Search for exclusively produced top quark pairs at the LHC

Beatriz Ribeiro Lopes
beatrice.ribeiro.lopes@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

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Abstract

This thesis focuses on the search for exclusively produced top quark pairs at the Large Hadron Collider (LHC). This process, although quite rare, is expected to be sensitive to anomalous couplings of the top quark with the photon, and thus can be used to look for new physics. The Standard Model expected cross-section is of the order of 1 fb, however, some Beyond the Standard Model (BSM) theories predict its enhancement. For the search, data collected in 2017 by the Compact Muon Solenoid (CMS) is used, including information collected by the Precision Proton Spectrometer (PPS), a forward proton detector. CMS central data and tracks recorded by PPS are matched. As a first step, a cut-based selection is performed, and signal and control regions are defined. This allowed the setting of an expected upper limit for the cross-section of this process, of $1.1^{+0.5}_{-0.4}$ pb. The observed limit is 7.2 pb.

The search is then improved using a Multivariate Analysis approach, which brought the expected limit down to $0.9^{+0.7}_{-0.4}$ pb and the observed limit to 1.4 fb. This is the first experimental result concerning the search for exclusive production of top quark pairs, and the first upper limit set using PPS data.

Keywords: top quark pairs, exclusive production, CMS, Precision Proton Spectrometer (PPS), LHC

1. Introduction

The Standard Model (SM) of Particle Physics encloses the current knowledge on the fundamental constituents of matter and their interactions. It is a successful theory that is able to make accurate predictions, and that passed a great majority of the experimental tests performed so far. However, it is known that it is not the full theory, since it does not explain a set of phenomena, like the origin of neutrino masses, the matter-anti matter asymmetry observed in the universe, and does not accommodate General Relativity. All the fundamental particles predicted by the SM have now been discovered. Being the heaviest of SM particles, and one of the last to be discovered (in 1995, [8]), the top quark is one of the current focuses when searching for New Physics. Due to its large mass, it is potentially more sensitive to deviations from the SM. It has an electric charge $+2/3e$ and a mass $m_{\text{top}} = 173.0 \pm 0.4$ GeV [22], nearly in the same order of the electroweak symmetry breaking energy scale. Top quarks are produced at the Large Hadron Collider (LHC) mainly in top anti-top quark pairs ($t\bar{t}$), via the strong interaction.

The top quark decays almost exclusively in the SM (branching ratio $\approx 95.7\%$ [22]) through the $t\rightarrow Wb$ process, that is, into a $W$ boson and a $b$ quark. The $t\bar{t}$ decay channels are then labelled according to how the $W$ bosons decay: the all-jets channel (when both $W$ bosons decay to $q\bar{q}$ pairs which then hadronise), the lepton+jets channel (when one $W$ decays to a $q\bar{q}$ pair and the other to a lepton and the corresponding neutrino) and the dilepton channel (when both $W$ bosons decay each into a lepton and the corresponding neutrino).

In most $pp$ collisions, including the usual $t\bar{t}$ events (via quark or gluon fusion), the initial colliding protons are disrupted in the process. In some collisions, however, these protons may exchange either energetic gluons or photons, which interact producing new particles, while either one or both of the initial protons are kept intact. We call these exclusive processes (or semi-exclusive, in case only one of the protons remains intact). This kind of process is rare but extremely interesting, in particular if one can have experimental access to the energy of the escaping proton(s). That is now the case at the CMS experiment in the LHC, with the Precision Proton Spectrometer (PPS) described in the next section. Such collisions provide very clean experimental signals and are a very promising way to search for a possible Beyond Standard Model (BSM) signal [16]. In this work, we are interested in the central exclu-
sive production (CEP) of top quark pairs by either photon or gluon fusion, as shown in figure 1.

Figure 1: Exclusive $t\bar{t}$ production diagrams, via $\gamma\gamma$ fusion (left) and $gg$ fusion (right).

The SM prediction for the cross-section (quantum mechanical measure of the probability of occurrence) of this process is extremely low, $\sim 1$ fb for photo-production [6, 7], but if identified in data, it offers the possibility of determining the $t\bar{t}$ production threshold with a better resolution than that which can be attained based only on the reconstruction of the final states of the decay. Besides, if new physics is present, the low cross-section is expected to be significantly enhanced, either in the production of $t\bar{t}$ (due to couplings of the top quark with BSM particles) or in the production of similar final states containing at least two leptons [9–12]. Another reason why this search is interesting is that this process is expected to be sensitive to top anomalous couplings (couplings which are not predicted by the SM). Unlike other quarks, the top quark couplings are not yet thoroughly studied, and SM predictions still have to be tested more. Moreover, if large amounts of CP violation are seen in top quark events, this can be strong evidence of BSM physics.

2. Experimental considerations

Particle physics experiments are mainly performed using high-energy particle accelerators. The Large Hadron Collider (LHC) is a 27km long circular accelerator at CERN, Switzerland, designed to collide hadrons at high energies. It is capable of colliding protons at a centre-of-mass energy of 13 TeV and heavy ions at about 5 TeV, thus being the world’s largest and most powerful accelerator. The final products of these collisions are then detected and recorded by the detectors of the LHC experiments. The largest of these experiments are the ATLAS detector [4] and the Compact Muon Solenoid (CMS) - two general-purpose experiments. There is also the LHCb [18], which focuses on the study of processes involving the bottom quark and ALICE [2], which studies mainly heavy-ion collisions.

The work in this thesis used data from the CMS detector. This detector has a cylindrical shape and consists of a central region where the collisions occur, followed by a silicon tracker, then an electromagnetic calorimeter, and a hadronic calorimeter. Continuing outwards, there is a superconducting solenoid which produces the 3.8 T magnetic field, and the muon chambers (a full description can be found in [11]). A scheme of a slice of CMS is in figure 2.

Figure 2: Transverse cut of the CMS detector, depicting the trajectory and detection of different particles.

The Precision Proton Spectrometer (PPS) [9] is a detector which was recently built by the CMS and TOTEM collaborations. It is located at about 210 m from the interaction point (IP5), on both sides of CMS. The scheme of one arm is shown in figure 3. It measures the trajectories of protons that have left the collision intact and lost from about 2 to 20% of their momentum. These protons remain inside the beam pipe, and can be measured using position-sensitive detectors, complemented by timing counters to measure the proton arrival time. PPS consists of several detector planes, inserted in specially designed vacuum chambers called “Roman Pots” (RPs), which are movable near-beam devices located a few mm ($\sim 15\sigma$ in standard runs) from the LHC beam, without damaging it or compromising the functioning of the accelerator.

2.1. Exclusive $t\bar{t}$

The exclusive $t\bar{t}$ process, in the dilepton channel, has the Feynman diagram of figure 4. The final-state particles in the central detector are two $b$-quarks, two leptons and two neutrinos. The $b$-quarks hadronise and form jets. In the analysis, leptons means electrons and muons (taus are not considered). Additionally, the two protons, intact after the collision, can in principle be detected if they hit PPS, thus adding a decisive signature to this process.
For this process, the main background is expected to be non-exclusive tt production. The final state of this process is expected to be exactly the same as described for the signal, with very few kinematic differences. The most significant difference is, naturally, the absence of outgoing protons. Another important background is Drell-Yan production, when a quark and an anti-quark interact to produce a Z-boson or a virtual photon which then decays into a pair of leptons, as in figure 5.

The easiest background to separate from is Drell-Yan production. On the one hand, in this process, the final state leptons are necessarily of the same flavour (two electrons or two muons). On the other hand, this process is dominated by Z-boson production, and in this case, the distribution of the invariant mass of the two leptons will have a large concentration of events (peak) around the Z-boson mass ($\sim 91.2$ GeV).

When it comes to the inclusive t\bar{t} background, the story is more complicated. Selecting events with PPS tracks is the most obvious choice, however, the PPS signal is overwhelmed with protons coming from pileup, which randomly reach PPS. There is, then, the need to explore kinematic differences in the central process. The main difference would be the fact that exclusive tt events are expected to be produced more back-to-back (higher angular difference) than the inclusive ones. There are two main reasons for this:

- The top quark pair, in the exclusive process, is produced through an electroweak vertex, so no extra activity (from soft gluons or initial state radiation) is expected in the event, and thus there are no particles for the tops to recoil against - by momentum conservation, they are expected to be back-to-back;
- The electromagnetic form factor of the proton heavily suppresses photon-exchange with large transverse momentum when the protons stay intact. So the t\bar{t} system is expected to have a total $p_T \sim 0$, that is, the tops must be produced back-to-back [19].

The second effect is illustrated in figure 6, where the difference in the expected tt transverse momentum between the exclusive (elastic-elastic) and the inclusive (elastic-inelastic or inelastic-inelastic) cases is shown.

3. State of the art
The first measurement of the cross-section of t\bar{t} production, performed by CMS in 2010 (in [12]), was an extremely important milestone for the LHC and the CMS experiment, since most of the new physics
models that the LHC was designed to test either include top quarks or have $t\bar{t}$ production as one of the main backgrounds. One of the latest measurements is in [14] and reveals a cross-section of $\sigma_{t\bar{t}} = 803 \pm 125 \text{(stat)} \pm 25 \text{(syst)} \pm 20 \text{(lumi)} \text{ pb}$.

About PPS, the central (semi)exclusive production of two high-energy leptons was observed by the CMS-TOTEM collaboration using the Precision Proton Spectrometer, in 2018 [10]. This is a significant result, being the first observation of proton-tagged $\gamma\gamma$ collisions at the electroweak scale, and showing that PPS performs according to its specifications. This work was taken as a starting point for the work done in this thesis.

4. Analysis

The analysis is performed using proton-proton collisions data at $\sqrt{s} = 13 \text{ TeV}$ collected in 2017 by CMS. The total integrated luminosity corresponds to $41.8 \text{ fb}^{-1}$. Specific datasets which contain events with electron or muon tags were used. For the correlation between the central detector and the PPS, only data from RPs 003, 023, 103 and 123 were used, since no alignment parameters exist for other pots. Besides, only collisions with crossing angle of 120, 130, 140 or 150 $\mu$rad are considered, because there are no dispersion values available for other crossing angles. The total integrated luminosity where combined CMS-PPS data have been analysed with calibrated pixels is thus reduced to $39.5 \text{ fb}^{-1}$.

The official Monte Carlo production samples were used for the background. These were produced using Madgraph/Powheg/MC@NLO [3, 20], with Pythia8 [21] used to do the showering and hadronization.

In addition, a signal $pp \rightarrow p\gamma p \rightarrow t\bar{t}pp$ sample has been produced privately using FPMC [7] as the matrix element generator and HERWIG++ [5] as the parton shower.

4.1. Cut-based analysis

Central detector selection

Two charged leptons (electron or muon) with $p_T > 20 \text{ GeV}$ are required. Both have to be reconstructed within $|\eta| < 2$. At least one of the leptons is required to have $p_T > 30 \text{ GeV}$ and $|\eta| < 2$. Furthermore, the dilepton system is required to have an invariant mass above $20 \text{ GeV}$ ($M_{ll} > 20 \text{ GeV}$). Depending on the flavour and invariant mass of the dilepton system, the events are classified in the following exclusive categories:

- same flavour leptons ($ee$ or $\mu\mu$) with reconstructed $M_{ll}$ around the $Z$ boson mass ($M_{ll} \in [76, 106] \text{ GeV}$): $Z$ control region;
- same flavour leptons outside the $Z$-peak region: $ee$ and $\mu\mu$ regions;
- opposite flavour leptons ($e\mu$): $e\mu$ region.

After categorising the events, the following selection is applied:

- $\geq 1 \text{ jet (} p_T > 30 \text{ GeV, } |\eta| < 2.4 \text{ passing a loose pileup jet id criteria [17])};$
- $\geq 1 \text{ b-jet (} p_T > 30 \text{ GeV, } |\eta| < 2.4 \text{ passing the deepCSV "medium" working point [13])};$
- at least one lepton-b combination verifies $M_{tb} < 160 \text{ GeV}$.
Events failing these selection requirements are not excluded but categorised separately. In the last requirement, $M_{lb}$ refers to the invariant mass of the lepton-$b$ jet system. The $b$ jet with the highest momentum is matched with the lepton more likely to have come from the same top quark. The criterion stems from the fact that, by energy conservation, one expects at leading order (LO), that $M_{lb} < \sqrt{m_t^2 - m_W^2} \approx 160$ GeV for $m_t = 172.5$ GeV and $m_W = 80.4$ GeV [22]. Thus, by applying such requirement, we expect that higher $t\bar{t}$ purity is attained.

Figures 8 and 9 show the distribution of the invariant mass of the dilepton system for the $ee$ and $e\mu$ channel. As expected, the same-flavour channels are dominated by Drell-Yan (DY) production. A clear peak is observed around the Z boson mass region. The opposite flavour category, however, is fairly pure in $t\bar{t}$ events, although there is significant Multiboson and W production.

In order to increase this purity, the $M_{lb}$ cut is applied. Figure 10 shows the distribution of the invariant mass of the dilepton system, for opposite flavour leptons ($e\mu$), but now for events with at least one b-jet, satisfying $M_{lb} < 160$ GeV. Comparing with the plot of figure 9, one clearly sees the high background rejection efficiency.

We have compared the signal and the inclusive $t\bar{t}$ sample concerning specific variables reconstructed in the central detector. The variables were chosen to be sensitive to the additional hadronic activity, which is expected to be suppressed in the case the production is exclusive and via electroweak vertices. The variables chosen are:

- $H_T = \sum_{j=1}^{N_j} |\vec{p}_T(j)|$, the scalar sum of the transverse momentum of all jets except the b-jets;
- Hadronic recoil $h = |\vec{p}_{T\text{miss}} + \vec{p}_T(\ell_1) + \vec{p}_T(\ell_2) + \sum_{j=1}^{N_b} \vec{p}_T(j)|$, obtained from the sum of the missing transverse energy with the two charged leptons and up to two b-jets. In the analysis, we make use of the so-called pupperMET estimator for $\vec{p}_{T\text{miss}}$ [1].

In the simulations we observe that signal $t\bar{t}$ has a considerably small fraction of events which have extra activity, that is, most of the events have $H_T=0$ given there are no extra jets in the event. Conversely signal $t\bar{t}$ events tend to have lower $h$ when compared to inclusive $t\bar{t}$ production.
In fact, requiring $H_T = 0$ GeV preserves 63% of exclusive $t\bar{t}$ (signal) events and only 22% of inclusive $t\bar{t}$ (background). In this analysis, $H_T = 0$ GeV is used in defining the signal region.

Another variable that I found to be important was $\Delta R(l,l)$. One can see by looking at the distribution in figure 11 that, as expected, the exclusive $t\bar{t}$ events are distributed towards higher values of $\Delta R(l,l)$.

Figure 11: Distribution of the $\Delta R$ between the two leptons, after selecting 2 leptons and $\geq 1$ b and requiring $M_{lb} < 160$ GeV, for the $e\mu$ channel.

**PPS detector selection**

For the final selection, we use data from the pixel detectors. The choice for the pixels is made given that they are able to reconstruct more than one track per event, so in case of pileup the signal is not lost due to inefficiency of the reconstruction.

For each track reconstructed in the pixel detector, one is able to reconstruct the fractional momentum loss ($\xi$) of the proton, between 0.02 and 0.25, approximately. From the value of $\xi$, one reconstructs the mass and rapidity of the $t\bar{t}$ in the central system, using the following equations:

$$M_{RP} = \sqrt{s\xi_0\xi_1} \quad (1)$$

$$y_{RP} = \frac{1}{2} \ln \left( \frac{\xi_0}{\xi_1} \right) \quad (2)$$

where the subscripts 0 and 1 refer to the arm number.

Due to pileup (the average vertex multiplicity in the 2017 data is $\sim 30$), there is often more than one track per event in each pixel detector. Thus there is the need to reconstruct the mass and rapidity for every combination of tracks.

For this analysis, we selected events in the $M_{RP} \in [300, 600]$ GeV range, which is chosen to be compatible with the bulk of the production threshold of exclusive $t\bar{t}$. The events are categorised depending on whether or not there is a combination of tracks that leads to a reconstructed $t\bar{t}$ mass in this range.

**PPS information** is only available for data and simulated signal sample; the official 2017 MC samples used for the background do not contain this information. In order to circumvent this problem, I use a data-driven method to attribute a "fake" PPS information to the MC samples. For that, I take the number of forward tracks and the $\xi$ distributions from data (as observed at pre-selection level where possible contribution from signal is negligible), and...
attribute, to each MC event, a "fake" number of tracks, randomly picked from the distribution, as well as a "fake" $\xi$ value for each track, and then compute the mass and rapidity using equations 1 and 2. The obtained distributions presented an overall shape agreement between data and MC. However, when looking at the data/MC ratio, a visible slope showed that this method presents some problems. In order to overcome these problems, only events with one track on each side of PPS were considered, and the distributions in figures 12 and 13 were obtained. Now, the distributions agree and the previously observed discrepancies disappeared.

**Reconstructing the central system**

We apply the algorithm described in [6] to reconstruct the kinematics of the central system for the selected events. The algorithm is applied to the events which pass the full central selection described before, and also have 2 b-tagged jets, since this is necessary for the algorithm. Given the ambiguity in the pairing of the leptons and the b jets and in the kinematics of the two outgoing neutrinos, up to 8 solutions can be found per event. We have chosen the solution which yields the lowest $M_{t\bar{t}}$. The performance of this algorithm was tested. In order to evaluate the resolution with which $M_{t\bar{t}}$ and $y_{t\bar{t}}$ are reconstructed, we have used the simulated $t\bar{t}$ events. Then, in order to improve this performance, a boosted regression trees method was implemented. A set of trees was trained, using ROOT’s TMVA ([15]), to regress the true value of $M_{t\bar{t}}$ and $y_{t\bar{t}}$, based on the output of the algorithm and some extra kinematic variables. The obtained reconstruction resolution before (blue) and after (red) regression can are shown for $M_{t\bar{t}}$ in figure 14. An improvement of 21% was obtained.

**4.2. Multivariate analysis**

For training the classifier with Boosted Decision Trees (BDTs), $t\bar{t}$ background and signal simulated events are used. Several training parameters were tested, and the ones that gave optimal results were used in the final classification. 13 kinematic variables were used to discriminate between signal and background. The most discriminating ones were found to be $M_{pp}$, $y_{pp}$, $M_{t\bar{t}}$ (after regression), $y_{t\bar{t}}$ (after regression), $y_{vis} = y(b_1 + b_2 + l_1 + l_2)$ and $\Delta R_{ll}$. The output weights are then applied to the full data and simulation, and the obtained distribution is shown in figure 16. The separation between signal and background is visible in the distribution, and this is what will be used in the definition of signal and control regions in the statistical analysis described in the next section. One must keep in mind, however, that the background is overwhelmingly large, and therefore the signal region will still be quite rich in background events.

**Figure 14:** Resolution of the mass reconstruction - blue: using the algorithm, red: using the algorithm + regression technique

Finally, the ratio of signal/$\sqrt{\text{background}}$ events is computed for each possible BDT cut, and the cut which maximises this ratio (BDT output $> 0.4$) was applied.

**Inputs to the statistical analysis**

For the statistical analysis, signal and control regions were defined, both in the cut-based and BDT-based selections.

In the first case, the regions were defined as follows:

**SR$_{e\mu}$** - $e\mu$ events with $\geq 1$b, low $M_{bb}$, $M_{RP} \in [300, 600]$ GeV and $H_T = 0$ GeV;

**SR$_{ee}$** - similar to SR$_{e\mu}$ for $ee$ events outside the $Z$ peak;

**SR$_{\mu\mu}$** - similar to SR$_{e\mu}$ for $\mu\mu$ events outside the $Z$ peak.

**Figure 15:** Comparison between training and test samples, in terms of the response of the BDT classifier, in order to check for agreement between samples and evaluate if there was overtraining.
Figure 16: Output of the BDT classifier, when applied to the full data and MC samples. One can observe the separation between signal and background works as expected, with signal events clustering in larger BDT output values and background events in lower BDT output values.

\[ \text{ttCR}_{e\mu} - e\mu \text{ events with } \geq 1b, \text{ low } M_{lb} \text{ and failing the } M_{RP} \in [300, 600] \text{ GeV cut;} \]

\[ \text{ttCR}_{ee} - \text{ similar to ttCR}_{OF} \text{ for } ee \text{ events outside the } Z \text{ peak;} \]

\[ \text{ttCR}_{\mu\mu} - \text{ similar to ttCR}_{OF} \text{ for } \mu\mu \text{ events outside the } Z \text{ peak;} \]

\[ \text{dyCR} - \text{ for same flavour events inside the } Z \text{ peak.} \]

The corresponding observed and expected yields are shown in table 1.

For the BDT selection, the definition is made such that events with BDT output < 0.4 are considered the control region, and the others the SR. The yields are in table 2.

The list of systematic uncertainties which were considered is in table 3.

5. Results

5.1. Cut-based approach

By feeding the yields of signal and control regions, together with the systematic uncertainties listed in the previous chapter, to the Higgs Combination Tool, and excluding the DY control region, we set limits on the production of pp → t\bar{t}pp of \( \sigma < 1.1^{+0.5}_{-0.3} \text{ pb (95\% confidence level)} \). The observed limit is 7.2 pb, > 2\sigma away from the expected. The likelihood scan for a cross-section scenario of 1.1 pb is shown in figure 17 b). For this hypothesis, we expect to measure the signal strength with an associated uncertainty of \( +1.1_{-1.1} \text{ pb at 95\% CL} \). In figure 17 a), one can see the contour plot for the scale factors of the two dominant backgrounds (DY and QCD t\bar{t}). The minimum is, as expected, at (1,1), showing that the correct factors are being applied.

5.2. BDT approach

As for the BDT approach, the same procedure was used, but now with the BDT signal and control regions. The observed upper limit is measured to be 1.4 pb, and the median expected limit \( \sigma < 0.9^{+0.4}_{-0.2} \text{ pb (68\% confidence level)} \), or \( 0.9^{+0.7}_{-0.4} \text{ pb (95\% confidence level)} \). The observed limit is within 1\sigma from the expected. The likelihood scan for a cross-section scenario of 195 pb is shown in figure 18 b). For this scenario, the measurement of signal strength is expected to be done with uncertainties \( +0.9_{-0.9} \text{ pb} \). In figure 18 a), one can see the contour plot for the scale factors of the two dominant backgrounds (DY and QCD t\bar{t}), fitted using the dedicated control regions. The minimum is, as expected, at (1,1), showing that the correct factors are being applied.

6. Conclusions

The goal of the work behind this master thesis was to develop an analysis strategy to search for exclusive production of top quark pairs. This was successfully achieved. A set of selection criteria was de-
<table>
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<tr>
<th></th>
<th>SR_{ee}</th>
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<th>SR_{em}</th>
<th>ttCR_{ee}</th>
<th>ttCR_{mm}</th>
<th>ttCR_{em}</th>
<th>dyCR</th>
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<td>inclusive tt</td>
<td>300±32</td>
<td>359±37</td>
<td>650±50</td>
<td>613±97</td>
<td>745±83</td>
<td>1458±115</td>
<td>540±93</td>
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<td>DY</td>
<td>127±29</td>
<td>144±36</td>
<td>2±2</td>
<td>604±47</td>
<td>728±56</td>
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<td>707±193±2740</td>
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<td>302±2</td>
<td>113±2</td>
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<td>total</td>
<td>429±44</td>
<td>504±56</td>
<td>653±50</td>
<td>6798±533</td>
<td>8191±35</td>
<td>14610±42</td>
<td>71562±42879</td>
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Table 1: Yields for signal and control regions, for different background contributions, for signal and for observed data. The expected yields for signal are normalised to a cross-section of 1 pb. Exactly one track on each side of PPS is required. Only the statistical uncertainty is being represented.

<table>
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<tr>
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<th>SR_{hBDT}</th>
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<tr>
<td>inclusive tt</td>
<td>10785±213</td>
<td>213±56</td>
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<td>DY</td>
<td>1138±100</td>
<td>0±5</td>
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<tr>
<td>others</td>
<td>25±3</td>
<td>1±1</td>
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<tr>
<td>total</td>
<td>11947±329</td>
<td>213±11</td>
</tr>
<tr>
<td>exclusive tt</td>
<td>47</td>
<td>38</td>
</tr>
<tr>
<td>data obs.</td>
<td>11680</td>
<td>231</td>
</tr>
</tbody>
</table>

Table 2: Yields in the signal and control region, for different background contributions, for signal and for observed data, using a cut on the BDT output of 0.2. The expected yields for signal are normalised to a cross-section of 1 pb. Only the statistical uncertainty is being represented.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Value</th>
<th>Affects</th>
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<tr>
<td>Luminosity</td>
<td>2.7%</td>
<td>all</td>
</tr>
<tr>
<td>σ_{inclusive tt}</td>
<td>5.1%</td>
<td>inclusive tt</td>
</tr>
<tr>
<td>σ_{others}</td>
<td>30%</td>
<td>others</td>
</tr>
<tr>
<td>DY uncertainty</td>
<td>30%</td>
<td>Drell-Yan</td>
</tr>
<tr>
<td>”fake“ PPS info.</td>
<td>15%</td>
<td>background</td>
</tr>
<tr>
<td>Lepton sel. eff.</td>
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<td>all</td>
</tr>
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</table>

Table 3: Systematic uncertainties used in the analysis.

I developed, based on the exclusive dilepton search, as well as the existing tt analyses and measurements. The functioning of the PPS detector was studied, and its acceptance and fake ratio were computed using data and simulated signal samples. Furthermore, the selection using both CMS central and PPS forward information was optimised. Correlations between the central and forward kinematics were established for signal simulation. An existing algorithm to reconstruct tt kinematics in the dilepton decay channel was used, and a regression technique was used to improve its resolution in 20%.

A BDT classifier was built out of the central and forward kinematic variables, which was shown to be able to efficiently separate signal from background.

Using statistical concepts and a fitting software, I was able to estimate two upper limits for the cross-section of the exclusive tt production, one based on the cut selection (σ < 257±238 fb @ 95% confidence level), and the other on the BDT classifier output (σ < 195±181 fb @ 95% confidence level). I compared the two and verified that the BDT approach brings approximately 30% improvement, with respect to the classical approach, thus showing the power of machine learning techniques in high-energy physics.

These limits represent the first experimental result on this particular search and may allow the comparison with existing theoretical predictions,
which was not possible until now. Furthermore, it is the first upper limit measurement using PPS information. This result is being reported in an internal CMS analysis note, and we will start the procedure to submit it for publication.

An interesting future work would be to perform phenomenological studies in order to estimate the sensitivity of this process to the anomalous couplings between the top quark and the photon. On the experimental side, more data should be included, the latest available proton reconstruction techniques should be used, and more sophisticated MVA techniques could be explored.

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References
[19] M. Luszczak, L. Forthomme, W. Schäfer, and A. Szczurek. Production of $t\bar{t}$ pairs via $\gamma\gamma$ fusion with photon transverse momenta and proton dissociation. 2018.