Comment on the evidence of the Higgs boson at LHC

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Abstract

We comment on the Standard Model Higgs boson evidence from LHC. We propose that the new resonance at 125 GeV could be interpreted as a pseudoscalar meson with quantum number $J^{PC} = 0^{-+}$. We show that this pseudoscalar could mimic the decays of the Standard Model Higgs boson in all channels with the exception of the decay into two leptons that is strongly suppressed due to charge-conjugation invariance.

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Recently the ATLAS \cite{1, 2} and CMS \cite{3, 4} experiments at the LHC reported an evidence of a new particle consistent with the Standard Model Higgs boson \cite{5–8} at a mass of $M_H \simeq 125$ GeV. In fact, the evidence of a new resonance was already present in the 2011 data and has been consistently confirmed in several decay channels by both the ATLAS and CMS experiments.

In order to check that the new resonance is, indeed, the Standard Model Higgs boson one may measure the rate for production of the Higgs boson in a given decay channel by introducing the relative signal strength $\mu$, defined by:

$$\mu = \frac{\text{signal rate from fit to data}}{\text{expected SM signal rate at given } M_H},$$

where SM denotes the Standard Model prediction.

The ATLAS \cite{2}, CMS \cite{4}, and TEVATRON \cite{9} experiments have presented values of the signal strength $\mu$ for various decay channels. In Fig. \ref{fig:1} we summarize the combined analyses of ATLAS and CMS results at 7 and 8 TeV with the Tevatron experiments data. It is worthwhile to stress that our combination must be intended as merely indicative, for the full combination of different experimental data is much more involved. Nevertheless, it is amusing that the emerging picture is quite consistent with various experimental analyses. In fact, the signal strength data roughly resemble what would be expected of a Standard Model Higgs boson despite the moderate enhancement in the diphoton channel and the deficit in $\tau^+\tau^-$ decay channel. We see, then, that the newly discovered particle is not inconsistent with the SM Higgs boson, but it also may be different from the SM Higgs boson. In fact, the true identity of any putative Higgs boson will remain ambiguous until one has experimentally excluded other possible assignments of quantum numbers and couplings. In particular, we believe that the lack of signal in the leptonic decay could require an alternative explanation for the new particle detected at the LHC.

The aim of the present note is to discuss a possible alternative to the generally assumed Higgs boson interpretation. Since up to now there is no signs of new physics, we looked for alternative explanations within the Standard Model physics. The absence of signal with respect to SM background in the leptonic decay channels suggests that the new resonance could be interpreted as a pseudoscalar meson with quantum number $J^{PC} = 0^{-+}$. Indeed, for a pseudoscalar meson the decay into two leptons is naturally suppressed due to charge-conjugation invariance. The most natural pseudoscalar candidate within the Standard Model
FIG. 1: Values of signal strength for individual decay modes. The ratio $\frac{\sigma}{\sigma_{SM}}$ denotes the production cross section times the relevant branching fractions relative to the Standard Model expectations. The data are based on the combination of the LHC [2, 4] and TEVATRON [9] data. The dashed line is the Standard Model value $\frac{\sigma}{\sigma_{SM}} = 1$.

is a $q\bar{q}$ bound state with $L=S=0$. Given the large mass of the new resonance we consider the pseudoscalar $t\bar{t}$ which, for obviously reasons, we will refer to as $\eta_t$. Since the top quark mass is very large:

$$m_t \approx 173 \text{ GeV},$$

(2)

to estimate the mass of the pseudoscalar meson $\eta_t$, we may safely employ the non-relativistic potential model. Quarkonium potential models typically take the form of a Schrödinger like equation:

$$[T + V] \Psi = m \Psi$$

(3)

where $T$ represents the kinetic energy term and $V$ the potential energy term. The quark - antiquark potential is typically motivated by the properties expected from QCD. At short distances one-gluon-exchange leads to the Coulomb like potential. At large dis-
tances the one-gluon-exchange is no longer a good representation of the quark-antiquark potential. The qualitative picture is that the chromoelectric lines of force bunch together into a flux tube which leads to a distance independent force or linearly rising confining potential. To be definite we will use the so-called Cornell potential \[ V_C = -\frac{4}{3} \alpha_s \frac{\sigma}{r} + \sigma r, \alpha_s \simeq 0.40, \sigma \simeq 0.18 \text{ GeV}^2. \] (4)

We are interested in a qualitative estimate of the low-lying \( L=S=0 \) bound state. Since the contribution of the linearly rising confining potential can be safely neglected due to the very large top mass, we obtain at once the wave function of the low-lying \( L=S=0 \) bound state:

\[ \Psi_{00}(r) \simeq \frac{1}{(\pi a_0^3)^{\frac{3}{2}}} \exp\left(-\frac{r}{a_0}\right), \] (5)

where \( a_0 \) is the Bohr radius:

\[ a_0 = \frac{3}{2} \frac{m_t}{\alpha_s}. \] (6)

We may, then, estimate the pseudoscalar mass as follows:

\[ m_{\eta_t} \simeq 2 m_t - \frac{4}{3} \frac{\alpha_s}{a_0} \simeq 321 \text{ GeV}. \] (7)

Even though our analysis has been somewhat qualitative, it is evident that the pseudoscalar \( \eta_t \) meson is too heavy to be identified with the new LHC resonance. To overcome this problem we must admit that the \( \eta_t \) meson can have sizable mixing with a much more lighter pseudoscalar meson. During the completion of the present note, we were aware of Ref. [11] were it is suggested that the new resonance could originate from a sizable mixing between the pseudoscalar \( t\bar{t} \) meson (\( \eta_t \)) and the pseudoscalar \( b\bar{b} \) meson (\( \eta_b \)). It should be stressed that for \( q\bar{q} \) pseudoscalar states it is believed [12] that the mixing is expected to proceed via the annihilation into two gluons which form a color singlet. However, this annihilation amplitude is strongly suppressed by the large top mass. In fact, the experimental observation of the pseudoscalar \( \eta_b \) meson at the mass \( m_{\eta_b} = 9391.0 \pm 2.89 \text{ MeV} \) [13] implies that the \( \eta_b - \eta_t \) mixing (if any) is completely negligible. On the other hand, the self-coupling of gluons in QCD suggests that additional mesons made of bound gluons (glueballs) may exist. In fact, lattice calculations, flux tube and constituent glue models agree that the lights glueballs have quantum number \( J^{PC} = 0^{++}, 2^{++} \) (for a recent review see Refs. [14, 15]). Moreover, there is a general agreements on the existence of pseudoscalar states with \( J^{PC} = 0^{-+} \) above 2 GeV. In the following we will indicate the lowest glueball pseudoscalar state with \( \eta_g \) and
follow the lattice calculations for the mass of the lowest pseudoscalar glueball to set the value \[15\]:

\[ m_{\eta_g} \simeq 2.6 \text{ GeV} . \]  

We see, then, that the pseudoscalar \( \eta_t \) meson can also mix with the pseudoscalar \( \eta_g \) meson through color singlet gluon intermediate states. In this case there are no reasons to restrict the intermediate states to two gluons. In fact, if more gluons are involved then one gets large effective couplings due to the small typical momentum going into each one making the theory strongly coupled \[16\]. If this is the case, then the large top mass gives rise to a sizable mixing amplitude. We shall proceed as in Ref. \[12\] for the mesons \( \eta \) and \( \eta' \). In fact, if we assume that the annihilation process contribute the flavor independent amount \( A \), we obtain the following mass matrix:

\[
\mathcal{M} = \begin{pmatrix} m_{\eta_g} + A & A \\ A & m_{\eta_t} + A \end{pmatrix} .
\]  

The mass matrix can be easily diagonalized by writing the physical mass eigenstates as:

\[
\eta_{gt} = \eta_g \cos \theta - \eta_t \sin \theta
\]

\[
\eta'_{gt} = \eta_g \sin \theta + \eta_t \cos \theta
\]

where \( \theta \) is the mixing angle. Inverting Eq. (10) leads to:

\[
\eta_g = \eta_{gt} \cos \theta + \eta'_{gt} \sin \theta
\]

\[
\eta_t = \eta'_{gt} \cos \theta - \eta_{gt} \sin \theta
\]

We denote with \( \eta_{gt} \) the state with lowest mass eigenvalue. Moreover we impose that:

\[
m_{\eta_{gt}} \simeq 125 \text{ GeV} .
\]  

A standard calculation gives:

\[
m_{\eta'_{gt}} \simeq 850 \text{ GeV} , \quad \theta \simeq 19^\circ .
\]

Since the mass eigenstate \( \eta'_{gt} \) lies well above the \( t \bar{t} \) threshold, it hardly can be detected as a hadronic resonance. On the other hand, the eigenstate \( \eta_{gt} \) could be a serious candidate
for the new resonance detected at LHC. To check this, we need to estimate the total width and the decay channels of the pseudoscalar meson $\eta_{gt}$. Obviously, the main channels are given by the decay of $\eta_{gt}$ into ordinary hadrons, which are suppressed by the OZI rule. To estimate the contribution of the $\eta_t$ component to the decay width we may use well known heavy quarkonium model \[17\]:

$$\Gamma[\eta_t \rightarrow \text{hadrons}] \simeq \Gamma[\eta_t \rightarrow gg] \simeq \frac{32\pi \alpha_s^2(m_{\eta_t})}{3 m_{\eta_t}^2} |\Psi_{00}(0)|^2,$$

where $\Psi_{00}$ is given by Eq. (5). Note that the decay into hadrons is proportional to $\alpha_s^2$ since by charge conjugation conservation $\eta_t$ can decay into two gluons. Since the hadronic decay width depends on the wave function, we see that the glueball contributions can be safely neglected. This is consistent with the general expectation that glueball should be narrower than $q\bar{q}$ mesons. Thus we obtain:

$$\Gamma[\eta_{gt} \rightarrow \eta_t \rightarrow \text{hadrons}] \simeq \Gamma[\eta_t \rightarrow gg] \sin^2 \theta .$$

(15)

As concern the coupling of the pseudoscalar meson $\eta_{gt}$ to the gauge vector bosons, we note that the glueballs are made of electrically neutral gluons, so that naively we expect suppressed couplings to the gauge vector bosons. Thus we may neglect the glueball contributions to the $\eta_{gt}$ decay. We shall return on this subject later on. The most sizable decay should be the decay into two photons. Accordingly we get:

$$\Gamma[\eta_{gt} \rightarrow \eta_t \rightarrow \gamma\gamma] \simeq \Gamma[\eta_t \rightarrow \gamma\gamma] \sin^2 \theta ,$$

(16)

where \[17\]:

$$\Gamma[\eta_t \rightarrow \gamma\gamma] \simeq \frac{256 \pi}{27} \frac{\alpha^2(m_{\eta_t})}{m_{\eta_t}^2} |\Psi_{00}(0)|^2 .$$

(17)

Assuming:

$$\alpha_s(m_{\eta_t}) \simeq 0.10 \quad \alpha(m_{\eta_t}) \simeq \frac{1}{127} ,$$

(18)

we get:

$$\Gamma[\eta_{gt} \rightarrow \eta_t \rightarrow \text{hadrons}] \simeq 11 \text{ MeV} ,$$

(19)

$$\Gamma[\eta_{gt} \rightarrow \eta_t \rightarrow \gamma\gamma] \simeq 60 \text{ KeV} .$$

(20)

Up to now we have neglected the glueball component of the pseudoscalar meson $\eta_{gt}$ on the basis that glueballs should be narrower than ordinary $q\bar{q}$ mesons. This general rule has an exception for the $\gamma\gamma$ coupling. In fact, it is known since long time that glueballs may have
\( \gamma \gamma \) couplings as large as \( q \bar{q} \) mesons [18]. This remarkable property follows from the trace and chiral anomalies. Indeed, from low energy theorems one obtains for the \( \gamma \gamma \) widths of the lightest pseudoscalar glueball [18]:

\[
\Gamma[\eta_g \to \gamma \gamma] \simeq \frac{\alpha^2}{24 \pi^3} \frac{m_{\eta_g}^3}{f_{\eta_g}^2},
\]

(21)

where \( f_{\eta_g} \) is the analogous of the pion decay constant \( f_\pi \) [19]. Accordingly, we may write:

\[
\Gamma[\eta_{gt} \to \eta_g \to \gamma \gamma] \simeq \Gamma[\eta_g \to \gamma \gamma] \cos^2 \theta.
\]

(22)

To estimate the contribution to the \( \gamma \gamma \) decay width of the glueball component of the pseudoscalar meson \( \eta_{gt} \), we assume \( f_{\eta_g} \simeq f_\pi \). Thus, from Eqs. (21) and (22) we get:

\[
\Gamma[\eta_{gt} \to \gamma \gamma] \simeq 110 \text{ KeV}.
\]

(23)

Equation (23) confirms that, indeed, the glueball component of the pseudoscalar meson \( \eta_{gt} \) gives a contribute to the \( \gamma \gamma \) decay width of the same order as the \( t \bar{t} \) component, Eq. (20).

To summarize, the main decay channels of our pseudoscalar meson are determined by the heavy quarkonium component with the exception of the \( \gamma \gamma \) decay where there is a sizable contribution from the glueball component. Note that this jeopardizes the recent phenomenological analysis presented in Ref. [20]. We see, then, that this peculiar pseudoscalar could mimic the decays of the Standard Model Higgs boson in all channels with the exception of the decay into two leptons that turns out to be naturally suppressed. Indeed, the decays of the pseudoscalar meson \( \eta_{gt} \) into charged leptons proceeds mainly through two virtual photons by charge conjugation conservation. Thus, as an order of magnitude estimate, we obtain:

\[
\frac{\Gamma[\eta_{gt} \to \ell^+ \ell^-]}{\Gamma[\eta_{gt} \to \gamma \gamma]} \sim \alpha^2 \sim 10^{-4}.
\]

(24)

In conclusion we are suggesting that to identify the new LHC resonance with the Standard Model Higgs boson it is of fundamental importance to determine experimentally both the spin and the parity. Fortunately, angular analysis based with analytical likelihood can separate pseudoscalar-scalar hypotheses at a 3\( \sigma \) level with about 30 fb\(^{-1} \) [21]. So that the forthcoming data from LHC will be enough to fix the spin and parity of the new resonance. If the new state at 125 GeV should turn out to be a pseudoscalar, then one faces with the problem of the spontaneous symmetry breaking mechanism and the related scalar Higgs.
boson. In a recent paper \[22\] the scenario is discussed where the Higgs boson without self-interaction (Trivial Higgs) could coexist with spontaneous symmetry breaking. Due to the peculiar rescaling of the Higgs condensate, the relation between Higgs mass $m_H$ and the physical Higgs condensate $v_R$ is not the same as in perturbation theory. According to this picture one expects that the ratio $m_H/v_R$ would be a cutoff-independent constant. In fact, the lattice studies \[22\] showed that the extrapolation to the continuum limit leads to the quite simple result:

$$m_H \simeq \pi v_R \quad (25)$$

pointing to a rather massive Trivial Higgs boson $m_H \simeq 750$ GeV.

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