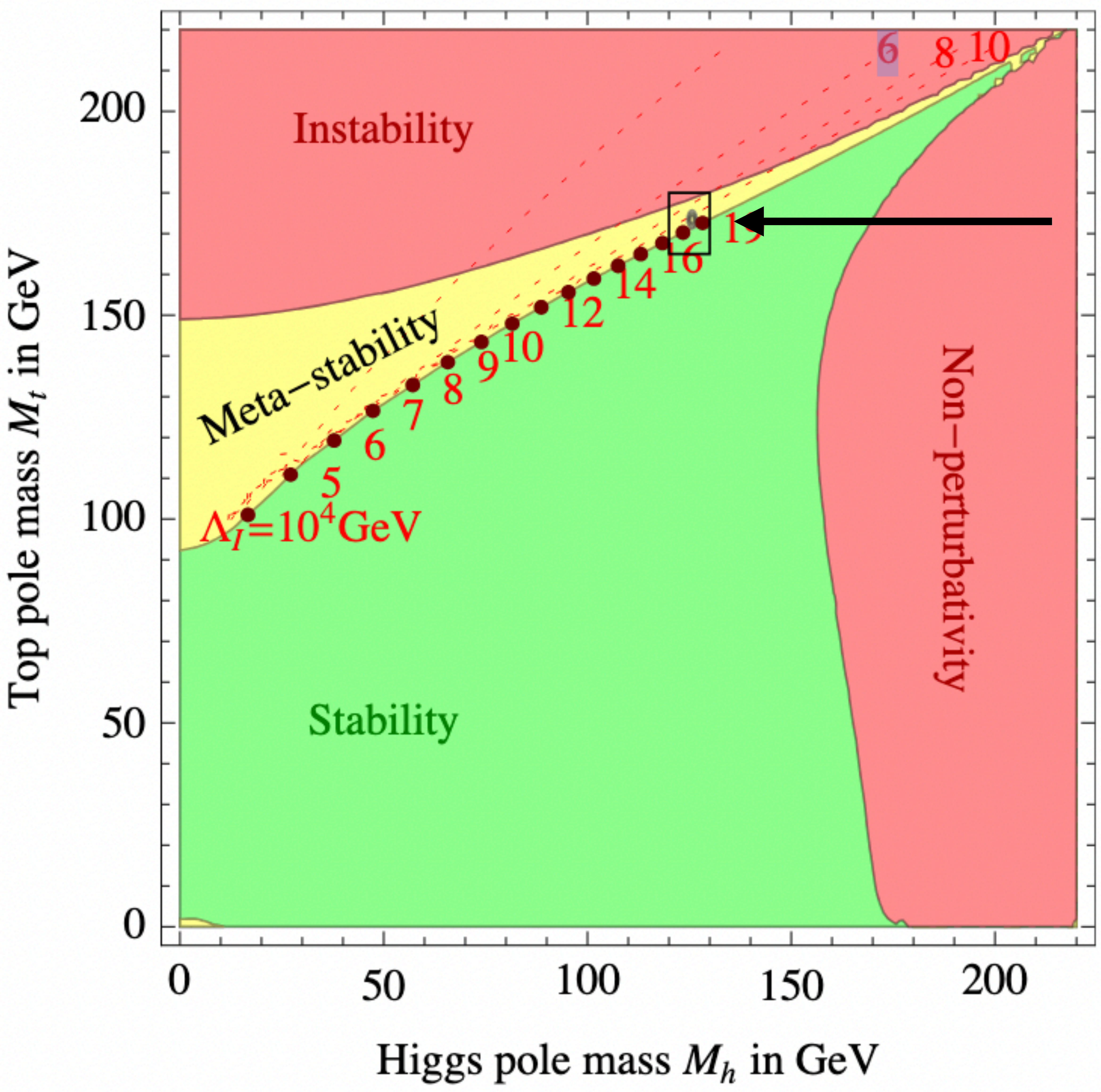
vacuum metastability



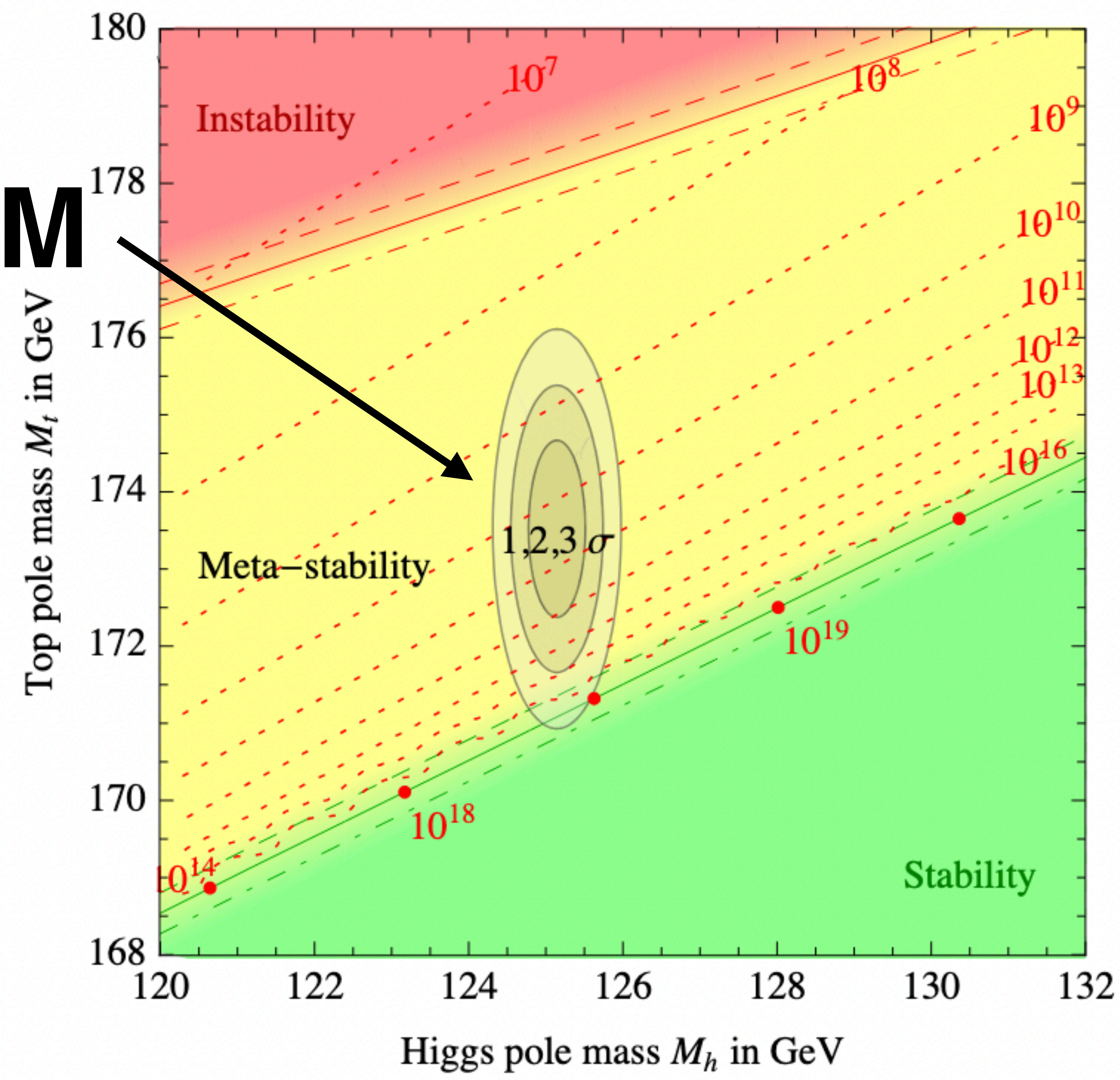
Plot taken from T Steudtner @ “Asymptotic Safety Meets Particle Physics” (Desy ’24)

SM vacuum stability 2012

(Degrassi et al. 1205.6497v2)
Buttazzo et al. 1307.3536v4



SM



Plots taken from Buttazzo et al. 1307.3536v4

Q: can we ascertain or refute vacuum stability at the 5-sigma level?

SM vacuum stability revisited

Input from theory:

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

$$\frac{1}{(4\pi)^2} V_{\rm eff} = \frac{1}{4} \alpha_{\lambda,\rm eff}(h) e^{4\bar{\Gamma}(h)} h^4 .$$

stability: $\alpha_{\lambda,\rm eff} > 0$

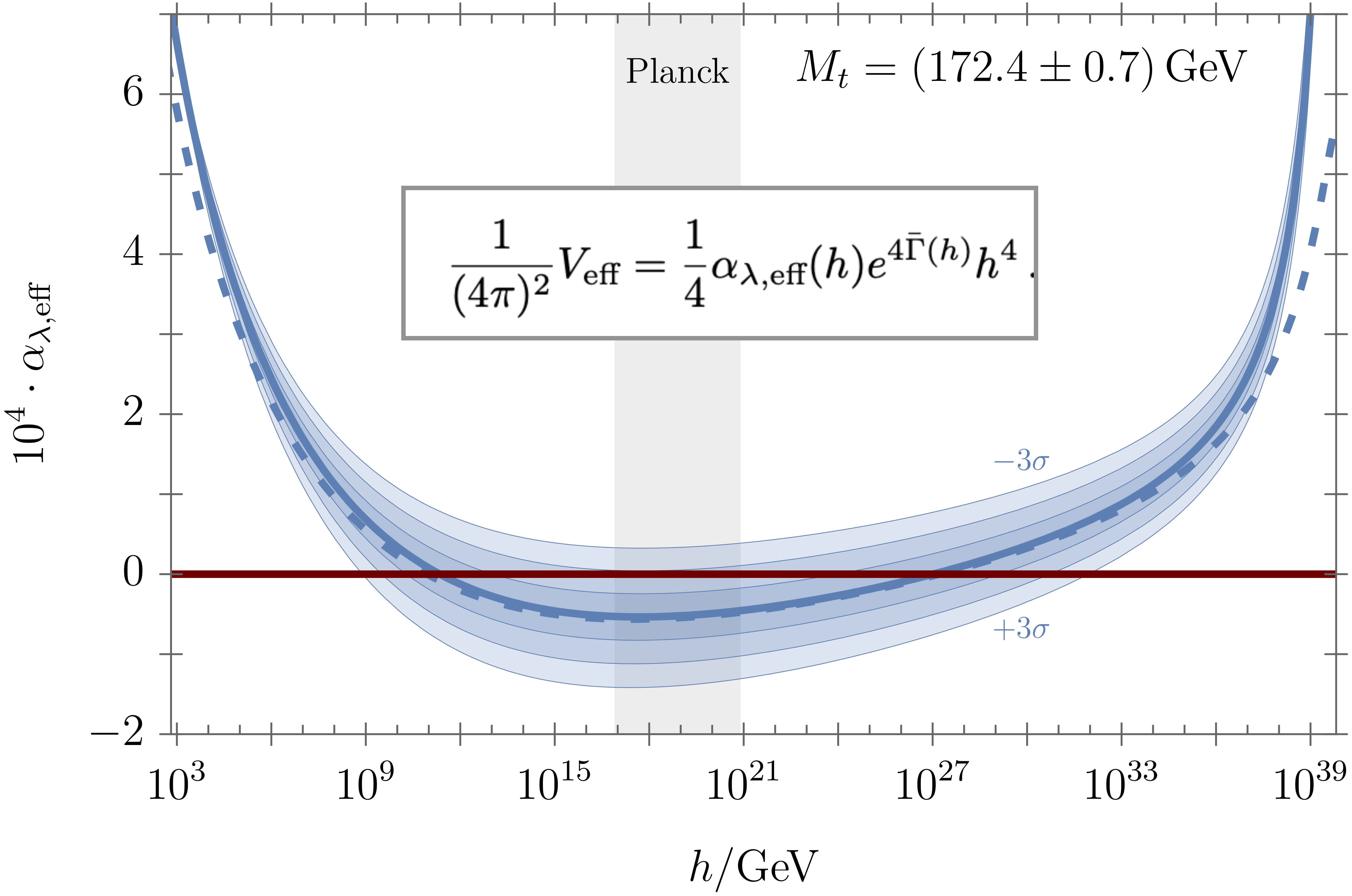
matching observables to MSbar

at least 2L (+ 3L QCD) Martin, Patel '18

matching at reference scale $\mu_{\rm ref} = 200\,{\rm GeV}$

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

SM vacuum stability revisited



Stability is dominated by RG running

SM vacuum stability revisited

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

Input from experiment: observables that determine vacuum stability

Z, Higgs, Top pole mass	$M_Z \quad M_h \quad M_t$
strong coupling	$\alpha_s^{(5)}(\mu = M_Z)$
fine structure constant	$\alpha_e \quad \Delta\alpha_e^{(5),\mathrm{had.}}$
Fermi constant	G_F
lepton masses	$M_{e,\mu,\tau}$
light quark masses	$m_b(\mu = m_b)$ $m_c(\mu = m_c)$ $m_{u,d,s}(\mu = 2\,\mathrm{GeV})$

data from PDG 2024

SM vacuum stability revisited

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

Input from experiment: observables that determine vacuum stability

Z, Higgs, Top pole mass	M_Z M_h M_t	most relevant
strong coupling	$\alpha_s^{(5)}(\mu = M_Z)$	
fine structure constant	α_e $\Delta\alpha_e^{(5),\text{had.}}$	uncertainty small
Fermi constant	G_F	
lepton masses	$M_{e,\mu,\tau}$	impact small
light quark masses	$m_b(\mu = m_b)$ $m_c(\mu = m_c)$ $m_{u,d,s}(\mu = 2\,\text{GeV})$	

SM vacuum stability revisited

Obs.	Value	$\alpha_\lambda > 0$	$\alpha_{\lambda,\mathrm{eff}} > 0$
PDG 2024 [69]:			
M_h/GeV	125.20(11)	127.97 $+25.2\sigma$	127.85 $+24.0\sigma$
M_t^σ/GeV	172.4(7)	171.04 $-\ 1.9\sigma$	171.10 $-\ 1.9\sigma$
$M_t^{\mathrm{MC}}/\mathrm{GeV}$	172.57(29)	$-\ 5.3\sigma$	$-\ 5.1\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.3 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1215 $+\ 3.9\sigma$	0.1213 $+\ 3.7\sigma$
PDG 2023 [9]:			
M_h/GeV	125.25(17)	128.17 $+17.2\sigma$	128.05 $+16.5\sigma$
M_t^σ/GeV	172.5(7)	171.06 $-\ 2.1\sigma$	171.13 $-\ 2.0\sigma$
$M_t^{\mathrm{MC}}/\mathrm{GeV}$	172.69(30)	$-\ 5.4\sigma$	$-\ 5.2\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.4 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1217 $+\ 4.1\sigma$	0.1215 $+\ 3.9\sigma$
CMS [1904.05237]			
M_t/GeV	170.5(8)	169.25 $-\ 1.6\sigma$	169.31 $-\ 1.5\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1135(^{+21}_{-17})$	0.1167 $+\ 1.5\sigma$	0.1165 $+\ 1.4\sigma$

uncertainty small

most relevant

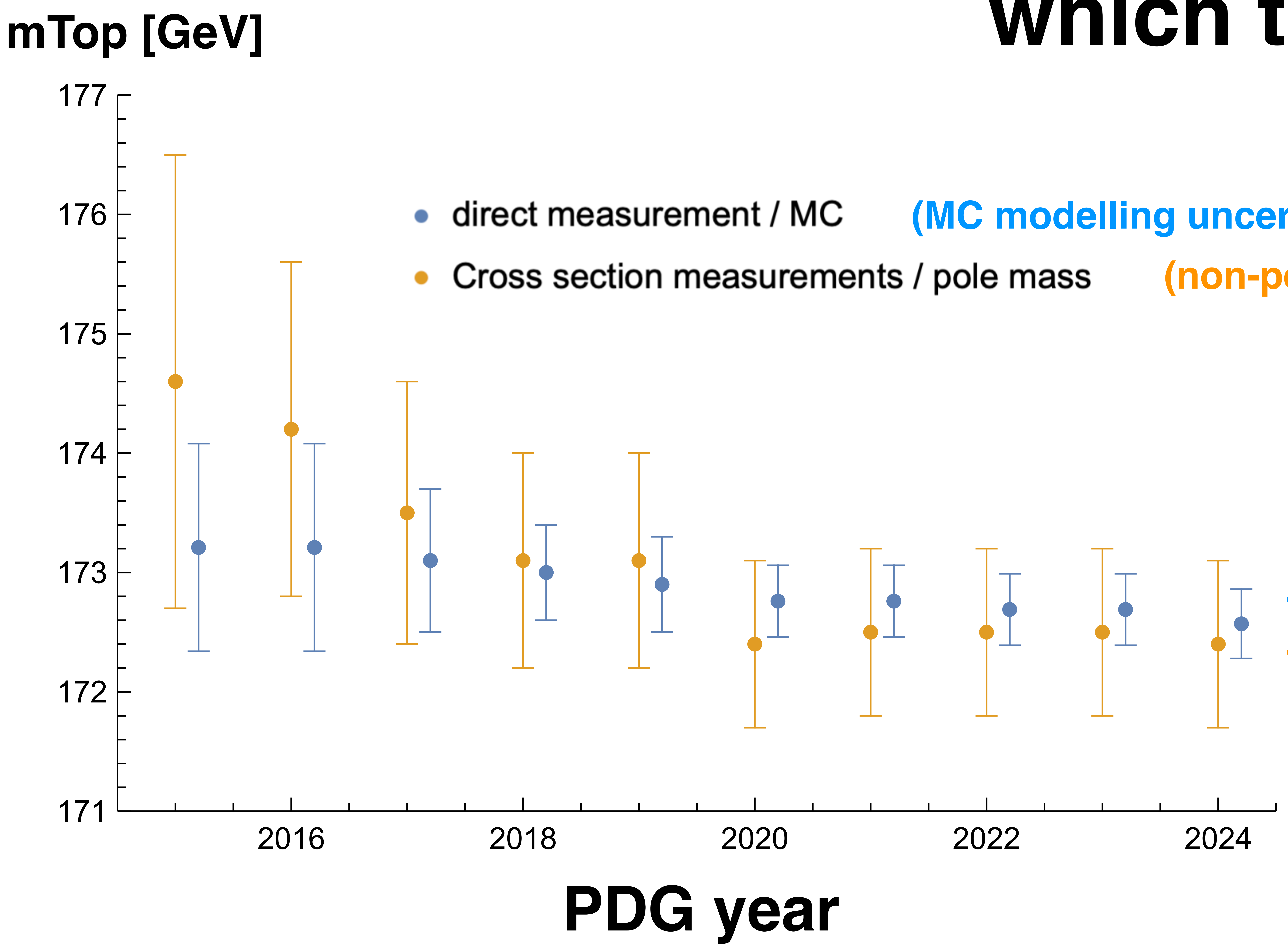
SM vacuum stability revisited

Obs.	Value	$\alpha_\lambda > 0$	$\alpha_{\lambda,\mathrm{eff}} > 0$
PDG 2024 [69]:			
M_h/GeV	125.20(11)	127.97 $+25.2\sigma$	127.85 $+24.0\sigma$
M_t^σ/GeV	172.4(7)	171.04 $-\ 1.9\sigma$	171.10 $-\ 1.9\sigma$
$M_t^{\mathrm{MC}}/\mathrm{GeV}$	172.57(29)	$-\ 5.3\sigma$	$-\ 5.1\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.3 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1215 $+\ 3.9\sigma$	0.1213 $+\ 3.7\sigma$
PDG 2023 [9]:			
M_h/GeV	125.25(17)	128.17 $+17.2\sigma$	128.05 $+16.5\sigma$
M_t^σ/GeV	172.5(7)	171.06 $-\ 2.1\sigma$	171.13 $-\ 2.0\sigma$
$M_t^{\mathrm{MC}}/\mathrm{GeV}$	172.69(30)	$-\ 5.4\sigma$	$-\ 5.2\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.4 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1217 $+\ 4.1\sigma$	0.1215 $+\ 3.9\sigma$
CMS [1904.05237]			
M_t/GeV	170.5(8)	169.25 $-\ 1.6\sigma$	169.31 $-\ 1.5\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1135(^{+21}_{-17})$	0.1167 $+\ 1.5\sigma$	0.1165 $+\ 1.4\sigma$

cross section / pole mass

direct / MC mass

which top mass?



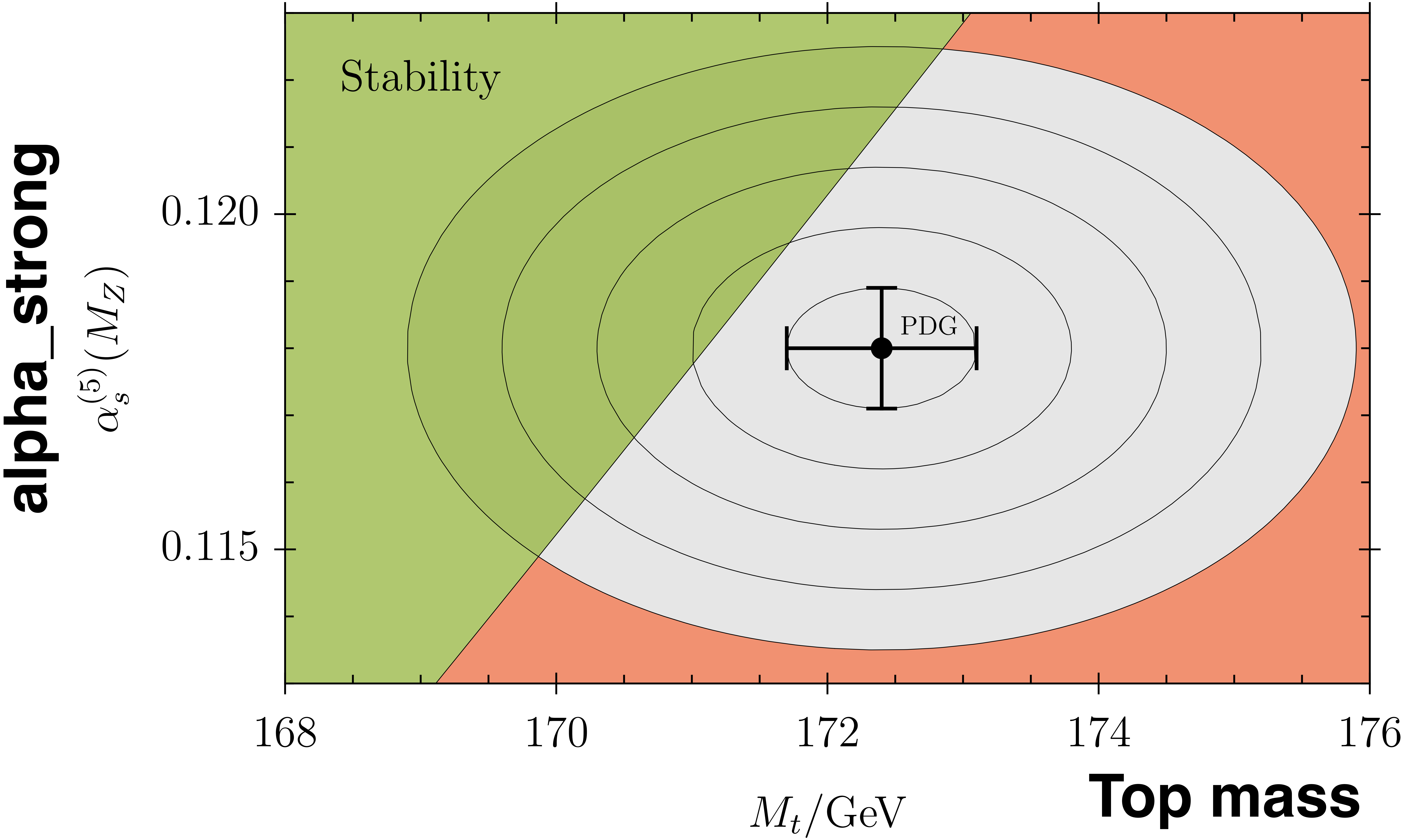
(MC modelling uncertainty +/- 500 MeV)

(non-perturbative effects)

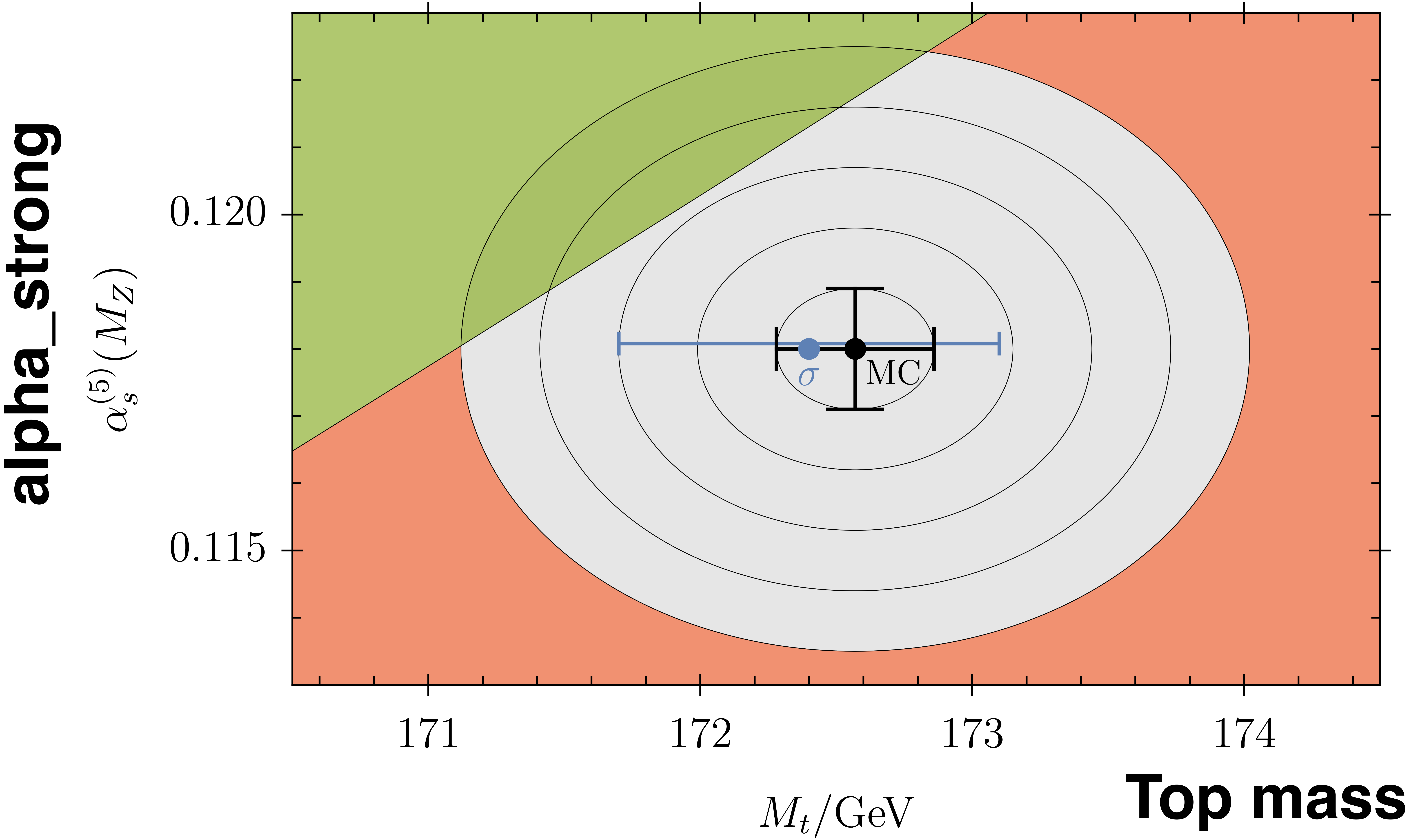
172.57(29) GeV

172.40(70) GeV

SM vacuum stability



SM vacuum stability



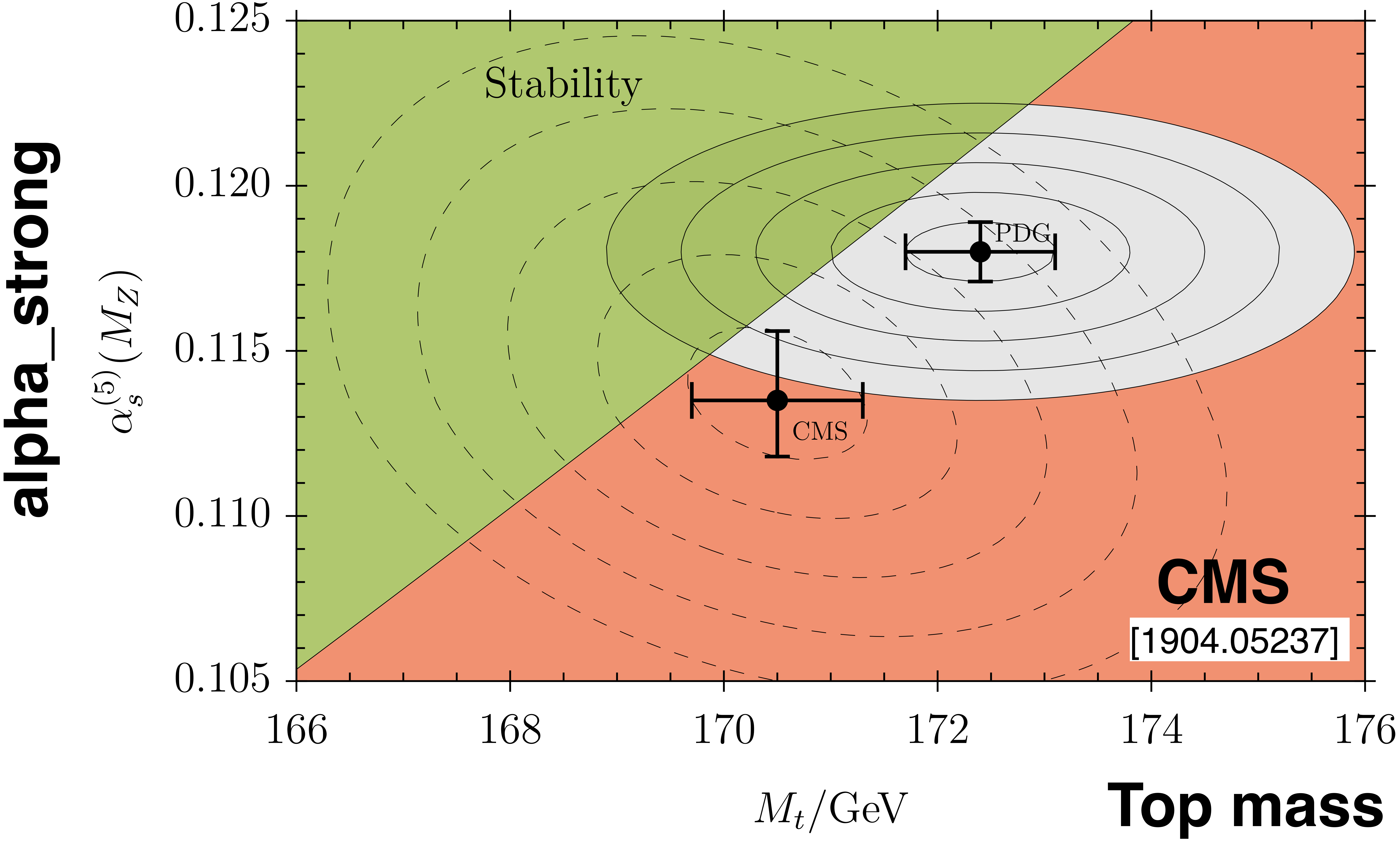
SM vacuum stability revisited

Obs.	Value	$\alpha_\lambda > 0$	$\alpha_{\lambda,\text{eff}} > 0$
PDG 2024 [69]:			
M_h/GeV	125.20(11)	127.97 $+25.2\sigma$	127.85 $+24.0\sigma$
M_t^σ/GeV	172.4(7)	171.04 $-\ 1.9\sigma$	171.10 $-\ 1.9\sigma$
$M_t^{\text{MC}}/\text{GeV}$	172.57(29)	$-\ 5.3\sigma$	$-\ 5.1\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.3 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1215 $+\ 3.9\sigma$	0.1213 $+\ 3.7\sigma$
PDG 2023 [9]:			
M_h/GeV	125.25(17)	128.17 $+17.2\sigma$	128.05 $+16.5\sigma$
M_t^σ/GeV	172.5(7)	171.06 $-\ 2.1\sigma$	171.13 $-\ 2.0\sigma$
$M_t^{\text{MC}}/\text{GeV}$	172.69(30)	$-\ 5.4\sigma$	$-\ 5.2\sigma$
m_t/GeV	$162.5(^{+2.1}_{-1.5})$	161.4 $-\ 0.8\sigma$	161.4 $-\ 0.7\sigma$
$\alpha_s^{(5)}(M_Z)$	0.1180(9)	0.1217 $+\ 4.1\sigma$	0.1215 $+\ 3.9\sigma$
CMS [1904.05237]			
M_t/GeV	170.5(8)	169.25 $-\ 1.6\sigma$	169.31 $-\ 1.5\sigma$
$\alpha_s^{(5)}(M_Z)$	$0.1135(^{+21}_{-17})$	0.1167 $+\ 1.5\sigma$	0.1165 $+\ 1.4\sigma$

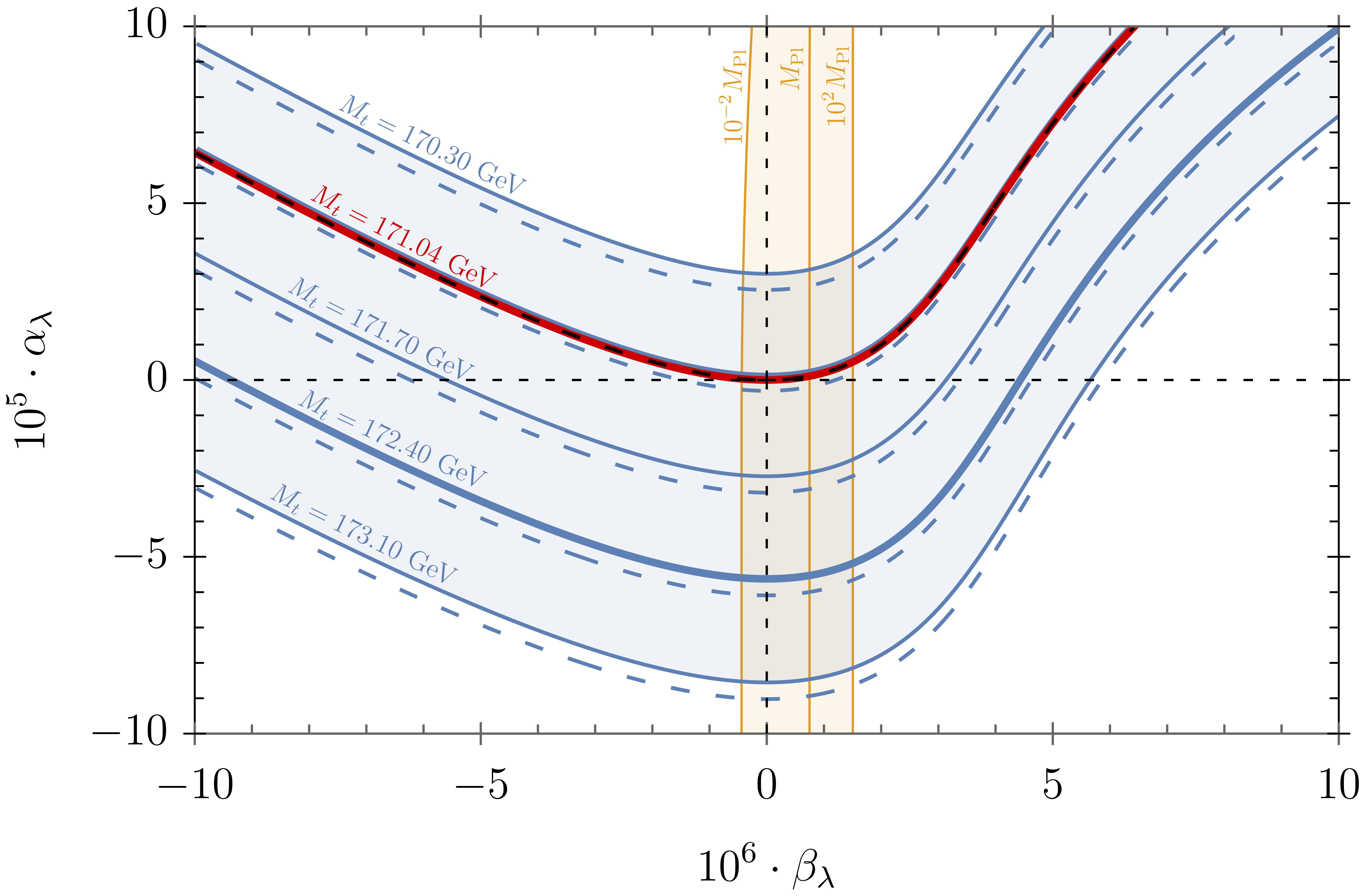
PDG: no correlations

CMS: correlations

correlations



accuracy



comparison of 222 vs 433 loop running

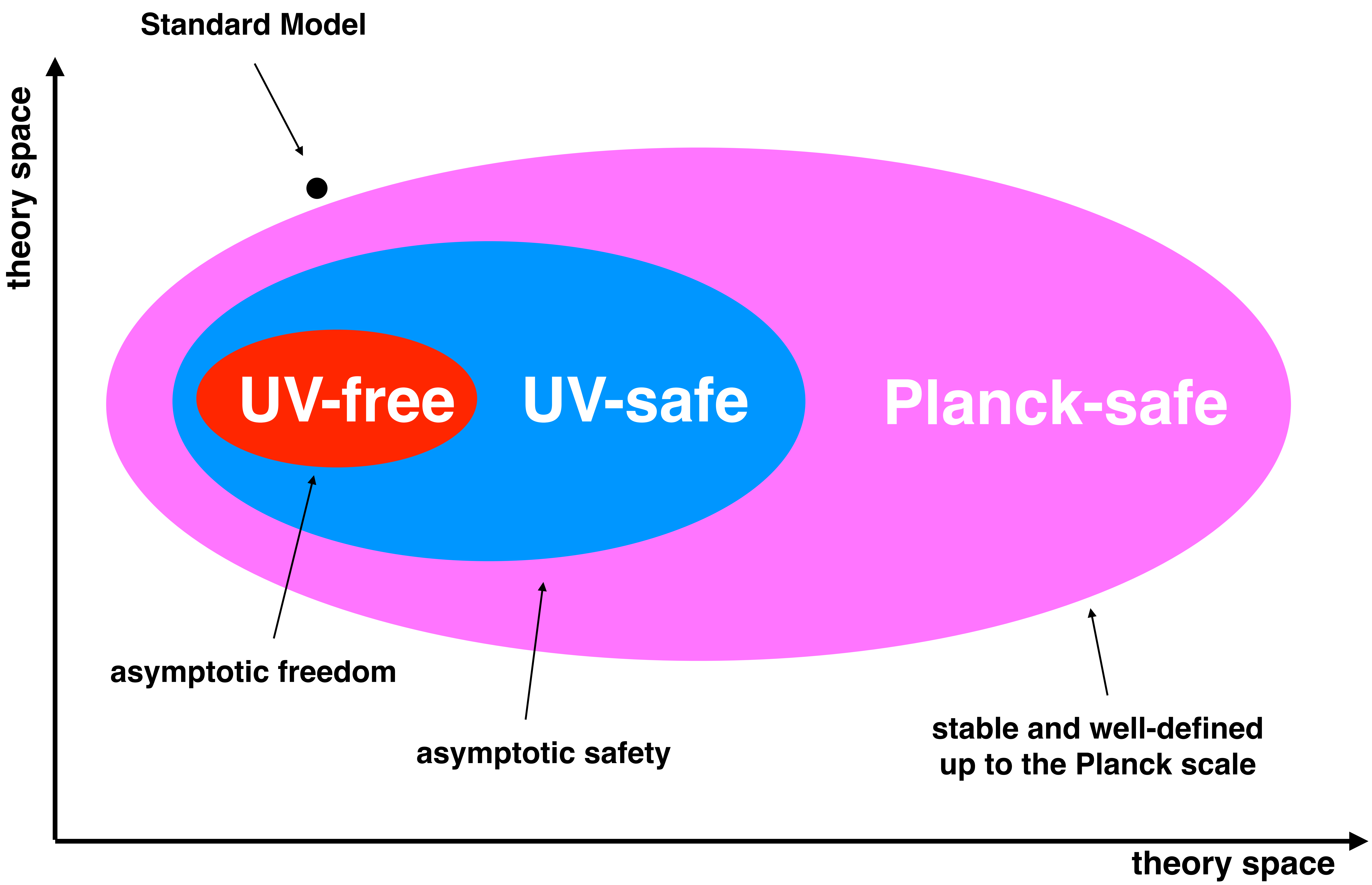
uncertainties dominated by central values and errors for top mass and strong coupling constant

Q: What does it take to

achieve vacuum stability?

… and make it safely up to the Planck scale?

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

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''

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

Portals into Stability

Gauge Portals **Yukawa Portals**

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

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

Yukawa (κ), VLFs ($\bar{\psi}$), Higgs (H), SM fermion ($f_{\rm SM}$)

⟶ new interactions

⟶ new RG beta functions
modified RG running

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

Portals into Stability

Gauge Portals

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

Yukawa Portals

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

Higgs Portals

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

Portals → δ_i; Higgs → H; BSM scalars → S_i

→ new scalars

→ new interactions

→ new RG beta functions
modified RG running

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

Higgs Portals

Main new RG effect

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

``good”

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

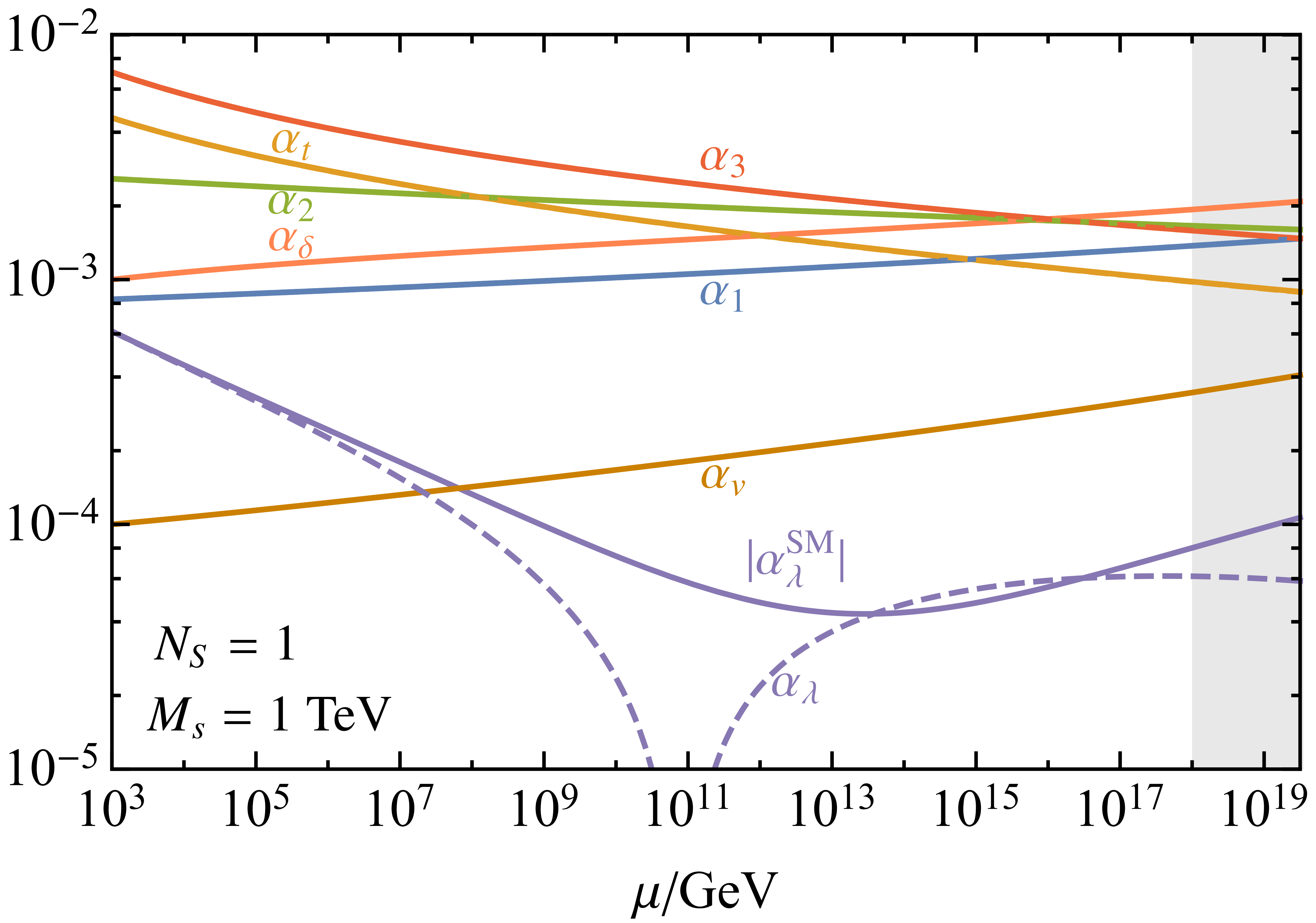
$$\alpha_\lambda(\Lambda) - \alpha_\lambda^{\rm SM}(\Lambda) \propto \sum_i 2\, N_i\, \alpha_{\delta_i}^2 > 0$$

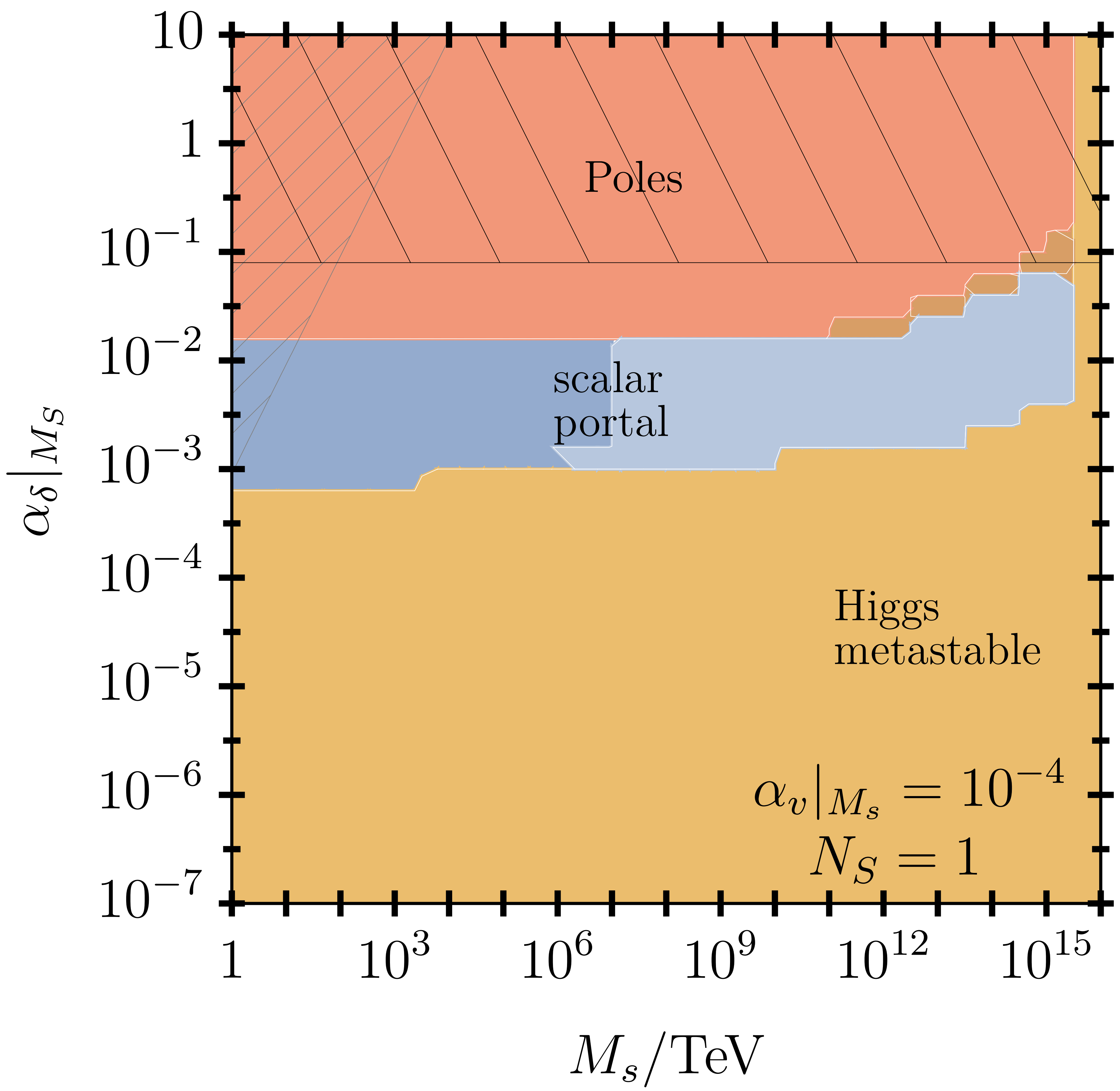
genuine uplift

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

Higgs Portals

single real BSM scalar



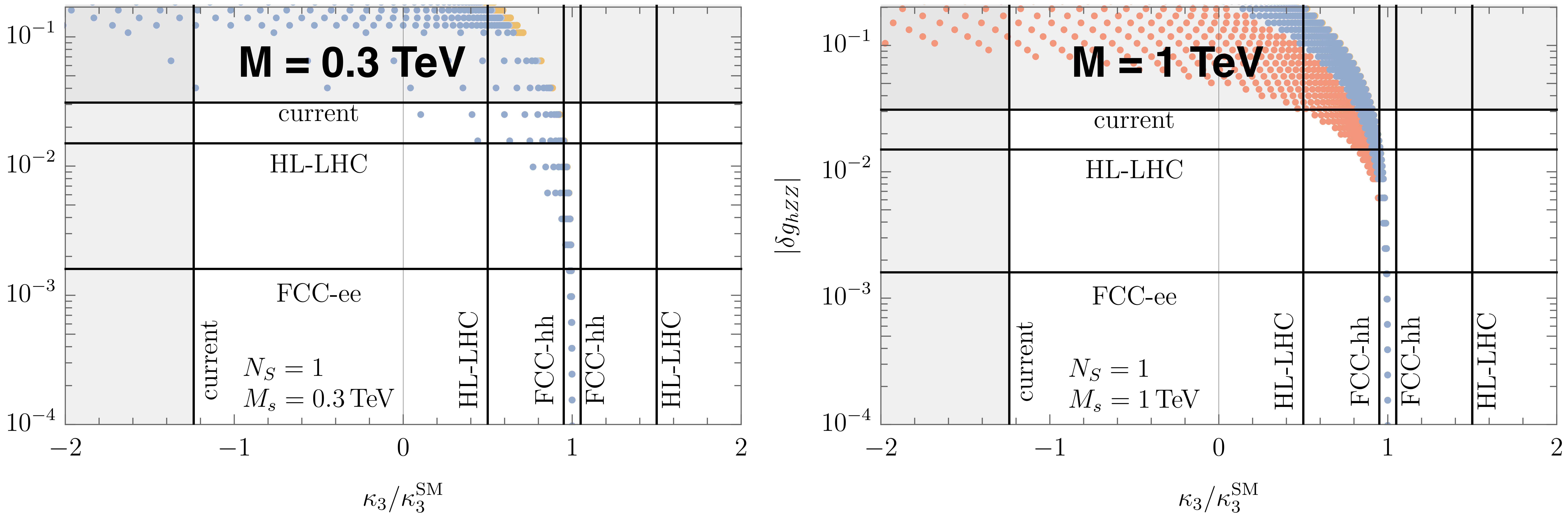


G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

Higgs Portals

Signatures

BSM scalar obtains VEV
modified hZZ, 3h vertices → FCC-ee

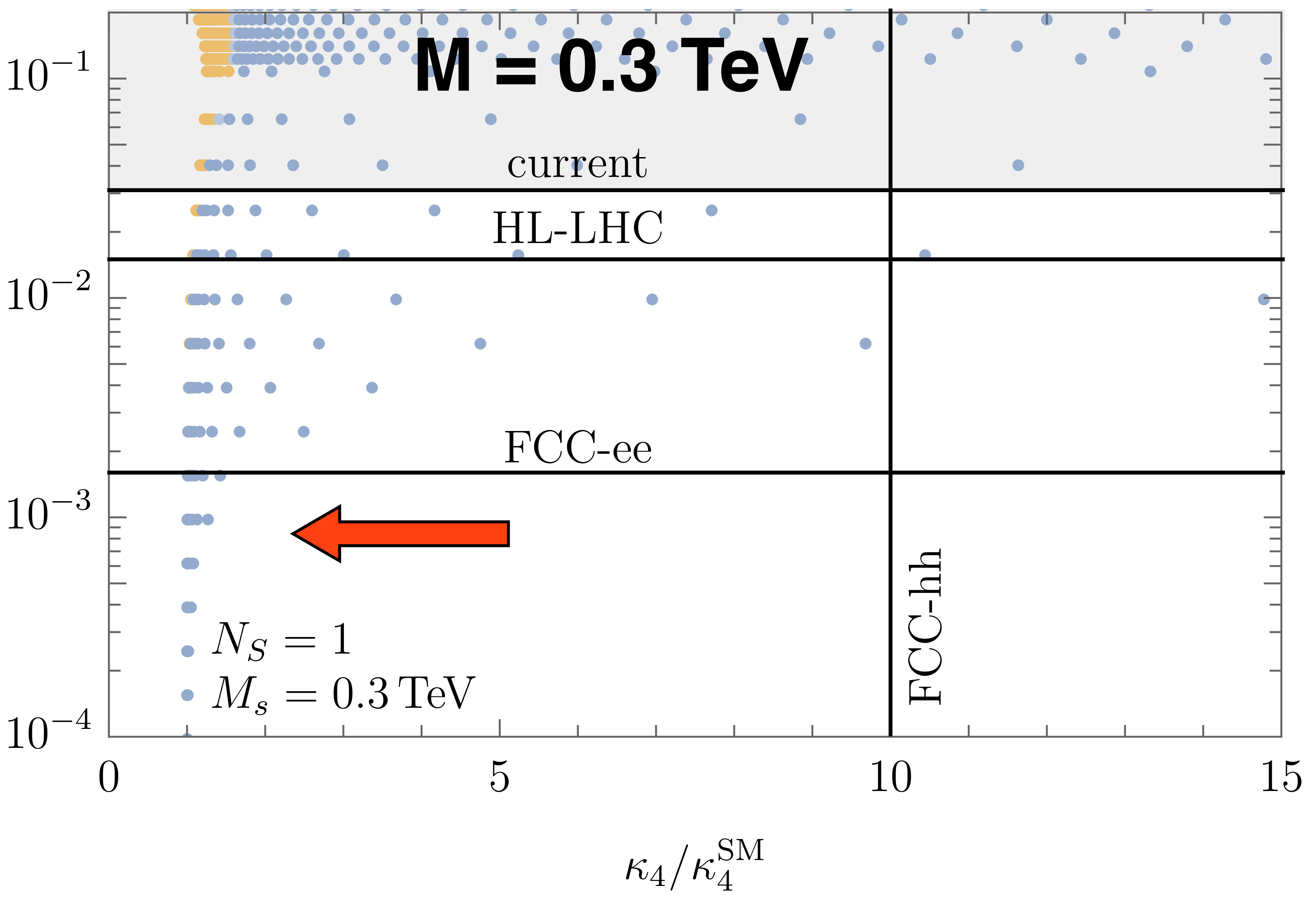


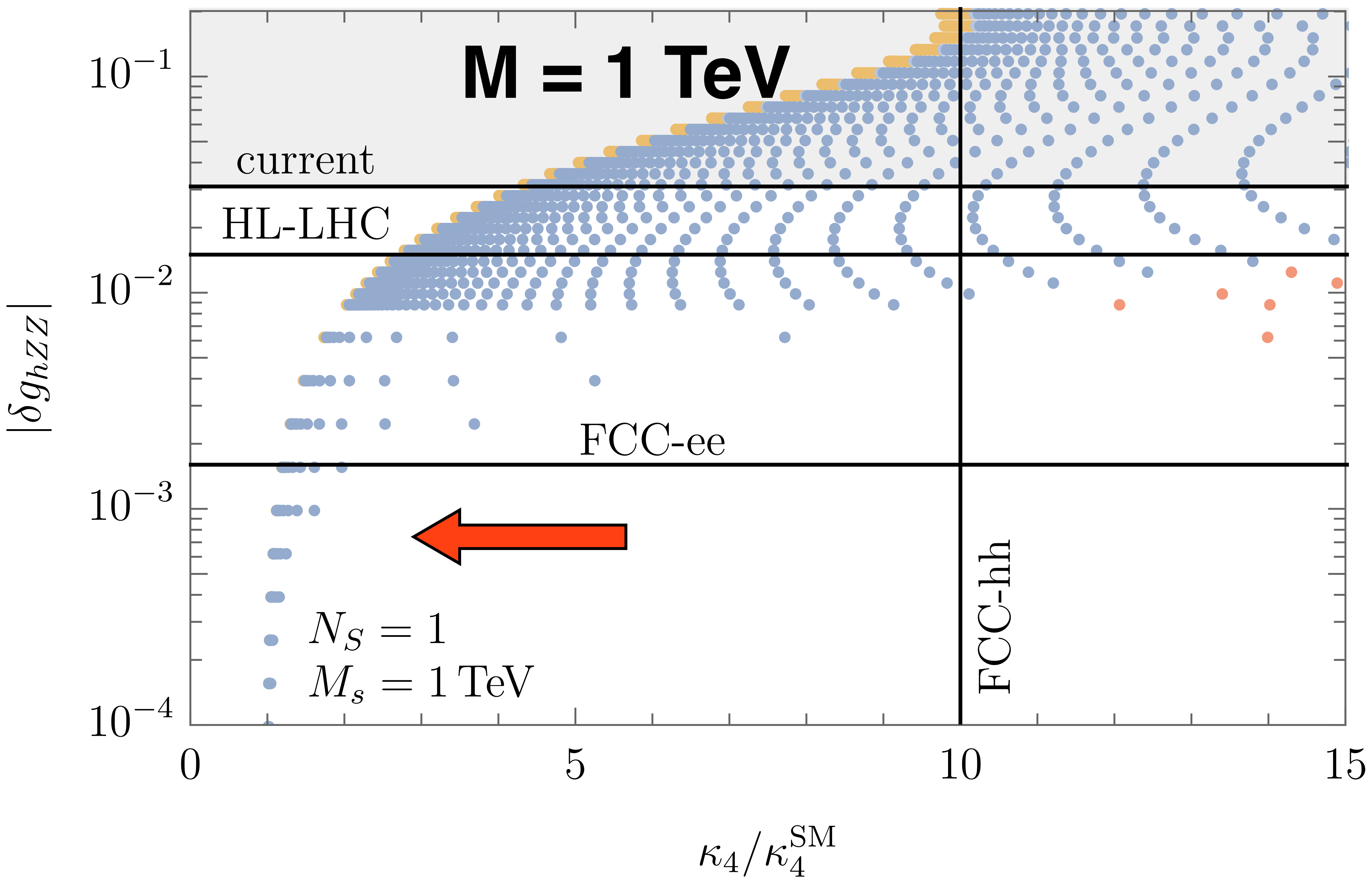
G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

Higgs Portals

Signatures

BSM scalar obtains VEV
modified 4h vertices → **FCC-ee** **FCC-hh**



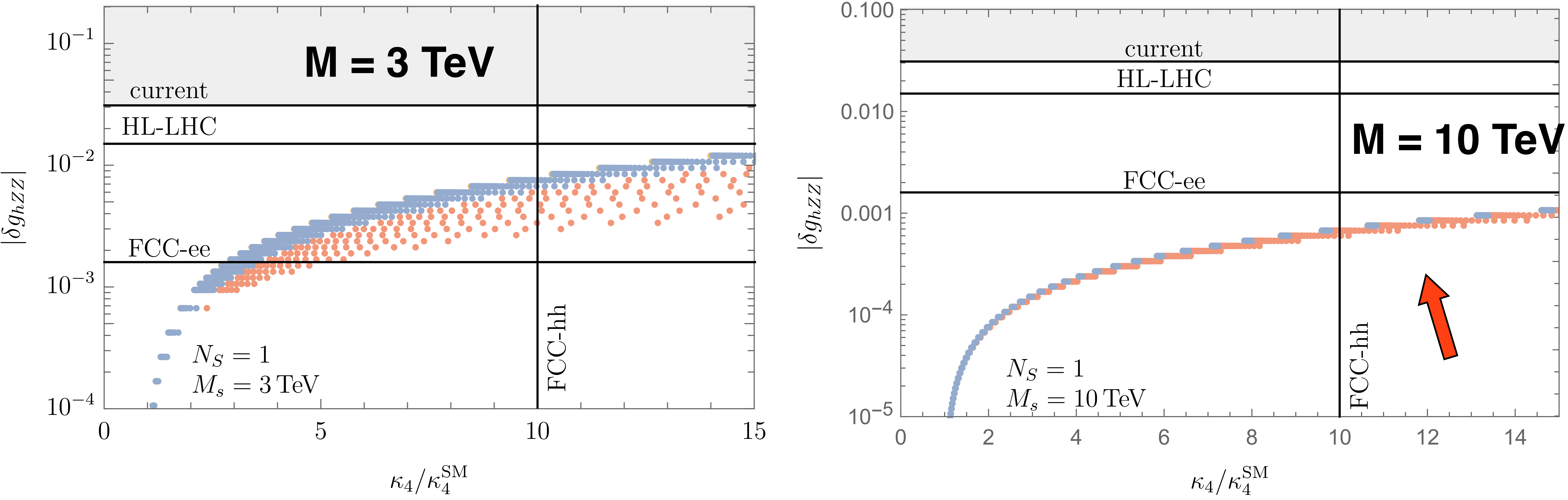


G Hiller, T Hoehne, DF Litim, T Steudtner, **Vacuum stability in the SM and beyond** 2401.08811

Higgs Portals

Signatures

BSM scalar obtains VEV
modified 4h vertices
higher mass → FCC-hh O(1) effects



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

conclusions

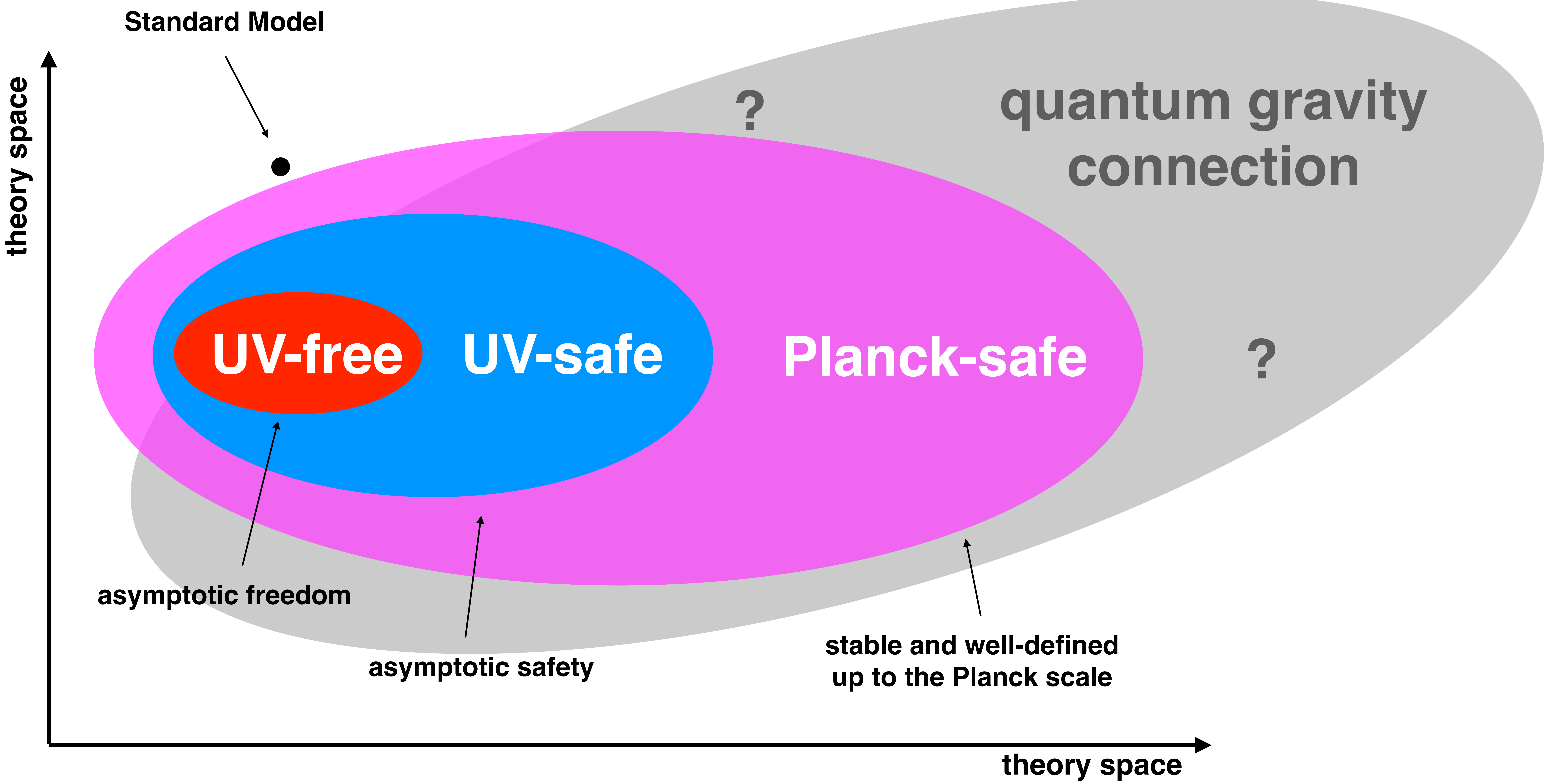
status of SM metastability

evidence for metastability persists
uncertainty dominated by top mass and strong coupling
5-sigma necessitates precision extractions
correlations matter

turn SM metastability into BSM task

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

Outlook


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