New Hadrons Formed by the Fourth SM Family and Iso-singlet Quarks

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Abstract

The properties of new heavy mesons containing new heavy quarks have been investigated. As an example, the fourth SM family quarks and weak iso-singlet quarks predicted by E$_6$ GUT are considered. Production of these hadrons at TeV energy lepton colliders have been analyzed.

1 Introduction

It is known that $t$ quark does not form meson and baryon states because of the high value of $m_t$ and full strength of $tbW$ vertex. On the other hand, there are strong reasons that the fourth Standard Model (SM) family should exist [1,2]. We expect that the masses of the fourth family quarks lie between 300 and 700 GeV with preferable value $m_4 = 4g_W^2 = 8m_W \approx 640$ GeV [3]. New heavy quarks are also predicted by various extensions of SM and the most wide-known examples are weak iso-singlet quarks predicted by E$_6$ GUT [4], which is favored by super string theory [5]. In spite of the fact that the masses of new quarks are larger than $m_t$, they can form hadrons because of the smallness of mixing between new heavy and ordinary quarks. Indeed, according to the parametrization of mass matrices given in [6], mixing between the fourth and third family quarks is predicted to be $|V_{qt4}| \approx 10^{-3}$. Similar situation is expected for iso-singlet quarks. The condition for forming new hadrons states is [7]
\[ m_Q \leq (100\,\text{GeV}) |V_{Qq}|^{-2/3}. \]  

New quarks will be copiously produced at the LHC. The observation of
the fourth SM family quarks in ATLAS has been considered in \cite{8, 9}. In
this paper, we discuss the properties of new heavy mesons formed by new
quarks. In section 2, the properties and the systematics of new hadrons
have been investigated. Production of these hadrons at TeV energy lepton
colliders have been considered in section 3. Finally, we give some concluding
remarks.

2 New Heavy Mesons

According to the Eq. (1), fourth SM family and \( E_6 \) isosinglet quarks have
formed hadron states if their mixing with known quarks is sufficiently small.
In the case of fourth family quarks, parametrization given in \cite{6} satisfies this
condition, whereas new hadrons are not formed in the case of parametriza-
tion given in \cite{1}. Concerning \( E_6 \) isosinglet quarks, we do not have similar
parametrization (in this case one deals with \( 6 \times 6 \) mass matrix) and one
can make only qualitative estimations. For example, if the lightest isosin-
glet quark has the mass \( m_D \approx 0.5 \) TeV, new heavy hadrons are formed for
\( |V_{qD}| < 0.09 \).

In order to calculate the masses of new mesons we use the logarithmic
potential

\[ V(r) = A\log(r) + V_0, \]  

where \( r \) is the radial distance between quarks. For two particles system,
Schrodinger equation has the form \( (\hbar = c = 1) \)

\[ \left[ \frac{p^2}{2\mu} + V(r) \right] \Psi(r) = E \Psi(r), \]  

where \( \mu = m_1 m_2 / (m_1 + m_2) \). One can find the binding energy of meson for
arbitrary \( n, l \) states as

\[ E_{nl} \approx V_0 + A\eta_{nl}, \]  

where \( \eta_{nl} \) is solution of the equation

\[ \left[ -\frac{d^2}{dr^2} + \log(r) + \frac{l(l + 1)}{r^2} \right] g(r) = \eta g(r). \]  

Below, instead of numerical calculations, we use simplified analytical proce-
dure (for details see \cite{10}) to solve Eq. (5), which gives the results coinciding
with numerical ones with precision of order \( 10^{-3} \). Thus the bound state
mass of the \( q_i\overline{q}_j \) system is
\[ M(q_{i} \bar{q}_{j})_{nl} = m_{q_{i}} + m_{q_{j}} + V_{0} + A_{nl} \]  

(6)

The calculations involve the potential parameters of the model \((A, V_{0})\) and the quark masses \((m_{u} = m_{d}, m_{s}, m_{c}, m_{b})\). The potential parameters and the quark masses are obtained from the experimental masses of \(\Psi(1S), \Psi(2S), \Upsilon(1S), \Upsilon(2S), D^{0}(1S)\) and \(s\sigma(1S)\) by fitting Eq. (6): \((A, V_{0}) = (0.7328 \text{ GeV}, -0.8684 \text{ GeV}), m_{u} = m_{d} = 0.367 \text{ GeV}, m_{s} = 0.561 \text{ GeV}, m_{c} = 1.6 \text{ GeV}, m_{b} = 4.7816 \text{ GeV}.\) In addition to these parameters, the fourth SM family up-quark and \(E_{6}\) isosinglet quark masses are chosen as 638.6 GeV [6] and 0.5 TeV, respectively. With these parameters, we calculate the masses of bound states of \(c\sigma\) and \(b\bar{b}\), which are given in Table 1. It is seen that our results are in good agreement with experimental data [11] (for comparison see [12, 13]).

In Table 2 we present the masses of quarkonia and mesons formed by the fourth SM family up-quark and \(E_{6}\) isosinglet quark, respectively. It is seen that the decay of \(3S\) quarkonia states into mesons containing \(u\) and \(d\) quarks is admitted. In the case of \(4S\) quarkonia decays into mesons containing \(s\) quark is added. In our opinion, the best mechanism for the production of heavy mesons formed by \(u_{4}\) and \(D\) quarks is the resonance formation of \(3S\) and \(4S\) quarkonia at lepton colliders with subsequent decay into corresponding meson-antimeson states.

### 3 Production of New Mesons at Future Lepton Colliders

The spin averaged Breit-Wigner cross section for a spin-\(J\) resonance produced in the collision of the particles of spin \(S_{1}\) and \(S_{2}\) [11] is

\[ \sigma_{BW}(E) = \frac{2J + 1}{(2S_{1} + 1)(2S_{2} + 1)} \frac{4\pi}{k^{2}} \frac{B_{in}B_{out} \Gamma_{tot}^{2}}{4(E - R_{R})^{2} + \Gamma_{tot}^{2}} \]  

(7)

where \(k\) is the c.m. momentum, \(E\) is the c.m. energy, and \(B_{in}\) and \(B_{out}\) are the branching fractions of the resonance into the entrance and exit channels. In our case, at \(E = E_{R}\) Eq. (7) takes the form

\[ \sigma^{res} = \frac{12\pi}{M^{2}} B_{in} B_{out} \]  

(8)

where \(M\) is the mass of corresponding quarkonium.

Since lepton colliders have the certain energy spread, the average cross section at \(\sqrt{s} \approx M\) can be estimated from

\[ \sigma^{ave} \approx \frac{\Gamma_{tot}}{\Delta E_{coll}} \sigma^{res}. \]  

(9)
Here, we take into account that $\Gamma_{\text{tot}} \ll \Delta E_{\text{coll}}$. Indeed, $\Delta E_{\text{coll}} = O(1 \text{ GeV})$ for muon collider [14] and $\Delta E_{\text{coll}} = O(10 \text{ GeV})$ for CLIC [15]. Concerning $\Gamma_{\text{tot}}$, we use Coulomb potential in order to estimate partial decay widths to $e^+e^-$ and $W^+W^-$ (which is dominant one among the decays into fundamental SM particles [16, 17]) taking into account that distance between quarks and antiquarks is much less than $1 \text{ fm}$ due to large value of new quarks masses. Results are presented in Table 3. Then, decay width of 3S levels into meson-antimeson states is expected to be $O(100 \text{ MeV})$. Multiplying average cross-sections with integrated luminosity, which are $50 \text{ fb}^{-1}$ per year for muon collider [14] and $200 \text{ fb}^{-1}$ per year for CLIC [15], one can easily obtain numbers of new mesons produced via formation and decays of 3S resonance per working year, namely, $\sim 1000$ at muon collider and $\sim 400$ at CLIC for mesons containing $u_4$ and first family quarks. Corresponding numbers for mesons formed by $D$ and first family quarks are $\sim 340$ and $\sim 140$, respectively.

If these new mesons are sufficiently long-lived (which means very small mixing of heavy quarks with light quarks [18,19]) we will observe corresponding traces in the detector. The decay length is given by $\beta\gamma c\tau$. In our case, $\gamma \approx 1$ and $\beta \approx 6 \cdot 10^{-4}$. For mesons containing $u_4$ quarks (here we assume the dominance of mixing between fourth and third SM families and take into account that $m_{u_4} \gg m_{W,Z}$) we have

$$\tau \approx \frac{8x_W}{\alpha_{em}|V_{u_4b}|^2} \times \frac{m_W^2}{m_{u_4}^3}$$  \hspace{1cm} (10)$$

where $x_W = \sin^2 \theta_W \approx 0.21$. Therefore, $l = 6 \cdot 10^{-2} \text{ m}/|V_{u_4b}|^2$ and taking into account present experimental resolution $\sim 100 \mu\text{m}$ we conclude that $|V_{u_4b}|$ should be less than $2.5 \cdot 10^{-9}$. Similar consideration for meson containing $D$ quarks leads to $\sin \phi = |V_{Du}| < 1.5 \cdot 10^{-9}$ (here we assume the dominance of $D - d$ mixing and taking account flavor changing interactions [5,20]). In our opinion, this scenario is hardly to be realized.

Let us finish this section with some remarks on mesons containing $D$ quark. As mentioned above, in this case, flavor changing neutral current appear at tree level and for $m_D - m_W \approx m_D - m_Z \gg m_Z - m_W$ one has $Br(D \to u + W) \approx 0.6$ and $Br(D \to u + Z) \approx 0.4$ [20]. Therefore, we expect $Br(D \to jet + l^+l^-) \approx 0.012$ and $Br(D \to jet + \nu\bar{\nu}) \approx 0.072$ for decay modes which differ isosinglet quark from the fourth SM family quarks. For a most spectacular cases, namely one of the mesons decays into jet and $l^+l^-$ pairs ($l = e, \mu$) or jet and $\nu\bar{\nu}$ pairs and the other one decays into three jets we expect $\sim 60$ events per working year at muon collider and $\sim 20$ events at CLIC.
4 Conclusion

We show that mesons formed by new heavy quarks can be observed at future lepton colliders due to formation (and corresponding decay) of heavy quarkonia. The numbers of events are not huge (hundreds events comparing to tens thousands $QQ$ pairs which will be produced at LHC [8, 9]). However, pure experimental environment provide an advantage for clarifying the properties of new hadrons.

5 References

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Table 1. The masses of the $c\bar{c}$ and $b\bar{b}$ bound states (in MeV).

| Level | $c\bar{c}$ calculated | $c\bar{c}$ experiment [11] | $b\bar{b}$ calculated | $b\bar{b}$ experiment [11] |
|-------|------------------------|-----------------------------|------------------------|-----------------------------|
| 1S    | 3097                   | 3096.87±0.04                | 9461                   | 9460.30±0.26                |
| 2S    | 3686                   | 3685.96±0.09                | 10050                  | 10023.26±0.31               |
| 3S    | 4010                   | 4040±10                     | 10374                  | 10355.2±0.5                 |
| 4S    | 4234                   | 4159±20                     | 10598                  | 10580.0±3.5                 |
| 5S    | 4405                   | 4415±9                      | 10769                  | 10865±8                     |
| 1P    | 3523                   | 3510.5±0.12                 | 9898                   | 9892.7±0.6                  |
| 2P    | 3888                   | -                           | 10272                  | 10268.5±0.4                 |

Table 2. The masses of the bound states formed by the fourth SM family $u_4$ and isosinglet $D$ quarks (in GeV).

| Level | $u_4\bar{u}_4$ | $u_4\bar{u}$ | $u_4\bar{c}$ | $DD$ | $D\bar{D}$ | $D\bar{c}$ | $D\bar{c}$ |
|-------|----------------|--------------|--------------|------|------------|------------|------------|
| 1S    | 1277.10        | 638.86       | 639.06       | 999.90 | 500.26     | 500.46     |
| 2S    | 1277.69        | 639.45       | 639.65       | 1000.49 | 500.85     | 501.05     |
| 3S    | 1278.01        | 639.78       | 639.97       | 1000.81 | 501.18     | 501.37     |
| 4S    | 1278.23        | 640.00       | 640.20       | 1001.03 | 501.40     | 501.60     |

Table 3. Partial decay widths of heavy quarkonia to $e^-e^+$ (in keV) and $W^-W^+$ (in MeV). 1 and 2 correspond to $u_4\bar{u}_4$ and $D\bar{D}$, respectively.

| Level | Mass(1) | $\Gamma_{e^+e^-}(1)$ | $\Gamma_{W^-W^+}(1)$ | Mass(2) | $\Gamma_{e^+e^-}(2)$ | $\Gamma_{W^-W^+}(2)$ |
|-------|---------|-----------------------|-----------------------|---------|-----------------------|-----------------------|
| 1S    | 1277.10 | 35                    | 400                   | 999.90  | 6.6                   | 142                   |
| 2S    | 1277.69 | 4.4                   | 50                    | 1000.49 | 0.8                   | 18                    |
| 3S    | 1278.01 | 1.3                   | 15                    | 1000.81 | 0.24                  | 5                     |
| 4S    | 1278.23 | 0.5                   | 6.2                   | 1001.03 | 0.1                   | 2.2                   |