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Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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A search for long-lived particles decaying to displaced, nonprompt jets and missing transverse momentum is presented. The data sample corresponds to an integrated luminosity of $137\,\text{fb}^{-1}$ of proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment at the CERN LHC in 2016–2018. Candidate signal events containing nonprompt jets are identified using the timing capabilities of the CMS electromagnetic calorimeter. The results of the search are consistent with the background prediction and are interpreted using a gauge-mediated supersymmetry breaking reference model with a gluino next-to-lightest supersymmetric particle. In this model, gluino masses up to 2100, 2500, and 1900 GeV are excluded at 95% confidence level for proper decay lengths of 0.3, 1, and 100 m, respectively. These are the best limits to date for such massive gluinos with proper decay lengths greater than ∼0.5 m.

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1. Introduction

A large number of models for physics beyond the standard model predict long-lived particles that may be produced at the CERN LHC and decay into final states containing jets with missing transverse momentum, $p_{\mathrm{T}}^{\text{miss}}$ [1]. These models include supersymmetry (SUSY) with gauge-mediated SUSY breaking (GMSB) [2], split and stealth SUSY [3–5], and hidden valley models [6]. The $p_{\mathrm{T}}^{\text{miss}}$ may arise from a stable neutral weakly interacting particle in the final state or from a heavy neutral long-lived particle that decays outside the detector.

The timing capabilities of the CMS electromagnetic calorimeter (ECAL) [7] are used to identify nonprompt or "delayed" jets produced by the displaced decays of heavy long-lived particles within the ECAL volume or within the tracking volume bounded by the ECAL. The delay is expected to be a few ns for a TeV scale particle that travels ∼1 m before decaying. A representative GMSB model is used as a benchmark to quantify the sensitivity of the search. In this model, pair-produced long-lived gluinos each decay into a gluon, which forms a jet, and a gravitino, which escapes the detector causing significant $p_{\mathrm{T}}^{\text{miss}}$ in the event. A diagram showing the benchmark model is shown in Fig. 1 (upper figure).

There have been multiple searches for long-lived particles decaying to jets by the ATLAS [8], CMS [9] and LHCb [10] Collaborations at $\sqrt{s} = 7\,\text{TeV}$, $\sqrt{s} = 8\,\text{TeV}$ and $\sqrt{s} = 13\,\text{TeV}$ [11–25]. The use of calorimeter timing has so far been limited to searches targeting displaced photons at $\sqrt{s} = 8\,\text{TeV}$ [26,27]. The present study represents the first application of ECAL timing to a search for nonprompt jets from long-lived particle decays. This technique allows the reduction of background contributions to the few event level, while retaining high efficiency for signal signatures of one or more displaced jets and $p_{\mathrm{T}}^{\text{miss}}$ in the final state. As detailed in Ref. [28], this approach brings significant new sensitivity to long-lived particle searches. A diagram of a characteristic event targeted by this analysis is shown in Fig. 1 (lower figure). Such an event would escape reconstruction in a tracker-based search because of the difficulty in reconstructing tracks that originate from decay points separated from the primary vertex by more than ∼50 cm in the plane perpendicular to the beam axis. There are two effects that contribute to the time delay of jets from the decay of heavy long-lived particles. First, the indirect path, composed of the initial long-lived particle and the subsequent jet trajectories, will be longer, and second, the long-lived particle will move with a lower velocity owing to its high mass. The latter is the dominant effect for the signal models considered in this analysis.

2. The CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal ECAL, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and

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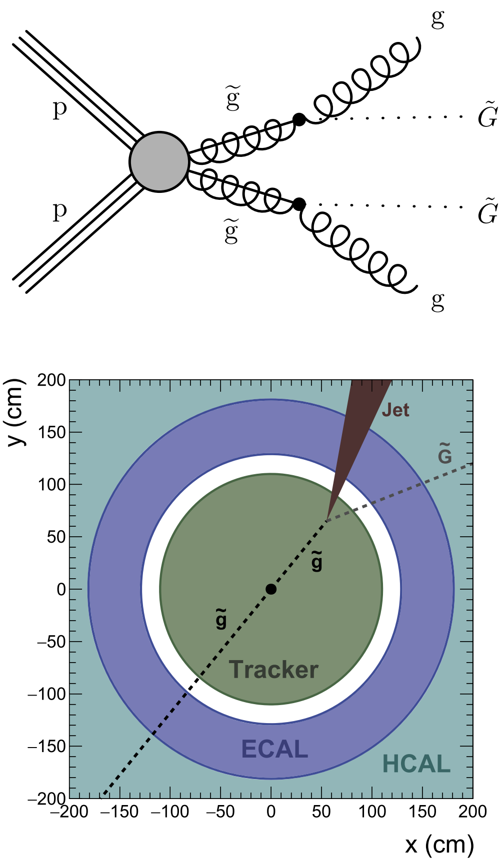

Fig. 1. Diagram showing the GMSB signal model (upper figure), and diagram of a typical event (lower figure), expected to pass the signal region selection. The event has delayed energy depositions in the calorimeters but no tracks from a primary vertex.

two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles with $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$, in the region $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [29]. The HCAL is segmented into individual calorimeter cells along pseudorapidity (η), azimuth (ϕ), and depth. The barrel muon system is composed of drift-tubes (DTs) and resistive plate chambers (RPCs). These provide high resolution hit positioning and timing to determine the muon trajectory. The hits in the DTs are clustered into track segments, referred to as DT segments, as detailed in Ref. [30]. In the forward region, RPCs are used along with cathode strip chambers (CSCs), which have greater resistance to the higher radiation flux occurring along the beamline than DTs. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematical variables, can be found in Ref. [9].

The CMS ECAL consists of 75 848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.00$ in two endcap regions (EE). This analysis relies on the timing capabilities of the EB [7]. The ECAL measures the energy of incoming electromagnetic particles through the scintillation light produced in the lead tungstate crystals. Silicon avalanche photodiodes (APDs) are used as photodetectors in the barrel region. These are capable of measuring the time of incoming particles with a resolution as low as $\sim$200 ps for energy deposits above 50 GeV [31]. Each ECAL crystal with an APD unit attached is referred to as an ECAL cell.

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 in ϕ. In the η–ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum 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, subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system [32]. 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.

3. Object and event reconstruction

The primary physics objects used in this analysis are jets reconstructed from the energy deposits in the calorimeter towers, clustered using the anti-k_{T} algorithm [33,34] with a distance parameter of 0.4. The contribution from each calorimeter tower is assigned the coordinates of the tower and a momentum, the absolute value and the direction of which are found from the energy measured in the tower assuming that the contributing particles originated at the center of the detector. The raw jet energy is obtained from the sum of the tower energies, and the raw jet momentum by the vectorial sum of the tower momenta, which are found from the energy measured in the tower. The raw jet energies are then corrected to reflect a uniform relative response of the calorimeter in η and a calibrated absolute response in transverse momentum p_{T} [35]. Jets reconstructed using the CMS particle flow (PF) algorithm [36] are not used in this analysis because nonprompt jets do not produce reliable information in the tracker and out-of-time energy deposits are not included in the PF jet reconstruction.

All reconstructed vertices in the event, consistent with originating from a proton-proton (pp) interaction, are considered to be primary vertices (PVs) [29]. Each track that is identified as originating from a PV is associated with a jet if the separation of the track from the jet axis $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$, where $\Delta\eta$ and $\Delta\phi$ represent the difference (in radians) between the jet axis and the track in the pseudorapidity and in the azimuthal direction, respectively.

The jet timing is determined using all ECAL cells that satisfy $\Delta R < 0.4$ between the jet axis and cell position, that exceed an energy threshold of 0.5 GeV and that satisfy reconstruction quality criteria. For each cell within the ECAL detector, the timing offset is defined such that a particle traveling at the speed of light from the center of the collision region to the cell position arrives at time zero. Energy deposits with a recorded time that is either less than -20 ns or greater than 20 ns are rejected, to remove events originating from preceding or following bunch collisions, respectively. The time of the jet, t_{jet}, is defined by the median cell time. The jet-based requirements used to reject the dominant background sources, referred to as the signal jet requirements, are detailed in Section 5.

The missing transverse momentum vector, $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, used for this analysis is defined as the projection on the plane perpendicular to the beams of the negative vector sum of calorimeter momenta deposits in an event satisfying reconstruction quality criteria chosen to reduce instrumental noise effects, but with no rejection of out-of-time ECAL cells.

4. Data sets and simulated samples

The data sample was collected in 2016, 2017, and 2018 by the CMS detector in pp collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $137 \pm 3.3\,\mathrm{fb}^{-1}$ [37–39]. The trigger required the events to satisfy $p_{\mathrm{T}}^{\mathrm{miss}}$ (trigger) > 120 GeV. This is computed as the negative vector $\vec{p}_{\mathrm{T}}$ sum of all HLT PF candidates, which include out-of-time deposits [40].

The search is interpreted using the GMSB signal model with samples produced with gluino masses from 1000 to 3000 GeV, and proper decay lengths ($c\tau_0$) varying from 0.3 to 100 m. The gluino pair production cross sections are determined at approximate-NNLO+NNLL order in α_s [41–47]. All other SUSY particles, apart from the gravitino, are assumed to be heavy and decoupled from the interaction. Signal samples are produced with PYTHIA 8.212 [48], and NNPDF3.1LO [49] is used for parton distribution function (PDF) modeling. If a gluino is long-lived, it will have enough time to form a hadronic state, an R-hadron [50–52], which is simulated with PYTHIA 8.212. For underlying event modeling the CP2 tune is used [53].

Systematic uncertainties in the modeling of the jet-based variables discussed in Section 5 are derived using a simulated sample of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events. This sample is simulated with the MADGRAPH5_aMC@NLO 2.2.2 [54] event generator at leading-order (LO) accuracy. This generator is interfaced with PYTHIA 8.212 for hadronization and fragmentation. The jets from the matrix element calculations are matched to parton shower jets using the MLM algorithm [54]. The underlying event is modeled using the CUETP8M1 (CP5) tune [53] for simulation with NNPDF3.0NLO (NNPDF3.1NNLO) [49] used for PDF modeling for the 2016 (2017 and 2018) detector operating conditions.

The description of the detector response is implemented using the GEANT4 [55] package for all simulated processes. To model the effect of additional pp interactions within the same bunch crossing (in-time pileup) or nearby bunch crossings (out-of-time pileup), minimum bias events generated with PYTHIA are added to the simulated event sample, with a frequency distribution per bunch crossing weighted to match that observed in data.

5. Event and object selection

The selection criteria are optimized taking into account the principal background sources that produce delayed timing signals, which are detailed below.

- ECAL time resolution tails: these tails affect the collisions of in-time ("core") bunches and arise from intercalibration uncertainties, crystal-dependent variations in scintillation rise time, loss of crystal transparency because of radiation, and run-by-run shifts associated with the readout electronics [31].
- Electronic noise: electronic noise in the ECAL can cause individual cells to record deposits at arbitrary times, typically with low energies, and uncorrelated with surrounding cells.
- Direct ionization in the APD: the traversal of a charged particle produces a signal that is $\sim$11 ns earlier than the signal from scintillation light. However, the ionization signal may arrive later if the associated charged particle travels back from the HCAL, or is associated with a later bunch crossing.
- In-time pileup: additional pp collisions in the same bunch crossing can produce particles with a spread in collision time and with varying flight paths, depending on the point of origin along the beam axis. These effects result in timing shifts of up to a few hundred ps.
- Out-of-time pileup: additional pp collisions in neighboring bunch crossings can result in deposits that are delayed by integer multiples of the bunch spacing (25 ns).
- Satellite bunches: the LHC radiofrequency (RF) cavities operate at a frequency of 400 MHz, such that RF "buckets" are separated by $\sim$2.5 ns. In order to achieve the desired bunch spacing, only one in ten of these buckets (separated by 25 ns) is filled. However, adjacent "satellite" bunches may also contain protons at a level corresponding to $\mathcal{O}(10^{-5})$ times that of the main bunch.
- Beam halo: collisions between beam protons and an LHC collimator [56] can result in muons that pass through the detector approximately parallel to the beam line. These "beam halo" muons can deposit energy within the ECAL, causing an early signal if the beam halo is from the current or previous bunch or a delayed signal if the beam halo originates from a following bunch.
- Cosmic ray muon hits: cosmic ray muons may cause deposits in the ECAL that occur at random times.

The events considered in this analysis as including candidate long-lived particles are required to satisfy a series of selections that define the signal region (SR). Each requirement is chosen to be at least $\sim$90% efficient for jets from the decay of a TeV scale long-lived particle while allowing at least a factor $\sim$10 rejection of the identified background process. In order to predict background contributions to the SR, some of these requirements are inverted to enhance particular background processes, as detailed in Section 6.

5.1. Jet selection

5.1.1. Baseline jet selection

All jets considered in this analysis must pass baseline p_{T} and η requirements. A requirement of $p_{\mathrm{T}} > 30$ GeV is imposed to reduce contributions from pileup jets. For the SR, further mitigation of pileup jets is achieved through selections detailed in Section 5.1.2. The jets are required to satisfy $|\eta| < 1.48$ so that they are reconstructed in the EB. The barrel requirement is made because the timing resolution is significantly better in this region compared with the endcap [31], and jets of the targeted signal model are strongly peaked in the central η region.

5.1.2. Signal jet selection

The SR requirement on the jet time is $t_{\mathrm{jet}} > 3$ ns. The timing resolution improves for higher energy ECAL deposits before reaching a plateau [31]. A requirement on the ECAL energy component of the jet of $E_{\mathrm{ECAL}} > 20$ GeV is applied as this threshold was found to optimize the timing resolution of the jets while ensuring high signal efficiency.

Jets from signal events are expected to have a large number of ECAL cells ($N_{\mathrm{ECAL}}^{\mathrm{cell}}$) hit, while jets dominated by direct APD hits or ECAL noise often have a low number of cells hit. A threshold of $N_{\mathrm{ECAL}}^{\mathrm{cell}} > 25$ is applied to reject these background sources.

Jets from signal events will typically have similar energy depositions in the ECAL and HCAL, while jets originating from noise or beam halo typically have a small or zero HCAL energy component (E_{HCAL}). In order to reject such background sources, jets are required to have a hadronic energy fraction $\mathrm{HEF} = E_{\mathrm{HCAL}}/(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}}) > 0.2$. An additional requirement of $E_{\mathrm{HCAL}} > 50$ GeV is made to reject background contributions from noise and beam halo as well as to ensure a well-measured hadronic component.

Signal jets typically have a small RMS in the time of the constituent cells ($t_{\mathrm{jet}}^{\mathrm{RMS}}$) as all the component cells originate from the same delayed jet. Jets that are significantly delayed because of contributions from uncorrelated noise often contain cells that are widely spread in time. In such cases the $t_{\mathrm{jet}}^{\mathrm{RMS}}$ will be correlated with t_{jet}, so a requirement is made on both $t_{\mathrm{jet}}^{\mathrm{RMS}} < 0.4 t_{\mathrm{jet}}$ and $t_{\mathrm{jet}}^{\mathrm{RMS}} < 2.5\,\mathrm{ns}$.

Jets that originate from a PV and have a mismeasured time or originate from satellite bunch collisions typically contain significant total momentum in tracks associated with their PV. The $\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}}$, defined as the ratio of the total p_{T} of all PV tracks matched to the jet ($\Delta R < 0.5$) to the transverse calorimeter energy of the jet, is used to select potential signal jets that do not originate from a PV. A requirement of $\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}} < 0.08$ is applied.

Beam halo muons will travel directly through the CSCs before leaving energy deposits in the ECAL, so the fraction of ECAL energy that can be associated with CSC hits provides rejection of background contributions from beam halo. The ratio of the total energy of ECAL cells matched to a CSC hit ($\Delta\phi < 0.04$) to E_{ECAL}, defined as $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}}$, is used to discriminate beam halo background contributions. A requirement of $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} < 0.8$ is applied.

5.2. Event selection

The events are required to contain at least one jet satisfying the requirements outlined in Section 5.1. In addition, a requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$ is applied to reject background contributions from multijet production from core and satellite bunch collisions.

The DT and RPC muon systems are used to reduce the background contribution from cosmic ray muons. Signal events could also have deposits in the muon systems if the jets contain muons, if there is "punch-through" of jet constituents to the muon system, or if the long-lived particle decays within the muon system. To mitigate the inefficiency for signal events, only the DT segments and RPC hits with $r > 560\,\mathrm{cm}$ (where r is the transverse radial distance to the interaction point) and RPC hits with $|z| > 600\,\mathrm{cm}$ (where z is the distance along the beamline to the interaction point) are considered. In order to reduce the effect of noise, DT segments and RPC hits are required to be within $\Delta R < 0.5$ of a DT segment with a hit. The maximal $\Delta\phi$ between such "paired" DT segments and RPC hits is defined as $\max(\Delta\phi_{\mathrm{DT}})$ and $\max(\Delta\phi_{\mathrm{RPC}})$, respectively. Events satisfying $\max(\Delta\phi_{\mathrm{DT}}) > \pi/2$ or $\max(\Delta\phi_{\mathrm{RPC}}) > \pi/2$ are rejected to reduce the contribution of cosmic ray muon events.

Finally, events are required to satisfy a series of filters designed to reject anomalous high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events, which can be due to a variety of reconstruction failures, detector malfunctions and backgrounds not arising from pp collisions [40]. All SR requirements are summarized in Table 1.

Table 1
Summary of the requirements used to define the signal region.

Baseline jet selection
$\lvert\eta\rvert < 1.48$
$p_{\mathrm{T}} > 30\,\mathrm{GeV}$
Signal jet selection
$E_{\mathrm{ECAL}} > 20\,\mathrm{GeV}$
$N_{\mathrm{ECAL}}^{\mathrm{cell}} > 25$
HEF > 0.2 and $E_{\mathrm{HCAL}} > 50\,\mathrm{GeV}$
$t_{\mathrm{jet}}^{\mathrm{RMS}}/t_{\mathrm{jet}} < 0.4$ and $t_{\mathrm{jet}}^{\mathrm{RMS}} < 2.5\,\mathrm{ns}$
$\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}} < 0.08$
$E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} < 0.8$
$t_{\mathrm{jet}} > 3\,\mathrm{ns}$
Event level selection
At least one signal jet
$p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$
Quality filters
$\max(\Delta\phi_{\mathrm{DT}}) < \pi/2$
$\max(\Delta\phi_{\mathrm{RPC}}) < \pi/2$

6. Background estimation

This section details the characterization of the dominant background sources and the methods used to estimate residual contributions to the SR. The background contributions are investigated by inverting the requirements on the discriminating variables summarized in Table 1 to define control regions (CRs) enriched in particular background processes. There are three main background sources: beam halo muons deposits, which typically have low HEF and large $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}}$; out-of-time jets from core and satellite bunch collisions, which have large $\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}}$; and jets originating from cosmic ray muons, which have high $\max(\Delta\phi_{\mathrm{DT/RPC}})$ and $t_{\mathrm{jet}}^{\mathrm{RMS}}$. The background sources are estimated from the CRs using methods that rely on data. These predictions are tested using validation regions (VRs) that do not overlap with the SRs to ensure they are unbiased. The agreement of the observation with prediction in the VRs is used to estimate systematic uncertainties in the prediction in the SR. For jets in the CRs and VRs with $|t_{\mathrm{jet}}| < 3\,\mathrm{ns}$, the $t_{\mathrm{jet}}^{\mathrm{RMS}}/t_{\mathrm{jet}} < 0.4$ requirement is replaced with a requirement of $t_{\mathrm{jet}}^{\mathrm{RMS}} < 1.2\,\mathrm{ns}$.

6.1. Beam halo

The beam halo contribution is estimated by measuring the pass/fail ratio of the $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} > 0.8$ requirement for events with HEF < 0.2 and applying it to the observed number of events with HEF > 0.2. The prediction is made without any requirement on E_{HCAL} and can therefore be considered an upper limit on the contribution from the beam halo background contribution.

The VR for this prediction is defined by selecting events with $t_{\mathrm{jet}} < -2\,\mathrm{ns}$ and applying all signal requirements except those on $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}}$, HEF, and E_{HCAL}. To enhance the contribution of beam halo events relative to the contributions from satellite bunches and cosmic ray muons in the VR, the ϕ values of the jets are required to be within 0.2 radians of 0 or $\pm\pi$. The correlation between $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}}$ and HEF in the VR is consistent with zero, meaning they can be used to make an unbiased prediction. The prediction from this method for the number of events passing signal thresholds on $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}}$ and HEF in the VR is $0.02^{+0.06}_{-0.02}$ events, in agreement with the 0 events observed.

The level of agreement between prediction and observation in the VR is used to derive a systematic uncertainty in the prediction. The slope of a linear fit to the pass/fail ratio of the $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} > 0.8$ requirement as a function of HEF is found to be consistent with zero. The uncertainty is then propagated to the region with $E_{\mathrm{ECAL}}^{\mathrm{CSC}}/E_{\mathrm{ECAL}} > 0.8$ and HEF > 0.2. The final prediction for the SR is $0.02^{+0.06}_{-0.02}\,(\mathrm{stat})^{+0.05}_{-0.01}\,(\mathrm{syst})$ events.

6.2. Core and satellite bunch background prediction

The core and satellite bunch background contribution is estimated by measuring the pass/fail ratio of the requirement $\mathrm{PV}_{\mathrm{track}}^{\mathrm{fraction}} < 0.08$ for events with $1 < t_{\mathrm{jet}} < 3\,\mathrm{ns}$ and applying it to the observed number of events with $t_{\mathrm{jet}} > 3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} > 0.08$. Two VRs are defined to verify the prediction of the satellite bunch and timing tail background contributions.

The first VR is selected to contain events with $t_{\mathrm{jet}} < -1$ ns and passing all signal requirements except for that on $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}}$. The pass/fail ratio of the $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ requirement is measured for events with $-3 < t_{\mathrm{jet}} < -1$ ns and applied to the number of events with $t_{\mathrm{jet}} < -3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} > 0.08$. The upper bound on t_{jet} ensures the sample is enriched with jets in the tail of the t_{jet} distribution. The correlation between the variables in the VR is confirmed to be consistent with zero, which allows an unbiased prediction to be made. The prediction from this method for the number of events passing $t_{\mathrm{jet}} < -3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ is $0.09^{+0.2}_{-0.06}$ events, to be compared with 1 observed event. The event passing selection has no paired RPC or DT hits and is therefore unlikely to originate from a cosmic ray muon. The compatibility with expectation is within two standard deviations, however, to ensure the prediction is unbiased, a further validation is carried out. The requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV is inverted and the prediction repeated. The events must still satisfy the $p_{\mathrm{T}}^{\mathrm{miss}}$ (trigger) > 120 GeV requirement. The number of events satisfying $t_{\mathrm{jet}} < -3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ is predicted to be 1.95 ± 0.29 events, to be compared with 1 event observed. As the validation with $p_{\mathrm{T}}^{\mathrm{miss}} < 300$ GeV probes a similar phase space to the validation with $p_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV, but with a significantly increased number of events, an excess due to a systematic effect would be enhanced. The observation in the region with $t_{\mathrm{jet}} < -3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$, for $p_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV, is therefore considered to be consistent with a statistical fluctuation.

A second VR is defined using events with $1 < t_{\mathrm{jet}} < 3$ ns. The pass/fail ratio of the $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ requirement is measured for events with $1 < t_{\mathrm{jet}} < 2$ ns and applied to the number of events with $2 < t_{\mathrm{jet}} < 3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} > 0.08$. The estimation from this method for the number of events passing $2 < t_{\mathrm{jet}} < 3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ is $0.03^{+0.08}_{-0.03}$ events, in agreement with the 0 events observed.

The prediction for the SR relies on using the efficiency of the $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}}$ requirement of events with $1 < t_{\mathrm{jet}} < 3$ ns to predict the efficiency of the $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}}$ requirement for $t_{\mathrm{jet}} > 3$ ns. Because of differences in the reconstruction of the calorimeter energy and tracker p_{T}, this efficiency may be expected to have some small time dependence. In order to measure any such t_{jet} dependence and derive an associated systematic uncertainty, a data sample with the offline $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement inverted (but passing trigger requirements) and $t_{\mathrm{jet}} > 2$ ns is used. The region of $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.08$ is not included to avoid contamination from cosmic ray or beam halo muon deposits. The slope of a linear fit to the pass/fail ratio of a looser requirement of $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} < 0.5$ against t_{jet} is consistent with zero. As for the beam halo prediction, the uncertainty from the fit is propagated to the region with $t_{\mathrm{jet}} > 3$ ns and $\mathrm{PV}^{\mathrm{fraction}}_{\mathrm{track}} > 0.08$. The final prediction for the core and satellite bunch background contribution is $0.11^{+0.09}_{-0.05}\,(\mathrm{stat})^{+0.02}_{-0.02}\,(\mathrm{syst})$ events.

6.3. Cosmic ray events

The discriminating variables used for the cosmic background prediction are the $t^{\mathrm{RMS}}_{\mathrm{jet}}$ of the jet and the larger of $\max(\Delta\phi_{\mathrm{DT}})$ and $\max(\Delta\phi_{\mathrm{RPC}})$, labeled as $\max(\Delta\phi_{\mathrm{DT/RPC}})$. The pass/fail ratio of the $t^{\mathrm{RMS}}_{\mathrm{jet}} < 2.5$ ns requirement is measured for events with $\max(\Delta\phi_{\mathrm{DT/RPC}}) > \pi/2$ and applied to events with $\max(\Delta\phi_{\mathrm{DT/RPC}}) < \pi/2$. Cosmic ray muons that radiate a photon via bremsstrahlung while passing through the HCAL will typically deposit significant energy in a single isolated cell. The HCAL noise rejection quality filters are designed to reject events containing such isolated deposits, thus inverting these filters, with all other requirements applied, provides a validation region enriched in events with cosmic ray muons.

The correlation between $t^{\mathrm{RMS}}_{\mathrm{jet}}$ and $\max(\Delta\phi_{\mathrm{DT/RPC}})$ in the validation sample is consistent with zero, allowing them to be used to make an unbiased prediction. The estimation in the VR for the number of events passing signal thresholds in $t^{\mathrm{RMS}}_{\mathrm{jet}}$ and $\max(\Delta\phi_{\mathrm{DT/RPC}})$ is $1.1^{+1.9}_{-1.1}$ events, in agreement with the 1 event observed. A systematic uncertainty in the SR prediction is derived from the statistical uncertainty in the VR. The final prediction in the SR is $1.0^{+1.8}_{-1.0}\,(\mathrm{stat})^{+1.8}_{-1.0}\,(\mathrm{syst})$ events.

Table 2
Summary of the estimated number of background events.

Background source	Events predicted
Beam halo muons	$0.02^{+0.06}_{-0.02}\,(\mathrm{stat})^{+0.05}_{-0.01}\,(\mathrm{syst})$
Core and satellite bunch collisions	$0.11^{+0.09}_{-0.05}\,(\mathrm{stat})^{+0.02}_{-0.02}\,(\mathrm{syst})$
Cosmic ray muons	$1.0^{+1.8}_{-1.0}\,(\mathrm{stat})^{+1.8}_{-1.0}\,(\mathrm{syst})$

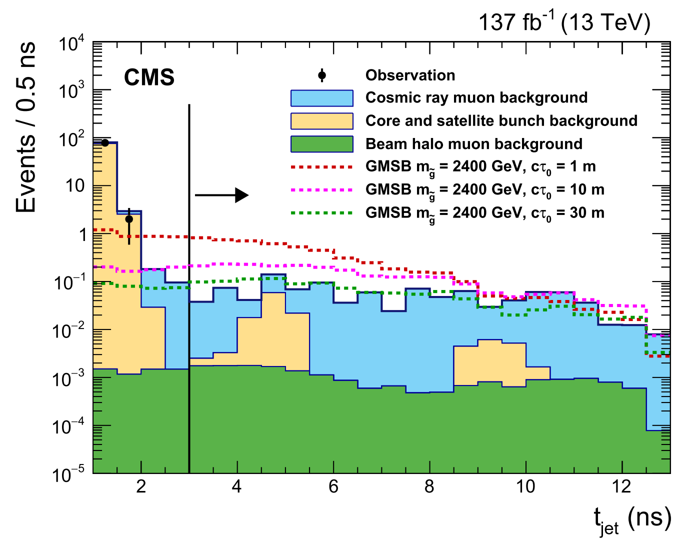

Fig. 2. The timing distribution of the background sources predicted to contribute to the signal region, compared to those for a representative signal model. The time is defined by the jet in the event with the largest t_{jet} passing the relevant selection. The distributions for the major background sources are taken from control regions and normalized to the predictions detailed in Section 6. The observed data is shown by the black points. No events are observed in data for $t_{\mathrm{jet}} > 3$ ns (indicated with a vertical black line).

6.4. Background summary

The estimated background yields and uncertainties are summarized in Table 2. The total background prediction is $1.1^{+2.5}_{-1.1}$ events.

7. Results and interpretation

Fig. 2 shows the timing distribution for events with jets passing all the SR requirements. The distributions for the major background sources are taken from control regions and normalized to the predictions detailed in Section 6. These distributions are shown for illustration only and are not used for the statistical interpretation. The overall background prediction for the SR is $1.1^{+2.5}_{-1.1}$ events, which is consistent with the observation of 0 events.

The model used for the interpretation is the GMSB SUSY model in which gluinos are pair produced and form R-hadrons. The long-

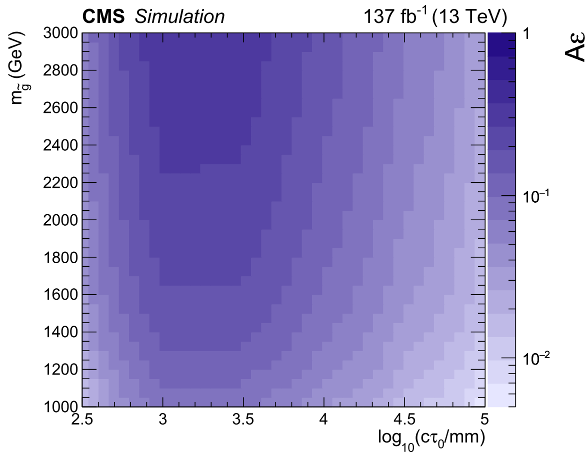

Fig. 3. The product, $\mathcal{A}\varepsilon$, of the acceptance and efficiency in the $c\tau_0$ vs. $m_{\tilde{g}}$ plane for the GMSB model, after all requirements.

lived gluinos then decay to a gluon and gravitino producing a delayed jet and p_T^{miss}.

The trigger efficiency for the simulated samples is evaluated from an emulation. The inefficiency due to the p_T^{miss} trigger requirement ranges from ∼5 to ∼15% for $c\tau_0 = 1$ and 10 m, respectively. The trigger emulation is validated with data using an independent sample collected with a single muon reference trigger.

The product of the experimental acceptance and efficiency ($\mathcal{A}\varepsilon$), shown in Fig. 3, is evaluated independently for each model point, defined in terms of the gluino mass ($m_{\tilde{g}}$) and proper decay length. The efficiency is maximized for high gluino masses and for a range in $c\tau_0$ bounded by the requirements that the gluino must have sufficient lifetime for its decay products to pass the $t_{jet} > 3$ ns requirement and that the gluino must decay before or within the ECAL. For a gluino model with $m_{\tilde{g}} = 2400$ GeV the efficiency is highest (up to ∼35%) for the range $1 < c\tau_0 < 10$ m. The efficiency is larger for higher masses because of the increased p_T^{miss} in the event and the reduced velocity of the gluino.

Interactions of the R-hadrons with the detector lead to signatures exploited by searches for heavy stable charged particles and, in order to maintain model independence, are not considered for the interpretation of this analysis. However, the impact of such interactions was evaluated for two benchmark signal points, $m_{\tilde{g}} = 1500$ GeV and $c\tau_0 = 1$ m, and $m_{\tilde{g}} = 1500$ GeV and $c\tau_0 = 10$ m, using the "cloud" model of R-hadron/matter interactions [51,57], which assumes that the R-hadron is surrounded by a cloud of colored, light constituents that interact during scattering. The fraction of $\tilde{g}$ which hadronize to a neutral $\tilde{g}$-gluon state was taken to be 0.1. Compared to non-interacting R-hadrons, the relative reduction in selection efficiency for both benchmark signal points was found to be ∼15% with the largest effect being on the $\mathrm{PV}_{track}^{fraction}$ and $\max(\Delta\phi_{DT/RPC})$ requirements.

7.1. Signal systematic uncertainties

In order to evaluate systematic uncertainties in the modeling of the variables used to select signal jets (defined in Section 5.1.2), the corresponding distributions for events from the multijet simulation are compared with data. For each variable, the threshold used for the selection is varied in the simulation to match the efficiency measured in data. The change in acceptance from this variation is shown for each of the jet-based variables in Table 3, using an example model point. This variation is taken as a systematic uncertainty in the signal model acceptance. In addition, the variation in t_{jet}^{RMS} is propagated to t_{jet}^{RMS}/t_{jet}.

Table 3
The derived uncertainty in the product, $\mathcal{A}\varepsilon$, of the acceptance and efficiency from the modeling of the variables discussed in Section 5.1.2, for a representative model with $m_{\tilde{g}} = 2400$ GeV.

Variable	Derived uncertainty (%)	
	$c\tau_0 = 1$ m	$c\tau_0 = 10$ m
$\mathrm{PV}_{track}^{fraction}$	0.01	0.03
N_{ECAL}^{cell}	3.2	4.2
HEF	2.8	2.5
E_{ECAL}^{CSC}/E_{ECAL}	0.9	0.9
t_{jet}^{RMS}	22	15

In addition to the uncertainty in the modeling of the variables used to select signal jets, the systematic uncertainties in the signal $\mathcal{A}\varepsilon$ are summarized below.

- Integrated luminosity: 2.5% [37], 2.3% [38], and 2.5% [39] uncorrelated uncertainties for the 2016, 2017, and 2018 data taking periods, respectively.
- Trigger inefficiency: typically 5–15%.
- Limited simulated sample size: up to ∼10%, depending on SR $\mathcal{A}\varepsilon$.
- Pileup reweighting: 4.6% uncertainty in the total inelastic pp cross section [58], which corresponds to an uncertainty in the SR $\mathcal{A}\varepsilon$ of 1–5%.
- Jet energy resolution/scale: a 1–5% percent uncertainty [35].

7.2. Interpretation

Under the signal plus background hypothesis, a modified frequentist approach is used to determine observed upper limits at 95% confidence level (CL) on the cross section (σ) to produce a pair of gluinos, each decaying with 100% branching fraction to a gluon and a gravitino, as a function of $m_{\tilde{g}}$ and $c\tau_0$. The approach uses the LHC-style profile likelihood ratio as the test statistic [59] and the $\mathrm{CL_s}$ criterion [60,61]. The expected and observed upper limits are evaluated through the use of pseudodata sets. Potential signal contributions to event counts in the SR and CRs are taken into consideration.

Fig. 4 shows the observed upper limit on σ as a function of lifetime and gluino mass for the GMSB model. Gluino masses below 2100 GeV are excluded at 95% confidence level for $c\tau_0$ between 0.3 and 30 m. The dependence of the expected and observed upper limit as a function of $c\tau_0$ is shown in Fig. 5 for $m_{\tilde{g}} = 2400$ GeV. The observed limit is compared to the results of the CMS displaced jet search [20], based on a data sample with integrated luminosity of 36.1 fb^{-1}, showing the complementary coverage. These results extend the reach beyond previous searches for models with jets and significant p_T^{miss} in the final state for $c\tau_0 \gtrsim 0.5$ m [17,20,21].

8. Summary

An inclusive search for long-lived particles has been presented, based on a data sample of proton-proton collisions collected at $\sqrt{s} = 13$ TeV by the CMS experiment, corresponding to an integrated luminosity of 137 fb^{-1}. The search uses the timing of energy deposits in the electromagnetic calorimeter to select delayed jets from the decays of heavy long-lived particles, with residual background contributions estimated using measurements in control regions in the data. The results are interpreted using the gluino gauge-mediated supersymmetry breaking signal model and gluino

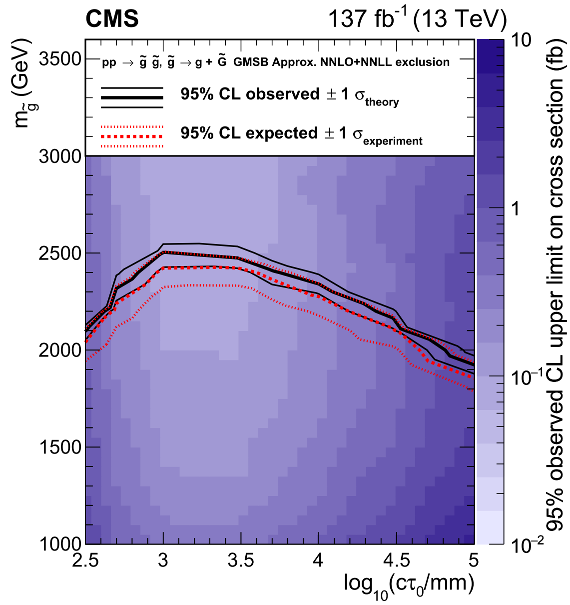

Fig. 4. The observed upper limits at 95% CL for the gluino pair production cross section in the GMSB model, shown in the plane of $m_{\tilde{g}}$ and $c\tau_0$. A branching fraction of 100% for the gluino decay to a gluon and a gravitino is assumed. The area below the thick black curve represents the observed exclusion region, while the dashed red lines indicate the expected limits and their ± 1 standard deviation ranges. The thin black lines show the effect of the theoretical uncertainties on the signal cross section.

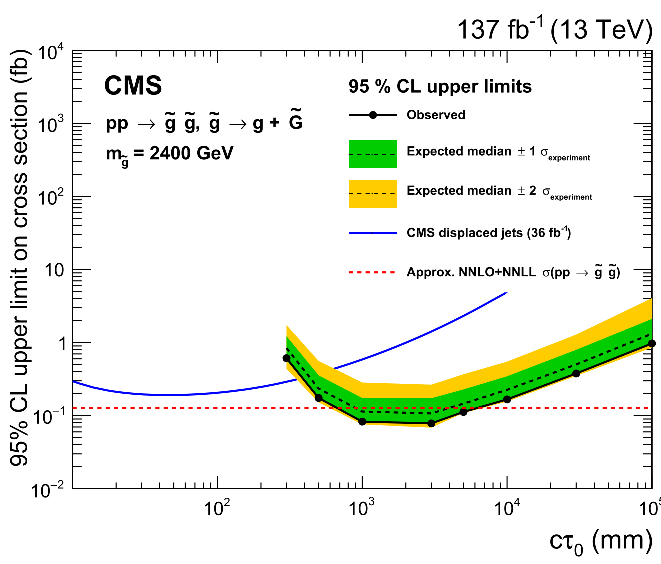

Fig. 5. The observed and expected upper limits at 95% CL on the gluino pair production cross section for a gluino GMSB model with $m_{\tilde{g}} = 2400$ GeV. The one (two) standard deviation variation in the expected limit is shown in the inner green (outer yellow) band. The blue solid line shows the observed limit obtained by the CMS displaced jet search [20].

masses up to 2100, 2500, and 1900 GeV are excluded at 95% confidence level for proper decay lengths of 0.3, 1, and 100 m, respectively. The reach for models that predict significant missing transverse momentum in the final state is significantly extended beyond all previous searches, for proper decay lengths greater than ∼0.5 m.

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