Scalar Bosons and Supersymmetry

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Abstract. The recent discovery of a spin-0 Brout–Englert–Higgs boson leads to further enquire about other fundamental scalars. Supersymmetric theories involve, in relation with the electroweak breaking, five such scalars at least, two charged and three neutral ones, usually denoted as \( H^\pm, H, h \) and \( A \). They also introduce spin-0 squarks and sleptons as the superpartners of quarks and leptons.

Supersymmetric extensions of the standard model lead to the possibility of gauge/BEH unification by providing spin-0 bosons as extra states for spin-1 gauge bosons within massive gauge multiplets. Depending on its properties the 125 GeV boson observed at CERN may then also be interpreted, up to a mixing angle induced by supersymmetry breaking, as the spin-0 partner of the \( Z \) under two supersymmetry transformations, i.e., as a \( Z \) that would be deprived of its spin.

1. The electroweak symmetry breaking

Special relativity and quantum mechanics, operating within quantum field theory, led to the Standard Model of particles and interactions. It has met a long series of successes with the discoveries of weak neutral currents (1973), charmed particles (1974–76), gluons mediators of strong interactions (1979), \( W^\pm \) and \( Z \)’s mediators of weak interactions (1983), and the sixth quark known as the top quark (1995).

Weak, electromagnetic and strong interactions are all understood from the exchanges of spin-1 mediators, \( W^\pm \)'s and \( Z \)'s, photons and gluons, between spin-\( \frac{1}{2} \) quarks and leptons, generically referred to as the constituents of matter. The \( u \) and \( d \) quarks are the building blocks for the protons \( uud \) and neutrons \( ddu \), and the leptons include the electrons, muons and taus with their three neutrinos. The known fundamental particles are shown in Table 1, without any fundamental spin-0 boson yet.

The spin-1 bosons mediators of interactions are associated with local gauge symmetries. The eight gluons mediate the strong interactions, invariant under the color \( SU(3) \) gauge group. The \( W^\pm, Z \) and photon, mediators of the electroweak
interactions, are associated with the \( SU(2) \times U(1) \) electroweak gauge group [1–3]. It gives very much the same role to the left-handed quark fields \( u_L \) and \( d_L \), and similarly to the left-handed lepton fields \( \nu_e L \) and \( e_L \).

The electroweak symmetry requires in principle the corresponding spin-1 gauge bosons to be massless. The weak interactions, mediated by virtual \( W^\pm \) and \( Z \) production or exchanges, would then be long-ranged. They have instead a very short range \( \approx 2 \times 10^{-16} \) cm, corresponding to the large masses \( m_W \approx 80 \) GeV/c\(^2\) and \( m_Z \approx 91 \) GeV/c\(^2\) of their mediators, almost 100 times the mass of a proton. The electroweak symmetry should also require the charged leptons and quarks to be massless, which is not the case.

Both problems are solved within the standard model through the spontaneous breaking of the electroweak gauge symmetry induced by a doublet of complex spin-0 fields \( \varphi \) [3]. Three of its four real components, instead of being associated with three unwanted massless Goldstone bosons [4] as it would be the case if the electroweak \( SU(2) \times U(1) \) symmetry were only global, are eliminated by the Brout–Englert–Higgs mechanism [5–7] to provide the additional degrees of freedom required for the \( W^\pm \) and \( Z \) to acquire masses.

The fourth component of the spin-0 doublet, taken as \( \phi = \sqrt{2} \varphi^* \varphi \), adjusts uniformly in space-time so that the potential

\[
V(\varphi) = \lambda (\varphi^* \varphi)^2 - \mu^2 \varphi^* \varphi, \quad (1)
\]

with its famous mexican-hat shape, is minimum, for \( \phi = v = \sqrt{\mu^2/\lambda} \) [3–6]. The electroweak symmetry is then said to be “spontaneously broken” (even if \( \phi \) itself remains gauge-invariant), meaning by this expression that the \( W^\pm \) and \( Z \) are no longer massless. The local gauge symmetry, which strictly speaking still remains unbroken, gets now hidden. The \( W^\pm \) and \( Z \) acquire masses fixed in terms of the electroweak gauge couplings \( g \) and \( g' \) by

\[
m_W = \frac{gv}{2}, \quad m_Z = \frac{\sqrt{g^2 + g'^2}}{2} v = \frac{m_W}{\cos \theta}. \quad (2)
\]

The electroweak mixing angle \( \theta \) which enters in the definitions of the \( Z \) and photon fields is fixed by \( \tan \theta = g'/g \), the photon staying massless.