Scalar Quarks at the Large Hadron Collider

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(Dated: May 11, 2014)

PACS numbers: 14.80.Ec, 12.39.Ki, 14.40.Lb, 14.40.Nd

The properties of scalar quarks are studied, especially the formation of fermionic mesons with an anti-quark. On the basis of this theoretical investigation together with the experimental data, both from last year and from this year, of the ATLAS Collaboration and the CMS Collaboration at the Large Hadron Collider, it is proposed that the standard model of Glashow, Weinberg, and Salam should be augmented by scalar quarks, scalar leptons, and additional fermions. If these scalar quarks and scalar leptons are in one-to-one correspondence with the ordinary quarks and ordinary leptons, either in number or in the degrees of freedom, then there may be a fermion-boson symmetry. The fermion-boson symmetry obtained this way is of a different nature from that of supersymmetry.

I. INTRODUCTION

One year ago, in the summer of 2012, a new particle was discovered by the ATLAS Collaboration\textsuperscript{1} and the CMS Collaboration\textsuperscript{2} at CERN. This particle is almost certainly the long-sought one proposed on theoretical grounds in 1964\textsuperscript{3}, and is commonly referred to as the Higgs particle. This particle is the first observed elementary particle of spin zero. A particle of such novel feature may open up an entirely new field of physics.

In as much as the first spin-0 particle – the Higgs particle – has been observed experimentally, it seems likely that this is not the only spin-0 elementary particle and that there are other spin-0 elementary particles. What can these additional spin-0 particles be, and is there any experimental indication that they may be present?

We believe that there is such an indication. In both\textsuperscript{1} by the ATLAS Collaboration and\textsuperscript{2} by the CMS Collaboration, the decay rate for

\[ H \rightarrow \gamma \gamma, \]  \hspace{1cm} (1)

is higher than that predicted by the standard model\textsuperscript{4}. It is purpose of this paper to analyse the possible consequences of the proposal that this excess remains for future data.

Since this decay (1) proceeds through a virtual loop, its excess is most naturally explained by the contributions of additional charged, heavy particles to this loop. What are the possible properties of these additional heavy particles?

Since elementary particles of spin higher than 1 has never been seen, let us consider the three cases that the additional heavy particle for the loop is of spin 1, 1/2, and 0.

If the spin is 1, it is likely to be a new gauge particle. Such a gauge particle would enlarge the gauge group of \( U(1) \times SU(2) \times SU(3) \) of the standard model. This would change the properties of the standard model.

If the two cases above of spin 1 and spin 1/2 are considered to be unlikely, then we are left with the possibility that the additional heavy particle is of spin 0. This is the possibility to be investigated in this paper.

Scalar quarks have been discussed in the framework of supersymmetric theories\textsuperscript{5}. However, the scalar quarks under consideration here do not need to the squarks of supersymmetry. We simply assume that the scalar quarks have color 3, and hence participate into the confining interaction of QCD. Note that scalar quarks have been considered in different contexts, for instance in some studies of chiral dynamics, confinement and diquark clustering within QCD\textsuperscript{6}.

In summary, the scenario to be investigated here is the one that the standard model is augmented by scalar quarks and scalar leptons.

II. SOME IMMEDIATE CONSEQUENCES

Nearly a quarter century ago, one of the first results from the Large Electron-Positron collider (LEP) at CERN was that there are three generations of quarks and leptons\textsuperscript{7}. This implies that the \( Z \) cannot decay into a pair of scalar quarks or scalar leptons, meaning that the mass of each scalar quark and each scalar lepton must be larger than half of the \( Z \) mass, i.e., 46 GeV/c\(^2\). (Strictly speaking, this limit should be slightly reduced because of phase space).

On the other hand, if the scalar quarks and the scalar leptons are responsible for the excess in the decay process (1), then they cannot be too heavy, or more precisely cannot be much heavier than the \( Z \). If only these scalar quarks and the scalar leptons are added to the standard model, then both the lightest scalar quark and the lightest scalar lepton are stable. One of

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the important questions to be answered in the present paper is: Is it possible that the LHC experiments have failed to detect such a stable lightest scalar quark with a mass of the order of magnitude of that of the $Z$?

The answer is No. In particular, the CMS collaboration has published a thorough search for new charged particles and set stringent constraints [8]. We will show below that if there is a long-lived scalar quark of color 3, with either electric charge 2/3 or $-1/3$, there should be at least a long-lived new hadron that is charged and thus should have been seen, contradicting the CMS result. Therefore, there must be some additional new particles for the lightest scalar quark to decay into. At the moment, there does not seem to be enough information from the data in [1] and [2] to pin down what these additional new particles may be.

Scalar quarks can of course be pair produced. Since scalar quarks are confined just like ordinary quarks, a scalar quark, denoted $Q$, thus produced picks up an anti-quark to form a new kind of meson. This anti-quark can be either an ordinary anti-quark of spin 1/2, especially the $u$ or the $d$ anti-quarks, or a scalar anti-quark $\bar{Q}$ of spin 0. Since a scalar anti-quark has a mass of at least half of that of $Z$, it is much heavier than that of the $u$ or $d$ anti-quarks. While both possibilities exist, it is more likely that the first detected bound state will consist of a scalar quark together with an $u$ or $d$ anti-quark, say $(Q\bar{q})$, and that the “scalaronium” $(Q\bar{Q})$ will be more difficult to be produced. In the case of a $(Q\bar{q})$ bound state, the resulting meson is different from the known mesons in that it is a fermion. Similarly the first baryon including a scalar quark is very likely of the type $(Qqq')$ with two light ordinary quarks. It is a boson.

### III. HADRONS CONTAINING A SCALAR QUARK

Let us consider some hadrons formed by a scalar quark $Q$ with ordinary quarks $q$ ($u, d, s, c$ or $b$) or antiquarks $\bar{q}$.

The first set of new hadrons contains a single scalar quark. For any given $q$, the ground state of $(Q\bar{q})$ is not degenerate, and has an angular momentum $j = \frac{1}{2}$. The same holds for its radial excitations. The orbital excitations with angular momentum $\ell > 0$ are split by spin-orbit forces into a state with $j = \ell - 1/2$ and another one with $j = \ell + 1/2$.

For any given $q$, the lightest $(Qqq')$ baryon has spin $j = 1$, and is slightly pushed up by the repulsive chromomagnetic interaction among the two $q$ quarks. If one introduces two ordinary quarks $q$ and $q'$ with $q \neq q'$, the lightest $(Qqq')$ baryon has spin 0, and above lies a spin 1 baryon. The spacing can be estimated from the phenomenology of hyperfine interactions in baryons [9, 10]. As discussed in some detail in Sec. V, one can in particular estimate $1\ (dud)_{S=1} - (dud)_{S=0} \simeq 200$ MeV for the lightest baryons. This means that the isovector, vector state will easily decay into the isoscalar, scalar one by pion emission.

In the second set come hadron states containing two scalar quarks. The scalaronium $(Q\bar{Q})$ certainly deserve special discussions. The spectrum of scalaronium has been discussed in several papers [11], by extrapolation of the models describing the charmonium and bottomonium states. These papers made explicit reference to supersymmetry.

In this second set, there are also baryons with two scalar quarks. If $Q \neq Q'$, the ground state of the $(QQQ'\bar{q})$ has spin 1/2 and is not degenerate. It can be studied in the Born–Oppenheimer limit, as done for double-charm baryons [12], in which the effect of the light quark and gluon field are integrated out and generate an effective $Q\bar{Q}'$ interaction. For the baryons with two identical scalar quarks, $(QQ\bar{q})$, the $(QQ)$ pair is in a 3 state, which is an antisymmetric coupling of two colour 3 objects, and thus the orbital momentum among the two heavy scalar quarks is $\ell = 1$. Hence the lightest $(QQ\bar{q})$ have $j = 1/2$ and $j = 3/2$, split by spin-orbit forces.

The second set also includes $(Q\bar{q}q')$ tetraquarks, whose mass is lighter than the threshold made of two $(Q\bar{q})$ mesons, thanks to the strong attraction between the two heavy scalar quarks, which are in a relative P-wave. This is the same mechanism that binds ordinary tetraquarks $(Q\bar{Q}q'\bar{q})$ in the limit of a large quark-to-antiquark mass ratio, see, e.g., [13] and refs. therein.

In the far future, one should aim at detecting baryons with three scalar quarks. If the scalar quarks are all different, then the ground state of $(QQQ'\bar{q}')$ is a non-degenerate scalar, with any possible radial and orbital excitations. If $Q \neq Q'$, the ground state of $(QQQ')$ is a non degenerate $j = 1$ state, due to the Bose statistics of the two $Q$. If the masses are such that $Q < Q'$, the first excitation is likely an $\ell' = 1$ promotion of the relative motion of $Q'$ with respect to the two $Q$, and this will give $j = 0, 1$ or 2, with some spin-orbit splitting among them. If $Q > Q'$, then the first excitation is in the relative motion between the two $Q$.

Let $Q$ be the lightest of the scalar quarks, then the first baryon with three scalar quarks is of the type $(QQQ)$ with an antisymmetric color wavefunction, and thus an antisymmetric orbital wave function, with $\ell = 1$ among the first two constituents and also $\ell' = 1$ for the relative motion of the third one, and an overall angular momentum $j = 1$. In the particular case of harmonic confinement, the wave function is of the type $\rho \times \lambda \exp[-\alpha(\rho^2 + \lambda^2)]$, where $\rho = r_2 - r_1$ and $\lambda = (2r_3 - r_1 - r_2)/\sqrt{3}$ are the usual Jacobi variables. In the ordinary quark–model, this orbital wave function is associated to the long sought [20, 1+] representation in the specific jargon of this field, a state just with two levels of excitation above the nucleon-$\Delta$ multiplet. See, for instance, the reviews [14]. The lack of experimental evidence for this state is one of the motivations for the quark–diquark model of ordinary baryons [15]. It is amazing that the antisymmetric orbital wavefunction of three confined constituents reappears in the context of scalar quarks.

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1 Hereafter, the name of particle also denotes its mass. For example, here $(udd)_{S=1}$ means the mass of the particle that consists of the scalar quark $q$, together with the ordinary quarks $u$ and $d$, in the spin $S = 1$ state.
IV. LIGHTEST MESON WITH A SCALAR QUARK

For the experimental search of scalar quarks, it is important to know whether the lightest meson containing a scalar quark is neutral or charged. Let \( \bar{d} \) denote a scalar quark \( Q \) with electric charge \(-1/3\), and \( u \) one with electric charge \(+2/3\). It is important to know whether the lightest meson is the neutral \((\bar{d}d)\) or the charged \((\bar{d}u)\), and similarly the charged \((ud)\) or the neutral \((uu)\) meson. In this section, we calculate the masses of \((u\bar{q})\) and \((d\bar{q})\) mesons assuming that the scalar quarks \( u \) and \( d \) are stable or long-lived, and analyze whether these results into stable or long-lived charged mesons that could be seen in the LHC detectors.

We therefore proceed to analyze to which extent our present understanding of the isospin-breaking mass differences allows us an extrapolation toward the mesons containing a scalar quark. In particular, the mass differences \( D^+ - D^0 \) and \( B^0 - B^- \) are now well measured [16, 17], with the results
\[
D^+ - D^0 = 4.76 \pm 0.06 \text{ MeV}, \\
B^0 - B^- = 0.32 \pm 0.06 \text{ MeV}. \tag{2}
\]

There is a long history of studies of the mass splittings among members of the same hadron multiplets. Some milestones references are given in [18]. For our purpose, it is important to note that the splittings (2) can be well reproduced by quark models that include a relativistic kinematics, a flavor-independent central potential, and a spin-spin interaction that depends explicitly upon the constituent masses. In such quark models, the mass difference \( (Q\bar{d}) - (Q\bar{u}) \) between the isospin partners originates from

- the change \( m_d - m_u \) in the constituent masses,
- the induced change of the binding energy, i.e., the change in the expectation value of the kinetic energy and central potential,
- the change in the spin–spin term,
- the electrostatic energy (the magnetic term is very small).

There are cancellations, making the adjustment of the parameters delicate. In particular, the effects a) and b) are opposite. In non-relativistic models, it might even happen that b) overcome a). This is not the case with a relativistic form of kinetic energy such as \( \sqrt{p^2 + m^2} \). For the \( D \), the electrostatic contribution \( d \) supplements the mass effect a) and b), but for the \( B \), there is a cancellation. This explains the hierarchy observed in Eq. (2).

For \( D \) and \( B \) mesons, the spin–spin effect c) plays a minor role. First, there is an overall \( 1/m_c \) or \( 1/m_b \) factor in most models. Also, when the light quark mass increases, the strength of the hyperfine interaction decreases, but the wave function becomes more compact, and this increases the expectation value of the contact or contact-like terms associated to the hyperfine interaction. As noted, e.g., in [19], it is observed experimentally that \( D_s^+ - D_s \approx D^+ - D \) and \( B_s^+ - B_s \approx B^+ - B \), a kind a SU(3) restoration. Thus, if the hyperfine interaction does not change significantly when \( u \) is replaced by \( s \), it will remain almost constant when \( u \) is replaced by \( d \).

As a consequence, if the heavy quark is made scalar, the removal of the hyperfine term will not affect significantly the isospin splitting. Moreover, with \( c \) and \( b \), we are already in a regime of heavy-quark symmetry for the wave function. In a non-relativistic language, one can say that the reduced mass is nearly saturated by the light-quark mass. This means that when the scalar quark is made heavier, say from a few GeV to 46 GeV or more, the Coulomb energy and the binding energy do not change much. On this basis, one expects that all quark models will give
\[
(\bar{u}u) - (\bar{u}d) \simeq (\bar{c}u) - (\bar{c}d), \\
(\bar{d}u) - (\bar{d}d) \simeq (\bar{b}u) - (\bar{b}d), \tag{3}
\]

where the approximate equalities (3) mean that
\[
\left| (\bar{u}u) - (\bar{u}d) \right| - \left| (\bar{c}u) - (\bar{c}d) \right| \lesssim 1 \text{ MeV}, \\
\left| (\bar{d}u) - (\bar{d}d) \right| - \left| (\bar{b}u) - (\bar{b}d) \right| \lesssim 1 \text{ MeV}. \tag{4}
\]

Indeed, these inequalities (4) are verified in the explicit computation presented below.

In order to make some quantitative predictions, we adopt an explicit semi-relativistic model, similar to the ones used, e.g., in [18, 20], namely
\[
H = H_0 + V_{ss}, \quad V_{ss} = d \frac{\sigma_s \cdot \sigma_s}{m_1 m_2} \tilde{\delta}(r), \\
H_0 = \sqrt{p^2 + m_1^2} + \sqrt{p^2 + m_2^2} - a/r + b r + c, \tag{5}
\]

where \( a, b, \) and \( c \) are independent of the quark masses \( m_i \), as suggested by flavor independence. The term \( V_{ss} \) is a smeared version of the contact interaction which describes the hyperfine splittings [9], analogous to the Breit–Fermi interaction in QED. In practice, we use
\[
\tilde{\delta}(r) = (\mu/\pi)^{3/2} \exp(-\mu r^2), \quad \mu = \left( \frac{2 m_1 m_2}{m_1 + m_2} \right)^f, \tag{6}
\]

where \( f \) is an empirical parameter close to 2, so that the range of the smearing is of the order of magnitude of the de Broglie wavelength of the relative motion. Many refinements can be envisaged, as, e.g., in [21], but we start from the simplest version of the model and discuss some possible corrections later in this section.

It is obviously impossible to fit all meson levels with any flavor content with such a simple model, so we focus on reproducing the lightest quarkonium levels, and the ground states in the heavy-light sector. To solve the Schrödinger equation \( \Psi = M \Psi \), we expand the wave function into Gaussians, as
\[
\Psi = \sum_{i=1}^N \gamma_i \exp(-\alpha_i r^2/2), \tag{7}
\]

with the non-linear parameters \( \alpha_i \) imposed to follow an arithmetic progression, to avoid ambiguities in the minimization,
following the strategy of [22]. For a variant, see [23]. The results are presented in Tables I, II and III.

Comments are in order.

• The variational calculation converges rapidly. The results in the Tabs. II and III correspond to $N = 6$ Gaussians. The change with respect to $N = 5$ is only 0.4% for $D^+ - D^0$ and -3% for $B^0 - B^-.$

• The results are very stable. One can play with, e.g., the difference of constituent masses, $m_d - m_u$, or the parameters entering the potential, but it always turns out that $D^+ - D^0$ is about 5 MeV, while $|B^0 - B^-|$ is less than 1 MeV. For instance, if we repeat our calculation with $m_d = 310$ MeV instead of 305 MeV, the results are changed to (in MeV) $(cd) - (cu) = 7.3$, $(qd) - (q\bar{u}) = 8.8$, $(yd) - (y\bar{u}) = 8.9$ MeV (for 100 GeV or 200 GeV scalar quark, respectively), and $(bd) - (b\bar{u}) = 2.6$, $(d\bar{d}) - (d\bar{u}) = 2.3$, $(\bar{d}\bar{d}) - (d\bar{u}) = 2.3$ MeV. The fit to $D$ and $B$ mesons somewhat deteriorates, but the validity of (3) remains.

• If one introduces a form factor for the Coulomb interaction, as per Eq. (4) of Godfrey and Isgur [18], the electrostatic energy is considerably reduced, by a factor of about 2, and it becomes difficult to get a good agreement for both $D^+ - D^0$ and $B^0 - B^-.$ In our case, such a form factor would give $D^+ - D^0 = 2.9$ MeV instead of 4.9, and $B^0 - B^- = 1.5$ MeV instead of 0.4. However, the isospin splittings remain of the same order of magnitude, and the inequalities (3) and (4) remain valid for the extrapolation to scalar quarks. One motivation in [18] is to account for “relativistic nonlocalities”, but this effect is in principle an output rather than an input of the relativistic equations such as (5).

• The mass differences evolve very smoothly with the mass of the scalar quark $Q$. This is illustrated in Fig. 1.

• If the scalar quark $y$ is long lived, the lightest charged meson, $(yd)$, could decay weakly into $(y\bar{u})$. But with an energy release of about 6 MeV, the lifetime for such a decay would be very long, so both $(yd) - (y\bar{u})$ would be long lived.

• Similarly, if the scalar quark $d$ is long lived, the beta decay from $(dd)$ to $(d\bar{u})$, or vice-versa, is either kinematically forbidden or very slow. So both $(dd)$ to $(d\bar{u})$ would be long lived.

• Therefore, as no charged track has been seen in the CMS detector [8], one can exclude a scenario where the standard model is augmented by scalar quarks and scalar leptons only.

V. LIGHTEST BARYON WITH A SCALAR QuARK

Here the situation is simpler than in the meson case. For each scalar quark $Q = u$ or $d$, the lightest baryons are $(Quu)$, $(Qdd)$ and $(Qud)$. For the two former baryons, the ground state, with mainly an overall s-wave in the relative motion, correspond to the identical light quarks being in a color 3, spin 1 and isospin 1 state. For the latter, there is one state, say $\Sigma[Q]$, with $(u, d)$ in a spin 1 and isospin 1 state, and another one, $\Lambda[Q]$, with spin 0 and isospin 0. We expect the vector, isovector states $(Quu)$, $(Qdd)$ and $\Sigma[Q] = (Qud)$ to be very close, and about 200 MeV above the scalar, isoscalar $\Lambda[Q\bar{Q}] = (Qud)$, because the $\Sigma - \Lambda$ mass difference comes from the light-quark part of the baryons, and thus should be very similar for $\Sigma_c - \Lambda_c$. More precisely, if the spin-spin interaction in $(Qqq)$ is treated at first order, one gets, in an obvious

\begin{table}[h]
\centering
\caption{Parameters of the quark model of Eqs. (5) and (6). The units are powers of GeV.}
\begin{tabular}{ccccccc}
\hline
\textit{m}_d & \textit{m}_u & \textit{m}_c & \textit{m}_6 & \textit{m}(Q) & \textit{m}(Q') \\
0.305 & 0.300 & 1.500 & 4.900 & 100. & 200. \\
\hline

\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Contributions (in MeV) to the isospin-breaking mass difference of $D$ and $B$ mesons in a specific version of the model of Eqs. (5) and (6). $h_0 = H_0 - m_1 - m_2$ is the sum of kinetic energies and central potential.}
\begin{tabular}{cccccc}
\hline
\textit{m}_d - \textit{m}_u & (h_0) & (V_{ss}) & Coulomb & Total & Exp. [16] \\
\hline
\textit{D}_d - \textit{D}_u & 5. & -2.5 & -0.08 & 3.5 & 5.9 & 4.76 \pm 0.10 \\
\textit{B}_d - \textit{B}_u & 5. & -2.3 & -0.5 & -1.9 & 0.2 & -0.32 \pm 0.06 \\
\hline

\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Isospin breaking mass differences in the model (in MeV), for two values of the mass of the scalar quark (in GeV).}
\begin{tabular}{cccc}
\hline
\textit{m}(Q) & (yd) - (y\bar{u}) & (dd) - (d\bar{u}) \\
100. & 6.6 & 0.06 \\
200. & 6.6 & 0.04 \\
\hline

\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics{fig1.png}
\caption{Mass difference $\delta M = (yd) - (y\bar{u})$ and $\delta M = (dd) - (d\bar{u})$ (multiplied by 10) in our model, as a function of the scalar-quark mass $M$. The dotted part corresponds to low values of $M$ that has been experimentally excluded.}
\end{figure}
and thus a fictitious charmed or bottom baryon in which the spin-spin interaction of the heavy quark is switched off would correspond to
\[
\langle \Sigma Q \rangle = \frac{2 \Sigma^* + \Sigma}{3} = M_0 + \delta_{qq} ,
\]
and from the known masses of charmed and beauty baryons [16], one obtains
\[
\langle \Sigma_c \rangle - \Lambda_c \simeq 212 \text{ MeV} , \quad \langle \Sigma_b \rangle - \Lambda_b \simeq 207 \text{ MeV} .
\]
This spacing is remarkably stable when going from charm to beauty. It is thus very easy to extrapolate to
\[
(Qqq)_{I=1,J=1} - (Qqq)_{I=0,J=0} \sim 200 \text{ MeV} .
\]

In short, the chromomagnetic mechanism by which \( \Lambda_Q \) is lighter than \( \Sigma_Q \) for the quarks \( Q = s, c \) and \( b \), implies that the lightest baryons containing a scalar quark are the charged, scalar, isoscalar \((q\bar{u}d)\) and the neutral, scalar, isoscalar \((dud)\).

VI. FURTHER PROPERTIES OF SCALAR QUARKS

The results obtained so far about the scalar quarks are largely independent of their detailed properties. What has been used consists mainly of their existence, their being color 3, and their masses being at least half of the mass of \( Z \).

In this Section, some further possible properties of the scalar quarks are to be discussed briefly.

(A) Since these scalar quarks are unstable, how do they decay? There are two distinct types of decays.

i) Similar to ordinary quarks, the scalar quarks have the decay mode

\[
\text{heavier scalar quark} \rightarrow \text{lighter scalar quark} + W ,
\]
where the \( W \) may be real or virtual. Of course, the heavier and lighter quarks must have different charges.

ii) Since the lightest scalar quark is not stable, there is also the decay mode

\[
\text{scalar quark} \rightarrow \text{quark} + \text{fermion} ,
\]
where the fermion on the decay product is a new particle that has not been observed experimentally, see Sec. II. This fermion can of course be real or virtual. In MSSM, this fermion can be higgsino, wino, or zeno.

(B) How many different scalar quarks are there? There is no way at present to answer this important question, but there are two natural guesses.

i) There are six scalar quarks and six scalar leptons;

ii) There are twelve scalar quarks and twelve scalar leptons.

In i) there is one scalar quark or lepton for each fermion in the standard model; in ii) the number of degrees of freedom for the scalar quarks and leptons is the same as that for the ordinary quarks and leptons. In MSSM, ii) holds but not i).

(C) The starting point of the present consideration is the branching ratio for the decay \((1)\); it requires the masses of several scalar quarks and/or charged scalar leptons to be of the order of the \( Z \) mass. In the case of quarks, the qualitative features of the CKM matrix has been attributed to the large differences of masses for the three generations of quarks [24]. If this argument holds also for scalar quarks, then it may be expected that several off-diagonal elements of the scalar-quark CKM matrix elements are large in the sense of being of the order of 1. This is likely to lead to interesting physics for the scalar quarks.

(D) Quarks are seen experimentally as jets. How do the scalar-quark jets differ from quark jets? It is believed that a major difference is due simply to the fact the masses of the scalar quarks being much larger than those of the first two generations of quarks.

Let us compare a scalar-quark jet with, say, a \( b \) quark jet. In both cases, pairs of light quarks are produced from the sea. Thus the leading \( b \) quark becomes a \( B \) meson, and the leading scalar quark \( Q \) becomes a \((Q\bar{q})\) meson. Both the \( B \) meson and the \((Q\bar{q})\) meson decay. Since the mass of the \( B \) meson is only about 5 GeV, its decay products and those of the mesons from the sea have momenta in nearly the same direction; this is how a \( b \) jet is formed and looked for. On the contrary, since the \((Q\bar{q})\) meson is much heavier, its decay products have in general momenta in different directions. Therefore, a scalar-quark jet has in general much more complicated structure and cannot be found by the usual jet finding programs. In fact, it is perhaps more accurately described as consisting of several jets, not a single jet.

(E) Let the above considerations be combined with the very recent results from the ATLAS and CMS Collaborations [25] together with those from the CDF and D0 Collaborations [26]. These experimental results indicate that the couplings of the Higgs particle [1, 2] to the \( Z \), the \( W \), the top quark and the bottom quark are all in agreement with those of the standard model [4]. If this agreement is verified to higher accuracies in the future, there are important implications such as follows.

The first implication is that there is very little room for a second Higgs particle to couple also to these \( Z \), \( W \), \( t \), and \( b \). It may be recalled that, in super-symmetric theories such as the MSSM, there are necessarily two Higgs doublets, where, in the simplest version, one couples to the top quark while the other couples to the bottom quark.

Consider this first implication together with the (B) above, where there is a pairing between quarks and scalar quarks, and also leptons with scalar leptons through either i) or ii). Such pairings mean that there is some form of fermion-boson symmetry, but this symmetry may well be of a different nature than that of super-symmetry, which is based on graded Lie algebra.

Let us speculate what this fermion-boson symmetry may
be. From the (C) above, the masses of the scalar quarks and scalar leptons are likely to be much higher than those of the quarks and leptons, except that of the top quark. In other words, the structure of the masses for the scalar quarks and leptons are certainly qualitatively different from that of the ordinary quarks and leptons. It would be most interesting to learn what the mass relations are and where they may come from, but this is beyond reach at present. On the experimental level, the main issue is of course to figure out ways to observe these scalar quarks and scalar leptons. A step in that direction may be searching for scalar-quark jets as distinct from the jets from ordinary quarks, as discussed in (D) above. Searching for scalar leptons may be equally important or perhaps even more important, and one way to carry out this search is through the decays

$$\text{heavier scalar lepton} \rightarrow \text{lighter scalar lepton} + W, \quad (14)$$

where the $W$ may be either real or virtual, a process very similar to that of ordinary leptons.

On a most fundamental level, it is the purpose of the present work to think about, on the basis of the experimental results from the Large Hadron Collider and the Tevatron Collider, what this fermion-boson symmetry might be. In order to have any such symmetry, it is of course necessary to have three generations of scalar quarks and scalar leptons. However, it is not sufficient merely to augment the standard model with the scalar quarks and the scalar leptons, and one, or more likely several, new fermions are needed – See (A) above. There is at present essentially no information about these new fermions, and an interesting exercise is to list the various attractive possibilities for them and then compare with future experimental results.

VII. CONCLUSION AND OUTLOOK

Last year, there were two epoch-making papers, one by the ATLAS Collaboration [1] and one by the CMS Collaboration [2], describing the discovery of the Higgs particle [3]. It is the purpose of the present paper to discuss some of the possible consequences of the data presented in these two papers. The starting point is the proposal that, with the discovery of the first spin-0 elementary particle, there may well be other spin-0 elementary particles. These additional spin-0 particles can be used to explain the observed excess on the decay of the Higgs particle into two photons [1, 2]. Later data from the ATLAS Collaboration [25] and from the CDF and D0 Collaborations [26] are then used to reach the conclusion that these spin-0 particles are not additional Higgs particles, but rather scalar quarks and scalar leptons, which remain to be observed experimentally.

If the standard model [4] is augmented only by these scalar quarks and scalar leptons, then the lightest scalar quark is necessarily stable. It is shown in Sec. IV that this stable lightest scalar quark is incompatible with the data from the CMS Collaboration [8]. This means that, in addition to the scalar quarks and the scalar leptons, there must be additional fermions which also remain to be observed experimentally. At present there is no way to answer the important question of how many scalar quarks and scalar leptons there are. However, the natural guess is that these scalar particles are in one-to-one correspondence with the known fermions in the standard model, either in number or in the degrees of freedom. If this is the case, then it suggests a fermion-boson symmetry. Since there is no additional Higgs particle, this fermion-boson symmetry is necessarily of a fundamentally different nature from that of supersymmetry, including MSSM in particular. It is thus seen that the discovery of the Higgs particle last year [1, 2] not only completes the list of particles in the standard model, but also shows a possible direction to go beyond the standard model. In other words, it is likely that this discovery of the Higgs particle will open up a new and exciting era of particle physics [27, 28].

ACKNOWLEDGMENTS

We are very grateful to André Martin and Jacques Soffer for several fruitful and enjoyable discussions that motivated this investigation. JMR would like to thank Suzanne Gascon, Bernard Ille and Louis Sgandurra for very useful information. The work of JMR is partially supported by the Labex-LIO (Lyon Institute of Origins).

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