CMS Physics Analysis Summary

Search for new physics in events with collimated photons and gluons

The CMS Collaboration

Abstract

This letter reports the results of a search for physics beyond the standard model. The search is performed with events containing jets with substructure resulting from new particles decaying into a photon and two gluons. Jet substructure techniques are adapted to develop a new approach for photon identification in a dense hadronic environment. The proton-proton collision data analyzed were collected by the CMS experiment at $\sqrt{s} = 13$ TeV during 2016 and correspond to an integrated luminosity of 35.9 fb^{-1}. No statistically significant excess is observed and the first cross section limits on processes yielding such events are set.

Despite the success of the standard model of particle physics (SM), there are a number of indications, such as the cosmological observations of dark matter, the measured value of the Higgs boson mass, as well as theoretical and aesthetic considerations such as naturalness, that suggest the existence of new physics at the TeV energy scale. No evidence for new physics has been uncovered currently by the LHC. Signs of new phenomena could be hidden in large SM background processes which have yet to be investigated. The most common such processes at the LHC are multijet events. A multitude of well motivated theoretical scenarios predict the appearance of new physics in events with low missing transverse momentum (p_T^{miss}) and lacking isolated photons and leptons, which would manifest as multijet events in the collider. These include Hidden Valley models [1, 2] and a number of supersymmetric (SUSY) models, such as R-parity violating SUSY [3] and stealth supersymmetry [4–6].

Stealth supersymmetry predicts a hidden sector of particles with minimal coupling to the SUSY breaking mechanism. As a result superpartners in this sector are nearly mass degenerate. In this analysis a simplified stealth SUSY model is used as a benchmark with only one light hidden sector superparticle pair, the singlino and the singlet ($\tilde{S}$, S). Gluinos ($\tilde{g}$), the gluon superpartners, are expected to be created with large cross sections at the LHC and decay to neutralinos $\tilde{\chi}_1^0$ and a quark anti-quark pair. Stealth SUSY assumes gauginos (either neutralinos or charginos) to be the portal to the hidden sector which decay to the $\tilde{S}$ and a photon. The $\tilde{S}$ is expected to decay to a S and a gravitino ($\tilde{G}$) with the subsequent decay of the S to a pair of gluons. Because of the mass degeneracy of the hidden sector pair, the $\tilde{G}$ is expected to be produced with low momentum and thus the event to be characterized with low p_T^{miss}. A diagram depicting the decay chain of a gluino according to this simplified stealth SUSY model is presented in Fig. 1.

Previous searches at CMS for stealth SUSY [7, 8] required two isolated photons. The isolation requirement reduces the sensitivity to cases where a mass gap exist between the electroweak charged gauginos, in this case the $\tilde{\chi}_1^0$, and the colored superparticle ($\tilde{g}$). If this strong mass hierarchy is present, the $\tilde{\chi}_1^0$ is expected to be produced with a large Lorentz boost and its decay products to collimate, resulting in non-isolated photons. We follow a complementary strategy, to previous searches, by identifying jets composed of one photon from the $\tilde{\chi}_1^0$ decay and a pair of gluons from the S decay, which we refer to as photon-jets. It is possible to identify photon-jets by utilizing a combination of existing and novel jet substructure tools. Within the simplified stealth SUSY model we consider, superparticle production at the LHC is predicted to appear as events that have two photon-jets associated with a large total event hadronic activity. The distribution of the total hadronic activity of events containing photon-jets is evaluated to uncover new physics hidden in the SM multijet background.
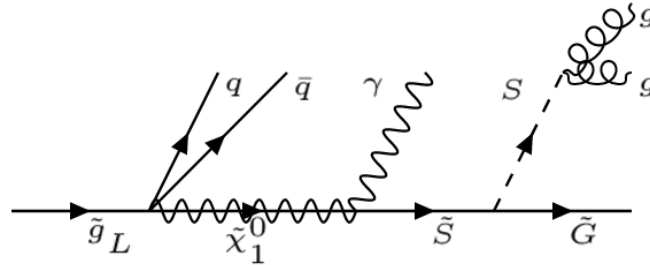

Figure 1: The decay diagram for a gluino predicted by stealth SUSY. The S and $\tilde{S}$ states are predicted to have a small mass gap resulting in soft $\tilde{G}$ emissions. This analysis mainly explores cases where the mass difference between the $\tilde{g}$ and $\tilde{\chi}_1^0$ is large and results in a high momentum $\tilde{\chi}_1^0$ with the photon and the gluons merging into a single jet.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diame-

ter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. 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.[9].

Particles are reconstructed by the particle-flow algorithm [10] and are clustered into jets using the anti-k_T algorithm [11] implemented with FastJet[12] with a radius parameter of 0.8 (AK8) and 0.4 (AK4) jets. Charged particle candidates not associated with the primary vertex are ignored, to reduce pileup effects in the event reconstruction. Jets are required to pass loose jet identification criteria [13] . In addition, energy corrections are applied to jets [14]. Kinematic requirements of a minimum jet p_T of 200 GeV and $|\eta| < 2$ are applied to AK8 jets. The AK8 jet p_T is used to measure the total hadronic activity in the event, defined as $H_\text{T} = \sum p_\text{T}$. For the analysis, we consider events that contain at least 3 such AK8 jets as well as an H_T greater than 1 TeV.

The data analyzed were collected by the CMS experiment at the LHC from proton-proton collisions at $\sqrt{s} = 13$ TeV during the 2016 data taking period and corresponds to an integrated luminosity of 35.9 fb^{-1}. Events are selected by the triggering system [15] if they pass a minimum H_T requirement of 900 GeV, calculated using AK4 jets with a minimum p_T of 50 GeV. For the purpose of extracting an efficiency correction for signal, events were also collected with a combination of muon triggers, selecting events containing at least one muon with p_T greater than 50 GeV.

Pair production of gluinos for a range of different $\tilde{g}$ and $\tilde{\chi}_1^0$ masses, with the S and $\tilde{S}$ masses fixed to 90 and 100 GeV respectively, are simulated using MADGraph_MC@NLO [16]. The decay and hadronization was done with PYTHIA8 [17] using the underlying event CUETP8M1 tune [18] and the NNPDF2.3 parton distribution function [19]. The detector simulation is done using the CMS Fast Simulation (FastSIM) [20, 21]. To estimate systematic uncertainties related to the detector simulation, the full CMS detector simulation (FullSIM) in GEANT4 [22] is also used and compared to the Fast Simulation results. An uncertainty due to the hadronizer choice is evaluated by simulating signal events using Herwig [23] with the TuneEE5C tune [24] and comparing them events hadronized by PYTHIA8. Signal events are normalized using the theoretical gluino pair-production cross sections [25].

We simulate SM processes to study the background behavior, to construct templates from which we estimate efficiency corrections used for simulated signals, and to estimate uncertainty effects. Simulation of QCD processes is done using MADGraph_MC@NLO with MLM matching [26] and hadronized with PYTHIA8 with the CUETP8M1 tune. The production of hadronically and leptonically decaying W bosons in conjunction with jets (W+jets) is also simulated this way. The production of top pairs ($t\bar{t}$) is simulated with Powheg [27–30] and hadronized by PYTHIA8 using the CUETP8M2T4 tune [18]. Hadronization for $t\bar{t}$ is also performed with Herwig and the TuneEE5C tune. All samples are simulated with the NNPDF2.3 parton distribution function. The detector response is simulated with GEANT4.

To identify photon-jets we extract the AK8 jet subjets and identify the photon from the $\tilde{\chi}_1^0$ decay. We require that there is at least one photon cluster in the jet, with $p_\text{T} > 20$ GeV and at least 95% of the energy deposited in ECAL, consistent with a photon shower shape. The photon candidate is also required to not have any associated hits in the pixel detector (pixel veto). Photons showering in the tracker material can give multiple clusters in the calorimeter and

these are removed from the jet constituent collection and replaced by the reconstructed photon object 4-vector. The photon and the jet constituents are re-clustered using the k_T algorithm [31] and the merging history is examined to identify the three subjets of the jet. The clustering algorithm combines two objects into one at each step. We identify as the first subjet, the lightest of the two objects merged in the last step of the clustering sequence. The other object, the most massive of the two, specifies the 2nd and 3rd subjets. This is done by retrieving the two objects that merged to formed it by the clustering algorithm. Jets are only considered further if three subjets with $p_T > 10$ GeV are found. We examine in which subjet the clustering algorithm grouped the photon. The photon subjet fraction (f_γ), defined as the ratio of the photon p_T to p_T of the subjet it is a part of, is calculated and presented in Fig. 2. This variable is as a measure of the activity around the photon and serves as a strong discriminator against QCD jets.

We define a loose and a tight photon-jet category. The loose photon-jet selection requires that the AK8 jet has an N-subjettiness [32] ratio $\tau_3/\tau_1 < 0.4$. Tight photon-jets have to satisfy the loose photon-jet criteria and a requirement on the f_γ to be greater than 0.9. Events are characterized based on their multiplicity of loose and tight photon-jets and labeled as X-Y where X is the number of loose jets of which Y also satisfy the tight photon-jet criteria. We define the signal region (SR) to be events with at least 2 loose jets, while the background dominated region (BR) is the set of events with a loose jet count of 1 or less. The SR is further split into 3 categories, 2-0, 2-1, and 2-2 with the last one being the most sensitive.
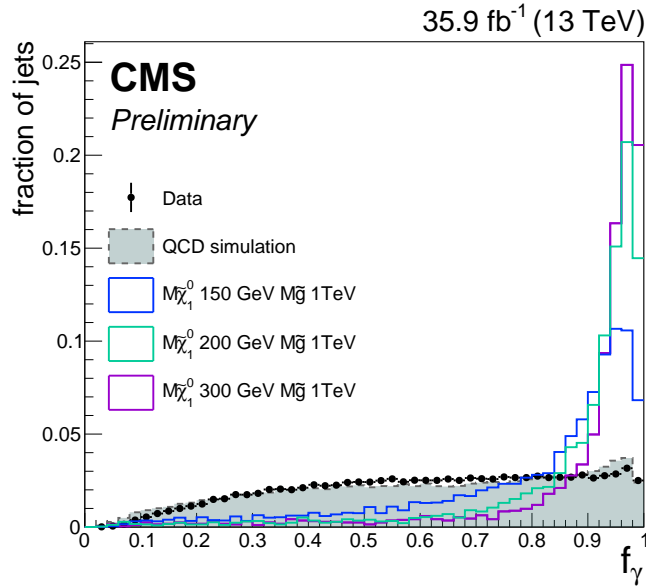

Figure 2: Normalized distribution of the f_γ variable. Simulated signal jets are denoted with the colored lines, each depicting a different mass of $\tilde{\chi}_1^0$ and $\tilde{g}$. The shaded area represents the QCD jets distribution. The black points present data. The jet distributions presented here are required to satisfy the loose photon-jet requirements.

The SM multijet background is estimated from data. Loose and tight jet mistag rates are measured in the BR, as a function of the jet p_T and η. The loose mistag rate is measured by taking the ratio of the number of jets jets passing the loose selection in the 1-0 and 1-1 events, to number of the jets in the BR region as a function of the jet p_T and η. The tight mistag rate is the ratio of tight jets in the 1-1 category to the all the loose jets in the 1-0 and 1-1 events. By throwing 10^4 toys for each event in the BR using the event's jet kinematics and measured mistag rates, the probability for each event to populate the three SR categories is calculated. One can then obtain the background H_T distributions, for each SR category, by constructing an H_T distribution of all

Table 1: Systematic uncertainties considered. The starred $*$ uncertainties are evaluated as shape uncertainties while the rest as uncertainties on the normalization. The magnitude of each uncertainty refers to the effect on signal event efficiencies.

Source	Magnitude
Data-Simulation Signal efficiency correction uncertainty $*$	$30 - 50\%$
Background Estimation $*$	10%
Jet Energy Resolution $*$	$< 10\%$
Jet Energy Scale corrections $*$	$< 10\%$
Pileup re-weighting $*$	$< 5\%$
Int. Luminosity	2.5%
Detector FullSIM - FastSIM simulation	$[1 - 2\%]$
PDF choice uncertainty	1%

events in the BR, weighting each event by the calculated probabilities for each to appear in the signal region. The mistag rates are varied within their systematic uncertainties to determine the uncertainty on the background prediction. Overlap between neighboring jets was found to affect the method's ability to correctly predict the background estimate. Therefore a selection of events with $\Delta R_{min} > 1.5$ between AK8 jets, is applied. The method is validated using a simulated QCD sample. Other SM processes such as $t\bar{t}$ and W+jets are modeled and using simulation and found to have a negligible contribution in the SR.

No SM process predicts jets composed of a collimated photon and with two gluons which can be used to measure a signal efficiency correction for the loose and tight photon-jet selections. We select top quarks jets that are composed of an electron, a b quark and a final state radiation gluon. This is done by requiring an electron instead of photon in the jet, by reversing the pixel veto. These jets are used for the extraction of a signal efficiency correction. We select a $t\bar{t}$ dominated sample by tagging events with a muon, a loose b tagged jet [33] and $p_{\mathrm{T}}^{\mathrm{miss}}$ that are back-to-back to an AK8 jet (probe jet). The probed jets are used for the measurement of loose and tight rates. The measurement is done by fitting simulation derived templates to the probed jets, estimating the data composition (e.g. jets originating from light quarks or gluons, or fully-merged hadronic W or top quark decays) and measuring the loose and tight photon-jets selection efficiency. The procedure is repeated in simulation and the efficiency correction is the ratio of the loose/tight efficiency measured in data over the same efficiency obtained with $t\bar{t}$ simulation. Signal H_{T} expectation shapes are corrected by scaling the signal simulation rates to match the data efficiency rates.

The dominant source of systematic uncertainty is the data-to-simulation efficiency correction for signal-like jets. This ranges from 30% to 50% depending on the event jet composition. All the uncertainties considered and their magnitudes are listed in Table 1. These include the background estimation uncertainty, jet calibration effects, simulation effects for signal such as the PDF choice, FullSIM-FastSIM detector simulation effects, pileup correction uncertainties, and the measured total luminosity error. Initial state radiation effects on signal efficiency and triggering efficiency uncertainties are deemed to be negligible and not included. Systematic uncertainties are introduced as shape or yield variations for the limit setting procedure.

The search is performed separately on events with exactly 3 and 4 or more jets. The results are combined for the final statistical analysis. The H_{T} distributions in the SR are presented in Fig. 3 and the observed data appear consistent with the background predictions. We interpret the results as cross section upper limits for gluino pair production decaying according to the simplified stealth SUSY model, using a Bayesian limits method and a flat signal strength prior [34].

The combined cross section limit results for all SR categories are shown in Fig. 4. Production of $\tilde{g}$ with mass up to 1.68 TeV are excluded with a 95% confidence level (CL) for an assumed $\tilde{\chi}_1^0$ mass of 200 GeV. For neutralino masses between 1 to 1.2 TeV the maximum excluded gluino mass is 1.59-1.61 TeV. This is the first result on boosted final states with photons and gluons merged into a jet, exceeding previous limits set by analysis searching for isolated photons.
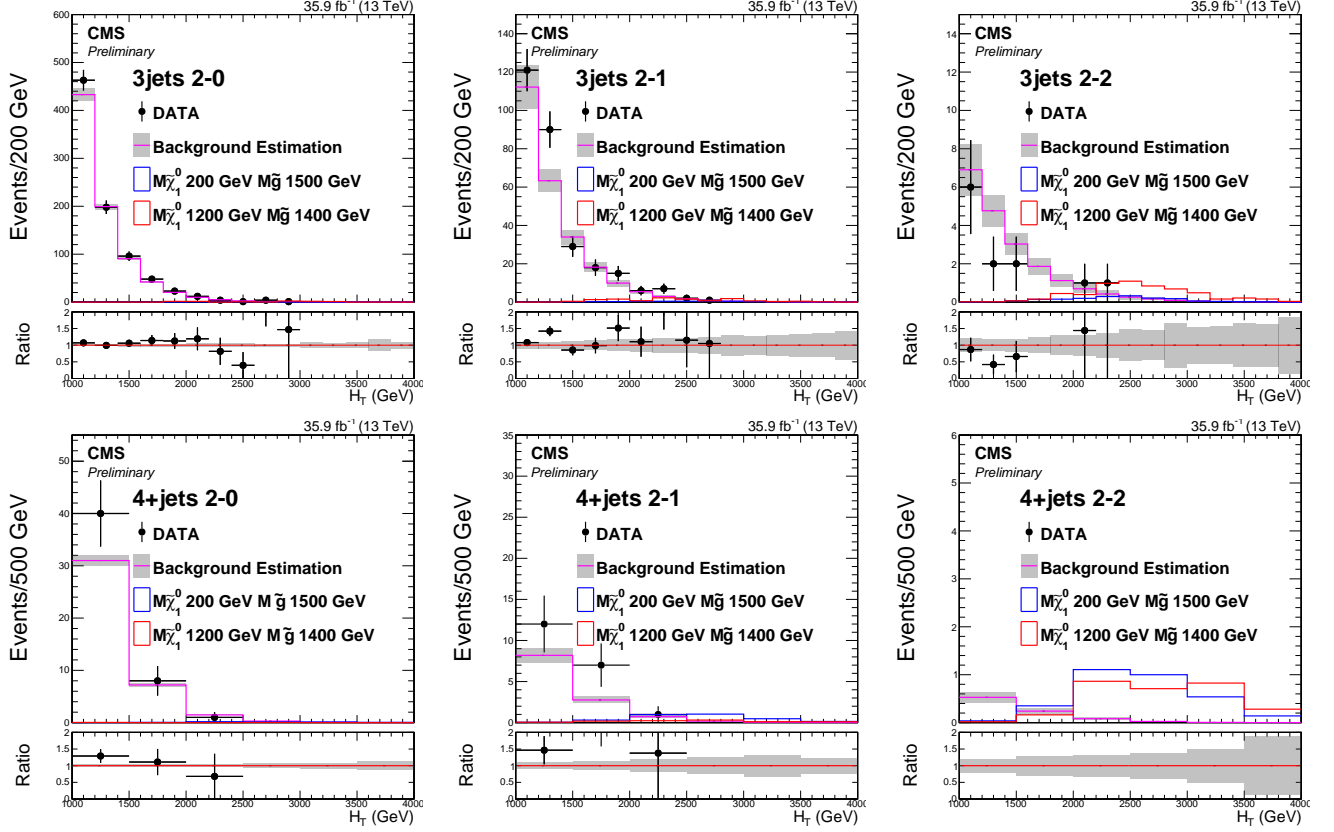

Figure 3: Signal region H_T distributions for the AK8 3 jet category (top row) and the 4+ AK8 category (bottom). Events with zero, one and two tight photon-jets are presented from left to right, present events with different number of tight photon-jets. The balck points denote the observed data H_T distributions. The magenta line with the gray band, presents the data based background estimation prediction while the other colored lines present expected singla H_T distributions.

To summarize, a search for superparticle production is presented, perfomed in events with two substructure rich jets composed of a photon and two gluons, using a pp collisions dataset collected by the CMS experiment and corresponding to an integrated luminosity of 35.9 fb^{-1}. This is the first search of its kind targeting the region of parameter space where photons from neutralino decays are not isolated. We use existing jet-substructure variables and novel techniques to identify the unsual jets. The total hadronic activity distributions of events are compared to distributions directly estimated from data. No statistically significant excess is observed above the SM expectation. We establish upper limits with 95% confidence level on gluino pair production cross section using a simplified stealth SUSY model. The excluded gluino masses extend up to 1.5 - 1.7 TeV depending on the neutralino mass with the highest exclusion set for neutralinos with a mass of about 200 GeV.
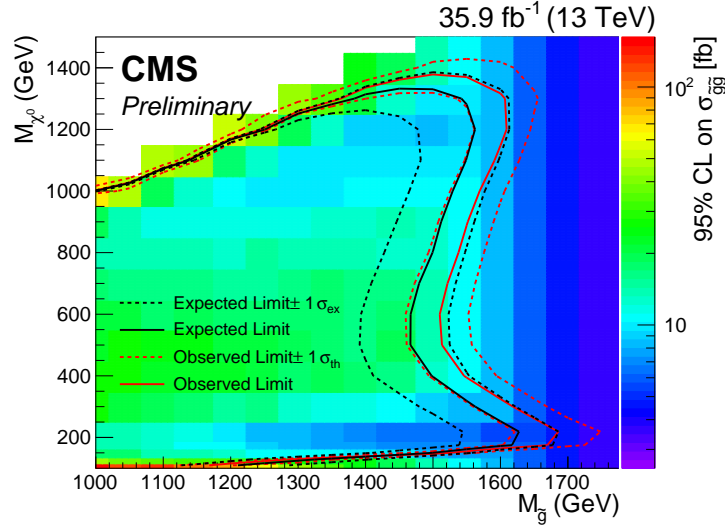
Figure 4: The excluded mass parameter space for the gluino and neutralino masses. The region left of the red exclusion line is excluded. The black line defines the expected excluded area based on the data driven background estimation. The error on the observed limit corresponds to the cross section theoretical uncertainties. The color scale denoted the the upper limits on the cross section for pair production of $\tilde{g}$, for each mass point at the 95% confidence level. Exclusion in the low $\tilde{\chi}_1^0$ high $\tilde{g}$ mass region is a result of the implementation of substructure techniques.

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