Physics Letters B 780 (2018) 432–454

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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ARTICLE INFO

Article history:
Received 24 November 2017
Received in revised form 19 February 2018
Accepted 7 March 2018
Available online 14 March 2018
Editor: M. Doser

Keywords:
CMS
Physics
Long-lived particles

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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https://doi.org/10.1016/j.physletb.2018.03.019
0370-2693/

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 $\text{IP}^{2D} > 5\sigma_{\text{IP}^{2D}}$, where $\sigma_{\text{IP}^{2D}}$ 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, $\alpha_{\text{jet}}(\text{PV})$ is defined for each PV as

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

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 $\alpha_{\max}$ is the largest value of $\alpha_{\text{jet}}(\text{PV})$ 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, $\text{IP}^{2D}_{\text{sig}}$, is computed as the ratio of the track's IP^{2D} and its