Search for supersymmetry in the all-hadronic final state using top quark tagging in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search for supersymmetry in all-hadronic events with missing transverse momentum using top quark tagging is presented. The data were collected during 2016 in proton-proton collisions at a center-of-mass energy of 13 TeV with the CMS detector at the LHC and correspond to an integrated luminosity of 12.9 fb$^{-1}$. Search regions are defined using the properties of reconstructed jets, the presence of bottom and top quark candidates, and missing transverse momentum. No statistically significant excess of events above the expected contribution from standard model processes is observed. Exclusion limits are set on the masses of potential new particles in the context of simplified models of direct and gluino-mediated top squark production.
1 Introduction

Supersymmetry (SUSY) [1–9] is one of the most compelling models of new physics beyond the standard model (SM). SUSY proposes a superpartner, or ‘sparticle’, for each SM particle with the same quantum numbers except for spin, which differs by a half-integer unit. In R-parity conserving models [10, 11], sparticles are produced in pairs and the lightest SUSY particle (LSP) is stable. Models with a weakly interacting neutralino ($\tilde{\chi}_1^0$) as the LSP are especially attractive because the $\tilde{\chi}_1^0$ would be a candidate for dark matter [12]. The introduction of extra sparticles also helps to stabilize the Higgs boson mass [13–19], in particular in so-called “natural” SUSY models [20–25]. These models feature a gluino $\tilde{g}$, lightest top squark $\tilde{t}$, and lightest bottom squark $\tilde{b}$ with a mass around the TeV scale and have a higgsino mass parameter $\mu$ of the order of 100 GeV. The masses of the other sparticles can be beyond the reach of the CERN LHC [26].

Based on these considerations, we perform a search for $\tilde{t}\tilde{t}$ production, either directly or via the gluino, with the decay of each sparticle resulting in a stable $\tilde{\chi}_1^0$ and SM particles. Previous SUSY searches at the LHC have found no evidence of physics beyond the SM. The latest results using the 2015 data set at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 2.3 fb$^{-1}$ for CMS and 3.2 fb$^{-1}$ for ATLAS, place limits on the top squark mass, $m(\tilde{t})$, extending to 800 GeV [27–29], and limits on the gluino mass, $m(\tilde{g})$, extending to 1750 GeV [30–32], depending on the assumed decay modes.

The search strategy for this analysis follows closely the one of the “HETT analysis” reported in Ref. [28]. We select events with no identified isolated leptons, large missing transverse momentum, at least four jets and at least one jet identified as originating from the hadronization of a b quark. The analysis relies on the use of a highly efficient algorithm to tag objects consistent with top quark decay and uses their kinematic properties as input to the computation of the “stransverse” mass ($M_{T2}$) variable [33, 34]. Exclusive search regions are constructed using the number of identified b jets and top-like objects, and different thresholds on the missing transverse momentum and $M_{T2}$.

One of the dominant sources of the SM background originates from $t\bar{t}$ or W boson production in association with jets in events with leptonic W boson decays, where the lepton is not reconstructed or identified. Events in which a Z boson, produced in association with jets, decays to neutrinos also provide a significant contribution to the SM background. The SM backgrounds are estimated with data control samples that are orthogonal but kinematically similar to the search sample. The selection criteria for these control samples are chosen to yield a sample with high purity for a particular background process. With the aid of simulated data samples, the experimental measurement of each background process in its corresponding data control sample is translated into a prediction for the number of SM events in each of the search regions.

The search is performed on a data sample corresponding to an integrated luminosity of 12.9 fb$^{-1}$ of proton-proton collisions collected during 2016 at a center-of-mass energy of 13 TeV with the CMS detector [35] at the LHC. The event reconstruction and simulation are described in Section 2. Details of the analysis optimization, including the signal models considered, the top quark tagging algorithm, and the event categorization, are presented in Section 3. The SM background estimation strategy is detailed in Section 4. The results and their interpretation in the context of SUSY are discussed in Section 5, followed by a summary in Section 6.
2 Event reconstruction and simulation

Events are reconstructed using the particle-flow (PF) algorithm [36], which reconstructs charged hadrons, neutral hadrons, photons, muons, and electrons using information from all subdetectors. The negative vector sum of the transverse momentum of all particles reconstructed in the event is denoted by $\vec{p}_{T}^{\text{miss}}$ and the missing transverse momentum $E_{T}$ is its magnitude. All photons and neutral hadrons in an event, but only those charged particles which originate from the primary interaction, are clustered into jets using the anti-$k_{T}$ clustering algorithm with size parameter 0.4 (AK4) [37]. Neutral particles from overlapping pp interactions (“pileup”), and from the underlying event, are subtracted on an event-by-event basis using the FASTJET technique [38, 39]. The energy and momentum of each jet is corrected using factors derived from simulation, and, for jets in data, an additional residual energy-momentum correction is applied to account for differences in the jet energy-momentum scales [40] between simulation and data. Only jets with $p_{T} > 30$ GeV and $|\eta| < 2.4$ or $|\eta| < 5$, depending on the use case, are used in this search. They are required to pass a set of jet identification criteria as described in Ref. [41].

For this analysis, a jet (with $|\eta| < 2.4$) is considered a b quark jet (b-tagged) if it passes the medium operating point requirements of the “Combined Secondary Vertex” (CSV) method [42]. The b quark identification efficiency is approximately 60%. The probability of a jet originating from a light quark or gluon to be misidentified as a b quark jet is 1.4%, averaged over $p_{T}$ in $t\bar{t}$ events [42].

To obtain a sample of all-hadronic events, events with isolated electrons and muons are vetoed. Muons are reconstructed by matching tracks in the muon detectors to compatible track segments in the silicon tracker, and are required to have $p_{T} > 10$ GeV and $|\eta| < 2.4$. Electron candidates are reconstructed starting from a cluster of energy deposited in the ECAL that is then matched to a track in the silicon tracker. Electron candidates are required to have $p_{T} > 10$ GeV and satisfy $|\eta| < 1.44$ or $1.56 < |\eta| < 2.5$ to avoid the transition region between the ECAL barrel and the endcap. Muon and electron candidates are required to originate within 2 mm of the beam axis in the transverse plane. The isolation of electron and muon candidates is defined as the $\sum p_{T}$ of PF candidates in a cone around the candidate’s trajectory with a radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. The cone size depends on the lepton $p_{T}$ as follows:

$$\Delta R = \begin{cases} 
0.2, & p_{T} \leq 50 \text{ GeV} \\
\frac{10 \text{ GeV}}{p_{T}}, & 50 \text{ GeV} < p_{T} < 200 \text{ GeV} \\
0.05, & p_{T} \geq 200 \text{ GeV}
\end{cases}$$

(1)

The decrease in the cone radius for higher-$p_{T}$ candidates is motivated by the consideration that the decay products of more boosted heavy objects should be contained in a region defined with a smaller radius. The isolation sum is corrected for contributions originating from pileup interactions using an estimate of the pileup energy in the cone. Electron and muon candidates are considered to be isolated if their relative isolation, i.e. the ratio of the isolation sum to the candidate $p_{T}$, is less than 0.1 and 0.2, respectively.

In order to further reduce the contribution from background events with low-$p_{T}$ leptons originating from leptonic W boson decays, an additional veto on the presence of isolated tracks is used. These tracks are required to have $p_{T} > 5$ GeV, $|\eta| < 2.5$, and relative track isolation less than 0.2. This is the same as the relative isolation described above except that it is only computed with charged PF candidates within a fixed cone of $\Delta R = 0.3$ around the track. In
order to preserve signal efficiency, events are only vetoed when the transverse mass ($M_T$) of the isolated track-$E_T$ system

$$M_T(\text{track}, E_T) = \sqrt{2 \cdot p_T^{\text{track}} \cdot E_T \cdot (1 - \cos \Delta \phi)} ,$$

with $p_T^{\text{track}}$ denoting the track $p_T$, and $\Delta \phi$ the azimuthal separation between the isolated track and $p_T^{\text{miss}}$, is less than 100 GeV to be consistent with a W boson decay.

Following the veto on the presence of isolated electrons and muons, a significant fraction of the remaining SM background originates from events with hadronically-decaying $\tau$ leptons ($\tau_h$). In order to reduce this background contribution, a veto is placed on the presence of isolated charged hadron PF candidates in the tracker volume with $p_T > 10$ GeV that are consistent with $\tau_h$ decays. The $\tau_h$ candidate-$E_T$ system is also required to have a transverse mass $M_T(\tau_h, E_T) < 100$ GeV. Candidates satisfying the selection on $M_T(\tau_h, E_T)$ are categorized as being isolated if their relative track isolation is less than 0.1.

Monte Carlo (MC) simulated event samples are used to study the properties of the SM background processes as well as signal models. The MadGraph5 generator [43] is used to simulate events originating from $t\bar{t}$, $W$+jets, $Z$+jets, Drell-Yan (DY)+jets, QCD multijet, gluino pair production, and top squark pair production processes based on leading-order (LO) NNPDF3.0 [44] parton distribution functions (PDFs). Single-top events produced in the tW channel are generated with POWHEG v1.0 [45–48], and rare SM processes such as $t\bar{t}Z$ and $t\bar{t}W$ using the MadGraph5_AMC@NLO program [49]. Next-to-leading-order (NLO) NNPDF3.0 PDFs are used in both cases. The parton showering and hadronization is simulated with PYTHIA 8.1 [50] using underlying-event tune CUETP8M1 [51]. A GEANT4-based model [52] is used to simulate the response of the CMS detector to the SM background. The CMS fast simulation package [53] is used in the case of signal samples and is verified to provide results that are consistent with those obtained from the full GEANT4-based simulation. Event reconstruction is performed in the same manner as for collision data. The signal production cross sections are calculated using NLO plus next-to-leading-logarithm (NLL) calculations [54]. The most precise available cross section calculations are used to normalize the SM simulated samples, corresponding to NLO or next-to-NLO accuracy in most cases ([49, 55–61]).

In cases where the simulation does not adequately describe the data, correction factors are applied to the simulation to account for the observed discrepancies. The corresponding uncertainties are propagated to the predicted SM yields in the search regions. Differences in the efficiencies for selecting isolated leptons between simulation and data are measured in $Z \rightarrow \ell\ell$ events in the case of electrons and muons and in a $t\bar{t}$-enriched sample for hadronically-decaying taus. Correction factors and their uncertainties for the $b$ tagging efficiency are derived using multijet- and $t\bar{t}$-enriched event samples and are parametrized by the jet kinematics [62].

3 Analysis description

The analysis is designed for maximum sensitivity to models containing top quarks in their decay chains. The data are first divided into regions based upon the number of tagged top quarks ($N_t$) and $b$ jets ($N_b$) found in each event. The search regions are defined by further subdivision of each $N_t$, $N_b$ bin in $E_T$ and $M_{T2}$.

3.1 Benchmark signal models

This document describes a search for direct and gluino-mediated top squark production. For direct top squark pair production, we consider one decay scenario within the Simplified Model
Spectra (SMS) framework \[63–67\]. In this scenario, denoted by ‘T2tt’ and illustrated in Fig. 1, the \( \tilde{t} \) decays via a top quark: \( \tilde{t} \rightarrow t \tilde{\chi}_0^0 \), in which \( \tilde{\chi}_0^0 \) is the LSP.

Two scenarios are considered for gluino-mediated top squark production, as shown in Fig. 2. In the main model, denoted by ‘T1tttt’, the gluino decays to top quarks via an off-shell top squark: \( \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_0^0 \). The second scenario, denoted by ‘T5ttcc’, features on-shell top squarks in the decay chain and the mass difference between top squark and LSP is assumed to be \( \Delta m(\tilde{t}, \tilde{\chi}_1^0) = 20 \text{ GeV} \). For this model, the gluino decays to a top quark and a top squark, \( \tilde{g} \rightarrow \tilde{t} \tilde{t} \), and the top squark decays to a charm quark and the LSP, \( \tilde{t} \rightarrow c \tilde{\chi}_0^0 \).

All scenarios described above share similar final states, containing two \( \tilde{\chi}_1^0 \)'s and up to four top quarks. Given that the \( \chi_1^0 \) is stable and only interacts weakly, it does not interact with the detector. Therefore, \( E_T \) is one of the most important discriminators between signal and SM background, especially for models with large mass differences. Since top quarks decay to a b quark and a W boson, one hadronically-decaying top quark can result in up to three identified jets, depending on the top quark \( p_T \) and jet size.

### 3.2 Top quark reconstruction and identification

The procedure to reconstruct and identify the hadronically-decaying top quarks (top tagging) presented here is identical to the one used in Ref. [28], and is based partially on Refs. [68–
The top quark tagging algorithm takes as input all AK4 jets that satisfy $p_T > 30$ GeV and $|\eta| < 5$. These jets are clustered into three categories of top candidates; trijet, dijet, and monojet candidates. Trijet candidates are formed from jets that lie within a cone of radius 1.5 in $(\eta, \phi)$ space and are subject to a set of conditions that impose kinematic consistency with a top quark decay, as detailed in Refs. [28, 69]. The second category of top candidates is clustered from dijets where one jet originates from the merged decay products of a W boson (W jet). The jet mass is used to determine if a jet represents a W jet with a required mass window of 70–110 GeV. Additionally, the ratio between the mass of the W jet and the mass of the dijet is required to be consistent with the ratio of W boson to top quark masses. The final category of candidates, monojets, are constructed from single jets which have a jet mass in the range of 110–220 GeV.

After all possible top candidates are constructed, the final reconstructed top objects are determined by requirements on the total object mass and the number of b jets. Any top candidate containing more than one b jet is rejected, as well as all top candidates with a mass outside the range 100–250 GeV. Top candidates that share a jet with another candidate are removed, in favor of the candidate with the mass closer to the true top quark mass. However, if there is only one b jet in the event, the first top is chosen differently to ensure that there are two objects for the $M_T^2$ calculation (described below). In these events, the first top object chosen is not allowed to contain the b jet, though subsequent top candidates may contain the b jet.

By considering not only fully resolved (trijet) top quark decays, but also decays from boosted top quarks, manifesting themselves as dijet or monojet topologies, this top tagger achieves a good efficiency for tagging top quarks over a wide range of top quark $p_T$, from ~30% at 200 GeV to close to 85% at 1 TeV. Since the top quark $p_T$ spectrum for signal events depends strongly on $m_t$ and $\Delta m(t, \tilde{\chi}_0^0)$, this insures good acceptance for a wide range of signal models. The event mistag rate of the top tagger is about 30–40% for processes that do not contain hadronically-decaying top quarks. These processes, as well as the $t\bar{t}$ process, are suppressed by using $M_T^2$ as a complement to the top tagger.

The transverse mass variable $M_T^2$ [33, 34] is an extension of the transverse mass variable that is sensitive to the pair production of heavy particles, each of which decays to an invisible particle. The $M_T^2$ variable is defined for two heavy particles ($(1)$ and $(2)$) as:

$$M_T^2 \equiv \min_{\vec{p}_{\text{miss}}^{(1)}, \vec{p}_{\text{miss}}^{(2)}} \left[ \max \left( M_T^{(1)^2}, M_T^{(2)^2} \right) \right]$$

(3)

where $\vec{p}_{\text{miss}}^{(i)}$ (with $i = 1,2$) are the unknown $p_T$’s of the two invisible particles and $M_T^{(i)}$ the transverse masses obtained by pairing the invisible particles with the visible daughters of each heavy particle. The minimization is performed with the constraint that the sum of the $p_T$’s of both invisible particles equals $\vec{p}_{\text{miss}}$ in the event. The invisible particles are assumed to be massless.

We construct the visible portions of each heavy particle (($1$) and $(2)$) from the list of top-tagged objects. In the case where two top-tagged objects are identified, each is used as one visible component. If more than two top-tagged objects are found, $M_T^2$ is calculated for all combinations and the lowest $M_T^2$ value is taken. In the case where only one top-tagged object is identified (the pre-selection requires $N_t \geq 1$), the second visible portion is taken from the remaining jets not included in the top-tagged object using a b-tagged jet as a seed to reconstruct a partial top quark. The b-tagged jet is combined with the closest jet that yields an invariant mass between 50 GeV and the top quark mass, and the combined dijet is used as the second visible system. In case no jet combination satisfies that invariant mass requirement, the b-tagged jet itself is used as the second visible system. For direct top squark production, $M_T^2$ has a kinematic upper limit
at the $\tilde{t}$ mass, whereas for gluino pair production, the interpretation of $M_{T2}$, as defined here, depends on the decay scenario.

3.3 Event selection and categorization

Events in the search regions are collected with a trigger that applies a lower threshold of 300 GeV on $H_T$ in coincidence with a threshold on $E_T$ above 100 GeV. This trigger is fully efficient at selecting events that have at least 400 GeV of $H_T$ together with at least 175 GeV of $E_T$.

Initially, a pre-selection is applied, preserving 2–20% of the signal events. All events must pass filters designed to remove detector- and beam-related noise. The minimum number of jets with $|\eta| < 2.4$ in an event must be $N_j \geq 4$, with the leading two jets required to have $p_T > 50$ GeV. The missing transverse momentum must satisfy $E_T \geq 200$ GeV and $H_T$ must be larger than 500 GeV, where the thresholds are chosen to be past the trigger efficiency turn-on and to allow a low $175 < E_T < 200$ GeV sideband for background studies. A requirement on the angle between $E_T$ and the first three leading jets, $\Delta \phi(E_T, j_{1,2,3}) > 0.5, 0.5, 0.3$, is applied to remove events from QCD multijet processes. Finally, requirements that $N_t \geq 1, N_b \geq 1$, and $M_{T2} > 200$ GeV are applied.

We define independent search regions in terms of $E_T$, $M_{T2}$, and the number of b-tagged jets and top-tagged objects. Figure 3 demonstrates the background composition following the pre-selection cuts as a function of $N_t, N_b, E_T$ and $M_{T2}$. Due to the potential to contain more than two top quarks in the final state, the gluino models are interpreted using 59 bins with $N_b = 1$, $N_b = 2, N_t \geq 3$ and $N_t = 1, N_t = 2, N_t \geq 3$, while the direct top squark production models are interpreted without the $N_t \geq 3$ bins (for a total of 53 bins). To improve background suppression, in particular of the $t\bar{t}$ contribution, each $(N_b, N_t)$ bin is further subdivided by placing requirements on the $E_T$ and $M_{T2}$ variables as shown in Fig. 4. This figure also lists the search region bin numbers used throughout this document.

4 Background estimation

4.1 Estimation of the lost-lepton background

About 70% of the expected SM background (integrated over all search bins) comes from $t\bar{t}$ and $W+$jets events with leptonic $W$ decays. If the $W$ boson decays to a $\tau$ lepton that decays hadronically, this $\tau$ lepton is reconstructed as a jet and passes the lepton vetoes. The estimation of this background is explained in the next section. If, on the other hand, the $W$ boson decays to an electron or muon, the lepton vetoes can be satisfied when the electron or muon is “lost”, i.e., not isolated, not identified/reconstructed, or out of the acceptance region.

These lost leptons (LL) are modeled using appropriately weighted data events from a control sample which consists mainly of $t\bar{t}$ events. This control sample is collected using the search trigger and is defined to match the pre-selection, but the muon veto is replaced by the requirement that there be exactly one identified and isolated muon with $p_T > 10$ GeV and $|\eta| < 2.4$, and the isolated track veto is removed. To reduce possible signal contamination in this control sample, only events with $M_T$ less than 100 GeV are considered, with $M_T$ reconstructed from the muon $p_T$ and $E_T$ as $M_T = \sqrt{2p_T^\mu E_T (1 - \cos(\Delta \phi))}$, where $\Delta \phi$ is the distance in $\phi$ between the muon and the $E_T$ vector.

The predicted number of events with lost leptons, originating from $t\bar{t}$, $W+$jets, and single-top processes, contributing to the search region is calculated as the sum over the events in the
4.1 Estimation of the lost-lepton background

Figure 3: Comparison of the simulated distributions for $N_{\ell}$, $N_{b}$, $M_{T2}$ and $E_{T}$ (clock-wise) between SM backgrounds (filled histograms) and several example signal models (dashed lines), after the pre-selection requirements have been applied. The T2tt signal model with $m_{\tilde{t}} = 850$ GeV and $m_{\tilde{\chi}^{0}_1} = 100$ GeV is shown with a red solid line, the T2tt signal model with $m_{\tilde{t}} = 500$ GeV and $m_{\tilde{\chi}^{0}_1} = 325$ GeV with a blue dashed line, the T1tttt signal model with $m_{\tilde{g}} = 1200$ GeV and $m_{\tilde{\chi}^{0}_1} = 800$ GeV with a green dotted line, and the T1tttt signal model with $m_{\tilde{g}} = 1500$ GeV and $m_{\tilde{\chi}^{0}_1} = 100$ GeV with a black dashed-dotted line. The distributions for the signal models have been normalized to the same area as the total background distribution. The black points show the observed data events for each bin. The numbers associated with each MC background and data are the yield of each sample. The numbers associated with the signal points are the scale. The lower panels show the ratio between data and simulation.
Figure 4: Search bin definitions and bin numbers after pre-selection cuts defined in the text.
single-muon control region weighted by a factor that takes into account acceptance, reconstruction and identification, and isolation efficiencies (typically this factor is around 0.5), multiplied by a factor that accounts for dilepton events where both leptons are lost (typically 0.99 for muons and 0.97 for electrons). This is further corrected to compensate for the efficiency of the $M_T < 100\text{ GeV}$ requirement (typically 0.9). Finally, the isolated track veto efficiency (typically 60%) is applied to get the final number of predicted lost lepton background events.

A closure test is performed comparing the LL background in the search regions as predicted by applying the LL background determination procedure to the simulated muon control sample to the expectation obtained directly from $t\bar{t}$, single top quark, and W+jets simulation. The result of the closure test is shown on the top plot of Fig. 5. The closure uncertainty is 2–63% depending on the search bin and it is the dominant systematic uncertainty in the LL background prediction. In addition, the following other sources of systematic uncertainty are included: lepton isolation efficiency (effect on prediction is between 2% and 8%), lepton reconstruction and identification efficiency (3% to 13% effect), lepton acceptance from uncertainty in the PDFs (2% to 24%), corrections due to the presence of dilepton events (around 1%), efficiency of the $M_T$ selection cut (less than 1%), and isolated-track veto (3% to 11%).

4.2 Estimation of the hadronic $\tau$ background

Events from $t\bar{t}$, W+jets and single-top processes in which a $\tau$ lepton decays hadronically are one of the largest components of the SM background contributing to the search regions. When a W boson decays to a neutrino and a hadronically-decaying $\tau$ lepton ($\tau_h$), the presence of neutrinos in the final state results in $\not{E}_T$, and the event passes the lepton veto because the hadronically-decaying $\tau$ is reconstructed as a jet.

The estimate of the remaining $\tau_h$ background in the signal region after applying the isolated track veto is based on a control sample of $\mu+$jets events selected from data using a muon- and $H_T$-based trigger, and requiring exactly one muon with $p_T^{\mu} > 20\text{ GeV}$ and $|\eta| < 2.4$. A cut on the transverse mass of the W boson, $M_T < 100\text{ GeV}$, is required to select events containing a $W \to \mu\nu$ decay and to suppress potential signal events from being present in the $\mu+$jets sample.

Since both $\mu+$jets and $\tau_h+$jets production arise from the same underlying process, the hadronic component of the events is expected to be the same aside from the response of the detector to a muon or $\tau_h$. The muon $p_T$ is smeared by response template distributions derived for a hadronically-decaying $\tau$ lepton to correct the leptonic part of the event. The response templates are derived using $t\bar{t}$ and W+jets MC by comparing the true $\tau$ lepton $p_T$ with the reconstructed $\tau_h$ jet $p_T$. The kinematic variables of the event are recalculated with this $\tau_h$ jet, and the search selections are applied. The probability to mistag a $\tau_h$ jet as a $b$ jet is significant and affects the $N_b$ distribution of $\tau_h$ background events. This effect is taken into account in the same way as in Ref. [28].

The $\tau_h$ background prediction is calculated as a sum over all events in the $\mu+$jets control sample weighted by the $\tau_h$ response. Additional corrections are applied and include the branching fraction ratio $B(W \to \tau_h)/B(W \to \mu) = 0.65$, the muon reconstruction/identification efficiency and the muon isolation efficiency, the muon acceptance, the $M_T$ selection efficiency, the contamination in the control sample from muons from $\tau$ decays, the isolated track veto efficiency, the $\tau_h$ contribution that overlaps with the lost-lepton prediction due to contamination of dileptonic events in the control sample, and the trigger efficiency. The muon reconstruction, identification, and isolation efficiency are the same as used for the lost-lepton background determination.
The main systematic uncertainty is derived from a closure test comparing the \( \tau_h \) background in the search regions as predicted by applying the \( \tau_h \) background determination procedure to the simulated muon control sample to the expectation obtained directly from simulation. The result of the closure test is shown in the lower plot of Fig. 5. A closure uncertainty of 2–35% depending on the search bin, becoming as large as 66% in a few bins, is included as a systematic uncertainty in the \( \tau_h \) background prediction. Additional systematic uncertainties are evaluated for each of the ingredients in the prediction, which arise from uncertainties in the following sources: the \( \tau_h \) response template (up to 3%), the muon reconstruction and isolation efficiency (2.3%), the acceptance due to uncertainties in the PDFs (up to 4%), the b-mistag rate of the \( \tau_h \) jet (up to 24%), the \( M_T \) selection efficiency due to uncertainties in the \( \mathcal{E}_T \) scale (up to 2.5%), the efficiency of the isolated track veto (up to 30%), contamination from lost leptons (3.5%), and the trigger efficiency (up to 0.6%).

4.3 Estimation of the \( Z \to \nu\nu \) background

The \( Z \to \nu\nu \) background is derived using simulated \( Z \to \nu\nu \) events that have been corrected for observed differences between data and simulation. Each simulated event is weighted using two scale factors, \( R_{\text{norm}} \) and \( S_{DY}(N_j) \), that correct the normalization of the simulation and the shape of the simulated \( N_j \) distribution, respectively. Both scale factors are calculated in a dimuon control region including events with two muons, with \( 81 < m_{\mu\mu} < 101 \text{ GeV} \), and no muon or isolated track vetoes. In this region the two muons are treated as if they were neutrinos.

The first scale factor, \( R_{\text{norm}} = 0.783 \pm 0.065 \), is derived in a dimuon control region in data to which the same selection as the search region pre-selection has been applied, apart from the muon requirement and without any requirements on b-tagged jets. The scale factor is computed by comparing the expected event yield in this region in the DY simulation with the observed event yield in data after subtraction of the other SM processes.

The second scale factor, \( S_{DY} \), depends on the number of jets \( (N_j) \) in the event and is derived in a loose dimuon control region in which the signal region requirements on \( \mathcal{E}_T, N_t \) and \( M_{T_2} \) are removed, and the \( H_T \) requirement is relaxed to \( H_T > 200 \text{ GeV} \). The \( S_{DY} \) scale factor is derived for each \( N_j \) bin as the ratio between the data, with non-DY backgrounds subtracted, and the DY simulation. Its value ranges between 0.6 and 1.1, depending on the \( N_j \) bin. The \( N_b \) and \( \mathcal{E}_T \) distributions in this loose control region after applying the \( S_{DY}(N_j) \) scale factor are shown in Fig. 6. The \( N_b \) distribution agrees very well between data and simulation, whereas some discrepancies remain for the \( \mathcal{E}_T \) distribution.

The systematic uncertainties for the \( Z \to \nu\nu \) background prediction can be divided in two broad categories: those associated with the use of MC simulation and those specifically associated with the background prediction method. The first category includes uncertainties from PDF and renormalization/factorization scale choices (1–10%), jet and \( \mathcal{E}_T \) energy scale uncertainties (2–80% with one bin up to 150%), b tag scale factor uncertainties (1–8%), trigger efficiency uncertainties (1%), and MC statistical uncertainty (3–80%). The second category includes uncertainties from the method used to determine \( R_{\text{norm}} \) (8%) and \( S_{DY}(N_j) \), and uncertainties based on the residual shape disagreement between data and DY+jets simulation in the loose dimuon control region. The uncertainties associated with \( S_{DY} \) are the dominant uncertainties and are related to residual shape uncertainties (after applying the \( S_{DY} \) scale factor) in the search region variables \( \mathcal{E}_T, M_{T_2}, N_b \) and \( N_t \). These uncertainties are evaluated in the loose control region with the additional requirement that \( N_t \geq 1 \) so that \( M_{T_2} \) is well defined. The resulting shift of the central value of the search bin predictions is used as the systematic uncer-
Figure 5: (upper plot) The lost-lepton background in the 59 search regions of the analysis as determined directly from $t\bar{t}$, single top quark, and W+jets simulation (points) and as predicted by applying the lost-lepton background determination procedure to the simulated muon control sample (histograms). The lower panel shows the same results following division by the predicted value. Only statistical uncertainties are shown. (lower plot) The corresponding simulated results for the background from hadronically-decaying $\tau$ leptons. For both plots, vertical lines indicate search regions with different $N_t$, $N_b$, and $M_{T^2}$ values. Within each $(N_t, N_b, M_{T^2})$ region, the bins indicate the different $E_T$ selections, as defined in Fig. 4.
4 Background estimation

Figure 6: $N_b$ (left) and $E_T$ (right) distribution in data and simulation in the loose dimuon control region after applying the $S_{DY}(N_j)$ scale factor to the simulation. The lower panels show the ratio between data and simulation. Only statistical uncertainties are shown. The values in parentheses in the legend indicate the integrated yield for each given process.

The dominant sources of systematic uncertainty in the QCD multijet prediction are the statistical uncertainties in the $T_{QCD}$ factors (30–76%) and the uncertainties from residual shape disagreements and ranges between 20% and 80% depending on the search bin. The statistical uncertainties in the ratios between data and simulation, as well as in $S_{DY}$, are also included as a 7–50% systematic uncertainty in the prediction.

4.4 Estimation of the QCD multijet background

The procedure to predict the QCD multijet background starts by selecting a signal-depleted, QCD multijet-rich data control sample. This control sample is defined by inverting the pre-selection requirements on $\Delta\phi(E_T,j_{1,2,3})$ and subtracting contributions of other SM backgrounds, such as $tt$, $W+jets$, and $Z+jets$. The same methods as described in the previous sections are used to estimate the contributions from lost leptons and $\tau_h$, but applied to this QCD multijet-enriched control region. Simulation is used to estimate the contribution from $Z \rightarrow \nu\nu$, since it is expected to be small. Following that, a translation factor, partly determined by data and partly by simulation, is used to convert the number of QCD multijet events measured in the data control region into a QCD multijet prediction for each search region bin. The translation factor, $T_{QCD}$, is computed as the simulated ratio between the signal region and the inverted-$\Delta\phi$ control region, in bins of $E_T$ and $M_{T2}$ where the bin boundaries follow those of the signal bins. The $T_{QCD}$ shape is kept from the simulation measurement, while its value is normalized to a data measurement in a sideband of the pre-selection region, defined by the requirement $150 < E_T < 200$ GeV, where the amount of data is sufficiently large to make an accurate measurement.

A closure test is performed in simulation to assess the performance of the method. In this closure test the expectation for the signal region event yields as obtained directly from the QCD multijet simulation is compared to the prediction obtained by applying the QCD multijet background prediction procedure to simulated event samples. The result of this test is shown in Fig. 7, and any observed non-closure is taken into account as a systematic uncertainty in the QCD multijet prediction.
from the closure test (17–95%, with a few bins up to 800%).

Figure 7: The QCD multijet background in the 59 search regions of the analysis as determined directly from QCD multijet simulation (points) and as predicted by applying the QCD multijet background determination procedure to simulated event samples in the inverted-Δφ control region (histograms). The lower panel shows the same results following division by the predicted value. Only statistical uncertainties are shown. The labeling of the search regions is the same as in Fig. 5.

5 Results and interpretation

The predicted number of SM background events and the number of events observed in data for each of the search regions defined in Section 3.3 are summarized in Fig. 8 and Tables 1–2. Typically, the most significant background across the search regions comes from the SM t ¯t or W boson production, where either W → ℓν and the lepton (ℓ = e, µ) is not detected or W → τν and the τ lepton decays hadronically. Generally, the next largest contribution comes from Z → νν production in association with jets (including heavy-flavor jets) in which the neutrino pair gives large E_T and the top quark tagging conditions are satisfied by an accidental combination of the jets. For search bins with very high E_T requirements, the Z → νν background can become the dominant background. The QCD multijet contribution and the contribution from rare SM processes are sub-dominant across all bins. The largest rare SM process contribution (though still small) comes from t ¯tZ with the Z boson decaying into a pair of neutrinos. For these rare processes we rely on simulation to predict the contribution of events to each search region bin. The t ¯tZ simulation is additionally validated using a trilepton control sample in data, and the 30% statistical uncertainty in this data measurement is propagated to the t ¯tZ prediction for each search region bin.

In addition to the finely segmented search regions of Fig. 8, we provide the background prediction and observed data in aggregate search regions, using groups of bins relevant for the three interesting signal topologies as described in Section 3.1. The results for these aggregate regions are reported in Table 3. The first region corresponds to the preselection and is, together with the
second region, sensitive to direct top squark production models with compressed mass spectra. Aggregate regions 2–5 target direct top squark production with a larger mass splitting between top squark and LSP, and regions 5–7 are sensitive to models with gluinos.

Figure 8: Observed event yields in data (black points) and predicted SM background (filled solid area) for the 59 search bins. The lower panel shows the ratio of data over total background prediction in each search bin. Only statistical uncertainties of observed data are propagated to the ratio. The shaded bands indicate uncertainties of total predictions with dark grey for systematic uncertainty and light grey for statistical uncertainty.

The statistical interpretation of the results in terms of exclusion limits for the signal models considered is based on a binned likelihood fit to the observed data, taking into account the predicted background and expected signal yields with their uncertainties in each bin. The extraction of exclusion limits is based on a modified frequentist approach [71] using a profile likelihood ratio as the test statistic. Signal models for which the 95% upper limit on the production cross section falls below the theoretical cross section (based on NLO+NLL calculations [54]) are considered to be excluded by the analysis.

The uncertainties in the signal modeling are determined per search region bin and include the following sources: simulation sample size (up to 100%), luminosity determination (6.2%), lepton and isolated track veto (up to 7%), b tag efficiency corrections used to scale simulation to data (up to 17%), trigger efficiency (< 1%), QCD renormalization and factorization scales (up to 3%), initial-state radiation (up to 45%), jet energy scale corrections (up to 33%), and the modeling of the fast simulation compared with the full simulation for top quark reconstruction and mistagging (up to 19%). All these uncertainties, apart from those arising from the simulation sample size, are treated as fully correlated between search bins when computing exclusion limits. Potential contamination of signal events in the single-lepton control regions is taken into account for each signal model considered in the interpretation. The potential contamination in
Table 1: Observed yields from the data compared to the total background predictions for the search bins. Uncertainties are listed as ± statistical ± systematic.

| $N_t$ | $N_b$ | $M_{T2}$ [GeV] | $E_T$ [GeV] | Data | Predicted background |
|-------|-------|----------------|-------------|------|----------------------|
| 1     | 1     | 200–350        | 200–350     | 582  | 574 $^{+15+48}_{-15-45}$ |
| 1     | 1     | 200–350        | 350–500     | 61   | 63 $^{+5+8}_{-5-7}$     |
| 1     | 1     | 200–350        | 500–650     | 6    | 11 $^{+2+3}_{-2-2}$     |
| 1     | 1     | 200–350        | 650+        | 1    | 3.5 $^{+1.8+1.0}_{-1.1-0.9}$ |
| 1     | 1     | 350–450        | 200–350     | 68   | 58 $^{+5+8}_{-5-8}$     |
| 1     | 1     | 350–450        | 350–500     | 34   | 33 $^{+3+7}_{-3-6}$     |
| 1     | 1     | 350–450        | 500–650     | 4    | 6 $^{+2+2}_{-1-2}$      |
| 1     | 1     | 350–450        | 650+        | 1    | 2.4 $^{+1.4+2.1}_{-0.9-1.1}$ |
| 1     | 2     | 200–350        | 200–350     | 391  | 377 $^{+13+29}_{-13-27}$ |
| 1     | 2     | 200–350        | 350–500     | 43   | 38 $^{+4+4}_{-4-4}$     |
| 1     | 2     | 200–350        | 500–650     | 3    | 3.2 $^{+1.6+1.2}_{-0.6-1.1}$ |
| 1     | 2     | 200–350        | 650+        | 0    | 1.0 $^{+0.9+0.6}_{-0.4-0.3}$ |
| 1     | 2     | 350–450        | 200–350     | 25   | 27 $^{+5+4}_{-4-4}$     |
| 1     | 2     | 350–450        | 350–500     | 16   | 14 $^{+2+2}_{-2-2}$     |
| 1     | 2     | 350–450        | 500–650     | 3    | 1.6 $^{+2.0+0.4}_{-0.2-0.4}$ |
| 1     | 2     | 350–450        | 650+        | 0    | 1.7 $^{+2.2+0.6}_{-0.8-0.6}$ |
| 1     | 2     | 450+           | 200–500     | 1    | 4.3 $^{+1.6+1.3}_{-0.7-1.3}$ |
| 1     | 2     | 450+           | 500–650     | 2    | 4.0 $^{+1.9+1.7}_{-0.9-1.7}$ |
| 1     | 2     | 450+           | 650+        | 5    | 1.6 $^{+1.1+1.0}_{-0.2-1.0}$ |
| 1     | 3+    | 200–350        | 200–350     | 71   | 72 $^{+6+9}_{-6-9}$     |
| 1     | 3+    | 200–350        | 350–500     | 8    | 8 $^{+2+6}_{-2-1}$     |
| 1     | 3+    | 200–350        | 500+        | 4    | 0.4 $^{+1.5+0.1}_{-0.1-0.1}$ |
| 1     | 3+    | 350+           | 200–350     | 4    | 8 $^{+3+6}_{-3-1}$     |
| 1     | 3+    | 350+           | 350+        | 0    | 5.3 $^{+2.0+3.4}_{-1.1-0.9}$ |
Table 2: Continued table: observed yields from the data compared to the total background predictions for the search bins. Uncertainties are listed as ± statistical ± systematic.

| $N_t$ | $N_b$ | $M_{T2}$ [GeV] | $E_T$ [GeV] | Data   | Predicted background |
|-------|-------|----------------|-------------|--------|----------------------|
| 2     | 1     | 200–350       | 200–350     | 188    | 164 $^{+6}_{-6}$ $^{+16}_{-16}$ |
| 2     | 1     | 200–350       | 350–500     | 14     | 14 $^{+2}_{-2}$ $^{+2}_{-2}$ |
| 2     | 1     | 200–350       | 500–650     | 4      | 1.7 $^{+1.2}_{-0.6}$ $^{+0.8}_{-0.7}$ |
| 2     | 1     | 200–350       | 650+        | 0      | 0.12 $^{+0.76}_{-0.26}$ $^{+0.22}_{-0.06}$ |
| 2     | 1     | 350–450       | 200–350     | 23     | 21 $^{+3}_{-2}$ $^{+3}_{-3}$ |
| 2     | 1     | 350–450       | 350–500     | 9      | 6.4 $^{+1.6}_{-1.0}$ $^{+1.1}_{-1.1}$ |
| 2     | 1     | 350–450       | 500–650     | 3      | 1.8 $^{+1.7}_{-0.7}$ $^{+0.3}_{-0.3}$ |
| 2     | 1     | 350–450       | 650+        | 1      | 0.31 $^{+1.15}_{-0.13}$ $^{+0.10}_{-0.10}$ |
| 2     | 1     | 450+          | 200–350     | 1      | 1.2 $^{+1.1}_{-0.3}$ $^{+0.8}_{-0.8}$ |
| 2     | 1     | 450+          | 350–500     | 3      | 5 $^{+1}_{-1}$ $^{+2}_{-2}$ |
| 2     | 1     | 450+          | 500–650     | 6      | 2.8 $^{+1.6}_{-0.8}$ $^{+0.9}_{-0.9}$ |
| 2     | 1     | 450+          | 650+        | 4      | 4 $^{+2}_{-1}$ $^{+2}_{-2}$ |
| 2     | 2     | 200–350       | 200–350     | 90     | 103 $^{+6}_{-6}$ $^{+9}_{-8}$ |
| 2     | 2     | 200–350       | 350–500     | 6      | 10 $^{+3}_{-2}$ $^{+1}_{-1}$ |
| 2     | 2     | 200–350       | 500+        | 1      | 1.5 $^{+1.2}_{-0.6}$ $^{+0.3}_{-0.3}$ |
| 2     | 2     | 350–450       | 200–350     | 9      | 11 $^{+2}_{-1}$ $^{+1}_{-1}$ |
| 2     | 2     | 350–450       | 350–500     | 5      | 4.5 $^{+1.5}_{-1.0}$ $^{+0.6}_{-0.5}$ |
| 2     | 2     | 350–450       | 500+        | 2      | 1.2 $^{+1.4}_{-0.7}$ $^{+0.3}_{-0.3}$ |
| 2     | 2     | 450+          | 200–350     | 0      | 1.6 $^{+1.2}_{-0.6}$ $^{+0.6}_{-0.6}$ |
| 2     | 2     | 450+          | 350–500     | 2      | 2.5 $^{+1.8}_{-1.1}$ $^{+0.4}_{-0.4}$ |
| 2     | 2     | 450+          | 500+        | 1      | 1.0 $^{+1.5}_{-0.2}$ $^{+0.4}_{-0.4}$ |
| 2     | 3     | 200–350       | 200–350     | 19     | 23 $^{+3}_{-3}$ $^{+2}_{-2}$ |
| 2     | 3     | 200–350       | 350+        | 1      | 1.8 $^{+1.0}_{-0.6}$ $^{+0.6}_{-0.6}$ |
| 2     | 3     | 350+          | 200–350     | 2      | 1.5 $^{+1.3}_{-0.5}$ $^{+0.3}_{-0.3}$ |
| 2     | 3     | 350+          | 350+        | 1      | 1.5 $^{+1.2}_{-0.5}$ $^{+0.4}_{-0.4}$ |
| 3+    | 1     | 200+          | 200–350     | 4      | 6 $^{+2}_{-1}$ $^{+2}_{-2}$ |
| 3+    | 1     | 200+          | 350+        | 0      | 0.5 $^{+0.9}_{-0.2}$ $^{+0.2}_{-0.2}$ |
| 3+    | 2     | 200+          | 200–350     | 6      | 3.2 $^{+1.3}_{-1.0}$ $^{+0.8}_{-0.4}$ |
| 3+    | 2     | 200+          | 350+        | 2      | 0.27 $^{+0.78}_{-0.15}$ $^{+0.08}_{-0.07}$ |
| 3+    | 3     | 200+          | 200–350     | 2      | 0.8 $^{+1.1}_{-0.4}$ $^{+0.2}_{-0.2}$ |
| 3+    | 3     | 200+          | 350+        | 0      | 0.3 $^{+0.7}_{-0.2}$ $^{+1.1}_{-0.3}$ |
Table 3: Observed number of events and background predictions in the aggregate search regions as defined in the text. A plus-sign is used as shorthand for the listed value or more. Uncertainties are listed as ± statistical ± systematic.

| Search Bin | $N_t$ | $N_b$ | $M_{T2}$ [GeV] | $E_T$ [GeV] | Data | Predicted background |
|------------|-------|-------|----------------|-------------|------|---------------------|
| 0          | 1+    | 1+    | 200+           | 200+        | 1790 | 1742 $^{+26}_{-26}$ $^{+199}_{-26}$ |
| 1          | 2+    | 1+    | 200–350        | 200–350     | 309  | 299 $^{+9}_{-9}$ $^{+36}_{-9}$ $^{+7}_{-9}$ $^{+9}_{-9}$ $^{+7}_{-9}$ |
| 2          | 1+    | 2+    | 350+           | 350+        | 39   | $^{+4}_{-3}$ $^{+7}_{-7}$ |
| 3          | 1+    | 2+    | 450+           | 650+        | 6    | $^{+11}_{-0.2}$ $^{+13}_{-0.2}$ $^{+9}_{-1.3}$ $^{+9}_{-1.3}$ |
| 4          | 2+    | 2+    | 350+           | 350+        | 12   | $^{+2.1}_{-1.7}$ $^{+1.4}_{-1.4}$ $^{+0.4}_{-1.7}$ $^{+0.4}_{-1.7}$ |
| 5          | 2+    | 2+    | 450+           | 500+        | 1    | $^{+15}_{-0.3}$ $^{+0.4}_{-0.4}$ $^{+0.4}_{-0.4}$ |
| 6          | 3+    | 2+    | 200+           | 350+        | 2    | $^{+0.5}_{-0.3}$ $^{+1.2}_{-1.2}$ $^{+0.5}_{-0.3}$ $^{+1.2}_{-1.2}$ |
| 7          | 1+    | 3+    | 350+           | 350+        | 1    | $^{+19}_{-1.2}$ $^{+2.2}_{-1.2}$ $^{+19}_{-1.2}$ $^{+2.2}_{-1.2}$ |

the dilepton and inverted-$\Delta\phi$ region is negligible.

Figure 9 shows the 95% CL exclusion limits obtained for simplified models in the T2tt scenario. Using the 12.9 fb$^{-1}$ dataset, top squark masses up to 910 GeV and LSP masses up to 400 GeV are excluded. The results improve significantly compared to analyses at 13 TeV using 2015 data, which excluded top squark masses up to 760 GeV and LSP masses up to 260 GeV. Figure 10 and Figure 11 show the 95% CL exclusion limits obtained for simplified models in the T1tttt and T5ttcc scenarios, respectively. Using the 12.9 fb$^{-1}$ dataset, gluino masses up to 1780 GeV and LSP masses up to 1020 GeV are probed for the T1tttt model, whereas gluino masses up to 1700 GeV and LSP masses up to 1060 GeV are probed for the T5ttcc model. These results significantly extend the reach compared to analyses at 13 TeV using 2015 data, which excluded gluino masses up to about 1550 (1450) GeV and LSP masses up to about 900 (820) GeV for the T1tttt (T5ttcc) model. The search bins with $N_t \geq 3$ give this analysis extra strength for T1tttt models with a high gluino and LSP mass, since they allow suppressing SM backgrounds while keeping a low $E_T$ threshold.

6 Summary

The results of a search for direct and gluino-mediated top squark production in final states including top-like objects have been presented. The search uses all-hadronic events with at least four jets and large $E_T$, selected from a data sample corresponding to an integrated luminosity of 12.9 fb$^{-1}$ collected in proton-proton collisions at a center-of-mass energy of 13 TeV with the CMS detector during 2016. A set of search regions is defined based on $E_T$, $M_{T2}$, the number of top-like objects, and the number of b-tagged jets. No statistically significant excess of events above the expected standard model background is observed, and exclusion limits are set at the 95% confidence level for simplified models of direct top squark pair production and gluino pair production where the gluinos decay to final states including top quarks. For simplified models of pair production of top squarks, which decay to a top quark and a neutralino, top squark masses up to 910 GeV and neutralino masses up to 400 GeV are excluded at 95% CL. For models with gluino pair production, gluino masses up to 1700 (1780) GeV and neutralino masses up to 1060 (1020) GeV are excluded for the T5ttcc (T1tttt) models.
Figure 9: Exclusion limits at 95% CL for simplified models of top squark pair production in the T2tt scenario. The solid black curves represent the observed exclusion contours with respect to NLO+NLL cross section calculations [54] and the corresponding ±1 standard deviations. The dashed red curves indicate the expected exclusion contour and the ±1 standard deviations with experimental uncertainties.
Figure 10: Exclusion limits at 95% CL for simplified models of top squarks produced through decays of gluino pairs in the T1tttt scenario. The solid black curves represent the observed exclusion contours with respect to NLO+NLL cross section calculations [54] and the corresponding ±1 standard deviations. The dashed red curves indicate the expected exclusion contour and the ±1 standard deviations with experimental uncertainties.
Figure 11: Exclusion limits at 95% CL for simplified models of top squarks produced through decays of gluino pairs in the T5ttcc scenario. The solid black curves represent the observed exclusion contours with respect to NLO+NLL cross section calculations [54] and the corresponding ±1 standard deviations. The dashed red curves indicate the expected exclusion contour and the ±1 standard deviations with experimental uncertainties.
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References

[1] R. Barbieri, S. Ferrara, and C. A. Savoy, “Gauge Models with Spontaneously Broken Local Supersymmetry”, Phys. Lett. B119 (1982) 343, doi:10.1016/0370-2693(82)90685-2.

[2] J. Wess and B. Zumino, “Supergauge transformations in four-dimensions”, Nucl. Phys. B 70 (1974) 39, doi:10.1016/0550-3213(74)90355-1.

[3] Y. A. Gol’fand and E. P. Likhtman, “Extension of the algebra of Poincaré group generators and violation of P invariance”, JETP Lett. 13 (1971) 323.

[4] D. V. Volkov and V. P. Akulov, “Possible universal neutrino interaction”, JETP Lett. 16 (1972) 438.
[5] A. H. Chamseddine, R. L. Arnowitt, and P. Nath, “Locally supersymmetric grand unification”, *Phys. Rev. Lett.* 49 (1982) 970, doi:10.1103/PhysRevLett.49.970.

[6] G. L. Kane, C. F. Kolda, L. Roszkowski, and J. D. Wells, “Study of constrained minimal supersymmetry”, *Phys. Rev. D* 49 (1994) 6173, doi:10.1103/PhysRevD.49.6173, arXiv:hep-ph/9312272.

[7] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, *Nucl. Phys. B* 90 (1975) 104, doi:10.1016/0550-3213(75)90636-7.

[8] L. J. Hall, J. D. Lykken, and S. Weinberg, “Supergravity as the messenger of supersymmetry breaking”, *Phys. Rev. D* 27 (1983) 2359, doi:10.1103/PhysRevD.27.2359.

[9] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* 3 (1971) 2415, doi:10.1103/PhysRevD.3.2415.

[10] J. Wess and B. Zumino, “Supergauge Transformations in Four-Dimensions”, *Nucl. Phys.* B70 (1974) 39, doi:10.1016/0550-3213(74)90355-1.

[11] G. R. Farrar and P. Fayet, “Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry”, *Phys. Lett.* B76 (1978) 575, doi:10.1016/0370-2693(78)90858-4.

[12] J. L. Feng, “Dark Matter Candidates from Particle Physics and Methods of Detection”, *Ann. Rev. Astron. Astrophys.* 48 (2010) 495, doi:10.1146/annurev-astro-082708-101659, arXiv:1003.0904.

[13] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* 716 (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[14] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* 716 (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[15] S. Dimopoulos and S. Raby, “Supercolor”, *Nucl. Phys. B* 192 (1981) 353, doi:10.1016/0550-3213(81)90430-2.

[16] E. Witten, “Dynamical Breaking of Supersymmetry”, *Nucl. Phys. B* 188 (1981) 513, doi:10.1016/0550-3213(81)90066-7.

[17] M. Dine, W. Fischler, and M. Srednicki, “Supersymmetric Technicolor”, *Nucl. Phys. B* 189 (1981) 575, doi:10.1016/0550-3213(81)90582-4.

[18] S. Dimopoulos and H. Georgi, “Softly Broken Supersymmetry and SU(5)”, *Nucl. Phys. B* 193 (1981) 150, doi:10.1016/0550-3213(81)90522-8.

[19] R. K. Kaul and P. Majumdar, “Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories”, *Nucl. Phys. B* 199 (1982) 36, doi:10.1016/0550-3213(82)90565-X.

[20] S. Dimopoulos and G. Giudice, “Naturalness constraints in supersymmetric theories with non-universal soft terms”, *Phys. Lett. B* 357 (1995) 573, doi:10.1016/0370-2693(95)00961-J.
[21] N. Sakai, “Naturalness in supersymmetric GUTS”, Z. Phys. C 11 (1981) 153, doi:10.1007/BF01573998.

[22] M. Papucci, J. T. Ruderman, and A. Weiler, “Natural SUSY Endures”, JHEP 09 (2012) 035, doi:10.1007/JHEP09(2012)035, arXiv:1110.6926.

[23] C. Brust, A. Katz, S. Lawrence, and R. Sundrum, “SUSY, the Third Generation and the LHC”, JHEP 03 (2012) 103, doi:10.1007/JHEP03(2012)103, arXiv:1110.6670.

[24] J. L. Feng, “Naturalness and the Status of Supersymmetry”, Ann. Rev. Nucl. Part. Sci. 63 (2013) 351, doi:10.1146/annurev-nucl-102010-130447, arXiv:1302.6587.

[25] A. Delgado et al., “The light stop window”, Eur. Phys. J. C 73 (2013) 2370, doi:10.1140/epjc/s10052-013-2370-5, arXiv:1212.6847.

[26] L. Evans and P. Bryant (editors), “LHC Machine”, JINST 3 (2008) S08001, doi:10.1088/1748-0221/3/08/S08001.

[27] ATLAS Collaboration, “Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector”, arXiv:1606.03903.

[28] CMS Collaboration, “Search for direct production of top squark pairs decaying to all-hadronic final states in $pp$ collisions at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-SUS-16-007, CERN, Geneva, 2016.

[29] CMS Collaboration, “Search for direct top squark pair production in the single lepton final state at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-SUS-16-002, CERN, Geneva, 2016.

[30] ATLAS Collaboration, “Search for pair production of gluinos decaying via stop and bottom in events with $b$-jets and large missing transverse momentum in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, arXiv:1605.09318.

[31] CMS Collaboration, “Search for supersymmetry in the multijet and missing transverse momentum final state in $pp$ collisions at 13 TeV”, Phys. Lett. B 758 (2016) 152, doi:10.1016/j.physletb.2016.05.002, arXiv:1602.06581.

[32] CMS Collaboration, “Search for new physics with the MT2 variable in all-jets final states produced in $pp$ collisions at $\sqrt{s} = 13$ TeV”, arXiv:1603.04053. Submitted to JHEP.

[33] C. Lester and D. Summers, “Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders”, Phys. Lett. B463 (1999) 99–103, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349.

[34] A. Barr, C. Lester, and P. Stephens, “$m(T2)$: The Truth behind the glamour”, J. Phys. G29 (2003) 2343–2363, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226.

[35] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[36] CMS Collaboration, “Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_T$”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.

[37] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_t$ jet clustering algorithm”, JHEP 0804:063 (2008) doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
[38] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2007) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

[39] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[40] CMS Collaboration, “Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS”, *JINST* **6** (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[41] CMS Collaboration, “Jet Performance in pp Collisions at 7 TeV”, CMS Physics Analysis Summary CMS-PAS-JME-10-003, CERN, Geneva, 2010.

[42] CMS Collaboration, “Identification of b quark jets at the CMS Experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, CERN, Geneva, 2016.

[43] J. Alwall et al., “MadGraph5: going beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.

[44] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[45] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[46] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[47] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[48] E. Re, “Single-top Wt-channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J.* **C71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.

[49] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[50] T. Sjostrand, S. Mrenna, and P. Z. Skands, “A Brief Introduction to PYTHIA 8.1”, *Comput. Phys. Commun.* **178** (2008) 852–867, doi:10.1016/j.cpc.2008.01.036, arXiv:0710.3820.

[51] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J.* **C76** (2016), no. 3, 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[52] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[53] S. Abdullin et al., “The fast simulation of the CMS detector at LHC”, *J. Phys. Conf. Ser.* **331** (2011) 032049, doi:10.1088/1742-6596/331/3/032049.
[54] C. Borschensky et al., “Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and $100$ TeV”, *Eur. Phys. J.* C74 (2014), no. 12, 3174, doi:10.1140/epjc/s10052-014-3174-y, arXiv:1407.5066.

[55] M. Czakon and A. Mitov, “Top++: A Program for the Calculation of the Top-Pair Cross-Section at Hadron Colliders”, *Comput. Phys. Commun.* 185 (2014) 2930, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.

[56] P. Kant et al., “HatHor for single top-quark production: Updated predictions and uncertainty estimates for single top-quark production in hadronic collisions”, *Comput. Phys. Commun.* 191 (2015) 74–89, doi:10.1016/j.cpc.2015.02.001, arXiv:1406.4403.

[57] M. Aliev et al., “HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR”, *Comput. Phys. Commun.* 182 (2011) 1034–1046, doi:10.1016/j.cpc.2010.12.040, arXiv:1007.1327.

[58] T. Gehrmann et al., “$W^+W^-$ Production at Hadron Colliders in Next to Next to Leading Order QCD”, *Phys. Rev. Lett.* 113 (2014), no. 21, 212001, doi:10.1103/PhysRevLett.113.212001, arXiv:1408.5243.

[59] J. M. Campbell and R. K. Ellis, “An Update on vector boson pair production at hadron colliders”, *Phys. Rev.* D60 (1999) 113006, doi:10.1103/PhysRevD.60.113006, arXiv:hep-ph/9905386.

[60] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, *JHEP* 07 (2011) 018, doi:10.1007/JHEP07(2011)018, arXiv:1105.0020.

[61] Y. Li and F. Petriello, “Combining QCD and electroweak corrections to dilepton production in FEWZ”, *Phys. Rev.* D86 (2012) 094034, doi:10.1103/PhysRevD.86.094034, arXiv:1208.5967.

[62] CMS Collaboration, “Identification of b quark jets at the CMS Experiment in the LHC Run 2”, CMS Physics Analysis Summary CMS-PAS-BTV-15-001, CERN, 2016.

[63] J. Alwall, P. Schuster, and N. Toro, “Simplified Models for a First Characterization of New Physics at the LHC”, *Phys. Rev.* D79 (2009) 075020, doi:10.1103/PhysRevD.79.075020, arXiv:0810.3921.

[64] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, “Model-Independent Jets plus Missing Energy Searches”, *Phys. Rev.* D79 (2009) 015005, doi:10.1103/PhysRevD.79.015005, arXiv:0809.3264.

[65] LHC New Physics Working Group Collaboration, “Simplified Models for LHC New Physics Searches”, *J. Phys.* G39 (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.

[66] D. Alves, E. Izaguirre, and J. G. Wacker, “Where the sidewalk ends: jets and missing energy search strategies for the 7 TeV LHC”, *JHEP* 10 (2011) 012, doi:10.1007/JHEP10(2011)012, arXiv:1102.5338.

[67] CMS Collaboration, “Interpretation of searches for supersymmetry with simplified models”, *Phys. Rev. D* 88 (2013) 052017, doi:10.1103/PhysRevD.88.052017, arXiv:1301.2175.
[68] D. E. Kaplan, K. Rehermann, M. D. Schwartz, and B. Tweedie, “Top Tagging: A Method for Identifying Boosted Hadronically Decaying Top Quarks”, *Phys. Rev. Lett.* **101** (2008) 142001, doi:10.1103/PhysRevLett.101.142001, arXiv:0806.0848.

[69] T. Plehn, M. Spannowsky, M. Takeuchi, and D. Zerwas, “Stop Reconstruction with Tagged Tops”, *JHEP* **1010** (2010) 078, doi:10.1007/JHEP10(2010)078, arXiv:1006.2833.

[70] D. E. Kaplan, K. Rehermann, and D. Stolarski, “Searching for Direct Stop Production in Hadronic Top Data at the LHC”, *JHEP* **1207** (2012) 119, doi:10.1007/JHEP07(2012)119, arXiv:1205.5816.

[71] ATLAS and CMS Collaborations, “Procedure for the LHC Higgs boson search combination in summer 2011”, Technical Report ATL-PHYS-PUB-2011-011, CMS NOTE-2011/005, CERN, Geneva, Aug, 2011.