New Bound States of Top and Beauty Quarks at the Tevatron and LHC

C.R. Das 1 *, C.D. Froggatt 2 †, L.V. Laperashvili 3 ‡ and H.B. Nielsen 4 §

1 Centre for Theoretical Particle Physics, Technical University of Lisbon, Lisbon, Portugal
2 Department of Physics and Astronomy, Glasgow University, Glasgow, Scotland
3 Institute of Theoretical and Experimental Physics, Moscow, Russia
4 The Niels Bohr Institute, Copenhagen, Denmark

Abstract

The present paper is based on the assumption that heavy quarks bound states exist in the Standard Model (SM). Considering New Bound States (NBS) of top-anti-top quarks (named T-balls) we have shown that: 1) there exists the scalar 1S-bound state of 6t + 6t; 2) the forces which bind the top-quarks are very strong and almost completely compensate the mass of the twelve top-anti-top-quarks in the scalar NBS; 3) such strong forces are produced by the Higgs-top-quarks interaction with a large value of the top-quark Yukawa coupling constant $g_t \simeq 1$. Theory also predicts the existence of the NBS 6t + 5t, which is a color triplet and a fermion similar to the $t'$-quark of the fourth generation. We have also considered the “b-quark-replaced” NBS. We have estimated the masses of the lightest fermionic NBS: $M_{NBS} \gtrsim 300$ GeV, and discussed the larger masses of T-balls. Searching for heavy quarks bound states at the Tevatron and LHC is discussed.

*crdas@cftp.ist.utl.pt
†c.froggatt@physics.gla.ac.uk
‡laper@itep.ru
§hbech@nbi.dk
1 Introduction

Although the Standard Model (SM) was confirmed by all experiments of the world accelerators, the mechanism of the Electroweak (EW) symmetry breaking (EWSB) has not yet been tested. According to the SM, the Higgs boson is responsible for generating the masses of fermions due to the Higgs mechanism. However, the mass of the Higgs boson is not predicted by theory.

Direct searches in the previous experiments (mainly at LEP2 [1]) set a lowest limit for the Higgs boson mass $M_H$:

$$M_H \gtrsim 114.4 \text{ GeV at } 95\% \text{ CL}. \quad (1)$$

The recent Tevatron result [2] is:

$$115 \lesssim M_H \lesssim 160 \text{ GeV.} \quad (2)$$

We hope that LHC will provide a solution of main puzzles of EWSB.

The Higgs boson couples more strongly to the heavy top quarks than to the light ones. As a result, the Higgs exchanges between top quarks produce new type of bound states [3–15].

The present paper is devoted to the properties of the new bound states (NBS): estimates of their masses and observation at modern colliders (Tevatron, LHC, etc.). The predictions of Refs. [3–12] are:

- There exists a scalar $1S$–bound state of $6t + 6ar{t}$. The forces which bind these top-quarks are so strong that almost completely compensate the mass of the 12 top-quarks forming this bound state.
- There exists a new bound state $6t + 5ar{t}$, which is a fermion similar to the quark of the fourth generation having quantum numbers of top quark.
- Theory also predicts the existence of new bound states with b-quark replaced the t-quark: for example, NBS $n_b b + (6t + 6ar{t} - n_t t)$, etc., where $n_b = 1,...6$.

A new (earlier unknown) bound state $6t + 6ar{t}$, which is a color singlet (that is, ‘white’ state), was first suggested by Froggatt and Nielsen in Ref. [4]. Now all these NBS are named T-balls, or T-fireballs.

2 Higgs and gluon interactions of quarks

If the Higgs particle exists, then between quarks $qq$, quarks and anti-quarks $qar{q}$, and also between anti-quarks $qar{q}$ there exist virtual exchanges by Higgs bosons (see Fig. 1), leading only to the attractive forces.

It is well-known that the bound state $tar{t}$ – so called toponium – is obliged to the gluon virtual exchanges of Fig. 2. Among a considerable quantity of articles devoted to the toponium, we distinguish the following backward papers [16–21].
Fig. 1:

(a)

(b)

(c)

Fig. 2:

(a)

(b)

(c)
In the case of the toponium the contributions of the Higgs scalar particles are essential, but less than gluon interactions. Toponium is very unstable due to the decay of the top quark itself. However, putting more and more top and anti-top quarks together in the lowest energy bound states, we notice that the attractive Higgs forces continue to increase. Simultaneously gluon (attractive and repulsive) forces first begin to compensate themselves, but then begin to decrease relatively to the Higgs effect with growth of the number of top-anti-top constituents in the NBS.

The maximum of the binding energy value corresponds to the $1S$-wave state of the NBS $6t + 6\bar{t}$. The explanation is simple: top-quark has two spin states and three states of colors: $2 \times 3 = 6$ degrees of freedom. This means that, according to the Pauli principle, only 6 pairs of $t\bar{t}$ can simultaneously exist in the ‘white’ $1S$-wave state. If we try to add more $t\bar{t}$-pairs, then some of them will turn out to the $2S$-wave state, and the NBS binding energy will decrease at least 4 times. For P-,D-, etc. wave states the NBS binding energy decreases more and more.

3 T-ball mass estimate.

The kinetic energy term of the Higgs field and the top-quark Yukawa interaction are given by the following Lagrangian density:

$$L = \frac{1}{2} D_\mu \Phi_H D^\mu \Phi_H + \frac{g_t}{\sqrt{2}} \bar{\psi}_t \psi_t \Phi_H + h.c.,$$

(3)

where $\Phi_H$ and $\psi_t$ are the Higgs and top-quark fields, respectively, and $g_t$ is the Yukawa coupling constant of their interaction.

The VEV of the Higgs field in the EW-vacuum is:

$$v = \langle |\Phi_H| \rangle = 246 \text{ GeV}.$$  

(4)

According to the Salam-Weinberg theory the top-quark mass $M_t$ and the Higgs mass $M_H$ are given by the following relations:

$$M_t = \frac{g_t}{\sqrt{2}} v \quad \text{and} \quad M_H^2 = \lambda v^2,$$  

(5)

where $\lambda$ is the Higgs self interaction coupling constant.

According to the Ref. [22], we have

$$M_t \approx 172.6 \text{ GeV},$$  

(6)

and

$$g_t \approx 0.93,$$  

(7)
Let us imagine now that the NBS is a bubble in the EW-vacuum and contains \( N_{\text{const.}} \) top-like constituents. It is known that insight the bubble (bag) the Higgs field can modify its VEV. Implications related with this phenomenon have been discussed in Refs. [5, 21, 23–27]. Then insight T-balls the VEV of the Higgs field is smaller than \( v \):

\[
v_0 = \langle |\Phi_h| \rangle, \quad \text{where} \quad \frac{v_0}{v} < 1,
\]

and the effective masses insight the bubble (bag) are smaller than the corresponding experimental masses:

\[
m_{t,h} = \frac{v_0}{v} M_{t,H}.
\]

In this case the attraction between the two top (or anti-top) quarks is presented by the Yukawa type of potential:

\[
V(r) = -\frac{g_t^2/2}{4\pi r} \exp(-m_h r).
\]

Assuming that the radius \( R_0 \) of the bubble is small:

\[
m_h R_0 << 1,
\]

we obtain the Coulomb-like potential:

\[
V(r) \simeq -\frac{g_t^2/2}{4\pi r}.
\]

The attraction between any pairs \( tt, t\bar{t}, \bar{t}\bar{t} \) is described by the same potential (12).

By analogy with Bohr Hydrogen-atom-like model, the binding energy of a single top-quark relatively to the nucleus containing \( Z = N_{\text{const.}} - 1 \) top-quarks have been estimated in Refs. [4–6]. The total potential energy for the NBS with \( N_{\text{const.}} = 12 \) is:

\[
V_{\text{tot}}(r) = -11 \frac{g_t^2/2}{4\pi r}.
\]

Here we would like to comment that the value of the mass \( m_h \), which belongs to the Higgs field insight the NBS \( 6t + 6\bar{t} \), can just coincide with estimates given by Refs. [13–15]. The results: \( \text{max}(m_h) = 29 \text{ Gev} \) and \( \text{max}(m_h) = 49 \text{ Gev} \) correspond to Ref. [13] and Ref. [15], respectively.

Considering a set of Feynman diagrams (the Bethe-Salpeter equation) and including the contributions of all \( (s-, t- \text{ and } u-) \) channels for the Higgs and gluon exchange forces (see Ref. [6]), we obtain the following Taylor expansion:

\[
M_T^2 = \left( N_{\text{const.}} M_t \right)^2 \times \left\{ 1 - 2(N_{\text{const.}} - 1) \left( \frac{N_{\text{const.}}}{12} \right)^2 \left( \frac{g_t^2 + \frac{1}{\pi^2} g_s^2}{\pi} \right)^2 + \ldots \right\}.
\]
Here the QCD coupling constant $g_s$ is given by its fine structure constant value at the EW-scale [22]:

$$\alpha_s(M_Z) = g_s^2(M_Z)/4\pi \approx 0.118.$$  (15)

Now the value of the total binding energy for arbitrary $N_{\text{const.}}$ is equal to:

$$E_T = N_{\text{const.}} (N_{\text{const.}} - 1) \left( \frac{N_{\text{const.}}}{12} \right)^2 \left( \frac{g_t^2 + \frac{1}{6}g_s^2}{\pi} \right)^2 m_t.$$  (16)

The mass of T-ball containing $N_{\text{const.}}$ top or anti-top quarks is:

$$M_T = N_{\text{const.}} m_t - E_T.$$  (17)

Approximately this dependence is described by the following expression:

$$M_T = N_{\text{const.}} m_t \left\{ 1 - (N_{\text{const.}} - 1) \left( \frac{N_{\text{const.}}}{12} \right)^2 \left( \frac{g_t^2 + \frac{1}{6}g_s^2}{\pi} \right)^2 \right\}.$$  (18)

Below we shall use the following notations: $T_s$-ball is a scalar NBS $6t + 6\overline{t}$, having the spin $S = 0$, and $T_f$-ball presents the NBS $6t + 5\overline{t}$, which is a fermion: $T_f = 5t + 6\overline{t}$.

Let us consider now the condition:

$$\frac{11}{\pi^2} \cdot (g_t^2 + \frac{1}{6}g_s^2)^2 = 1.$$  (19)

In this case the binding energy $E_T$ compensates the NBS mass $12m_t$ so strongly that the mass of the scalar $T_s$-ball becomes zero:

$$M_{T_s} = 11m_t \left\{ 1 - \frac{11}{\pi^2} \cdot (g_t^2 + \frac{1}{6}g_s^2)^2 \right\} = 0.$$  (20)

It is necessary to emphasize that the experimental values given by (7) and (15) [22]:

$$g_t^2 \simeq 0.86 \quad \text{and} \quad g_s^2 \simeq 1.48$$  (21)

are just very close to this limit.

Fig. 3 shows the dependence of T-ball masses on the number of NBS constituents $N_{\text{const.}}$. In the case when $M_{T_s} = 0$, we have:

$$M_T = N_{\text{const.}} m_t \left\{ 1 - \frac{(N_{\text{const.}} - 1) N_{\text{const.}}^2}{112} \right\}.$$  (22)

We easily see that the light scalar Higgs bosons with mass $m_h < M_H$ can bind the 12 top-like quarks so strongly that the mass $M_{T_s}$ becomes almost zero, and even tachyonic: $M_{T_s}^2 < 0$. In the last case we obtain the Bose-Einstein condensate of T-balls – a new vacuum at the EW-scale [11, 12]. Previously the condensation of $tt$, arising from four-fermion interaction models ( [28–30], etc.), was reviewed in Ref. [31]. We have suggested a new type of condensation of top-quarks via T-balls, what is very important for the solution of the hierarchy problem in the SM [9, 10].
Fig. 3: T-ball mass depending on the number $N_{\text{const.}}$ of the NBS constituents.
3.1 $T_f$-ball mass estimate

As we have discussed above, the Higgs interaction of the eleven top-anti-top quarks ($N_{\text{const.}} = 11$) creates a $T_f$-ball – a new fermionic bound state $6t + 5\bar{t}$, which is similar to the $t'$-quark of the fourth generation. The estimate of the mass of $T_f$-ball $6t + 5\bar{t}$ by Eq. (22) gives:

$$M_{T_f} \approx 11m_t \cdot 0.236 \gtrsim 300 \text{ GeV}. \tag{23}$$

We hope that the forthcoming numerical calculations of the T-ball masses by Monte-Carlo simulations on lattice will give us more exact answers.

4 New “b-replaced” bound states

Constructing T-balls from $t$- and $\bar{t}$-quarks, we also can take into account considerable contributions of left b-quarks insight NBS [3, 6, 11].

If we had no $b\bar{b}$-pairs in T-balls, then there would be an essential superposition of different states of the weak isospin. The presence of b-quarks in the NBS leads to the dominance of the isospin singlets of EW-interactions only. Now such a “b-replaced” scalar NBS would be stable. We predict the following scalar “b-replaced” NBS:

$$T_s(b - \text{replaced}) = b + 5t + 6\bar{t}, \tag{24}$$

$$T_s(\bar{b} - \text{replaced}) = 6t + \bar{b} + 5\bar{t}. \tag{25}$$

In general case we can construct the following scalar “b-replaced” T-balls:

$$T_s(nb - \text{replaced}) = n_b b + (6t + 6\bar{t} - n_b t), \tag{26}$$

and

$$T_s(n\bar{b} - \text{replaced}) = n_{\bar{b}} \bar{b} + (6t + 6\bar{t} - n_{\bar{b}} \bar{t}). \tag{27}$$

Of course, we also can construct the fermionic “b-replaced” NBS:

$$T_f(b - \text{replaced}) = b + 5t + 5\bar{t}, \tag{28}$$

and

$$\overline{T_f}(\bar{b} - \text{replaced}) = 5t + 5\bar{t} + \bar{b}. \tag{29}$$

In general case we obtain:

$$T_f(nb - \text{replaced}) = n_b b + (6t + 5\bar{t} - n_b t), \tag{30}$$

and

$$\overline{T_f}(n\bar{b} - \text{replaced}) = n_{\bar{b}} \bar{b} + (5t + 6\bar{t} - n_{\bar{b}} \bar{t}). \tag{31}$$

We have $n_b, n_{\bar{b}} = 1, ... 6$ in Eqs. (26)-(31).
There is a simple way to estimate the mass of the “b-replaced” T-ball with one t-quark replaced by a b-quark. It is well-known that b-quark does not interact significantly with NBS. Thus, we can add a b-quark (or anti-b-quark) to the NBS having eleven constituents without essential changing its energy, or mass. Then the b-replaced scalar NBS $T_s(b - \text{replaced})$, or $T_s(\bar{b} - \text{replaced})$, given by Eqs. (24) and (25), respectively, will have a mass $\lesssim 300$ GeV.

As to the NBS $T_f(b - \text{replaced}) = 5t + b + 5\bar{t}$ and $T_f(b - \text{replaced}, \bar{b}b) = 5t + b + n_b \bar{b}b + 5\bar{t}$, they will have a mass very close to the NBS with ten constituents, e.g. $M_{T_f} \simeq 500$ GeV (see Fig. 3).

We also can consider more heavy T-balls with $M_T > 500$ GeV, but they will have very small cross-sections of their production.

5 Can we observe T-balls at LHC or Tevatron?

If our NBS are strongly bound states with small radius, they can be observed at colliders (Tevatron, LHC, etc.) in the following processes:

1) First of all, in the possible H-decay process:

$$H \to 2T_s,$$

if $M_{T_s} < \frac{1}{2}M_H$. Using limits given by Tevatron experiments [2]: $115 \lesssim M_H \lesssim 160$ GeV, we obtain the requirement for the Higgs decay mechanism:

$$M_{T_s} \lesssim 80 \text{ GeV.}$$

Here we have argued that T-balls can explain why it is difficult to observe the Higgs boson H at colliders: T-balls can strongly enlarge the decay width of the Higgs particle.

2) If $M_{T_s} > \frac{1}{2}M_H$, then the first decay (32) is absent in Nature, and the $T_s$-balls fly away, forming jets which produce hadrons with a high multiplicity:

$$T_s \to \text{JETS.}$$

3) Second, we can observe at Tevatron all processes given by Fig. 4 with the replacement $t\bar{t} \to t'\bar{t'}$, $T_f\overline{T_f}$.

In the most optimistic cases the NBS $6t + 5\bar{t}$ (fermionic fireball) plays a role of the fundamental quark of the fourth generation, say, with the mass $M_{T_f} \gtrsim 300$ GeV, given by our preliminary estimate. We expect that the Tevatron-LHC experiments should find either a fourth family t'-quark, or the fermionic NBS $T_f$, or both of them.

The scalar NBS $T_s$ cannot be produced simply in a pair by a gluon vertex, because it is a color singlet 1. But a pair $T_f\overline{T_f}$ can be produced by a gluon, because $T_f$ is a color triplet 3.

At LHC the pairs of $T_s$-balls, or $T_f$-balls might be produced in $pp$ collisions via the two gluon diagram with strong vertices shown in Fig. 5 [3].

9
Fig. 4: A typical process observed at the Tevatron in $p\bar{p}$ collisions.
6 CDF II Detector experiment at the Tevatron

Recent experiments with CDF II Detector of the Tevatron [32,33] searching for heavy top-like quarks in $p\bar{p}$-collisions with $\sqrt{s} \simeq 1.96$ TeV do not exclude the existence of T-balls with masses $\geq 300$ GeV up to 500 GeV.

Here we can assume that the very strange events observed at the Tevatron as a fourth family $t'$, which decays into a $W$-boson and a presumed quark-jet, might find another explanation in our model: maybe it is a decay of T-balls into a $W$-boson and a gluon jet.

Tevatron experiments exclude a fourth-generation $t'$ quark with a mass below 300 GeV (see Refs. [32, 33]). Assuming that fourth generation $t'$-quarks does not exist in Nature, but only the pairs of fermionic NBS $T_f$ are produced at the Tevatron, we can give an explanation of the observed cross-sections shown in Fig. 6. The curve for the cross-section

$$\sigma(p\bar{p} \rightarrow t'\bar{t}') \simeq 0.1 \, pb$$

(35)

can correspond to the production of pairs of fermionic $T_f$-balls with mass $M_{T_f} \gtrsim 300$ GeV.

7 Estimate of the NBS form-factors in the Tevatron CDF-experiment

Assuming that the fourth-generation $t'$-quarks does not exist in Nature, but only the fermionic $T_f$-balls with mass $M_T > 300$ GeV are produced at the Tevatron in the CDF-
Fig. 6: Tevatron CDF-experiment given by Refs. [32, 33]: upper limit, at 95% CL, a fourth-generation \( t' \) quark with a mass below 300 GeV is excluded. Blue line presents a theoretical curve for the fourth-generation quarks cross-section.
Fig. 7: The form-factor $F(M_T)$ of the fermionic new bound state $T_f$ obtained from Tevatron CDF-experiment [32, 33] in absence of the four generation.

experiment [32, 33], we can imagine the existence of form-factors of the NBS $T_f$, which determine the cross-section of the production of the fermionic T-balls (see Fig. 6):

$$\sigma(p\bar{p} \rightarrow T_f T_f) = F^2(M_T)\sigma_{\text{theor}}(M_T). \quad (36)$$

Here $\sigma(p\bar{p} \rightarrow T_f T_f)$ is given by the observed red line curve of Fig. 6 and $\sigma_{\text{theor}}(M_T)$ is given by the theoretical (blue) curve obtained by Bonciani et al. [34, 35] for the point-like particle $t'$. Our numerical calculations of the form-factor shown in Fig. 7 gives the results in the region of $M_T$ from 311 GeV (where $F(M_T) = 1$) up to 500 GeV. We conclude that for $M_T = 500$ GeV the form-factor is large enough:

$$F(M_T) \approx 7.6. \quad (37)$$

8 Conclusions

At present, a lot of physicists, theorists and experimentalists, are looking forward to the New Physics. However, it is quite possible that LHC will discover only the Salam-
Weinberg Higgs boson and nothing more. Nevertheless, T-balls considered in the present paper could exist in the framework of the SM.

The present investigation is based on the assumption that there exist in Nature new bound states of top-like quarks, so called T-balls, or T-fireballs. First, we predict that there exists $1S$-bound state of $6t + 6\bar{t}$. The forces in the NBS can bind top-like quarks so strongly that they can almost completely compensate the mass of the 12 top-quarks in the scalar bound state. Such strong forces are produced by interactions of top-quarks via the virtual exchanges of the scalar Higgs bosons, when the top-quark Yukawa coupling constant is large: $g_t \simeq 1$.

Present theory also predicts the existence of the new bound state $6t + 5\bar{t}$, which is a color triplet and a fermion similar to the quark of the fourth generation.

We have also predicted the existence of the “b-replaced” NBS: $T_s(n_b b - \text{replaced}) = n_b b + (6t + 6\bar{t} - n_b t)$ and $T_f(n_b b - \text{replaced}) = n_b b + (6t + 5\bar{t} - n_b t)$, where $n_b, n_\bar{b} = 1, 2, ..., 6$.

The presence of b-quarks in the NBS leads to the dominance of the isospin singlets.

We have estimated masses of the lightest NBS and showed that the mass of the scalar T-balls $M_{T_s}$ can be zero, and even tachyonic: $M_{T_s}^2 < 0$, what leads to the condensation of T-balls and formation of a new vacuum at the EW-scale.

Also we have estimated masses of the fermionic T-balls predicted $M_{T_f} \gtrsim 300$ GeV.

It was shown that CDF II Detector experiments searching for heavy top-like quarks at the Tevatron in $p\bar{p}$-collisions with $\sqrt{s} \simeq 1.96$ GeV can observe fermionic $T_f$-balls up to 500 GeV.

We have considered the processes with T-balls, which can be observed at LHC, especially the decay $H \rightarrow 2T_s$ and the production of the pair $T_f\bar{T}_f$ combined with the production of fourth-generation quarks $t\bar{t}'$-pairs.

We also have constructed the possible form-factors of T-balls.

9 Acknowledgments

We deeply thank for the courtesy of CDF collaboration for the presentation of figures from there.

H.B.N. is grateful to J. Conway, R. Erbacher, J. Frost, H. Jensen, C. Issever, E. Lytken, K. Loureiro and A. Parker for the advices and fruitful discussions.

L.V.L. thanks A.B. Kaidalov, O.V. Pavlovsky and M.A. Trusov for the useful discussions.

References

[1] 1. CDF Collaboration and D0 Collaboration (D. Benjamin for the collaboration) in: Proceedings of 44th Rencontres de Moriond EW 2009: Electroweak Interactions and Unified Theories, La Thuile, Italy, 7-14 March 2009, ArXiv: 0906.1403 [hep-ex].
2. CDF Collaboration and D0 Collaboration (S. Pagan Griso for the collaboration) in: *Proceedings of 44th Rencontres de Moriond on QCD and High Energy Interactions*, La Thuile, Valle d’Aosta, Italy, 14-21 March 2009, ArXiv: 0905.2090 [hep-ex].

[2] OPAL Collaboration (G. Abbiendi et al.), *Search for a low mass CP odd Higgs boson in $e^+ e^-$ collisions with the OPAL detector at LEP-2*, Eur.Phys.J.C 27, 483 (2003) [ArXiv: hep-ex/0209068].

[3] C.D. Froggatt, L.V. Laperashvili, R.B. Nevzorov and H.B. Nielsen, *The Production of 6t + 6t bar bound state at colliders* A talk given by Holger Bech Nielsen at CERN, 2008, preprint CERN-PH-TH/2008-051.

[4] C.D. Froggatt and H.B. Nielsen, *Trying to understand the Standard Model parameters* Invited talk by H.B. Nielsen at the “XXXI ITEP Winter School of Physics, Moscow, Russia, 18-26 February 2003, Surveys High Energy Phys 18, 55–75 (2003) [ArXiv: hep-ph/0308144].

[5] C.D. Froggatt, H.B. Nielsen and L.V. Laperashvili, *Hierarchy-problem and a bound state of 6 t and 6 anti-t* in: Proceedings of Coral Gables Conference on Launching of Belle Epoque in High-Energy Physics and Cosmology (CG 2003), Ft. Lauderdale, Florida, 17-21 December 2003, Int.J.Mod.Phys. A20, 1268 (2005) [ArXiv: hep-ph/0406110].

[6] C.D. Froggatt and H.B. Nielsen, *Remarkable coincidence for top Yukawa coupling, approximately massless bound states*, ArXiv: 0811.2089[hep-ph].

[7] C.D. Froggatt and H.B. Nielsen, *New Bound States of several Top-quarks bound by Higgs Exchange* in: Proceedings of the 34th Int.Conf. on High Energy Physics, Philadelphia, 2008, arXiv:0810.0475 [hep-ph].

[8] C.D. Froggatt, L.V. Laperashvili and H.B. Nielsen, *A New bound state 6t + 6 anti-t and the fundamental-weak scale hierarchy in the Standard Model* in: Proceedings of 13th International Seminar on High-Energy Physics: QUARKS-2004, Pushkinskie Gory, Russia, 24-30 May 2004 [ArXiv: hep-ph/0410243].

[9] C.D. Froggatt, *The Hierarchy problem and an exotic bound state* in: Proceedings of 10th International Symposium on Particles, Strings and Cosmology, (PASCOS 04 and Pran Nath Fest), Boston, Massachusetts, 16-22 Aug 2004, Published in: “Boston 2004, Particles, strings and cosmology”, pp.325-334 [ArXiv: hep-ph/0412337].

[10] C.D. Froggatt, L.V. Laperashvili and H.B. Nielsen, *The Fundamental-weak scale hierarchy in the Standard Model*, Phys.Atom.Nucl. 69, 67 (2006) [Yad.Fiz. 69, 3 (2006), ArXiv: hep-ph/0407102].
[11] C.D. Froggatt, L.V. Laperashvili, R.B. Nevzorov, H.B. Nielsen and C.R. Das, *New Bound States of Top-anti-Top Quarks and T-balls Production at Colliders (Tevatron, LHC, etc.)*, ArXiv: 0804.4506 [hep-ph].

[12] C.R. Das, C.D. Froggatt, L.V. Laperashvili and H.B. Nielsen, *New Bound States of Heavy Quarks at LHC and Tevatron.*, ArXiv: 0812.0828 [hep-ph].

[13] M. Yu. Kuchiev, V.V. Flambaum and E. Shuryak, Phys.Rev. **D78**, 077502 (2008) [ArXiv: 0808.3632 [hep-ph]], ArXiv: 0811.1387.

[14] M. Yu. Kuchiev, V.V. Flambaum and E. Shuryak, *Light bound states of heavy fermions.*, ArXiv: 0811.1387 [hep-ph].

[15] Jean-Marc Richard, *About the stability of the dodecatoplet*, Few Body Syst. **45**, 65 (2009) [ArXiv: 0811.2711 [hep-ph]].

[16] Yu.P. Goncharov, Nucl.Phys. **A808**, 73 (2008) [ArXiv: 0806.4747 [hep-ph]].

[17] Y. Kiyo and Y. Sumino, Phys.Rev. **D67**, 071501 (2003) [ArXiv: hep-ph/0211299].

[18] W. Kummer and W. Modritsch, Nucl.Phys. **B430**, 3 (1994) [ArXiv: hep-ph/9307202]; Phys.Lett. **B349**, 525 (1995) [ArXiv: hep-ph/9501406].

[19] N. Fabiano, A. Grau and G. Pancheri, Phys.Rev. **D50**, 3173 (1994); Nuovo Cim. **A107**, 2789 (1994).

[20] J.H. Kuhn and E. Mirkes, Phys.Rev. **D48**, 179 (1993) [Arxiv: hep-ph/9301204].

[21] A.L. Macpherson and B.A. Campbell, Phys.Lett. **B306**, 379 (1993) [ArXiv: hep-ph/9302278].

[22] Particle Data Group, C. Amster *et al.*, Phys.Lett. **B667**, (2008).

[23] A. Chodos, R.L. Jaffe, K. Johnson, C.B. Thorn and V.F. Weisskopf, Phys.Rev. **D9**, 3471 (1974).

[24] W.A. Bardeen, M.S. Chanowitz, S.D. Drell, M. Weinstein and T.-M. Yan, Phys.Rev. **D11**, 1094 (1975).

[25] R. Friedberg and T.D. Lee, Phys.Rev. **D15**, 1694 (1977).

[26] R. MacKenzie, F. Wilczek and A. Zee, Phys.Rev.Lett. **53**, 2203 (1984).

[27] R. MacKenzie, Mod.Phys.Lett. **A7**, 293 (1992).

[28] Y. Nambu and G. Jona-Lasinio, Phys.Rev. **122**, 345 (1961).
[29] W.A. Bardeen, C.T.Hill and M. Lindner, Phys.Rev. D41, 1647 (1990).

[30] V.A. Miransky, M. Tanabashi and K. Yamawaki, Phys.Lett. B221, 177 (1989); Mod.Phys.Lett. A4, 1043 (1989).

[31] G. Cvetic, Rev.Mod.Phys. 71, 513 (1999) [Arxiv: hep-ph/9702381].

[32] CDF Collaboration (T. Aaltonen et al.), Phys.Rev.Lett. 100, 161803 (2008) [ArXiv: 0801.3877 [hep-ex]].

[33] CDF Collaboration (A. Lister et al.). Search for Heavy Top-like Quarks $t' \rightarrow Wq$ Using Lepton Plus Jets Events in 1.96 TeV $p\bar{p}$ Collisions, Oct 2008. Presented at 34th International Conference on High Energy Physics (ICHEP 2008), Philadelphia, Pennsylvania, 30 July - 5 August 2008, ArXiv: 0810.3349 [hep-ex].

[34] R. Bonciani, A. Ferroglia, T. Gehrmann, D. Maitre and C. Studerus, JHEP 0807, 129 (2008) [ArXiv: 0806.2301]; ArXiv: 0810.0598.

[35] R. Bonciani, S. Catani, M.L. Mangano and P. Nason, Nucl.Phys.B 529, 424 (1998), Erratum-ibid. B 803, 234 (2008) [ArXiv: hep-ph/9801375].