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Search for new long-lived particles at $\sqrt{s} = 13$ TeV

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ABSTRACT

A search for long-lived particles was performed with data corresponding to an integrated luminosity of 2.6 fb^{-1} collected at a center-of-mass energy of 13 TeV by the CMS experiment in 2015. The analysis exploits two customized topological trigger algorithms, and uses the multiplicity of displaced jets to search for the presence of a signal decay occurring at distances between 1 and 1000 mm. The results can be interpreted in a variety of different models. For pair-produced long-lived particles decaying to two b quarks and two leptons with equal decay rates between lepton flavors, cross sections larger than 2.5 fb are excluded for proper decay lengths between 70–100 mm for a long-lived particle mass of 1130 GeV at 95% confidence. For a specific model of pair-produced, long-lived top squarks with R-parity violating decays to a b quark and a lepton, masses below 550–1130 GeV are excluded at 95% confidence for equal branching fractions between lepton flavors, depending on the squark decay length. This mass bound is the most stringent to date for top squark proper decay lengths greater than 3 mm.

1. Introduction

The observation of physics beyond the standard model (BSM) is one of the main objectives of the ATLAS and CMS experiments at the CERN LHC. With no signal yet observed, these experiments have placed stringent bounds on BSM models. The majority of these searches focus on particles with lab frame decay lengths of $c\tau < 1$ mm and incorporate selection requirements that reject longer-lived particle decays. This leaves open the possibility that long-lived particles could be produced but remain undetected. The present analysis exploits information originating from the CMS calorimeters to reconstruct jets and measure their energies. The information from reconstructed tracks, in particular the transverse impact parameter, is used to discriminate the signal of a jet whose origin is displaced with respect to the primary vertex, from the background of ordinary multijet events. The analysis is performed on data from proton–proton collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector in 2015. The data set corresponds to an integrated luminosity of 2.6 fb^{-1}. Results for similar signatures at $\sqrt{s} = 8$ TeV have been reported by ATLAS [1–3], CMS [4], and LHCb [5,6]. In this Letter, we present a new, more general approach to searching for long-lived particles decaying to combinations of jets and leptons, which is inclusive in event topology and does not require the reconstruction of a displaced vertex.

2. The CMS detector

The central feature of the CMS apparatus 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 (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles with $|\eta| < 2.5$. It consists of silicon pixels and silicon strip detector modules. The innermost pixel (strip) layer is at a radial distance of 4.3 (44) cm from the beamline.

The ECAL consists of lead tungstate crystals and provides coverage in $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). A preshower detector composed of two planes of silicon sensors interleaved with a total of 3 radiation lengths of lead is located in front of the EE. The inner face of the ECAL is at a radial distance of 129 cm from the beamline.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity and 0.087 radians in azimuth (ϕ). In the η–ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $1.74 < |\eta| < 3.00$, the coverage of the towers increases progressively to a maximum

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of 0.174 in $\Delta\eta$ and $\Delta\phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies and are subsequently used to provide the energies of jets. The inner face of the HCAL is at a radial distance of 179 cm from the beamline.

For each event, jets are clustered from energy deposits in the calorimeters, using the FastJet [7] implementation of the anti-k_T algorithm [8], with the distance parameter 0.4. Tracks that are within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ of a jet are considered to be associated with the jet.

Events of interest are selected using a two-tiered trigger system [9]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

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. [10].

3. Data sets and simulated samples

Events are selected using two dedicated HLT algorithms, designed to identify events with displaced jets. Both algorithms have a requirement on H_T, which is defined as the scalar sum of the transverse momentum p_T of the jets in the event, considering only jets with $p_T > 40$ GeV and $|\eta| < 3.0$. The inclusive algorithm accepts events with $H_T > 500$ GeV and at least two jets, each with $p_T > 40$ GeV, $|\eta| < 2.0$, and no more than two associated prompt tracks. Tracks are classified as prompt if their transverse impact parameter relative to the beam line, IP^{2D}, is less than 1 mm. The exclusive algorithm requires $H_T > 350$ GeV and at least two jets with $p_T > 40$ GeV, $|\eta| < 2.0$, no more than two associated prompt tracks, and at least one associated track with $IP^{2D} > 5\sigma_{IP^{2D}}$, where $\sigma_{IP^{2D}}$ is the calculated uncertainty in IP^{2D}. Data collected by algorithms with identical H_T requirements and no tracking requirements are used to study the performance of the online selection algorithms.

Events are selected offline by requiring at least two jets with $p_T > 60$ GeV and $|\eta| < 2.0$. Two classes of events are considered: events (i) passing the inclusive online algorithm and with $H_T > 650$ GeV and (ii) passing the exclusive online algorithm and with $H_T > 450$ GeV. Combining these two classes of events results in 786 002 unique events. We refer to these events as passing the event selection or simply "Selection" in the efficiency tables.

The main source of background events originates from multijet production. The properties of this background process are studied using a simulated multijet sample, generated with MadGraph5 [11] and interfaced with pythia8 [12] for parton showering and hadronization. The NNPDF 2.3 [13] parton distribution functions (PDFs) are used to model the parton momentum distribution inside the colliding protons. The event simulation includes the effect of additional proton–proton collisions in the same bunch crossing and in bunch crossings nearby in time, referred to as pileup. Simulated samples are reweighted to match the pileup profile observed in data. The detector response is simulated in detail using Geant4 [14].

The analysis is interpreted with a set of benchmark signal models. The Jet-Jet model predicts pair-produced long-lived scalar neutral particles X^0, each decaying to a quark–antiquark pair, where possible pairs include u, d, s, c, and b quarks. The two scalars are produced through a $2 \to 2$ scattering process, mediated by a Z^* propagator, and the decay rate to each flavor is assumed to be the same. The resonance mass m_{X^0} and average proper decay length $c\tau_0$ are varied between 50 and 1500 GeV and between 1 and 2000 mm, respectively. The model resembles hidden valley models that produce long-lived neutral final states [15]. The trigger efficiencies for $m_{X^0} = 300$ GeV and $c\tau_0 = 1, 30$, and 1000 mm are 30%, 81%, and 42%, respectively. For example, the trigger efficiencies are 2%, 14%, and 92% for $c\tau_0 = 30$ mm and $m_{X^0} = 50, 100$, and 1000 GeV respectively. The trigger efficiency is calculated from the total number of events passing only the logical OR of the two trigger paths.

The B-Lepton model contains pair-produced long-lived top squarks in R-parity [16] violating models of supersymmetry (SUSY) [17]. Each top squark decays to one b quark and a lepton, with equal decay rates to each of the three lepton flavors. The resonance mass $m_{\tilde{t}}$ and proper decay length $c\tau_0$ are varied between 300 and 1000 GeV and between 1 and 1000 mm, respectively. For example, the trigger efficiencies for $m_{\tilde{t}} = 300$ GeV and $c\tau_0 = 1, 30$, and 1000 mm are 15%, 41%, and 23%, respectively. The trigger efficiencies are 64%, 71%, and 74% for $c\tau_0 = 30$ mm and $m_{\tilde{t}} = 500, 700$, and 1000 GeV, respectively.

Variations of these models with modified branching fractions are also investigated. The Light-Light model is the Jet-Jet model excluding decays to b quarks (equal decays to lighter quarks) and the B-Muon, B-Electron, and B-Tau models are derived from the B-Lepton model with 100% branching fraction to muons, electrons, and τ leptons, respectively. Both leptonic and hadronic τ lepton decays are included in the B-Tau interpretation. All signal samples are generated with pythia8, with the same configuration as for the multijet sample.

4. Event selection and inclusive displaced-jet tagger

In general, events contain multiple primary vertex (PV) candidates, corresponding to pileup collisions occurring in the same proton bunch crossing. The PV reconstruction employs Gaussian constraints on the reconstructed position based on the luminous region, which is evaluated from the reconstructed PVs in many events. A description of the PV reconstruction can be found in Ref. [18]. The displaced-jet identification variables utilize the PV with the highest p_T^2 sum of the constituent tracks. The results of the analysis are found to be insensitive to the choice of the method used to select the PV, since the uncertainty in the transverse position of the primary vertex is small relative to the signal model decay lengths.

The analysis utilizes a dedicated tagging algorithm to identify displaced jets. For each jet, the algorithm takes as input the reconstructed tracks within $\Delta R < 0.4$ of the jet. All tracks with $p_T > 1$ GeV that are selected by all iterations of track reconstruction are considered. A detailed list of requirements for the CMS track collection can be found elsewhere [18]. Three variables are considered for each jet in the event. The first variable quantifies how likely it is that the jet originates from a given PV. For a given jet, $\alpha_{jet}(PV)$ is defined for each PV as

$$\alpha_{jet}(PV) = \frac{\sum_{tracks \in PV} p_T^{tracks}}{\sum_{tracks} p_T^{tracks}}, \quad (1)$$

where the sum in the denominator is over all tracks associated with the jet and the sum in the numerator is over just the subset of these tracks originating from the given PV. The tagging variable α_{max} is the largest value of $\alpha_{jet}(PV)$ for the jet.

The second variable quantifies the significance of the measured transverse displacement for the jet. For each track associated with the jet, the significance of the track's transverse impact parameter, IP^{2D}_{sig}, is computed as the ratio of the track's IP^{2D} and its

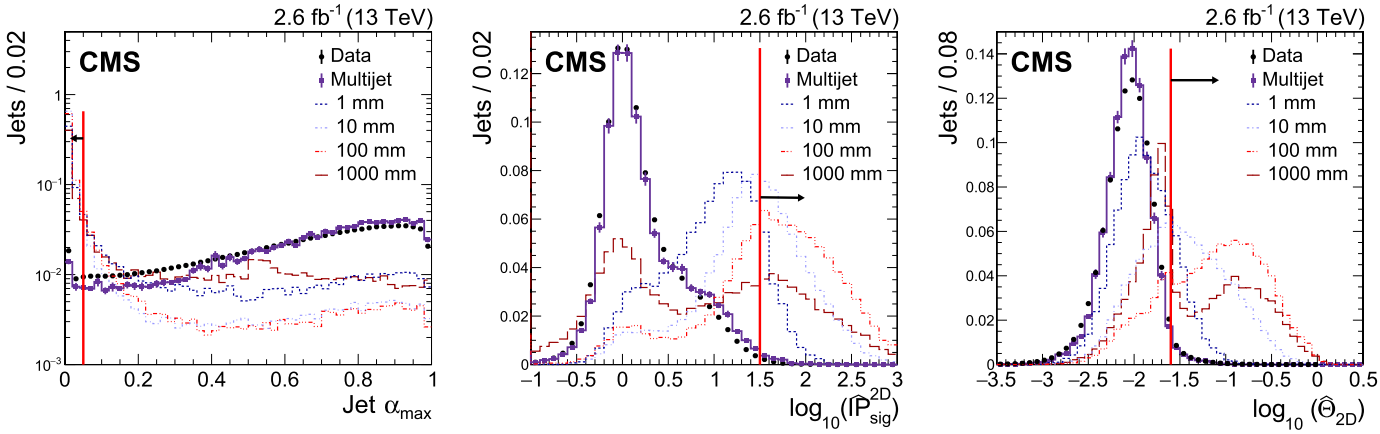

Fig. 1. Comparison of distributions for the displaced-jet tagging variables $\alpha_{\max}$ (left), $\widehat{\mathrm{IP}}^{\mathrm{2D}}_{\mathrm{sig}}$ (center), and $\widehat{\Theta}_{\mathrm{2D}}$ (right) in data and simulation. The data distributions (circles) are compared to the expected background distributions from multijet events (squares) and several Jet-Jet benchmark models (dotted histograms) of pair-produced long-lived neutral scalar particles with $m_{\chi^0} = 700$ GeV and different values of $c\tau_0$. The vertical lines designate the value of the requirement for the chosen displaced-jet tag. The direction of the arrow indicates the values included in the requirement. All distributions have unit normalization.

Table 1
Signal efficiencies (in %) for $m_{\chi^0} = m_{\tilde{\mathrm{t}}} = 300$ GeV for various values of $c\tau_0$ for the Jet-Jet and B-Lepton models. Selection requirements are cumulative from the first row to the last.

Jet-Jet				
$c\tau_0$ [mm]	1	10	100	1000
≥2 tags	2.33 ± 0.15	39.49 ± 0.63	54.54 ± 0.74	14.58 ± 0.38
Trigger	2.16 ± 0.15	38.12 ± 0.62	39.32 ± 0.63	8.07 ± 0.28
Selection	2.09 ± 0.14	37.09 ± 0.61	36.53 ± 0.60	6.67 ± 0.26
≥3 tags	0.17 ± 0.04	14.14 ± 0.38	16.72 ± 0.41	1.36 ± 0.12
≥4 tags	0.01 ± 0.01	4.73 ± 0.22	4.71 ± 0.22	0.17 ± 0.04
B-Lepton				
$c\tau_0$ [mm]	1	10	100	1000
≥2 tags	0.45 ± 0.02	15.82 ± 0.13	31.52 ± 0.19	8.55 ± 0.10
Trigger	0.29 ± 0.02	11.45 ± 0.11	17.08 ± 0.14	3.22 ± 0.06
Selection	0.27 ± 0.02	9.91 ± 0.11	13.33 ± 0.12	2.08 ± 0.05
≥3 tags	0.02 ± 0.01	2.46 ± 0.05	3.81 ± 0.07	0.37 ± 0.02
≥4 tags	–	0.30 ± 0.02	0.48 ± 0.02	0.03 ± 0.01

uncertainty. The tagging variable $\widehat{\mathrm{IP}}^{\mathrm{2D}}_{\mathrm{sig}}$ is the median of the $\mathrm{IP}^{\mathrm{2D}}_{\mathrm{sig}}$ distribution of all tracks in a jet.

The third variable quantifies the angular difference between the emission angle of a given track in a jet and the parent particle flight direction. For each track associated with the jet, Θ_{2D} is computed as the angle between the track $\vec{p}_{\mathrm{T}} = (p_{\mathrm{x}}, p_{\mathrm{y}})$ at the track's innermost hit and the vector connecting the chosen PV to this hit in the transverse plane. The tagging variable $\widehat{\Theta}_{\mathrm{2D}}$ is the median of the Θ_{2D} distribution for the tracks associated with the jet.

It should be noted that leptons giving rise to calorimeter energy deposits (tau leptons and electrons) will also be classified as "displaced jets", if the associated track(s) satisfies the tagging criteria, and thus contribute to the search sensitivity. Additionally, by not requiring the reconstruction of a displaced vertex, the analysis is becomes sensitive to pair-produced long-lived decays with a single reconstructed track per decay.

Fig. 1 shows the distributions of the three tagging variables for data events, simulated multijet events, and simulated signal events with $m_{\chi^0} = 700$ GeV and several values of $c\tau_0$. Note that any mismodeling resulting from the multijet background does not affect the analysis because the background estimate is derived from data. Simulation of the multijet background only describes misidentified displaced jets.

The displaced-jet identification criteria are $\alpha_{\max} < 0.05$, $\log_{10}(\widehat{\mathrm{IP}}^{\mathrm{2D}}_{\mathrm{sig}}) > 1.5$, and $\log_{10}(\widehat{\Theta}_{\mathrm{2D}}) > -1.6$. This selection was chosen by selecting parameters that yielded the best discovery sensitivity for the Jet-Jet model across all generated decay lengths and masses.

The average displaced-jet tagging efficiency with no trigger selection applied for $m_{\chi^0} = 700$ GeV is 4% for $c\tau_0 = 1$ mm, 57% for $c\tau_0 = 30$ mm, and 33% for $c\tau_0 = 1000$ mm. For $c\tau_0 > 1000$ mm, the long-lived particles typically decay beyond the tracker. For $c\tau_0 < 3$ mm, the experimental signature for signal events becomes increasingly difficult to distinguish from that of background b quark jets.

The search is performed by applying the selection criteria described above and by counting the number of tagged displaced jets, N_{tags}. In addition to the online and offline requirements described in Section 3, the analysis signal region requires $N_{\mathrm{tags}} \geq 2$. Efficiencies are reported for the Jet-Jet and B-Lepton models as a function of decay length with fixed mass (Table 1) as well as a function of mass with fixed decay length (Table 2). Efficiencies for the Light-Light, B-Tau, B-Electron, and B-Mu models are included in supplemental material as Tables 1 and 2.

5. Background prediction

Background events arise from jets containing tracks that are mismeasured as displaced and jets containing tracks from the weak decays of strange, charm, and bottom hadrons.

To maintain the statistical independence of the events that are used to perform the prediction and the events in the signal region, the misidentification rate is measured in a control sample defined

Table 2
Signal efficiencies (in %) for the Jet-Jet and B-Lepton models with $c\tau_0 = 30$ mm and for various values of mass. Selection requirements are cumulative from the first row to the last.

Jet-Jet					
m_{χ^0} [GeV]	50	100	300	1000	1500
≥2 tags	2.71 ± 0.10	14.80 ± 0.22	54.24 ± 0.74	79.93 ± 0.89	82.55 ± 0.91
Trigger	0.50 ± 0.04	5.39 ± 0.13	46.41 ± 0.68	74.05 ± 0.86	77.65 ± 0.88
Selection	0.30 ± 0.03	3.70 ± 0.11	44.75 ± 0.67	73.99 ± 0.86	77.53 ± 0.88
≥3 tags	0.05 ± 0.01	1.09 ± 0.10	20.87 ± 0.46	49.42 ± 0.70	55.28 ± 0.74
≥4 tags	–	0.22 ± 0.03	6.81 ± 0.26	25.45 ± 0.50	32.26 ± 0.57

B-Lepton				
$m_{\tilde{t}}$ [GeV]	300	600	800	1000
≥2 tags	31.52 ± 0.19	47.32 ± 0.23	52.53 ± 0.24	55.88 ± 0.35
Trigger	17.08 ± 0.14	35.03 ± 0.20	40.40 ± 0.21	43.14 ± 0.30
Selection	14.70 ± 0.13	32.34 ± 0.19	36.94 ± 0.20	39.26 ± 0.29
≥3 tags	4.11 ± 0.07	10.76 ± 0.11	13.29 ± 0.12	15.00 ± 0.18
≥4 tags	0.55 ± 0.03	1.83 ± 0.05	2.69 ± 0.05	3.09 ± 0.08

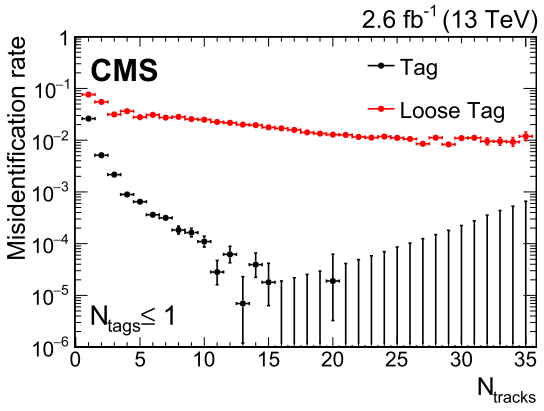

Fig. 2. The fraction of jets passing the displaced-jet tagging criteria as a function of the number of tracks associated with the jet. The results are from data events with $N_{\text{tags}} \leq 1$, collected with the displaced-jet triggers and passing the offline selection criteria.

as events with $N_{\text{tags}} \leq 1$ (as shown in Fig. 2), while the signal region requires $N_{\text{tags}} \geq 2$. Additionally, this control sample definition limits signal contamination. There are 1391 events in data with $N_{\text{tags}} = 1$. The size of the bias introduced by only measuring the misidentification rate in events with $N_{\text{tags}} \leq 1$ is quantifiable. For the chosen tag requirement, the effect of removing events with $N_{\text{tags}} > 1$ on the predicted number of two tag events is negligible (0.4%) compared to the statistical uncertainty of the prediction.

Since the proportion of tracks identified as being displaced is small and approximately constant, the likelihood of tagging a nondisplaced jet as a displaced jet decreases approximately exponentially with the number of tracks associated with the jet, N_{tracks}. Fig. 2 shows the fraction of jets that are tagged as displaced jets in data as a function of N_{tracks}. This function is the misidentification rate of tagging a prompt jet as displaced (assuming no signal contamination) and is interpreted as the probability $p(N_{\text{tracks}})$ of being tagged. This parameterization allows an event by event estimation of the probability of tagging any multiplicity of displaced jets.

Because of the high jet production cross section, even though the misidentification rate is small, events with one tagged displaced jet are completely dominated by standard model backgrounds, and signal contamination can be ignored, even if the associated cross section is large. This is explicitly verified with signal injection tests, which are discussed below.

The misidentification rate is used to predict the probability $P(N_{\text{tags}})$ for an event to have N_{tags} tagged jets. For instance, for an event m with three jets j_1, j_2, and j_3, there is one jet configuration with no tags, with a probability:

$$P^m(N_{\text{tags}} = 0) = (1 - p_1)(1 - p_2)(1 - p_3),$$

where $p_i = p(N_{\text{tracks}}(j_i))$. Similarly, there are three jet configurations for this same event to have $N_{\text{tags}} = 1$:

$$P^m(N_{\text{tags}} = 1) = p_1(1 - p_2)(1 - p_3) + (1 - p_1)p_2(1 - p_3) + (1 - p_1)(1 - p_2)p_3.$$

The probability of finding N_{tags} tags in the m event is:

$$P^m(N_{\text{tags}}) = \sum_{\text{jet-configs}} \prod_{i \in \text{tagged}} p_i \prod_{k \in \text{nontagged}} (1 - p_k). \quad (2)$$

Tagged jets enter the product as p_i and nontagged jets enter as $(1 - p_i)$. Equation (2) is used to compute $P^m(N_{\text{tags}})$, under the assumption that the sample does not contain any signal. The number of events expected for a given value of N_{tags} is computed as

$$N_{\text{events}}(N_{\text{tags}}) = \sum_m P^m(N_{\text{tags}}), \quad (3)$$

where m runs only over events with fewer than two tagged jets. The prediction is then compared to the observed N_{tags} multiplicity in events with two or more tagged jets, to assess the presence of a signal.

We validate this procedure in the absence (background-only test) and presence (signal injection test) of a signal, using simulated events.

The background-only test is performed by predicting the tag multiplicity from the simulated multijet sample, using the distribution obtained for the misidentification rate. In order to populate the large-N_{tags} region of the distribution, a looser version of the displaced-jet tagger is employed in this test. The loose displaced-jet identification criteria are $\alpha_{\text{max}} < 0.5$, $\log_{10}(\widehat{\text{IP}}^{\text{2D}}_{\text{sig}}) > 0.4$, and $\log_{10}(\widehat{\Theta}_{\text{2D}}) > -1.7$. The average misidentification rate of the loose (chosen) tag definition is 2.6% (0.05%). The loose definition requirements were relaxed until a minimal number of two tag events were available to perform the background-only test. The full sample of events passing the event selection is divided into multiple independent samples and the background prediction validated. The predicted background of N_{tags} events in simulated multijet events is found to be consistent with the observed number of events. The associated pull distributions are found to have mean 0 and variance 1 as expected in the ideal case.

Table 3
Summary of the signal systematic uncertainties. When the uncertainty depends on the specific features of the models (mass, decay length, and decay mode of the long-lived particle) a range is quoted, which refers to the computed uncertainty for $N_{\text{tags}} = 2$ events.

Signal systematic uncertainty	Effect on yield
H_{T} trigger inefficiency	5%
Jet p_{T} trigger inefficiency	5%
Trigger online tracking modeling	1–35%
Integrated Luminosity	2.3%
Acceptance due to the PDF choice	1–6%
Displaced-jet tag variable modeling	1–30%

The signal injection test is performed by adding events of pair-produced resonances decaying to two jets to the multijet sample and repeating the procedure described above. In this case, the chosen displaced-jet tagger is used. The injected signal has $m_{\chi^0} = 700$ GeV and $c\tau_0 = 10$ mm with a cross section varied in the range from 30 fb to 3 pb. The jet probability is computed as in the data, where no prior knowledge of the nature of the events (signal or background) is available. In this case, the misidentification rate is derived from the mixed sample itself, including the contamination from the injected signal sample. The signal contamination is found to have a minimal impact on the predicted number of events in the signal region. For example, with an injected signal cross section of 30 fb, 19 events are observed with two tags, while the two tag prediction is consistent with the predictions obtained for zero injected events: $N_{\text{events}}(N_{\text{tags}} \geq 2) = 1.3$. As another example, with an injection signal cross section of 3 pb, no three tag events are predicted, while 1520 events with three tags are observed. Given the insensitivity of the predicted background to large amounts of injected signal, the analysis is robust to signal contamination of the control region.

6. Systematic uncertainties

6.1. Background systematic uncertainties

There is an uncertainty in the estimated background level associated with the choice of method used. This uncertainty is evaluated by repeating the background prediction procedure described in Section 5 using the looser version of the displaced-jet tagging algorithm. The result is compared with that obtained using the nominal method and the observed difference of 7.5% is taken as the systematic uncertainty from this source. This value for the uncertainty is used also for the three or more tags case.

The statistical uncertainty in the measured misidentification rate as a function of N_{tracks} is propagated to the predicted N_{tags} distribution as a systematic uncertainty. This systematic uncertainty is calculated for each tag multiplicity bin. The uncertainty for the two tag bin is 13%.

6.2. Signal systematic uncertainties

All signal systematic uncertainties are calculated individually for each model, for each mass and decay length point, and for each value of N_{tags} in the signal region. In cases where the uncertainty depends on the mass, decay length, and/or decay mode of the long-lived particle, a range is quoted, referring to the uncertainty for $N_{\text{tags}} = 2$ events. A summary of the systematic uncertainties associated with the signal is given in Table 3.

The uncertainty in the trigger emulation is measured by comparing the predicted efficiency for simulated multijet events with that measured for data collected with a loose H_{T} trigger. The observed difference at the offline H_{T} threshold (5%) is taken as an estimate of the uncertainty in the emulation of the online H_{T} requirement. Similarly, the uncertainty induced by the online versus offline jet acceptance is obtained from the shift in the trigger efficiency when the offline minimum jet p_{T} requirement is increased from 60 to 80 GeV (5%).

The systematic uncertainty in the modeling of the online tracking efficiency is obtained by studying the online regional track reconstruction in data and in simulation. The online values of IP^{2D} and $\text{IP}^{\text{2D}}_{\text{sig}}$ are varied by the magnitude of the mismodeling found in events collected by control sample triggers consisting of only an H_{T} requirement ($H_{\text{T}} > 425$ and $H_{\text{T}} > 275$). The new values are used to determine if the event would still pass at least one of the trigger paths and its associated offline H_{T} requirement. The N_{tags} distribution is recalculated with the values varied up and down. The relative change in the number of events per N_{tags} bin is taken as the systematic uncertainty. For $N_{\text{tags}} = 2$, this uncertainty varies from 1 to 35%.

The systematic uncertainty in the luminosity is 2.3% [19].

The uncertainty arising from the choice of PDFs for pair-produced particles with masses in the range of 50–1500 GeV is found to be 1–6%. An ensemble of alternative PDFs is sampled from the output of the NNPDF fit. Events are reweighted according to the ratio between these alternative PDF sets and the nominal ones. The distribution of the signal prediction for these PDF ensembles is used to quantify this uncertainty.

The systematic uncertainty in the modeling of the jet tagging variables in the signal simulation samples is estimated from the displaced track modeling in multijet events in data and simulation. The mismodeling of the measured value of Θ_{2D} and $\text{IP}^{\text{2D}}_{\text{sig}}$ for single tracks is propagated to the final tag distribution by varying the individual measured values in simulation by the difference in the measured value relative to data (3–10%). The tagging variables are then recalculated. The N_{tags} distribution is recalculated with the new values. The systematic uncertainty is assigned as the relative change in the number of events for each N_{tags} bin. For the two tag bin, this varies from 1 to 30% depending on the mass and decay length. The mismodeling of α_{max} is found to have a negligible effect on the signal efficiency, as the requirement is relatively loose.

Table 4
The predicted and observed number of events as a function of the number of tagged displaced jets. The prediction is based on the misidentification rate derived from events with fewer than two tags. The full event selection is applied. The uncertainty corresponds to the total background systematic uncertainty.

N_{tags}	Expected	Observed
2	1.09 ± 0.16	1
≥ 3	$(4.9 \pm 1.0) \times 10^{-4}$	0

7. Results and interpretation

The numerical values for the expected and observed yields are summarized in Table 4. The observed yields are found to be consistent with the predicted background, within the statistical and systematic uncertainties. No evidence for a signal at large values of N_{tags} is observed.

Exclusions for each model are obtained from the predicted and observed event yields in Table 4 and the signal efficiencies in Tables 1 and 2 and Tables 1 and 2 in supplemental material. All bounds are derived at 95% confidence level (CL) according to the CL_{s} prescription [20–23] in the asymptotic approximation. For each limit derivation, we consider events with $N_{\text{tags}} \geq 2$, using independent bins for $N_{\text{tags}} = 2$ and $N_{\text{tags}} \geq 3$. Finer binning of the tag multiplicity for $N_{\text{tags}} > 3$ is found to have a negligible effect on the expected limits. Cross section upper limits are presented as a

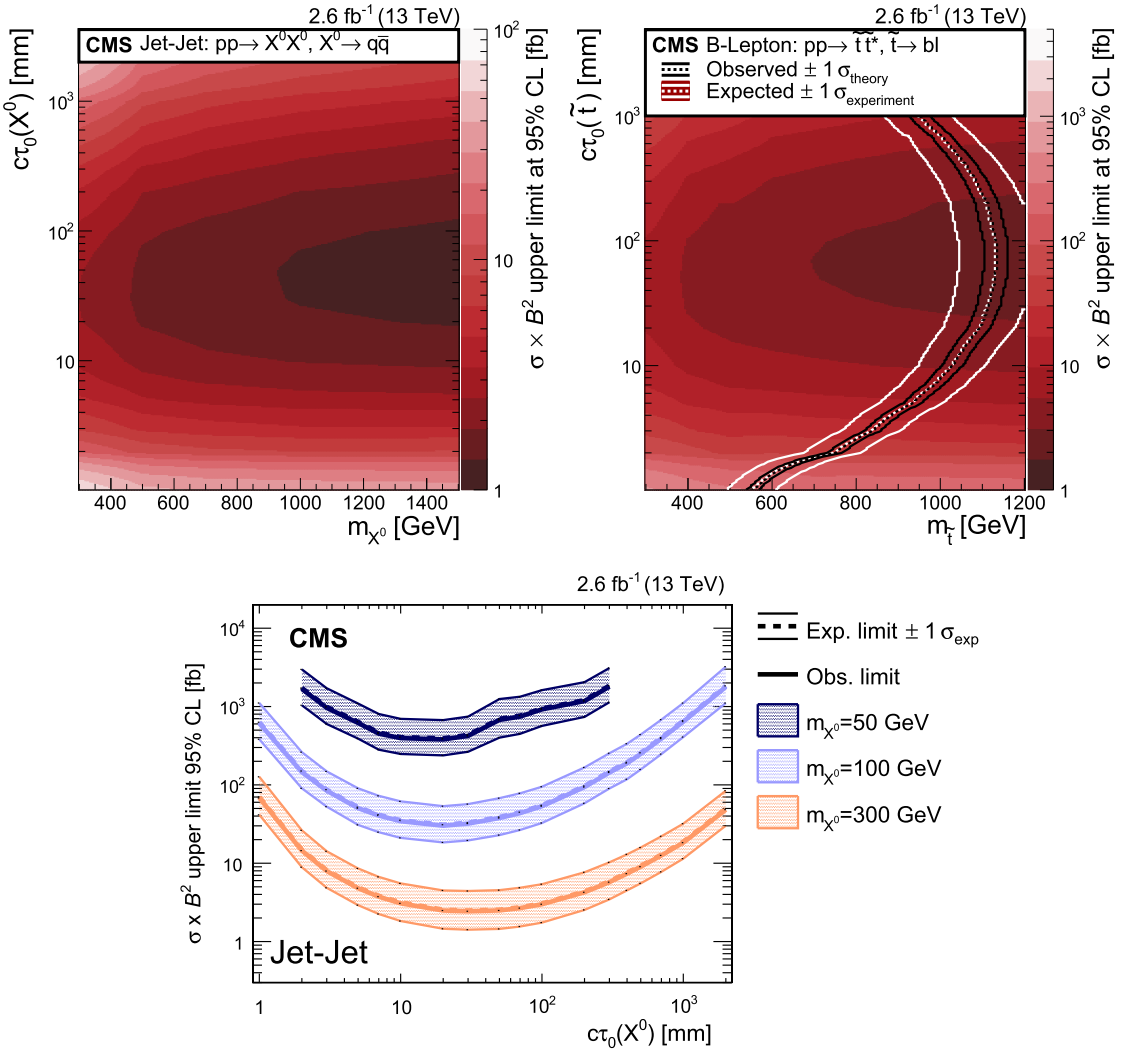

Fig. 3. The excluded cross section at 95% CL for the Jet-Jet model (upper left) and the B-Lepton model (upper right) as a function of the mass and proper decay length of the parent particle. The B-Lepton plot also shows the expected (observed) exclusion region with one standard deviation experimental (theoretical) uncertainties, utilizing a NLO+NLL calculation of the top squark production cross section. The lower plot shows the excluded cross section at 95% CL for the Jet-Jet model as a function of the proper decay length for three illustrative smaller values of the mass. The shaded bands in the lower plot represent the one standard deviation uncertainties in the expected limits.

function of the mass and proper decay length of the parent particle. The analysis sensitivity is maximal for $c\tau_0$ ranging from 10 to 1000 mm. Mass exclusion bounds at fixed decay length are also derived by comparing the excluded cross section with the values predicted for the benchmark models described in Section 3. In the case of SUSY models, the next-to-leading order (NLO) and next-to-leading logarithmic (NLL) $\widetilde{\mathrm{t}}\widetilde{\mathrm{t}}^*$ production cross section computed in the large-mass limit for all other SUSY particles [24–29] is used as a reference.

Fig. 3 shows the excluded pair production cross section for the Jet-Jet and B-Lepton models. The Light-Light model is shown in Figure 1 of supplemental material and has nearly identical performance to the Jet-Jet model. The B-Lepton sensitivity is similar to that observed for the Jet-Jet model, although it is less stringent as additional jets give higher efficiency than additional leptons from both the tagging and triggering perspectives. Cross sections larger than 2.5 fb are excluded at 95% CL, for $c\tau_0$ in the range 70–100 mm, which corresponds to the exclusion of parent masses below 1130 GeV.

The exclusions for the B-Tau, B-Electron and B-Muon models are shown in Figs. 2–4 of supplemental material, respectively. The B-Tau and B-Electron models have similar performance at high mass with slightly stronger limits for the B-Electron model at lower mass ($m_{\widetilde{\mathrm{t}}} = 300$ GeV) and longer decay length ($c\tau_0 > 10$ mm). The highest mass excluded in the B-Electron (B-Tau) model is $m_{\widetilde{\mathrm{t}}} = 1145\,(1150)$ GeV at $c\tau_0 = 70$ mm, corresponding to a cross section of 2.3 (2.2) fb at 95% CL.

In the case of the B-Muon model, the analysis uses jets reconstructed from calorimetric deposits and the two muons have small or no associated calorimeter deposits, thus the signal reconstruction efficiency and the displaced-jet multiplicity are smaller. This results in a weaker exclusion bound. The highest mass excluded in the B-Muon model is $m_{\widetilde{\mathrm{t}}} = 1085$ GeV at $c\tau_0 = 70$ mm, corresponding to a cross section upper limit of 3.5 fb at 95% CL.

8. Summary

A search for long-lived particles has been performed with data corresponding to an integrated luminosity of 2.6 fb^{-1} collected at a center-of-mass energy of 13 TeV by the CMS experiment in 2015. This is the first search for long-lived particles decaying to jet final states in 13 TeV data and the first search to demonstrate explicit sensitivity to long-lived particles decaying to τ leptons. The analysis utilizes two customized topological trigger algorithms

and an offline displaced-jet tagging algorithm, where the multiplicity of displaced jets is used to search for the presence of a signal. As no excess above the predicted background is found, upper limits are set at 95% confidence level on the production cross section for long-lived resonances decaying to two jets or to a lepton and b quark. The limits are calculated as a function of the mass and proper decay length of the long-lived particles. For resonances decaying to a b quark and a lepton, cross sections larger than 2.5 fb are excluded for proper decay lengths of 70–100 mm. The cross section limits are also translated into mass exclusion bounds, using a calculation of the top squark production cross section as a reference. Assuming equal lepton branching fractions, pair-produced long-lived R-parity violating top squarks lighter than 550–1130 GeV are excluded, depending on the squark proper decay length. This mass exclusion bound is currently the most stringent bound available for top squark proper decay lengths greater than 3 mm.

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Appendix A. Supplementary material

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