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# Top-quark physics in hadronic collisions

**Abstract.** This article is devoted to the processes with the participation of the t-quark. The top quarks are one of the most amazing elementary particles. Predictions of the characteristics of various interactions involving the $t$-quark have high theoretical accuracy, as well as $t$-quark has large production cross section which makes it a unique laboratory for testing the Standard Model and beyond. The top quark is one of the important objects in the searches for new effects.

The review includes the main properties of the top quark, the complete theoretical analysis and experimental measurements of top quark processes and the possibilities of searching for manifestations of New physics (NF) beyond the Standard Model (SM).

Interactions of t-quarks are described in the framework of the model-independent way and gauge-invariant methods.

Another distinctive feature of study of the t-quark processes is the absence of hadrons containing t-quark in nature. So there is a unique opportunity to study the fundamental properties of a t -quark without any hadronization effects.

**Key words:** Higgs boson, top quark, Feynman diagram, model independent and gauge invariant method, Form factor, partial width, Standard Model.

## Introduction

In this review, we give a brief description of the top quark physics, which is the most amazing among the elementary particles.

The name "elementary" particle has two meanings: the term "elementary" particle is used for all for all subatomic particles whose dimensions are smaller than $10^{-10}$m (the characteristic atomic dimensions). Namely all baryons, mesons, quarks, leptons, photons, gluons, massive vector bosons ($W^{\pm}$, $Z^{0}$), and the Higgs boson are "elementary" particles.

More precise scientific meaning of the term "elementary" is that an "elementary" particle is an object that does not have an internal structure and behaves like a point like object in all currently known interactions and at all available interaction energies. The modern point like particles are all quarks, leptons, photons, gluons, massive vector bosons, ($W^{\pm}$, $Z^{0}$), and the Higgs boson. Baryons and mesons are composite particles that consist of quarks and gluons.

The t quark was discovered by the collaborations D0 and CDF [2, 3]. Historical overview of the $t$-quark discovery and the results of the study of the $t$-quark physics are described in [4]. A more detailed description of the $t$-quarks physics with full theoretical and experimental aspects can be found in the review [1].

The past ten year results of the Large Hadron Collider (LHC -Large Hadron Collider) led to a set of surprising discoveries and interesting results. Some rare processes with the participation of the t-quark have been detected experimentally. It has been measured their characteristics with high accuracy. A search for possible manifestations of the "New Physics" in the t-quark sector was carried out. It wasn't observed statistically significant experimental deviations from the SM predictions. And according to the results of measurements, restrictions were established on the parameters of new models, which lead to deviations from the SM predictions.

## 1 The properties of the top quark

In the Standard Model (SM), the $t$-quark is the heaviest particle of the third generation and has the same quantum numbers us the "up" and "charm" quarks. It is a fermion with spin ½ and electric charge Q = +2/3. As known fermions described by the Dirac fermion field which can be decomposed into two projections with left and right chiralities. Therefore the left chiral part of the $t$-quark is the upper component of the weak isospin doublet, and the right chiral component is the weak isospin singlet. In strong interaction $t$-quark is considered as a colored triplet with respect to the SU(3) gauge group.

There are two distinctive features of the t quark from the other quarks. The first is its mass which is much larger than others. Also the t-quark very weak mixes by the first and second generation quarks.

The magnitude of the $t$-quark mass $m_t$ is not predicted by theory. From the experimental measurements at Tevatron and LHC we have:

$$m_t = 173.1 \pm 0.6 GeV$$

with an error less than 0.35%, which is the most accurate mass determination among all quarks [5]. The mass of the $t$-quark is only slightly less than the mass of the gold nucleus (for example, the mass of the 186th isotope of the nucleus is 173.2 GeV). Despite such a large value of the mass the $t$-quark behaves point like particle in all known creation and decay processes.

In the SM the mixing of quarks if expressed in terms of unitary Cabibbo-Kobayashi-Maskawa (CKM) $|V_{qq'}|$ matrix [6, 7]. The value of the element $|V_{tb}|$ is very close to one, while the value of the elements $|V_{ts}|$ and $|V_{td}|$ are much less than one. This suggests that within the SM the $t$-quark decays into a W-boson and $b$-quark with a probability close to 100%.

## 2 The study of the processes involving the top quarks within the sm and beyond

### *2.1 Interaction Lagrangian of the top quarks*

Let us start from the Lagrangian which provides all interaction rules of the quarks. The Lagrangian of the $t$-quark interaction within the SM has the form (see [1, 8]):

$$L_{SM} = -Q_t e\bar{t}\gamma^{\mu}A_{\mu} - \frac{g}{2cos\upsilon_W}\bar{t}\gamma^{\mu}\left[\left(\frac{1}{2} - 2Q_t sin^2\upsilon_W\right) - \frac{1}{2}\gamma_5\right]tZ_{\mu} - \frac{y_t}{\sqrt{2}}\bar{t}tH - g_s\bar{t}\gamma^{\mu}t^a tG^a_{\mu} - \frac{g}{\sqrt{2}}\sum_{q=d,s,b}\frac{V_{tq}}{2}\bar{t}\,\gamma^{\mu}(1-\gamma^5)qW^+_{\mu} + h.c. \quad (1)$$

where $g_s$, $e$ and $g$ are the coupling constants of the strong, electromagnetic and weak interactions correspondingly, charge of the t-quark is $Q_t = +2/3$.

$$y_t = \sqrt{2}\frac{m_t}{\upsilon_{ew}}, \quad \upsilon_{ew} \approx 246 GeV \quad (2)$$

where $\upsilon_{ew}$ is the electroweak scale, i.e. the vacuum average of the Higgs field.

In expression (1) the matrix $(1-\gamma^5)$ corresponds to the fact that only the left-hand component of the $t$-quark participates in the interaction.

### *2.2 Lagrangian of anomalous top-quark interactions*

Currently it is unknown what type of New Physics will be responsible for possible deviations from the predictions of the Standard Model. There exists a number of different scenarios of the Standard Model extensions: SUSY, models with extra space-time dimensions, composite or partially composite models. This lead either to predictions of new mechanisms of the interactions or to a significant change (enhancement) of rare processes involving the $t$-quarks. The experimental discovery of this new mechanisms and the enhancement of rare processes would indicate the existence of New Physics.

Anomalous interactions of the top quarks can be described by the effective field theory [9]. The effective field theory is more universal model-independent approach which is based on phenomenological Lagrangian [1,10,11]. This Lagrangian must be gauge-invariant with respect to the gauge group (otherwise, the introduced anomalous interactions would immediately lead to contradictions with modern precision measurements) and consists of a number of terms with increasing dimensions, suppressed by ever higher degrees of NF scale, which, as follows from the existing constraints, should be significantly larger than the electroweak scale $\upsilon_{ew} \approx 246GeV$:

$$L = L_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)} + \cdots. \quad (3)$$

The effective Lagrangian include the gauge-invariant operators $O_i^{(N)}$ and the corresponding coefficients $c_i^{(N)}$. The complete set of operators of the lowest possible dimension 6, contributing to the interactions of the top quark with other SM fields, is given in the review [12]. This set of operators involving the $t$-quark field is the subset of the complete set of operators called the Warsaw basis [11].

In the framework of the effective field theory (EFT) the Lagrangian of anomalous $t$-quark interactions can be represented in the following form

$$L_{EFT} = L_{sm} + k_4 \bar{\psi}_q \hat{O}^{(4)} \psi_t + + \frac{k_5}{\Lambda} \bar{\psi}_q \hat{O}^{(5)} \psi_t + \frac{k_6}{\Lambda^2} \bar{\psi}_q \hat{O}^{(6)} \psi_t + \cdots \quad (4)$$

where $\Lambda$ is the scale parameter of NF, $k$ is anomalous constants that have a natural order of magnitude $\upsilon_{ew}^2/\Lambda^2$.

The question of constructing the effective gauge-invariant Lagrangians was also studied in earlier papers (see, for example, [9, 13, 14, 1]). For historical reasons, an effective Lagrangian in the unitary gauge of the following form is widely used in the analysis of experimental data:

$$\left.\begin{array}{r} L_{anoum} = -\frac{1}{\sqrt{2}} \sum_{q=u,c,t} \bar{t}\left(\upsilon_{tq}^H + \gamma_5 a_{tq}^H\right) q H \\ -\frac{g}{\sqrt{2}} \bar{t}\gamma^\mu (f_V^L P_L + f_V^R P_R) b W_\mu^+ \\ -\frac{g}{2cos\upsilon_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu \left(\upsilon_{tq}^Z + a_{tq}^Z \gamma_5\right) q Z_\mu \\ -g_s \sum_{q=u,c,t} \frac{k_{tq}^g}{\Lambda} \bar{t}\sigma^{\mu\upsilon} t^\alpha \left(f_{tq}^g + i h_{tq}^g \gamma_5\right) q G_{\mu\upsilon}^a \\ -\frac{g}{\sqrt{2}} \bar{t} \frac{\sigma^{\mu\upsilon}\partial_\upsilon W_\mu^+}{M_W} (f_T^L P_L + f_T^R P_R) b \\ -e \sum_{q=u,c,t} \frac{k_{tq}^\gamma}{\Lambda} \bar{t}\sigma^{\mu\upsilon} \left(f_{tq}^\gamma + i h_{tq}^\gamma \gamma_5\right) q A_{\mu\upsilon} \\ -\frac{g}{2cos\upsilon_W} \sum_{q=u,c,t} \frac{k_{tq}^Z}{\Lambda} \bar{t}\sigma^{\mu\upsilon} \left(f_{tq}^Z + i h_{tq}^Z \gamma_5\right) q Z_{\mu\upsilon} \end{array}\right\} + h.c. \quad (5)$$

where $g$ is the interaction constant of the gauge group of weak isospin SU(2)L, $P_{L,R} = (1 \mp \gamma_5)/2$, $\sigma_{\mu\upsilon} = i/2\left(\gamma_\mu \gamma_\upsilon - \gamma_\upsilon \gamma_\mu\right)$, the field strength tensors are defined as usual $\left(G_{\mu\upsilon}^q = \partial_\mu G_\upsilon^a - \partial_\upsilon G_\mu^a, + \cdots\right)$; parameter $\Lambda$ is the scale of New physics of the order of several TeV; k is anomalous constants which is assumed to be a real numbers, f and h are constants generally considered as complex numbers with the normalization $|f|^2 + |h|^2 = 1$.

Values for the parameters from the Lagrangian (5) are:

$$\left.\begin{array}{c} \upsilon_{tt}^H = y_t = \sqrt{2}\frac{m_t}{\upsilon_{ew}}, \qquad a_{tt}^H = 0 \\ \upsilon_{tt}^H = a_{tt}^H = 0, \qquad q \neq t \\ f_V^L = \frac{V_{tq}}{2}, \qquad f_V^R = f_T^L = f_T^R = 0 \\ \upsilon_{tt}^Z = \frac{1}{2} - 2Q_t sin^2\upsilon_W, \quad a_{tt}^Z = \frac{1}{2} \\ \upsilon_{tt}^Z = a_{tq}^Z = 0, \quad q \neq t \end{array}\right\} \quad (6)$$

The experimental results are presented in terms of restrictions on the values of the anomalous coupling constants $k$ in (4). In a number of cases the obtained constraints are re-expressed through limits on the probabilities of certain rare decays of the $t$-quarks. To explain the above, let us consider a typical (and very promising) example of such an anomalous interaction in the vertex $tWb$ (see Figure 1). In the CM, such a vertex describes the interaction of the "left" $t$-quark and has the form:

$$L_{SM} = \bar{\psi}_q \hat{O}_{SM} \psi_t; \hat{O}_{SM} = \psi_t \frac{e}{2\sqrt{2} sin\Theta_W} V_{tb} \gamma^{\mu}(1-\gamma^5);$$

$$\frac{e}{2\sqrt{2} sin\Theta_W} = M_W \sqrt{\frac{G_F}{\sqrt{2}}}$$

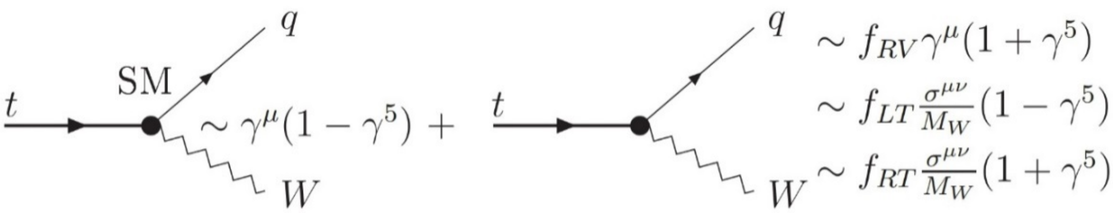



**Figure 1** – Anomalous interaction at the vertex $tWb$ [15]

At such interaction vertices the effects of so called New Physics can be manifested in the presence of "right" currents and anomalous magnetic and electrical moments. We can introduce a possible deviations from the SM by using the model-independent approach in terms of all possible Lorentz-invariant structures in the effective $tWb$ interaction Lagrangian.

*2.3 Basic mechanisms of top-quark production*

Total width of $t$-quark calculated in the NLO approximation is [5]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2 + \left(1+2\frac{M_W^2}{m_t^2}\right)\left[1+\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3\pi}-\frac{5}{2}\right)\right] \quad (7)$$

Within the Standard Model, the main mechanisms for the production of $t$-quarks in terms of the corresponding cross sections in hadron interactions are the gluon – gluon and quark – antiquark annihilation leading to the formation of tt-couple (see Figure 2):

$$gg \to t\bar{t} \quad (8)$$

$$q\acute{q} \to t\bar{t}. \quad (9)$$

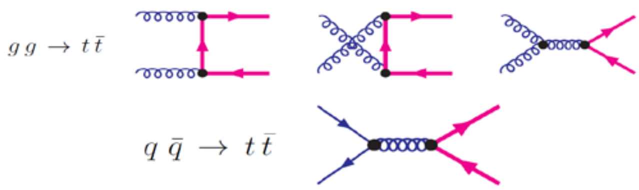


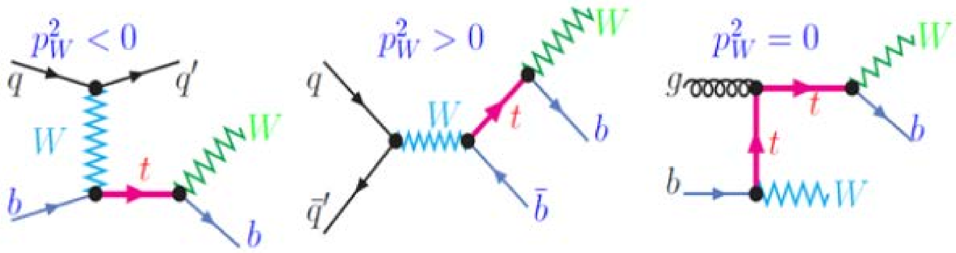

**Figure 2** – Diagrams describing the formation of a couple $t\bar{t}$- quarks [15]

The next processes in terms of cross-section are electroweak (“single”) $t$-quark production. These processes are usually classified according to the magnitude of the square of the 4-momentum of the virtual W-boson participating in the process (see Figure3):

$$qb \to tq', p_W^2 < 0 \quad : t - \text{channel} \tag{10}$$

$$q\bar{q}' \to t\bar{b}, p_W^2 > 0 \quad : s - \text{channel} \tag{11}$$

$$gb \to tW, p_W^2 = M_W^2 \quad : tW - \text{channel} \tag{12}$$




*t-channel* *s-channel* *tW-channel*

**Figure 3** – Representative diagrams which describe the sub-processes of electroweak production of $t$-quarks [15]

## 3 Experimental searches of top quark

*3.1 Top quark mass measurement*

The first measurements of the cross-sections and mass of the $t$-quark were carried out at the Tevatron collider (Fermilab, USA) in 1995. The CMS and ATLAS experiments of LHC have been measured the mass of the $t$-quark at different energies, as well as in various decay channels by different methods.

- The most accurate $t$-quark mass is measured in the distribution over the invariant mass of the decay products of the reconstructed $t$-quark:

$$t \to bW \to j_b jj \Rightarrow M\left(j_b'' W''(jj)\right),$$

$$t \to bW \to j_b l^{\pm} \upsilon \Rightarrow M_T\left(l E_T^{miss}\right).$$

- The $t$-quark mass can also be determined by examining the correlations of the distribution of the decay products. For example, in the decays

$$t \to bW, b \to B(b\bar{q}) \to \mathrm{J}/\psi\, X,$$
$$W \to l^{\pm} \upsilon \Rightarrow M(l^{\pm}\, \mathrm{J}/\psi).$$

- It is also possible to determinethe $t$-quark mass from the total cross-section for the production of $t\bar{t}$- quarks:

$$\sigma(pp \to t\bar{t}) = f(m_t).$$

Figure 4 shows an example of "measurement" of $t$-quark mass from the spectrum $M(l^{\pm}\, \mathrm{J}/\psi)$ and $pp \to t\bar{t}$.

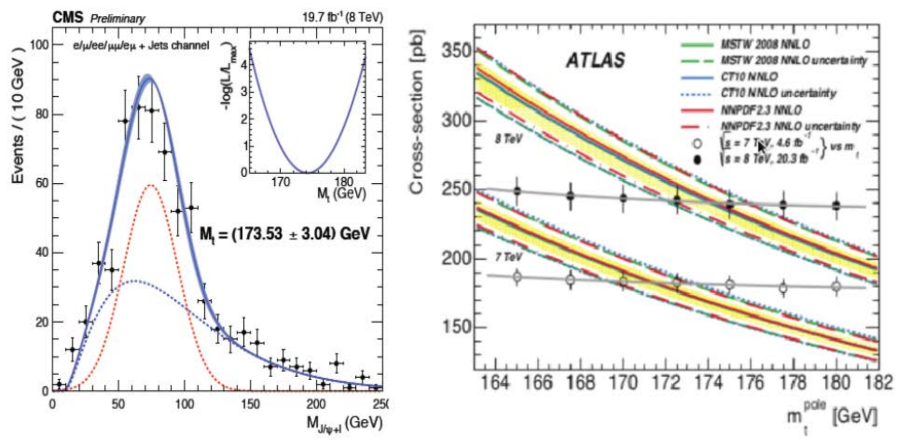



**Figure 4** – Measurement results for the $t$-quark mass from the spectrum $M(l^{\pm}\, \mathrm{J}/\psi)$ and $pp \to t\bar{t}$ [16]

In Figure 5 it is given the results of mass measurements of the $t$-quark with the decay channel combinations, as well as the total results from the experiments.This datas were collected by the LHC group [16]. You can see that at the end of 2017 the $t$-quark mass has already been measured independently with anaccuracy of about 0.5 GeV (0.3%). From the CMS experiment $\Delta = m_t - m_{\bar{t}} = -0.15 \pm 0.19(stat) \pm 0.09(syst)$ [17]. Within the framework of measurement errors, the mass of the $t$-quark and antiquark coincide.

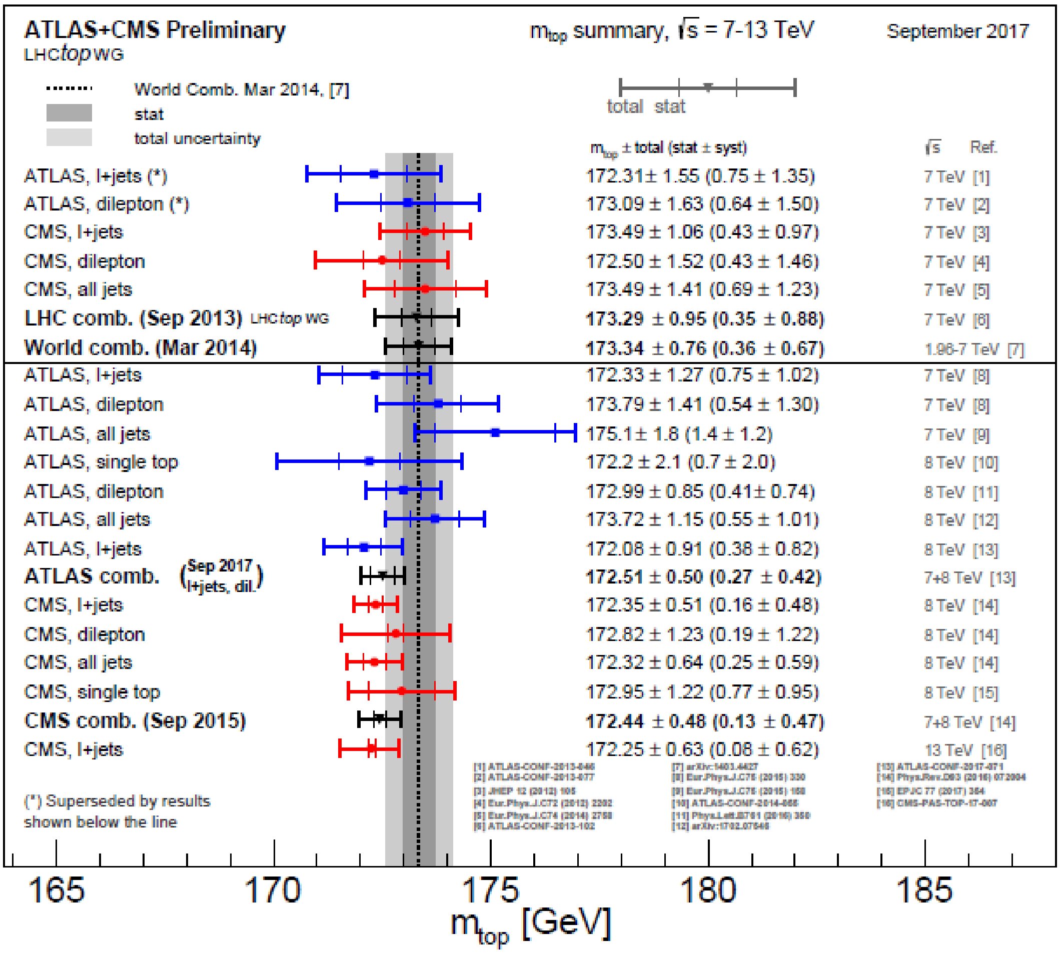



**Figure 5** – Measurements of the $t$-quark mass in the CMS and ATLAS experiments in differen t $t$-quark decay channels and at different energies. The results of combining measurements in different channels are presented [16]

*3.2 Top quark width measurements*

To measure the width of a $t$-quark, it is necessary to study the distributions of the number of events over the $M(bW)$ invariant mass of its decay products. The peak in this distribution determines the mass of the $t$-quark, and the width of the distribution determines the total width $\Gamma_t$ of the decay.

However, such fitting of the distribution over $M(bW)$ does not give an acceptable accuracy (in the lepton mode of W-boson decay due to the presence of an unregistered neutrino; in the hadron channel of W-boson decay, the distribution is blurred by the combinatorial factors of jet permutation during the reconstruction of $t$-quarks). In the ATLAS [18] experiment, the $t$-quark width was measured by quoting the invariant mass of a charged lepton and a $b$-quark in the processes of paired $t$-quark generation. At the same time, signal events with different values (from 0.1 to 5.0 GeV in increments = 0.1 GeV) were generated to determine the width $\Gamma_t$. The value of $\Gamma_t$ was determined from the minimum value of the negative logarithm of probability (see Figure 6).

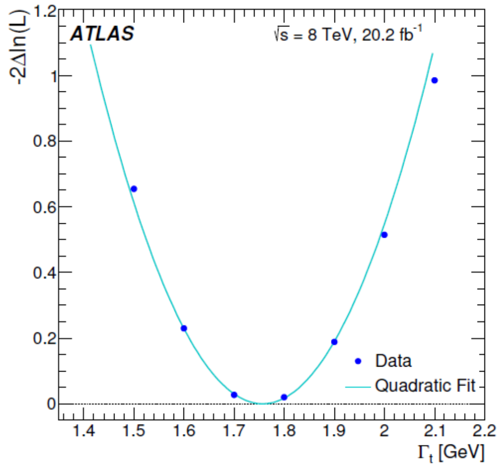



**Figure 6** – Determination of the width $\Gamma_t$ from the distribution of the negative logarithm of the probability [18]

In the CMS experiment [19] an indirect measurement of the width of the $t$-quark was carried out from the determined measurements of the decay probabilities of the t quark in pair production and the measurements of the cross-section for the electroweak production of the $t$-quark:

$$\Gamma_t = \frac{\sigma_{t-ch}^{exp}}{B(t \to Wb)} \times \frac{\Gamma^{th}(t \to Wb)}{\sigma_{t-ch}^{th}}$$

where $\sigma_{t-ch}^{exp}(\sigma_{t-ch}^{th})$ is the measured (theoretical) value of the cross-section for the productionof a single $t$-quark, $\Gamma^{th}(t \to Wb) = 1.329$ GeV is the theoretical value of the decay width $t \to Wb$ (calculated at $t = 172.5\ GeV$ [5]).

The measurement results are given in Table 1.

**Table 1** – Measured values of $\Gamma_t$, in experiments ATLAS [18] and CMS [19]

| Experiment | $\Gamma_t^{exp}$, GeV |
|---|---|
| ATLAS<br>CMS | $\Gamma_t = 1.76 \pm 0.33\ (stat.)^{+0.79}_{-0.68}(syst.)$<br>$\Gamma_t = 1.36 \pm 0.03\ (stat.)^{+0.14}_{-0.11}(syst.)$ |

A new theoretical method to measure the $t$-quark width was proposed in [20] by comparing invariant mass distributions below and above $t$-quark pair and single $t$-quark thresholds.

*3.3 Coupling constant of the top quark and Higgs boson*

The next important point is the calculation of the coupling constant of the Higgs boson with the $t$-quark ($y_t$). It plays an important role in the SM as well as in its extensions. The value of this parameter can be measured in the reactions of pair and single production of $t$-quarks accompanied by the Higgs-boson:

$$(t\bar{t}H) \quad pp \to tH\bar{t}X \qquad (13)$$
$$(tH) \quad pp \to tHX \qquad (14)$$

The different decay modes of the Higgs boson were studied experimentally: $H \to b\bar{b}$, $WW^*$, $ZZ^*$, $\tau^+\tau^-$, $\gamma\gamma$. Results of measurements of the parameter $y_t$ are presented in Table 2.

**Table 2** – The magnitude of the coupling of the Higgs boson with the $t$-quark

| ATLAS[21] | CMS[22] |
|---|---|
| $y_t$=1.15±0.12 | $126^{+0.31}_{-0.26}$ |

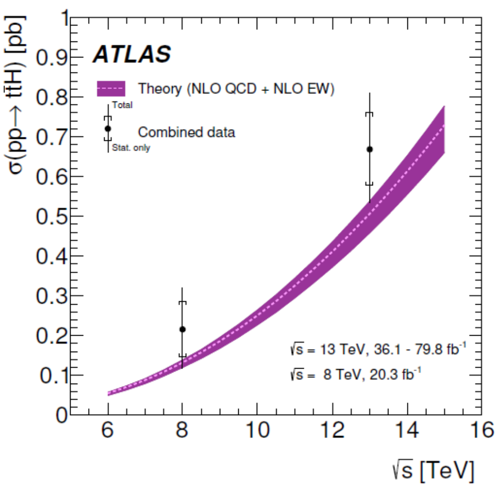



**Figure 7** – Cross section for production of the Higgs boson accompanied by $t$- and $t$-quarks [21]

*3.4 Top-quark pair production reactions*

Within the Standard Model by using the known mass of the $t$-quark, it is possible to calculate the cross sections for the processes of its production and compare with the experimental values. In Figure 8 it is given the results of measuring the cross section for the pair production of the $t$-quark [16] obtained by the CMS and ATLAS experiments in different decay channels at different energies. The theoretical results of the cross sections obtained within the SM and the results from the experiments are in good agreement.

*3.5 Processes of a single $t$-quark production and a few rare t-quark production processes*

The processes of pair production of $t$-quarks have the largest cross section. The processes of single $t$-quark generation are the next in terms of the cross-section. In Figure 9 it is shown the results of the cross section measurements for a single $t$-quark production in $t$-, $tW$- and $s$-channels [16]. Due to the very small value of the cross section and the huge background, the registration of the s-channel process of a single $t$-quark production presents significant complexity at the LHC, in contrast to the Tevatron collider, where this cross section approximately corresponds to the t-channel process of a single production. The presented results demonstrate excellent agreement between the SM predictions for a single electroweak $t$-quark production and the measurements.

It was carried out calculations for more rare processes with the $t$-quark production. Obtained results are in Figure 10. It is shown the cross sections measured both in the SM and in the CMS experiment for the processes of pair $t$-quarks production in association with gauge bosons and Higgs boson, $b$-quark pair, as well as the production of four-quarks [23]. The shown level of measurement errors makes it possible to judge the current measurement sensitivity in the $t$-quark sector at the LHC.

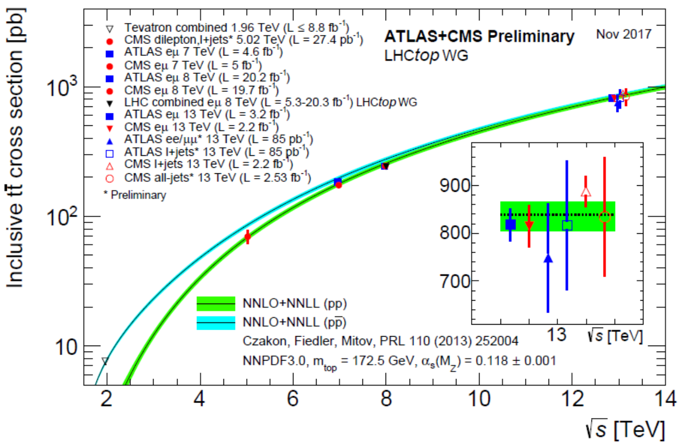



**Figure 8** – Cross sections for $t$-quark pair production measured in the CMS and ATLAS experiments in different $t$-quark decay channels and at different energies. The blue lines show the values of the cross sections calculated within the framework of the SM, the measurement error is highlighted in color [16]

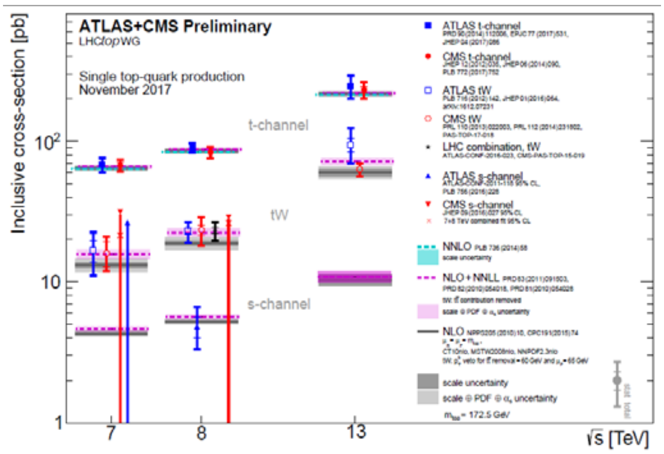



**Figure 9** – The cross sections for a single $t$-quark production are given, measured in the CMS and ATLAS experiments in various channels of electroweak $t$-quark production at different energies. The cross sections calculated in the framework of the Standard Model are shown, with the corresponding error marked with a colored region [16]

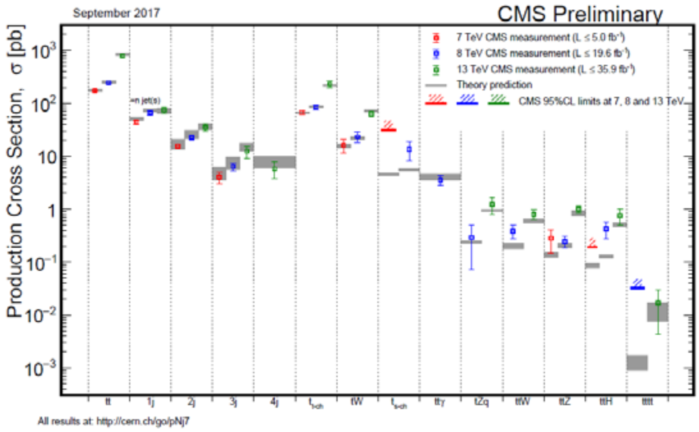



**Figure 10** – Cross sections of $t$-quark production processes. The results of measurements in the CMS experiment are presented, the predictions are obtained in the framework of the Standard Model [16]

## 4 Search for deviations from the standard model predictions in the production of top quarks

All obtained results of studies of the $t$-quark physics are in enough agreement with the SM predictions within the measurement uncertainty. Even if there is a good agreement between experimental and theoretical results, existing problems of the Standard Model presuppose the searches for interactions beyond the Standard Model. Can be said about two scenarios for the manifestation of possible deviations. The first is the deviations manifested in the interaction between $t$-quark and other particles. The second scenario is related to the production of a new unknown particles which decays into $t$-quark or emerges in the decay of the t-quark.

### *4.1 Studies for $gt\bar{t}$ and $tWb$ interaction processes*

In $gt\bar{t}$ interaction the deviations can be found from the studies of energy distributions or angular observables. At the Tevatron collider it was noticed a symmetry breaking in the number of $t$-quarks that flew into the front hemisphere of the detector and into the rear hemisphere of the detector [24, 25] and vice versa. In a number of distributions which represent the charge-space asymmetry was observed a statistically significant deviation from the SM. Continuous studies in experiments at the LHC and Tevatron colliders, as well as more precice theoretical calculations, led to the agreement of the observed asymmetry. In Figure 11 it is shows the theoretical calculations of the asymmetry of $t$ and $\bar{t}$-quark production in various decay channels and the results obtained in the ATLAS and CMS experiments at collision energies of 7-8 TeV [16].

Deviations from the SM also was searched in the interaction $tWb$ at CMS experiment [26] (see expressions 7). All kinematical properties were simulated depending on the values of the parameters characterizing possible effects of New Physics. In the single $t$-quark production processes the existence of anomalous interactions both in the production of the $t$-quark and in its decay make it difficult to simulate. Physicists created Bayesian neural networks which are sensitive to the effects of New Physics. This increases the efficiency of the experimental analysis.

Systematic errors of uncertainties in the obtained results are studied in detail. In Figure 12 it is given output distributions of Bayesian neural networks for CMS experimental data and modeled processes that contribute to the studying final state. The hypothetical deviations from the CM shown by the lines. On the basis of the statistical analysis of the behavior of the experimental data distributions and modeling at the output of Bayesian neural networks, was obtained an upper limits on possible deviations from the CM predictions in the $Wtb$ vertex. The results are shown in Figure 13.

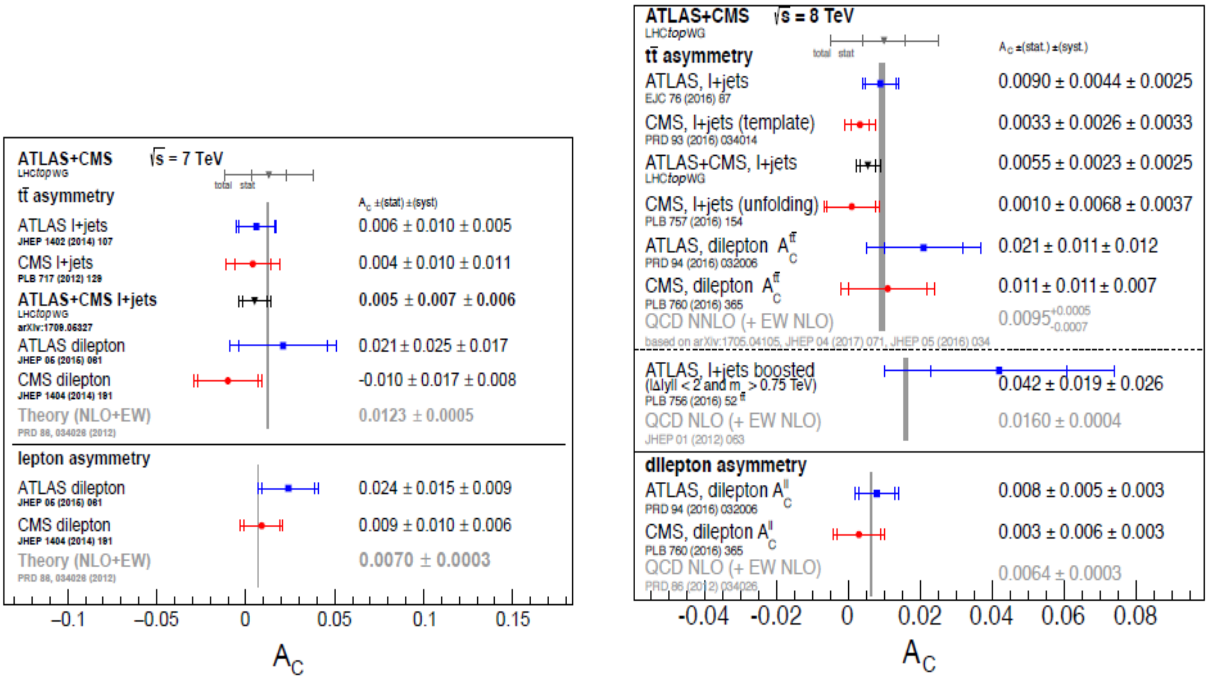



**Figure 11** – The measured and predicted SM values of the asymmetry of $t$ и $\bar{t}$ quark production in various experiments and of the production channel. The values obtained for collision energies of 7 TeV (left figure) and 8 TeV (right figure) are given [16]

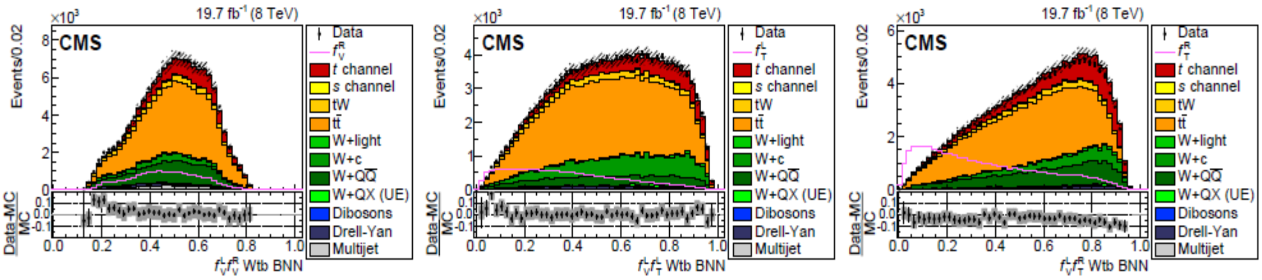



**Figure 12** – Output distributions of Bayesian neural networks for CMS experimental data (points) and simulated processes that contribute to the investigated final state (contribution of exact process corresponds to the area marked with the corresponding color). The lines show the distributions of events for possible effects of New Physics corresponding to the contribution of the right vector (left figure), left tensor (middle figure) and right tensor (right figure) currents. The shaded area shows the full systematic uncertainty of the simulation. The vertical line shown together with the data distribution points corresponds to the value of the statistical uncertainty of the measurement [26]

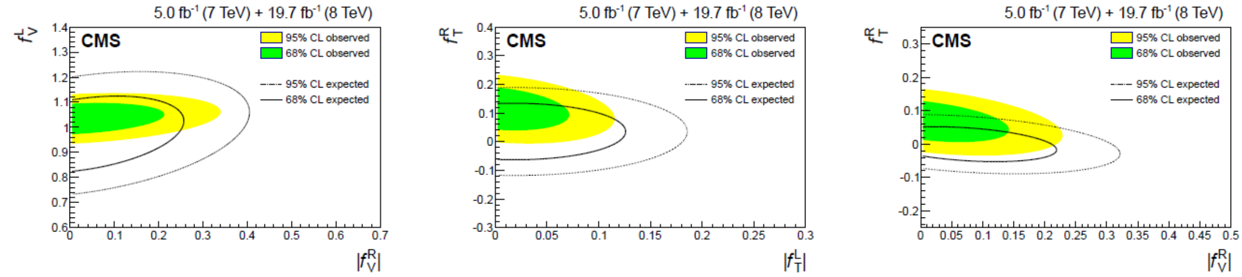



**Figure 13** – The contours of the upper bounds on the parameters obtained which characterize the possible effects of New Physics in the $tWb$ vertex. It is shown the expected (lines) and observed (colored areas) limitations with the statistical confidence of 68% and 95% [26]

The similar analysis was carried out at ATLAS experiment [27] on the basis of studying the asymmetry of the kinematic characteristic which presents the correlation of spin states in the production and decay of the $t$-quark. The asymmetry is a consequence of the exchange of the left charged current in the $tWb$ vertex and is sensitive to the possible contributions of other currents. In addition to direct search for anomalous currents in the $tWb$ interaction, the limits on the contribution of such anomalous currents are established by the help of measurement of the chiral states of the W boson. The contours of the upper limitations obtained in the ATLAS experiment [28] are shown in Figure 14. These limitations are on the parameters characterizing the possible contributions of left tensor ($g_L = f_T^L$), right vector ($V_R = f_V^R$) and right tensor ($g_R = f_T^R$) currents normalized to the contribution of left vector currents $V_L = f_V^L$.

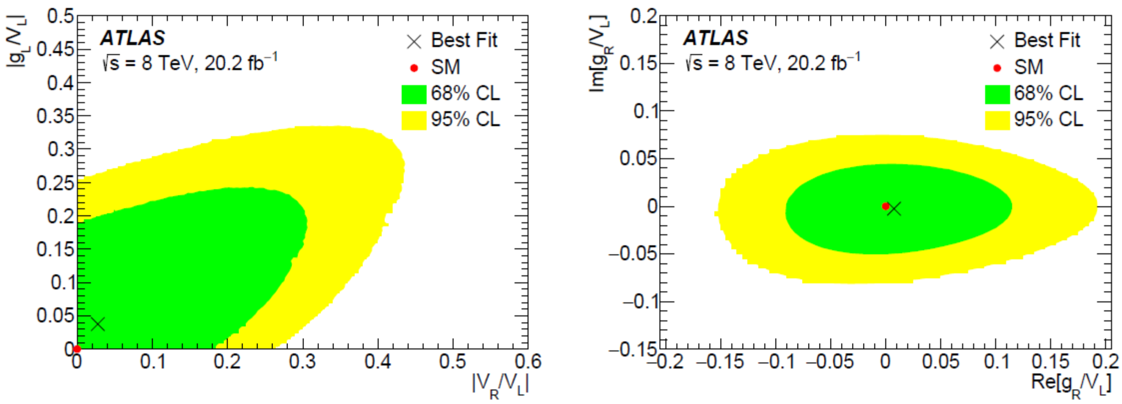



**Figure 14** – The contours of the upper bounds on the parameters obtained in the ATLAS experiment, which characterize the possible effects of New physics in the $tWb$ vertex. Restrictions on the possible contributions of the left tensor $g_L \equiv f_T^L$, right vector: (VR)) and right tensor $g_R \equiv f_T^R$ currents are given, normalized to the contribution of left vector currents $V_R \equiv f_V^R$ present in the SM [28]

*4.2 Investigations of rare processes with top quarks*

The processes with the flavor changing neutral currents (FCNC) are strongly suppressed within the Standard Model. But the probability of such processes can be increased by the extensions of the SM. As well as an experimental searches was done for $t$-quark interactions with FCNC by the exchange of gluons, Z boson, photon, or Higgs boson. A number of production or decay processes of a t-quark with FCNC were investigated.

Figure 15 shows the results of CMS and ATLAS experiments [16]. Predictions of the SM labeled by the black line. The points label the upper limits on the probabilities of rare decays obtained in the CMS and ATLAS experiments. The dashed areas show theoretical predictions beyond the CM. The obtained restrictions on the FCNC interactions of top quarks [16] are given in Table 3.

**Table 3** – Limitations on the probability of $t$-quark decays [26, 29-33]

| | $B$(95% CL) | |
|---|---|---|
| Decay | ATLAS | CMS |
| $t \to Hu$ | $1.9 \times 10^{-3}$ | $4.7 \times 10^{-3}$ |
| $t \to Hc$ | $1.9 \times 10^{-3}$ | $1.9 \times 10^{-3}$ |
| $t \to gu$ | $4.0 \times 10^{-5}$ | $2.0 \times 10^{-5}$ |
| $t \to gc$ | $20.0 \times 10^{-5}$ | $41 \times 10^{-5}$ |
| $t \to \gamma u$ | | $130 \times 10^{-5}$ |
| $t \to \gamma c$ | | $170 \times 10^{-5}$ |
| $t \to Zu$ | $17 \times 10^{-5}$ | $22 \times 10^{-5}$ |
| $t \to Zc$ | $24 \times 10^{-5}$ | $44 \times 10^{-5}$ |

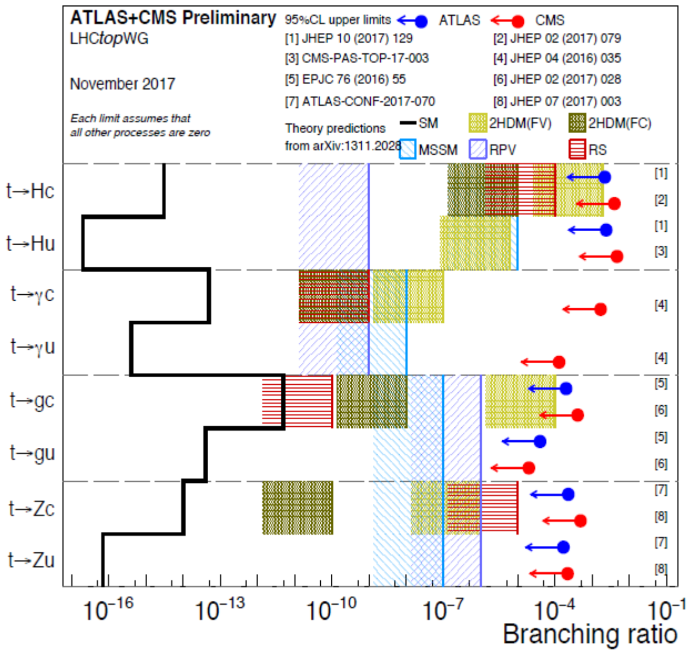



**Figure 15** – The generalized results of CMS and ATLAS experiments which was carried out for the searches of flavor changing neutral currents. The results are presented as limitations on the probabilities of rare $t$-quark decays involving the flavor changing neutral currents vertices. The SM predictions are labelled by the black line. The points show the upper limits of the probabilities of rare decays. The shaded areas represent the predictions of various theories beyond the SM [16]

## 5 Main projects of future accelerators

The $t$-quark has been observed at Tevatron and LHC accelerators in proton-antiproton and proton-proton collisions respectively. At an early date it is planned to study the $t$-quark at HL-LHC project [34, 35], which represents a significant modernization of the LHC. The main goal of this is to increase the luminosity of the accelerator by 10 times in comparison with LHC and to increase the total center-of-mass energy of the proton-proton collision ($\sqrt{s_{pp}} = 14Tev$).

The project annual integrated luminosity of HL-LHC for the CMS and ATLAS installations is

$$L_{tot} = 300fb^{-1}$$

which means approximately 3 billion paired and 1 billion single $t$-quark production events over the full design life of the accelerator over ten years. For a comparison, during 2017 year an integrated luminosity of $45fb^{-1}$was obtained at the CMS facility.

The main characteristics of the LHC and future accelerators are listed in Table 4. The behavior of the cross sections for $t\bar{t}$ production of a pair of quarks and single production of $t$-quarks are shown in Figure 16.

**Table 4.** Comparison of the main characteristics of LHC and future accelerators [34, 36, 37]. We listed the center of mass energy of colliding particles, the peak luminosity $L$ and the integral luminosity $\int L$, the average number of accompanying interactions $<\mu>$ for a single intersection of bunches

| Accelerator | $\sqrt{s}, TeV$ | $L$, см$^{-2}\cdot$ с$^{-1}$ | $\int L$, аб$^{-1}$ | $\mu >$ |
|---|---|---|---|---|
| LHC | 7-13 | $\approx 10^{34}$ | 0.3 | 10-40 |
| HL-LHC | 14 | $10^{35}$ | 3 | 140-200 |
| HE-LHC | 27 | $2.5 \times 10^{35}$ | 12 | 800 |
| SppC | 75 | $1.2 \times 10^{35}$ | 15 | 400-500 |
| FCC-hh | 100 | $3 \times 10^{35}$ | 30 | 500-1000 |

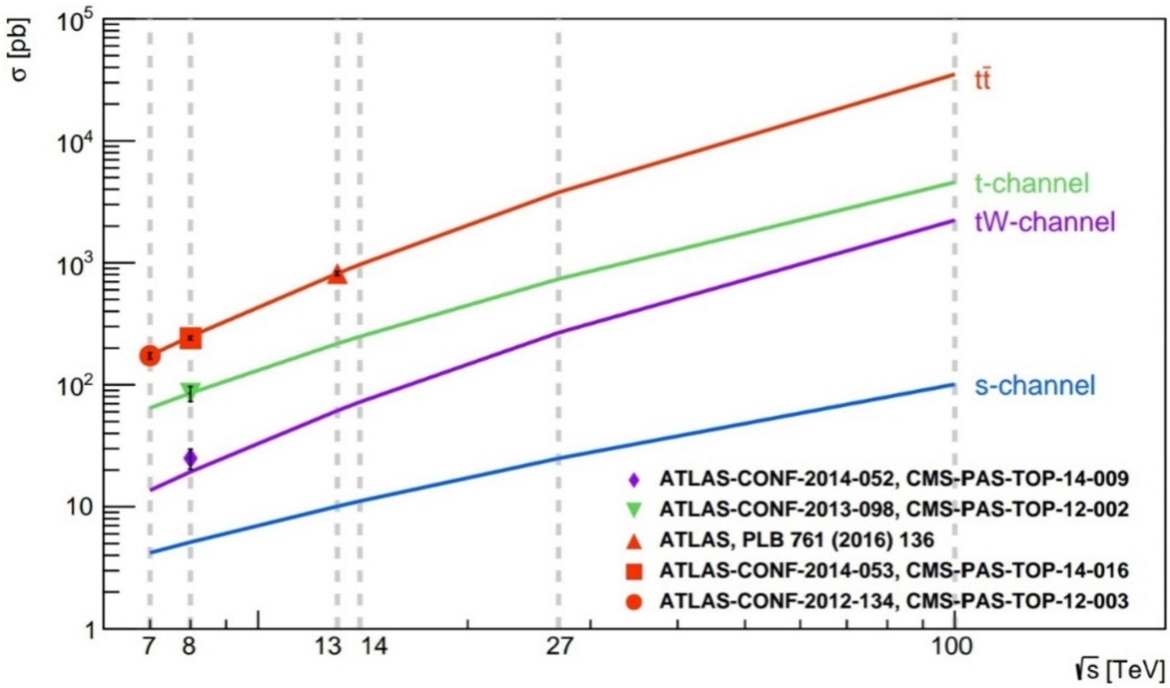



**Figure 16** – Plot of $t$-quark production cross section versus of the total energy of colliding protons in the system of centers of mass for the processes of paired and single production in the $s-, t-, tW-$ channels according to NLO calculations in MCFM. The experimental data were taken from [38-45]

Another accelerator is the developing FCC-hh accelerator. The nearest possible launch date for this accelerator may be 2043 year.

The main goal of this project is to create a proton-proton collider capable of achieving a record value of collision energy in the center-of-mass system equal to 100 TeV. Also planned to create the electron-electron accelerator FCC-*ee*, as an intermediate stage in the development of FCC-*hh* and the accelerator HE-LHC. Proton-proton collider HE-LHC uses the existing LHC tunnel and obtains the energy of 27 TeV by using the technology of FCC-hh accelerator [36].

## Conclusion

The $t$-quark is the heaviest elementary particle in the Standard Model and plays a unique role in particle physics. Due to large mass of the $t$-quark and extremely short lifetime There are no hadrons consisting of a $t$-quark in nature. Lifetime of the $t$-quark is much shorter than the time required for the creation of quark-antiquark bound states from the vacuum and the formation of hadrons. So it gives the possibility to study the fundamental properties of a $t$-quark that are not masked by hadronization effects. Predictions of the characteristics of various interactions involving the $t$-quark have high theoretical accuracy, as well as $t$-quark has large production cross section which makes it a unique laboratory for testing the Standard Model and beyond. In experiments at the LHC in the first and second sessions of operation, the $t$-quark mass, the cross sections for pair and single production, the mixing parameter $V_{tb}$, various distributions and spin correlations, and the cross sections for processes with a dominant contribution of virtual $t$-quarks have already been measured with a sufficiently high accuracy as the creation of the Higgs boson in a gluon-gluon fusion, the constants of the Yukawa interaction with the Higgs boson, and others. We determine the restrictions on the anomalous parameters of the interactions of the $t$-quark with gauge bosons, on the masses various resonances decaying into states containing an $t$-quark, into the parameters of theoretically possible interactions with violation of flavor.

The top quark is a key element in almost all SM extensions. We expect that the study of $t$-quarks will continue to be that portal that leads to new discoveries and will allow us to take a new step in understanding the structure of the depths of matter.

This will also mean a qualitatively new level in understanding the structure of the Universe, because in the first instant after its birth, various processes took place in the Universe, in particular, processes involving the $t$-quark.

The top quark is a key element in almost all CM extensions. We expect that the study of the $t$-quark will continue to be that portal which leads to new discoveries and will allow us to take a new step in understanding the structure of matter in depths. This will also mean a qualitatively new level in understanding the structure of the Universe, since in the first moment after its birth, various processes took place in the Universe, in particular, processes involving the $t$-quark.

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