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Letter

What has been discovered at 125 GeV by the CMS and the ATLAS experiments?

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Abstract. While looking for the putative Higgs boson of the Standard Model of particle physics, recently, the CMS and the ATLAS experiments at CERN have found strong signals of a new particle at about 125 GeV. However in July 2012 the decay channels of this particle had some unexpected and puzzling anomalies not explainable by the Standard Model. By March 2013 they had seen these signals at about well less than 3σ confidence level. It is expected that the final definitive analysis shall still take quite some time. Here we show that what they may have found at 125 GeV is the long sought for and missing ingredient of the strong interaction: the sigma-meson of the Chiral Sigma Model, within the framework of the Skyrme model with a topological interpretation of the baryons. Just like a massless gauge boson is a requirement, and hence a prediction of the local gauge theories, in the the same manner, a very heavy scalar meson is a requirement and hence a prediction of the Skyrme model of the hadrons. The 125 GeV particle discovered by the CMS and the ATLAS groups may be an experimental confirmation of this unique prediction of the topological Skyrme model. However the bottom line is that even if the experimentalists finally confirm that this 125 GeV entity is the expected Higgs boson, then there still remains to discover another heavier scalar particle as the sigma-meson of the chiral sigma model/Skyrme model, which remains its unique prediction, as shown in this paper.

Recently at CERN, the CMS Group [1] and the ATLAS Group [2] announced the discovery of a new boson of mass 125 GeV. As the Higgs boson of the Electro-Weak (EW) model was expected to be seen in this region, most of the physicists thought that this was it. Except for the mass of the Higgs boson itself, the EW model is quite restrictive as to how this putative Higgs will decay in which channels and as to what fractions of the total decay in each channel. However, both the groups, as of July 2012, discovered some anomalous signals which cannot be explained on the basis of the EW model. These anomalies were firstly too much decay into the gamma-gamma channel and secondly no signals for the tau-antitau, where many more were expected. However by March 2013 both groups were observing the lack of these anomalies at well less than 3σ confidence level. However the machine has already been turned off and the continued analysis of the data may take quite some time before any definitive result may arise in this context. Hence this new particle does not necessarily appear to be the putative Higgs boson of the Standard Model (SM). So the field is wide open. However the fact remains that they are getting strong signals of over 5σ confidence level for a new particle at 125 GeV. So, if not the expected Higgs boson, then what may it be?

Several papers have already been written to explain these anomalous signals within the framework of models which may generically be called "non-conservative". In this paper we shall however adopt a strict "conservative" approach. This means that we ask whether it is still possible to seek solution for this new puzzle strictly within the ambit of already successful and empirically varified model frameworks of particle physics. A careful scrutiny of the latest *Review of Particle Properties* [3] indicates that there is indeed an entity which fills the bill.

There is this rather unconfirmed particle $f_0(500)$ which is identified with the sigma-meson σ of the sigma-meson model of the hadron physics. The Particle Data Group [3] themselves state that "the interprettion of this entity as a particle is controversial". Most of the hadron theorists, in the past, have taken into account the fact that the σ-meson was so reluctant in showing up in the laboratory, and they started taking seriously the so-called non-linear sigma-meson model (see below) where the σ-meson remains hidden inside a so-called chiral circle. Hence, still

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adopting a conservative approach and agreeing with the big majority of physicists, we believe that in spite of the intense search, for the last fifty years or so, the σ-meson of the sigma-meson model has not yet been observed in the laboratory. Hence this should be treated as the "missing link" of hadron physics.

Also, as pointed out by the Particle Data Group [3], in the hadron physics jargon, this missing σ particle is called "the Higgs boson of the strong interaction". So actually there are *two* missing Higgs bosons: one is the Higgs boson of the EW model (which both the CMS and the ATLAS groups were actually looking for at 125 GeV and may not have found!) and the other one is this "Higgs boson of the strong interaction" (which they were not even aware of, and which as I shall show below, is what they might have actually discovered!). I shall therefore show that with this, now the long sought for and missing link of the strong interaction may at last have been discovered.

A doubt may arise in the mind of some readers, and that may be related with the high scale of 125 GeV for the σ-meson. So the question is: is it a basic requirement of hadron physics that the σ-meson should be light, say of the scale of the other hadrons, at about 1 GeV? This was actually the point of view which has made people view the very broad $f_0(500)$ [3] as a possible though weak candidate for the same.

On the basis of the original Gell-Mann-Levy model ([4], p. 186), where the baryon masses are generated through the SSB of the chiral $SU(2)_R \otimes SU(2)_L$ model, it would be a natural expectation that the σ-meson have a mass of the typical hadronic scale of 1 GeV or so. So would also be the situation for the large number of variants of the linear sigma model and the non-linear sigma models, which are popularly being used in hadron physics today [4–6]. In fact, the σ-meson has been so reluctant in showing up in the laboratory at these low energies, that it was found pragmatic to have it as a "hidden" state inside the so-called chiral circle [4–6]. So, it is true that, on the basis of chiral sigma models and their various extensions [4–6], it is a natural physical expectation that the sigma meson have a mass of the order of the strong interaction, and that is about 1 GeV or so. It is because of this that one still hears now and then that this sigma-meson may actually be the $f_0(500)$ or $f_0(1370)$ particles, although, as discussed above, there are serious doubts about these weak claims.

Within the area of hadron physics there is one narrow window which does allow one to look beyond the above constraints within the chiral sigma-model framework. Herein the sigma-meson is expected, or in fact demanded, to be very heavy, or even infinitely heavy. Though in the original chiral sigma model of Gell-Mann-Levy, the degrees of freedom were an isotriplet of pions, a scalar sigma-meson and an isodoublet of nucleons. However, the presence of fermionic nucleons is not absolutely essential for the analysis and indeed the non-linear sigma model without the initial fermions has been used to generate the nucleon as a topological soliton of the interacting Nambu-Goldstone pion fields ([4], p. 186) in the Skyrme model.

The linear sigma model in the absence of nucleons is given by

$$L = \frac{1}{2}[(\partial_\mu \sigma)^2 + (\partial_\mu \pi)^2] - V(\sigma^2 + \pi^2), \qquad (1)$$

where

$$V(\sigma^2+\pi^2) = \frac{\mu^2}{2}(\sigma^2+\pi^2) + \frac{\lambda^2}{4}(\sigma^2+\pi^2)^2; \quad \mu^2 < 0. \qquad (2)$$

The SSB of this $SU(2)_R \otimes SU(2)_L$ model occurs because $\mu^2 < 0$ so that the minimum of the potential is at

$$\sigma^2 + \pi^2 = f^2; \qquad f = \left(-\frac{\mu^2}{\lambda}\right)^{\frac{1}{2}}. \qquad (3)$$

If we take $\langle 0|\sigma|0\rangle = f$ and $\langle 0|\pi|0\rangle = 0$ and working with the shifted fields, one finds that the isosinglet mass is $m_\sigma = \sqrt{2}|\mu|$ and the isotriplet pion mass is zero that is that these are the Nambu-Goldstone bosons.

From this linear sigma model one obtains the non-linear sigma model in the standard methods [5,6]. This involves taking the limit $m_\sigma \to \infty$ and placing π in a non-linear representation of the group $SU(2)$. We thus get the non-linear sigma-model Lagrangian ([4], p. 638). Supplemented with the Skyrme stabilizing term, it looks as follows [7]:

$$L_S = \frac{{f_\pi}^2}{4}\,\mathrm{Tr}(L_\mu L^\mu) + \frac{1}{32e^2}\,\mathrm{Tr}[L_\mu, L_\nu]^2, \qquad (4)$$

where $L_\mu = U^\dagger \partial_\mu U$. The U field for the three-flavour case, for example, is

$$U(x) = \exp\left[\frac{i\lambda^a \phi^a(x)}{f_\pi}\right],$$

with ϕ^a the pseudoscalar octet of π, K and η mesons. In the full topological Skyrme, this is supplemented with a Wess-Zumino effective action,

$$\Gamma_{WZ} = \frac{-i}{240\pi^2}\int_\Sigma \mathrm{d}^5 x \epsilon^{\mu\nu\alpha\beta\gamma}\,\mathrm{Tr}[L_\mu L_\nu L_\alpha L_\beta L_\gamma], \qquad (5)$$

on the surface Σ. Let the field U be transformed by the charge operator Q as

$$U(x) \to e^{i\Lambda Q} U(x) e^{-i\Lambda Q},$$

where all the charges are counted in units of the absolute value of the electronic charge.

Note that the above Skyrme Lagrangian demands the existence of a very heavy scalar sigma-meson. This demand is of the same nature as the corresponding requirement of a massless gauge boson in a local gauge theory.

Making $\Lambda = \Lambda(x)$ a local transformation the Noether current is

$$J_\mu{}^{em}(x) = j_\mu{}^{em}(x) + j_\mu{}^{WZ}(x), \qquad (6)$$

where the first one is the standard Skyrme term and the second is the Wess-Zumino term

$$j_\mu{}^{WZ}(x) = \frac{N_c}{48\pi^2}\epsilon_{\mu\nu\lambda\sigma}\,\mathrm{Tr}\,L^\nu L^\lambda L^\sigma(Q + U^\dagger QU). \qquad (7)$$

For the hypercharge we take $Y = \frac{N_3}{3}$ [7] and, demanding that the proton charge be the unit for any arbitrary value of N_c, we find all the charges. Hence, as per the Skyrme model, the electric charges are [7]

$$Q(u) = \frac{1}{2}\left(1 + \frac{1}{N_c}\right), \qquad (8)$$

$$Q(d) = \frac{1}{2}\left(-1 + \frac{1}{N_c}\right). \qquad (9)$$

These electric charges and their colour dependence should be viewed as a unique prediction of the Skyrme model. Also, as we shall discuss below, these charges from the Skyrme model have the correct colour dependence as demanded by the SM as well. So the colour dependence of the electric charge as required by the structure of the SM as shown below are exactly reproduced by the Skyrme model. Hence it is heartening to conclude that the Skyrme model is fully consistent with the Standard Model. This should be taken as an indication that the Skyrme model should be taken as a good model to study hadrons at low energies [7].

It is well known that in $SU(N_c)$ Quantum Chromodynamics in the limit of N_c going to infinity, the baryons behave as solitons in an effective meson field theory [7,8]. A popular candidate for such an effective field theory is the topological Skyrme model [4–6]. It has been extensively studied for two or more flavours and it has been shown that the resemblance of the topological soliton to the baryon, in the quark model in the large N_c limit, is very strong [4,6]. Its baryon number and the fermionic character are also well understood [8].

Theoretically the most well-studied and experimentally the best established model of particle physics is the Standard Model (SM) based on the group $SU(3_c) \otimes SU(2)_L \otimes U(1)_Y$

Also, analytically, the author obtained the colour dependence of the electric charge in the SM as given above in eqs. (8) and (9). For $N_c = 3$ this gives the correct charges. It was also demonstrated by the author [8] that these were the correct charges to use in studies for QCD for arbitrary N_c. This was contrary to many who had been using static (*i.e.* independent of colour) charges 2/3 and $-1/3$ [8].

Hence, in addition to the other well-known properties of the SM, I would like to stress that the quantization of the electric charge and the structure of the electric charge arising therein, especially its colour dependence, should be treated as an intrinsic property of the SM. Consistency with the SM should be an essential requirement for phenomenological models which are supposed to work at low energies and for any extensions of the SM which should be relevant at high temperatures, especially in the context of the early universe.

So, the above Skyrme model which finds justification as a good description of the QCD at low energies —not only because it has the right symmetries [4–6] of the QCD but also because, as emphasized here, it has the right structure of the electric charge (as especially the electric charge surprisingly has colour dependence arising from the structure of the Standard Model)— is the correct model to study the low-energy properties of the hadrons. As shown above this particular model demands a very heavy sigma-meson. Hence, what has been seen at 125 GeV by the CMS and the ATLAS experiments is very likely this particluar scalar particle. As per Skyrme model, as above, in fact it may even be that $m_\sigma \to \infty$. Now mathematically infinities are perfectly fine. However in physics, physical particles are observables and to be observables they might have very large, but still finite masses. We treat 125 GeV being close to fulfilling this condition as the nucleon mass is about 1 GeV, much smaller that 125 GeV. Note that the situation here is analogous to the other complementary case where, canonically, the pion mass of 140 MeV being considerably smaller than the scale of 1 GeV, is taken as effectively being massless [4–6].

Next, the CMS [1] and the ATLAS [2] experiments have observed two puzzling anomalies in the decay of the 125 GeV new particle. Firstly as per the electro-weak Higgs particle sector, a good 6 percent of these decays should have occurred in the tau-antitau channels, and these two expereiments found none. Secondly a much smaller gamma-gamma channel was expected and they obtain many more of these events. The above was the situation in July 2012. By March 2013 at well less than the 3σ confidence level, these anomalies show weak indications of disappearing. However the field is still wide open, since these weak signals might disappear.

If these anomalies persist then it would be unjustified to associate this new particle at 125 GeV with the EW Higgs particle. However both these anomalies are naturally understood as arising from a sigma-meson. As this sigma-meson arises fron the strong interaction, it will not couple to the leptons. So this sigma-meson should not decay into a tau-antitau pair. And this is exactly what has been observed by the CMS and the ATLAS groups. This lack of tau-antitau decay is a clear, distinguishing feature of the sigma-meson model in contrast to the EW Higgs boson where this channel should exist on fundamental grounds. On this account itself, the sigma-model interpretation for the 125 GeV boson is clearly winning out.

Also the vector dominance model of the Skyrme model [6] would predict stronger gamma-gamma decays of the sigma-meson in our model, akin to what was observed by the CMS and th ATLAS eperiments. Hence, clearly, these so-called anomalies are a clean signature of this new particle at 125 GeV interpreted as the sigma-meson of the chiral sigma model forming the basis of the Skyrme model of the strong interaction.

Now a look at the scalar particles which are known to exist as per the *Particle Data Tables* [3] and their observed decay properties, we find the following examples: 1) $f_0(500)$ with $m = (400–500)$ MeV and full width $\Gamma = (400–700)$ MeV, 2) $f_0(980)$, 3) $f_0(1370)$, 4) $f_0(1500)$ and 5) $f_0(1760)$.

Taking their decays as a guide, we notice that there are hints of the vector domination in the gamma-gamma channels in these scalar particles, but these seem to defy any simplistic pattern. So to predict more precise numbers for the various decay channels for a very heavy sigma-meson at 125 GeV would require careful modelling. We intend to do so in the future. But that it is indeed the sigma-meson of the strong interaction that has been observed by the CMS and the ATLAS experiments is quite clear on the basis of the arguments presented above.

We follow Feynman's *dictum* that one good/strong/ clean proof/evidence is better than several weak ones all put together. So the sigma-meson of the Skyrme model of the strong interaction, not decaying into tau-antitau should be treated as a smoking-gun kind of evidence, especiallly with respect to the Higgs boson of the electroweak model. Of course, one has to study the whole gamut of its decay channels in the future.

Another point that should be made is that, even if at the end of the day, this 125 GeV particle is experimentally finally shown to be the Higgs boson of the electro-weak model, the prediction of an even heavier scalar meson —the sigma-meson of the Skyrme model— cannot and *should not* be sidelined. As we have shown here, it is a strong and clean prediction of this model. So if not the 125 GeV entity, it should be sought at still higher energies.

In summary, we have demostrated here, quite convincingly, that what has been observed at 125 GeV by the CMS and the ATLAS experiments recently [1,2] may be the long sought for and missing link of the strong interaction, the "Higgs boson of the strong interaction" (PDT, 2012, ref. [3]). This arises because though most of the variants of the chiral sigma-meson model of Gell-Mann-Levy require a lighter sigma-meson [4], the non-linear sigma-meson model required as a base for the topological structure model of Skyrme, demands a very heavy sigma-meson. This demand for a very heavy sigma-meson mass in the Skyrme Lagrangian is of the same nature as that of a massless gauge boson in a local gauge theory. We have also shown why this topological interpretation of baryons should be taken seriously as a model of the strong interaction of baryons. Hence the Skyrme model uniquely predicts a very heavy sigma-meson and the 125 GeV particle disovered at CERN may be a confirmation of this prediction.

In the end, we would like to quote Ellis, Gaillard and Nanopoulos [9] who, after a thorough analysis of the SM Higgs, said, "We apologize to experimentalists for having no idea what is the mass of the Higgs boson. . . , and for not being sure of its couplings to other particles, except that they are probably all very small." Here we would like to paraphrase our own feelings about the sigma-meson of the Skyrme model in somewhat the same manner at present. More careful work has to be done in the near future to overcome this shortcoming. However it does not mean that we have no predictive power. As shown above we have a very clear and discriminating prediction as to the sigma-meson of the Skyrme model. And it is that it shall not show any decay to tau-antitau especially as distinguishing it from the Higgs boson of the Standard Model. The case of the 125 GeV particle is still very open. We look forward to future analysis with great anticipation.

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