Vacuum Stability in the Standard Model and Beyond

Tom Steudtner
Technische Universität Dortmund

in collabortation with
Gudrun Hiller, Tim Höhne, Daniel Litim
[arXiv 2401.08811]

TOP 2024
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Motivation

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» Higgs discovery in 2012 [ATLAS,CMS 2012] $\longrightarrow$ Metastability [Buttazzo et al, 2013]

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Outline

» Stability in the SM – An update
» BSM solutions

How to compute vacuum stability

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   - Higgs mass M_h
   - Top mass M_t
   - Strong coupling $\alpha_s^{(5)}(M_Z)$
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   - Fine structure & hadronic threshold $\alpha_e,\ \Delta\alpha_e^{(5),\text{had}}$
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PDG 2024

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   at least 2L + 3L QCD [Martin, Patel, 2018]

   $\longrightarrow$ running couplings at a referce scale $\alpha_x(\mu_{\mathrm{ref}})$

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   → minima

4. ~~Compute Decay Rate for Metastability~~

   only interested in absolute stability

Effective Potential

– pontential of classical field h & quantum effects, RG invariant, physical extrema

$$V_{\text{eff}}(h,\, \mu) = \tfrac{1}{4}\lambda(\mu)h^4 + \mathcal{O}(\alpha^2)$$

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$$\bar{\alpha}_i(h_0) = \alpha_i(\mu_{\text{ref}}) \qquad \bar{\beta}_i(\bar{\alpha}) \equiv \frac{\partial\bar{\alpha}_i(h)}{\partial\ln h} = \frac{\beta_i(\bar{\alpha})}{1+\gamma(\bar{\alpha})} \qquad \bar{\Gamma}(h,h_0) = \int_{h_0}^{h}\frac{\mathrm{d}h'}{h'}\frac{\gamma(\bar{\alpha})}{1+\gamma(\bar{\alpha})}$$

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– evolve λ_{eff} to $h \gg h_0$

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4L gauge (+ 5L QCD)

[Davies,Herren,Poole,Steinhauser,Thomsen, 2019]

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$\longrightarrow$ completely resum all logs $\ln h/\mu_{\text{ref}}$

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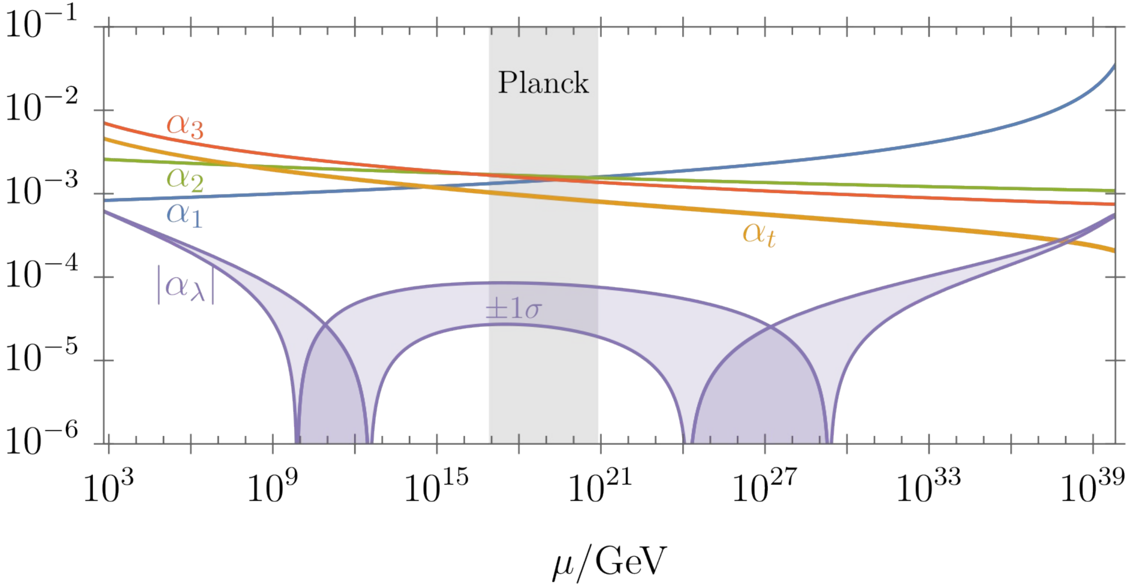

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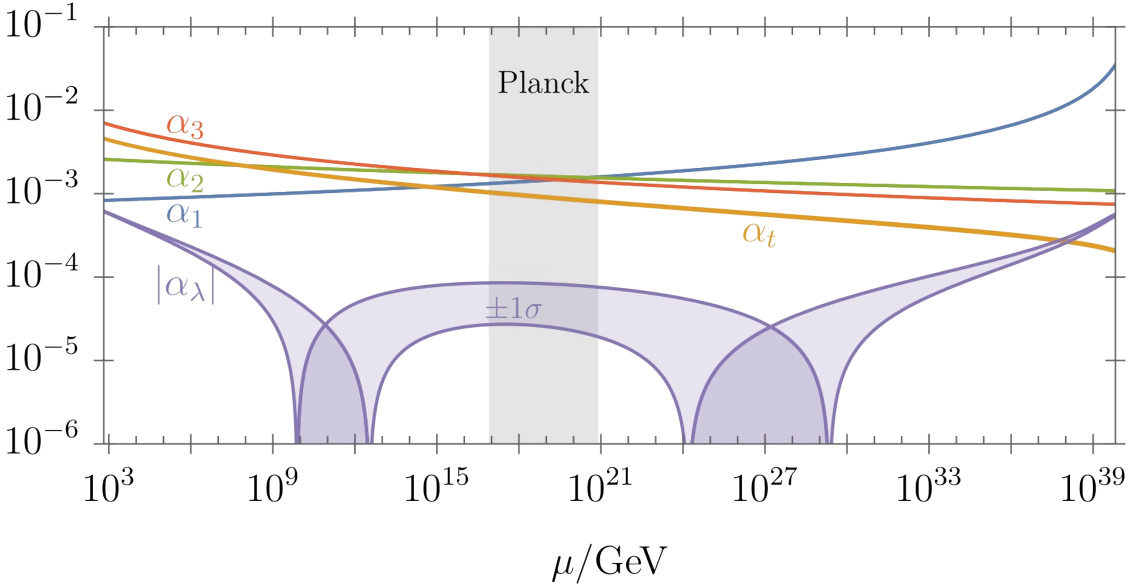
Impact small



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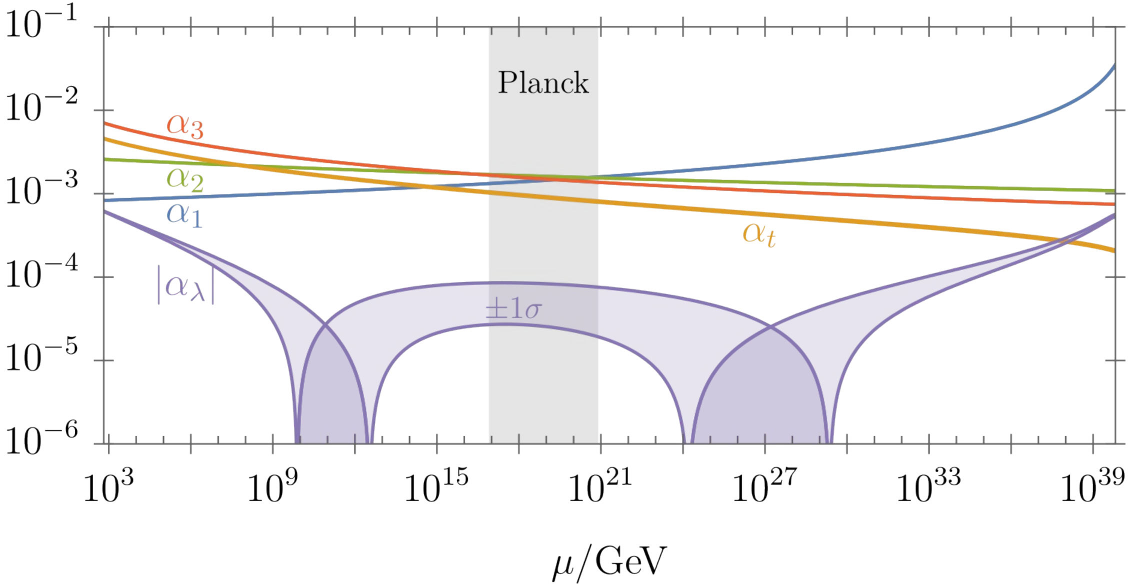

What Observables impact vacuum stability?

1. Observables PDG 2024
   - Higgs mass $M_h = 125.20(11)$ GeV Uncertainty small $+24\,\sigma$
   - Strong coupling
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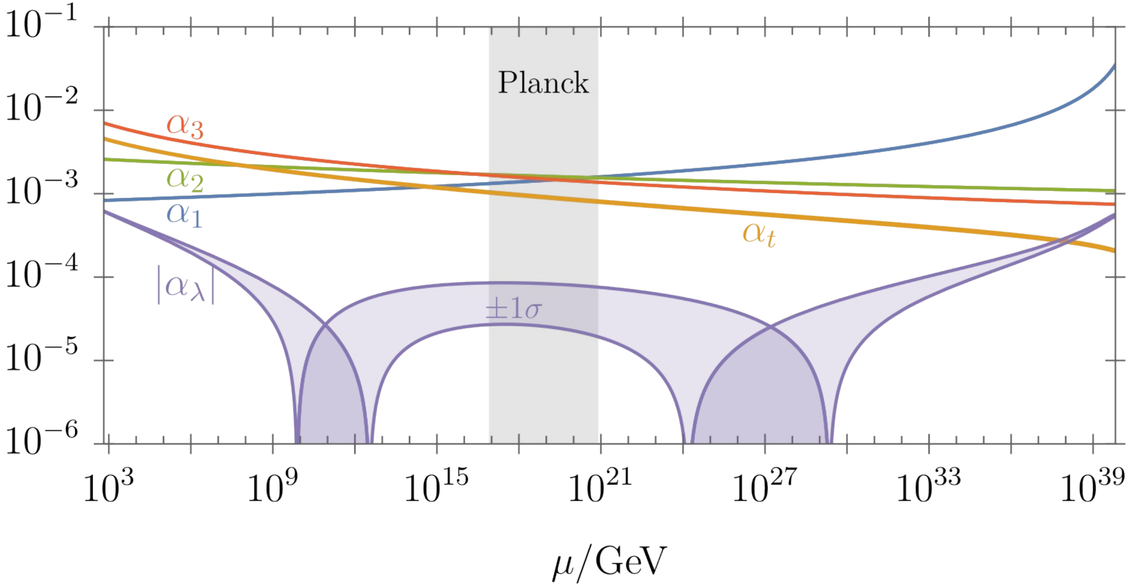

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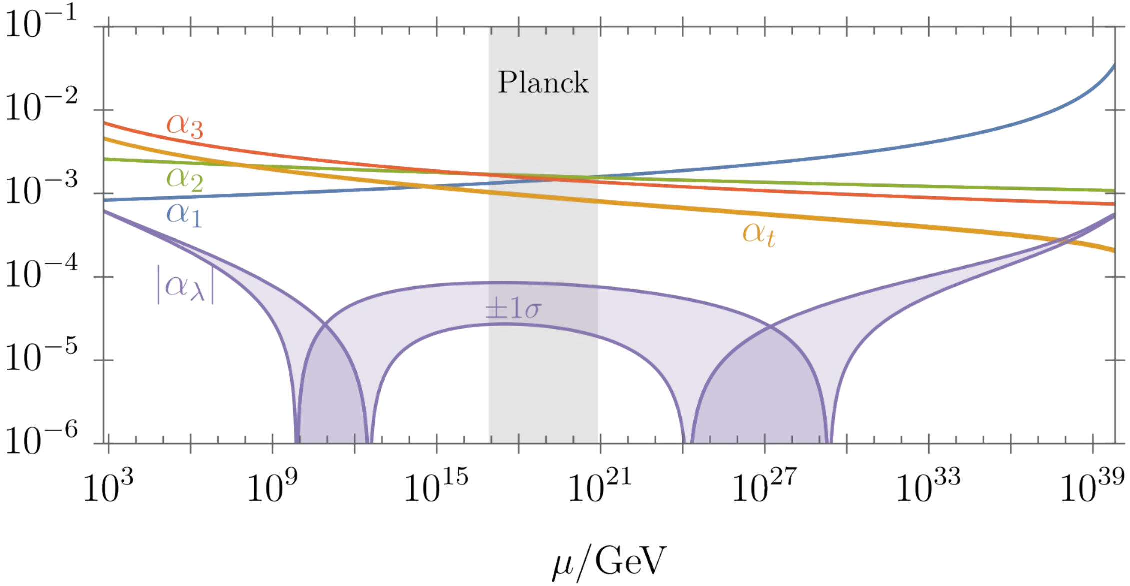

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- Strong coupling $\alpha_s^{(5)}(M_Z) = 0.1180(9)$ — $+3.7\ \sigma$
- Top mass $M_t^\sigma = 172.40(70)$ GeV — $-1.9\ \sigma$
  $M_t^{\rm MC} = 172.57(29)$ GeV — $-5.1\ \sigma$
  which one?

~~– Z mass M_Z~~
~~– Fermi constant G_F~~
~~– Fine structure & hadronic threshold $\alpha_e,\ \Delta\alpha_e^{(5),\rm had}$~~
Uncertainty small

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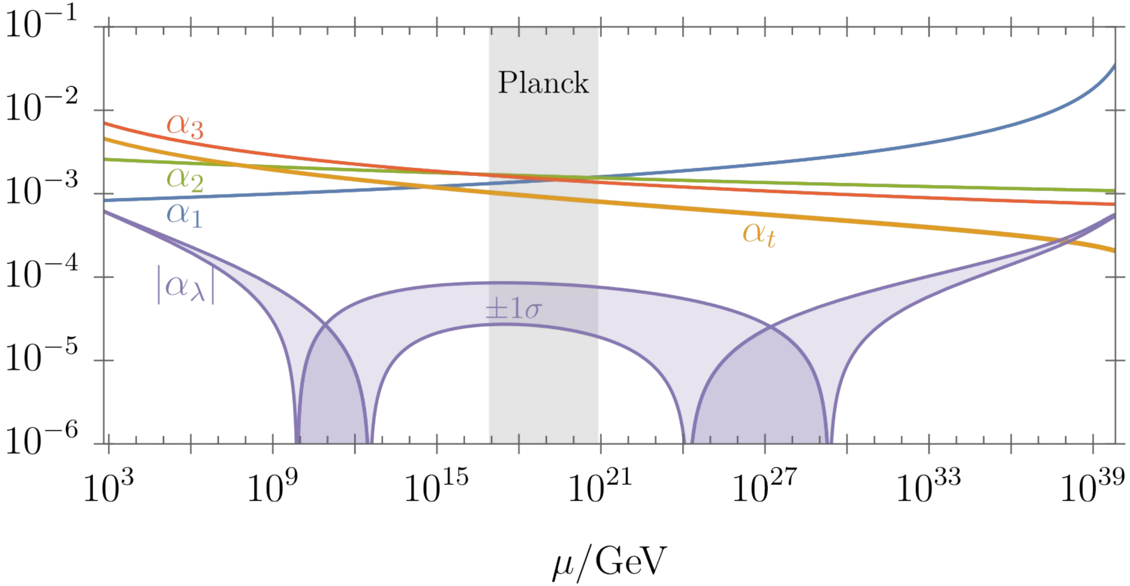
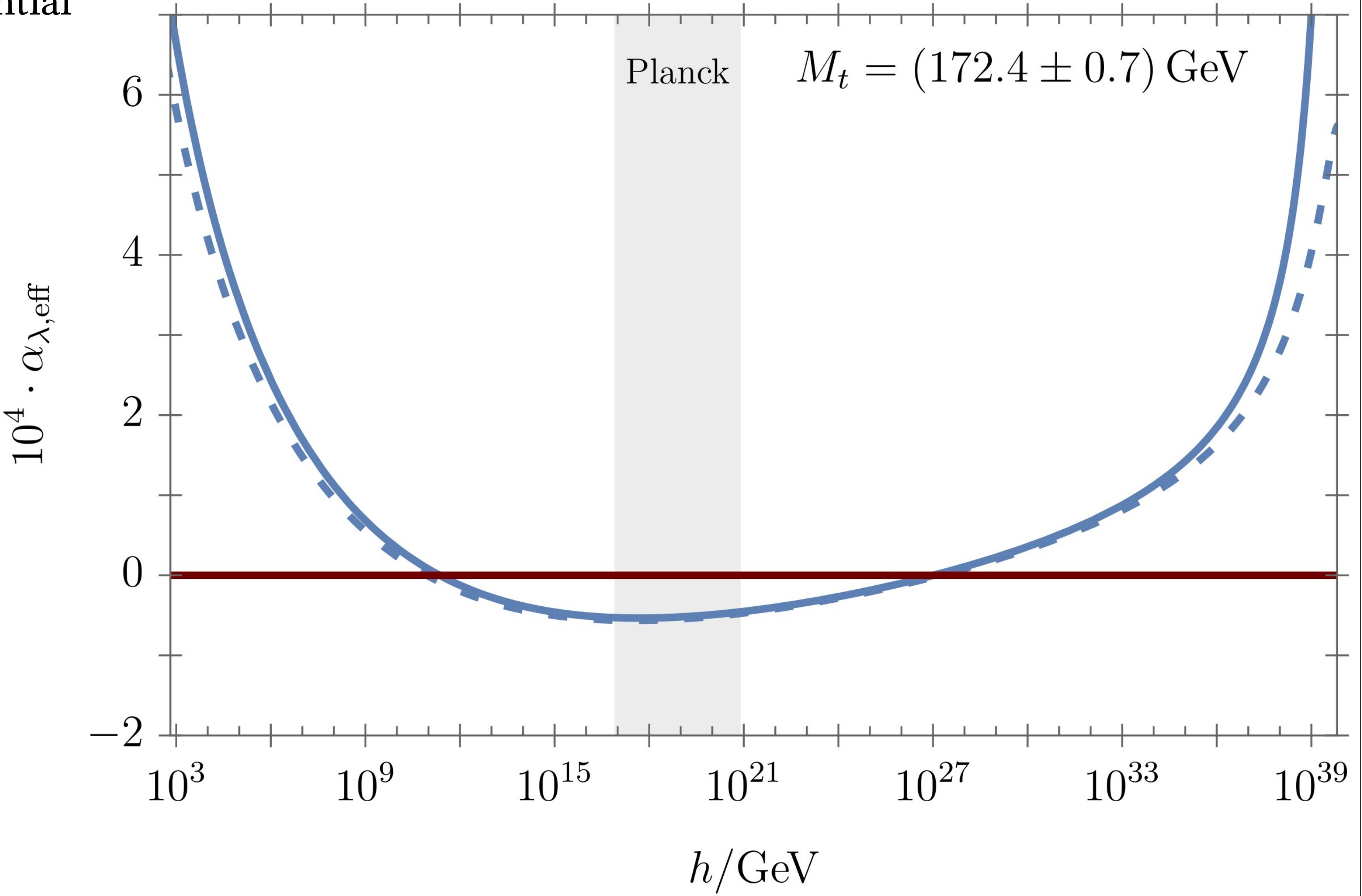
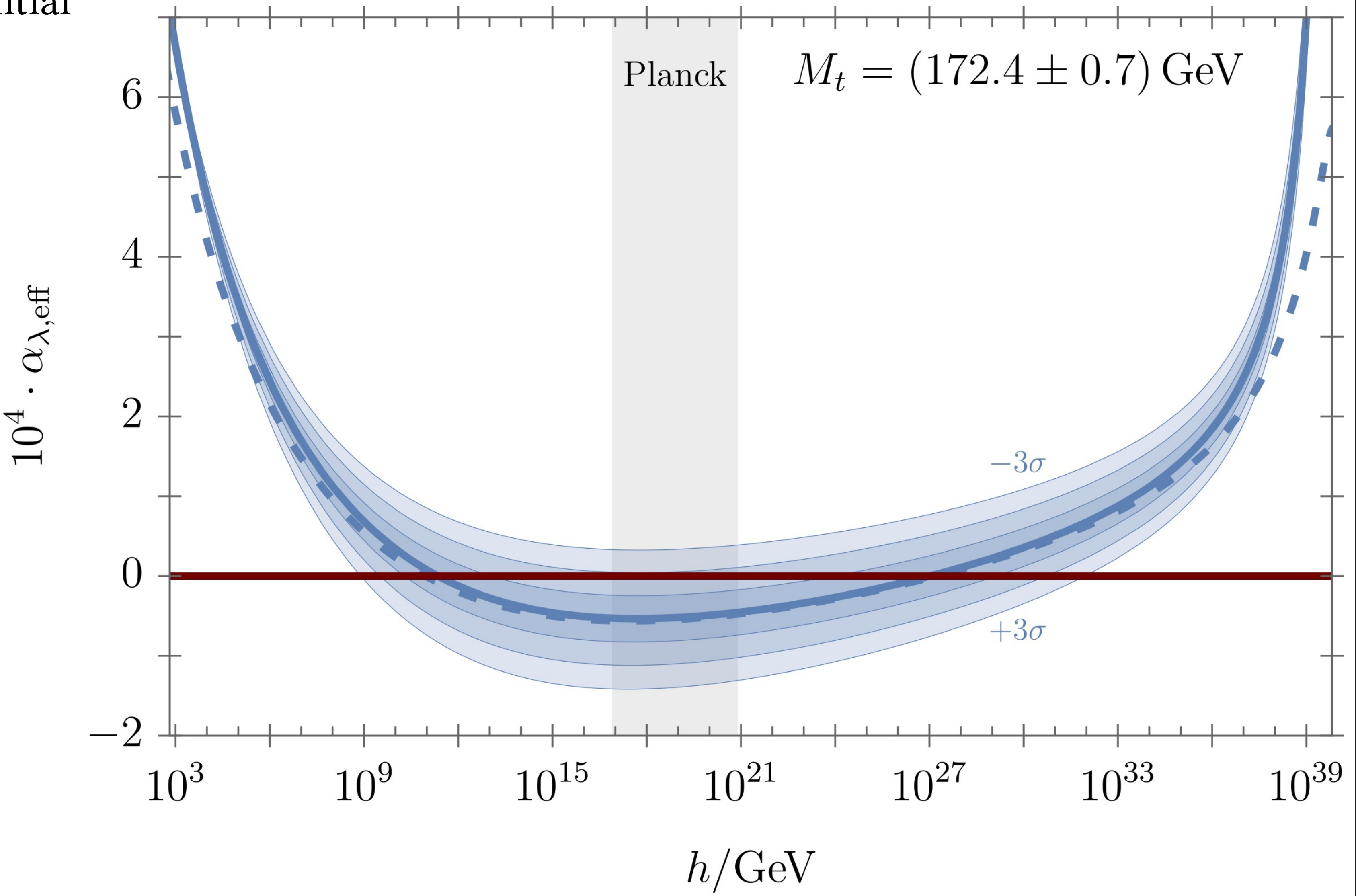
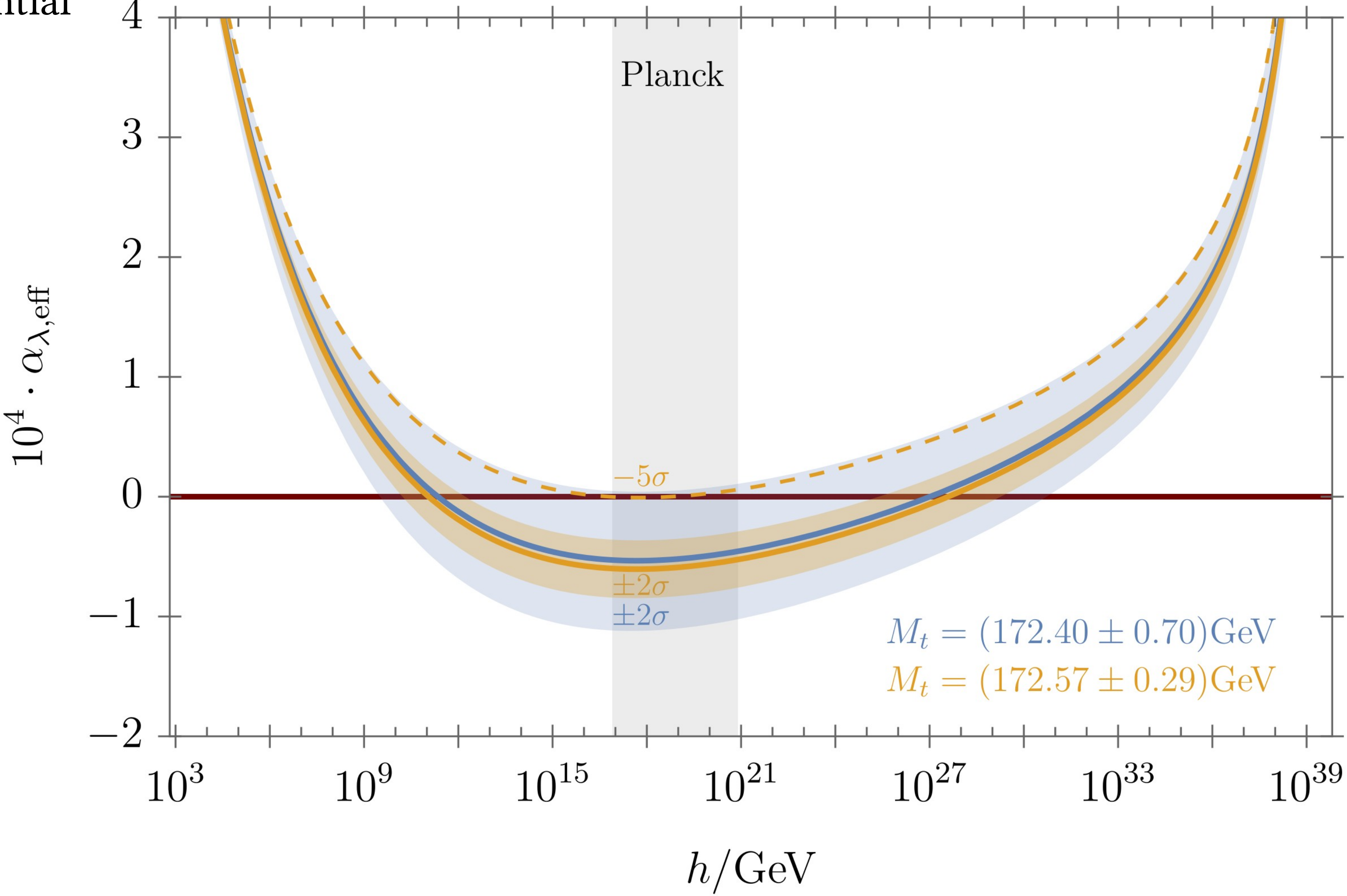


Effective Potential

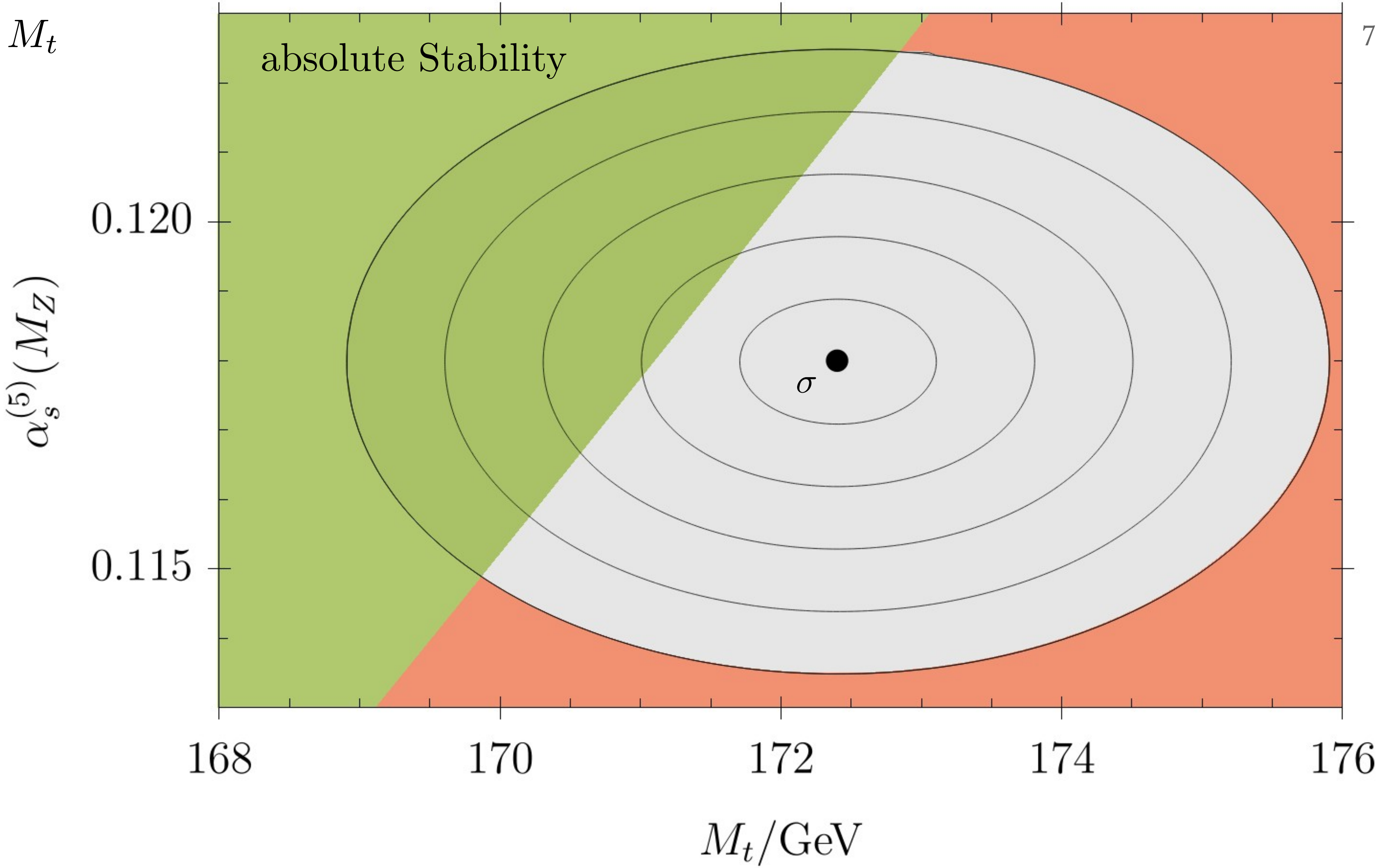



Planck
$M_t = (172.4 \pm 0.7)$ GeV
-3σ
$+3\sigma$
$10^4 \cdot \alpha_{\lambda,\text{eff}}$
6
4
2
0
−2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
10^{39}
h/GeV

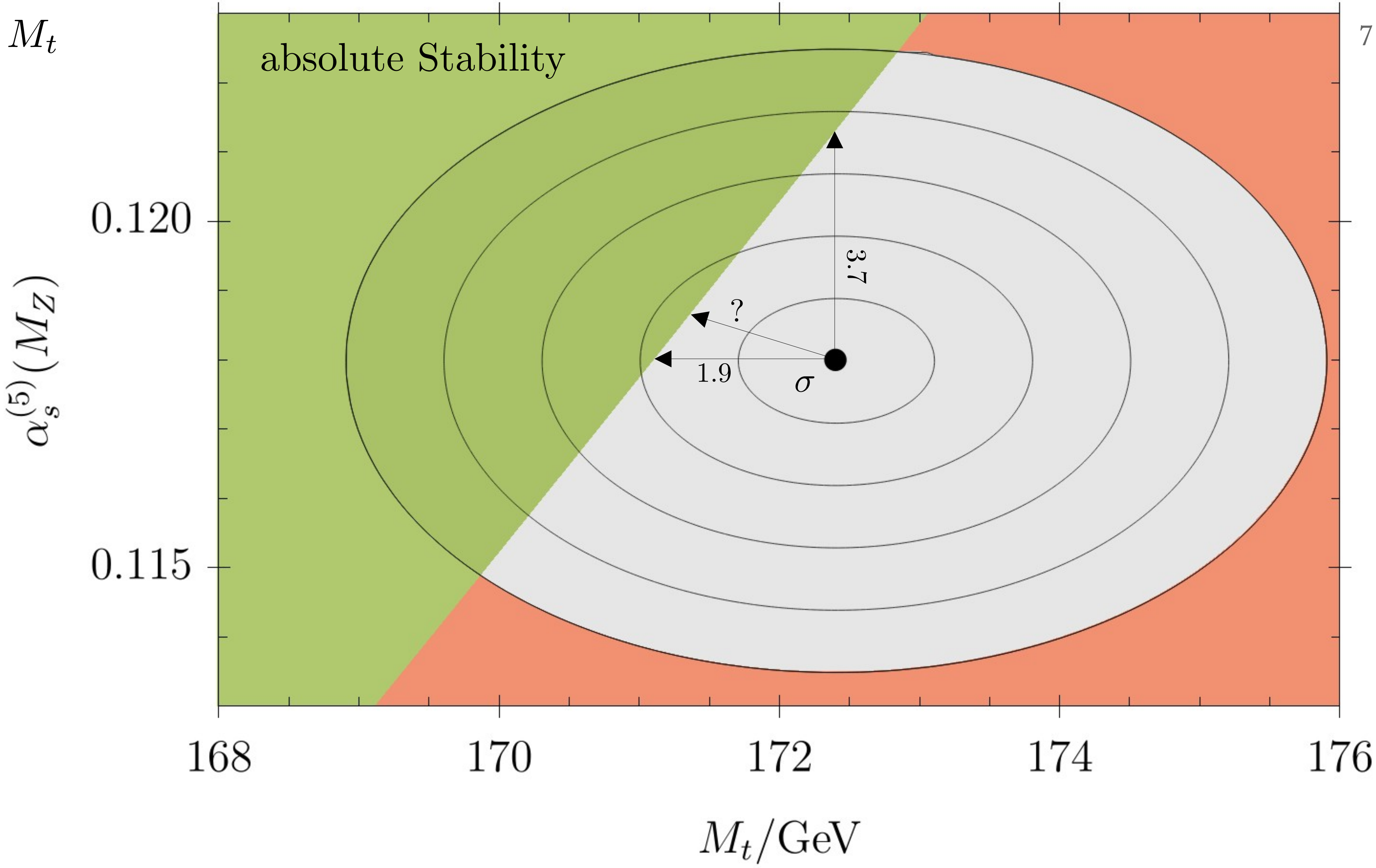


Planck
-5σ
$\pm 2\sigma$
$\pm 2\sigma$
$M_t = (172.40 \pm 0.70)\mathrm{GeV}$
$M_t = (172.57 \pm 0.29)\mathrm{GeV}$
$10^4 \cdot \alpha_{\lambda,\mathrm{eff}}$
h/GeV
4
3
2
1
0
−1
−2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
10^{39}

α_s vs. M_t


absolute Stability
σ
0.120
0.115
$\alpha_s^{(5)}(M_Z)$
168
170
172
174
176
M_t/GeV

α_s vs. M_t



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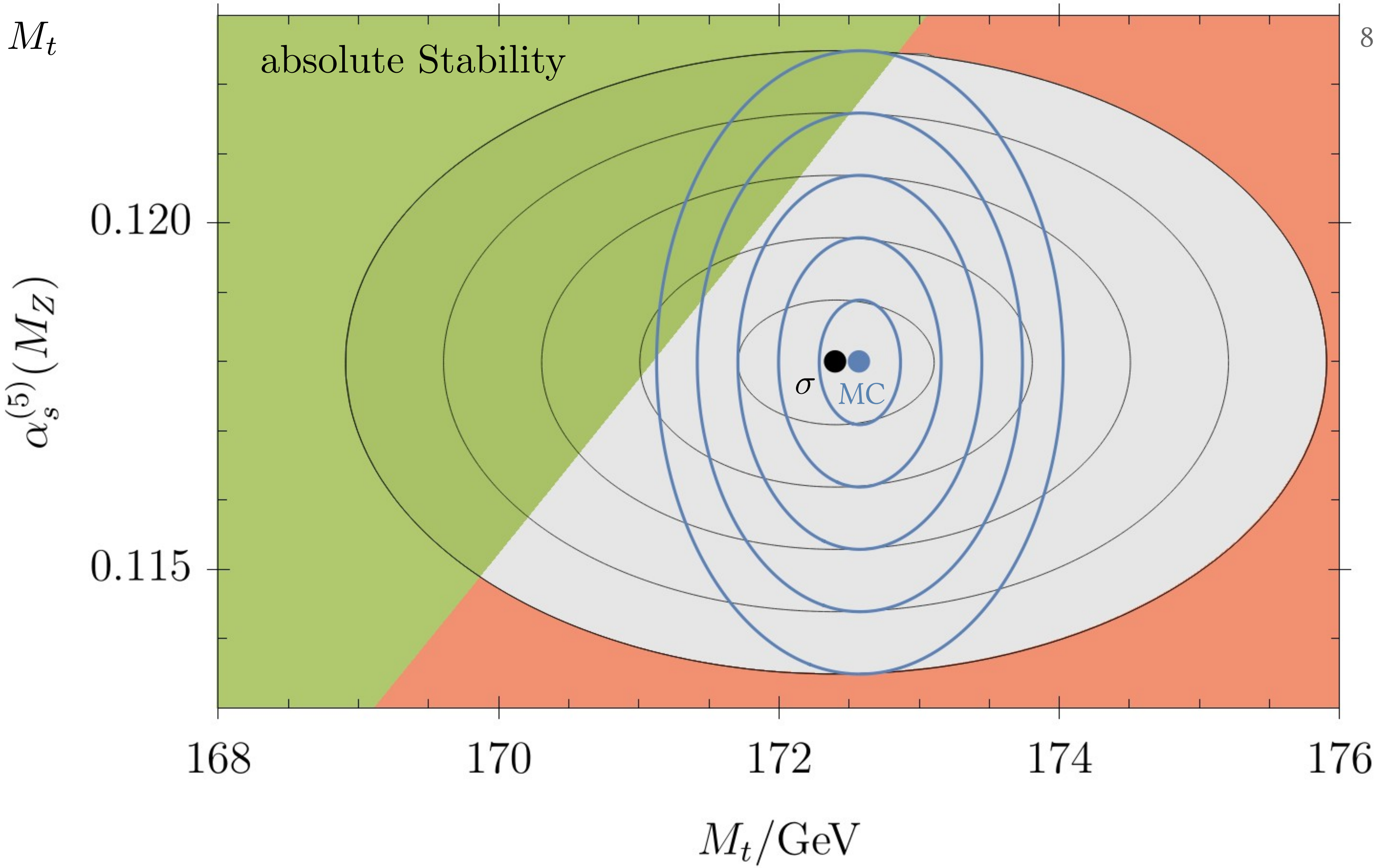

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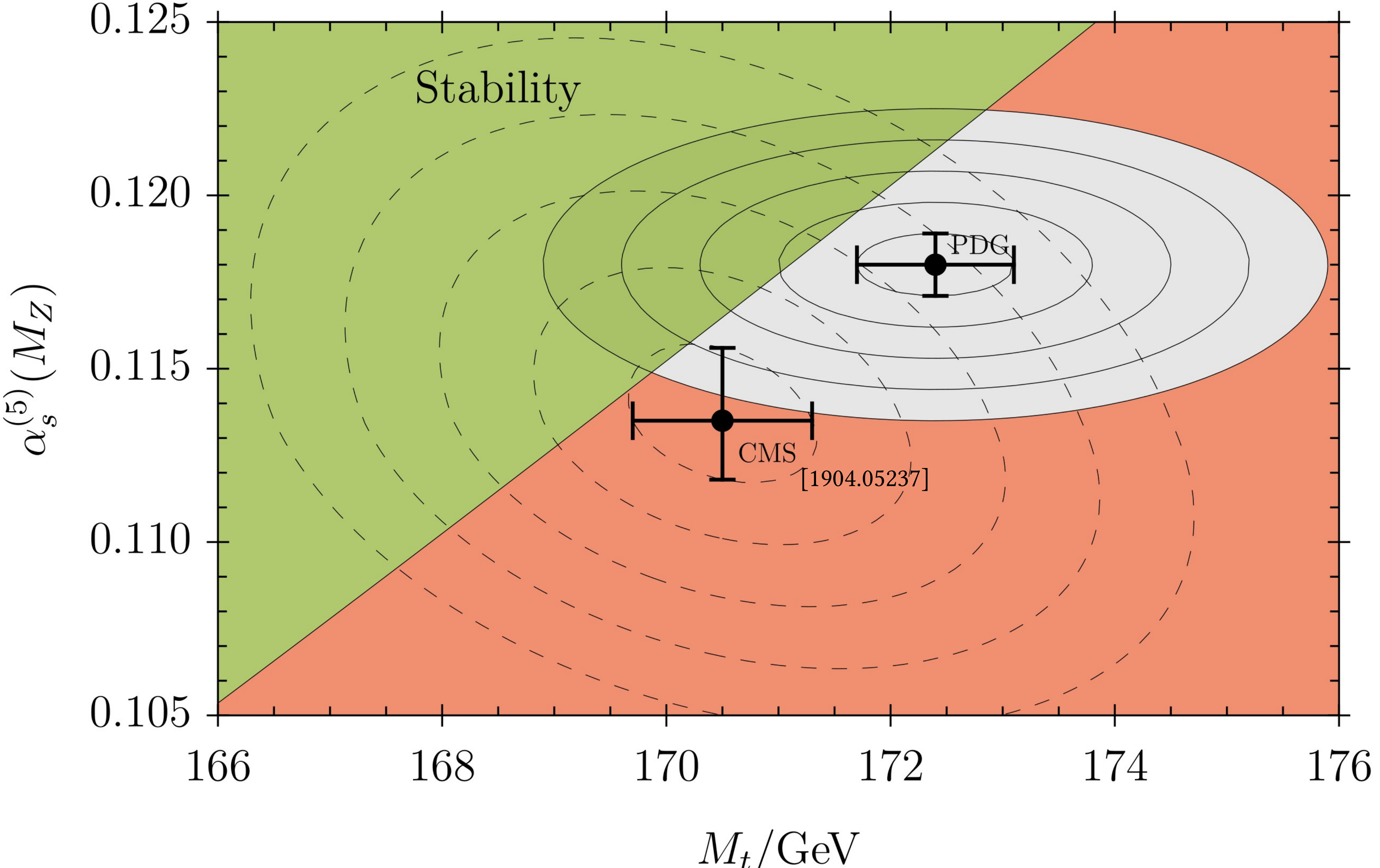
Stability
PDG
CMS
[1904.05237]
0.125
0.120
0.115
0.110
0.105
$\alpha_s^{(5)}(M_Z)$
166
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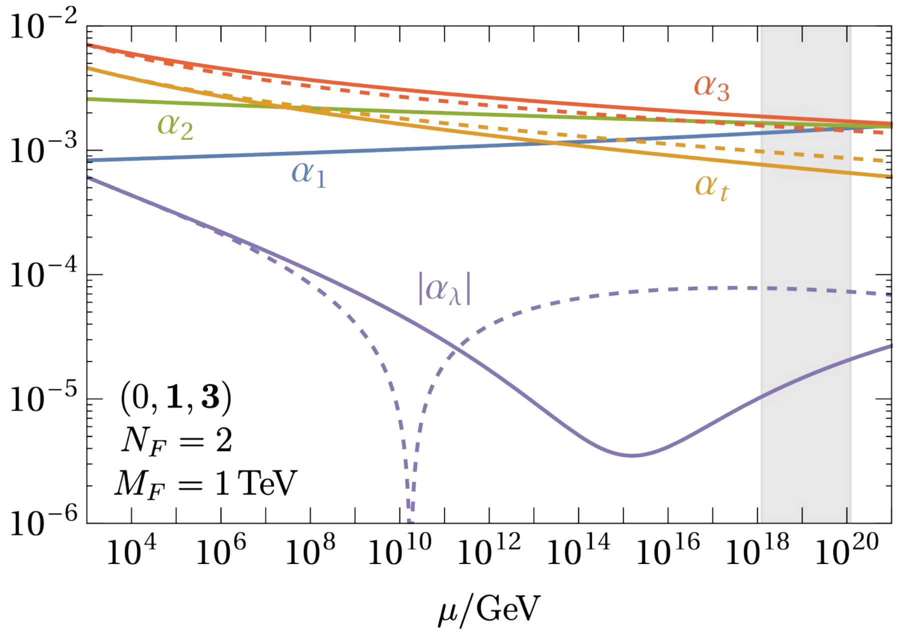
Stability via BSM?

» Gauge Portal – adding new charged fermions
[Hiller, Höhne, Litim, TS 2022]



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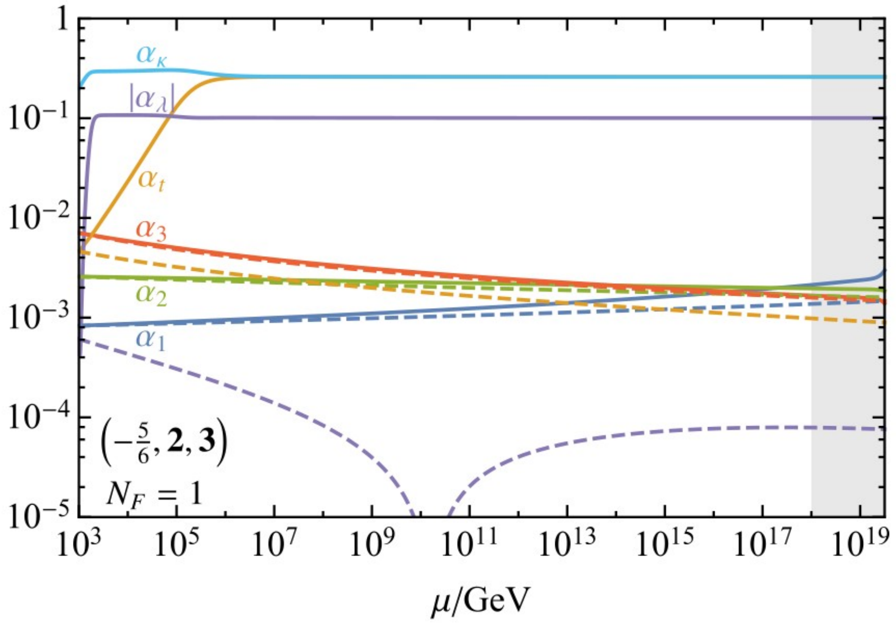
» Yukawa Portal – sizable new Yukawa interactions
[Hiller, Höhne, Litim, TS 2022]



Stability via BSM?

» Gauge Portal – adding new charged fermions
[Hiller, Höhne, Litim, TS 2022]

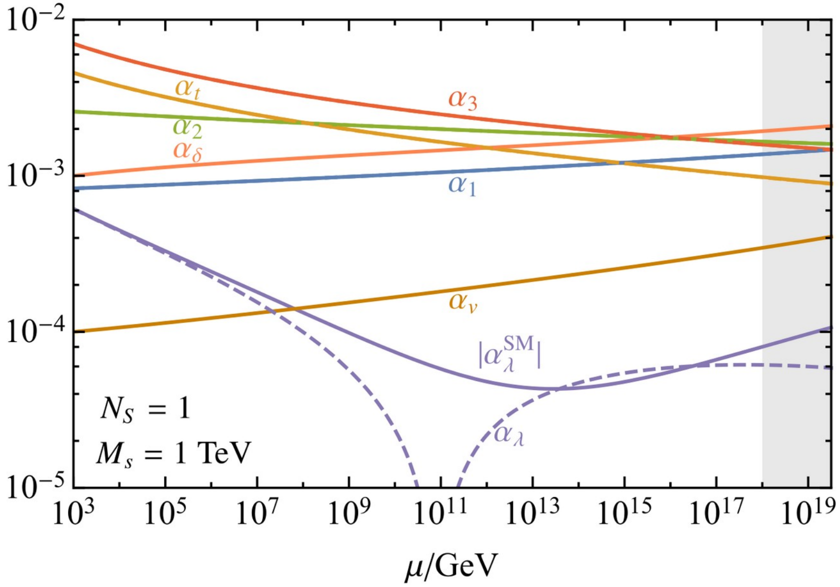
» Yukawa Portal – sizable new Yukawa interactions
[Hiller, Höhne, Litim, TS 2022]

» Scalar Portal
[Hiller, Höhne, Litim, TS 2024]

$$V_{H,S} = \lambda\,(H^\dagger H)^2 + \delta\,(H^\dagger H)(S^T S) + v\,(S^T S)^2$$

Portal coupling

$$\beta_\lambda = \beta_\lambda{}^{\rm SM} + \mathcal{N}\delta^2$$



Summary

» evidence for metastability of SM persists
» more precision measurements of $\alpha_s^{(5)}(M_Z)$ and M_t necessary to exlude stability at 5σ
» correlation important
» understanding of MC Top mass required
» instability is RG dominated

Summary

» evidence for metastability of SM persists
» more precision measurements of $\alpha_s^{(5)}(M_Z)$ and M_t necessary to exlude stability at 5σ
» correlation important
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» instability is RG dominated

» many BSM approaches to address SM instability
» can be valid until Planck scale
» testable at current and future colliders