Higgs Mass and the Scale of New Physics

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in collaboration with

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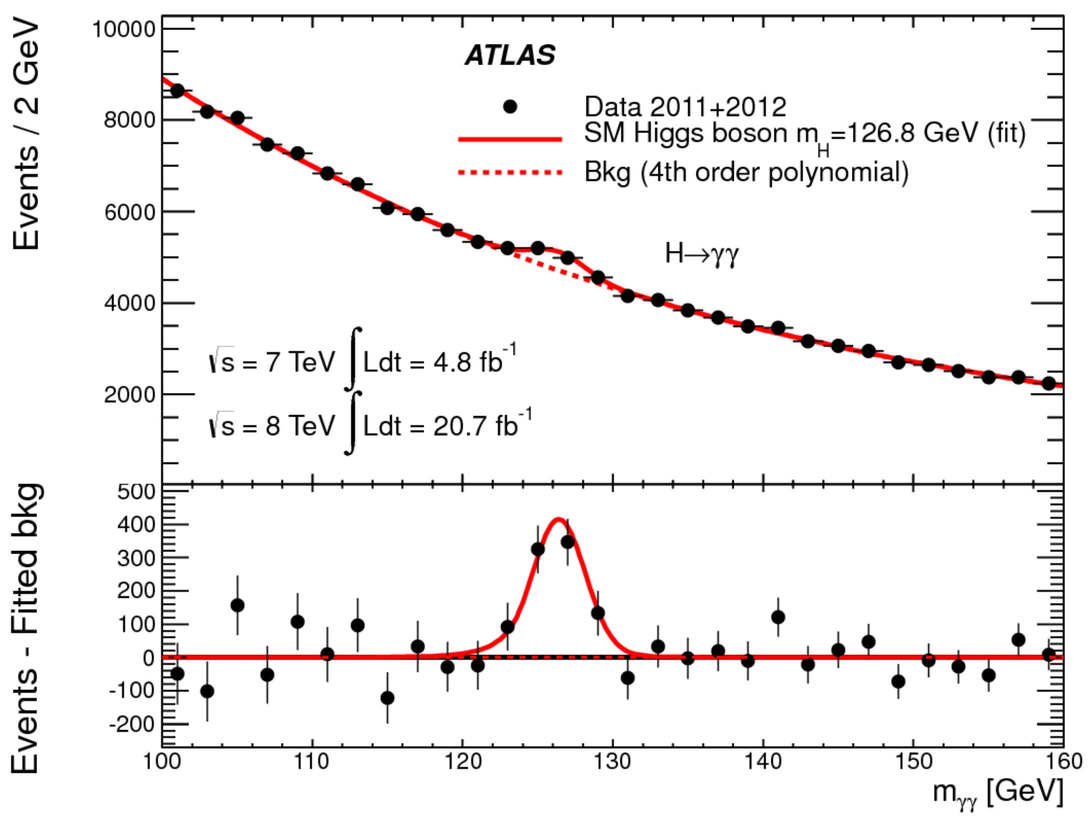
Outline

- **Introduction**
  - Higgs Mass Bounds
  - Vacuum Instability
  - The Scale of New Physics
- **Standard Model as Low-Energy Effective Field Theory**
  - Gauged Higgs-Top Model
  - Impact of Higher-Dimensional Operators
  - Generation of Higher-Dimensional Operators
- **Conclusions**

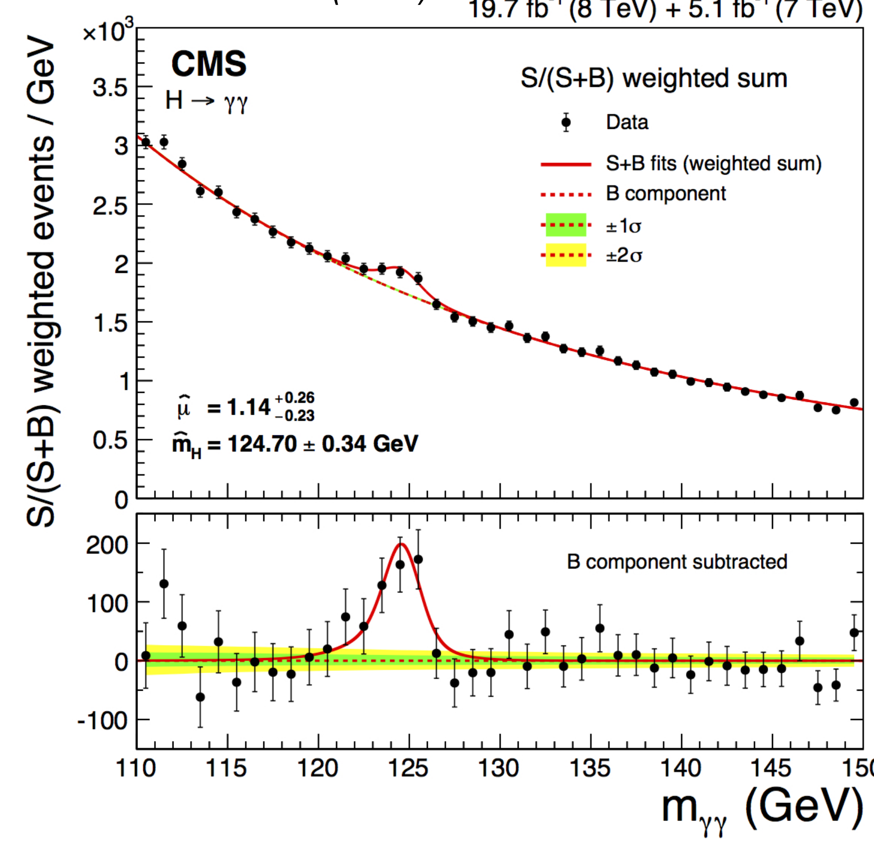
The Standard Model and the Higgs

- Discovery of the **Higgs** @ LHC:

ATLAS collaboration (2012)



CMS collaboration (2012)

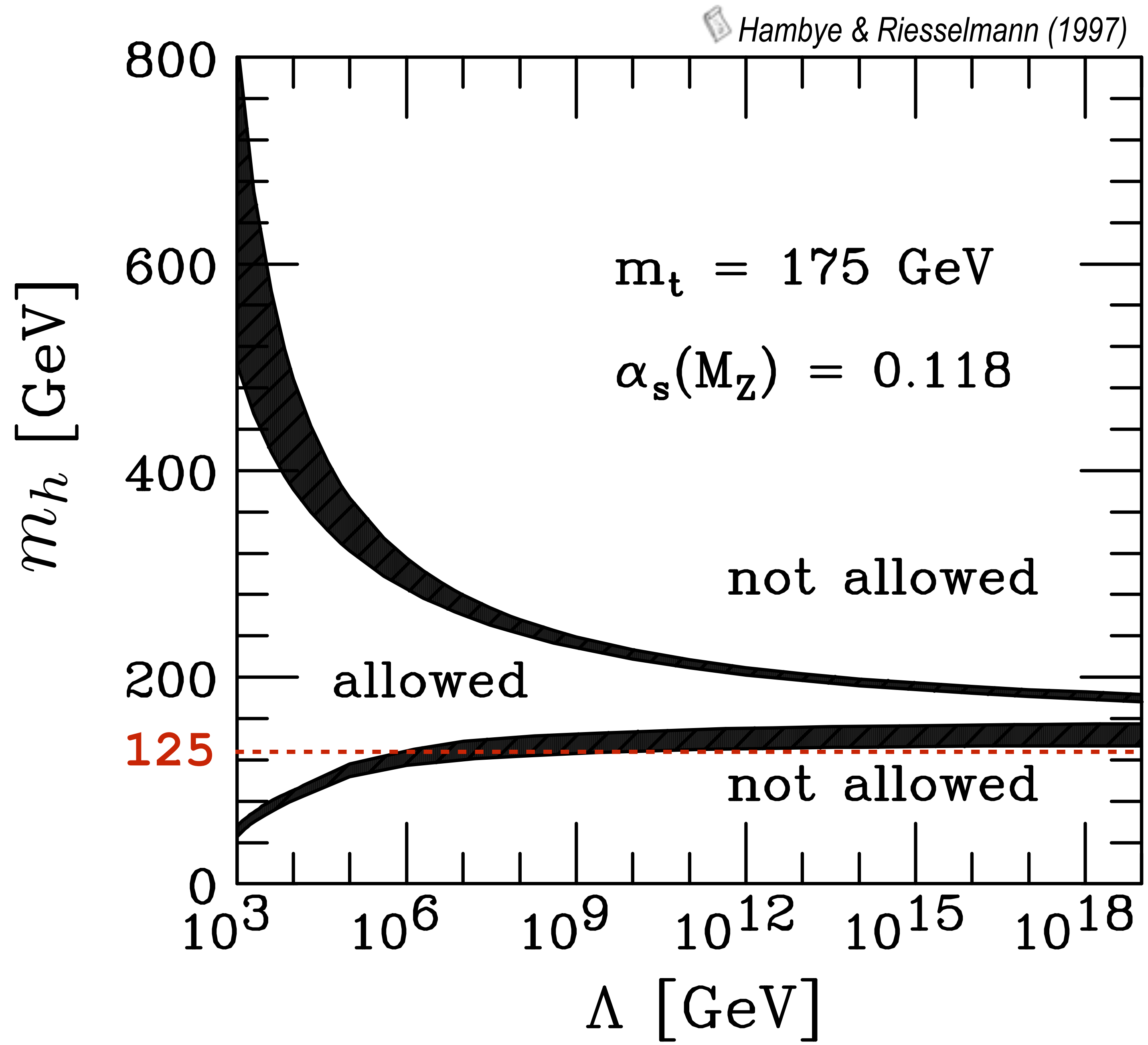


$$\boxed{M_H \approx 125 \text{ GeV}}$$

- **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

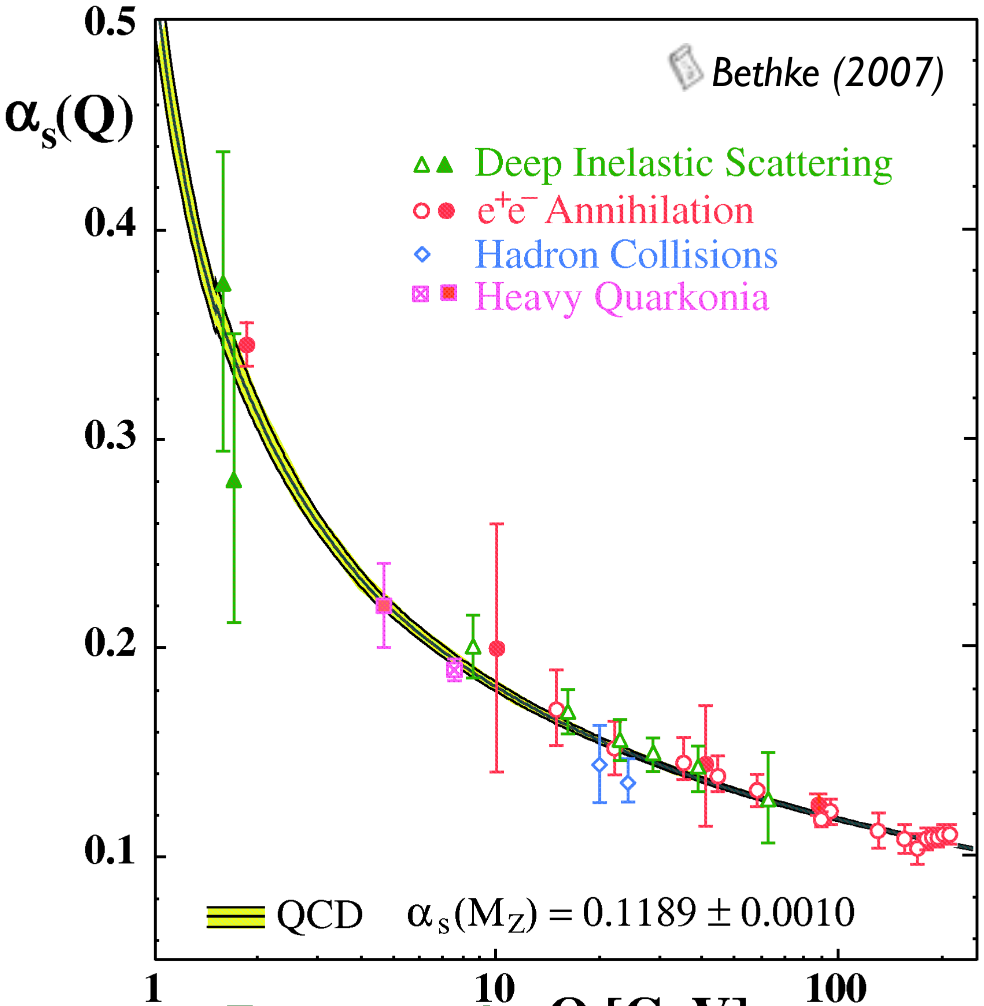


Krive, Linde (1976)
Maiani, Parisi, Petronzio (1978)
Krasnikov (1978)
Politzer, Wolfram (1978)
Hung (1979)
Lindner (1985)
Wetterich (1987)
Lindner, Sher, Zaglauer (1989)
Ford, Jones, Stephenson, Einhorn (1993)
Altarelli, Isidori (1994)
Schrempp, Wimmer (1996)…

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

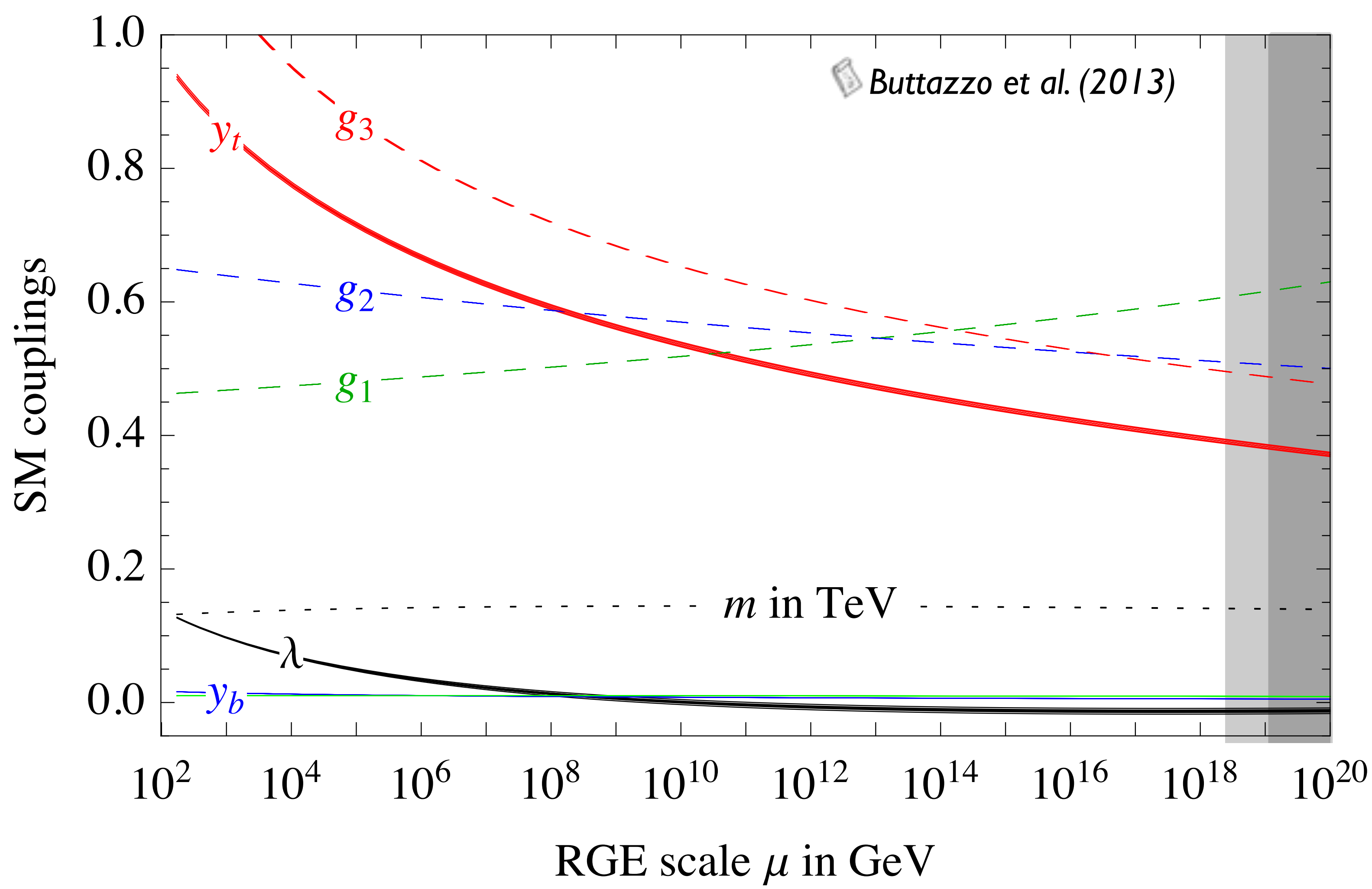
Standard Model Running Couplings

- Running strong coupling α_S:



Energy scale

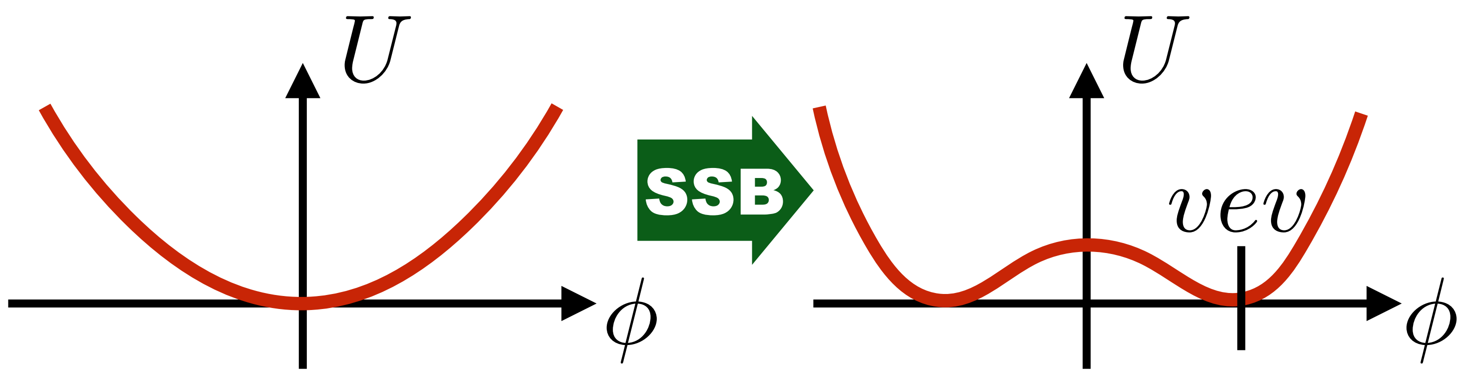
- Standard model running couplings:



renormalization group β functions

Mechanism for Lower Higgs Mass Bound

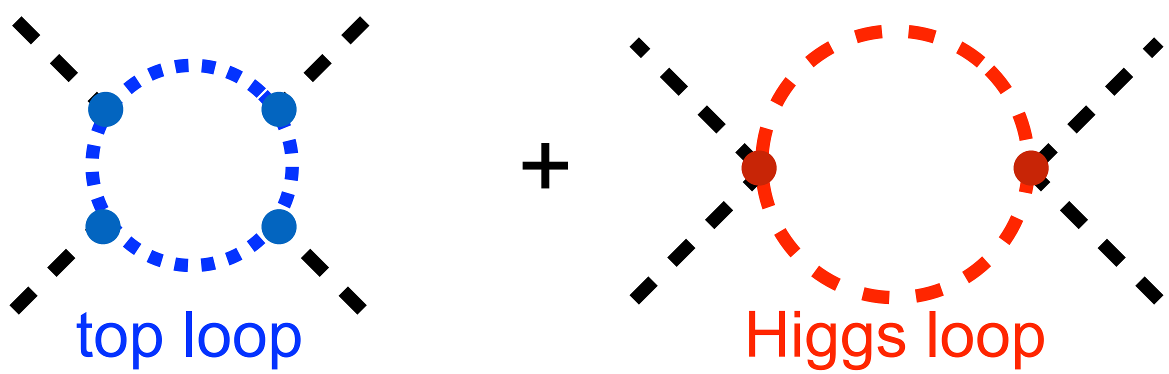
- **Higgs potential:** $\frac{\mu}{2}H^2 + \frac{\lambda_4}{4}H^4$

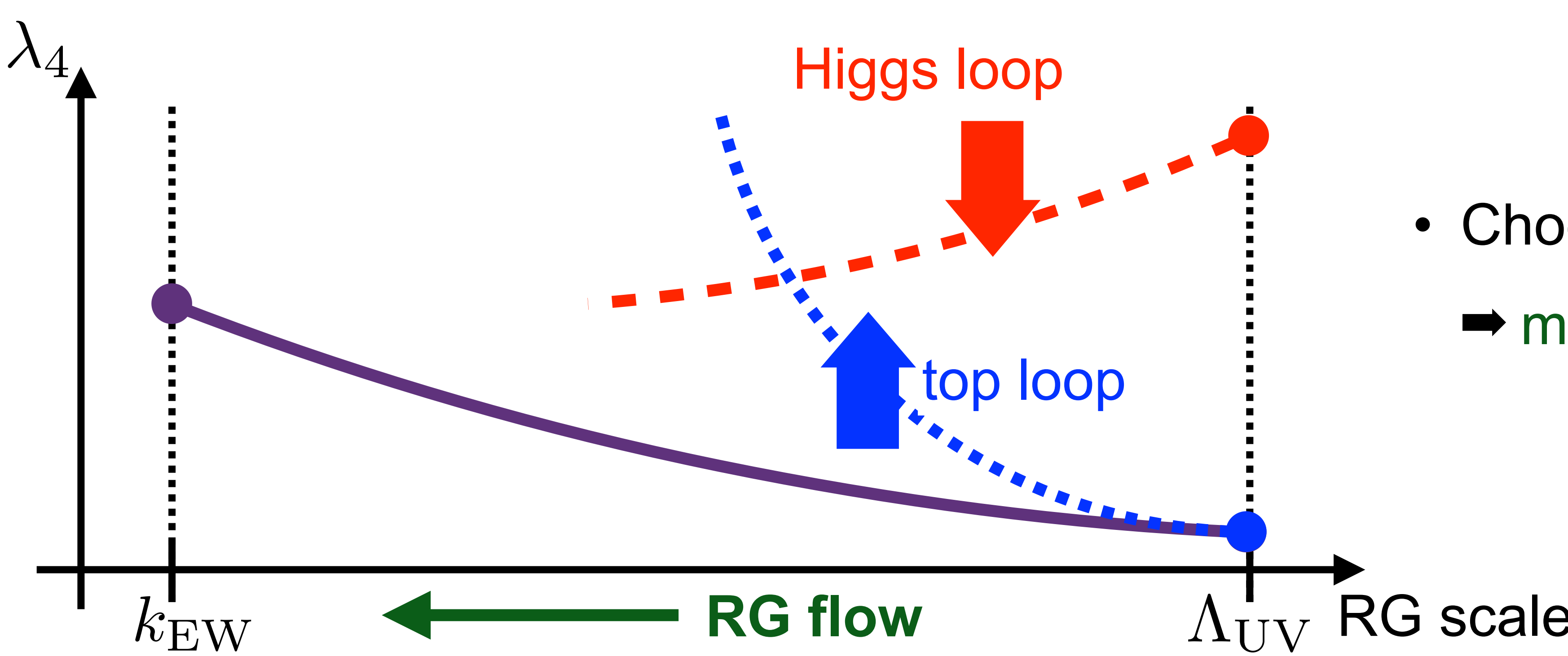


$$m_h = \sqrt{2\lambda_4} \cdot vev$$

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

- **Running Higgs self-coupling:**

$\beta_{\lambda_4} =$ -  + gauge contributions

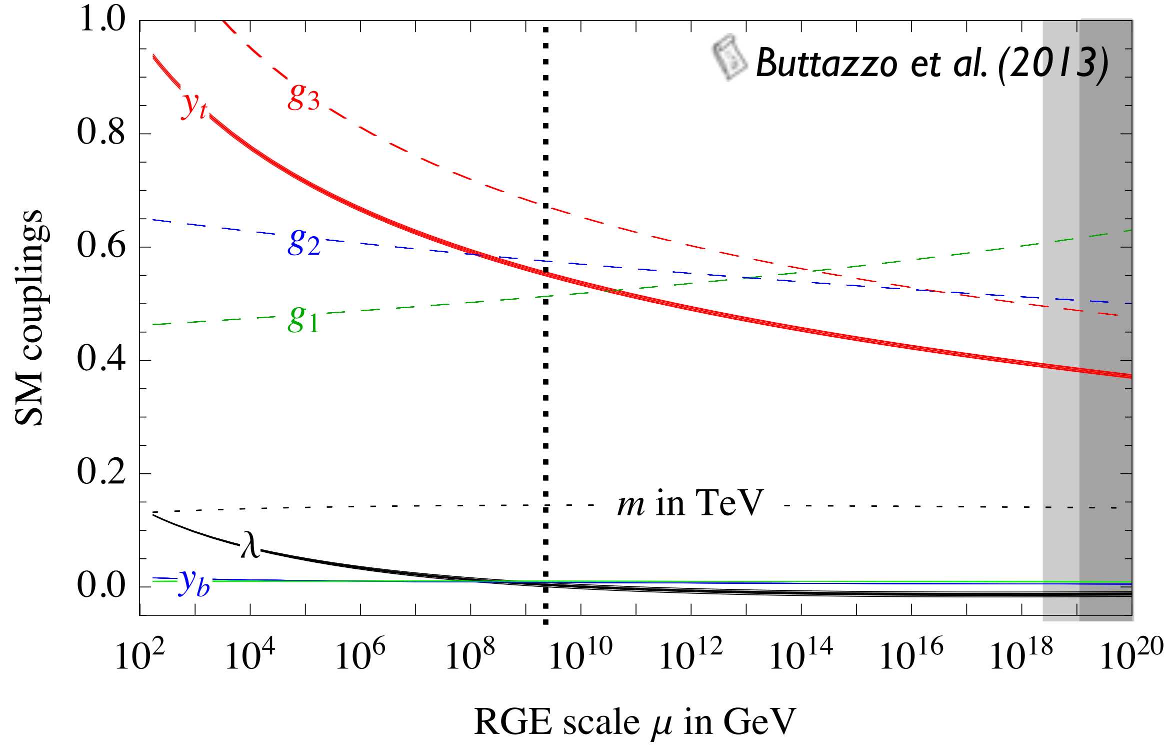


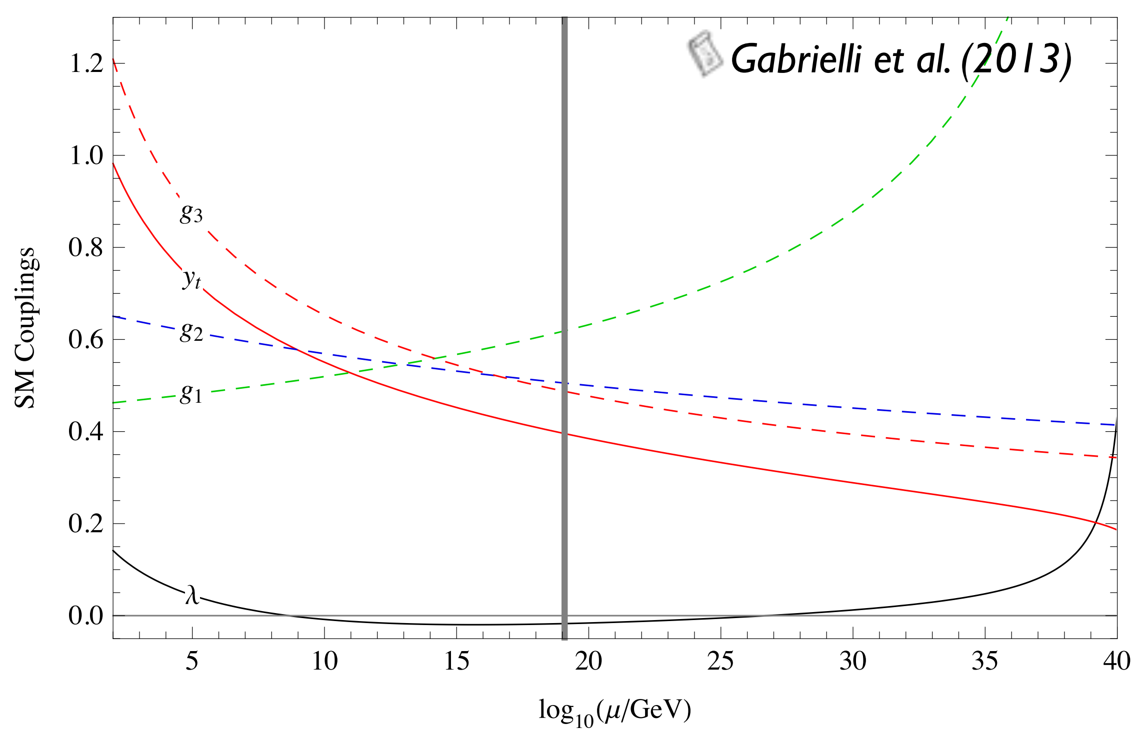
- Choose $\lambda = 0$ at Λ_{UV}:

  ➡ minimal value of Higgs mass

Lower Mass Bound in the Standard Model

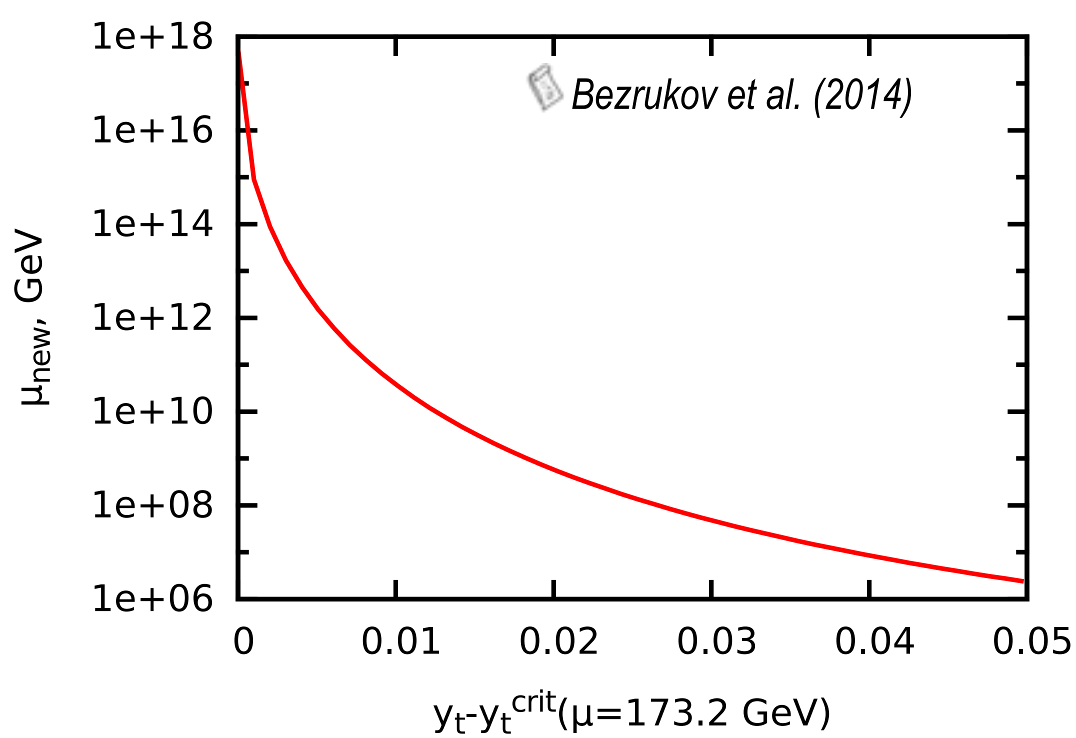
$$\beta_{\lambda_4} = \frac{d\,\lambda_4}{d\,\log k} = \frac{1}{8\pi^2}\left[12\lambda_4^2 + 6\lambda_4 y^2 - 3y^4 - \frac{3}{2}\lambda_4\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2+g_1^2)^2\right)\right]$$





- **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:

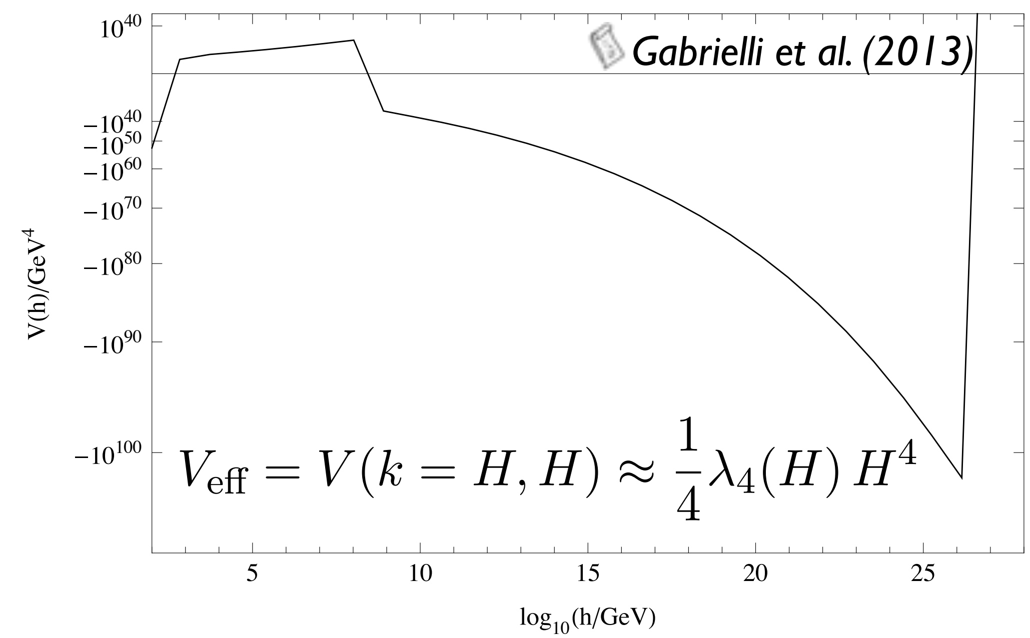


Scenarios at the Scale of New Physics

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

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

2. Stable minimum might appear for large field values



➡ True minimum @ $H \sim 10^{25}$ GeV?

➡ *Metastability* of Higgs vacuum?

➡ Small tunnelling 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?

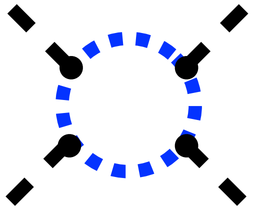
Stability & Higher-Dimensional Operators

Does the top loop induce an instability in the potential?

- Vacuum stability in presence of a finite UV-cutoff Λ:

  ➡ start with stable bare potential $V_{\mathrm{UV}} = V_{\mathrm{eff}}(\Lambda) = \frac{\mu^2(\Lambda)}{2} H^2 + \frac{\lambda_4(\Lambda)}{4} H^4$

  ➡ consider: $\beta_{\lambda_4} = -3y^4/(8\pi^2) + \cdots$



  ➡ top loop contribution to effective potential @ EW scale ($k_{\mathrm{EW}} << \Lambda$):

$$\Delta V_{\mathrm{top}} = -c_2 \Lambda^2 H^2 \underbrace{+c_4 \frac{y^4}{4} H^4 \log \frac{\Lambda}{k_{\mathrm{EW}}} + \ldots}_{\text{positive terms}}$$

  ➡ Higgs potential @ EW scale:

$$V_{\mathrm{eff}}(k_{\mathrm{EW}}) \approx V_{\mathrm{UV}} + \Delta V_{\mathrm{top}}$$

  ➡ contribution to quartic term: $\lambda_4(k_{\mathrm{EW}}) = \lambda_4(\Lambda) + c_4 y^4 \log \frac{\Lambda}{k_{\mathrm{EW}}} \approx \frac{1}{8}$ ➡ $M_H \approx 125$ GeV

  ➡ Large Λ forces us to choose $\lambda_4(\Lambda) < 0$ to obtain measured Higgs mass!

Stabilizing the UV potential

- No instability induced by top loop!
- However: have to chose unstable Φ^4 potential @ $\Lambda_{\rm UV}$ to reproduce $M_H = 125$ GeV
- Idea: include higher-dimensional operators!

fixed by $vev = 246$ GeV

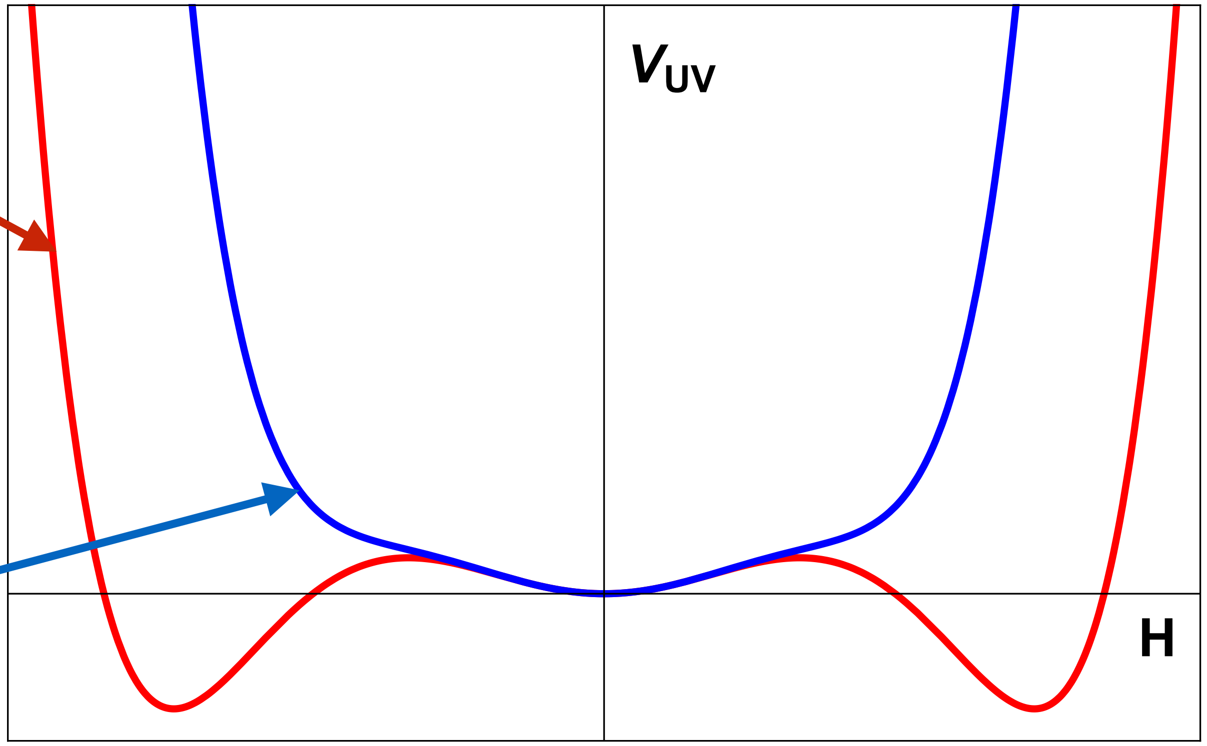
free parameter

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

fixed by Higgs mass

- positive $\lambda_6(\Lambda) \rightarrow$ UV potential is stable
- remove 2nd minimum for $\lambda_4(\Lambda) < 0$:

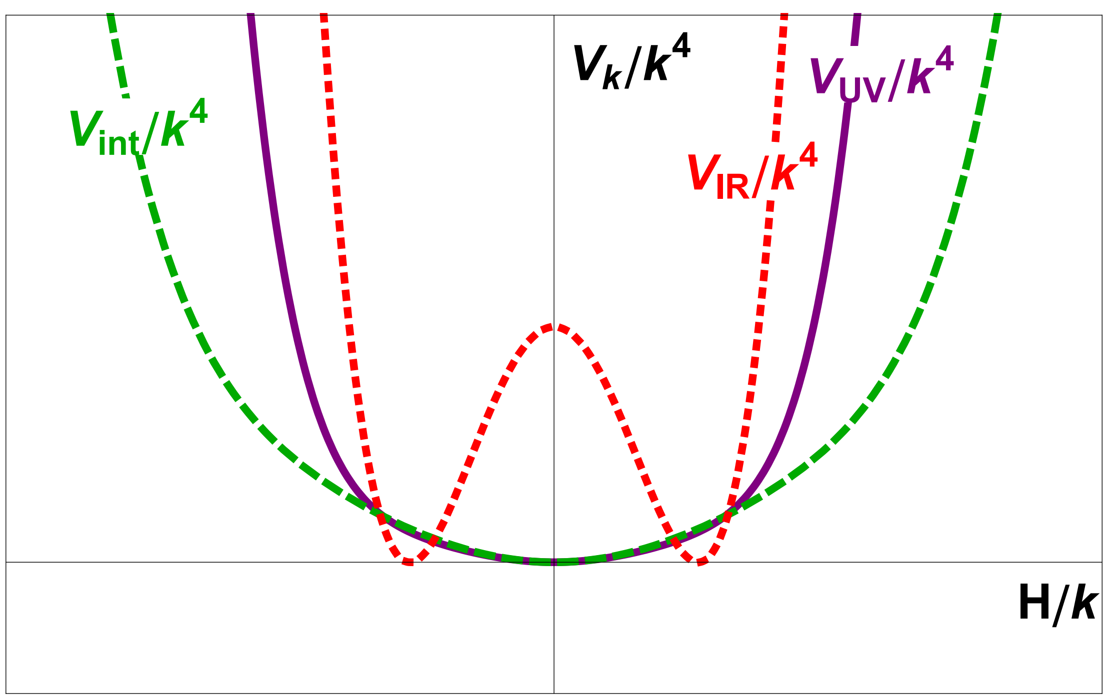
$$\boxed{\lambda_6(\Lambda) > \lambda_4^2(\Lambda)\,\frac{\Lambda^2}{3\mu^2(\Lambda)}}$$



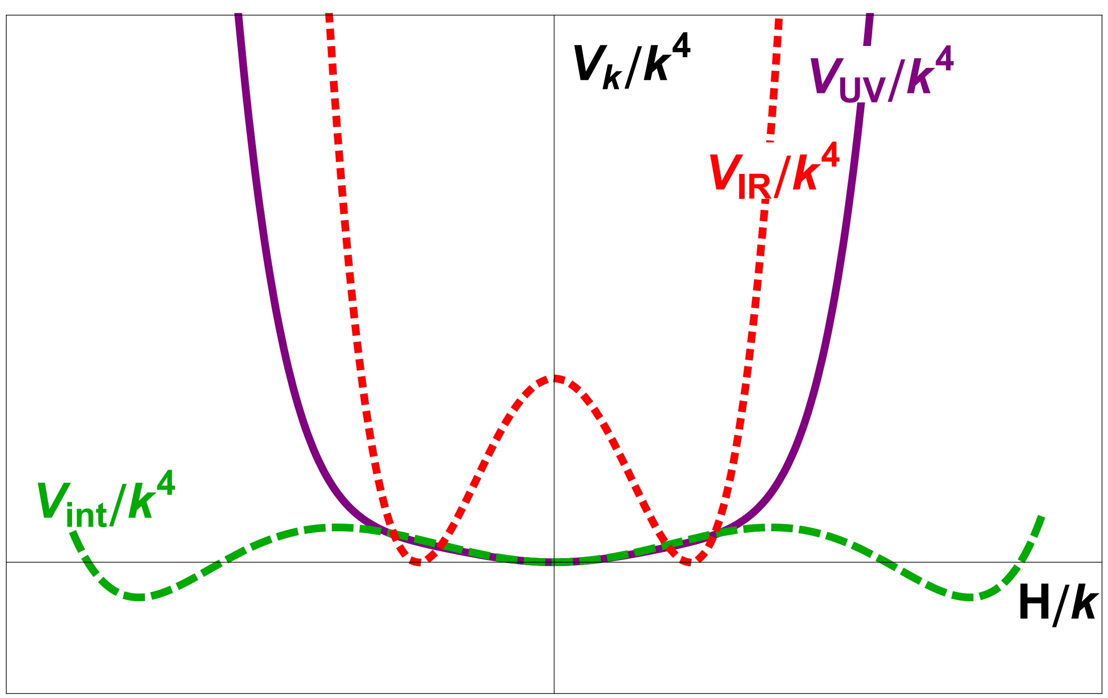
RG Flow of Generalized Potentials

$$V_{\text{eff}}(k) = \frac{\mu(k)^2}{2}H^2 + \sum_{n=2} \frac{\lambda_{2n}(k)}{k^{2n-4}} \left(\frac{H^2}{2}\right)^n = \frac{\mu^2(k)}{2}H^2 + \frac{\lambda_4(k)}{4}H^4 + \frac{\lambda_6(k)}{8k^2}H^6 + \cdots$$

- RG flow from UV to IR:



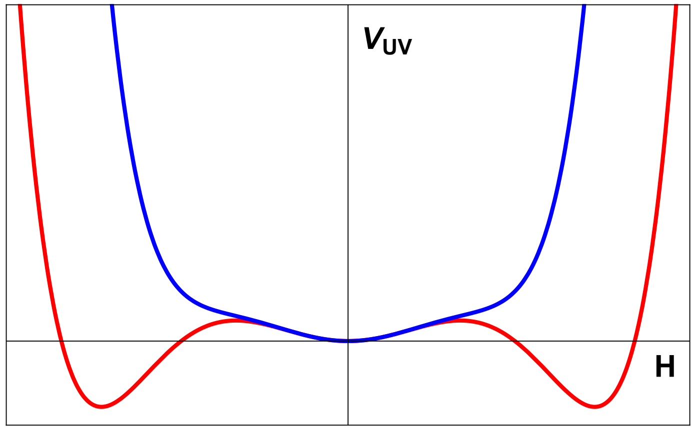
- unique minimum between Λ and k_{EW}
- EW minimum forms in the IR @ 246GeV

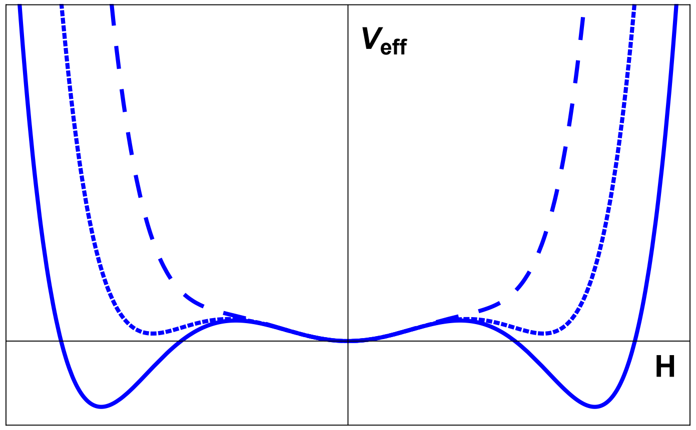


- smaller $\lambda_6(\Lambda)$
- ‘meta-stable’ behavior for intermediate k
- EW minimum forms in the IR @ 246GeV

→ *distinguish between stability of UV potential and IR potential!*

Stability with Higher-Dimensional Operators





- UV potential and effective potential can have quite different shapes
- presence of higher-dimensional operators modifies UV potential in general way
- higher-dimensional operators contribute to RG flow of renormalizable operators
- take this into account with scale-dependent effective potential $V_{\rm eff}(k;H)$:

$$V(k=\Lambda;H) = V_{\rm UV} \qquad \text{and} \qquad V(k=0;H) = V_{\rm eff}$$

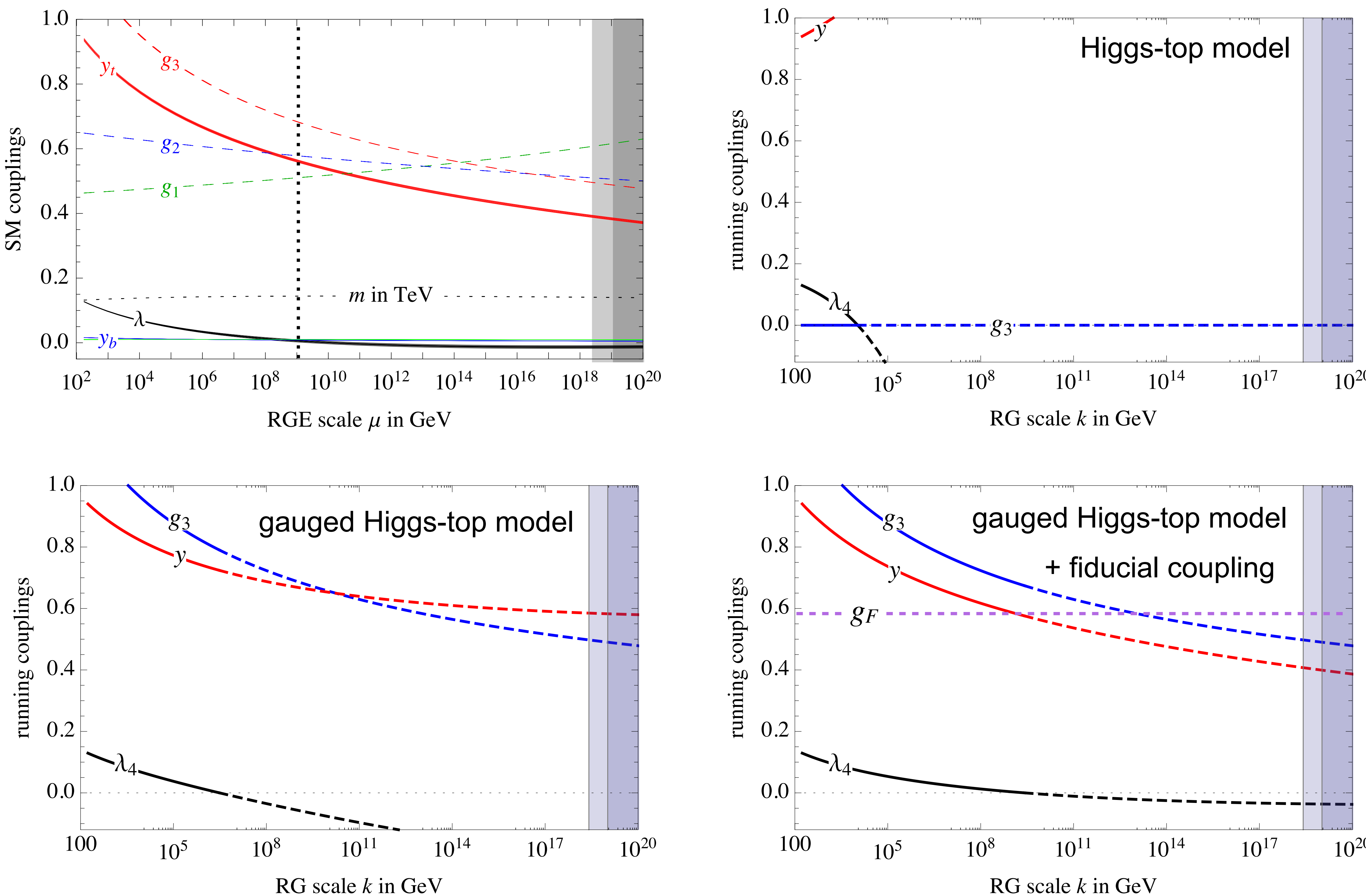
- follow (meta-)stability properties in scale-dependent manner

➡ need non-perturbative approach → functional RG

Gauged Higgs-Top Model

Gauged Higgs-Top Model - 1-Loop Running

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



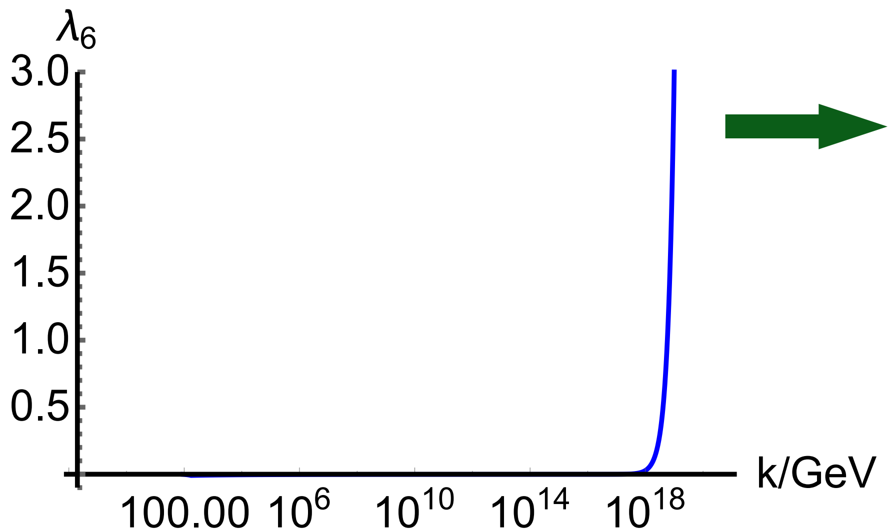
Standard Model as a Low-Energy Effective Theory

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

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

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

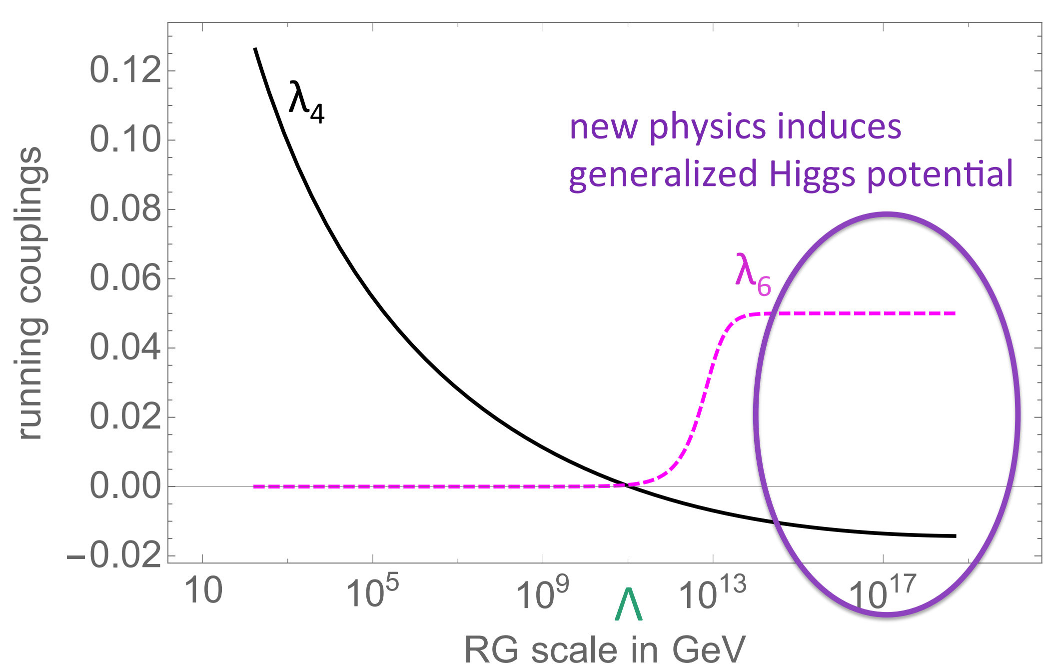
Fodor et al. (2008)
Branchina & Messina (2013)
Gies et al. (2013)

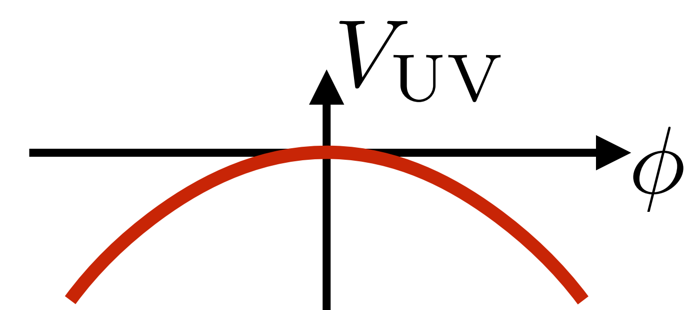


→ becomes tiny very fast!

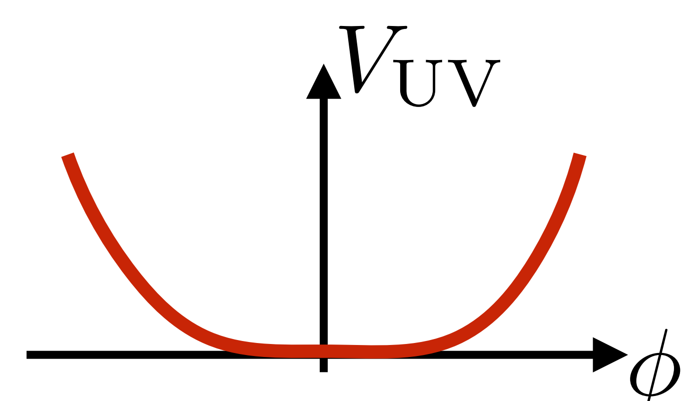
- Nevertheless: impact on mass bounds
- Or: impact on maximal UV extension

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





without Φ^6-coupling

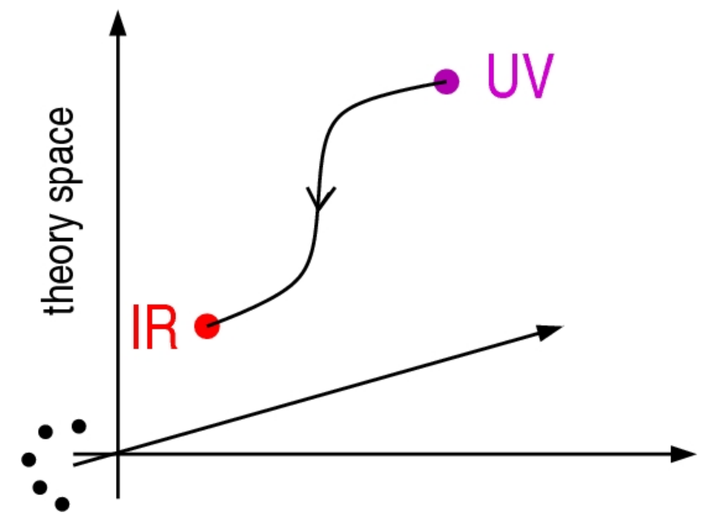


with Φ^6-coupling

Functional RG for Gauged Higgs-Yukawa Model

- Use functional RG method as an appropriate tool to obtain β functions:
  - allows to include all quantum fluctuations in presence of higher-dim operators
  - flowing action Γ_k with RG scale k interpolates between

$$\text{microscopic action } (k \to \Lambda): \quad \Gamma_k[\Phi] \to S[\Phi]$$
$$\text{full effective action } (k \to 0): \quad \Gamma_k[\Phi] \to \Gamma[\Phi]$$



  - FRG flow equation:

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \mathrm{STr}\{[\Gamma_k^{(2)}[\Phi] + R_k]^{-1} (\partial_t R_k)\} .$$

Wetterich (1993)

  - truncation: $\Gamma_k = \int d^4x \left[V + \frac{Z_H}{2} (\partial_\mu H)^2 + \sum_{j=1}^{n_f} Z_{\psi_j} \bar{\psi}_j i \not{D} \psi_j + i \frac{1}{\sqrt{2}} \sum_{j=1}^{n_y} \bar{y}_j H \bar{\psi}_j \psi_j + \frac{Z_G}{4} F^a_{\mu\nu} F^{a\mu\nu} \right]$
  - effective potential: $V_{\text{eff}}(k) = \frac{\mu(k)^2}{2} H^2 + \sum_{n=2} \frac{\lambda_{2n}(k)}{k^{2n-4}} \left(\frac{H^2}{2} \right)^n$

e.g., FRG flow of effective potential:

$$\frac{d\, V(H)}{d\, \log k} = \frac{k^4}{32\pi^2} \left[\frac{1 - \frac{\eta_H}{6}}{1 + \frac{V''(H)}{k^2 Z_H}} - 4 \sum_{j=1}^{n_y} N_{\mathrm{c}} \frac{1 - \frac{\eta_{\psi_j}}{5}}{1 + \frac{\bar{y}_j^2 H^2}{2k^2 Z_{\psi_j}^2}} \right]$$

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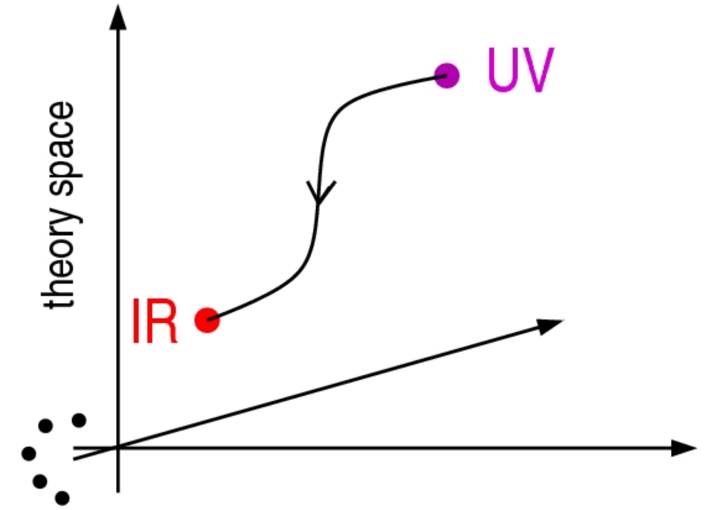

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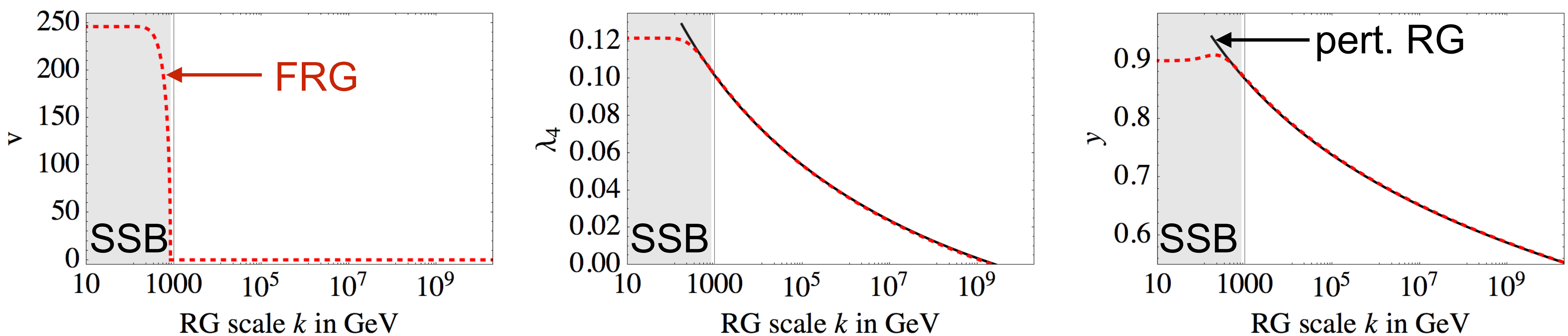
Wetterich (1993)

  - Threshold contributions allow for dynamical mass generation by SSB



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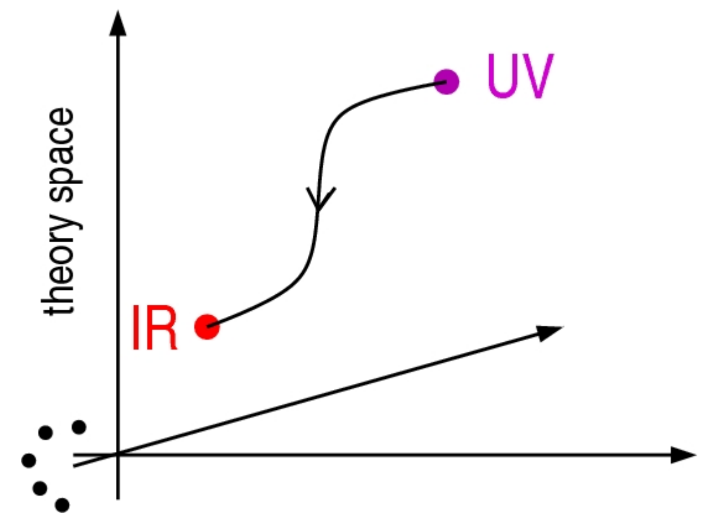


  - FRG flow equation:

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \mathrm{STr}\{[\Gamma_k^{(2)}[\Phi] + R_k]^{-1}(\partial_t R_k)\} \, .$$

Wetterich (1993)

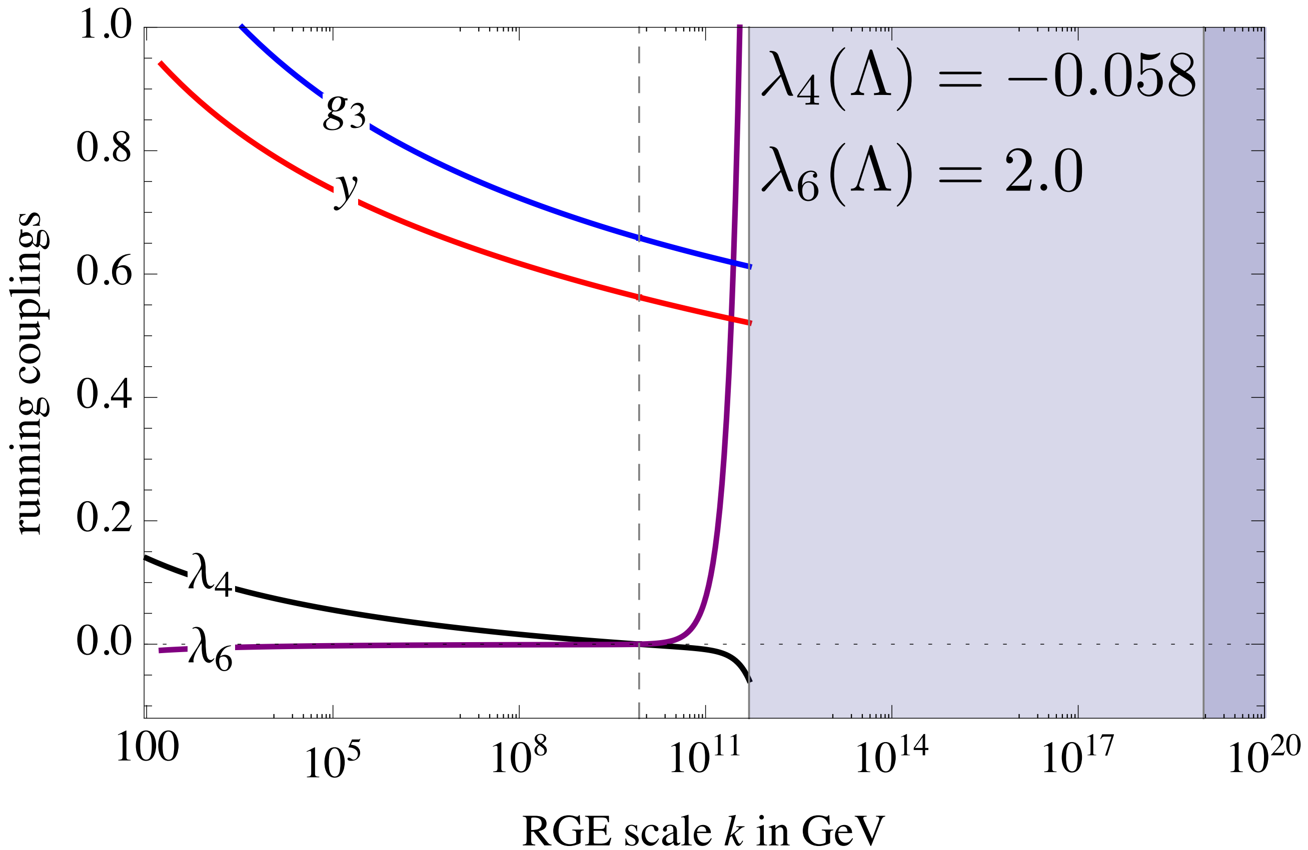
β functions for model couplings…

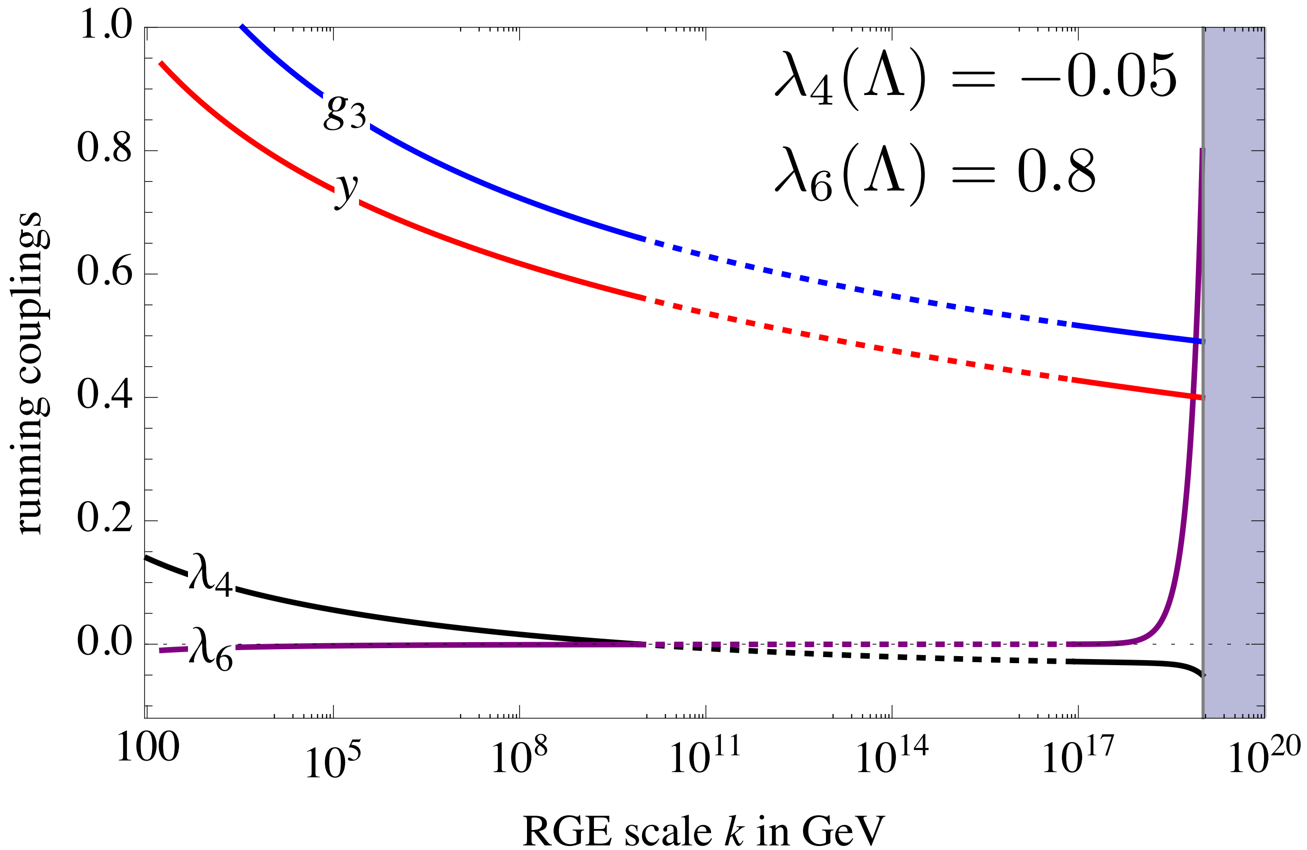
…(e.g. reproduce 1-loop β functions from PT, include threshold effects, higher-dim operators,…)

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 unique minimum at H=0





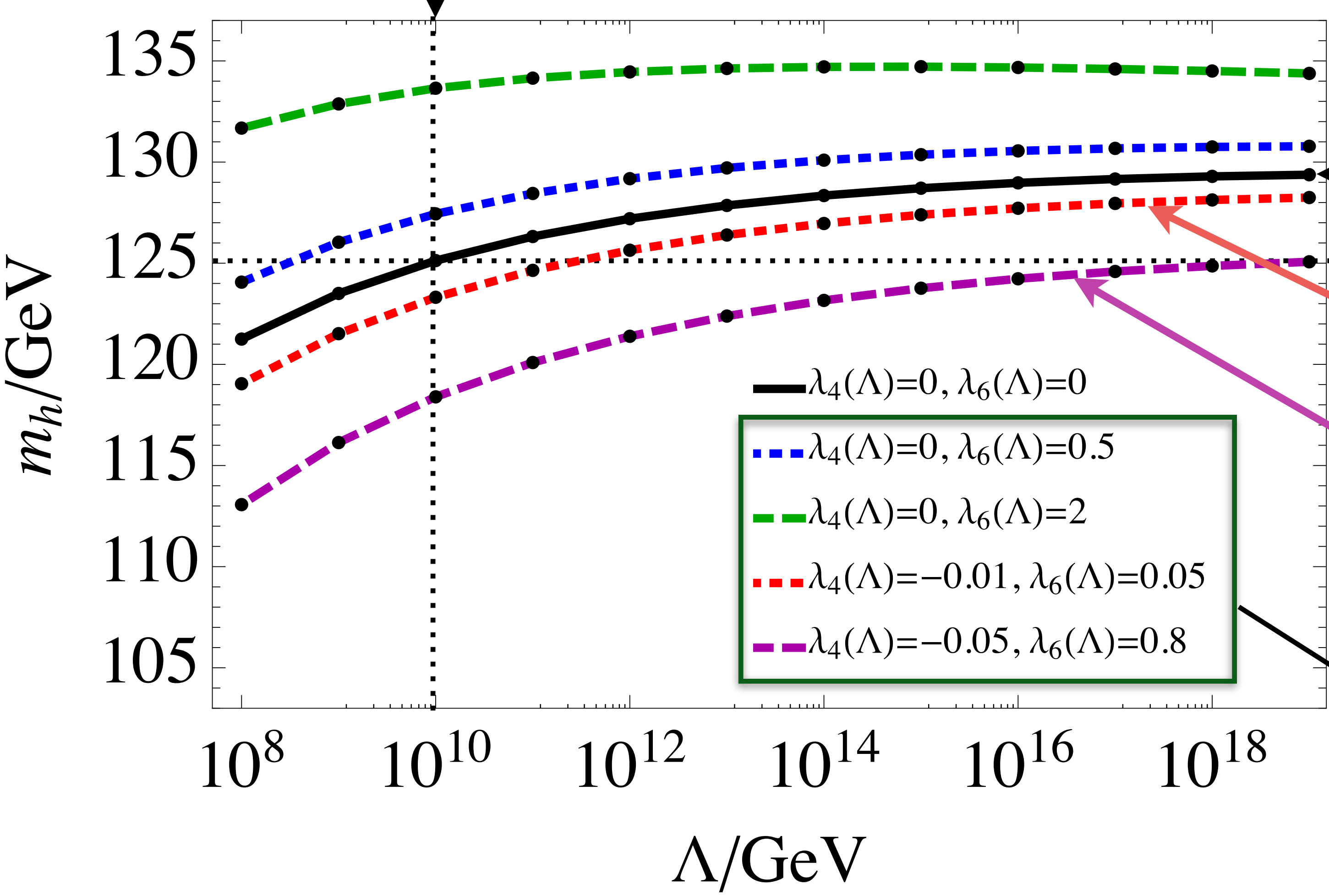
- Potential completely stable during entire RG flow
- Extend UV cutoff by orders of magnitude (~ 2)

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

Higgs Mass Bounds

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

Λ for observed Higgs mass



conventional mass bound ~ 129 GeV

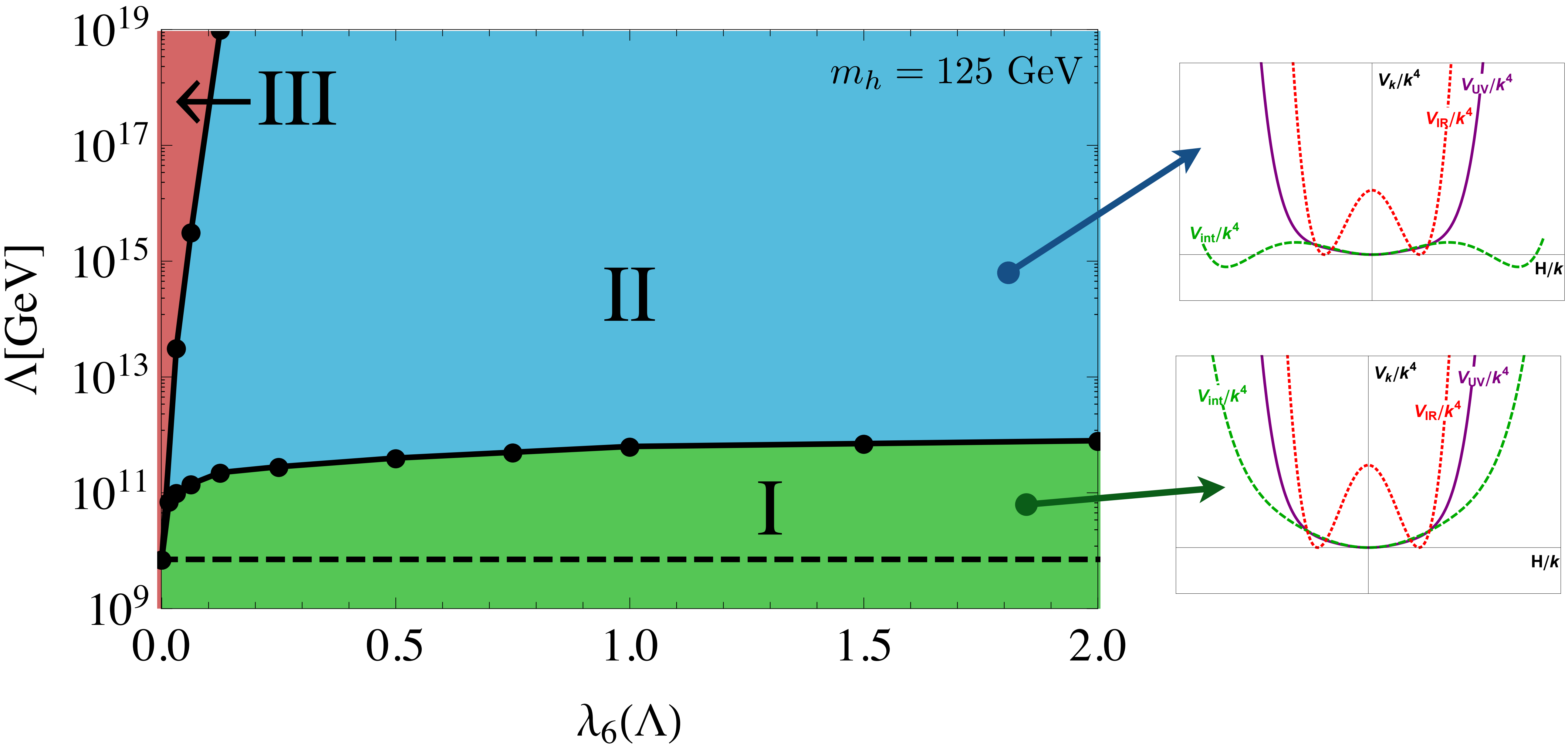
relax mass bounds/increase UV cutoff

dip into possible metastable phase

generalized UV potentials

- shifts at level of 1-5% seem viable

Stability regions



- Moderately small $\lambda_6(\Lambda)$ extend UV cutoff by 2 orders of magnitude at full stability (green)
- Pseudo-stable region (blue) - allows for more orders of magnitude

  ➡ extend FRG study

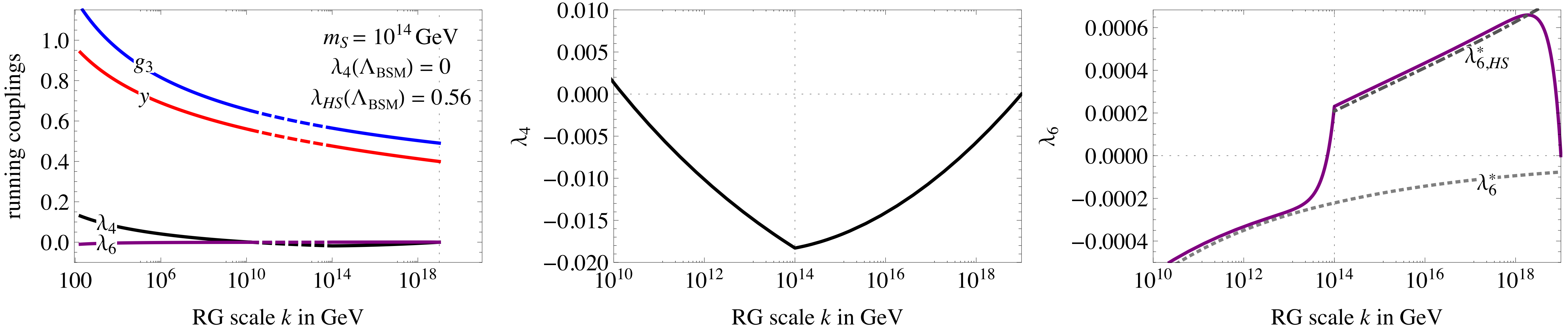
  ➡ possibility of meta-stable effective potential at $k \approx 0$

Models for High-Scale Physics

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. @$\Lambda_{\mathrm{BSM}}=M_{\mathrm{Pl}}$

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



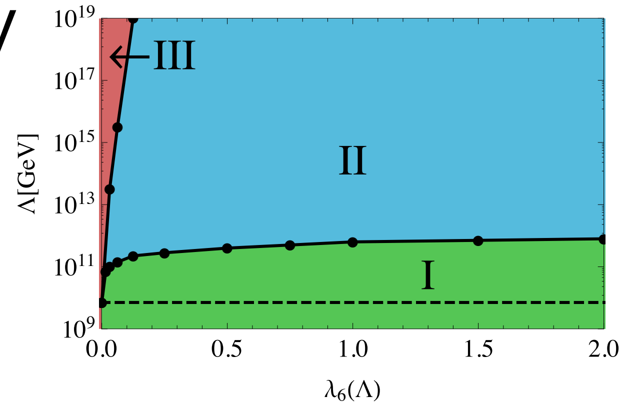
- Generated λ_6 at 10^{14} GeV: $$\lambda_6(\Lambda) = \frac{-12y^6(\Lambda) + 216\lambda_4^3(\Lambda) + N_S\lambda_{HS}^3(\Lambda)}{4\left(16\pi^2 + 9y^2(\Lambda) + 45\lambda_4(\Lambda)\right)}$$

➡ 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 sizeable portal coupling

Summary & Outlook

- measured Higgs mass very close to lower bound $m_h(\Lambda = M_{\mathrm{Pl}})$
- 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

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