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WHY SHOULD WE CARE ABOUT THE TOP QUARK YUKAWA COUPLING?

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In the cosmological context, for the Standard Model to be valid up to the scale of inflation, the top quark Yukawa coupling y_t should not exceed the critical value y_t^{crit}, coinciding with good precision (about 0.2 ‰) with the requirement of the stability of the electroweak vacuum. So, the exact measurements of y_t may give an insight on the possible existence and the energy scale of new physics above 100 GeV, which is extremely sensitive to y_t. We overview the most recent theoretical computations of y_t^{crit} and the experimental measurements of y_t. Within the theoretical and experimental uncertainties in y_t, the required scale of new physics varies from 10^7 GeV to the Planck scale, urging for precise determination of the top quark Yukawa coupling.

Contribution for the JETP special issue in honor of V. A. Rubakov's 60th birthday

Contents

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1. INTRODUCTION

In the Spring of 2014, Valery Rubakov was visiting CERN and joined a bunch of theorists for lunch at a CERN canteen. As often happens, the conversation turned to the future of high-energy physics: what kind of questions should be answered and what kind of experiments should be done. Valery was arguing for the high-energy frontier that would allow searching for new physics, whereas the authors of this article brought attention to the precision measurements of the top-quark Yukawa coupling. We remember Valery asking: "Why should we care about the top-quark Yukawa coupling?" For some reasons, the interesting discussion was interrupted and we did not have a chance to explain our point of view in detail. We use this opportunity to congratulate Valery on his coming jubilee and give an answer to his question in writing. We apologize to Valery for describing a number of facts well-known to him, which we included to make this essay accessible to a wider audience.

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2. STANDARD MODEL AND THE SCALE OF NEW PHYSICS

After the discovery of the Higgs boson at the LHC, the Standard Model (SM) became a complete theory in the sense that all the particle degrees of freedom that it contains theoretically have been found experimentally. Moreover, there are no convincing deviations from the SM in any type of high-energy particle physics experiments. This raises a number of questions: "Have we obtained at last the ultimate theory of Nature?" and "If not, where we should search for the new physics?"

The answer to the first question is well known and is negative. The reasons are coming from the observations of neutrino oscillations, absent in the SM, and from cosmology: the SM cannot accommodate dark matter and baryon asymmetry of the Universe. The last but not the least is the inflation, or, to stay strictly on the experimental evidence side, the flatness and homogeneity of the Universe at large scales and the origin of the initial density perturbations. On a more theoretical side, the list of drawbacks of the SM is quite long and includes incorporation of gravity into a quantum theory, the hierarchy problem, the strong CP problem, the flavor problem, and so on.

The answer to the second question is not known. Theoretically, it is clear that some type of new physics must appear near the Planck energies $M_P = 2.435 \cdot 10^{18}$ GeV, where gravity becomes important, but these energies are too high to be probed by any experimental facility. The naturalness arguments put the scale of the new physics close to the scale of electroweak symmetry breaking (see, e. g., [1, 2]), but it is important to note that the SM in and of itself is a consistent quantum field theory up to the very high energies exceeding the Planck mass by many orders of magnitude, where it eventually breaks down due to the presence of Landau poles in the scalar self-interaction and in the U(1) gauge coupling.

As for the experimental evidence in favor of the new physics, it does not give any idea of its scale: the neutrino oscillations can be explained by addition of Majorana leptons with the masses ranging from a fraction of electron-volt to 10^{16} GeV, the mass of particle candidates for dark matter discussed in the literature varies by at least 30 orders of magnitude, the mass of the inflaton can be anywhere from hundreds of MeV to the GUT scale, whereas the masses of new particles responsible for baryogenesis can be as small as a few MeV and as large as the Planck scale.

As we argue in this paper, at the present moment the only quantity that can help us to get an idea about the scale of the new physics is the top Yukawa coupling y_t. It may happen that the situation will change in the future: the signals of new physics may appear at the second stage of the LHC, or the lepton number violation will be discovered, or the anomalous magnetic moment of the muon will convincingly be out of the SM prediction, or something unexpected will show up.

3. VACUUM STABILITY AND COSMOLOGY

In the absence of beyond-the-SM (BSM) signals, the only way to address the question of the scale of the new physics is to define the energy where the SM becomes theoretically inconsistent or contradicts some observations. Because the SM is a renormalizable quantum field theory, the problems can appear only because of the renormalization evolution of some coupling constants, i. e., when they become large (and the model enters strong coupling at that scale), or additional minima of the effective potential develop, changing the vacuum structure. The most dangerous constant[1)] turns out to be the Higgs boson self-coupling constant λ with the RG evolution at one loop

$$16\pi^2 \frac{d\lambda}{d\ln\mu} = 24\lambda^2 + 12\lambda y_t^2 - 9\lambda\left(g^2 + \frac{1}{3}g'^2\right) - 6y_t^4 + \frac{9}{8}g^4 + \frac{3}{8}g'^4 + \frac{3}{4}g^2 g'^2.$$

The right-hand side depends on the interplay between the positive contributions of the bosons and negative contribution from the top quark. Before the discovery of the Higgs boson, it was customary to show the results as a function of the Higgs mass $M_h \approx \sqrt{2\lambda(\mu = M_h)}\, v$, with other parameters of the SM fixed by experiment. The Landau pole in the Higgs self-coupling constant λ occurs at energies smaller than the Planck scale for the Higgs mass $M_h > 175$ GeV, and comes closer to the Fermi scale when the Higgs boson mass increases [3–5]. For small Higgs masses, the coupling becomes negative at some scale, and if the Higgs mass is below 113 GeV, the top quark loops give an essential contribution to the Higgs effective potential, making our vacuum unstable with the lifetime smaller than the age of the Universe [6–8][2)].

The Higgs boson found at the LHC has a mass $M_h \approx 125.7 \pm 0.4$ GeV [10], which is well within this

[1)] The only other problematic parameter is the U(1) hypercharge, which develops a Landau pole, but only at the energy scale significantly exceeding the Planck mass.

[2)] We note that, strictly speaking, the Universe lifetime depends strongly on the form of the Planck-scale-suppressed higher-dimensional operators in the effective action [9].

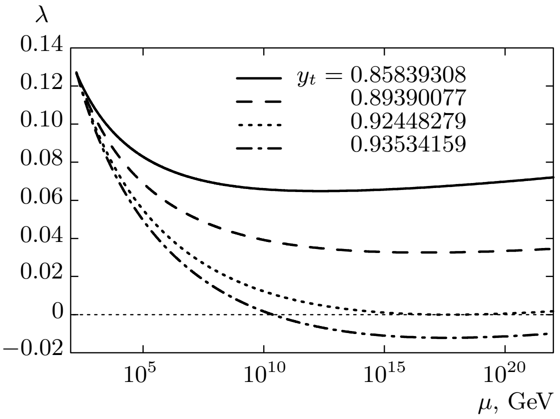

Fig. 1. Renormalization group running of the Higgs coupling constant λ for the Higgs mass $M_h = 125.7$ GeV and several values of the top-quark Yukawa coupling $y_t(\mu = 173.2$ GeV)

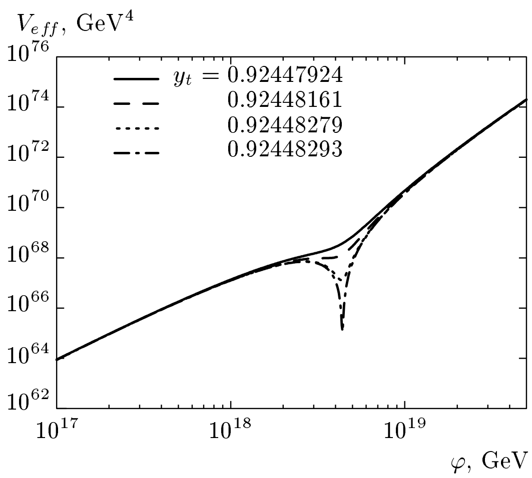

Fig. 2. A very small change in the top-quark Yukawa coupling y_t (taken at the scale $\mu = 173.2$ GeV) converts a monotonic behavior of the effective potential for the Higgs field to that with an extra minimum at large values of the Higgs field

interval. This means that the lifetime of our vacuum exceeds that of the Universe by many orders of magnitude (see, e. g., [11]) and that the SM without gravity is a weakly coupled theory even for energies exceeding the Planck scale also by many orders of magnitude. Hence, it looks that we cannot obtain any hint about the scale of the new physics from these considerations. However, this is not true if we include the history of the Universe in analysis, starting from inflation till the present time.

Because we want to gain an insight into the new physics, a way to proceed is to assume that there is none up to the Planck scale and see if we run into any contradiction. We can start from the SM without gravity and consider the effective potential for the Higgs field. The contribution of the top quark to the effective potential is very important, because it has the largest Yukawa coupling to the Higgs boson. Moreover, it comes with the minus sign and is responsible for the appearance of the extra minimum of the effective potential at large values of the Higgs field. We fix all parameters of the SM to their experimental values except the top Yukawa coupling (we see below that presently it is the most uncertain one for the problem under consideration). For definiteness, we use the $\overline{\text{MS}}$ subtraction scheme and take y_t at some specific normalization point $\mu = 173.2$ GeV. Then the RG evolution of the Higgs coupling λ for various top-quark Yukawa couplings is illustrated by Fig. 1. Close to the "critical" value of the top Yukawa coupling, to be defined exactly momentarily, effective potential (4.2) behaves as shown in Fig. 2. For $y_t < y_t^{crit} - 1.2 \cdot 10^{-6}$, it increases while the Higgs field increases; for $y_t > y_t^{crit} - 1.2 \cdot 10^{-6}$, a new minimum of the effective potential develops at large values of the Higgs field; at $y_t = y_t^{crit}$, our electroweak vacuum is degenerate with the new one, while at $y_t > y_t^{crit}$, the new minimum is deeper than ours, meaning that our vacuum is metastable. If $y_t > y_t^{crit} + 0.04$ (this corresponds roughly to the top quark mass $m_t \gtrsim 178$ GeV), the lifetime of our vacuum is smaller than the age of the Universe.

The case $y_t < y_t^{crit} - 1.2 \cdot 10^{-6}$ is certainly the most cosmologically safe, because our electroweak vacuum is unique. However, if $y_t > y_t^{crit} - 1.2 \cdot 10^{-6}$, the evolution of the Universe should lead the system to our vacuum rather than to the vacuum with a large Higgs field (as far as our vacuum is the global minimum). In the interval $y_t \in (y_t^{crit} - 1.2 \cdot 10^{-6}, y_t^{crit})$, our vacuum is deeper than another one, and so that the happy end is quite plausible, but it is not so for $y_t > y_t^{crit}$, when the situation is just the opposite.

In order to understand how far we can go from the (absolutely) safe values $y_t \le y_t^{crit}$ into the dangerous region, we can consider yet another feature of the effective potential: the value of the potential barrier that separates our electroweak vacuum from that at large values of the Higgs field. The energy density corresponding to this extremum is gauge-invariant and does not depend on the renormalization scheme. It is presented in Fig. 3. Now, if the Hubble scale at inflation does not exceed that of the potential barrier, it is conceivable to think that the presence of another vacuum is not important, while in the opposite situation, de Sitter fluctuations of the Higgs field would drive the system to another vacuum. And, indeed, several papers [12, 13] argued that this is exactly what is going to happen.

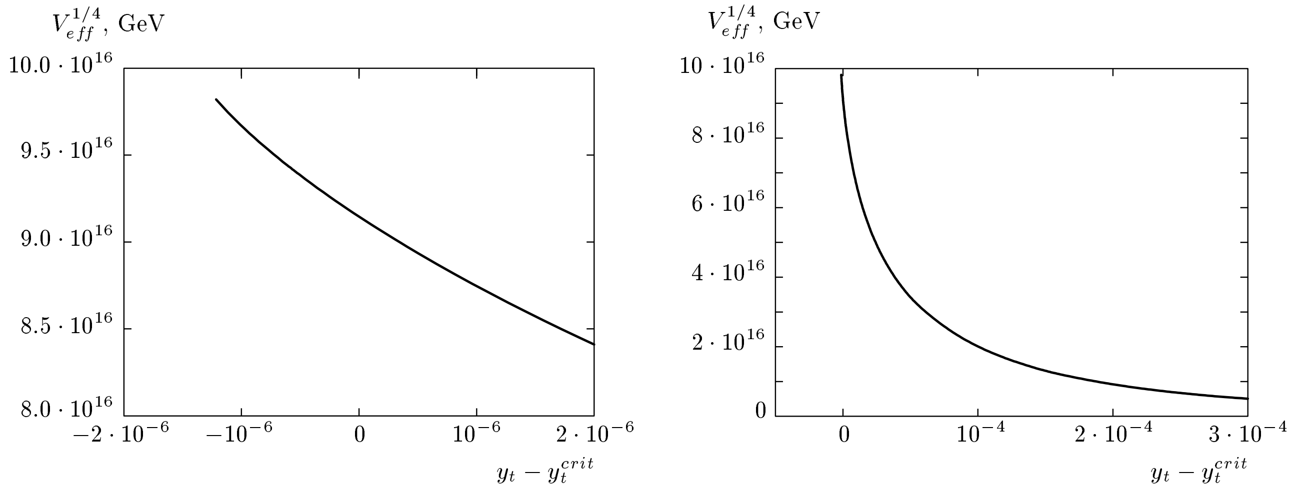

Fig. 3. Height of the potential barrer near the critical value y_t^{crit} ($\mu = 173.2$ GeV)

Of course, this statement is only true if the potential for the Higgs field is not modified by the gravitational effects or by the presence of some new physics at the inflationary scale. For example, as has been in [14], the addition of even a small non-minimal coupling $\xi < 0$, $|\xi| \sim 10^{-2}$ of the Higgs field ϕ to the Ricci scalar R,

$$\left(\frac{M_P^2}{2} + \xi\phi^2\right) R \tag{0.1}$$

increases the barrier height and thus stabilise the vacuum against fluctuations induced by inflation. Taken at the face value the action (0.1) with negative ξ leads to instabilities at large values of the background Higgs field, but this can be corrected by considering a more general case, replacing $\xi\phi^2$ by a function of the Higgs field that never exceeds $M_P^2/2$ [15]. At the same time, the presence of the non-minimal coupling with the opposite sign would severely destabilise the vacuum.

We do not know yet what the energy density V_{inf} was at inflation, because this depends on the value r of the tensor-to-scalar ratio as

$$V_{inf}^{1/4} \sim 1.9 \cdot 10^{16}\ \text{GeV} \left(\frac{r}{0.1}\right)^{1/4}. \tag{3.1}$$

For the BICEP II value $r \approx 0.2$ [16], this energy is $2.3 \cdot 10^{16}$ GeV. Then the requirement discussed above leads to the constraint on the top-quark Yukawa coupling $y_t < y_t^{crit} + 0.00009$, with the deviation from y_t^{crit} being numerically very small. Because of a very weak dependence of V_{inf} on r, even for Starobinsky's R^2 inflation [17] or for noncritical Higgs inflation [18], which have a much smaller tensor-to-scalar ratio $r \approx 0.003$, the resulting constraint is just a bit weaker, $y_t < y_t^{crit} + 0.00022$. We let this small positive deviation from y_t^{crit} be denoted by δy_t, depending on r.

To summarize, if the measurement of the top quark Yukawa coupling give $y_t < y_t^{crit} + \delta y_t$, the embedding of the SM without any kind of new physics in cosmology does not lead to any troubles and hence no information on the scale of the new physics can be derived. This would however be a great setting for the "SM like" theories without new particles with masses larger than the Fermi scale [18–22].

We now suppose that $y_t > y_t^{crit} + \delta y_t$. In this case, we can have some idea on the scale of the new physics by the following argument (see, e. g., [23] and the references therein). We consider the value of the scalar field at which the effective potential crosses zero (we normalize V_{eff} in such a way that it is equal to zero in our vacuum), or, almost the same, the normalization point μ_{new} where the scalar self-coupling λ crosses zero, indicating an instability at this energy[3)].

To make the potential or scalar self-coupling positive for all energies, something new should intervene at the scale around or below $E \approx \mu_{new}$. There are many possibilities to do so, associated with the existence of new thresholds, new scalars or fermions with masses $\lesssim \mu_{new}$ [28–35]. Figure 4 shows the dependence of the

[3)] To be precise, the value of the scalar field where the effective potential is equal to zero is gauge-noninvariant and depends on the renormalization scheme. The value of μ where the scalar self-coupling constant crosses zero is scheme-dependend but is gauge invariant, if the gauge-invariant definition of λ is used, as in the $\overline{\text{MS}}$. In what follows, we use the $\overline{\text{MS}}$ subtraction scheme and the effective potential in the Landau gauge. The use of other schemes or gauges can change μ_{new} by about two orders of magnitude [24–27].

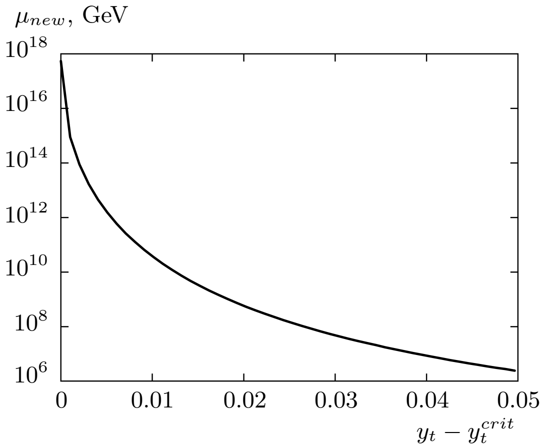

Fig. 4. Scale μ_0 where the Higgs self-coupling λ becomes negative (possibly requiring the new physics at lower energies) depending on the top-quark Yukawa coupling y_t ($\mu = 173.2$ GeV)

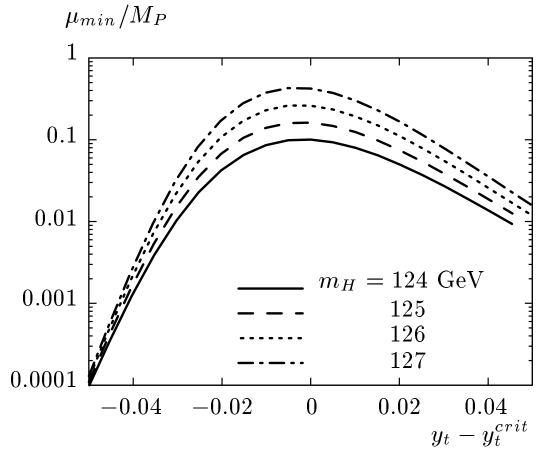

Fig. 5. Scale of the minimum of the Higgs boson self-coupling depending on the top-quark Yukawa coupling $y_t(\mu = 173.2$ GeV) near the critical value y_t^{crit}

scale μ_{new} on y_t. We can see that it is very sharp: in the vicinity of y_t^{crit}, the change of y_t by a tiny amount leads to a change in μ_{new} by many orders of magnitude! Although exactly what kind of new physics would be needed remains to be an open question, these facts call for a precise experimental measurement of y_t.

4. COMPUTATION OF THE CRITICAL TOP-QUARK YUKAWA COUPLING

To find the numerical value of y_t^{crit}, we should compute the effective potential for the Higgs field $V(\phi)$ and determine the parameters at which it has two degenerate minima:

$$V(\phi_{SM}) = V(\phi_1), \quad V'(\phi_{SM}) = V'(\phi_1) = 0. \tag{4.1}$$

The renormalization-group-improved potential has the form

$$V(\phi) \propto \lambda(\phi)\phi^4 \left[1 + O\left(\frac{\alpha}{4\pi}\ln\left(\frac{M_i}{M_j}\right)\right)\right], \tag{4.2}$$

where α is the common name for the SM coupling constants, and M_i are the masses of different particles in the background of the Higgs field. Therefore, instead of computing the effective potential, we can solve the "criticality equations"

$$\lambda(\mu_0) = 0, \quad \beta_\lambda^{SM}(\mu_0) = 0. \tag{4.3}$$

This simplified procedure works with an accuracy better than $\delta y_t \approx 0.001$ if λ is taken in the $\overline{\text{MS}}$ scheme.

In numbers, criticality equations (4.3) give

$$y_t^{crit} = 0.9244 + 0.0012 \cdot \frac{M_h/\text{GeV} - 125.7}{0.4} + \\ + 0.0012 \cdot \frac{\alpha_s(M_Z) - 0.1184}{0.0007}, \tag{4.4}$$

where α_s is the QCD coupling at the Z-boson mass. Although all the required components are present in [23, 36–38], a comment is now in order as to how Eq. (4.4) was obtained. First, instead of defining the critical Higgs boson mass M_h, the critical value of the top pole mass was defined, and then converted back to the value of the top-quark Yukawa coupling, accounting for known QCD and electroweak corrections. However, it is not immediate to read these numbers from the papers mentioned, as far as the matching conditions relating the physical masses and $\overline{\text{MS}}$ parameters are scattered over the published works. The three-loop beta functions can be found in [39–44] and are given in a concise form in the code in [36] or [37]. The one-loop contributions to the matching conditions between the W, Z, and Higgs boson masses and the $\overline{\text{MS}}$ coupling constants at $\mu \sim m_t$ of the order $O(\alpha)$ and $O(\alpha_s)$ are known for a long time [45] and can be extracted from [36, 37]. The two-loop contribution of the order $O(\alpha\alpha_s)$ to the Higgs coupling constant λ was calculated in [36, 37] and for the practical purposes can be taken from Eq. (34) in [37]. The two-loop contribution of the order $O(\alpha^2)$ to λ was calculated in [37], with the numerical approximation given by Eq. (35). Recently, an independent evaluation at the order $O(\alpha^2)$ was obtained in [38], which differs slightly from [37], but the difference has a completely negligible impact on (4.4) (we note that even the whole $O(\alpha^2)$ contribution to λ changes y_t^{crit} by only $0.5 \cdot 10^{-3}$). However,

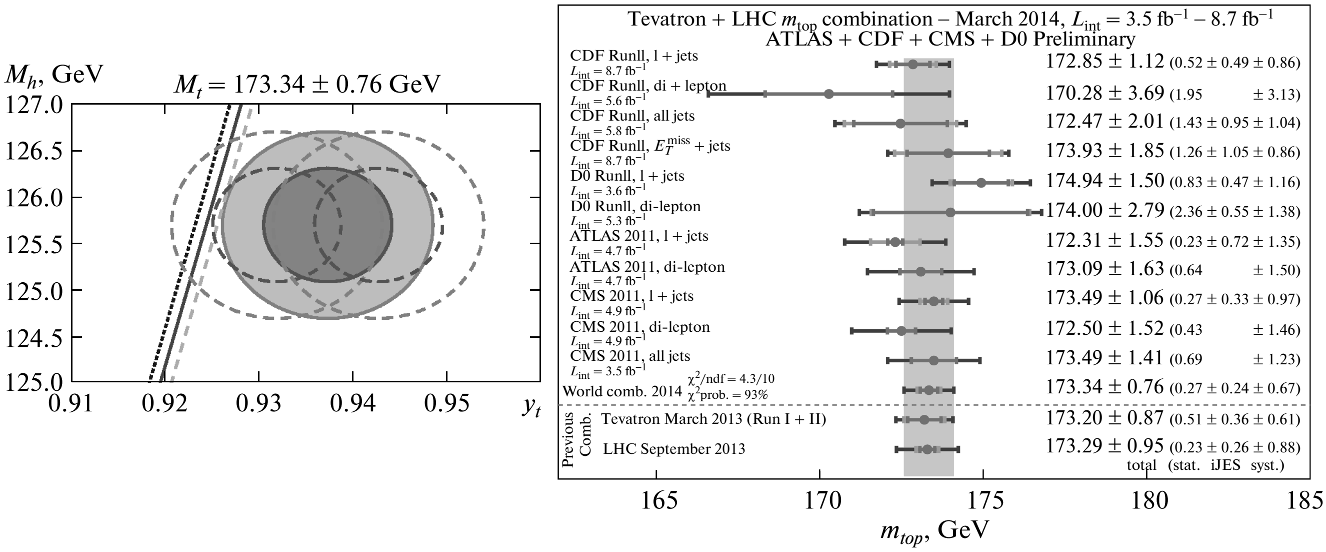

Fig. 6. The plot demonstrating the relation of the current measurements of the top-quark mass M_t and the critical value of the top-quark Yukawa coupling y_t ($\mu = 173.2$ GeV). The diagonal line is the critical value of the Yukawa coupling, with the uncertainties associated with the experimental error of the α_s indicated by dashed lines. To the left of these lines, the SM vacuum is absolutely stable, and to the right it is metastable. The filled ellipses correspond to the 1 and 2σ experimental errors of the determination of the top-quark MC mass, converted to the Yukawa top as if it were the pole mass. Dashed ellipses demonstrate the possible shift due to the ambiguous relation of the pole and MC masses. The top-quark mass is from the combined LHC and Tevatron analysis [53], with the individual experiments results shown on the right (plot from [53])

care should be taken in using the final numerical values of the $\overline{\text{MS}}$ couplings the Sec. 3 in [37], because the value of the strong coupling at $\mu = M_t$ that was used there (Eq. (60)) does not correspond to the value obtained from the Particle Data Group value at M_Z by RG evolution.

Thanks to complete two-loop computations in [37, 38] and three-loop beta functions for the SM couplings found in [39–44], formula (4.4) may have a very small theoretical error, $2 \cdot 10^{-4}$, with this number coming from "educated guess" estimates of even higher-order terms — four-loop beta functions for the SM and three-loop matching conditions at the electroweak scale, which relate the physically measured parameters such as W, Z, and Higgs boson masses with the $\overline{\text{MS}}$ parameters (see the discussion in [36] and more recently in [46]). We stress that the experimental value of the mass of the top quark is not used in this computation; we come to this point in Sec. 4 below.

Yet another interesting quantity that can be derived from Eq. (4.3) is the "criticality" scale μ_0, where both the scalar self-coupling and its β-function are equal to zero. Figure 5 plots it as a function of the top-quark Yukawa coupling for several Higgs masses. It is amazing that μ_0 happens to be very close to the reduced Planck scale M_P: taking the SM parameters as an input, we obtain μ_0 numerically very close to the scale of gravity! This fact was noted a long time ago in [47] and may indicate the asymptotically safe character of the SM and gravity, as has been discussed in [48]. In recent work [49], it was argued that this may be a consequence of enhanced conformal symmetry at the Planck scale. At the same time, it could be a pure coincidence. It is also interesting to note that the extremum of μ_0 as a function of the top-quark Yukawa coupling (with other parameters fixed) is maximal at y_t close to y_t^{crit}. We have no clue why this is so.

5. TOP YUKAWA COUPLING AND EXPERIMENT

The top Yukawa coupling can be extracted from a number of experiments. At present, the most precise determination of y_t comes from the analysis of hadron collisions at the Tevatron in Fermilab and the LHC at CERN. A specific parameter (called Monte Carlo (MC) top mass) in the event generators such as PYTHIA [50, 52] or HERWIG [52] is used to fit the data. The most recent determinations of the MC top mass are $M_t = 173.34 \pm 0.27(\text{stat}) \pm 0.71(\text{syst})$ GeV from the combined analysis of ATLAS, CMS, CDF, and D0 (at 8.7 fb^{-1} of Run II of the Tevatron) [53], $M_t = 174.34 \pm 0.37(\text{stat}) \pm 0.52(\text{syst})$ GeV from the

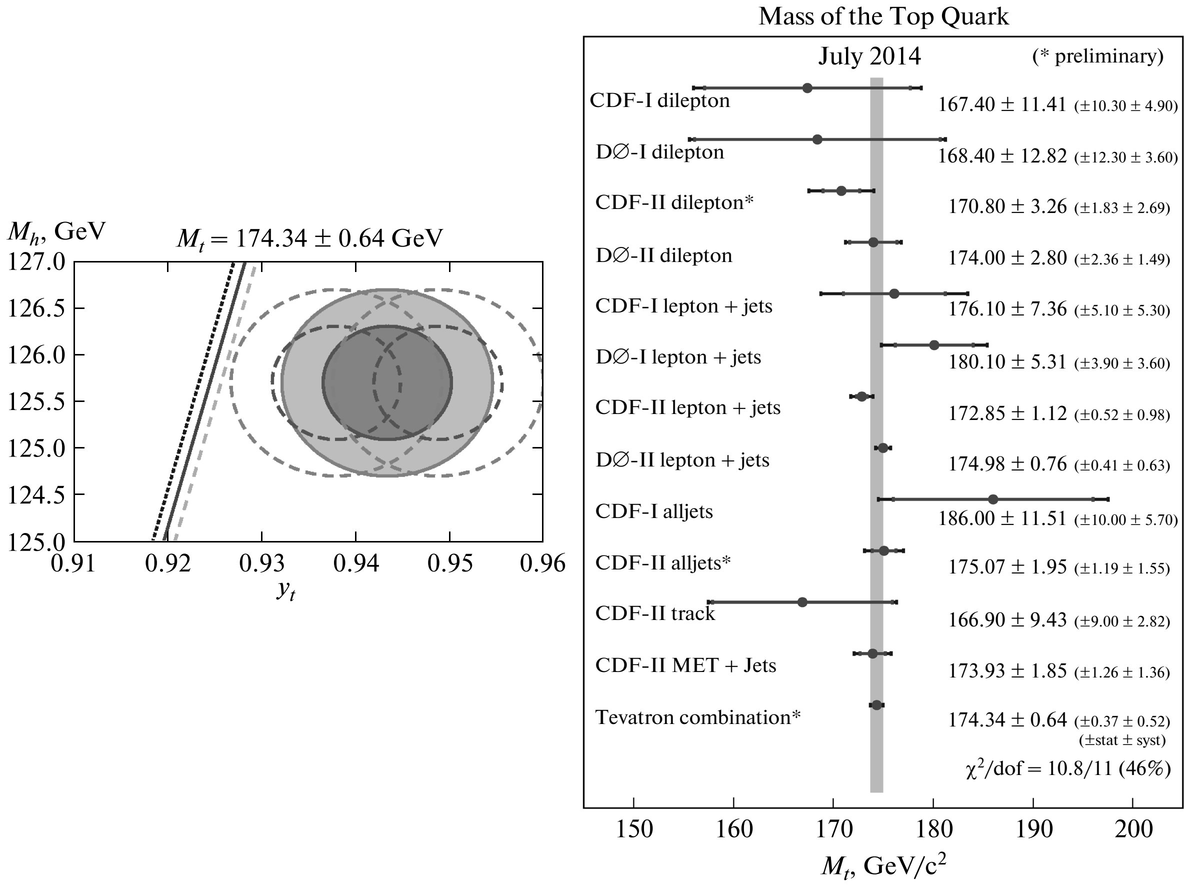

Fig. 7. The same as in Fig. 6 but for the higher top mass reported by the latest Tevatron analysis [54]. The right plot (taken from [54]) indicates the individual measurements

CDF and D0 combined analysis of Run I and Run II of the Tevatron [54], and $M_t = 172.38 \pm 0.10(\mathrm{stat}) \pm \pm 0.65(\mathrm{syst})$ GeV from the CMS alone [55] (at 25 fb^{-1} of Run I LHC).

The problem at hand is to compute the top-quark Yukawa coupling in the $\overline{\mathrm{MS}}$ scheme, which was used in the previous sections, from the MC top quark mass and other relevant electroweak parameters, determined experimentally. Unfortunately, there are no theoretical computations relating these quantities with error bars small enough to make a clear-cut determination of the scale of the new physics. Presumably, the best way to proceed would have an event generator where the top Yukawa coupling in the $\overline{\mathrm{MS}}$ scheme[4)] (rather than the MC top mass) enters directly in the computation of different matrix elements. Then the generated events can be compared with the experimental one, leading to the direct determination of y_t.

At present, the extraction of y_t from experiment proceeds in a somewhat different way[5)]. The analysis goes as follows.

First, it is assumed that the MC top mass, taken from the analysis of the decay products of the top quark, is close to the pole mass, with the difference of the order of 1 GeV [57–59]. Second, the pole top mass is related to the top Yukawa coupling, accounting for strong and electroweak corrections [36, 37].

Presently, the largest theoretical uncertainty is associated with the first step [57]. Yet another source of uncertainties may come from the fact that, to the best of our knowledge, the electroweak effects are not included in MC generators [58]. This, naively, could introduce a relative error of the order of $\mathcal{O}(\alpha_W/\pi) \sim \sim 10^{-2}$ in the pole mass of the top quark.

The second step adds further ambiguities. The pole quark mass is not well defined theoretically, since the

4) Or any other parameter that has a well-defined infrared-safe relation to the Yukawa copling.

5) The difficulties in extracting y_t from experiments at the LHC or Tevatron are discussed in [56, 57].

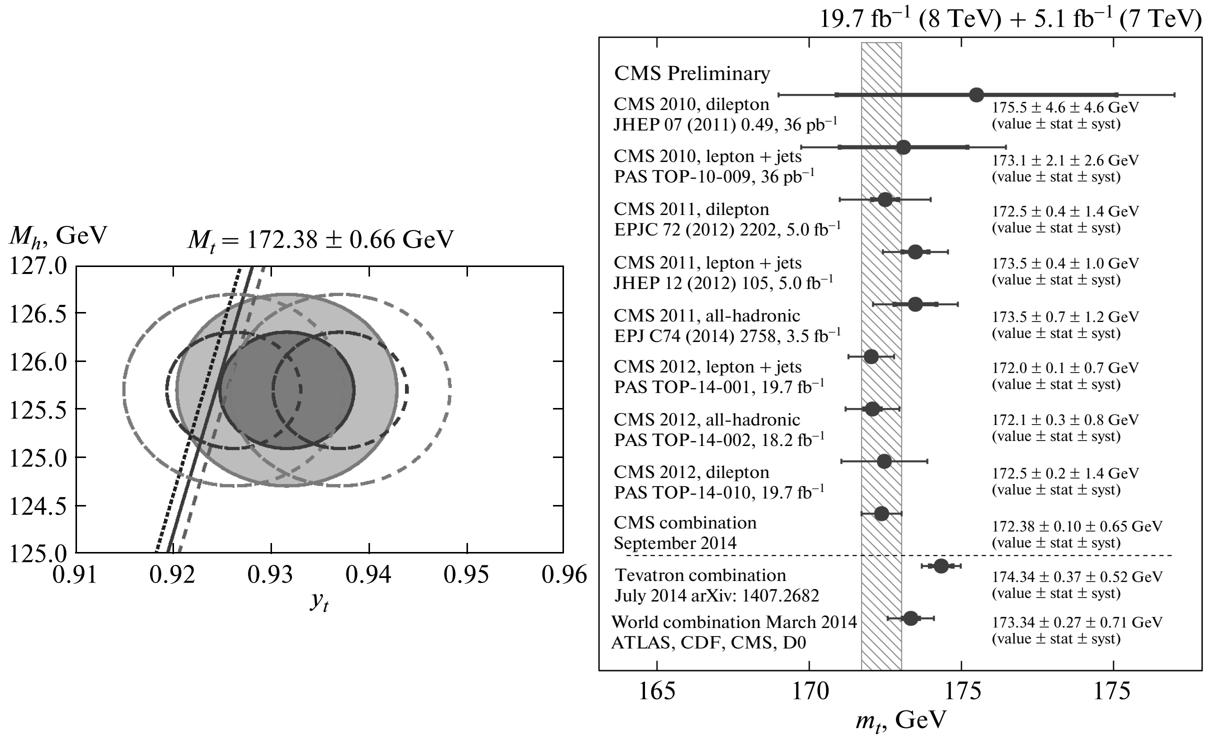

Fig. 8. The same as in Fig. 6 but for the lower top mass reported by CMS from LHC run I [55]. Right plot (taken from [55]) indicates the individual measurements

top quark carries color and thus does not exist as an asymptotic state. The nonperturbative QCD effects of the order of $\Lambda_{QCD} \approx \pm 300$ MeV would lead to $\delta y_t / y_t \sim 10^{-3}$. An effect similar in amplitude comes from (unknown) $\mathcal{O}(\alpha_s^4)$ corrections to the relation between the pole and $\overline{\text{MS}}$ top quark masses. According to [60], this correction can be as large as $\delta y_t / y_t \approx \approx -750(\alpha_s/\pi)^4 \approx -0.002$.

The theoretically more clean extraction of the top Yukawa coupling comes from the measurements of the total cross section of the top production [56], which can be directly calculated in the $\overline{\text{MS}}$ scheme, but has much larger errors.

In Figs. 6, 7, and 8 we show the comparison between experiment and the theoretical computation of the critical value of the top Yukawa coupling. The difference between the two is within 1–3 standard deviations, accounting for systematic uncertainties. In other words, it is perfectly possible that our vacuum is absolutely stable and the SM is a valid theory up to the Planck scale even in the cosmological context. It is also perfectly possible that the opposite is true and we need some kind of new physics at energies around 10^7 GeV or below.

6. CONCLUSIONS

Obviously, the energy scale of the new physics is crucial for the possible outcome of the high energy (LHC [61], FCC [62], ILC [63]), intensity (LHCb [64], SHiP [65]), and accuracy (searches for baryon and lepton number violation, LAGUNA [66], LBNE [67]) frontiers of high-energy physics. The theoretical prejudice about the scale of the new physics is quite subjective and does not give a unique answer, especially given the discovery of the Higgs boson with a very peculiar value of its mass and the absence of deviations from the Standard Model in accelerator experiments. Under these circumstances, the precise measurement of the top-quark Yukawa coupling is very important.

Varying the top-quark Yukawa coupling in the interval allowed by experimental and theoretical uncertainties changes the place where the scalar self-coupling crosses zero from 10^7 GeV to infinity, without a clear indication of the necessity of new thresholds in particle physics between the Fermi and Planck scales. For the largest allowed top Yukawa coupling (we take 2 sigma in determination of the Monte Carlo top mass and add to it 1 GeV uncertainty in comparison between the pole and MC masses), the scale μ_{new} is as small as 10^7 GeV, whereas if the uncertainties are pushed in the other direction, no new physics would be needed below the Planck mass.

A precise measurement of y_t would be possible at e^+e^- colliders such as the ILC [63] or FCC-ee [68]. Otherwise, a theoretical breakthrough in the understanding of the precise top Yukawa coupling extraction from pp collisions is needed. At present, the evidence for the new physics beyond the SM coming from the top and Higgs mass measurements is at the level of 1–3σ, having roughly the same statistical significance as other reported anomalies, for example, the muon magnetic moment [69], MiniBooNE [70], and LSND [71]. It remains to be seen which of them (if any) will eventually be converted into undisputed signal of the new physics between the Fermi and Planck scales.

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REFERENCES

1. G. F. Giudice, in: *Perspectives on LHC Physics*, ed. by G. Kane and A. Pierce (2008), p. 155; arXiv:0801.2562 [hep-ph].
2. G. F. Giudice, PoS **EPS-HEP2013**, 163 (2013), arXiv:1307.7879 [hep-ph].
3. L. Maiani, G. Parisi, and R. Petronzio, Nucl. Phys. B **136**, 115 (1978).
4. N. Cabibbo, L. Maiani, G. Parisi, and R. Petronzio, Nucl. Phys. B **158**, 295 (1979).
5. M. Lindner, Zeit. Phys. C **31**, 295 (1986).
6. N. V. Krasnikov, Yad. Fiz. **28**, 549 (1978).
7. P. Q. Hung, Phys. Rev. Lett. **42**, 873 (1979).
8. H. D. Politzer and S. Wolfram, Phys. Lett. B **82**, 242 (1979).
9. V. Branchina and E. Messina, Phys. Rev. Lett. **111**, 241801 (2013); arXiv:1307.5193 [hep-ph].
10. K. Olive et al. (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).
11. J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto, and A. Strumia, Phys. Lett. B **709**, 222 (2012); arXiv:1112.3022 [hep-ph].
12. A. Kobakhidze and A. Spencer-Smith, Phys. Lett. B **722**, 130 (2013); arXiv:1301.2846 [hep-ph].
13. K. Enqvist, T. Meriniemi, and S. Nurmi, JCAP **1407**, 025 (2014); arXiv:1404.3699 [hep-ph].
14. M. Herranen, T. Markkanen, S. Nurmi, A. Rajantie, Phys. Rev. Lett. **113**, 211102 (2014); arXiv:1407.3141 [hep-ph].
15. K. Kamada, arXiv:1409.5078 [hep-ph].
16. P. Ade et al. (BICEP2 Collaboration), Phys. Rev. Lett. **112**, 241101 (2014); arXiv:1403.3985 [astro-ph.CO].
17. A. A. Starobinsky, Phys. Lett. B **91**, 99 (1980).
18. F. L. Bezrukov and M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008); arXiv:0710.3755 [hep-th].
19. T. Asaka and M. Shaposhnikov, Phys. Lett. B **620**, 17 (2005); arXiv:hep-ph/0505013.
20. T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys. Lett. B **631**, 151 (2005); arXiv:hep-ph/0503065.
21. M. Shaposhnikov and I. Tkachev, Phys. Lett. B **639**, 414 (2006); arXiv:hep-ph/0604236.
22. F. Bezrukov and D. Gorbunov, JHEP **1307**, 140 (2013); arXiv:1303.4395 [hep-ph].
23. G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, and A. Strumia, JHEP **1208**, 098 (2012); arXiv:1205.6497 [hep-ph].
24. W. Loinaz and R. Willey, Phys. Rev. D **56**, 7416 (1997); arXiv:hep-ph/9702321 [hep-ph].
25. L. Di Luzio and L. Mihaila, JHEP **1406**, 079 (2014); arXiv:1404.7450 [hep-ph].
26. A. Andreassen, W. Frost, and M. D. Schwartz, Phys. Rev. Lett. **113**, 241801 (2014); arXiv:1408.0292 [hep-ph].
27. N. Nielsen, Phys. Rev. D **90**, 036008 (2014); arXiv: 1406.0788 [hep-ph].
28. C.-S. Chen and Y. Tang, JHEP **1204**, 019 (2012); arXiv:1202.5717 [hep-ph].
29. J. Elias-Miro, J. R. Espinosa, G. F. Giudice, H. M. Lee, and A. Strumia, JHEP **1206**, 031 (2012); arXiv: 1203.0237 [hep-ph].
30. S. Baek, P. Ko, W.-I. Park, and E. Senaha, JHEP **1211**, 116 (2012); arXiv:1209.4163 [hep-ph].
31. K. Allison, JHEP **1305**, 009 (2013); arXiv:1210.6852 [hep-ph].

32. S. Kanemura, T. Matsui, and T. Nabeshima, Phys. Lett. B **723**, 126 (2013); arXiv:1211.4448 [hep-ph].

33. H. M. Lee, Phys. Rev. B **722**, 198 (2013); arXiv: 1301.1787 [hep-ph].

34. C. Coriano, L. Delle Rose, and C. Marzo, Phys. Lett. B **738**, 13 (2014); arXiv:1407.8539 [hep-ph].

35. G. Bélanger, K. Kannike, A. Pukhov, and M. Raidal, JCAP **1406**, 021 (2014); arXiv:1403.4960 [hep-ph].

36. F. Bezrukov, M. Kalmykov, B. Kniehl, and M. Shaposhnikov, JHEP **1210**, 140 (2012); arXiv:1205.2893 [hep-ph].

37. D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala et al., JHEP **1312**, 089 (2013); arXiv: 1307.3536 [hep-ph].

38. A. Pikelner, A. Bednyakov, B. Kniehl, V. Velizhanin, and O. Veretin, (2014), talk at QUARKS'14 conference.

39. L. N. Mihaila, J. Salomon, and M. Steinhauser, Phys. Rev. Lett. **108**, 151602 (2012); arXiv:1201.5868 [hep-ph].

40. L. N. Mihaila, J. Salomon, and M. Steinhauser, Phys. Rev. D **86**, 096008 (2012); arXiv:1208.3357 [hep-ph].

41. K. Chetyrkin and M. Zoller, JHEP **1206**, 033 (2012); arXiv:1205.2892 [hep-ph].

42. K. Chetyrkin and M. Zoller, JHEP **1304**, 091 (2013); arXiv:1303.2890 [hep-ph].

43. A. Bednyakov, A. Pikelner, and V. Velizhanin, Phys. Lett. B **722**, 336 (2013); arXiv:1212.6829.

44. A. Bednyakov, A. Pikelner, and V. Velizhanin, Nucl. Phys. B **875**, 552 (2013); arXiv:1303.4364.

45. A. Sirlin and R. Zucchini, Nucl. Phys. B **266**, 389 (1986).

46. M. Shaposhnikov, PoS EPS-HEP **2013**, 155 (2013); arXiv:1311.4979 [hep-ph].

47. C. Froggatt and H. B. Nielsen, Phys. Lett. B **368**, 96 (1996); arXiv:hep-ph/9511371.

48. M. Shaposhnikov and C. Wetterich, Phys. Lett. B **683**, 196 (2010); arXiv:0912.0208 [hep-th].

49. A. Gorsky, A. Mironov, A. Morozov, and T. Tomaras, Zh. Eksp. Teor. Fiz. **147** (2015); arXiv:1409.0492 [hep-ph].

50. T. Sjostrand, S. Mrenna, and P. Z. Skands, Comp. Phys. Comm. **178**, 852 (2008); arXiv:0710.3820 [hep-ph].

51. T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP **0605**, 026 (2006); arXiv:hep-ph/0603175 [hep-ph].

52. M. Bahr, S. Gieseke, M. Gigg, D. Grellscheid, K. Hamilton et al., Eur. Phys. J. C **58**, 639 (2008); arXiv: 0803.0883 [hep-ph].

53. ATLAS Collaboration, CDF Collaboration, CMS Collaboration, D0 Collaboration (2014), ATLAS-CONF-2014-008, CDF-NOTE-11071, CMS-PAS-TOP-13-014, D0-NOTE-6416; arXiv:1403.4427 [hep-ex].

54. Tevatron Electroweak Working Group (CDF Collaboration, D0 Collaboration) (2014), FERMILAB-CONF-14-227-E-TD, TEVEWWG-top2014-01, CDF-Note-11105, DO-Note-6444; arXiv:1407.2682 [hep-ex].

55. CMS Collaboration, (2014), CMS-PAS-TOP-14-015.

56. S. Alekhin, A. Djouadi, and S. Moch, Phys. Lett. B **716**, 214 (2012); arXiv:1207.0980 [hep-ph].

57. S. Frixione and A. Mitov, JHEP **1409**, 012 (2014); arXiv:1407.2763 [hep-ph].

58. A. Buckley, J. Butterworth, S. Gieseke, D. Grellscheid, S. Hoche et al., Phys. Rep. **504**, 145 (2011); arXiv: 1101.2599 [hep-ph].

59. A. Juste, S. Mantry, A. Mitov, A. Penin, P. Skands et al., Europ. Phys. J. C **74**, 3119 (2014); arXiv:1310.0799 [hep-ph].

60. A. Kataev and V. Kim, Phys. Part. Nucl. **41**, 946 (2010); arXiv:1001.4207 [hep-ph].

61. http://lhc.web.cern.ch/.

62. https://espace2013.cern.ch/fcc/.

63. https://www.linearcollider.org/ILC.

64. http://lhcb.web.cern.ch/.

65. http://ship.web.cern.ch/.

66. http://laguna.ethz.ch/laguna-eu/.

67. http://lbne.fnal.gov/.

68. http://tlep.web.cern.ch/.

69. G. Bennett et al. (Muon G-2 Collaboration), Phys. Rev. D **73**, 072003 (2006); arXiv:hep-ex/0602035 [hep-ex].

70. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Phys. Rev. Lett. **102**, 101802 (2009); arXiv:0812.2243 [hep-ex].

71. A. Aguilar-Arevalo et al., (LSND Collaboration), Phys. Rev. D **64**, 112007 (2001); arXiv:hep-ex/0104049 [hep-ex].