Physics Letters B 771 (2017) 313–317

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Bound states via Higgs exchanging and heavy resonant di-Higgs

Zhaofeng Kang

School of Physics, Korea Institute for Advanced Study, Seoul 130-722, Republic of Korea

ARTICLE INFO

Article history:
Received 8 December 2016
Received in revised form 29 April 2017
Accepted 19 May 2017
Available online 29 May 2017
Editor: J. Hisano

ABSTRACT

The existence of Higgs boson h predicted by the standard model (SM) was established and hunting for clues to new physics (NP) hidden in h has become the top priority in particle physics. In this paper we explore an intriguing phenomenon that prevails in NP associated with h, bound state (B_h, referring to the ground state only) of relatively heavy particles ϕ out of NP via interchanging h. This is well-motivated due to the intrinsic properties of h: It has zero spin and light mass, capable of mediating Yukawa interactions; moreover, it may be strongly coupled to ϕ in several important contexts, from addressing the naturalness problem by compositeness/supersymmetry (SUSY)/classical scale invariance to understanding neutrino mass origin radiatively and matter asymmetry by electroweak baryogensis. The new resonance B_h, being a neutral scalar boson, has important implications to the large hadron collider (LHC) di-Higgs search because it yields a clear resonant di-Higgs signature at the high mass region ($\gtrsim$ 1 TeV). In other words, searching for B_h offers a new avenue to probe the hidden sector with a Higgs-portal. For illustration in this paper we concentrate on two examples, the stop sector in SUSY and an inert Higgs doublet from a radiative neutrino model. In particular, h-mediation opens a new and wide window to probe the conventional stoponium and the current date begins to have sensitivity to stoponium around TeV.

1. Force mediator: a new face of Higgs boson

The main focus of particle physics lies on aspects of the newly discovered member of SM, the Higgs boson h. It is commonly believed to be the portal to the mysterious new physics world where the gauge hierarchy problem, dark matter, neutrino mass or/and baryon asymmetry origins may be addressed. Specific to LHC, di-Higgs search is of particular interest since it could help to reveal the Higgs potential [1,2].

In this paper we explore the thought-provoking hypothesis that h plays the role of force carrier and mediates new interaction between particles (collectively denoted as ϕ) out of the NP sector, making them form bound state B_h. This hypothesis is well motivated grounded on three basic properties of h. First of all, it is a spin-0 particle and thus mediates Yukawa interaction. Next, its mass $m_h \approx 125$ GeV is much lighter than the NP states, which are expected to be around the TeV scale, and thus h can be regarded almost massless. Last but not least, the interacting strengths of h to ϕ are unknown but there are convincing examples indicating that they are, or at least can be fairly strong, e.g., in the theories addressing naturalness problem by classical scale invariance and understanding matter asymmetry via electroweak baryogensis, the Higgs field may strongly couple to some new scalar fields so as to trigger classical scale symmetry breaking and strong first-order EWPT, respectively; in particular, in the composite Higgs scenario, h, being a pseudo Goldstone boson, is a strong reminiscence[1] of the pion of Hideki Yukawa, which has large couplings with nucleons and thus bound them in nuclei.[2] Therefore, the existence of B_h in NP is in expectation.

The bound state B_h via Higgs boson exchanging shows a remarkable feature, i.e., it dominantly decays into a pair of force carrier, namely di-Higgs boson. Therefore, as long as the bound state B_h has an abundant production at LHC, we are going to observe a remarkable resonant di-Higgs signature; see Fig. 1. This new observation is one of the key difference between our paper and the quite old papers which considered Higgs exchange effect restricted to quarkonium, bound state of hypothetical heavy quarks [4] (or even Higgs–Higgs bound state [5]). Furthermore, now we already largely pin down the Higgs boson and know it should lead to a

E-mail address: zhaofengkang@gmail.com.

[1] For instance, it may bound the exotic spin-1 resonance [3] despite not the spin-1/2 top partners, the more robust prediction but with suppressed couplings to h owing to the small composite-fundamental mixing.

[2] In the chiral perturbative theory, pions are pseudo Goldstone boson (composite) particles from chiral symmetry breaking.

http://dx.doi.org/10.1016/j.physletb.2017.05.062

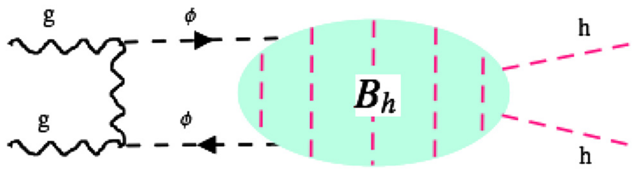

Fig. 1. Production and decay of bound state B_h, which looks like a new resonance dominantly decaying into di-Higgs boson.

new type of interaction other than the gauge interactions, so it is the right time to explore B_h in a wide context of NP.

2. General aspects of B_h

2.1. Formalism for B_h

We start with a simplified model which captures the main features of B_h at LHC. The ingredients include the force carrier h and the constituent ϕ, which is assumed to be a scalar (complex for the time being) field, along with the Higgs-portal interactions

$$-\mathcal{L}_h = u_{h\phi\phi} h|\phi|^2 + m_\phi |\phi|^2. \tag{1}$$

The discussions can be easily generalized to other cases, says a fermionic or vector ϕ. Probably, ϕ carries the SM charges such as $SU(3)_C$ and/or $U(1)_Y$, which is important in the production of B_h at LHC.

In the bound state of ϕ, the internal motion is nonrelativistic and thus its dynamics can be described by quantum mechanism or concretely, the Schrodinger equation

$$\left(-\frac{\nabla^2}{2\mu_r} + V(\vec{r})\right)\Psi(\vec{r}) = E\Psi(\vec{r}), \tag{2}$$

where $\mu_r = m_\phi/2$ is the reduced mass and V is the central potential, which, specific to Higgs interchanging, is the Yukawa potential $-\frac{\alpha_h}{r}e^{-m_h r}$ with $\alpha_h = u_h^2/(16\pi m_\phi^2)$ [6]. Although the exact analytical solution to Eq. (2) is not available, an approximate one can be found based on the scaled Hulthen potential [7]

$$V_{SH}(r) = -\alpha_h \frac{R_s m_h e^{-R_s m_h r}}{1 - e^{-R_s m_h r}}, \tag{3}$$

where $R_s \approx 1.75$ [7]. Both the standard Hulthen [8] and rescaled Hulthen potential resemble the Yukawa potential and admits an exact solution, but the latter is better when the bound state is just marginally formed. Consider the squared bound state wavefunction (S-wave) at the origin

$$|\Psi_n(0)|^2 \approx \frac{\epsilon(R_s/D_h)}{n^3}\frac{1}{\pi a_0^3} = \frac{\left(1 - \frac{R_s^2}{4D_h^2}\right)^{\frac{3}{2}}}{n^3}\frac{\alpha_h^3 m_B^3}{64\pi}, \tag{4}$$

where $m_B = 2m_\phi$ and $a_0 \simeq 1/\alpha_h \mu_r$ is the characteristic scale of B_h, the Bohr radius; $D_h \equiv m_h^{-1}/a_0$ is a good measurement of how Coulomb-like the system is. Hereafter we will consider the ground state only, hence dropping the subscript.

The Coulomb limit is $D_h \gg 1$, i.e., the screening length $1/m_h$ is much longer than the Bohr radius. If D_h approaches one, the screening effect is strong; the critical condition for the existence of at least one bound state, i.e., the ground state, is $D_h \gtrsim 0.84$ [9,10] (note that the above approximation may be valid only for $D_h \gtrsim 1$). This condition is fulfilled when

$$m_\phi \gtrsim 0.84 \times \frac{2}{\alpha_h} m_h \approx 0.7 \times \left(\frac{0.3}{\alpha_h}\right) \text{TeV}. \tag{5}$$

Due to the heaviness of force carrier h, bound state can exist only for either heavy constitutes or rather strong self-coupling close to the perturbative bound. On the other hand, one can derive an upper bound for the massive coupling by requiring that the lifetime of the bound state should be longer than the time scale of its formation, the inverse of the binding energy [11], namely

$$\Gamma_{B_h} \lesssim E_b \Rightarrow \alpha_h \lesssim 1/N_c^{1/3}. \tag{6}$$

We have used $\Gamma_{B_h} \approx \Gamma_{B_h \to hh}$ in Eq. (8). N_c is the color factor from ϕ and for $N_c = 3$ one has $\alpha_h \lesssim 0.7$, while for $N_c = 1$ the bound coincides with the perturbativity bound.[3]

2.2. Resonant di-Higgs signature from B_h

At hadron colliders like LHC, the bound state B_h can be created when the pairly produced ϕ have center-of-mass (CM) energy just below the threshold m_B. B_h is not stable and overwhelmingly decays into a pair of Higgs boson.[4] Therefore, provided a sizable cross section of B_h, a clear prediction of new resonance in the di-Higgs channel is furnished. In this subsection we will detail the production and decay of B_h.

Let us begin with the annihilation decay of B_h (neglecting the open "flavor" decay). In general, the partial decay widths of B_h into XY can be calculated in terms of the amplitude of annihilation $\phi\phi^* \to XY$ and the bound state wave function at the origin [13]

$$\Gamma_{B\to XY} = \frac{1}{2m_B}\frac{N_c}{1+\delta_{XY}}\int d\Pi_2 \frac{2}{m_B}|\mathcal{M}_{\phi\phi^*\to XY}|^2 |\Psi(0)|^2, \tag{7}$$

with δ_{XY} the statistic factor. For instance, for $A = B = h$ one has

$$\Gamma_{B\to hh} \approx \frac{N_c}{16\pi}\frac{|\Psi(0)|^2}{m_B^2}\left[\frac{4u_{h\phi\phi}^4}{\left(\frac{1}{2}m_B^2 - m_h^2\right)^2}\right]\beta_h, \tag{8}$$

with $\beta_h = \left(1 - 4m_h^2/m_B^2\right)^{1/2}$. Since a relatively heavy ϕ is required because of Eq. (5), thus $m_\phi^2 \gg m_h^2$. Then the squared amplitude (the factor in the squared bracket) can be approximated as $\sim (u_{h\phi\phi}/m_\phi)^4 = (16\pi\alpha_h)^2 = 404 \times (\alpha_h/0.4)^2$, a large value. Therefore it tends to dominate over other modes. As a comparison, consider a colored ϕ, for concreteness in the fundamental representation of $SU(3)_c$ such as stop/sbottom that will be discussed later. Then B_h can decay into gg with width [14,15]

$$\Gamma_{B_h\to gg} \approx \frac{N_c}{16\pi}\frac{|\Psi(0)|^2}{m_B^2}\left[\frac{256\pi^2}{9}\alpha_s^2\right] \ll \Gamma_{B_h\to hh}. \tag{9}$$

Note that for a scalar ϕ with electroweak (EW) charges, the annihilation $\phi\phi^* \to Z^*/\gamma^* \to qq$ is p-wave suppressed and hence the corresponding B_h production via $q\bar{q} \to B_h$ is inaccessible.

On top of those annihilation decay modes via the u/t-channels ϕ mediation or contact interactions, the decay modes via s-channel Higgs mediation may be also important. This is particularly true for the VV modes with $V = W, Z$, because we are considering a TeV scale bound state and thus they obtain the Goldstone enhancement factor $m_B^2/m_V^2 \gg 1$[5]:

[3] It may be the right place to make a comment on the possible issue on the unstable force mediator. Naively, in this case the Yukawa potential obtained from one-Higgs boson exchange diagram will be modified as $e^{-m_h r}/(4\pi r) \to e^{-(m_h + i\Gamma_h/2)r}/(4\pi r)$ with Γ_h the Higgs boson width, around 4 MeV in SM. It is much smaller than the Higgs boson mass and thus is of no numerical importance. In other words, as long as the force mediator is sufficiently long-lived compared to the bound state forming time scale, we can treat it as a stable particle.

[4] In the context of bound state, some authors investigated this but just for exploring the possibility [12].

[5] The decay width can be also simply obtained via the $B_h - h$ mixing discussed below.