ÉCOLE POLYTECHNIQUE
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Higgs boson mass and the scale of new physics

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KMI/GCOE Workshop SCGT 12

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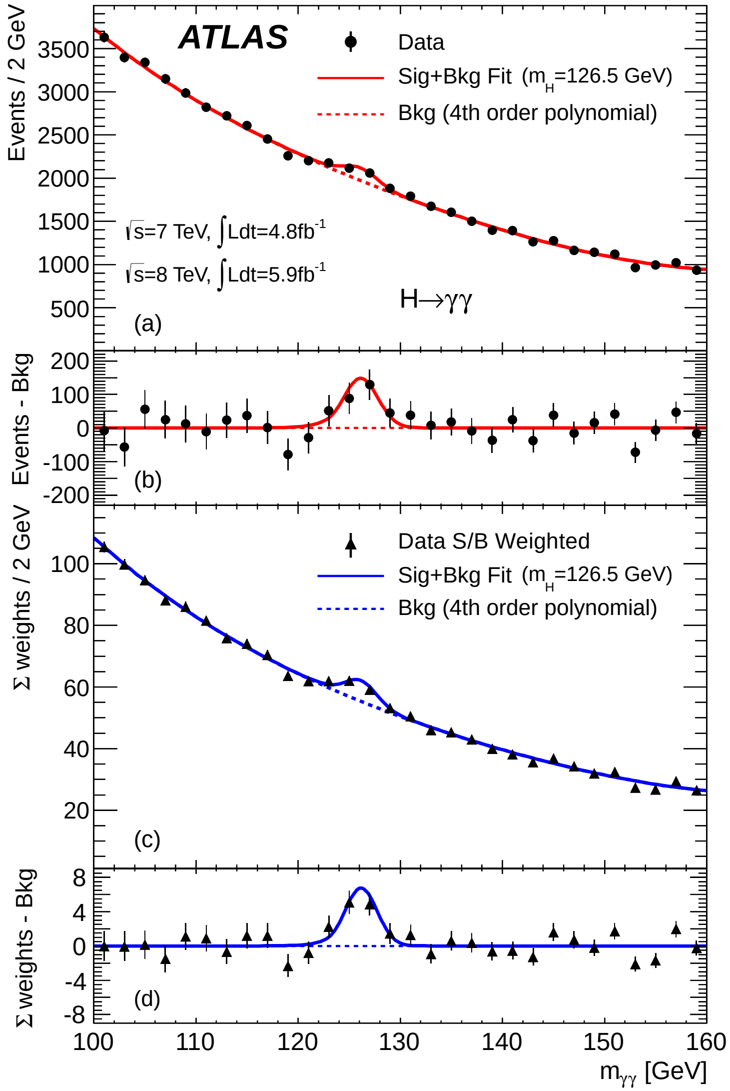
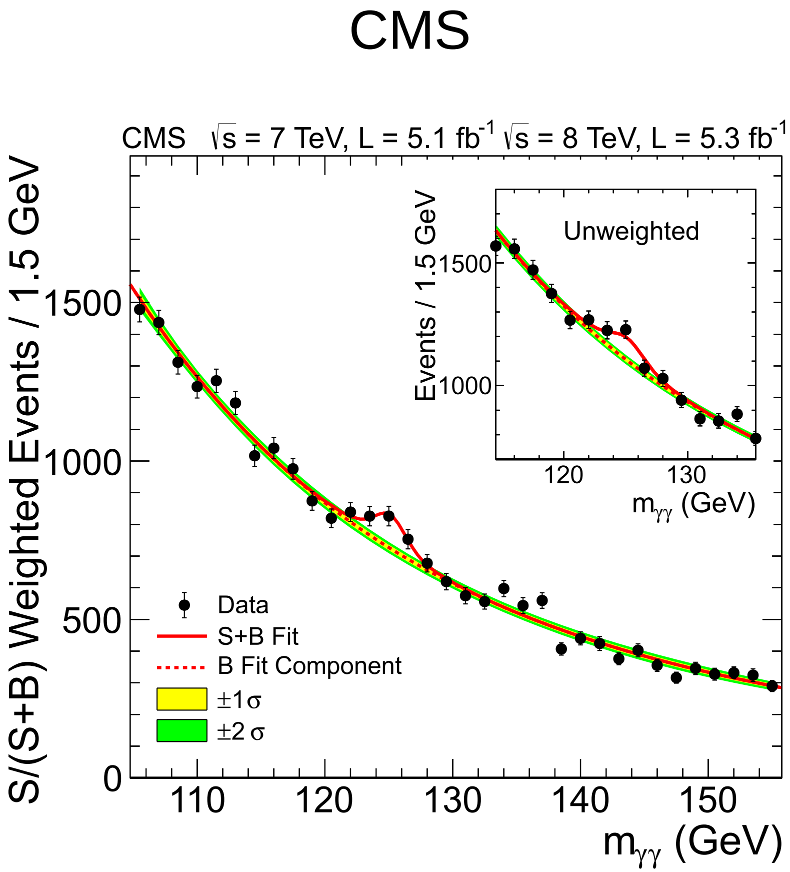
Origin of Particles and the Universe

July 4, 2012, Higgs at ATLAS and CMS





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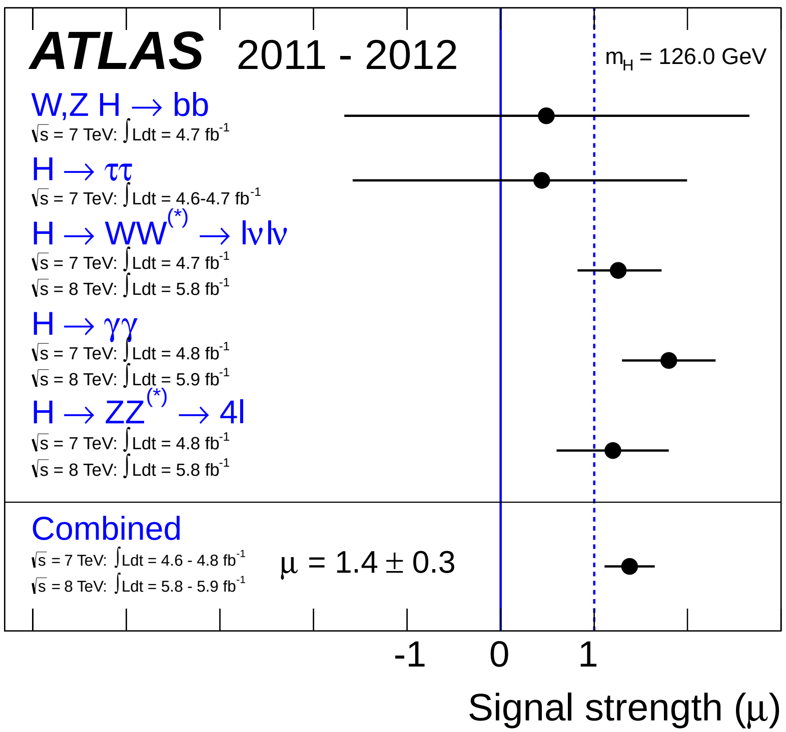

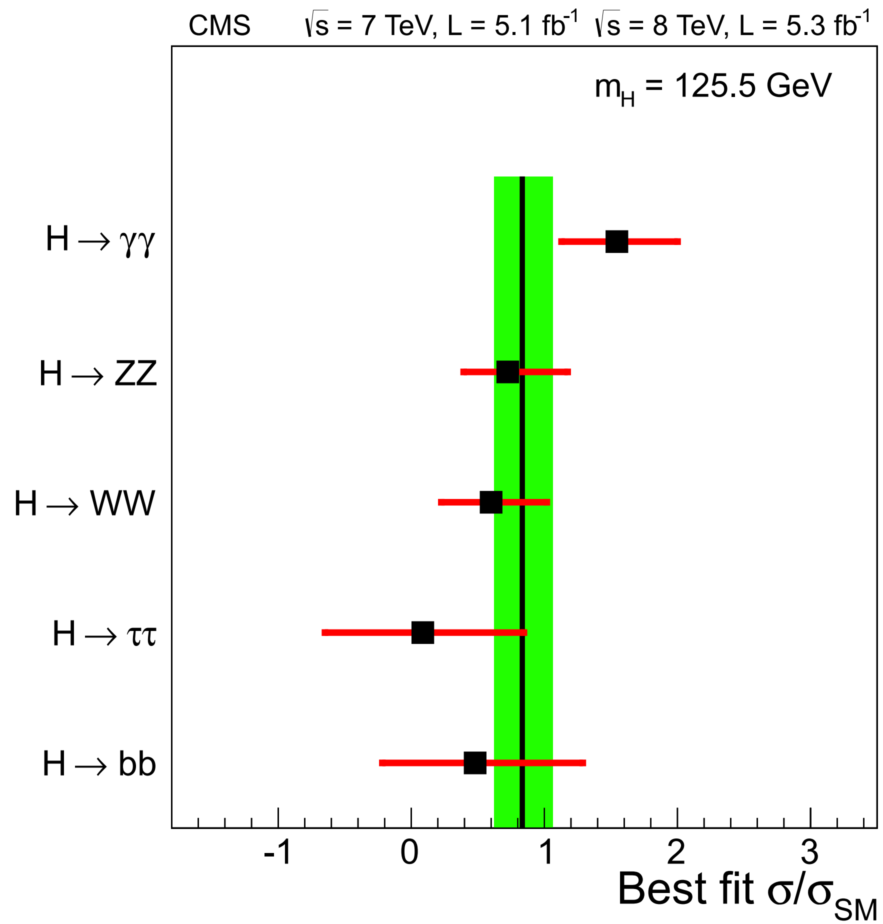

Kyoto, November 2012

According to CMS,

$$M_H = 125.8 \pm 0.4(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV},$$

According to ATLAS,

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

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What does it mean for high energy physics?

Possible answer

- Electroweak scale is determined by Planck physics
- There is no new energy scale between the Fermi and Planck scales
- New BSM physics responsible for dark matter, baryon asymmetry of the universe and neutrino masses is hidden below the Fermi scale

Outline

- What did we know about the Higgs boson mass before its discovery?
- Vacuum stability bounds updated
- Higgs mass from asymptotically safe SM+gravity
- Higgs mass from inflation
- New physics between the Fermi and Planck scales?
- Conclusions

Higgs boson mass before LHC

Compilation of 81 predictions, Thomas Schücker (as of November 2, 2010)

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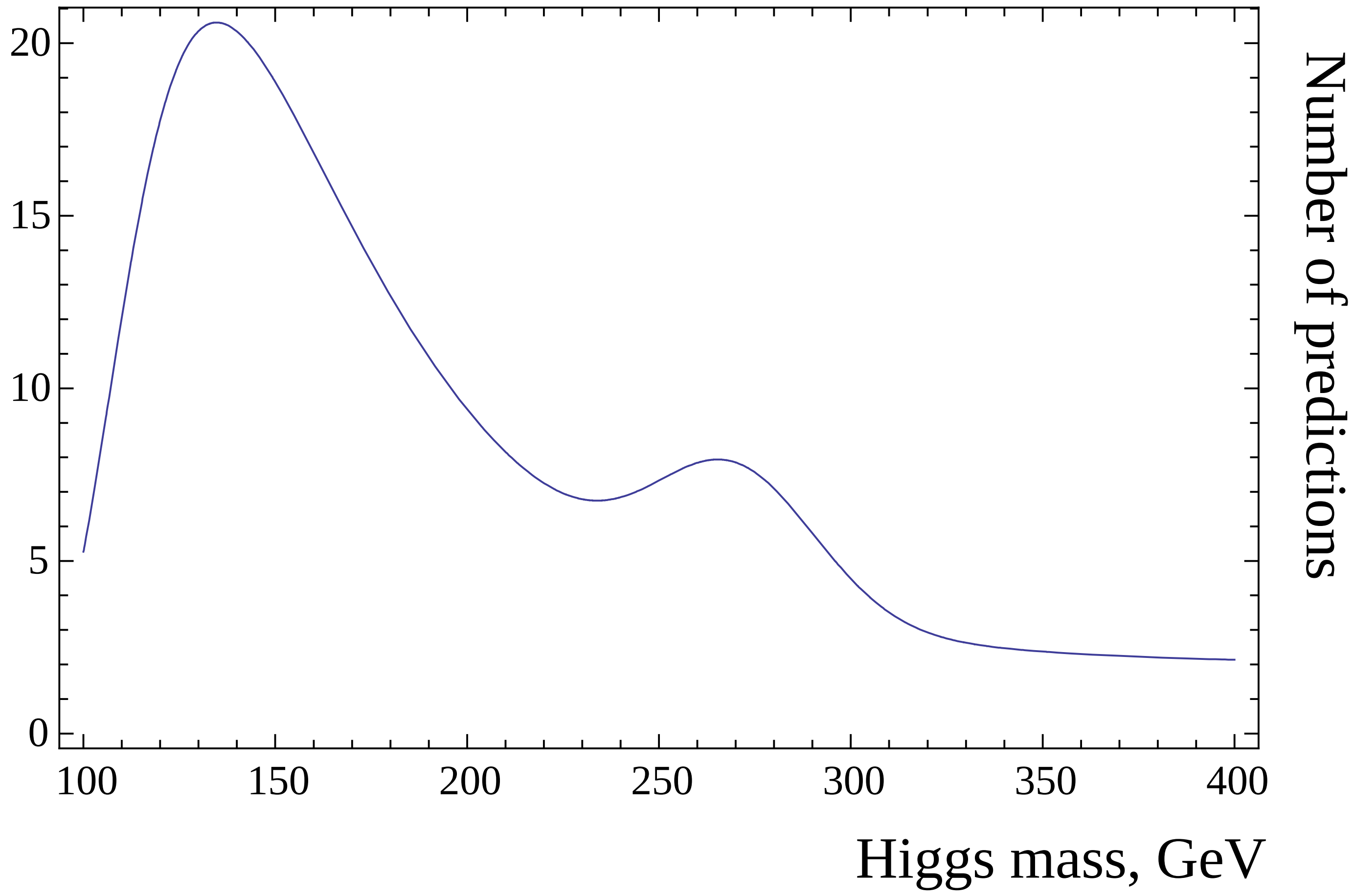
- The most precise prediction: $m_H = 161.8033989$ by El Naschie
- The highest number of predictions by one person (Gogoladze): 12
- No predictions in intervals:

  $600 - 739,\ 781 - 1800,\ 2000 - 10^{18}$ GeV

Bayesian approach

(as of November 2, 2010)



Bayesian “prediction” : $m_H \simeq 140$ GeV

Self-consistency of the SM

Within the SM the mass of the Higgs boson is an arbitrary parameter which can have any value (if all other parameters are fixed) from

$$m_{\rm meta} \simeq 111 \text{ GeV (metastability bound)}$$

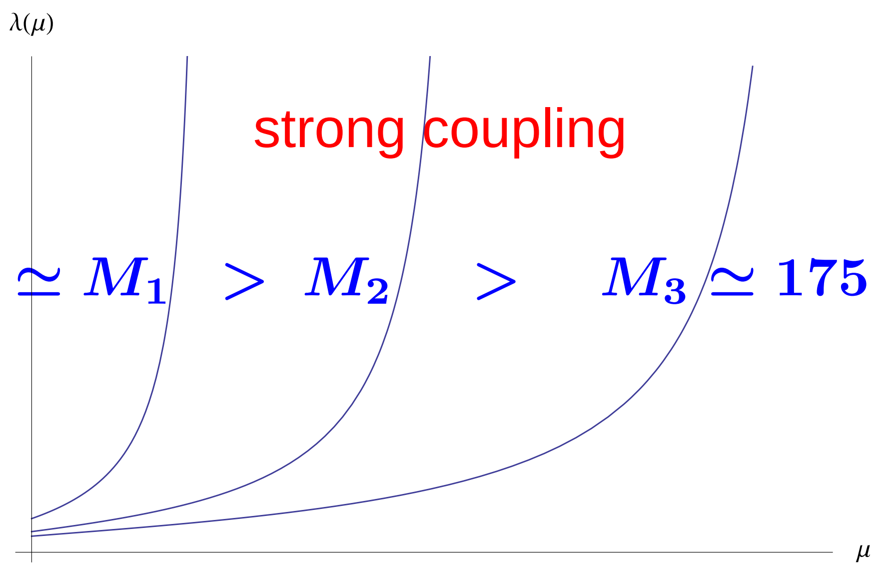
to

$$m_{\rm Landau} \simeq 1 \text{ TeV (triviality bound)}$$

Triviality bound

L. Maiani, G. Parisi and R. Petronzio '77; Lindner '85; T. Hambye and K. Riesselmann '96;...

The Higgs boson self-coupling has a Landau pole at some energy determined by the Higgs mass. For $M_H \simeq m_{\mathbf{Landau}} \simeq 1$ TeV the position of this pole is close to the electroweak scale.



strong coupling

Higgs mass 1 TeV $\simeq M_1 > M_2 > M_3 \simeq 175$ GeV

Fermi Planck

Triviality bound

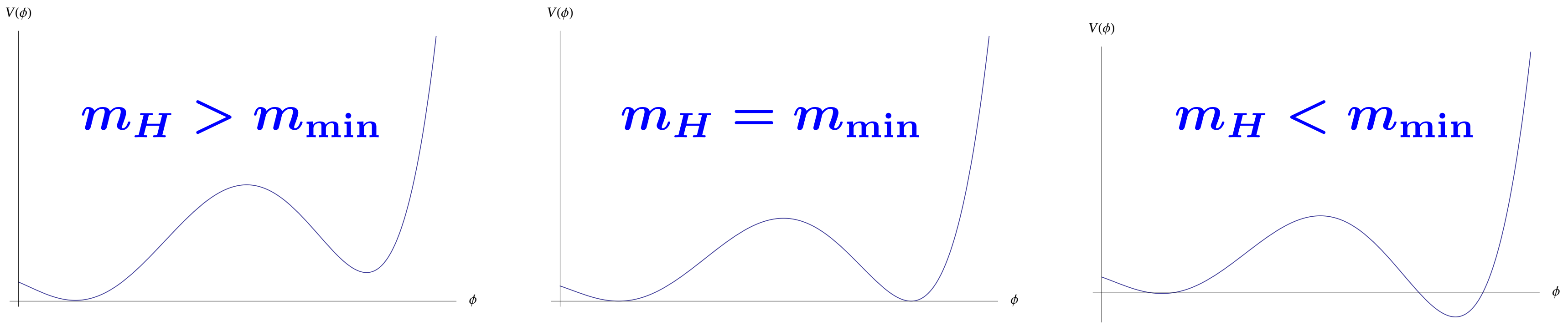
If $m_H < m_{\mathbf{max}} \simeq \mathbf{175}$ GeV the Landau pole appears at energies higher than the Planck scale $E > M_P$.

LHC: The Standard Model is weakly coupled all the way up to the Planck scale

Metastability bound

Krasnikov '78, Hung '79; Politzer and Wolfram '79; Altarelli and Isidori '94; Casas, Espinosa and Quiros '94,'96;...

If $m_H < m_{\rm min}$, there is a deeper vacuum with the Higgs vacuum expectation value larger than the EW vev.



The life-time of our vacuum is smaller than the age of the Universe if $m_H < m_{\rm meta}$, with $m_{\rm meta} \simeq 111$ GeV Espinosa, Giudice, Riotto '07

Metastability bound

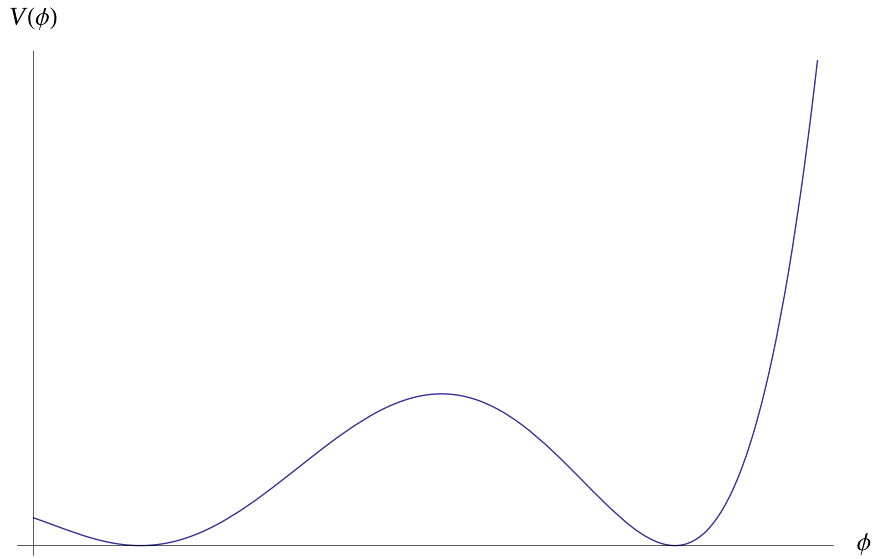
If the Higgs mass happened to be smaller than $m_{\mathrm{meta}} \simeq 111$ GeV, we would be forced to conclude that there must be some new physics beyond the SM, which stabilizes the SM vacuum.

However, already since LEP we know that $m_H > m_{\mathrm{meta}}$ so that new physics is not needed from this point of view.

LHC: SM is a consistent effective theory all the way up to the Planck scale!

Stability bound updated

The value of $m_{\min}$ does not represent any “singular" point in the parameter space of the pure SM, if time scales smaller than the age of the universe are considered . If $M_H = m_{\min}$, effective potential for the Higgs field has two degenerate minima, one corresponding to the EW vev and another one much larger



Still, let us discuss the value of $m_{\min}$.

Most recent computation of M_H (Bezrukov, Kalmykov, Kniel, M.S., May 13, 2012), incorporating $\mathcal{O}(\alpha\alpha_s)$ two-loop matching and 3-loop running of coupling constants (Chetyrkin, Zoller, May 13, 2012)

$$m_{crit} = \left[129.0 + \frac{m_t - 172.9}{1.1} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56\right] \text{GeV} \; ,$$

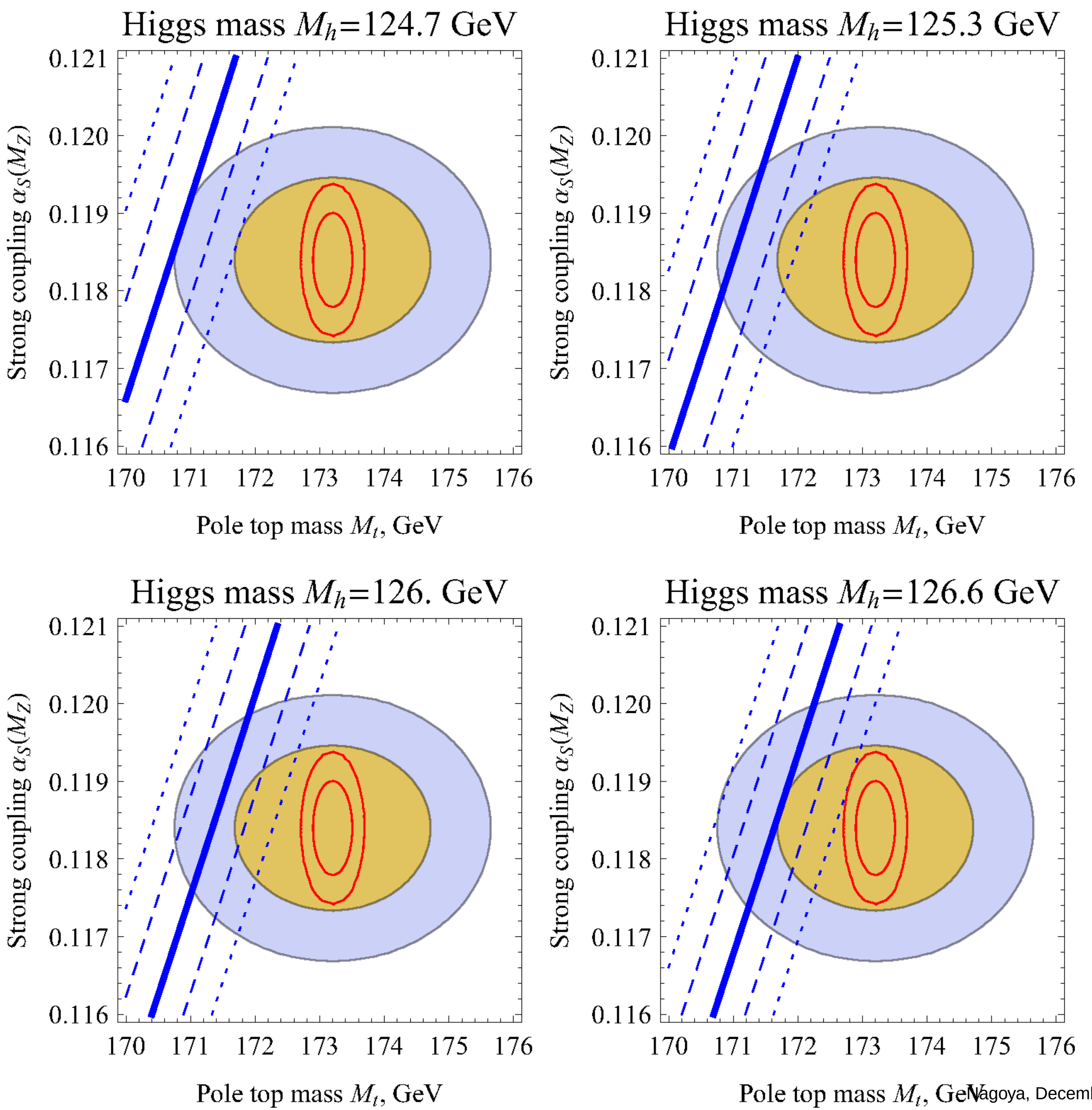
Theoretical uncertainties: ± 1.2 GeV (different sources are summed quadratically) or ± 2.3 GeV (different sources are summed linearly).

Effect of contributions $\propto y_t^4, y_t^2\lambda^2, \lambda^4$ (Degrassi et al., May 29, 2012): shift of the Higgs mass by $100 - 200$ MeV. Quadratic theoretical uncertainty is reduced to ~ 0.8 GeV.

Procedure

1. Matching of physical parameters (such as W, H, t and Z masses, fine structure constant, etc) to $\overline{MS}$ values of g_1, g_2, g_3, λ and y_t at EW scale (usually m_t). Currently done at 2-loop level (Bezrukov et al, Degrassi et al, ’12), but corrections of the order α_W^2 are not known.
2. Determination of the values of g_1, g_2, g_3, λ and y_t at any scale with the use of RG equations. Currently done at 3-loop level, thanks to (Chetyrkin, Zoller, ’12)
3. Computation of RG improved effective potential for the Higgs field and solution of $V_{eff}(\phi_1) = V_{eff}(\phi_2)$. Effective potential is known at 2-loop order (Ford, Jack, Jones ’92)

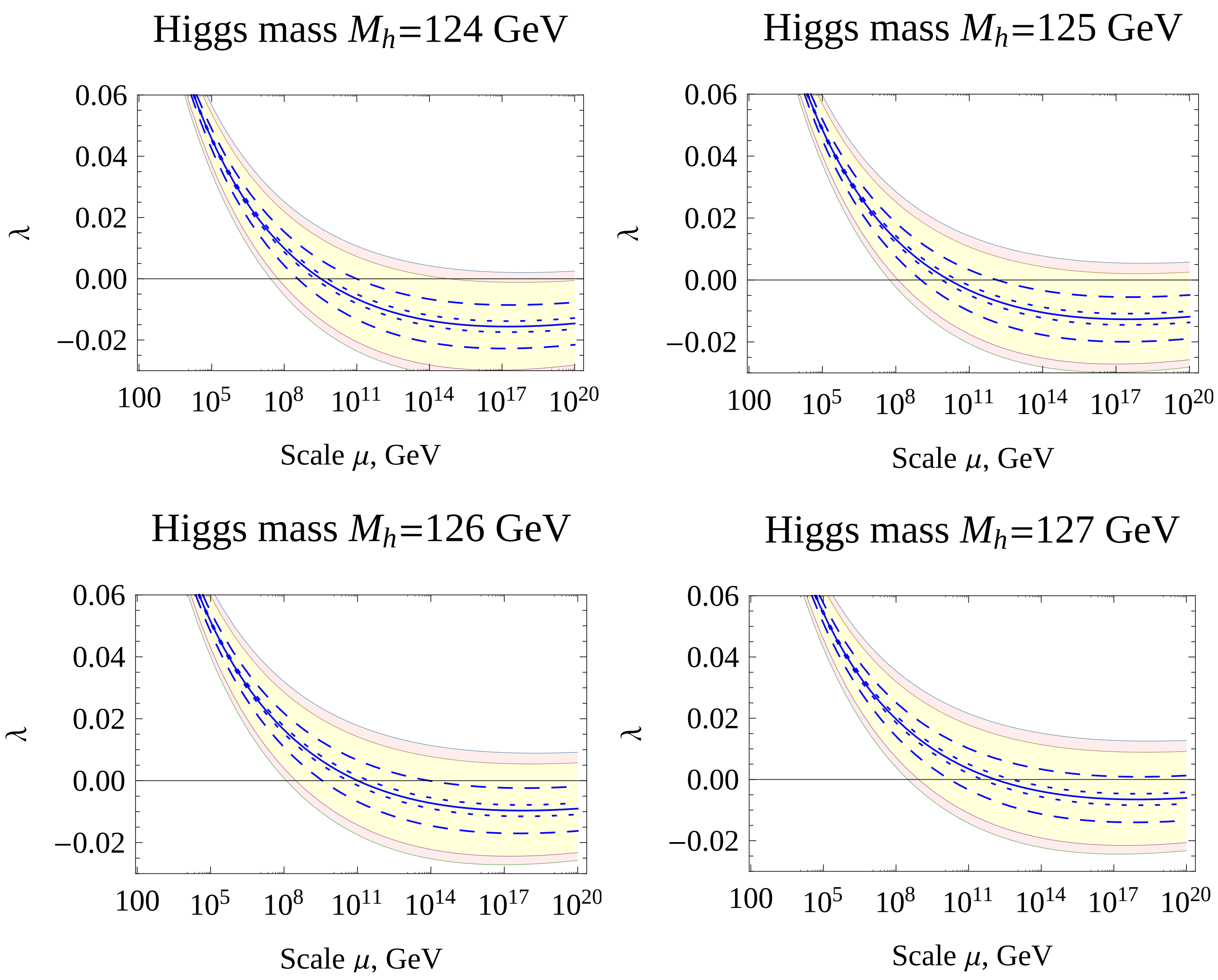
2 and 3 have reached the ultimate necessary presision (change in the Higgs mass on the level of MeV)


Higgs mass M_h=124.7 GeV
Higgs mass M_h=125.3 GeV
Higgs mass M_h=126. GeV
Higgs mass M_h=126.6 GeV
Strong coupling $\alpha_S(M_Z)$
Pole top mass M_t, GeV
0.116
0.117
0.118
0.119
0.120
0.121
170
171
172
173
174
175
176

To decrease uncertainty: (the LHC accuracy can be as small as $\mathbf{200}$ MeV!)

- Compute remaining two-loop $\mathcal{O}(\alpha^2)$ corrections to pole - $\overline{\mathrm{M}S}$ matching for the Higgs mass and top masses. Theoretical uncertainty can reduced to $\sim \mathbf{0.5}$ GeV, due to irremovable non-perturbative contribution $\sim \Lambda_{QCD}$ to top quark mass.
- Measure better t-quark mass (present error in m_H due to this uncertainty is $\simeq 4$ GeV at 2σ level): construct t-quark factory – e^+e^- or $\mu^+\mu^-$ linear collider with energy $\simeq \mathbf{200} \times \mathbf{200}$ GeV. The same conclusion - Alekhin et al, '12
- Measure better α_s (present error in m_H due to this uncertainty is $\simeq 1$ GeV at 2σ level)

Behaviour of the Higgs self-coupling



Prediction $M_H = m_{\min}$ has been made a number of years before the Higgs boson was discovered:

Froggatt, Nielsen ’95:

“...Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima (vacua), one of which should be - order of magnitudewise - at the Planck scale, leads to the top mass being 173 $\pm$ 5 GeV and the Higgs mass 135 $\pm$ 9 GeV...”

M.S., Wetterich ’09:

Asymptotic safety of gravity and the Higgs boson mass

“... This results in $M_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty...”

Also, $M_H = m_{\min}$ is a critical point for Higgs inflation

Bezrukov, M.S., ’09

Higgs mass from asymptotically safe gravity

MS, Wetterich

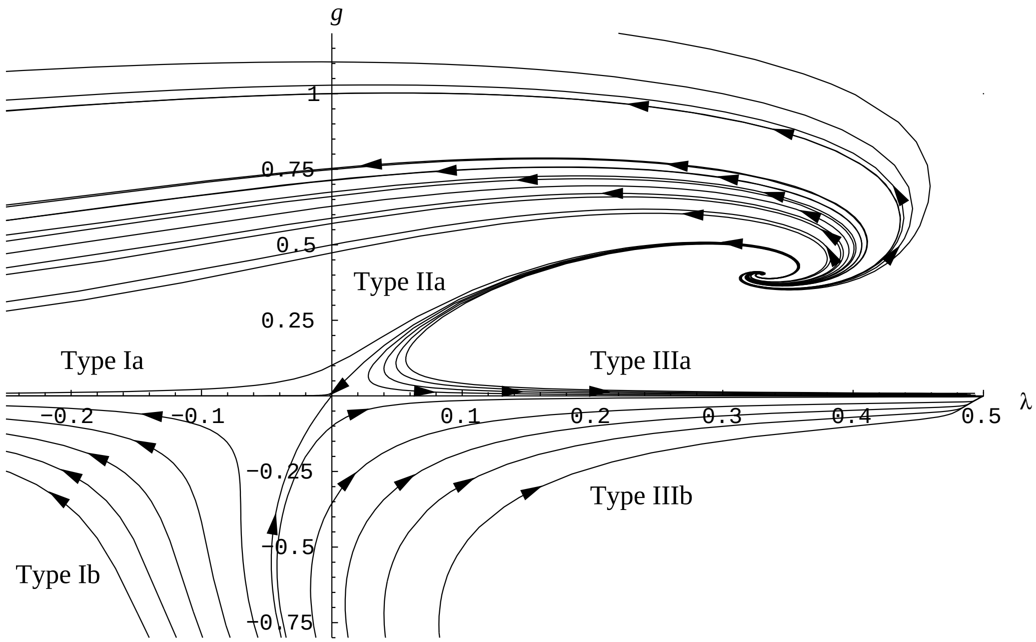
What if gravity is asymptotically safe?

Asymptotic safety = existence of non-Gaussian UV fixed point for gravity Weinberg ’79. Though the theory is non-renormalizable, it is predictive and self-consistent.

Functional RG analysis - Reuter '96, Percacci et al, Niedermaier '09, ...

$$S_{\mathrm{EH}} = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\, \{-R + 2\Lambda\} \ ,$$

$$k\, \partial_k \Gamma_k = \frac{1}{2}\, \mathrm{STr} \left[\left(\Gamma_k^{(2)} + \mathcal{R}_k \right)^{-1} k\, \partial_k \mathcal{R}_k \right] \ .$$



Reuter and Saueressig '02

Possible consequence: SM + Gravity is a final theory

To be true: all the couplings of the SM must be asymptotically safe or asymptotically free

Problem for:

- U(1) gauge coupling g_1, $\mu \frac{dg_1}{d\mu} = \beta_1^{\mathrm{SM}} = \frac{41}{96\pi^2} g_1^3$
- Scalar self-coupling λ, $\mu \frac{d\lambda}{d\mu} = \beta_\lambda^{\mathrm{SM}} =$

$$= \frac{1}{16\pi^2}\left[(24\lambda + 12h^2 - 9(g_2^2 + \frac{1}{3}g_1^2))\lambda - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\right]$$

- Fermion Yukawa couplings, t-quark in particular h, $\mu \frac{dh}{d\mu} = \beta_h^{\mathrm{SM}} =$

$$= \frac{h}{16\pi^2}\left[\frac{9}{2}h^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2\right]$$

Landau pole behaviour

Gravity contribution to RG running

Let x_j is a SM coupling. Gravity contribution to RG:

$$\mu \frac{dx_j}{d\mu} = \beta_j^{\rm SM} + \beta_j^{grav} \; .$$

On dimensional grounds

$$\beta_j^{grav} = \frac{a_j}{8\pi} \frac{\mu^2}{M_P^2(\mu)} x_j \; .$$

where

$$M_P^2(\mu) = M_P^2 + 2\xi_0 \mu^2 \; ,$$

with $M_P = (8\pi G_N)^{-1/2} = 2.4 \times 10^{18}$ GeV, $\xi_0 \approx 0.024$
from a numerical solution of FRGE

Computations of a_j are ambiguous and controversial

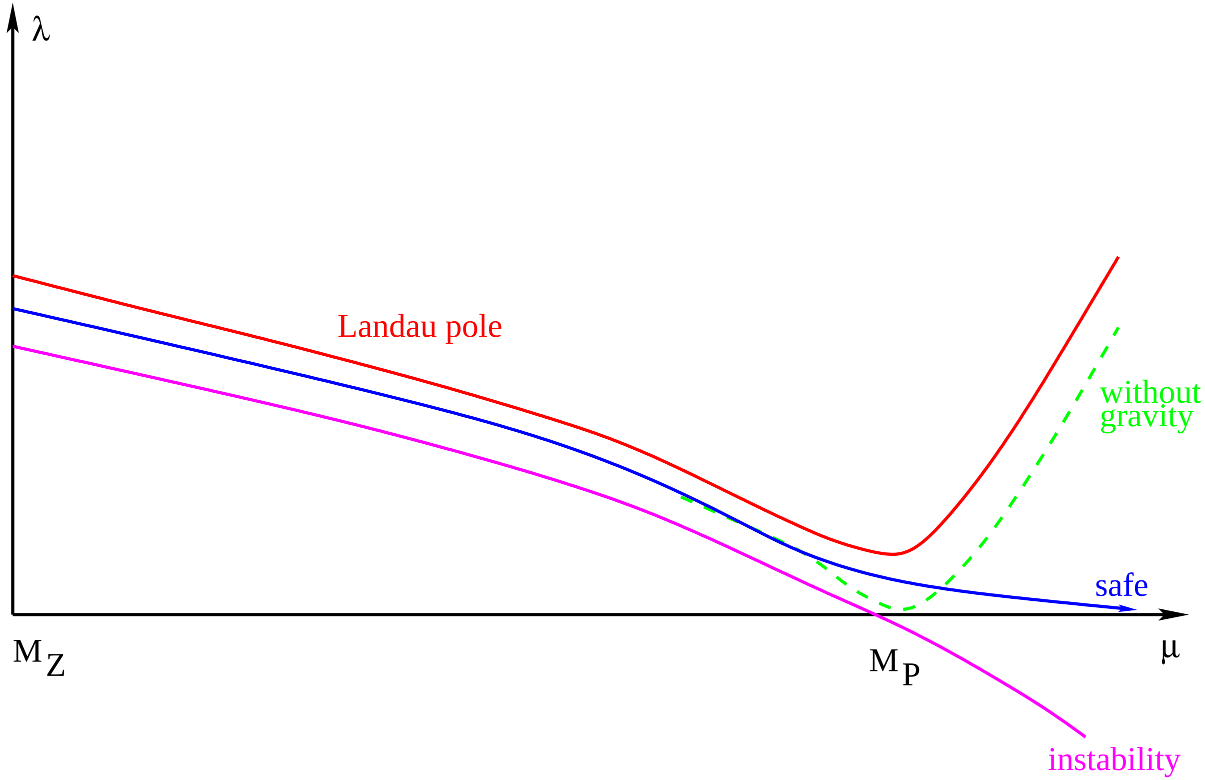
Robinson and Wilczek '05, Pietrykowski '06, Toms '07&'08, Ebert, Plefka and Rodigast '07, Narain and Percacci '09, Daum, Harst and Reuter '09, Zanusso et al '09, ...

- Most works get for gauge couplings a universal value $a_1 = a_2 = a_3 < 0$: U(1) gauge coupling get asymptotically free in asymptotically safe gravity
- $a_\lambda \simeq 2.6 > 0$ according to Percacci and Narain '03 for scalar theory coupled to gravity
- $a_h >< 0$?? The case $a_h > 0$ is not phenomenologically acceptable - only massless fermions are admitted

Suppose that indeed $a_1 < 0,\ a_h < 0,\ a_\lambda > 0$, what is found in a number of computations. Then the Higgs mass is predicted

$$M_H = m_{\min}$$

with uncertainty of few hundreds of MeV



Higgs mass and inflation

non-minimal coupling of Higgs field to gravity

$$\Delta S = \int d^4x\sqrt{-g}\Big\{-\frac{\xi h^2}{2}R\Big\}$$

Feynman, Brans, Dicke,...

Consider large Higgs fields h.

- Gravity strength: $M_P^{\text{eff}} = \sqrt{M_P^2 + \xi h^2} \propto h$
- All particle masses are $\propto h$

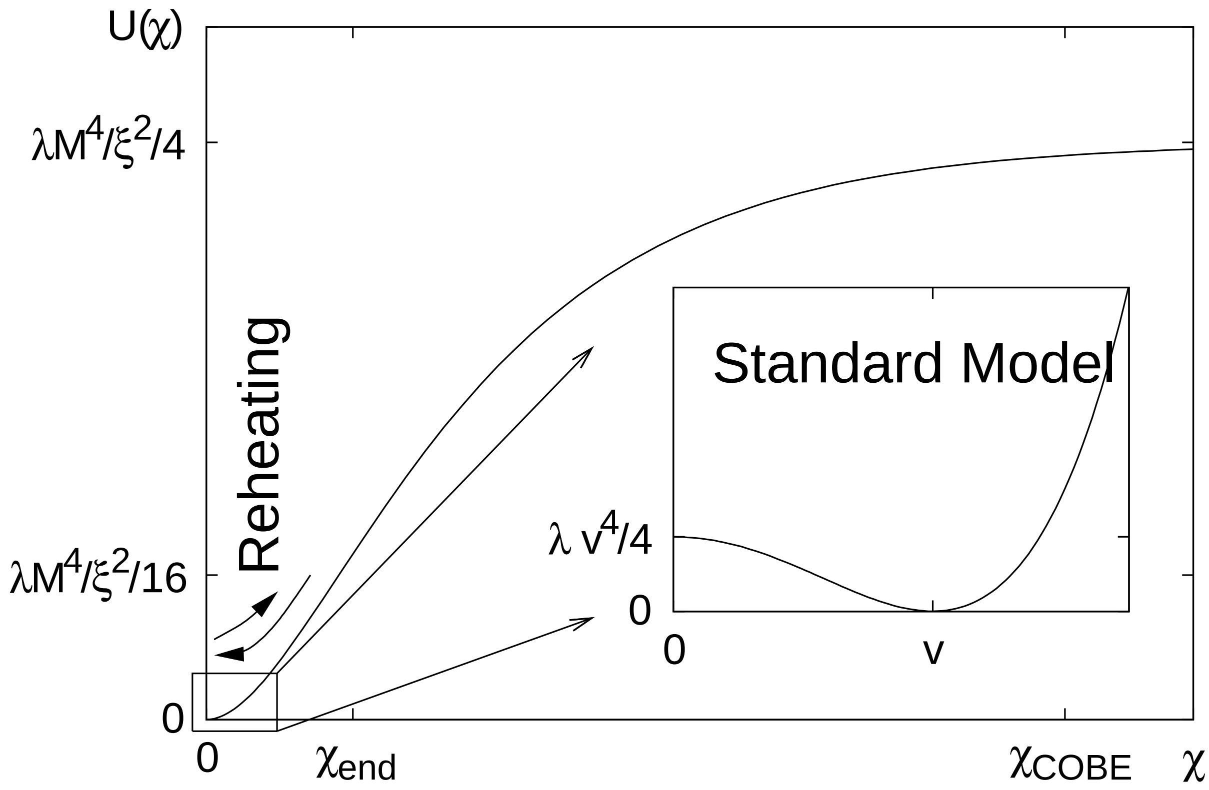
For $h > \frac{M_P}{\xi}$ (classical) physics is the same (M_W/M_P^{eff} does not depend on h)!

Existence of effective flat direction, necessary for successful inflation.

Formalism: go from Jordan frame to Einstein frame with the use of conformal transformation:

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

Potential in Einstein frame



Inflaton potential and observations

If inflaton potential is known one can make predictions and compare them with observations.

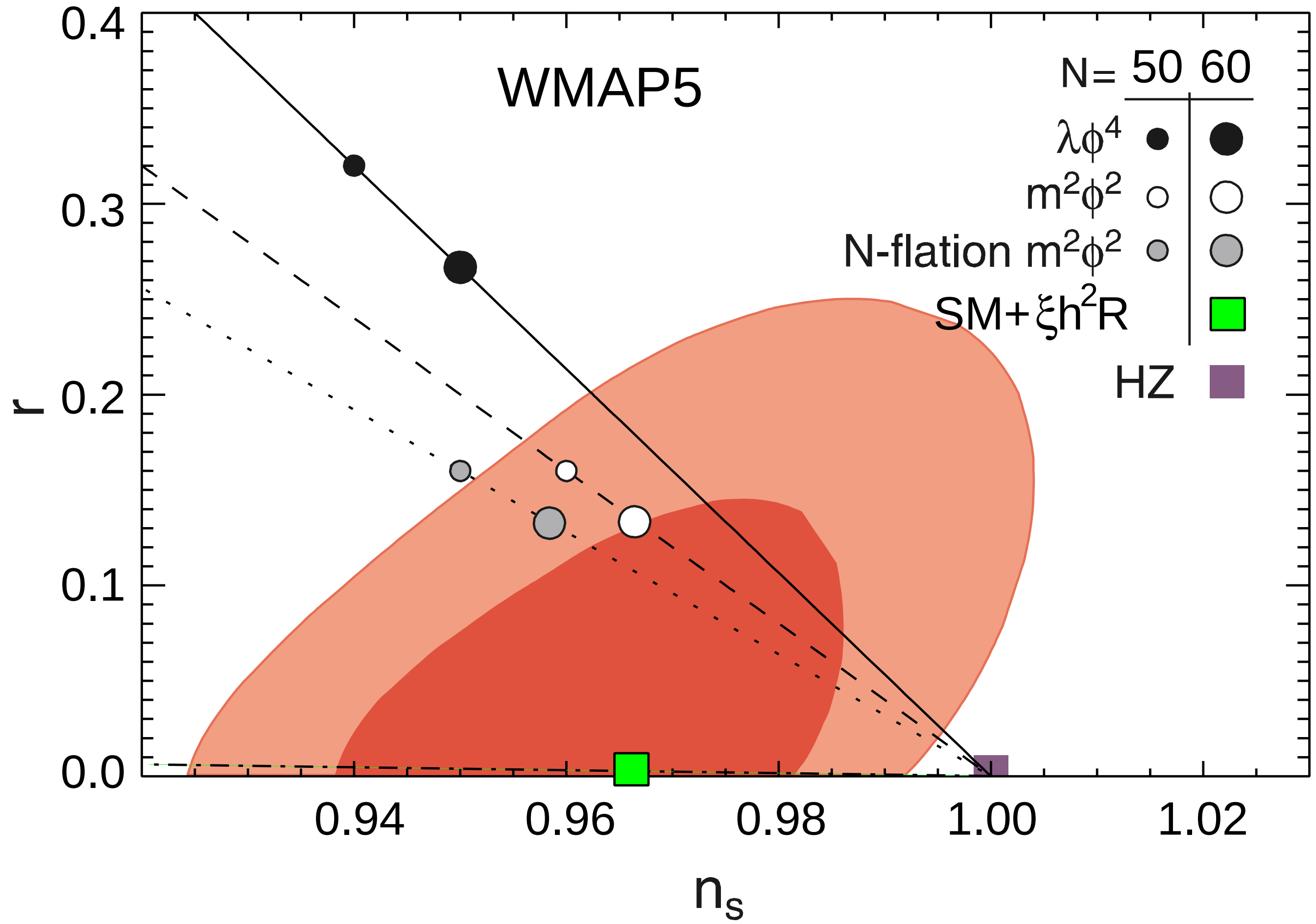
- $\delta T/T$ at the WMAP normalization scale ~ 500 Mpc
- The value of spectral index n_s of scalar density perturbations

$$\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle \propto \int \frac{d^3k}{k^3} e^{ik(x-y)} k^{n_s - 1}$$

- The amplitude of tensor perturbations $r = \frac{\delta \rho_s}{\delta \rho_t}$

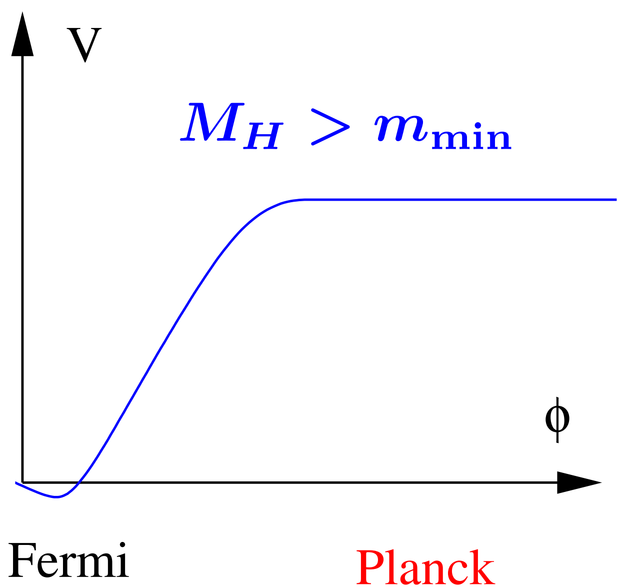
These numbers can be extracted from WMAP observations of cosmic microwave background. Higgs inflation: one new parameter, $\xi \Longrightarrow$ two predictions.

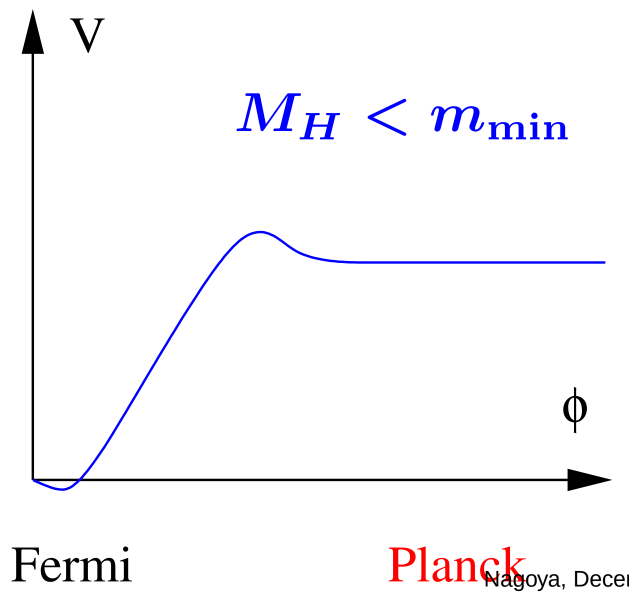
CMB parameters—spectrum and tensor modes



Inflation and the Higgs mass

Radiative corrections to inflationary potential: Higgs inflation works only for $\lambda(M_P/\sqrt{(\xi)}) > 0$ (Bezrukov, MS). Numerically, $M_H > m_{\rm min} - 200$ MeV. The equality leads to the minimal value of non-minimal coupling, $\xi \simeq 700$, what extends the region of weak coupling of the theory.





New Physics between the Fermi and Planck scales?

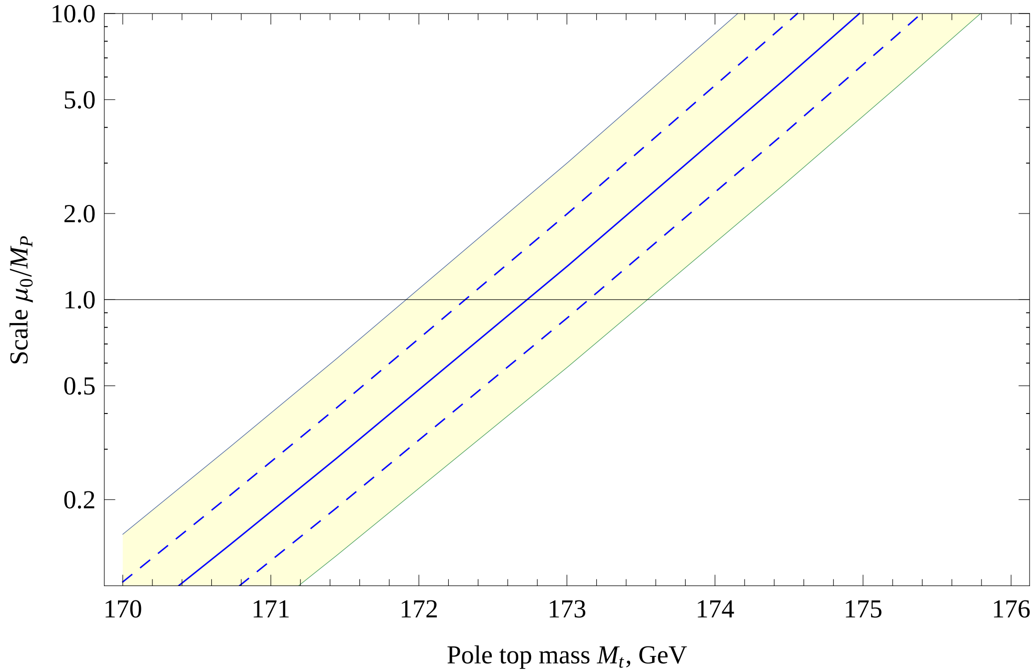
Why the values of the Higgs mass associated with the stability of the SM vacuum, with asymptotic safety of the SM and Higgs inflation are so close to each other?

Definition: "$\overline{MS}$ benchmark Higgs mass M_{crit}" is defined from equations

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{\rm SM}(\mu_0) = 0$$

together with parameter μ_0, assuming that all parameters of the SM, except the Higgs mass, are fixed.

Two equations $\Longrightarrow$ two parameters can be determined. Choose the Higgs mass and μ_0. Then this Higgs mass is about 200 MeV away from $m_{\min}$, since $V(\phi) \approx \lambda(\phi)\phi^4$.



μ_0 determined by the EW physics gives the Planck scale, $\mu_0 \simeq M_P$!

Explains why all three numbers for the Higgs mass are nearly the same (stability, asymptotic safety, Higgs inflation)

Numerical coincidence?

Fermi scale is determined by the Planck scale (or vice versa)?

This relation is generically spoiled if new physics exists between the Fermi and Planck scales.

$$\Downarrow$$

Argument in favour of absence of new physics scales between Fermi and Planck.

SM + Gravity

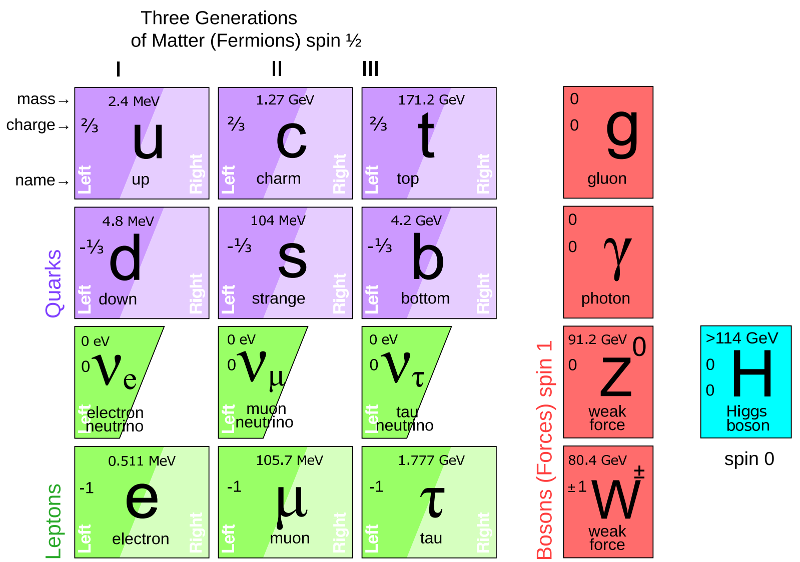
The most conservative hypothesis: we have Standard Model + Gravity and nothing else.

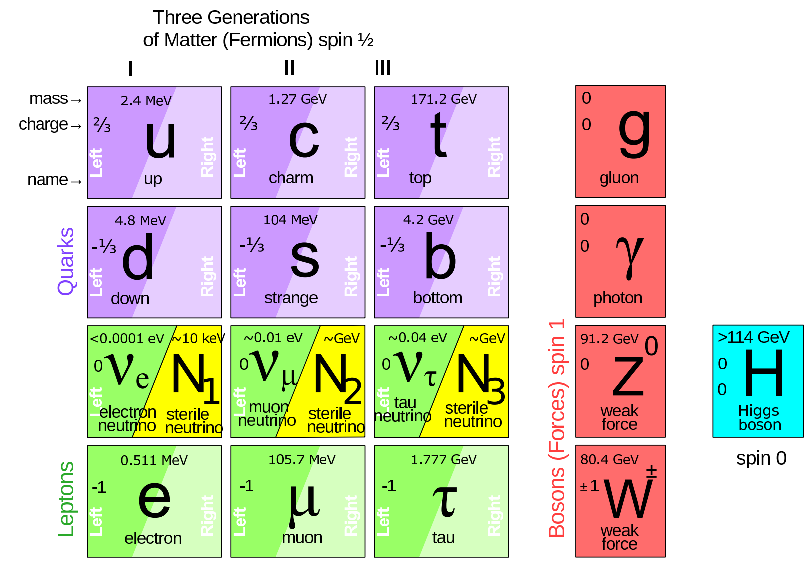
Ruled out by:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM)
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)

SM + Gravity + new physics below the EW scale

The less conservative hypothesis: there are no intermediate energy scales between the Fermi scale 100 GeV and the Planck scale 10^{18} GeV. Three new fermions: the νMSM





Role of N_1 with mass in keV region: dark matter

Role of $N_2, \ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Conclusions

The Higgs boson is an essential ingredient of the Standard Model:

- It unitarizes high energy scattering amplitudes.
- It makes the Standard Model renormalizable.
- LHC experiments provide a strong evidence that the SM is a self-consistent effective theory all the way up to the Planck scale.
- The case of $M_H = m_{min}$ is very peculiar: if this is indeed the case, this is a strong indication for the absence of new energy scales between the Fermi and Planck scales
- The new physics responsible for neutrino masses, dark matter and baryon asymmetry of the Universe can be below the Fermi scale and associated with extension of the SM by 3 Majorana fermions with masses in keV - GeV region.