Search for resonant $t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for a heavy resonance decaying into top quark and antiquark ($t\bar{t}$) pairs is performed using proton-proton collisions at $\sqrt{s} = 13$ TeV. The search uses the full data set collected with the CMS detector in 2016, which corresponds to an integrated luminosity of 36 fb$^{-1}$. The analysis is split into three exclusive final states and uses reconstruction techniques that are optimized for top quarks with high Lorentz boosts, which requires the use of nonisolated leptons and jet substructure techniques. No significant excess of events relative to the expected yield from standard model processes is observed. Upper limits on the production cross section of heavy resonances decaying to $t\bar{t}$ are calculated. Limits are derived for a leptophobic topcolor $Z'$ resonance with widths of 1%, 10%, and 30% relative to the mass of the resonance. Additional exclusion limits are set for a Kaluza–Klein (KK) excitation of the gluon in the Randall–Sundrum model and a model where a narrow $Z'$ resonance is exclusively produced in association with jets. To date, these are the most stringent limits on a $t\bar{t}$ resonance.
1 Introduction

The top quark (t) is the most massive fundamental particle [1, 2]. It has a Yukawa coupling to the Higgs potential that is near unity. It is also closely connected to the hierarchy problem, where the largest corrections to the vacuum expectation of the Higgs field arise from top quark loops. The top quark warrants additional studies as it may provide insight into the mechanism of electroweak (EW) symmetry breaking, especially in light of the Higgs boson discovery [3–5] and the precision measurement of its mass [6–8].

There are many theories beyond the standard model (SM) that predict heavy resonances on the TeV scale, which would decay to t̅t̅ pairs. These resonances can present themselves as a peak on top of the falling t̅t̅ invariant mass spectrum or a distortion of the t̅t̅ spectrum if the resonance has a large width and a mass above the center-of-mass energy of the colliding partons. Resonances decaying to t̅t̅ pairs can be found in models that contain TeV scale color-singlet Z’ bosons [9–11], a pseudoscalar Higgs that may couple strongly to t̅t̅ pairs [12], axigluons [13, 14], or colorons [15–17], and especially models that contain a leptophobic topcolor Z’ [18]. Additionally, extensions of the Randall–Sundrum model [19] with extra dimensions predict KK excitations of the gluons g_{KK} [20] or gravitons G_{KK} [21], which can have large couplings to t̅t̅ pairs. Previous searches at the Tevatron have excluded a leptophobic Z’ up to 900 GeV [22–27]. Experiments at the LHC have excluded various Z’ and g_{KK} models at 95% CL in the 1–4 TeV mass range [28–34].

This paper presents a model-independent search for Z’ → t̅t̅ production. The resulting t̅t̅ system, and all its daughter particles, decay as described by the SM. The top quark primarily decays to a W boson and a bottom quark. The two W bosons in the event can decay to either a lepton and its corresponding neutrino or to hadrons. The analysis is split into three sub-analyses based on the decay mode of the two W bosons: dilepton, single lepton, and fully hadronic decay modes of the t̅t̅ system. In the fully hadronic channel, both W bosons decay to hadrons. In the single lepton channel, one W boson decays to an electron (e) or muon (μ) and its neutrino (ν) counterpart, while the other W boson decays to hadrons. In the dilepton channel, both W bosons decay to an e or μ and a ν. Unless otherwise stated, the Z’ symbol refers to any resonance decaying to t̅t̅ pairs, regardless of the specific model. The search uses a total integrated luminosity of 36 fb^{-1} of pp collision data collected during 2016 by the CMS experiment with the LHC operating at √s = 13 TeV.

The dilepton final state consists of two leptons (μμ, μe, or ee) and two b-quark jets with high transverse momentum (p_{T}), and missing transverse momentum (p_{T}^{miss}). The dominant irreducible SM background arises from t̅t̅ continuum production. Smaller contributions are due to a Z boson produced in association with jets (Z+jets), EW single top quark, and diboson processes. The large mass of the Z’ resonance causes significant Lorentz boost for the decaying top quarks, which leads to collimated lepton-b-jet pairs. This feature is exploited to reduce SM background and to validate its modeling.

The single lepton final state consists of one lepton (μ or e), at least two high-p_{T} jets, and p_{T}^{miss}. Similar to the dilepton channel, the final-state objects from the decay of the t̅t̅ pairs have a large Lorentz boost because of the mass of the Z’ resonance. Leptons from the decay of the W boson are found in near proximity to the jet from the fragmentation of the bottom quark. To account for the overlap between the lepton and the bottom quark, special triggering, reconstruction, and selection criteria are used to ensure high lepton selection efficiency. A t tagging algorithm is used to identify top quarks where the daughter W boson decays hadronically (t → Wb → q̅q′b). Events with a jet that passes the top tagging criteria are sorted into a category with higher sensitivity. The largest irreducible background is the t̅t̅ continuum, while the largest reducible
background is W bosons produced with associated jets (W+jets). The latter background is separated from the signal region using a multivariate technique.

The fully hadronic channel searches for events with a dijet topology, where two jets are selected and required to be consistent with the hadronic decay of a Lorentz-boosted top quark. Because of the dijet topology of the search region, the largest reducible background arises from dijet events produced from quantum chromodynamic (QCD) interactions between the colliding protons. This background, referred to as non-top quark multijet (NTMJ) production, can be reduced considerably by requiring one of the subjets in each of the two top quark candidates to be consistent with the fragmentation of a bottom quark. The use of subjet b quark tagging for categorization nearly eliminates the NTMJ background leaving only the $t\bar{t}$ continuum in the highest sensitivity category.

Except the NTMJ backgrounds in the fully hadronic channels, the shapes of all SM backgrounds are estimated from simulation. The total normalization of each simulated sample is obtained from a simultaneous binned maximum likelihood fit to the reconstructed $t\bar{t}$ invariant mass ($M_{t\bar{t}}$) distribution for the single lepton and fully hadronic analysis and $S_T$ for the dilepton analysis, where $S_T$ is defined as

$$S_T = \sum_{i=1}^{N_{\text{jet}}} p_T^i + 2 \sum_{i=1}^{N_{\text{jet}}} p_T^i + \vec{p}_T^\text{miss},$$

and is used because it has a greater sensitivity to signal in the dilepton final state. A limit on the production cross section of heavy resonances is extracted by performing a template-based statistical evaluation of the $M_{t\bar{t}}$ and $S_T$ distributions in all of the channels.

This paper is organized the following way. Section 2 provides a description of the CMS detector. The reconstruction and identification of electrons, muons, and jets are described in Section 3. Section 3 also gives an overview of the $t$ tagging algorithms used. The data sets and triggering techniques are described in Section 4. The simulated Monte Carlo (MC) samples used in the analysis are given in Section 5. Section 6 describes the event selection for the three different channels. Section 7 describes the evaluation of the SM background processes. Systematic uncertainties affecting the signal and background shapes and normalization are discussed in Section 8. The statistical analysis and the results are given in Sections 9 and 10, and a final summary is presented Section 11.

## 2 CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. Muons are detected by four layers of gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The inner tracker measures charged particle trajectories within the pseudorapidity range $|\eta| < 2.5$, and provides an impact parameter resolution of approximately $15 \mu m$. A two-stage trigger system selects pp collision events of interest for use in physics analyses. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [35].
3 Event reconstruction

The CMS experiment uses particle-flow (PF) techniques that aggregates input from all subdetectors for event reconstruction [36]. An example of a typical PF input is charged particle tracks from the tracking system and energy deposits from the electromagnetic and hadronic calorimeters. This enables the global event description to take advantage of the excellent granularity of the CMS detector. Clusters of tracks and energy deposits are iteratively classified as muons, electrons, photons, charged hadrons, and neutral hadrons. Primary vertices are reconstructed from tracks using a deterministic annealing filter algorithm [37]. The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [38, 39] with the tracks assigned to the vertex as inputs, and the associated $\vec{p}_T^{\text{miss}}$, taken as the negative vector sum of the $p_T$ of those jets.

Muons are reconstructed in the pseudorapidity range $|\eta| < 2.4$ using the information collected in the muon and tracker detectors [37]. Tracks associated with muon candidates must be consistent with a muon originating from the primary event vertex, and tracks must satisfy fit quality requirements.

Electrons are detected and measured in the pseudorapidity range $|\eta| < 2.5$, by combining tracking information with energy deposits in the ECAL [40, 41]. Candidate electrons are required to originate from the primary vertex. The track quality, electromagnetic shower shape, displacement between the track and electromagnetic shower, and ratio of energy between the hadronic calorimeter and electromagnetic calorimeter are used to discriminate between prompt and non-prompt electrons. Reconstructed electrons that originate from photon conversions are rejected.

No isolation requirements are placed on the leptons at the trigger or analysis level. This is because the lepton, bottom quark, and neutrino from the top quark decay are highly collimated and the lepton is not well separated from the fragmentation of the bottom quark. Additionally, jets that contain an electron are reclusted and corrected with the track and calorimeter deposit of the electron removed.

The $\vec{p}_T^{\text{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed PF objects in an event [42]. Its magnitude is referred to as $p_T^{\text{miss}}$. Corrections to the jet energy scale and jet energy resolution are propagated to the measurement of $p_T^{\text{miss}}$.

PF candidates are clustered into jets using the FASTJET software package [39]. Charged hadrons that are not associated with the primary vertex in the event are excluded from the jet clustering procedure (CHS). All jets are required to have an $|\eta| < 2.4$. Jets are clustered using the anti-$k_T$ jet-clustering algorithm [38] with a distance parameter of 0.4 (AK4 jets). If a lepton is found within a $\Delta R < 0.5$ of an AK4 jet, its four-momentum is subtracted from that of the jet. The single lepton and all hadronic analyses also use anti-$k_T$ clustered jets with a distance parameter of 0.8 (AK8 jets). These larger radius jets are used to tag the hadronic decay of top quarks. A high-mass resonance decay creates daughter particles with significant Lorentz boost. The three jets from the top quark decay merge into a single larger AK8 jet. Jets in all three analyses are contaminated with neutral particles that are generated from additional proton-proton collisions in the event (pileup). The extra energy in each jet is corrected based on the average expectation of the pileup within the jet footprint [43]. The expected energy offset due to pileup is modeled as a function of the number of primary vertices in the event [42]. Jets that are produced from the decay of charm and bottom quarks are identified using the combined secondary vertex
algorithm (CSV) [44]. The loose, medium, and tight operating points are used in this analysis. They have a probability of 10%, 1%, and 0.1%, respectively, of misidentifying a light-parton jet as heavy flavor, where the light-flavor jet has a \( p_T \) of at least 30 GeV and is from a simulated multijet sample with a momentum exchange between 80 and 120 GeV [45]. All jets are required to pass a minimal set of criteria to separate them from calorimeter noise and other sources of jets that do not originate from the primary interaction [46]. Events are also required to pass a set of selections that remove spurious \( p_T^{\text{miss}} \) that is generated from calorimeter noise [47].

The CMS \( t \) tagging algorithm [48, 49], which is based on the algorithm described in Ref. [50], is applied to AK8 jets that use pileup per particle identification corrections (PUPPI) [51] in order to separate hadronically decaying top quarks from light quark or gluon jets. PUPPI jets are used for \( t \) tagging because they have better performance as a function of pileup when compared to CHS jets. The CMS \( t \) tagging algorithm only considers jets with \( p_T > 400 \) GeV, as lower momentum top quarks frequently decay into resolved jets. The algorithm declusters the AK8 PUPPI jet into its two highest \( p_T \) subjets, and removes particles that are soft or have a wide separation from the central core of the jet. The two subjets are then used to calculate the softdrop mass [52], which is required to be near the mass of the top quark (105 \( < M_{\text{jet}} \) < 210 GeV). The CMS \( t \) tagging algorithm also requires that the \( N \)-subjettiness [53, 54] ratio (\( \tau_{32} \equiv \tau_3/\tau_2 \)) must be less than 0.65. The \( N \)-subjettiness (\( \tau_N \)) is a measure of the consistency of an AK8 PUPPI jet with \( N \) or fewer subjets, and is defined as

\[
\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min[\Delta R_{1,i}, \Delta R_{2,i}, \cdots, \Delta R_{N,i}],
\]

where \( i \) is a summation over all jet constituents, \( d_0 \) is a normalization constant, and \( \Delta R \) is the distance between a given jet constituent \( i \) and a candidate subjet axis \( N \).

### 4 Trigger and data set

The events in the dilepton channel are triggered by single and dilepton triggers without isolation requirement. The triggers for \( \mu \mu \) and \( e\mu \) events require one muon with \( p_T > 50 \) GeV or track \( p_T > 50 \) GeV within \( |\eta| < 2.4 \). The \( ee \) events are selected using a dielectron trigger that requires the presence of two electrons with \( p_T > 33 \) GeV within an \( |\eta| < 2.5 \).

The events used in the single lepton channel rely on single lepton triggers. The triggers for the muon channel require one muon with a \( p_T > 50 \) GeV or track \( p_T > 50 \) GeV within \( |\eta| < 2.4 \). The triggers for the electron channel require one electron with a \( p_T > 115 \) GeV or an electron with a \( p_T > 55 \) GeV and a particle flow jet with a \( p_T > 165 \) GeV. Both triggers require electrons within an \( |\eta| < 2.5 \), and the electron-jet combination trigger requires the jet to be within \( |\eta| < 2.4 \). In the combination trigger, if the electron lies within the jet footprint, the Lorentz vector of the electron is subtracted from the uncorrected Lorentz vector of the jet, and then the jet energy corrections are reapplied. An isolation requirement is not applied to any of the leptons in triggers used in the single lepton channel.

The fully hadronic analysis uses events that are selected by an amalgam of five different triggers. The first trigger requires a single AK8 jet with a \( p_T > 450 \) GeV, a second trigger requires an AK4 jet with a \( p_T > 360 \) GeV and a mass \( M_{\text{jet}} > 30 \) GeV. A third trigger requires an \( H_T > 800 \) GeV, where the \( H_T \) is the scalar sum of the \( p_T \) of every AK4 PF jet in the event. A fourth trigger requires \( H_T > 900 \) GeV, and is used as a backup trigger. The final trigger requires that the \( H_T > 700 \) GeV, but also requires a jet with a \( M_{\text{jet}} > 50 \) GeV.

The total integrated luminosity of all data is 36 fb\(^{-1}\). Differences in trigger efficiency between
data and simulation in the dilepton and single lepton channels are resolved with corrections determined from orthogonal data sets.

5. Simulated Events

The $Z' \to t\bar{t}$ process is simulated using the MADGRAPH 5 [55] event generator, which produces a generic resonance with the same spin and left- and right-handed couplings to fermions as the SM $Z$ boson. Low energy parton radiation is calculated for up to three additional tree-level partons. The $Z' \to t\bar{t}$ process is simulated at masses ($M_{Z'}$) between 500 GeV and 5 TeV for resonances with a relative decay width ($\Gamma / M$) of 1% (narrow-width), 10% (wide-width), and 30% (extra wide-width). Matching between the hard matrix element interactions and the lower energy parton showers is done using the MLM algorithm [56]. The $Z'$ is a spin-1 resonance, so there is no interference from SM $t\bar{t}$ production. The KK gluon excitation is simulated without SM interference using PYTHIA 8 [57] with the couplings described in Ref. [58]. The $\Gamma / M$ of the $g_{KK}$ resonance lies between the wide and extra wide-width $Z'$ resonances and is dependent its coupling to the top quark.

The invariant mass distribution of the $t\bar{t}$ system at the parton level for the $Z'$ at 3 different widths and a $g_{KK}$ can be seen in Fig. 1. The plots are normalized such that the total integral of each signal model is 1. A clear peak structure can be seen at 3 TeV, but this structure smears to a much broader shape as the resonance mass increases beyond the available parton energy at the LHC. The largest effects can be seen for the $g_{KK}$ and $Z'$ extra wide-width samples. For these samples, the peak in the $t\bar{t}$ quark invariant mass distribution is far from the pole mass of the resonance because of off-shell production.

$t\bar{t}$ pair production is simulated using the next-to-next-leading order plus next-to-next-leading loop (NNLO+NNLL) generator POWHEG [59–61]. POWHEG is also used to simulate single top quark production via EW interactions at next-to-leading order (NLO) [62] and single top quark production with an associated W boson at NNLO [63]. W+jets are simulated using aMC@NLO [64] and PYTHIA 8 for the fragmentation and hadronization. The Drell-Yan process with an invariant mass below 50 GeV is simulated using aMC@NLO, and the Drell-Yan process above 50 GeV with associated jets is simulated using MADGRAPH and PYTHIA 8 at leading order (LO) and then corrected with a k-factor to NNLO. Diboson production is simulated using PYTHIA 8 at NNLO for WW boson production and NLO for WZ and ZZ boson production. The multijet background from the strong interaction is modeled with PYTHIA 8 at LO. It should be noted that the simulated multijet process is only used when it is a non-dominant background. In the case of the fully hadronic analysis, the multijet background is measured from a control region in data.

All samples are processed through a GEANT-based simulation [65] that models the propagation of the particles through the CMS apparatus and the corresponding detector response. For all samples, the hard interaction collision is overlaid with an average of 21 simulated minimum bias collisions, and the resulting events are weighted to reproduce the pileup distribution measured in data. The same event reconstruction software is used for data and simulated events. Small differences in the resolutions and efficiencies for reconstructed objects are corrected to match those measured in data using dedicated data samples [66].
6 Reconstruction and categorization of \( t \bar{t} \) events

6.1 Dilepton channel

Events in the dilepton channel are selected by requiring oppositely charged high-\( p_T \) lepton pairs: \( \mu \mu \), ee or e\( \mu \). Leptons with a \( p_T > 53 \) and 25 GeV (45 and 36 GeV) in the \( \mu \mu \) (ee) channel are selected. In the e\( \mu \) channel, muons are required to have \( p_T > 53 \) GeV and electrons are required to have \( p_T > 25 \) GeV. Muons (electrons) are required to be within an \( |\eta| < 2.4 \) (2.5). To remove contributions from the low mass resonances and from \( Z \rightarrow \ell\ell + \text{jets} \) production in events with same-flavor lepton pairs, the dilepton invariant mass (\( M_{\ell\ell} \)) is required to be above 20 GeV and outside of the Z-boson mass window of 76 to 106 GeV. Contamination from QCD multijet background is reduced by applying a 2D-cut for both leptons: \( \Delta R_{\text{min}}(\ell, j) > 0.4 \) or \( p_{T,\text{rel}}(\ell, j) > 15 \) GeV, where \( \Delta R_{\text{min}}(\ell, j) \) is the minimum \( \Delta R \)-distance between the lepton candidate and any AK4 jet with \( p_T > 15 \) GeV and \( |\eta| < 3 \), and \( p_{T,\text{rel}}(\ell, j) \) is the \( p_T \) of the lepton with respect to the axis of the \( \Delta R \)-nearest AK4 jet. The 2D-cut reduces the QCD multijet background by a factor of \( \approx 100 \). Events are further required to contain at least two AK4 jets with an \( |\eta| < 2.4 \) and \( p_T > 100 \) GeV and 50 GeV for the leading and sub-leading jets, respectively. It is required that at least one of the two leading jets must be b tagged as determined by the loose CVS tagger operating point. Finally, \( p_T^{\text{miss}} \) is required to be above 30 GeV. The resulting sample is dominated by the irreducible \( t \bar{t} \) production, which amounts to \( >90\% \) of the total background.

Figure 2 shows the distributions of \( \Delta R_{\text{sum}} = \Delta R_{\text{min}}(\ell_1, j) + \Delta R_{\text{min}}(\ell_2, j) \) in \( \mu \mu \), ee and e\( \mu \) sub-channels, where \( \Delta R_{\text{min}}(\ell_1, j) \) and \( \Delta R_{\text{min}}(\ell_2, j) \) are the \( \Delta R \)'s between the leading and subleading lepton and the nearest jet. The lepton-jet pairs from the \( Z' \) decays are expected to be collimated and populate the low \( \Delta R_{\text{sum}} \) region. This variable is used to separate events into signal and background-enriched samples: \( \Delta R_{\text{sum}} < 1 \) and \( 1 < \Delta R_{\text{sum}} < 2 \) defines our signal region, whereas \( \Delta R_{\text{sum}} > 2 \) defines our background-enriched region. The shape and normalization is in agreement between data and simulation at low \( \Delta R_{\text{sum}} \), which is the region of interest for separating boosted and resolved events.
6. Reconstruction and categorization of \(t\bar{t}\) events

Figure 2: Distributions of \(\Delta R_{\text{sum}}\) before the fit to data in \(\mu\mu\) (left), ee (middle) and \(e\mu\) (right) events. The hashed band on the simulation represents the statistical and pre-fit systematic uncertainties.

### 6.2 Single lepton channel

The offline selection for events used in the single lepton analysis requires the presence of a muon with a \(p_T^\mu > 55\) GeV and an \(|\eta^\mu| < 2.4\) or an electron with a \(p_T^e > 80\) GeV and an \(|\eta^e| < 2.5\). Neither lepton has an isolation requirement other than passing the lepton 2D selection, which requires that the \(\Delta R_{\text{min}}(\ell,j) > 0.4\) or that the \(p_{T,\text{rel}}(\ell,j) > 25\) GeV, where both quantities are calculated with respect to all AK4 jets with \(p_T > 15\) GeV. Events with a second lepton are removed from the sample to avoid any overlap with the dilepton channel. Events are also required to contain at least two AK4 jets with \(|\eta| < 2.4\) and a minimum \(p_T\) of 150 (185) GeV for the leading jet in the muon (electron) channel, and 50 GeV for the subleading jet. To reduce the contributions to the sample from QCD multijet events, additional requirements are imposed on the selection. In the muon channel, \(p_T^{\text{miss}}\) and \(H_T^{\ell\text{lep}}\) are required to be greater than 50 and 150 GeV, respectively, where \(H_T^{\ell\text{lep}} = p_T^{\text{miss}} + p_T^\mu\). In the electron channel, it is required that \(p_T^{\text{miss}} > 120\) GeV. To suppress the contamination from events originating in the production \(W + \)jets, a boosted decision tree [67] (W+jets BDT) was trained using the TMVA software package [68] on the jet-related variables listed below, in order of importance:

- \(\Delta R_{\text{min}}(\ell,j)\), the separation between the lepton and its closest jet
- The CSV score of the subleading and the leading AK4 jets
- The number of jets
- \(p_{T,\text{rel}}(\ell,j)\)
- The reconstructed mass of the leading AK4 jet
- \(\Delta R_{\text{min}}(\ell,j) \times p_T(j)\)
- The reconstructed mass of the subleading AK4 jet
- The shape variable \(S_{33}\) of the sphericity tensor \(S^\alpha_\beta = \sum \frac{p_{\alpha} \cdot p_{\beta}}{|p|^2}\) where \(\alpha, \beta\) correspond to the \(x, y\) and \(z\) components of the momentum vectors of the jets
- \(S_T \equiv H_T + H_T^{\ell\text{lep}}\), where \(H_T\) is the scalar sum of the \(p_T\) of the jets

Figure 3 shows the W+jets BDT distribution in the muon and electron channels. A requirement of W+jets BDT \(\geq 0.5\) is applied to the events in our signal region, which is further separated in two depending on the presence of a t-tagged AK8 jet with a \(p_T > 400\) GeV and an \(|y| < 2.4\). Events with no t-tagged AK8 jet and a W+jets BDT < −0.75 or a 0 < W+jets BDT < 0.5...
are dominated by $W$+jets and $t\bar{t}$ events, respectively, and constitute our background-enriched control regions.

The $t\bar{t}$ system is reconstructed by assigning the four-vectors of the reconstructed final-state objects (charged lepton, $p_T^{\text{miss}}$, and jets) to the leptonic or hadronic legs of the $t\bar{t}$ decay. For events with no AK8 jet, several hypotheses are built based on possible assignments of each AK4 jet to either the leptonic $t$ decay, the hadronic $t$ decay, or neither. For events with an AK8 jet, that jet is associated with the hadronic $t$ decay, and the leptonic $t$ decay hypotheses only consider AK4 jets that are separated from the AK8 jet by $\Delta R > 1.2$. In both cases, the combination chosen is the one that minimizes the $\chi^2$ discriminator, where

$$
\chi^2 = \chi^2_{\text{lep}} + \chi^2_{\text{had}} = \left[ \frac{M_{\text{lep}} - \bar{M}_{\text{lep}}}{\sigma_{M_{\text{lep}}}} \right]^2 + \left[ \frac{M_{\text{had}} - \bar{M}_{\text{had}}}{\sigma_{M_{\text{had}}}} \right]^2.
$$

In this equation, $M_{\text{lep}}$ and $M_{\text{had}}$ are the invariant masses of the reconstructed leptonic and hadronic top quarks, respectively. The parameters $\bar{M}_{\text{lep}}$, $\sigma_{M_{\text{lep}}}$, $\bar{M}_{\text{had}}$, and $\sigma_{M_{\text{had}}}$ in the $\chi^2$ discriminator were determined from simulation by matching reconstructed objects of the hypothesis to the corresponding GEN particles from the $t\bar{t}$ decay. Events in our signal and background-enriched regions are all required to have $\chi^2 < 30$. Events with two AK8 jets that were $t$ tagged are removed from the sample to avoid any overlap with the fully hadronic channel.

### 6.3 Fully hadronic channel

All events used in the fully hadronic analysis are required to fulfill certain kinematic and $t$ tagging criteria. In order to reach a trigger efficiency of $\sim 100\%$, each event must have an $H_T > 950$ GeV. Events are reconstructed using the two $p_T$-leading AK8 jets, both of which are required to have $p_T > 400$ GeV and rapidity $|y| < 2.4$. In order to ensure a back-to-back topology, the two jets must have an azimuthal separation of $|\Delta\phi| > 2.1$. Both AK8 jets are required
to be \( t \) tagged for events to enter our signal region. These events are then separated into six signal-region categories based on two criteria:

- Rapidity difference between the two jets (\( |\Delta y| < 1.0 \) or \( |\Delta y| > 1.0 \))
- Number of jets with a b-tagged subjet (0, 1, or 2)

The categories with more subject bottom quark tags are expected to provide more sensitivity, while those with fewer subject bottom quark tags are included to provide better constraints on the backgrounds and additional sensitivity to the analysis. The low \( |\Delta y| \) rapidity region is expected to be more sensitive than the high \( |\Delta y| \) region, as illustrated in Fig. 4.

![Dijet rapidity difference for events passing the fully hadronic event selection: (left) \( \Delta Y \) (inclusive in \( M_{tt} \)), (right) \( \Delta Y \) (\( M_{tt} > 2 \) TeV). The hashed band on the simulation represents the post-fit uncertainties.](image)

Figure 4: Dijet rapidity difference for events passing the fully hadronic event selection: (left) \( \Delta Y \) (inclusive in \( M_{tt} \)), (right) \( \Delta Y \) (\( M_{tt} > 2 \) TeV). The hashed band on the simulation represents the post-fit uncertainties.

7 Estimation of the background normalization

7.1 Dilepton channel

The dominant irreducible background in the dilepton channel is \( t\bar{t} \) production. Other secondary backgrounds arise from \( Z+jets \), EW single top quark, and diboson processes. Simulated events are used to model the shape of the kinematic distributions for the background processes, including modeling of the \( S_T \) variable used in the statistical interpretation of the observations. The overall normalization of the background processes is based on the corresponding theoretical cross sections. The distributions are allowed to vary within prior bounds of rate and shape uncertainties during the statistical treatment, which employs six signal and three background-enriched regions. Modeling of the background is separately checked in the background-rich control region obtained by the \( \Delta R_{sum} > 2 \) requirement. Figure 5 shows the distributions of the \( S_T \) variable in the control sample for \( \mu\mu \), \( ee \) and \( e\mu \) subchannels. The simulation is in agreement with data within the uncertainties.
The two main sources of background in the fully hadronic channel are NTMJ and $t\bar{t}$ production. For the latter background, simulated events are used to model the shape of the $M_{\ell\ell}$ distribution.

7.2 Single lepton channel

SM $t\bar{t}$ production is also the main irreducible background in the single lepton channel as well. Other processes include $W+\text{jets}$, single top quark, $Z+\text{jets}$ and diboson production. QCD multijet background is a minor contribution to the muon channel ($\approx 3\%$), but is suppressed to a negligible level in the electron channel. As in the dilepton channel, the shape of the kinematic distributions for the background processes is taken from simulation, and the overall normalization is obtained from theoretical predictions. The rate and shape are allowed to vary during the binned likelihood maximization. The final background estimates are determined by fitting the background-only hypothesis to data. The observable used in the binned maximum-likelihood fit is the $M_{\ell\ell}$ distribution restricted to the $M_{\ell\ell} < 2 \text{ TeV}$ region. During the fitting procedure, the SM cross sections for the backgrounds are left unconstrained by using a flat prior distribution. The remaining systematics are included in the fit as nuisance parameters using a log-normal distribution as prior constrain. This includes the rate at which light flavor quarks and gluons are misidentified as originating from top quarks ($t$ mistag). The $t$ mistag rate is measured in data and simulation using a $W+\text{jets}$ dominated sample with $\chi^2_{\text{lep}} > 30$ and $W+\text{jets BDT} < -0.5$. The $p_T$ and $M_{5\Delta}$ distributions in the $W+\text{jets}$ background can be seen in Fig. 6. The $t$ tagging efficiency is not measured separately, as is not possible to select a control region that might not be contaminated by our signal. Instead, it is introduced as a free nuisance parameter in the fit, that is performed simultaneously in two signal and two background-enriched control regions, defined as follows:

- Signal Region (SR1T): $\chi^2 < 30$, $W+\text{jets BDT} \geq 0.5$, 1 $t$-tagged AK8 jet
- Signal Region (SR0T): $\chi^2 < 30$, $W+\text{jets BDT} \geq 0.5$, no $t$-tagged AK8 jet
- Control Region (CR1): $\chi^2 < 30$, $W+\text{jets BDT} < -0.75$
- Control Region (CR2): $\chi^2 < 30$, $0.0 < W+\text{jets BDT} < 0.5$

CR1 is dominated by $W+\text{jet}$ events, while CR2 is dominated by $t\bar{t}$ events. For all regions, events are separated based on lepton flavor ($\mu$, $e$), which results in eight exclusive categories used in the binned maximum likelihood fit.

7.3 Fully hadronic channel

The two main sources of background in the fully hadronic channel are NTMJ and $t\bar{t}$ production. For the latter background, simulated events are used to model the shape of the $M_{\ell\ell}$ distribution.
7. Estimation of the background normalization

Figure 6: Distributions of the $p_T$ and $M_{SD}$ for the W+jets background in the muon (left) and electron (right) channels. The hashed band on the simulation represents the post-fit uncertainties.
This distribution is initially normalized to the theoretical cross section, but it is allowed to vary within the bounds of rate and shape uncertainties during the statistical treatment. The final normalization and shape are determined by fitting the distributions in the six signal regions. The \( \bar{t}t \) shape systematics affect the signal regions in which both AK8 jets are subjet b tagged, as \( \bar{t}t \) production is the dominant background in these regions.

A data driven method is employed to estimate the NTMJ background, similar to the techniques described in Ref. [33]. For all events considered, the preselection described in Section 6.3 is enforced in order to select a back-to-back dijet event topology. In the first step of the background estimate, the top quark mistag rate in NTMJ events is measured. An NTMJ enriched region is selected by requiring one of the two jets to be “anti-tagged,” meaning it has a PUPPI softdrop mass in the top tag mass window of \( 105 < M_{SD} < 210 \text{ GeV} \), but the N-subjettiness requirement is inverted to \( \tau_3 > 0.65 \). The top tag rate of the opposite “probe” jet is determined to be the NTMJ top mistag rate. This rate is parameterized as a function of probe jet momentum and is measured for each of the three bottom quark tag categories, as shown in Fig. 7. This “anti-tag and probe” procedure has been found to contain a small number of SM \( \bar{t}t \) events. Therefore, the method is repeated for the \( \bar{t}t \) simulation, and the \( \bar{t}t \) contamination is subtracted from the anti-tag and probe data selection.

After the top quark mistag rate has been measured in the NTMJ control region, it is used to estimate the \( M_\Delta \) NTMJ distribution in the signal region. First, a “single-tagged” region is selected, in which at least one of the two jets is t tagged. One of the two top quark jet candidates is randomly selected, in order to avoid bias. If the selected jet is t tagged, the event is included in the NTMJ estimate. The event is weighted by the previously measured top quark mistag rate, based on the momentum of the opposite jet and the number of subjet b tags in the event. Again, the procedure is repeated for the \( \bar{t}t \) simulation, and the \( \bar{t}t \) contamination is subtracted from the
NTMJ background estimate. This eliminates double counting between the \( t\bar{t} \) and NTMJ distributions.

Finally, a “mass-modified” procedure is employed in order to ensure that the jets used in the NTMJ estimate mimic the relevant kinematics of the jets in the signal region. If the mass of the second NTMJ jet is not in the top mass window, it assigned a random value within the top mass window. This modified mass is randomly selected from the distribution of simulated light flavor jets from QCD interactions with masses in the top quark tag window, \( 105 < M_{SD} < 210 \) GeV. Once this is done, the data-derived NTMJ \( M_{t\bar{t}} \) templates are ready for analysis by the Theta software package. The entire background estimation method has been validated with simulated QCD multijet events.

8 Systematic uncertainties

Several sources of uncertainty that impact the final results of this search are considered. In all cases, the uncertainties in object reconstruction efficiency, event interpretation, and analysis methodology are propagated to the \( t\bar{t} \) invariant mass distribution that is used to extract the search results. These uncertainties can be broadly grouped into two categories: those uncertainties that affect only the overall normalization of expected background events, and those uncertainties that can result in a different reconstruction of the \( t\bar{t} \) system, and therefore change the shape of the \( M_{t\bar{t}} \) distribution. Each source of systematic uncertainty is accounted for through unique nuisance parameters applied to the likelihood described in Section 10. For contributions that apply to multiple analysis channels, the nuisance parameters are fully correlated, allowing for better constraints on sources of systematic uncertainties. The individual sources of uncertainty are described in detail below, and are summarized in Table 1.

- **Process cross sections**: Uncertainties in the cross sections used to normalize simulated background processes are obtained from the fitting procedure derived above for the single lepton control region and are applied to the other analysis channels. For the \( t\bar{t} \), W+jets and Z+jets backgrounds, uncertainties of 3%, 8%, and 15% are obtained, respectively. For the subdominant diboson and single top quark backgrounds, an uncertainty in the cross section value of 15% is applied.

- **Integrated luminosity**: The uncertainty in the measurement of the integrated luminosity recorded during the 2016 data-taking period by CMS is 2.7%, and is applied to all simulated signal and background samples.

- **Pileup reweighting**: All simulated samples used in the analysis are reweighted to ensure that the distribution of the number of pileup interactions per event matches the corresponding distribution in data events for the 2016 run. This pileup distribution is obtained using a proton-proton inelastic (minimum bias) cross section value of 69.2 mb. A systematic uncertainty in the distribution is obtained by varying the value by \( \pm 4.6\% \), resulting in an uncertainty with both a normalization and shape component.

- **Lepton reconstruction and triggers**: Simulated events are corrected by scale factors to account for differences in efficiencies in the identification criteria for electrons and muons. By applying the scale factors shifted up or down by their uncertainties, templates are obtained that corresponded to these uncertainties and can be used as the nuisance parameters, which are correlated between channels, as identical identification criteria are used. The scale factors are parameterized as functions of lepton \( p_T \) and \( \eta \) to account for different detector response. In the same way, uncertainties in the
Table 1: Sources of systematic uncertainty that affect the $M_{tt}$ distribution in each analysis channel. For uncertainty sources that apply to multiple channels, the corresponding nuisance parameter is fully correlated across these channels if the symbol ✓ appears in the same row of the table. For normalization uncertainties, the size of the effect on the prior distribution is shown. Shape uncertainties have priors of one standard deviation (s.d.), and the dependence on kinematic quantities is shown.
trigger efficiency are also accounted for, in the electron and muon trigger selections for this analysis.

- **Jet energy scale and resolution**: Uncertainties in the corrections applied to jets are propagated to the final discriminating distributions by reconstructing events with the jet level corrections shifted within their corresponding uncertainties, which have dependence on the jet $p_T$ and $\eta$.

- **Jet b tagging**: Simulated events are corrected by scale factors to account for differences in the efficiency for identifying a b-jet between data and simulation. There are two components to this process, each with an independent, uncorrelated nuisance parameter: one that accounts for the scale factor applied to the rate of identifying b-tagged jets (efficiency) and one that accounts for the scale factor applied to the rate of mistakenly identifying light flavor jets (mistag rate). In each case, the uncertainty is obtained by shifting these $p_T$-dependent scale factors within their uncertainties. The b-tagging uncertainties are fully correlated between the dilepton and fully hadronic analyses, as they use the same b-tagging criteria.

- **CSV shape**: The CSV tagger provides a continuous variable that can be used to identify b-tagged jets. This continuous variable is used as an input to the W+jets BDT described above. The W+jets BDT is only used in the signal lepton analysis, therefore the CSV shape systematic uncertainty only applies to that analysis. Several sources of systematic uncertainties are evaluated, including jet energy scale, flavor effects, and statistical effects. Each of these effects contributes an additional uncertainty in the CSV value that is propagated to the final signal discrimination process.

- **Jet t tagging**: As there is no control region available where it is possible measure the t tagging scale factor that is orthogonal to the signal regions presented here. Therefore, the t tagging efficiency scale factor is determined during the statistical analysis. This is done by including a nuisance parameter with a flat prior distribution that is unconstrained and correlated between the fully hadronic and single lepton channels. Sources of misidentified t-tagged jets are different in the single lepton channel, where they originate from W+jets processes, and in the fully hadronic channel, where they originate from QCD multijet processes. Therefore, the nuisance parameter corresponding to the uncertainty in the top quark mistag rate are treated as uncorrelated between the channels, and are also uncorrelated with the nuisance parameter assigned to the t tagging efficiency.

- **Parton distribution functions**: For the t$t$ simulated sample, the PDFs from the NNPDF3.0 set are used [69], and evaluate the systematic uncertainty in the choice of PDF according to the process described in Ref. [70].

- **Scale uncertainties**: For the t$t$ sample, the renormalization and factorization scales were varied up and down independently by factors of 4 to account for uncertainties in the choice of $Q^2$ used to generate the simulated sample.

- **Top quark $p_T$ reweighting**: Due to an observed disagreement in the reconstructed top quark $p_T$ distribution, which worsens toward high $p_T$ [71, 72], the simulated SM t$t$ process was reweighted based on the generator level top quark $p_T$. The uncertainty in this process is estimated by taking the difference between the unweighted and weighted results applied symmetrically on the nominal value as a function of $p_T$.

- **NTMJ background estimation**: The ‘mass-modified’ procedure described above to predict the shape of the background in the fully hadronic channel includes an uncer-
tainty in the resulting distribution, equivalent to half of the difference between the uncorrected and ‘mass-modified’ background shapes. This difference affects both the shape and normalization of the final distributions and the corresponding nuisance parameter is independent from all other effects. The uncertainties in the top quark mistag rates are propagated to the final distributions and the corresponding uncertainty is handled via the top quark mistag rate nuisance parameter described above. A closure test is performed in simulated QCD multijet events to test the accuracy of the method. An additional systematic uncertainty is included, equal to the magnitude of the discrepancy observed from the closure tests results, evaluated and applied on a bin-by-bin basis to the fully hadronic signal categories.

9 Statistical analysis

Before extracting the final results of the analysis, a maximum-likelihood fit is performed to determine the preferred values of the background process normalizations and shapes, using constraints from the sources of systematic uncertainty described above. Each source of systematic uncertainty is included through a unique nuisance parameter that is allowed to vary within the rate and shape constraints described above, using a log-normal prior distribution. The post-fit values of the nuisance parameters are used to correct the normalizations and shapes of the $M_{tt}$ or $S_T$ distributions, as shown in Figs. 8, 9–10, and 11, for the dilepton, single lepton, and fully hadronic channels, respectively. The mild deficits at low $M_{tt}$ in the two plots on the left in Fig. 10 do not significantly impact the limit because this region is used to evaluate the $t\bar{t}$ and $W+$jets cross-sections and is not sensitive to the resonance signal. During the maximum-likelihood fit, a value of $1.001 \pm 0.012$ for the $t$ tagging efficiency scale factor is extracted, which is left unconstrained prior to the fit.

Good agreement is observed in each of the categories considered in this analysis. Two bins have data that are greater than 3 s.d. away from the expected background. Limits on the production cross section times branching fraction are calculated, $\sigma(pp \to X) \cdot B(X \to t\bar{t})$, for heavy resonances decaying to a pair of top quarks. In this analysis, the branching fraction of $B(X \to t\bar{t})$ is assumed to be 1. Using the distributions of $M_{tt}$ ($S_T$ for the dilepton channel) in each of the exclusive categories from the three analysis channels, a shape-based analysis is performed with the Theta software package [73]. For the limit calculation, a Bayesian likelihood-based method is used with each bin of the distributions combined statistically along with the implementation of unique nuisance parameters that correspond to the systematic uncertainties described in Section 8. The signal normalization is fluctuated with a distinct nuisance parameter having a uniform prior, while the other nuisance parameters have log-normal prior distributions. Finally, to account for the limited number of simulated events, an additional statistical uncertainty is included for each process relying on simulated events through the “Barlow-Beeston lite” method [74]. Prior to the statistical analysis, the $M_{tt}$ distributions are rebinned. For the all hadronic and dileptonic channels, the total statistical uncertainty on the background is required to be below 30% in any given bin. In the single lepton channel, the total statistical uncertainty on the background expectation for the sum of small backgrounds (single top quark, multijet, Z+jets, W+b or c jets) is limited to 10% in each bin.

Figure 12 shows a comparison of the expected sensitivities in each of the three analysis channels in terms of the expected limits for the $g_{\phi\phi}$ signal model. The fully hadronic and lepton+jets channels provide most of the sensitivity for high-mass resonances, while the dilepton channel contributes significantly in the low-mass range.
Figure 8: Distributions of $S_T$ for the $\mu\mu$ (top), ee (middle), and $e\mu$ (bottom) signal regions in the boosted (left) and non-boosted (right) regions. The hashed band on the simulation represents the post-fit uncertainties.
Figure 9: Distributions of $M_{t\bar{t}}$ for the single lepton channel signal regions for the muon (left) and electron (right) categories with (top) and without (bottom) $t$ tagging. The hashed band on the simulation represents the post-fit uncertainties.
Figure 10: Distributions of $M_{tt}$ for the single lepton channel control regions for the muon (left) and electron (right) categories that are light (top) and heavy (bottom) flavor enriched. The hashed band on the simulation represents the post-fit uncertainties.
Figure 11: Distributions of $M_{tt}$ for the fully hadronic channel signal region categories, used to extract the final results. The hashed band on the simulation represents the post-fit uncertainties.
Figure 12: Comparison of sensitivities for each analysis channel contributing to the combination. The expected limits are shown for each channel in the colored lines, while the combination result is shown in the black line. These results are shown specifically for the $g_{KK}$ signal hypothesis as this model has characteristics that are common to many $t\bar{t}$ resonance searches.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>33</td>
<td>25</td>
<td>[13, 45]</td>
<td>[7.2, 71]</td>
</tr>
<tr>
<td>0.75</td>
<td>0.87</td>
<td>2.20</td>
<td>[1.40, 3.10]</td>
<td>[0.97, 4.20]</td>
</tr>
<tr>
<td>1.00</td>
<td>0.37</td>
<td>0.50</td>
<td>[0.35, 0.72]</td>
<td>[0.25, 0.98]</td>
</tr>
<tr>
<td>1.25</td>
<td>0.33</td>
<td>0.16</td>
<td>[0.11, 0.23]</td>
<td>[0.075, 0.330]</td>
</tr>
<tr>
<td>1.50</td>
<td>0.092</td>
<td>0.074</td>
<td>[0.049, 0.110]</td>
<td>[0.035, 0.160]</td>
</tr>
<tr>
<td>2.00</td>
<td>0.026</td>
<td>0.026</td>
<td>[0.017, 0.039]</td>
<td>[0.012, 0.059]</td>
</tr>
<tr>
<td>2.50</td>
<td>0.018</td>
<td>0.012</td>
<td>[0.0082, 0.0190]</td>
<td>[0.0056, 0.0280]</td>
</tr>
<tr>
<td>3.00</td>
<td>0.0045</td>
<td>0.0073</td>
<td>[0.0049, 0.0110]</td>
<td>[0.0034, 0.0170]</td>
</tr>
<tr>
<td>3.50</td>
<td>0.0042</td>
<td>0.0050</td>
<td>[0.0034, 0.0076]</td>
<td>[0.0023, 0.0120]</td>
</tr>
<tr>
<td>4.00</td>
<td>0.0040</td>
<td>0.0040</td>
<td>[0.0026, 0.0062]</td>
<td>[0.0018, 0.0098]</td>
</tr>
<tr>
<td>4.50</td>
<td>0.0033</td>
<td>0.0033</td>
<td>[0.0023, 0.0052]</td>
<td>[0.0016, 0.0079]</td>
</tr>
<tr>
<td>5.00</td>
<td>0.0023</td>
<td>0.0031</td>
<td>[0.0020, 0.0047]</td>
<td>[0.0013, 0.0071]</td>
</tr>
</tbody>
</table>

Table 2: Limits on the product of the resonance production cross section times branching fraction, for the narrow (1%) width $Z'$ boson resonance hypothesis.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>27</td>
<td>20</td>
<td>[9.3, 38]</td>
<td>[5.2, 58]</td>
</tr>
<tr>
<td>0.75</td>
<td>2.0</td>
<td>3.3</td>
<td>[2.0, 5.0]</td>
<td>[1.3, 7.0]</td>
</tr>
<tr>
<td>1.00</td>
<td>0.85</td>
<td>0.68</td>
<td>[0.45, 1.00]</td>
<td>[0.32, 1.40]</td>
</tr>
<tr>
<td>1.25</td>
<td>0.55</td>
<td>0.23</td>
<td>[0.16, 0.35]</td>
<td>[0.11, 0.53]</td>
</tr>
<tr>
<td>1.50</td>
<td>0.170</td>
<td>0.110</td>
<td>[0.072, 0.170]</td>
<td>[0.049, 0.270]</td>
</tr>
<tr>
<td>2.00</td>
<td>0.043</td>
<td>0.040</td>
<td>[0.026, 0.061]</td>
<td>[0.017, 0.095]</td>
</tr>
<tr>
<td>2.50</td>
<td>0.027</td>
<td>0.019</td>
<td>[0.012, 0.029]</td>
<td>[0.0085, 0.0420]</td>
</tr>
<tr>
<td>3.00</td>
<td>0.0087</td>
<td>0.0130</td>
<td>[0.0085, 0.019]</td>
<td>[0.0058, 0.0290]</td>
</tr>
<tr>
<td>3.50</td>
<td>0.0088</td>
<td>0.0100</td>
<td>[0.0069, 0.016]</td>
<td>[0.0048, 0.0240]</td>
</tr>
<tr>
<td>4.00</td>
<td>0.0091</td>
<td>0.0094</td>
<td>[0.0062, 0.015]</td>
<td>[0.0044, 0.0220]</td>
</tr>
<tr>
<td>4.50</td>
<td>0.0099</td>
<td>0.0096</td>
<td>[0.0064, 0.014]</td>
<td>[0.0045, 0.0230]</td>
</tr>
<tr>
<td>5.00</td>
<td>0.0100</td>
<td>0.0110</td>
<td>[0.0078, 0.018]</td>
<td>[0.0054, 0.0280]</td>
</tr>
</tbody>
</table>

Table 3: Limits on the product of the resonance production cross section times branching fraction, for the wide (10%) width $Z'$ boson resonance hypothesis.

10 Results

The statistical analysis is performed for each of the BSM signal models considered in this analysis: three variations of a $Z'$ boson having a width-to-mass ratio of 1%, 10%, and 30%, as well as a $g_{KK}$. In each case a 95% confidence level (CL) limit is obtained on the resonance production cross section times branching fraction. The observed and expected limits and 1 and 2 standard deviation (s.d.) bands are calculated for resonance masses ranging from 500 GeV to 5 TeV and are listed in Tables 2–5.

New exclusion limits on resonances decaying to $t\bar{t}$ are set by comparing the observed limit to the theoretical cross section. As shown in Fig 13, the analysis excludes narrow (1% width) $Z'$ bosons with masses up to 3.8 TeV (3.75 TeV expected), and wide and extra-wide (10% and 30% width, respectively) $Z'$ bosons with masses up to 5 TeV (5 TeV expected). For the $g_{KK}$ resonance hypothesis, the analysis excludes masses up to 4.55 TeV (4.45 TeV expected). These results represent a significant improvement on the previous results in this channel from the 2015 data-taking period, due to not only the increase in integrated luminosity, but also the reduction in the uncertainty on the multijet background estimate in the fully hadronic channel, the improved W+jets rejection via the W+jets BDT in the single lepton channel, and the inclusion
11. Summary

A search for a generic massive $t\bar{t}$ resonance has been presented. The analysis was performed on $36 \text{ fb}^{-1}$ of data collected by the CMS experiment in 2016 at the LHC with a $\sqrt{s} = 13$ TeV. The analysis focused on searches for $t\bar{t}$ resonances above 2 TeV, where the decay products of the top quark have become collimated due to a large Lorentz boost. The analysis performs an in-situ measurement of the analysis backgrounds and the $t$ tagging efficiency. The measured data are consistent with the background-only hypothesis, and no evidence for a massive $t\bar{t}$ resonance has been found. Since no signal was observed, limits at 95% CL are calculated for the production cross-section for a spin-1 resonance decaying to $t\bar{t}$ pairs with a variety of decay widths.

Limits are calculated for two benchmark BSM processes that decay to $t\bar{t}$ pairs. The topcolor $Z'$ boson with relative widths $(\Gamma / M)$ of 1%, 10%, and 30% are excluded in the mass ranges 0.5–3.8, 0.5–5.0, and 0.5–5.0 TeV, respectively. KK excitations of the gluon in the Randall–Sundrum scenario are excluded between 0.5–4.55 TeV. This is the first search by CMS at $\sqrt{s} = 13$ TeV for $t\bar{t}$ resonances that combines all three decay topologies of the $t\bar{t}$ system: dilepton, single lepton, and all hadronic.

The sensitivity of the analysis exceeds previous searches at $\sqrt{s} = 8$ and 13 TeV, particularly at high $t\bar{t}$ invariant mass. The absolution cross-section limits are 10–40% better, for $M_{t\bar{t}}$ above 2 TeV, than the previous result released by CMS scaled to $36 \text{ fb}^{-1}$. Previous measurements ex-

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.00</td>
<td>0.99</td>
<td>[0.60, 1.60]</td>
<td>[0.39, 2.60]</td>
</tr>
<tr>
<td>2.0</td>
<td>0.074</td>
<td>0.065</td>
<td>[0.040, 0.100]</td>
<td>[0.027, 0.170]</td>
</tr>
<tr>
<td>3.0</td>
<td>0.020</td>
<td>0.025</td>
<td>[0.017, 0.039]</td>
<td>[0.012, 0.060]</td>
</tr>
<tr>
<td>4.0</td>
<td>0.019</td>
<td>0.022</td>
<td>[0.015, 0.033]</td>
<td>[0.011, 0.052]</td>
</tr>
<tr>
<td>5.0</td>
<td>0.022</td>
<td>0.024</td>
<td>[0.016, 0.037]</td>
<td>[0.011, 0.057]</td>
</tr>
</tbody>
</table>

Table 4: Limits on the product of the resonance production cross section times branching fraction, for the extra-wide (30%) width $Z'$ boson resonance hypothesis.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>6.7</td>
<td>25</td>
<td>[11, 48]</td>
<td>[5.5, 72]</td>
</tr>
<tr>
<td>0.75</td>
<td>2.8</td>
<td>4.2</td>
<td>[2.4, 7.0]</td>
<td>[1.5, 9.9]</td>
</tr>
<tr>
<td>1.00</td>
<td>0.76</td>
<td>0.93</td>
<td>[0.61, 1.50]</td>
<td>[0.42, 2.10]</td>
</tr>
<tr>
<td>1.25</td>
<td>0.82</td>
<td>0.39</td>
<td>[0.25, 0.62]</td>
<td>[0.17, 0.96]</td>
</tr>
<tr>
<td>1.50</td>
<td>0.28</td>
<td>0.18</td>
<td>[0.12, 0.30]</td>
<td>[0.079, 0.470]</td>
</tr>
<tr>
<td>2.00</td>
<td>0.091</td>
<td>0.063</td>
<td>[0.041, 0.100]</td>
<td>[0.028, 0.160]</td>
</tr>
<tr>
<td>2.50</td>
<td>0.044</td>
<td>0.035</td>
<td>[0.022, 0.054]</td>
<td>[0.015, 0.083]</td>
</tr>
<tr>
<td>3.00</td>
<td>0.021</td>
<td>0.025</td>
<td>[0.016, 0.038]</td>
<td>[0.011, 0.058]</td>
</tr>
<tr>
<td>3.50</td>
<td>0.018</td>
<td>0.020</td>
<td>[0.014, 0.032]</td>
<td>[0.0096, 0.0480]</td>
</tr>
<tr>
<td>4.00</td>
<td>0.021</td>
<td>0.020</td>
<td>[0.013, 0.031]</td>
<td>[0.0093, 0.0470]</td>
</tr>
<tr>
<td>4.50</td>
<td>0.019</td>
<td>0.023</td>
<td>[0.015, 0.036]</td>
<td>[0.010, 0.056]</td>
</tr>
<tr>
<td>5.00</td>
<td>0.024</td>
<td>0.028</td>
<td>[0.019, 0.044]</td>
<td>[0.013, 0.068]</td>
</tr>
</tbody>
</table>

Table 5: Limits on the product of the resonance production cross section times branching fraction, for the $g_{KK}$ gluon resonance hypothesis.

of dilepton event categories in the combination. These results are the most stringent exclusion limits for a $t\bar{t}$ resonances produced to date.
Figure 13: Observed and expected limits for each of the four signal hypotheses considered in this analysis.
cluded the $g_{KK}$ up to 3.3 TeV and the topcolor $Z'$ up to 2.5, 3.9, and 4.0 TeV for relative widths of 1%, 10%, and 30%, respectively. The presented analysis improves upon those limits, extending the $g_{KK}$ exclusion to 4.55 TeV and the $Z'$ exclusions to 3.8, 5.0, and 5.0 TeV. These are the most stringent limits on the $g_{KK}$ and the topcolor $Z'$ to date.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Secretariat for Higher Education, Science, Technology and Innovation, Ecuador; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Research, Development and Innovation Fund, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, the Russian Foundation for Basic Research and the Russian Competitiveness Program of NRNU “MEPhI”; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación, Programa Consolidador-Ingenio 2010, Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016, Plan de Ciencia, Tecnología e Innovación 2013-2017 del Principado de Asturias and Fondo Europeo de Desarrollo Regional, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, Unizh, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand;
the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science - EOS” - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület (“Momentum”) Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Scientific and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa de Excelencia María de Maeztu and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Somphot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).
References


