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# Ultraheavy Yukawa-bound states of fourth-generation at Large Hadron Collider

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**Abstract.** A study of bound states of the fourth-generation quarks in the range of 500–700 GeV is presented, where the binding energies are expected to be mainly of Yukawa origin, with QCD subdominant. Near degeneracy of their masses exhibits a new 'isospin'. The production of a colour-octet, isosinglet vector meson via $q\bar{q} \rightarrow \omega_8$ is the most interesting. Its leading decay modes are $\pi_8^{\pm}W^{\mp}$, $\pi_8^0 Z^0$, and constituent quark decay, with $q\bar{q}$ and $t\bar{t}'$ and $b\bar{b}'$ subdominant. The colour octet, isovector pseudoscalar $\pi_8$ meson decays via constituent quark decay, or to $Wg$. This work calls for more detailed study of fourth-generation phenomena at LHC.

**Keywords.** Fourth-generation; Yukawa-bound states; Large Hadron Collider phenomenology.

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## 1. Introduction

The fourth-generation (4G), if exists, can play a crucial role in electroweak symmetry breaking [1] and baryon asymmetry of the Universe [2] due to their strong Yukawa couplings. Current experimental bounds on their masses are rather close to the unitarity bound (UB) of 500–550 GeV [3], beyond which we enter strong-coupling regime [4] rendering perturbative approach inadequate. We present our study of early LHC phenomenology for possible bound states of 4G quarks by strong Yukawa couplings [5] in the range 500–700 GeV.

The electroweak precision tests require $t'$ and $b'$ to be nearly degenerate, which institutes a new 'isospin'. This enables one to classify meson-like $Q\bar{Q}$ states: borrowing the QCD nomenclature we have ultraheavy isovectors $\pi$, $\rho$ and isoscalars $\eta$, $\omega$ in colour-singlet and octet modes.

Examining the existing studies from relativistic expansion [6] and relativistic Bethe-Salpeter approach [7], we identify $\omega_8$, isosinglet, colour-octet state to be most interesting for the early stage of LHC phenomenology. This is in clear contrast with the widely studied technicolour models where $\rho$-like state is usually the main signal.

## 2. Phenomenology of $\omega_8$

To be consistent with the electroweak precision, Higgs must be heavier than 600 GeV. QCD is subdominant at this scale. This leaves Nambu–Goldstone potential to be dominant. Relativistic expansion and Bethe-Salpeter treatments show that the tightest bound state is $\pi_1$ followed by isoscalar vector meson $\omega_1$. Their colour-octet counter parts $\pi_8$ and $\omega_8$ are the next lightest states. On the other hand, this potential is repulsive for $\eta_{1,8}$ and $\rho_{1,8}$ making them most likely unbound. As far as LHC is concerned, the production of colour-octet modes are more efficient due to strong interactions. The lightest two isovector states $\pi_{1,8}$ must be produced in pairs, while $\omega_1$ is produced weakly. This leaves the colour-octet isosinglet vector boson $\omega_8$ to be phenomenologically the most interesting at least for the earlier stage of LHC. Production cross-section is estimated using the decay constant $\xi \equiv f_{\omega_8}/m_{\omega_8}$ and shown in figure 1 along with open production of $Q\bar{Q}$ pair at LO and NLO. We see that the bound state production can be at the same order as open production, even dominant at least for 7 TeV. There are three types of decay channels: (i) annihilation decay: $\omega_8 \to q\bar{q}$, $t\bar{t}$; $t\bar{t}'$, $b\bar{b}'$, (ii) free-quark decay: $\omega_8 \to bW\bar{t}'$, $tW\bar{b}'$; (iii) meson transition: $\omega_8 \to \omega_1 g$; $\pi_8 W$. We choose the following parameters for our numerical study: the decay constant $\xi = f_{\omega_8}/m_{\omega_8}$ of $\omega_8$, $\omega_8$ and $\pi_8$ mass difference $\Delta m$ which signifies strong Yukawa binding, the third- and fourth-generation mixing $V_{t'b}$. We show the decay rates for four different cases: $\{\xi, \Delta m, V_{t'b}\} = \{(0.1, 100\,\text{GeV}, 0.1), (0.03, 100\,\text{GeV}, 0.1), (0.1, 200\,\text{GeV}, 0.1), (0.1, 100\,\text{GeV}, 0.01)\}$. We plot various decay rates for Cases 1 to 4 in figure 2.

For Case 1, the dominant decay modes are the transition decay into $\pi_8 W$, especially for lighter mass region, and free quark decay. The branching ratios of free quark decay and the $V_{t'b}$-dependent annihilation ($W$ boson exchange) decay increase with $m_{\omega_8}$, due to larger Yukawa coupling. The $q\bar{q}$ is of the order of 10% and drops slightly at higher $m_{\omega_8}$, with $t\bar{t}$ branching ratio a factor of 5 lower, at the percent level. The transition decay into $\omega_1 g$ is at the percent level or less.

For Case 2, because of the small decay constant, the annihilation decay channels $t\bar{t}'$, $b\bar{b}'$, $q\bar{q}$ and $t\bar{t}$ are suppressed. In this case, free quark decay and transition decay into $\pi_8 W$ are the two predominant modes.

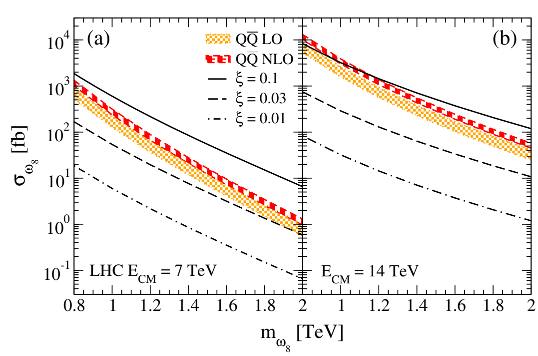


**Figure 1.** Production cross-section of $\omega_8$ at the LHC running at (**a**) 7 TeV and (**b**) 14 TeV for various $\xi = f_{\omega_8}/m_{\omega_8}$ values.

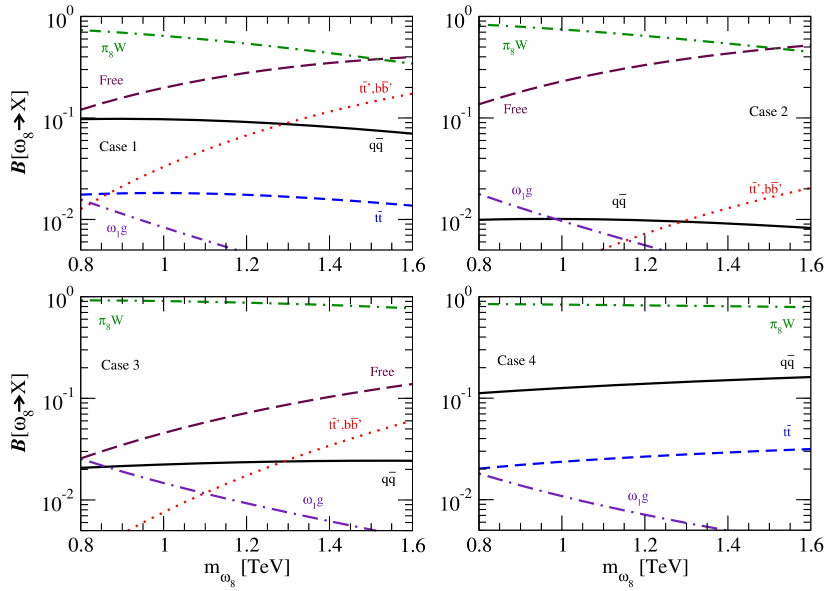


**Figure 2.** Branching ratio of $\omega_8$ as a function of $m_{\omega_8}$ for Cases 1–4.

For Case 3, the large mass differences enhance the branching ratio of the transition decays, and the $\pi_8 W$ mode dominates. The other transition decay into $\omega_1 g$ can also be enhanced, especially in the lighter mass region.

For Case 4, the free quark decay and the $V_{t'b}$-induced annihilation decay are suppressed, due to small $V_{t'b}$. The decay width of 4G quarks is also suppressed for the same reason. In this case, the transition decay into $\pi_8 W$ dominates, and the annihilation decay into dijets can be subdominant with branching ratio at 10% order. If $\pi_8 W$ becomes kinematically suppressed, dijets would be dominant.

In summary, the transition decay into $\pi_8 W$ is large, because Yukawa coupling is large and there is no suppression effect by bound state deformation. This decay mode can be more enhanced if the mass difference is larger, but much suppressed for smaller value, especially if it is less than $M_{\mathrm{W}}$. Free quark decay has a sizable contribution for the heavier mass region, if $V_{t'b}$ is close to the current upper limit of 0.1.

We have estimated the width of $\omega_8$ and $\pi_8$ to be of the order of a few GeV which makes them narrow resonances. For detailed discussion of $\pi_8$ decay modes we refer readers to ref. [5].

## 3. Conclusion

We have presented our study [5] on possible ultraheavy bound states of 4G quarks formed due to strong Yukawa couplings in the range 500–700 GeV of heavy quark masses. If there are such bound states, while potentially interesting for LHC phenomenology, it will be also necessary to study their impact on the search of new generations. We show that, while being illustrative compared to the ongoing genuine non-perturbative lattice efforts [8], our study demonstrates the importance of possible Yukawa-bound states.

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