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Precise predictions for electroweak $t\bar{t}$ production at the LHC in models with flavour non-diagonal Z' boson couplings and W' bosons

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We report on our re-calculation of electroweak top-quark pair production in Standard Model extensions with extra heavy neutral and charged spin-1 particles at the LHC with substantial improvements. In particular, we allow for flavour–non-diagonal Z' couplings and take into account non-resonant production in the Standard Model and beyond. As in our previous work we include NLO QCD corrections and match to parton showers with the POWHEG method fully taking into account the Standard Model and new physics interference effects. We consider the Sequential Standard Model, the Topcolour model as well as the Third Family Hypercharge Model featuring non-flavour diagonal Z' couplings which has been proposed to explain the anomalies in B decays. Numerical results for $t\bar{t}$ cross sections at hadron colliders with $\sqrt{s}$ of up to 100 TeV are presented. We also investigate the numerical impact of the new non-resonant contributions.

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1. Introduction

The Standard Model (SM) of particle physics, based on a $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry, is an extremely successful theory accounting for a wide range of high energy experiments at both the intensity and energy frontiers. Nevertheless, it is widely believed to be incomplete for multiple reasons: it doesn't provide a candidate for a dark matter particle; the CP violation in the SM is not sufficient to explain the observed matter–anti-matter asymmetry; and massive neutrinos are, a priori, not accounted for. Furthermore, its scalar sector is plagued by naturalness problems related to the stability of the Higgs mass under quantum correction and to the suppression of CP violation in the strong interaction. Hence, the general expectation has been for a long time that new physics beyond the SM should be present close to the electroweak (EW) scale.

Despite the fact that no signals of new physics were found in the first two runs of the Large Hadron Collider (LHC) at CERN, there are still high hopes that new particles will show up in future high-luminosity runs. Such signals will likely appear as small deviations from the SM predictions which makes precise predictions for both the SM background and the new physics signals increasingly important.

We focus on new heavy electrically charged or neutral spin-1 resonances with EW-like couplings, denoted $W'^{\pm}$ and Z', respectively. They are predicted by several well-motivated extensions of the SM and are extensively looked for at the LHC. In this context it is noteworthy that Z' models with a non-universal flavour structure [1–4], where the Z' couples differently to the fermions of the three SM families, are viable candidates to explain the current B-flavour anomalies [5–14].

In many cases, the strongest constraints on the parameter space of models with Z' and W' resonances come from searches with dilepton final states. In this case, precise predictions at next-to-leading order (NLO) accuracy including a resummation of soft gluon terms at next-to-leading logarithmic accuracy can be obtained with the `Resummino` code [15–17]. However, top quark observables are also very interesting since the 3rd generation plays a prominent role in the SM due to the Yukawa coupling of the top quark, which is the only Yukawa coupling in the SM which is of order one. Therefore, it is quite conceivable that new physics couples predominantly to the top quark.

In 2015, some of us performed a calculation of NLO QCD corrections to the EW $t\bar{t}$ production in the presence of a Z' resonance matched to parton showers (PS) with the POWHEG method [18]. In this proceedings we report on a complete re-calculation including a number of improvements, among which the most noteworthy are: (a) the generalisation of Z' couplings also allowing for flavour–non-diagonal fermion vertices; (b) addition of non-resonant contribution such as the t-channel W and W' exchange. In Sec. 2 we provide a description of the calculation with a focus on those aspects which differ from our previous calculation in [18]. Then in Sec. 3 we briefly summarise the models considered here. The tool setup is described and the numerical results are presented in Sec. 4. Finally, in Sec. 5 we present a summary and our conclusions.

2. Description of the calculation

The cross section for the hadroproduction of a $t\bar{t}$ pair, $AB \to t\bar{t}X$, is given by the usual convolution of the parton distribution functions (PDFs) inside the two incoming hadrons A and B, with the short distance cross sections $\hat{\sigma}_{ab}$ summed over partonic channels, $ab \to t\bar{t}X$. Here we work in a 5-Flavour Number Scheme including all relevant contributions with u, d, s, c, b (anti-)quarks, gluons and unless explicitly stated also photons in the initial state.

Up to NLO the hard scattering cross sections have the following perturbative expansion in the strong (α_s) and electroweak (α) coupling constants:

$$\hat{\sigma} = \hat{\sigma}_{2;0}(\alpha_S^2) + \hat{\sigma}_{3;0}(\alpha_S^3) + \hat{\sigma}_{2;1}(\alpha_S^2\alpha) + \boldsymbol{\hat{\sigma}_{0;2}(\alpha^2)} + \boldsymbol{\hat{\sigma}_{1;2}(\alpha_S\alpha^2)} + \boldsymbol{\hat{\sigma}_{1;1}(\alpha_S\alpha)} + \hat{\sigma}_{0;3}(\alpha^3)\,, \quad (1)$$

where the numerical indices $(i; j)$ in $\hat{\sigma}_{i;j}$ represent the powers in α_s and α, respectively, the parton flavour indices and the dependence on the scales have been suppressed, and the terms considered in our calculation have been highlighted in bold.

In our calculation we focus on the tree-level EW top-quark pair production, $\boldsymbol{\hat{\sigma}_{0;2}}$, and its NLO QCD corrections, $\boldsymbol{\hat{\sigma}_{1;2}}$. $\boldsymbol{\hat{\sigma}_{0;2}}$ receives contributions from the s-channel amplitudes $q\bar{q} \to Z', Z, \gamma \to t\bar{t}$, including the Z' signal and its interference with the photon and SM Z boson. Due to the resonance of the Z' boson, we expect these terms to be the most relevant for new physics searches. In addition, we include new contributions from diagrams with non-resonant exchanges of W, W' and Z' bosons that were not considered in Ref. [18]. Note that out of these, the first two take into account CKM mixing and the last one is only allowed in models with flavour non-diagonal couplings. A particular advantage of the $\boldsymbol{\hat{\sigma}_{0;2}}$ contribution is that the calculation of $\boldsymbol{\hat{\sigma}_{1;2}}$ can then be carried out in a model-independent way. We also consider the term $\boldsymbol{\hat{\sigma}_{1;1}}$ that includes both the contribution from the photon induced subprocess and the previously not considered interference of the s-channel QCD and the t-channel EW top-pair production[1]. The photon induced subprocess, $\gamma g \to t\bar{t}$, is included for a consistent treatment of the mass singularities in the process $gq \to t\bar{t}q$ when the t-channel photon is collinear to the quark and is numerically important. However, we neglect photon-initiated contributions to $\boldsymbol{\hat{\sigma}_{0;2}}$ and $\boldsymbol{\hat{\sigma}_{1;2}}$.

We do not consider any of the remaining terms in Eq. (1). The terms $\hat{\sigma}_{2;0}$ and $\hat{\sigma}_{3;0}$ do not get affected by the presence of Z' or W' bosons and are readily available in many NLO+PS event generators [19–24]. The EW corrections in terms $\hat{\sigma}_{2;1}$ and $\hat{\sigma}_{0;3}$ would receive corrections from new Z' and W' running in the loops. However, they are parametrically suppressed relative to their underlying Born processes $\hat{\sigma}_{2;0}$ and $\hat{\sigma}_{0;2}$[2] and, unfortunately, do not lend themselves to model independent calculations.

Born, virtual and real amplitudes are calculated using the public library `Recola2`, an extension of `Recola` [27] for the computation of tree and one-loop amplitudes in the SM and beyond.[3] We implement calls to `Recola` subroutines in the `POWHEG BOX` event generator [28] that allows matching NLO calculations to PS (jointly referred to as NLO+PS) using the POWHEG method [29, 30].

3. Models

We consider three extensions of the SM: the Sequential Standard Model (SSM) [31], the Top Colour model (TC) and the Third Family Hypercharge Model (TFHM) [1]. The SSM is a toy

[1]That is the interference of $q\bar{q} \to g \to t\bar{t}$ and $q\bar{q} \to W^*, W'^*, Z'^* \to t\bar{t}$, where * indicates t-channel exchange.

[2]Despite the parametric suppression they have been shown to be important in the SM in regions with large top transverse momentum [25, 26].

[3]The model file used here can be found on the official website https://recola.hepforge.org/ under model files.

model which introduces copies of the W and Z bosons that only differ in mass. It has no free parameters except for the Z' and W' masses. Due to its simplicity and convenience it is a widely used benchmark model in which LHC data are analyzed. In the TC model, which can generate a large top-quark mass through the formation of a top-quark condensate, the Z' boson is leptophobic and couples only to the quarks of the first and the third generation. It has three parameters: the ratio of the two $U(1)$ coupling constants, $\cot\theta_H$, which should be large to enhance the condensation of top quarks, but not bottom quarks, as well as the relative strengths f_1 and f_2 of the couplings of right-handed up- and down-type quarks with respect to those of the left-handed quarks. THFM extends the SM by an anomaly-free, spontaneously-broken $\mathrm{U}(1)_F$ gauge symmetry. Apart from the new gauge boson and a SM singlet, complex scalar field, needed for the spontaneous symmetry breaking of the $\mathrm{U}(1)_F$ symmetry, no new particles are introduced. The model has flavour-dependent couplings and provides an explanation of the heaviness of the third generation of SM particles and the smallness of the quark mixing. Recently, the TFHM has been slightly modified to make it more natural in the charged lepton sector [2], however, in the following we will use the original TFHMeg from Ref. [1, 32]. It has three free parameters: the extra U(1) coupling, g_F, the angle controlling the mixing of the second and third family quarks, θ_{sb} and the Z' boson mass.

The most stringent exclusion limits for the SSM are derived from searches with dilepton and charged lepton plus missing transverse momentum final states. They exclude Z' and W' with masses respectively below 5.2 and 6.0 TeV [33–37]. The TC model is excluded with Z' masses below $3.8 - 6.65$ TeV in $t\bar{t}$ channel [38, 39]. The parameter space of the THFMeg model has been investigated in [40] and for the choice $\theta_{sb} = 0.095$, $g_F/m_{Z'} = 0.265$ roughly corresponds to the range $m_{Z'} \in (2, 5)$ TeV. The intention of this work is to demonstrate the variety of SM extensions that our calculation can be applied to. Therefore, these exclusion limits are disregarded in the comparisons that follow.

4. Numerical results

We present NLO+PS predictions for EW top-pair production for a pp collider with a range of collider energies $\sqrt{s} \in \{14, 27, 50, 100\}$ TeV. We consider the SSM, TC and THFM models and a range of Z' masses $m_{Z'} \in [2, 8]$ TeV. In the SSM we set the mass of W' equal to the mass of Z'. The widths of Z' and W' bosons must then be $\Gamma_{Z'}/m_{Z'} = 3\%$, $\Gamma_{W'}/m_{W'} = 3.3\%$. The parameters of the TC model are chosen as follows: we set $f_1 = 1$ and $f_2 = 0$ and calculate $\cot\theta_H$ such that $\Gamma_{Z'}/m_{Z'} = 3.1 - 3.2\%$. In THFM we set $\theta_{sb} = 0.095$, $g_F/m'_Z = 0.265$ which implies $\Gamma_{Z'}/m_{Z'} = \{0.012, 0.028, 0.050, 0.078, 0.112, 0.152\}$ for $m'_Z = \{2, 3, 4, 5, 6, 7\}$ TeV.

We employ a top quark pole mass $m_t = 172.5$ GeV. Furthermore, the masses and widths of the weak gauge bosons are given by $m_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV, $m_W = 80.385$ GeV, $\Gamma_W = 2.085$ GeV [41]. The weak mixing angle is fixed by $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = 0.222897$ and the fine-structure constant is set to $\alpha(2m_t) = 1/126.89$. We neglect the running of this coupling to higher scales.

For the proton PDFs, we use the NLO luxQED set of NNPDF3.1 [42–44] as implemented in the LHAPDF library (ID = 324900) [45, 46] both at NLO+PS and at LO+PS. This set provides, in addition to the gluon and quark PDFs, a precise determination of the photon PDF inside the proton

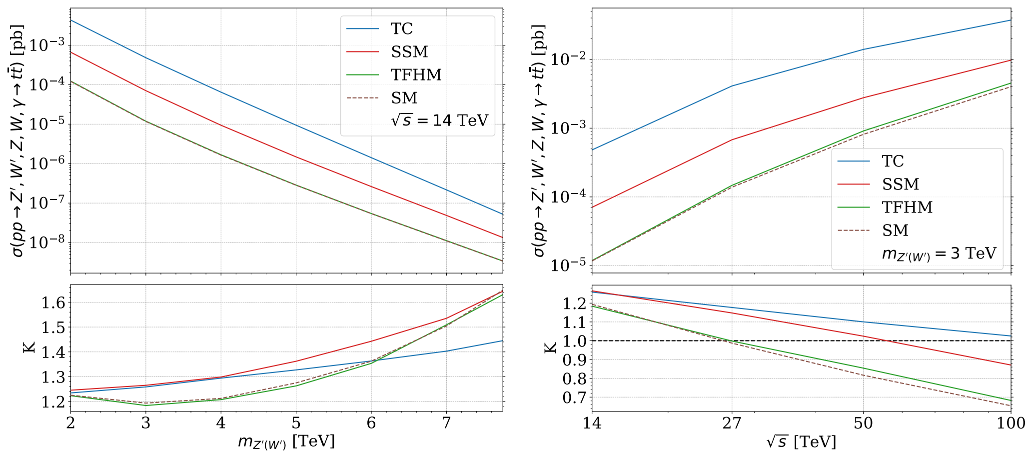

Figure 1: Fiducial cross section for EW $t\bar{t}$ production in SM, SSM, TC and THFM with an invariant mass cut $m_{t\bar{t}} \geq 0.75 m_{Z'}$ at NLO+PS (upper panels) and in ratio to LOPS (lower panels). Left panel: Cross section at $\sqrt{s} = 14$ TeV as a function of $m_{Z'}$. Right panel: Cross section at $m_{Z'} = 3$ TeV as a function of $\sqrt{s}$.

which we need for our cross section predictions. The running strong coupling $\alpha_s(\mu_R)$ is evaluated at NLO in the $\overline{\text{MS}}$ scheme and is provided together with the PDF set[4].

For our numerical predictions we choose equal values for the factorisation and renormalisation scales, μ_F and μ_R respectively, which we identify with the partonic centre-of-mass energy: $\mu_F = \mu_R = \sqrt{\hat{s}}$.

We generate events in the Les Houches Events format [47] using `POWHEG BOX` with stable on-shell top quarks requiring the underlying Born kinematics to satisfy a cut on the $t\bar{t}$ invariant mass, $m_{t\bar{t}} \geq 0.75 m_{Z'}$, in order to enhance the signal over background ratio. We then decay both top quarks leptonically and shower the events using `PYTHIA 8.2` [48]. The branching ratio of the leptonic top decay of 10.5% [49] squared is applied. We use `PowhegHooks` to veto shower emissions harder than the POWHEG emission and disable QED shower emissions.

We perform further event selection and histogram on the fly using `Rivet` [50, 51]. Events are required to have two or more charged leptons, two or more neutrinos and two or more anti-k_T [52] $R = 0.5$ jets, each containing at least one b-parton. All these objects have to fulfil the acceptance cuts $p_T > 25$ GeV and $|y| < 2.5$. Furthermore we combine charged leptons and neutrinos into W bosons based on their MC truth PDG id and require each event to feature at least one such W^+ and one such W^- boson.

In Fig. 1 we show the fiducial cross sections as a function of $m_{Z'}$ for $\sqrt{s} = 14$ TeV and as a function of $\sqrt{s}$ for $m_{Z'} = 3$ TeV, on the left and right respectively, in the SSM, TC and THFM models as well as in the SM. The upper panels show the NLO+PS cross sections while the lower panels the corresponding K-factors, i.e. the ratio of NLO+PS over LO+PS cross sections. First we note that the SM cross sections depend on the $m_{Z'}$ indirectly through the invariant mass cut. The TC cross sections are almost two orders of magnitude above the SM ones over the entire $m_{Z'}$ and $\sqrt{s}$ ranges. Similarly, the SSM cross sections are about one order magnitude larger than in the SM. The THFM curves overlap with the SM curve almost everywhere except for the $\sqrt{s} \geq 50$ TeV where

[4]Its value is fixed by the condition $\alpha_s(m_Z) = 0.118$.

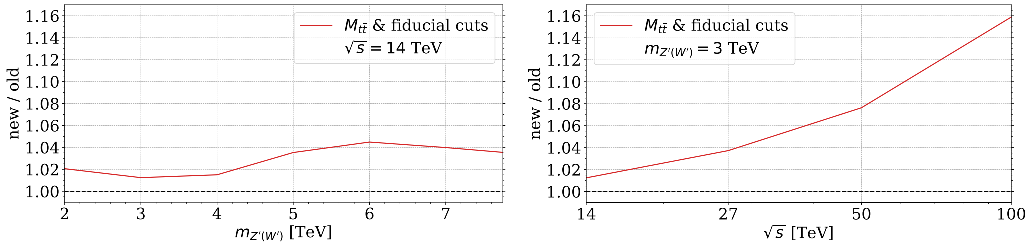

Figure 2: The ratio of fiducial cross section for EW $t\bar{t}$ production in SSM, with over without contributions due to t-channel W boson exchange as a function of $m_{Z'}$. We set for $\sqrt{s}$ = 14 TeV and apply the usual invariant mass cut $m_{t\bar{t}} \geq 0.75 m_{Z'}$.

a slight excess over SM can be observed. From this we conclude that the invariant mass cut for suppressing the SM contribution to the EW top-pair production (background) designed to enhance the Z' mediated top-pair production (signal) is adequate in the cases of the SSM and TC model. However the THFM cross sections are very small even in the presence of this cut and further cuts may be required for such production to be observable at the LHC. The higher order QCD corrections are moderate and grow with the mass of $m_{Z'}$. With $\sqrt{s}$ the K-factor drops instead with higher order corrections for SSM turning negative at $\sqrt{s}$ = 100 TeV.

Now we turn our attention to the impact of newly included contributions on the fiducial cross section. In the SM and at LO when all the cuts are relaxed, the EW $t\bar{t}$ production is dominated by the contribution due to t-channel W-boson exchange, which is in fact about factor 6 larger than the resonant production. Once the invariant mass cut is applied, both the resonant and non-resonant SM contributions are reduced by about the same factor (by roughly 5 orders of magnitude) and both drop well below the BSM signal. However, the SM contributions respond quite differently to the fiducial cuts, where the resonant production is reduced at the same rate as the BSM signal (about 30%), while the non-resonant production is reduced by over 90%.

In Fig. 2 we show the ratio of the fiducial cross sections with and without the new contributions. We find that at $\sqrt{s}$ = 14 TeV invariant mass and fiducial cuts turn the new contributions to a correction of a mere few percent with respect to our previous predictions. However, it can become quite important as we increase the centre-of-mass energy.

5. Summary and conclusions

We presented a re-calculation of NLO QCD corrections to EW hadroproduction of $t\bar{t}$ pairs in SM extensions with new heavy hypothetical neutral and charged gauge bosons, Z' and W' bosons respectively. In comparison to our previous calculation in Ref. [18], we now allow flavour–non-diagonal Z' couplings and include contributions due to t-channel exchange of W and W' bosons. This significantly extends the range of SM extensions that can be considered.

We demonstrate this calculation on the SSM, TC and TFHM models for which we calculate NLOPS fiducial cross sections as a function of Z' mass and the centre-of-mass energy. We also show the impact of the new non-resonant contributions which are mild at $\sqrt{s}$ = 14 TeV but can be relatively important at higher energies. A more detailed and complete study is in preparation [53].

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