Higgs-Dark Matter Connection and the Scale of New Physics

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in collaboration with

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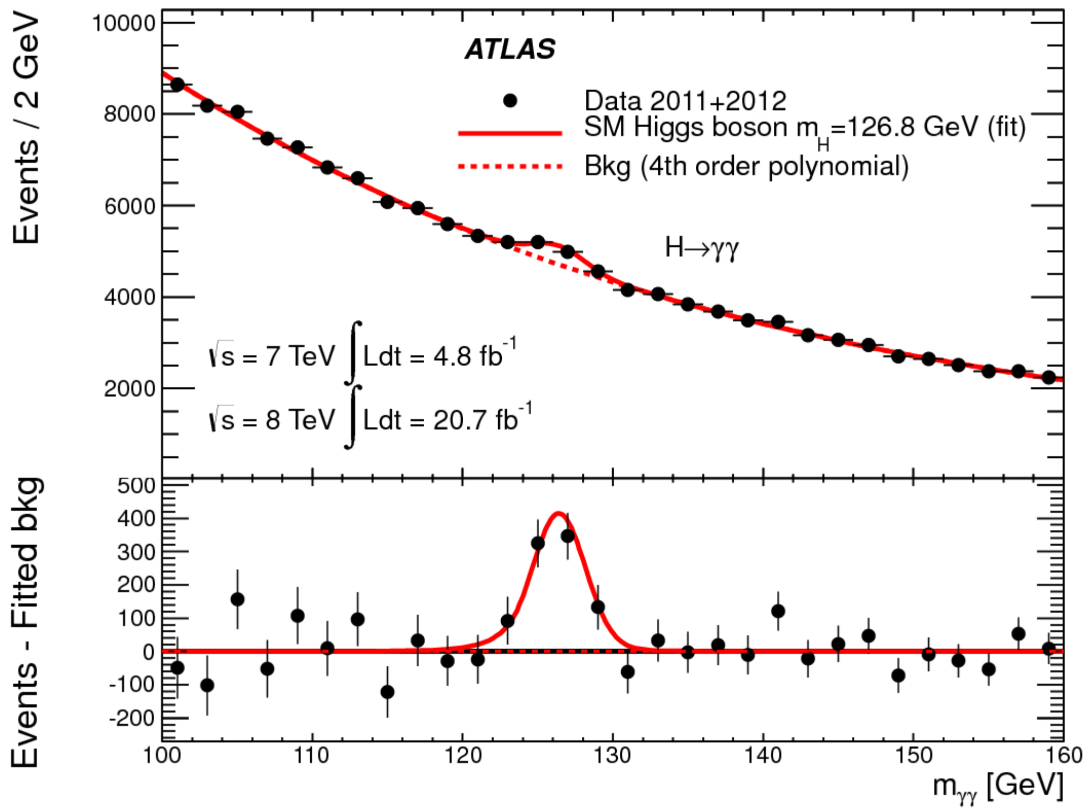
The Standard Model and the Higgs

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

ATLAS collaboration (2012)



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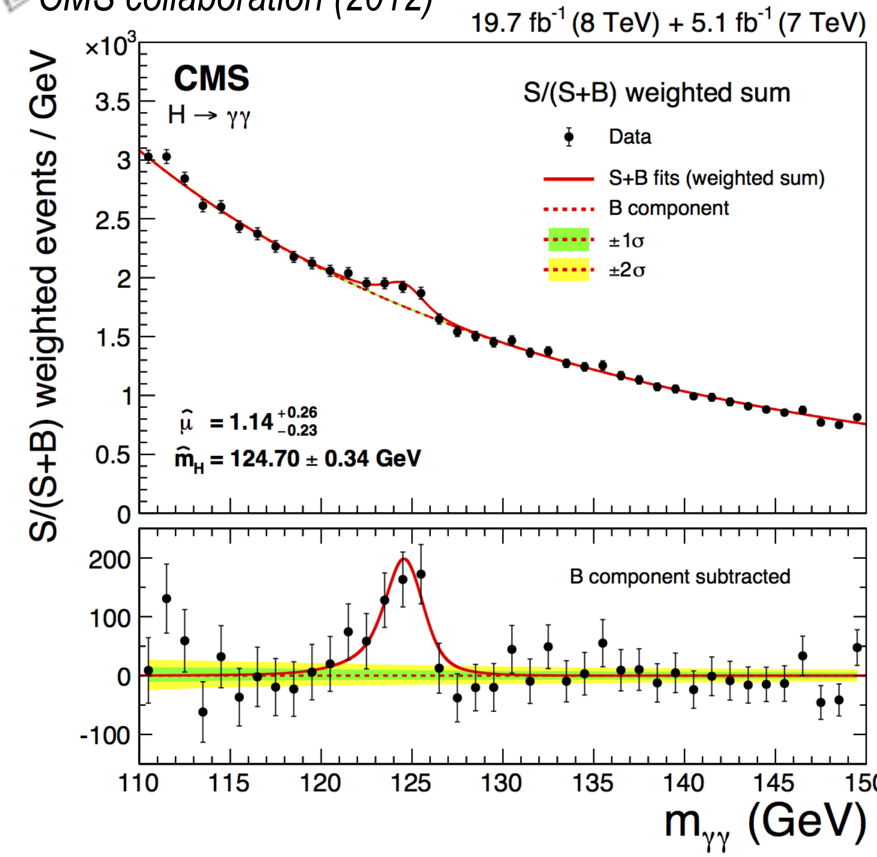

→ $M_H \approx 125$ GeV

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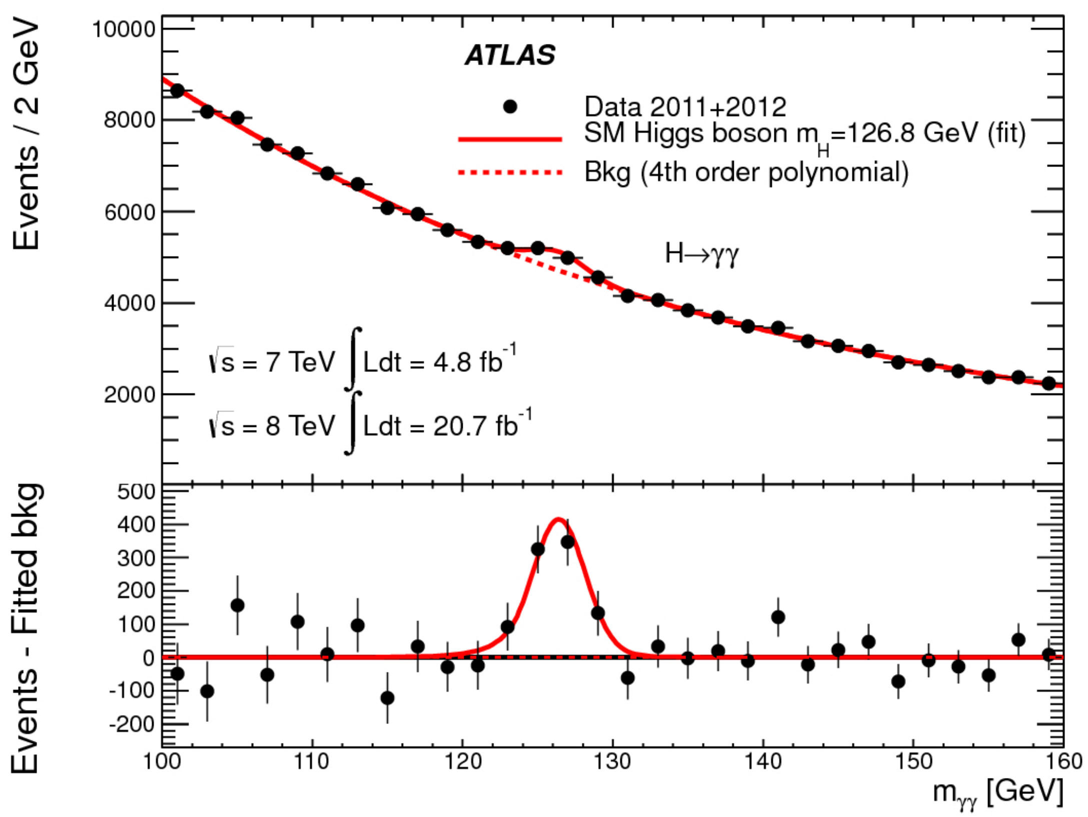

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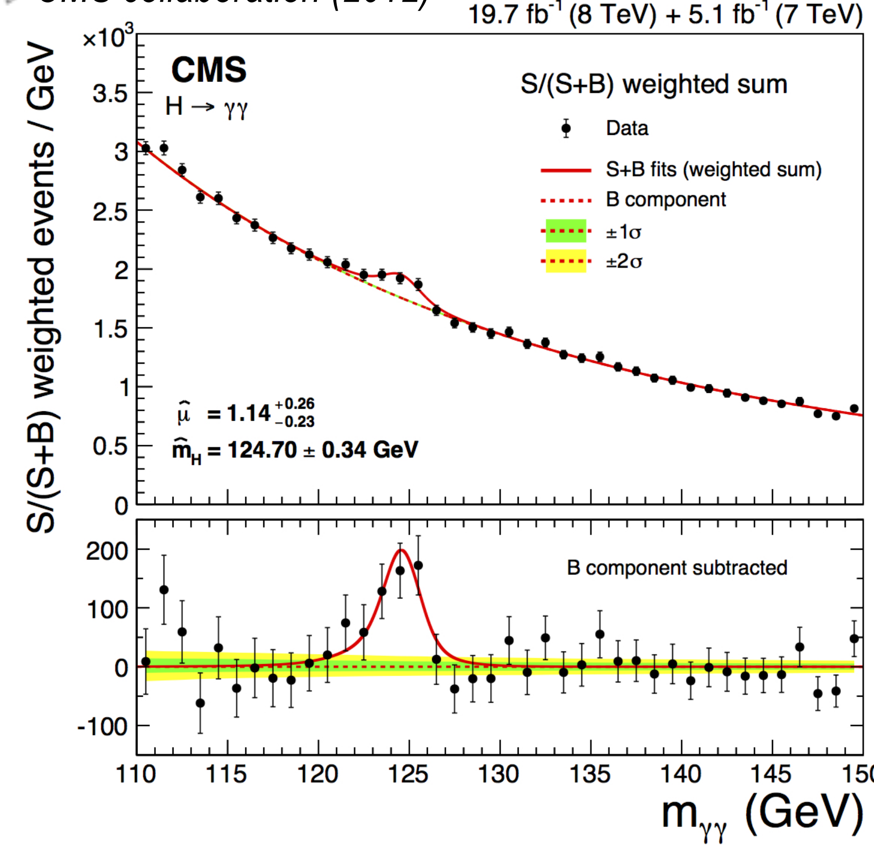

$$\Rightarrow \quad M_H \approx 125 \text{ GeV}$$

- **Standard model:**
  - effective theory
  - physical cutoff Λ
  - "New Physics" beyond Λ

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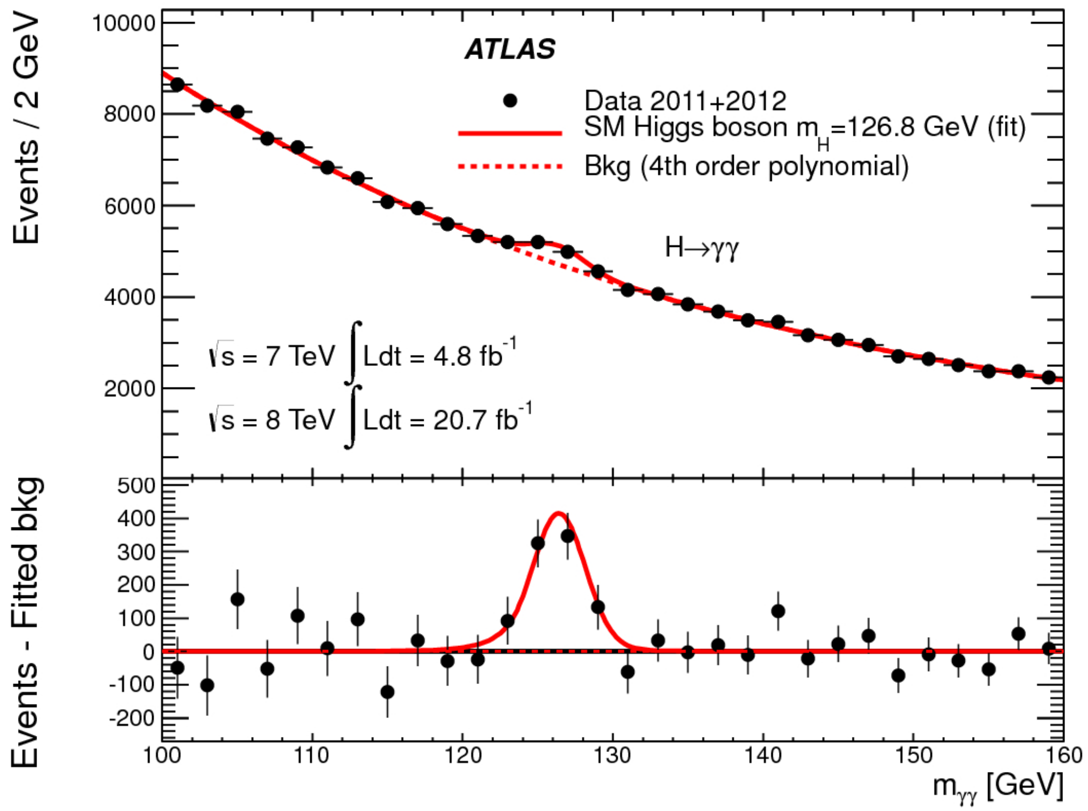

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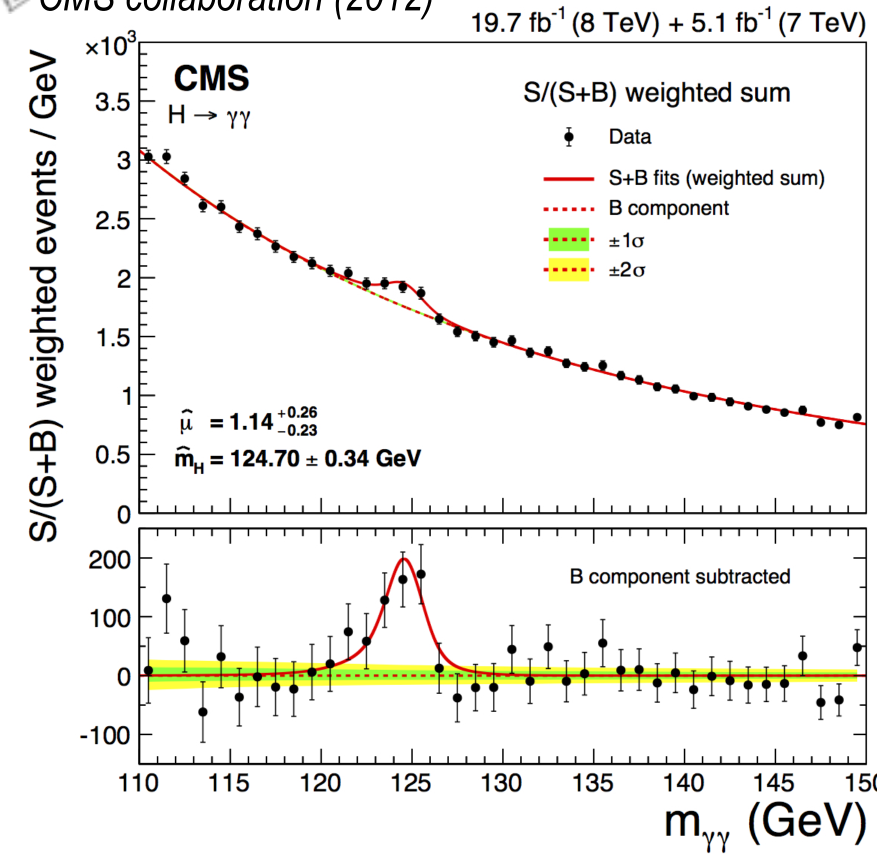

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- **Standard model:**
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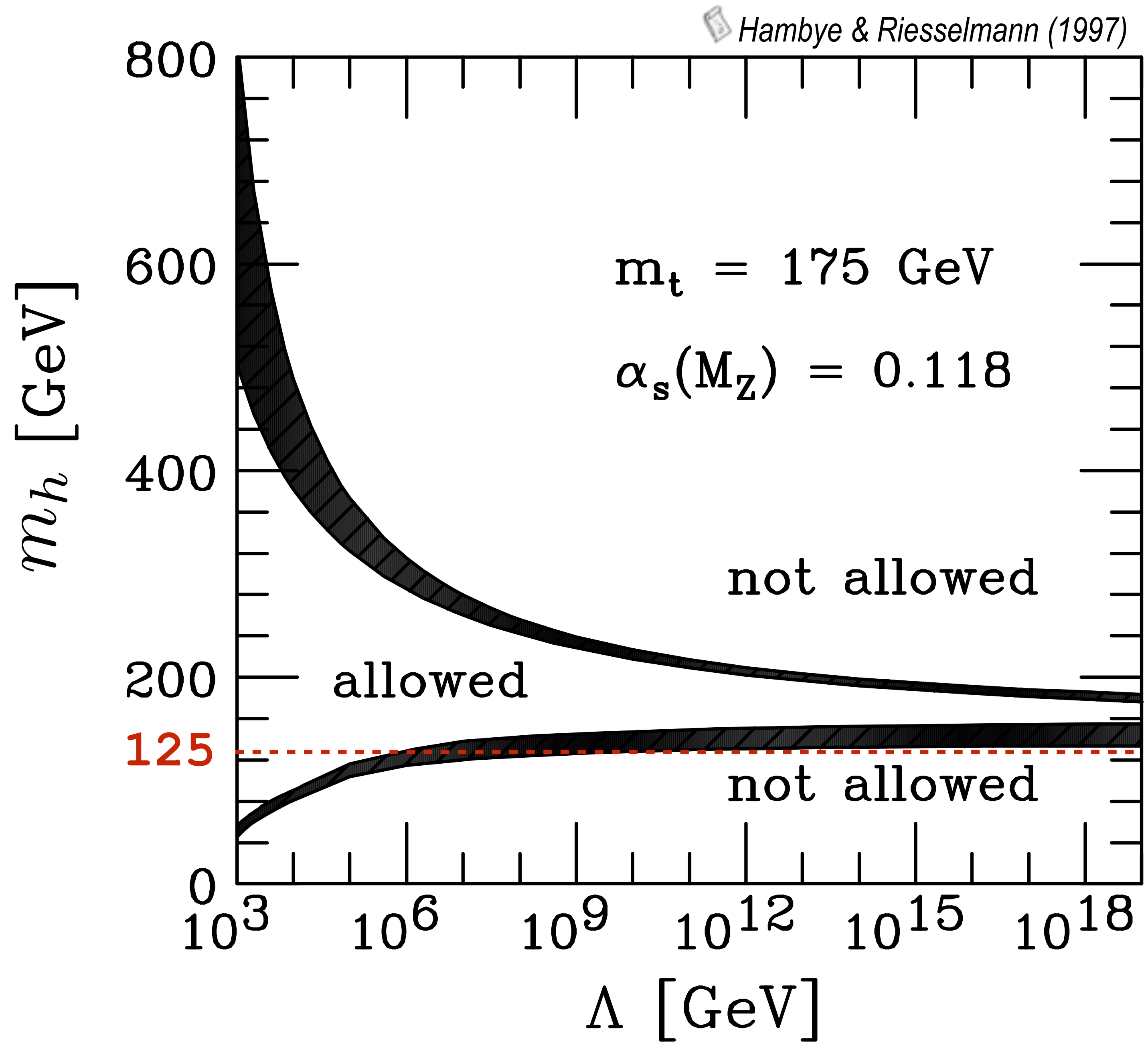
- **Range of validity of SM?**
  - Gravity effects: $\Lambda \sim M_{\rm Pl} = \sqrt{\hbar c/G} \approx 10^{19}\text{GeV}$
  - Landau pole in $U(1)_{\text{hypercharge}}$: $\Lambda > M_{\rm Pl}$
  - **Higgs potential…**

Higgs Mass Bounds

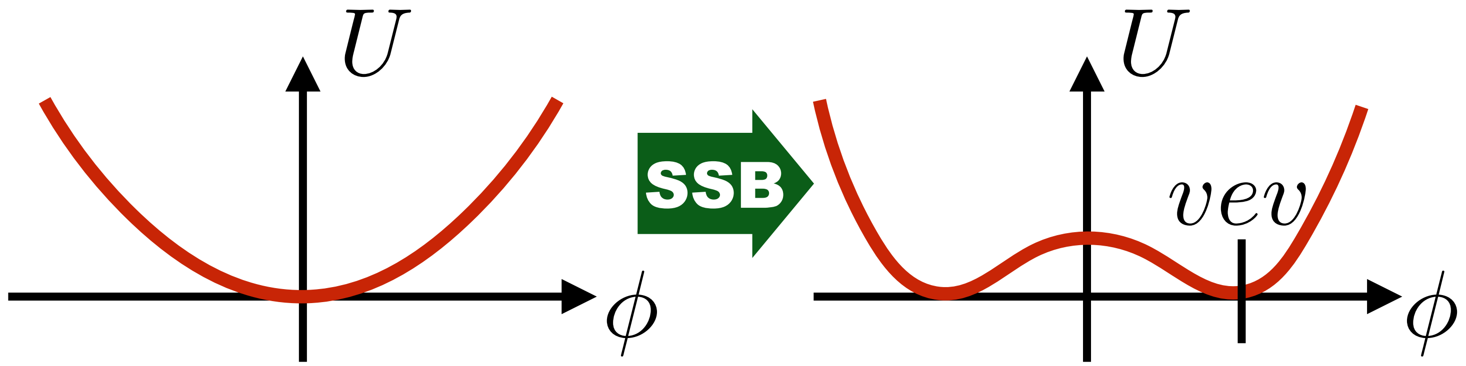


Krive, Linde (1976)
Maiani, Parisi, Petronzio (1978)
Krasnikov (1978)
Politzer, Wolfram (1978)
Hung (1979)
Lindner (1985)
Wetterich (1987)
Lindner, Sher, Zaglauer (1989)
Ford, Jones, Stephenson, Einhorn (1993)
Altarelli, Isidori (1994)
Schrempp, Wimmer (1996)…

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

Mechanism for Lower Higgs Mass Bound

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



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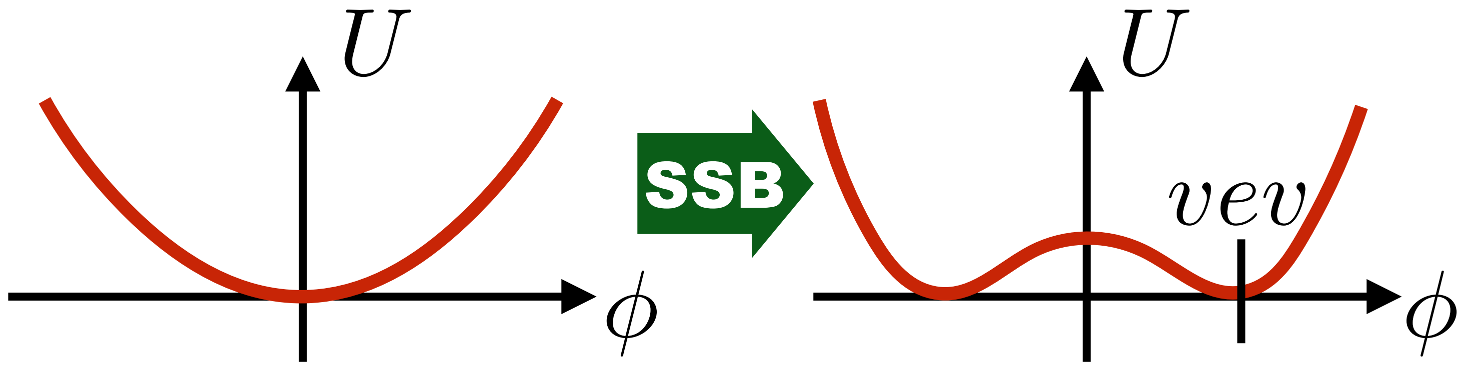

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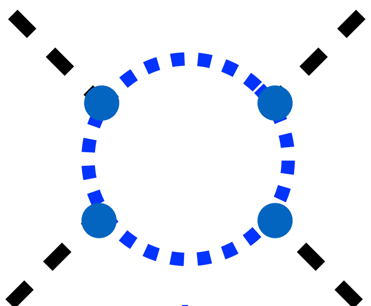
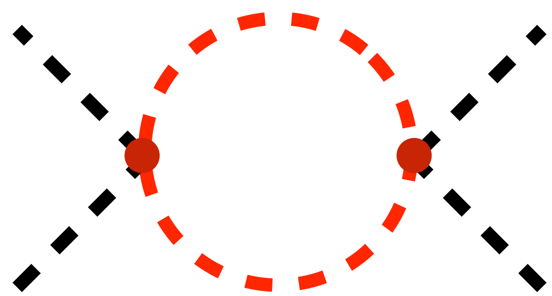
- **Running Higgs self-coupling:**

$\beta_{\lambda_4} =$ -



top loop

\+



Higgs loop

\+ gauge contributions

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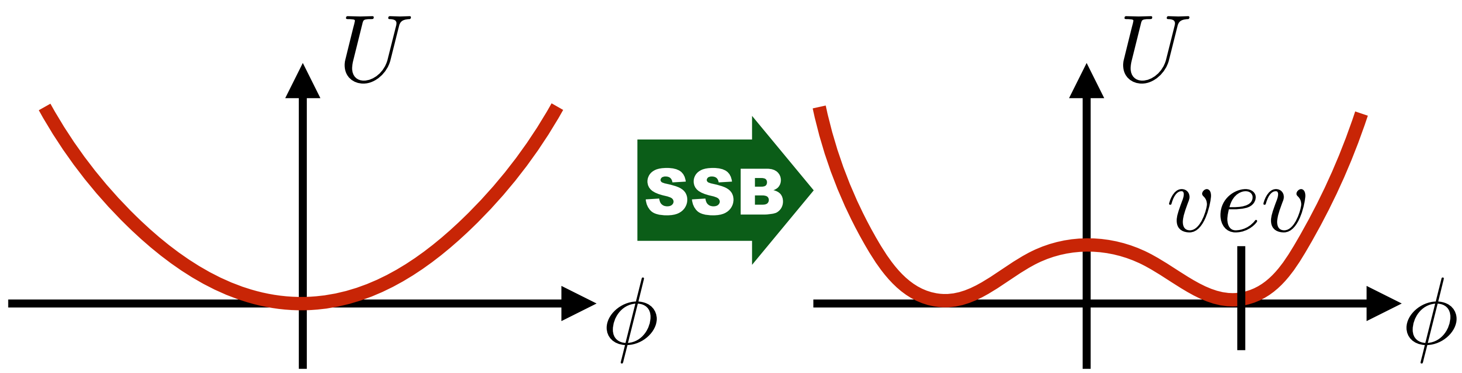

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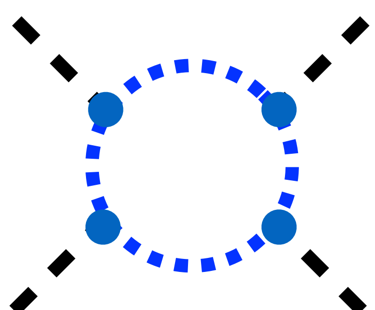
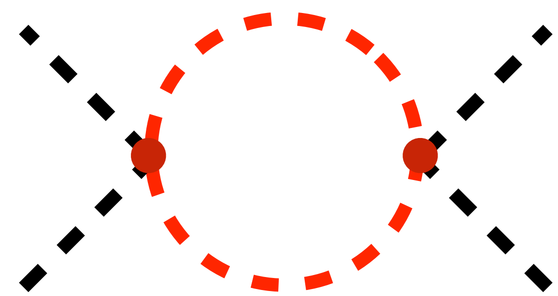
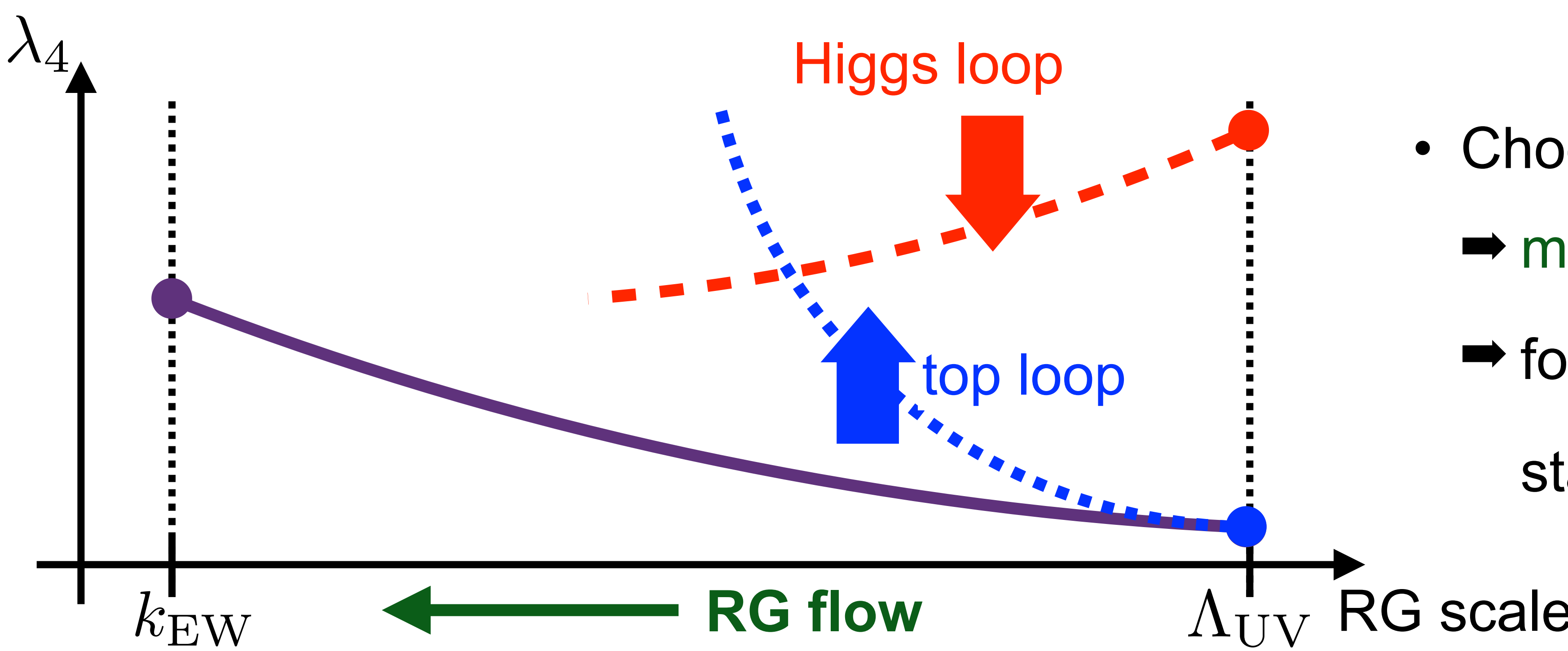
$\beta_{\lambda_4} =$ -  +  + gauge contributions

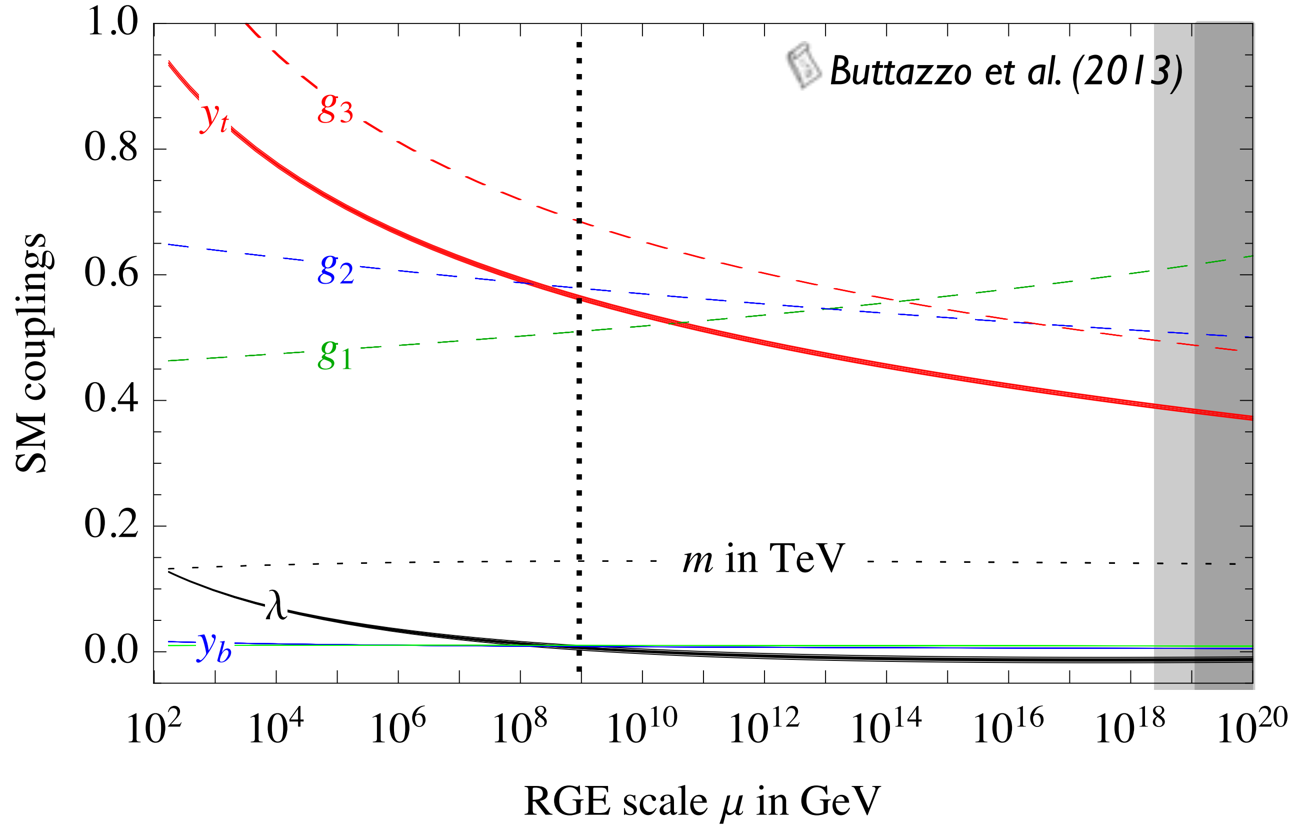


- Choose $\lambda = 0$ at Λ_{UV}:
  - ➡ minimal value of Higgs mass
  - ➡ for smaller m_h:

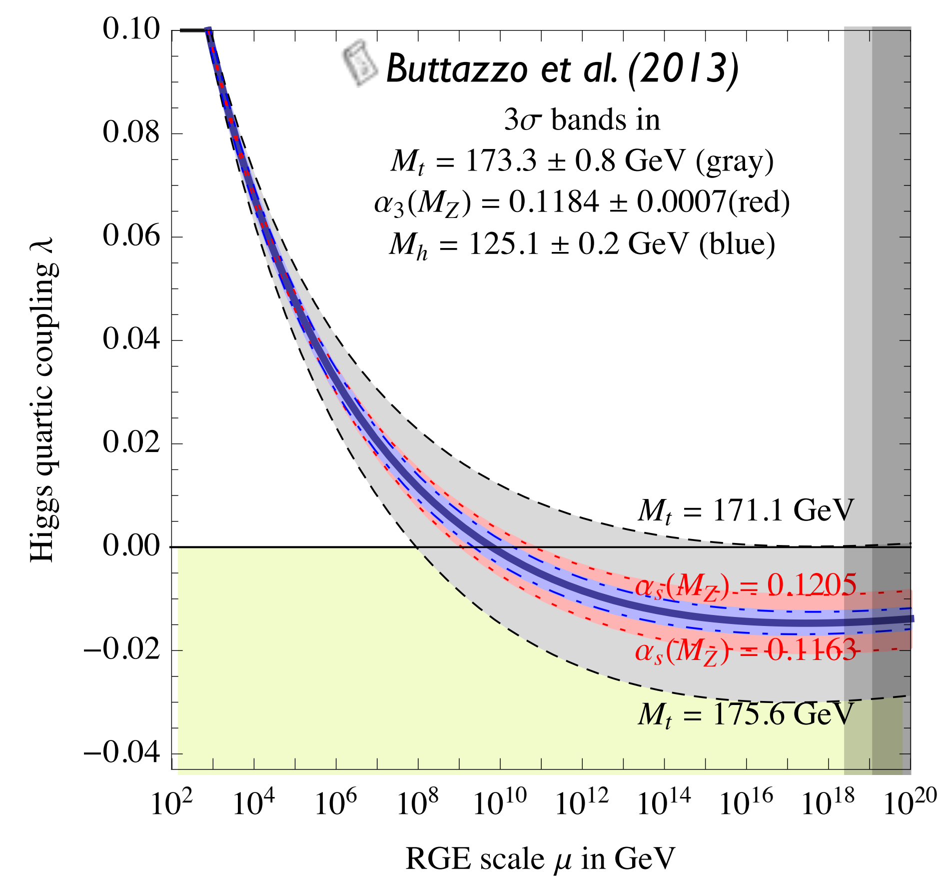
    start with unstable potential?!

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:



- **Lower Higgs mass bound**

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

Scenarios at the Scale of New Physics

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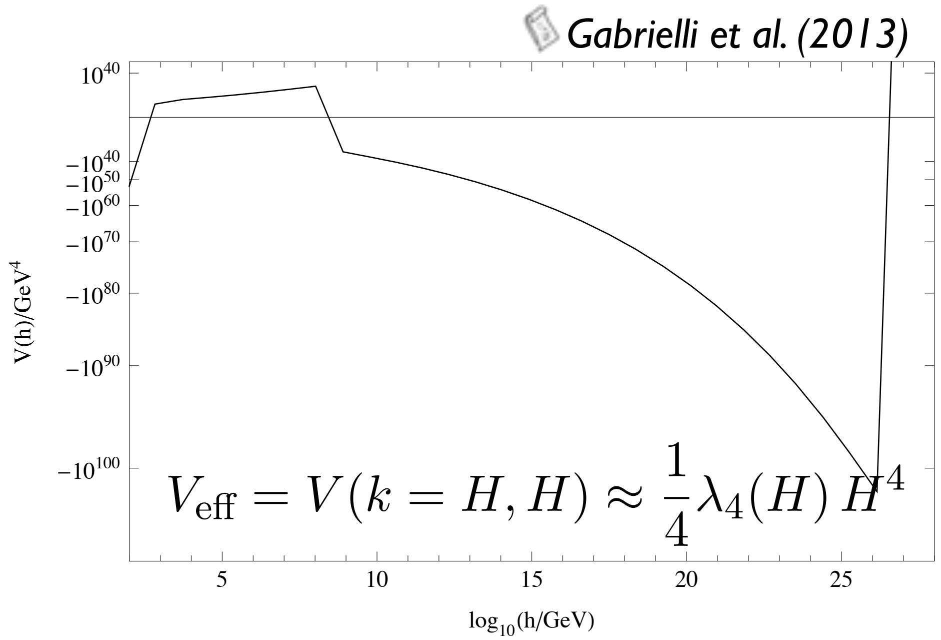
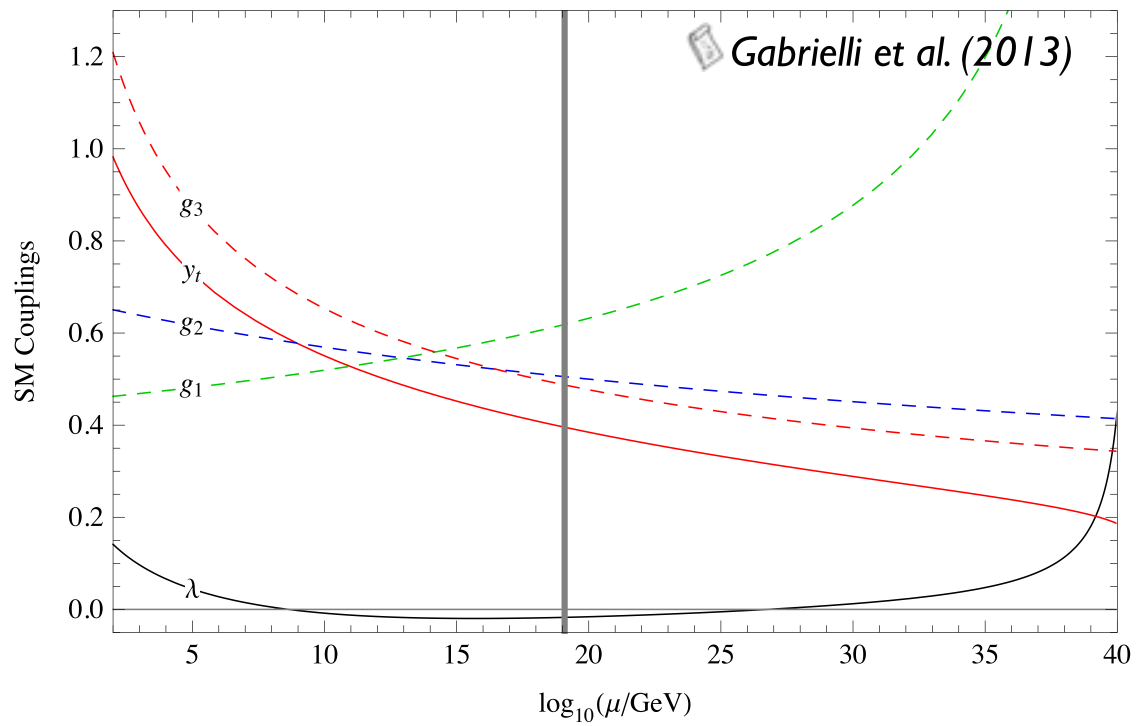
➡ True minimum @ large H ($< M_{\rm Pl}$)?

➡ *Metastability* of Higgs vacuum?

➡ Small tunnelling rates to stable minimum?





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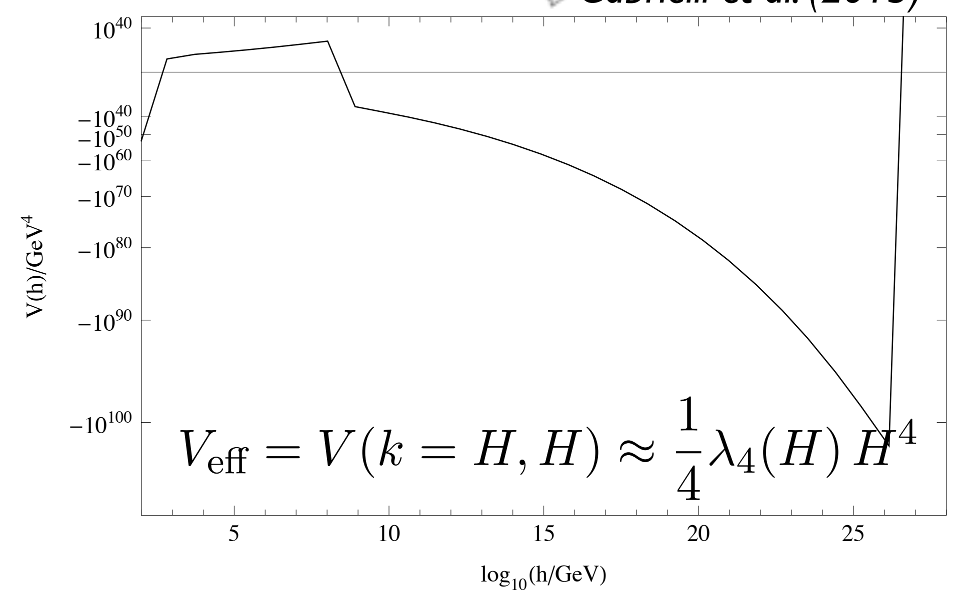
Gabrielli et al. (2013)



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 $\Lambda_{\rm UV}$ when approaching underlying theory

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

➡ Link to BSM particle physics models?

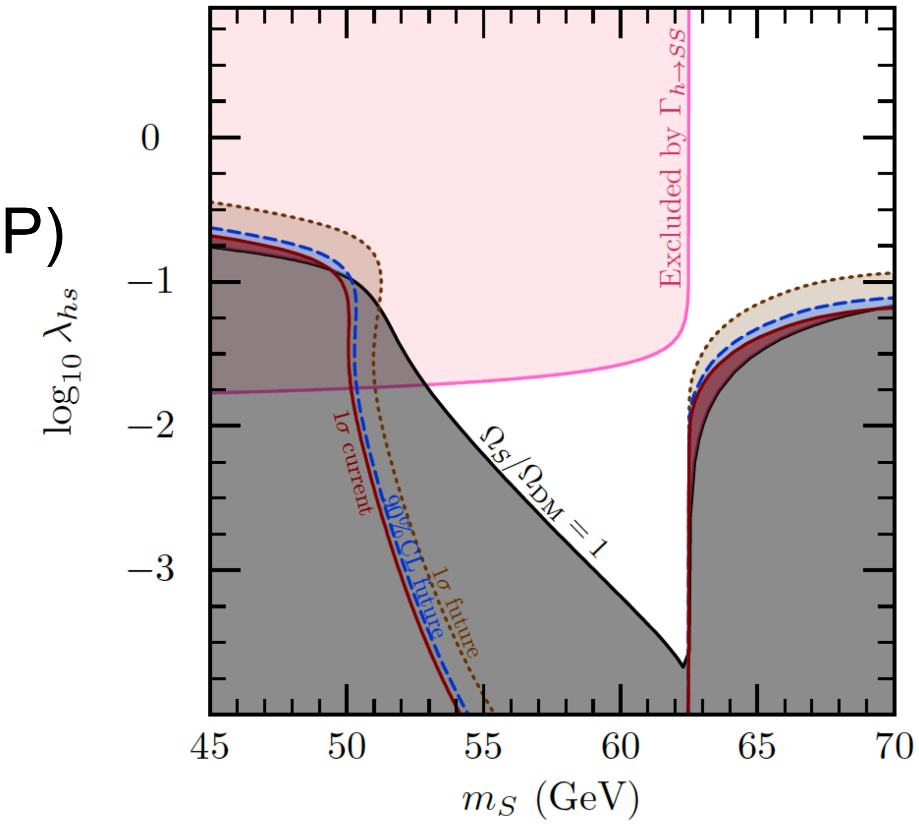
Higgs Portal to Dark Matter

- Evidence for DM: *gravitational lensing, galaxy rotation curves, CMB, …*
- Single scalar field serves as **stable DM** candidate (WIMP)

$$\Gamma_{\rm DM} = \int d^4x \Big(\frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2} m_S^2 S^2 + \frac{\lambda_{02}}{8} S^4 \Big)$$

  - with $\mathbb{Z}_2 - \text{symmetry:} \quad S \to -S$
  - **Portal coupling to Higgs:** $\frac{\lambda_{11}}{4} h^2 S^2$

Cline et al. (2013)



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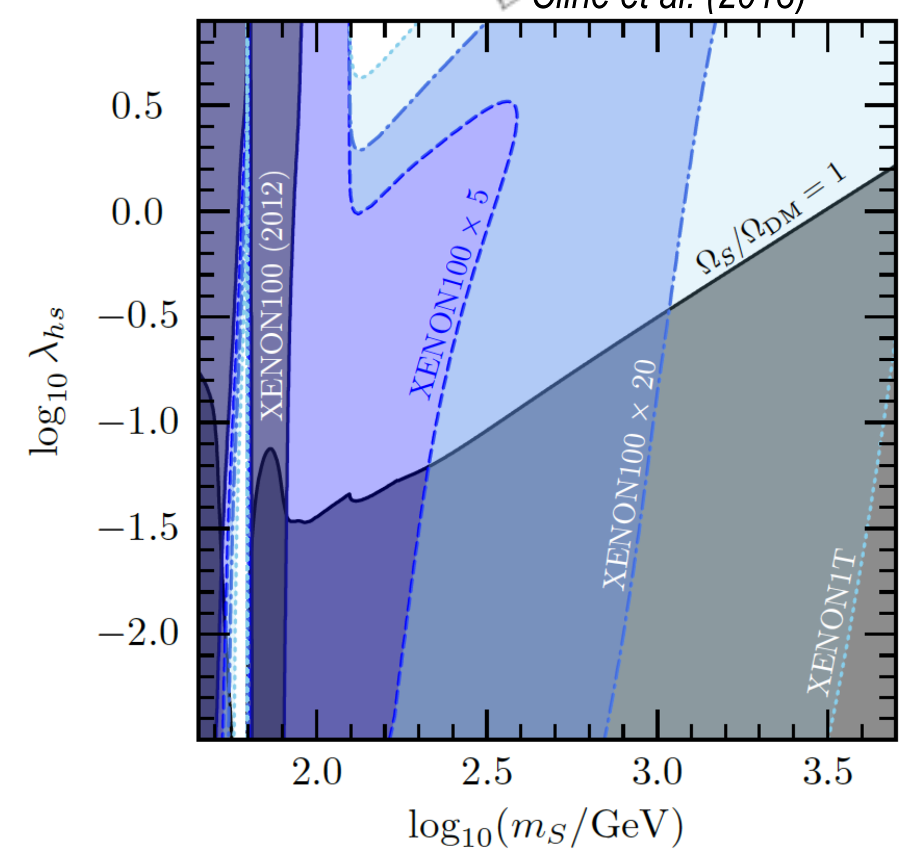
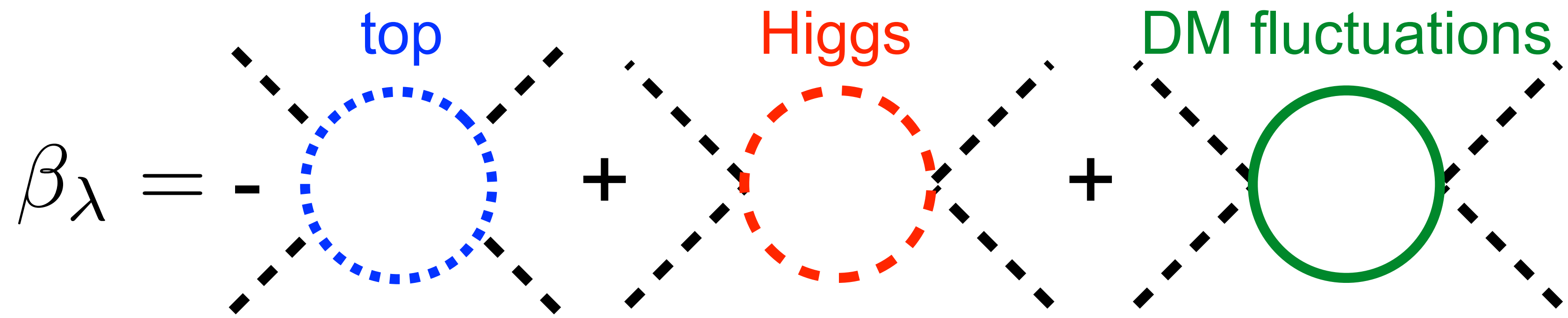


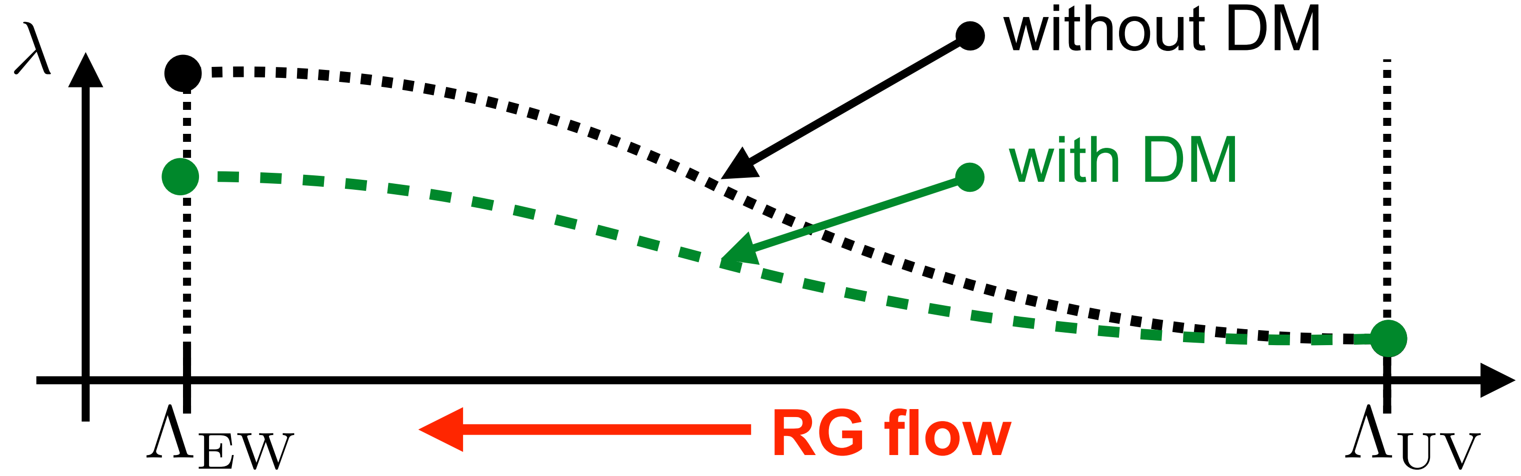
- S can reproduce observed dark matter relic density
  - Condition on scattering cross section
  - Relation between m_S and λ_{11}
  - For $m_S > m_h/2$:

$$\log_{10}\Big(\frac{\lambda_{11}}{2}\Big) = -3.63 + 1.04 \log_{10}\Big(\frac{m_S}{\rm GeV}\Big)$$

Effect of Dark Matter on Higgs Mass

- **Running Higgs self-coupling:**





$\lambda_{11} > 0$: lower Higgs mass

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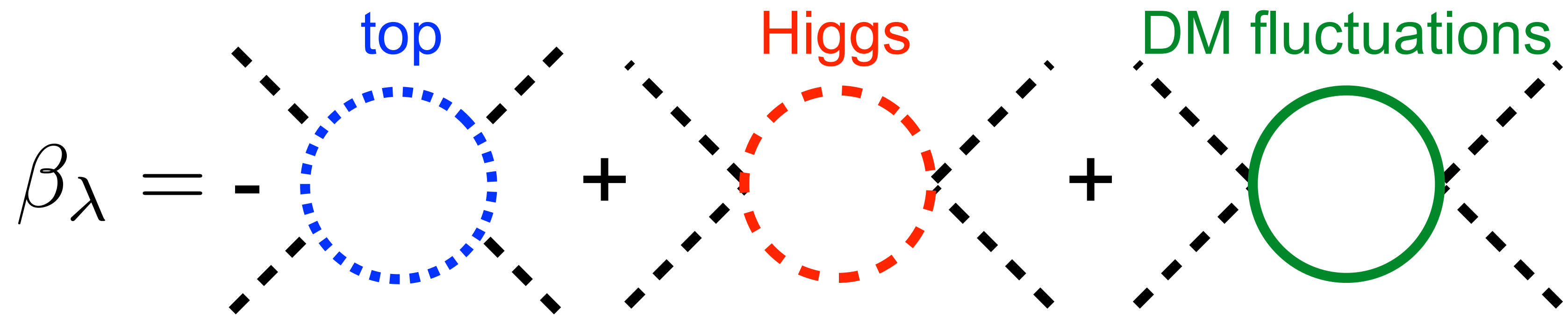
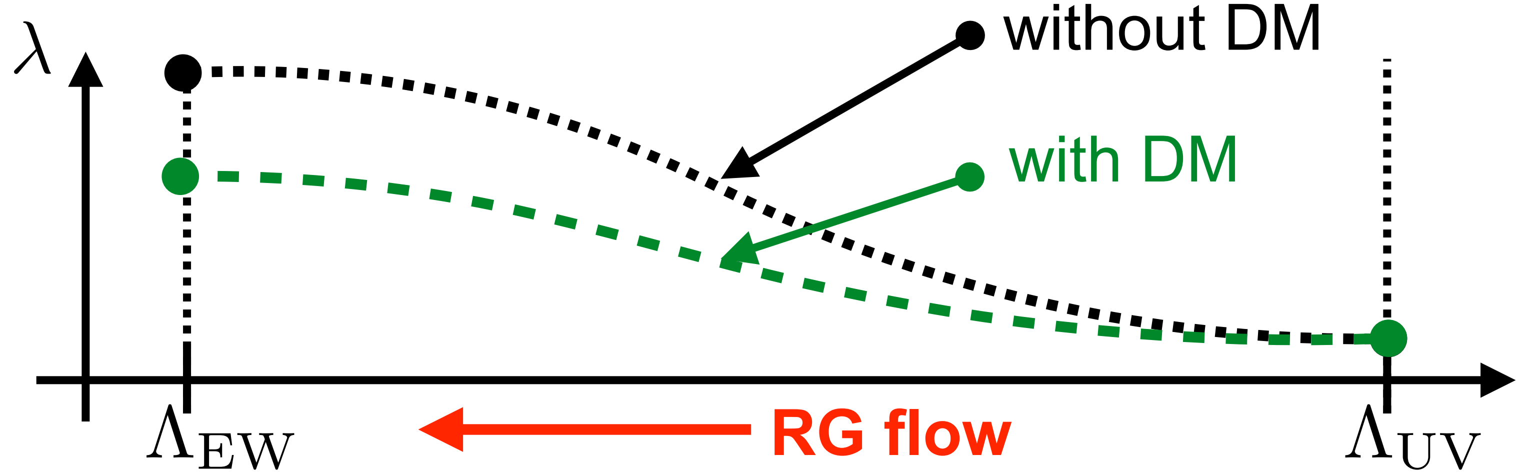
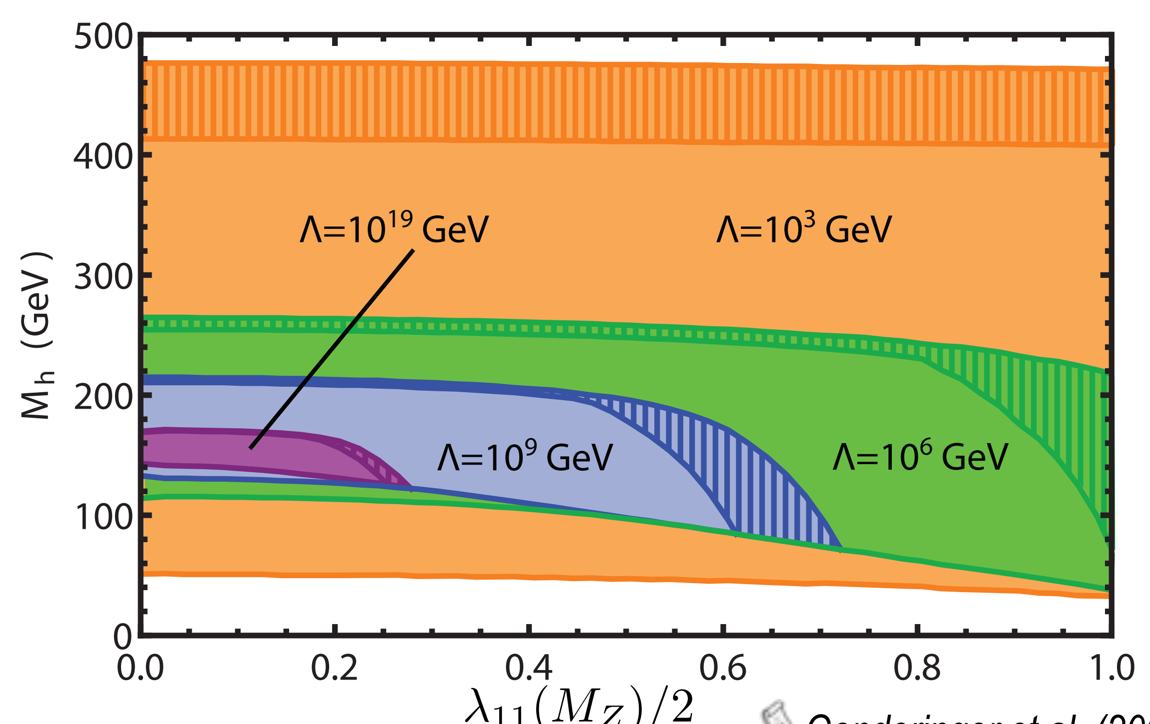




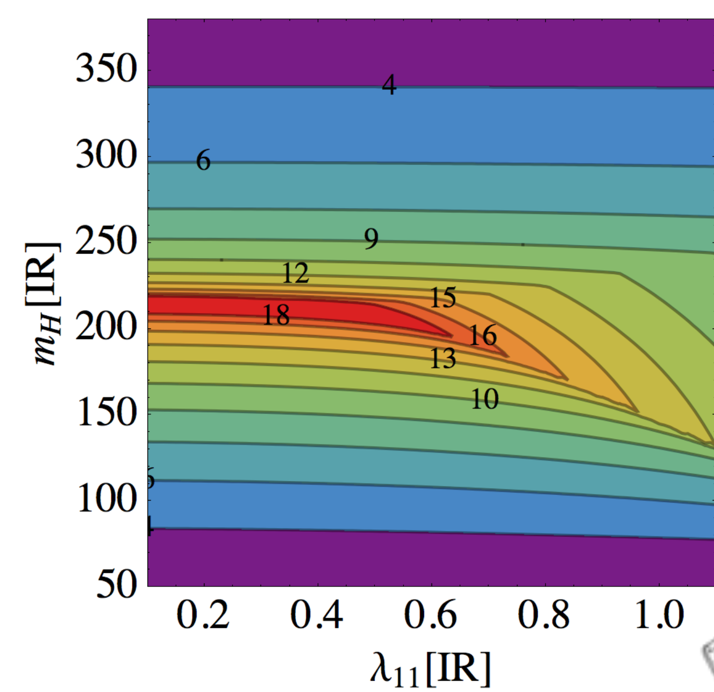
$\lambda_{11} > 0$: lower Higgs mass

- **Contours of fixed cutoff scale:**
  - SM:

$$S_{\rm UV} = \int d^4x \{\bar{\psi} i \partial\!\!\!/ \psi + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu S)^2 + i\bar{y}h\bar{\psi}\psi + \bar{V}(h,S)\}$$



Gonderinger et al. (2009)



Eichhorn, MMS (2014)

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)

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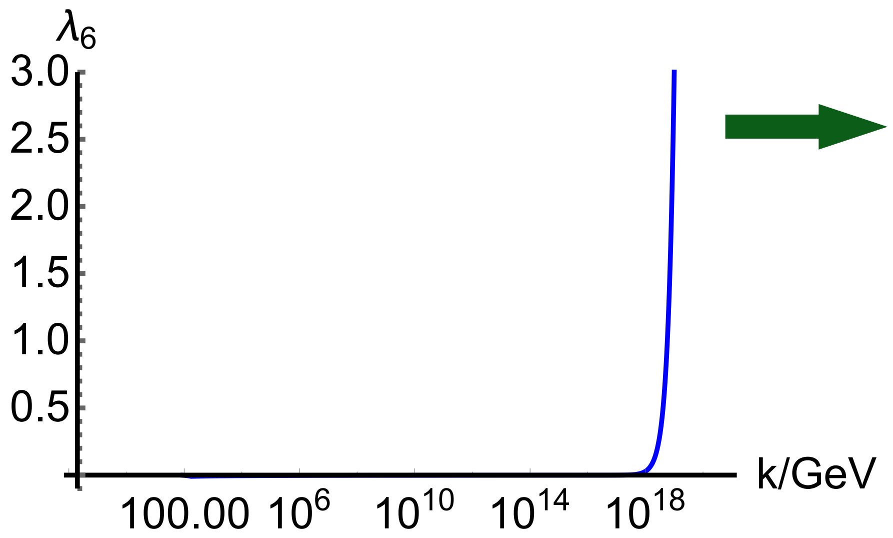

→ becomes tiny very fast!

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

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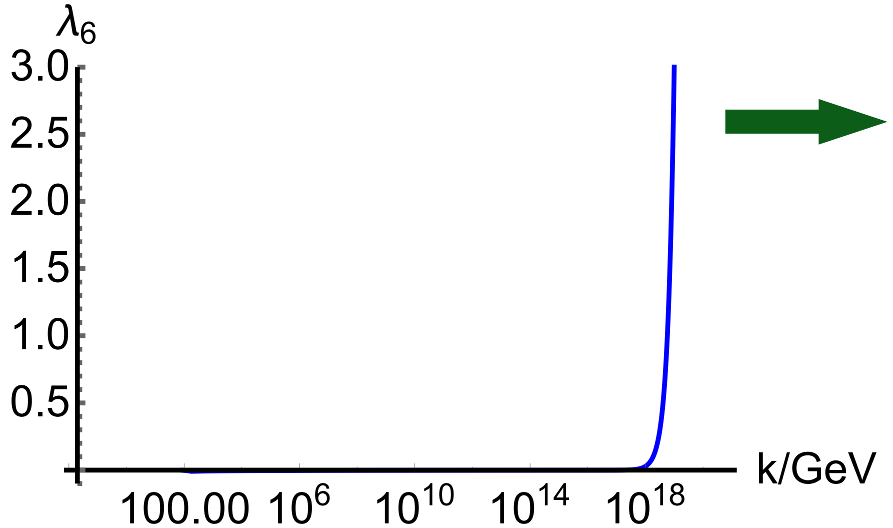

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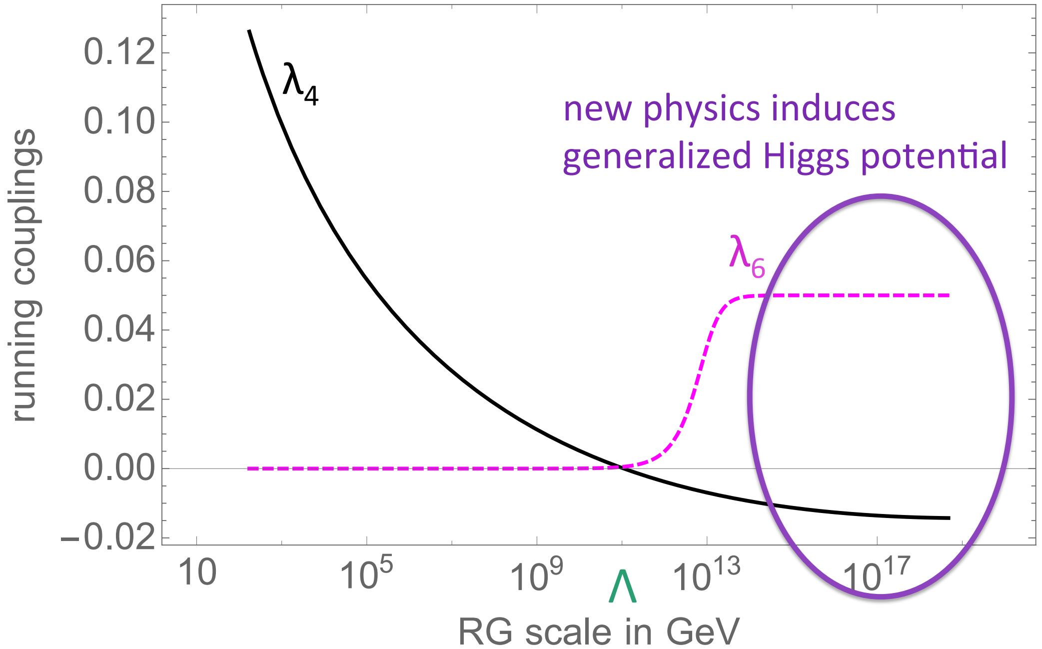
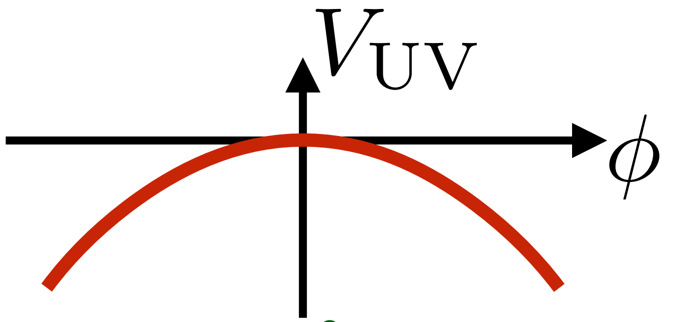
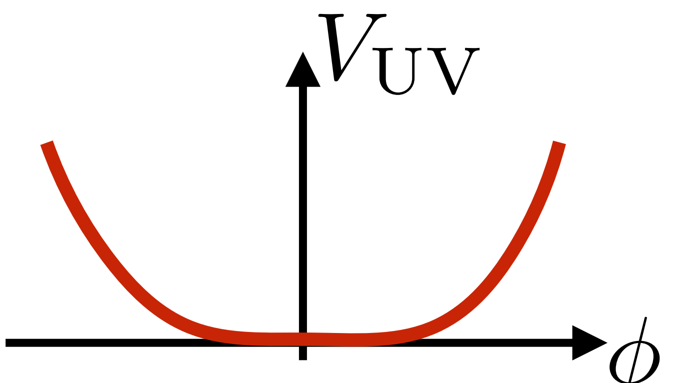
- **Mechanism to go below lower mass bound:**





without Φ^6-coupling

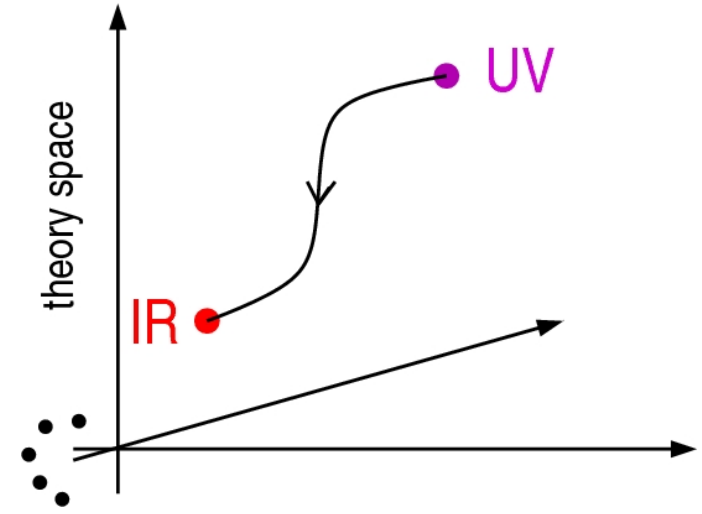


with Φ^6-coupling

Functional RG

- 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)

β functions for model couplings…

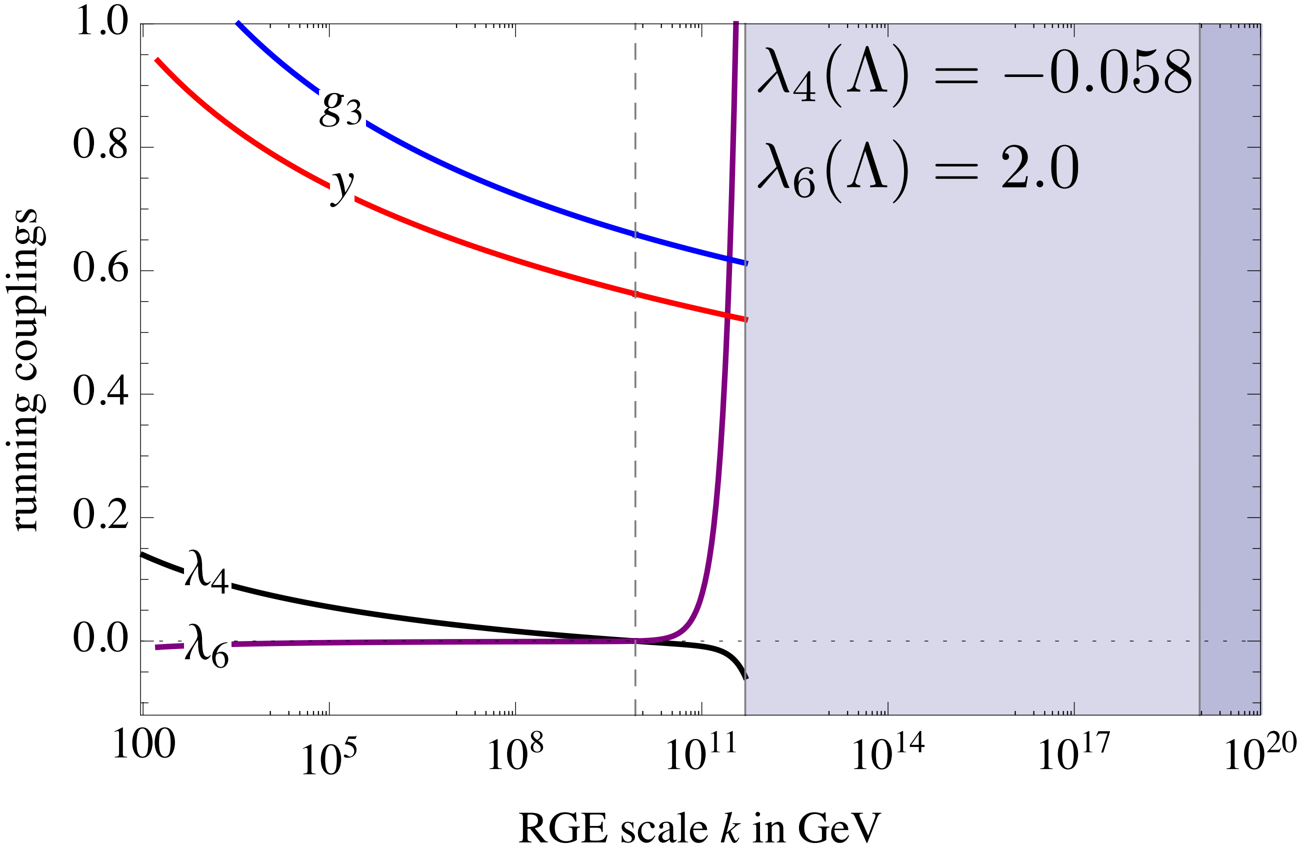
…(reproduce 1-loop β functions from PT, ~~include threshold effects~~, higher-dim operators,…)

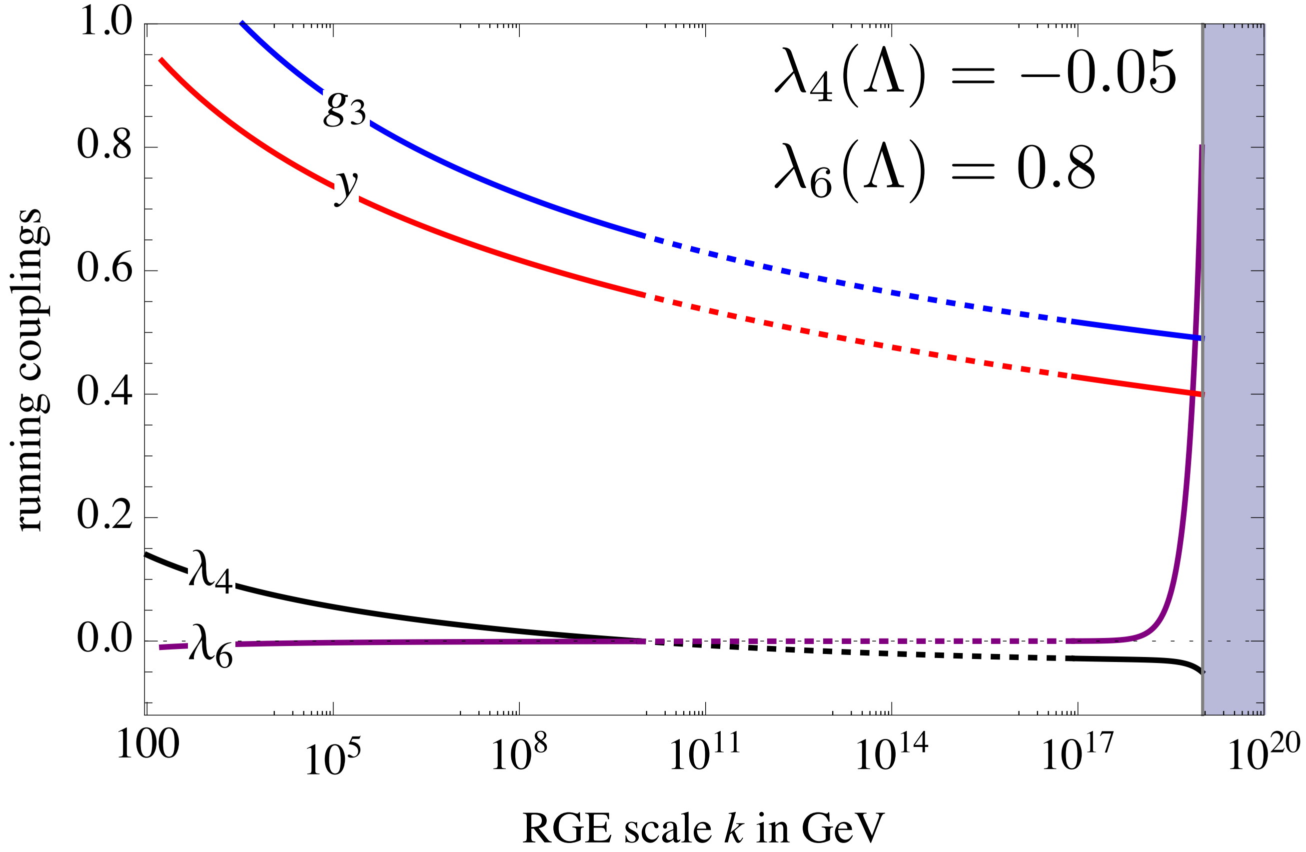
Gauged Higgs-Top Model - Higher-dimensional operators

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

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

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





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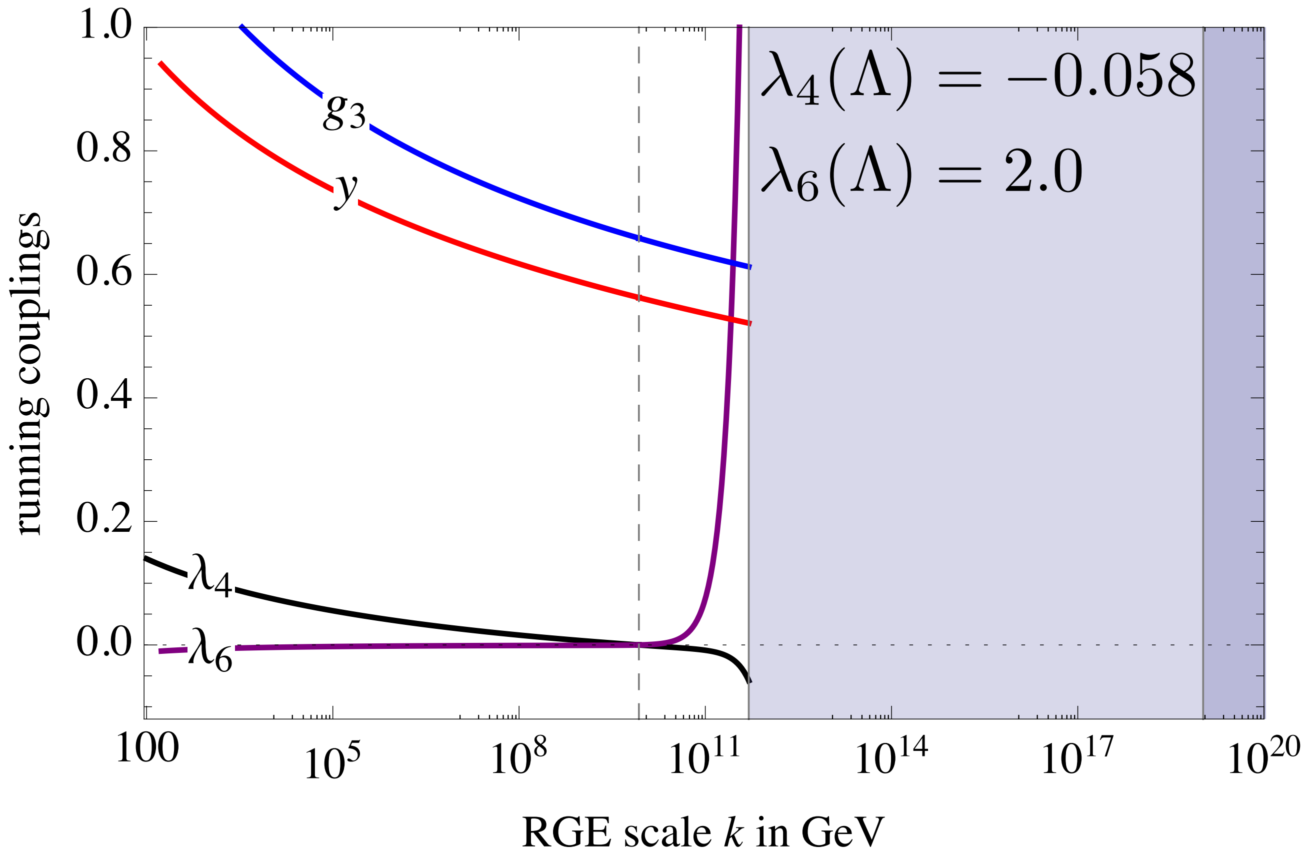

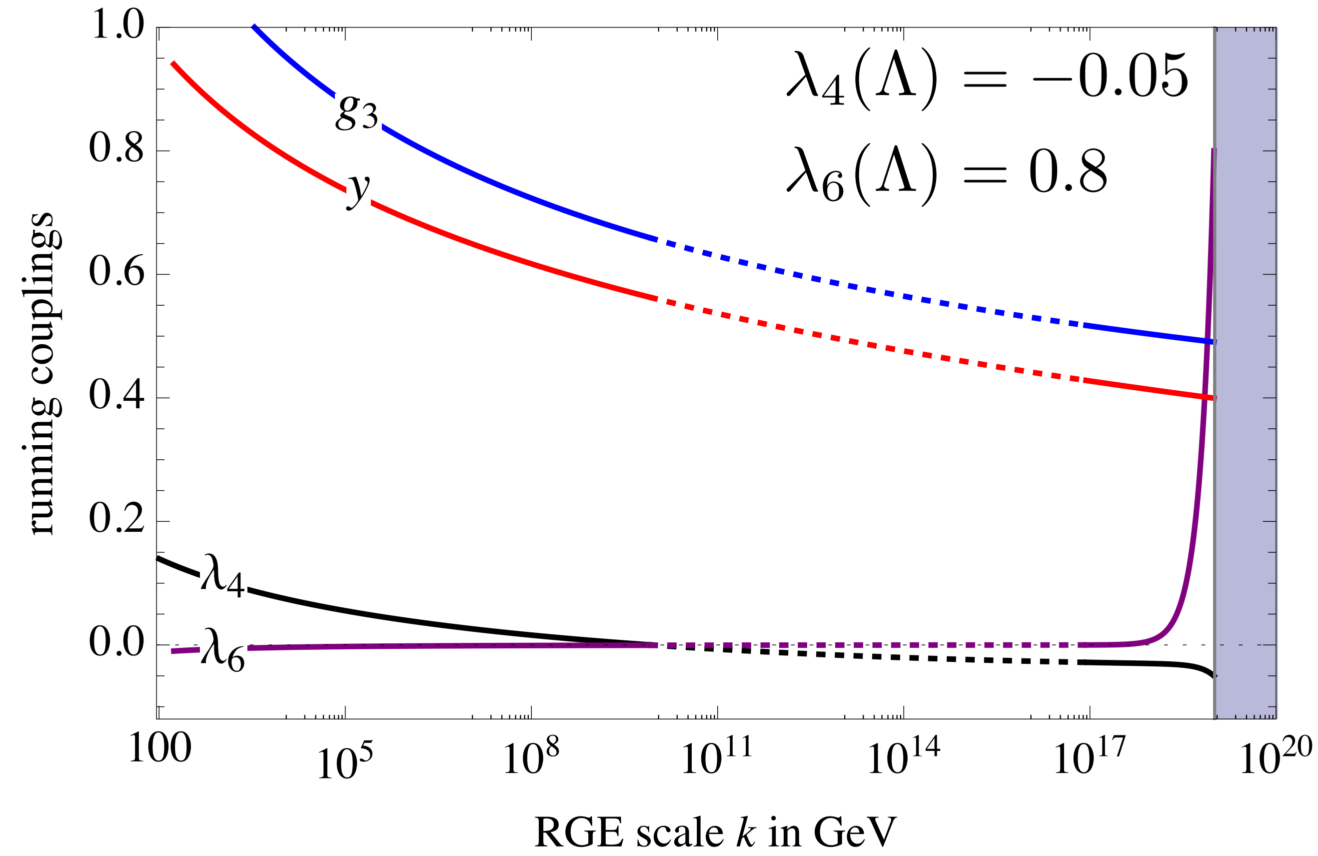

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- Extend UV cutoff by orders of magnitude (~ 2)

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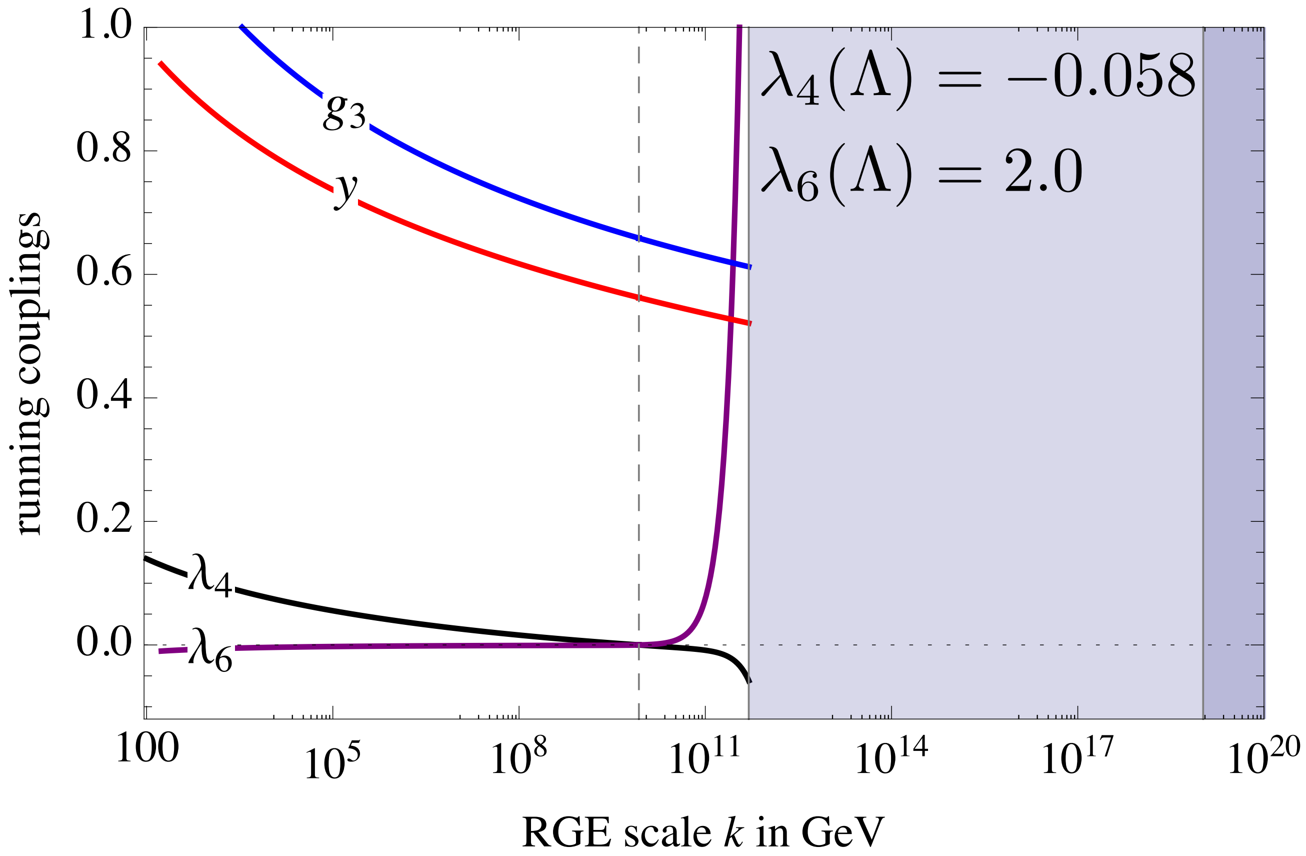

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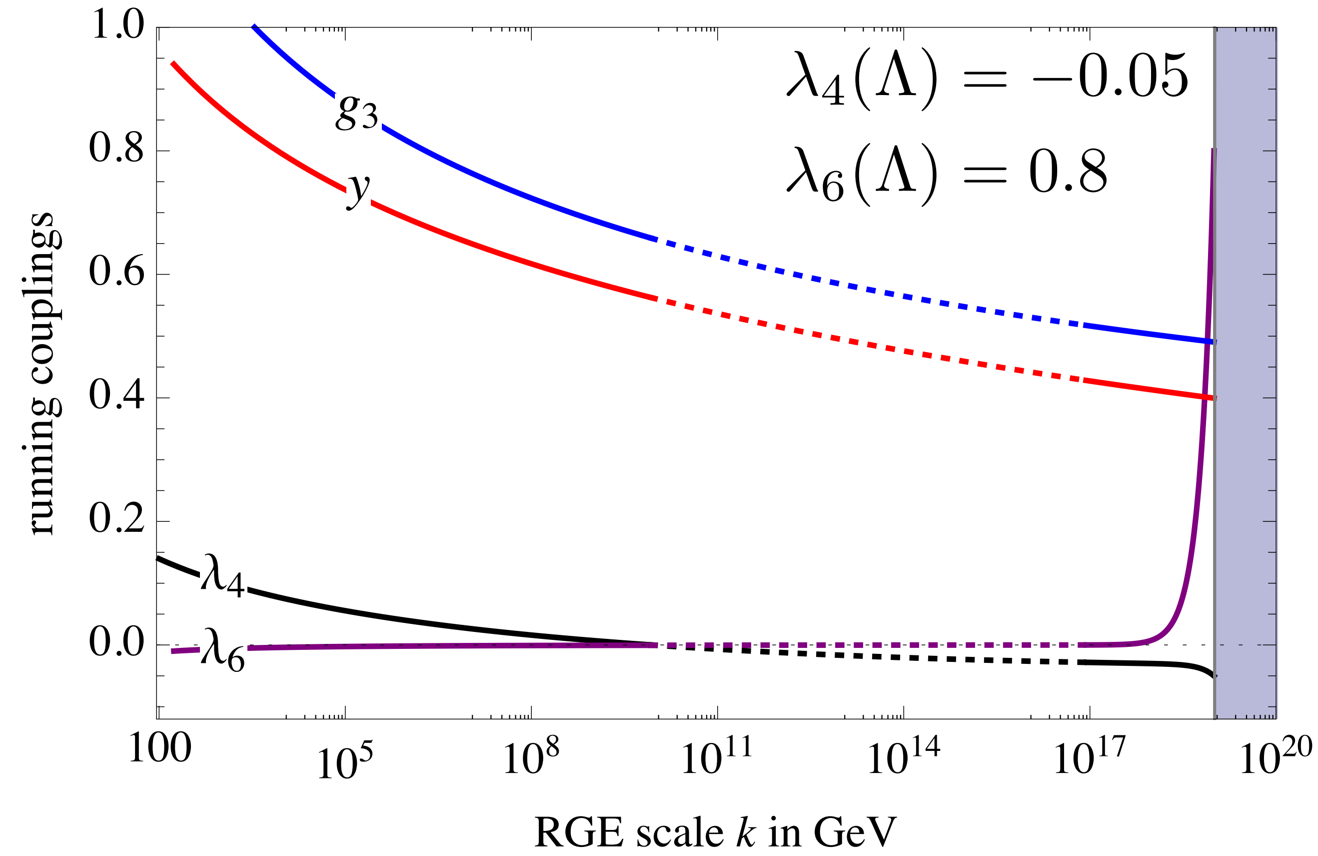

- Potential develops 2nd Minimum during RG flow
  - Min @ H=0 only metastable
- Small λ_6 sufficient to stabilize UV potential
- Further studies required…

Mass Bounds with Higher-Dimensional Operators

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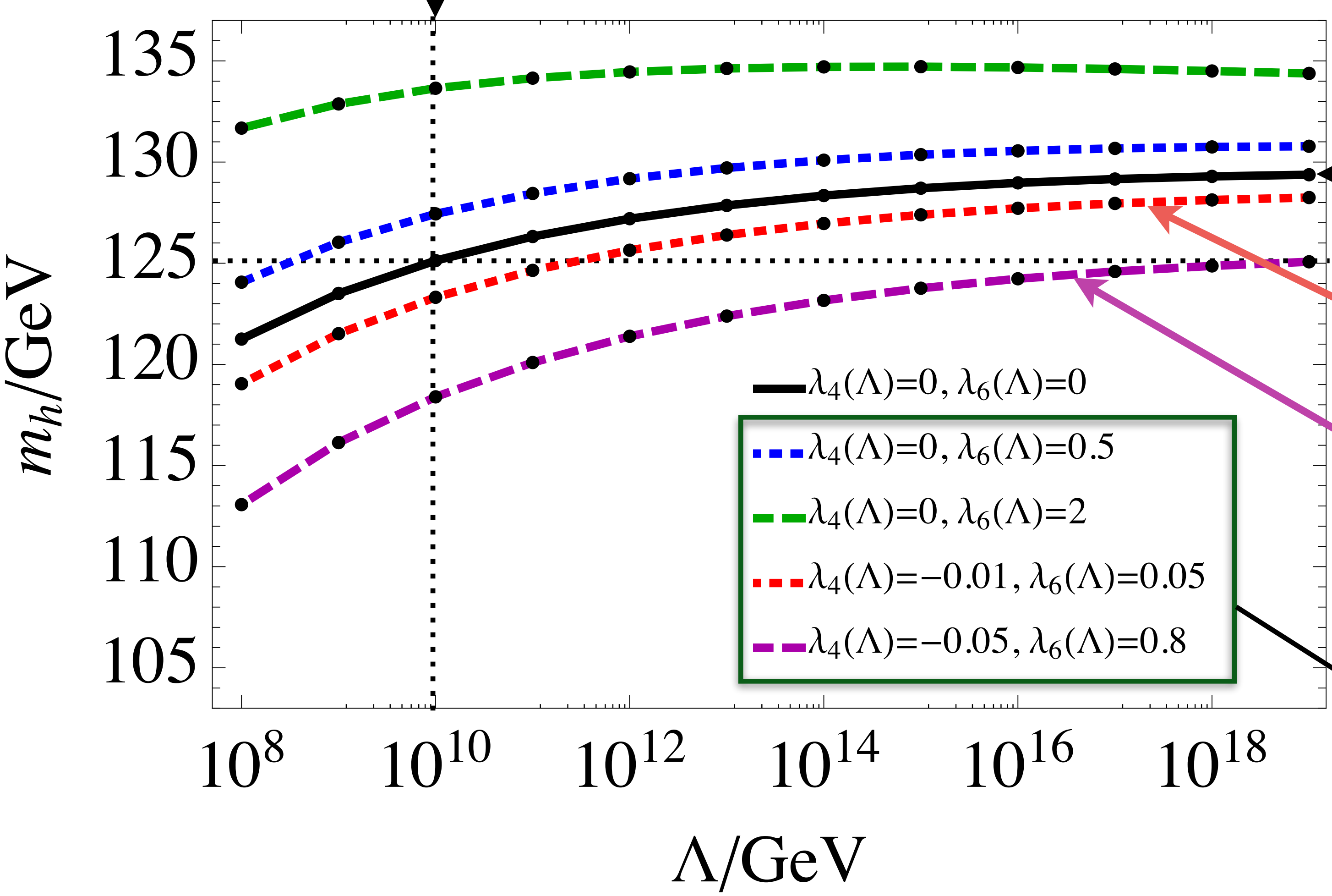
$$m_h^{\rm exp} \approx 125\text{GeV}$$

Λ for observed Higgs mass



conventional mass bound ~ 129 GeV

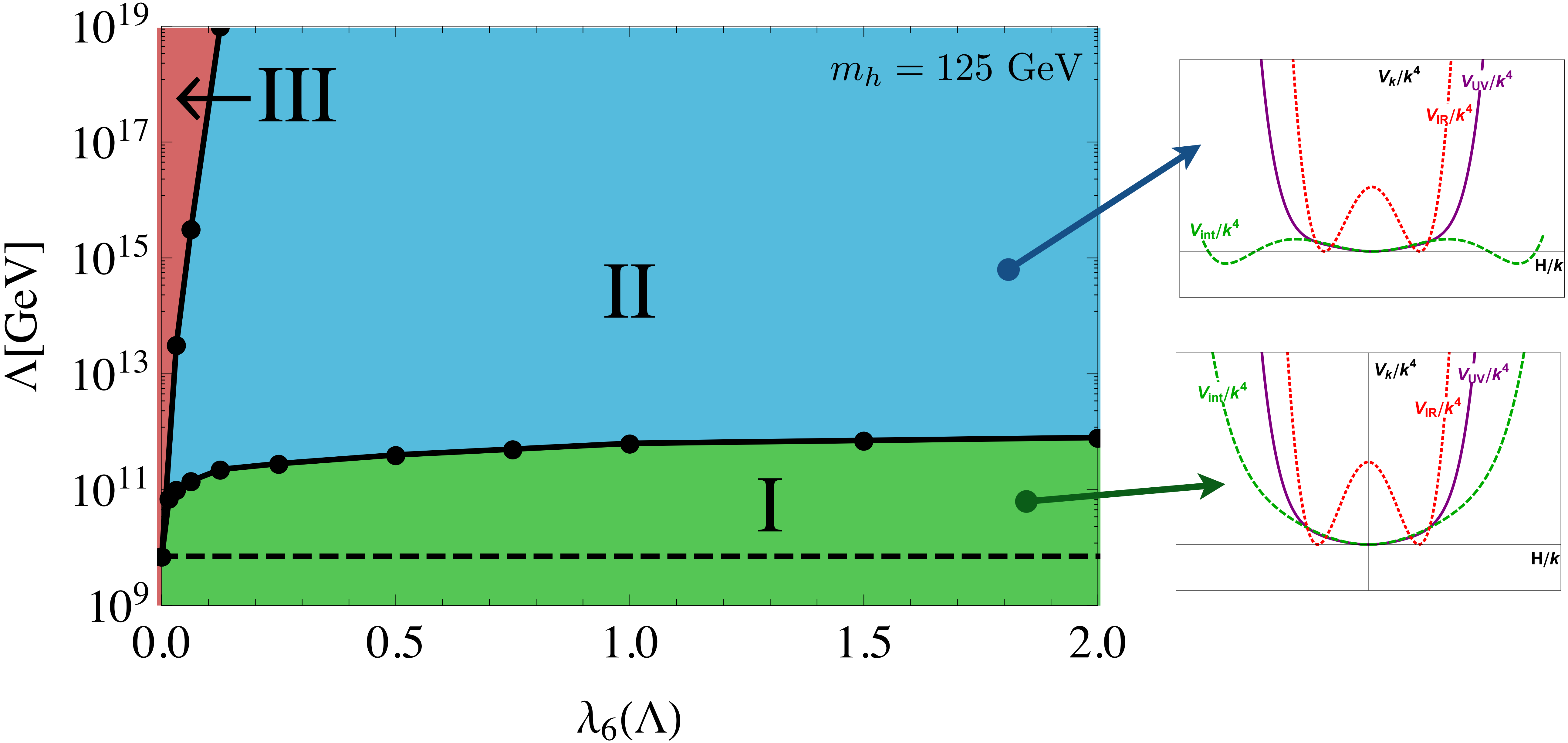
relax mass bounds/increase UV cutoff

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 $k \approx 0$

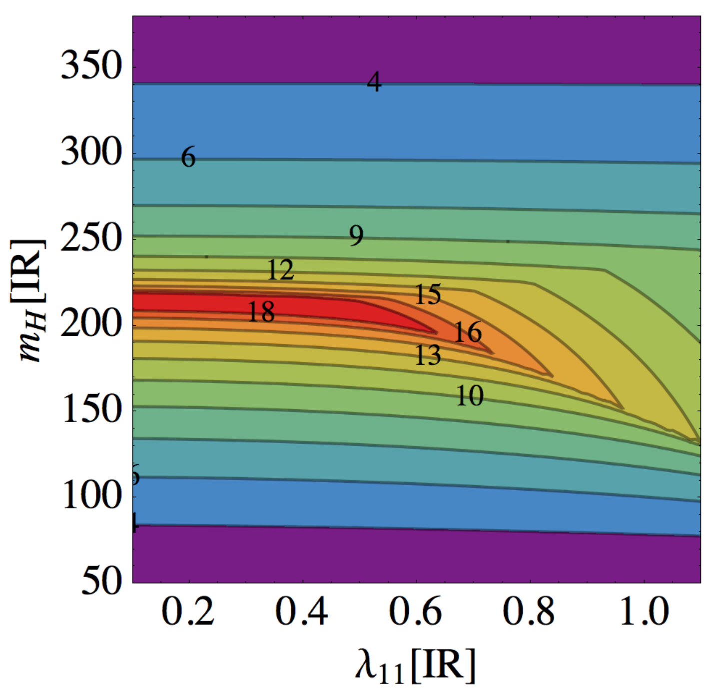
Higgs Mass (Bounds) with Light Dark-Matter Scalar

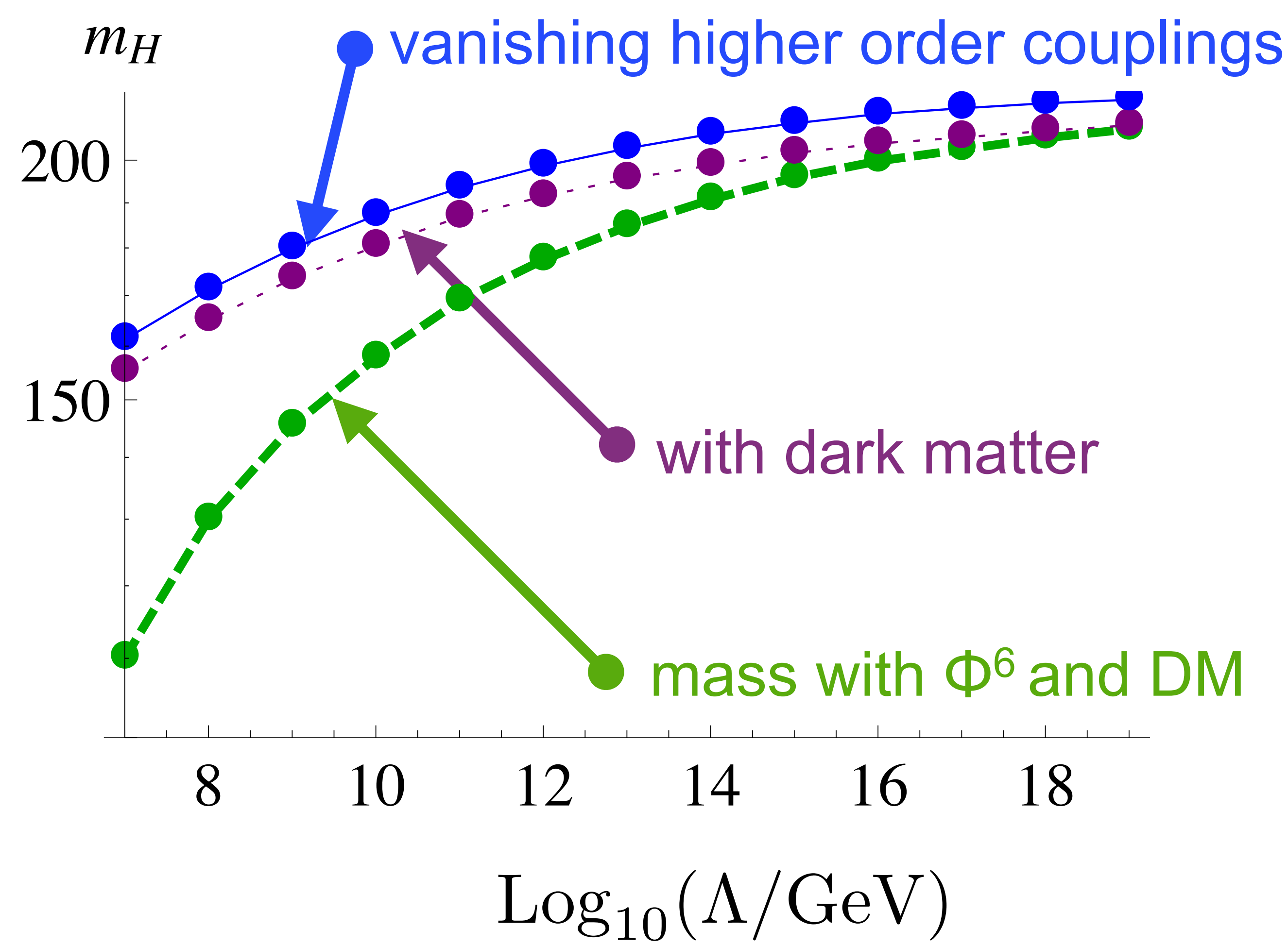
- toy model: $S_{\mathrm{UV}} = \int d^4x \{ \bar{\psi} i \partial\!\!\!/ \psi + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu S)^2 + i\bar{y}h\bar{\psi}\psi + \bar{V}(h,S) \}$

- Fix *vev* = 246 GeV and m_{top} = 173 GeV
- Choose $\lambda_4 = -0.05$ and $\lambda_6 = 0.5$

➡ Higgs masses with dark matter and new couplings:

‣ toy model!

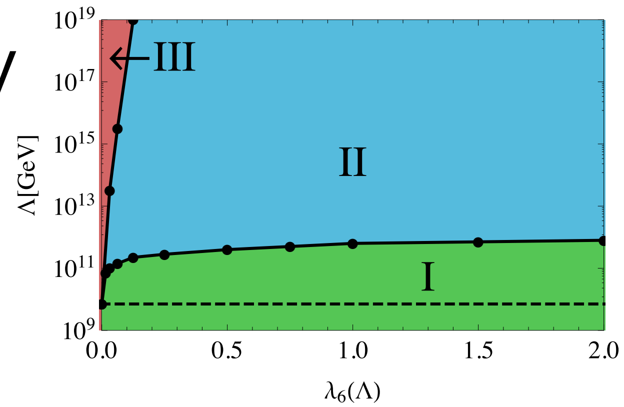




Eichhorn, MMS (2014)

Conclusion

- 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

✓ DM fluctuations allow for smaller Higgs masses at fixed Λ (~ a few GeV @ $\Lambda = M_{Pl}$)

✤ 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

JHEP 04 (2015) 022 and *arXiv:1501.02812*

Phys. Rev. D 90 (2014) 025023 and *arXiv:1404.5962*