Available on CMS information server

**CMS CR -2019/045**

The Compact Muon Solenoid Experiment

**Conference Report**

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

**03 May 2019 (v3, 31 December 2019)**

# SUSY searches with photons in CMS

Danilo Meuser for the CMS Collaboration

**Abstract**

Two searches and a combination of searches for supersymmetry in events with photons using data collected by the CMS experiment during Run 2 of the LHC are presented. In stealth supersymmetric models the gauginos couple to a stealth sector via photon emission, while its superpartner in the stealth sector decays to two gluons. Jet substructure techniques are used to identify the photon within the gluon jets. In gauge-mediated supersymmetry breaking models neutralinos with a large bino component predominantly decay to a photon and a gravitino. In this context a search in final states with two photons and a combination of multiple searches in final states with at least one photon are presented.

Presented at *Moriond/EW2019 54th Rencontres de Moriond 2019 Electroweak Interactions and Unified Theories*

# SUSY SEARCHES WITH PHOTONS IN CMS

DANILO MEUSER ON BEHALF OF THE CMS COLLABORATION
*I. Physikalisches Institut B, RWTH Aachen University,*
*Sommerfeldstraße 14, Turm 28, 52072 Aachen, Germany*

Two searches and a combination of searches for supersymmetry in events with photons using data collected by the CMS experiment during Run 2 of the LHC are presented. In stealth supersymmetric models the gauginos couple to a stealth sector via photon emission, while its superpartner in the stealth sector decays to two gluons. Jet substructure techniques are used to identify the photon merged with the gluon jets. In gauge-mediated supersymmetry breaking models, neutralinos with a large bino component predominantly decay to a photon and a gravitino. In this context a search in final states with two photons and a combination of multiple searches in final states with at least one photon are presented.

## 1 Introduction

The search for supersymmetry (SUSY) is a central mandate of the physics program of the CMS and the ATLAS experiments at the LHC. Supersymmetry, which is a possible theoretical extension of the standard model (SM) of particle physics, provides explanations for several unsolved problems in particle physics. The searches for SUSY in events with photons presented here, which are based on data collected by the CMS experiment [1] at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 35.9 fb$^{-1}$, are motivated by two different SUSY models.

In stealth SUSY an additional stealth sector of particles, which has a small coupling to the SUSY breaking mechanism, is introduced. As a result, the superpartners in the stealth sector are nearly mass degenerate. Furthermore, it is assumed that the gauginos, either neutralinos or charginos, couple to the stealth sector via photon emission, leading to final states with photons.

In scenarios with gauge-mediated SUSY breaking (GMSB) the symmetry breaking is mediated via SM gauge interactions. The gravitino ($\widetilde{\mathrm{G}}$) is the lightest supersymmetric particle and escapes undetected, leading to missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$). The next to lightest supersymmetric particle (NLSP) is formed by a mixture of the SUSY partners of electroweak gauge bosons. In case of a NLSP with a large bino component, its decay to a photon and a gravitino is enhanced, leading to final states with photons and $p_{\mathrm{T}}^{\mathrm{miss}}$.

## 2 Search with photons in boosted jets

The analysis [2] discussed here explores stealth SUSY scenarios in events with collimated photons and gluons. A simplified stealth SUSY model, shown in Figure 1, with only one light hidden sector superparticle pair, the singlino ($\widetilde{\mathrm{S}}$) and the singlet (S), is used as a benchmark. Within this model the gluinos ($\widetilde{\mathrm{g}}$) decay to a neutralino ($\widetilde{\chi}_1^0$) and a quark anti-quark pair. The neutralino couples to the stealth sector via its decay to a photon and a singlino, which further decays to a singlet and a gravitino. Finally, the singlet decays to a pair of gluons, leading to final states with photons, gravitinos, as well as quark and gluon jets. Because of the small coupling between the stealth sector and the SUSY breaking mechanism, the singlino and the singlet are almost mass degenerate and the outgoing gravitino is produced with a small momentum, motivating final states with low $p_{\mathrm{T}}^{\mathrm{miss}}$. In case of a large mass gap between the gluino and the neutralino, the neutralino can have a large Lorentz boost, resulting in events where the photon is not isolated from the gluon jets. By using existing and novel jet substructure tools, this analysis focuses on identifying photons inside gluon jets, in the following referred to as "photon-jets".

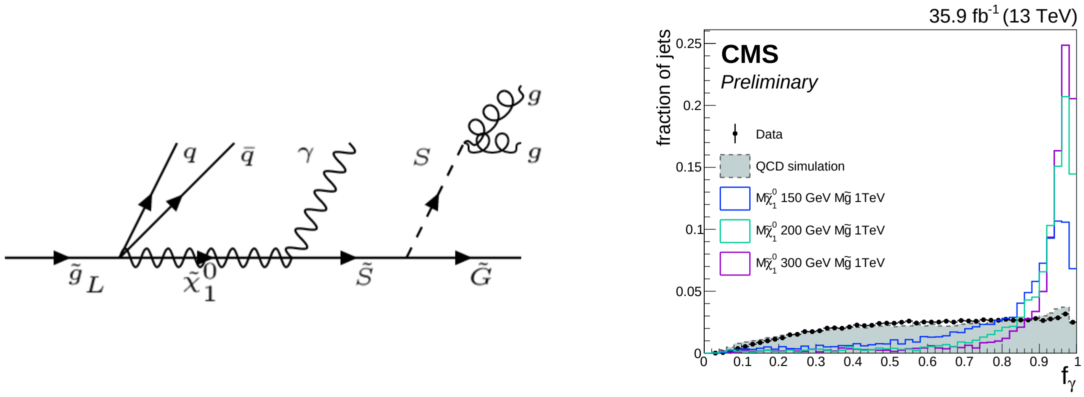


Figure 1 – Left figure [2]: Diagram for a gluino ($\tilde{\mathrm{g}}$) decay predicted by stealth SUSY. The neutralino ($\tilde{\chi}_1^0$) couples to the stealth sector via photon emission. The singlino ($\tilde{\mathrm{S}}$) decays to its superpartner (S) and a low momentum gravitino ($\tilde{\mathrm{G}}$). Right figure [2]: Normalized distribution of the photon subject fraction ($f_\gamma$) for data, QCD background, as well as three different stealth SUSY signal points with different neutralino and gluino masses.

Photon-jets are selected based on jets with $p_{\mathrm{T}} > 200$ GeV and $|\eta| < 2$, which are clustered with a distance parameter of 0.8. In addition, the jet has to contain an ECAL cluster with a photon like shower shape and $p_{\mathrm{T}} > 20$ GeV. Based on the ECAL cluster a photon is reconstructed and used to replace the cluster in the reclustering of the jet. Within the reclustered jet the existence of three subjets with $p_{\mathrm{T}} > 10$ GeV is required. To further classify the selected photon-jets, two photon-jet categories are defined. The loose photon-jet category requires that the jet has an N-subjetiness ratio $\tau_3/\tau_1 < 0.4$. To define the tight category the photon subjet fraction ($f_\gamma$), given by the ratio of the photon $p_{\mathrm{T}}$ and the $p_{\mathrm{T}}$ of the subjet it is part of, is used. Since the photon subjet fraction for signal events, shown in the right part of Figure 1, peaks at larger values compared to the QCD background, tight photon-jets have to fulfill $f_\gamma > 0.9$ in addition to the loose category requirement.

The signal region (SR) is defined by events with exactly two loose photon-jets, out of which zero, one, or two jets also match the tight requirement. To predict QCD background contributions to the SR, a background dominated region (BR) is defined as the set of events with one or less loose photon-jets. The prediction itself is performed in data evaluating loose and tight mistag rates in the BR as a function of jet $p_{\mathrm{T}}$ and $|\eta|$ and throwing toys to determine the probability for BR events to migrate to the SR. This probability is then used to weight each data event in the BR to construct the background distribution of the hadronic activity ($H_{\mathrm{T}}$) for each of the three SR categories.

The search is performed separately on events with exactly three and four or more jets. The $H_{\mathrm{T}}$ distributions for the three jet category are shown in Figure 2. The observed data is consistent with the background prediction and the results of both categories are combined and interpret as upper cross section limit for gluino pair production according to the simplified stealth SUSY model. The cross section limit result is shown in Figure 3. In the context of gluino pair production gluino masses up to 1.68 TeV for a neutralino mass of 200 GeV are excluded at a 95% confidence level (CL). For the largest neutralino masses this limit is slightly reduced to gluino masses of around 1.6 TeV. Based on final states with photons in boosted jets this analysis exceeds previous limits set by searches for isolated photons [3,4].

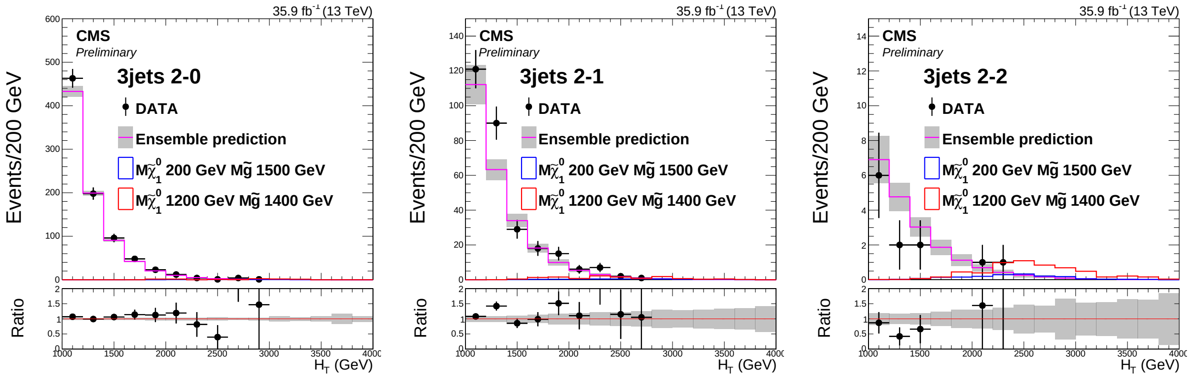


Figure 2 – The $H_{\mathrm{T}}$ distributions [2] in the signal region for the three jet category. Events with zero, one, and two tight photon-jets are presented from left to right. The background prediction is shown as magenta line with the gray band corresponding to total uncertainty in the prediction. The observed data yields are shown as black points and the blue and red lines represent two different expected signal distributions.

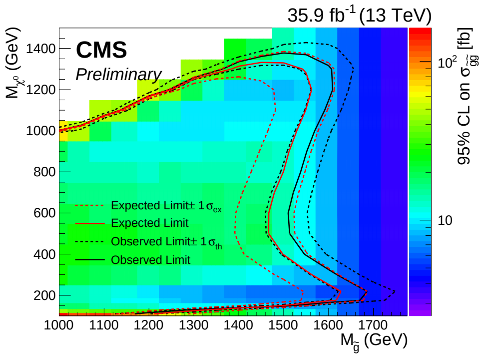


Figure 3 – The 95% CL upper cross section limit [2] for the simplified stealth SUSY model in the parameter space of the gluino and neutralino mass. The region left from the lines is excluded. The black line respresents the observed and the red line the expected exclusion limit. The band around the expected limit indicates the region containing 68% of the distribution of limits expected under the background-only hypothesis. The band around the observed limit shows the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

## 3 Search in diphoton events

The search [5] presented in the following mainly targets GMSB models with bino-like NLSPs, leading to final states with two photons and large missing transverse momentum. One of the benchmark scenarios used in this search is shown in the left part of Figure 4. In this simplified SUSY model, which is based on gluino ($\widetilde{\mathrm{g}}$) pair production, two neutralinos ($\widetilde{\chi}_1^0$) are produced along with additional quark anti-quark pairs from the gluino decays. Due to the large bino component of the neutralino it is assumed that both neutralinos decay to a photon and a nearly massless gravitino ($\widetilde{\mathrm{G}}$).

The event selection ($\gamma\gamma$ sample) of this search is based on the presence of two photons with $p_{\mathrm{T}} > 40$ GeV and a requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV. Motivated by the choice of the diphoton trigger used in this analysis, the invariant mass of the diphoton system has to exceed 105 GeV. In addition to these requirements, any event with a muon or an electron satisfying $p_{\mathrm{T}} > 25$ GeV and $|\eta_{\mu(\mathrm{e})}| < 2.4(2.5)$ is vetoed.

Based on this event selection one of the main SM background contributions arises from QCD processes. To predict this contribution in a data driven way, a control sample with two misidentified photons, also called "fake" photons, is defined ($ff$ sample). The ratio between $\gamma\gamma$ and $ff$ events is calculated in the region of $p_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV and fitted with an exponential function. The exponential is then used to estimate the QCD contribution to the $\gamma\gamma$ sample

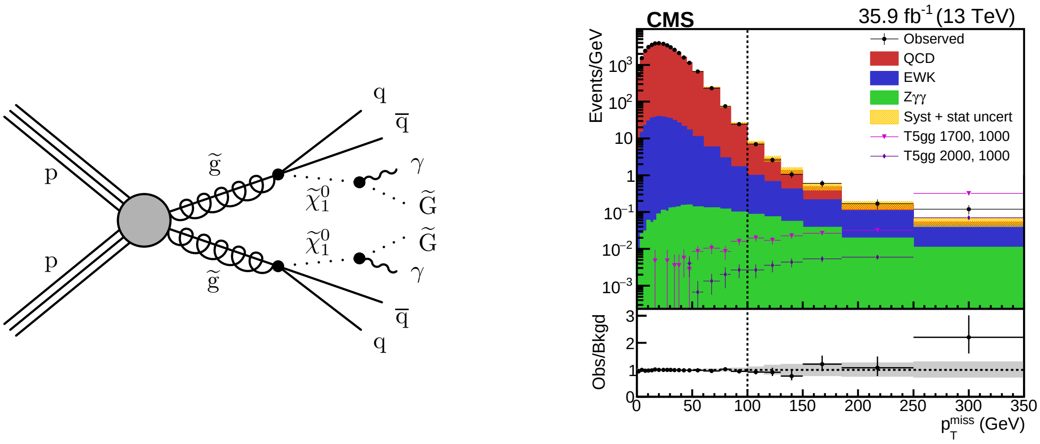


Figure 4 – Left figure [5]: Diagram showing gluino ($\widetilde{g}$) pair production, where both gluinos decay to a neutralino and a quark anti-quark pair with the neutralino further decaying to a gravitino and a photon. Right figure [5]: The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution (top panel) of the observed data (black points), the QCD (red), misidentified electron (blue) and irreducible (green) background. The total uncertainty of the background prediction is shown in yellow. In addition, the expected distribution of two gluino pair production signal points is displayed. The bottom panel shows the ratio of observed events to the expected background yields, with the gray band corresponding to the total background uncertainty.

for $p_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV by multiplying the exponential with the $ff$ yields for individual bins in $p_{\mathrm{T}}^{\mathrm{miss}}$. Additional background contributions arise from electrons, which are misidentified as photons. For this background an electron-to-photon misidentification factor, derived using the tag-and-probe method, is applied to an e$\gamma$ control sample. Irreducible contributions from Z$\gamma\gamma$ events with the vector boson decaying to neutrinos are predicted by simulation.

The final $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution is presented in the right part of Figure 4, which shows a good agreement between data and background prediction with the largest fluctuation in the last bin. Based on this result upper cross section limits on gluino and squark pair production, shown in Figure 5, are derived. Gluino masses up to 1.8 TeV and squark masses up to 1.6 TeV can be excluded at a CL of 95 %. This corresponds to an increased sensitivity of more than 300 GeV compared to a previous iteration [6] of this search.

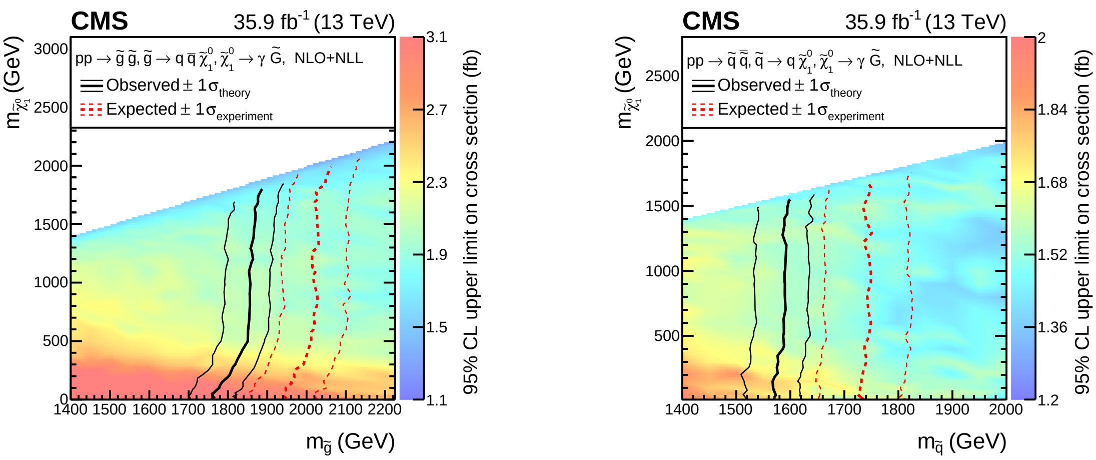


Figure 5 – The 95% CL exclusion limit [5] for gluino (left) and squark (right) pair production in the parameter space of the gluino (squark) and neutralino mass. The region left from the lines is excluded. The black line respresents the observed and the red line the expected exclusion limit. The band around the expected limit indicates the region containing 68% of the distribution of limits expected under the background-only hypothesis. The band around the observed limit shows the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

## 4 GMSB combination

In this analysis [7] a combination of four different SUSY searches in final states with photons is performed. In addition to the Diphoton search [5] presented in the previous section, the combination includes a search in final states with photons and charged leptons (Photon+Lepton) [8], as well two more inclusive searches based on final states with at least one photon (Photon+$S_{\mathrm{T}}^{\gamma}$ and Photon+$H_{\mathrm{T}}^{\gamma}$) [9,10]. While the Diphoton and the Photon+Lepton search target events with $p_{\mathrm{T}}^{\mathrm{miss}}$ above the order of 100 GeV , the $p_{\mathrm{T}}^{\mathrm{miss}}$ requirements in the two inclusive searches exceed 300 GeV and new variables are defined to classify selected events. In case of the Photon+$S_{\mathrm{T}}^{\gamma}$ search, $S_{\mathrm{T}}^{\gamma}$ is given by the sum of $p_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}$ of all photons, whereas in the Photon+$H_{\mathrm{T}}^{\gamma}$ search, $H_{\mathrm{T}}^{\gamma}$ corresponds to the sum of the leading photon $p_{\mathrm{T}}$ and $p_{\mathrm{T}}$ off all jets.

The events used in the combination are divided into four categories, where each category is based on one of the individual searches. To enable a statistical combination of these categories, the overlap between the categories is removed as explained in the following. Events with charged leptons or two photons that are also selected in the Photon+$S_{\mathrm{T}}^{\gamma}$ or Photon+$H_{\mathrm{T}}^{\gamma}$ category, are removed from those categories and kept in the Photon+Lepton and Diphoton category, respectively. Events with a large hadronic activity ($H_{\mathrm{T}}^{\gamma} > 2$ TeV) are vetoed from the Photon+$S_{\mathrm{T}}^{\gamma}$ category, while events with a lower hadronic activity ($H_{\mathrm{T}}^{\gamma} < 2$ TeV) are vetoed from the Photon+$H_{\mathrm{T}}^{\gamma}$ category. Based on these additional vetoes, four exclusive categories are created.

The observed yields and background predictions for the search bins of all four categories with the additional vetoes applied are shown in Figure 6. While a few bins show small fluctuations in the observed data compared to the background prediction, no significant deviation from the SM is observed. This result is interpreted in a full general gauge-mediation (GGM) scenario, shown in the left part of Figure 7. Within this scenario pair production of electroweak gauginos is probed, while gluinos and squarks are assumed to be too heavy to be produced. The right plot of Figure 7 shows the 95% CL upper exclusion limit for the combination as well as for the individual searches. Chargino masses up to 890(1090) GeV can be excluded by the observed (expected) limit of the combination. This corresponds to a gain of around 100 GeV for the expected limit compared to the individual searches.

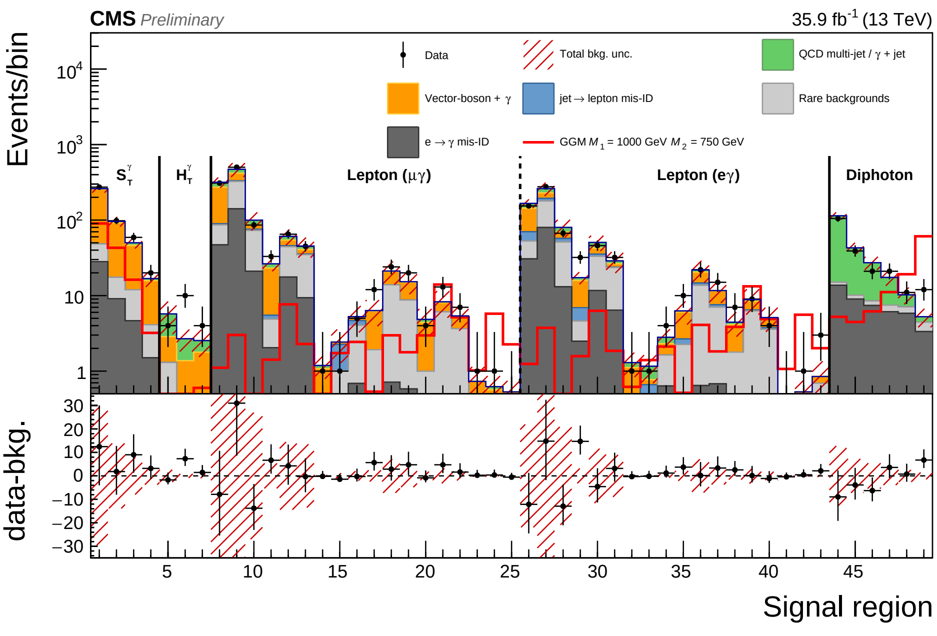


Figure 6 – Comparions between the observed yields and the background predictions for all search bins used in the combination [7]. The hatched bands in both parts of the plot correspond to the total uncertainty in the background prediction. The red line in the top panel represent the expected yield for one specific GGM signal point.

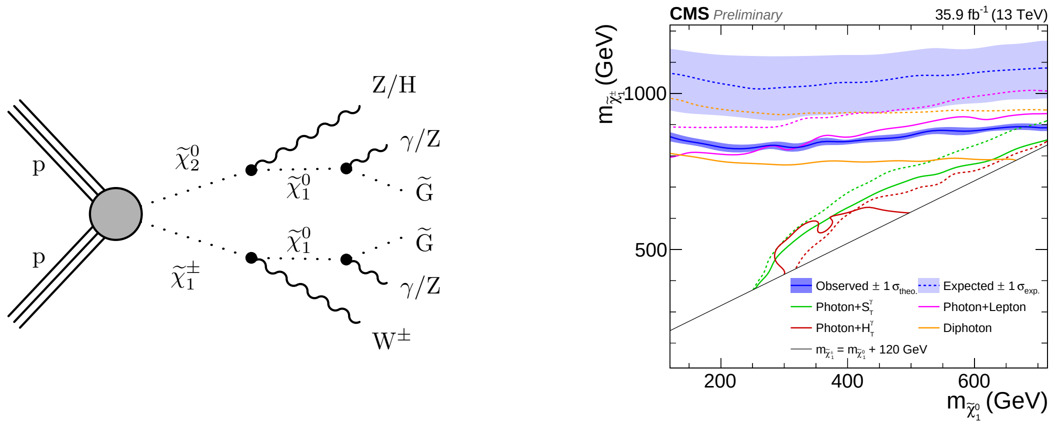


Figure 7 – Left figure [7]: Diagram of one possible GGM process based on $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ production, where the gaugino decays depend on the gaugino composition of the gauge eigenstates. Right figure [7]: The 95% CL exclusion limits [5] for the GGM scenario in the parameter space of the neutralino and chargino mass. The solid lines respresent the observed and the dotted lines the expected exclusion limits. The band around the expected limit of the combination indicates the region containing 68% of the distribution of limits expected under the background-only hypothesis. The band around the observed limit of the combination shows the change in the observed limit due to variation of the signal cross sections within their theoretical uncertainties.

## 5 Summary

In this proceeding, two searches and a combination of searches for supersymmetry in events with photons based on data collected by the CMS exeriment at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 35.9 fb$^{-1}$ have been presented. No significant deviation from the SM is observed in any of the analyses and exclusion limits on stealth and GMSB SUSY scenarios are derived. Within a simplified stealth SUSY scenario gluino masses up to around 1.6 TeV can be excluded, while for a simplified GMSB scenario this limit can be extended up to 1.8 TeV. In addition, an upper limit of 1.6 TeV on squark masses in the context of the GMSB scenario is derived. In a combination of four individual SUSY searches in events with photons chargino masses up to 890 GeV are excluded for a GGM scenario based on electroweak production, where the combination improves the expected limit by 100 GeV compared to the individual searches.

## References

1. CMS Collaboration, JINST 3 S08004 (2008)
2. CMS Collaboration, CMS-PAS-B2G-18-007, https://cds.cern.ch/record/2667271
3. CMS Collaboration, Phys. Lett. B 743 (2015)
4. CMS Collaboration, Phys. Lett. B 719 (2013)
5. CMS Collaboration, Submitted to: JHEP, 2019, https://arxiv.org/abs/1903.07070
6. CMS Collaboration, Phys. Lett. B 769 (2017)
7. CMS Collaboration, CMS-PAS-SUS-18-005, https://cds.cern.ch/record/2668332
8. CMS Collaboration, JHEP 1901 (2019)
9. CMS Collaboration, Phys. Lett. B 780 (2018)
10. CMS Collaboration, JHEP 12 (2017)