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

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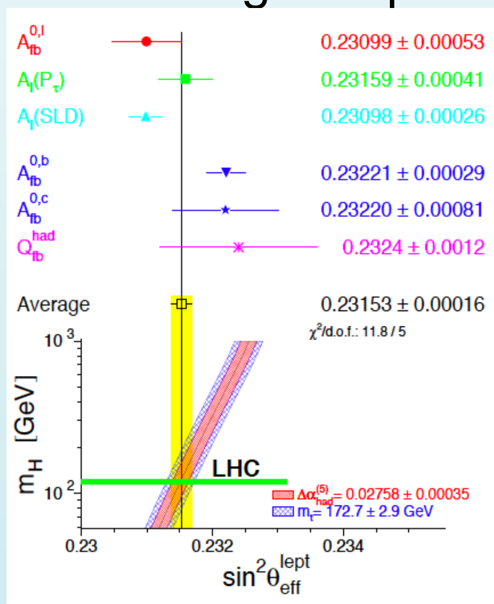
Outline of Talk:

- ❖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

✌ LHC ATLAS&CMS Higgs discovered ⇒ the SM completion

Higgs mass found by ATLAS and CMS agrees perfectly with the indirect bounds

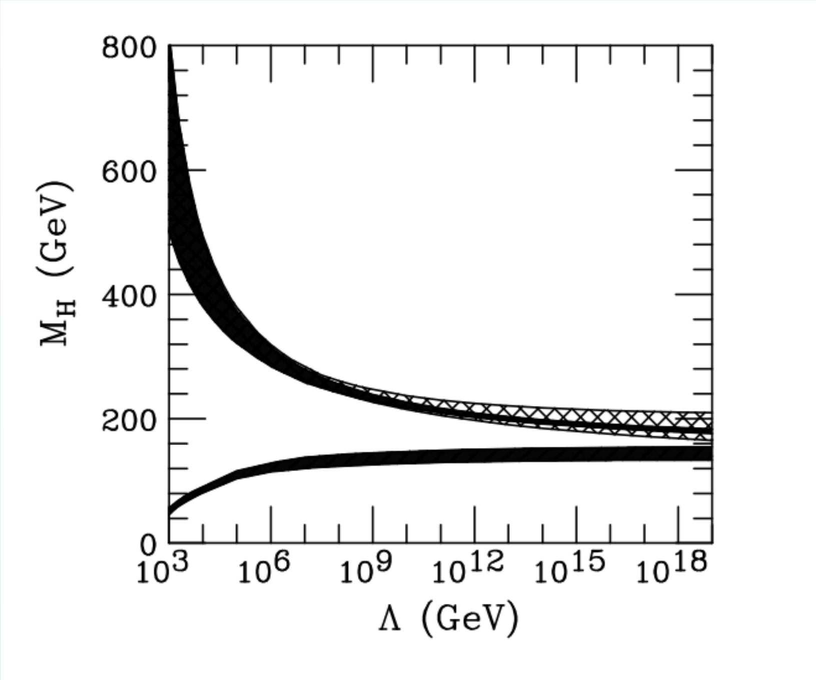


Plot of the LEP Electroweak Working Group 2005

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

$M_H < 180$ GeV

– first 2-loop analysis, knowing M_t –

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

$$V = \frac{m^2}{2} H^2 + \frac{\lambda}{24} H^4$$

❒ 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

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

- low energy expansion in E/Λ lets us see a renormalizable effective QFT: the SM
  – as present (and future) accelerator energies $E <<<< M_{\rm Pl}$
  all operators $\dim > 4$ far from being observable

- in this scenario the relation between bare and renormalized parameters is physics: bare parameters predictable from known renormalized ones

- all so called UV singularities (actually finite now) must be taken serious including quadratic divergences – cutoff finite ⇒no divergences!

- impact of the very high Planck cutoff 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.

The low energy expansion:

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

tamed by symmetries

⇒require chiral symmetry, gauge symmetry, supersymmetry???

- infinite tower of dim > 4 irrelevant operators not seen at low energy
  $\Rightarrow$simplicity of SM!

- 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 field, 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!

Matching conditions

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

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

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

❐ $\overline{\mathrm{MS}}$ 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 $\overline{\mathrm{MS}}$ renormalized parameters

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

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

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

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

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 $v = (\sqrt{2}G_\mu)^{-1/2}$.

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

For the Higgs mass we adopt $M_H = 125.5 \pm 1.5\ \mathrm{GeV}$.

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, ... G. Degrassi talk

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

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

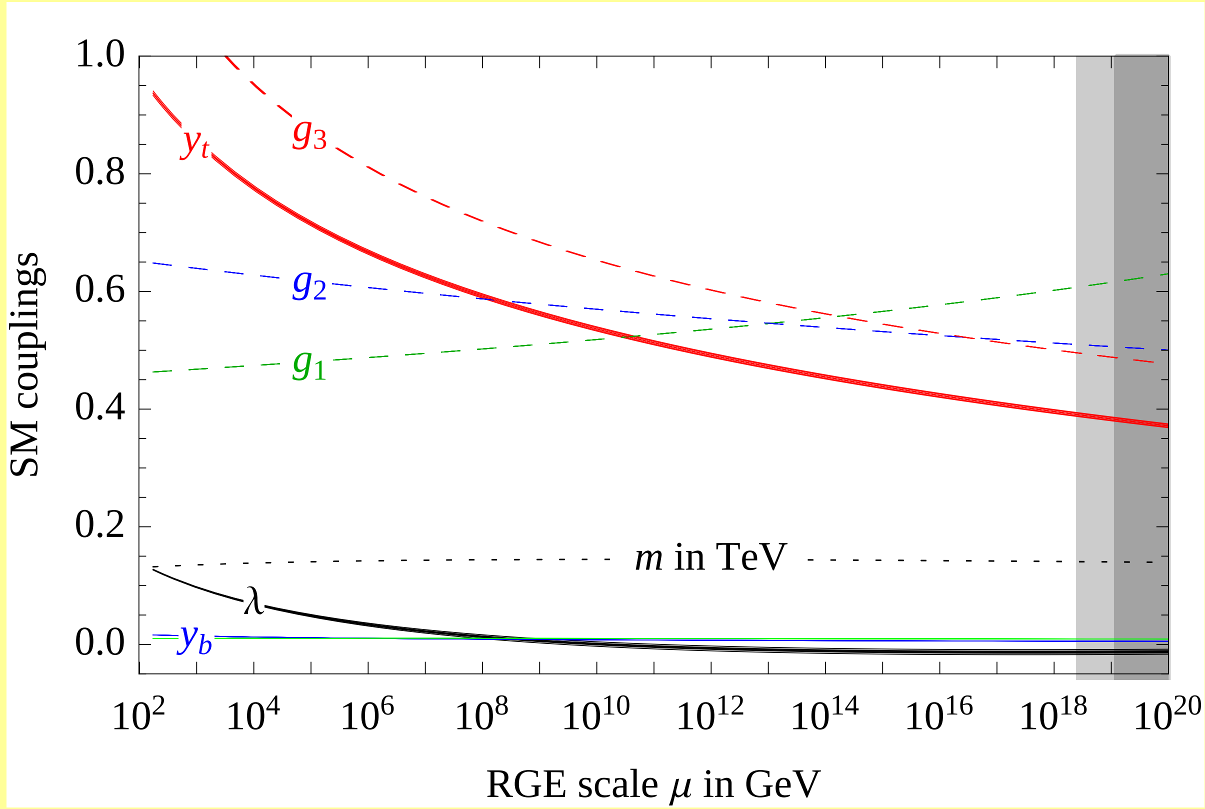
The RG equation for $v^2(\mu^2)$ follows from the RG equations for masses and massless coupling constants using one of the relations

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

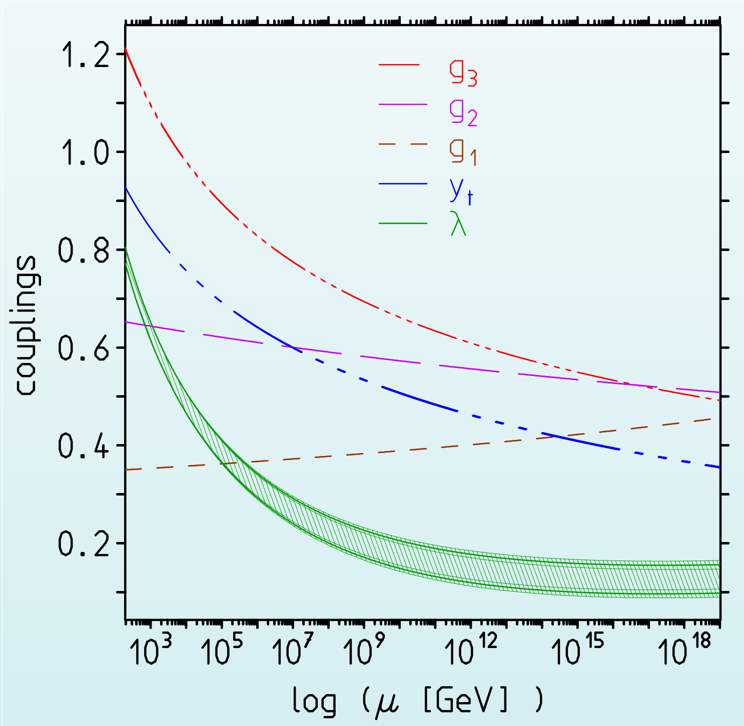
As a key relation we will use F.J., Kalmykov, Veretin 2003

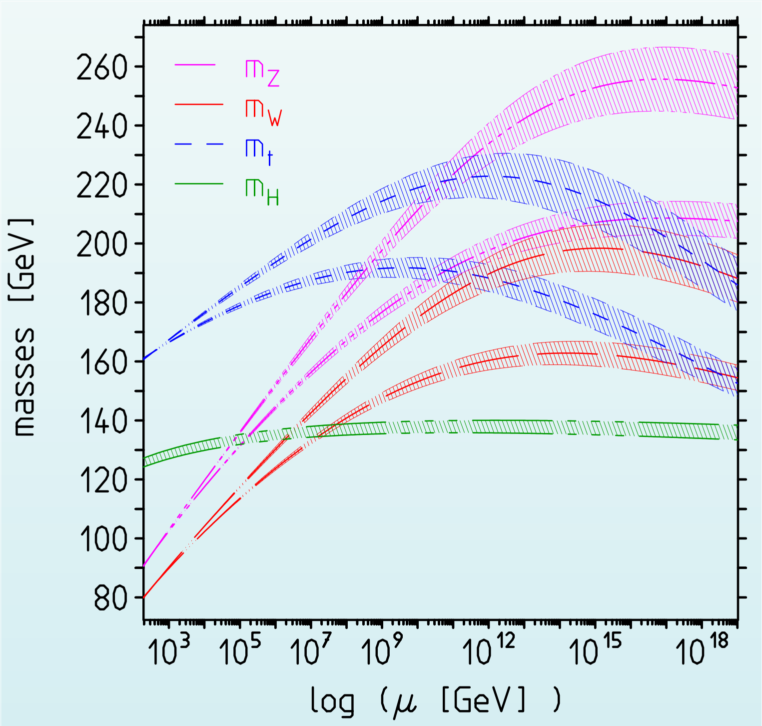
$$\mu^2\frac{d}{d\mu^2}v^2(\mu^2) = 3\,\mu^2\frac{d}{d\mu^2}\left[\frac{m_H^2(\mu^2)}{\lambda(\mu^2)}\right] \equiv v^2(\mu^2)\left[\gamma_{m^2} - \frac{\beta_\lambda}{\lambda}\right]$$

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



Renormalization of the SM gauge couplings $g_1 = \sqrt{5/3}g_Y, g_2,\ g_3$, of the top, bottom and τ couplings (y_t, y_b, y_τ), of the Higgs quartic coupling λ and of the Higgs mass parameter m. All parameters are defined in the $\overline{\mathrm{MS}}$ scheme. We include two-loop thresholds at the weak scale and three-loop RG equations. The thickness indicates the $\pm 1\sigma$ uncertainties in M_t, M_h, α_3.





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.

- 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 $\mu = M_{\rm Pl}$

❐ running top Yukawa QCD takes over: IR free ⇒UV free

❐ running Higgs self-coupling top Yukawa takes over: IR free ⇒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 $\mu = M_{\rm Pl}$.

➠ 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 $\mu = M_{\rm Pl}$ gauge couplings are all close to $g_i \sim 0.5$, $y_t \sim 0.35$, $\sqrt{\lambda} \sim 0.32$.

- 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.

Comparison of results at $M_{\rm Pl}$:

	my findings	Degrassi et al
$g_1(M_{\rm Pl})$	0.4561	0.4777
$g_2(M_{\rm Pl})$	0.5084	0.5057
$g_3(M_{\rm Pl})$	0.4919 ± 0.0046	0.4873
$y_t(M_{\rm Pl})$	0.3551 ± 0.0037	0.3823
$\sqrt{\lambda}(M_{\rm Pl})$	$0.2993 \div 0.4060$	i 0.1131
$\lambda(M_{\rm Pl})$	$0.0896 \div 0.1648$	-0.0128

Most groups find tachyonic Higgs above $\mu \sim 10^9$ GeV!

Note: $\lambda = 0$ is an essential singularity and the theory cannot be extended beyond a possible zero of λ: remind $v = \sqrt{6m^2/\lambda}$!!!

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.

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

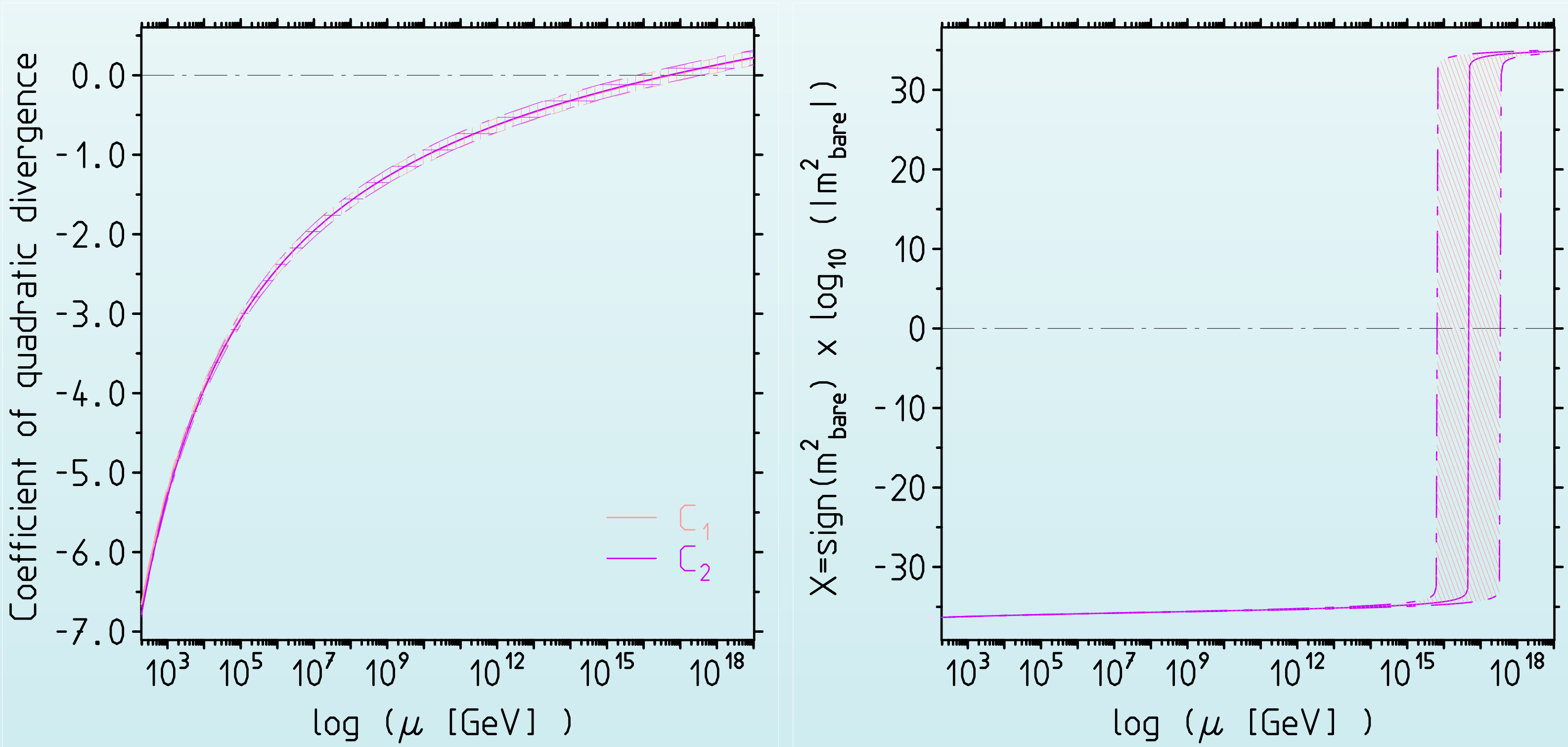
Veltman 1978 modulo small lighter fermion contributions, one-loop coefficient function C_1 is given by

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

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.

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: the zero in C_1 and C_2 for $M_H = 125.5 \pm 1.5$ GeV. Right: shown is $X = \mathrm{sign}(m^2_{\rm bare}) \times \log_{10}(|m^2_{\rm bare}|)$, which represents $m^2_{\rm bare} = \mathrm{sign}(m^2_{\rm bare}) \times 10^X$.

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

➡ the coefficient $C_n(\mu)$ exhibits a zero, for $M_H = 125$ GeV at about $\mu_0 \sim 7 \times 10^{16}$, not far below $\mu = M_{\text{Planck}}$

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

➡ this represents a phase transition which triggers the Higgs mechanism and seems to play an important role for cosmic inflation

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

➡ the jump in vacuum density, thus agrees with the renormalized one: $-\Delta\rho_{\text{vac}} = \frac{\lambda(\mu_0^2)}{24} v^4(\mu_0^2)$, and thus is $O(v^4)$ and **not** $O(M^4_{\text{Planck}})$.

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 $M_{\rm Planck}$.

Comment on finite temperature effects:

- finite temperature effective potential $V(\phi, T)$:

$T = 0$: $V(\phi, 0) = -\frac{\mu^2}{2}\,\phi^2 + \frac{\lambda}{24}\,\phi^4$

$T \neq 0$: $V(\phi, T) = \frac{1}{2}\left(g_T\,T^2 - \mu^2\right)\phi^2 + \frac{\lambda}{24}\,\phi^4 + \cdots$

Usual assumption: Higgs is in the broken phase $\mu^2 > 0$

EW phase transition is taking place when the universe is cooling down below the critical temperature $T_c = \sqrt{\mu^2/g_T}$.

My scenario: above the PT μ_0 Higgs is in symmetric phase $-\mu^2 \to m^2 = m_H^2 + \delta m_H^2$

Is the phase transition is triggered by δm_H^2 or by $g_T\, T^2$ term? Which term is larger in the early universe?

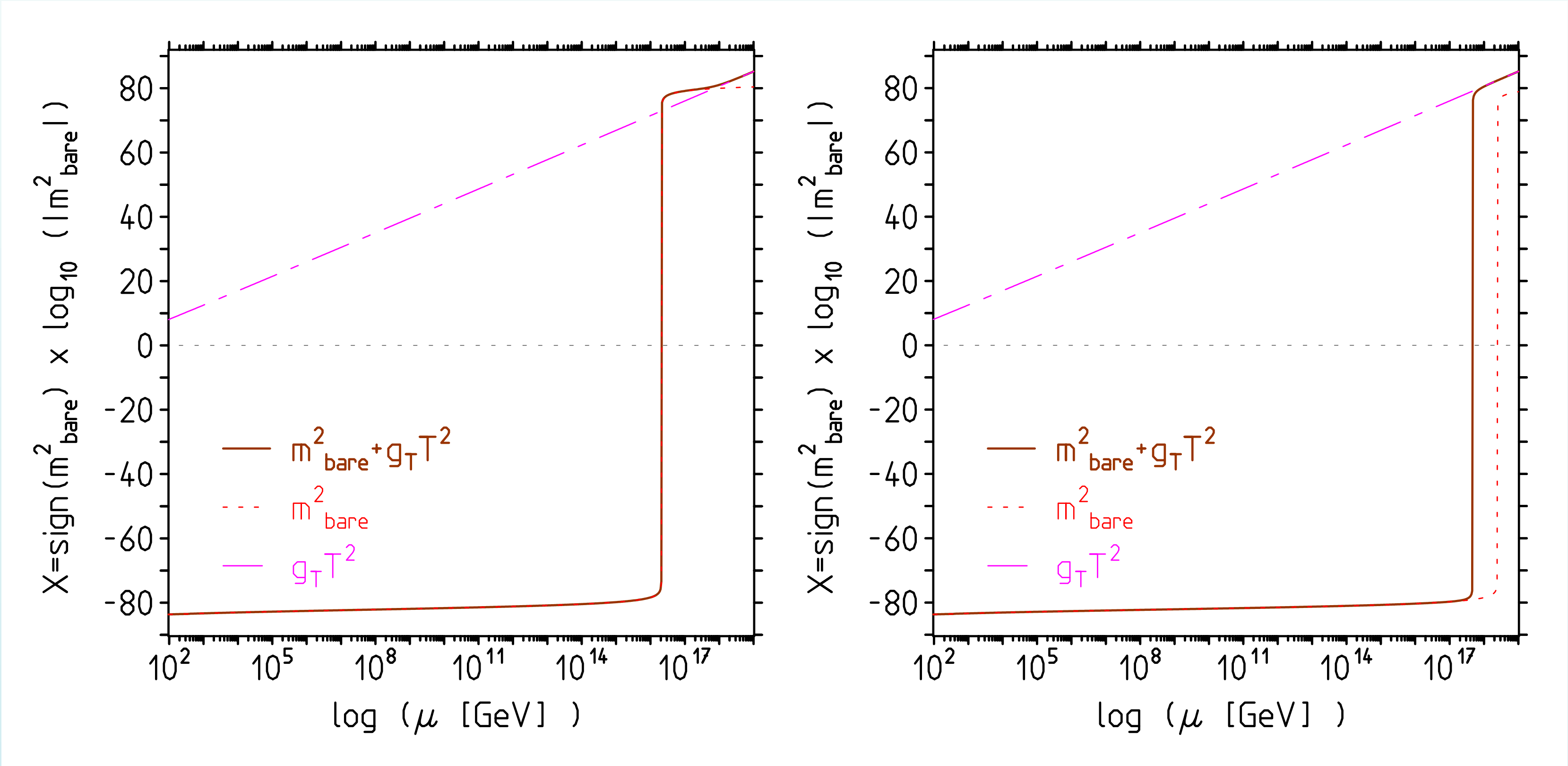
I find $m^2(\mu = M_{\rm Pl}) \simeq 1.27 \times 10^{-3}\, M_{\rm Pl}^2$ such that $T(\mu = \mu_0) \simeq 8.12 \times 10^{29}\ {}^\circ{\rm K}$ and $T(\mu = m(M_{\rm Pl})) \simeq 5.04 \times 10^{30}\ {}^\circ{\rm K}$

Note $T_{\rm Pl} \simeq 1.42 \times 10^{32}\ {}^\circ{\rm K}$ (Temperature of the Big Bang)

g_T at $M_{\rm Pl}$ in SM:

$$g_T = \frac{1}{4v^2}\left(2m_W^2 + m_Z^2 + 2m_t^2 + \frac{1}{2}\,m_H^2\right) = \frac{1}{16}\left[3\,g^2 + g'^2 + 4\,y_t^2 + \frac{2}{3}\,\lambda\right] \approx 0.0983 \sim 0.1$$

- the dramatic jump in $m^2_{\rm bare}$ at μ_0 in any case drags the Higgs into the broken phase not far below μ_0



Effect of finite temperature on the phase transition

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 ⇒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

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

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

may be written as

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

field equation

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

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

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

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

➠ harmonic oscillator with friction

Clearly supported by observation: Planck 2013 results

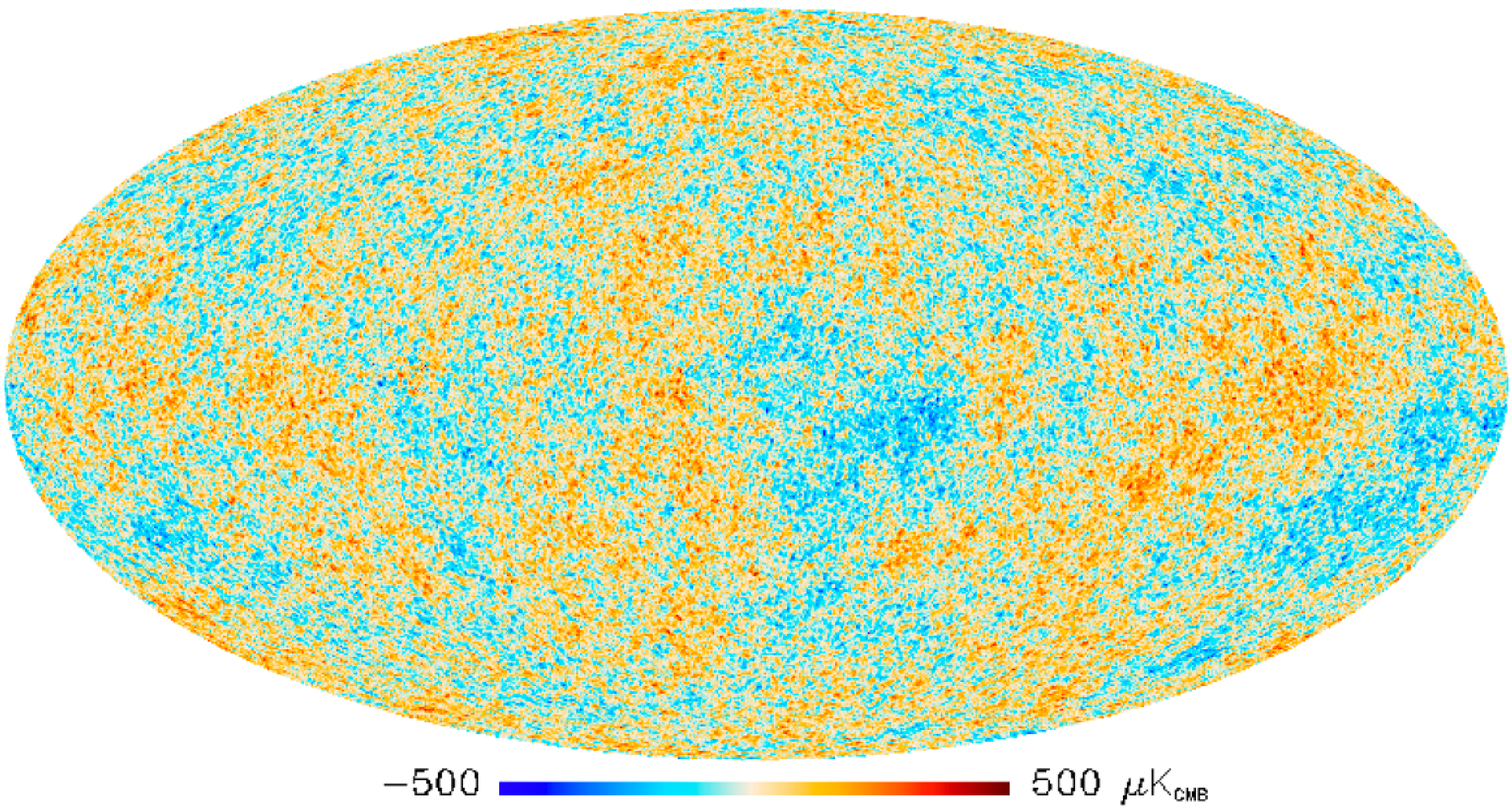


Fig. 14. The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization).

The cosmological constant is characterized by the equation of state $w = p/\rho = -1$, in my scenario a prediction of the SM before the PT ($\mu > \mu_0$) which triggers inflation, and which is stopped by the PT ($\mu = \mu_0$); indeed Planck (2013) finds $w = -1.13^{+0.13}_{-0.10}$.

Scalar density fluctuations: $\delta\rho = \frac{\mathrm{d}V}{\mathrm{d}\phi}\,\delta\phi$

spectrum $A_s^2(k) = \left.\frac{V^3}{M_{\rm Pl}^6\,(V')^2}\right|_{k=aH}$ to be evaluated at the moment when the physical scale of the perturbation $\lambda = a/k$ is equal to the Hubble radius H^{-1}.

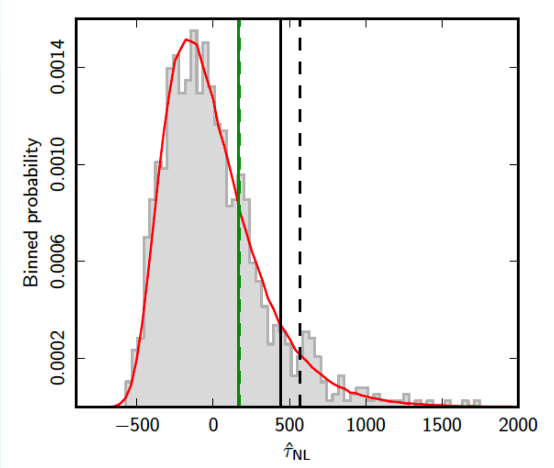
Observations are parametrized by a power spectrum
$A_s^2(k) \propto k^{n_s-1}\ ; \quad n_s = 1 - 6\epsilon + 2\eta$

slow-roll for a long enough time requires $\epsilon, \eta \ll 1$

$\epsilon \equiv \frac{M_{\rm Pl}^2}{8\pi}\,\frac{1}{2}\left(\frac{V'}{V}\right)^2 \sim 6 \times 10^{-4}$ and $\eta \equiv \frac{M_{\rm Pl}^2}{8\pi}\,\frac{V''}{V} \sim 9 \times 10^{-4}$

I find $n_s \approx 0.998$, confronts Planck mission result $n_s = 0.9603 \pm 0.0073$ ballpark OK.

Planck data are consistent with Gaussian primordial fluctuations. There is no evidence for primordial Non Gaussian (NG) fluctuations in 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)

- 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.

- numbers depend sensibly on what $\lambda(M_H)$ and $y_t(M_t)$ are (ILC!)

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 $M_{\rm Pl}$ consolidated; crucial point $M_{\rm Pl}$ >>>> ... from what we can see!

- 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 dimension 5 and/or dimension 6 **operators** as leading corrections. These corrections are expected to get relevant only closer to the Planck scale.

- Last but not least in Higgs phase:

There is no hierarchy problem in the SM!

It is true that in the relation

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

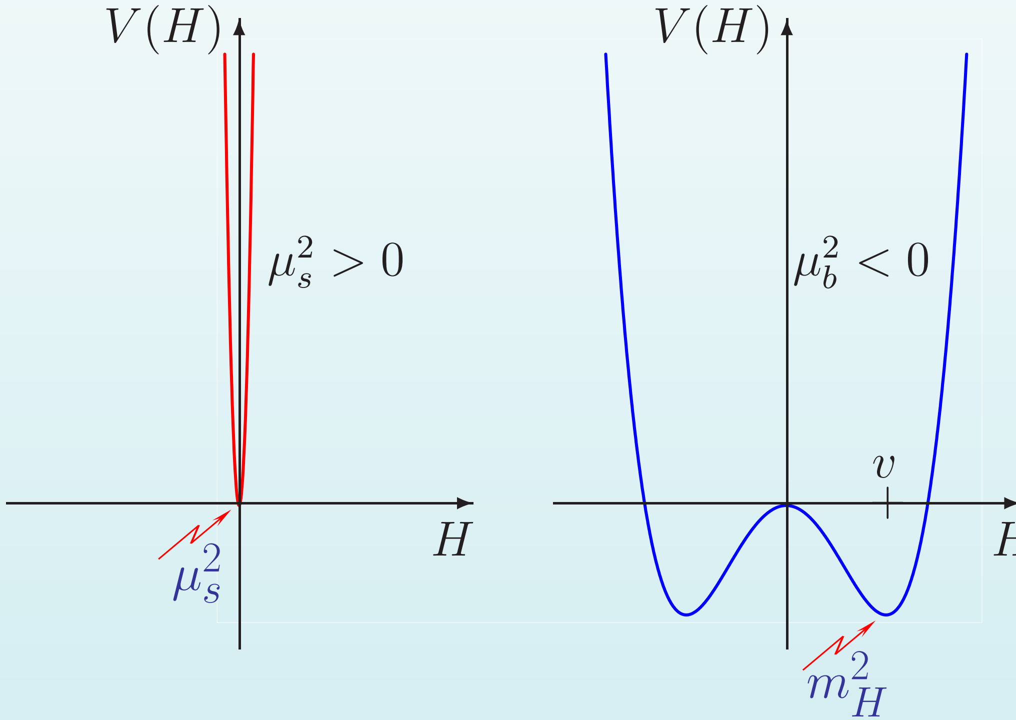
both $m^2_{H\,\mathrm{bare}}$ and δm^2_H are many many orders of magnitude larger than $m^2_{H\,\mathrm{ren}}$. However, in the broken phase $m^2_{H\,\mathrm{ren}} \propto v^2(\mu_0^2)$ is $O(v^2)$ not $O(M^2_{\mathrm{Pl}})$, i.e. in the broken phase the Higgs is naturally light. That the Higgs mass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

$$m_W^2(\mu^2) = \frac{1}{4}\, g^2(\mu^2)\, v^2(\mu^2)\ ; \quad m_Z^2(\mu^2) = \frac{1}{4}\, (g^2(\mu^2) + g'^2(\mu^2))\, v^2(\mu^2)\ ;$$

$$m_f^2(\mu^2) = \frac{1}{2}\, y_f^2(\mu^2)\, v^2(\mu^2)\ ; \quad m_H^2(\mu^2) = \frac{1}{3}\, \lambda(\mu^2)\, v^2(\mu^2)\ .$$

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. Note not only sign of μ^2 changes but also its value!

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. My view: inflation is an unavoidable prediction of the SM

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

- for running $\alpha_{\rm em}$ and $\sin^2\Theta_{\rm eff}$ $\Leftrightarrow$ 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

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

? key problems

dark energy , dark matter , baryon asymmetry

persist, but must be reanalyzed in the new scenario!

? 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!

! new physic (cold dark matter etc.) still must exist; however, if needed help to stabilize vacuum, should not deteriorate the gross features of the SM including MFV scenario.

Bare in mind: the Higgs mass miraculously turns out to have a value as it was expected form vacuum stability. It looks like a tricky conspiracy with other couplings to reach this “purpose”. If it misses to stabilize the vacuum, why does it just miss it almost not?

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

Thanks you for your attention!

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Thanks you for your attention!