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THE TOP–HIGGS COUPLING AT THE LHC*

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The factorization scale dependence of the anomalous top–Higgs coupling effects in the leading order differential cross sections and distributions of the secondary lepton in the process of associated production of the top-quark pair and the Higgs boson at the LHC is discussed. It is also shown that the differential cross section as a function of the rapidity of the secondary lepton in the process is practically insensitive to a sign of the anomalous pseudoscalar coupling.

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1. Introduction

If the new particle with mass of about 125 GeV discovered at the LHC is indeed the Higgs boson of the Standard Model (SM), then practically the only model-independent way to constrain its coupling to the top quark is to measure the process of associated production of the top-quark pair and Higgs boson. First observation of the process

$$pp \rightarrow t\bar{t}h \quad (1)$$

was already reported by the CMS Collaboration [1]. At the LHC, process (1) is dominated by the gluon fusion mechanism. If the dominant decay modes: $h \rightarrow b\bar{b}$, $t \rightarrow bW^+$, $\bar{t} \rightarrow \bar{b}W^-$, and the subsequent decays of the W -bosons are taken into account, then the hard scattering partonic processes such as

$$gg \rightarrow bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu b\bar{b} \quad (2)$$

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that corresponds to one of the W -bosons decaying hadronically and the other leptonically, should be considered. Already in the leading order (LO) of the SM, the matrix element of process (2) in the unitary gauge, if calculated with the unit Cabibbo–Kobayashi–Maskawa mixing matrix and neglecting masses of particles lighter than the b -quark, receives a contribution from 67 300 Feynman diagrams some examples of which are shown in Fig. 1. The diagrams depicted in the first row represent the 56 signal diagrams of associated production of the top-quark pair and Higgs boson. The remaining 53 signal diagrams can be obtained from those of Figs. 1 (a), (b) and (c) by attaching the Higgs boson line of $hb\bar{b}$ -vertex to another top- or bottom-quark line and interchanging the identical b - and \bar{b} -quarks in each of the 3 diagrams, and by interchanging the two gluon lines in Fig. 1 (c). The diagrams shown in the second row of Fig. 1 are just a few examples of the off-resonance background contributions to associated production of the top-quark pair and Higgs boson. It should be noted that, in the narrow width approximation, where the cross section of process (2) factorizes into the cross section of process (1) times the branching fractions of $t \rightarrow b\bar{u}$, $\bar{t} \rightarrow b\mu^- \bar{\nu}_\mu$ and $h \rightarrow b\bar{b}$, there are only 4 Feynman diagrams of process (2).

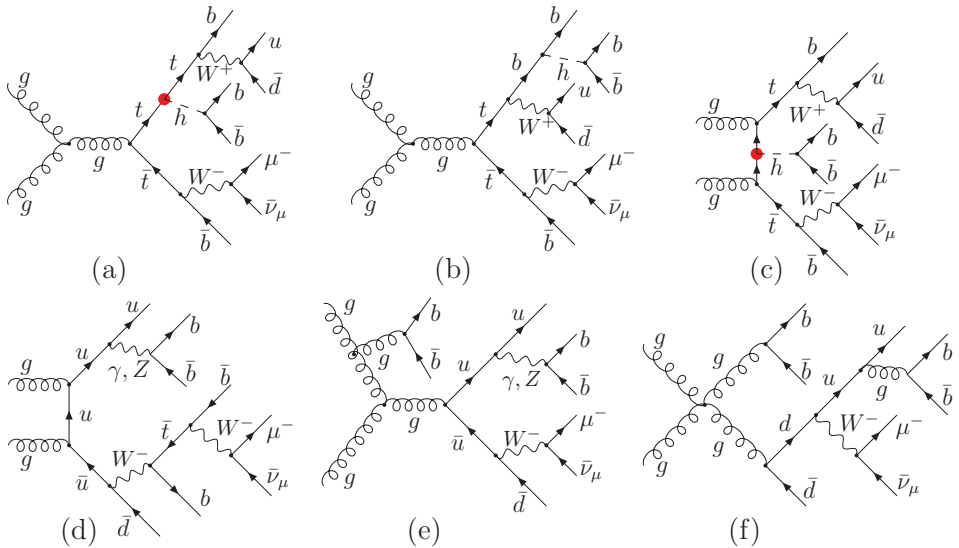


Fig. 1. Examples of the lowest order Feynman diagrams of process (2): (a), (b) and (c) are the signal diagrams of $t\bar{t}h$ production, (d), (e) and (f) are the $t\bar{t}h$ background contributions. Blobs indicate the top–Higgs coupling.

It has been shown in [2] that the LO differential distributions in rapidity and angles of the secondary lepton in the associated production of the top-quark pair and Higgs boson in proton–proton collisions at the LHC are

quite sensitive to modifications of the SM top–Higgs Yukawa coupling. In the present paper, we will discuss the question to which extent the effects of anomalous couplings in the LO differential cross sections and distributions depend on the choice of factorization scale in perturbative quantum chromodynamics.

2. Non-standard top–Higgs interaction

Departures of the top–Higgs coupling from its SM form that include corrections from dimension-six operators can be best parametrized in terms of the effective Lagrangian which, after eliminating the redundant operators with the use of equation of motion, has the following form [3]

$$\mathcal{L}_{t\bar{t}h} = -g_{t\bar{t}h}\bar{t}(f + if'\gamma_5)th, \quad (3)$$

where real couplings f and f' describe, respectively, scalar and pseudoscalar departures from the purely scalar top–Higgs interaction of SM that corresponds to $f = 1$ and $f' = 0$. f and f' are amongst least constraint couplings of the SM. Currently, only the following indirect constraints on f at 95% C.L. exist:

$$\begin{aligned} f &\in [-1.2, -0.6] \cup [0.6, 1.3] && \text{ATLAS [4],} \\ f &\in [0.3, 1.0] && \text{CMS [5].} \end{aligned}$$

They are derived from the process of Higgs boson production through the gluon fusion, which is dominated by the top-quark loop, and from the Higgs boson decay into 2 photons that also receives a significant contribution from the top-quark loop. However, the derivation relies on the assumptions that there is no new physical degrees of freedom in the loops and that there are two universal scale factors: one for all the Higgs boson Yukawa couplings to the SM fermion species and the other one for the Higgs boson couplings to electroweak gauge bosons. The interval in the range of negative numbers is highly disfavoured, as the opposite sign of the Higgs boson coupling to fermions with respect to its coupling to the gauge bosons is required in the Lagrangian for the unitarity and renormalizability of the theory [6] and vacuum stability [7].

3. Results

The Lagrangian (3) has been implemented in `carlomat` [8], a general purpose program for Monte Carlo (MC) computation of lowest order cross sections. A new version of the program has already been made publicly available [9]. The cross section of

$$pp \rightarrow bu\bar{d}\bar{b}\mu^-\bar{\nu}_\mu b\bar{b} \quad (4)$$

is computed by folding the cross section of the dominant hard scattering gluon fusion process (2) with the MSTW parton density functions (PDFs) [10] at the LO.

The complex mass scheme [11] is used in the computation and the initial physical input parameters are the same as in [2] except for $\alpha_s(m_Z) = 0.13939$ and the b -quark mass $m_b = 4.75$ GeV, both being transferred to `carlomat` from the MSTW LO PDFs, and the Higgs boson width $\Gamma_h = 7.1161$ MeV. The MC events of the associated production of the top-quark pair and Higgs boson in process (4) are selected by identifying jets with their original partons and imposing cuts given by Eqs. (3.2)–(3.7) of [2], with the $b\bar{b}$ invariant mass $m_{b\bar{b}}^{\text{cut}} = 20$ GeV in Eq. (3.7).

In order to test the scale dependence of the LO differential cross sections and distributions of process (4), the factorization scale in MSTW PDFs is set to $Q = q(2m_t + m_h)$, where the scale factor q is chosen to be either $q = 0.5$ or $q = 2$.

The differential cross sections and normalized distributions as functions of the rapidity of the final state μ^- of process (4) in pp collisions at $\sqrt{s} = 14$ TeV are shown in Fig. 2. The plots in the upper left-hand side panel

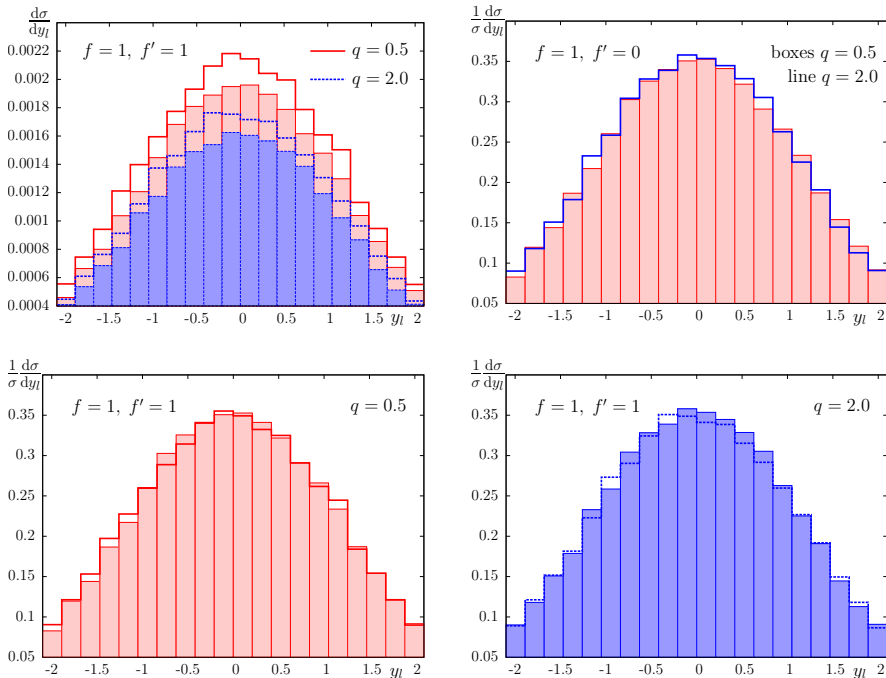


Fig. 2. Distributions in rapidity of the final state μ^- of process (4) in pp collisions at $\sqrt{s} = 14$ TeV.

of Fig. 2 show the SM results, corresponding to $f = 1$ and $f' = 0$, for $q = 0.5$ (boxes shaded in light grey) and $q = 2$ (boxes shaded in dark grey), and the results for $f = 1$ and $f' = 1$ that are plotted with lines: solid for $q = 0.5$ and dashed for $q = 2$. The scale dependence of the LO cross sections is substantial, as expected. It is to large extent reduced if the differential cross sections are normalized. This can be seen in the upper right-hand side panel, where the SM results for rapidity distributions of μ^- are plotted for $q = 0.5$ (boxes) and $q = 2$ (solid line). The distributions computed with the anomalous choice of couplings $f = 1$ and $f' = 1$, plotted with lines, are compared against the SM result, plotted with boxes, in the two lower panels of Fig. 2 for $q = 0.5$ (left panel) and $q = 2$ (right panel). The effects of the anomalous couplings in the distributions are not big, as they are to large extent obscured by the off resonance background contributions to the associated production of the top-quark pair and Higgs boson, which was shown in [2].

Practically, the same observations hold for the differential cross sections and normalized distributions as functions of the angle between μ^- and the reconstructed momentum of the Higgs boson of process (4) in pp collisions at $\sqrt{s} = 14$ TeV that are shown in Fig. 3.

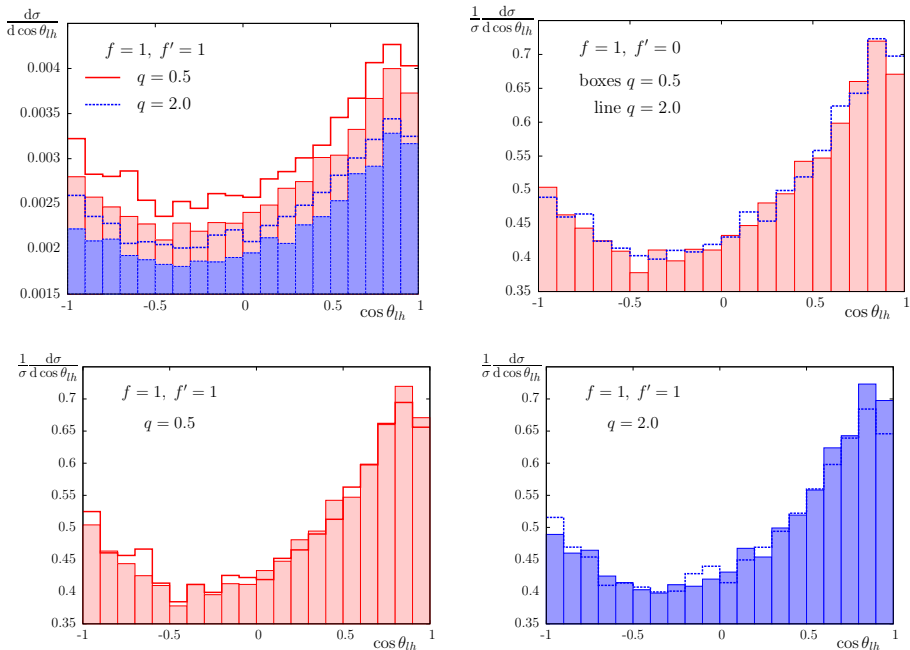


Fig. 3. Distributions in cosine of the angle between μ^- and the reconstructed Higgs boson momentum of process (4) in pp collisions at $\sqrt{s} = 14$ TeV.

It would be interesting to see whether or not the differential cross sections of process (4) are sensitive to a sign of f' . For the sake of clarity, let us assume $f = 0$ which, despite being beyond limits of (4), is still not excluded by direct constraints. In Fig. 4, the differential cross sections as functions of the rapidity of the final state μ^- of process (4) at $\sqrt{s} = 14$ TeV for two other anomalous combinations of couplings: $f = 0$ and $f' = \pm 1$ with $q = 0.5$ and $q = 2$ are plotted with lines together with the corresponding SM results that are plotted with boxes shaded in light grey for $q = 0.5$ and in dark grey for $q = 2$. The left panel shows the results for $f = 0$ and $f' = 1$, while the right panel shows the results for both $f = 0$ and $f' = 1$, and $f = 0$ and $f' = -1$. It can be seen that the cross sections show rather little sensitivity to a sign of the anomalous pseudoscalar coupling.

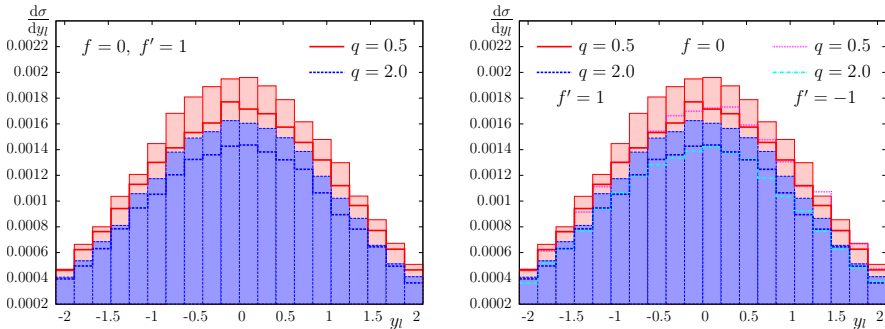


Fig. 4. Distributions in rapidity of the final state μ^- of process (4) in pp collisions at $\sqrt{s} = 14$ TeV.

4. Summary and outlook

The factorization scale dependence of the LO differential cross sections and distributions in the process of associated production of the top-quark pair and Higgs boson at the LHC in the presence of the anomalous top-Higgs coupling has been discussed. The substantial scale dependence of the LO cross sections is to large extent reduced if the corresponding normalized distributions are considered. It has also been shown that the differential cross section as a function of the rapidity of the final state μ^- of process (4) at $\sqrt{s} = 14$ TeV is practically not sensitive to a sign of the anomalous pseudoscalar coupling.

Process (4) may be affected by many other possible deviations from the SM couplings that have not been discussed in this lecture, where we have focused just on the effects of the anomalous $t\bar{t}h$ interaction on the distributions of the secondary lepton. However, some of the deviations could be easily included in the discussion as they have been already implemented in

carlomat [9]. This holds, in particular, for the anomalous Wtb coupling whose effects on the process of top-quark pair production in hadronic collisions was studied in [12] and [13].

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