LHC AND THE STRONGLY-INTERACTING EXTENSIONS OF THE STANDARD MODEL

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A NEW 125-GEV BOSON

On July 4, 2012, the representatives of two major LHC experiments, Fabiola Gianotti of the ATLAS collaboration and Joseph Incandela of the CMS, presented at the CERN's Main Auditorium discovery of a new particle [1]. The discovery was an outcome of the long-lasting effort to find or exclude the Standard model (SM) Higgs boson, a possible participant of physics responsible for electroweak symmetry breaking (ESB). The ATLAS collaboration announced the 5.9σ signal of a boson of the mass of 126.0 ± 0.4(stat.)±0.4(sys.) GeV. The CMS collaboration observed similar signal of a boson with the mass of 125.3 ± 0.4(stat.) ± 0.5(sys.).

The crossing of the magical "five sigma" deviation which in the high energy physics is traditionally considered as a "must" for claiming a discovery has been a result of combining events from more than two decay channels. Nevertheless, two of the channels have contributed far the most to the achievements of both experiments. The crucial channels have been $h \to \gamma\gamma$ and $h \to ZZ^* \to \ell\ell\ell\ell$, where h stands for the newly discovered 125-GeV boson; do not read h as "Higgs boson", though. The question if the discoveree is a/the Higgs boson will be discussed below. The discoveries of both collaborations have been published in [2, 3].

Shortly after the announcement, the CDF and D0 collaborations of the Tevatron $p\bar{p}$ collider in Fermilab, USA, published their findings [4], potentially related to the new discovery. In the Tevatron Run II, the CDF and D0 observed together the 3.1σ excess of events in the would-be $h \to b\bar{b}$ channel over the invariant mass interval of $(120; 135)$ GeV.

While the discovery and all accompanying observations resulted from the dedicated effort to find or exclude the SM Higgs boson the current data does not prove that the new 125-GeV particle really is the SM Higgs. Let us try to summarize what can and cannot be said about the new particle at the very moment. We can claim the discovery of a new particle of the mass of about 125 GeV. It is not clear whether it is elementary or composite. Based on its decay products and the conservation laws the particle is electrically neutral and cannot be a fermion. Thus, it is a boson. Since it decays to two photons the Landau-Yang theorem [5, 6] excludes also the spin 1. The new particle is color-neutral, i.e. it does not "feel" the strong nuclear force. Finally, based on the number of the observed events one can deduce that the coupling of the new particle to Z boson is two orders of magnitude stronger than its coupling to photon.

IS IT A HIGGS?

The Higgs particle is a possible byproduct of the mechanism responsible for ESB.

The obvious fact that the masses of many of the known elementary particles, the W and Z bosons at the first place, have non-zero values seems to break the gauge symmetry of the electroweak Lagrangian. The gauge symmetry represents a very useful and well verified guiding principle in building interaction structure of the SM Lagrangian. However, the straightforward introduction of the non-zero mass terms into the Lagrangian breaks the symmetry. Fortunately, Peter Higgs and others [7, 8, 9] found the solution to the problem. Particle fields can obtain non-zero masses without sacrificing the Lagrangian's gauge symmetry if the symmetry of the theory's vacuum is properly lower than the gauge symmetry. This concept is known as *spontaneous symmetry breaking* (SSB). Thus, through SSB we can reconcile the apparent fact of ESB with the observed symmetry of the electroweak interactions. It is certainly encouraging that we know physical systems in nature where SSB is actually at work. The classical examples are represented by the phenomenon of superconductivity and by physics of hadrons.

The SM contains a particular formulation of the ESB mechanism. It is based on introducing a new $SU(2)_L$ complex scalar doublet field with non-zero vacuum expectation value, $v \approx 250$ GeV. Out of the four real scalar fields of the doublet three fields are unphysical and the fourth one is a real particle called the SM Higgs boson. However, this is not the only possibility how to realize ESB spontaneously. It is the simplest possibility, in a sense, and thus, naturally, the first candidate for investigation. Many alternative mechanisms have been formulated, though. The numbers of Higgs-like particles predicted by them range from zero to several. We can say that the question of the mechanism responsible for ESB has become a centerpiece of all speculations about physics beyond the SM.

When we turn to the recent 125-GeV boson discovery we should ask if the new particle has any relation to the ESB mechanism. The particle should be called a Higgs boson of some sort only if the answer is yes.

Since the W and Z boson obtain their masses through the ESB mechanism we expect that the coupling of a Higgs boson to W and Z will be significantly stronger than the coupling to the massless photon. If, on the other hand, the new particle h had no connection to ESB we would expect $g(h\gamma\gamma) \approx g(hZZ) \approx g(hWW)$. The existing data supports the claim that the new particle *is* related to the mechanism of ESB.

The spontaneous ESB can provide masses for fermions as well. As in the case of the electroweak bosons W and Z, the couplings of a Higgs particle to fermions should be proportional to fermion masses. Is it the case? Unfortunately, there is not enough data at this moment to make clear conclusion about this question and we have to wait till the end of the 2012 LHC run, at least.

We can proceed a one step further in questioning

the nature of the newly discovered boson: what is the data support for the boson being the SM Higgs boson? Should it be answered in a single sentence, then the data roughly resembles the SM Higgs boson and cannot exclude it.

To distinguish the SM Higgs boson nature of the observed particle we have to compare theory with experiment. Since we know the mass of the SM Higgs boson candidate, 125 GeV, we can calculate its total decay width, $\Gamma_{\text{tot}}^{\text{SMHiggs}} = 4.2$ MeV, and the branching ratios of individual decay channels. They can be read off of Fig. 1. There we can see that the dominant decay channel of the 125-GeV SM Higgs boson is $h \to b\bar{b}$. On the other hand, the branching ratios of $h \to ZZ^*$

TAB. 1. The most pronounced statistical significances of the 125-GeV boson signals observed in particular decay channels at the ATLAS, CMS, and CDF+D0 detectors [2, 3, 4].

channel	ATLAS	CMS	Tevatron
$\gamma\gamma$	4.5σ	4.1σ	-
ZZ^*	3.6σ	3.2σ	-
WW^*	2.8σ	1.6σ	-
$b\bar{b}$	-	-	3.1σ

of the individual decay channels with the SM predictions. The relative signal strength can be defined as

$$\mu \equiv \frac{(\sigma_{\text{prod}} \times \text{BR})_{\text{observed}}}{(\sigma_{\text{prod}} \times \text{BR})_{\text{SM}}}, \tag{1}$$

where σ_{prod} is the Higgs boson production cross section and BR is the branching ratio of the Higgs boson to a particular channel. The "no decay" in a particular channel would result in $\mu = 0$, while the signal strength equal to that of the SM would result in $\mu = 1$.

In Fig. 2, there are signal strengths of individual decay channels observed at the ATLAS detector depicted. Similarly, in Figs. 3 and 4, the signal strengths
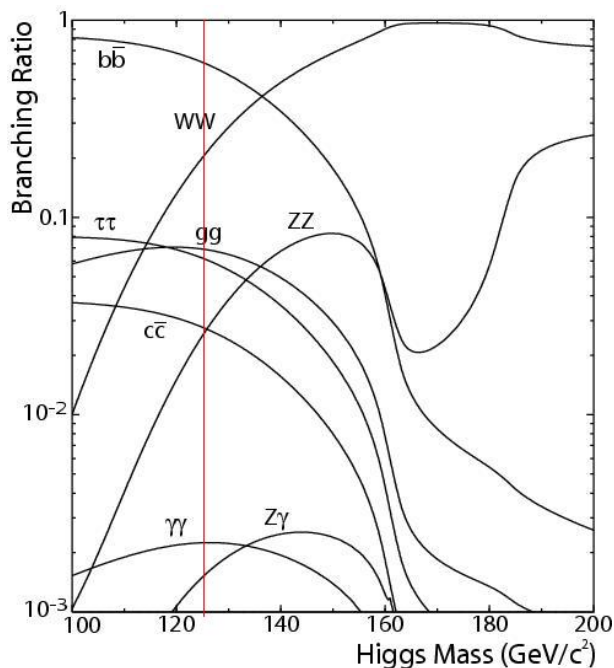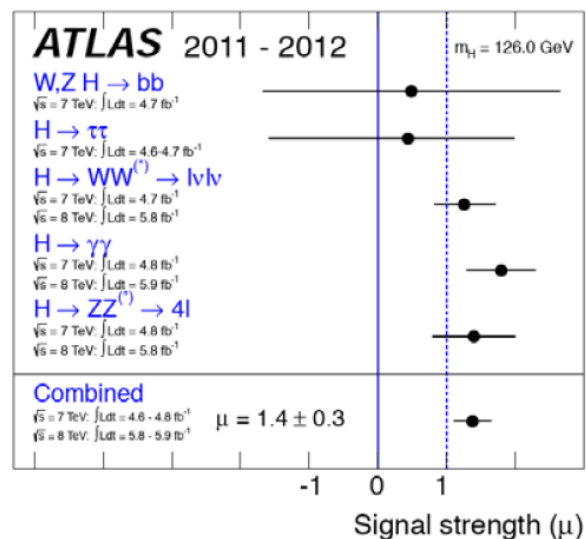

Fig. 1. The SM Higgs boson branching ratios as functions of the Higgs boson mass. The mass of 125 GeV is indicated by the vertical line.

and $h \to \gamma\gamma$, are the one and two orders of magnitude, respectively, smaller. Despite that, these were the major discovery channels of the 125-GeV boson. This is because the more dominant channels are plagued by the huge backgrounds of the LHC pp collisions. Thus, to discover the Higgs particle of this particular mass was difficult. On the other hand, this particular mass provides us with a large number of decay channels to study once the difficulties are overcome.

Probing the SM Higgs boson nature of the 125-GeV boson can be split into two steps. First, the new 125-GeV particle should be discovered in all SM Higgs boson decay channels. That would confirm the existence of all the decay channels. In Table 1 we show the decay channels of the greatest statistical significance currently observed. There is a good chance that the question of the existence of the channels listed in Table 1 and $h \to \tau\tau$ will be settled by the full 2012 LHC data. Unfortunately, the LHC is not capable to detect the $h \to c\bar{c}$ channel.

The second step is intimately related to the first one. It includes comparing the relative signal strengths

Fig. 2. The signal strengths μ of the 125-GeV boson decay channels observed at the ATLAS detector [2].

observed at the CMS detector and the CDF+D0 detectors, respectively, are shown. Notice slightly stronger than SM-expected signal in the $h \to \gamma\gamma$ channel in both, ATLAS and CMS, graphs. While this observation might be inspiring for theorists, it is not statistically strong enough to draw any serious conclusions. Again, the full 2012 LHC data will probably shed more light into this question.

If the 125-GeV boson is the SM Higgs one there are no good reasons to expect that the LHC will discover more new particles. If it is not the SM Higgs boson new particles and forces are expected to exist.
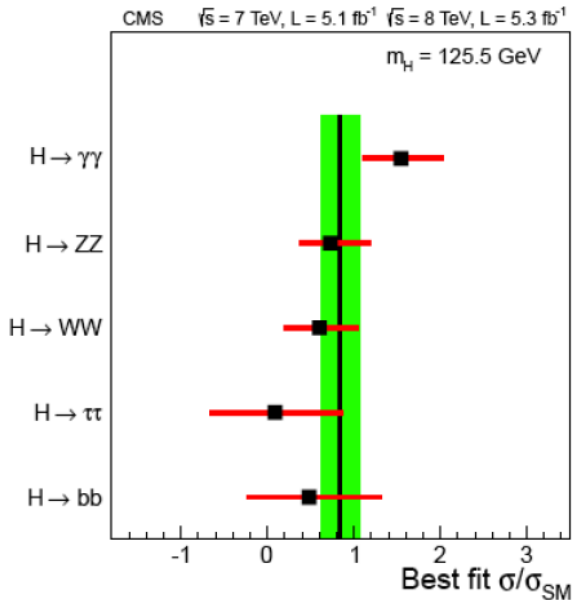
Fig. 3. The signal strengths of the 125-GeV boson decay channels observed at the CMS detector [3].

The question remains though weather they would be within the reach of the LHC.

THEORY AFTER JULY, 4

The 125-GeV boson discovery along with various exclusion limits derived from the 2011 and 2012 LHC data sets put a pressure on the existing theories beyond the SM. The new findings have forced the SUSY as well as Technicolor theories to begin "organized retreat": while SUSY theorists have to come to terms with the absence of superpartner particles in quite a large range of masses, Technicolorists have to deal with the fact of the existence of the light boson of probably spin 0. Nevertheless, this is a very healthy process promising a significant progress on the theory frontier, the progress of the extent unmatched for decades.

Now, the interesting question is how the current LHC data enables to discriminate among various candidates of beyond the SM (BSM) physics. Aside from the (non)observation of new particles, the existing data can be used to limit free parameters (like new couplings, energy scales, etc.) of the particular BSM theories or of the Effective Lagrangians which would be a more model-independent approach.

There are BSM theories which predict $\mu \approx 1$. The SUSY as well as the strongly-interacting theories can result in deviations of the couplings of the 125-GeV boson from the SM Higgs boson values smaller than 10%. This is illustrated in Table 2.

In [11], M. Peskin estimates the h coupling measurement accuracy that can be achieved when the LHC collects 300 fb^{-1} of data at the collision energy of 14 TeV. The estimates are shown in Fig. 5. Following the estimates it becomes clear that the LHC can hardly become sensitive to the deviations cited in Table 2 even after reaching its full performance. In Fig. 5 there are
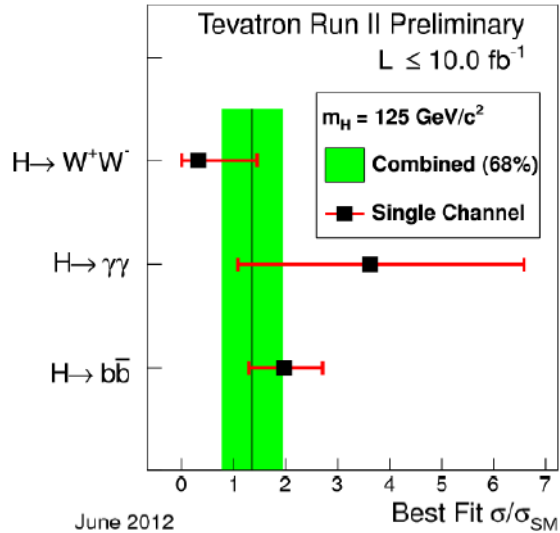

Fig. 4. The combined signal strengths of the 125-GeV boson decay channels observed at the CDF and D0 detectors of Tevatron [4].

TAB. 2. Deviations of the couplings of the 125-GeV boson from the SM Higgs boson values predicted by some BSM theories; m_A stands for the mass of a heavy A^0 Higgs boson, and F is the Goldstone boson decay constant [10].

theory	coupling	deviation
SUSY	$h\tau\tau$	$10\% \cdot \left(\frac{400 \text{ GeV}}{m_A}\right)^2$
SUSY (large β)	$hb\bar{b}$	$\text{dev}(h\tau\tau) + (1 \leftrightarrow 3)\%$
composite Higgs	$hf\bar{f}$	$(3 \leftrightarrow 9)\% \cdot \left(\frac{1 \text{ TeV}}{F}\right)^2$
Little Higgs	hgg	$(5 \leftrightarrow 9)\%$

also the estimates of the h coupling measurement accuracy achievable at various designs of future e^+e^- colliders. This graph underlines the need for construction of such a collider in order to measure the couplings of the 125-GeV boson with the precision necessary to distinguish the individual BSM theories. Of course, we should keep in mind that if other new particles were discovered at the LHC in the future it would provide complementary information and significantly alter the overall picture.

In a more model independent way, the electroweak symmetry breaking sector with a scalar field h can be parameterized by the non-linear effective Lagrangian [12]

$$\mathcal{L}_{eff} = \frac{v^2}{4}\text{Tr}\left(D_\mu U D^\mu U^\dagger\right) \times \left[1 + 2a\frac{h}{v} + \dots\right]$$

$$-\left\{\frac{v}{\sqrt{2}}\sum_f \bar{f}_L \lambda_f f_R \left[1 + c_f\frac{h}{v} + \dots\right] + \text{h.c.}\right\}, \quad (2)$$

where U is a unitary 2×2 matrix parameterizing the three unphysical Nambu-Goldstone bosons, v is the conventional ESB scale, and λ_f's are the SM Yukawa couplings of the fermions f. The coefficients a and c_f
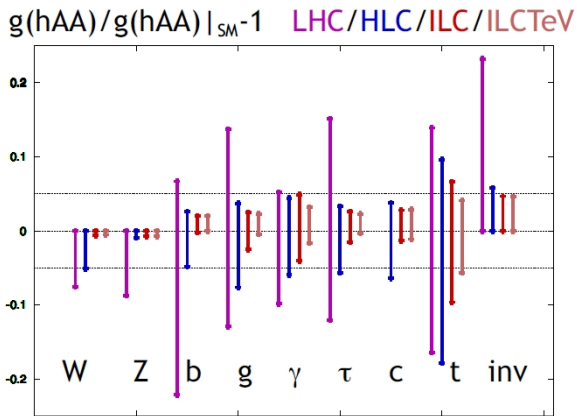
Fig. 5. The h coupling measurement precisions achievable at the LHC(14 TeV, 300fb^{-1}) and various designs of future e^+e^- colliders: HLC(250 GeV, 250 fb^{-1}), ILC(500 GeV, 500 fb^{-1}), and ILCTeV(1 TeV, 1 ab^{-1}), [11].

parameterize the deviations of the h couplings to massive electroweak gauge bosons and to fermions, respectively, from those of the SM Higgs boson. Note that the custodial symmetry is assumed in writing the Lagrangian.

In the following we will assume the flavor universality of the Yukawa coupling deviations c_f: $c_t = c_b = c_c = c_\tau = \ldots \equiv c$. The SM situation correspond to $a = c = 1$.

The global analysis of the available CMS, ATLAS, CDF and D0 data results in the constraints on the deviations a and c [12]. The constraints are shown in Fig. 6 along with the values of a and c predicted by some strongly-interacting BSM theories. As we can see
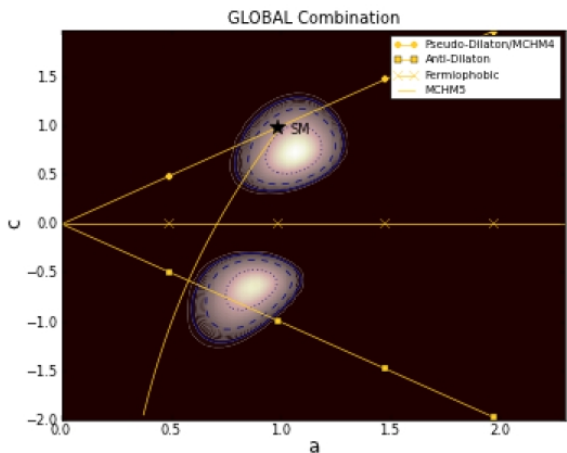

Fig. 6. The constraints on the deviations a and c of the 125-GeV boson couplings to the massive electroweak gauge bosons and fermions, respectively. The constraints have been obtained from the global analysis of the CMS, ATLAS, CDF and D0 data in [12]. The SM is represented by the black star, the yellow lines represent various composite Higgs models.

the data excludes fermiophobic models ($c \to 0$) while

they admit pseudo-dilaton and MCHM4[1] models with parameters close to the SM model case.

Other global fit has been performed in [12] testing the possibility that h couples to other particles proportionally to some powers of their masses. In the SM,

$$\lambda_f = \sqrt{2}\frac{m_f}{v}, \quad g_V = 2\frac{M_V}{v}, \qquad (3)$$

where g_V and M_V are the gauge coupling and the mass of the massive gauge boson V. The coupling-mass linear relations can be generalized to the following anomalous scaling laws

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \quad g_V = 2\left(\frac{M}{v}\right)^{1+2\epsilon}, \qquad (4)$$

which in terms of the effective Lagrangian (2) translates to the deviations

$$a = \frac{v}{M}\left(\frac{M_V}{M}\right)^{2\epsilon}, \quad c_f = \frac{v}{M}\left(\frac{m_f}{M}\right)^{\epsilon}, \qquad (5)$$

where M is a free parameter of the mass dimension. The SM is being recovered when $\epsilon = 0$ and $M = v$. The mass independent scenario would require $\epsilon = -1$.

The constraints on the parameters M and ϵ obtained [12] from the global fit of the CMS, ATLAS, CDF and D0 data are shown in Fig. 7. Clearly, the
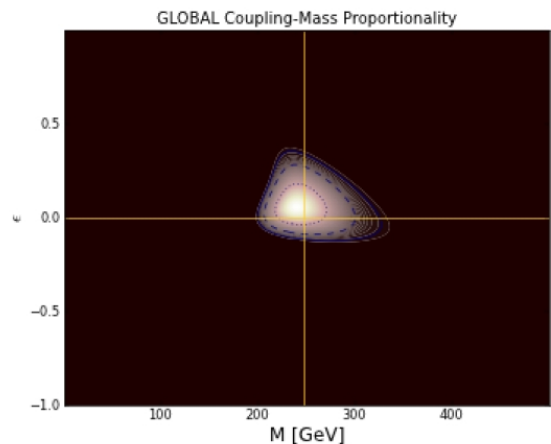

Fig. 7. The constraints on the scaling parameters M and ϵ of the 125-GeV boson. The constraints have been obtained from the global analysis of the CMS, ATLAS, CDF and D0 data in [12]. The SM corresponds to the intersection of the yellow lines.

preferred values of the parameters are consistent with the SM Higgs boson scenario

$$\epsilon = 0.05 \pm 0.08, \quad M = 241 \pm 18 \text{ GeV}. \qquad (6)$$

Even though the current data are consistent with the 125-GeV SM Higgs boson alternative possibilities remain well open. Fitting the alternative theories to the existing data to recognize survivors is the task of the utmost importance. At the same time, equally important is the experimental search for new particles.

[1]The Minimal Composite Higgs Model embedded into spinorial representation of $SO(5)$.

Any such discovery (or a new exclusion limit) will provide a supplementary information the value of which cannot be overestimated. For both these tasks the formalism of the effective Lagrangians is a very useful tool as it was illustrated above by the parameter analysis based on the effective Lagrangian (2).

THE 125-GEV BOSON AND THE TOP-BESS MODEL

The strongly-interacting BSM theories typically introduce new strong interactions and new elementary fields which are subject to them. Thus, it is reasonable to expect that the new fields will form the bound states of various masses, spins, etc., as in the QCD. And as it the case in the QCD, the new strong interactions are not treatable perturbatively. Following the QCD experience, physics of the new bound states can be described by the effective Lagrangian formulated in terms of the bound state fields and obeying the new physics symmetries.

We have formulated the top-BESS model [13] as a modification of the BESS model [14]. The BESS model is an example of the effective Lagrangian describing the Higgsless ESB sector with an extra $SU(2)$ vector bound state triplet. Recently, the model has been utilized in the context of the extra-dimensional theories [15, 16].

Both, the BESS and top-BESS models, have been formulated without scalar resonances of any kind because their primary motivation was the systematic effective description and study of a vector bound state physics. Nevertheless, the introduction of a scalar resonance to the BESS-like effective Lagrangian is not a difficult task; actually, it is much less involved than in the case of the vector resonance.

Both, BESS and top-BESS, Lagrangians possess the same symmetry. Their global symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(2)_{HLS}$ is spontaneously broken down to $SU(2)_{L+R} \times U(1)_{B-L}$ while the local symmetry $SU(2)_L \times U(1)_Y \times SU(2)_{HLS}$ is spontaneously broken down to $U(1)_{em}$. The electroweak gauge symmetry is enlarged by the auxiliary $SU(2)_{HLS}$ gauge group where "HLS" stands for the Hidden Local Symmetry. In the BESS model, the new vector triplet is introduced as a gauge field of $SU(2)_{HLS}$ with the gauge coupling g''.

In the top-BESS model we modify the direct interactions of the vector triplet with fermions. While in the BESS model there is a universal direct coupling of the triplet to all fermions of a given chirality, in our modification we admit direct couplings of the new triplet to top and bottom quarks only. Our modification is inspired by the speculations about a special role of the top quark (or the third quark generation) in the mechanism of ESB. The speculations are fueled by the observation that the large top mass is surprisingly close to the ESB scale: $m_t \approx v/\sqrt{2}$.

In the top-BESS model, we take the possible chirality dependence of the triplet-to-top/bottom coupling into account multiplying the $SU(2)_{HLS}$ gauge coupling g'' by the b_L and b_R parameters for the left and right
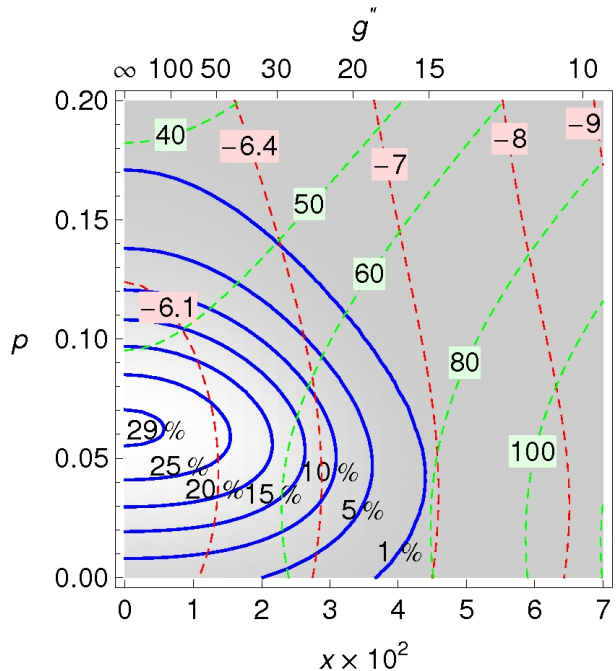

Fig. 8. The most preferred values of the (p, g'') parameters (white area) when there is no real scalar field in the top-BESS Lagrangian. The blue iso-lines join (p, g'') points with the same statistical support; the values of the support are shown in percents placed next to the lines.

fermion doublets, respectively. In addition, we can disentangle the triplet-to-top-quark right coupling from the triplet-to-bottom-quark right coupling. This breaks the $SU(2)_R$ symmetry which is broken by the SM interactions, anyway. For the sake, we have introduced a free parameter, $0 \leq p \leq 1$. The p parameter can weaken the strength of the triplet-to-b_R coupling. However, the $SU(2)_L$ symmetry does not allow us to do the same splitting for the left quark doublet.

We have performed a multi-observable fit of the top-BESS parameters [17] using (pseudo)observables ϵ_1, ϵ_2, ϵ_3, $\Gamma(Z \to b\bar{b})$, and $BR(B \to X_s\gamma)$. The epsilons are related to the *basic observables* [18]: the ratio of the electroweak gauge boson masses, $r_M \equiv M_W/M_Z$, the inclusive partial decay width of Z to the charged leptons, $\Gamma_\ell(Z \to \ell\bar{\ell} + \text{photons})$, the forward-backward asymmetry of charged leptons at the Z-pole, $A_\ell^{FB}(M_Z)$, and the inclusive partial decay width of Z to bottom quarks, $\Gamma_b(Z \to b\bar{b} + X)$.

In Fig. 8 we show the most preferred values of the (p, g'') parameters when there is no real scalar field in the top-BESS Lagrangian. We can see that data pushes g'' to infinity. In the limit $g'' \to \infty$ the influence of the vector triplet on low-energy physics disappears, though.

In Fig. 9 we can see the impact of adding the 125-GeV scalar particle into the top-BESS Lagrangian. The addition is performed by extending the top-BESS Lagrangian with the Lagrangian (2). We have calculated the preferred (p, g'') values in the limit $a = c = 1$. Then, the best value of g'' moved to about 40 and the best value of p is close to 0.2. Also, the statistical backing for the best values has grown. Hence, the inclusion of the 125-GeV scalar into the top-BESS model im-
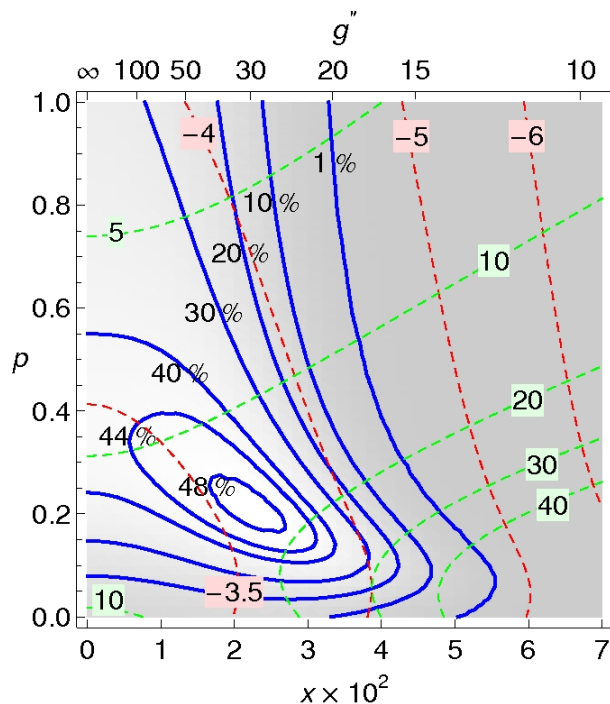
Fig. 9. The most preferred values of the (p, g'') parameters (white area) with the 125-GeV scalar field in the top-BESS Lagrangian. The blue iso-lines join (p, g'') points with the same statistical support; the values of the support are shown in percents placed next to the lines.

proves its chance that it might correspond to the actual strongly-interacting situation in nature. Data suggests that should it be the case the new vector triplet would interact with the right bottom quark some five times weaker than with the right top quark.

CONCLUSIONS

On July, 2012, the new Higgs era in high energy physics started by discovering the 125-GeV boson. While we are not yet sure if the boson is the SM Higgs boson the LHC data resembles it. To settle down this question more LHC data will be needed. Yet it might be the case that even all LHC data will not be enough to solve this question. Particularly, if there will be no more new particles discovered at the LHC, new $e^+ e^-$ colliders will be needed to measure the 125-GeV boson couplings with sufficient precision.

Major BSM scenarios, like the SUSY and Technicolor, are not excluded by the current LHC data. Nevertheless, in both camps many representatives have not survived the LHC findings. And the process continues as we speak. The full 2012 LHC data can be full of surprises or reveal nothing new. It is really exciting time for high energy physics!

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