New Bound States of Heavy Quarks at LHC and Tevatron

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14th Lomonosov Conference on Elementary Particle Physics, Moscow, 19 - 25 August, 2009

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The talk is based on the following papers:

1. The Production of $6t + 6\bar{t}$ bound state at colliders.
   C.D. Froggatt, L.V. Laperashvili, R.B.Nevzorov, H.B. Nielsen.
   A talk given by Holger Bech Nielsen at CERN, 2008;
   preprint CERN-PH-TH/2008-051.
2. New Bound States of Heavy Quarks at LHC and Tevatron.
   C.D. Froggatt, L.V. Laperashvili, H.B. Nielsen, C.R. Das,
   to be published in Int.J.Mod.Phys.A **24**,(2009); arXiv:0812.0828 [hep-ph].
3. Trying to understand the Standard Model parameters.
   Froggatt C.D. and Nielsen H.B.
   Invited talk by H.B. Nielsen at the "XXXI ITEP Winter School of Physics", (February 18–26, 2003, Moscow, Russia),
   published in: *Surveys High Energy Phys.* **18**, 55-75 (2003);
   ArXiv: hep-ph/0308144.
4. Remarkable coincidence for top Yukawa coupling, approximately massless bound states.
   Froggatt C.D. and Nielsen H.B.,
   to be published in Nucl.Phys.B (2009); arXiv: 0811.2089[hep-ph].

5. Hierarchy-problem and a bound state of 6 t and 6 anti-t.
   C.D. Froggatt, H.B. Nielsen, L.V. Laperashvili,
   in: Proceedings of Coral Gables Conference on Launching of Belle Epoque in High-Energy Physics and Cosmology *(CG 2003)*, Ft. Lauderdale, Florida, 17-21 Dec 2003.
   Published in: Int.J.Mod.Phys.A **20**, 1268 (2005);
   ArXiv: hep-ph/0406110.

6. The Fundamental-weak scale hierarchy in the Standard Model.
   C.D. Froggatt, L.V. Laperashvili, H.B. Nielsen,
   Phys.Atom.Nucl. **69**, 67 (2006) [Yad.Fiz. **69**, 3 (2006)];
   ArXiv: hep-ph/0407102.

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

Contents:

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 the SM 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) give a lowest limit for the Higgs boson mass $\mathbf{M_H}$:

$$\mathbf{M_H \gtrsim 114.4\ \ GeV\ \ at\ \ 95\%\ \ CL}.$$

The recent Tevatron result is:

$$\mathbf{115 \lesssim M_H \lesssim 160\ \ GeV}.$$

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 a whole spectroscopy of new bound states.

The present talk is devoted to the following predictions:

- There exists a scalar **1S**–bound state of $\mathbf{6t} + \mathbf{6\bar{t}}$.

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 $\mathbf{6t} + \mathbf{5\bar{t}}$, which is a fermion similar to the quark of the fourth generation having quantum numbers of top quark.

A new (earlier unknown) bound state $\mathbf{6t}+\mathbf{6\bar{t}}$, which is a color singlet (that is, 'white' state), was first suggested
by Froggatt and Nielsen in Ref. [3].
Now all these NBS are named T-balls, or T-fireballs.

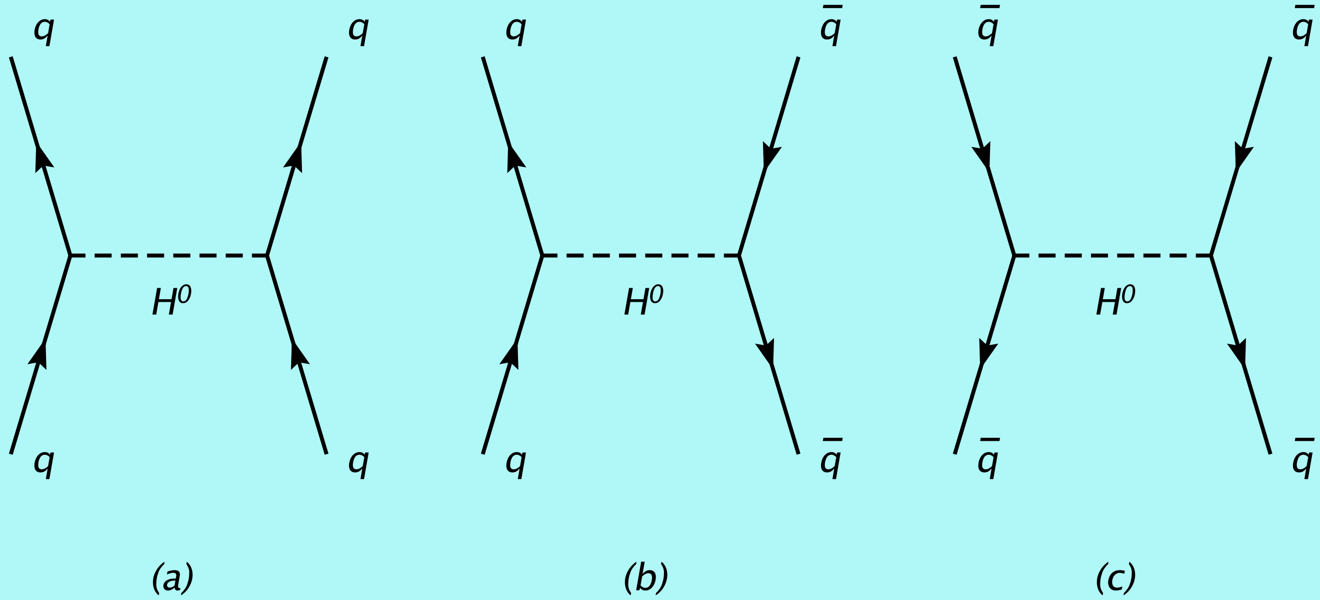

Fig. 1:

2 Higgs and gluon interactions of quarks.

If the Higgs particle exists, then between quarks $\mathbf{qq}$, quarks and anti-quarks $\mathbf{q\bar{q}}$, and also between anti-quarks $\mathbf{\bar{q}\bar{q}}$ there exist virtual exchanges by Higgs bosons (see **Fig. 1**).

In all these three cases we have attractive forces.

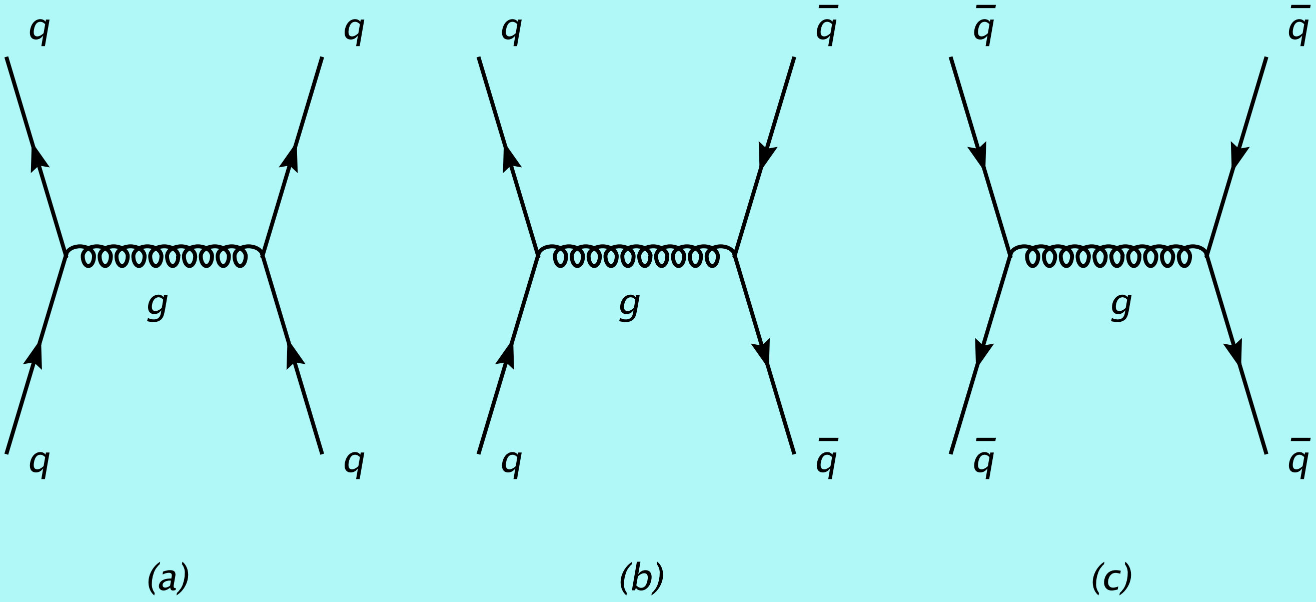

Fig. 2:

It is well-known that the bound state $\mathbf{t\bar{t}}$ – so called **toponium** – is obliged to the gluon virtual exchanges (see **Fig. 2**).

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, when we increase a 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 $\mathbf{6t + 6\bar{t}}$.
The explanation is simple:
top-quark has **two spin states** and **three states of colors:**

$$\mathbf{2} \times \mathbf{3} = \mathbf{6} \text{ degrees of freedom.}$$

This means that, according to the Pauli principle, only 6 pairs of $\mathbf{t\bar{t}}$ 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, 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:

$$\mathbf{L} = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{D}_\mu \mathbf{\Phi_H} \mathbf{D}^\mu \mathbf{\Phi_H} + \frac{\mathbf{g_t}}{\sqrt{\mathbf{2}}}\overline{\psi_{\mathbf{tL}}}\psi_{\mathbf{tR}}\mathbf{\Phi_H} + \mathbf{h.c.}, \qquad (1)$$

where $\mathbf{\Phi_H}$ and $\psi_{\mathbf{t}}$ are the Higgs and top-quark fields, respectively, and $\mathbf{g_t}$ is the Yukawa coupling constant of their interaction.

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

$$\mathbf{v} =< |\mathbf{\Phi_H}| >= \mathbf{246}\ \mathrm{GeV}.$$

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

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

where λ is the Higgs selfinteraction coupling constant.

According to the Particle Data Group, we have

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

$$\mathbf{g_t \approx 0.93}.$$

Let us imagine now that the NBS is a bubble in the EW-vacuum and contains $\mathbf{N_{const.}}$ top-like constituents. Insight this bubble (bag) we have the following VEV of the Higgs field:

$$\mathbf{v_0} =< |\mathbf{\Phi_h}| >,$$

which is smaller than EW VEV value $\mathbf{v}$:

$$\frac{\mathbf{v_0}}{\mathbf{v}} < \mathbf{1}.$$

Then the effective masses insight the bubble are smaller than the corresponding experimental masses:

$$\mathbf{m_{t,h}} = \frac{\mathbf{v_0}}{\mathbf{v}} \mathbf{M_{t,H}}.$$

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

$$\mathbf{V(r) = -\frac{g_t^2/2}{4\pi r}\exp(-m_h r)}. \tag{2}$$

Assuming that the radius $\mathbf{R_0}$ of the bubble is small:

$$\mathbf{m_h R_0 << 1},$$

we obtain the Coulomb-like potential:

$$\mathbf{V(r) \simeq -\frac{g_t^2/2}{4\pi r}}. \tag{3}$$

The attraction between any pairs $\mathbf{tt}$, $\mathbf{t\bar{t}}$, $\mathbf{\bar{t}\bar{t}}$ is described by the same potential (3).

Now we can estimate the binding energy of a single top-quark relatively to the nucleus having $\mathbf{Z = N_{const.} - 1}$. The total potential energy for the NBS with $\mathbf{N_{const.} = 12}$ is:

$$\mathbf{V_{tot}(r) = -11\frac{g_t^2/2}{4\pi r}}. \tag{4}$$

Considering a set of Feynman diagramms (the Bethe-Salpeter equation) and including the contributions of all (s-,t- and u-) channels for the Higgs and gluon exchange forces (see Ref. [4]), we obtain the following Taylor expansion:

$$\mathbf{M_T^2 = (N_{const.}M_t)^2 \times}$$

$$\left\{\mathbf{1 - 2(N}_{\text{const.}}\mathbf{- 1)\left(\frac{N_{const.}}{12}\right)^2\left(\frac{g_t^2 + \frac{1}{6}g_s^2}{\pi}\right)^2} + ...\right\}.$$

Here the QCD coupling constant $\mathbf{g_s}$ is given by its fine structure constant value at the EW-scale (Particle Data group):

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

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

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

The mass of T-ball containing $\mathbf{N}_{\mathrm{const.}}$ top or anti-top quarks is:

$$\mathbf{M_T} = \mathbf{N}_{\mathrm{const.}}\mathbf{m_t} - \mathbf{E_T}.$$

Approximately this dependence is described by the following expression:

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

Below we shall use the following notations:

$\mathbf{T_s}$-ball is a scalar NBS:
$\mathbf{6t + 6\bar{t}}$,
having the spin $\mathbf{S = 0}$,

and $\mathbf{T_f}$-ball presents the NBS:
$\mathbf{6t + 5\bar{t}}$,
which is a fermion:
$\overline{\mathbf{T_f}} = \mathbf{5t + 6\bar{t}}$,

Let us consider now the condition:

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

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

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

It is necessary to emphasize that the experimentally given values:

$$\mathbf{g_t^2 \simeq 0.86} \quad \text{and} \quad \mathbf{g_s^2 \simeq 1.48}$$

are just very close to this limit.

Fig. 3 shows the dependence of T-ball masses on the number of NBS constituents $\mathbf{N}_{\text{const.}}$.

In the case when $\mathbf{M_{T_s} = 0}$, we have:

$$\mathbf{M_T = N_{\text{const.}} m_t \left\{ 1 - \frac{(N_{\text{const.}} - 1)}{11} \frac{N^2_{const.}}{12^2} \right\}} \tag{5}$$

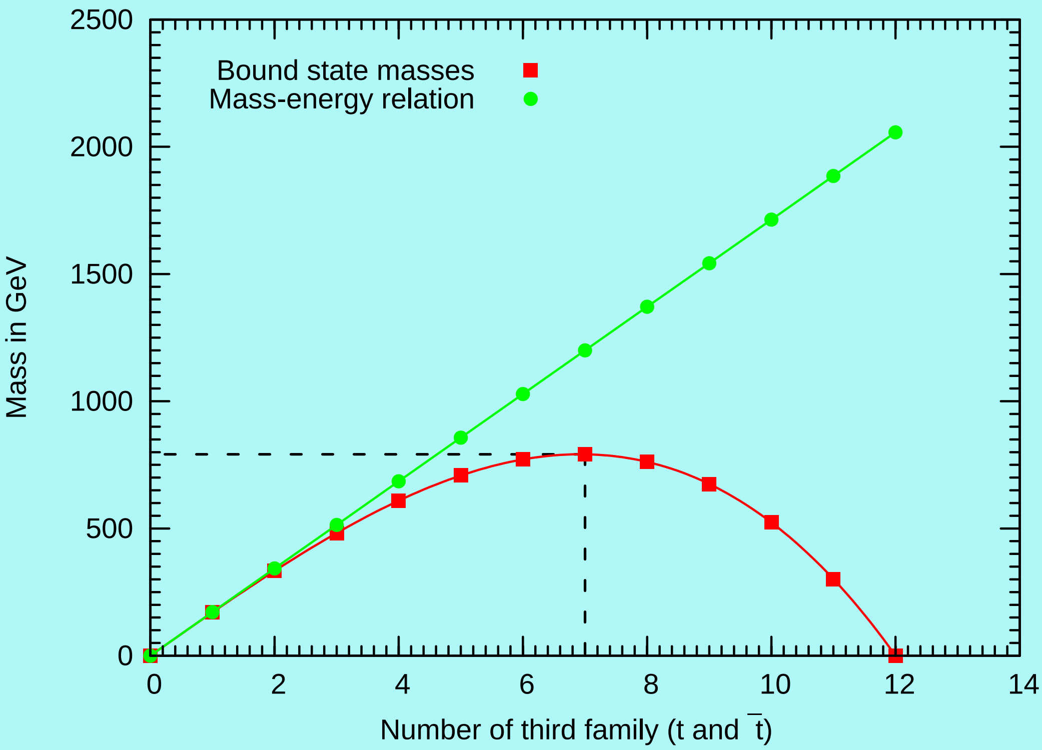

Fig. 3: The dependence of T-ball masses on the number $N_{\mathrm{const.}}$ of the NBS constituents.

We easily see that the light scalar Higgs boson with mass $\mathbf{m_h} < \mathbf{M_H}$ can bind the 12 top-like quarks so strongly that the mass $\mathbf{M_{T_s}}$ becomes almost zero, and even tachyonic:

$$\mathbf{M^2_{T_s} < 0}.$$

In the last case we obtain **the Bose-Einstein condensate of T-balls – a new vacuum at the EW-scale.** This is very important for the solution of the hierarchy problem.

We hope that the forthcoming numerical calculations of the masses of T-balls, using Monte-Carlo simulations on lattice, will give us a more exact answer.

3.1 T_f-ball mass estimate

One of the main ideas of the present investigation is to show that the Higgs interaction of the 11 top-anti-top quarks creates a $\mathbf{T_f}$-ball – a new fermionic bound state $\mathbf{6t + 5\bar{t}}$, which is similar to the $\mathbf{t'}$-quark of the fourth generation.

The estimate of the mass of $\mathbf{T_f}$-ball $\mathbf{6t + 5\bar{t}}$ by Eq. (5) gives :

$$\mathbf{M_{T_f} \approx 11m_t \cdot 0.236 \ \gtrsim \ 300\ GeV}. \tag{6}$$

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, the T-balls considered in the framework of the SM could exist.

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

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

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

$$\mathbf{H \to 2T_s},$$

if $\mathbf{M_{T_s} < \frac{1}{2}M_H}$.

Using limits given by Tevatron experiments

$$\mathbf{115 \lesssim M_H \lesssim 160\ \ GeV},$$

we obtain the requirement for the Higgs decay mechanism:

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

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

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

3) Second, we can observe at Tevatron all processes

given by **Fig. 4**

with the replacement

$$\mathbf{t\bar{t} \to t'\bar{t}',\ \ T_f\overline{T_f}}.$$

In the most optimistic cases the NBS $\mathbf{6t + 5\bar{t}}$ (fermionic fireball) plays a role of the fundamental quark of the fourth generation, say, with the mass $\mathbf{M_{T_f}} \gtrsim \mathbf{300}$ 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 $\mathbf{T_f}$, or both of them.

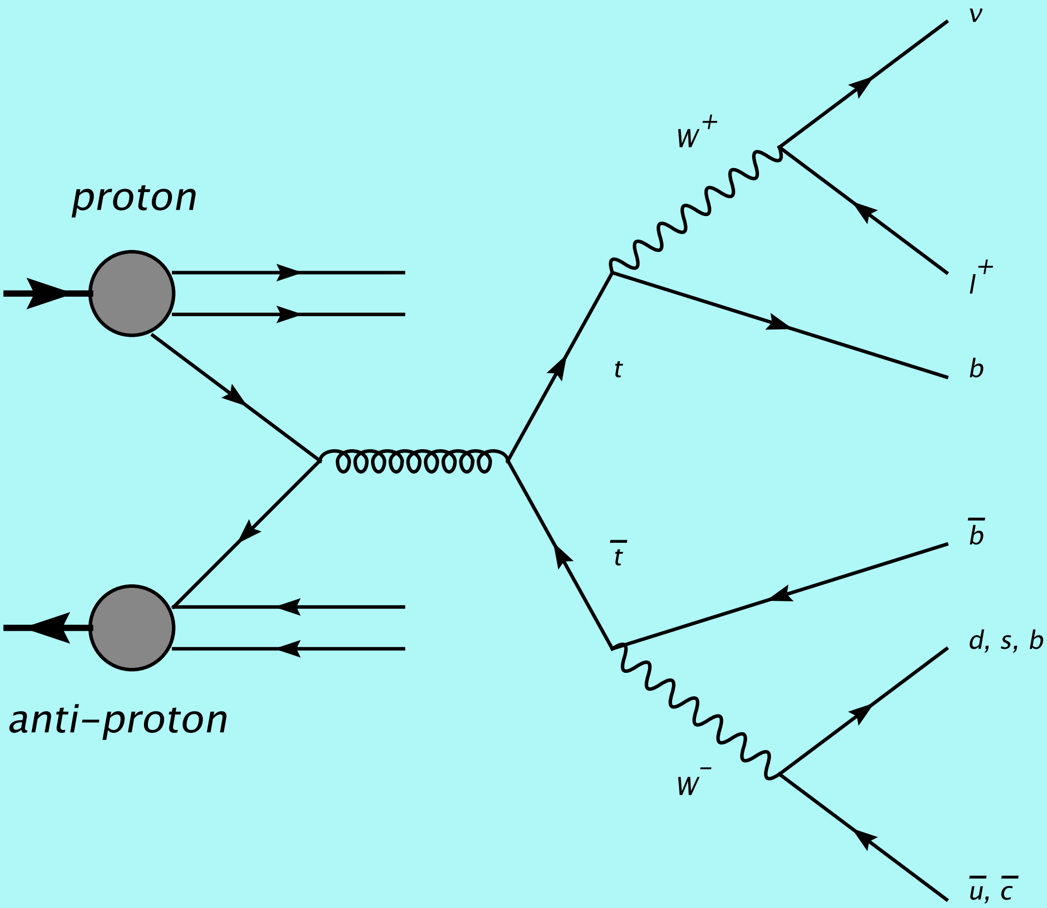

Fig. 4: A typical process observed at the Tevatron in $p\bar{p}$ collisions.

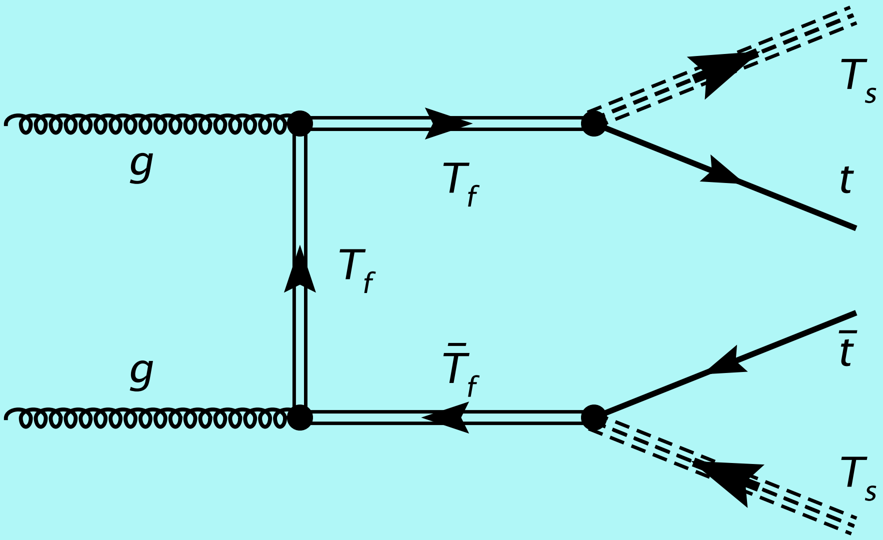

Fig. 5: Two gluon production of T_s-balls

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

At LHC the pairs of $\mathbf{T_s}$-balls or $\mathbf{T_f}$-balls might be produced in **pp** collisions via the two gluon diagram with strong vertices (see **Fig. 5**).

5 CDF II Detector experiment at the Tevatron.

Recent experiments with CDF II Detector of the Tevatron searching for heavy top-like quarks in $\mathbf{p\bar{p}}$-collisions with $\sqrt{\mathbf{s}} \simeq \mathbf{1.96}$ TeV:

CDF Collaboration (T. Aaltonen et al.). FERMILAB-PUB-08-017-E, Jan 2008. Phys.Rev.Lett. **100**, 161803 (2008); arXiv: 0801.3877 [hep-ex].

CDF Collaboration (A. Lister et al.). *Search for Heavy Top-like Quarks* $t' \to Wq$ *Using Lepton Plus Jets Events in 1.96 TeV* $p-\bar{p}$ *Collisions.* FERMILAB-CONF-08-473-E, Oct 2008. Presented at 34th International Conference on High Energy Physics (ICHEP 2008), Philadelphia, Pennsylvania, 30 Jul - 5 Aug 2008; arXiv: 0810.3349 [hep-ex].

do not exclude the existence of T-balls with masses $\gtrsim \mathbf{300}$ GeV, up to 500 GeV.

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

Tevatron experiments exclude a fourth-generation t' quark with a mass below 300 GeV.

Assuming that a fourth family $\mathbf{t'}$-quarks does not exist in Nature, but only the pairs of fermionic NBS $\mathbf{T_f}$ are produced at the Tevatron, we can give an explanation of the observed cross-section shown in **Fig. 6**. The curve for the cross-section

$$\sigma(\mathbf{p\bar{p}} \to \mathbf{t'\bar{t}'}) \simeq \mathbf{0.1\ pb}$$

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

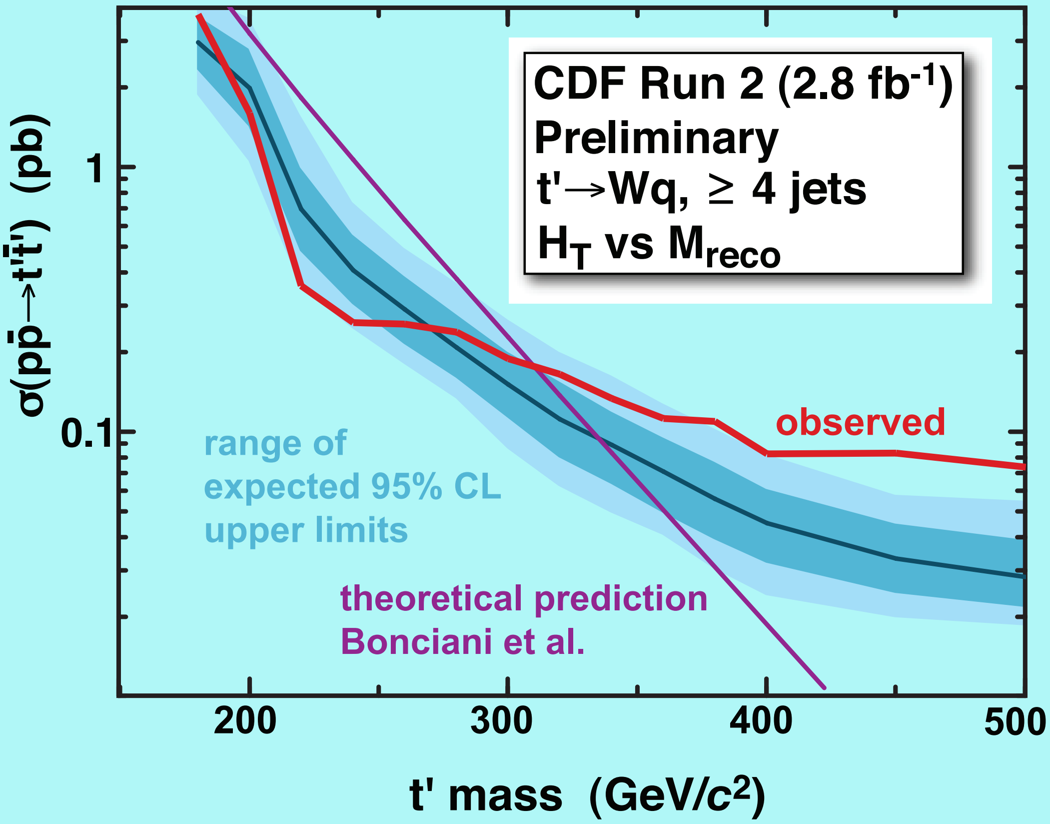

Fig. 6: Tevatron CDF-experiment: upper limit, at 95% CL, a fourth-generation t' quark with a mass below 300 GeV is excluded. Blue line presents a theoretical curve for the fourth-generation quarks cross-section.

6 Conclusions

1. The present investigation is based on the following three assumptions: 1) there exists $\mathbf{1S}$–bound state of $\mathbf{6t + 6\bar{t}}$; 2) the forces which bind these top-quarks are so strong that they almost completely compensate the mass of the 12 top-quarks forming this bound state; 3) such strong forces are produced by the interactions of top-quarks via the virtual exchange of the scalar Higgs bosons, when the top-quark Yukawa coupling constant is large: $\mathbf{g_t \simeq 1}$.

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

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

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

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

6. We have considered all processes with T-balls, which can be observed at LHC, especially the decay $\mathbf{H \to 2T_s}$ and the production of $\mathbf{T_f\overline{T_f}}$ together with $\mathbf{t'\overline{t'}}$, where $\mathbf{t'}$ is a quark of the fourth generation.

7. 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.