Particle Physics as a Conspiracy

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Introduction

The path to physics at the Planck scale

TOE type Paradigm: the closer we look the more symmetric the world looks

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

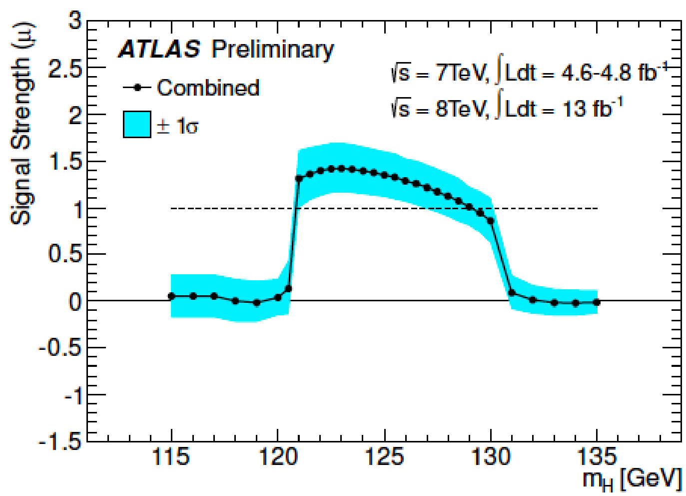
Emergence Paradigm: the less close you look the simpler it looks

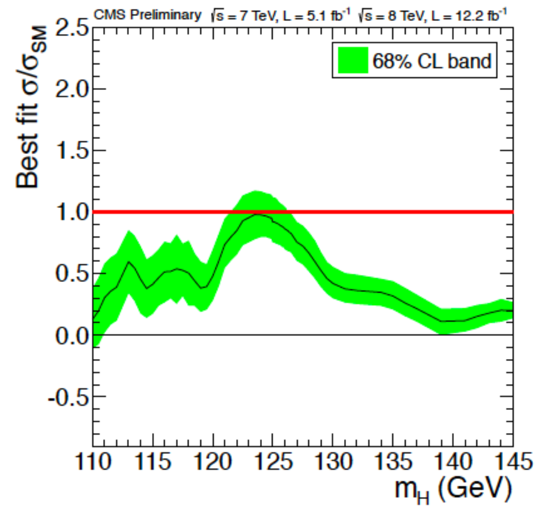
ETHER $\sim$ Planck medium $\rightarrow$ low energy effective QFT $\rightarrow$ SM.

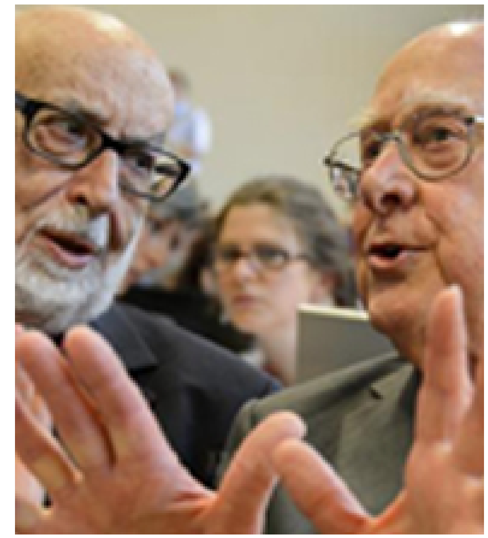
The “true world” seen from far away: unlike in renormalized QFT, here the relationship between bare and renormalized parameters obtains a physical meaning (Landau 1955 [NP 1962], Wilson 1971 [NP 1982], $\cdots$)

top-down approach versus bottom-up approach

✌ 4th July 2012 LHC ATLAS&CMS Higgs discovered ⇒ the SM completion





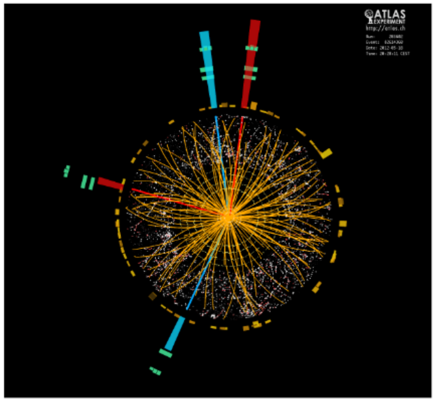


Higgs mass scan by ATLAS and CMS Englert&Higgs Nobel Prize 2013

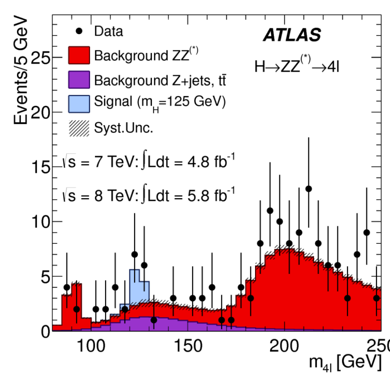
Higgs finally found as expected, so what? A milestone of particle physics in any case!

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

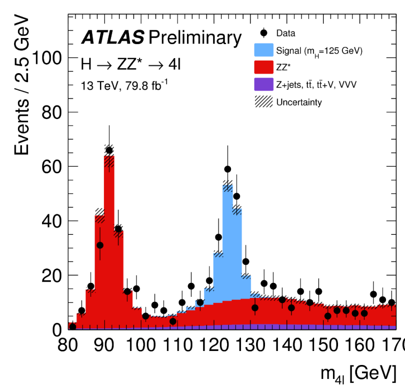
... from discovery to properties, example $H \to ZZ^* \to 4\ell$



2012



2017



$$M_H = 125.10 \pm 0.14$$

More surprising than its existence is the value of its mass below the Fermi scale!

Fermi scale=Higgs VEV $v = \sqrt{1/\sqrt{2}\,G_F} \simeq 246$ GeV

❒ in broken phase (SSB at low energy), non-vanishing Higgs field VEV v, all masses are determined by mass-coupling relations

$$M_W^2 = \frac{1}{4} g^2 v^2 \; ; \quad M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2 \; ; \quad M_f^2 = \frac{1}{2} y_f^2 v^2 \; ; \quad M_H^2 = \frac{1}{3} \lambda v^2 \, .$$

❒ like all other particles the Higgs mass appears generated by the non-vanishing VEV $v \neq 0$

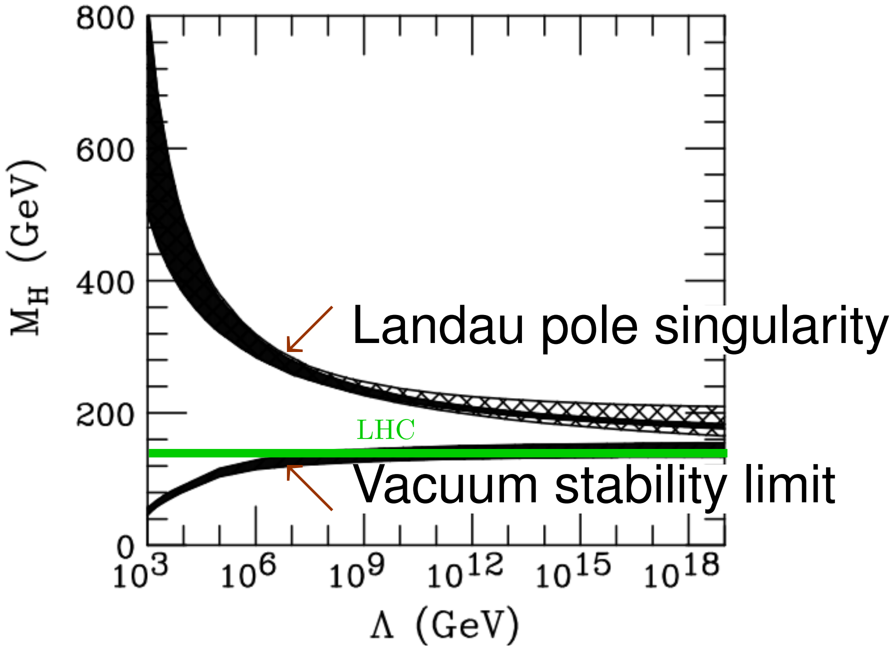
❒ Higgs naturally in the ballpark of the other particles! No naturalness problem! All couplings perturbative!

- going to high energy = temperature (early universe) a transition to the symmetric phase in expected to take place at some scale μ_0 where $v(\mu) \equiv 0 \; ; \;\; \mu \geq \mu_0$, i.e. $M_W, \, M_Z, \, M_f \equiv 0$, while M_H unconstrained in unbroken phase at very high energy (early universe) [SSB is a LE feature].

- only in the symmetric phase the Higgs mass plays a very different role from all other particles (not protected by a symmetry $\Rightarrow$hierarchy problem?)

Common Folklore: hierarchy problem requires SUSY extension of the SM (killing quadratic divergences), otherwise M_H expected to be huge.

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



Riesselmann, Hambye 1996

$M_H < 180$ GeV

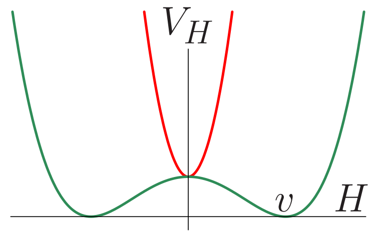
– first 2-loop analysis, knowing M_t –

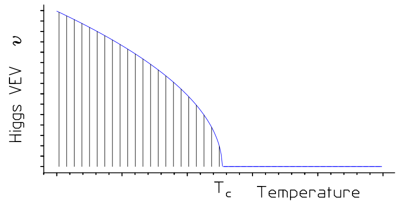
SM Higgs remains perturbative up to scale Λ_{Planck} if it is light enough (upper bound=avoiding Landau pole) and Higgs potential remains stable ($\lambda > 0$) if Higgs mass is not too light [parameters used: $m_t = 175[150 - 200]$ GeV ; $\alpha_s = 0.118$]

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

Key object of our interest: the Higgs potential

❒ Higgs mechanism





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

❖ vacuum jumps from $v = 0$ to $v = \sqrt{-6m^2/\lambda} \neq 0$

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

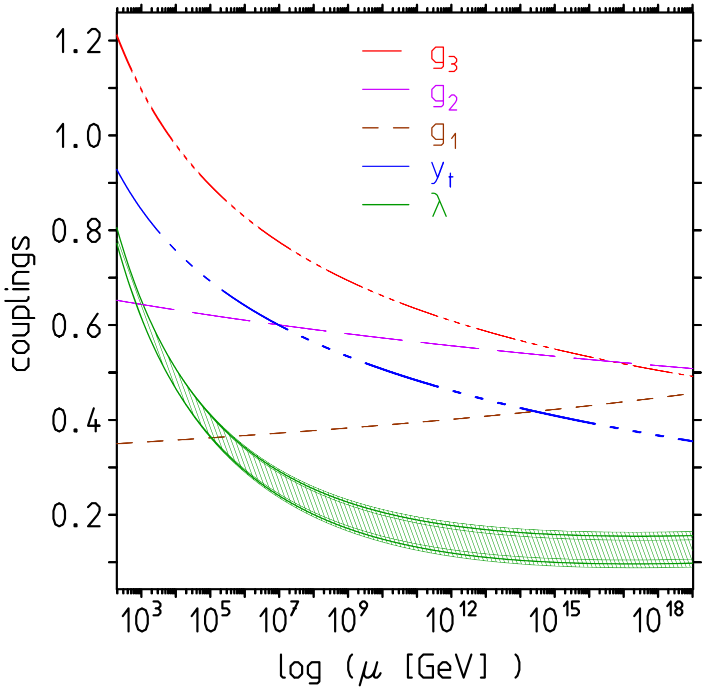
- low energy expansion in E/Λ lets us see a renormalizable effective QFT: the SM
  –as at present (and future) accelerator energies $E <<<< M_{\rm Pl}$
  all operators $\mathrm{dim} > 4$ far from being observable

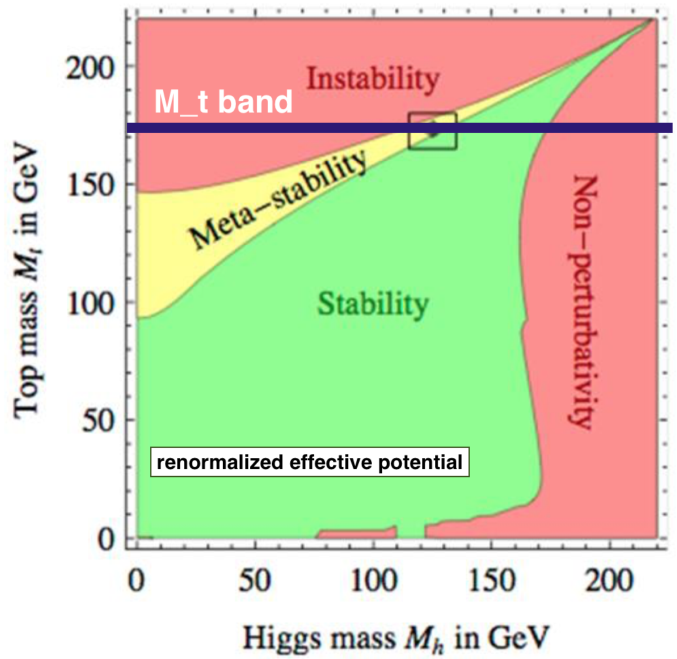
- in this scenario the relation between bare and renormalized parameters is physics: bare parameters predictable from known renormalized ones

- all so called UV singularities (actually finite now) must be taken serious including quadratic divergences – cutoff finite $\Rightarrow$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.

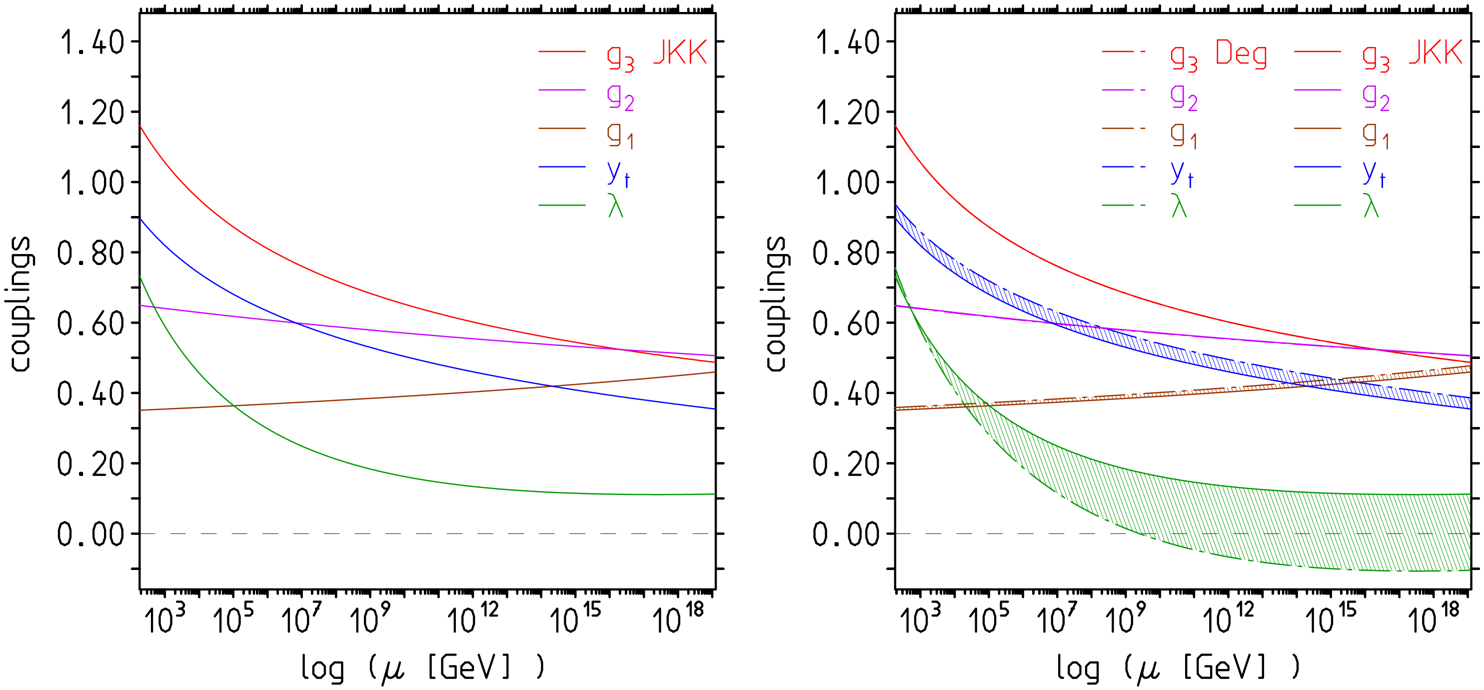
The SM running parameters





The SM dimensionless couplings in the $\overline{\mathrm{MS}}$ scheme as a function of the renormalization scale for $M_H = 124 - 126$ GeV. Right: Buttazzo et al 13

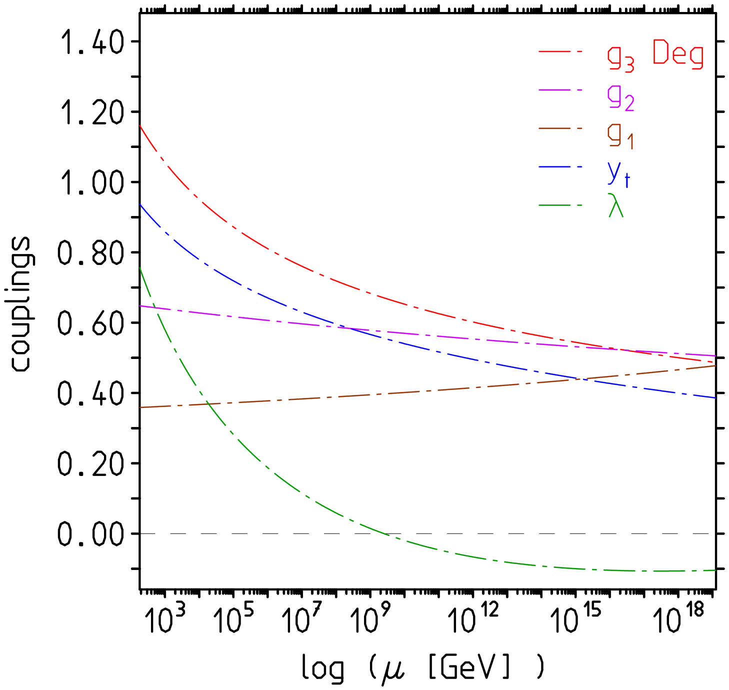
- very narrow stability window given M_t and other SM masses $\Rightarrow$largely fixes the Higgs boson mass by a stability requirement!?

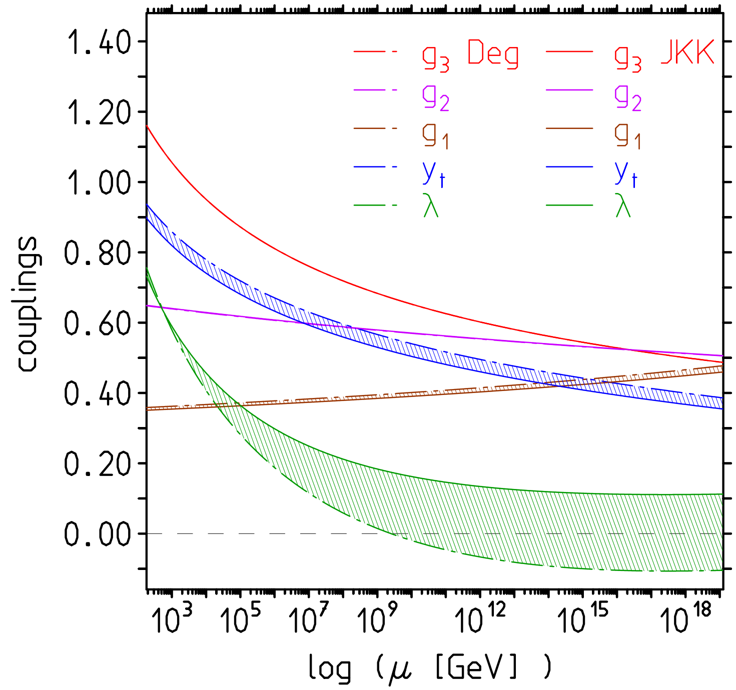


F.J.,Kalmykov,Kniehl, On-Shell vs $\overline{\mathrm{MS}}$ parameter matching

❖ the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever $\Rightarrow$ the challenge for LHC and ILC/FCC-ee: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties in $\alpha(M_Z)$ and $\alpha_2(M_Z)$

New gate to precision cosmology of the early universe!





Shaposnikov et al., Degrassi et al. matching

- the big issue is the very delicate conspiracy between SM couplings: precision determination of parameters more important than ever $\Rightarrow$ the challenge for LHC and ILC/FCC-ee: precision values for λ, y_t and α_s, and for low energy hadron facilities: more precise hadronic cross sections to reduce hadronic uncertainties in $\alpha(M_Z)$ and $\alpha_2(M_Z)$

New gate to precision cosmology of the early universe!

- perturbation expansion works up to the Planck scale!
  no Landau pole or other singularities, Higgs potential likely remains stable!
- $U(1)_Y$ screening (IR free), $SU(2)_L$, $SU(3)_c$ antiscreening (UV free): g_1, g_2, g_3

as expected (standard wisdom)

- Top Yukawa y_t and Higgs λ: screening if standalone (IR free, like QED)

as part of SM, transmutation from IR free to UV free

As SM couplings are as they are: QCD dominance in top Yukawa RG requires $g_3 > \frac{3}{4} y_t$, top Yukawa dominance in Higgs RG requires $\lambda < \frac{3(\sqrt{5}-1)}{2} y_t^2$ in the gaugeless ($g_1, g_2 = 0$) limit.

In the focus:

- does Higgs self-coupling stay positive $\lambda > 0$ up to $\Lambda_{\rm Pl}$?
- the key question/problem concerns the size of the top Yukawa coupling y_t
  decides about stability of our world! — [$\lambda = 0$ would be essential singularity!]

Will be decided by:
- more precise input parameters
- better established EW matching conditions

Low energy effective QFT of a cutoff system

The low energy expansion:

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

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

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

Low energy effective: drop power suppressed terms

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

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

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

- Crucial point: cutoff $\Lambda_{\rm Pl}$ 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 $\overline{\rm MS}$ scale μ i.e. $\kappa = \Lambda/\mu$.

- the preasymptotic theory is a local relativistic QFT Wilson 1972

- Key observation: elementary particle interactions have rather weak coupling such that perturbation theory works in general (besides low enrgy QCD)

- Keep in mind: $\Lambda_{\rm Pl}$ is very very high, all cutoff structure killed at present accelerator energies

In contrast: low energy effective hadron theories suffer from close-by cutoff
in practice

The low energy expansion at a glance

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

tamed by symmetries

Note: d=6 operators at LHC suppressed by $(E_{\rm LHC}/\Lambda_{\rm Pl})^2 \approx 10^{-30}$

⇒ require chiral symmetry, gauge symmetry, $\cdots$??? self-organized!

– just looks symmetric as we cannot see the details –

The low energy expansion at a glance

		operator	scaling behavior
depends on UV-completion		∞–many irrelevant operators	
	cutoff dependent regime	$(\Box\phi)^2, (\bar{\psi}\psi)^2, \cdots$	$(E/\Lambda_{\mathrm{Pl}})^2$
		$\bar{\psi}\sigma^{\mu\nu}F_{\mu\nu}\psi, \cdots$	$(E/\Lambda_{\mathrm{Pl}})$
renormalizable QFT	universal low energy tail	$(\partial\phi)^2, \phi^4, (F_{\mu\nu})^2, \cdots$	$\ln(E/\Lambda_{\mathrm{Pl}})$
		$\phi^3, \bar{\psi}\psi$	$(\Lambda_{\mathrm{Pl}}/E)$
		$\phi^2, (A_\mu)^2$	$(\Lambda_{\mathrm{Pl}}/E)^2$
		ϕ	$(\Lambda_{\mathrm{Pl}}/E)^3$

in tail all cutoff effects get removed by renormalization

– physical reparametrization –

! independent of UV-completion !

- infinite tower of dim > 4 irrelevant operators not seen at low energy

⇒simplicity of SM! Blindness to details implies more symmetries (Yang-Mills structure [gauge cancellations] with small groups: doublets, triplets besides singlets, Lorentz invariance, anomaly cancellation and family structure, triviality for space-time dimensions $D > 4$ [D=4 boarder case for interacting world at long distances, has nothing to do with compactification, extra dimensions just trivialize by themselves], etc.)

- 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.

> Who is tuning the temperature of the "thermostat"? ⇒ it is the expansion of the universe providing a temperature scan from the hot symmetric phase to the cold broken phase, where the Higgs VEV v appears as an order parameter! i.e. our thermostat (heat bath) is the expanding universe.

❒ In the symmetric phase at very high energy we see the bare system:

the Higgs field is a collective field exhibiting an effective mass generated by radiative effects

$$m^2_{\rm bare} \approx \delta m^2 \text{ at } M_{\rm Pl}$$

eliminates fine-tuning problem at all scales!

Many examples in condensed matter systems, Coleman-Weinberg mechanism

❒ "free lunch" in Low Energy Effective SM (LEESM) scenario:

- renormalizability of long range tail automatic!
- so are all ingredients required by renormalizability:
- non-Abelian gauge symmetries, chiral symmetry, anomaly cancellation, fermion families etc
- last but not least the existence of the Higgs boson!

*** all emergent ***
non-renormalizable stuff
heavily suppressed

Deriving renormalizability by a low energy expansion

We only include SM fields and exclude dim 5 and higher operators which are non-renormalizable in any case. Fermions in bilinears only (currents).
The starting point is the general form of the fermion current. Let the spinor $\Psi_\alpha = (e, \nu_e, \mu, \nu_\mu, \ldots)$ include the known fermion fields. The current has the form

$$J^{\mu a} = \bar{\Psi}_\alpha \gamma^\mu \{L^a_{\alpha\beta} P_- + R^a_{\alpha\beta} P_+\} \Psi_\beta \,,$$

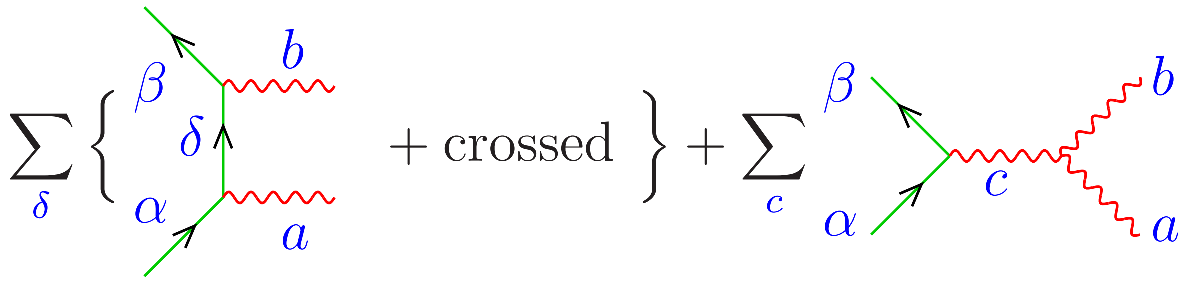
where $P_\pm = \frac{1}{2}(1 \pm \gamma_5)$ are the right and left handed projections, respectively. The intermediate vector boson Lagrangian then reads

$$\mathcal{L}_1 = J^{\mu a} W_{\mu a}$$

which leads to s^2–terms ($s = E^2_{\mathrm{cm}}$) in $\Psi \bar{\Psi} \to WW$. This can be cured by adding new interactions, the triple gauge vertices (TGV's):

$$\mathcal{L}_2 = D_{abc} W^c_\mu W^b_\nu \partial^\mu W^{\nu a} \quad .$$

The condition of compensation of the s^2-terms in



leads to the algebraic relationships

$$\left[L^a, L^b\right] = iD_{abc}L^c \ ; \ \left[R^a, R^b\right] = iD_{abc}R^c \ ,$$

telling us that there is symmetry needed, the coupling structure of a Lie–group $G_L \otimes G_R$. Next, inspection of $WW \to WW$ scattering again exhibits s^2-terms. They can be canceled by new quartic interactions

$$\mathcal{L}_3 = \frac{1}{4} E_{abcd} W^a_\mu W^{\mu b} W^c_\nu W^{\nu d} \quad .$$

The absence of s^2-terms implies that D_{abc} is antisymmetric and satisfies the Jacobi identity and

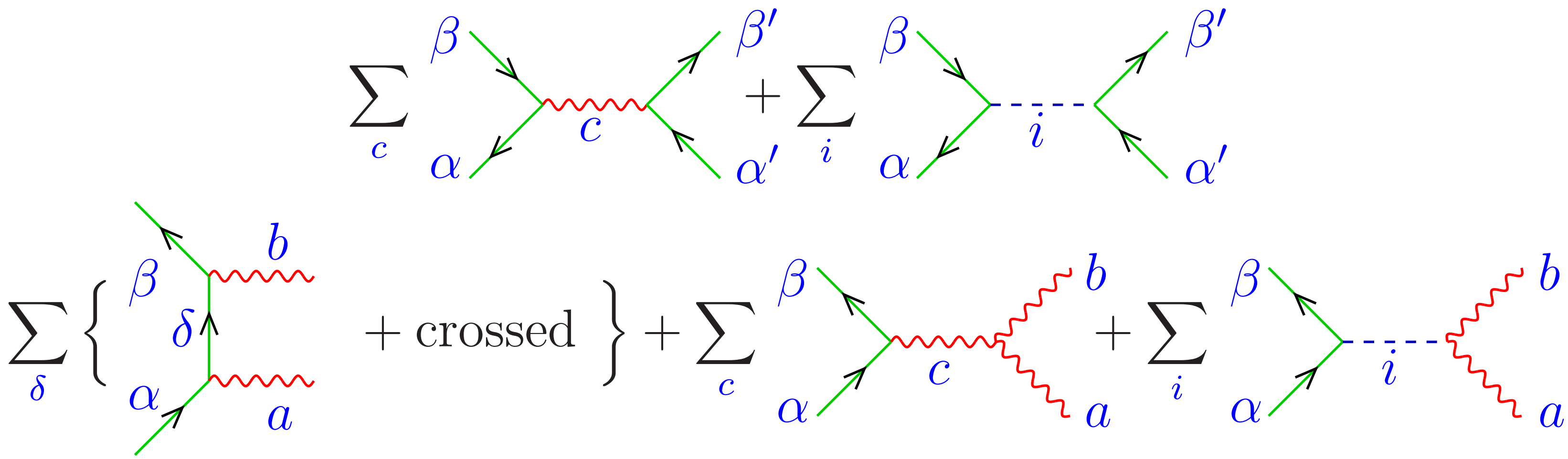
$$2E_{abcd} = D_{ade}D_{cbe} + D_{ace}D_{dbe} \quad .$$

Thus one finds that, provided

- all couplings surviving in the tail have dimension ≤ 0 (otherwise they are not renormalizable anyway), and
- s^2–terms are absent,

we obtain a theory with *Yang–Mills couplings* in the fermion and gauge boson sector. This works for all channels at the tree level.

There are still unacceptable terms growing linearly with s. Since spin 1/2 and spin 1 fields have been taken into consideration in a general way there are no further compensations possible without adding new types of fields. Adding particles of spin higher than 1 in any case would led to a non-renormalizable theory. Hence, we are left with only one possibility: to introduce spin 0 particles, *the Higgs boson*. The condition of compensation of the s-terms in



fixes the couplings of the Higgs to the gauge bosons as well as the Yukawa couplings. The Higgs self-coupling remains a free parameter.

In fact the condition of absence of linear s-terms requires the "Goldstone solution with locally gauged fields," which means the *Higgs mechanism* (Cornwall, Levin, Tiktopoulos 1973).

Here we consider the SM to be a LEET and we do not have to impose the absence of s - power enhanced terms, because powers of s only come into play in conjunction with a $\Lambda_{\rm Pl}^2$ suppression. And since $\Lambda_{\rm Pl}$ is so large the $s/\Lambda_{\rm Pl}^2$ terms are not seen. What is seen is what conspires as a non-Abelian gauge symmetry structure or more generally, as in the SM, as 'SBGT'.

Most mysterious seems the existence of a strictly massless photon! The $U(1)_{\rm em}$ does not seem to be dynamically generated similarly to the weak sector.

As noted by Veltman 1989 the SM derives from the assumptions:
1) local field theory
2) interactions follow from a local gauge principle
3) renormalizability
4) masses derive from the minimal Higgs system (i.e. one scalar only)
5) ν_R which we know must exist does not carry hypercharge.
Note that all points besides the last one are emergent structures in a LEESM as we may learn from Veltman, Llewellyn Smith, Bell,Cornwall et al.

the consequences of the assumptions are:

- breaking $SU(2)_L$ by a minimal Higgs automatically leads to a global $U(1)_Y$, which can be gauged
- parity violation of $SU(2)_L$ automatic
- $\rho = M_W^2/(M_Z^2 \cos^2 \Theta_W) = 1$ derives from "custodial" accidental global $SU(2)_{\mathrm{cust}}$
- the existence of the photon (one zero eigenvalue in spin 1 mass matrix)
- parity conservation of QED
- the validity of the Gell-Mann-Nishijima relation $Q = T_3 + \frac{Y}{2}$
- family structure (lepton-quark conspiracy – $U(1)_Y$ anomaly cancellation)

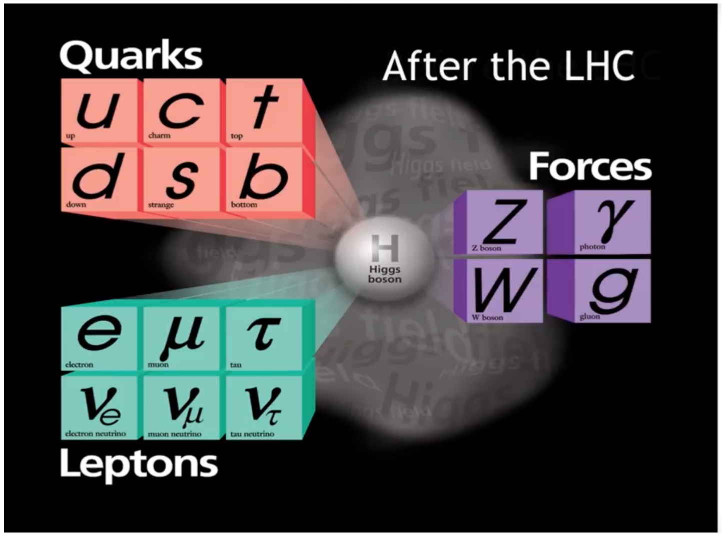
❖ charge quantization (if $Y_{\nu R} = 0$ then $Q_i = T_{3i} + \frac{Y_i}{2}$ fixes Q_i)

- we thus understand how various excitations in the chaotic Planck medium develop a pattern like the SM as a low energy effective structure

- renormalizability as a consequence of the low energy expansion and the very large gap between the EW and the Planck scales plus a certain minimality (not too little but not too much e.g. only up to symmetry triplets) determines the SM structure without much freedom

- minimality is not a new concept in physic as we know e.g. from the principle of least action.

- 3 fermion families are required in order CP violation emerges in a natural way, and to make baryogenesis eventually possible within the LEESM scenario.



The SM is a minimal renormalizable completion of Fermi weak interaction + QED, supplemented by QCD and two more families

- "What is not capable of surviving at long distances does not exist there" (Darwin revisited)

The SM appears as a natural minimal emergent structure in a low energy expansion from a cutoff system sitting at the Planck scale!

More consequences:
This kind of scenario, the SM which we supplemented by the Planck cutoff, leads to unexpected consequences concerning its high energy behavior. The latter is governed by the bare theory, which must have been the relevant theory in the very hot early universe.

❖The relationship between the renormalized and bare theory is calculable

❖The energy dependence of parameters now crucial, this also concerns possible power corrections (relevant operators: Higgs mass term and vacuum energy=Higgs potential VEV $\langle V(\phi)\rangle \neq 0$)

❖Leading irrelevant operators: dim 5 (neutrino masses) and dim 6 baryon number violating (baryogenesis) likely relevant at epoch of EW phase transition.

❖Within the SM charge screening is an exceptional property, anti-screening the rule. Above non-perturbative QCD regime, the SM and in particular the high energy phase (early cosmology) perturbatively accessible

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.

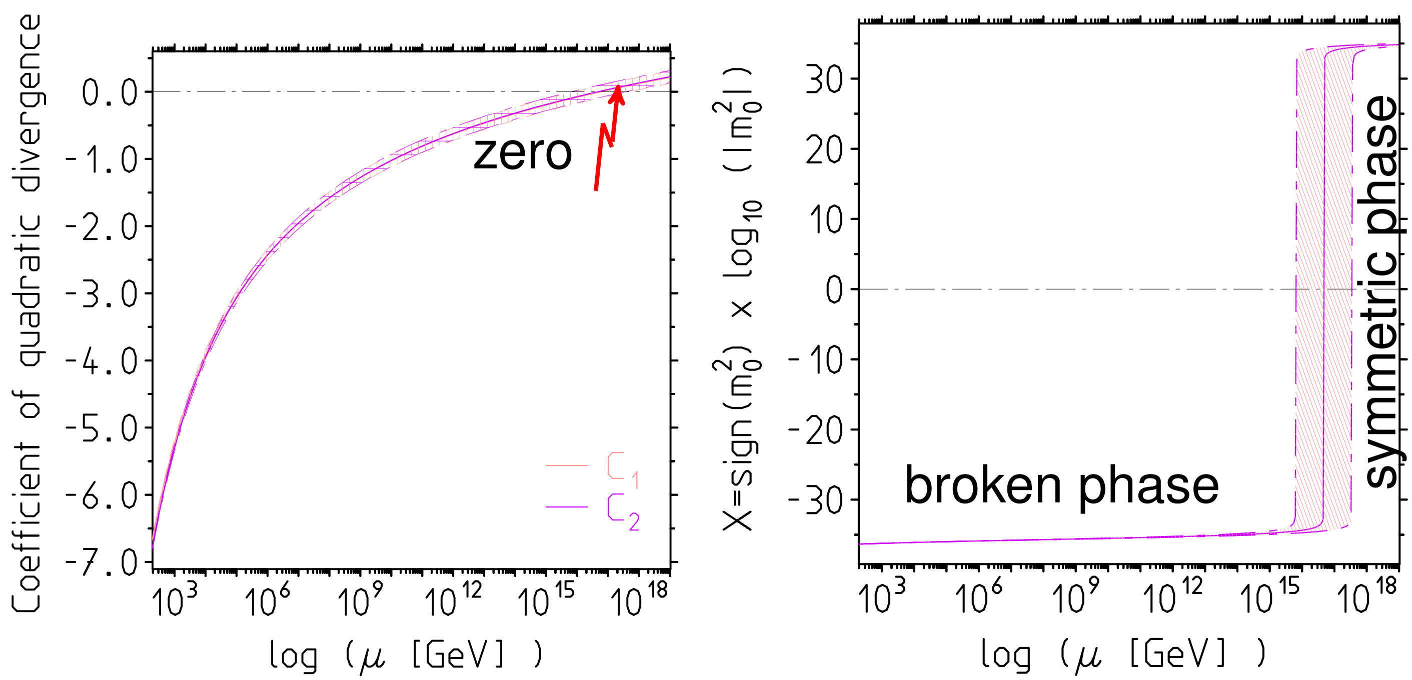
$$\delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\, C_1$$

Veltman's 1981 "The Infrared - Ultraviolet Connection" 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: parameters are running; C_1 is universal and depends on dimensionless gauge, Yukawa and Higgs self-coupling only, the RGs of which are unambiguous, the two-loop contribution ΔC_2 is numerically small.

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 $M_H = 125.9 \pm 0.4$ GeV. Right: shown is $X = \text{sign}(m^2_{\text{bare}}) \times \log_{10}(|m^2_{\text{bare}}|)$.

$$m^2_{\text{bare}} = \text{sign}(m^2_{\text{bare}}) \times 10^X$$

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

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

- 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 (PT), which triggers the Higgs mechanism as well as cosmic inflation as $\boxed{V(\phi) \gg \frac{1}{2}\,\dot{\phi}^2}$ by the large $m_{H\,\rm bare}$ for $\mu > \mu_0$

- at the transition point μ_0 we have $m_{H\,\rm bare} = m_H(\mu_0^2)$ and $v_{\rm bare} = v(\mu_0^2)$, where $v(\mu^2)$ is the $\overline{\rm MS}$ renormalized VEV; power cutoff effects nullified!

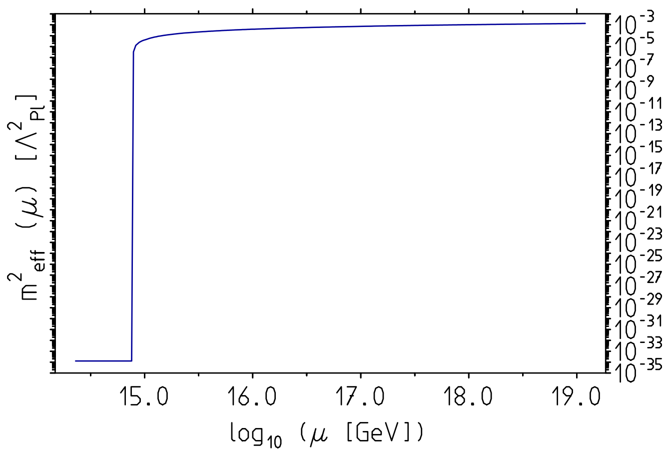
- the jump in vacuum density, thus agrees with the renormalized one: $-\Delta\rho_{\rm vac} = \frac{\lambda(\mu_0^2)}{24}\, v^4(\mu_0^2)$, and thus is $O(v^4)$ and **not** $O(M^4_{\rm Planck})$.

Remark on the impact on inflation

You know the SM hierarchy problem? True SM predicts large bare Higgs boson mass!

The renormalized Higgs boson mass is small (at EW scale) the bare one is huge due to radiative corrections going with the UV cutoff assumed to be given by the Planck scale $\Lambda_{\rm Pl} \sim 10^{19}$ GeV.

$$m^2_{\rm Higgs,\ bare} = m^2_{\rm Higgs,\ ren} + \delta m^2$$
$$\delta m^2 = \frac{\Lambda^2_{\rm Pl}}{(16\pi^2)}\, C(\mu)$$



- Is this a problem? Is this unnatural?
- It is a prediction of the SM!

❒ At low energy we see what we see (what is to be seen): the renormalizable, renormalized SM as it describes close to all we know up to LHC energies.

● What if we go to very very high energies even to the Planck scale?

❒ Close below Planck scale we start to sees the bare theory i.e. a SM with its bare short distance effective parameters, so in particular a very heavy Higgs boson, which can be moving at most very slowly, i.e.

❶ the potential energy

$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{24}\phi^2$$ is large

❷ the kinetic energy

$$\frac{1}{2}\dot{\phi}^2$$ is small.

The Higgs boson contributes to energy momentum tensor providing

pressure
energy density

$$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

❒ As we approach the Planck scale (bare theory): slow–roll condition satisfied

$\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$ then $\longrightarrow$ $p \approx -V(\phi)\,;\;\; \rho \approx +V(\phi)$ $\longrightarrow$ $p = -\rho$

$\rho = \rho_\Lambda$ DARK ENERGY! system exhibits unusual equation of state, like ferromagnetic systems, as noted by Steven Bass

- The SM Higgs boson in the early universe provides a huge dark energy!
- In fact in the cutoff system the vacuum energy (CC) is well defined as

$$\rho_{\Lambda\,\mathrm{bare}} = \rho_{\Lambda\,\mathrm{ren}} + \delta\rho_{\mathrm{vac}} \; ; \quad \delta\rho_{\mathrm{vac}} = \langle V(\phi) \rangle = \frac{\Lambda^4}{(16\pi^2)^2} X(\mu)$$

with $8\,X(\mu) \simeq 2C(\mu) + \lambda(\mu) = 5\,\lambda + 3\,g_1^2 + 9\,g_2^2 - 24\,y_t^2$ which has a zero close to the zero of $C(\mu)$, when $2\,C(\mu) = -\lambda(\mu)$. Matching point $\rho_{\Lambda\,\mathrm{bare}} = \rho_{\Lambda\,\mathrm{ren}}$ cutoff effects nullified! Supports inflation above the zero of $X(\mu)$.

❒ What does the huge DE do? Provides anti-gravity inflating the universe!

Friedman equation: $\frac{\mathrm{d}a}{a} = H(t)\,\mathrm{d}t \longrightarrow a(t) = \exp Ht$ exponential growth of the radius $a(t)$ of the universe. $H(t)$ the Hubble constant $H \propto \sqrt{V(\phi)}$. Inflation stops quite quickly as the field decays exponentially. Field equation: $\ddot{\phi} + 3H\dot{\phi} \simeq -V'(\phi)$, for $V(\phi) \approx \frac{m^2}{2}\,\phi^2$ harmonic oscillator with friction ⇒Gaussian inflation (Planck 2013)

- the Higgs boson is the inflaton!

- Inflation tunes the total energy density to be that of a flat space, which has a particular value $\rho_{\rm crit} = \mu^4_{\rm crit}$ with $\mu_{\rm crit} = 0.00247$ eV!

$\rho_\Lambda = \mu^4_\Lambda$: $\mu_{0,\Lambda} = 0.00171$ eV today → approaching $\mu_{\infty,\Lambda} = 0.00247$ eV with time

i.e. the large cosmological constant gets tamed by inflation to be part of the critical flat space density. No cosmological constant problem either?

- Note: inflation is proven to have happened by observation!

Comic Microwave Background (CMB) radiation tells it ✓

- Inflation requires the existence of a scalar field,

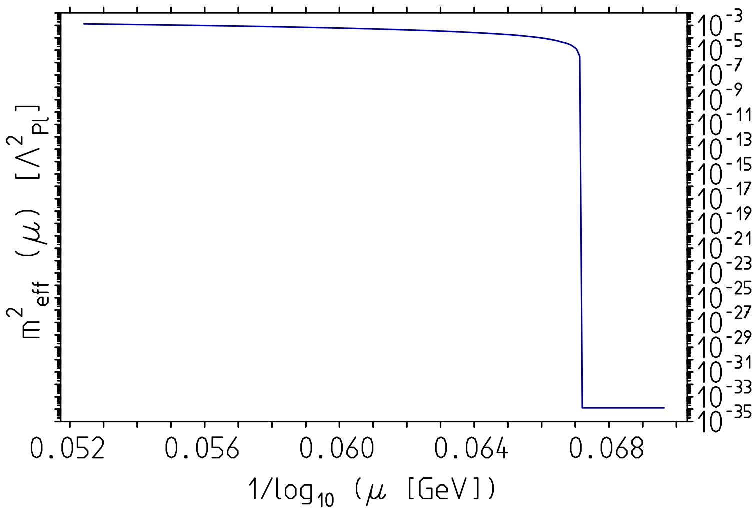
- The Higgs field is precisely such a field we need and within the SM it has the properties which promote it to be the inflaton.

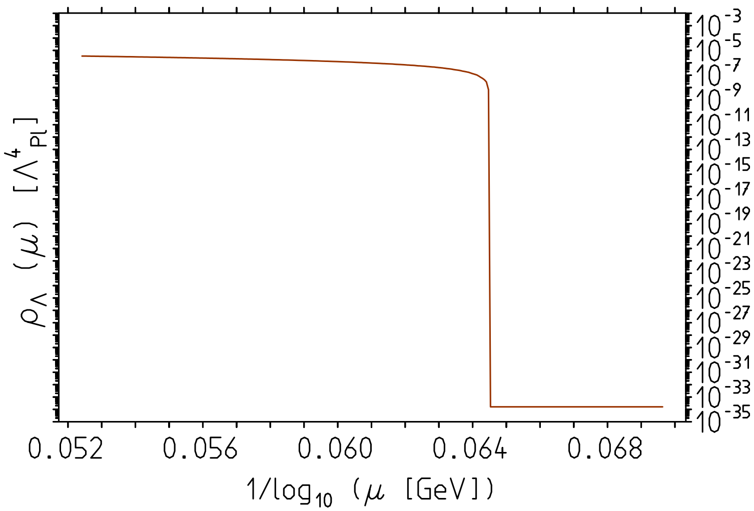
Note: the Higgs inflaton is special: almost all properties are known or predicable!

All other inflatons put by hand: all predictions are direct consequences of the respective assumptions

SM Higgs inflation sounds pretty simple but in fact is rather subtle, because of the high sensitivity to the SM parameters uncertainties and SM higher order effects

> Precondition: a stable Higgs vacuum, taking into account the relevant power corrections and a sufficiently large Higgs field at $M_{\rm Pl}$!





Conclusion

- 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!

- Higgs potential provides huge dark energy in early universe which triggers inflation; excludes supersymmetric and GUT extensions

The SM predicts dark energy and inflation!!!

dark energy and inflation are unavoidable consequences of the SM Higgs

(provided new physics does not disturb it substantially)

Epilogue: The sharp dependence of the Higgs vacuum stability on the SM input parameters and on possible SM extensions and the vastly different scenarios which can result as a consequence of minor shifts in parameter space makes the stable vacuum case a particularly interesting one and it could reveal the Higgs particle as “the master of the universe”. After all, it is commonly accepted that dark energy is the“stuff” shaping the universe both at very early as well as at the late times.

- open issues: where is dark matter?, can we explain baryon asymmetry? what triggers the see-saw mechanism explaining smallness of neutrino masses? what is tuning the strong CP problem?

- many issues like baryogenesis, details of the EW phase transition etc. need be reconsidered; plenty of details to be clarified! Crucial are more precise input parameters (incl. appropriate higher order corrections).

✌As a LEET the SM seems more natural than most its BSM constructions

– it does not exclude BSM physics at all of course –

! except those which have been designed to solve the hierarchy problem !

⇒dark matter, Majorana neutrinos, axions etc. may well fit such a scenario!

- searching for emergent structures beyond the SM seems to me a more promising strategy to actually find what is missing in the SM

Thanks for your attention!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B. Touschek

References:

"The Standard model as a low-energy effective theory: what is triggering the Higgs mechanism?," Acta Phys. Polon. B **45** (2014) 1167 [arXiv:1304.7813 [hep-ph]].

"Higgs inflation and the cosmological constant," Acta Phys. Polon. B **45** (2014) 1215 [arXiv:1402.3738 [hep-ph]].

"The Hierarchy Problem and the Cosmological Constant Problem Revisited"
– A new view on the SM of particle physics –
Foundations of Physics (2019), `https://doi.org/10.1007/s10701-019-00262-2`
arXiv:1812.03863 [hep-ph].

Krakow/Durham Lectures:
`http://www-com.physik.hu-berlin.de/~fjeger/SMcosmology.html`