The Higgs boson mass — its meaning for the Standard Model?

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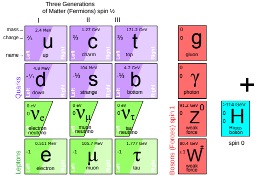
Outline

1. Introduction
   - Standard Model and the reality of the Universe
   - Minimal extension – still “Standard Model”
2. Higgs from EW scale up to Planck scale
   - Renormalization evolution of Higgs self coupling
   - Current Higgs boson results
   - Critical Higgs mass
3. “Standard” model examples
   - Asymptotic safety
   - Higgs inflation
   - R^2 inflation
4. Summary

Standard Model – describes nearly everything



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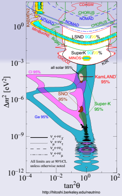
Einstein gravity

Describes

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

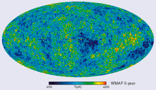
Experimental problems:

- Laboratory
  - ? Neutrino oscillations



- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter

  - ? Inflation

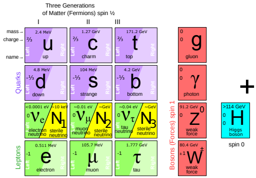


  - ? Dark Energy

Can we describe everything with as small extension as possible?

- Minimal number of new particles
- No new scales before inflation/gravity

νMSM+inflation – describes everything



+

Einstein gravity

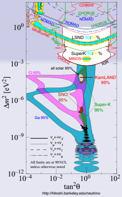
with νMSM

- Right handed neutrinos
  - generation of active neutrino masses
  - keV scale DM
  - Baryogenesys via very low scale leptogenesys

+ comological constant

Experimental problems:

- Laboratory
  - ✓ Neutrino oscillations



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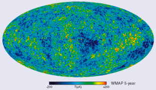


  - ✓ Dark Energy

SM everywhere?

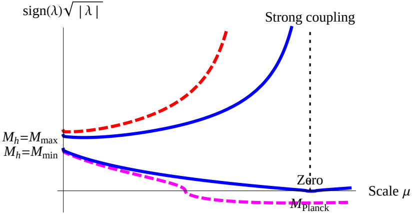
What happens if there is nothing else up to the Planck scales?
(or at least up to the scale of inflation)

Renormalization evolution of the Higgs self coupling λ

$$
\begin{aligned}
(4\pi)^2\beta_\lambda &= 24\lambda^2 - 6y_t^4 \\
&+ \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) \\
&+ (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda
\end{aligned}
$$

- High M_h – strong coupling
- Low M_h – our (EW) vacuum is metastable.
- Boundary situation – $M_h = M_{\text{min}}$

Coupling constant evolution:



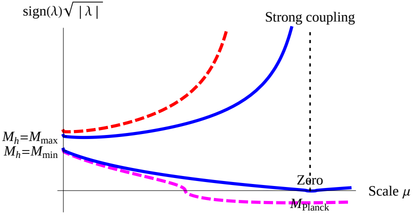
$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\mu_0) \equiv \mu\frac{d\lambda}{d\mu} = 0$$

Which case is realized?

Renormalization evolution of the Higgs self coupling λ

$$(4\pi)^2\beta_\lambda = 24\lambda^2 - 6y_t^4 + \frac{3}{8}(2g_2^4 + (g_2^2 + g_1^2)^2) + (-9g_2^2 - 3g_1^2 + 12y_t^2)\lambda$$

Coupling constant evolution:



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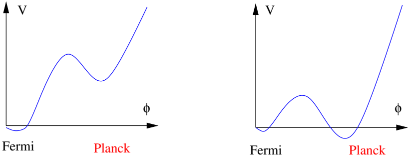
Higgs effective potential $V(\varphi) \simeq \lambda(\varphi)\frac{\varphi^4}{4}$



$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\mu_0) \equiv \mu\frac{d\lambda}{d\mu} = 0$$

Which case is realized?

The boundary case defines both M_h and $\mu_0 \sim M_P$

Let us fix all the SM constants, except for the Higgs mass:

$$\alpha, M_W, M_Z, \alpha_S, M_t$$

Then *two* requirements:

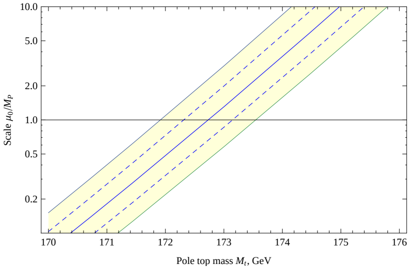
$$\lambda(\mu_0) = 0, \quad \beta_\lambda(\mu_0) \equiv \mu \frac{d\lambda}{d\mu} = 0$$

define *two* parameters:

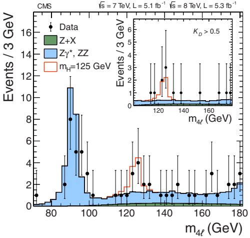
$$m_H, \quad \mu_0$$

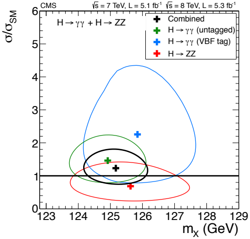
Planck scale!

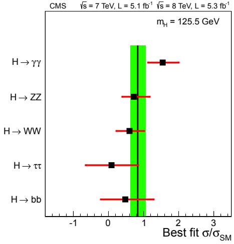
SM with $m_t \sim 173\,\text{GeV}$ leads to $\mu_0 \sim M_P$



CMS "new boson" results







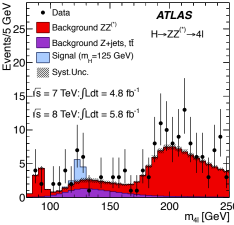
"New boson" mass

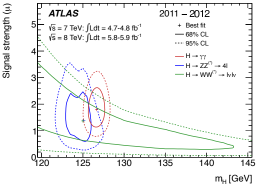
$$M_h = 125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV}$$

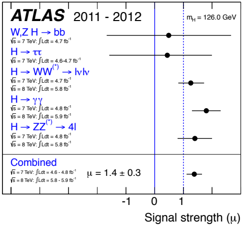
5.8σ for SM Higgs boson of this mass

[CMS'12]

ATLAS “new particle” results







“New particle” mass

$$M_h = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})\,\text{GeV}$$

5.9σ for SM Higgs boson of this mass

[ATLAS’12]

Calculation steps

Experiment

constants: α, $\sin\theta_W$, α_S

Pole masses: M_h, M_t

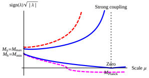
$\overline{\text{MS}}$ constants (at EW scale $\mu \sim M_t$):

$$y_t(\mu) = 2^{3/4}\sqrt{G_F}M_t \times \left[1 + \delta y_t(M_t, \alpha_S, \alpha, s_W^2, M_Z; \mu)\right]$$

$$\lambda(\mu) = \sqrt{2}G_F M_h^2 \times \left[1 + \delta\lambda(M_t, \alpha_S, \alpha, s_W^2, M_Z; \mu)\right]$$

RG running: $\frac{d\lambda}{d\ln\mu} = \beta_\lambda(\lambda, y_t, g_i), \ldots$

High scale behavior of constants:



Calculation steps: state of the art

- Convert to $\overline{\text{MS}}$ constants $\lambda(\mu)$, $y_t(\mu)$ at a scale μ between M_Z and M_t

  δy_t Up to $O(\alpha_s^2)$, $O(\alpha)$

  $O(\alpha_s^3)$ [Chetyrkin, Steinhauser'99, Melnikov,Ritbergen'00]

  $O(\alpha\alpha_s)$ [FB, Kalmykov, Kniehl, Shaposhnikov'12]

  $\delta\lambda$ Up to $O(\alpha)$

  $O(\alpha\alpha_s)$ [FB, Kalmykov, Kniehl, Shaposhnikov'12]

  $O(y_t^4)$ (Yukawa part of $O(\alpha^2)$)

  [Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia'12]

- Evolve with RG up to Planck scales

  β_{g_i} two loops

  three loops [Mihaila, Salomon, Steinhauser'12]

  β_{y_t}, β_λ two loops

  three loops (no EW gauge contributions)

  [Chetyrkin, Zoller'12]

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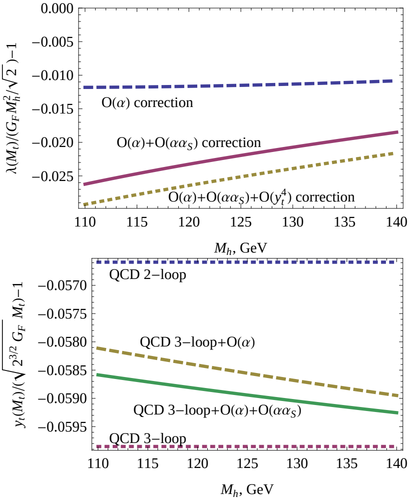
Size of contributions to $M_{\rm min}$

Contribution	$\Delta M_{\rm min}$, GeV
Three loop	
beta functions	-0.23
$\delta y_t \propto O(\alpha_s^3)$	-1.15
$\delta y_t \propto O(\alpha\alpha_s)$	-0.13
$\delta\lambda \propto O(\alpha\alpha_s)$	0.62
$\delta\lambda \propto O(y_t^4)$	0.2



Error budget

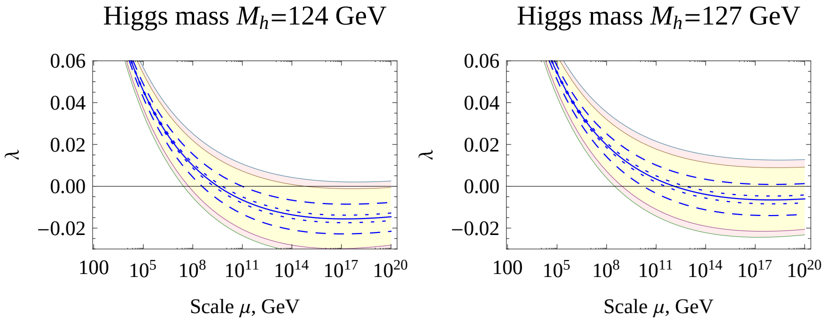
Theoretical

Source of uncertainty	Nature of estimate	$\Delta_{\text{theor}} M_{\text{min}}$, GeV
3-loop matching λ	Sensitivity to μ	1.0
3-loop matching y_t	Sensitivity to μ	0.2
4-loop α_s to y_t	educated guess	0.4
confinement, y_t	educated guess	0.5
4-loop RG $M_W \to M_P$	educated guess	< 0.2
total uncertainty	sum of squares	1.2
total uncertainty	linear sum	2.3

Experimental

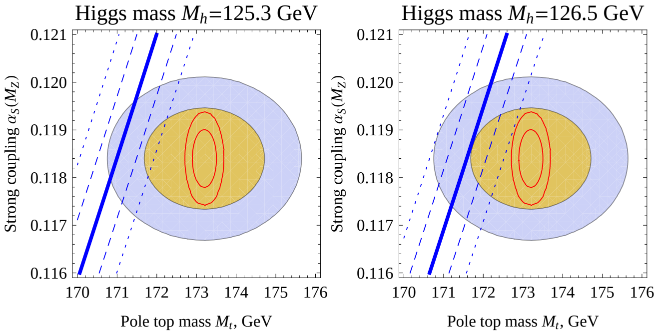
Source of uncertainty		$\Delta_{\text{exp}} M_{\text{min}}$, GeV
M_t		~ 2
α_s		~ 0.6
total uncertainty	sum of squares	2.1

Scale for λ turning negative is high



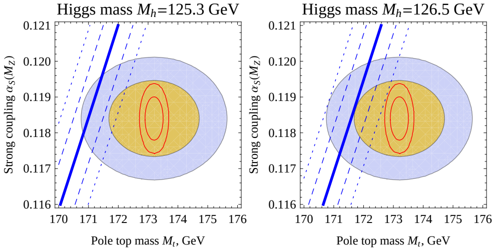
Critical Higgs mass is compatible with M_t and α_s

Tevatron value: $M_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})\,\text{GeV}$
$\alpha_s(M_Z) = 0.1184 \pm 0.0007$



$$M_{\text{min}} = \left[129.5 + \frac{M_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right]\text{GeV}$$

Is this coincidence really there?



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We do not really know now! Yet to be done:

- Build a lepton collider at $\gtrsim$ 350 GeV! (Higgs *and* top masses)
- Calculate higher order relations between $\overline{\rm MS}$ parameters and masses

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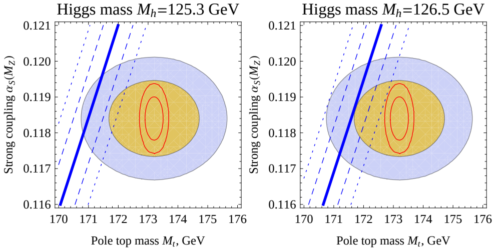

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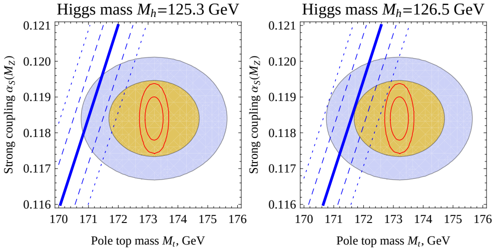

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Outline

Asymptotic safe model predicts M_h

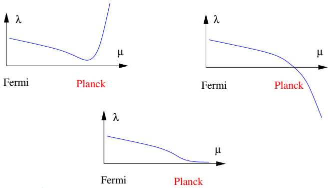
Above Planck scale beta functions for coupling constant $h \in \{g_1, g_2, g_3, \lambda, y_t\}$ get additional terms

$$\beta_h^{\text{grav}} = \frac{a_h}{8\pi} \frac{\mu^2}{M_P^2 + 2\xi 0 \mu^2} h$$

leading to a *fixed point* at high energies

$a_\lambda > 0$ leads to the prediction $M_h = M_{\text{min}}$

(up to a difference of 0.1–0.2 GeV)



[Shaposhnikov, Wetterich'09]

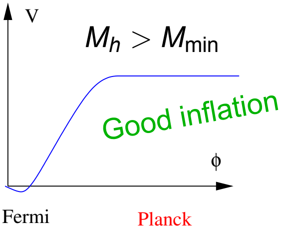
For other M_h no finite fixed point for λ

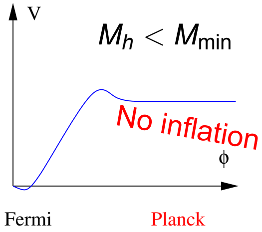
There are other models predicting the same Higgs mass

- Forggart, Nielsen’96 – Multiple point principle.
  All the vacua should be degenerate – thus, the same prediction $M_h = M_{\text{min}}$
- Masina, Notari’11 – inflation from the decay of the metastable Planck scale vacuum – $M_h \simeq M_{\text{min}}$
- …

Higgs inflation works only for $M_h > M_{min}$

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R - \xi\frac{h^2}{2}R + g_{\mu\nu}\frac{\partial^\mu h\partial^\nu h}{2} - \frac{\lambda}{4}(h^2-v^2)^2\right\}$$





Bound on the Higgs mass

$$M_h > M_{\rm min}$$

Up to a difference of 0.1–0.2 GeV

[FB, Shaposhnikov’09]

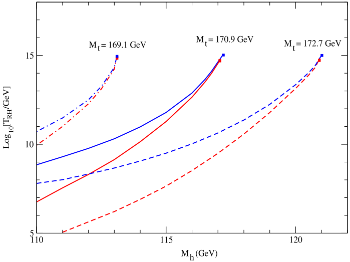
Modifying the gravity action gives inflation for any M_h

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R + \frac{\zeta^2}{4}R^2\right\} + S_{SM}$$

[Starobinsky'80]

The electroweak vacuum may decay at high temperature. But reheating is due to M_P suppressed operators $\Rightarrow$ temperature is low

$T_r \sim 10^7 - 10^9$ GeV



[Espinosa, Giudice, Riotto'07]

Higgs mass bounds in R^2 is weak

$$m_H > 116\,\text{GeV}$$

Summary

Coincidence in Standard Model

- $\lambda(M_P) = \left.\frac{d\lambda}{d\mu}\right|_{\mu=M_P} = 0$
  Higgs self couling is vanishing with its derivative at Planck scale
- for $M_h = M_{\rm min} =$
  $$M_{\rm min} = \left[129.5 + \frac{M_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right] \text{GeV}$$

- We may be learning about Planck scale physics!

To disprove/confirm this the following is needed

- e^+e^- collider up to $\gtrsim 350\,\text{GeV}$
  - Higgs factory — M_H
  - top factory — M_t

- FB, M. Kalmykov, B. Kniehl, M. Shaposhnikov, arXiv:1205.2893 [hep-ph]
- G. Degrassi, S. Di Vita, J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori, A. Strumia arXiv:1205.6497 [hep-ph]
- A.Starobinsky, Phys.Lett. B91 (1980) 99
- J. R. Espinosa, G. F. Giudice and A. Riotto, JCAP **0805** (2008) 002
- K. G. Chetyrkin and M. Steinhauser, *Phys. Rev. Lett.* **83** (1999) 4001
- K. Melnikov and T. v. Ritbergen, *Phys. Lett.* **B482** (2000) 99
- L. N. Mihaila, J. Salomon, and M. Steinhauser, *Phys. Rev. Lett.* **108** (2012) 151602
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- FB, M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)
- FB, M. Shaposhnikov, JHEP **0907** (2009) 089
- M. Shaposhnikov and C. Wetterich, Phys. Lett. B **683** (2010) 196

- CMS Collaboration, [arXiv:1207.7235 [hep-ex]]
- ATLAS Collaboration, [arXiv:1207.7214 [hep-ex]]

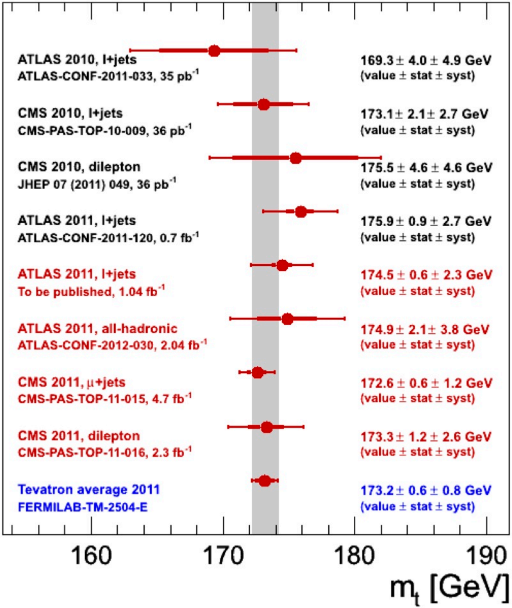
Exact effective potetnial definition

$$V(\varphi) = \lambda(\mu)\varphi^4 \left[1 + \sum \left(\frac{M_i^4(\varphi)}{64\pi} \log(M_i^2/\mu^2) \right)\right],$$

choosing μ to minimize logarithms

$$V(\varphi) \propto \lambda(\varphi)\varphi^4 \left[1 + O\left(\frac{\alpha}{4\pi} \log(M_i/\varphi)\right)\right],$$

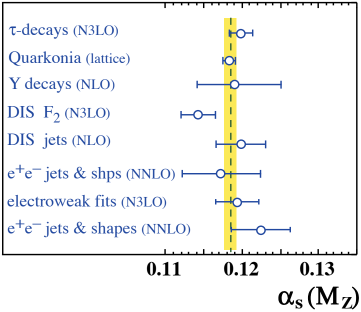
Top mass determination

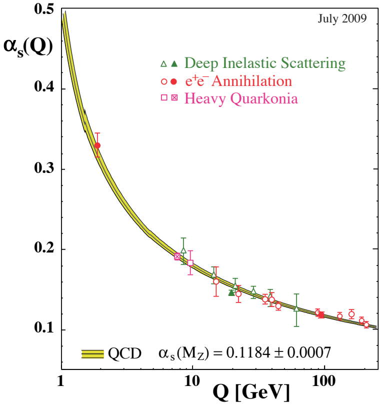


In addition:

- Problems with relation of M_{Pythia} and M_{pole} – up to $\sim$ 1 GeV

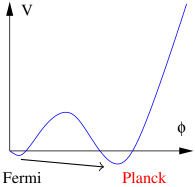
α_s determination

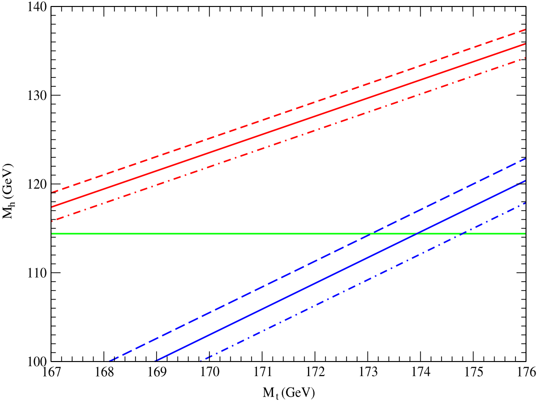




Even metastable EW vacuum overlives the Universe

Will the vacuum decay?





[Espinosa, Giudice, Riotto'07]

EW vacuum lifetime $> \tau_{\text{Universe}}$

$M_h > 111\,\text{GeV}$

RG scale dependence