New Bound States of Top-anti-Top Quarks and T-balls Production at Colliders (Tevatron, LHC, etc.)[1]

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Abstract

The present talk is based on the assumption that New Bound States (NBSs) of top-anti-top quarks (named T-balls) exist in the Standard Model (SM): a) there exists the scalar $1S$–bound state of $6t + 6\bar{t}$ — the bound state of 6 top-quarks with their 6 anti-top-quarks; b) the forces which bind these top-quarks are very strong and almost completely compensate the mass of the 12 top-anti-top-quarks forming this bound state; c) such strong forces are produced by the interactions of top-quarks via the virtual exchange of the scalar Higgs bosons having the large value of the top-quark Yukawa coupling constant $g_t \simeq 1$. Theory also predicts the existence of the NBS $6t + 5\bar{t}$, which is a color triplet and a fermion similar to the t'-quark of the fourth generation. We have also considered "b-replaced" NBSs: $n_b b + (6t + 6\bar{t} - n_b t)$ and $n'_b b + (6t + 5\bar{t} - n'_b t)$, etc. We have estimated the masses of the lightest "b-replaced" NBS: $M_{NBS} \simeq (300 - 400)$ GeV, and discussed the larger masses of the NBSs. We have developed a theory of the scalar T-ball's condensate, and predicted the existence of the three SM phases, calculating the top-quark Yukawa coupling constant at the border of two phases (with T-ball's condensate and without it) equal to: $g_t \approx 1$. The searching for the Higgs boson H and T-balls at the Tevatron and LHC is discussed.

Contents:

1 Introduction: New colliders, the Higgs boson and T-balls.

The Salam-Weinberg theory of Electroweak (EW) interactions describes very well the Standard Model (SM) which is confirmed by all experiments of the world accelerators. This theory predicts the existence of a scalar particle – the Higgs boson. However, this Higgs boson was not observed up to now in spite of the careful searching for this particle. The main problem of the future colliders: LHC, Tevatron, etc. – is just the searching for the Higgs boson H.

The Tevatron collider at Fermilab (Illinois, USA) produces the high energy collisions of proton-antiproton beams.

Fermilab has been the site of several important discoveries that have helped to confirm the SM of elementary particle physics. Tevatron experiments observed the first evidence of the bottom quark's existence (in 1977), and completed the quark sector of the SM with the first observation of the top quark (in 1995).

Tevatron has the center-of-mass energy $\sqrt{s} = 1.96$ TeV, and therefore is currently the world's highest energy particle collider.

The Large Hadron Collider (LHC) is a new accelerator being built at the European Organization for Nuclear Research (CERN).

The physics motivation provides the guidance for the construction specifications of the LHC machine.

At the new frontier of the LHC of the High Energy Physics, the areas that we aim to study with LHC can be summarized as follows.

1.1 Explore the mechanism of the EW symmetry breaking.

Although the SM of the EW interactions provides a successful description of particles physics phenomenology (its predictions have been verified by the experiments at LEP and Tevatron), the mechanism of the EW symmetry breaking (EWSB) has not yet been tested.

Within the SM, the EWSB is explained by the Higgs mechanism. **However, the mass of the Higgs boson is not predicted by the theory.**

Direct searches in the previous experiments (mainly at LEP2) set a low mass limit:

$$\mathbf{m_H \gtrsim 114.4} \quad \text{GeV} \quad \text{at} \quad 95\% \quad \text{CL.}$$

This limit can be indirectly constrained from global fits to high precision EW data which suggest a mass

$$\mathbf{m_H = 89^{+42}_{-30}} \quad \text{GeV.}$$

If we assume that there is not physics beyond the SM up to a large scale $\mathbf{\Lambda}$, then, on theoretical grounds, the upper limit on the Higgs mass can be set to 1 TeV. Therefore,
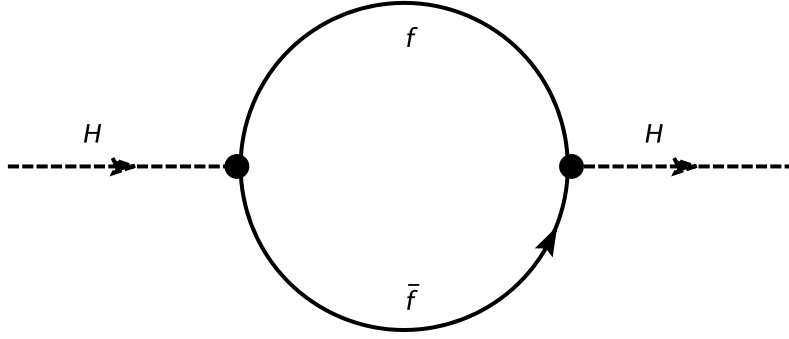
Fig. 1:

there is a need for a machine that can probe the whole mass range, and LHC has been designed for that.

The recent Tevatron result is:

$$120 \lesssim M_H \lesssim 160 \text{ GeV}.$$

1.2 Physics beyond the SM.

There are several arguments which indicate that the SM is not the final and complete theory. One of these, probably the strongest, is the so-called **hierarchy problem:** if the Higgs particle exists, then the fermionic radiative corrections to its mass will be described (at one-loop level) by the diagram of **Fig. 1**.

Then the Higgs mass given by theoretical calculations depends on the cut-off Λ for the momentum in loop. Now, if there is not new physics up to the Planck scale, then:

$$\Lambda \simeq M_{Planck} \simeq 10^{19} \text{ GeV},$$

and

$$M_H(\text{renormalized}) >> (1 \text{ TeV})^2,$$

unless we fine tune so as to avoid that. Since the last value does not agree with experimental limits, we start to believe that possible new physics exists beyond the SM (for example, SUSY models, etc.).

1.3 EW precision measurements.

Because of the high energy and luminosity achieved, the LHC will be a factory of W and Z bosons, as well as of top and bottom quarks.

It is estimated that the LHC, during the first year of operation, will give the following events:

$$10^8, \quad W \to e\nu,$$

$$10^7, \quad Z \to e^+e^-,$$

$$10^7, \quad t\bar{t},$$

$$10^{12}, \quad b\bar{b}.$$

LHC will establish the SM parameters. Any observed deviation from the predicted values of the SM observables will be a signal for new physics.

The LHC is currently being constructed in the already existing LEP tunnel of (approximately) 27 km circumference.

The machine will provide mainly proton-proton collisions. Also it will provide heavy ion collisions as well.

The LHC will produce two counter-rotating proton beams with energy of 7 TeV each.

This gives 14 TeV center of mass energy ($\sqrt{s} = 14$ TeV):

7 times bigger than the center of mass energy provided by Tevatron at Fermilab!

The completion of the LHC is expected at the end of 2008:

at October, 21, 2008.

1.4 New bound states of top-anti-top quarks.

We hope that the LHC will provide a solution of the main puzzles of EWSB. The present investigation is devoted to this problem and based on the following three assumptions:

• there exists **1S**–bound state of $\mathbf{6t + 6\bar{t}}$, e.g. bound state of 6 quarks of the third generation with their 6 anti-quarks;

• 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.

• such strong forces are produced by the Higgs interactions — the interaction of top-quarks via the virtual exchange by scalar Higgs bosons. They are determined by the large value of the top-quark Yukawa coupling constant $\mathbf{g_t}$.

A new (earlier unknown) bound state

$$6t + 6\bar{t},$$

which is a color singlet, that is, "white state", was first suggested in **Ref. [2] by Froggatt and Nielsen** and now is named T-ball, or T-fireball.

- Theory also predicts the existence of **the new bound state**

$$6t + 5\bar{t},$$

which is a fermion similar to the quark of the fourth generation having quantum numbers of t-quark.

The properties of T-balls are intimately related with the problem of the Higgs boson observation.

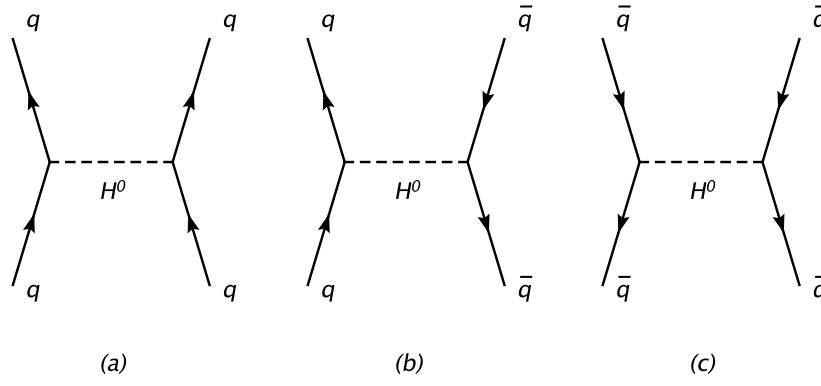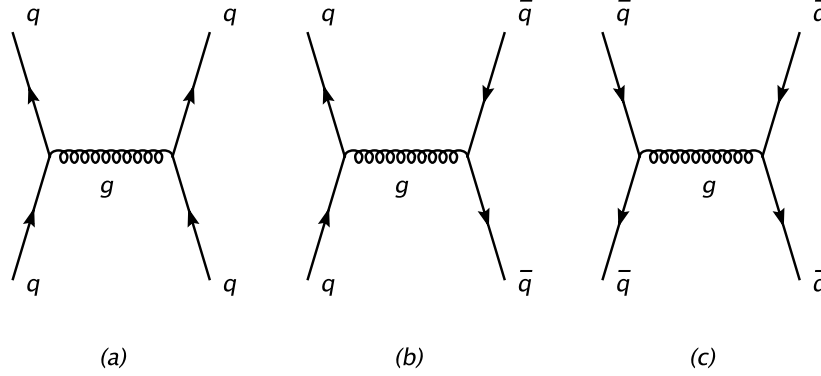The talk is based on the papers [1-9].

Fig. 2:

Fig. 3:

2 Higgs and gluon interactions of quarks.

If the Higgs particle exists, then between quarks **qq**, quarks and anti-quarks **q̄q**, and also between anti-quarks **q̄q̄** there exist virtual exchanges by Higgs bosons (see **Fig. 2**). And in all these three cases we deal with attractive forces.

It is well-known that the bound state **tt̄** – so called **toponium** – is obligatory of the gluon virtual exchanges (see **Fig. 3**).

In the case of 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. Had the latter been indeed stable it would have been a very loosely bound state.

However, adding to the NBS more and more top and anti-top quarks, we begin to notice that attractive Higgs forces increase and increase. Simultaneously gluon (attractive and repulsive) forces first begin to compensate themselves, and thus begin to decrease relatively to the Higgs effect with the growth of the number of NBS constituents **t** and **t̄**. The maximum of the special binding energy value ϵ (the binding energy per top or anti-top) corresponds to the **S**-wave NBS **6t + 6t̄**. The explanation is given as follows:

top-quark has two spin states (two spin degrees of freedom corresponding to the two projections of the spin $\frac{1}{2}$) and three states of colors. This means that, according to the Pauli principle, only

$$2 \times 3 = 6 \ \mathbf{t - quarks}$$

can create $\mathbf{S1 - wave\ function}$ together with $\mathbf{6\bar{t} - quarks}$. So we deal with the 12 quark (or anti-quark) constituents, that is, with 6 pairs $\mathbf{t\bar{t}}$), which simultaneously can exist in the $\mathbf{S}$-wave state. If we try to add more top-constituents $\mathbf{t\bar{t}}$, then some of them will turn out to the S2-wave, and the NBS binding energy will decrease at least 4 times. For P-,D-, etc. waves the NBS binding energy decreases more and more.

3   T-ball mass estimate [2-4].

T-ball mass containing the number $N_{const.}$ of top and anti-top quarks is:

$$\mathbf{M_T = N_{const.}M_t - E_T = N_{const.}(M_t - \epsilon)\ GeV}, \tag{1}$$

where $\mathbf{M_t}$ is the top-quark pole mass, $\mathbf{E_T}$ is a total binding energy and $\epsilon = \mathbf{E_T/N_{const.}}$ presents the specific binding energy.

Below we use the notation: **the scalar NBS $6t + 6\bar{t}$, having the spin $S = 0$, is named as T_s-ball, and T_f-ball presents the NBS $6t + 5\bar{t}$, which is a fermion ($\overline{T_f} = 5t + 6\bar{t}$).**

3.1 T_s-ball mass estimate.

According to the Particle Data Group [10], the top-quark mass is

$$\mathbf{M_t = 172.6 \pm 1.4\ GeV},$$

therefore the mass of the $\mathbf{T_s}$-ball is given by the following expression:

$$\mathbf{M_T = 12M_t - E_T = 12 \cdot (172,6 - \epsilon)\ GeV}. \tag{2}$$

With aim to estimate the binding energy $\mathbf{E_T}$ of the NBS $\mathbf{6t + 6\bar{t}}$, first we will determine the binding energy of the single top-quark relatively to the remaining 11 quarks, which we shall call nucleus. Assuming, that the radius of this nucleus is small enough in comparison with the Compton wave length of the Salam-Weinberg Higgs particle, we are able to use the usual Bohr formula for the binding energy of the Hydrogen atom, replacing the electric charge $\mathbf{e}$ into the top-quark Yukawa coupling constant (YCC) $\mathbf{g_t/\sqrt{2}}$.

Here we use the normalization, in which the kinetic energy term of the Higgs field $\mathbf{\Phi_H}$ and the top-quark Yukawa interaction are given by the following Lagrangian density:

$$\mathbf{L = \frac{1}{2}D_\mu\Phi_H D^\mu\Phi_H + \frac{g_t}{\sqrt{2}}\overline{\psi_{tL}}\psi_{tR}\Phi_H + h.c.} \tag{3}$$

In this case the attraction between the two top (anti-top) quarks is presented by the potential similar to the Coulomb one:

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

It is easy to see that the attraction between any pairs $\mathbf{tt}$, $\mathbf{t\bar{t}}$, $\mathbf{\bar{t}\bar{t}}$ is described by the same potential (4).

Now we can estimate the binding energy of a single top-quark relatively to the nucleus having $\mathbf{Z = 11}$, using the well-known equation for the n energy level of the Hydrogen atom :

$$E_n = -\left(\frac{Zg_t^2/2}{4\pi}\right)^2 \frac{M_t^{\text{reduced}}}{2n^2}, \tag{5}$$

where $\mathbf{M_t^{reduced}}$ is the top-quark reduced mass. Then:

$$M_t^{\text{reduced}} = \frac{ZM_t}{Z+1}, \tag{6}$$

and we obtain the following equation:

$$E_n = -\left(\frac{Zg_t^2/2}{4\pi}\right)^2 \frac{ZM_t}{2(Z+1)n^2}. \tag{7}$$

The level with $\mathbf{n = 1}$ corresponds to the ground $\mathbf{S}$-wave state, e.g.

$$E_1 = -\left(\frac{11g_t^2}{8\pi}\right)^2 \frac{11M_t}{24}. \tag{8}$$

Here $\mathbf{g_t}$ is the top-quark YCC.

In our normalization we obtain the following expression by the Salam-Weinberg theory:

$$M_t = \frac{g_t}{\sqrt{2}}v \approx 174g_t \text{ GeV}. \tag{9}$$

A total binding energy of $\mathbf{T_s}$-ball, containing the 12 particles, can be obtained by adding the binding energy of the remaining constituents, that is, by multiplying the formula (8) with a general number of constituents, e.g. 12, taking into account a duplication.

Finally, in this **<u>non-relativistic case</u>** the value of the total binding energy is equal to:

$$E_T = 6\left(\frac{11g_t^2}{8\pi}\right)^2 \frac{11M_t}{24} = \left(\frac{11g_t^2}{4\pi}\right)^2 \frac{11M_t}{16}. \tag{10}$$

However, by analogy with a hydrogen-like atom, we have considered only $\mathbf{t}$-channel exchange by the Higgs bosons between the two top (or anti-top) quarks in the system of the NBS.

Let us consider now $\mathbf{u}$-channel exchange.

8

From the first point of view, it is expected the absence of the difference between the quarks of different colors. But if we consider a formalism, in which both degrees of freedoms (colors and spin states of quarks) are fixed, then the NBS $\mathbf{6t + 6\bar{t}}$ is completely antisymmetric under the permutation of its color and spin states. In this case, we can easily estimate $\mathbf{u}$-channel contributions. Assuming that the NBS is antisymmetrized in such a manner, we formally consider a quark as a particle having no degrees of freedom. In this case, we shall take into account "minus" under the permutation of two quarks. It is natural, that in this approach a quark plays a role of a boson, but not a fermion.

As a result of s-, t-, and u-channel exchanges, we have the following expression for the total binding energy:

$$\mathbf{E_T} = \frac{33\mathbf{g_t^4}}{(4\pi)^2} \cdot \mathbf{12M_t}. \tag{11}$$

Considering a set of Feynman diagramms (e.g. the Bethe-Salpeter equation), we obtain the following Taylor expansion in $\mathbf{g_t^2}$ for the mass of the NBS $\mathbf{T_s}$, containing 12 top-anti-top quarks:

$$\mathbf{M_T^2} = (\mathbf{12M_t})^2 - 2(\mathbf{12M_t})\mathbf{E_T} + ...$$

$$= (\mathbf{12M_t})^2(1 - \frac{33}{8\pi^2}\mathbf{g_t^4} + ...). \tag{12}$$

3.2 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 – **the new fermionic bound state $\mathbf{6t + 5\bar{t}}$, which is similar to the quark of the fourth generation with quantum numbers of the top quark.** We have tried to estimate the $\mathbf{T_f}$-ball's mass.

In general, the binding energy of the top-quark in the NBS depends on the number of the NBS constituents $\mathbf{N_{cost.}}$, and is proportional to the following expression:

$$\mathbf{E_{binding}} \propto \frac{1}{2}\mathbf{N_{const.}}(\mathbf{N_{const.}} - 1). \tag{13}$$

The dependence of the T-ball's mass of $\mathbf{N_{cost.}}$ is given by **Fig. 4**.
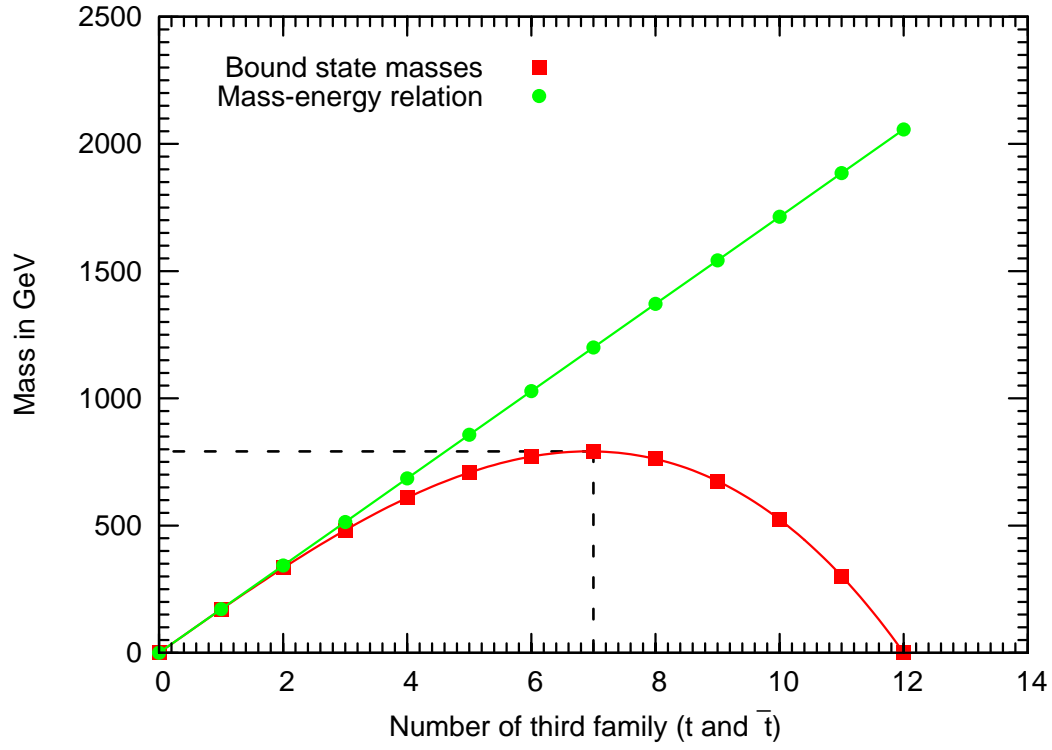
Fig. 4: The dependence of the T-ball's mass of the number $\mathbf{N_{cost}}$ of the NBS constituents.

This dependence is described by the following equation:

$$\mathbf{M_T = M_{NBS} = M_t \cdot N_{const.}(1 - \frac{N_{const.}^2}{12^2}).} \tag{14}$$

According to the formula (14), we have obtained the estimate of the $\mathbf{T_f}$-mass of the NBS $\mathbf{6t + 5\bar{t}}$, using Particle Data Group result $\mathbf{M_t = 172,6 \pm 1.4}$ GeV:

$$\mathbf{M_{T_f} \approx (172,6) \cdot 11 \cdot 0.16 \ GeV \simeq 300 \ GeV}.$$

It is necessary to notice the increasing of the mass of $\mathbf{T_s(b-replaced)}$-ball, which is formed by the replacement of a t-quark by a b-quark in $\mathbf{T_s}$-ball (see Ref. [7] and Section 8):

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

in comparison with mass of $\mathbf{T_s}$.

It is obvious that

$$\mathbf{M_{T_s(b-replaced)} > M_{T_s}},$$

giving

$$\mathbf{M_{T_s(b-replaced)} \simeq M_{T_f}}.$$

It is obvious that considering the different T(b-replaced)-balls we can obtain more heavy T-balls:

$$\mathbf{M_{T(b-replaced)} \gtrsim 400 \ GeV}.$$

4 <u>The calculation of the top-quark YCC at the two phases border.</u>

According to the Salam-Weinberg theory (SM), we have Eq. (9), from which using the experimental value of the top-quark mass [10]

$$\mathbf{M_t \approx 172.6 \pm 1.4 \ GeV},$$

we obtain:

$$\mathbf{g_t \approx \frac{M_t}{v/\sqrt{2}} \approx (172.6 \pm 1.4)/174.5 \approx 0.989 \pm 0.008,} \tag{15}$$

that is, top-quark YCC is of order of unity at the EW-scale.

At present, a lot of investigators, theorists and experimentalists, are looking forward to the New Physics. And it is quite possible that the **"Bjorken-Rosner night-mare"** will take place: LHS will discover the Salam-Weinberg Higgs boson and nothing more. Nevertheless, the NBS T-ball can exist, because it is calculated in the framework of the SM. Supersymmetry, for instance, cannot exclude this phenomenon: only can change the details of calculations.
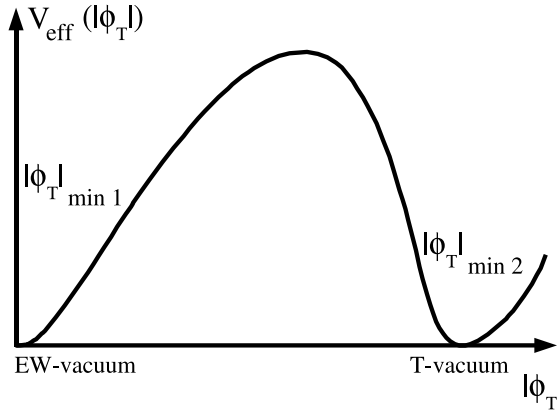
Fig. 5: The effective potential $\mathbf{V_{eff}}(|\phi_{\mathbf{T}}|)$, depending on the norm of the T-ball scalar field $\phi_{\mathbf{T}}$, has two minima: at $\phi_{\mathbf{T}} = \mathbf{0}$ (EW-vacuum) and at $\phi_{\mathbf{T}} \neq \mathbf{0}$ (T-vacuum).

The light scalar Higgs bosons can bind top-quarks so strongly that finally we shall obtain **the Bose-condensate of T-balls in the vacuum**, in which we live, e.g. in the EW-vacuum. Indeed, it is quite possible: for example, if $\mathbf{g_t}$ increases when the number of top-quarks in T-ball grows, then the binding energy compensates the NBS mass $\mathbf{12M_t}$ in the $\mathbf{T_s}$-ball (having $\mathbf{6t + 6\bar{t}}$) so strongly that the mass $\mathbf{M_{T_s}}$ becomes almost zero, and even tachyonic, e.g. $\mathbf{M^2_{T_s} < 0}$, what means the formation of the scalar T-balls' condensate in the vacuum. The result $\mathbf{g_t \sim 1}$ means that the experimentally observed value of the top-quark YCC belongs to the border of two phases – phase-I and phase-II:

I) the phase-I has no the Bose-condensate of T-balls,

II) but the phase-II contains such a condensate.

In this case the effective potential $\mathbf{V_{eff}}(|\mathbf{\Phi_T}|)$, depending on the norm of the T-ball scalar field $\mathbf{\Phi_T}$, is presented by **Fig. 5**.

We see that the main requirement of the appearance of the new phase of the condensed $\mathbf{T_s}$-balls is a condition:

$$\mathbf{m^2_{NBS} = M^2_{T_s} = 0}.$$

Using Eq. (12), which describes the square mass of the scalar fireballs, it is easy to obtain the estimate of the YCC value of top-quark at the border of the two phases I and II [3]:

$$\mathbf{g_t}\big|_{\mathbf{p.t.b.}} \equiv \mathbf{g_t}\big|_{\mathbf{phase\ transition\ border}} \approx (\frac{8\pi^2}{33})^{1/4} \approx 1.24. \tag{16}$$

However, there is an additional problem.

The fluctuations of the Higgs field $\mathbf{\Phi_H}$ insight the NBS $\mathbf{T_s}$ become stronger and stronger when YCC $\mathbf{g_t}$ increases and the NBS radius decreases. As a result, the mean value of the Higgs field can become negative, in comparison with its vacuum value. Taking into account the configuration of the top-quark Dirac sea insight the NBS, we see that in this case the Higgs field with an opposite sign can become a vacuum value. Such a Higgs field configuration is described by the situation when the non-relativistic kinetic term for quarks together with the mass energy of the NBS are equal to zero (at least approximately). The estimate of such fluctuations were obtained in the paper [3] and gave the following result:

$$\mathbf{g_t}\big|_{\mathbf{p.t.b.}} = \mathbf{1.06 \pm 0.18,} \tag{17}$$

which is in agreement with the experimental value (15) obtained at the EW-scale. With b-quarks contributions see Ref. [7] and Section 8) we have:

$$\mathbf{g_t}\big|_{\mathbf{(p.t.b.)}} \approx \sqrt{(1/2)} \cdot \mathbf{1.24} \approx \mathbf{0.87_7}. \tag{18}$$

The calculation of accuracy, given below and equal to 8.5%, gives the following result:

$$\mathbf{g_t}\big|_{\mathbf{(p.t.b.)}} \approx \mathbf{0.88 \pm 0.07.} \tag{19}$$

5 Main corrections to the top-quark YCC calculation.

What is the main corrections to the value of the top-quark YCC given by Eq. (18) at the border of the two phases I and II ?

As will be discussed below in Section 8, we first take into account that there virtually will be $\mathbf{b\bar{b}}$ pairs replacing the top pairs, but only the left handed components can come in (see Ref. [7]). On top of that we then have the following minor corrections listed:

1) The first correction comes from gluon interactions if we take into account simultaneously the Higgs and gluon interactions of top-quarks in all (s-, t-, u-) channels.

2) The correction from the one-loop interaction of top-quarks.

3) The correction due to that the effective Higgs mass $\mathbf{m_H}$ is not zero - as we first calculate with - but rather varies as a function of the distance $\mathbf{r}$ from the center, first reaching the normal effective Higgs mass value — say, the LEP finding value $\mathbf{m_H} \cong \mathbf{115}$ GeV — in the outskirts of the T-ball.

4) Relativistic corrections.

5) Renormgroup corrections.

6) The corrections from manybody effects — from the contributions of not only one-, but n-Higgs-bosons.

In general, all these corrections lead to **the accuracy 8.5%** and give the result (19).

As it was shown in papers [2–4], the further increasing of YCC $\mathbf{g_t}$ can give:

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

and T-balls begin to condense, forming a new phase of the SM — the phase of the condensed T-balls.

6   New phases of the SM.

Now we are in confrontation with a question: do the new phases of the SM exist? Are they different from the well-known Salam-Weinberg Higgs phase? Does a phase of the condensed T-balls exist?

The answer on this question is related with the SM parameters.

6.1   Three EW phases of the SM.

Taking into account seriously our results in the estimates of $\mathbf{g_t}$ and $\mathbf{M_T}$, we can have three phases – three vacua of the SM at the EW-scale:

I) $< \Phi_H > \neq 0, < \Phi_T > = 0$ — "Vacuum 1", the phase in which we live;

II) $< \Phi_H > \neq 0, < \Phi_T > \neq 0$ — "Vacuum 2" (honestly speaking it is a bit speculative, because it is also possible that in the $< \Phi_T >$-condensate phase $< \Phi_H > = 0$):

III) $< \Phi_H > = 0, < \Phi_T > \neq 0$ — "Vacuum 3",

which are presented symbolically by the phase diagram of **Fig. 6**.
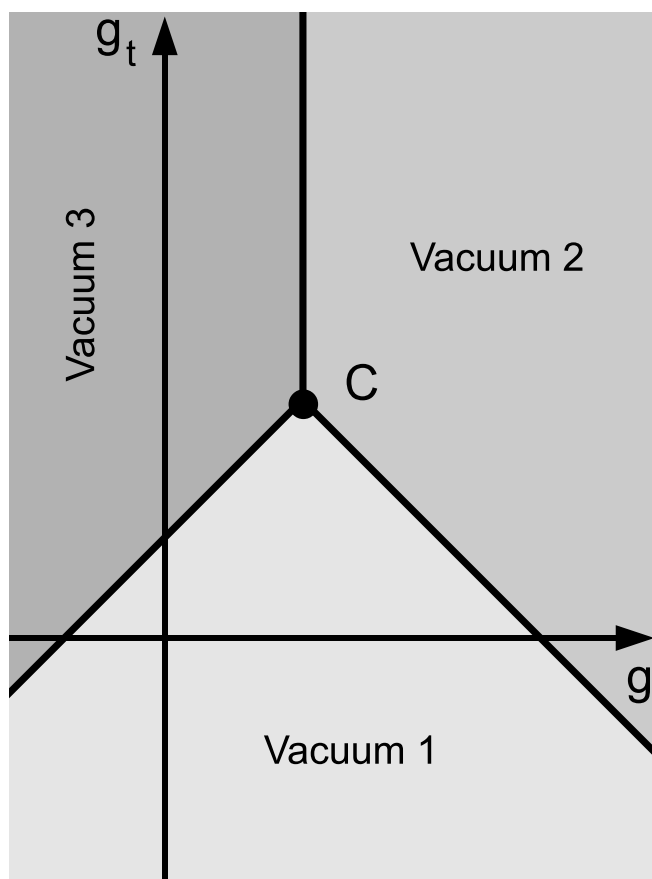
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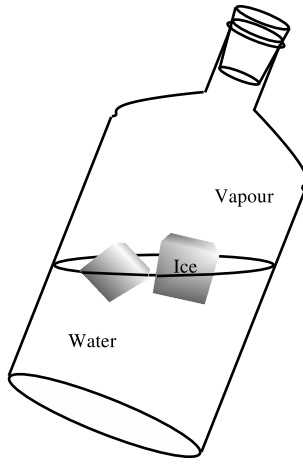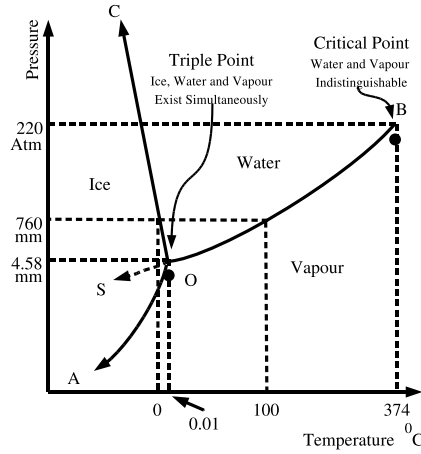Fig. 6: A symbolic phase diagram for the SM at the EW-scale.

Fig. 7:

Fig. 8:

Fig. 6 shows the critical point C (triple point), in which three phases meet together: this triple point is similar to the critical point considered in thermodynamics where the density of the vapor, water and ice are equal (see **Figs. 7,8**).

The existence of the new phases near the EW-scale can solve the problem of hierarchy. Here we recall **The Multiple Point Principle (MPP)**, suggested in Refs. [11–18].

The calculation of the NBS mass have used only the SM parameters. The MPP determines the coupling constants in the SM and therefore — the structure of the NBSs $\mathbf{T_{s,f}}$. Since at the border of the two phases I and II the top-quark YCC leads to zero mass of the NBS $\mathbf{T_s}$, we can assume that the MPP manifests the phase transitions in the SM in such a way that we have the finetuning in the SM, which solves the hierarchy problem.
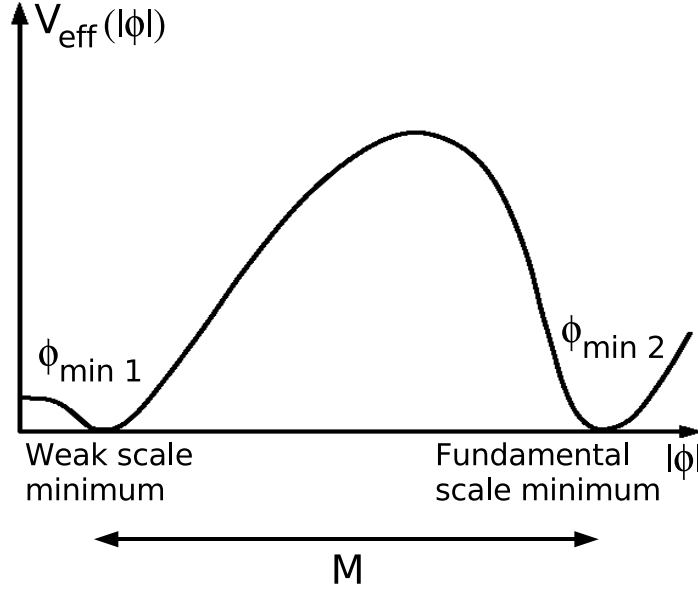
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Fig. 9: The first (our) vacuum at $|\phi| \approx 246$ GeV and the second vacuum at the fundamental scale $|\phi| \sim M_{Pl}$.

6.2 The fundamental (Planck) scale of the SM.

A priori it is quite possible for a quantum field theory to have several minima of its effective potential as a function of its scalar fields $\mathbf{\Phi}$ (exactly speaking of its norm $|\mathbf{\Phi}|$). These minima can be degenerate. Moreover, it is assumed that all vacua existing in Nature (there can be a number of several vacua) are degenerate and have the same zero, or almost zero, vacuum energy densities which coincide with the cosmological constant Λ determined by Einstein. This is confirmed by the phenomenological Cosmology.

According to the MPP, the SM has the two minima of its effective potential considered as a function of the variable $|\mathbf{\Phi_H}|$. These minima are degenerate and have $\mathbf{\Lambda = 0}$:

$$\mathbf{V_{eff}|_{min1} = V_{eff}|_{min2} = 0}, \tag{20}$$

$$\mathbf{V'_{eff}|_{min1} = V'_{eff}|_{min2} = 0}, \tag{21}$$

what is shown in **Fig. 9**.

It is assumed that the second minimum exists near the Planck scale:

$$|\mathbf{\Phi_{min2}}| \sim \mathbf{M_{Pl}}.$$

This scale is considered as a fundamental one.

7 Physical mass of scalar T_S-ball.

If we have a condensate of scalar $\mathbf{T_s}$-balls with the mass $\mathbf{m_{NBS}}$, then we can consider the potential similar to the Higgs one. In general, we have the potential:

$$\mathbf{U} = \frac{1}{2}\mathbf{m_{NBS}^2}|\mathbf{\Phi_{NBS}}|^2 + \frac{\lambda_s}{4}|\mathbf{\Phi_{NBS}}|^4 + \mathbf{C}, \tag{22}$$

where C is a cosmological constant.

If NBS is a tachyon, then $\mathbf{m_{NBS}^2} = -\mu^2$, and we have a condensate of $\mathbf{T_s}$-balls given by the second vacuum of **Fig. 5**, when:

$$\mathbf{U'} = \mathbf{0}.$$

This condensate is described by the field:

$$< |\mathbf{\Phi_{NBS}}| >= \frac{\mu}{\sqrt{\lambda_s}}. \tag{23}$$

Now we are able to determine a physically existing scalar NBS which can be observed experimentally. This NBS is similar to the fundamental particle, which can be described by the field $\mathbf{\Phi_{phys.NBS}}$.

Its mass $\mathbf{m_{phys.NBS}}$ is determined by the following requirement:

$$\frac{\partial^2\mathbf{U}}{\partial|\mathbf{\Phi_{NBS}}|^2} = \mathbf{m_{phys.NBS}^2}. \tag{24}$$

Calculating:

$$\frac{\partial\mathbf{U}}{\partial|\mathbf{\Phi_{NBS}}|} = \mathbf{m_{NBS}^2}|\mathbf{\Phi_{NBS}}| + \lambda_s|\mathbf{\Phi_{NBS}}|^3, \tag{25}$$

we obtain:

$$\frac{\partial^2\mathbf{U}}{\partial|\mathbf{\Phi_{NBS}}|^2} = \mathbf{m_{NBS}^2} + 3\lambda_s|\mathbf{\Phi_{NBS}}|^2. \tag{26}$$

Taking into account Eqs. (23) and (26), we obtain:

$$\frac{\partial^2\mathbf{U}}{\partial|\mathbf{\Phi_{NBS}}|^2} = -\mu^2 + 3\lambda_s \cdot \frac{\mu^2}{\lambda_s} = 2\mu^2 = \mathbf{m_{phys.NBS}^2}. \tag{27}$$

Then the mass of this physical scalar NBS $\mathbf{T_S} \equiv \mathbf{T_s(phys.)}$ is

$$\mathbf{M_{T_S}^2} = \mathbf{m_{phys.NBS}^2} = \mathbf{2}\mu^2. \tag{28}$$

This particle is not tachyon already. This is a scalar particle. Its mass will be estimated later.

8   Contributions of b-quarks in the "b-replaced NBS".

Up to the year 2008, we were sure that only **t**- and **t̄**-quarks are the constituents of T-balls. But at present we know that we can take into account considerable contributions of left b-quarks (see Ref. [7]).

If we had no **b** − **b̄**-quark pairs in T-balls, then there would be an essential super-position of different states of the weak isospin. The presence in the condensate of the not pure singlet states of the EW-theory could create serious problems, so it is better to live in the vacuum phase-I without T-ball condensate having

$$< \Phi_{\mathbf{T}} >= 0.$$

But the presence of b-quarks in the NBS leads to the dominance of the isospin singlets of EW-interactions only, and even that we should live in the phase-II, it can be considered without any problems, w.r.t. agreement with the SM LEP precission data.

With the inclusion of both b and t quarks we think of a more weak isospin invariant picture, and it becomes natural to think of replacing one (or several) of the t-quarks in the NBSs by b-quark(s).

Now the "b-replaced" scalar NBS still would have a mass very close to "11" NBS $\mathbf{M_{T_f}}$, say, of the order of 400 GeV, by our estimate. It is a boson:

$$\mathbf{T_S(b - replaced) = b + 5t + 6\bar{t}}. \tag{29}$$

We have also:

$$\mathbf{T_S(\bar{b} - replaced) = 6t + \bar{b} + 5\bar{t}}. \tag{30}$$

Of course, we also can consider the fermionic b-replaced NBS:

$$\mathbf{T_f(b - replaced) = b + 5t + 5\bar{t}}, \tag{31}$$

and

$$\mathbf{\overline{T_f}(\bar{b} - replaced) = 5t + 5\bar{t} + \bar{b}}. \tag{32}$$

In general case we can construct:

$$\mathbf{T_S(n_b b - replaced) = n_b b + (6t + 6\bar{t} - n_b t)}, \tag{33}$$

and

$$\mathbf{T_S(n_{\bar{b}} \bar{b} - replaced) = n_{\bar{b}} \bar{b} + (6t + 6\bar{t} - n_{\bar{b}} \bar{t})}. \tag{34}$$

Correspondingly we can obtain:

$$\mathbf{T_f(n_b b - replaced) = n_b b + (6t + 5\bar{t} - n_b t)}, \tag{35}$$

and

$$\mathbf{\overline{T_f}(n_{\bar{b}} \bar{b} - replaced) = n_{\bar{b}} \bar{b} + (5t + 6\bar{t} - n_{\bar{b}} \bar{t})}. \tag{36}$$
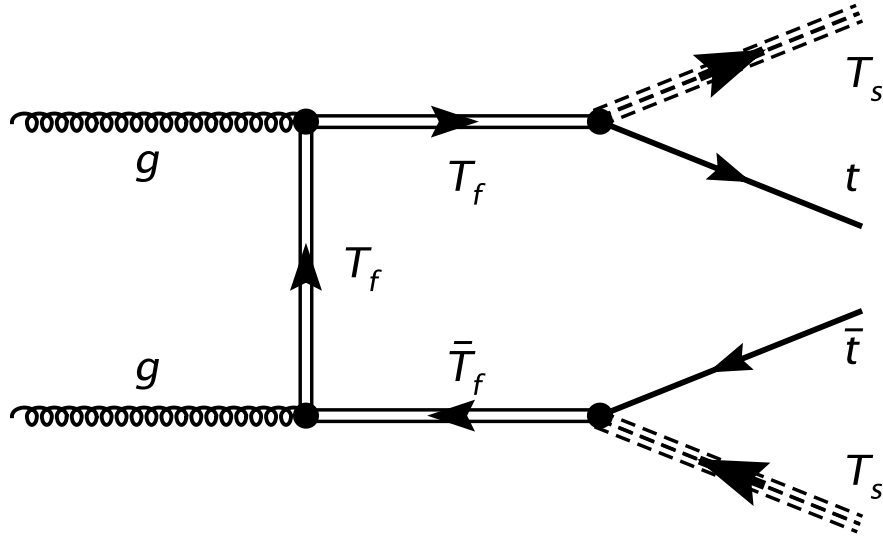
Fig. 10: Two gluon production of T-balls.

8.1 The important estimate of the mass of the "b-replaced NBS".

There is a simple way to estimate the mass of the NBS with one t replaced by a b, what we called "b-replaced NBS": $\mathbf{T_f(b-replaced) = 5t + b + 5\bar{t}}$, or $\mathbf{T_f(b-replaced, b\bar{b}) = 5t + b + n_b b\bar{b} + 5\bar{t}}$, etc.

We have seen that the b does not interact significantly (in the first approximation) with the NBS. Thus we can add a b-quark (or anti-b-quark) to the NBS "11" without changing the energy or mass. Then the b-replaced scalar NBS will have a mass $\simeq \mathbf{300}$ GeV. And the balls $\mathbf{T_f(b-replaced) = 5t + b + 5\bar{t}}$ and $\mathbf{T_f(b-replaced, b\bar{b}) = 5t + b + n_b b\bar{b} + 5\bar{t}}$ will have a mass $> \mathbf{300}$ GeV. We can consider more heavy T-balls with $\mathbf{M_T > 400}$ GeV, but they will have smaller cross-sections of their production, because they are less strongly bound and can a less extend to be considered approximately fundamental particle.

8.2 Two-gluon diagrams for the NBS production.

The "b-replaced NBS" $\mathbf{T_S(b-replaced)}$ cannot be produced simply in a pair by a gluon vertex, because it is a color singlet $\underline{\mathbf{1}}$.

A pair $\mathbf{T_f\overline{T_f}}$ of "11" NBS can be produced by a gluon, because it is a color triplet, and then "11" could make a rather soft emission of a b-quark and also a scalar "b-replaced NBS". But such a "soft b" emission may be difficult to detect at FNAL (Tevatron).

There also is an alternative idea (see Ref. [8]).

According to the idea by Li-Nielsen, the t or b emission and the scalar "b-replaced NBS" might be produced via the two gluons diagram with strong vertices (see, for example, the diagram given by **Fig. 10**.)

Let us stress that if our description works, then the fermionic

"b-replaced NBS" would make a perfect simulation of a fourth family $\mathbf{t'}$.

It only deviates:

1) by needing either a more complicated diagrams for its production,

2) or by the emission of soft b-quarks,

3) or by simultaneously emitted a $\mathbf{W}$-boson and $\mathbf{T_S}$:

$$''\mathbf{b - replaced''} \ \mathbf{NBS} \rightarrow \mathbf{T_S} + \mathbf{W}.$$

Now we take in our model the particle simulating the $\mathbf{t'}$: a fermionic "b-replaced NBS", for instance,

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

or

$$\mathbf{T_f(b - replaced, n_a b\bar{b})} = \mathbf{5t + b + n_a b\bar{b} + 5\bar{t}}, \quad \text{etc.}$$

So then we could really claim: **we expect that the Tevatron-LHC experiments should find or a fourth family t'-quark, or the fermionic "b-replaced NBS", or both of them.**

We have shown that the bound states $\mathbf{T_S(b-replaced)}$ and $\mathbf{T_S(b-replaced, n_a b\bar{b})}$ can have masses very close to "11" NBS: $\mathbf{M_{T_f}}$ ($\sim 300 - 400$ GeV, by our prediction). We also have considered more heavy "b-replaced" NBS (T-balls) with $\mathbf{M_T > 400}$ GeV. All of them can be investigated at LHC.

Concerning how to distinguish the two hypotheses:

I) the true fourth family,

II) our bound state "b-replaced NBS",

we can immediately say: we do not expect exactly the same cross-section times branching ratio as that to be estimated for the true fourth family. Thus if the cross-section agrees extremely precisely with the calculation for a simple fundamental fourth family t'-quark, then it is suggested that our model is not the right explanation, but if it is in the same range, but do not match perfectly, then it would support our model.

There are several deviations in the case of the "b-replaced NBS" particle production:

A) form-factors;

B) the soft b-emission;

C) some diagrams not having analogues in the fundamental $\mathbf{t'}$ production;

D) possibly alternative decays.

9 The Tevatron-LHC experiments searching for W, Z, t, t' and different jets.

This talk, as the talk by Holger Bech Nielsen at CERN [1], is devoted to the main purpose of the experiment – to search for the Higgs boson, and in this connection to search for T-balls, just what we were considering as the b-replaced NBSs.
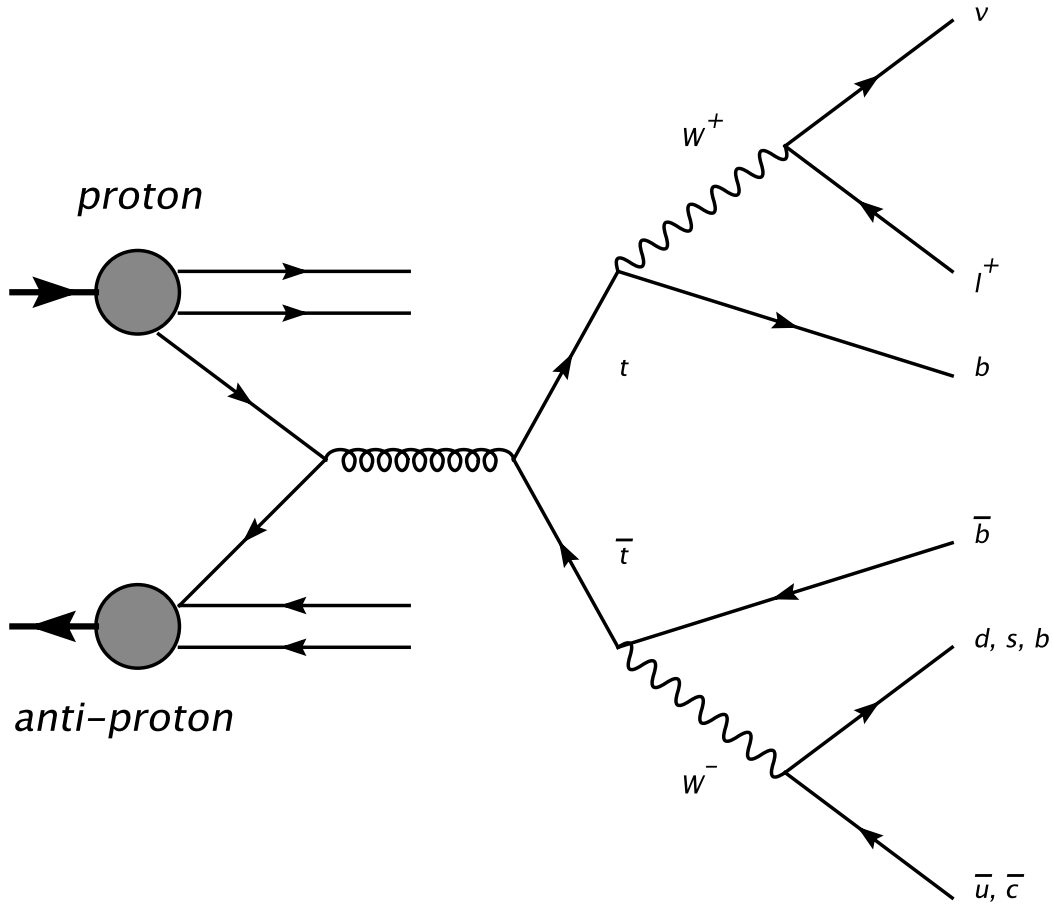
Fig. 11:

From the beginning, we have considered the following NBSs:

$$\mathbf{6t + 6\bar{t}}, \qquad \mathbf{6t + 5\bar{t}}.$$

First of these NBS is a scalar boson $\mathbf{T_S}$, and the second one is a fermion $\mathbf{T_f}$ with quantum numbers of t-quark, which is difficult to distinguish from the quark of the fourth generation.

A typical process which is observed at the Tevatron ($\mathbf{p\bar{p}}$-collisions, $\sqrt{\mathbf{s}} \simeq \mathbf{1.96}$ GeV) is shown in **Fig. 11**. Unfortunately, the cross-section for the Higgs boson production at the Tevatron is predicted to be rather small and sufficient data for a discovery of H is unlikely to be collected before the date when more powerful LHC experiment begins to work in 2008.
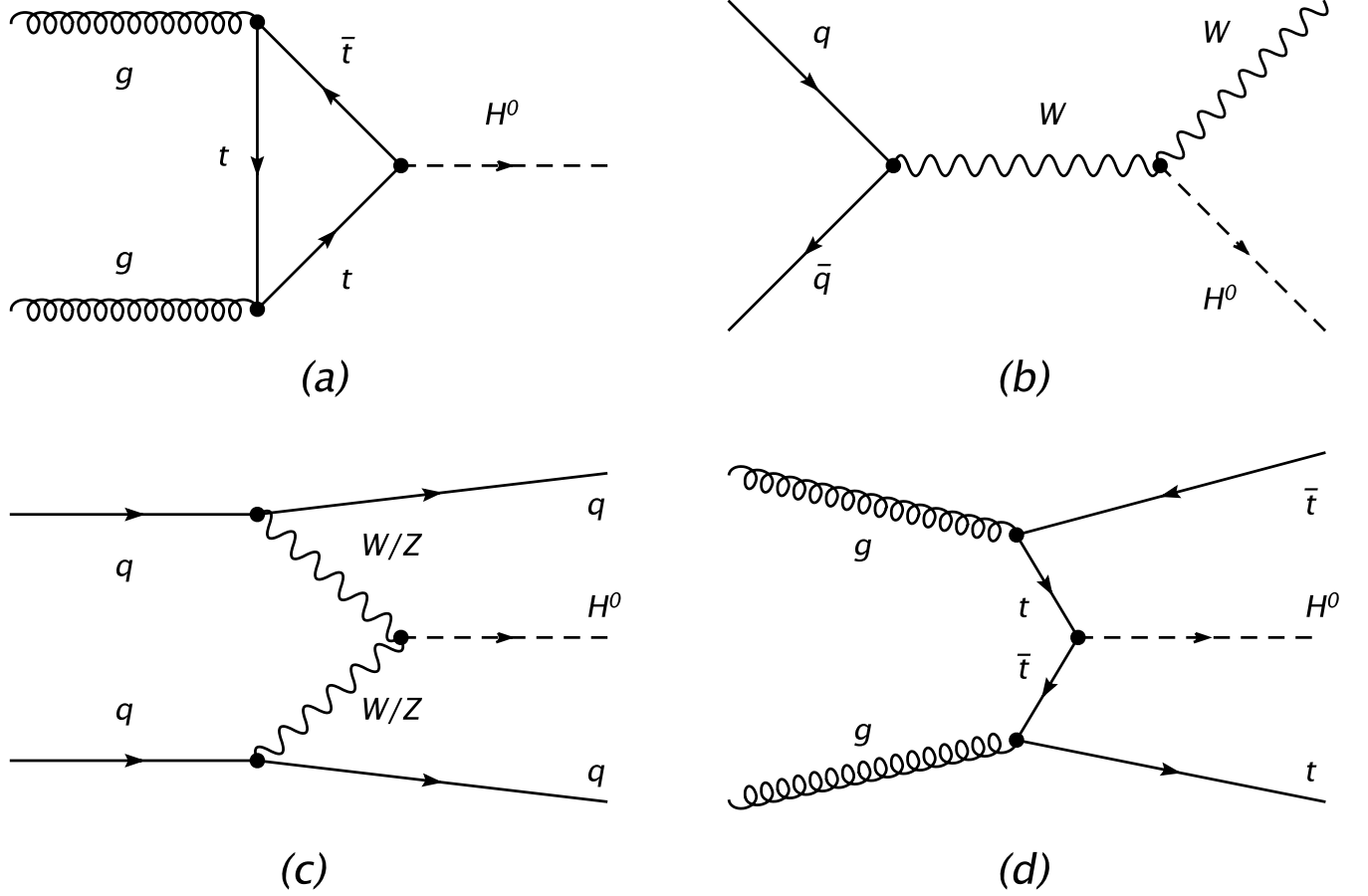
Fig. 12: Feynman diagrams for the processes (a) $gg \to t\bar{t}H^0$, (b) $q\bar{q} \to t\bar{t}H^0$, (c) $gg \to t\bar{t}b\bar{b}$, (d) $gg \to Z/W/\gamma^* \to H^0(t\bar{t} \ or \ b\bar{b})$.

There are several Higgs production methods at the LHC, which lead to the observable Higgs production cross-sections $\sigma(\mathbf{pp} \to \mathbf{HX})$. These include:

- gluon-gluon fusion;
- WW and ZZ fusion;
- Associated production of W and Z bosons;
- Associated production of $\mathbf{t\bar{t}}$, or $\mathbf{t'\bar{t}'}$.

Typical Feynman diagrams for the signal and background processes are shown in **Figs. 12 and 13**.

Fig. 13: Feynman diagrams for the production of leptons and jets.
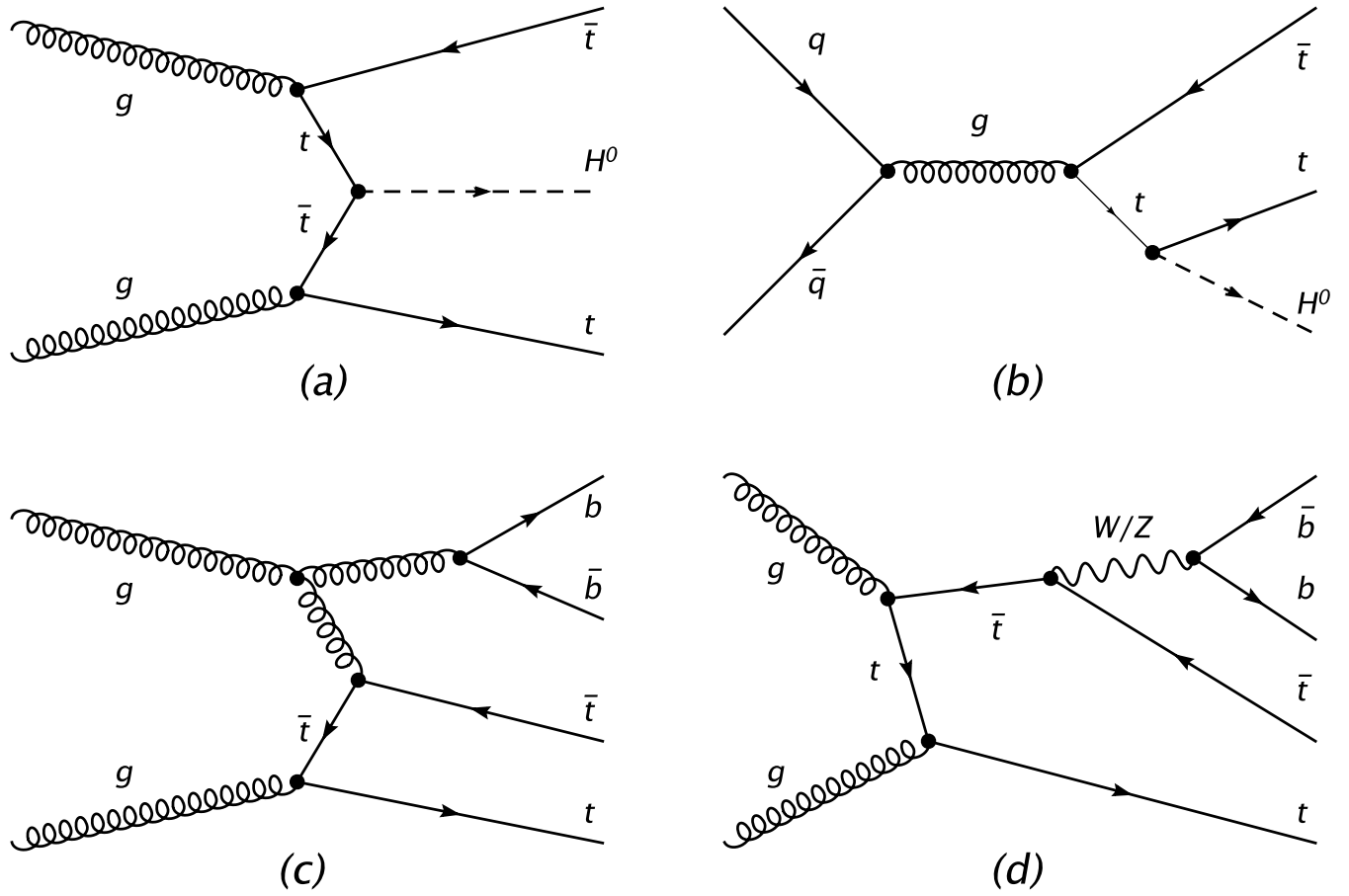
At the LHC, $t\bar{t}H^0$ is produced 90% of the time via a gluon-gluon interaction and only by a qq-interaction in the remaining 10%.

Once produced, a top-quark decays almost exclusively to the W-boson and b-quark.

W-bosons decay hadronically about 2/3 of the time, producing two jets in the final state.

The branching ratios for these processes are shown in the **Table 1**:

<div align="center">

Table 1

t → Wb	**0.998**,
W → lν	**0.108**,
W → hadrons	**0.676**,
t̄t → lνbjjb̄	**0.291**.

</div>

The final state with the highest branching fraction is where both top-quarks decay hadronically, producing light-jets and two b-jets. When the decay of the Higgs boson to the two b-quarks is taken into account, this produces a purely hadronic final state. Requiring one of the W-bosons to decay leptonically produces a final state with four b-jets, two light-jets, one lepton missing momentum (see **Fig. 14**).

Only **l** and μ ($l = e$, μ) are considered in this analysis.

10 <u>Can we see T-balls at LHC or Tevatron?</u>

At present, the first question is: can we observe the NBSs T-balls at LHC or Tevatron?

If the mean square radius of the T-ball is small in comparison with its Compton wave length:

$$\mathbf{r_0} \approx (\sqrt{2}\mathbf{M_t})^{-1} << \frac{1}{\mathbf{m_{NBS}}}, \tag{37}$$

then the NBS can be considered as an almost fundamental particle. Then our NBS are strongly bound and can be observed at colliders. As $\mathbf{t'}$-quark of the fourth generation the fermionic NBS $\mathbf{T_f}$ will belong to the fundamental representation $\underline{3}$ (color triplet).

What processes with the participation of T-balls have to play the main role in the experiments at colliders?

A) First, the possible decay mechanism:

$$\mathbf{H} \rightarrow \mathbf{2T_S}, \tag{38}$$

if $\mathbf{M_{T_S}} < \frac{1}{2}\mathbf{m_H}$.
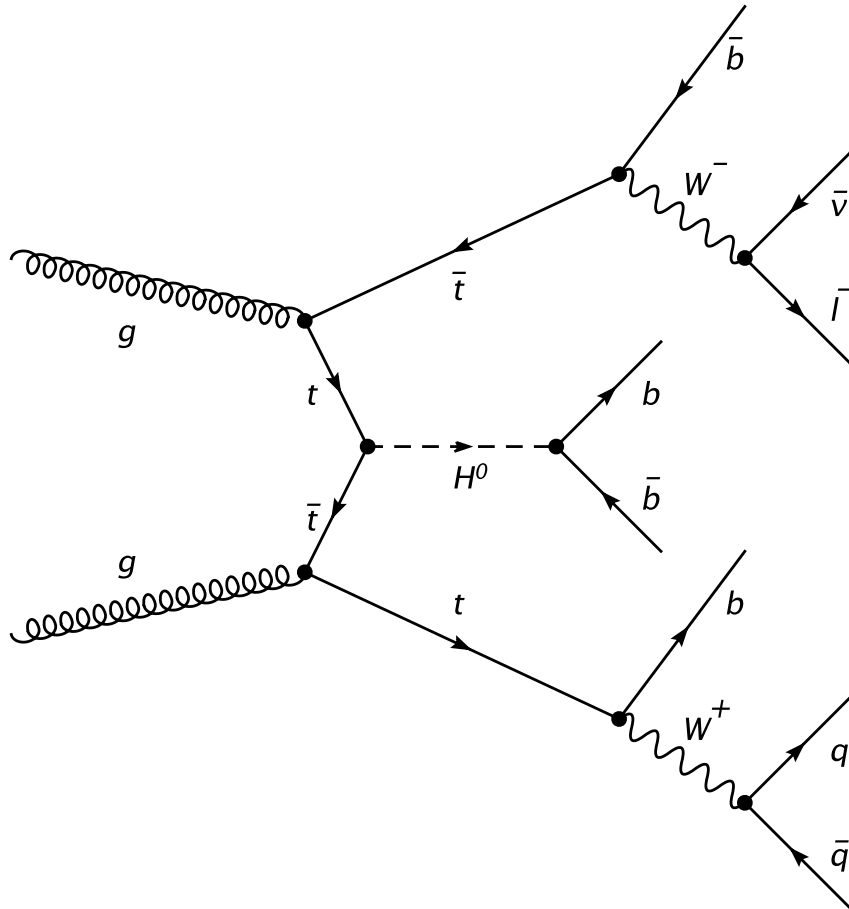
Fig. 14: Feynman diagrams for the production of leptons and jets.

Using limits given by the Tevatron experiments:

$$120 \lesssim m_H \lesssim 160 \ \mathbf{GeV}, \tag{39}$$

we obtain the requirement for the Higgs decay mechanism to work (on shell):

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

If $M_{T_S} > \frac{1}{2}m_H$, then the decay (38) is absent in nature, and in the above-mentioned process the $\mathbf{T_S}$-balls fly away forming jets. As a result, we have the production of hadrons with high multiplicity :

$$\mathbf{T_S(b - replaced) \rightarrow JETS}.$$

Jets create a lot of hadrons [2] .

Since the coupling of H with T-balls is very strong, then **the total decay width of the Higgs boson is enlarged due to the decays of H in $\mathbf{T_S}$,** while the decay width of H into leptons and photons (these channels are easily observed experimentally) is essentially less.

We see now that the present theory of T-balls predicts the observation of the Salam-Weinberg Higgs boson H as a broad peak at colliders.

B) Second, the all processes with the replacement $\mathbf{t\bar{t} \rightarrow T_f \overline{T_f}}$ (see, for example, **Fig. 10**.)

In the most optimistic cases the NBS $\mathbf{6t + 5\bar{t}}$ plays a role of the fundamental quark of the fourth generation, say, with mass $\simeq 300$ GeV, given by our preliminary estimate.

The most important production mechanism for producing pairs of T-balls is **two initial gluons** that must be provided, say, from the Tevatron hadronic $\mathbf{p + \bar{p}}$ collisions (see Refs. [8] and **Fig. 10**).

According to the diagram of **Fig. 10** , the following decay is possible to observe at high energy colliders:

$$\mathbf{T_f(b - replaced) \rightarrow T_S + t + n_a b\bar{b}},$$

since the mass of $\mathbf{T_S}$ is expected to be less than the $\mathbf{T_f}$-mass.

---

[2]In Ref. [8] Li and one of us (H.B.N) have though argued that for the very light bound states the number of jets will be more moderate and the number of hadrons not so enormous again.
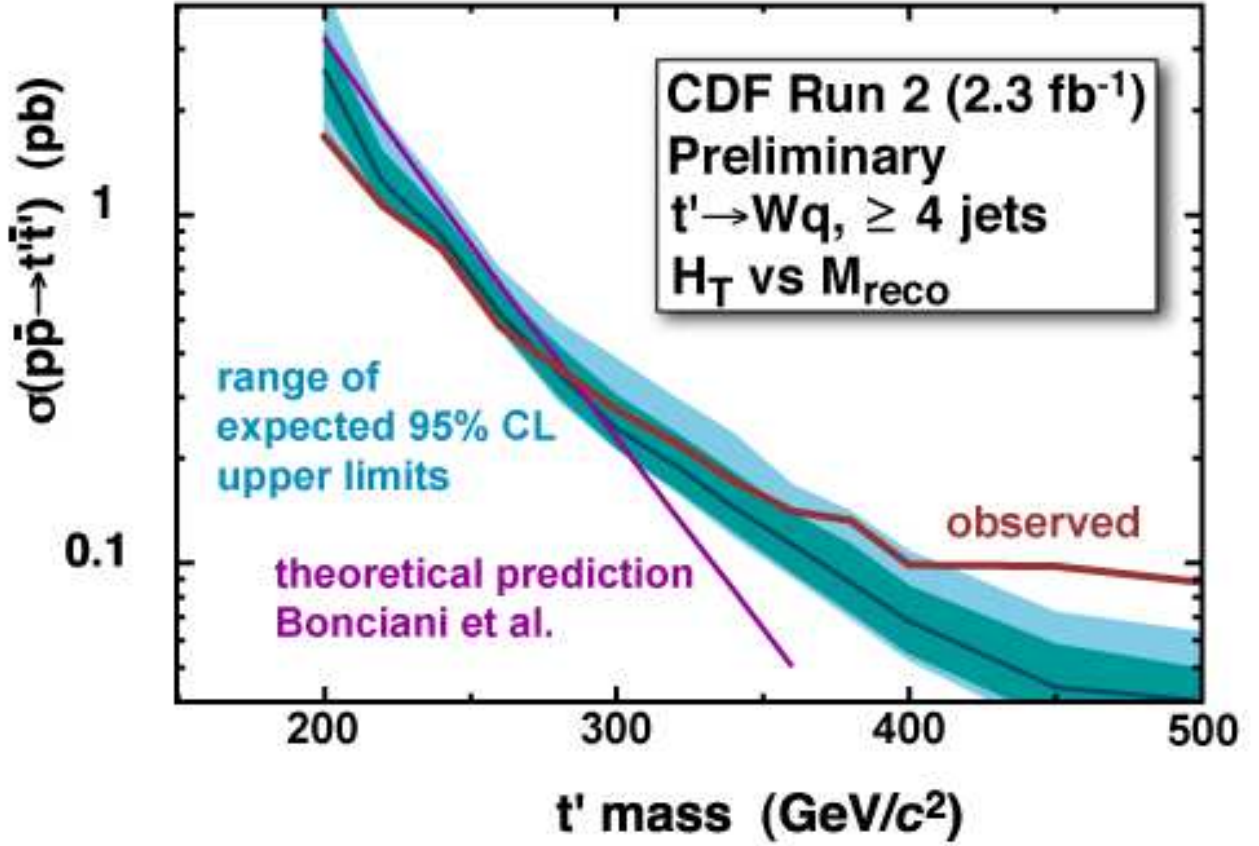
Fig. 15: Upper limit, at 95% CL, a fourth-generation t' quark with a mass below 284 GeV is excluded.

11 CDF II Detector experiment searching for heavy top-like quarks at the Tevatron.

Have we seen at colliders $\mathbf{t'}$ or $\mathbf{T_f}$, or both of them?

Recent experiments with CDF II Detector of the Tevatron [22, 23] do not exclude the existence of $\mathbf{t'}$ or T-balls if the mass is over 284 GeV (see **Figs. 15-18**). Here we shall argue for that the very strange events, observed at the Tevatron as a fourth family $\mathbf{t'}$, which decays into a **W** and a presumed quark-jet, might in our model find another explanation: maybe it is the decay of a b-replaced NBS (T-ball) into a **W** and a gluon jet. But, of course, it is very difficult to measure whether the jet coming out is from a gluon or quark.
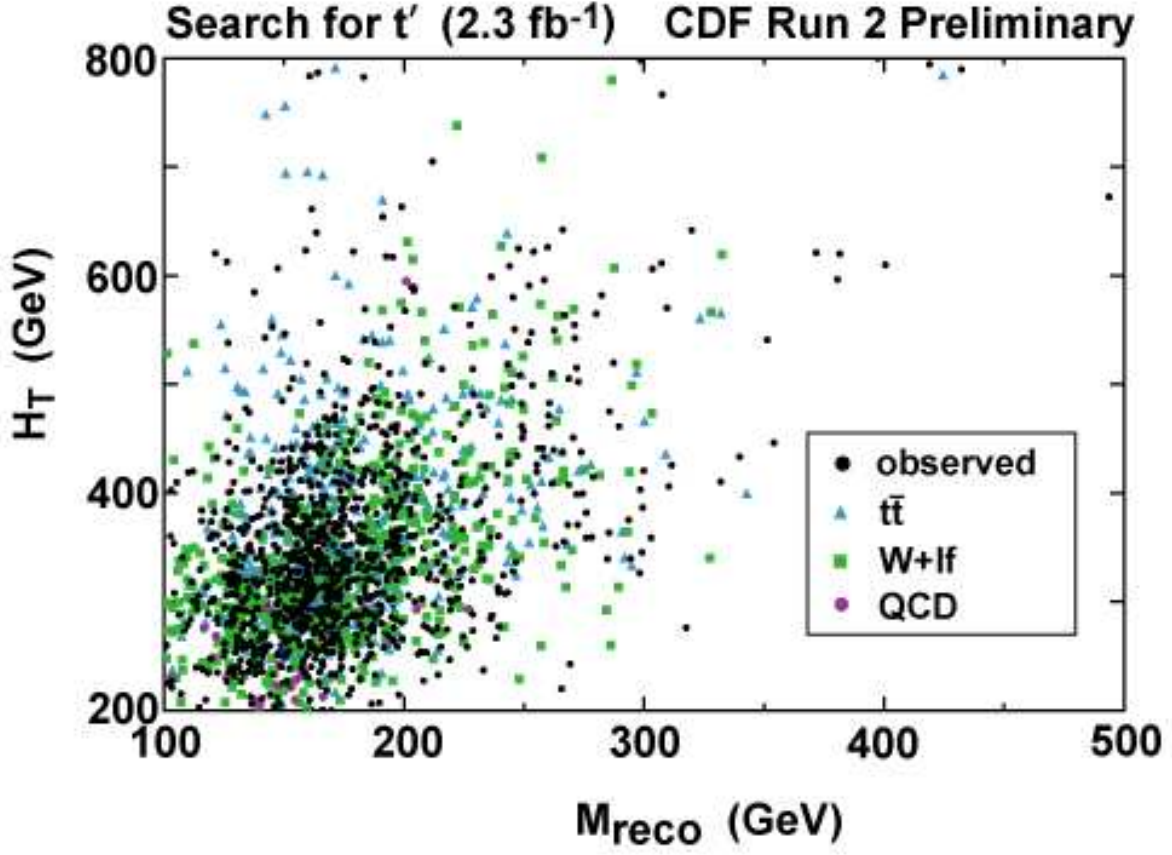
Fig. 16: 2D distribution of H_T vs M_{rec} distribution showing the data (black points) and the fitted number of background events; QCD (purple circles), W+JETS (green squares) and $t'\bar{t}'$ (blue triangles)
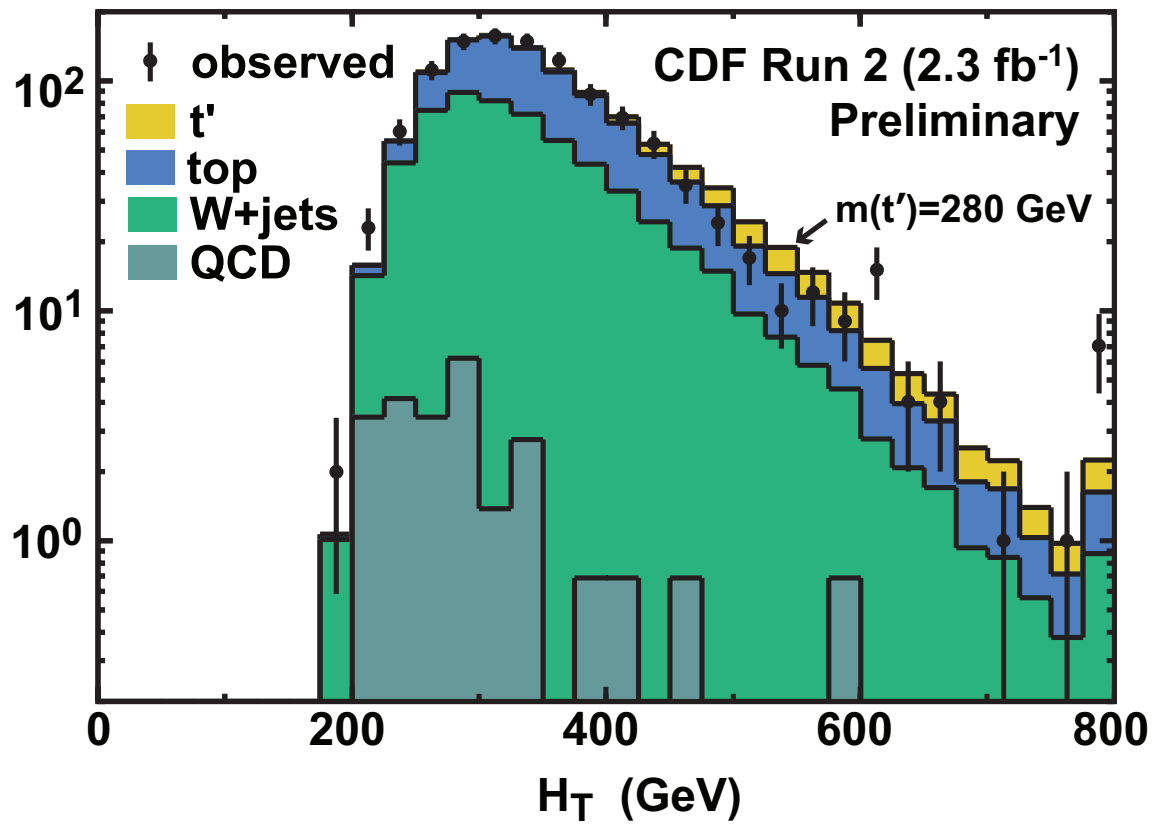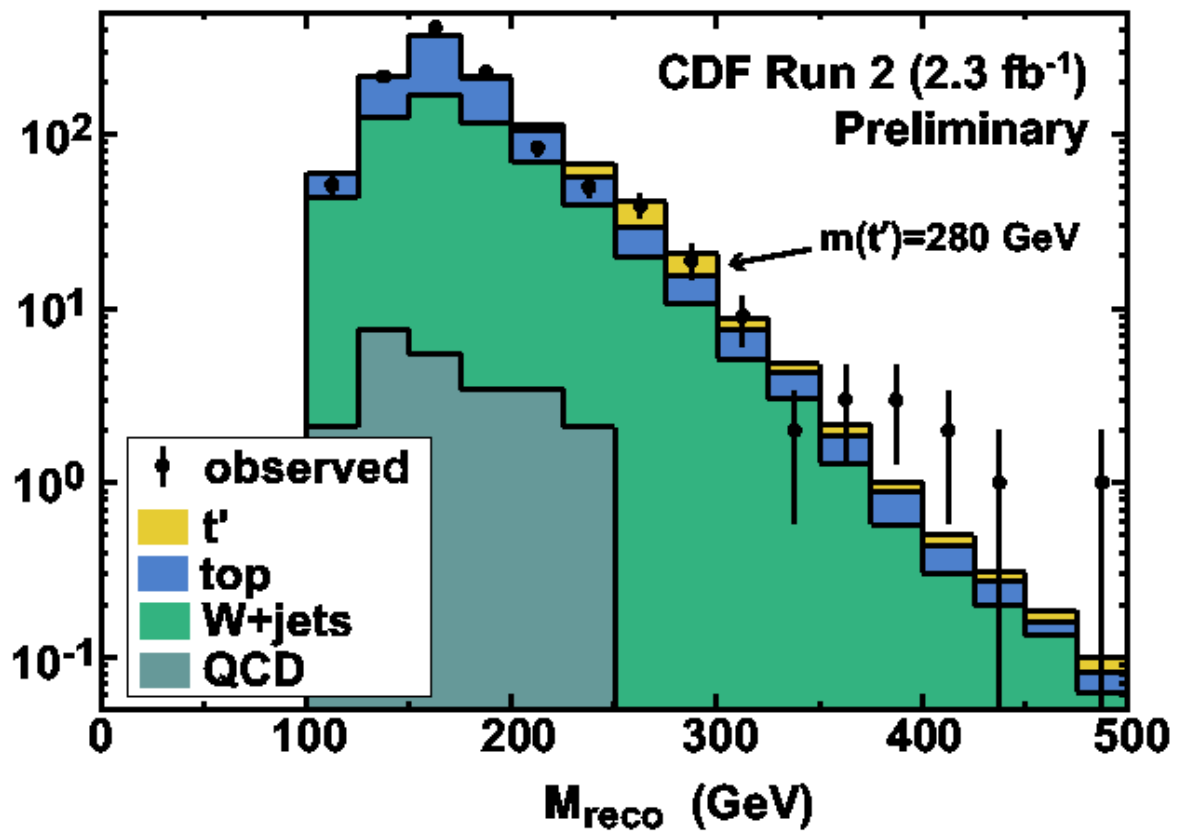
Fig. 17:

Fig. 18:

12 Charge multiplicity in decays of T-balls.

Actually Li and Nielsen suggested in Ref. [8] that the NBSs would decay to a rather low number of jets, but at first one might very reasonably think that since we have to do with bound states of very many constituents and actually $6t\bar{t}$ pairs, it sounds that the possibility of them decaying into as many jets as there are pairs to annihilate, say - or even the number of constituents - has some intuitive appeal and should not just be thrown away as a possibility by the Li-Nielsen rather non-safe argument. We shall therefore here develop what we would expect in the case of the separate $t\bar{t}$ pairs decaying essentially separately, although we do not really believe that any longer: if the mass of the NBS, containing 6 pairs of $t\bar{t}$, is M_S, then the energy per one annihilation of $t\bar{t}$ approximately is equal to the following value:

$$E_{an} = E_{(for\ one\ annihilation)} \approx \frac{1}{6}M_S, \tag{40}$$

e.g.

$$E_{(for\ one\ annihilation)} \approx 10\ \textbf{GeV},$$

if

$$M_S \approx 60\ \text{GeV}.$$

In this case, during the annihilation produced by e^+e^--collisions, the special charge multiplicity is

$$< N_{ch}(e^+e^-) > \approx 10,$$

while the annihilation produced by pp-collisions, the special charge multiplicity is

$$< N_{ch}(pp) > \approx 6.$$

Such calculations of $< N_{ch} >$ vs E_{an} are based on the investigation of Ref. [23]. Here for $M_S \approx 60\ \textbf{GeV}$ we obtain the following values for the charge multiplicity:

$$N_{ch}(e^+e^-) \approx 6 \cdot 10 \approx 60, \tag{41}$$

$$N_{ch}(pp) \approx 6 \cdot 6 \approx 36. \tag{42}$$

The value of the charge multiplicity weakly depends on the NBS mass. For instance, if $M_S \approx 80\ \textbf{GeV}$, then:

$$< N_{ch}(pp) > \approx 6.5,$$

and

$$N_{ch}(pp) \approx 6 \cdot 6.5 \approx 39. \tag{43}$$

But if $M_S \approx 100\ \textbf{GeV}$, then:

$$< N_{ch}(pp) > \approx 7,$$
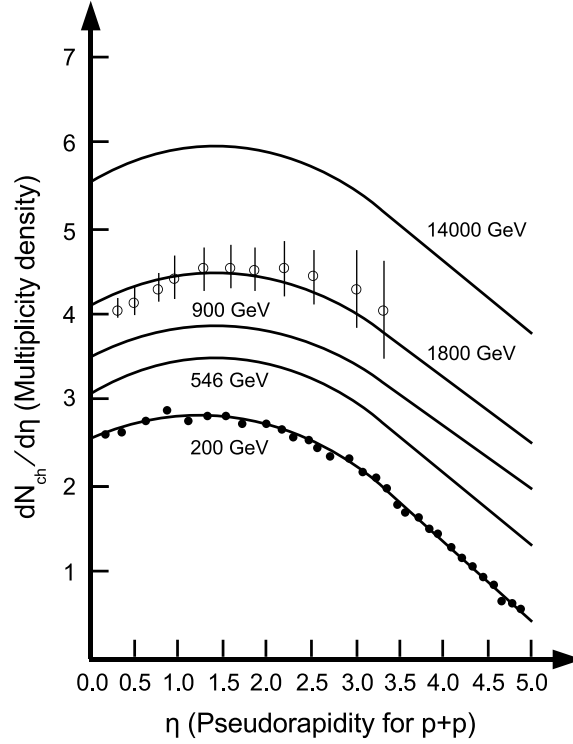
Fig. 19:

and

$$N_{ch}(pp) \approx 6 \cdot 7 \approx 42. \tag{44}$$

However, such a maximally possible charge multiplicity will not be realized in practice, because between the produced in the final state pairs $t\bar{t}$, or $b\bar{b}$, can exist extra exchanges by gluons and the Higgs bosons giving new annihilations. And we shall obtain less jets.

Indeed, it would be very strange if the decay width of the T-balls was small. Then we would have narrow peaks in JETS. It would be exactly a good way to see that our model were right if you could find some narrow peak in the distribution of the total mass of some JETS.

For **pp**-collisions the estimates [8] give :

$$\frac{dN_{ch}}{d\eta}|_{max} \approx 6. \tag{45}$$

Such a value is expected for this derivative at LHC (see **Fig. 19**). The maximum of this curve corresponds to the LHC energy $W = 14$ TeV in **pp**-collisions.

Fig. 20:

The dependence N_{ch} vs W is presented in **Fig. 20**. Here
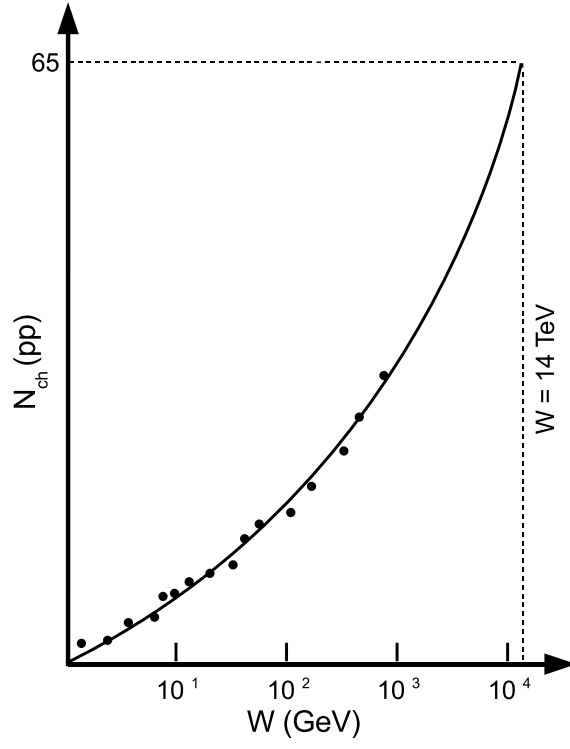
$$N_{ch}(pp)|_{W=14 \text{ TeV}} \approx 65. \tag{46}$$

These calculations (figures) show that T-balls can give an essential contributions to charge multiplicity in **pp**-collisions, provided that their decays really go as if each $t\bar{t}$ pair decayed separately and not as the recent estimate by Li-Nielsen [8].

13   Conclusions.

1. The present investigation is devoted to the main problems of the Standard Model connected with searching for the Higgs boson and based on the following three assumptions:

   a) there exists **1S**–bound state of $\mathbf{6t + 6\bar{t}}$, e.g. bound state of 6 quarks of the third generation with their 6 anti-quarks;

   b) 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;

   c) such strong forces are produced by the Higgs interactions: the interactions of top-quarks via the virtual exchange of the scalar Higgs bosons coupling with a large value of the top-quark Yukawa coupling constant $\mathbf{g_t}$.

   A new bound state $\mathbf{6t + 6\bar{t}}$, which is a color singlet, was first suggested **by Froggatt and Nielsen** and now was named T-ball, or T-fireball.

2. Our theory also predicts the existence of the new bound state (NBS) $\mathbf{6t + 5\bar{t}}$, which is a color triplet and a fermion similar to the quark of the fourth generation having quantum numbers of t-quark.

3. We have also considered "b-replaced" NBSs:

$$\mathbf{T_S(n_b b - replaced) = n_b b + (6t + 6\bar{t} - n_b t)}$$

   and

$$\mathbf{T_f(n_b b - replaced) = n_b b + (6t + 5\bar{t} - n_b t),}$$

   where $\mathbf{n_b}$ is the integer number. The presence of b-quarks in the NBS leads to the dominance of the isospin singlets: with the inclusion of both b and t quarks we obtain a more weak isospin invariant picture.

4. We have estimated the masses of the lightest "b-replaced" NBSs:

$$\mathbf{M_{T(b-replaced)} \simeq (300 - 400) \text{ GeV},}$$

   and predicted the existence of the more heavy "b-replaced" NBSs:

$$\mathbf{M_{T(n_b b-replaced)} > 400 \text{ GeV}}$$

   with $\mathbf{n_b > 1}$.

5. We have developed a theory of the T-ball's condensate, and predicted the possibility of the existence of the three SM phases at the EW-scale, calculating the top-quark Yukawa coupling constant at the border of the two phases (with T-ball's condensate and without it) equal to: $\mathbf{g_t \approx 1}$.

6. It was shown that CDF II Detector experiment searching for heavy top-like quarks at the Tevatron ($\mathbf{p\bar{p}}$-collisions, $\sqrt{\mathbf{s}} \simeq \mathbf{1.96}$ GeV) can observe $\mathbf{T_f}$-balls with masses up to 400 GeV.

7. We have considered all processes with T-balls, which can be observed at LHC, especially the decay

$$\mathbf{H \rightarrow 2T_S}$$

and the production of

$$\mathbf{T_f, \overline{T_f}}$$

as an alternative of the $\mathbf{t'\overline{t'}}$ production (where $\mathbf{t'}$ is the quark of the fourth generation with t-quark quantum numbers).

8. We have estimated the charge multiplicity at the energy W=14 GeV at LHC:

$$\mathbf{N_{ch}(pp)|_{W=14}} \, \text{TeV} \approx \mathbf{65},$$

and have shown that the charge multiplicity coming from the T-ball's decays is of order of this value.

9. In this investigation we have argued that T-balls can explain why it is difficult to observe the Higgs boson H at colliders as sharp peak: T-balls can strongly enlarge the decay width of the Higgs particle.

14 Appendix. The Standard Model Lagrangian.

The standard model is a gauge theory of the microscopic interactions. The strong interaction part (QCD) is described by the Lagrangian

$$\mathrm{L}_{SU_3} = -\frac{1}{4}F^i_{\mu\nu}F^{i\mu\nu} + \sum_r \bar{q}_{r\alpha}i\,\slashed{D}^\alpha_\beta\,q^\beta_r,\tag{47}$$

where g_s is the QCD gauge coupling constant,

$$F^i_{\mu\nu} = \partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_s f_{ijk}\,G^j_\mu\,G^k_\nu\tag{48}$$

is the field strength tensor for the gluon fields $G^i_\mu,\ i = 1,\cdots,8$, and the structure constants $f_{ijk}\ (\mathbf{i},\mathbf{j},\mathbf{k} = \mathbf{1},\cdots,\mathbf{8})$ are defined by

$$[\lambda^i, \lambda^j] = 2if_{ijk}\lambda^k,\tag{49}$$

where λ^i are the Gell-Mann SU_3 matrices.

The F^2 term leads to three and four-point gluon self-interactions. The second term in L_{SU_3} is the gauge covariant derivative for the quarks: q_r is the rth quark flavor, $\alpha, \beta = 1, 2, 3$ are color indices, and

$$D^\alpha_{\mu\beta} = (D_\mu)_{\alpha\beta} = \partial_\mu\delta_{\alpha\beta} + ig_s\,G^i_\mu\,L^i_{\alpha\beta},\tag{50}$$

where the quarks transform according to the triplet representation matrices $L^i = \lambda^i/2$. The color interactions are diagonal in the flavor indices, but in general change the quark colors. They are purely vector (parity conserving). There are no bare mass terms for the quarks in (47). These would be allowed by QCD alone, but are forbidden by the chiral symmetry of the electroweak part of the theory. The quark masses will be generated later by spontaneous symmetry breaking. There are in addition effective ghost and gauge-fixing terms which enter into the quantization of both the SU_3 and electroweak Lagrangians, and there is the possibility of adding an (unwanted) term which violates CP invariance.

The electroweak theory is based on the $SU_2 \times U_1$ Lagrangian:

$$\mathrm{L}_{SU_2 \times U_1} = \mathrm{L}_{\text{gauge}} + \mathrm{L}_\varphi + \mathrm{L}_f + \mathrm{L}_{\text{Yukawa}}.\tag{51}$$

The gauge part is

$$\mathrm{L}_{\text{gauge}} = -\frac{1}{4}F^i_{\mu\nu}F^{\mu\nu i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu},\tag{52}$$

where $W^i_\mu,\ (i = 1,\ 2,\ 3)$ and B_μ are respectively the SU_2 and U_1 gauge fields, with field strength tensors

$$\begin{aligned}B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu\\ F_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\epsilon_{ijk}W^j_\mu W^k_\nu,\end{aligned}\tag{53}$$

where $g(g')$ is the SU_2 (U_1) gauge coupling and ϵ_{ijk} is the totally antisymmetric symbol. The SU_2 fields have three and four-point self-interactions.

The field B belongs to the U_1 theory and is associated with the weak hypercharge $Y = Q - T_3$, where Q and T_3 are respectively the electric charge operator and the third component of weak SU_2. It has no self-interactions. The B and W_3 fields will eventually mix to form the photon and Z boson.

The scalar part of the Lagrangian is

$$\text{Ł}_\varphi = (D^\mu \varphi)^\dagger D_\mu \varphi - V(\varphi), \tag{54}$$

where $\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$ is a complex Higgs scalar, which is a doublet under SU_2 with U_1 charge $Y_\varphi = +\frac{1}{2}$. The gauge covariant derivative is

$$D_\mu \varphi = \left(\partial_\mu + ig \frac{\tau^i}{2} W^i_\mu + \frac{ig'}{2} B_\mu \right) \varphi, \tag{55}$$

where the τ^i are the Pauli matrices. The square of the covariant derivative leads to three and four-point interactions between the gauge and scalar fields.

$V(\varphi)$ is the Higgs potential. The combination of $SU_2 \times U_1$ invariance and renormalizability restricts V to the form

$$V(\varphi) = +\mu^2 \varphi^\dagger \varphi + \lambda (\varphi^\dagger \varphi)^2. \tag{56}$$

For $\mu^2 < 0$ there will be spontaneous symmetry breaking. The λ term describes a quartic self-interaction between the scalar fields. Vacuum stability requires $\lambda > 0$.

The fermion term is

$$\text{Ł}_F = \sum_{m=1}^{F} \left(\bar{q}^0_{mL} i \not{D} q^0_{mL} + \bar{l}^0_{mL} i \not{D} l^0_{mL} + \bar{u}^0_{mR} i \not{D} u^0_{mR} + \bar{d}^0_{mR} i \not{D} d^0_{mR} + \bar{e}^0_{mR} i \not{D} e^0_{mR} \right). \tag{57}$$

In (57) m is the family index, $F \geq 3$ is the number of families, and $L(R)$ refer to the left (right) chiral projections $\psi_{L(R)} \equiv (1 \mp \gamma_5)\psi/2$. The left-handed quarks and leptons

$$q^0_{mL} = \begin{pmatrix} u^0_m \\ d^0_m \end{pmatrix}_L \qquad l^0_{mL} = \begin{pmatrix} \nu^0_m \\ e^{-0}_m \end{pmatrix}_L \tag{58}$$

transform as SU_2 doublets, while the right-handed fields u^0_{mR}, d^0_{mR}, and e^{-0}_{mR} are singlets. Their U_1 charges are $Y_{q_L} = \frac{1}{6}$, $Y_{l_L} = -\frac{1}{2}$, $Y_{\psi_R} = q_\psi$. The superscript 0 refers to the weak eigenstates, i.e., fields transforming according to definite SU_2 representations. They may be mixtures of mass eigenstates (flavors). The quark color indices $\alpha = r$, g, b have been suppressed. The gauge covariant derivatives are

$$
\begin{aligned}
D_\mu q^0_{mL} &= \left(\partial_\mu + \tfrac{ig}{2} \tau^i W^i_\mu + i\tfrac{g'}{6} B_\mu \right) q^0_{mL} & D_\mu u^0_{mR} &= \left(\partial_\mu + i\tfrac{2}{3} g' B_\mu \right) u^0_{mR} \\
D_\mu l^0_{mL} &= \left(\partial_\mu + \tfrac{ig}{2} \tau^i W^i_\mu - i\tfrac{g'}{2} B_\mu \right) l^0_{mL} & D_\mu d^0_{mR} &= \left(\partial_\mu - i\tfrac{g'}{3} B_\mu \right) d^0_{mR} \\
& & D_\mu e^0_{mR} &= \left(\partial_\mu - ig' B_\mu \right) e^0_{mR},
\end{aligned} \tag{59}
$$

38

from which one can read off the gauge interactions between the W and B and the fermion fields. The different transformations of the L and R fields (i.e., the symmetry is chiral) is the origin of parity violation in the electroweak sector. The chiral symmetry also forbids any bare mass terms for the fermions.

The last term in (51) is

$$L_{\text{Yukawa}} = -\sum_{m,n=1}^{F} \left[Y_{mn}^u \bar{q}_{mL}^0 \tilde{\varphi} u_{mR}^0 + Y_{mn}^d \bar{q}_{mL}^0 \varphi d_{nR}^0 + Y_{mn}^e \bar{l}_{mn}^0 \varphi e_{nR}^0 \right] + \text{H.C.}, \qquad (60)$$

where the matrices Y_{mn} describe the Yukawa couplings between the single Higgs doublet, φ, and the various flavors m and n of quarks and leptons. One needs representations of Higgs fields with hypercharges $Y = \frac{1}{2}$ and $-\frac{1}{2}$ to give masses to the down quarks, the electrons, and the up quarks. The representation $\varphi^\dagger$ has $Y = -\frac{1}{2}$, and $\tilde{\varphi} \equiv i\tau^2 \varphi^\dagger = \begin{pmatrix} \varphi^{0\dagger} \\ -\varphi^- \end{pmatrix}$ has $Y = -\frac{1}{2}$. All of the masses can therefore be generated with a single Higgs doublet if one makes use of both φ and $\tilde{\varphi}$.

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