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Production mechanisms for predicted new Higgs-related spin 1/2 particles

Joshua Stenzel, Johannes Kroll, Minjie Lei, and Roland E. Allen[*],
Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
E-mail: *allen@tamu.edu*

The theory at arXiv:1101.0586 [hep-th] predicts new fundamental spin $1/2$ particles which can be produced in pairs through their couplings to vector bosons or fermions. The lowest-energy of these should have a mass $m_{1/2}$ comparable to the mass m_h of the recently discovered Higgs boson (with $m_{1/2} = m_h$ in the simplest model). These particles should therefore be detectable in collider experiments, perhaps in Run 2 or 3 of the LHC. Here we discuss possible production mechanisms.

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[*]Speaker.

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The particle discovered by the ATLAS and CMS collaborations at the LHC is almost certainly a Higgs boson [1, 2, 3]. After the electron was discovered in 1897, and the photon was introduced by Einstein in 1905, the richness of behavior associated with spin 1/2 fermions and spin 1 gauge bosons emerged slowly during the following decades. More than a century later, the third kind of Standard Model particle, with spin 0, has finally been discovered, and one should not be completely surprised if some of its implications are yet to be determined.

In an earlier paper [4], based on a novel fundamental picture, the following action for spin 1/2 fermions and scalar bosons was obtained as a low energy approximation:

$$S_f + S_{sb} = \int d^4x \left[\psi_f^\dagger(x)\, i e_\alpha^\mu \sigma^\alpha D_\mu \psi_f(x) - g^{\mu\nu} \left(D_\mu \phi_b(x)\right)^\dagger D_\nu \phi_b(x) + F_b^\dagger(x) F_b(x) \right]$$

where

$$g^{\mu\nu} = \eta^{\alpha\beta} e_\alpha^\mu e_\beta^\nu \,.$$

Here e_α^μ is the vierbein and $\eta^{\alpha\beta}$ is the Minkowski metric tensor in the $(-1,1,1,1)$ convention. The familiar form for a Lorentz-invariant and supersymmetric action was thus found to follow automatically from a picture that is intially quite unfamilar. The spin 1/2 fermion fields in ψ_f, the scalar boson fields in ϕ_b, and the auxiliary fields in F_b span the various physical representations of the fundamental gauge group, which must be $SO(N)$ in the present theory. (More precisely, the group is $Spin(N)$, but $SO(N)$ is conventional terminology.) One unfamiliar feature remains: There is no factor of $e = \left(-\det g_{\mu\nu}\right)^{1/2}$ in the integral, and this is related to the more general fact that the usual cosmological constant vanishes in the theory of Ref. [4].

At higher energies, including those currently achieved at the LHC, the theory implies that the above form for the action is no longer a valid approximation, because internal degrees of freedom can be excited in a 4-component field

$$\Phi_b = \begin{pmatrix} \Phi \\ \Phi_c^\dagger \end{pmatrix} .$$

This can be written as the inner product of two N_g-component fields ϕ_b and χ_b, where each component of ϕ_b is a complex scalar and each component of χ_b is a 4-component bispinor (and where N_g is the number of fields spanning all the physical gauge representations):

$$\Phi_b = \phi_b \chi_b = \phi_b^r \chi_b^r \tag{1}$$

with the usual summation over the repeated index r. The amplitude of each component Φ_b^r is given by ϕ_b^r, and the "spin configuration" by χ_b^r. If χ_b is constant, it is convenient to choose the normalization

$$\chi_b^{r\,\dagger} \chi_b^r = 1 \quad [\text{no sum on } r] \,. \tag{2}$$

The more general form of the Lagrangian corresponding to scalar bosons includes the internal degrees of freedom which are "hidden" at low energy. In a locally inertial frame of reference it is

$$\mathscr{L}_\Phi = \Phi_b^\dagger(x) D^\mu D_\mu \Phi_b(x) - \frac{1}{2} \left[\Phi_b^\dagger(x)\, S^{\mu\nu} F_{\mu\nu} \Phi_b(x) + h.c. \right] \tag{3}$$

where $F_{\mu\nu}$ is the field strength tensor and the $S^{\mu\nu} = \sigma^{\mu\nu}/2$ are the Lorentz generators which act on Dirac spinors. When the second term above is written out explicitly, it involves $\phi_b^{r\dagger}\phi_b^{r'}\chi_b^{r\dagger}\sigma^k\chi_b^{r'}$ interacting with the "magnetic" field strengths in $F_{\mu\nu}$ (and is thus analogous to the interaction of an electron spin with a magnetic field).

Some experimental implications are discussed in Appendix E of Ref. [4]. In particular, the theory predicts new fundamental spin 1/2 particles which can be produced in pairs through their couplings to vector bosons or fermions. The lowest-energy of these should have a mass $m_{1/2}$ comparable to the mass m_h of the recently discovered Higgs boson, with $m_{1/2} = m_h$ in the simplest model.

There are two unconventional features in the Lagrangian $\mathscr{L}_\Phi$: Each field Φ_b^r has four components rather than one, and there is a second term involving the gauge field strengths $F_{\mu\nu}$. One can read off the general Feynman-diagram vertices for virtual and real processes from the interactions in each term. These are relevant for all the Φ_b^r that correspond to scalar boson fields in standard physics, but let us now focus on the one Φ_h that corresponds to a single neutral Higgs field.

The vacuum expectation value of Φ_h has the form

$$\left\langle \Phi_h^0 \right\rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} .$$

In Ref. [4] it is shown that the condensate then has zero angular momentum and also no coupling to the gauge fields beyond that in the Standard Model (since the second term in $\mathscr{L}_\Phi$ vanishes when the internal degrees of freedom in Φ_h are not excited).

The simplest model for excitations of Φ_h has a mass term Lagrangian

$$\mathscr{L}_h^{\text{mass}} = m_h^2 \left(\Delta\Phi_h\right)^\dagger \Delta\Phi_h .$$

When the internal degrees of freedom are not excited, so that $\Delta\Phi_h = h\chi_0$ with $\chi_0^\dagger\chi_0 = 1$, the mass term is $m_h^2 h^2$ (for h real). I.e., m_h is the mass of the scalar Higgs boson.

For a spin 1/2 excitation with the form

$$\Delta\Phi_h = \begin{pmatrix} h_+ \\ 0 \end{pmatrix} \quad \text{or} \quad \Delta\Phi_h = \begin{pmatrix} 0 \\ h_- \end{pmatrix}$$

we obtain

$$\mathscr{L}_+^{\text{mass}} = m_h^2 h_+^\dagger h_+ \quad \text{or} \quad \mathscr{L}_-^{\text{mass}} = m_h^2 h_-^\dagger h_- .$$

In other words, in the simplest model the spin 1/2 particles h_+ and h_- have the same mass m_h as the scalar Higgs boson h. More generally, the masses $m_{1/2}$ of these particles should be comparable to m_h. A suggestive analogy is s-wave superconductivity, where there are single-particle excitations, two-particle excitations, and "Higgs mode" excitations with minimum energies Δ, 2Δ, and 2Δ respectively.

According to the spin-statistics theorem, spin $1/2$ bosonic excitations are impossible, but the requirements of this theorem are not satisfied in this one specific context, since $\mathscr{L}_\Phi$ is not fully Lorentz invariant: It is invariant under a rotation, but not a Lorentz boost with respect to the original (cosmological) coordinate system. The present theory is, however, fully Lorentz invariant (as well as initially supersymmetric) if the internal degrees of freedom in Φ_b are not excited – and these excitations can be observed only at the high energies that are now becoming available. Furthermore, the extremely weak virtual effects of these excitations are irrelevant to the many existing tests of Lorentz invariance, which probe those phenomena in various areas of physics and astrophysics where the present theory is fully Lorentz invariant.

The spin $1/2$ excitations of Φ_b can be produced in pairs through the coupling to gauge boson fields in $\mathscr{L}_\Phi$ – for example, by the coupling to virtual or real Z and W bosons. In addition, the Higgs-related spin $1/2$ particles should have the same basic Yukawa couplings to fermions as a Higgs boson, since $\Phi_h = \phi_h \chi_h$. Some possible production mechanisms are illustrated in Fig. 1.

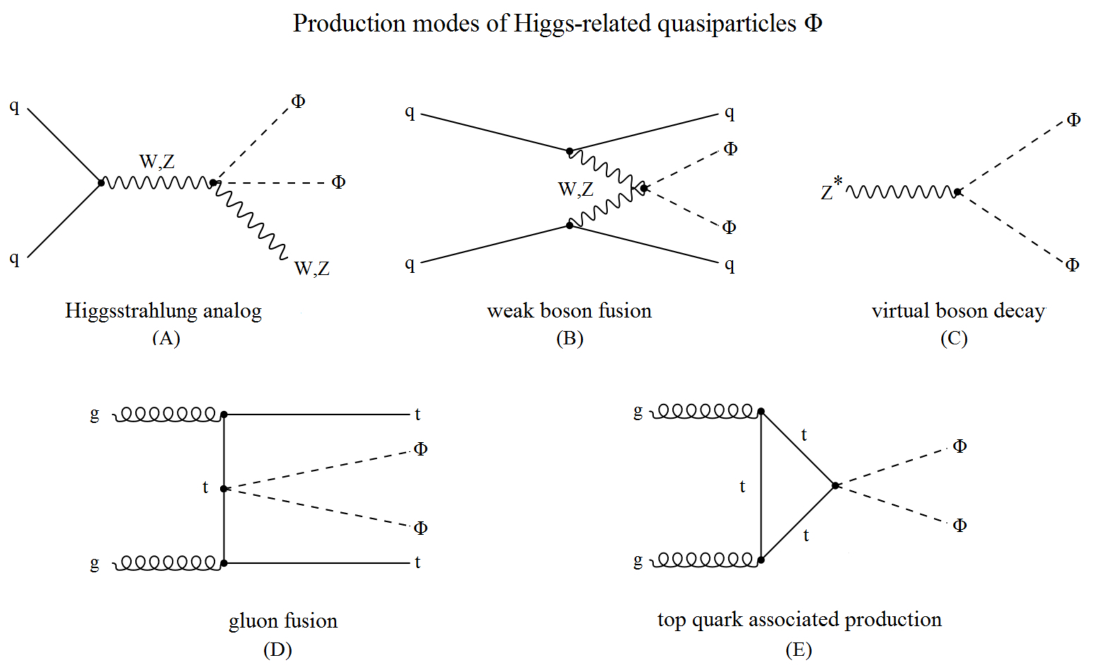

Figure 1: Some production mechanisms for the spin 1/2 particles predicted by the form of the field Φ, which are not named here but simply labeled Φ in the figure.

References

[1] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", Phys. Lett. B716, 1 (2012), arXiv:1207.7214 [hep-ex].

[2] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", Phys. Lett. B716, 30 (2012), arXiv:1207.7235 [hep-ex].

[3] See e.g. K. A. Olive et al. (Particle Data Group), "The Review of Particle Physics", Chin. Phys. C 38, 090001 (2014), updated at http://pdg.lbl.gov/.

[4] R. E. Allen, arXiv:1101.0586 [hep-th].