Higgs Boson and Z’ Boson

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ABSTRACT

The recent discovery of a Higgs boson at the LHC is a milestone in the quest to understand electroweak symmetry breaking. It is an important particle because it is responsible for the Higgs mechanism by which all particles acquire mass. The existence of a particle with zero spin suggests the need for new physics beyond the standard model. Z’ bosons are known to naturally exist in well-motivated extensions of the standard model. Since the Z’ boson has not yet been discovered, its exact mass is unknown. In this paper, we calculate the mass of Z’ boson using the recent data for the mass of Higgs boson and new parameters.

Keywords: Higgs boson, Z’ boson, electroweak symmetry breaking, Higgs mechanism, beyond standard model.

1. INTRODUCTION

In the standard model (SM) of particle physics, Brout-Englert-Higgs (BEH) mechanism (popularly known as Higgs mechanism) is the source of electroweak symmetry breaking (EWSB) and predicts appearance of Higgs boson [1–3]. In 2012 the ATLAS and CMS experiments at the LHC have announced the discovery of a new particle with mass \( m_H = 125–126 \) GeV [4, 5]. It is now confirmed that this newly discovered particle is the long sought Higgs boson. It [6] is claimed that graphene, the 2010 Nobel Prize winning two-dimensional nonmaterial, would help physicists to probe the Higgs boson’s secrets. When we compress graphene, it ripples and displays a sort of symmetry breaking. Again we know that the Higgs mechanism explains the symmetry breaking. That is why, it is expected that the ripple effect of graphene would give hints about the Higgs field and the Higgs boson, which gets its mass from vibrations in the Higgs field. Furthermore, it is expected that graphene might help us to understand the mechanisms behind the formation of the universe. Decays of Higgs boson may discriminate between matter and antimatter and might explain the cosmological matter-antimatter asymmetry [7]. Recently, it is claimed that the Higgs boson might interact with dark matter [8,9] and there exists relation between the Higgs boson and dark matter. Since (i) the Higgs field does not directly couple to the quanta of light (photons), and (ii) it generates mass. Dark matter is responsible for the discrepancy between the apparent observed mass of the universe and its actual mass. Again dark matter does not interact with the electromagnetic force, but whose presence can be inferred from gravitational effects on visible matter. Hertzberg [9] has predicted a correlation between the Higgs mass and the abundance of dark matter. His theoretical result is good agreement with current data. He has predicted the mass of Higgs boson as 125.7 ± 0.6 GeV. Thus, although the Higgs boson belongs to the SM of particle physics its study is a very challenging and fascinating topic which interplays between different branches of physics like particle physics, condensed matter physics and cosmology [10,11]. Although it is considered as the last missing piece of the SM its discovery portends discovery of a new realm of physics [12] specifically beyond the SM.

Since the discovery of Higgs boson, the search for new physics (NP) beyond standard model becomes one of the most important topics of high energy physics. In many NP models, an extra \( U(1)' \) gauge symmetry is often introduced resulting in an additional massive neutral gauge boson usually known as Z’ boson [13]. These Z’ bosons are predicted theoretically in many extensions of the SM [14] such as grand unified theories (GUTs), left-right symmetric models, Little Higgs models and superstring theories. It is surprising that a Z’ boson is predicted at the weak scale [15] in super symmetric \( E_6 \) models. However, there are stringent limits on the mass of an extra Z’ from the non-observation of direct production followed by decays into \( e^+e^- \) or \( \mu^+\mu^- \) by CDF [16], while indirect constraints from the precision data also limit the Z’ mass (weak neutral current processes and LEP II) and severely constrain the \( Z – Z' \) mixing angle \( \theta \) [17,18]. These limits are model-dependent, but are typically in the range \( m_{Z'} \geq 500 \) GeV and \( |\theta| \leq 10^{-3} \) for standard GUT models. Recently, the ATLAS collaboration [19] sets the mass limits for the sequential standard model Z’ as 2.90 Tiv and mass limits of 2.51–2.62 Tiv are set for different \( E_6 \)-motivated Z’ bosons. In this paper, we calculate the mass of Z’ boson using the recent data for the mass of Higgs boson and new parameters.

This paper is organized as follows: In Sec. 2, we discuss the Higgs boson in the standard model. In Sec. 3, using the recent data for the mass of Higgs boson and updated parameters from Particle Data Group 2014, we recalculate the mass of Z’ boson in the \( SU(2) \times U(1) \times U(1) \) model, which is a subgroup of \( SO(10) \). Finally, we present our conclusions in Section 4.
2. HIGGS BOSON IN THE STANDARD MODEL

The gauge group of the SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$. The $SU(3)_C$ group describes strong interaction, $SU(2)_L$ is the weak symmetry group and $U(1)_Y$ is the electromagnetic symmetry group. The Lagrangian of the SM is electroweak symmetric but this symmetry is not clear in our world. Therefore it must be broken. In the SM, it is postulated that the breaking of electroweak symmetry via the Higgs mechanism gives mass to all fundamental particles. The Higgs field $\phi$ is an SU (2) doublet and can be written as \[\phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix}\] with a vacuum expectation value \[\langle 0 | \phi | 0 \rangle = \begin{pmatrix} 0 \\ v / \sqrt{2} \end{pmatrix}\] (1)

(2)

In the standard model with a Higgs sector as described above, the scalar potential can be written as [22]:

\[V_{SM} = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2\] (3)

Spontaneous symmetry breaking in a gauge theory generates mass for gauge bosons and their masses are proportional to the Higgs vacuum expectation value

\[\langle \phi_0 \rangle = v / \sqrt{2}\]

Where

\[v = \sqrt{-\mu^2 / \lambda} = 246.218 \text{ GeV} \] (4)

The self-coupling of Higgs field shows that the Higgs field itself has mass. Higgs boson is an uncharged scalar boson. The top quark, W boson and Higgs boson masses are given [21,22] in terms of $v$ and their respective Yukawa couplings:

\[m_w = \frac{1}{2} g v,\]

\[m_z = \frac{1}{2} (g + g') v,\]

\[m_t = g_t v,\]

\[m_H^2 = 2 \lambda v^2.\]

Here, $g'/g = \tan \theta_W$, $\theta_W$ is the Weinberg angle and $g_t$ is the top Yukawa coupling. In the SM, the Higgs self-coupling $\lambda$ is not determined. That why Higgs mass is not determined in the SM and today scientists are trying to estimate it. Existence of this Higgs boson can be counted among the definitive predictions of the SM.

3. CALCULATION OF Z' BOSON MASS

In this section, we have recalculated the mass of $Z'$ boson using the recent data for the mass of Higgs boson and updated parameters. We consider the $SU(2) \times U(1) \times U(1)$ model, which is a subgroup of SO (10). This model is discussed in detail in [23]. In this model, the authors [23,24] have derived the relation between the mass squares of the particles in dimensional regularization (DREG) method at one loop in the standard model as

\[12 m_t^2 = 3 m_H^2 + 2 m_w^2 + m_Z^2 + m_{Z'}^2,\]

where $m_t, m_w, m_Z, m_H$ and $m_{Z'}$ are the masses of top quark, W boson, Z boson, Higgs boson and $Z'$ boson respectively.

Higgs boson is a central part of the standard model of electroweak interactions. Because it is responsible for the Higgs mechanism by which all particles acquire mass. But in the SM, the mass of Higgs boson is not specified. From the recent experimental results at the LHC, the mass of this particle is found to be $125.6 \pm 0.4$ (stat.) $\pm 0.2$ (syst.) GeV (CMS) [25] and $125.5 \pm 0.2$ (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV (ATLAS) [26]. In compactified string / M theories [27] it is predicted that for $\tan \beta > 7$ (the ratio of the Higgs vacuum expectation values in the MSSM), the mass of Higgs boson lies in the range $122$ GeV $\leq m_H \leq 129$ GeV. The SUGRA grand unification predicts an upper limit on the Higgs boson mass $\sim 130$ GeV [28–30]. Sahoo et al. [31] have predicted the mass of the Higgs boson as $m_H \approx 120$ GeV in a flavor-independent potential model where considering the $Z'$ boson contributions the authors have studied the mass differences $\Delta M_K$ (in $K^0 - \bar{K}^0$ system) and $\Delta M_{\theta^3}$ (in...
calculation of the mass of Higgs boson in the range 120–130 GeV for the discovery of the mass of Z’ boson.

Taking \( m_{H} = 120 \) GeV and using the current values from Particle Data Group 2014 [32], we get the mass of Z’ boson:

\[
\left( m_{Z'} \right)_{\text{min}} = 539.01 \text{ GeV} \quad (7)
\]

and

\[
\left( m_{Z'} \right)_{\text{max}} = 548.34 \text{ GeV} \quad (8)
\]

Similarly, for \( m_{H} = 130 \) GeV and using the current values from Particle Data Group 2014 [32], we get the mass of Z’ boson:

\[
\left( m_{Z'} \right)_{\text{min}} = 532 \text{ GeV} \quad (9)
\]

and

\[
\left( m_{Z'} \right)_{\text{max}} = 541.45 \text{ GeV} \quad (10)
\]

For other intermediate values of \( m_{H} \), one can get the corresponding values of the mass of Z’ boson. From equations (7) – (10), we conclude that the mass of Z’ boson lies in the range 250 GeV < \( m_{Z'} < 2 \) Tiv [33]. In a study of B meson decays with Z’-mediated flavor-changing neutral currents (FCNCs), Barger et al. [34] have studied Z’ boson in the mass range of a few hundred GeV to 1 Tiv. These facts lead to enrichment in the phenomenology of Z’ bosons and new physics beyond the standard model will show up after the discovery of the Z’ boson.

4. CONCLUSION

The Higgs discovery demonstrates the unity of physics. In the SM, it bridges the matter particles and force particles providing mass to both kinds of particles. Some of the problems in cosmology are related to the Higgs boson. Jackson et al. [8] have suggested that the Higgs boson might interact with weakly interacting massive particles of dark matter. The Higgs field does not directly couple to the quanta of light (photons) and it generates mass. Similarly, dark matter does not interact with the electromagnetic force and is responsible for the discrepancy between the apparent observed mass of the universe and its actual mass. Hence, it is expected that there is a relation between Higgs boson and dark matter. The Higgs boson could be coupled to the particle that constitutes all or part of the dark matter in the universe [35]. Hertzberg [9] has predicted a relation between the Higgs mass and the abundance of dark matter. From this relation he has predicted the mass of Higgs boson as 125.7 ± 0.6 GeV which consistent with the recent prediction at the LHC i.e. ~ 125–126 GeV [4,5]. Recently, Huang [36] has discussed phase dynamics of the Higgs field on a cosmic scale. According to him, the Higgs field fills all space. On microscopic scale, it gives mass to elementary particles. On macroscopic scale, it flows like a super fluid, due to phase variations. On cosmic scale, it makes the universe a super fluid. The energy of this cosmic super fluid can be identified with dark energy, and fluctuations of the super fluid density lead to dark matter.

It is also claimed [6] that graphene would help physicists to probe the Higgs boson’s secrets. When we compress graphene it ripples and displays a sort of symmetry breaking and we know that Higgs mechanism explains symmetry breaking. Thus, the Higgs boson can act as a bridge between particle physics as well as condensed matter physics and cosmology [10,37,38]. The ATLAS and CMS experiments at the LHC have discovered a Higgs boson but it is not confirmed whether it is the only one Higgs boson or there may be others. Further, the spin of Higgs boson is zero. The existence of an elementary scalar (spin 0) boson suggests the need for new physics beyond the SM [7,12,38].

The Z’ bosons are predicted in a number of theories that extend the SM gauge group by adding an extra U(1) symmetry [39,40]. Since the Z’ boson, often called as the 2nd Z boson, has not yet been discovered experimentally, its exact mass is not known. In this paper, we have recalculated the mass of Z’ boson. Our estimated value lies in the range 532 – 549 GeV. The new physics beyond the SM will be known after the discovery of the Z’ boson. The study of Higgs boson and Z’ boson is not only interesting but also opens an exciting window for new physics beyond the SM. We hope that LHC RUN II will reveal some of these issues.

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