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Search for decays of stopped long-lived particles produced in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

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Abstract

A search has been performed for long-lived particles that could have come to rest within the CMS detector, using the time intervals between LHC beam crossings. The existence of such particles could be deduced from observation of their decays via energy deposits in the CMS calorimeter appearing at times that are well separated from any proton-proton collisions. Using a data set corresponding to an integrated luminosity of $18.6\,\text{fb}^{-1}$ of 8 TeV proton-proton collisions, and a search interval corresponding to 281 hours of trigger livetime, 10 events are observed, with a background prediction of $13.2^{+3.6}_{-2.5}$ events. Limits are presented at 95% confidence level on gluino and top squark production, for over 13 orders of magnitude in the mean proper lifetime of the stopped particle. Assuming a cloud model of R-hadron interactions, a gluino with mass $\lesssim$1000 GeV and a top squark with mass $\lesssim$525 GeV are excluded, for lifetimes between 1 μs and 1000 s. These results are the most stringent constraints on stopped particles to date.

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*See Appendix A for the list of collaboration members

1 Introduction

Many extensions of the standard model (SM) predict the existence of new heavy long-lived particles [1–6]. At the CERN LHC the two general-purpose detectors, ATLAS and CMS, have already set stringent limits on the existence of such particles with searches that exploit the anomalously large ionization and/or long time-of-flight that they would exhibit as they traverse the detectors [7, 8]. Such searches are complemented by others using the technique described in this paper that targets the fraction of such particles that are produced with sufficiently low kinetic energy (KE) that they come to rest in the detectors [9]. In this approach, the subsequent decay of the "stopped" particle is directly targeted, allowing (in principle) the reconstruction of the long-lived particle and the study of its characteristics [10].

New long-lived heavy particles, such as heavy gluinos ($\widetilde{\mathrm{g}}$) and top squarks ($\widetilde{\mathrm{t}}$), could be pair-produced in proton-proton (pp) collisions and combine with SM particles to form R-hadrons [11–13]. These R-hadrons would then traverse the volume of the detector, interacting with detector materials via nuclear interactions and, if charged, by ionization. Below a critical velocity $\lesssim 0.45c$, the KE of the R-hadron is small enough and the energy loss per unit length ($\mathrm{d}E/\mathrm{d}x$) large enough that the particle can come to rest within the body of the detector. At some later time, the stopped R-hadron would then decay. Assuming at least one daughter particle is a SM particle and the R-hadron has stopped in an instrumented region of the detector, the decay could be observable. If this stopping location is in the calorimeter, as is most likely given its density, the experimental signature would be a randomly-timed, relatively large energy response spread over a few channels. Since these depositions might be difficult to differentiate from those of SM particles produced in pp collisions, they would be most easily observed at times between pp collisions. During these times the detector should be quiet with the exception of cosmic rays, some beam-related backgrounds, and instrumental noise. The results of such searches have previously been reported by the D0 collaboration at the Tevatron [14], and by the CMS [15, 16] and ATLAS collaborations [17, 18].

This paper provides an update to the CMS search for stopped particles. The new analysis benefits from a four-fold integrated luminosity increase and uses data resulting from higher energy pp collisions compared to the previous CMS publication [15].

2 The CMS detector and event reconstruction

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 superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL), each composed of a central (barrel) and two forward (endcap) sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid; drift tubes and resistive-plate chambers (RPC) provide coverage in the barrel, while cathode strip chambers (CSC) and RPC provide coverage in the endcaps. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. 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. [19].

Because a stopped particle is by definition at rest, the energy deposits in the calorimeter that result from its decay would not generally be oriented in towers radially towards the pp interaction point of CMS. Nevertheless, such depositions are sufficiently jet-like that they may be reconstructed offline using the anti-k_{T} clustering algorithm [20, 21] with a distance parameter

of 0.5.

3 Data set and Monte Carlo simulation samples

The search is performed using $\sqrt{s} = 8\,\text{TeV}$ pp collision data collected between May and December 2012, corresponding to an integrated luminosity of $18.6\,\text{fb}^{-1}$ and to 281 hours when the dedicated trigger used in this analysis was active ("livetime"). The maximum instantaneous luminosity achieved during this period was $7.5\times10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$. As a control sample, this analysis uses $\sqrt{s} = 7\,\text{TeV}$ pp collision data corresponding to an integrated luminosity of $3.6\,\text{pb}^{-1}$ collected at the beginning of LHC operations in 2010. The control sample includes 253 hours of trigger livetime. Though the integrated luminosity for this period is much smaller than that in 2012, the trigger livetime is comparable because of the longer time interval between collisions in 2010.

Simulated signal Monte Carlo (MC) events for this analysis are generated in three stages. First, we use PYTHIA 8.1 [22] to generate $\text{pp} \to \widetilde{\text{g}}\widetilde{\text{g}}$ and $\text{pp} \to \widetilde{\text{t}}\bar{\widetilde{\text{t}}}$ events. The colored sparticles are hadronized with the default parameters in the RHADRONS package included in PYTHIA 8. These parameters influence technical aspects of the hadronization process, e.g. the fraction of produced R-hadrons that contain a gluino and a valence gluon, which is set to 10%. Because of the nature of the stopped-particle technique, these parameters do not have a significant effect on the phenomenology. The passage of the R-hadrons through the detector is simulated with GEANT4 [23]. A phase-space driven "cloud model" of R-hadron interactions with the material of the CMS detector [24, 25], referred to as the "generic" model in Ref. [17], is used to simulate the interaction of these R-hadrons with the CMS detector. In this model, which has emerged as the standard benchmark for these searches, R-hadrons are treated as supersymmetric particles surrounded by a cloud of loosely bound quarks or gluons. Alternative models of R-hadronic interactions with matter could be used: for a model in which R-hadrons only dissipate energy via the electromagnetic interaction, the stopping probability would be slightly less, and in a "Regge" model where only one (electrically neutral) R-baryonic state is allowed [26, 27] the stopping probability would be significantly reduced. We do not report results using these alternative models.

The KE of these simulated R-hadrons is diminished though nuclear interactions and ionization, and they can thus come to rest within the body of the CMS detector. If this occurs, the position in the CMS coordinate system of the stopped R-hadron is recorded. The second stage of the simulation generates an R-hadron, translates it to the stopping position recorded in stage 1, and causes it to decay at rest via a second GEANT4 step. The gluino decay is simulated as $\widetilde{\text{g}} \to \text{g}\widetilde{\chi}^0$ and the top squark decay is simulated as $\widetilde{\text{t}} \to \text{t}\widetilde{\chi}^0$, where $\widetilde{\chi}^0$ is the lightest neutralino in both instances. The first stage allows estimation of the stopping probability $\varepsilon_{\text{stopping}}$, and the second stage allows estimation of the reconstruction efficiency $\varepsilon_{\text{reco}}$. While any spin correlation of the decaying gluino with its pair produced partner is lost in this approach, no observable effects of this omission are expected [28]. The probability for the subsequent decay of a stopped particle to occur at a time when the trigger is live is estimated with a custom third stage pseudo-experiment MC simulation. We randomly generate decay times according to the exponential distribution expected for a given lifetime hypothesis and compare these to the delivered luminosity profile and actual bunch structure of each LHC fill, and all relevant CMS trigger rules, in order to determine an effective luminosity (L_{eff}) for each lifetime hypothesis.

4 Event selection

We perform the search with a dedicated trigger used to select events out-of-time with respect to collisions. A series of offline selection criteria are then applied to exclude events likely due to background processes. We also consider samples for which the jet energy threshold requirement has been increased. Since the backgrounds fall off rapidly with jet energy, this is a powerful technique to isolate signal. However, increasing the jet energy threshold to isolate a signal also decreases the region of phase space available to the search. Therefore, results for a variety of jet energy thresholds are presented. For each threshold, a counting experiment is performed in which we compare the number of selected events to the number of predicted background events that have passed the offline selection criteria.

The LHC beams are composed of circulating bunches of protons. At the experiments, bunch crossings (BX) occur at intervals of 25 ns. However, not every BX contains protons. This search looks for events in the BXs that do not contain colliding bunches of protons, i.e. they are "out-of-time" with respect to normal collisions.

Such events are recorded using an updated version of the calorimeter trigger employed in the earlier CMS study [15, 16] that uses the two beam position and timing monitors (BPTX) that are positioned along the beam axis, at either end of the CMS detector close to the beams. These BPTX are sensitive electrostatic instruments that are able to detect the passage of an LHC proton bunch. Consequently, in order to search for out-of-time events, we employ a dedicated trigger that requires an energy deposit in the calorimeter trigger together with the condition that neither BPTX detects a bunch in that BX. We also require that at most one BPTX produces a signal in a window ± 1 BX around the triggered event. This rejects triggers due to out of time "satellite" bunches that occasionally accompany the colliding protons. The energy deposition in the calorimeter of a jet from the R-hadron decay is sufficiently similar to those of jets originating directly from pp collisions that a calorimeter jet trigger can be used. At the hardware trigger level (L1), the jet transverse energy, which is calculated assuming the jet was produced at the nominal interaction point, is required to be greater than 32 GeV, while in the software trigger (HLT) the jet energy is required to be greater than 50 GeV. At both L1 and HLT $|\eta_{\text{jet}}|$ is required to be less than 3.0. Finally, the trigger vetoes any event that is accompanied by a L1 endcap muon beam-halo trigger within a ± 1 BX window.

We select events more than ± 1 BX away from an in-time pp collision. Additionally, to remove rare events in which an out-of-time pp collision somehow occurred, usually caused by residual protons found in between proton bunches, we veto events that include reconstructed charged track vertices consistent with a pp collision. Finally, we require that a jet is reconstructed with an energy of at least 70 GeV. This threshold is set just above the turn-on plateau for the 50 GeV trigger.

Halo muons are a source of background for this analysis. Halo muons are produced when off-orbit protons in the LHC beam strike material in some limiting aperture of the LHC upstream of the CMS detector. The resulting collision produces a shower of particles, most of which decay before reaching CMS. Muons are produced in these decays and, given their long lifetimes and the fact that they undergo only electroweak interactions, they can survive long enough to traverse the detector. When they pass through the denser regions, they can emit a bremsstrahlung photon that strikes the calorimeter and can be reconstructed with large enough energy to be included in the search sample. We remove these events by vetoing any event in which there are hits recorded within the CSC forward muon chambers. The low-noise rate of the CSC detectors allows the requirement to be set at the single-hit level, which enables the maximal exclusion of this background.

Muons from cosmic rays incident on the CMS detector can also mimic the signal characteristics. Similar to the halo background, cosmic ray muons may emit a photon that strikes the calorimeter, leaving a large energy deposit. To remove such events, we consider the distribution of reconstructed hits within the barrel muon system. Compared to the expected signal, there are key differences with cosmic ray muons that can be exploited. It is possible that heavy R-hadron decay products have a large enough energy to "punch through" the outer region of the calorimeter and the first layers of the iron yoke of the solenoid, leaving energy deposits in the muon system. This phenomenon is easily distinguished from cosmic ray muons by considering the distribution of reconstructed hits. In the case of cosmic ray muons, we expect hits evenly distributed throughout the barrel of the muon system, whereas for signal events, we expect the hits to be restricted to the innermost layers of the muon system. Additionally, in the case of punch-through, the muon hits should be localized near the reconstructed jet. Unlike signal events, hits from cosmic ray muons may also appear at an azimuthal angle (ϕ) opposite to that of the reconstructed jet. Exploiting these properties, we are able to substantially reduce the cosmic background contaminating the signal region by removing events with hits in the outer layers of the muon system, events with hits recorded in both the top and bottom of the muon system, and events with hits in the muon system opposite in ϕ to the leading jet.

The final source of background stems from instrumental noise in the calorimetry system, primarily within the HCAL. Noise in the HCAL can give rise to events in which an errant spike in energy is recorded, unrelated to any physical interaction with particles produced inside the detector. These occurrences are rare, but the calorimeter response resembles the anticipated signal and must be removed. We use a series of offline criteria that exploit the well-defined timing and topology of these spikes to remove these events. These criteria are detailed in Ref. [16] and are applied as in that analysis with the exception of the requirement that the leading jet has at least 60% of its energy contained in fewer than 6 towers, which is now omitted.

5 Signal efficiency

Using the stage 1 MC simulation described in Section 3, we estimate the probability of an R-hadron to stop within the instrumented regions of the detector. In particular, we are interested in R-hadrons that stop in the barrel region of the calorimeter, since these are the regions where we can observe the subsequent jet-like energy deposits from the decay products. We exclude the endcap calorimeters since the signal-to-background ratio is less favorable in this region. R-hadrons could also stop within the iron yokes interleaved with the muon detector system, but we expect a negligible efficiency to detect the corresponding decays. The simulation demonstrates that the stopping probability is approximately constant over the range of R-hadron masses considered in this search. The probability that at least one R-hadron is stopped within the barrel region of the calorimeter is found to be 8% for gluinos with $m_{\tilde{g}} = 800\,\text{GeV}$ and 6% for top squarks with $m_{\tilde{t}} = 400\,\text{GeV}$. The slighter larger $\varepsilon_{\text{stopping}}$ obtained for gluinos is because of their greater propensity to form doubly charged states.

For the particles that stop and then decay within the calorimeter, we estimate an approximate trigger efficiency of 70%. We define $\varepsilon_{\text{reco}}$ as the number of signal events that pass all selection criteria (including the trigger requirement) divided by the number of signal events that stop within the barrel region of the calorimeter. The reconstruction efficiency depends principally on the energy of the visible daughter particle of the R-hadron decay, E_{g} or E_{t}. The reconstruction efficiencies obtained for gluinos and top squarks are plotted as a function of this energy in Fig. 1. Above the minimum energy threshold for the SM decay products, where $\varepsilon_{\text{reco}}$ becomes approximately constant, $E_{\text{g}} > 120\,\text{GeV}$ ($E_{\text{t}} > 150\,\text{GeV}$), we obtain $\varepsilon_{\text{reco}} \approx 45\%$ (32%) for $\widetilde{\text{g}}(\widetilde{\text{t}})$

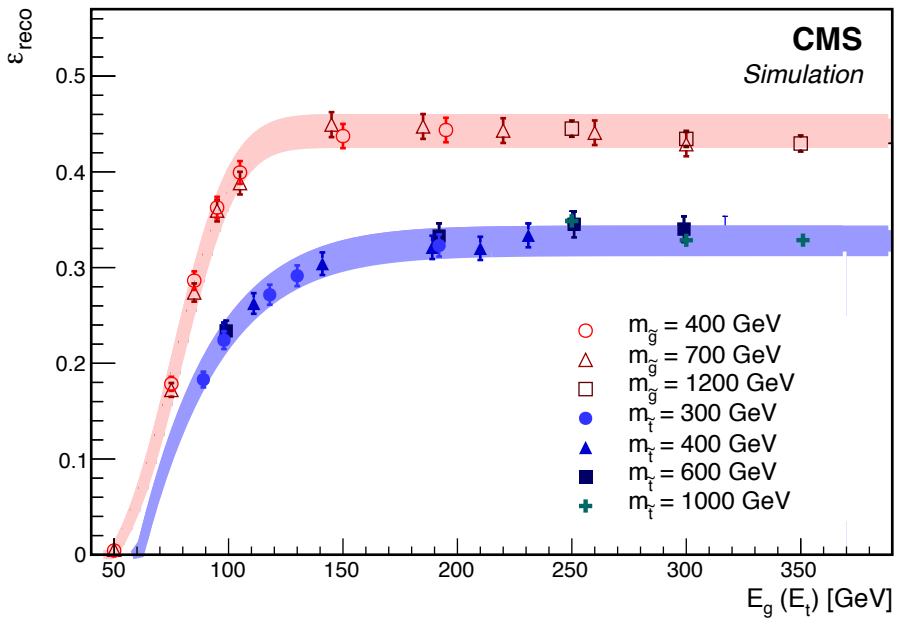

Figure 1: The reconstruction efficiency ε_{reco} for $\tilde{g}$ and $\tilde{t}$ R-hadrons that stop in the barrel region of the calorimeter as a function of the energy of the produced SM daughter particle. The shaded bands indicate the systematic uncertainty in ε_{reco}.

decays. The top squark efficiency is lower than the gluino efficiency primarily because of $t \to b\mu\nu$ decays that yield less visible energy in the calorimeter and are rejected by the muon vetoes. When E_t is below m_t, which can happen in cases when the mass splitting between the $\tilde{t}$ and $\tilde{\chi}^0$ is small, the top quark is off the mass-shell.

The signal efficiency is given by the product of $\varepsilon_{stopping}$ and ε_{reco}.

6 Backgrounds

It is possible for halo muons to escape detection in the endcap muon system. Escaping detection is uncommon, but owing to the high rate of halo production in the 2012 data collection period, the expected halo background is non-negligible. We estimate the halo veto inefficiency using a tag-and-probe method [29] that analyzes control samples to determine the rates at which we record hits on both ends of the endcap muon detectors, compared to the rate at which we see only the "incoming" or "outgoing" portions of the halo muon track. Because of timing and trigger effects, we may only observe the outgoing leg of the halo muon, with the incoming leg recorded in a previous BX. When the reverse occurs, we see only the incoming leg. Additionally, it is possible for the muon to lose all of its energy within the CMS detector before reaching the opposite side CSC chambers, which also results in an incoming-only event. We classify these events as to whether the halo originates from the clockwise or counterclockwise beam, and bin them by their geometric location in the endcap muon system. After integrating these distributions, we measure a halo veto inefficiency of 1×10^{-5}. This inefficiency is multiplied by the number of positively-identified halo events in the search sample, giving us an average halo background estimate of 8.0 ± 0.4 events.

To determine the rate at which cosmic ray muons escape detection by the cosmic muon veto, we generate a sample of 300 million simulated cosmic events. After requiring a substantial energy deposit in the calorimeter and the absence of any hits in the muon endcap system that would cause the event to be classified as a halo muon, we estimate the inefficiency of the cosmic muon veto by dividing the number of events that escape this veto by the total number of events. The inefficiency obtained in this manner is roughly 0.5%, corresponding to a predicted cosmic background of 5.2 ± 2.5 events.

Finally, the background owing to instrumental noise is estimated by considering data recorded in 2010. Figure 2 shows the measured noise rates in both periods. In these plots all selection criteria except those that are designed to reject noise are applied. Additionally, only events at least 5 BX from a bunch are considered. This is done to reduce halo contamination in the distributions, which is abundant directly after a bunch crossing. There is a greater variation in the 2012 noise rate because of increased halo background, which can mimic HCAL noise if no CSC hits are present. The small variation seen in the 2012 data, while larger than that seen in 2010, is nevertheless small compared to the systematic uncertainty in the noise event count. The larger variations observed in the 2012 data are attributed to residual halo contamination arising from non-standard LHC beam conditions.

Because the rate of instrumental noise is approximately constant between the two periods, and the data recorded in early 2010 were delivered with very low instantaneous luminosity, this sample is unlikely to contain either halo events or signal events. After applying the same selection criteria to the 2010 data sample as used in this analysis, two events remain. We estimate the cosmic ray muon contribution to this sample to be 4.8 ± 3.6 events. Because the cosmic ray background estimate exceeds the number of observed events, we assume a central value of zero events for the instrumental noise contribution to the 2010 sample, and allowing for Poisson fluctuations in both the noise and cosmic ray muon contributions, set a 68% confidence level (CL) upper limit on this contribution of 2.3 events. This estimate is then scaled by the ratio of the 2012 and 2010 livetimes, resulting in an expected noise contribution of $0.0^{+2.6}_{-0.0}$ events in the 2012 data set.

7 Sources of systematic uncertainties

The model-independent results of the counting experiment described in this paper have relatively few systematic uncertainties. There is a 2.5% uncertainty in the integrated luminosity [30]. There is a 13% uncertainty in the reconstruction efficiency resulting from the possibility that even above the minimum value of E_g (E_t), this efficiency is not completely independent of the energy of the daughter particle as is assumed. This uncertainty is determined by considering the difference between the individual values of ε_{reco} in Fig. 1 and the average value for all points above the minimum value of E_g (E_t). The shaded bands in the figure depict this uncertainty. Because the energy deposits resulting in reconstructed jets are not the result of jets originating from the center of the detector (as is the case for jets originating from pp collisions), they are not necessarily directed radially, and standard uncertainties in the jet energy scale (JES) do not apply. Instead, we determine the JES uncertainty by referencing a study performed on the HCAL during cosmic ray data taking in 2008 [31]. This study compares the reconstructed energy deposits in the HCAL for simulated cosmic ray events and cosmic ray events in 2008 data. These comparisons lead to an estimated uncertainty of $\sim$2% on the simulation. A similar study comparing data and simulation for dijets originating at the interaction point conducted with 2012 data yielded an uncertainty of $<$2% for jets striking the HCAL barrel with angles of incidence from 0 to 60 degrees [32]. While the study demonstrates that the HCAL response

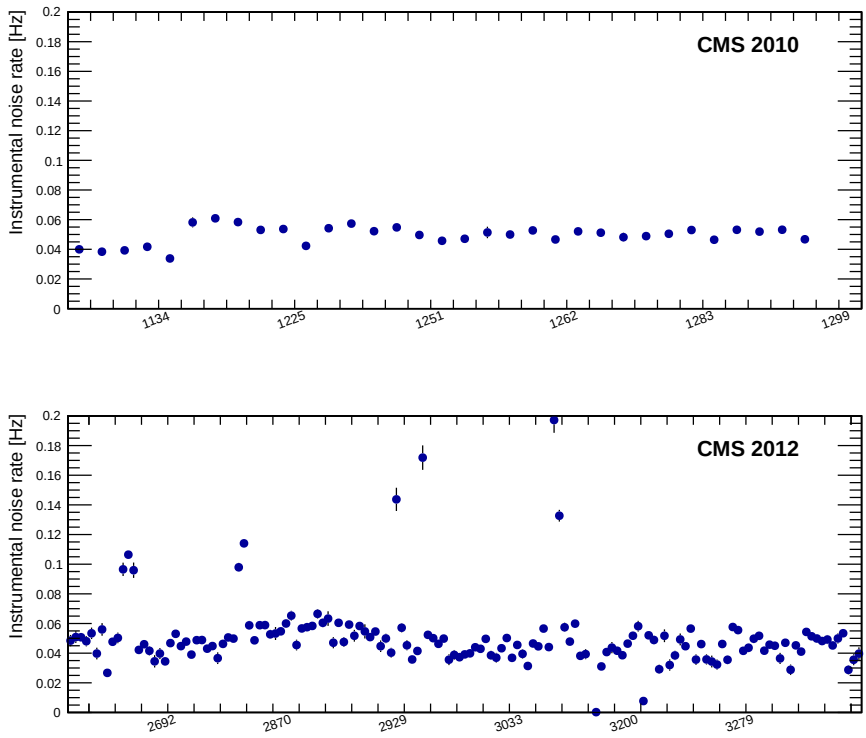

Figure 2: The noise rates from 2010 data (top) and 2012 data (bottom).

is well simulated with an uncertainty of about 1%, we take a conservative JES uncertainty of 3% to compensate for any effects of stopped particle decays that these studies cannot test because of the potentially large angles that could sometimes be expected in the signal decays. This value for the JES uncertainty leads to an uncertainty in the search results of about 2% at the minimum value of E_g. The value of 3% is somewhat pessimistic since the uncertainty falls rapidly as E_g increases. Variations in the reconstructed jet energy are only important for deposits with energies close to the jet energy threshold, which typically correspond to events in which E_g is small.

In obtaining constraints on a particular model, however, more substantial uncertainties arise since the signal yield is sensitive to the stopping probability. While the GEANT4 simulation used to derive the stopping probability very accurately models both the electromagnetic and nuclear interaction energy-loss mechanisms, the relative contributions of these energy-loss mechanisms to the stopping probability depends significantly on unknown R-hadron spectroscopy. We do not consider this dependence to be a source of error, however, since given a particular model for the spectrum the resultant uncertainty in the stopping probability is small.

In addition to these uncertainties in the signal efficiency, there is also a systematic uncertainty in the background estimate described in Section 6. This systematic uncertainty arises from the limited size of the data control samples that were used to estimate the contribution of each of the background processes to the search sample.

The systematic uncertainties are summarized in Table 1.

Table 1: Summary of systematic uncertainties.

Systematic uncertainty	Fractional uncertainty
JES uncertainty	$\pm 3\%$
Luminosity uncertainty	$\pm 2.5\%$
$\varepsilon_{\text{reco}}$ uncertainty	$\pm 13\%$
Background uncertainty	$+27\%, -19\%$

8 Results

The total and individual background estimates for both the 2012 search period and the 2010 control period used to determine the background from instrumental noise, are summarized in Table 2, together with the number of observed events.

Table 2: Background predictions and observed events for the 2010 control and 2012 search samples.

Period	Trigger livetime (h)	$N^{\text{bkg}}_{\text{noise}}$	$N^{\text{bkg}}_{\text{cosmic}}$	$N^{\text{bkg}}_{\text{halo}}$	$N^{\text{bkg}}_{\text{total}}$	N^{obs}
2010	253	$0.0^{+2.3}_{-0.0}$	4.8 ± 3.6	—	$4.8^{+4.3}_{-3.6}$	2
2012	281	$0.0^{+2.6}_{-0.0}$	5.2 ± 2.5	8.0 ± 0.4	$13.2^{+3.6}_{-2.5}$	10

With the assumption that the backgrounds listed in Table 2 are uniformly distributed in time, which is valid even for the halo background for times at least one BX away from the collision as our selection requires, we perform a counting experiment in equally spaced log(time) bins of gluino (top squark) lifetime hypotheses, $\tau_{\tilde{g}}(\tau_{\tilde{t}})$, from 10^{-7} to 10^{6} seconds. For lifetime hypotheses shorter than one orbit (89 μs), we count only candidates within a sensitivity-optimized time window of $1.3\tau_{\tilde{g}}(\tau_{\tilde{t}})$ from any pp collision. This restriction avoids the addition of backgrounds for time intervals during which the signal has a high probability to have already decayed. In order to resolve any time structure in the data within a single orbit, we test two additional lifetime hypotheses for each observed event for these counting experiments: the largest lifetime hypothesis for which the event lies outside $1.3\tau_{\tilde{g}}(\tau_{\tilde{t}})$, and the smallest lifetime hypothesis for which the event is contained within $1.3\tau_{\tilde{g}}(\tau_{\tilde{t}})$. Table 3 shows the results of the counting experiments for selected lifetime hypotheses. The observed number of events is consistent with the background expectation for all lifetime hypotheses tested.

Table 3: Results of counting experiments for selected lifetime hypotheses.

Lifetime hypothesis	L_{eff} (fb^{-1})	Trigger livetime (s)	Expected bkg.	Observed
50 ns	0.121	5.0×10^{4}	$0.66^{+0.18}_{-0.07}$	0
75 ns	0.271	1.0×10^{5}	$1.3^{+0.4}_{-0.2}$	3
100 ns	0.512	2.0×10^{5}	$2.6^{+0.7}_{-0.5}$	3
1 μs	2.864	8.4×10^{5}	$11.0^{+3.0}_{-2.1}$	6
10 μs	3.885	1.0×10^{6}	$13.1^{+3.6}_{-2.4}$	10
100 μs	3.972	1.0×10^{6}	$13.2^{+3.6}_{-2.5}$	10
10^{3} s	3.868	1.0×10^{6}	$13.2^{+3.6}_{-2.5}$	10
10^{4} s	3.004	1.0×10^{6}	$13.2^{+3.6}_{-2.5}$	10
10^{5} s	1.727	1.0×10^{6}	$13.2^{+3.6}_{-2.5}$	10
10^{6} s	1.181	1.0×10^{6}	$13.2^{+3.6}_{-2.5}$	10

8.1 Limits on gluino and top squark production

We obtain upper limits on the signal production cross section using a hybrid CL_S method [33, 34] to incorporate the systematic uncertainties [35]. These limits are presented in Fig. 3 as a function of particle lifetime τ. The two left-hand axes of Fig. 3 are production cross section times branching fraction ($\sigma \times \mathcal{B}$) for top squarks and gluinos, assuming the total energy of the SM particle in the decay satisfies either $E_g > 120\,\text{GeV}$ or $E_t > 150\,\text{GeV}$ for the gluino and top squark analyses, respectively. The minimum energy of the SM particle is set by considering the reconstruction efficiency shown in Fig. 1. Below this energy, the reconstruction efficiency drops off rapidly and we are significantly less sensitive to $\tilde{g}$ and $\tilde{t}$ decays. By not making a specific neutralino mass hypothesis, we are able to constrain a larger phase space of top squark decays, including the region where the top squarks are off mass-shell. The right-hand axis of Fig. 3 shows the quantity $\sigma \times \mathcal{B} \times \varepsilon_{\text{stopping}} \times \varepsilon_{\text{reco}}$, which is more model independent.

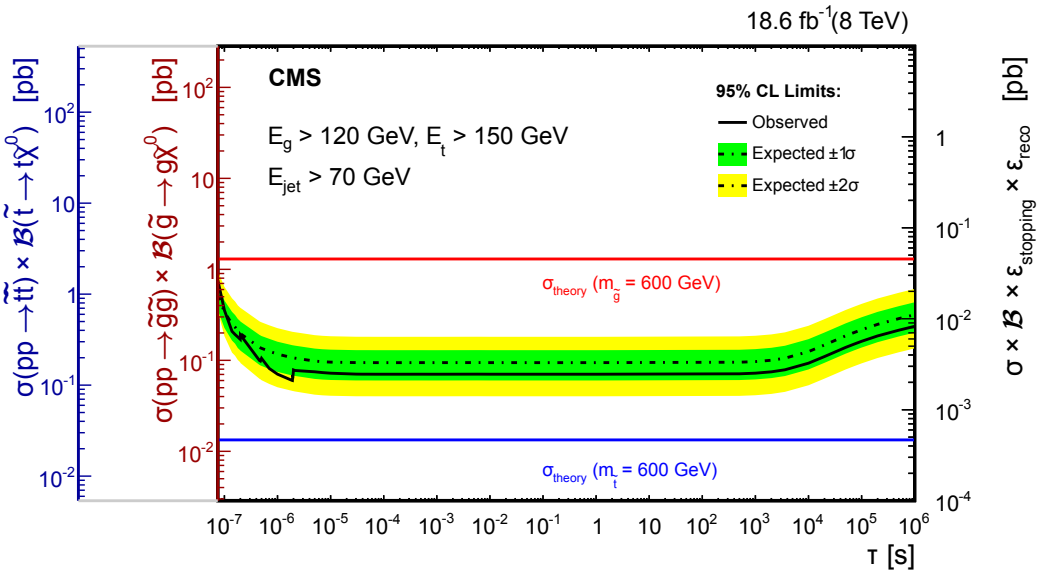

Figure 3: The left-hand axes present expected and observed 95% CL upper limits on top squark and gluino pair production cross sections using the cloud model of R-hadron interactions, as a function of particle lifetime. The NLO+NLL cross sections shown were obtained with NLL-FAST [36]. The right-hand axis shows the quantity $\sigma \times \mathcal{B} \times \varepsilon_{\text{stopping}} \times \varepsilon_{\text{reco}}$, which is more model independent. The structure observed between 10^{-7} and 10^{-5} s is due to the number of observed events incrementing when crossing boundaries between lifetime bins. When $E_t < m_t$, the top quark is off the mass shell.

8.2 Limits on gluino and top squark mass

Figure 4 shows the limits on gluino and top squark mass as a function of the particle lifetime. The production cross sections at $\sqrt{s} = 8\,\text{TeV}$ were obtained at next-to-leading order in α_s with next-to-leading-logarithmic soft gluon summation (NLO+NLL) using NLL-FAST [36], with the assumption that any other sparticles are decoupled. Assuming $\mathcal{B}(\tilde{g} \to g\tilde{\chi}^0) = 100\%$ and $\mathcal{B}(\tilde{t} \to t\tilde{\chi}^0) = 100\%$, we are able to exclude $m_{\tilde{g}} < 880\,\text{GeV}$ and $m_{\tilde{t}} < 470\,\text{GeV}$ at 95% CL for $1\,\mu\text{s} < \tau < 1000\,\text{s}$ with $E_g > 120\,\text{GeV}$ and $E_t > 150\,\text{GeV}$. Because of the requirements on the minimum energies for the gluon (top quark), these limits do not apply for all neutralino masses, as discussed in the next section.

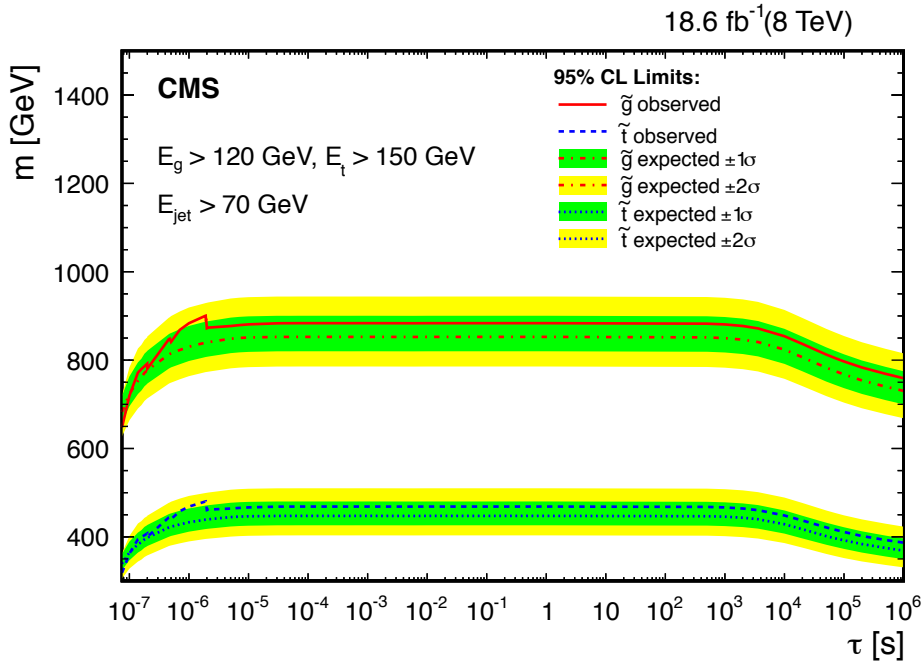

Figure 4: Lower limits at 95% CL on gluino and top squark mass as a function of particle lifetime, assuming the cloud model of R-hadron interactions and NLO+NLL production cross sections given in Ref. [37]. When $E_t < m_t$, the top quark is allowed to go off the mass shell.

8.3 Results for higher energy thresholds

With the selection criteria described previously, we are able to reduce background contamination to acceptable levels. We can, however, be more aggressive with the removal of backgrounds by increasing the jet energy threshold. Since ε_{reco} is essentially flat above the minimum energy of E_g or E_t, and the background falls steeply with energy, we potentially obtain stronger limits on the production cross section by running the analysis with an increased jet energy threshold. This more aggressive method of reducing background was performed for thresholds of 100, 150, 200, and 300 GeV. However, as the jet energy threshold increases, the sensitivity to heavy $\tilde{\chi}^0$ degrades. If there is a smaller mass splitting between $\tilde{g}(\tilde{t})$ and $\tilde{\chi}^0$, the amount of energy available for the visible decay product is small.

To perform the analysis at the higher jet energy thresholds, the threshold is first applied to the simulated signal to calculate the minimum energy of E_g or E_t and ε_{reco} for each threshold. Next, we repeat the analysis of the 2010 data to estimate the instrumental noise rate at the increased threshold, and then the cosmic and beam halo rates are determined as for the main analysis with the 70 GeV jet energy threshold. The resultant contributions of each background source to each signal region are presented in Table 4. Limits on gluino and squark masses for each threshold are presented in Table 5. These limits are valid for the minimum value of E_g and E_t that we calculate from the turn-on curves shown in Fig. 5. These minimum values are listed in Table 5 for each threshold; they increase with the increased jet energy threshold because the turn on plateau for ε_{reco} moves in response to the higher thresholds as seen in Fig. 5.

The systematic uncertainties in ε_{reco} and integrated luminosity are unaffected by the increase in the jet energy threshold. However, the systematic uncertainty resulting from the JES does vary somewhat with different thresholds. The final JES uncertainty is calculated by measuring the change in ε_{reco} when the jet energy threshold requirement is varied according to the JES

systematic uncertainty. Variations in the jet energy requirement have the largest impact for gluon (top) energies close to the threshold, so we perform this calculation on simulated signal samples corresponding to the minimum values of E_g (E_t).

As mentioned previously, increasing the jet energy threshold affects the masses of $\tilde{\chi}^0$ that are accessible to the analysis. Figure 6 summarizes how these different jet energy thresholds exclude different regions of the $(m_{\tilde{g}}, m_{\tilde{\chi}^0})$ phase space. Figure 7 does the same for the $(m_{\tilde{t}}, m_{\tilde{\chi}^0})$ phase space, though it only applies to on-shell top quark decays because $m_{\tilde{\chi}^0}$ is unknown when the top goes off mass-shell. It should be noted that the minimum lifetime for the higher threshold limits increases from 1 μs to 10 μs. This decrease in sensitivity to smaller lifetimes is due to the smaller sample size associated with the increased energy requirement.

Table 4: Background estimates for various energy thresholds.

Thresh. (GeV)	$N^{\text{bkg}}_{\text{noise}}$	$N^{\text{bkg}}_{\text{cosmic}}$	$N^{\text{bkg}}_{\text{halo}}$	$N^{\text{bkg}}_{\text{total}}$
70	$0.0^{+2.6}_{-0.0}$	5.2 ± 2.5	8.0 ± 0.4	$13.2^{+3.6}_{-2.5}$
100	$0.0^{+2.0}_{-0.0}$	3.1 ± 1.2	1.7 ± 0.4	$4.9^{+2.4}_{-1.2}$
150	$0.0^{+2.2}_{-0.0}$	1.6 ± 1.0	0.6 ± 0.1	$2.1^{+2.4}_{-1.0}$
200	$0.0^{+1.3}_{-0.0}$	0.5 ± 0.4	0.5 ± 0.1	$0.7^{+1.4}_{-0.4}$
300	$0.0^{+1.3}_{-0.0}$	0.4 ± 0.4	0.04 ± 0.02	$0.4^{+1.3}_{-0.4}$

Table 5: Lower limits on gluino and top squark masses obtained from the analyses with varied jet energy thresholds.

Threshold (GeV)	N_{bkg}	N_{obs}	E_g^{min}(GeV)	$m_{\tilde{g}}$ limit (GeV)	E_t^{min}(GeV)	$m_{\tilde{t}}$ limit (GeV)
70	$13.2^{+3.6}_{-2.5}$	10	120	880	150	470
100	$4.9^{+2.4}_{-1.2}$	1	150	990	200	530
150	$2.1^{+2.4}_{-1.0}$	0	220	1010	300	550
200	$0.7^{+1.4}_{-0.4}$	0	320	1020	360	550
300	$0.4^{+1.3}_{-0.4}$	0	430	1020	470	550

9 Summary

A search has been made for long-lived particles that have stopped in the CMS detector after being produced in 8 TeV pp collisions at the CERN LHC. The subsequent decay of these particles was looked for during gaps between proton bunches in the LHC beams. In a data set with a peak instantaneous luminosity of $7.5 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$, an integrated luminosity of $18.6\,\text{fb}^{-1}$, and a search interval corresponding to 281 hours of trigger livetime, no excess above background is observed. Limits are presented at 95% CL on gluino and top squark production over 13 orders of magnitude in the mean proper lifetime of the stopped particle. Assuming a cloud model of R-hadron interactions, for $E_g > 120\,\text{GeV}$, and $\mathcal{B}(\tilde{g} \to g\tilde{\chi}^0) = 100\%$, gluinos with lifetimes from 1 μs to 1000 s and $m_{\tilde{g}} < 880\,\text{GeV}$ are excluded. Under similar assumptions, $E_t > 150\,\text{GeV}$, and $\mathcal{B}(\tilde{t} \to t\tilde{\chi}^0) = 100\%$, long-lived top squarks with lifetimes from 1 μs to 1000 s and $m_{\tilde{t}} < 470\,\text{GeV}$ are excluded. By increasing the jet energy requirement, these mass exclusions increase to $m_{\tilde{g}} \lesssim 1000\,\text{GeV}$ and $m_{\tilde{t}} \lesssim 525\,\text{GeV}$ in a more restricted region of parameter space. In all cases, these exclusions require that $m_{\tilde{\chi}^0}$ is kinematically consistent with the minimum values of E_g and E_t. These results are the most stringent constraints on stopped particles to date.

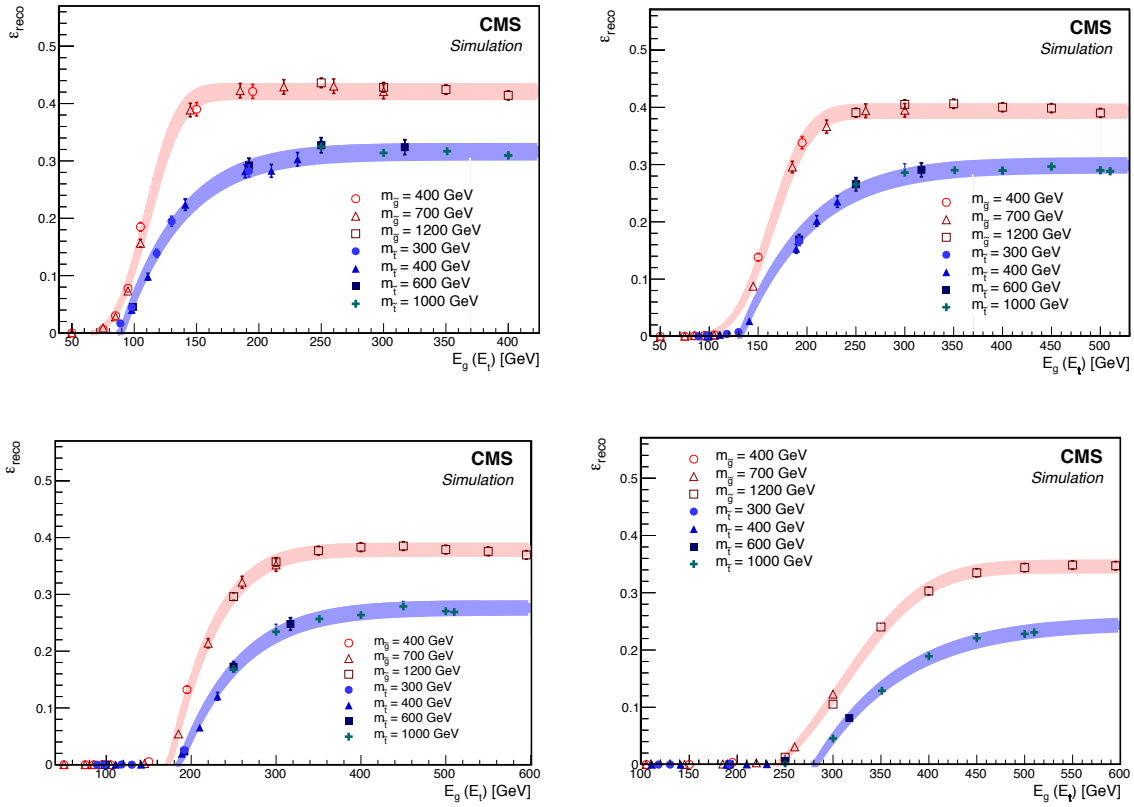

Figure 5: The reconstruction efficiency ε_{reco} for $\tilde{g}$ and $\tilde{t}$ R-hadrons that stopped in the barrel region of the calorimeter as a function of the energy of the SM daughter particle for jet energy thresholds of 100, 150, 200, and 300 GeV.

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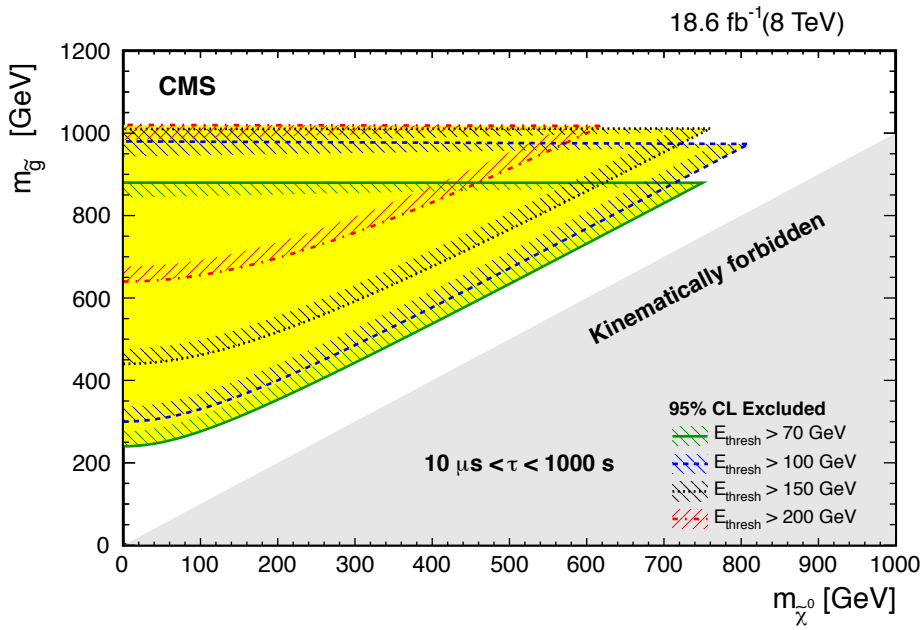

Figure 6: Regions of the $m_{\tilde{g}} - m_{\tilde{\chi}^0}$ plane excluded by the analysis, valid for 10^{-5} s $< \tau < 10^3$ s using thresholds as indicated in the legend.

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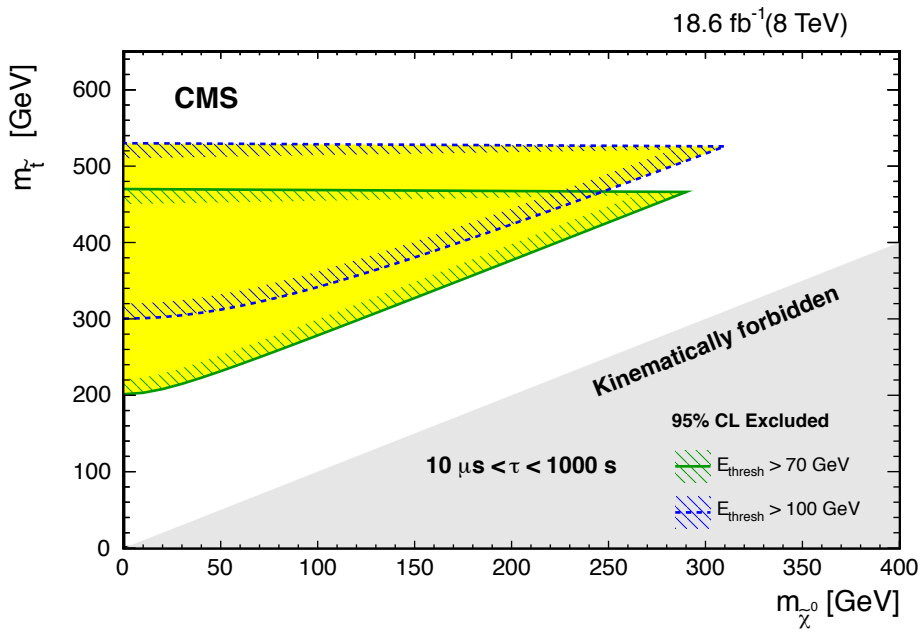

Figure 7: Regions of the $m_{\tilde{t}} - m_{\tilde{\chi}^0}$ plane excluded by the analysis, valid for 10^{-5} s $< \tau < 10^3$ s using two energy thresholds as indicated in the legend. The excluded regions only apply to on-shell top quarks.

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