PROCEEDINGS OF SCIENCE

Searches for long-lived particles with the CMS experiment

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The current status of the searches for exotic, long-lived particles with the CMS experiment at $\sqrt{s} = 13$ TeV is presented. Many theories beyond the Standard Model predict long-lived particles, for which different search approaches are utilized from those used in prompt searches. The searches discussed include the latest results at the time of the conference and cover a wide range of signatures. Searches for exotic, long-lived particles using inclusive displaced jets, displaced vertices in multijet events, disappearing tracks, heavy stable charged particles, and stopped particles are discussed, as well as reinterpretations of two recently published prompt searches, which complement the dedicated searches. The search and results are summarized for each analysis.

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1. Introduction

Searches for exotic, long-lived particles (LLP) play an important part in the search for physics beyond the Standard Model (BSM). In this paper, the current status of recently published searches with the CMS experiment at a center-of-mass energy of $\sqrt{s} = 13$ TeV is presented. Most BSM searches target promptly decaying particles with a decay length smaller than 0.1 mm. Specially designed searches for exotic LLPs with masses of the order 100 GeV on the other hand could potentially uncover a hidden sector of physics, as many BSM theories predict exotic LLPs, such as supersymmetry (SUSY) with split, anomaly-mediated, or gauge-mediated SUSY-breaking. Here, the production and decay happen at a distance greater than 0.1 mm from the interaction point. In comparison to prompt BSM searches, customized triggers and customized event reconstruction can become necessary, as for example in the searches using inclusive displaced jets or displaced vertices in multijet events. A description of the CMS detector can be found in [1]. The search and results are summarized for each analysis in the following sections.

2. Inclusive displaced jets

The search published in [2], performed with data corresponding to an integrated luminosity of 2.6 fb^{-1}, uses the multiplicity of displaced jets to search for new LLPs with decay lengths between 1 and 1000 mm. One possible theoretical motivation is a jet-jet model which resembles a hidden valley structure and predicts pair-produced long-lived scalar neutral particles X^0 decaying to a quark-antiquark pair. Another motivation is a b-lepton model with R-parity violation, in which long-lived top squarks decay to one b quark and a lepton. In addition, combinations of both models with varying branching fractions are considered.

Events with at least two displaced jets and up to two associated prompt tracks are selected and categorized using two custom-built high-level trigger algorithms. The transverse impact parameter is used to differentiate between displaced and prompt jets or tracks, with prompt jets or tracks having a small transverse impact parameter smaller than 1 mm. The exclusive algorithm further requires at least one associated, non-prompt track, while the inclusive algorithm is used without this limitation as a more general approach in the search. The dedicated displaced jet tagging algorithm uses three variables, one of which is the likelihood that a jet originates from the primary vertex (PV) with the highest p_T^2 sum of the constituent tracks. Additionally, the significance of the transverse displacement of the jet and the angular difference between the emission angle of a track in a jet and the parent particle flight direction are used in the jet tagging algorithm. The number of tagged jets is then counted for each category and each event. The Standard Model (SM) background is dominated by multijet production, which gives rise to mismeasured displaced jets and jets with tracks from weak decays. The background contribution is determined from a simulated multijet sample and constitutes the main systematic uncertainty. The observed yield is consistent with the predicted background within statistical and systematic uncertainties. For the b-lepton model, cross sections larger than 2.5 fb are excluded for proper decay lengths of 70–100 mm, which translates to most stringent constraints on this model for this range of lifetimes, assuming LLP masses between 550 and 1130 GeV.

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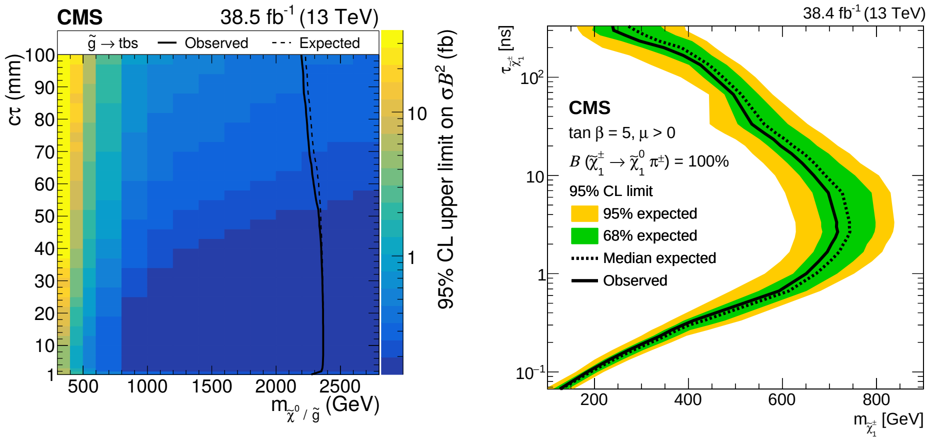

Figure 1: Left: Observed 95% CL upper limits on cross section times branching fraction squared for the multijet signal from the search using displaced vertices in multijet events [3]. Right: Observed constraints on the chargino mass and lifetime for the search using disappearing tracks [4].

3. Displaced vertices in multijet events

Displaced vertices are identified in multijet events using data corresponding to an integrated luminosity of 38.5 fb^{-1} in [3]. Two R-parity benchmark models are considered in this search. In the first model, a pair-produced long-lived neutralino or gluino decays into a pair of a quark and a squark, producing a multijet signature. In the second case, a pair-produced long-lived virtual top squark decays to a pair of quarks, producing a dijet signature. The separation between the vertices d_{VV} is then used to discriminate between signal and background, with signal events having two well-separated displaced vertices from two LLPs emitted approximately back-to-back, and background events which are dominated by only one displaced vertex. Events with at least four jets are selected. A custom vertex reconstruction algorithm produces multiple vertices per event by iteratively re-running the vertex reconstruction routine with tracks which are displaced from the beam axis. For signal, only well-reconstructed vertices with at least five tracks are considered in the search. The SM background is dominated by multijet and $t\bar{t}$ events and is estimated from data. The method is tested using a control sample in which events are selected with one reconstructed vertex having less than five tracks. The signal template is extracted from the simulated d_{VV} distribution, with each lifetime $c\tau$ yielding a distinctive shape. Vertices with the highest number of tracks are favored if events have more than two displaced vertices. The two displaced vertices in background events are primarily random coincidences of independently mis-reconstructed vertices. A two-vertex background template is constructed from data by combining information from one-vertex events, which includes the x-y distance from the beam axis to the vertex from $\geq$ 5-track one-vertex events and the azimuthal angle between two vertices. The latter can be approximated by the angle between pairs of jets in data, since in this case the vertex position vectors are correlated with the jet momentum vectors. A binned shape fit of the signal and background templates is used to extract the signal yield from the d_{VV} distribution. Fig. 1-left shows the observed 95% confidence level (CL) upper limits on the signal cross section times branching fraction squared for the multijet signal depending on the mass of the neutralino or gluino and the lifetime. Neutralino, gluino and top squark masses between 800 and 2600 GeV are excluded for mean proper decay lengths between 1 and 40 mm, while gluino masses below 2200 GeV and top squark masses below 1400 GeV are excluded for mean proper decay lengths between 0.6 and 80 mm.

4. Disappearing tracks

The decay of an exotic, charged LLP in the silicon tracking detector could also produce the signature of an isolated disappearing track, which is characterized by missing hits in the outer tracker layers, little or no deposited energy in the calorimeters and no associated hits in the muon detectors. This signature is searched for in Ref. [4] with an integrated luminosity of 38.4 fb^{-1}. The results are interpreted in the anomaly-mediated supersymmetry-breaking (AMSB) model, which predicts long-lived charginos due to the small mass splitting between the lightest chargino and the lightest supersymmetric particle of the model, which in this model is the neutralino. The small mass splitting reduces the available phase space of the chargino decay and thus gives rise to long chargino decay times. The chargino decays into a neutralino and a pion and leaves a disappearing track, as the pion momentum is generally too low to be reconstructed in the detector. Events are selected with $p_T^{\text{miss}} > 100$ GeV and an initial state radiation (ISR) jet with $p_T > 110$ GeV. The multijet background is reduced by requirements on the azimuthal angle $\phi(\text{jet}_{\text{ISR}}, p_T^{\text{miss}})$ and the maximum difference in ϕ between any two jets. Isolated, consecutive tracks with at least three hits in the pixel and at least seven hits in the tracker originating from close to the interaction point are then selected before applying the discriminant variables of the search. A disappearing track is required to have at least three missing outer hits and an associated deposited energy in the calorimeter of less than 10 GeV within a cone of radius $\Delta R = 0.5$ around the track. The background contributions are from charged leptons and spurious tracks, and are estimated from data. Charged leptons which produce a track but fail the lepton reconstruction can contribute to the background, provided the rest of the event passes the analysis cuts. The number of events in a single-lepton control region is multiplied by the probability that the lepton is not explicitly identified as a lepton, the probability to pass the offline requirements and the probability that a single-lepton event passes the triggers. The contribution from spurious tracks is determined by applying a loose disappearing track selection to a dimuon control region in order to derive a probability for a track to be spurious, which is then multiplied with the number of events in the control region. The observation in the signal region is consistent with the background-only hypothesis and 95% CL upper limits on the cross section times branching fraction are shown in Fig. 1-right. The search yields the most stringent constraints on direct chargino production within the AMSB model, with chargino masses excluded up to 715 (695) GeV for a lifetime of 3 (7) ns and chargino lifetimes excluded from 0.5 to 60 ns for a mass of 505 GeV.

5. Heavy stable charged particles

A search for heavy stable charged particles (HSCP) using an integrated luminosity of 12.9 fb^{-1} is documented in [5]. HSCPs are slow-moving particles with $\beta = v/c \lesssim 0.9$, and thus are expected to have a higher rate of energy loss via ionization (dE/dx) and a longer time-of-flight (TOF). Both aspects are investigated in the search to identify different kinds of HSCPs, one of which are strongly-interacting HSCPs forming R-hadrons in the context of split SUSY. Other possibilities are HSCPs that behave like leptons as in the minimal gauge-mediated supersymmetry-breaking model (mGMSB), or HSCPs which behave like long-lived lepton-like fermions in a modified Drell-Yan production. For the dE/dx measurement, a discriminator I_{as} is used to distinguish SM particles from HSCP candidates, which is dependent on the probability for a minimum-ionizing particle to produce a charge smaller than or equal to that of the n-th measurement for the observed path length in the detector. For the time-of-flight measurements, information from the muon drift tubes (DT) and cathode strip chambers (CSC) is used. The search employs both methods in the tracker+TOF analysis and the first method in the tracker-only analysis. Events with either a high transverse energy muon or with large missing transverse energy are selected. Track quality criteria are applied and, in the case of the tracker+TOF analysis, a reconstructed muon matched to a track in the tracker is required. For the tracker-only analysis, the SM background is determined from data with an ABCD method using two uncorrelated quantities, I_{as} and p_T. In the case of the tracker+TOF analysis, the estimation is further improved by a third variable $1/\beta$. The findings are interpreted in the context of long-lived gluinos, scalar top quarks, scalar tau leptons, and lepton-like fermions. The search shows good agreement between SM-only prediction and the observed data. Fig. 2-left shows the 95% CL cross section upper limits for the tracker+TOF analysis. Gluino masses below 1850 (1840) GeV are excluded[1], as well as top squark masses below 1250 (1220) GeV for the R-hadron cloud interaction (charge suppressed) models. Furthermore, $\tilde{\tau}_1$ masses below 660 GeV in the case of the mGMSB model and below 360 GeV for the pair production model are excluded. Modified Drell-Yan production is excluded below 730 GeV ($|Q| = 1e$) and 890 GeV ($|Q| = 2e$).

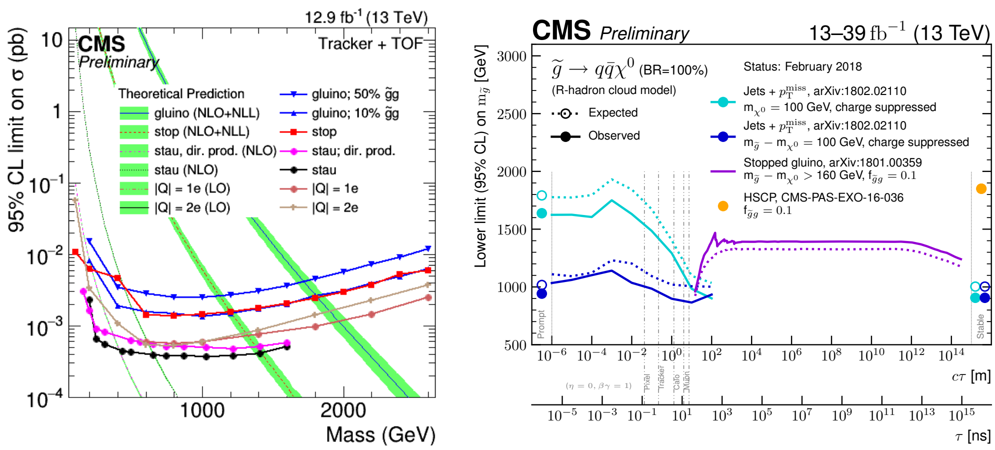

Figure 2: Left: Cross section 95% CL upper limits for different models of the HSCP tracker+TOF analysis [5]. Right: Observed 95% CL lower limits on $m_{\tilde{g}}$ for stopped gluinos, HSCPs and two reinterpretations of the prompt search for natural and split SUSY with jets and missing transverse momentum [6].

6. Stopped exotic, long-lived particles

While the HSCP search discussed in the previous section aims to detect the LLP itself, the complimentary search for stopped particles searches for the decay products of the LLP instead [7].

[1]The gluino masses are excluded for a fraction of $f = 0.1$ of gluinos hadronizing into a gluino-gluon state.

The slow-moving ($\beta = v/c \lesssim 0.5$) LLPs in question would come to rest in the CMS detector and either their hadronic or muonic decay can be reconstructed during the time between proton-proton collisions. Here, cosmic rays, beam-halo particles, and detector noise are considered as background. The search uses an integrated luminosity of 38.6 fb^{-1} (hadronic decay in calorimeters) and 39.0 fb^{-1} (muonic decay). The results are interpreted in terms of simplified models motivated by a split SUSY-breaking scheme, where gluinos are pair produced. For hadronic decays in the calorimeters, the gluinos decay into either $g\widetilde{\chi}^0$ or $q\bar{q}\widetilde{\chi}^0$. For the muonic decay, the gluinos decay into $q\bar{q}\widetilde{\chi}_2^0$, $\widetilde{\chi}_2^0 \rightarrow \mu^+\mu^-\widetilde{\chi}^0$. A simplified model predicting multiply charged massive particles (MCHAMPs) is also considered in the muonic decay. To suppress the dominant background of beam-halo particles, events which are at least two bunch crossings away from proton bunches are selected. For the calorimeter search, events are selected with at least one high-energy jet. The background is estimated from data, with inefficiencies for cosmic rays derived from air shower simulation. A tag-and-probe method is used to derive the beam-halo background from a high-purity sample of halo events, while the detector noise background is estimated using control data with no LHC beams. In the case of the muon search, events with a displaced pair of muons are selected. No deviation from the expectation has been observed, and the search places the most stringent limits to date on the mass of hadronically decaying stopped LLPs, as well as provides the first exclusion limits on the decay of LLPs to muons. For the calorimeter search, gluinos masses with lifetimes from 10 μs to 1000 s are excluded below 1385 GeV in the case of the two-body decay, as shown in Fig. 2-right, as well as top squark masses with the same lifetimes below 744 GeV. For the muon search, gluinos in the same lifetime range are excluded for masses between 400 and 1600 GeV and production cross sections between 1 and 0.01 pb. MCHAMPs with $|Q| = 2e$ are excluded between 100 and 800 GeV.

7. Reinterpretation of prompt searches

The search for pair production of second generation leptoquarks contains a reinterpretation in the context of LLPs for the final state with one muon, one jet and missing transverse energy [8]. Considering a split SUSY scenario with the top squark as the lightest supersymmetric particle and small couplings of the RPV operators, the top squark is expected to decay to a charged lepton and a b jet with a characteristic decay length $c\tau$. Complimentary results are found in the low-lifetime and high-mass regime, in which dedicated searches lose sensitivity, for which top squark masses are excluded below 1150 GeV ($c\tau = 0.1$ cm), 940 GeV ($c\tau = 1$ cm) and 305 GeV ($c\tau = 10$ cm). Another reinterpretation is contained in the search for natural and split SUSY with jets and missing transverse momentum in the final state [9]. The reinterpretation within split SUSY considers long-lived gluinos with proper decay lengths from 10^{-3} to 10^5 mm as well as metastable gluinos. Fig. 2-right shows the lower 95% CL limit on the gluino mass of the reinterpretation in comparison to the results using stopped particles and the HSCP search. Gluino masses below 1750 GeV ($c\tau = 1$ mm) and 900 GeV (metastable state) are excluded in the reinterpretation.

8. Conclusion

Although no evidence of exotic LLPs has been found, the searches presented in the previous sections already significantly constrain a host of LLP models. In particular, the searches for disappearing tracks and stopped particles put the most stringent exclusion limits on long-lived chargino production to date. Future searches are expected to benefit from recently upgraded detector subsystems such as the pixel detector upgrade in 2017, which among others increases the total number of barrel layers to four, yielding an increase in vertex resolution [10]. Overall sensitivity is also expected to improve with the high-luminosity LHC upgrade, which can be further enhanced by the proposed dedicated detector for long-lived particles (MATHUSLA[2]) [11].

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