Vacuum Stability in the Standard Model

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in collaboration with

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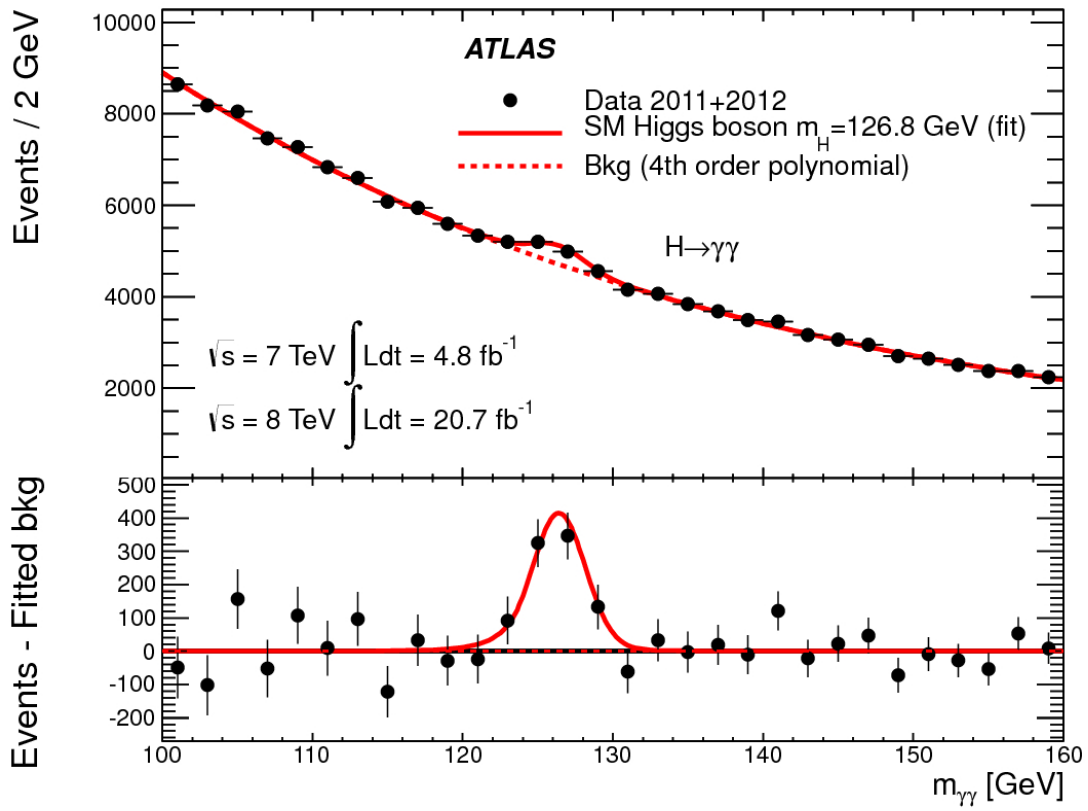
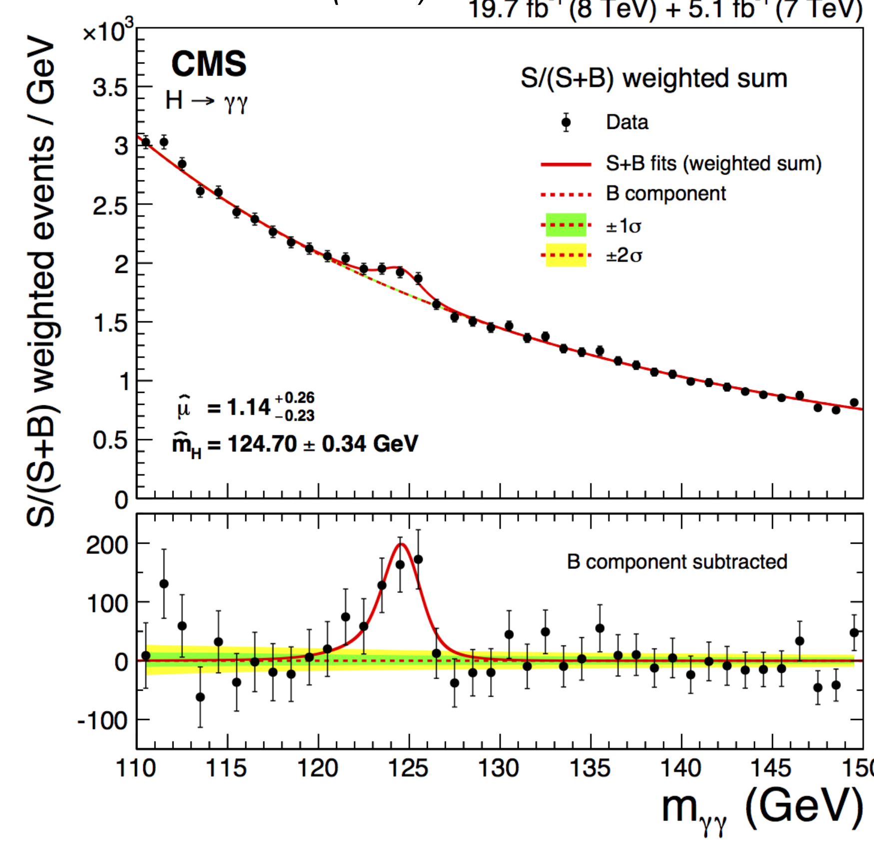
The Standard Model and the Higgs

- Discovery of the Higgs@LHC:

ATLAS collaboration (2012)



CMS collaboration (2012)



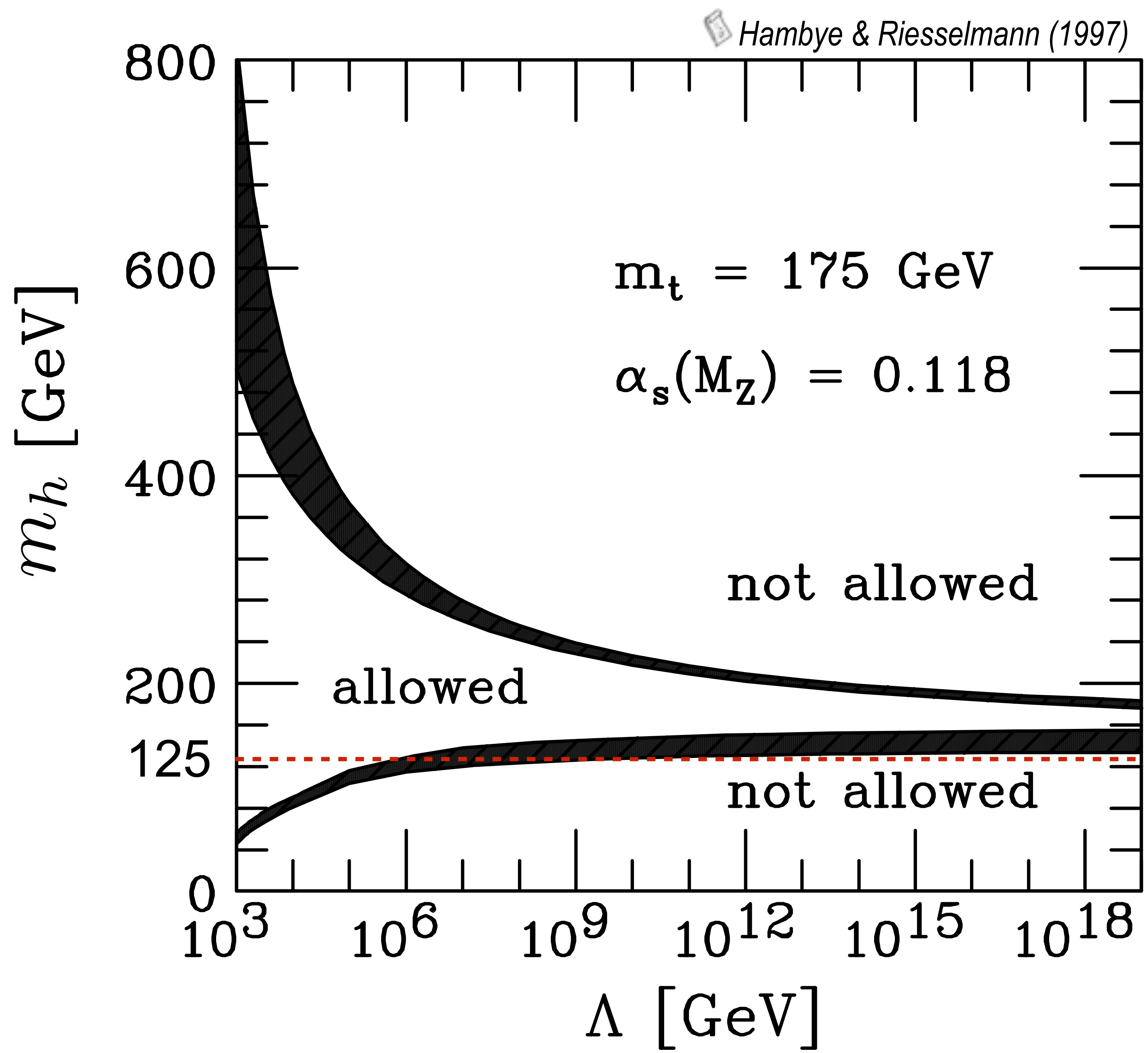
$$M_H \approx 125\ \text{GeV}$$

- **Standard model:**
  - effective theory
  - physical cutoff Λ
  - “new physics” beyond Λ

- **Range of validity of SM?**
  - Gravity effects: $\Lambda \sim M_{\rm Pl} = \sqrt{\hbar c/G} \approx 10^{19}\text{GeV}$
  - Landau pole in $U(1)_{\text{hypercharge}}$: $\Lambda > M_{\rm Pl}$
  - Higgs potential…

Higgs Mass Bounds

- Higgs mass is related to Higgs coupling and vev: $m_h = \sqrt{2\lambda_4} \cdot vev$

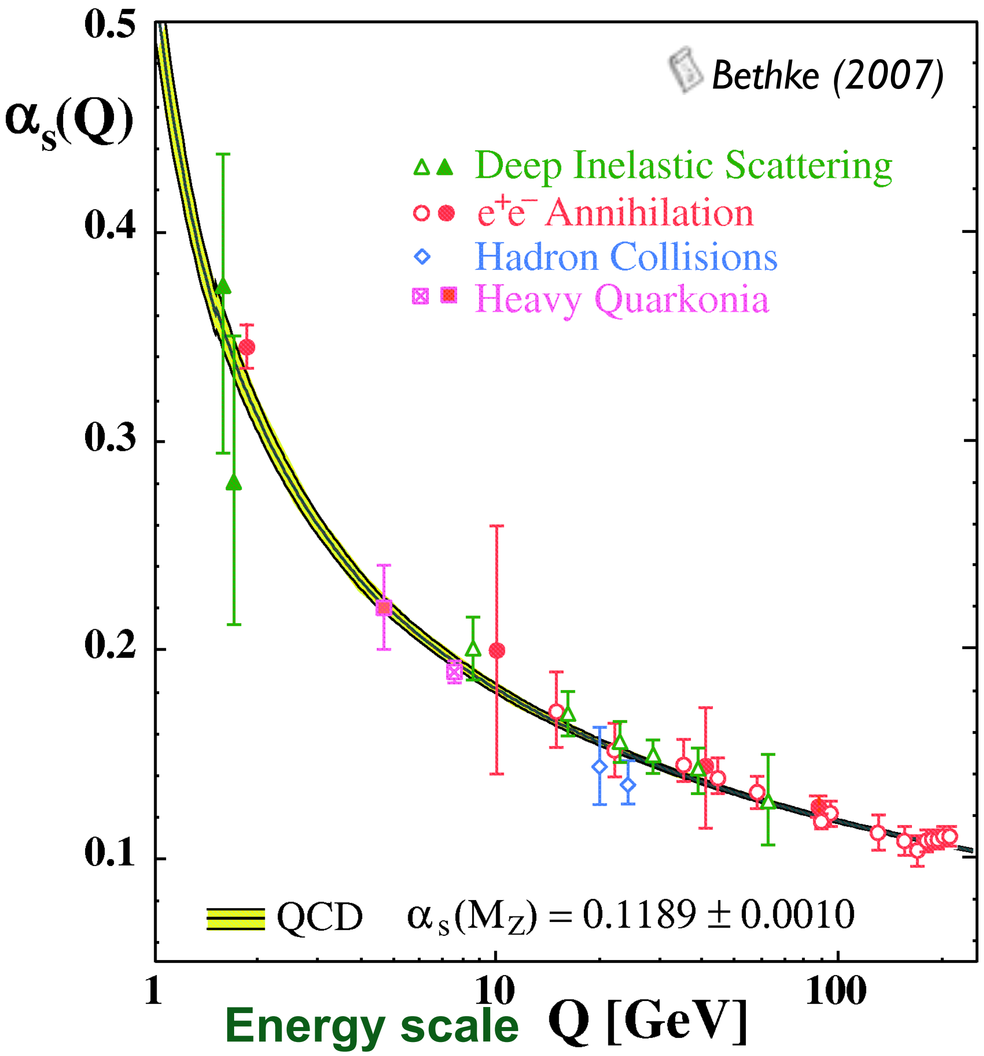


Krive, Linde (1976)
Maiani, Parisi, Petronzio (1978)
Krasnikov (1978)
Politzer, Wolfram (1978)
Hung (1979)
Lindner (1985)
Wetterich (1987)
Sher (1988)
Fort, Jones, Stephenson, Einhorn (1993)
Altarelli, Isidori (1994)
Schrempp, Wimmer (1996) …

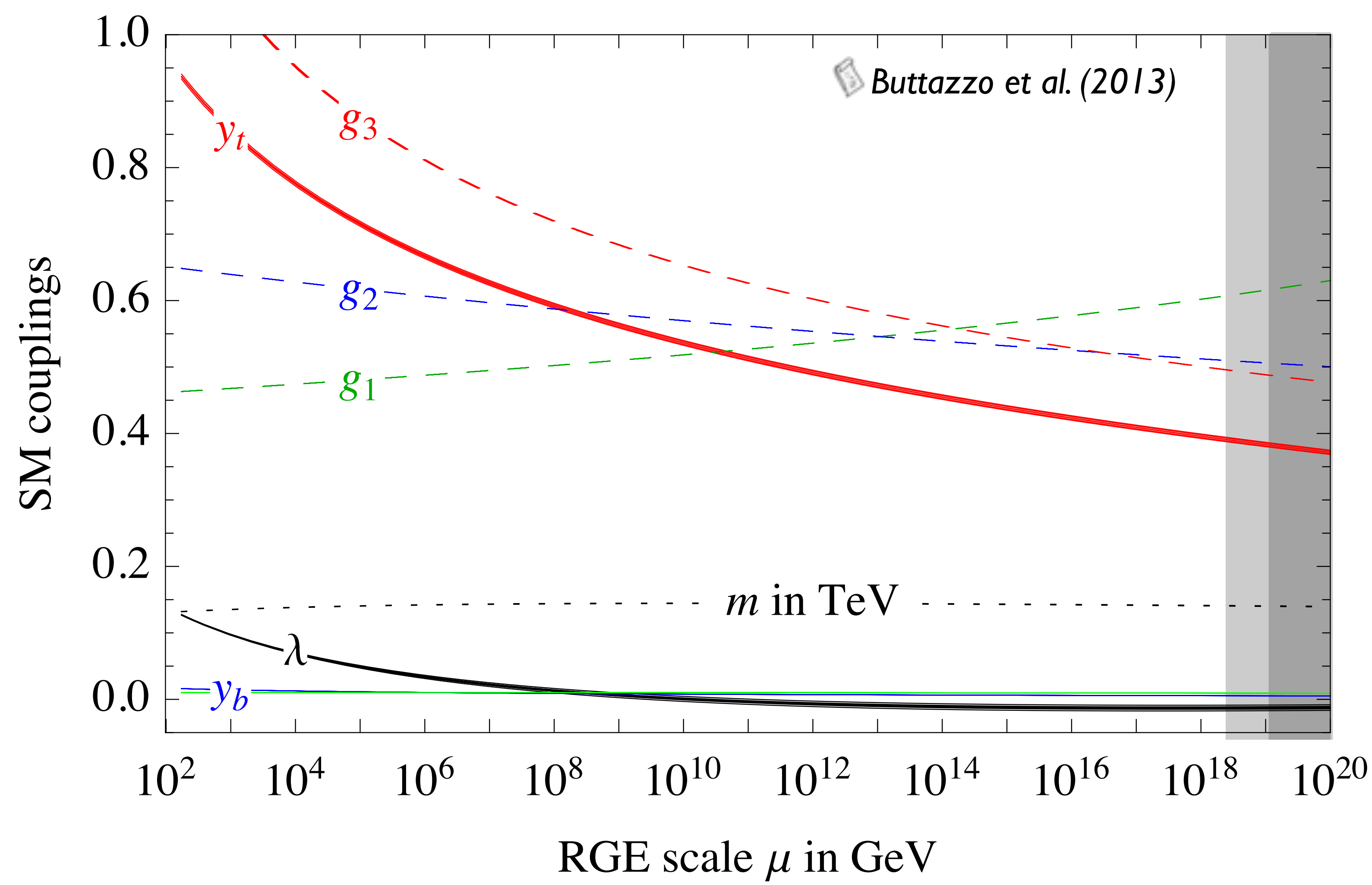
- Upper bound related to Landau pole

Standard Model Running Couplings

- Running strong coupling α_S:



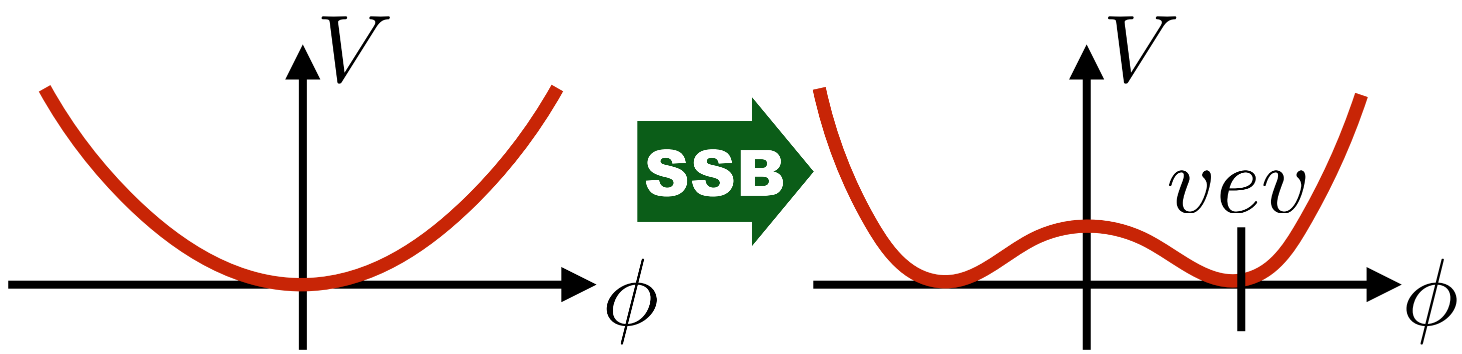
- Standard model running couplings:



→ running of couplings described by renormalization group β functions

Mechanism for Lower Higgs Mass Bound

- **Higgs potential:** $\frac{\mu}{2}H^2 + \frac{\lambda_4}{4}H^4$

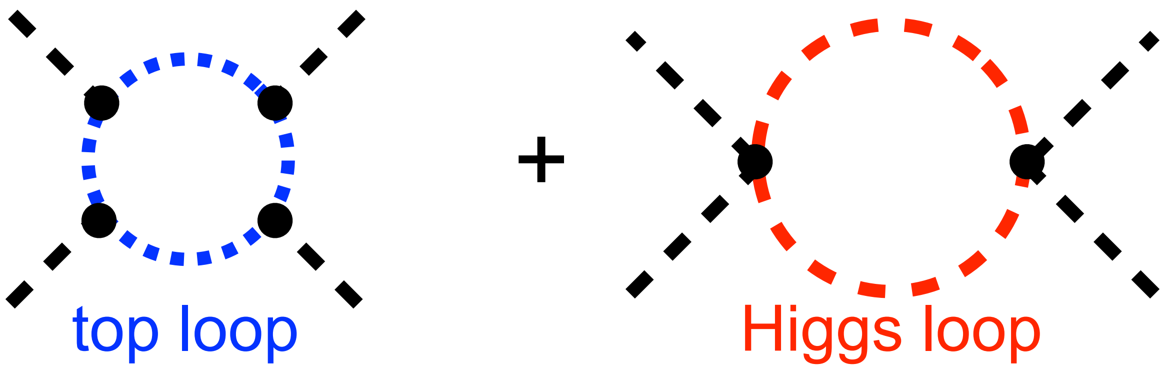


$$m_h = \sqrt{2\lambda_4} \cdot vev$$

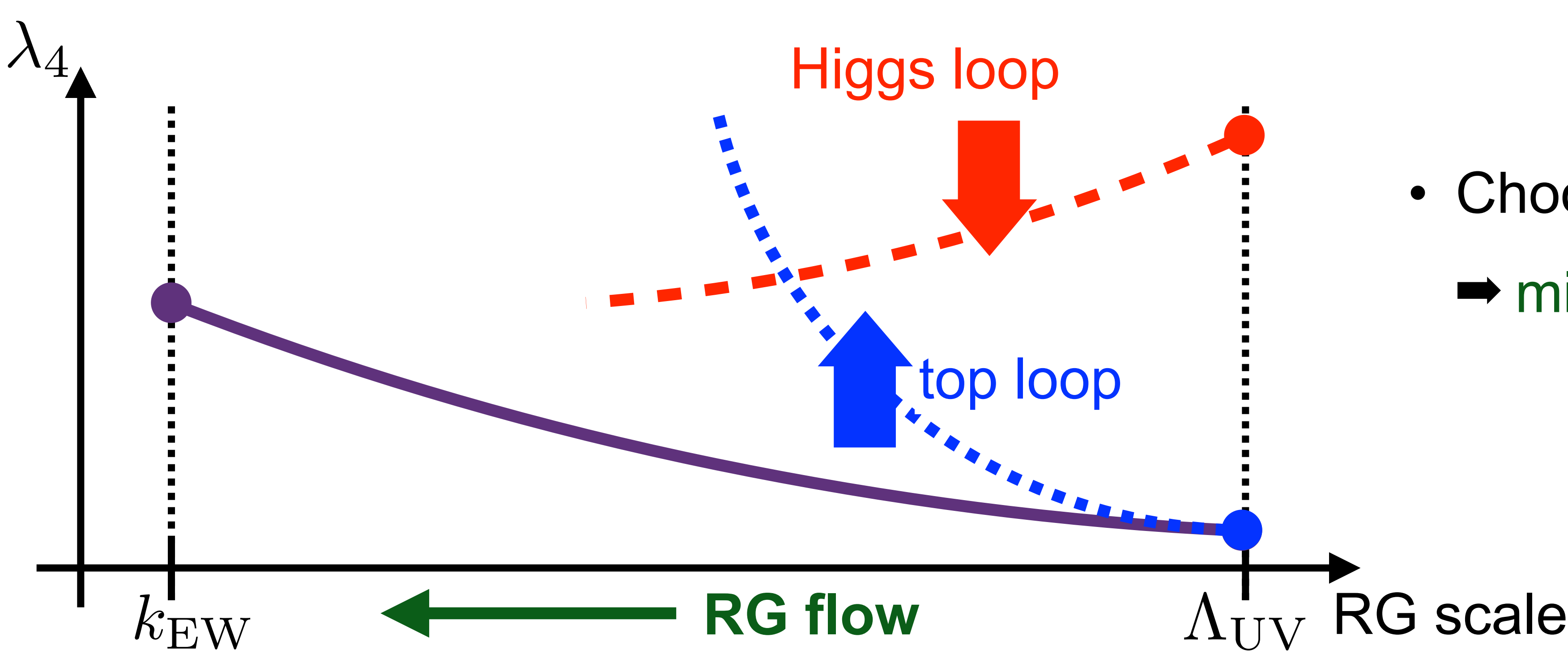
$$m_t = \frac{y}{\sqrt{2}} \cdot vev$$

- **Running Higgs self-coupling:**

$\beta_{\lambda_4} =$ -



\+ gauge contributions

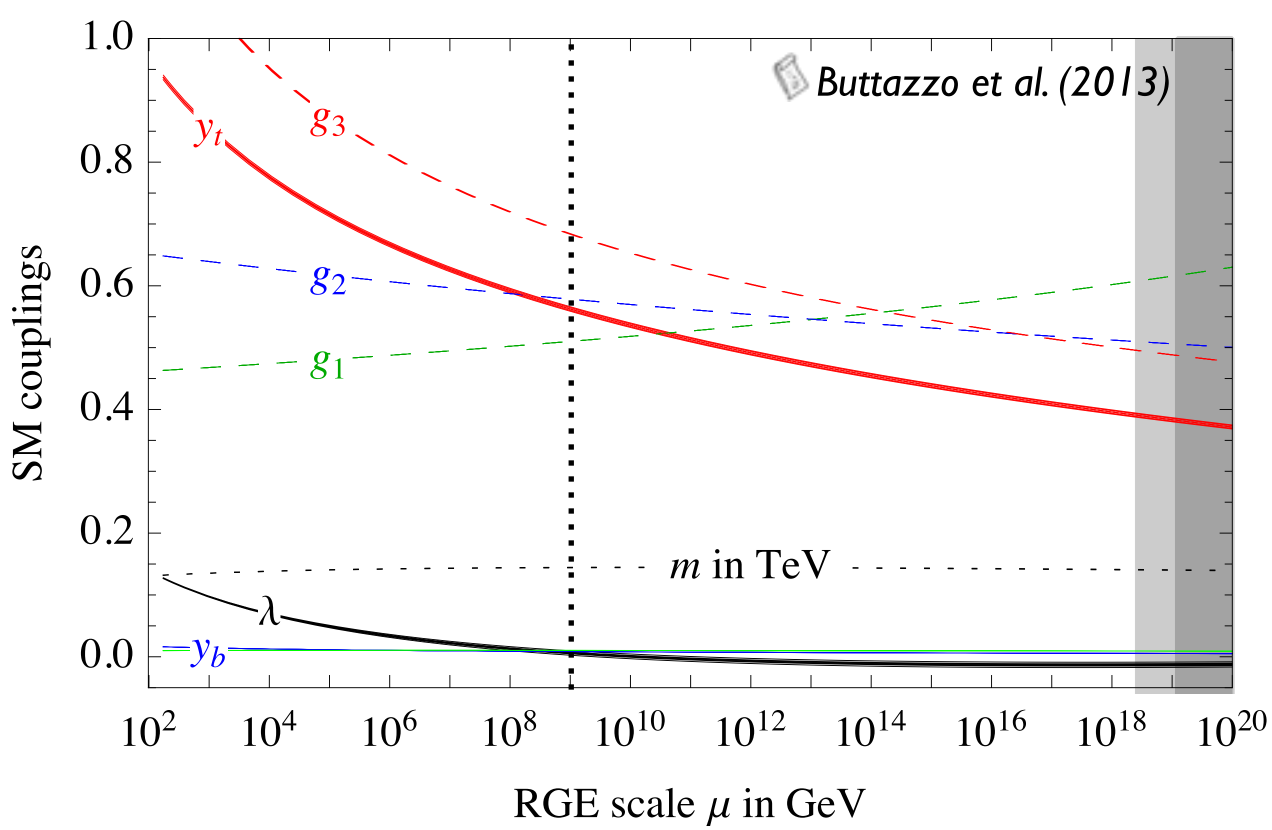


- Choose $\lambda = 0$ at Λ_{UV}:

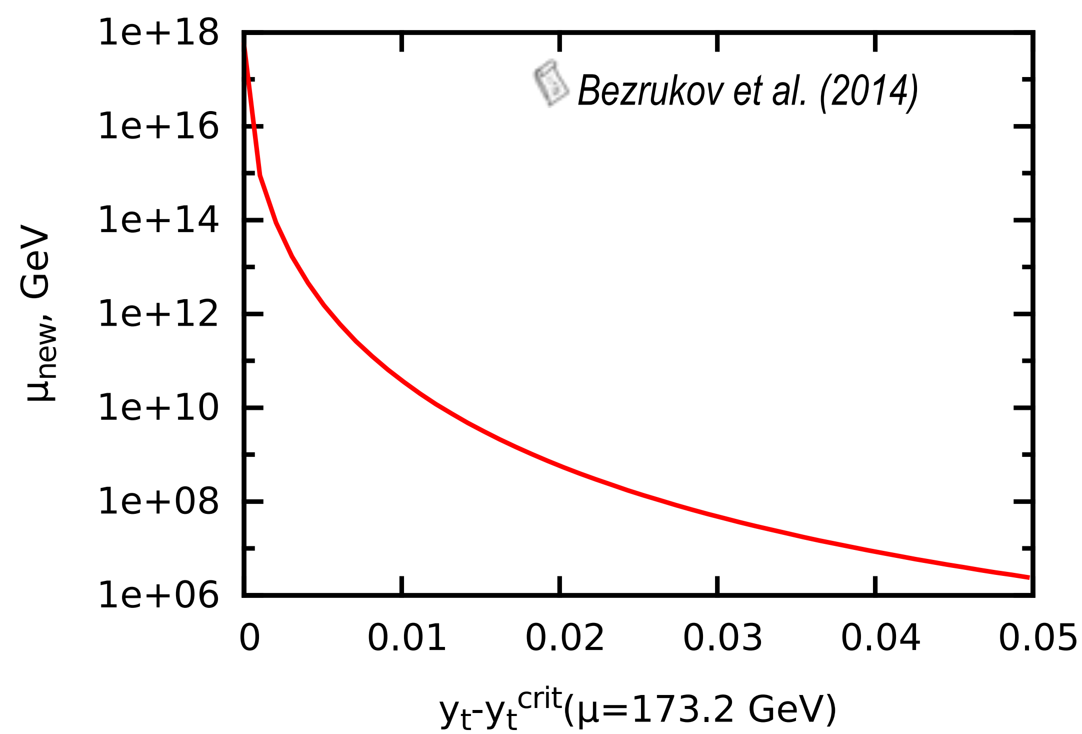
➡ minimal value of Higgs mass

Lower Mass Bound in the Standard Model

$$\beta_{\lambda_4} = \frac{d\,\lambda_4}{d\,\log k} = \frac{1}{8\pi^2}\left[12\lambda_4^2 + 6\lambda_4 y^2 - 3y^4 - \frac{3}{2}\lambda_4\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$



- **Vacuum instability**
  - λ_4 crosses zero in $\frac{\mu}{2}H^2 + \frac{\lambda_4}{4}H^4$
  - ➡ instability of Higgs vacuum
  - 'scale of new physics' ~ 10^{10} GeV
  - strongly depends on top Yukawa:



$$m_h(M_{\rm Pl}) \approx 129\text{GeV}$$
$$m_h^{\rm exp} \approx 125\text{GeV}$$

On the 'Scale of New Physics'

@ ~ 10^{10} GeV several scenarios are possible:

1. *New degrees of freedom* appear that render Higgs potential stable?

2. Stable minimum might appear for large field values (no new d.o.f.)

   ➡ *Metastability* of Higgs vacuum?

   ➡ Small tunneling rates to stable minimum?

3. Include higher powers in Higgs field (e.g. $\sim H^6, H^8, \ldots$) to render potential stable

   ➡ Do not appear in perturbatively renormalizable Higgs Lagrangian

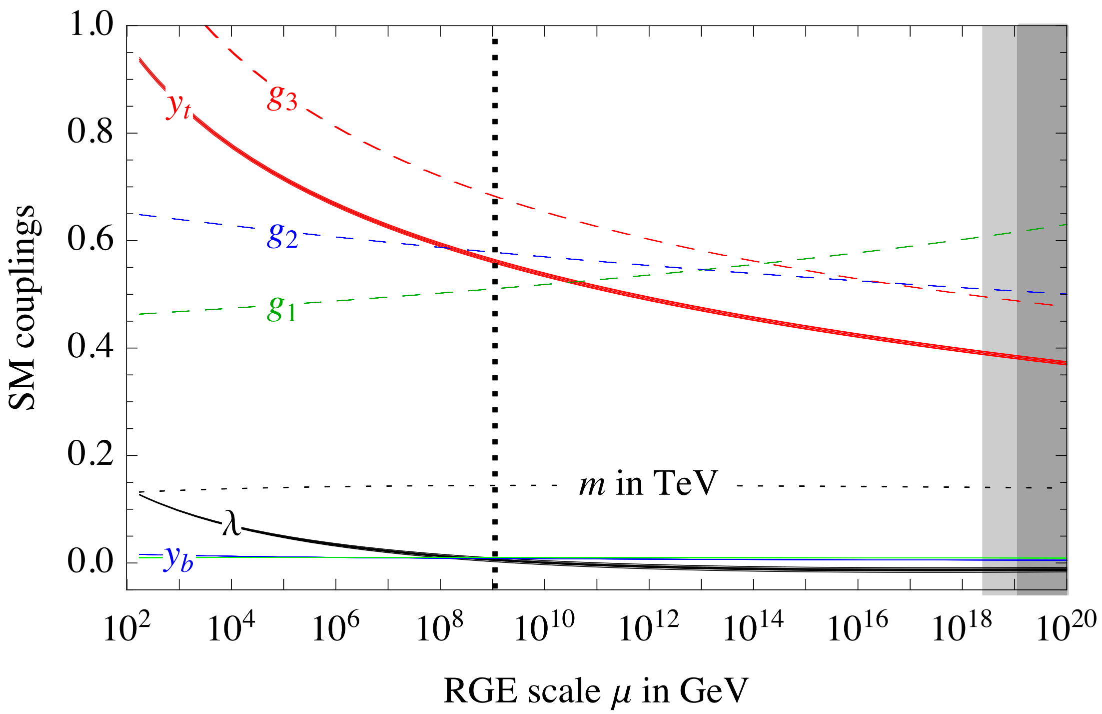
   ➡ Appear in *effective theories* with finite Λ_{UV} when approaching underlying theory

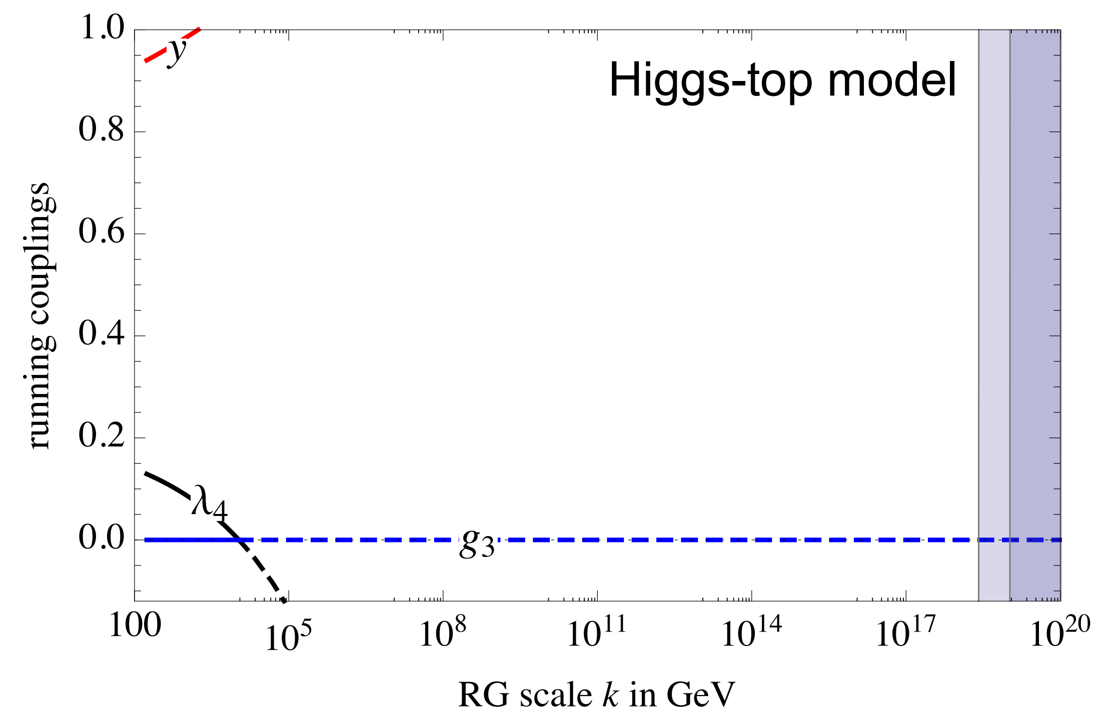
   ➡ New physics appears at higher scales $10^{?}$ GeV > 10^{10} GeV

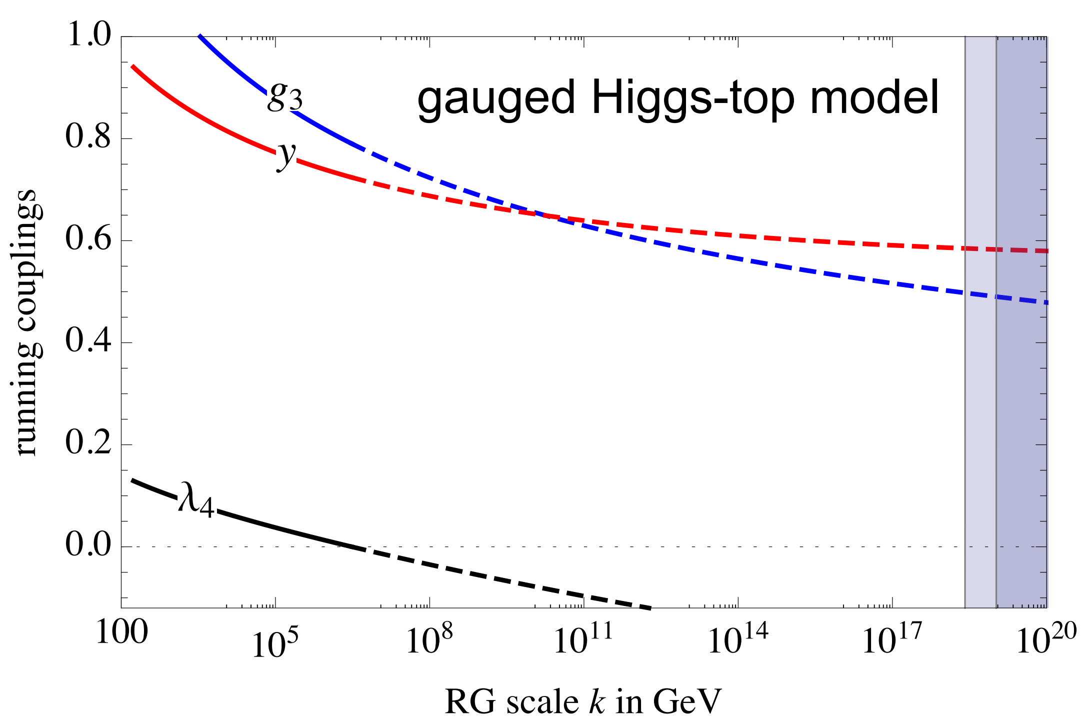
   ➡ Link to BSM particle physics models?

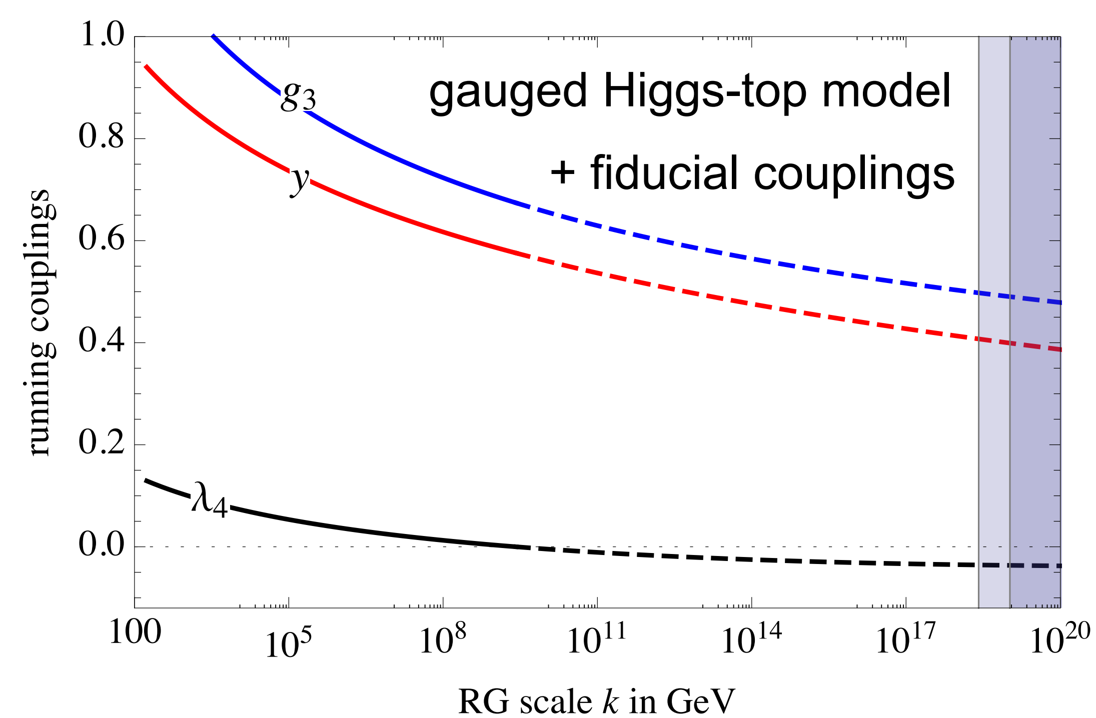
Gauged Higgs-Top Model

$$S_{\Lambda} = \int d^4x \left[\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial_\mu \varphi)^2 + V_{\mathrm{eff}}(\Lambda) + i \sum_{j=1}^{n_f} \overline{\psi}_j \not{D} \psi_j + i \frac{y}{\sqrt{2}} \sum_{j=1}^{n_y} \varphi \overline{\psi}_j \psi_j \right]$$









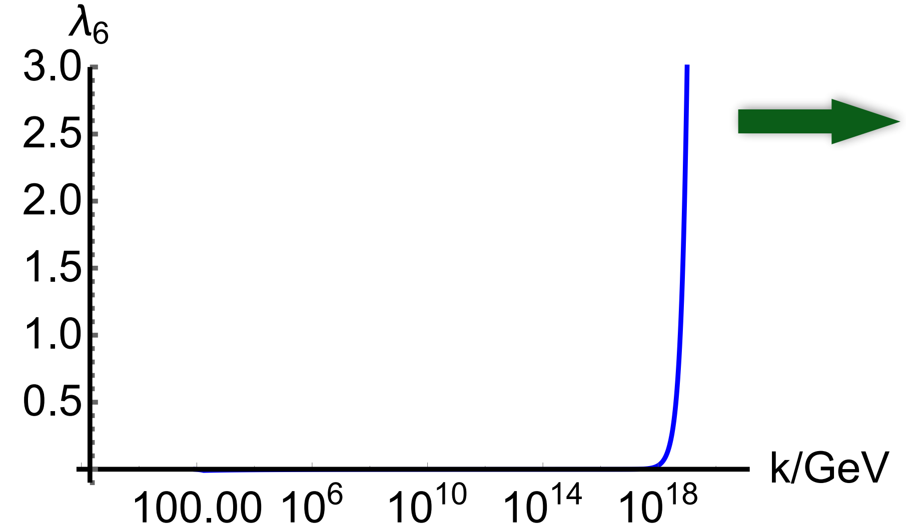
Standard model as a low-energy effective theory

- **Potential at UV scale:** all operators compatible with symmetries

$$V_{\mathrm{UV}} = \frac{\lambda_4(\Lambda)}{4} H^4 + \frac{\lambda_6(\Lambda)}{8\Lambda^2} H^6 + \ldots$$

- **Towards IR:** irrelevant operators follow canonical scaling

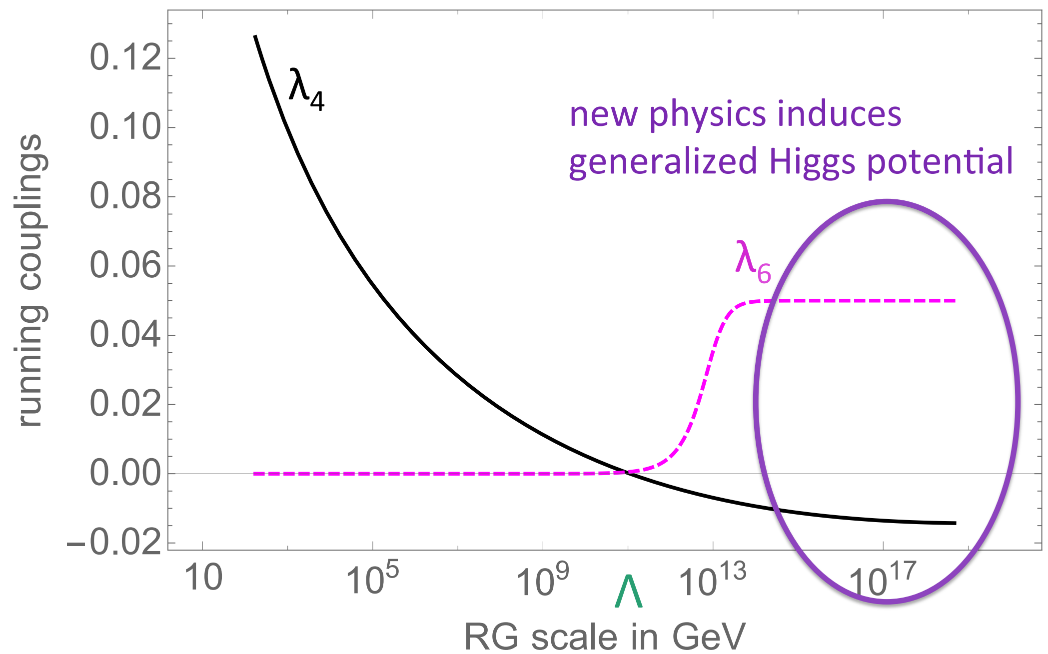
Fodor et al. (2008)
Branchina & Messina (2013)
Gies et al. (2013)

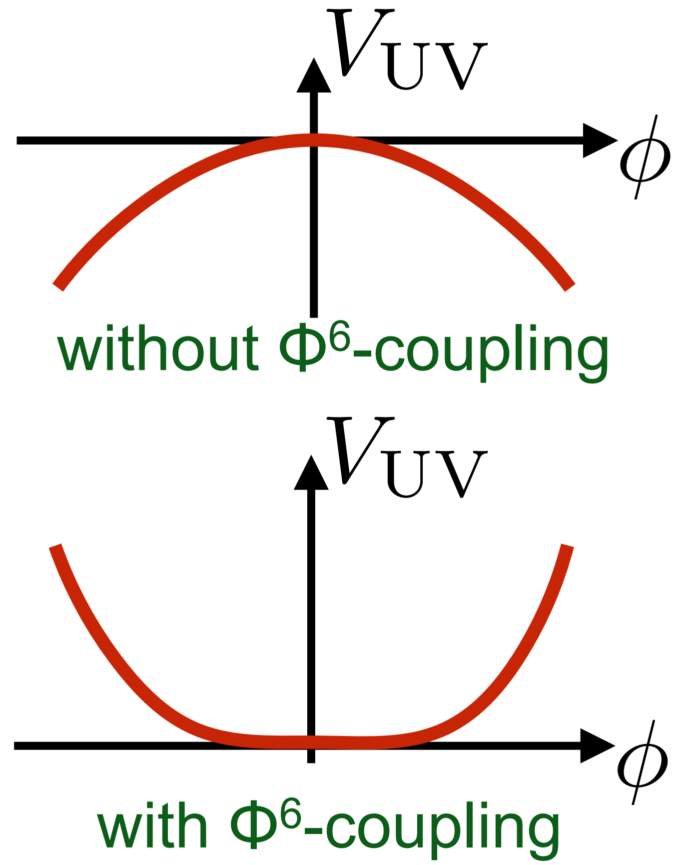


becomes tiny very fast!

- Nevertheless: impact on mass bounds
- Or: impact on maximal UV extension

- **Mechanism to go below lower mass bound:**

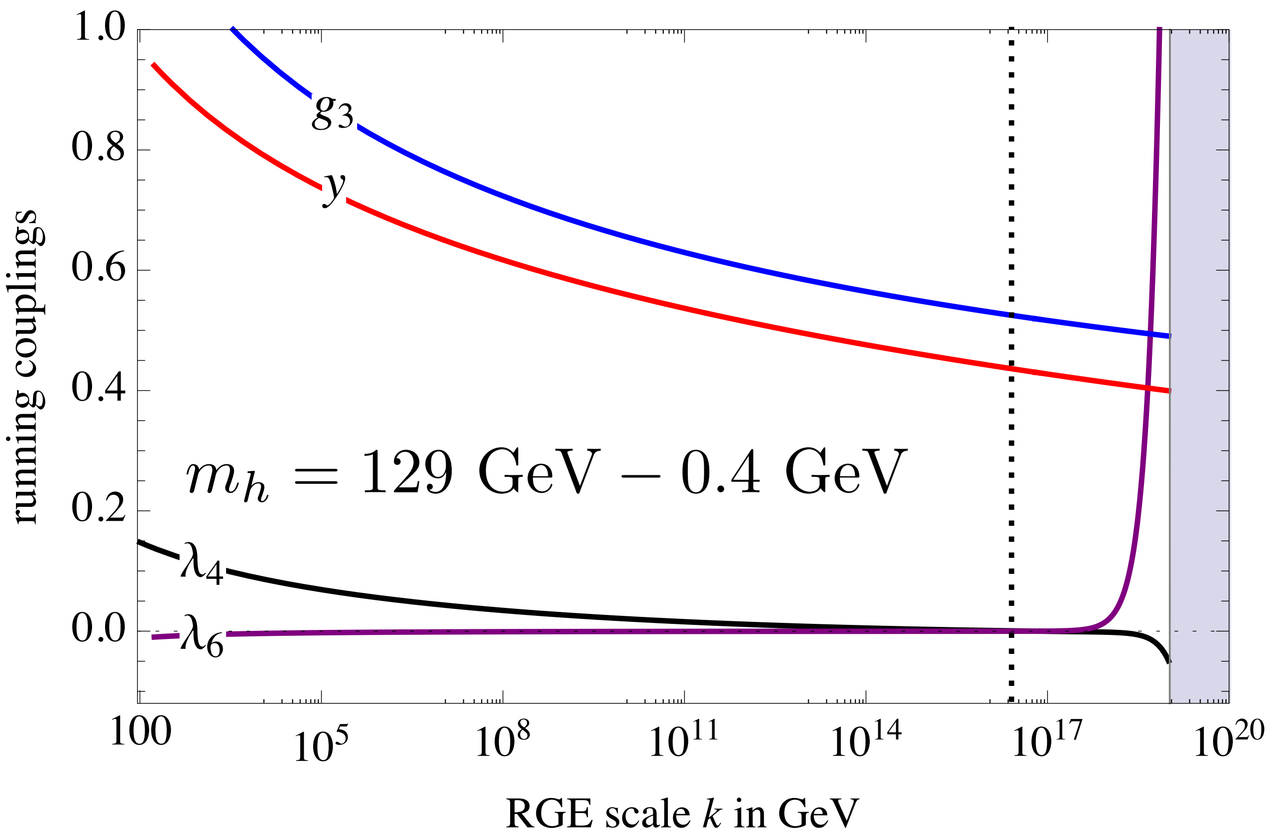


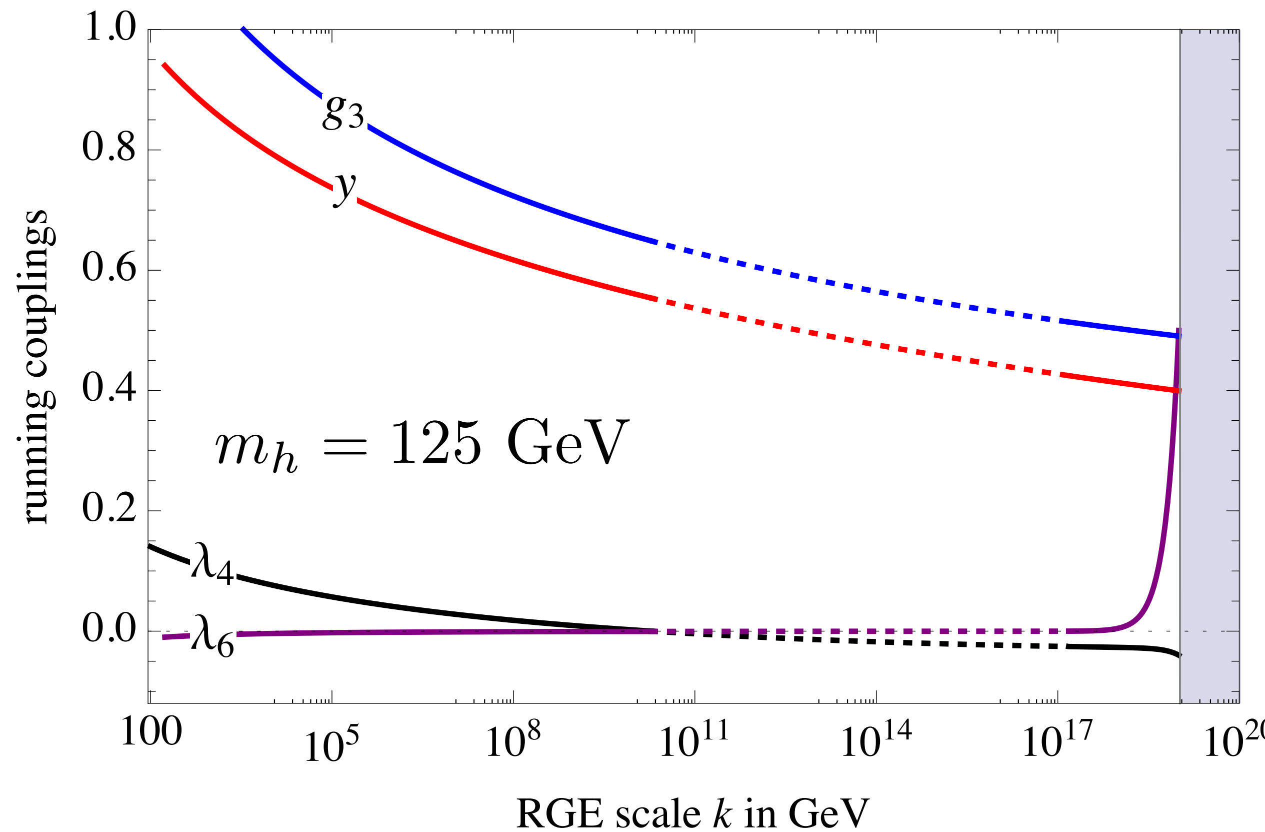


Gauged Higgs-Top Model - Higher-dimensional operators

$$V_{\mathrm{UV}} = \frac{\lambda_4(\Lambda)}{4} H^4 + \frac{\lambda_6(\Lambda)}{8\Lambda^2} H^6 + \ldots$$

- **Potential at UV scale:** completely stable with minimum at H=0



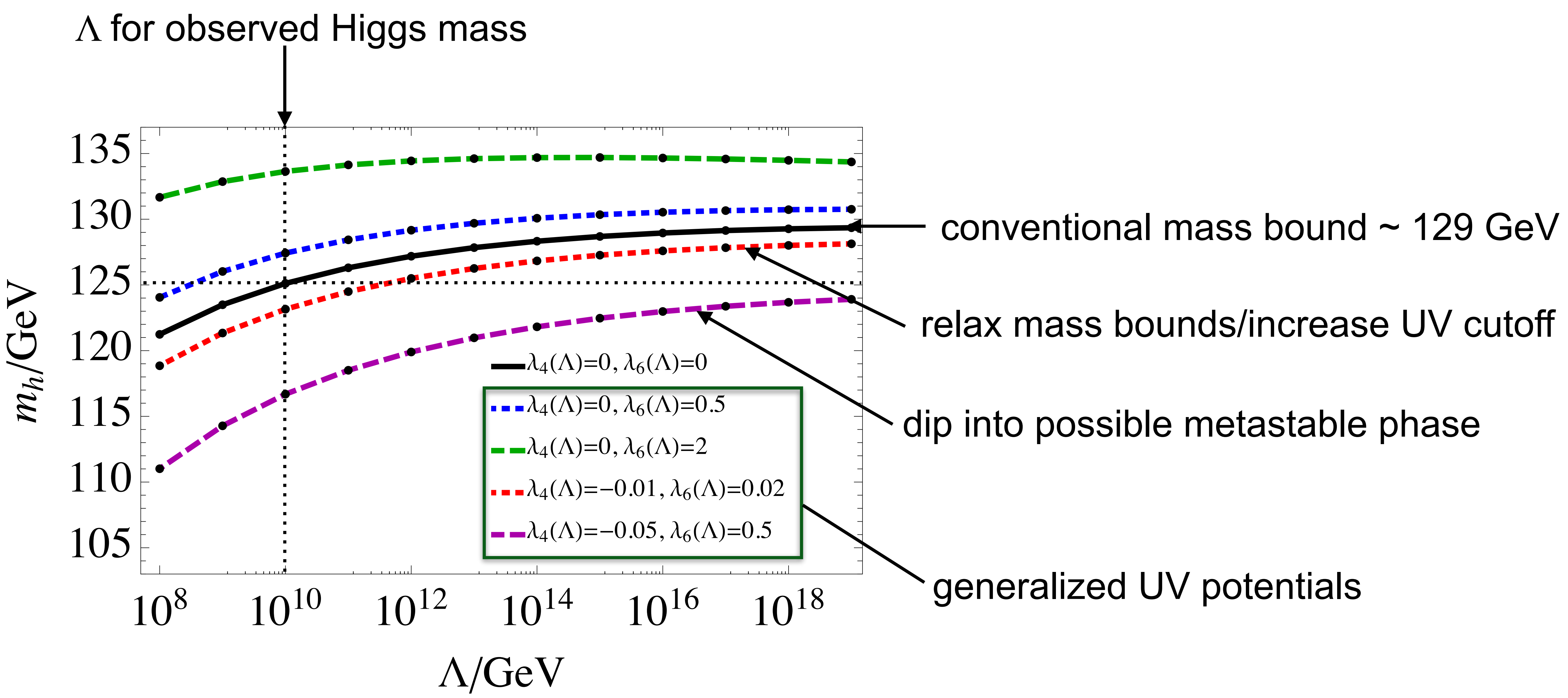


- Potential completely stable during entire RG flow
- Extend UV cutoff by orders of magnitude (~ 2)
- Small shift in allowed Higgs masses towards smaller values

- Potential develops 2nd Minimum during RG flow
  - Min @ H=0 only metastable
- Small λ_6 sufficient to stabilize UV potential
- Further RG studies required

Higgs Mass Bounds

- **Potential at UV scale:** completely stable with minimum at H=0

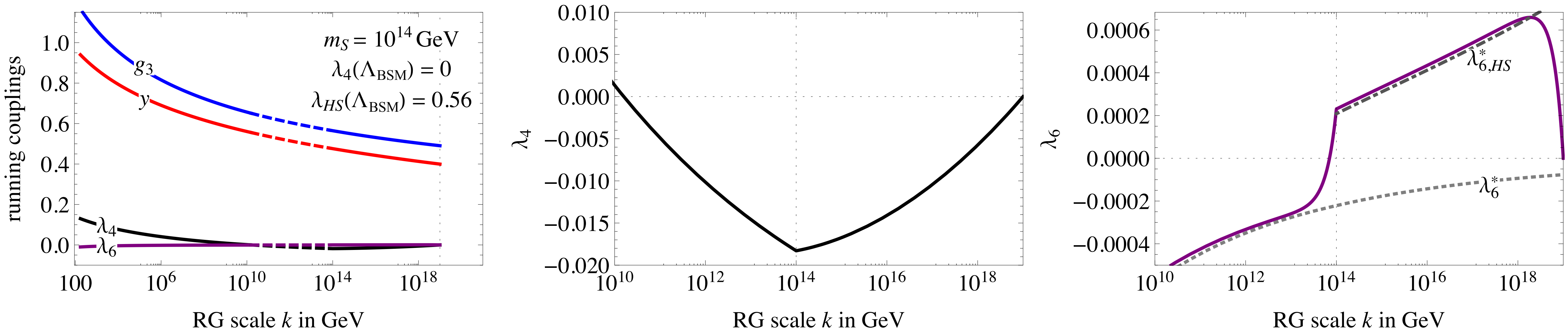


- Take care when translating shifts from toy model to SM
- Nevertheless: shifts at level of 1-5% seem viable

Models for High-Scale Physics

- How to generate suitable higher-dimensional couplings from high-scale physics?
- Induce potential with $\lambda_4<0$ and $\lambda_6>0$
- simple model: introduce N_S heavy scalars with inherent cutoff, e.g. @$\Lambda_{\text{BSM}}=M_{\text{Pl}}$

Higgs portal: $$\Delta V_{\text{eff}} = \lambda_{HS}\frac{H^2}{2}\frac{S^2}{2} + m_S^2\frac{S^2}{2} + \lambda_S\frac{S^4}{4}\,.$$



- Generated λ_6 at 10^{14} GeV: $$\lambda_6(\Lambda) = \frac{-12y^6(\Lambda) + 216\lambda_4^3(\Lambda) + N_S\lambda_{HS}^3(\Lambda)}{4\,(16\pi^2 + 9y^2(\Lambda) + 45\lambda_4(\Lambda))}$$

➡ Induce **stable** potential with $\lambda_4<0$ and $\lambda_6>0$: $$N_S\lambda_{HS}^3 \gtrsim 24$$

➡ For small number of new states need sizable portal coupling

Summary & Outlook

- measured Higgs mass very close to lower bound $M_h(\Lambda = M_{Pl})$
- Perturbative analysis: Higgs potential loses stability around 10^{10} GeV
- This statement can be relaxed:
  - higher-dimensional operators at UV scale Λ
  - non-perturbative treatment allows for more general values of higher-dim couplings

✓ Higgs masses below lower bound are possible

✓ With completely stable potential, we can extend UV cutoff by 2 orders of magnitude

✤ Question: What type of physics can predict higher-dim operators of suitable size?

- We have investigated simple SM extension with heavy scalars
- Required parameter choices in simple model are at border to non-perturbative