9 October 2013

$$m_H = 125.5\,(6)\,GeV$$

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\varepsilon}, \qquad g_V = 2\left(\frac{m_V}{M}\right)^{2(1+\varepsilon)}$$

CP3-Lunch Seminar

In memoriam Robert Brout (1928-2011)

One scalar boson and nothing more?[1]

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Abstract: After the discovery of the scalar boson at LHC (4 July 2012), we can ask: Isn't time to re-apply Occam's razor to the physics of elementary particles at the weak scale ? Supersymmetry, strings, theory of everything, anthropic principle: much ado about nothing for 30 years? Grasp all, lose all (qui trop embrasse mal étreint)?

The prevailing feeling among theoretical physicists before LHC started operations, can be summarized by the following quotation:

"The primary goal of the LHC is to discover the mechanism of electroweak symmetry breaking. Indeed, the Standard Model, including only particles known today, becomes inconsistent at an energy scale of about 1 TeV…

There is a second, more subtle, issue related to the existence of a fundamental Higgs boson, which will also be investigated by the LHC. The basic problem is the absence, within the Standard Model, of symmetries protecting the Higgs mass term, and therefore the expectation that the maximun energy up to which the theory can be naturally extrapolated is, again, the TeV. A new physics regime should set at that energy scale, and

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the hypothetical Higgs boson must be accompanied by new particles associated with the cancellation of the quantum corrections to m_H. This is not a problem of internal consistency of the theory, but an acute problem of naturalness" [G. Giudice, "NATURALLY SPEAKING: the naturalness criterion and the physics at the LHC", arxiv:0801.2562 [hep-ph]]

The electroweak standard model: an assessment

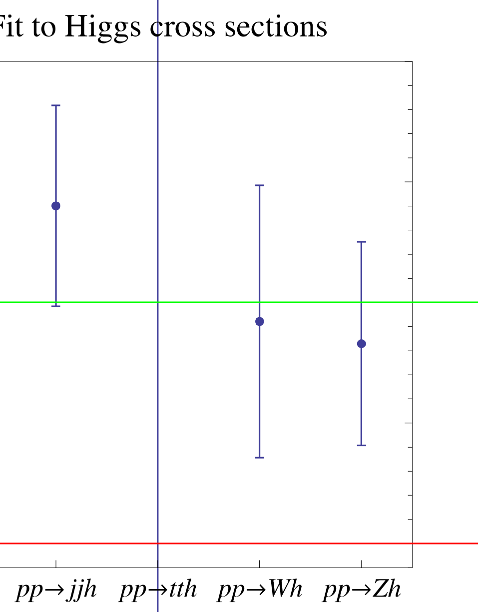
Experimental results:

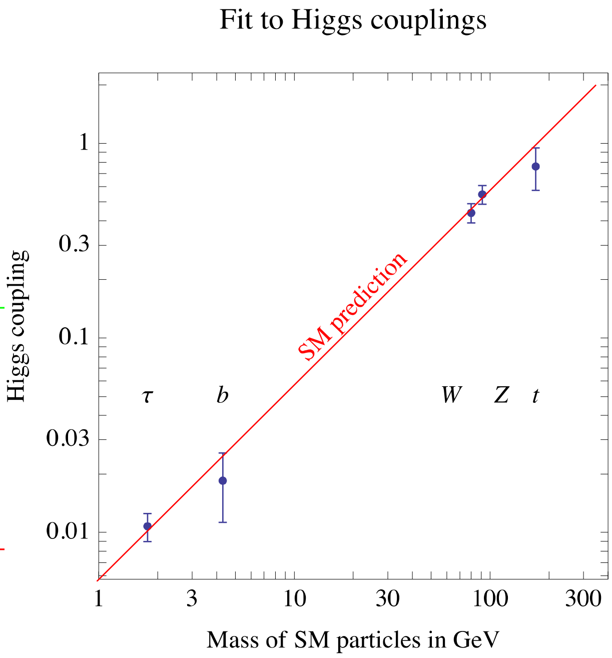
with V = W or Z, where in the Standard Model ε = 0, M = v = 246.22 GeV

The Standard Model prediction that the couplings should depend linearly on the particle masses is very compatible with the data: the g,lobal fits yield[3]:

$$\varepsilon = 0.022^{+0.042}_{-0.021}\,, \qquad M = (244^{+20}_{-10})\,GeV$$

From a fit to all measured Higgs boson channels (P. Giardino et al, arXiv:1303.3570v2 [hep-ph])





Our option: the electroweak standard model initiated by Weinberg (1967) in which all fundamental particles acquire their masses through one and the same Higgs doublet. By all particles, we mean: leptons, quarks, W, Z and H. We do not commit ourselves about hypothetical axions and right singlet (heavy) Majorana neutrinos.These latter particles may be necessary to account for the dark matter.

This choice has the following advantages:

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[3] J. Ellis and T. You, *JHEP* 1306 (2013) 101, arXiv :1303.3879 [hep-ph]

1. First and not least, it is not in disagreement with CMS and ATLAS findings (2011-2013), concerning the Higgs sector.

2. Lepton and quark vector neutral (electromagnetic) currents are coupled to a zero mass vector particle (photon) in a 'natural' way: *"The introduction of higher Higgs multiplets, or of more than one doublet has the obvious disadvantage that in general no zero mass vector boson survives. In other words, the observed zero photon mass is then an 'accident'. For this reason alone these schemes are very unattractive. In addition, the experimentally observed near equality $\varrho \approx 1$ gives no indication of any complications in the Higgs sector"* (M. Veltman)[4].

3. In agreement with Occam's razor. It is a principle of parsimony, economy. It states (1) that among competing hypotheses, the hypothesis with the fewest assumptions should be selected and (2) that one should proceed to simpler theories until simplicity can be traded for greater explanatory power. It hates the introduction of any kind of epicycles (cf. Ptolemy's Universe) in the theory and practice of science. Nevertheless, it should be used with caution.

4. All fundamental particles are treated in a unified and "democratic" way: see more later

The standard electroweak model, with only one scalar boson has obvious disavantages: no explanation of electron-muon mass difference, just a parametrization of CKM and of neutrinos' matrices, no proof of multiverse or of God's existence (cf. Templeton Foundation), insensible to anthropic principle etc.

But isn't not true who grasp all, lose all!

Naturalness, Hierarchy, Fine Tuning

But what about the **naturalness principle** which has been invoked since more than thirty years to question the standard model?

What is naturalness ?

Naturalness is the property that the free parameters appearing in a physical theory should take relative values of order 1. This is in contrast to the electroweak standard model where there are parameters that vary by many orders of magnitude and require extensive fine tuning of those values in order for the theory to predict a universe like the one we live in.

It is an aesthetic criterion, that arises from the seeming non-naturalness of the standard model and the broader topics of the hierarchy problem, fine-tuning, and the anthropic principle.

Three parameters in the effective action of the standard model we know seem to have far smaller coefficients than required by naturalness. Each of these coincidences require an explanation of some sort. The three parameters are:

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[4] M.J.G. Veltman, *Reflections on the Higgs System*. CERN Yellow Report, European Organization for Nuclear Research (1997), p. 2, 40, 46, http://igitur-archive.library.uu.nl/phys/2005-0622-155143/ReflectionsoftheHiggssystemVeltman.pdf

1. the strong theta angle (strong CP-problem)
2. the Higgs mass
3. the cosmological constant

In addition, the coupling of the electron, the neutrinos and the light quarks to the Higgs, (i.e. their masses) seem to be abnormally small.[5]

Despite all the fuss about naturalness, it is worthwhile to remember the electroweak standard model is renormalizable with solid predictions — independent of any cut off — validated up to now by forty years of experiments in the fermion (quarks and leptons) and gauge boson sectors.

“It is true that the SM is renormalizable, and if one introduces the observed mass values by hand, as an external input, and the hierachy problem is ignored, the resulting theory is completely finite and predictive. If you don’t care about fine tuning you are not punished! In this sense the naturalness argument for new physics at the EW scale is not a theorem but a conceptual demand: only if we see Λ not as a mathematical cut off but as the scale of new physics that removes the quadratic ultraviolet sensitivity, then the strong indication follows that the new physics threshold must be nearby. It is by now many years that the theorists are confronted with the hierarchy problem. […]” (G. Altarelli)[6]

“The only situation in which we expect supersymmetry to show up at the LHC is if supersymmetry is solving the naturalness problem of the Standard Model and thus stabilizing the hierarchy between the extreme weakness of gravity and the strength of the other forces (*). For short, let’s call this ‘natural supersymmetry’. If supersymmetry exists in nature but has nothing to do with the naturalness problem, we don’t have any reason to expect to find any sign of it at the LHC.” (M. Strassler)[7]

(*) $$(G_F / G_N)\square^2 / c^2 = 1.73859(15)\times 10^{33}$$

“The naturalness principle has been and still remains the main motivation for new physics at the weak scale. But at present our confidence on naturalness as a guiding principle is more and more challenged.” (G. Altarelli)

From now on we are going to tackle the mass problem (problem n° 1[8] in physics of fundamental interactions) in relation with naturalness starting from lepton self energy and not from BEH boson self energy.

Lepton self energy and naturalness

A. in classical Electrodynamics

Abraham (1901) and Lorentz (1902) consider the electron as a rigid charged sphere of radius R_e. By dimensional analysis, it is easy to see that the self energy **δ**E is expressed as

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[5] http://en.wikipedia.org/wiki/Naturalness_%28physics%29

[6] Guido Altarelli, “The Higgs so simple yet so unatural”, http://arxiv.org/abs/1308.0545

[7] Matt Strassler, http://profmattstrassler.com/2013/09/17/did-the-lhc-just-rule-out-string-theory/#more-6648, 17 September 2013

[8] L.B. Okun, *Physics Prospects : August 1981*, http://lss.fnal.gov/conf/C810824/p1018.pdf

$$\delta E = C\frac{\alpha\square}{R_e}$$

where C is of the order of unity and 1/ α = 137.0359991

If

$R_e < 3\times10^{-15}$ m

then

$$\delta E > m_e c^2$$

i.e electron self mass would be bigger than observed electron mass. (Equivalent cutoff is $\Lambda=1/R_e < 70$ MeV.)

It was noted the electron is subject to a self gravitational interaction of opposite sign to the self electromagnetic interaction but much too small to compensate the huge electromagnetic interaction. That was a first manifestation of a serious difficulty with naturalness. In 1938, Stueckelberg[9] conjectured that a classical electron could have a finite self energy if, in addition to the electromagnetic interactions, there is a new type of interaction with the same strength but opposite sign as the electromagnetic one.

B. in Quantum Electrodynamics

In 1934, Weisskopf[10] showed that QED — compared to classical electrodynamics — ameliorates, though it does not resolve the cut off problem of electron electromagnetic self mass: it is logarithmic only and self mass is proportional to the mass. In the limit $m_e \to 0$, δm_e also vanishes (this correction is only 0.091 MeV at Λ =Planck scale).

$$\delta m_e = \left(\frac{3\alpha}{4\pi}\right) m_e \ln\left(\frac{\Lambda^2}{m_e^2}\right)$$

And in 1939, Weisskopf[11] found the electromagnetic self mass of (pseudo)scalar bosons is not proportional to the corresponding mass m_s and is quadratically divergent

$$\delta m_s^2 = \frac{3\alpha}{4\pi}\times\Lambda^2$$

For example the charged pion self-mass can be expressed as: $\delta m_\pi^2 = \left(\frac{3\alpha}{2\pi}\right)\ln 2\times m_p^2$

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[9] E.C.G. Stueckelberg, *Nature* 144, 118 (1939)

[10] V. F. Weisskopf, *Zeits. f. Physik*, 90, 817 (1934)

[11] V.F. Weisskopf, *Phys. Rev.*, 56, 72 (1939)

The strong interaction (QCD) provides a physical cut off, the ϱ mass, and the pion self mass does not vanish when the pion mass vanishes[12].

Fermion and boson self masses appear to be quite different. And this perception pervades electroweak physics up to now.

After the Second World War, Pais[13] and, Sakata and Hara[14] found that to order α *“the electron’s self-energy could be made finite, and indeed small, and its stability insured, by introducing forces of small magnitude and essentially arbitrarily small range, corresponding to a new field, and quanta of arbitrarily high rest mass”*[15] It was the transposition to QED of the Stueckelberg proposal.

C. In pre-1967 Electroweak Standard Model

Later, attempts have been done to find if the Stueckelberg’s conjecture could be implemented in the frame of Q.E.D. and weak intermediate vector boson models. In view of cancellation of logarithmic divergences of electromagnetic self mass, were only considered logarithmic divergences of the weak selfmasses.
Taking into account just charged weak currents Terazawa[16] noticed that due to the presence of γ_5 matrix in the lepton weak boson coupling it was possible to have a negative sign between the logarithmic weak and electromagnetic divergencies.
The same idea has been applied[17]to the Glashow model[18] — i.e. the electroweak standard model without scalar boson — and the logarithmic divergence cancellation occurs if
$\sin^2 \theta_W = 3/14$, $m_W = 80.5$ GeV and $m_Z = 90.9$ GeV, not too far from the current experimental data.
This result is obtained easily[19], in the framework of the electroweak standard model, if we impose (1) that lepton self mass (at one loop level) is zero in the electroweak model and (2) the tadpole contributions are zero in the Feynman-’t Hooft gauge.
The Glashow model is not gauge invariant nor renormalizable.

D. in the Standard Electroweak Model

The Standard Electroweak Model of Weinberg-Salam is obtained from the Glashow model (improved in ref. 17) by adjonction of a scalar boson field doublet providing the Brout-Englert-Higgs mechanism requested for producing particles’ masses and preserving gauge invariance at the same time. The remaining neutral massive scalar boson and its couplings to all particle fields is at the origin of tadpoles’ terms.
In the case of fermion electroweak self energies, all the quadratic divergences are concentrated in those tadpoles terms as shown in ref.19[20] (1979). We are far from the

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[12] T. Das, G.S. Guralnik, V.S. Mathur, F.E . Low and J.E. Young, Phys. *Rev. Lett*. 18, 759 (1967)

[13] A. Pais, *Verhandelingen Roy. Ac*., Amsterdam, 19, 1 (1946)

[14] S. Sakata, O. Hara, *Prog.Theor. Phys*., 2, 30 (1947)

[15] J.R. Oppenheimer, *Electron Theory, Report to the Solvay Conference for Physics at Brussels*, Belgium, 1948, reprinted in J. Schwinger (ed), *Quantum Electrodynamics*, Dover Publications, (1958)

[16] H. Terazawa, *Phys. Rev. Lett*. 22, 254 (1969) ; 22, 442(E) (1969) ; *Phys. Rev*. D1, 2951 (1970)

[17] J. Pestieau and P. Roy, *Phys. Rev. Lett*. 23, 349 (1969). See also, H. Terazawa, *Phys. Lett*. D4, 1579 (1971); J. Pestieau and P. Roy, *Lett. Nuovo Cim*. 31, 625 (1981); M. Veltman, *Was Lorentz our first particle physicist?*, (2002) http://www.lorentz.leidenuniv.nl/history/zeeman/lorentzveltman/Leiden2002lect.pdf

[18] S.L. Glashow, *Nucl. Phys*. 22 , 579 (1961); A.Salam and J.C. Ward, *Phys. Lett*.13, 168 (1964)

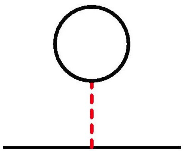
[19] R. Decker and J. Pestieau, “Lepton Self-mass, Higgs scalar and Heavy Quark Masses”, DESY Workshop, October 1979, Preprint UCL-IPT-79-19, reprinted in http://arxiv.org/abs/hep-ph/0512126

[20] See also : R. Decker and J. Pestieau, *Mod. Phys. Lett* **A4,** 2733 (1989) ; ibid. **A5** 2579 (1990) ; I-

findings of QED.

We have (at one loop-level) as quadratic divergences of the fermion electroweak self energy:

$$\left.\frac{\delta m_f^2}{m_f^2}\right|_{\Lambda^2} = \left(\frac{3G_F}{4\sqrt{2}\pi^2}\right)\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 - \square\right)\left(\frac{\Lambda^2}{m_H^2}\right) \qquad (1)$$



f = leptons or quarks
G_F is the Fermi coupling constant measured with precision in muon decay and related to v, the scalar boson vacuum expectation value (vev) :

$v^2 = 1/(\sqrt{2}\,.\,G_F) = 246.22$ GeV

$1/m_H^2$ is the scalar boson propagator at zero four-momentum appearing in all tadpoles

The right hand side of Eq (1) would be zero if $m_H = 317$ GeV in contradiction with ATLAS and CMS observations (using $m_t = 174.5$ GeV, $m_Z = 91.1876$ GeV, $m_W = 80.365$ GeV). So no possible annulation of quadratic divergences.

It is reasonable to argue that new physics would appear if $\left.\left(\frac{\delta m_f^2}{m_f^2}\right)\right|_{\Lambda^2} > 1$
With $m_H = 125.5$ GeV, this is the case when $\Lambda > 550$ GeV. Up to now, no new physics, no new threshold (due to supersymmetry, for example) has been observed at LHC.

But we have to be careful. There is no reason that cut off Λ has not to be the same for all particle loops. Following Bardeen[21], for example, let us choose a different cut off for bosons end fermions, Λ_b and Λ_f respectively.

In that case, we replace in Eq (1)

$$\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)\frac{\Lambda^2}{m_H^2} \rightarrow \left(m_H^2 + 2m_W^2 + m_Z^2\right)\frac{\Lambda_b^2}{m_H^2} - 4m_t^2\left(\frac{\Lambda_f^2}{m_H^2}\right)$$

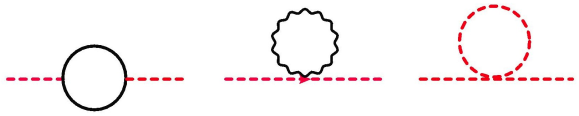
By demanding Eq (1)=0, we get : $\Lambda_b / \Lambda_f = 1.806$. There is not anymore a low/upper bound for new physics.

Hsiu Lee and S.D. Drell, SLAC-PUB-5423, RU 91-5-B (1991); Bég Memorial Volume; C.Newton, P.Osland and T.T. Wu, *Z. Phys*. **C61**, 421, 441 (1994) and references therein; G. López Castro and J. Pestieau, *Mod.Phys. Lett*. **A10**, 1155 (1995), arXiv: hep-ph/9504350; Z.Y. Fang, G. Lopez Castro, J.L. Lucio, J. Pestieau, *Mod. Phys. Lett*. **A12**, 1531 (1997), arXiv: hep-ph 9612430.

[21] W.A. Bardeen, *On Naturalness in the Standard Model*, 1995, see Eq. (2), http://lss.fnal.gov/archive/1995/conf/Conf-95-391-T.pdf

Electroweak Standard Model and naturalness

In 1980, Veltman[22] derived the quadratic divergences of the self energies of H, W and Z. In this case, in contradistinction with the self energies of leptons and quarks, quadratic divergences are provided not only by tadpole diagrams but by all types of diagram.
But the final result is identical to Eq. (1), namely



$$g_{l,q} = y_{l,q}/\sqrt{2},\quad g_W = g/2, \quad g_Z = \sqrt{g^2 + g'^2}/2, \quad g_H = \sqrt{2\lambda}$$

$$\left(\frac{\delta m_i^2}{m_i^2}\right)\Bigg|_{\Lambda^2} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 - \square\right)\left(\frac{\Lambda^2}{m_H^2}\right)$$
$$= \frac{3}{8\pi^2\upsilon}\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 - \square\right)\left(\frac{\Lambda^2}{m_H^2}\right) \qquad (2)$$

where i = H, W or Z [23]. Eqs (1) and (2) concerned quadratic divergences (at one loop level[24]) only but quadratic divergences strongly dominate over logarithmic divergences and finite parts when Λ >> 1 TeV. The hierarchy problem does not seem very important because all masses and vev are changing scale in the same way when Λ >> 1 TeV

Let us note that

$$\left(\frac{\delta\upsilon^2}{\upsilon^2}\right)\Bigg|_{\Lambda^2+\ln\Lambda} = \frac{3}{8\pi^2}\left\{\left(\frac{m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2 - \square}{\upsilon^2}\right)\frac{\Lambda^2}{m_H^2}\right.$$
$$\left.-\left[\left(\frac{m_H^4 + m_Z^4 + 2m_W^4 - 4m_t^4 - \square}{\upsilon^2 m_H^2}\right) - \left(\frac{m_H^2 + 2m_W^2 + m_Z^2 - 2m_t^2 - \square}{2\upsilon^2}\right)\right]\ln\left(\frac{\Lambda^2}{m_H^2}\right)\right\} \qquad (3)$$

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[22] M.Veltman, “The infrared-ultraviolet connection”, *Acta Physica Polonica*, B 12, 437 1981), http://igitur-archive.library.uu.nl/phys/2005-0622-155253/14044.pdf . It seems curious that in his paper, Veltman stated that “fermion masses are only logarithmically divergent” see page 451, 7 lines before equation (7.3)

[23] Degrassi and Sirlin [G. Degrassi and A. Sirlin, *Nucl. Phys*. B 383 (1992) 73 — see their appendix B] claimed that Eq.(2) is not correct when i = W or Z. But we disagree with their statement because they do not handle in an appropriate way, terms proportional to n/(n-2) in dimensional regularization. Veltman has the correct prescription to treat terms proportional to n in the numerator: take n=2 everywhere except if the n-dependence derives from the number of degree of freedom of a vector boson in n dimensions. In that last case, n = 4 in four dimensions. See ref. 22, discussion after equation (7.4) in *Acta Polonica Physica*, page 452. Using Veltman prescription, we agree with Degrassi and Sirlin’s result.

[24] It has been shown in Y. Hamada, H. Kawai, K.Y. Oda, *Phys.Rev*. D87 (2013) 053009 [arXiv:1210.2538 [hep-ph]] that the two-loop correction does not change significantly the one loop-result. See also, D.R.T. Jones, “The quadratic divergence in the Higgs mass revisited”, arXiv:1309.7335<http://arxiv.org/abs/1309.7335>[hep-ph]

where we added logarithmic divergence terms[25]

The universality of quadratic divergences[26] is not astonishing in the electroweak standard model with only one scalar boson doublet. In that case, all particle masses are proportional to the same vev, v:

$$m_i^2 = g_i^2 \upsilon^2 \tag{4}$$

with i= l, q, W, Z, H ; g_i are the corresponding (on-shell) coupling constants:

$$g_{l,q} = y_{l,q}/\sqrt{2},\ \ g_W = g/2,\quad g_Z = \sqrt{g^2 + g'^2}\,/2,\quad g_H = \sqrt{2\lambda}$$

Differentiating Eq. (4), we get

$$\frac{\delta m_i^2}{m_i^2} = \frac{\delta g_i^2}{g_i^2} + \frac{\delta \upsilon^2}{\upsilon^2} \tag{5}$$

δg_i^2 contain logarithmic divergences only. All quadratic divergences are concentrated in δv^2. Therefore they are universal.

Bare mass m_i^b, and bare vev b, v^b are defined as:

$$\left(m_i^b\right)^2 = m_i^2 + \delta m_i^2$$

$$\left(\upsilon^b\right)^2 = \upsilon^2 + \delta \upsilon^2$$

where m_i is the physical mass (pole mass) and v, the physical v.e.v [$v = 1/\sqrt{2}\, G_F$]

m_i^b and v^b are not defined univocally. Their contents depend on the content of δm_i and δv. Only physical masses are defined univocally: they satisfy Einstein's relation: $E^2 = \mathbf{p}^2 + m^2$. All other definitions of mass are depending of particular theoretical prescriptions and they are related to physical masses up to an additive constant. Naturalness does not seem to be so important.

Let us note that In recent works[27], Eq. (2) is used in the following way:

- restricted to the case i = H

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[25] F. Jegerlehner, arXiv:1304.7813 [hep-ph]. See Appendix. In the same way we can add logarithmic terms to Eqs (1) and (2) ; J. Fleischer, F. Jegerlehner, *Phys. Rev*. D23, 2001 (1981)

[26] J. Pestieau, Eqs. (17)-(19), p. 287 in J.L. Lucio and M. Zepeda (ed.), III Mexican School of Particle and Fields, December 1988, *World Scientific* (1989); Eqs (17)-(19) , p. 190, in P. Nicoletopoulos and J. Orloff (ed.), "The Gardener of Eden" (In honour of Robert Brout on his 60 years birthday in 1988), *Physicalia Magazine Vol*. 12 (1990). [There is a mistake in those equations : replace QT by QT x (MW2 /MH2).]

[27] Refs. 24, 25 and F. Jegerlehner, arXiv:1305.6652 [hep-ph] ; Isabella Masina, Mariano Quiros, arXiv : 1308.1242 [hep-ph] ; Ligong Bian, arXiv : 1308..2783 [hep-ph] ; Yoshiharu Kawamura, arXiv : 1308.5069 [hep-ph].

- physical masses replaced by masses defined in the $\overline{MS}$ regularization scheme depending of μ, a mass scale parameter

- when μ is a little below the Planck mass scale, it appears Eq. (2) is equal to zero, with the possibility of going from the broken to the unbroken phase in the Higgs sector of the electroweak standard model and of solving naturalness problem

Vev and masses in the standard electroweak model

Eqs (1) – (5) show that, as far as masses are concerned, all types of particles, leptons, quarks, W, Z and H are on the same footing (democracy) in the electroweak standard model with only one scalar boson doublet. All are proportional to the same vev, v.

We assume[28] that the vev, defined in the lowest energy quantum state in turn is a function of different masses of particles in an identical manner and we propose:

$$m_H^2 + m_Z^2 + m_W^2 + m_t^2 + m_b^2 + m_c^2 + m_\tau^2 + \square = \upsilon^2 \qquad (6)$$

or

$$2\lambda + \frac{g^2}{2} + \frac{g'^2}{4} + y_t^2 + y_b^2 + y_c^2 + y_\tau^2 + \square = 1 \qquad (7)$$

In Eq. (6) v can be viewed as the yield of the masses of fundamental particles, all of them lighter than v, which result from the quantum fluctuations in the electroweak vacuum. On the other hand, given that $v^2 = 1/[\sqrt{2}\ G_F]$, Eq. (6) lends the alternative interpretation that the Fermi constant may be fixed from the interactions of particles with the electroweak vacuum.

Eqs. (6) and (7) are in very good agreement with experimental observations. They insure naturalness at the electroweak scale, remembering naturalness is the property that the free parameters appearing in a physical theory should take relative values of order 1.

We don’t try to relate electroweak and gravitational scale. So we have not a super naturalness problem. The Fermi scale is assumed to be independent of gravitational scale. *“On the basis of naturalness one was expecting a more complicated reality. Nature appears to disregard our notion of naturalness and rather indicates an alternative picture where the SM, with a few additional ingredients, is valid up to large energies.”* (G. Altarelli)

END

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[28] G. Lopez, J. Pestieau, arXiv:1305.4208 [hep-ph].