Triple top quark production in Standard Model

E. Boos	extsuperscript{1} and L. Dudko	extsuperscript{1}

	extsuperscript{1}Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia, Moscow

The triple top quark production processes have been investigated and calculated in the scope of the Standard Model. The cross sections for different channels are provided for the proton-proton collision energies of $\sqrt{s} = 14$ and 100 TeV. The importance of the electroweak contribution has been demonstrated. For the main channels the interference between the gluon and the weak bosons mediated contributions is negative and significant, therefore the complete set of diagrams has to be taken into account. Estimated total rates are about 1.9 fb for $\sqrt{s} = 14$ TeV and 530 fb for $\sqrt{s} = 100$ TeV. A simple estimation of the uncertainty of the calculated cross sections gives about 20\%. The integrated luminosity of 3 ab$^{-1}$ at HL-LHC allows expecting about 5700 events, giving a chance to detect this rare process.

I. INTRODUCTION

Top quark was discovered in pair top anti-top quark production \[ p p \rightarrow t \bar{t} t \bar{t}, \] which have the highest cross section. The single production of the top quark occurs due to the electroweak interaction caused by the vertex $tWb$. The single top quark production was also discovered at the Tevatron experiments \[ 3, 4 \]. The associated production of the top quark with $W, Z$ or Higgs bosons was first observed at the LHC experiments. The present level of the experimental sensitivity is close to the top quark production \[ 12, 14 \]. In the Standard Model (SM) there are no production processes with exactly three top quarks, but there are several processes of the three top quark production in association with other particles. The SM total cross sections of the triple top quark production processes have been calculated previously \[ 13, 17 \]. The triple top quark production can be sensitive to a number of higher dimensional operators leading to flavor changing neutral currents involving the top quark \[ 18, 19 \] and production of new resonances \[ 20, 22 \]. Search for any beyond the SM (BSM) manifestation in the triple top quark production requires accurate computations of the SM contribution. The main aim of our study is to calculate the electroweak and QCD SM contributions, as well as interference between them, of all dominating triple top quark production processes in association with a lighter quark including the b-quark \[ (p, p \rightarrow t, t(t), t, q) \] or with the W boson \[ (p, p \rightarrow t(t), t, W) \]. All the computations are performed at LO by means of the CompHEP package \[ 23, 24 \] which allows getting symbolic and numerical results separately for different subsets of Feynman diagrams and, also, the interference terms. Numerical results are given for proton-proton collisions with energies $\sqrt{s} = 14$ and 100 TeV, using the PDF set NNPDF23-nlo-as-0118 \[ 25 \] as it is realized in LHAPDF5.9.1 \[ 26 \], factorization and renormalization scales are chosen as $Q = 3 M_{top}/2$. The paper is organized as follows. In the next section, we briefly discuss gauge invariant classes of contributing leading order 2 $\rightarrow$ 4 diagrams. In the next three sections some details of computations and numerical results for the cross sections are given for three main channels $pp \rightarrow t t t q / t t t q, q = u, d, c, s$; $pp \rightarrow t t t W^- / t t t W^+$; and $pp \rightarrow t t t b / t t t b$ respectively. The total cross section for the triple top quark production process is presented in the last section, followed by a short conclusion.

II. GAUGE INVARIANT SUBSETS OF FEYNMAN DIAGRAMS

The complete set of Feynman diagrams for any triple top quark production consists of several processes. As an example, let us consider the leading subprocess $u, b \rightarrow t, t, t, d$. There are two gauge invariant subsets \[ 27 \] of diagrams mediated by gluons and electroweak bosons. The Feynman diagrams for gluon mediated contribution are shown in Fig. 1. The diagrams are similar to the t-channel production of a single top quark with additional splitting of a gluon into a pair of top quarks. The fourteen diagrams for the electroweak mediated contribution are shown in Fig. 2. One can see the thirteen diagrams with virtual photon, Z or H boson decaying to top pair and the last t-channel diagram number 14. Since the diagrams with virtual photon, Z and H bosons are topologically the same as gluon mediated diagrams, one could expect that their contribution is much smaller and can be neglected in comparison with gluon mediated contribution. However, if we take four gluon mediated diagrams and add diagram 14 (Fig. 2) the rate will be about ten times larger than the correct one. The calculation of gluon mediated set of diagrams (Fig. 1) gives the cross section of 0.10 fb at $\sqrt{s} = 14$, in unitary gauge. The same result is obtained in tHooft-Feynman gauge, as it should be, for the gauge invariant subset of diagrams. In case we add diagram 14 of Fig. 2 to the gluon mediated diagrams, the cross section rises in ten times to 1.4 fb (in unitary gauge) reflecting the violation of gauge invariance. The complete weak bosons mediated set of diagrams shown in Fig. 2 gives the cross section 0.12 fb, which is of the same order as the gluon mediated set of diagrams. The gauge invariance of the subclasses listed in Fig. 1 and Fig. 2 has been checked with the calculation in both unitary and tHooft-Feynman gauges leading to the same results. The interference between these two
sets of Feynman diagrams in Figs. 1, 2 is also gauge invariant and has to be taken into account. Calculation of the complete set of all diagrams in Figs. 1, 2 including interference between them, provides the total cross section of 0.12 fb. The total cross section is a sum of three gauge invariant contributions: 0.12 fb (tot) = 0.10 fb (gluon) + 0.12 fb (electroweak) - 0.10 fb (interference).

One can see how significant the negative interference is. Therefore, such an example demonstrates that the complete set of Feynman diagrams has to be calculated in order to get the correct cross section of the triple top quark production. All numbers above are given with the requirement on transverse momenta of d-quark $P_T^d > 10$ GeV.

III. PROCESSES WITH $tt\bar{t}q$ AND $tt\bar{t}q$ FINAL STATES

One of the main contribution comes from the associated triple top quark production with the light flavor quark. There are eight representative processes $p, p \rightarrow t, t, \bar{t}, q$ listed in Table I and eight representative processes $p, p \rightarrow t, t, \bar{t}, q$ listed in Table II. As in the previous section, the requirement $P_T^d > 10$ GeV is used. In the tables, the cross sections for specific initial states are given as shown, but for the sums and total cross sections, an additional factor of two is included, reflecting the permutations of two partons in the initial states. As one can see from the tables, the rate of the process with signature $t, t, \bar{t}, q$ is about 2.6 times larger than for $t, t, \bar{t}, q$ signature due to the difference in parton distribution functions (PDF) of up-type and down-type quarks. This is similar to the difference in rates of $t$-channel single top and single anti-top quark production. The leading contribution comes from the first generation quarks in the initial states, subprocesses 1 in Table I and in Table II. The subprocesses 2, 4, 5 in Table I and subprocesses 2, 3, 4 in Table II are suppressed by PDF. The subprocesses 3 in Table II and 5 in Table II are suppressed by Cabibbo–Kobayashi–Maskawa (CKM) matrix elements. The subprocesses 6, 7, 8 in Table I and Table II are suppressed by both PDF and CKM. The contribution of the suppressed processes is about 13% to the total rate of all processes listed in Table I and about 29% of all processes listed in Table II. The contributions of $s$ and $\bar{s}$ in the initial states (subprocesses 4 in Table I and subprocess 3 in Table II) are slightly different due to the difference of $s$ and $\bar{s}$ PDF in NNPDF2.3 [28]. The total rate is about 0.38 fb allowing to expect more than a thousand events for High Luminosity LHC with 3 ab$^{-1}$ of integrated luminosity.

IV. PROCESSES WITH $ttW^-$ AND $ttW^+$ FINAL STATES

Consider the triple top quark production in association with $W$ boson. There are 59 $2 \rightarrow 4$ contributing Feynman diagrams with anti-b-quark in the initial state with $W^+$ in the final state and the same number of diagrams for the
TABLE I. Cross sections for individual contributing processes and total cross sections for the p,p→ t,t,t,q production. Permutations of the initial partons are included to the total cross sections. The \( P_T^K > 10 \text{ GeV} \) cut was applied.

| ttq subprocess | Cross section [pb] |
|----------------|-------------------|
| 1              | u, b → d, t, t, \( \bar{t} \) | 1.19e-04 |
| 2              | d, b → \( \bar{u} \), t, t, \( \bar{t} \) | 6.45e-06 |
| 3              | u, b → s, t, t, \( \bar{t} \) | 6.22e-06 |
| 4              | s, b → \( \bar{c} \), t, t, \( \bar{t} \) | 2.69e-06 |
| 5              | c, b → s, t, t, \( \bar{t} \) | 2.60e-06 |
| 6              | d, b → \( \bar{c} \), t, t, \( \bar{t} \) | 3.37e-07 |
| 7              | s, b → \( \bar{u} \), t, t, \( \bar{t} \) | 1.41e-07 |
| 8              | c, b → d, t, t, \( \bar{t} \) | 1.36e-07 |

**W**\(^-\) in final state with b-quark in the initial state. Since the b-quark and anti-b-quark PDF are the same in the proton, the cross sections are equal for charge symmetric final states with W\(^+\) and W\(^-\). As in previous example, 59 diagrams are split to two gauge invariant subclasses, gluon and electroweak mediated parts. In the Table III the cross sections for specific initial states are given, and for the sums and total cross sections, an additional factor of two for W\(^+\) and W\(^-\) are included, reflecting the permutations of two partons in the initial states. The contribution of electroweak diagrams is of the same order as a gluon mediated contribution, and the interference between them is significant and negative. All calculations are done in so called 5-flavour scheme (5FS) \cite{24,43} with a b-quark in the initial state as a parton in colliding proton. Similar to the case of associated tW-channel single top quark production in addition to the process \( g,b(\bar{b}) \rightarrow t,(t(\bar{t})),t,W^- (W^+) \) there is a process with two gluons in the initial and an extra b-quark in the final state \( g,g \rightarrow t,(t(\bar{t})),t,W^- (W^+),b(\bar{b}) \). The later process is a part of next-to-leading order (NLO) tree level corrections in 5FS. This part interferes with four top quark production including subsequent top quark decay and has to be taken into account for calculations at NLO level and especially for event simulation \cite{44,45}.

| tt(t)tW subprocess | Cross section [pb] |
|--------------------|-------------------|
| 1                  | b, g → W\(^+\), t, \( \bar{t} \), \( \bar{t} \) | 3.40e-04 |
| 2                  | b, g → W\(^-\), t, \( \bar{t} \), \( \bar{t} \) | 3.40e-04 |

**W**\(^-\) in final state with b-quark in the initial state. Since the b-quark and anti-b-quark PDF are the same in the proton, the cross sections are equal for charge symmetric final states with W\(^+\) and W\(^-\). As in previous example, 59 diagrams are split to two gauge invariant subclasses, gluon and electroweak mediated parts. In the Table III the cross sections for specific initial states are given, and for the sums and total cross sections, an additional factor of two for W\(^+\) and W\(^-\) are included, reflecting the permutations of two partons in the initial states. The contribution of electroweak diagrams is of the same order as a gluon mediated contribution, and the interference between them is significant and negative. All calculations are done in so called 5-flavour scheme (5FS) \cite{24,43} with a b-quark in the initial state as a parton in colliding proton. Similar to the case of associated tW-channel single top quark production in addition to the process \( g,b(\bar{b}) \rightarrow t,(t(\bar{t})),t,W^- (W^+) \) there is a process with two gluons in the initial and an extra b-quark in the final state \( g,g \rightarrow t,(t(\bar{t})),t,W^- (W^+),b(\bar{b}) \). The later process is a part of next-to-leading order (NLO) tree level corrections in 5FS. This part interferes with four top quark production including subsequent top quark decay and has to be taken into account for calculations at NLO level and especially for event simulation \cite{44,45}.

| tt(t)tW subprocess | Cross section [pb] |
|--------------------|-------------------|
| 1                  | b, g → W\(^+\), t, \( \bar{t} \), \( \bar{t} \) | 3.40e-04 |
| 2                  | b, g → W\(^-\), t, \( \bar{t} \), \( \bar{t} \) | 3.40e-04 |

TABLE III. Cross sections for individual contributing processes and total cross sections for the p,p→ t,t,t,b production. Permutations of the initial partons are included to the total cross sections. The \( P_T^K > 10 \text{ GeV} \) cut was applied.

| ttq subprocess | Cross section [pb] |
|----------------|-------------------|
| 1              | d, b → u, t, t, \( \bar{t} \) | 3.92e-05 |
| 2              | \( \bar{u} \), \( \bar{b} \) → \( \bar{d} \), t, t, \( \bar{t} \) | 7.33e-06 |
| 3              | s, b → c, t, t, \( \bar{t} \) | 3.20e-06 |
| 4              | \( \bar{c} \), \( \bar{b} \) → s, t, t, \( \bar{t} \) | 2.60e-06 |
| 5              | d, b → c, t, t, \( \bar{t} \) | 2.05e-06 |
| 6              | \( \bar{u} \), \( \bar{b} \) → s, t, t, \( \bar{t} \) | 3.83e-07 |
| 7              | s, b → u, t, t, \( \bar{t} \) | 1.67e-07 |
| 8              | \( \bar{c} \), \( \bar{b} \) → \( \bar{d} \), t, t, \( \bar{t} \) | 1.36e-07 |

**W**\(^-\) in final state with b-quark in the initial state. Since the b-quark and anti-b-quark PDF are the same in the proton, the cross sections are equal for charge symmetric final states with W\(^+\) and W\(^-\). As in previous example, 59 diagrams are split to two gauge invariant subclasses, gluon and electroweak mediated parts. In the Table III the cross sections for specific initial states are given, and for the sums and total cross sections, an additional factor of two for W\(^+\) and W\(^-\) are included, reflecting the permutations of two partons in the initial states. The contribution of electroweak diagrams is of the same order as a gluon mediated contribution, and the interference between them is significant and negative. All calculations are done in so called 5-flavour scheme (5FS) \cite{24,43} with a b-quark in the initial state as a parton in colliding proton. Similar to the case of associated tW-channel single top quark production in addition to the process \( g,b(\bar{b}) \rightarrow t,(t(\bar{t})),t,W^- (W^+) \) there is a process with two gluons in the initial and an extra b-quark in the final state \( g,g \rightarrow t,(t(\bar{t})),t,W^- (W^+),b(\bar{b}) \). The later process is a part of next-to-leading order (NLO) tree level corrections in 5FS. This part interferes with four top quark production including subsequent top quark decay and has to be taken into account for calculations at NLO level and especially for event simulation \cite{44,45}.

**V. PROCESSES WITH tt\(\bar{b}\) AND tt\(\bar{b}\) FINAL STATES**

Additional small contribution to triple top quark production comes from the associated production with b-quark. The diagrams correspond to s-channel single top quark production with additional top quarks coming from virtual gluon, photon, Higgs, Z- or W-bosons. There are four representative processes p,p→ t,t,\( \bar{t} \), b with b-quark listed in Table IV and four representative processes p,p→ t,t,\( \bar{t} \), b with b-quark listed in Table V. As for the light quark in Sec. III the requirement \( P_T^K > 10 \text{ GeV} \) is used. Similar to the tables in Sec. III in Tables IV V the cross sections for specific initial states are given as shown, but for the sums and total cross sections, an additional factor of two is included, reflecting the permutations of two partons in the initial states. As can be seen from the tables the main contribution comes from the processes with u, \( \bar{d} \) and d, \( \bar{u} \) initial states. The first contribution is about 2.4 times larger than the second due to the differences in PDF. The electroweak part (EW) is roughly 3% of the gluon mediated contribution (G). The interference (Int) is positive and of the same order as the electroweak contribution.

**VI. TOTAL CROSS SECTIONS AND UNCERTAINTIES**

The total cross sections for the triple top quark production in different channels are summarized in Table IV for the proton-proton collisions with \( \sqrt{s} = 14 \text{ TeV} \). The total rate of 1.9 fb allows to expect 5700 events for 3 ab\(^-1\) integrated luminosity giving a chance to detect the process at HL-LHC. If one excludes all-hadronic and \( \tau \)+jets channels (branching ratio is about 0.6) and estimates a total experimental acceptance as 10% one can expect about
TABLE IV. Cross sections for individual contributing processes and total cross sections for the $p, p \rightarrow t, t, \bar{t}, b$ production. Permutations of the initial partons are included to the total cross sections. The $P_T^{bb} > 10$ GeV cut was applied.

| Subprocess | Cross section [pb] |
|------------|--------------------|
| $t b \rightarrow t, b$ | $5.35 \times 10^{-4}$ |
| $t b \rightarrow t, b$ | $1.57 \times 10^{-3}$ |
| $t b \rightarrow t, b$ | $9.11 \times 10^{-4}$ |
| $t b \rightarrow t, b$ | $1.14 \times 10^{-3}$ |
| Total cross section | $1.06 \times 10^{-4}$ |

300 detected events. In Table [VII] the cross sections for the proton-proton collisions at FCC energy $\sqrt{s} = 100$ TeV are shown. In this case the same requirement for momentum transverse of light- or b-quark $P_T^{bb} > 10$ GeV is used. Note the significant increase of the total cross section. The main reason for this is a rapid growing of the gluon parton density $g(x)$ in protons with a decrease of the momentum fraction $x$. The uncertainties of the calculations are estimated as follows. The factorisation and renormalisation scales uncertainty is taken as $\Delta Q = |Q - Q_{top}|$, and the PDF uncertainty is estimated as $\Delta PDF = |PDF(CTEQ6L1) - PDF(NNPDF23)|$. The estimation of the $\Delta PDF$ is simple and does not follow the PDF4LHC recipe [19], but it gives qualitatively the order of the PDF uncertainty. As one can see from the Tables [VII], the scale uncertainty $\Delta Q$ is about two or three times higher than the PDF uncertainty $\Delta PDF$.

TABLE V. Cross sections for individual contributing processes and total cross sections for the $p, p \rightarrow t, t, \bar{t}, b$ production. Permutations of the initial partons are included to the total cross sections. The $P_T^{bb} > 10$ GeV cut was applied.

| Subprocess | Cross section [pb] |
|------------|--------------------|
| $t b \rightarrow t, b$ | $2.25 \times 10^{-3}$ |
| $t b \rightarrow t, b$ | $1.13 \times 10^{-3}$ |
| $t b \rightarrow t, b$ | $5.51 \times 10^{-4}$ |
| $t b \rightarrow t, b$ | $1.47 \times 10^{-4}$ |
| Total cross section | $4.90 \times 10^{-4}$ |

TABLE VI. Total cross sections of different contributions to triple top quark production in pp collisions at $\sqrt{s} = 14$ TeV.

| Process | Cross sec. [pb] | $\delta Q$, % | $\delta PDF$, % |
|---------|----------------|---------------|-----------------|
| $p, p \rightarrow W^-, t, t, \bar{t}$ | $6.8 \times 10^{-4}$ | 13 | 6 |
| $p, p \rightarrow W^+, t, t, \bar{t}$ | $6.8 \times 10^{-4}$ | 13 | 6 |
| $p, p \rightarrow q', t, t, \bar{t}$ | $2.7 \times 10^{-4}$ | 12 | 14 |
| $p, p \rightarrow q', t, t, \bar{t}$ | $1.1 \times 10^{-4}$ | 13 | 4 |
| $p, p \rightarrow b, t, t, \bar{t}$ | $1.1 \times 10^{-4}$ | 35 | 13 |
| $p, p \rightarrow b, t, t, \bar{t}$ | $4.9 \times 10^{-4}$ | 35 | 4 |
| Total p, p $\rightarrow X, t, t (t), t$ | $1.9 \times 10^{-3}$ | 15 | 7 |

TABLE VII. Total cross sections of different contributions to triple top quark production in pp collisions at $\sqrt{s} = 100$ TeV.

| Process | Cross sec. [pb] | $\delta Q$, % | $\delta PDF$, % |
|---------|----------------|---------------|-----------------|
| $p, p \rightarrow W^-, t, t, \bar{t}$ | $2.4 \times 10^{-4}$ | 15 | 4 |
| $p, p \rightarrow W^+, t, t, \bar{t}$ | $2.4 \times 10^{-4}$ | 15 | 4 |
| $p, p \rightarrow q', t, t, \bar{t}$ | $3.1 \times 10^{-4}$ | 4 | 7 |
| $p, p \rightarrow q', t, t, \bar{t}$ | $1.8 \times 10^{-4}$ | 4 | 4 |
| $p, p \rightarrow b, t, t, \bar{t}$ | $2.6 \times 10^{-4}$ | 12 | 4 |
| $p, p \rightarrow b, t, t, \bar{t}$ | $1.7 \times 10^{-4}$ | 12 | 4 |
| Total p, p $\rightarrow X, t, t (t), t$ | $3.6 \times 10^{-4}$ | 14 | 4 |

VII. CONCLUSION

Different channels of triple top quark production are considered in the scope of the SM. The performed calculations and the provided results demonstrate the importance of the electroweak contribution and a significant negative interference between gluon and weak boson mediated contributions. The total cross section of the triple top quark production is at the level of $1.9$ fb for the proton-proton collisions at $\sqrt{s} = 14$ TeV and $530$ fb at $\sqrt{s} = 100$ TeV. The calculated total cross sections at $\sqrt{s} = 14$ TeV are in a good agreement with previous independent calculations using the MadGraph package [15,17]. The cross section at $\sqrt{s} = 14$ TeV is rather small although its level seems to be enough to detect the triple top quark production taken into account expected luminosity $3 \times 10^{-3}$ at HL-LHC. From the other hand, the small SM rate provides a possibility to search for beyond of SM (BSM) contributions which may increase the cross section. However, dedicated calculations are needed to study concrete BSM manifestation.

ACKNOWLEDGMENTS

This research has been supported by the Interdisciplinary Scientific and Educational School of Moscow State University “Fundamental and Applied Space Research”.
[1] S. Abachi et al. (D0), Observation of the top quark, Phys. Rev. Lett. 74, 2632 (1995) arXiv:hep-ex/9503003
[2] F. Abe et al. (CDF), Observation of top quark production in pp collisions, Phys. Rev. Lett. 74, 2626 (1995) arXiv:hep-ex/9503002
[3] T. Aaltonen et al. (CDF), First Observation of Electroweak Single Top Quark Production, Phys. Rev. Lett. 103, 092002 (2009) arXiv:0903.0885 [hep-ex]
[4] V. M. Abazov et al. (D0), Observation of Single Top Quark Production, Phys. Rev. Lett. 103, 092001 (2009) arXiv:0903.0850 [hep-ex]
[5] S. Chatrchyan et al. (CMS), Observation of the associated production of a single top quark and a W boson in pp collisions at √s = 8 TeV, Phys. Rev. Lett. 112, 231802 (2014) arXiv:1401.2942 [hep-ex]
[6] G. Aad et al. (ATLAS), Measurement of the production cross-section of a single top quark in association with a W boson at 8 TeV with the ATLAS experiment, JHEP 01, 064 arXiv:1510.03752 [hep-ex]
[7] A. M. Sirunyan et al. (CMS), Observation of Single Top Quark Production in Association with a Z Boson in Proton-Proton Collisions at √s = 13 TeV, Phys. Rev. Lett. 122, 132003 (2019) arXiv:1812.05900 [hep-ex]
[8] S. Chatrchyan et al. (CMS), Measurement of associated production of vector bosons and top quark-antiquark pairs at √s = 7 TeV, Phys. Rev. Lett. 110, 172002 (2013) arXiv:1303.3239 [hep-ex]
[9] G. Aad et al. (ATLAS), Measurement of the tW and tZ production cross sections in pp collisions at √s = 8 TeV with the ATLAS detector, JHEP 11, 172 arXiv:1509.05276 [hep-ex]
[10] A. M. Sirunyan et al. (CMS), Observation of tH production, Phys. Rev. Lett. 120, 231801 (2018) arXiv:1804.02610 [hep-ex]
[11] M. Aaboud et al. (ATLAS), Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, Phys. Lett. B 784, 173 (2018) arXiv:1806.00425 [hep-ex]
[12] M. Aaboud et al. (ATLAS), Search for four-top-quark production in the single-lepton and opposite-sign dilepton final states in pp collisions at √s = 13 TeV with the ATLAS detector, Phys. Rev. D 99, 052009 (2019) arXiv:1811.02305 [hep-ex]
[13] A. M. Sirunyan et al. (CMS), Search for the production of four top quarks in the single-lepton and opposite-sign dilepton final states in proton-proton collisions at √s = 13 TeV, JHEP 11, 082 arXiv:1906.02805 [hep-ex]
[14] A. M. Sirunyan et al. (CMS), Search for production of four top quarks in final states with same-sign or multiple leptons in proton-proton collisions at √s = 13 TeV, Eur. Phys. J. C 80, 75 (2020) arXiv:1908.06463 [hep-ex]
[15] V. Barger, W.-Y. Keung, and B. Yencho, Triple-Top Signal of New Physics at the LHC, Phys. Lett. B 687, 70 (2010) arXiv:1001.0221 [hep-ph]
[16] C.-R. Chen, Searching for new physics with triple-top signal at the LHC, Phys. Lett. B 736, 321 (2014)
[17] M. Malekhooseini, M. Ghominejad, H. Khanpour, and M. Mohammadi Najafabadi, Constraining top quark flavor violation and dipole moments through three and four-top quark productions at the LHC, Phys. Rev. D 98, 095001 (2018) arXiv:1804.05598 [hep-ph]
[18] H. Khanpour, Probing top quark FCNC couplings in the triple-top signal at the high energy LHC and future circular collider, Nucl. Phys. B 958, 115141 (2020) arXiv:1909.03998 [hep-ph]
[19] Q.-H. Cao, S.-L. Chen, Y. Liu, and X.-P. Wang, What can We Learn from Triple Top-Quark Production?, Phys. Rev. D 100, 055035 (2019) arXiv:1901.04643 [hep-ph]
[20] S. Iguro and K. Tobe, R(D(1)) in a general two Higgs doublet model, Nucl. Phys. B 925, 560 (2017) arXiv:1708.06176 [hep-ph]
[21] M. Kohla, T. Modak, and W.-S. Hou, Searching for new scalar bosons via triple-top signature in σg → tS → ttH, Phys. Lett. B 776, 379 (2018) arXiv:1710.07290 [hep-ph]
[22] S. Cho, P. Ko, J. Lee, Y. Omura, and C. Yu, Top FCNC induced by a Z boson, Phys. Rev. D 101, 055015 (2020) arXiv:1910.05925 [hep-ex]
[23] E. Boos et al., CompHEP 4.4: automatic computations from Lagrangians to events, Nucl. Instrum. Meth. A 534, 250 (2004) arXiv:hep-ph/0403113 [hep-ph]
[24] A. Pukhov, E. Boos, M. Dubinin, V. Edneral, V. Ilyin, D. Kovalenko, A. Kryukov, V. Savrin, S. Shchamin, and A. Semenov, CompHEP: A Package for evaluation of Feynman diagrams and integration over multiparticle phase space (1999), arXiv:9908288 [hep-ph]
[25] R. D. Ball et al., Parton distributions with LHC data, Nucl. Phys. B 867, 244 (2013) arXiv:1207.1303 [hep-ph]
[26] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, and G. Watt, LHAPDF6: parton density access in Lagrangians, Eur. Phys. J. C 75, 132 (2015) arXiv:1412.7420 [hep-ph]
[27] E. Boos and T. Ohl, Minimal gauge invariant classes of tree diagrams in gauge theories, Phys. Rev. Lett. 83, 480 (1999) arXiv:hep-ph/9903357
[28] R. D. Ball, V. Bertone, L. Del Debbio, S. Forte, A. Guffanti, J. Rojo, and M. Ubiali (NNPDF), Theoretical issues in PDF determination and associated uncertainties, Phys. Lett. B 723, 330 (2013) arXiv:1303.1189 [hep-ph]
[29] J. Collins, Hard scattering factorization with heavy quarks: A General treatment, Phys. Rev. D 58, 094002 (1998) arXiv:hep-ph/9806259
[30] M. Krämer, F. T. Olness, and D. E. Soper, Treatment of heavy quarks in deeply inelastic scattering, Phys. Rev. D 62, 096007 (2000) arXiv:hep-ph/0003035
[31] D. L. Rainwater, M. Spira, and D. Zeppenfeld, Higgs boson production at hadron colliders: Signal and background processes, in 2nd Les Houches Workshop on
[32] F. Maltoni, Z. Sullivan, and S. Willenbrock, Higgs-Boson Production via Bottom-Quark Fusion, Phys. Rev. D 67, 093005 (2003) arXiv:hep-ph/0301033

[33] E. Boos and T. Plehn, Higgs boson production induced by bottom quarks, Phys. Rev. D 69, 094005 (2004) arXiv:hep-ph/0304034

[34] R. V. Harlander and W. B. Kilgore, Higgs boson production in bottom quark fusion at next-to-next-to leading order, Phys. Rev. D 68, 013001 (2003) arXiv:hep-ph/0304035

[35] S. Moretti and J. Rathsman, Pair production of charged Higgs bosons in association with bottom quark pairs at the LHC, Eur. Phys. J. C 33, 41 (2004) arXiv:hep-ph/0309204

[36] S. Dittmaier, M. Krämer, and M. Spira, Higgs radiation off bottom quarks at the Tevatron and the CERN LHC, Phys. Rev. D 70, 074010 (2004) arXiv:hep-ph/0308215

[37] J. M. Campbell, S. Dawson, S. Dittmaier, C. Jackson, M. Kramer, F. Maltoni, L. Reina, M. Spira, D. Wackeroth, and S. Willenbrock, Higgs boson production in association with bottom quarks, in 3rd Les Houches Workshop on Physics at TeV Colliders (2004) arXiv:hep-ph/0405302

[38] S. Dawson, C. B. Jackson, L. Reina, and D. Wackeroth, Higgs production in association with bottom quarks at hadron colliders, Mod. Phys. Lett. A 21, 89 (2006) arXiv:hep-ph/0508293

[39] F. Maltoni, G. Ridolfi, and M. Ubiali, b-initiated processes at the LHC, a reappraisal, JHEP 07, 022, [Erratum: JHEP 04, 095 (2013)], arXiv:1203.6393 [hep-ph]

[40] M. Wiesemann, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, and P. Torrielli, Higgs production in association with bottom quarks, JHEP 02, 132 arXiv:1409.5301 [hep-ph]

[41] R. V. Harlander, Higgs production in heavy quark annihilation through next-to-next-to-leading order QCD, Eur. Phys. J. C 76, 252 (2016) arXiv:1512.04901 [hep-ph]

[42] M. Spira, Higgs Boson Production and Decay at Hadron Colliders, Prog. Part. Nucl. Phys. 95, 98 (2017) arXiv:1612.07651 [hep-ph]

[43] C. Duhr, F. Dulat, V. Hirschi, and B. Mistlberger, Higgs production in bottom quark fusion: matching the 4- and 5-flavour schemes to third order in the strong coupling, JHEP 08, 017, arXiv:2004.04752 [hep-ph]

[44] S. Frixione, E. Laenen, P. Motylinski, B. R. Weber, and C. D. White, Single-top hadroproduction in association with a W boson, JHEP 07, 029 arXiv:0805.3067 [hep-ph]

[45] A. Denner, S. Dittmaier, S. Kallweit, and S. Pozzorini, NLO QCD corrections to WWbb production at hadron colliders, Phys. Rev. Lett. 106, 052001 (2011) arXiv:1012.3975 [hep-ph]

[46] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos, and M. Worek, Complete off-shell effects in top quark pair hadroproduction with leptonic decay at next-to-leading order, JHEP 02, 083 arXiv:1012.4230 [hep-ph]

[47] F. Cascioli, S. Kallweit, P. Maierhöfer, and S. Pozzorini, A unified NLO description of top-pair and associated Wt production, Eur. Phys. J. C 74, 2783 (2014) arXiv:1312.0546 [hep-ph]

[48] T. Ježo, J. M. Lindert, P. Nason, C. Oleari, and S. Pozzorini, An NLO+PS generator for t¯tt¯t and Wt production and decay including non-resonant and interference effects, Eur. Phys. J. C 76, 691 (2016) arXiv:1607.04538 [hep-ph]

[49] J. Butterworth et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43, 023001 (2016) arXiv:1510.03865 [hep-ph]