Planck scale, Higgs mass and scalar dark matter

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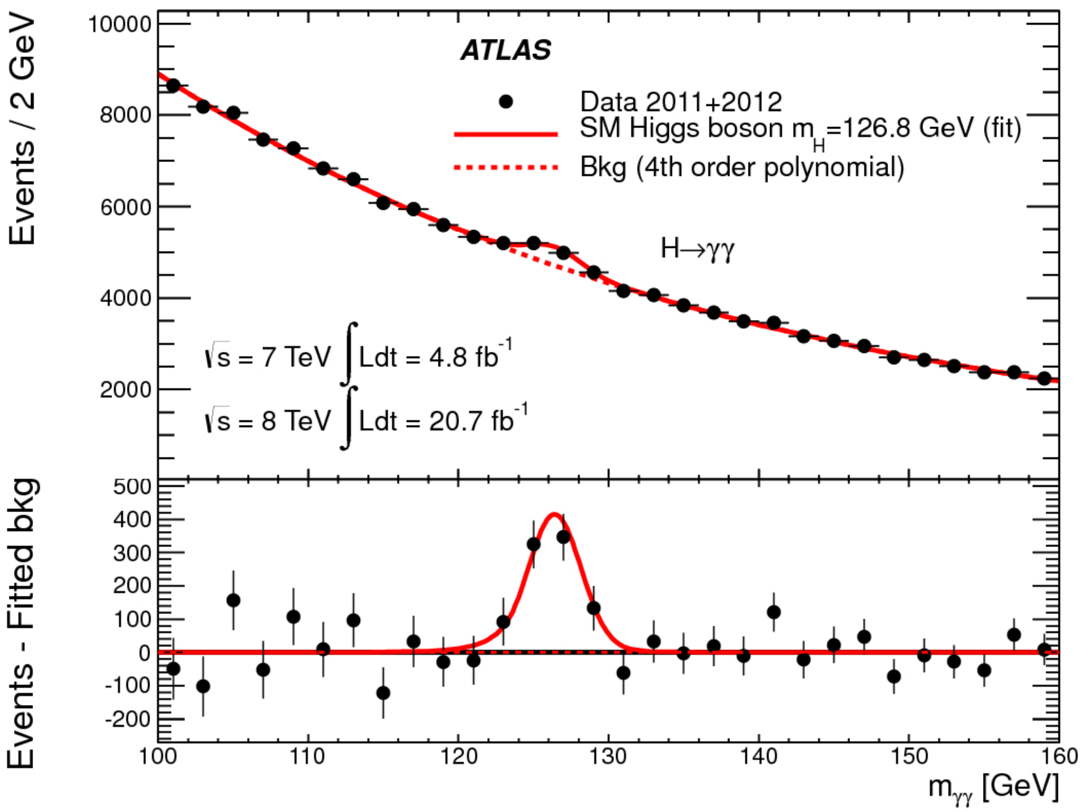
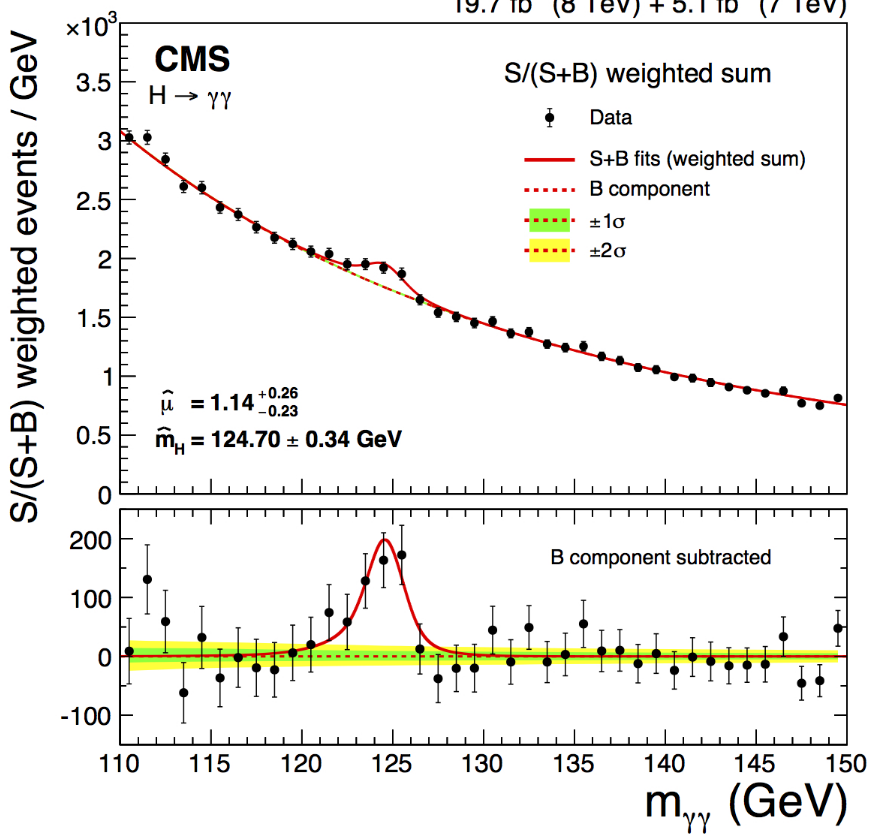
based on PRD ***90****, 025023 (2014) with A. Eichhorn*

November 13, 2014 @ 574. Wilhelm und Else Heraeus Seminar, Physikzentrum Bad Honnef

The standard model and the Higgs

- Discovery of the Higgs@LHC:


ATLAS collaboration (2012)


CMS collaboration (2012)

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

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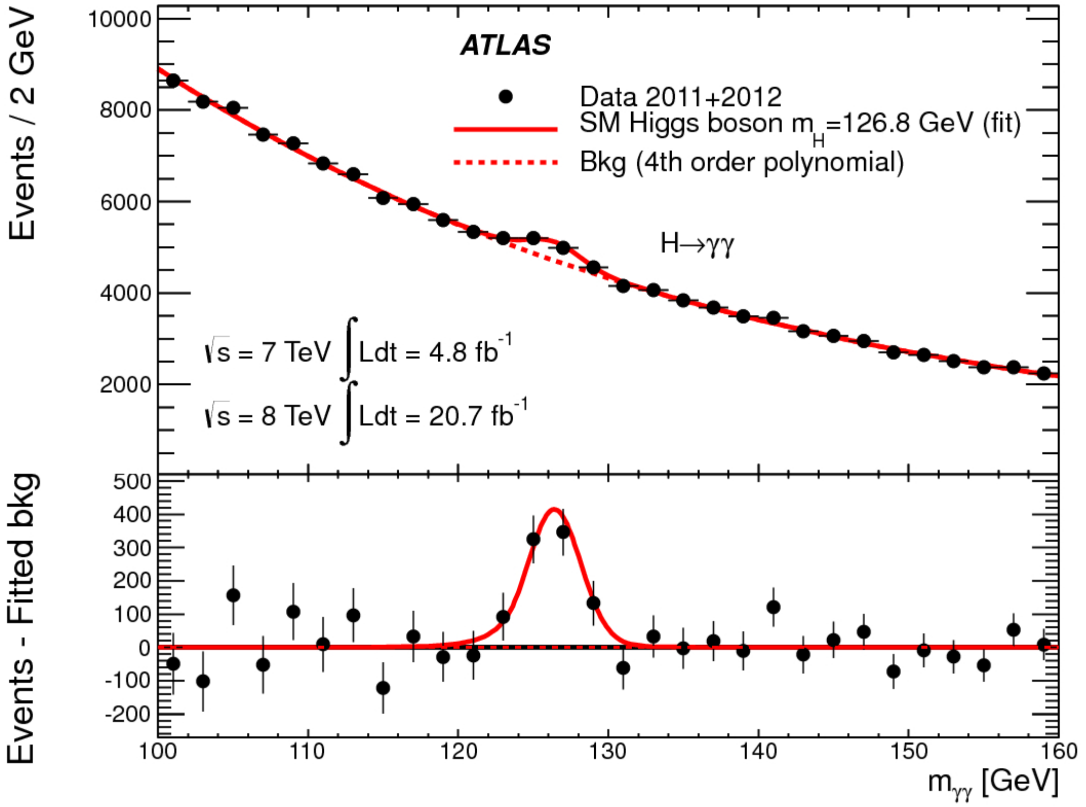

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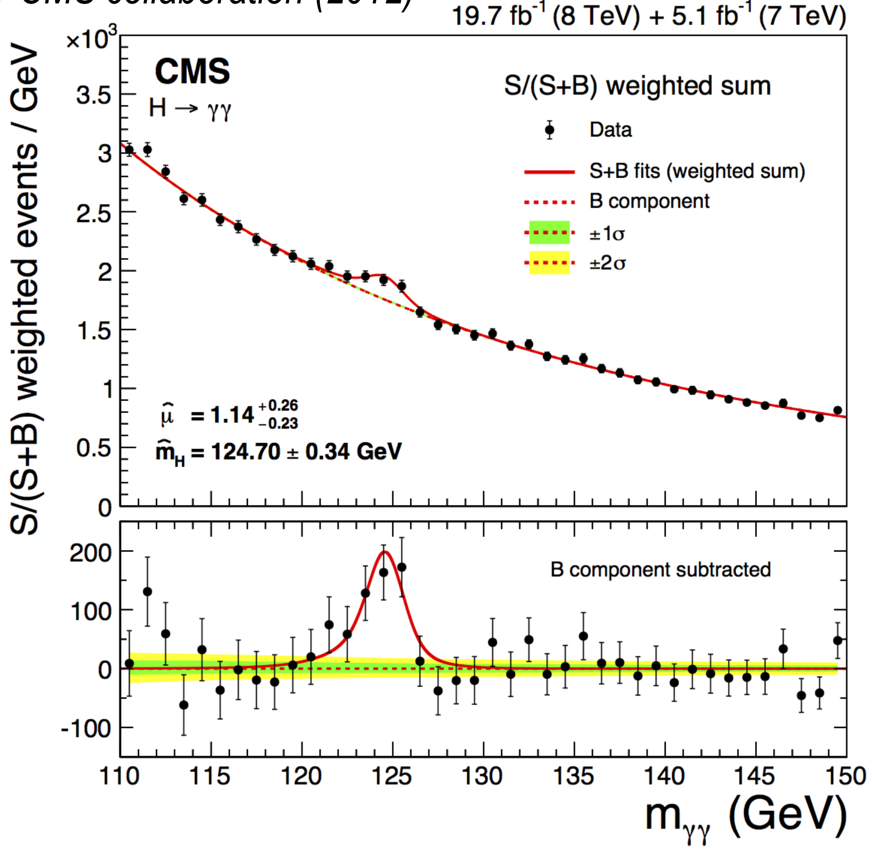


$$\boxed{M_H \approx 125\ \text{GeV}}$$

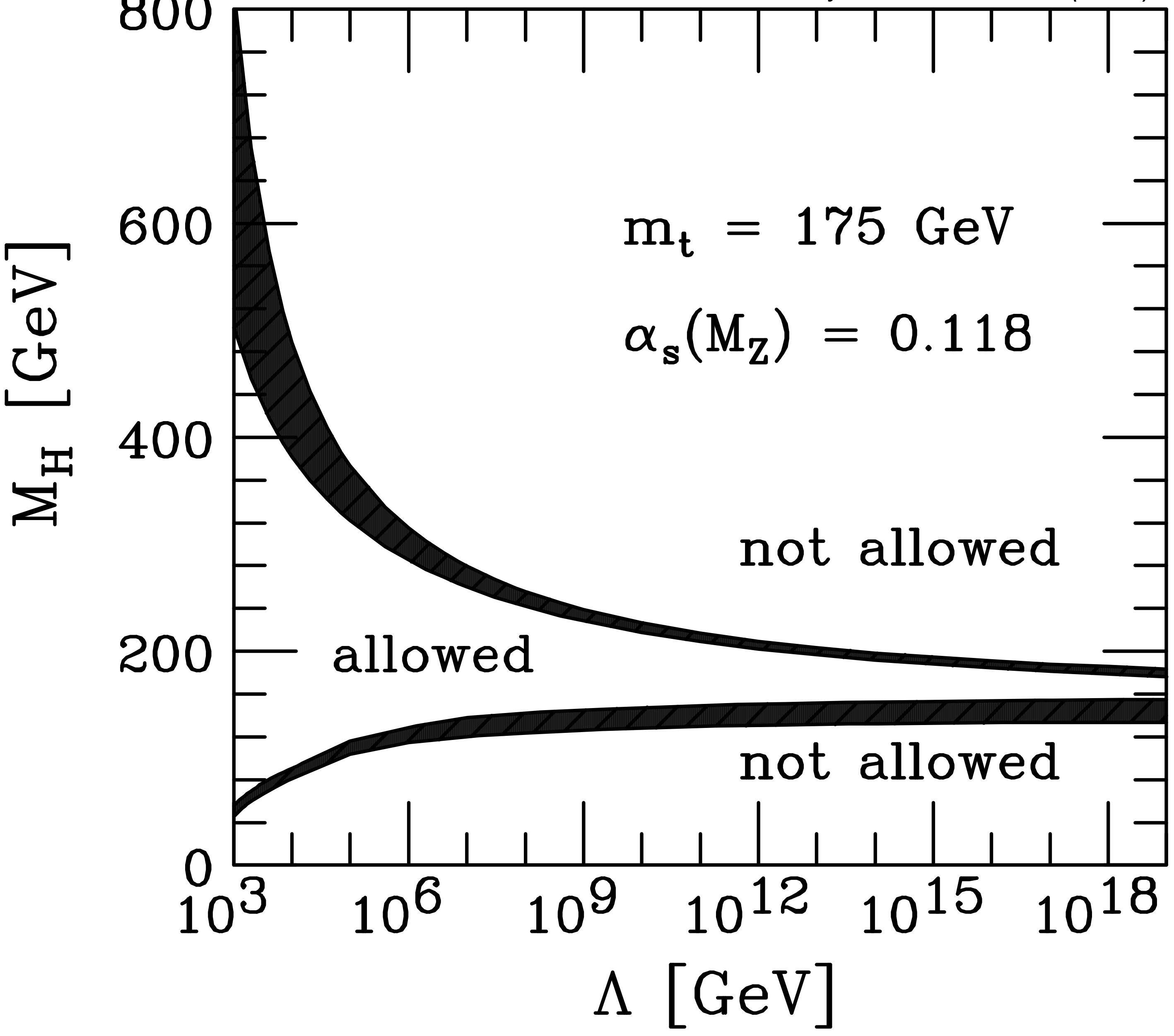
- **Standard model:**
  - low-energy effective theory
  - physical cutoff Λ
  - “new physics” beyond Λ

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

On Higgs mass bounds

- Higgs mass is related to Higgs coupling and vev: $M_H^2 \sim \lambda_4 v^2$

Hambye & Riesselmann (1997)



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)

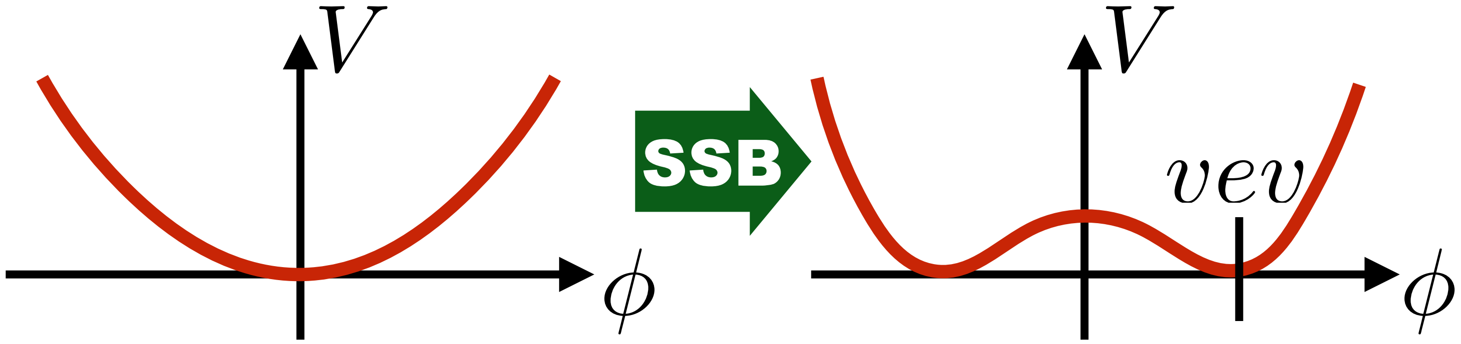
Altarelli, Isidori (1994)

Schrempp, Wimmer (1996) …

- Upper bound related to Landau pole

Main mechanism for lower Higgs mass bound

- **Higgs potential:**



$$m_H = \sqrt{\lambda} \cdot vev$$

$$m_t = y \cdot vev$$

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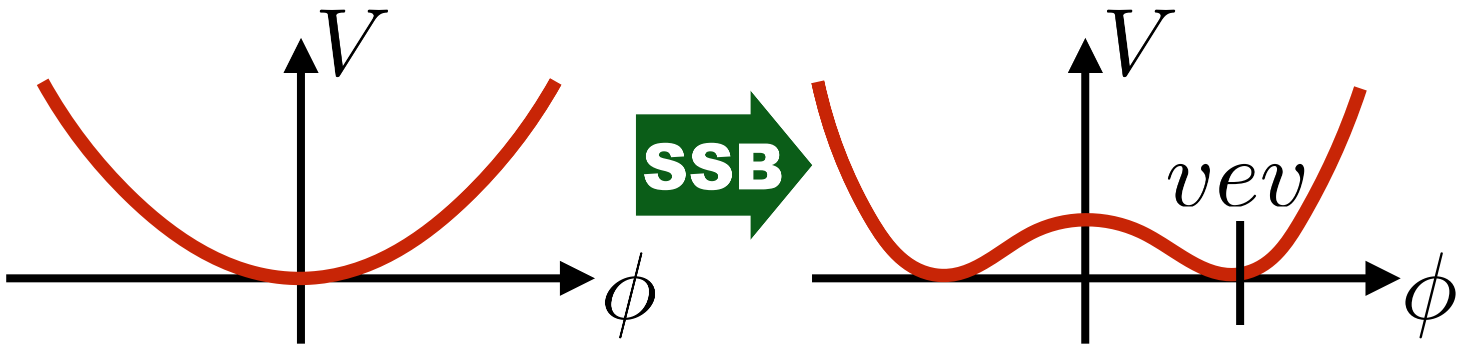

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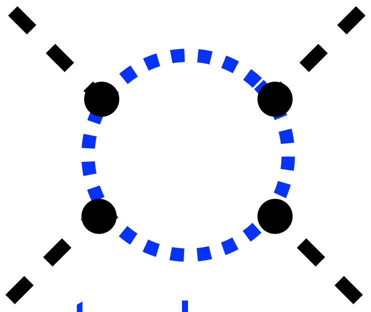
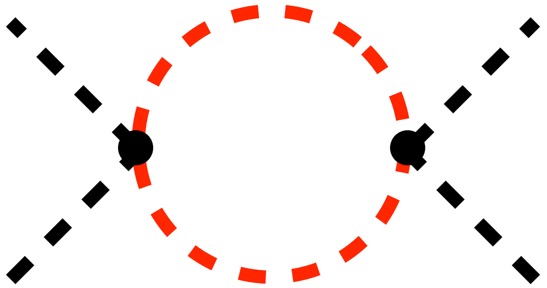
- **Running Higgs self-coupling:**

$\beta_\lambda =$ -


top loop

+


Higgs loop

+ gauge contributions

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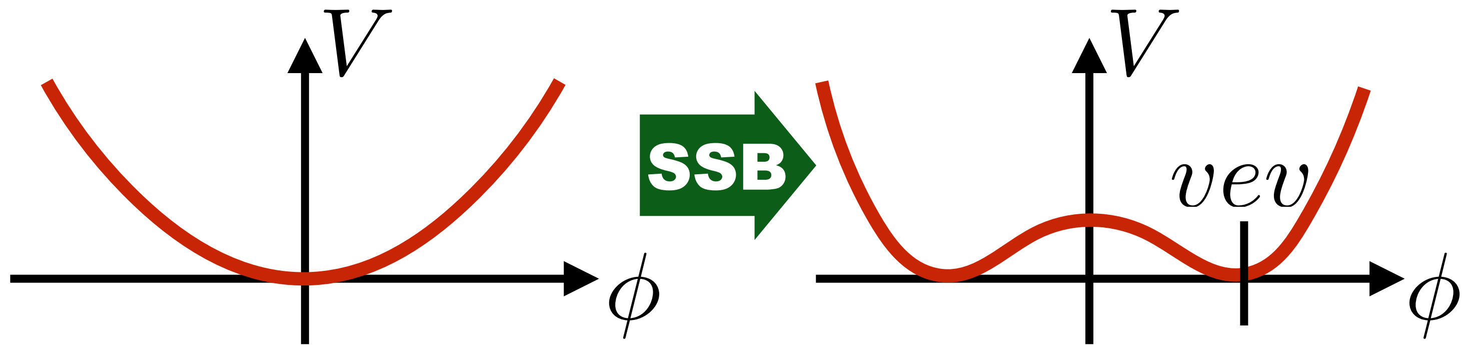

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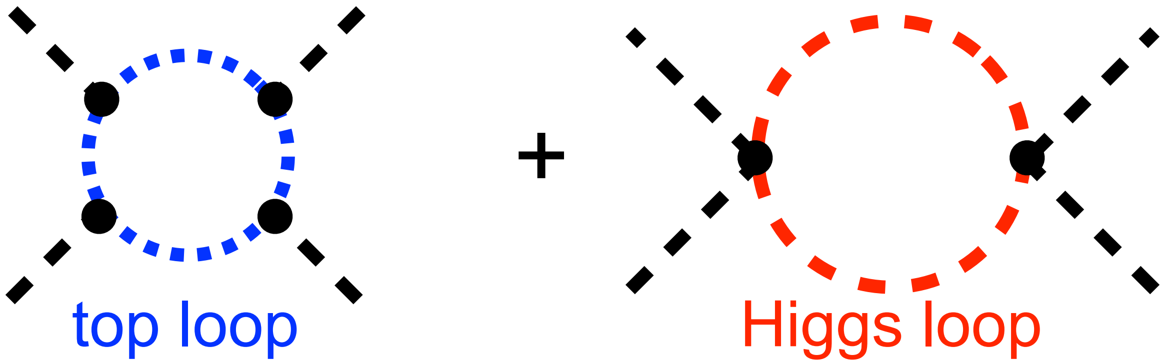

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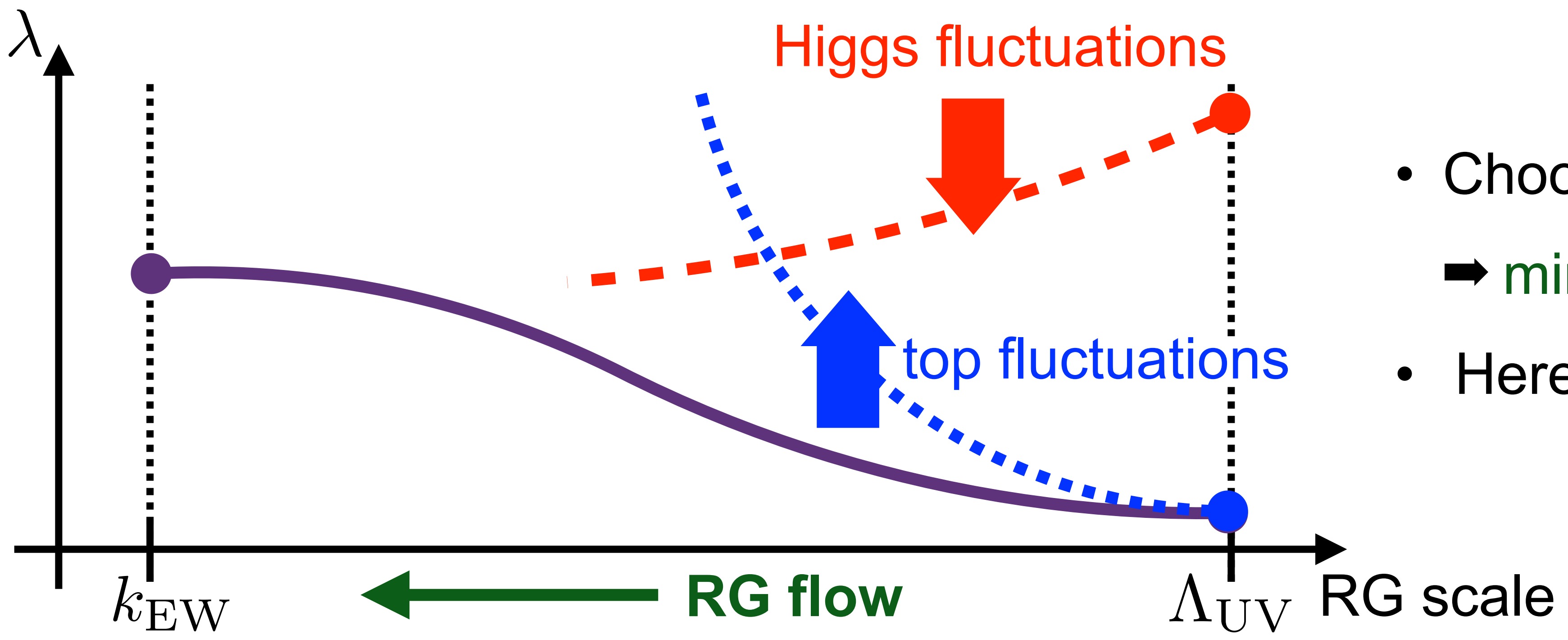
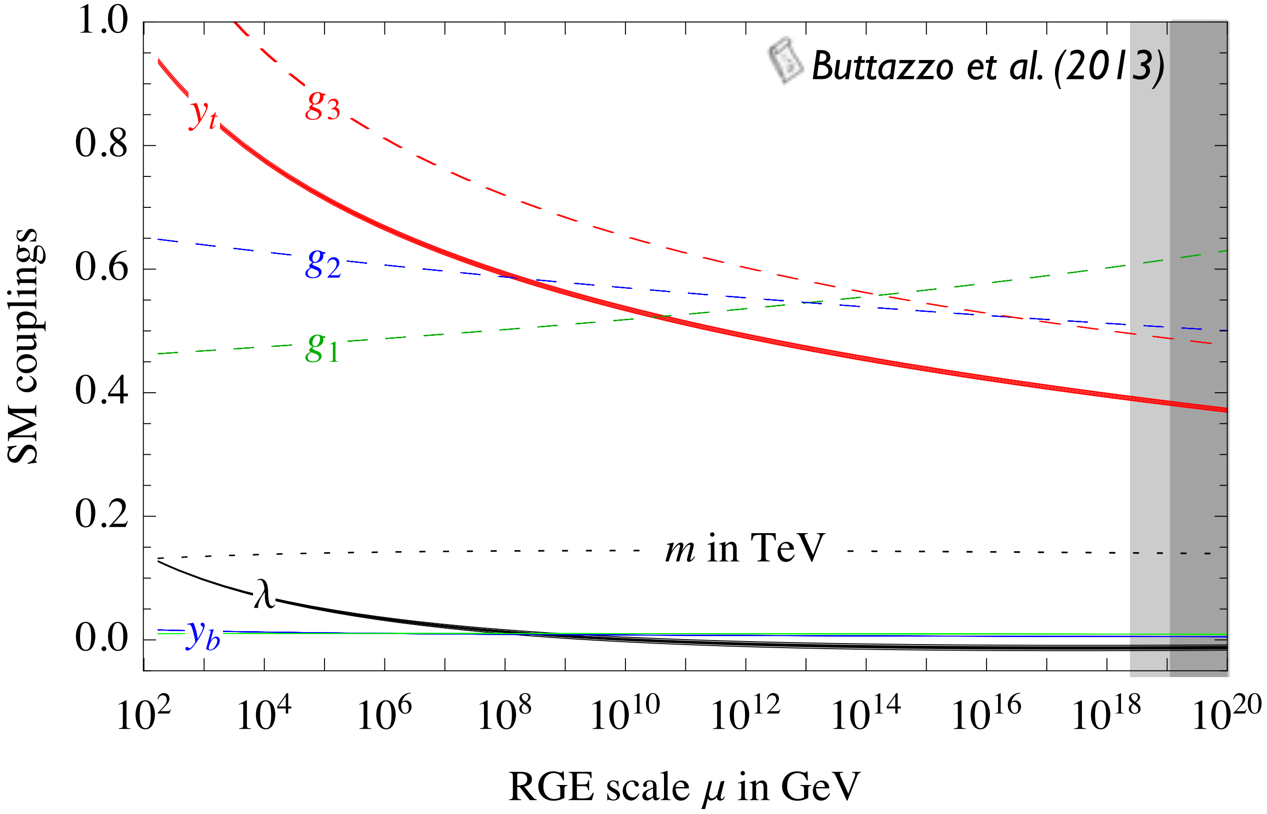


- Choose $\lambda = 0$ at Λ_{UV}:
  - ➡ minimal value of Higgs mass
- Here: focus on stability bound!

Lower mass bound in the standard model

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



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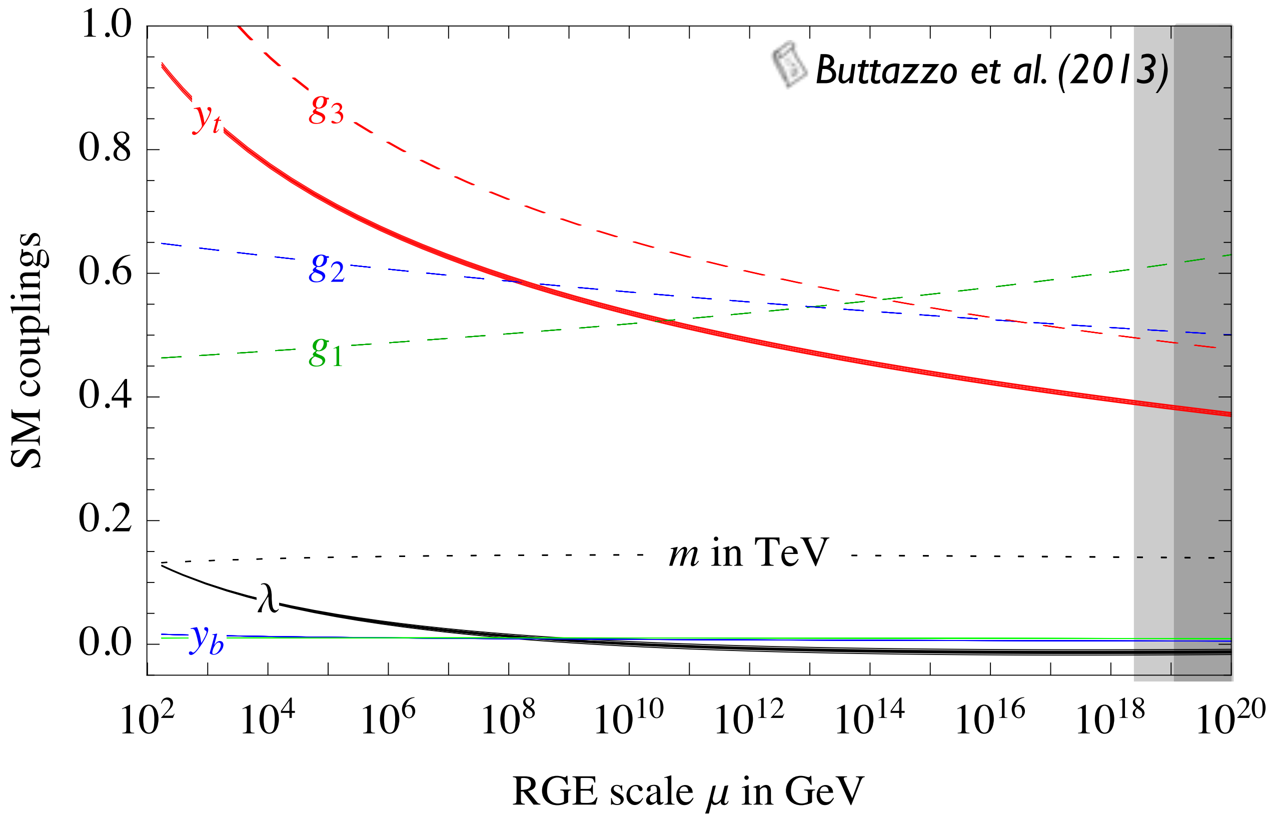


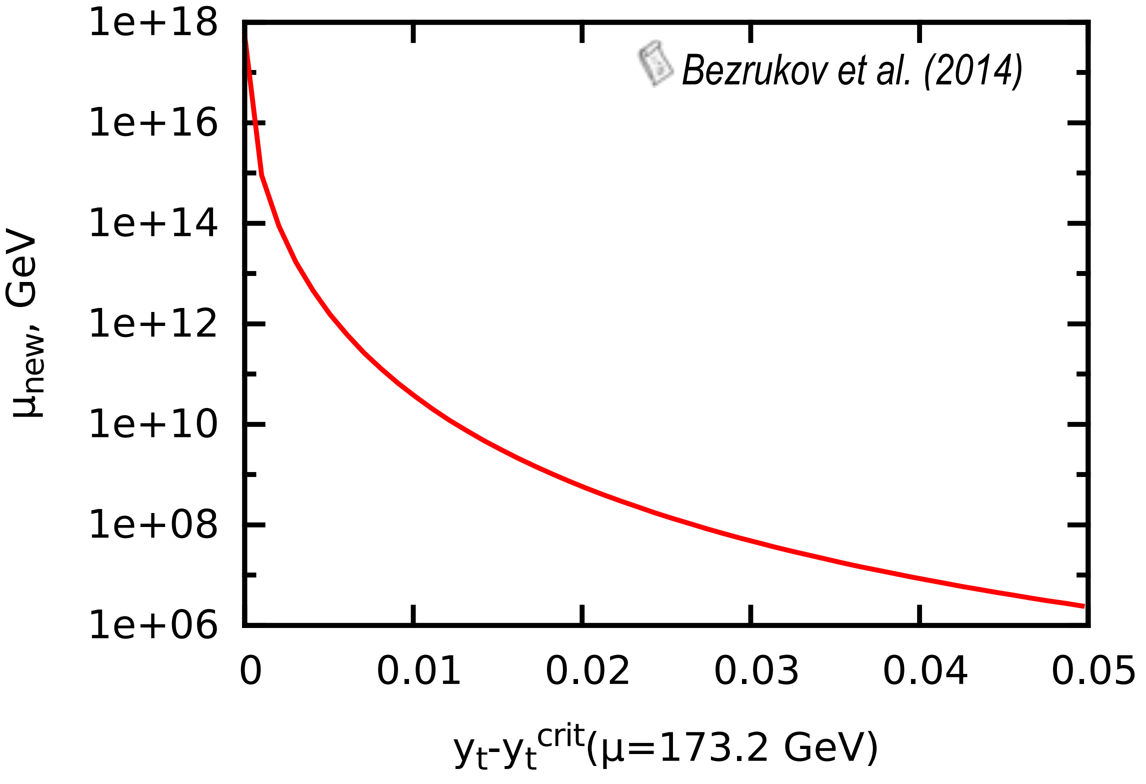
Buttazzo et al. (2013)

- **Scale of new physics**
  - ~ Higgs self-coupling crosses zero
  - strongly depends on top Yukawa!
  - precise determination of y_t required

$$M_H(M_{\rm Pl}) \approx 129\text{GeV}$$

Bezrukov et al. (2012)

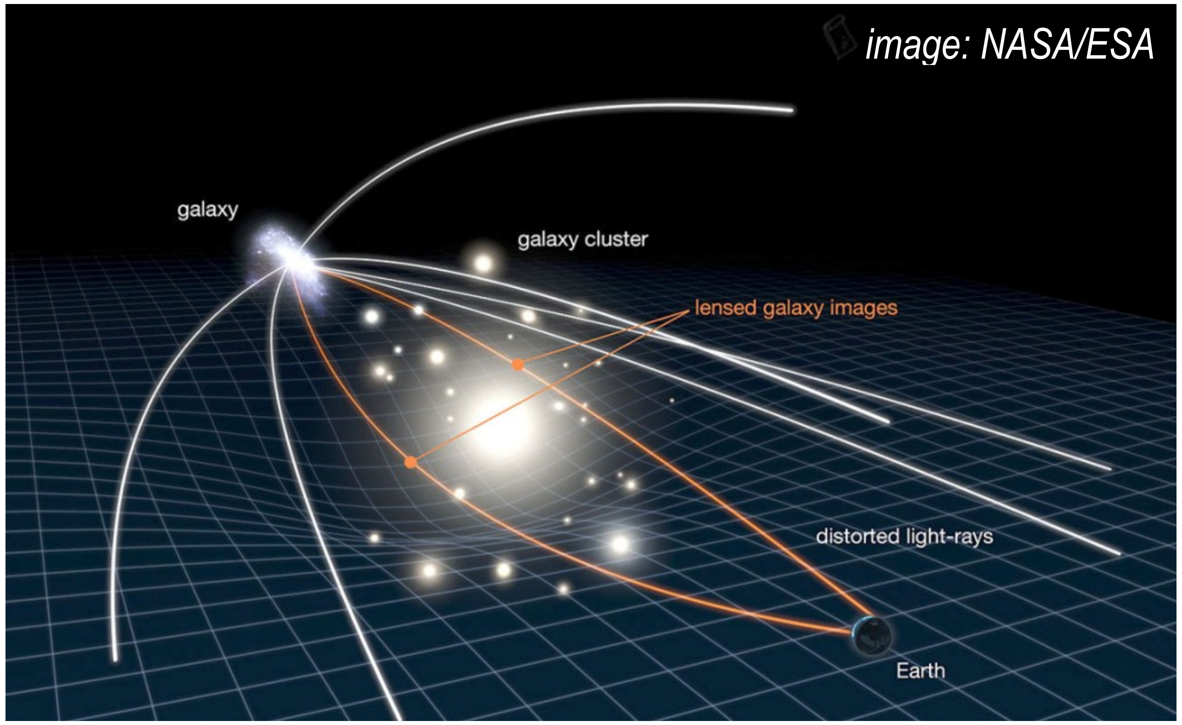
$$M_H^{\rm exp} \approx 125\text{GeV}$$



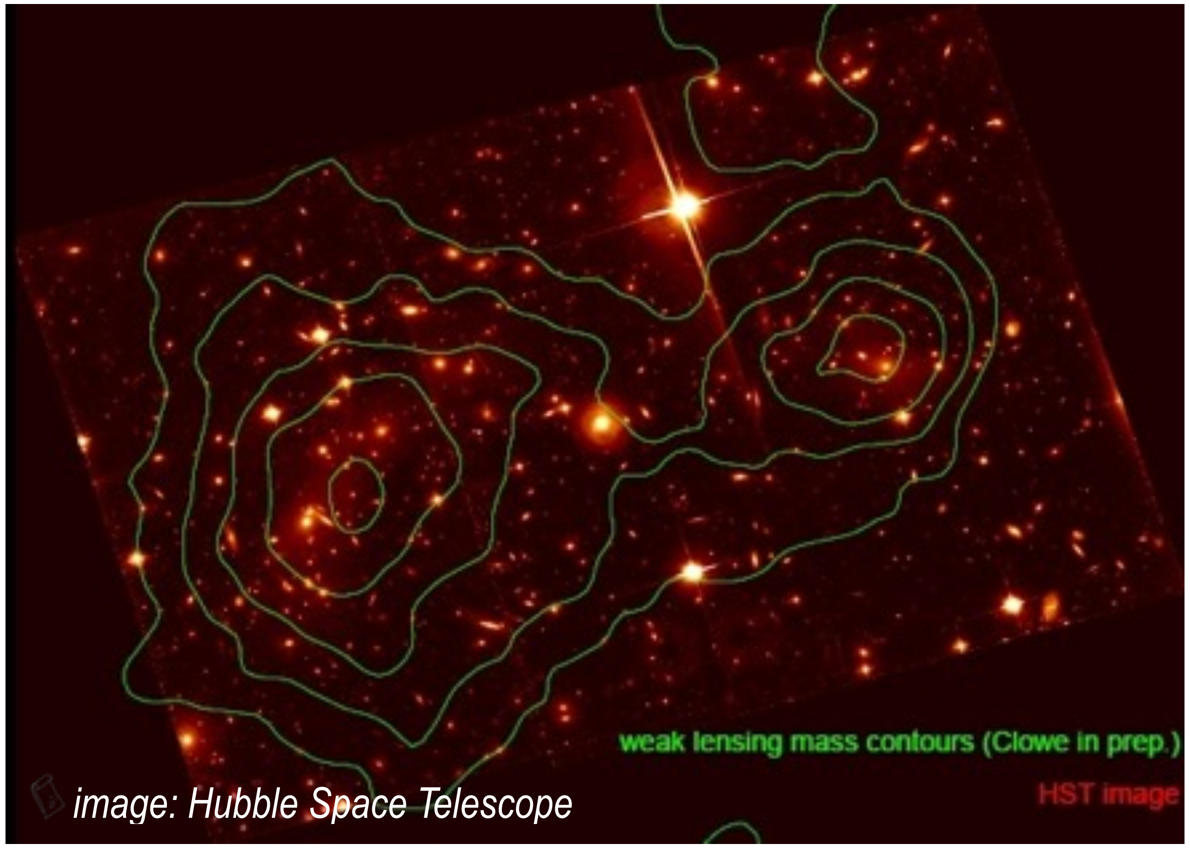
Bezrukov et al. (2014)

Evidence for dark matter

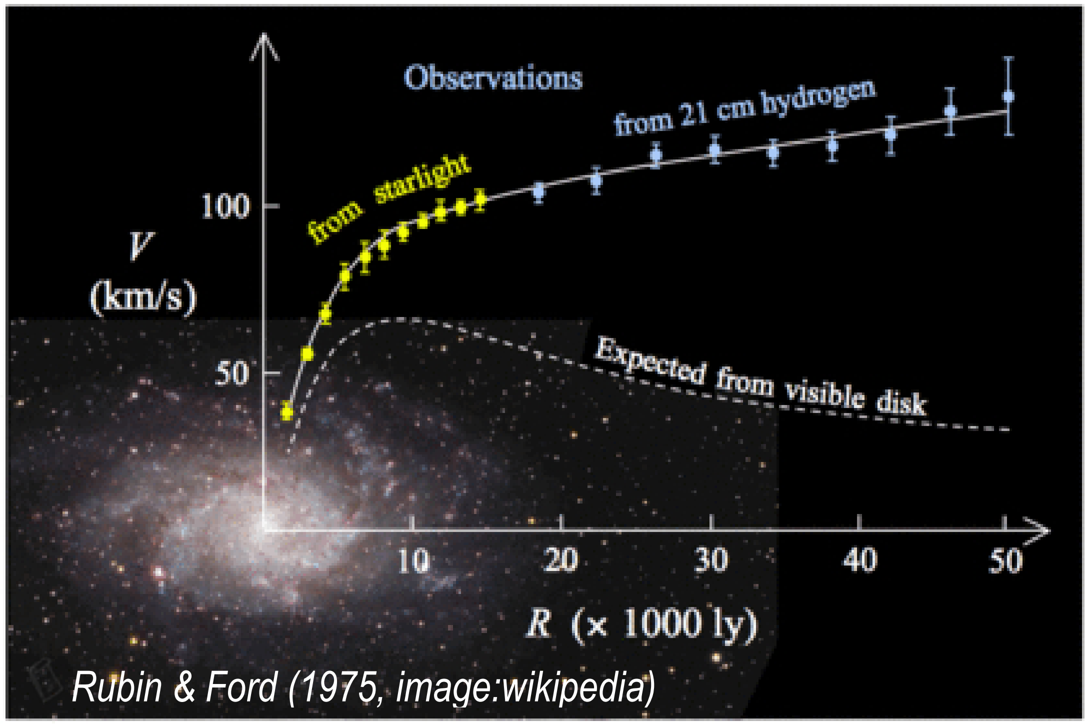
- Gravitational lensing



➡ Bullet cluster



- Galaxy rotation curves



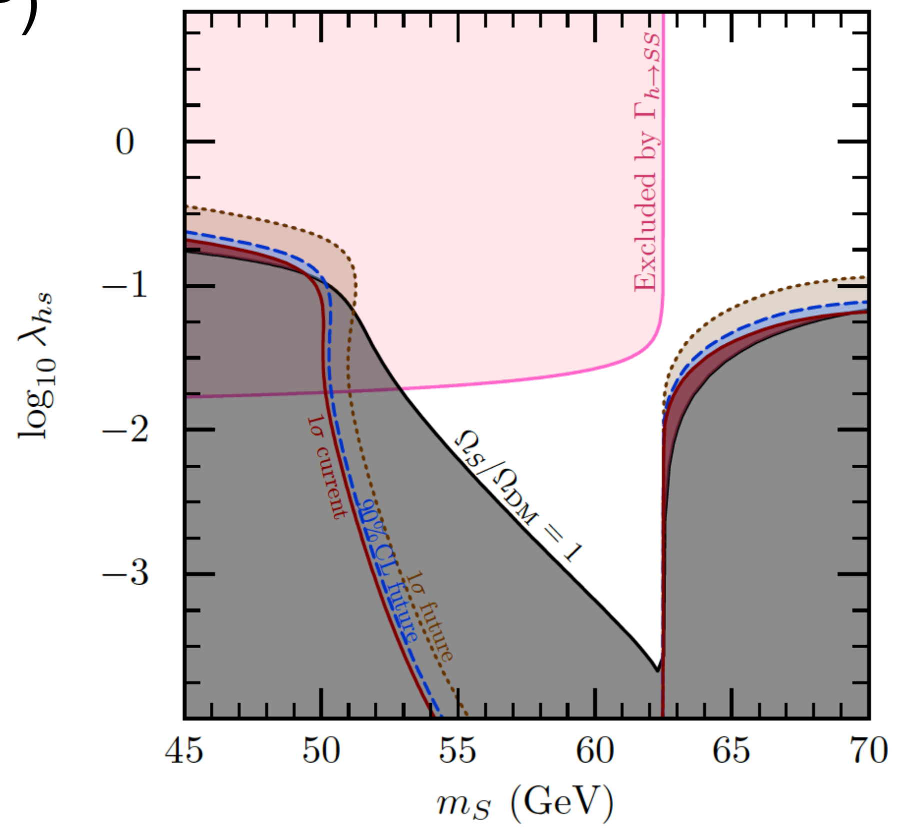
- CMB,…

Higgs portal to dark matter

- Single scalar field serves as **stable DM** candidate (WIMP)

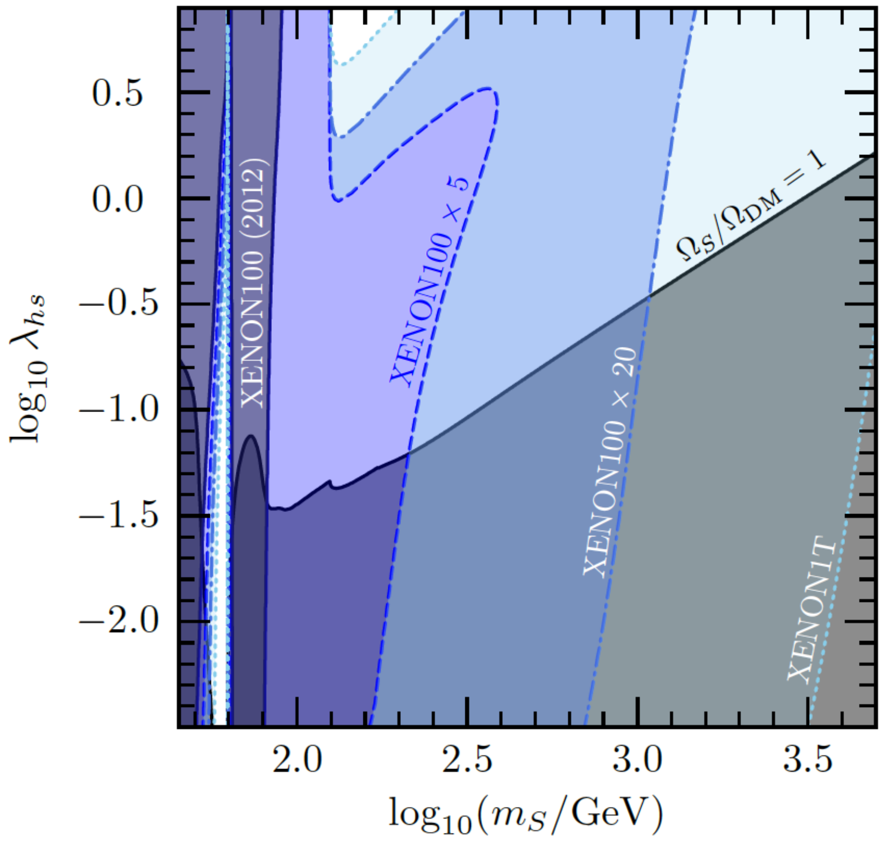
$$\Gamma_{\mathrm{DM}} = \int d^4x \Big(\frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2} m_S^2 S^2 + \frac{\lambda_{02}}{8} S^4 \Big)$$

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



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

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



top-Higgs-dark-matter model

- **Action:**

$$S_{\mathrm{UV}} = \int d^4x\{\overset{\substack{\text{Dirac fermion (top quark)}\\ \downarrow}}{\bar{\psi} i\partial\!\!\!/\psi} + \frac{1}{2}\underset{\substack{\uparrow\\ \text{scalar boson (radial Higgs)}}}{(\partial_\mu h)^2} + \frac{1}{2}\overset{\substack{\text{DM scalar}\\ \downarrow}}{(\partial_\mu S)^2} + \underset{\substack{\uparrow\\ \text{top-Higgs i.a.}}}{i\bar{y}h\bar{\psi}\psi} + \overset{\substack{\text{potential}\\ \downarrow}}{\bar{V}(h,S)}\}$$

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$$\psi \to e^{i\frac{\pi}{2}\gamma_5}\psi, \quad \bar{\psi} \to \bar{\psi}e^{i\frac{\pi}{2}\gamma_5}$$

$$h \to -h, \quad S \to S$$

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$$\bar V(h,S) = \overbrace{\frac{\bar m_h^2}{2}h^2 + \frac{\bar m_S^2}{2}S^2}^{\text{mass terms}} + \underset{\substack{\uparrow \\ \text{Higgs self-coupling}}}{\frac{\bar\lambda_{20}}{8}h^4} + \frac{\bar\lambda_{02}}{8}S^4 + \overset{\substack{\text{Higgs-DM portal}\\ \downarrow}}{\frac{\bar\lambda_{11}}{4}h^2S^2}$$

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- **spontaneous Z$_2$-symmetry breaking** → generation of vev, top mass & Higgs mass

RG evolution of top-Higgs-dark-matter model

- Use functional RG method as a tool to obtain β functions:
  - Flowing action Γ_k with RG scale k interpolates between

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

  - 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:

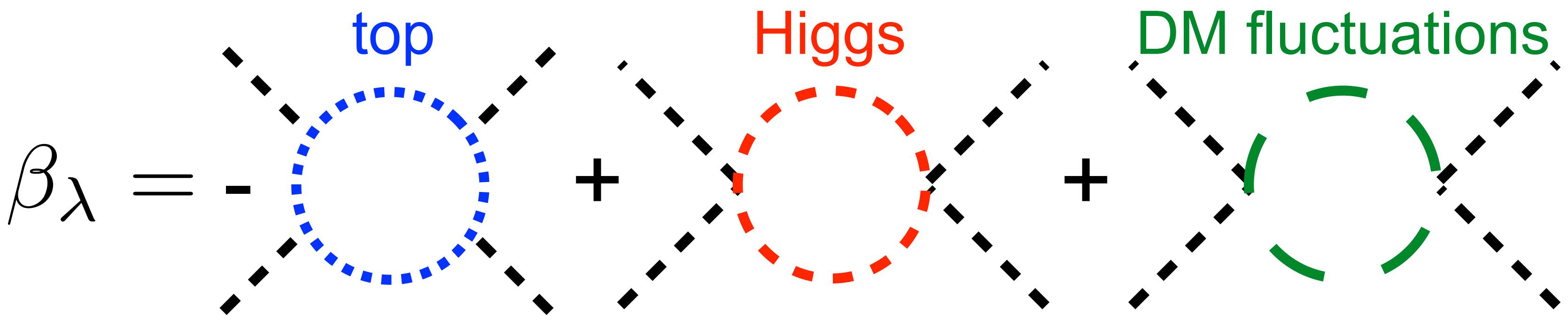
$$\Gamma_k = \int d^4x \Big(i\bar{\psi}\partial\!\!\!/\psi + (\partial_\mu h)^2 + (\partial_\mu S)^2 + iyh\bar{\psi}\psi + V_k(h,S) \Big)$$

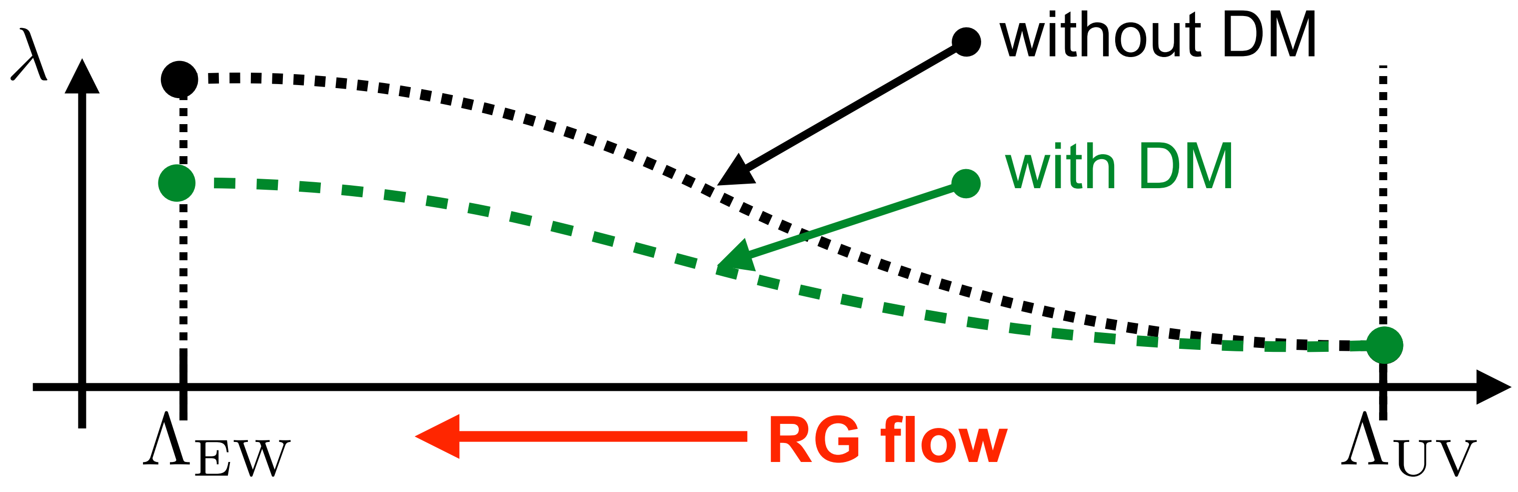
➡ **β functions for model couplings…**

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

Effect of dark matter on Higgs mass

- **Running Higgs self-coupling:**





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

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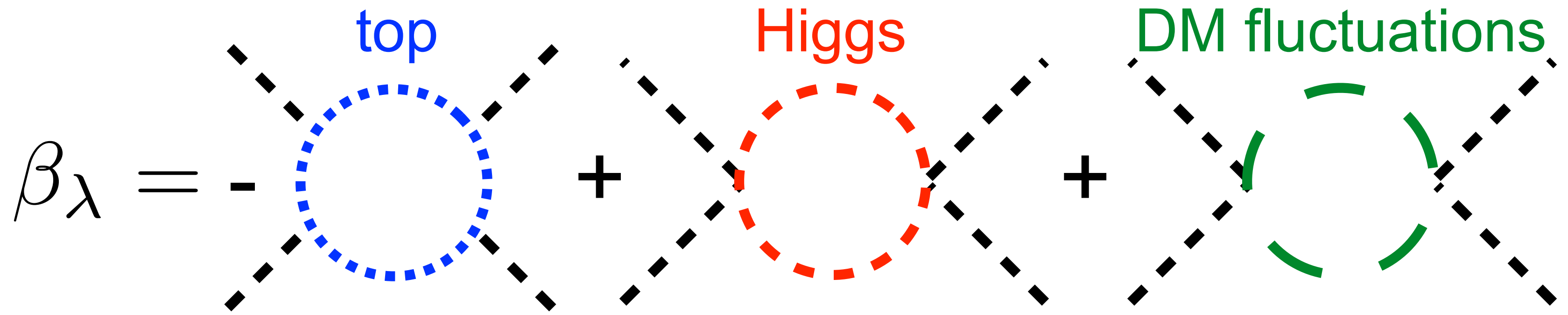

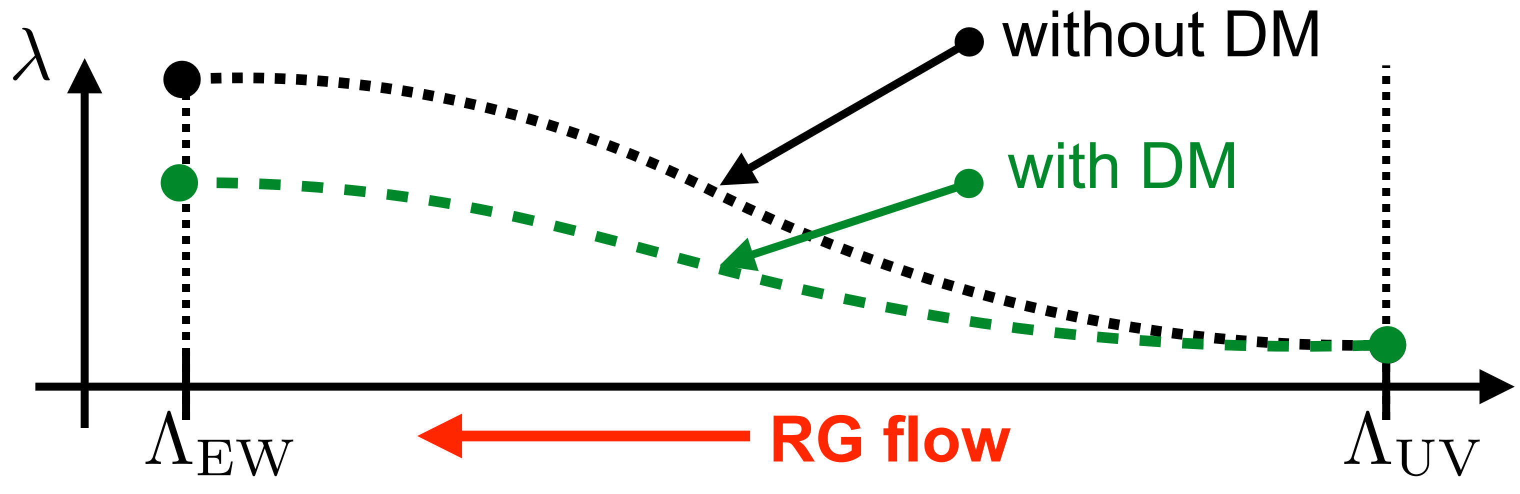

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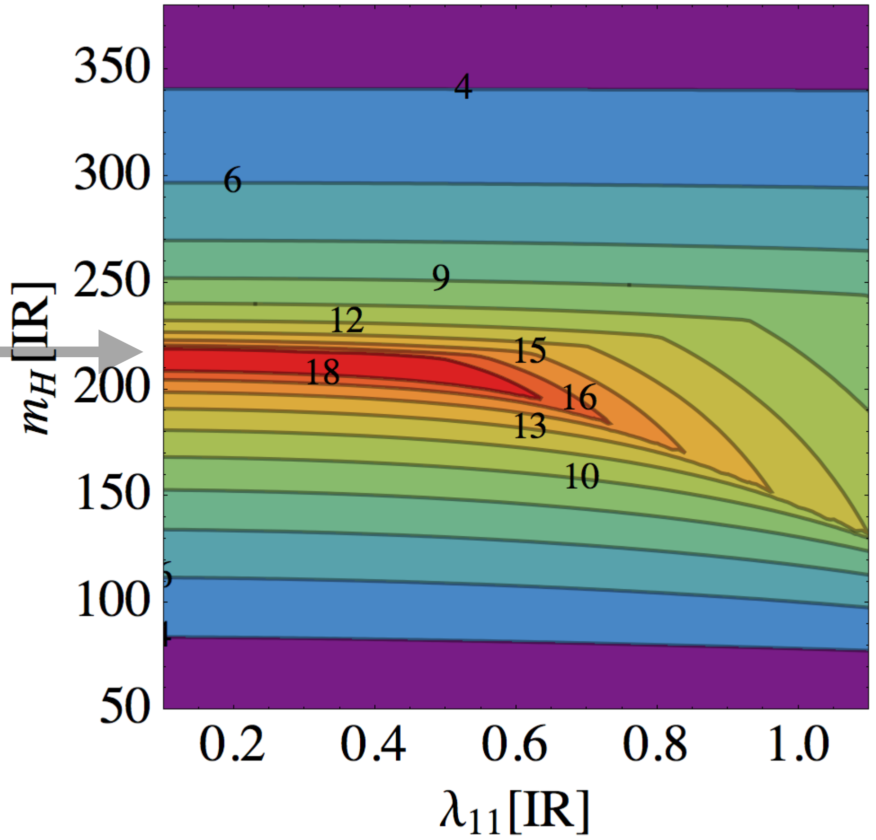
- **Contours of fixed cutoff scale:**
  - S constitutes complete DM relic density

toy model!



SM: Gonderinger et al. (2009)

Eichhorn, MMS (2014)

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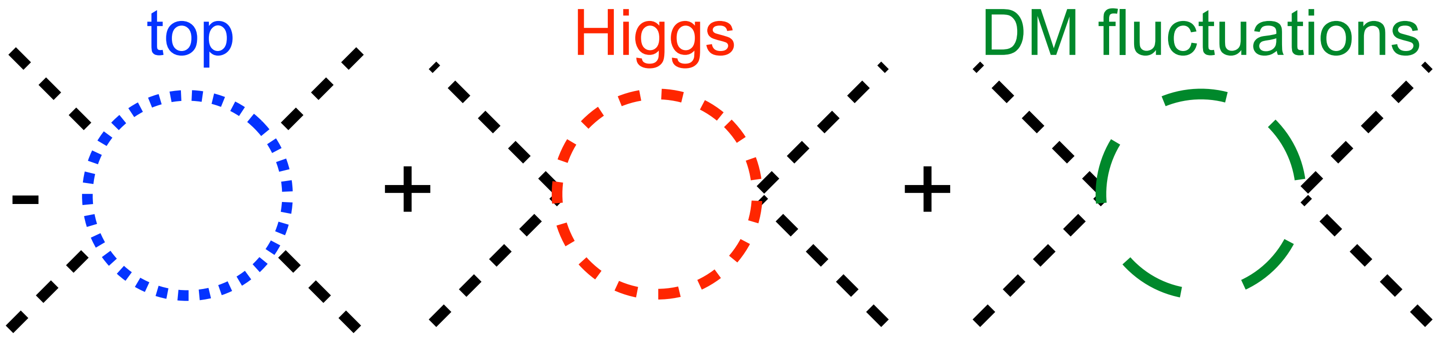

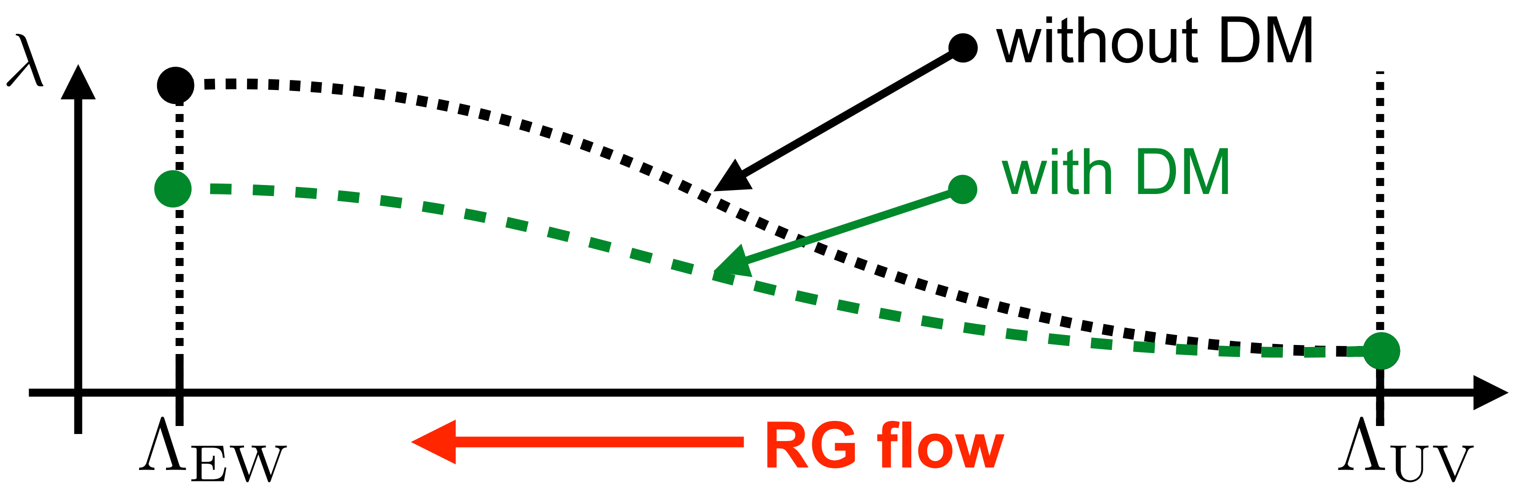

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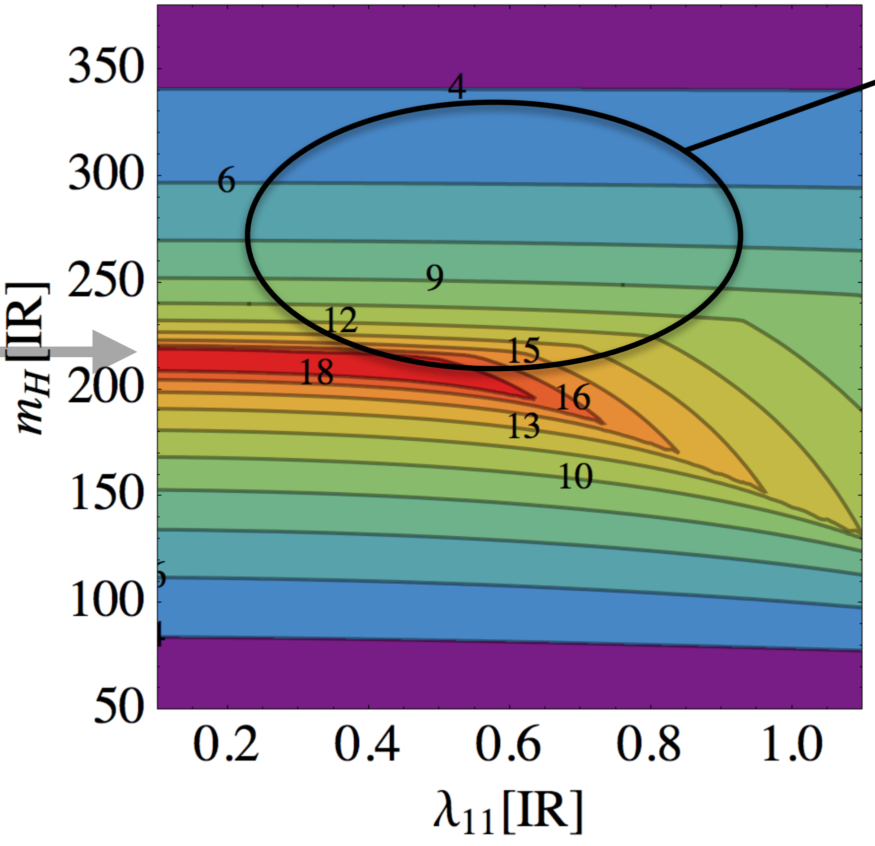

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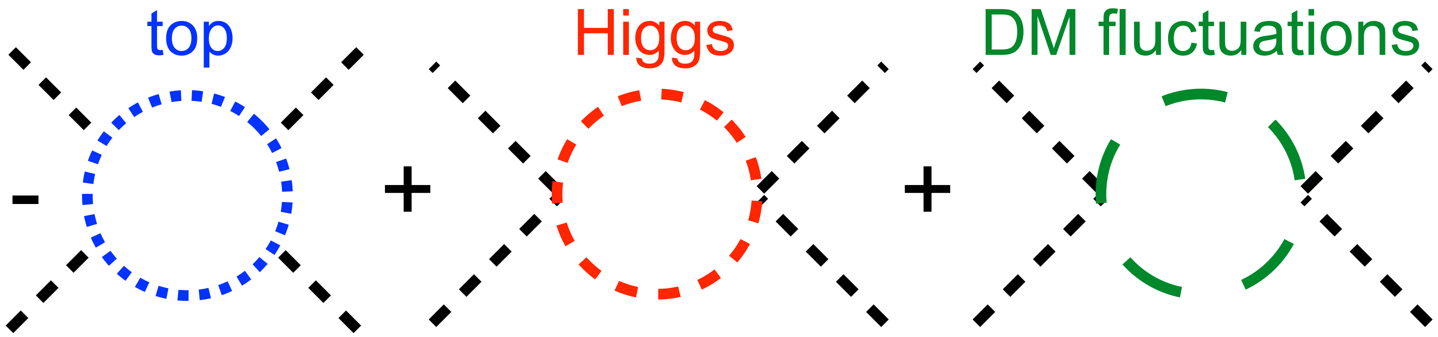

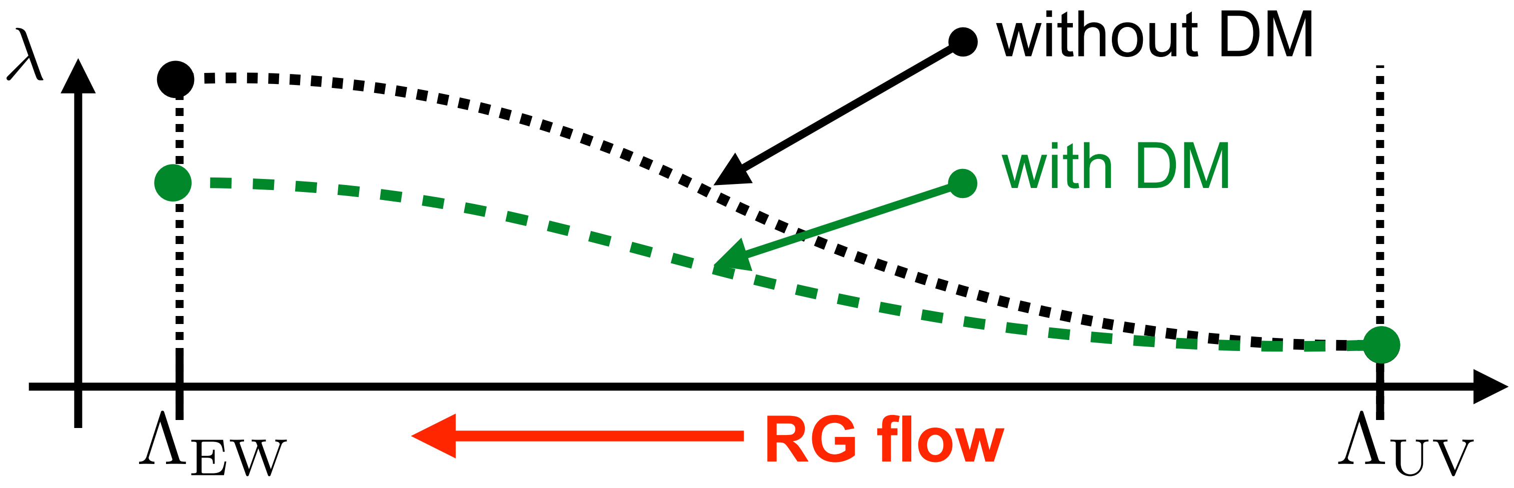

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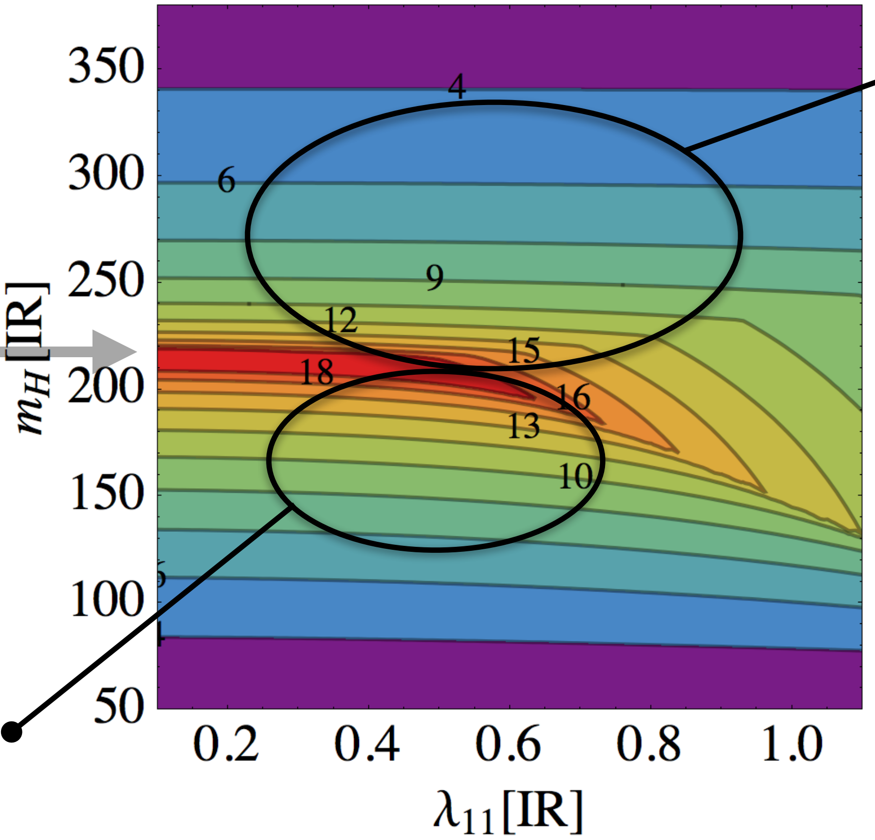

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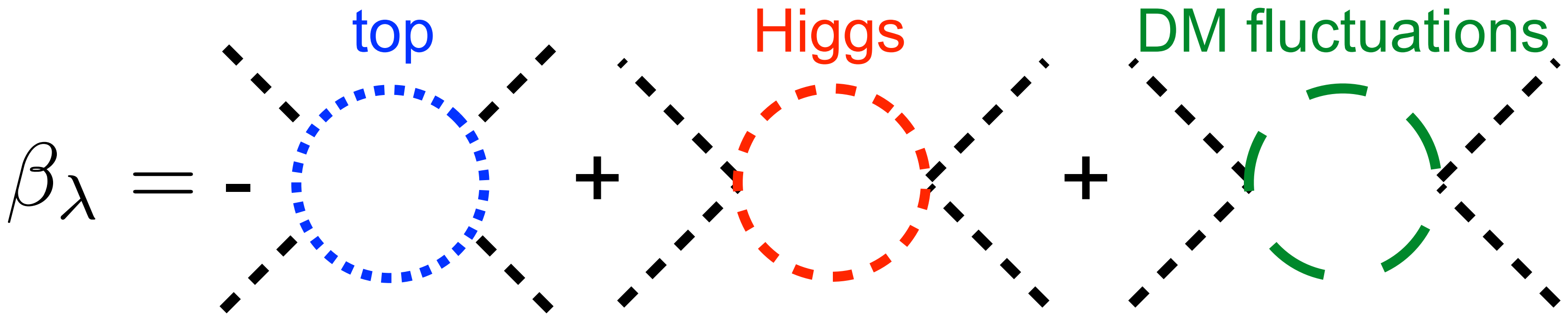

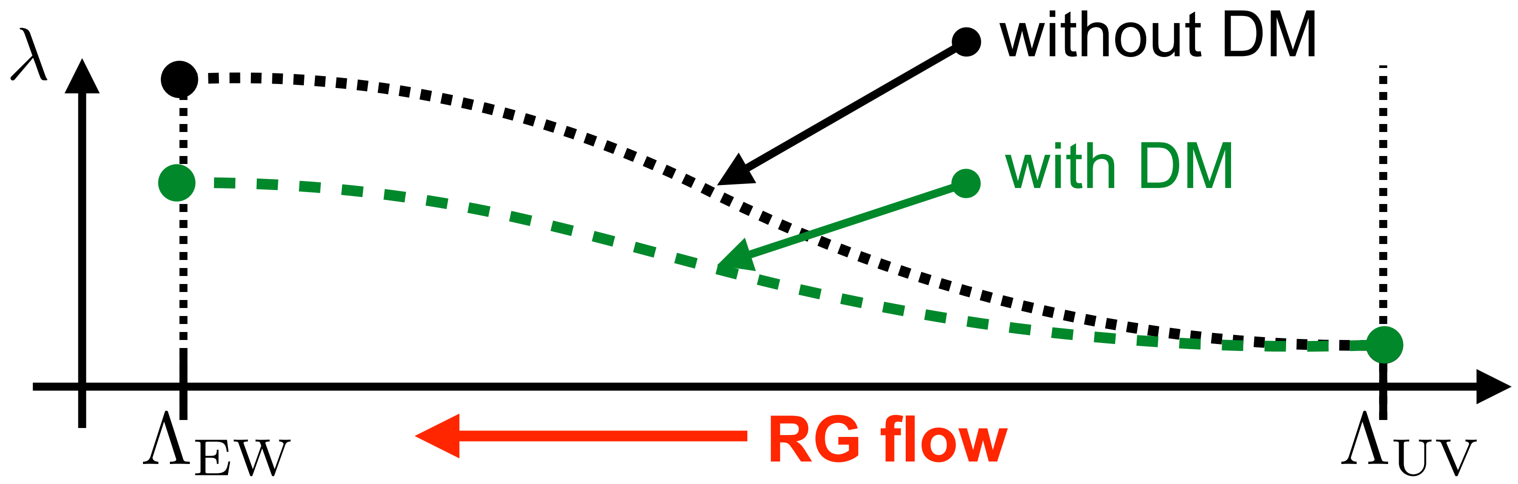

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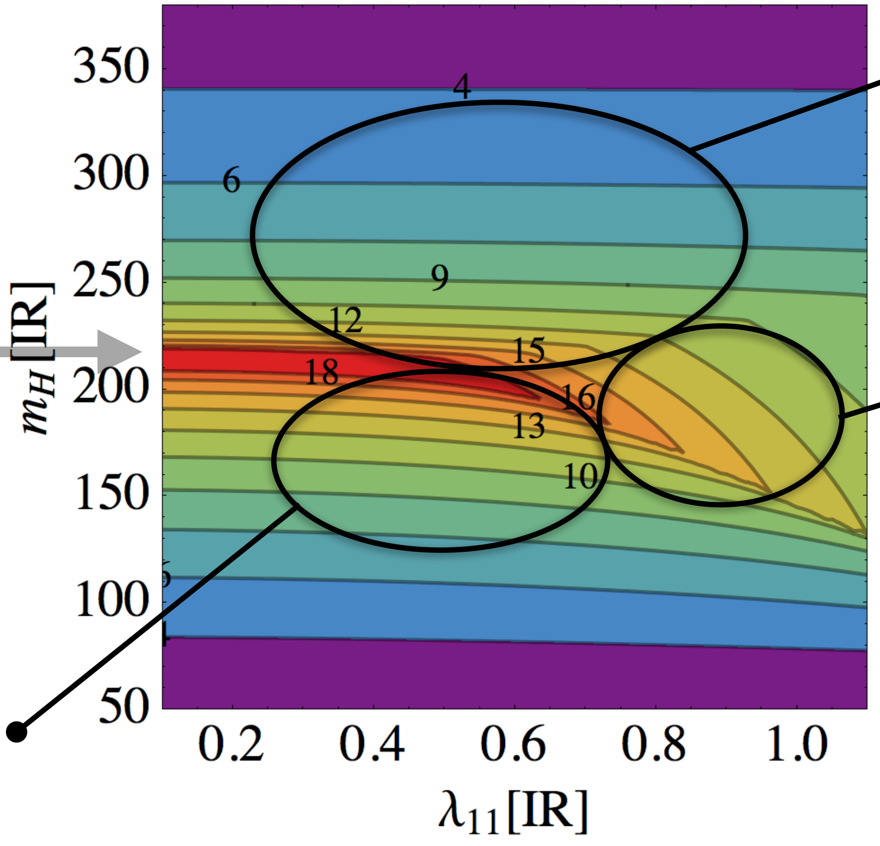

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Landau pole in Higgs portal coupling

Lower Higgs mass

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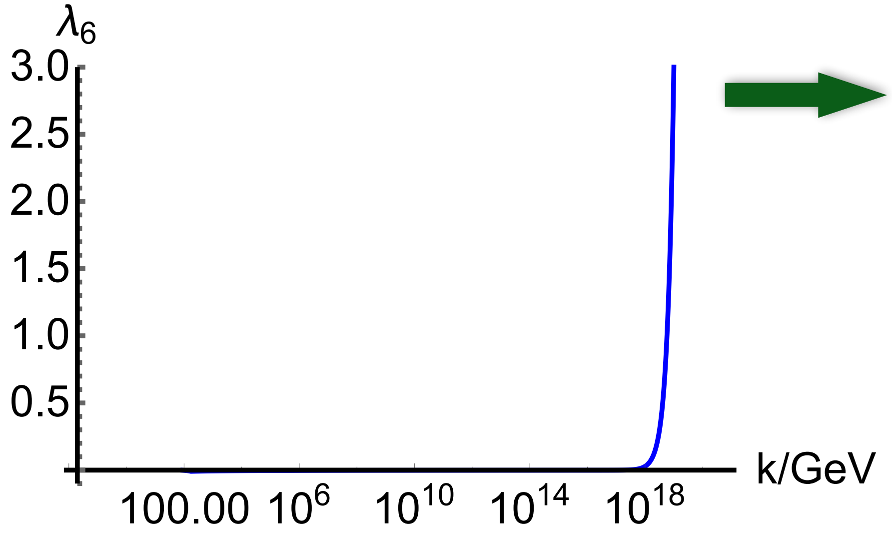
Eichhorn, MMS (2014)

Standard model as a low-energy effective theory

- **Induced potential at UV scale:** all operators compatible with symmetries

$$\Rightarrow \quad V_\Lambda = \lambda_4 \phi^4 + \frac{\lambda_6}{\Lambda^2}\phi^6 + \ldots \quad \text{with} \quad \lambda_n \sim \mathcal{O}(1)$$

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



→ becomes tiny very fast!

- Nevertheless: impact on mass bounds
  - *Fodor et al. (2008)*
  - *Branchina & Messina (2013)*
  - *Gies, Gneiting , Sondenheimer (2013)*

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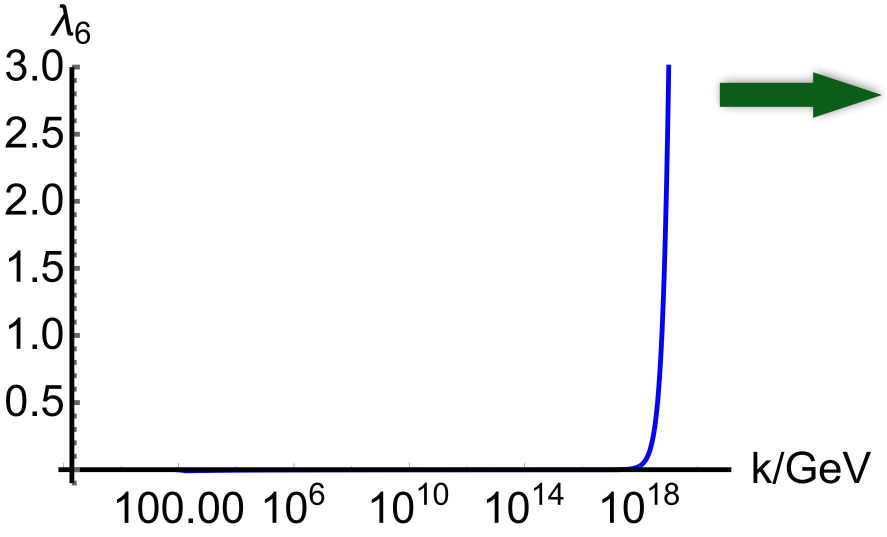

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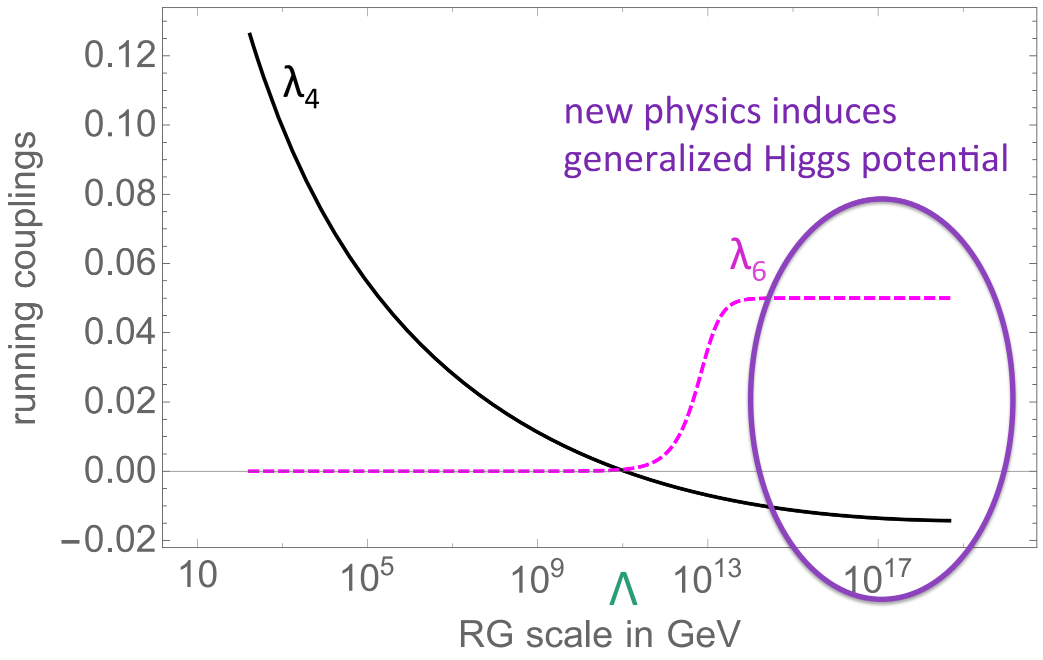
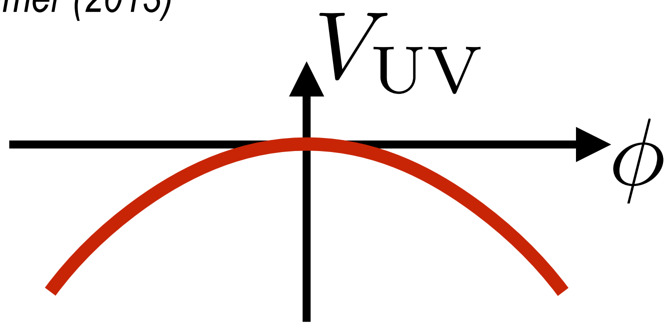
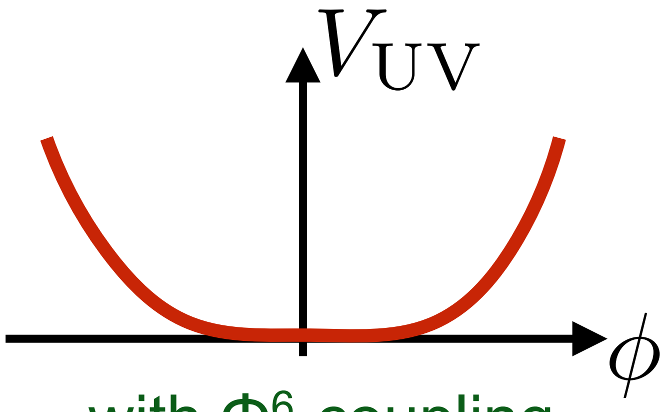
- **Mechanism to go below lower mass bound**:





without Φ^6-coupling

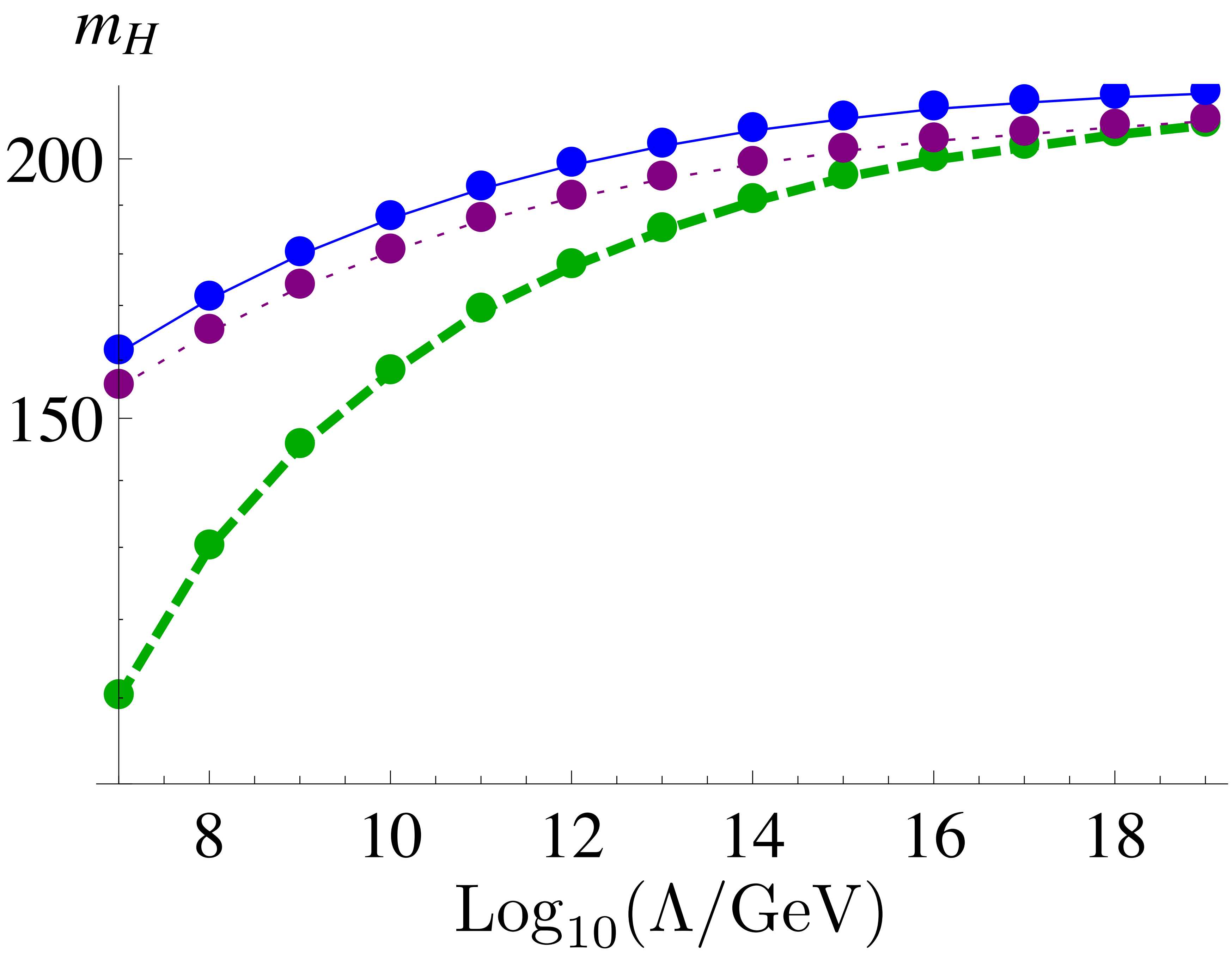


with Φ^6-coupling

Higgs mass (bounds) in top-Higgs-dark-matter model

- Fix vev = 246 GeV and m_{top} = 173 GeV
- Choose $\lambda_{20} = -0.1$ and $\lambda_{30} = 3.0$

➡ Higgs masses with dark matter and new couplings:



Eichhorn, MMS (2014)

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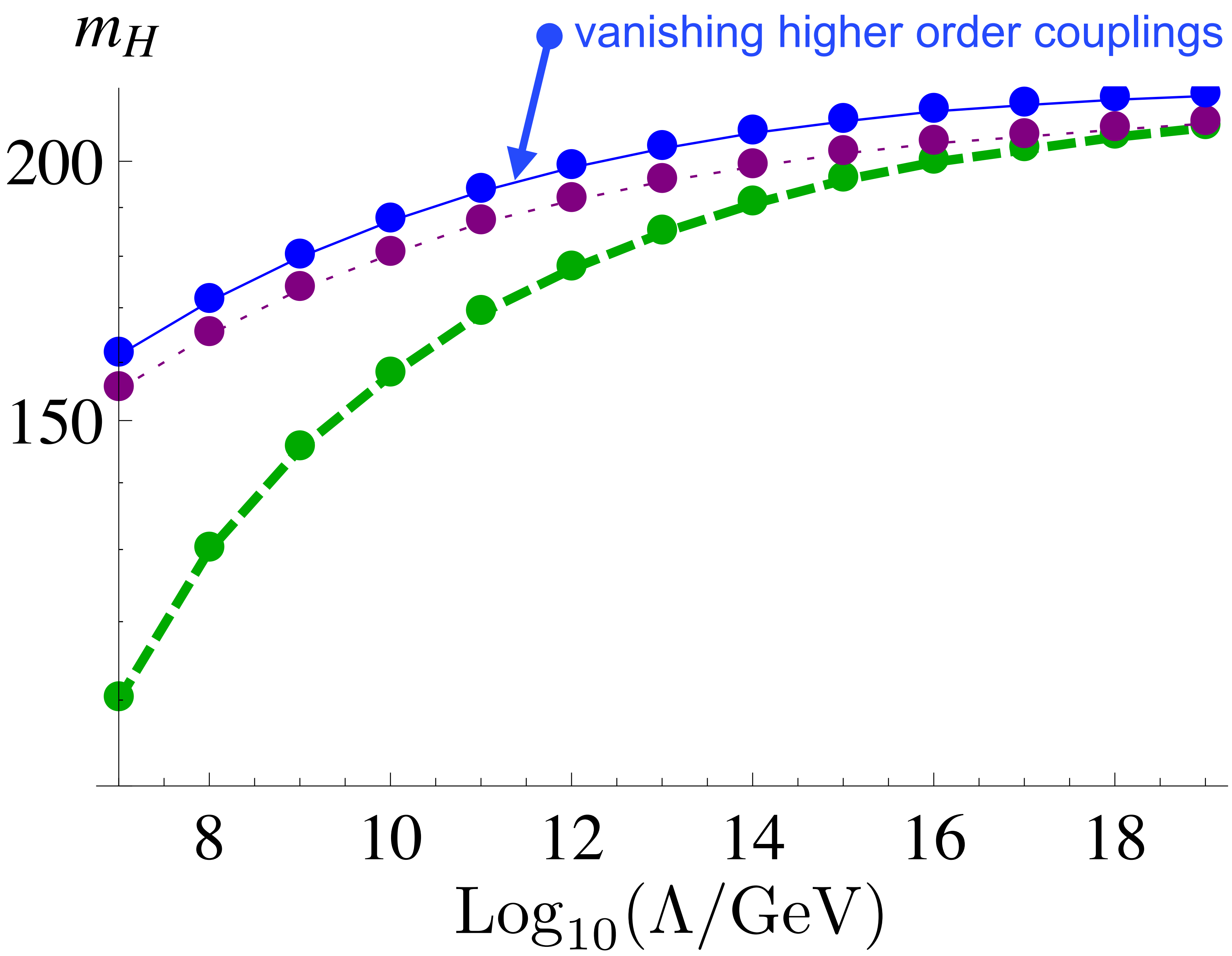
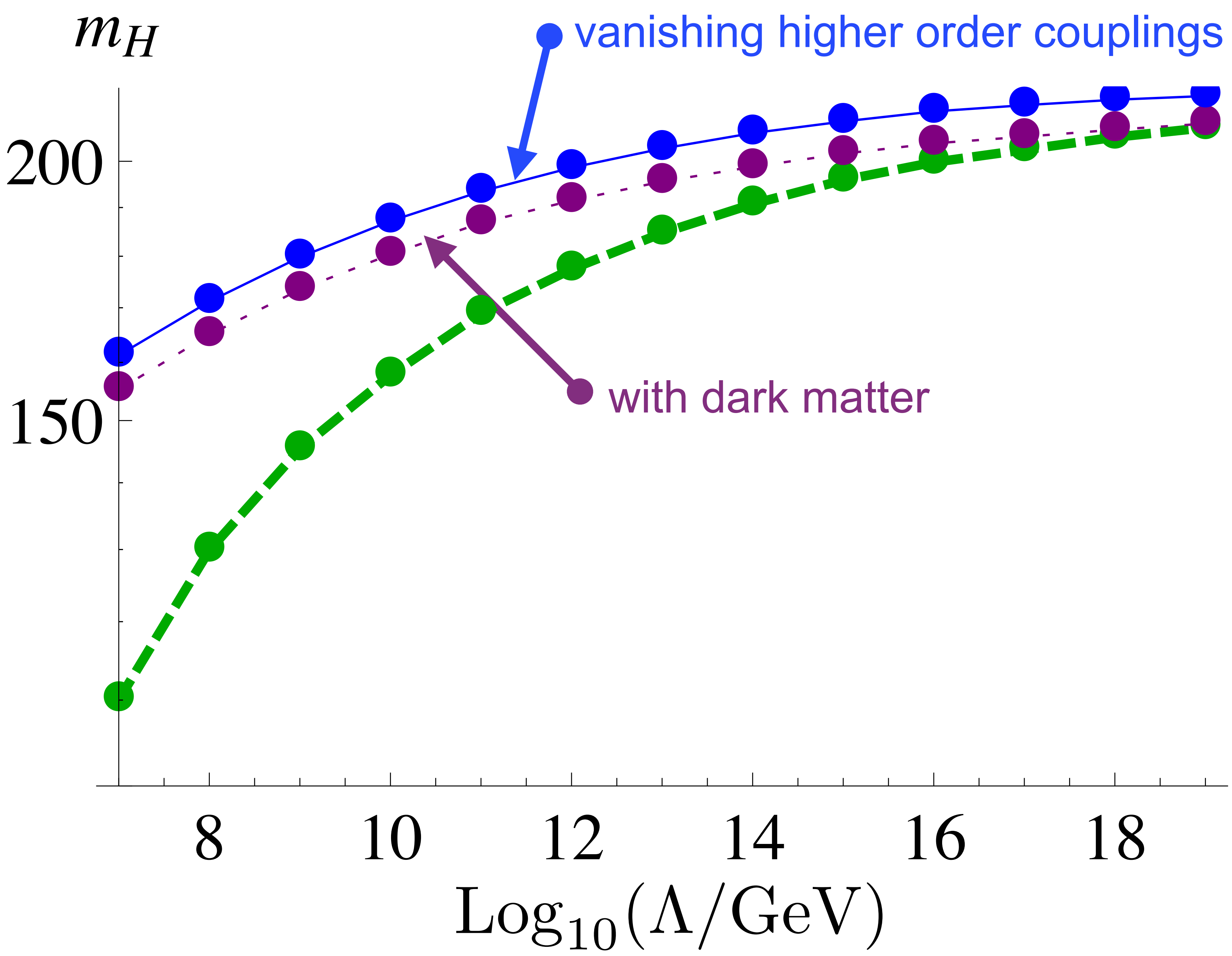


Eichhorn, MMS (2014)

Higgs mass (bounds) in top-Higgs-dark-matter model

- Fix vev = 246 GeV and m_{top} = 173 GeV
- Choose $\lambda_{20} = -0.1$ and $\lambda_{30} = 3.0$

➡ Higgs masses with dark matter and new couplings:



Eichhorn, MMS (2014)

Higgs mass (bounds) in top-Higgs-dark-matter model

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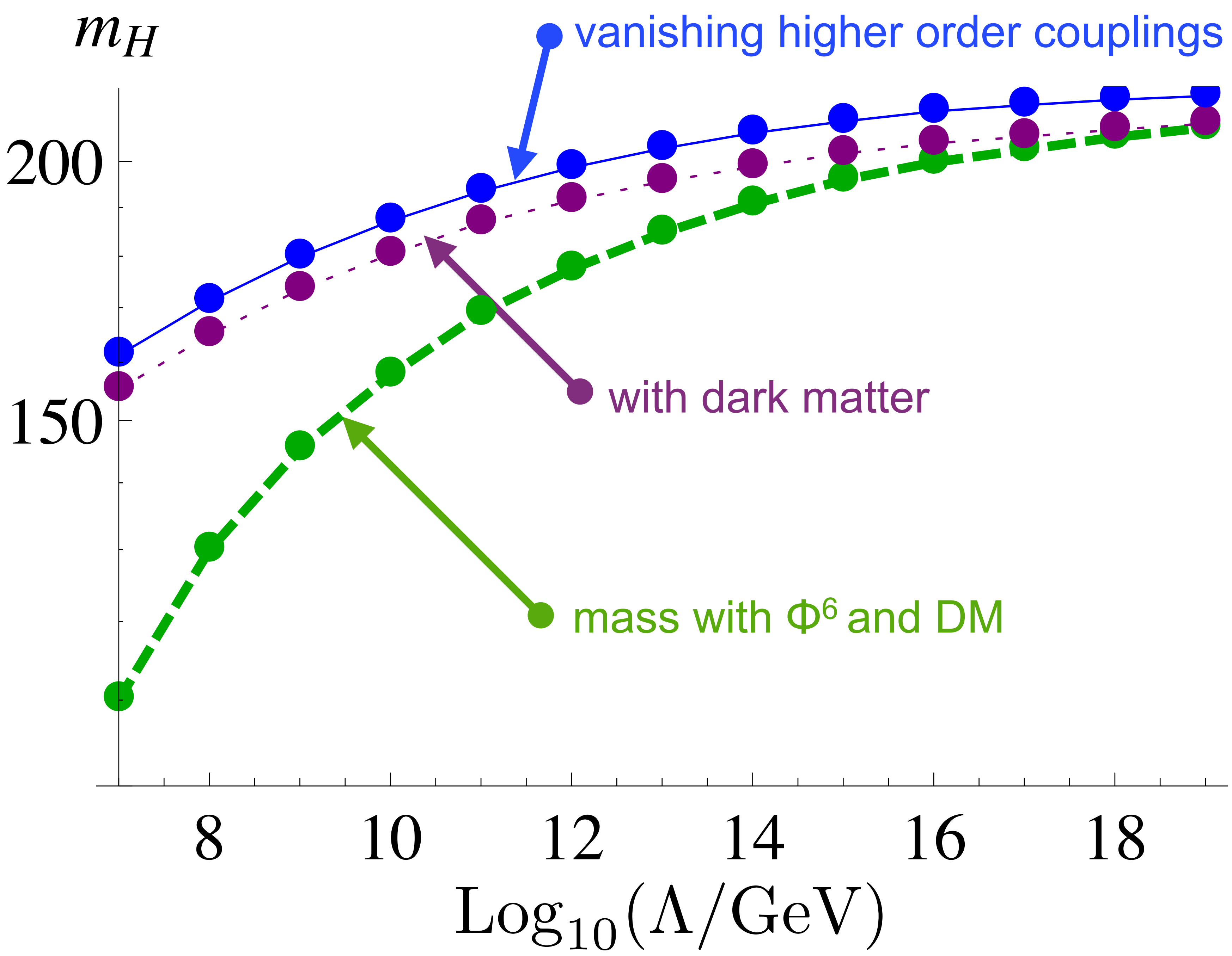

Eichhorn, MMS (2014)

Summary & Outlook

- measured Higgs mass very close to lower bound $M_h(\Lambda = M_{Pl})$
  - absolute **stability bound @ M_h=129 GeV** *Bezrukov et al. (2012)*
- simple dark matter model: scalar gauge singlet with Higgs portal
  - can constitute complete DM relic density
  - DM fluctuations increase Λ at fixed Higgs mass
  - DM fluctuations allow for smaller Higgs masses at fixed Λ (~ a few GeV @ $\Lambda = M_{Pl}$)
- generalized UV potentials as expected from EFT increase Λ for fixed Higgs mass
  - generalized UV potentials: Higgs masses below lower bound at fixed Λ (~ a few GeV)
- Combined effects from DM and higher order couplings: SM+DM could be valid up to M_{Pl}
- Ongoing research including gauge fields with A. Eichhorn, H. Gies, J. Jäckel, T. Plehn, R. Sondenheimer