The Standard Model as a low energy effective theory: what is triggering the Higgs mechanism?

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Outline of Talk:

- Introduction
- Low energy effective QFT of a cutoff system
- Matching conditions
- SM RG evolution to the Planck scale
- The issue of quadratic divergences in the SM
- Remark on the impact on inflation
- Conclusion

Introduction

The path to physics at the Planck scale

String Paradigm: the closer we look the more symmetric the world looks

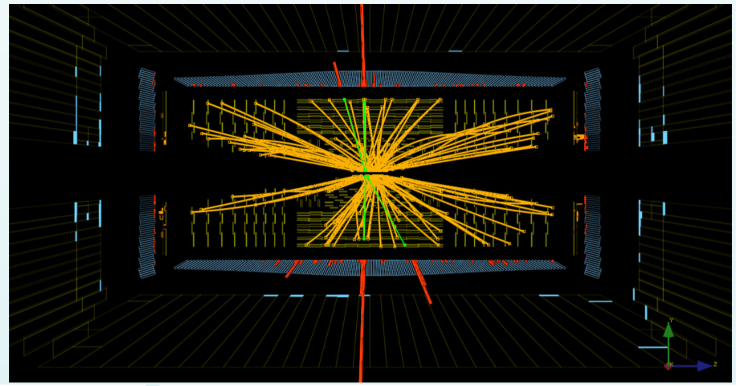
M–THEORY $\sim$ STRINGS $\leftarrow$ SUGRA $\leftarrow$ SUSY $\leftarrow$ SM,

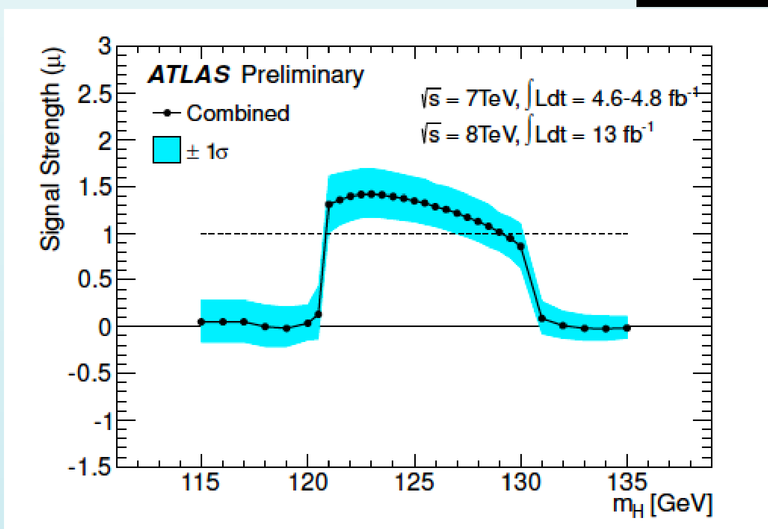
Emergence Paradigm: the less close you look the simpler it looks

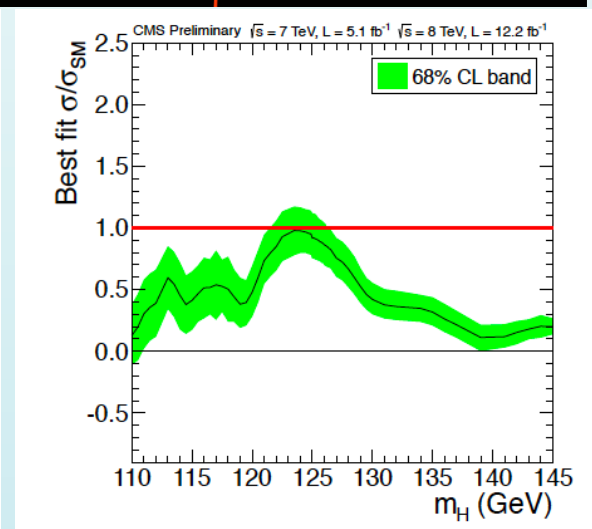
ETHER $\sim$ Planck medium $\rightarrow$ low energy effective QFT $\rightarrow$ SM.

The “true world” seen from far away: unlike in renormalized QFT, here the relationship between bare and renormalized parameters obtains a physical meaning (Landau 1955, Wilson 1971, $\cdots$)

✌ LHC $\Rightarrow$ the SM completion



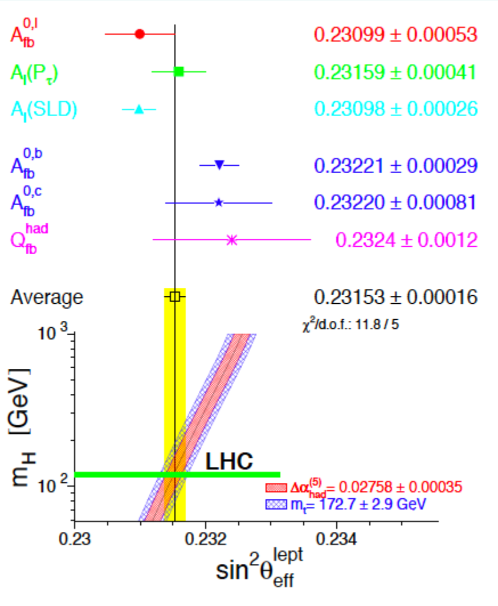




LHC Higgs mass scan by ATLAS and CMS

Higgs finally found as expected, so what?

The Higgs mass determined by ATLAS and CMS agrees perfectly with the indirect bounds obtained from combined LEP, SLD and Tevatron precision measurements of the weak mixing parameter

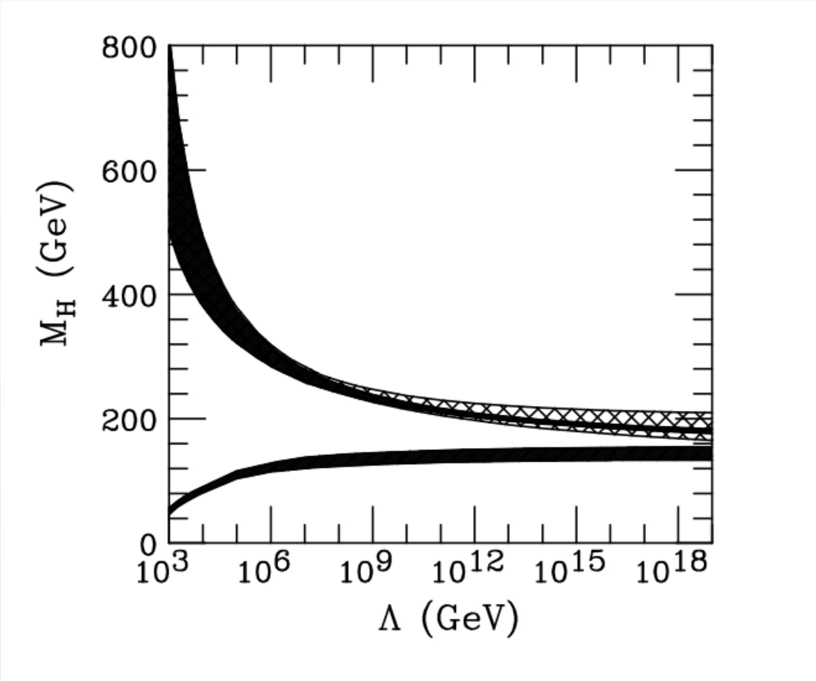


Plot of the LEP Electroweak Working Group: S. Schael et al. 2005, superimposed with the LHC result.

Higgs mass found in very special mass range 125.5 ± 1.5 GeV

Common Folklore: hierarchy problem requires SUSY extension of the SM (no quadratic divergences)

Do we need new physics? Stability bound of Higgs potential in SM:



Riesselmann, Hambye 1996

SM Higgs remains perturbative up to scale Λ if it is light enough (upper bound=avoiding Landau pole) and Higgs potential remains stable ($\lambda > 0$) if Higgs mass is not too light [parameters used: $m_t = 175[150 - 200]$ GeV ; $\alpha_s = 0.118$]

Key object of our interest: the Higgs potential $\boxed{V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4}$

❐ Higgs mechanism

❖ when m^2 changes sign and λ stays positive $\Rightarrow$first order phase transition

❖ vacuum jumps from $v = 0$ to $v \neq 0$

Note: the bare Lagrangian is the true Lagrangian (renormalization is just reshuffling terms) the change in sign of the bare mass is what determines the phase

❐ Hierarchy problem is a problem concerning the relationship between bare and renormalized parameters

● bare parameters are not accessible to experiment so who cares?

- SM as a low energy effective theory i.e. it is the long range tail of a physical bare cutoff theory

Remark: there is no way to to avoid UV regularization in QFT: reason likely is that the cutoff is real (e.g a lattice sitting at $M_{\rm Planck}$)

Our paradigm: at Planck scale a bare cutoff system exists ("the ether") with $\Lambda = M_{\rm Planck}$ as a real physical cutoff

- low energy expansion in E/Λ lets us see a renormalizable effective QFT: the SM
- in this scenario the relation between bare and renormalized parameters are physical ones
- all so called UV singularities (actually finite now) must be taken serious including quadratic divergences etc.

Low energy effective QFT of a cutoff system

The low energy expansion I:

$$G(p,\Lambda) = \sum_{n,\ell} c_{n,\ell} \left(\frac{p}{\Lambda}\right)^n \left(\ln \frac{p^2}{\Lambda^2}\right)^\ell$$

$$\left\{\Lambda \frac{\partial}{\partial \Lambda} + \beta(\cdots)\frac{\partial}{\partial g} + \delta(\cdots)\, m \frac{\partial}{\partial m} - N\,\gamma(\cdots)\right\} G(p,\Lambda) = \Delta_\Lambda G(p,\Lambda)$$

inhomogeneous response equation to change of cut–off (very complicated)

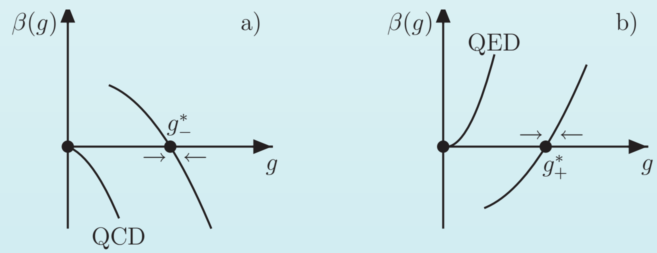
Low energy effective: drop power suppressed terms

$$G_{\rm preasymptotic}(p,\Lambda) = \sum_{\ell} c_{0,\ell} \left(\ln \frac{p^2}{\Lambda^2}\right)^\ell + O(p^2/\Lambda^2)$$

$$\left\{\Lambda\frac{\partial}{\partial\Lambda}+\beta(\cdots)\frac{\partial}{\partial g}+\delta(\cdots)\,m\frac{\partial}{\partial m}-N\,\gamma(\cdots)\right\}G_{\mathrm{preasymptotic}}(p,\Lambda)\equiv 0$$

satisfies homogeneous PDE = RG with respect to scale Λ (means Λ is not cut-off any more, just scale parameter)

Low energy effective theory usually near IR fixed point of RG



RG fixed points are zeros of the β–function: a) UV fixed points, b) IR fixed points

- Crucial point: cutoff Λ_{Pl} is physical i.e. a finite number and by a finite renormalization (renormalizing parameters and fields only) by change of scale $p_i \to \kappa\, p_i$

i.e. momenta in units of Λ rescaled to momenta in units of $\overline{\mathrm{MS}}$ scale μ i.e. $\kappa = \Lambda/\mu$.

- the preasymptotic theory is a local relativistic QFT
- Key observation: elementary particle interactions have rather weak coupling such that perturbation theory works in general

The low energy expansion II:

	dimension	operator	scaling behavior
	$\cdot$	∞–many	
	$\cdot$	irrelevant	
$\uparrow$	$\cdot$	operators	
no			
data	$d = 6$	$(\Box\phi)^2, (\bar{\psi}\psi)^2, \cdots$	$(E/\Lambda_{\mathrm{Pl}})^2$
$\mid$	$d = 5$	$\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi, \cdots$	$(E/\Lambda_{\mathrm{Pl}})$
$\mid$	$d = 4$	$(\partial\phi)^2, \phi^4, (F_{\mu\nu})^2, \cdots$	$\ln(E/\Lambda_{\mathrm{Pl}})$
experimental	$d = 3$	$\phi^3, \bar{\psi}\psi$	$(\Lambda_{\mathrm{Pl}}/E)$
data	$d = 2$	$\phi^2, (A_\mu)^2$	$(\Lambda_{\mathrm{Pl}}/E)^2$
$\downarrow$	$d = 1$	ϕ	$(\Lambda_{\mathrm{Pl}}/E)^3$

Up to date and for a long time to come there is and will be no direct experimental information on $O(E/\Lambda_{\rm Pl})$ effects (but bounds on absence of such terms).

- what we observe as the SM is a physical reparametrization (renormalization) of the preasymptotic bare theory

- one of the impacts of the very high Planck scale is that the local renormalizable QFT structure of the SM is presumably valid up to 10^{17} GeV This also justifies the application of the SM RG up to high scales.

- infinite tower of dim > 4 irrelevant operators not seen at low energy (simplicity of LEET)

- problems are the dim < 4 relevant operators , in particular the mass terms, require "tuning to criticality" . In the symmetric phase of the SM, where there is only one mass (the others are forbidden by the known chiral and gauge symmetries), the one in front of the Higgs doublet filed, the fine tuning has the form

$$m_0^2 = m^2 + \delta m^2 \; ; \quad \delta m^2 = \frac{\Lambda^2}{16\pi^2}\, C$$

with a coefficient typically $C = O(1)$. To keep the renormalized mass at some small value, which can be seen at low energy, m_0^2 has to be adjusted to compensate the huge number δm^2 such that about 35 digits must be adjusted in order to get the observed value around the electroweak scale.

Our Hierarchy Problem!

In the following we consider the SM as a strictly renormalizable theory, regularized as usual by dimensional regularization in $D = 4 - \varepsilon$ space-time dimensions, such that the $\overline{\mathrm{MS}}$ parametrization and the corresponding RG can be used in the well known form.

Matching conditions

Notation: m_{i0} bare, m_i the $\overline{\mathrm{MS}}$ and M_i the on-shell masses; μ_0 bare μ $\overline{\mathrm{MS}}$ scale parameters

Reg $= \frac{2}{\varepsilon} - \gamma + \ln 4\pi + \ln \mu_0^2$ UV regulator term in bare quantities

❖ bare $\to \overline{\mathrm{MS}}$: Reg $\to \ln \mu^2$

❐ $\overline{\mathrm{MS}}$ renormalization scheme is the favorite choice to study the scale dependence of the theory i.e. need $\overline{\mathrm{MS}}$ values of input parameters

❐ physical values of parameters determined by physical processes i.e in on-shell renormalization scheme primarily

What we need:

- relationship between bare and on-shell renormalized parameters

$$m_{b0}^2 \stackrel{\text{def}}{=} M_b^2 + \delta M_b^2 \quad \text{for bosons} \quad m_{f0} \stackrel{\text{def}}{=} M_f + \delta M_f \quad \text{for fermions}$$

- relationship between bare and $\overline{\mathrm{MS}}$ renormalized parameters

$$m_{b0}^2 \stackrel{\text{def}}{=} m_b^2 + \delta M_b^2\big|_{\overline{\mathrm{MS}}} = M_b^2 + \delta M_b^2\big|_{\mathrm{OS}} \;\; ; \quad \delta M_b^2\big|_{\overline{\mathrm{MS}}} = \left(\delta M_b^2\big|_{\mathrm{OS}}\right)_{\mathrm{UV\ sing}}$$

- relationship between $\overline{\mathrm{MS}}$ and on-shell renormalized parameters

$$m_b^2 = M_b^2 + \delta M_b^2\big|_{\mathrm{OS}} - \delta M_b^2\big|_{\overline{\mathrm{MS}}} = M_b^2 + \left(\delta M_b^2\big|_{\mathrm{OS}}\right)_{\mathrm{Reg}=\ln\mu^2} \; .$$

$$m_b^2 = M_b^2 + \delta M_b^2|_{\mathrm{Reg}=\ln\mu^2} \quad \text{for bosons} \quad m_f = M_f + \delta M_f|_{\mathrm{Reg}=\ln\mu^2} \quad \text{for fermions}$$

Similar relations apply for the coupling constants g, g', λ and y_f, which, however, usually are fixed using the mass-coupling relations in terms of the masses and the Higgs VEV v, which is determined by the Fermi constant $v = (\sqrt{2}G_\mu)^{-1/2}$.

$$M_Z = 91.1876(21) \text{ GeV}, \quad M_W = 80.385(15) \text{ GeV}, \quad M_t = 173.5(1.0) \text{ GeV},$$
$$G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}, \quad \alpha^{-1} = 137.035999, \quad \alpha_s(M_Z^2) = 0.1184(7).$$

For the Higgs mass we adopt

$$M_H = 125.5 \pm 1.5 \text{ GeV},$$

in accord with latest ATLAS and CMS reports. Furthermore, we take the effective fine-structure constant at the Z boson mass scale to be $\alpha^{-1}(M_Z^2) = 127.944$. All light-fermion masses $M_f\,(f \neq t)$ give negligible effects and do not play any role in our consideration. The top quark mass given above is taken to be the pole mass.

SM RG evolution to the Planck scale

Using RG coefficient function calculations by

Jones, Machacek&Vaughn, Tarasov&Vladimirov, Vermasseren&vanRitbergen, Melnikov&van Ritbergen, Czakon, Chetyrkin et al, Steinhauser et al, Bednyakov et al.

Recent application to SM vacuum stability

Shaposhnikov et al, Degrassi et al, Maina, Hamada et al, ...

Solve SM coupled system of RG equations:

- for gauge couplings $g_3 = (4\pi\alpha_s)^{1/2}$, $g_2 = g$ and $g_1 = g'$
- for the Yukawa coupling y_t (other Yukawa couplings negligible)
- for the Higgs potential parameters λ and $\ln m^2$

with $\overline{\mathrm{MS}}$ initial values obtained by evaluating the matching conditions

Note: all dimensionless couplings satisfy the same RG equations in the broken and in the unbroken phase

The $\overline{\mathrm{MS}}$ Higgs VEV square is then obtained by $v^2(\mu^2) = \frac{6m^2(\mu^2)}{\lambda(\mu^2)}$ and the other masses by the relations

The RG equation for $v^2(\mu^2)$ follows from the RG equations for masses and massless coupling constants using one of the relations

$$v^2(\mu^2) = 4\,\frac{m_W^2(\mu^2)}{g^2(\mu^2)} = 4\,\frac{m_Z^2(\mu^2) - m_W^2(\mu^2)}{g'^2(\mu^2)} = 2\,\frac{m_f^2(\mu^2)}{y_f^2(\mu^2)} = 3\,\frac{m_H^2(\mu^2)}{\lambda(\mu^2)}\;.$$

As a key relation we will use F.J., Kalmykov, Veretin 2003

$$\mu^2 \frac{d}{d\mu^2} v^2(\mu^2) = 3\,\mu^2 \frac{d}{d\mu^2}\left[\frac{m_H^2(\mu^2)}{\lambda(\mu^2)}\right] \equiv v^2(\mu^2)\left[\gamma_{m^2} - \frac{\beta_\lambda}{\lambda}\right]$$

$$\gamma_{m^2} \equiv \mu^2 \frac{d}{d\mu^2} \ln m^2 \;, \beta_\lambda \equiv \mu^2 \frac{d}{d\mu^2} \lambda \;, \gamma_{y_q} \equiv \mu^2 \frac{d}{d\mu^2} \ln y_q \;,$$

The proper $\overline{\mathrm{MS}}$ definition of a running fermion mass is

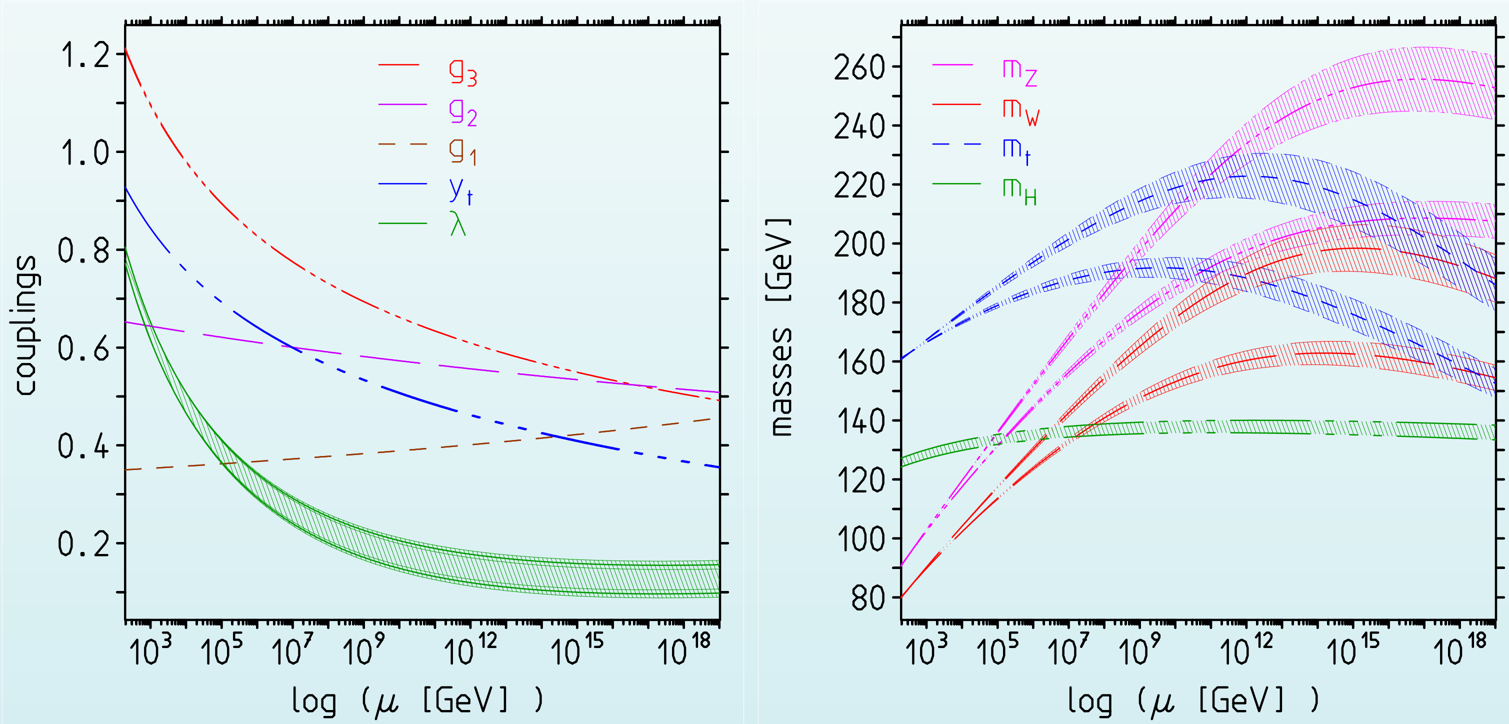
$$m_f(\mu^2) = \frac{1}{\sqrt{2}} v(\mu^2)\, y_f(\mu^2) \;.$$

RG for top quark mass

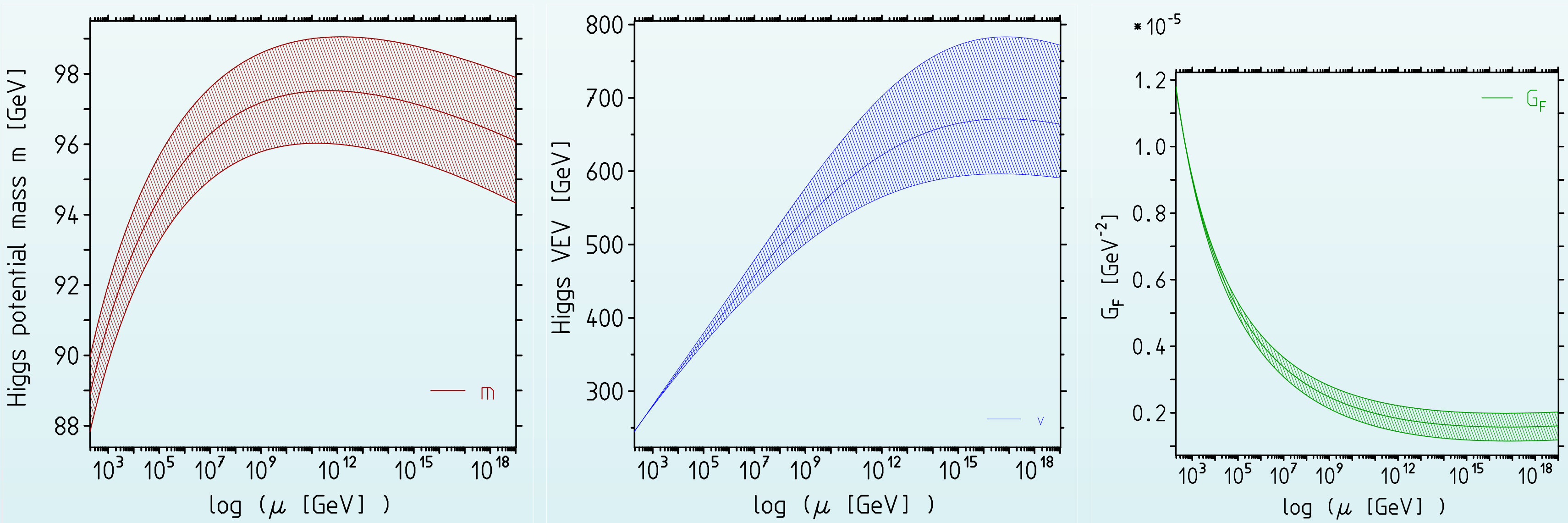
$$\mu^2 \frac{d}{d\mu^2} \ln m_t^2 = \gamma_t(\alpha_s, \alpha) \;; \quad \gamma_t(\alpha_s, \alpha) = \gamma_t^{QCD} + \gamma_t^{EW} \;; \quad \gamma_t^{EW} \quad = \quad \gamma_{y_t} + \frac{1}{2} \gamma_{m^2} - \frac{1}{2} \frac{\beta_\lambda}{\lambda} \;,$$

Similar for other masses.

Note: RG equations calculated in the broken phase are indeed as it should be identical to the ones in the symmetric phase. However, this is true if and only if tadpole terms are taken into account F.J., Kalmykov, Veretin 2003



Left: the SM dimensionless couplings in the $\overline{\mathrm{MS}}$ scheme as a function of the renormalization scale. The input parameter uncertainties as given above are exhibited by the line thickness. The green band corresponds to Higgs masses in the range [124-127] GeV. Right: the running $\overline{\mathrm{MS}}$ masses. The shadowed regions show parameter uncertainties , mainly due to the uncertainty in α_s, for a Higgs mass of 124 GeV, higher bands, and for 127 GeV, lower bands. The range also determines the green band for the Higgs mass evolution.



Non-zero dimensional $\overline{\mathrm{MS}}$ running parameters: m, $v = \sqrt{6/\lambda}\, m$ and $G_F = 1/(\sqrt{2}\, v^2)$. Error bands include SM parameter uncertainties and a Higgs mass range 125.5 ± 1.5 GeV which essentially determines the widths of the bands.

- perturbation expansion works up to the Planck scale!
  no Landau pole or other singularities

- Higgs coupling decreases up to the zero of β_λ at $\mu_\lambda \sim 3.5 \times 10^{17}$ GeV, where it is small but still positive and then increases up to $\mu = M_{\mathrm{Planck}}$

✶ What rules the β-functions:

Naively:

❐ $U(1)_Y$ screening (IR free), $SU(2)_L$, $SU(3)_c$ antiscreening (UV free) [asymptotic freedom (AF)]

Right – as expected

❐ Yukawa and Higgs: screening (IR free, like QED)

Wrong!!! – transmutation from IR free to AF

At the Z boson mass scale: $g_1 \simeq 0.350$, $g_2 \simeq 0.653$, $g_3 \simeq 1.220$, $y_t \simeq 0.935$ and $\lambda \simeq 0.796$

Leading (one-loop) β-functions at $\mu = M_Z$:

- gauge couplings:

$$\beta_1 = \frac{41}{6}\, g_1^3\, c \simeq 0.00185 \ ; \ \ \beta_2 = -\frac{19}{6}\, g_2^2\, c \simeq -0.00558 \ ; \ \ \beta_3 = -7\, g_3^3\, c \simeq -0.08045\,,$$

with $c = \frac{1}{16\,\pi^2}$

- top Yukawa coupling:

$$\begin{aligned}\beta_{y_t} &= \left(\frac{9}{2}\, y_t^3 - \frac{17}{12}\, g_1^2\, y_t - \frac{9}{4}\, g_2^2\, y_t - 8\, g_3^2\, y_t\right) c \\ &\simeq 0.02328 - 0.00103 - 0.00568 - 0.07046 \\ &\simeq -0.05389\end{aligned}$$

not only depends on y_t, but also on mixed terms with the gauge couplings g', g and g_3 which have a negative sign.

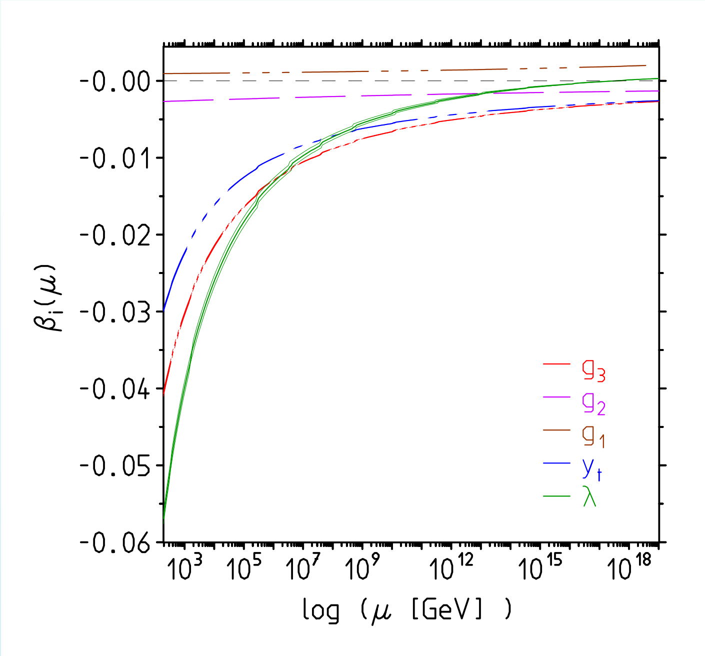
In fact the QCD correction is the leading contribution and determines the behavior.

Notice the critical balance between the dominant strong and the top Yukawa couplings: QCD dominance requires $g_3 > \frac{3}{4}\,y_t$ in the gaugeless limit.

❖ the Higgs self-coupling

$$\begin{aligned}
\beta_\lambda &= (4\,\lambda^2 - 3\,g_1^2\,\lambda - 9\,\lambda\,g_2^2 + 12\,y_t^2\,\lambda + \frac{9}{4}\,g_1^4 + \frac{9}{2}\,g_1^2\,g_2^2 + \frac{27}{4}\,g_2^4 - 36\,y_t^4)\,c \\
&\simeq 0.01606 - 0.00185 - 0.01935 + 0.05287 + 0.00021 + 0.00149 + 0.00777 - 0.17407 \\
&\simeq -0.11687
\end{aligned}$$

dominated by y_t contribution and not by λ coupling itself. At leading order it is not subject to QCD corrections. Here, the y_t dominance condition reads $\lambda < \frac{3\,(\sqrt{5}-1)}{2}\,y_t^2$ in the gaugeless limit.



The β-functions for gauge, top Yukawa and Higgs self-coupling.

- running top Yukawa QCD takes over: IR free $\Rightarrow$UV free
- running Higgs self-coupling top Yukawa takes over: IR free $\Rightarrow$UV free

Including all known RG coefficients (EW up incl 3–loop, QCD up incl 4–loop)

- except from β_λ, which exhibits a zero at about $\mu_\lambda \sim 10^{17}$ GeV, all other

β-functions do not exhibit a zero in the range from $\mu = M_Z$ to $\mu = M_{\text{Planck}}$.

- so apart form the $U(1)_Y$ coupling g_1, which increases only moderately, all other couplings decrease and perturbation theory is in good condition.

- at $\mu = M_{\text{Planck}}$ gauge couplings are all close to $g_i \sim 0.5$, while $y_t \sim 0.35$ and $\lambda \sim 0.1$.

- effective masses moderately increase (largest for m_Z by factor 2.8): scale like

$$m(\kappa)/\kappa \text{ as } \kappa = \mu'/\mu \to \infty,$$

i.e. mass effect get irrelevant as expected at high energies.

Given that m_H is weakly scale dependent, what determines the mass hierarchy are the relations

$$\frac{m_W(\mu^2)}{m_H(\mu^2)} = \sqrt{\frac{3}{4}\frac{g^2(\mu^2)}{\lambda(\mu^2)}}\,,\frac{m_Z(\mu^2)}{m_H(\mu^2)} = \sqrt{\frac{3}{4}\frac{g^2(\mu^2)+g'^2(\mu^2)}{\lambda(\mu^2)}}\,,\frac{m_t(\mu^2)}{m_H(\mu^2)} = \sqrt{\frac{3}{2}\frac{y_t^2(\mu^2)}{\lambda(\mu^2)}}\,.$$

Since g is decreasing while g' is increasing the Z boson mass grows most and exceeds m_H above about 8×10^4 GeV and even m_t above about 7×10^{10} GeV. The

W boson mass exceeds m_H above about 5×10^6 GeV. These crossing happen in the history of the universe some time after inflation, but long before processes like nucleosynthesis set in. Whether they play any special role in the evolution of the universe I don't know.

The issue of quadratic divergences in the SM

Hamada, Kawai, Oda 2012: coefficient of quadratic divergence has a zero not far below the Planck scale.

$$\boxed{\delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\, C_1}$$

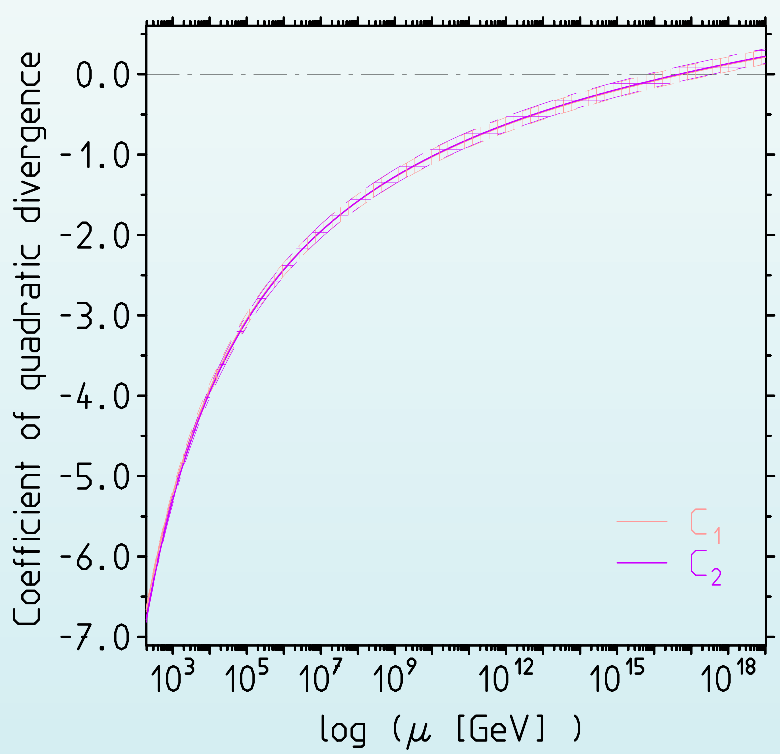
Veltman 1978 modulo small lighter fermion contributions, one-loop coefficient function C_1 is given by

$$C_1 = \frac{6}{v^2}(M_H^2 + M_Z^2 + 2M_W^2 - 4M_t^2) = 2\,\lambda + \frac{3}{2}\,g'^2 + \frac{9}{2}\,g^2 - 12\,y_t^2$$

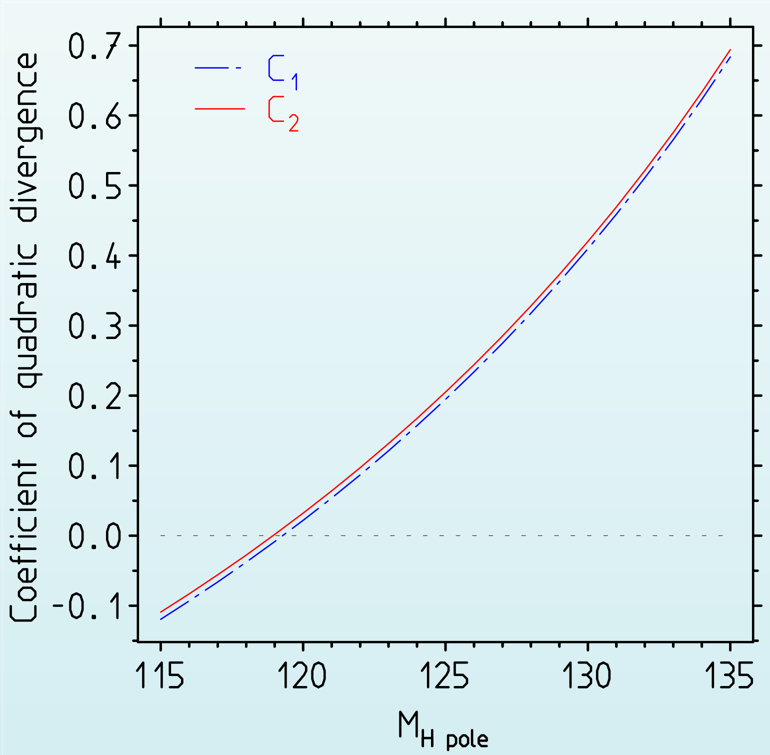
Two-loop

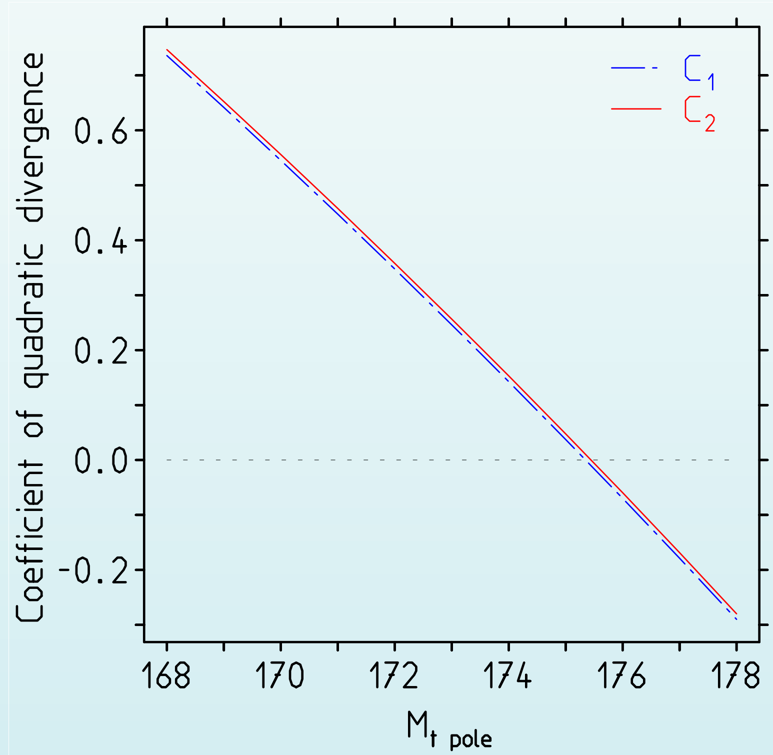
$$
\begin{aligned}
C_2 \quad = \quad & C_1 + \frac{\ln(2^6/3^3)}{16\pi^2}\,[18\,y_t^4 + y_t^2\,(-\frac{7}{6}\,g'^2 + \frac{9}{2}\,g^2 - 32\,g_s^2) \\
& + \frac{77}{8}\,g'^4 + \frac{243}{8}\,g^4 + \lambda\,(-6\,y_t^2 + g'^2 + 3\,g^2) - \frac{10}{18}\,\lambda^2]
\end{aligned}
$$

⇒key point: C_1 is universal and depends on dimensionless gauge, Yukawa and Higgs self-coupling only, the RGs of which are unambiguous, similarly for the two-loop coefficient C_2 (where however results differ by different groups [non-universal?]). The correction is numerically small, fortunately.



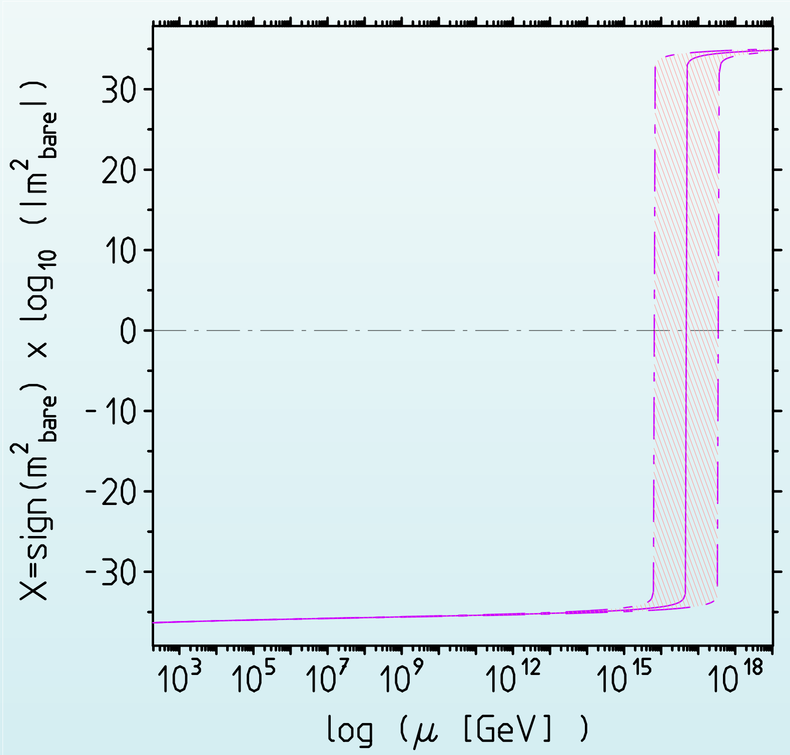
The coefficient of the quadratic divergence term at one and two loops as a function of the renormalization scale. The one-loop result essentially determines the behavior. The coefficient exhibits a zero, for $M_H = 125$ GeV at about $\mu_0 \sim 7 \times 10^{16}$, not far below $\mu = M_{\text{Planck}}$. The shaded band shows the parameter uncertainties.

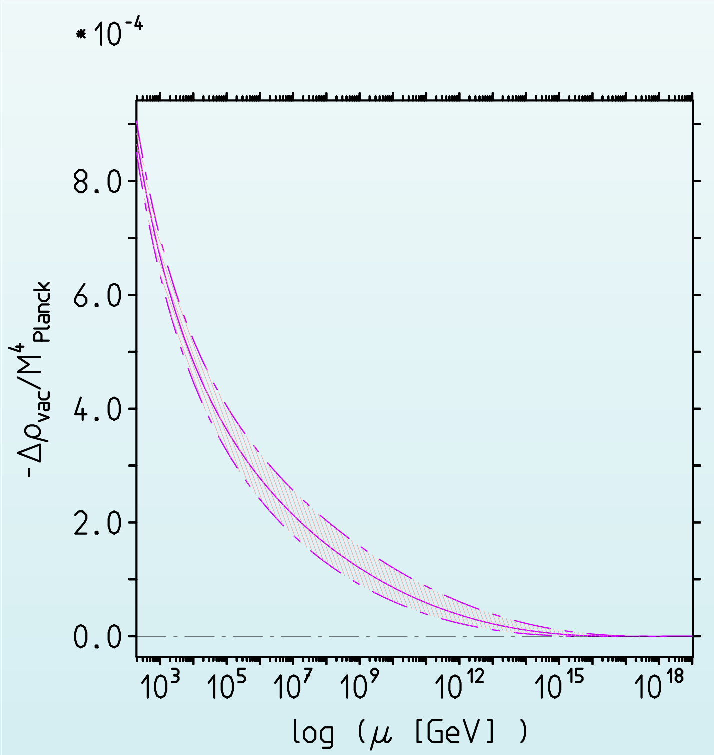




Left: the coefficient of the quadratic divergence term at $\mu = M_{\rm Planck}$ as a function of M_H. Right: the same as a function of M_t.

Now the SM for the given parameters makes a prediction for the bare mass parameter in the Higgs potential:





The EW phase transition in the SM. Left: shown is $X = \mathrm{sign}(m^2_{\rm bare}) \times \log_{10}(|m^2_{\rm bare}|)$ which represents $m^2_{\rm bare} = \mathrm{sign}(m^2_{\rm bare}) \times 10^X$. The band represents the parameter uncertainties. Right: the "jump" $-\Delta\rho_{\rm vac} = \frac{\lambda}{24}\, v^4_{\rm bare}$ in units of $M^4_{\rm Planck}$.

- in the broken phase $m^2_{\rm bare} = \frac{1}{2}\, m^2_{H\,{\rm bare}}$, which is calculable!

- at the zero of the coefficient function the counterterm $\delta m^2 = m^2_{\rm bare} - m^2 = 0$ (m the $\overline{\rm MS}$ mass) vanishes and the bare mass changes sign

- this represents a phase transition which triggers the Higgs mechanism and likely plays an important role for cosmic inflation

- at the transition point μ_0 we have $\boxed{v_{\rm bare} = v(\mu_0^2)}$, where $v(\mu^2)$ is the $\overline{\rm MS}$ renormalized VEV

- the jump, too small to be seen in this plot, thus agrees with the renormalized one: $-\Delta\rho_{\rm vac} = \frac{\lambda(\mu_0^2)}{24}\, v^4(\mu_0^2)$, and thus is $O(v^4)$ and **not** $O(M^4_{\rm Planck})$.

In any case at the zero of the coefficient function there is a phase transition, which corresponds to a restoration of the symmetry. Such transition would take place at a scale $\mu \sim 10^{16}$ to 10^{18} one to three orders of magnitude below the Planck scale, at cosmic times $\sim 0.23 \times 10^{-38}$ to 10^{-42} sec and could have triggered inflation. Note that at the zero of β_λ at about $\mu_\lambda \sim 3.5 \times 10^{17} > \mu_0$ the Higgs self-coupling λ although rather small is still positive and then starts slowly increasing up to $M_{\rm Planck}$.

Remark on the impact on inflation

Guth, Starobinsky, Linde, Albrecht et al, Mukhanov, ...

- the "inflation term" comes in via the SM energy-momentum tensor
- adds to the r.h.s of the Friedmann equation ($\dot{X}$ = time derivative of X)

$$\ell^2 \left(V(\phi) + \frac{1}{2}\,\dot{\phi}^2 \right)$$

$\ell^2 = 8\pi G/3$, $M_{\rm Pl} = (G)^{-1/2}$ is the Planck mass, G Newton's gravitational constant

- Inflation requires an exponential growth $a(t) \propto \mathrm{e}^{Ht}$ of Friedman radius $a(t)$ of the universe

$H(t) = \dot{a}/a(t)$ the Hubble constant at cosmic time t

- Higgs contribution to energy momentum tensor $\Rightarrow$contribution to energy density and pressure

$$\rho_\phi = \frac{1}{2}\,\dot{\phi}^2 + V(\phi)\;;\;\; p_\phi = \frac{1}{2}\,\dot{\phi}^2 - V(\phi)\;.$$

- second Friedman equation $\ddot{a}/a = -\frac{\ell^2}{2}\,(\rho + 3p)$

- condition for growth $\ddot{a} > 0$

- requires $p < -\rho/3$ and hence

$$\boxed{\tfrac{1}{2}\dot{\phi}^2 < V(\phi)}$$

- first Friedman equation reads $\dot{a}^2/a^2 + k/a^2 = \ell^2\,\rho$

may be written as

$$\boxed{H^2 = \ell^2 \left[V(\phi) + \tfrac{1}{2}\,\dot{\phi}^2\right] = \ell^2\,\rho}$$

field equation

$$\boxed{\ddot{\phi} + 3H\dot{\phi} = -V'(\phi)}$$

kinetic term $\dot{\phi}^2$: controlled by $\dot{H} = -\frac{3}{2}\ell^2\,\dot{\phi}^2 = \ell^2\,\rho\,(q-1)$

i.e. by observationally controlled deceleration parameter $q(t) = -\ddot{a}a/\dot{a}^2$.

"flattenization" by inflation: curvature term $k/a^2(t) \sim k\,\exp(-2Ht) \to 0$ ($k = 0, \pm 1$ the normalized curvature)

$\Rightarrow$universe looks effectively flat ($k = 0$) for any initial k

Inflation looks to be universal for quasi-static fields $\dot{\phi} \sim 0$ and $V(\phi)$ large positive

$\Rightarrow a(t) \propto \exp(Ht)$ with $H \simeq \ell\,\sqrt{V(\phi)}$

This is precisely what the transition to the symmetric phase suggests:

Now, as for the Higgs potential λ remains positive and the bare mass square also has been positive (symmetric phase) before it flipped to negative values at later times, this definitely supports the inflation condition. As both λ and m^2 for the first time are numerically fairly well known quantitative conclusions on the inflation patterns should be possible solely on the basis of SM properties.

The leading behavior is characterized by a free massive scalar field with potential

$$\boxed{V = \frac{m^2}{2}\,\phi^2}$$

$\Rightarrow$ $$H^2 = (\dot{a}/a)^2 = \frac{m^2}{6}\,\phi^2 \quad \text{and} \quad \ddot{\phi} + 3H(\dot{\phi}) = m^2\phi$$

➠ harmonic oscillator with friction

Clearly supported by observation: Planck 2013 results

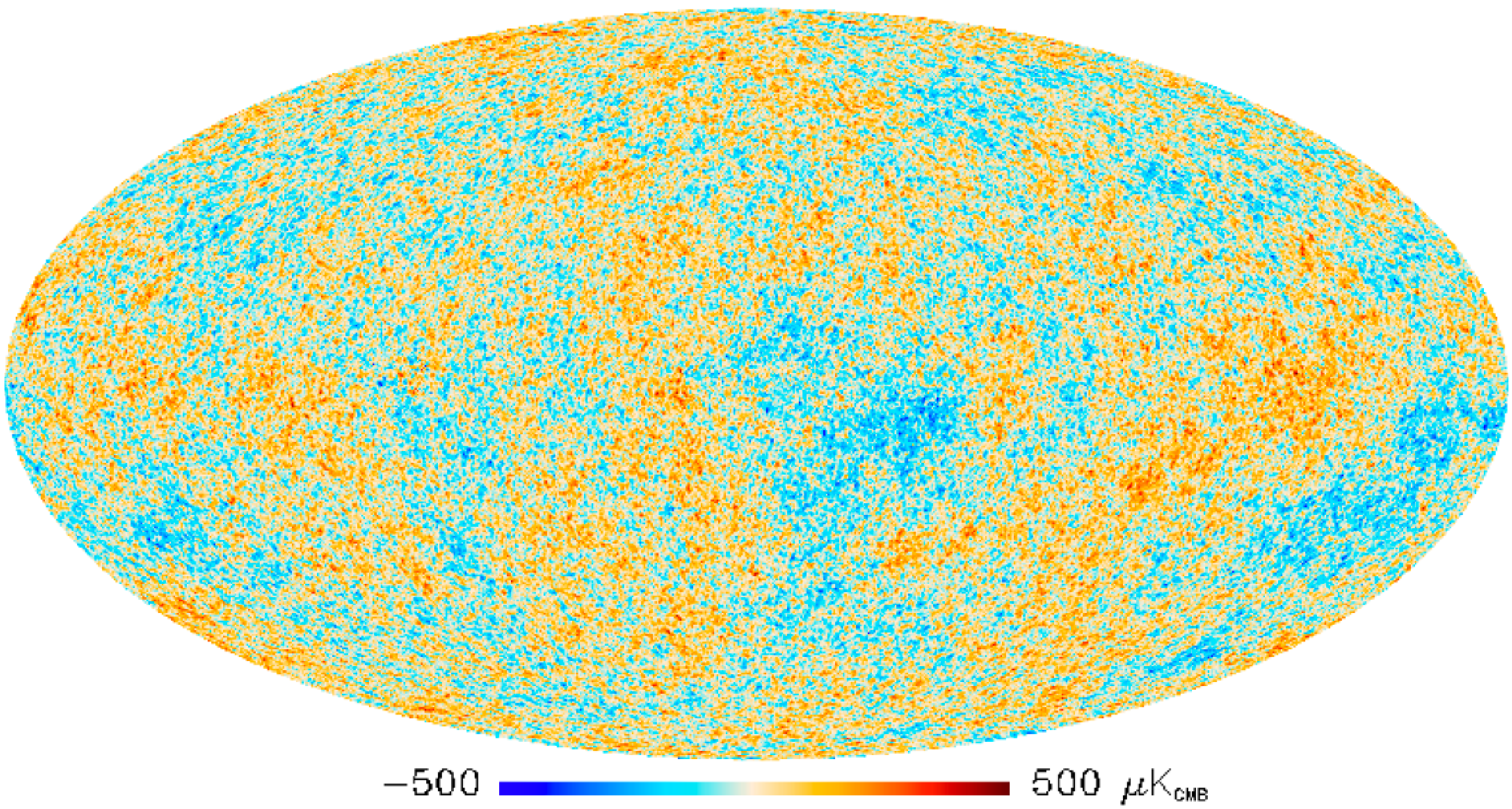
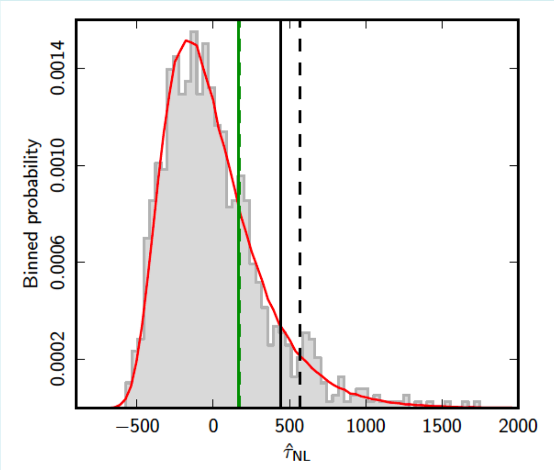


Fig. 14. The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization).

Planck data are consistent with Gaussian primordial fluctuations. The standard models of single-field slow-roll inflation have therefore survived the most stringent tests of Gaussianity performed to date. On the other hand, the NG constraints obtained on different primordial bispectrum shapes (e.g., local, equilateral and orthogonal), after properly accounting for various contaminants, severely limit various classes of mechanisms for the generation of the primordial perturbations proposed as alternatives to the standard models of inflation. There is no evidence for primordial NG of one of these shapes (local, equilateral and orthogonal).



shape non-linearity parameters:

$$f_{NL}^{loc} = 2.7 \pm 5.8,\ f_{NL}^{eq} = -42 \pm 75,\ f_{NL}^{orth} = -25 \pm 39$$

(68% CL statistical)

✶ Cosmological constant problem ✶

The cosmological constant is characterized by the equation of state $w = p/\rho = -1$, indeed Planck (2013) finds $w = -1.13^{+0.13}_{-0.10}$.

- A constant background field $\phi \to \phi_0 + \phi$ would imply a dark energy term (cosmological constant) of the right sign
- in contrast after the phase transition triggered by the change of sign in the bare m^2 the scalar VEV implies a cosmological constant contribution $\boxed{-\frac{\lambda}{24}\, v^4}$ of negative sign
- at phase transition point at scale $\mu_0 \sim 7 \times 10^{16}$ jump in vacuum density

  we have $\lambda \sim 0.115$ and $v \sim 695$ GeV $\Rightarrow$ $\boxed{\frac{\lambda}{24}\, v^4 \sim 1.1 \times 10^9\ \mathrm{GeV}^4}$

converted with the factor $\kappa = 8\pi G$ corresponds to a

shift $\boxed{\Delta\Lambda_{\rm EW} = \kappa\Delta\rho_{\rm vac} \simeq -0.5 \text{ cm}^{-2}}$ in the cosmological constant Λ

- observed value is given by $\Lambda_{\rm obs} = \kappa\,\rho_{\rm crit}\,\Omega_\Lambda = 1.6517 \times 10^{-56} \text{ cm}^{-2}$

used: $\Omega_\Lambda = 0.67^{+0.027}_{-0.023}$ (Planck 2013) the dark energy fraction of the critical energy density $\rho_{\rm crit} = 3\,H_0^2\,\kappa^{-1} = 1.878 \times 10^{-29}\,h^2\,\text{gr/cm}^3$ with $h = 0.67 \pm 0.02$ for which the universe is flat

- the chiral phase transition of QCD implies quark condensates contributing

$$T_{\mu\nu\,\rm QCD,vac} = -\langle 0|\mathcal{L}_{\rm QCD}|0\rangle\, g_{\mu\nu} = \left\{m_u\,\bar{u}u + m_d\,\bar{d}d + m_s\,\bar{s}s + \cdots\right\}\, g_{\mu\nu}$$

to the cosmological constant, has to be reconsidered under the aspect that the relation between bare an renormalized quantities are physical in the low energy effective approach. Especially the gluon condensate is not well defined.

- a mechanism to tame contributions to the dark energy is still not known to my knowledge
- The cosmological constant and the missing cold dark matter problems persist.
- The scenario suggested by the present analysis is a Gaussian potential with small anharmonic perturbations, since $m^2_{\rm bare}$ is predicted to be large while $\lambda_{\rm bare}$ remains small. Also the bare kinetic term is logarithmically "unrenormalized" only.
- This picture outlined should be valid in the renormalizable effective field theory regime below about 10^{17} GeV. Going to higher energies details of the cutoff system are expected to come into play, effectively in form of <u>dimension 5</u> and/or <u>dimension 6</u> **operators** as leading corrections. These corrections are expected to get relevant only closer to the Planck scale.

Conclusion

- Higgs not just the Higgs: its mass $M_H = 125.5 \pm 1.5$ GeV has a very peculiar value!!

➠ ATLAS and CMS results may “revolution” particle physics in an unexpected way, namely showing that the SM has higher self-consistency (conspiracy) than expected and previous arguments for the existence of new physics may turn out not to be compelling

➠ SM as a low energy effective theory of some cutoff system at M_{Planck} consolidated; crucial point $M_{\text{Planck}} >>>> \ldots$ from what we can see!

➠ SM is triggering the Higgs mechanism itself as a first order phase transition at about $\mu_0 \sim 10^{17}$ GeV as the hot universe cools down (the temperature sets the energy scale via $\boxed{E = k_B T}$)

➠ we have a handle to estimate parameters of the bare (true) effective Lagrangian $m_{\text{bare}} = m_{\text{ren}} + \delta m$ etc

➠ fully supports almost Gaussian bare Higgs potential at times of inflation as strengthened by Planck data

➠ there is no non-perturbative regime once pQCD starts to work at about 2 GeV. No strong coupling Higgs, no Landau pole or other singularities.

Folklore: normal forces get weaker with the distance

❖ besides gravitation, QED, Yukawa force law, scalar self-interacting fields, etc i.e. all but non-Abelian gauge theories

❖ not true in "reality" ["the stronger capture the weaker" couplings] i.e. in the SM all forces but $U(1)_Y$ are AF (get weaker when approaching the "ether")

❒ low energy effective tail of large (but finite) cutoff theory: bare quantities are finite

$$\delta M_H^2 = \frac{M_{\rm Planck}^2}{16\pi^2}\, C_2(\mu = M_{\rm Planck}),\ \text{with}\ C_2(\mu = M_{\rm Planck}) \sim 0.2$$

- before phase transition at $\mu_0 \sim 7 \times 10^{16}$ GeV symmetric phase, very different physics from LESM. Except from the four heavy physical Higgses and maybe heavy Majorana neutrinos only massless fields

- Last but not least:

There is no hierarchy problem in the SM!

It is true that in the relation

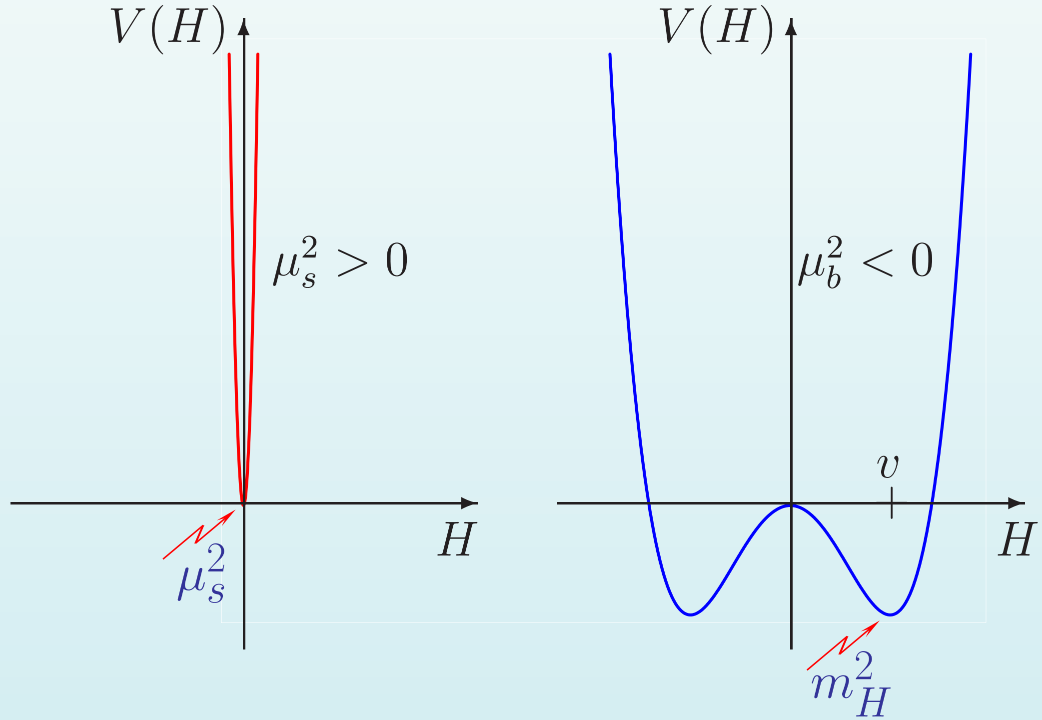
$$m^2_{H\,\mathrm{bare}} = m^2_{H\,\mathrm{ren}} + \delta m^2_H$$

both $m^2_{H\,\mathrm{bare}}$ and δm^2_H are many many orders of magnitude larger than $m^2_{H\,\mathrm{ren}}$. However, in the broken phase $m^2_{H\,\mathrm{ren}} \propto v^2(\mu_0^2)$ is $O(v^2)$ not $O(M^2_{\mathrm{Planck}})$, i.e. in the broken phase the Higgs is naturally light. That the Higgs mass likely is $O(M_{\mathrm{Planck}})$ in the symmetric phase is what realistic inflation scenarios favor.

In the broken phase, characterized by the non-vanishing Higgs field vacuum expectation value (VEV) $v(\mu^2)$, all the masses are determined by the well known mass-coupling relations

$$
\begin{aligned}
m_W^2(\mu^2) &= \frac{1}{4}\, g^2(\mu^2)\, v^2(\mu^2)\ ; \quad m_Z^2(\mu^2) = \frac{1}{4}\, (g^2(\mu^2) + g'^2(\mu^2))\, v^2(\mu^2)\ ; \\
m_f^2(\mu^2) &= \frac{1}{2}\, y_f^2(\mu^2)\, v^2(\mu^2)\ ; \quad m_H^2(\mu^2) = \frac{1}{3}\, \lambda(\mu^2)\, v^2(\mu^2)\ .
\end{aligned}
$$

According to these well known relations why the Higgs should be of order of $\Lambda_{\rm Pl}^2$ while the others are small, of order v^2? Higgs naturally in the ballpark of the other particles! No naturalness problem!



Higgs potential of the SM a) in the symmetric ($\mu_s^2 > 0$) and b) in the broken phase ($\mu_b^2 < 0$). For $\lambda = 0.5$, $\mu_b = 0.1$ and $\mu_s = 1.0$

Masses given by curvature of the potential at the ground state need not be correlated, and in fact are not.

From our analysis we expect

$$\mu_s = O(\Lambda_{\mathrm{Pl}}),$$

while

$$m_H = \sqrt{2}\,\mu_b = \sqrt{\lambda/3}\,v = O(v).$$

By the way: Higgs in broken phase has nothing to do with a Mexican hat potential. There is only **one** physical scalar field the Higgs itself, what is spontaneously broken is the discrete symmetry $H \leftrightarrow -H$. Note that the much more interesting and nicer Mexican hat potential necessarily implies Nambu-Goldstone bosons.

- need reconsider early pre Higgs epoch of cosmology (SM in symmetric phase very different form known physics in broken phase)

- need to reconsider the issues relater to EW phase transition and inflation

- can SM explain baryon asymmetry?
  what is dark matter?
  why is the cosmological constant so small?

$$\delta\rho_{\rm vac} = \frac{\Lambda^4}{(16\pi^2)^2}\, X(\mu)$$

Maybe

$$X(\mu) = X_2(g'(\mu), g(\mu), g_3(\mu), y_t(\mu), \lambda(\mu))$$

has a zero. Then $\rho_{\rm vac}$ is determined by some scale other that Λ! Examples, from condensed matter physics illustrating this possibility are known (see e.g. G.E. Volovik, Vacuum energy: Quantum hydrodynamics vs. quantum gravity, JETP Lett., 82, 319-324 (2005); gr-qc/0505104)

we are at the beginning of seeing the SM in a new light

My main theses:

- ❖There is no hierarchy problem of the SM
- ❖A super symmetric or any other extension of the SM cannot be motivated by the (non-existing) hierarchy problem
- ❖SM running couplings trigger the Higgs mechanism at about 10^{17} GeV as the universe cools down, in the broken phase the Higgs is naturally as light as other SM particles which are generated by the Higgs mechanism
- ❖in the early symmetric phase quadratically enhanced bare mass term in Higgs potential triggers inflation, if Higgs to be the inflaton this enhancement is mandatory

➠ Concluding remarks ⬅

- Conspiracy between SM couplings the new challenge
- Very delicate on initial values as we run over 16 orders of magnitude from the EW 250 GeV scale up to the

  Planck scale!

- Running couplings likely have dramatic impact on cosmology! The existence of the world in question?
- ILC will dramatically improve on Higgs self-coupling $\boxed{\lambda}$

  (Higgs factory) as well as on top Yukawa $\boxed{y_t}$ ($t\bar{t}$ factory)

- for running $\boxed{\alpha_{\rm em}}$ and $\boxed{\sin^2\Theta_{\rm eff}}$ $\Leftrightarrow$ g_1 and g_2 need more low energy information like what one could get from low energy hadron production facilities, in addition need improving QCD issues!

Precision determination of SM parameters more important than ever. Big challenge for the ILC in the search for the fundamentals of physics

? key problems

dark energy , dark matter , baryon asymmetry

persist, but may appear in new light

? does vacuum stability and the Higgs transition point persist as my analysis suggests or do we still need new physics to "stabilize" the picture?

! such scenario essentially rules out SUSY, GUTs and Strings altogether!

✌ the SM seems to be much better than its reputation!

Thanks you for your attention!