Search for supersymmetry with photons in pp collisions at $\sqrt{s} = 8$ TeV

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Two searches for physics beyond the standard model in events containing photons are presented. The data sample used corresponds to an integrated luminosity of 19.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 8$ TeV, collected with the CMS experiment at the CERN LHC. The analyses pursue different inclusive search strategies. One analysis requires at least one photon, at least two jets, and a large amount of transverse momentum imbalance, while the other selects events with at least two photons and at least one jet, and uses the razor variables to search for signal events. The background expected from standard model processes is evaluated mainly from data. The results are interpreted in the context of general gauge-mediated supersymmetry, with the next-to-lightest supersymmetric particle either a bino- or wino-like neutralino, and within simplified model scenarios. Upper limits at the 95% confidence level are obtained for cross sections as functions of the masses of the intermediate supersymmetric particles.

I. INTRODUCTION

Supersymmetry (SUSY) [1–7] is a popular extension of the standard model, which offers a solution to the hierarchy problem [8] by introducing a supersymmetric partner for each standard model particle. In models with conserved R-parity [9,10], as are considered here, SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. If the LSP is weakly interacting, it escapes without detection, resulting in events with an imbalance $\vec{p}_T^{\text{miss}}$ in transverse momentum. Models of SUSY with gauge-mediated symmetry breaking [11–17] predict that the gravitino ($\tilde{G}$) is the LSP. If the next-to-lightest SUSY particle is a neutralino ($\tilde{\chi}_1^0$) with a bino or wino component, photons with large transverse momenta (p_T) may be produced in $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decays. The event contains jets if the $\tilde{\chi}_1^0$ originates from the cascade decay of a strongly coupled SUSY particle (a squark or a gluino).

In this paper, we present two searches for gauge-mediated SUSY particles in proton-proton (pp) collisions: a search for events with at least one isolated high-p_T photon and at least two jets, and a search for events with at least two isolated high-p_T photons and at least one jet. The discriminating variables are E_T^{miss} for the single-photon analysis, and the razor variables M_R and R^2 [18,19] for the double-photon analysis, where E_T^{miss} is the magnitude of $\vec{p}_T^{\text{miss}}$. These studies are based on a sample of pp collision events collected with the CMS experiment at the CERN

LHC at a center-of-mass energy of 8 TeV. The integrated luminosity of the data sample is 19.7 fb^{-1}.

Searches for new physics with similar signatures were previously reported by the ATLAS and CMS collaborations at $\sqrt{s} = 7$ TeV, using samples of data no larger than around 5 fb^{-1} [20–23]. No evidence for a signal was found, and models with production cross sections larger than ≈ 10 fb^{-1} were excluded in the context of general gauge-mediation (GGM) SUSY scenarios [24–29].

This paper is organized as follows. In Sec. II we describe the CMS detector, in Sec. III the benchmark signal models, and in Sec. IV the part of the event reconstruction strategy that is common to the two analyses. The specific aspects of the single- and double-photon searches are discussed in Secs. V and VI, respectively. The results of the analyses are presented in Sec. VIII. A summary is given in Sec. IX.

II. CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting 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 end cap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and end cap detectors.

Events are recorded using a trigger that requires the presence of at least one high-energy photon. This trigger is utilized both for the selection of signal events, and for the selection of control samples used for the background determination. The specific trigger requirements for the two analyses are described below. Corrections are applied

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to account for trigger inefficiencies, which are evaluated using samples of data collected with orthogonal trigger conditions. 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. [30].

III. SUSY BENCHMARK MODELS

The two searches are interpreted in the context of GGM SUSY scenarios [24–29], and in terms of simplified model spectra (SMS) scenarios [31–34] inspired by GGM models. In these scenarios, *R*-parity is conserved and the LSP is a gravitino with negligible mass. Four models are considered:

GGMbino model.—In this model, squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) are produced and decay to a final state with jets and a bino-like $\tilde{\chi}_1^0$. This production process dominates over electroweak production in the squark- and gluino-mass region accessible to the analyses. The $\tilde{\chi}_1^0$ mass is set to 375 GeV, leading to a $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ branching fraction of about 80% [26]. The events are examined as a function of the squark and gluino masses. All other SUSY particles have masses set to 5 TeV, which renders them too heavy to participate in the interactions. In most cases, the final state contains two photons, jets, and E_T^{miss}.

GGMwino model.—This model is similar to the GGMbino model, except that it contains mass-degenerate wino-like $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ particles instead of a bino-like $\tilde{\chi}_1^0$. The common mass of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ is set to 375 GeV. The final state contains a $\gamma\gamma, \gamma V$, or VV combination in addition to jets and

E_T^{miss}, where *V* is a *Z* or *W* boson. With a $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ branching fraction of about 28%, approximately 48% of all events contain at least one photon.

T5gg model.—This SMS model is based on gluino pair production, with the gluinos undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^0$, followed by $\tilde{\chi}_1^0 \to \tilde{G}\gamma$. All decays occur with a branching fraction of 100%. The final state contains at least two photons, jets, and E_T^{miss}.

T5wg model.—This SMS model is also based on gluino pair production, with one gluino undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^0$, followed by $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, and the other gluino undergoing a three-body decay to $q\bar{q}\tilde{\chi}_1^\pm$, followed by $\tilde{\chi}_1^\pm \to \tilde{G}W^\pm$. All decays occur with a branching fraction of 100%. The final state contains at least one photon, jets, and E_T^{miss}.

Typical Feynman diagrams corresponding to these processes are shown in Fig. 1. Note that for the two GGM models, the events can proceed through the production of gluino-gluino, gluino-squark, or squark-squark pairs.

Signal events for the GGM models are simulated using the PYTHIA 6 [35] event generator. The squark and gluino masses are varied between 400 and 2000 GeV. Eight mass-degenerate squarks of different flavor (*u*, *d*, *s*, and *c*) and chirality (left and right) are considered. The production cross sections are normalized to next-to-leading order (NLO) in quantum chromodynamics, determined using the PROSPINO [36] program, and is dominated by gluino-gluino, gluino-squark, and squark-squark production.

The SMS signal events are simulated with the MadGraph 5 [37] Monte Carlo (MC) event generator in association with
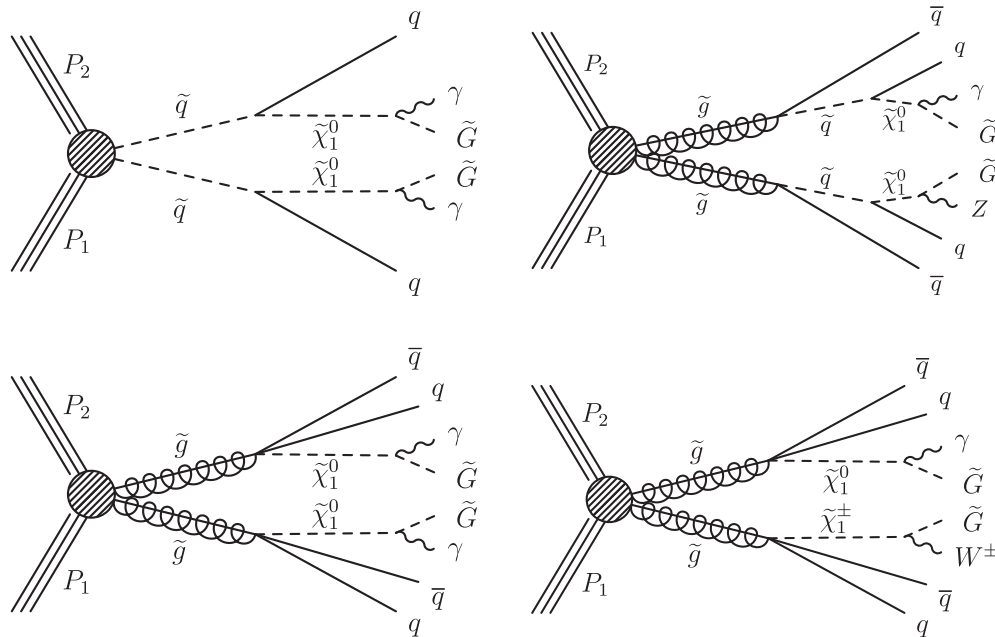

FIG. 1.   Typical Feynman diagrams for the general gauge-mediation model with bino- (top left) and wino-like (top right) neutralino mixing scenarios. Here, the $\tilde{\chi}_1^0$ can decay to $\tilde{G}\gamma$ or $\tilde{G}Z$, with the branching fraction dependent on the $\tilde{\chi}_1^0$ mass. The diagrams for the T5gg (bottom left) and T5wg (bottom right) simplified model spectra are also shown.

up to two additional partons. The decays of SUSY particles, the parton showers, and the hadronization of partons, are described using the PYTHIA6 program. Matching of the parton shower with the MADGRAPH5 matrix element calculation is performed using the MLM [38] procedure. The gluino pair-production cross section is described to NLO + NLL accuracy [36,39–42], where NLL refers to next-to-leading-logarithm calculations. All SUSY particles except the gluino, squark, LSP, and $\tilde{\chi}_1$ states are assumed to be too heavy to participate in the interactions. The NLO + NLL cross section and the associated theoretical uncertainty [43] are taken as a reference to derive exclusion limits on SUSY particle masses. Gluino masses of 400 (800) to 1600 GeV, and $\tilde{\chi}_1$ masses up to 1575 GeV, are probed in the T5wg (T5gg) model.

For all the signal models, detector effects are simulated through a fast simulation of the CMS experiment [44].

IV. EVENT RECONSTRUCTION

The events selected in this study are required to have at least one high quality reconstructed interaction vertex. The primary vertex is defined as the one with the highest sum of the p_T^2 values of the associated tracks. A set of detector- and beam-related noise cleaning algorithms is applied to remove events with spurious signals, which can mimic signal events with high energetic particles or large E_T^{miss} [45,46].

Events are reconstructed using the particle-flow algorithm [47,48], which combines information from various detector components to identify all particles in the event. Individual particles are reconstructed and classified in five categories: muons, electrons, photons, charged hadrons, and neutral hadrons. All neutral particles, and charged particles with a track pointing to the primary vertex, are clustered into jets using the anti-k_T clustering algorithm [49], as implemented in the FAST JET package [50], with a distance parameter of 0.5. The momenta of the jets are corrected for the response of the detector and for the effects of multiple interactions in the same bunch crossing (pileup) [51]. Jets are required to satisfy loose quality criteria that remove candidates caused by detector noise.

Photons are reconstructed from clusters of energy in the ECAL [52]. The lateral distribution of the cluster energy is required to be consistent with that expected from a photon, and the energy detected in the HCAL behind the photon shower cannot exceed 5% of the ECAL cluster energy. A veto is applied to photon candidates that match hit patterns consistent with a track in the pixel detector (pixel seeds), to reduce spurious photon candidates originating from electrons. Spurious photon candidates originating from quark and gluon jets are suppressed by requiring each photon candidate to be isolated from other reconstructed particles. In a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the candidate's direction, the scalar p_T sums of charged

hadrons (I_π), neutral hadrons (I_n), and other electromagnetic objects (I_γ) are separately formed, excluding the contribution from the candidate itself. Each momentum sum is corrected for the pileup contribution, computed for each event from the estimated energy density in the (η, ϕ) plane. Selected photons are required to be isolated according to criteria imposed on I_π, I_n, and I_γ as defined in Ref. [52].

V. SINGLE-PHOTON SEARCH

The single-photon analysis is based on a trigger requiring the presence of at least one photon candidate with $p_T \geq 70$ GeV. The trigger also requires $H_T > 400$ GeV, where H_T is the scalar sum of jet p_T values for jets with $p_T \geq 40$ GeV and $|\eta| \leq 3$, including photons that are misreconstructed as jets.

In the subsequent analysis, we make use of the variable p_T^*, which is defined by considering the photon candidate and nearby reconstructed particles, clustered as a jet as described in Sec. IV. If a jet (possibly including the photon) is reconstructed within $\Delta R < 0.2$ of the photon candidate and the p_T value of the jet is less than 3 times that of the photon candidate itself, it is referred to as the "photon jet." If such a jet is found, p_T^* is defined as the p_T value of the photon jet. Otherwise, p_T^* is the p_T value of the photon candidate. We require photon candidates to satisfy $p_T^* > 110$ GeV and $|\eta| < 1.44$. Also, in the subsequent analysis, we make use of the variable H_T^*, defined as for H_T in the previous paragraph but including the p_T^* values of all selected photon candidates. The variables p_T^* and H_T^* reduce differences between photon candidates selected with different isolation requirements compared to the unmodified variables p_T and H_T. We require events to satisfy $H_T^* \geq 500$ GeV. The sample of events with isolated photons so selected is referred to as the γ_{tight} sample. The trigger efficiency for the selected events to enter the sample is determined to be 97%, independent of p_T^* and H_T^*.

We require at least two jets with $p_T \geq 30$ GeV and $|\eta| \leq 2.5$. The jets must be separated by $\Delta R \geq 0.3$ from all photon candidates, to prevent double counting. In addition, the requirement $E_T^{miss} \geq 100$ GeV is imposed and events with isolated electrons or isolated muons are vetoed. The selection is summarized in Table I. Note that 0.16% of the selected events contain more than one photon candidate.

The relevant sources of background to the single-photon search are:

(i) multijet events with large E_T^{miss}, originating from the mismeasured momenta of some of the reconstructed jets. This class of events contains both genuine photons and spurious photon candidates from jets. This is by far the largest contribution to the background.

(ii) events with genuine E_T^{miss} originating from the leptonic decay of W bosons, both directly produced

TABLE I. Summary of the single-photon analysis selection criteria.

Selection criteria	γ_{tight} signal region	γ_{loose} control region	γ_{pixel} control region
Isolation requirement	Tight	Loose	Tight
Pixel seed	Vetoed	Vetoed	Required
Trigger		$\gamma - H_{\text{T}}$ trigger with $p_{\text{T}}^{\gamma} \geq 70$ GeV, $H_{\text{T}} \geq 400$ GeV (using $p_{\text{T}}^{\text{jets}} \geq 40$ GeV, $|\eta| \leq 3.0$)	
Photon(s)		≥ 1, $p_{\text{T}}^{*\gamma} \geq 110$ GeV, $|\eta| \leq 1.44$	
Jet(s)		≥ 2, $p_{\text{T}}^{\text{jets }1,2} \geq 30$ GeV, $|\eta| \leq 2.5$	
H_{T}^{*}		≥ 500 GeV (using $p_{\text{T}}^{\text{jets},\gamma} \geq 40$ GeV, $|\eta| \leq 3.0$)	
Isolated e,μ		veto, $p_{\text{T}} \geq 15$ GeV, $|\eta^{e(\mu)}| \leq 2.5(2.4)$	
$E_{\text{T}}^{\text{miss}}$		$E_{\text{T}}^{\text{miss}} \geq 100$ GeV (six ranges in $E_{\text{T}}^{\text{miss}}$)	

FIG. 2 (color online). Tests of the background estimation method for the single-photon analysis using simulated events in bins of $E_{\text{T}}^{\text{miss}}$. The direct simulation of γ_{tight} events is compared to the prediction of the multijet background from simulated γ_{loose} events (left). Simulated events with γ_{tight} originating from generated electrons are compared to the simulated prediction using the EW background method (right). The blue hatched area represents the total uncertainty and is the quadratic sum of the statistical (red vertical bars) and systematic (red hatched area) uncertainties. In the bottom panels, the ratio of the direct simulation to the prediction is shown.

and originating from top quark decays, which we refer to as electroweak (EW) background.

(iii) rare processes with initial- or final-state photon radiation (ISR/FSR), such as γW, γZ (especially $\gamma Z \to \gamma\nu\nu$), and $\gamma t\bar{t}$ production.

The kinematic properties of the multijet background are estimated from a control sample of photon candidates with isolation-variable values (I_{π}, I_{n}, I_{γ}) too large to satisfy the signal photon selection. We refer to these events as the γ_{loose} sample. Photon candidates of this kind typically originate from jets with anomalous fractions of energy deposited in the ECAL. Other than the orthogonal requirement of a γ_{loose} rather than a γ_{tight} candidate, events in this control sample are selected with the same requirements as the γ_{tight} sample, as summarized in Table I. Despite the different isolation requirement, this sample has properties similar to those of the γ_{tight} sample, due to the use of p_{T}^{*} rather than photon p_{T} in the definition of the event kinematic variables. Moreover, events in the γ_{loose} control sample are corrected for a residual difference with respect to the γ_{tight} sample in the distributions of p_{T}^{*} and hadronic recoil p_{T}, estimated from events with $E_{\text{T}}^{\text{miss}} < 100$ GeV. The corrected distribution of a given kinematic property (e.g., $E_{\text{T}}^{\text{miss}}$) for γ_{loose} events provides an estimate of the corresponding distribution for γ_{tight} events. The uncertainty in the correction factors, propagated to the prediction, is fully correlated among bins in the signal region and is treated as a systematic uncertainty in the background yield. The limited statistical precision of the control sample dominates the total systematic uncertainty. Figure 2 (left) shows the $E_{\text{T}}^{\text{miss}}$ distribution from the γ_{tight} sample and the corresponding prediction from the γ_{loose} sample, for simulated multijet and $\gamma + $ jet events. No discrepancy is observed within the quoted uncertainties.

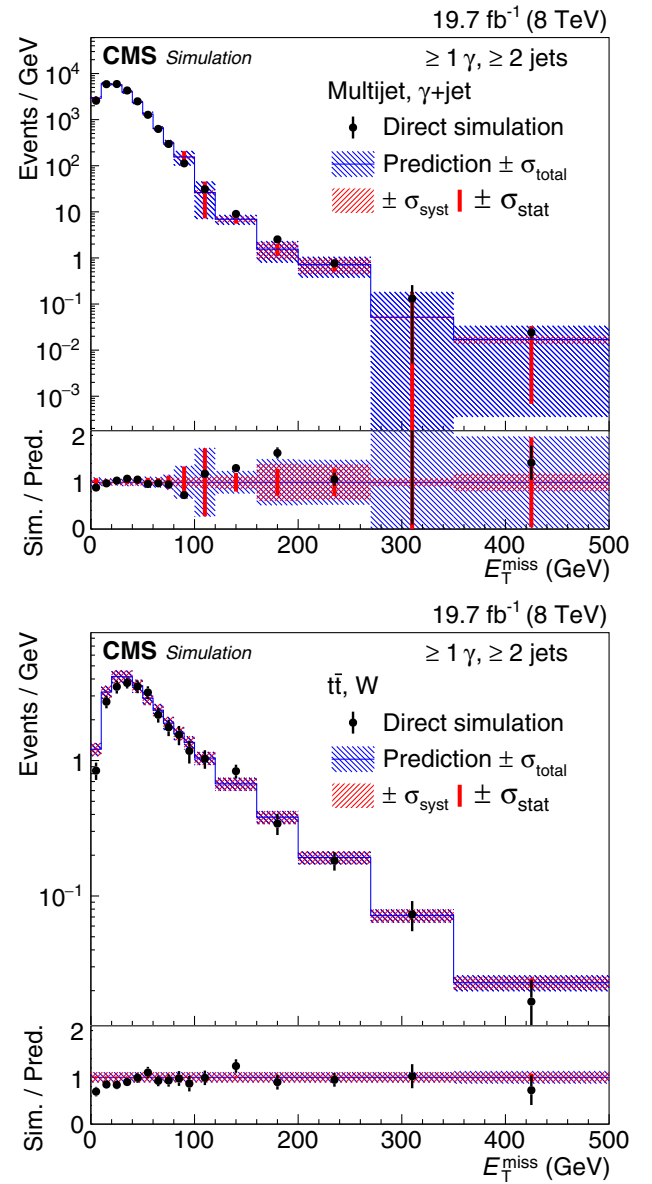The EW background is characterized by the presence of an electron misidentified as a photon. The kinematic properties of this background are evaluated from a second control sample, denoted the γ_{pixel} sample, defined by requiring at least one pixel seed matching the photon candidate but otherwise using the γ_{tight} selection criteria, as summarized in Table I. Events in the γ_{pixel} sample are weighted by the probability $f_{e \to \gamma}$ for an electron to be
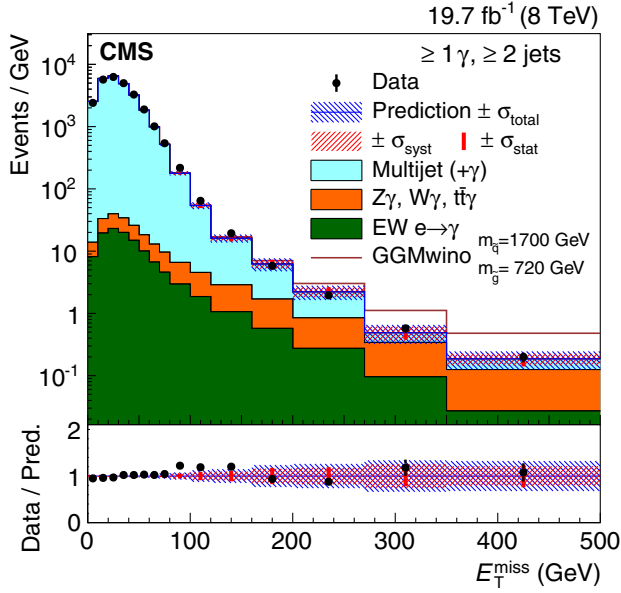
FIG. 3 (color online). Distribution of E_T^{miss} from the single-photon search in comparison to the standard model background prediction. The expectation from an example GGMwino signal model point is also shown. In the bottom panels, the ratio of the data to the prediction is shown. The representations of uncertainties are defined as in Fig. 2.

misidentified as a photon, which is measured as a function of the γ candidate p_T, the number of tracks associated with the primary vertex, and the number of reconstructed vertices in an event by determining the rate of events with reconstructed $e\gamma_{pixel}$ and $e\gamma_{tight}$ combinations in a sample of $Z \to e^+e^-$ events. The event-by-event misidentification rate is about 1.5%, with a weak dependence on the number of vertices. A systematic uncertainty of 11% is assigned to $f_{e\to\gamma}$ to account for the uncertainty in the shape of the function and for differences between the control sample in which the misidentification rate is calculated and the

control sample to which it is applied. The predicted E_T^{miss} distribution for the EW background, obtained from a simulated sample of W boson and $t\bar{t}$ events, is shown in Fig. 2 (right) in comparison with the results from the direct simulation of events with γ_{tight} originating from electrons. The distributions agree within the quoted uncertainties.

The contribution of ISR/FSR background events is estimated from simulation using leading-order results from the MadGraph 5 MC event generator with up to two additional partons, scaled by a factor of 1.50 ± 0.75 including NLO corrections determined with the MCFM [53,54] program.

The measured E_T^{miss} spectrum in the γ_{tight} sample is shown in Fig. 3 in comparison with the predicted standard model background. A SUSY signal would appear as an excess at large E_T^{miss} above the standard model expectation. Figure 3 includes, as an example, the simulated distribution for a benchmark GGMwino model with a squark mass of 1700 GeV, a gluino mass of 720 GeV, and a total NLO cross section of 0.32 pb.

For purposes of interpretation, we divide the data into six bins of E_T^{miss}, indicated in Table II. For each bin, Table II lists the number of observed events, the number of predicted standard model events, the acceptance for the benchmark signal model, and the number of background events introduced by the predicted signal contributions to the control regions, where this latter quantity is normalized to the corresponding signal yield.

No significant excess of events is observed. An exclusion limit on the signal yield is derived at 95% confidence level (CL), using the CL$_s$ method [55–57]. For a given signal hypothesis, the six E_T^{miss} signal regions are combined in a multichannel counting experiment to derive an upper limit on the production cross section. The results, presented in Sec. VIII, account for the possible contribution of signal events to the two control samples, which lowers the effective acceptance by 10%–20% depending on the assumed SUSY mass values.

TABLE II. Observed numbers of events and standard model background predictions for the single-photon search. The signal yield and acceptance for the GGMwino model with $m_{\tilde{q}} = 1700$ GeV and $m_{\tilde{g}} = 720$ GeV, with a total signal cross section of $\sigma_{NLO} = 0.32$ pb, are also shown. The last line gives the additional number of background events, normalized to the signal yield, which is associated with signal contributions to the two control regions.

E_T^{miss} range (GeV)	[100, 120)	[120, 160)	[160, 200)	[200, 270)	[270, 350)	[350, ∞)
Multijet	991 ± 164	529 ± 114	180 ± 69	96 ± 45	12 ± 12	9 ± 9
ISR/FSR	54 ± 27	73 ± 36	45 ± 23	40 ± 20	20 ± 10	15 ± 7
EW	37 ± 4	43 ± 5	23 ± 3	19 ± 2	8 ± 1	4 ± 1
Background	1082 ± 166	644 ± 119	248 ± 73	155 ± 50	39 ± 16	28 ± 12
Data	1286	774	232	136	46	30
Signal yield	19 ± 3	53 ± 5	51 ± 5	82 ± 7	78 ± 7	67 ± 6
Signal acceptance [%]	0.3	0.9	0.8	1.3	1.2	1.1
Background from signal relative to the signal yield [%]	2.1	5.0	5.6	9.9	26.7	13.5

VI. DOUBLE-PHOTON SEARCH

Events considered for the double-photon search are collected using triggers developed for the discovery of the Higgs boson in diphoton events [58–60]. These triggers use complementary kinematic selections:

  (i) two photons with $p_T > 18$ GeV, where the highest p_T photon is required to have $p_T > 26$ GeV, while the diphoton invariant mass is required to be larger than 70 GeV.
  (ii) two photons with $p_T > 22$ GeV, where the highest p_T photon is required to have $p_T > 36$ GeV.

In addition, each photon must satisfy at least one of two requirements: a high value of the shower shape variable R_9 [52] or loose calorimetric identification. For the targeted signals, the combination of the two triggers is found to be 99% efficient.

In the subsequent analysis, at least two photon candidates with $p_T > 22$ GeV and $|\eta| < 2.5$ are required. Events are selected if the highest p_T photon has $p_T > 30$ GeV. Jets must have $p_T > 40$ GeV and $|\eta| < 2.5$, with each jet required to lie a distance $\Delta R > 0.5$ from an identified photon. Only events with at least one selected jet are considered.

The background is dominated by multijet events, which mostly consist of events with at least one genuine photon. Due to the requirement of two photons in the event, the EW and ISR/FSR backgrounds are negligible.

The razor variables M_R and R^2 [18,19] are used to distinguish a potential signal from background. To evaluate these variables, the selected jets and photons are grouped into two exclusive groups, referred to as "megajets" [19]. The four-momentum of a megajet is computed as the vector sum of the four-momenta of its constituents. Among all possible megajet pairs in an event, we select the pair with the smallest sum of squared invariant masses of the megajets. Although not explicitly required, the two photons are associated with different megajets in more than 80% of the selected signal events.

The variable M_R is defined as

$$M_R \equiv \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2}|)^2 - (p_z^{j_1} + p_z^{j_2})^2}, \qquad (1)$$

where $\vec{p}^{j_i}$ and $p_z^{j_i}$ are, respectively, the momentum of the ith megajet and the magnitude of its component along the beam axis. The p_T imbalance in the event is quantified by the variable M_T^R, defined as

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(|\vec{p}_T^{j_1}| + |\vec{p}_T^{j_2}|) - \vec{p}_T^{miss} \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}, \qquad (2)$$

where $\vec{p}_T^{j_i}$ is the transverse component of $\vec{p}^{j_i}$. The razor ratio R is defined as

$$R \equiv \frac{M_T^R}{M_R}. \qquad (3)$$

For squark pair production in R-parity conserving models in which both squarks decay to a quark and LSP, the M_R distribution peaks at $M_\Delta = (m_{\tilde{q}}^2 - m_{LSP}^2)/m_{\tilde{q}}$, where $m_{\tilde{q}}$ (m_{LSP}) is the squark (LSP) mass. Figure 4
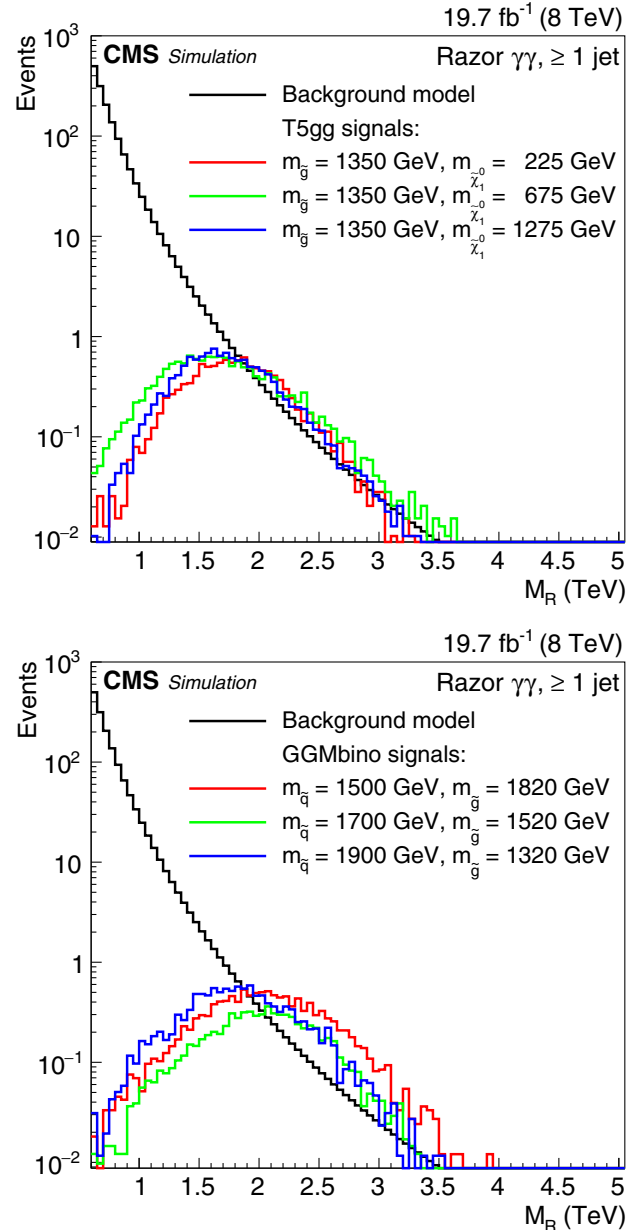

FIG. 4 (color online).   Distribution of M_R in the double-photon search for the background model, derived from a fit in the data control region, and for the T5gg (left) and GGMbino (right) signal models. The background model is normalized to the number of events in the signal region. The signal models are normalized to the expected signal yields.

demonstrates that M_R also peaks for gluino pair production (left) and in the GGMbino model (right).

The (M_R, R^2) plane is divided into two regions: (i) a signal region with $M_R > 600$ GeV and $R^2 > 0.02$, and (ii) a control region with $M_R > 600$ GeV and $0.01 < R^2 \leq 0.02$. The control region is defined such that any potential signal contribution to the control region is less than 10% of the expected number of signal events, producing a negligible bias on the background shape determination, corresponding to less than a 2% shift in the predicted number of background events for 20 expected signal events.

The background shape is determined through a maximum likelihood fit of the M_R distribution in the data control region, using the empirical template function

$$P(M_R) \propto e^{-k(M_R - M_R^0)^{\frac{1}{n}}}, \qquad (4)$$

with fitted parameters k, M_R^0, and n. The best-fit shape is used to describe the M_R background distribution in the signal region, fixing the overall normalization to the observed yield in the signal region. This implicitly assumes a negligible contribution of signal events to the overall normalization. We have studied the impact of the resulting bias and found it to be negligible for the expected signal distributions and magnitudes. The covariance matrix derived from the fit in the control region is used to sample an ensemble of alternative M_R background shapes. For each bin of the M_R distribution, a
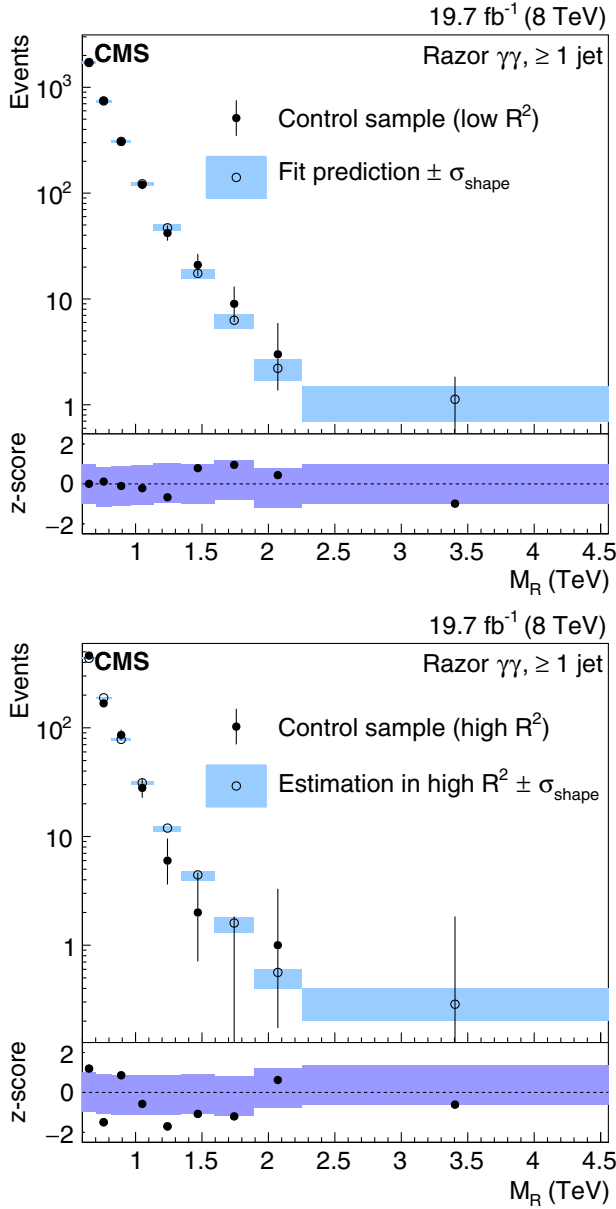

FIG. 5 (color online). Distribution of M_R in the double-photon search for a control sample of jets misreconstructed as photons (see text) in the control (left) and signal (right) regions. The data are compared to the 68% range obtained from a fit in the control region and extrapolated to the signal region (blue bands). The open dots represent the center of the 68% range. The rightmost bin in each plot contains zero data entries. The bottom panel of each figure gives the z-scores (number of Gaussian standard deviations) comparing the filled dots to the band. The filled band shows the position of the 68% window with respect to the expected value.
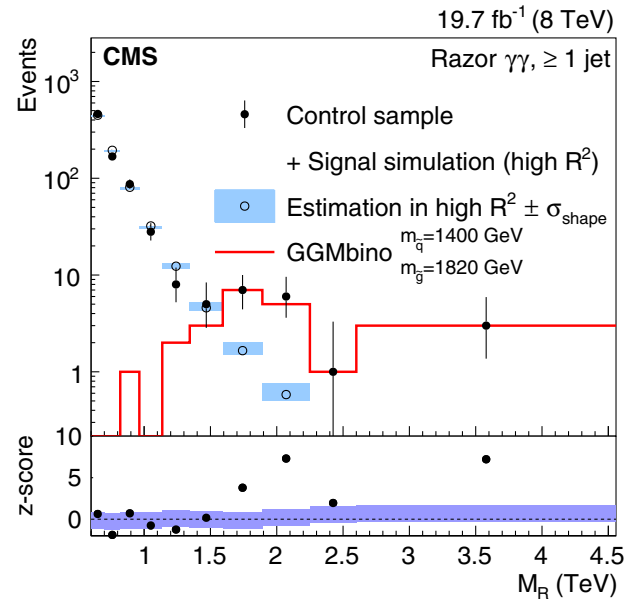

FIG. 6 (color online). Distribution of M_R in the double-photon search for a control sample of jets misreconstructed as photons to which a simulated sample of GGMbino events has been added. The squark and gluino masses are respectively set to $m_{\tilde{q}} = 1400$ GeV and $m_{\tilde{g}} = 1820$ GeV, and the production cross section is fixed to $\sigma = 2.7$ fb. The signal contribution is shown by the red histogram. The representations of the uncertainty bands, data points, and the information shown in the bottom panel are the same as in Fig. 5.

probability distribution for the yield is derived using pseudoexperiments. The uncertainty in each bin is defined by requiring 68% of the pseudoexperiments to be contained within the uncertainty band.

This background prediction method is tested by applying it to a control sample of events in which jets are misidentified as photons, obtained by selecting photon candidates that fail the requirement on the cluster shape or the photon isolation. The remainder of the photon-selection criteria are the same as for the signal sample. In Fig. 5 we
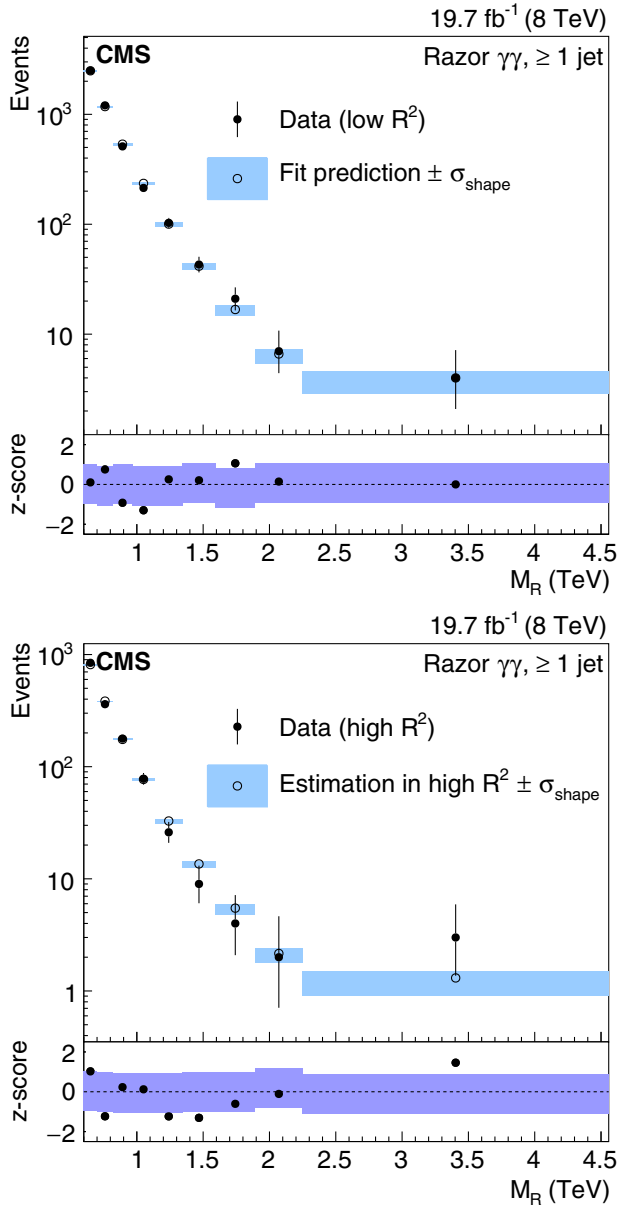

FIG. 7 (color online).   Distribution of M_R for the control (left) and signal (right) regions. The representations of the uncertainty bands, data points, and the information shown in the bottom panel are the same as in Fig. 5.

show the fit result in the control region (left) and the extrapolation to the signal region (right).

The contribution of the EW and ISR/FSR backgrounds, characterized by genuine E_T^{miss}, is evaluated from simulated events and is found to be negligible compared to the systematic uncertainty associated with the multijet background method, and is accordingly ignored.

A signal originating from heavy squarks or gluinos would result in a wide peak in the M_R distribution. This is shown in Fig. 6, where a GGMbino signal sample is added to the control sample of jets misreconstructed as photons, and the background prediction method is applied. The contribution of signal events to the control region is negligible and does not alter the background shape of Fig. 5 (left). The signal is visible as a peak at around 2 TeV.

Figure 7 (left) shows the result of the fit and the associated uncertainty band, compared to the data in the control region. The fit result is then used to derive the background prediction in the signal region. The comparison of the prediction to the observed data distribution is shown in Fig. 7 (right). No evidence for a signal is found. The largest positive and negative deviations from the predictions are observed for $M_R \gtrsim 2.3$ TeV and $1.1 \lesssim M_R \lesssim 1.9$ TeV, respectively, each corresponding to a local significance of ≈ 1.5 standard deviations.

VII. SIGNAL MODEL SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in the description of the signals are listed in Table III. Differences between the simulation and data for the photon reconstruction, identification, and isolation efficiencies are listed as Data/MC photon scale factors. The uncertainty associated with the parton distribution functions (PDF) is estimated using the difference in the acceptance when different sets of PDFs are used [61–65]. Similarly, different sets of PDFs and different choices for the renormalization scales yield different predictions for the expected production cross section.

TABLE III.   The systematic uncertainties associated with signal model yields. For the double-photon razor analysis, the contributions labeled as "shape" have different sizes, depending on M_R.

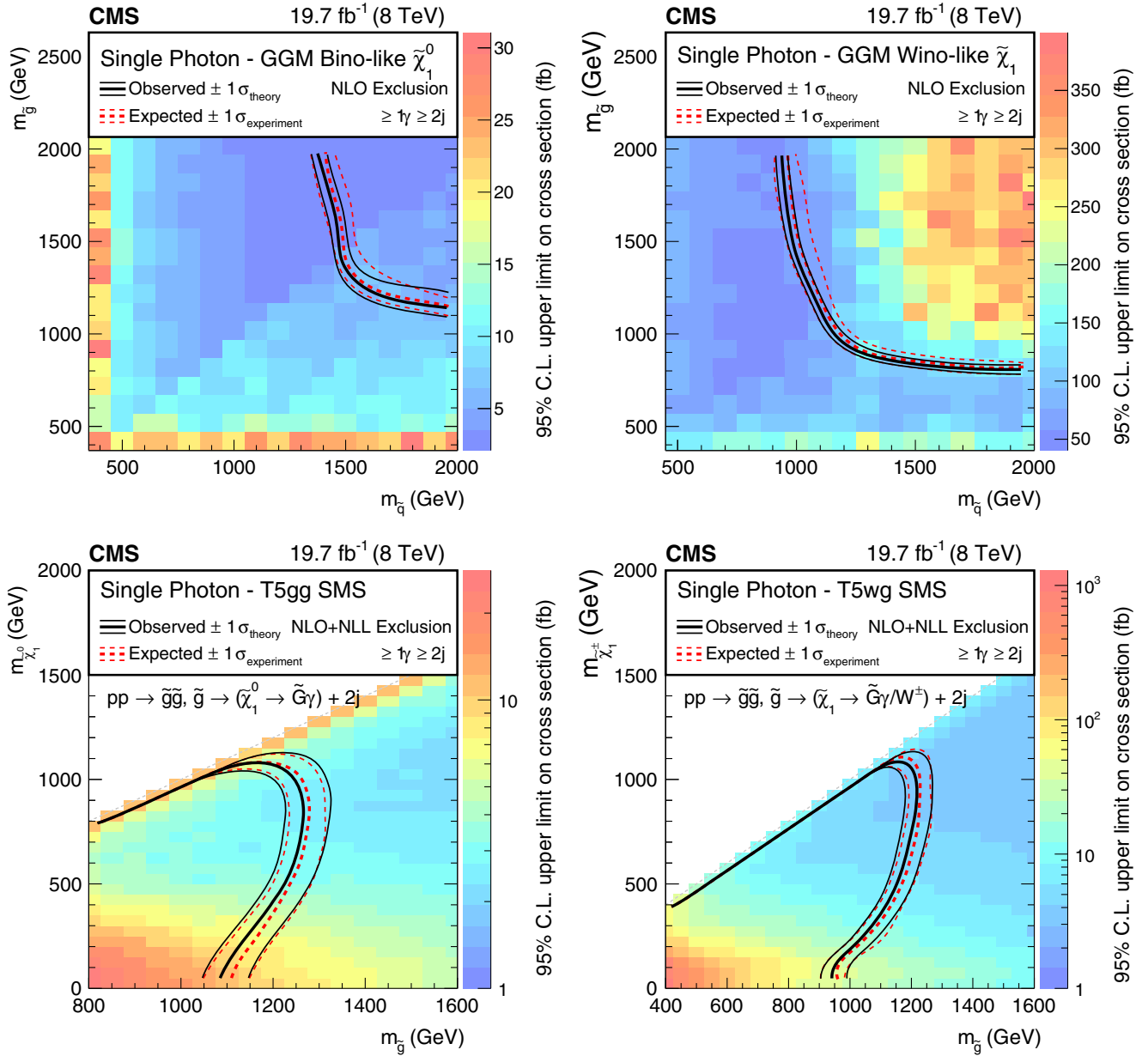| Systematic uncertainty	Single photon [%]	Double photon [%]
Data/MC photon scale factors	1	1–2
Trigger efficiency	2	1
Integrated luminosity [66]	2.6	2.6
Jet energy scale corrections [67]	2–3	shape (bin by bin) 2–5
Initial-state radiation	3–5	< 1
Acceptance due to PDF	1–3	1–3
Signal yield due to PDF and scales	5–20	1–50

FIG. 8 (color online). Single-photon analysis 95% CL observed upper limits on the signal cross section and exclusion contours in the gluino-squark (top) and gaugino-gluino (bottom) mass plane for the GGMbino (top left), GGMwino (top right), T5gg (bottom left), and T5wg (bottom right) models. The thick red dashed (black solid) line shows the expected (observed) limit. The thin dashed line and band show the 68% CL range about the expected limit. The solid line quantifies the impact of the theoretical uncertainty in the cross section on the observed limit. The color scale shows the excluded cross section for each set of mass values.

VIII. INTERPRETATION OF THE RESULTS

The result of the single-photon analysis is used to extract a limit on the production cross sections of the GGM and SMS models. Comparing the excluded cross section to the corresponding predicted value, a mass limit is derived in the squark versus gluino mass plane. This procedure allows comparisons with previous results [23]. In the SMS, the limits are derived in the gluino versus gaugino mass plane. The resulting cross section upper limits and the corresponding exclusion contours are shown in Fig. 8.

Figure 9 shows the excluded mass regions and the cross section upper limits for the GGMbino and T5gg models obtained from the double-photon analysis.

The single- and double-photon analyses are complementary with respect to the event selection and the search strategy. While the former is a multichannel counting experiment based on the absolute prediction of the standard model backgrounds, the latter uses kinematic information about the razor variables to perform a shape analysis. The best individual sensitivity is in the wino- and the bino-like
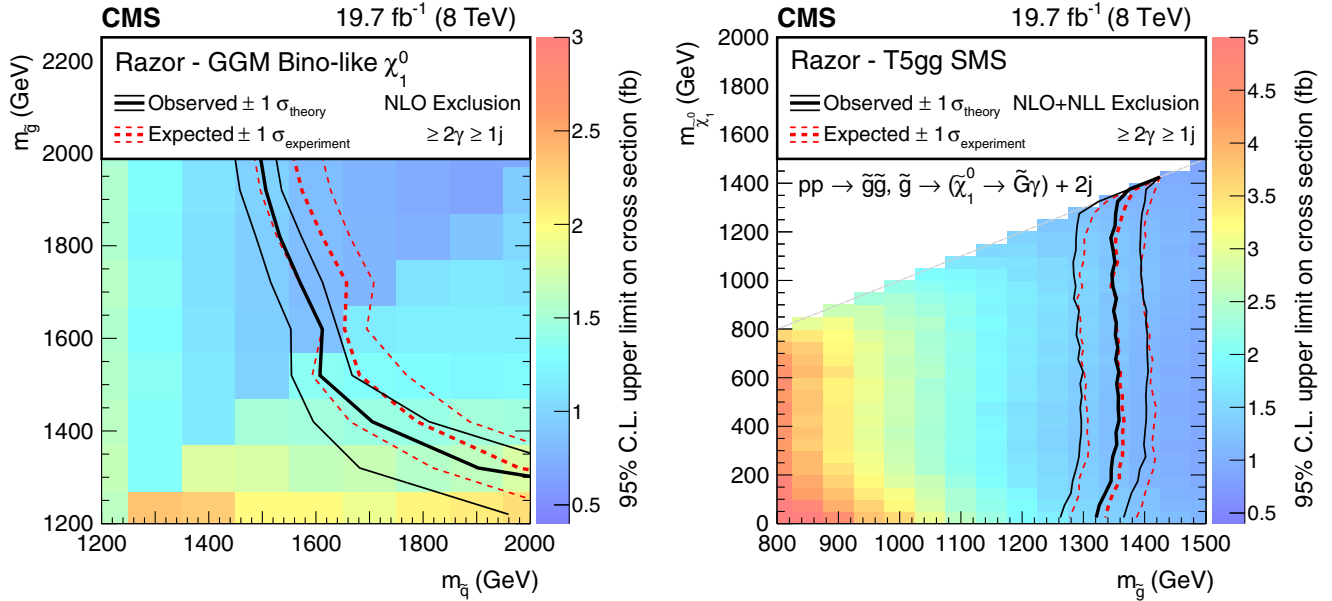
FIG. 9 (color online). Double-photon analysis 95% CL observed cross section upper limits and excluded mass regions for the GGMbino (left) and T5gg (right) models. The representations of excluded regions and cross sections are the same as in Fig. 8.

neutralino mixing scenario, respectively. The double-photon analysis performs slightly better compared to the single-photon search in the bino scenario, because of the high-H_T trigger requirement in the single-photon selection.

IX. SUMMARY

Two searches for gauge-mediated supersymmetry are presented: a search based on events with at least one photon and at least two jets, and a search based on events with at least two photons and at least one jet. The single-photon search characterizes a potential signal as an excess in the tail of the E_T^{miss} spectrum beyond 100 GeV, while the double-photon search exploits the razor variables M_R and R^2. These searches are based on pp collision data collected with the CMS experiment at a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. No evidence for supersymmetry production is found, and 95% CL upper limits are set on the production cross sections, in the context of simplified models of gauge-mediated supersymmetry breaking and general gauge-mediation (GGM) models. Lower limits from the double-photon razor analysis range beyond 1.3 TeV for the gluino mass and beyond 1.5 TeV for the squark mass for bino-like neutralino mixings in the studied GGM phase space, extending previous limits [23] by up to 300 and 500 GeV, respectively. The limits from the single-photon analysis for wino-like neutralino mixings range beyond 0.8 TeV for the gluino mass and 1 TeV for the squark mass in the same GGM phase space, extending previous limits by about 100 and 200 GeV. Within the discussed supersymmetry scenarios, these results represent the current most stringent limits.

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