Combined search for supersymmetry with photons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A combination of four searches for new physics involving signatures with at least one photon and large missing transverse momentum, motivated by generalized models of gauge-mediated supersymmetry (SUSY) breaking, is presented. All searches make use of proton-proton collision data at $\sqrt{s} = 13$ TeV, which were recorded with the CMS detector at the LHC in 2016, and correspond to an integrated luminosity of 35.9 fb$^{-1}$. Signatures with at least one photon and large missing transverse momentum are categorized into events with two isolated photons, events with a lepton and a photon, events with additional jets, and events with at least one high-energy photon. No excess of events is observed beyond expectations from standard model processes, and limits are set in the context of gauge-mediated SUSY. Compared to the individual searches, the combination extends the sensitivity to gauge-mediated SUSY in both electroweak and strong production scenarios by up to 100 GeV in neutralino and chargino masses, and yields the first CMS result combining various SUSY searches in events with photons at $\sqrt{s} = 13$ TeV.

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*See Appendix A for the list of collaboration members
1 Introduction

The search for supersymmetry (SUSY), a possible theoretical extension of the standard model (SM) of particle physics, is an important piece of the physics program at the CERN LHC. Supersymmetry provides solutions to several unsolved problems in particle physics, including a mechanism for stabilizing the Higgs boson mass at the electroweak (EW) energy scale. Supersymmetric models with a general gauge-mediated (GGM) SUSY breaking mechanism [1–6] and \( R \)-parity conservation [7] often lead to final states containing photons and a large transverse momentum imbalance [8–15]. These final states are probed by several searches based on proton-proton (pp) collisions at a center-of-mass energy (\( \sqrt{s} \)) of 13 TeV recorded with the ATLAS [16, 17] and CMS experiments [18–21].

In this Letter, a combination of four different searches focusing on GGM SUSY scenarios is presented. In GGM models, the gravitino (\( \tilde{G} \)) is the lightest SUSY particle (LSP) and escapes undetected, leading to missing transverse momentum (\( p_T^{\text{miss}} \)). For these scenarios, the experimental signature depends on the nature of the next-to-LSP (NLSP), which is an admixture of the SUSY partners of EW gauge bosons. The bino and wino are the superpartners of the SM U(1) and SU(2) gauge eigenstates, respectively. In most GGM models, the NLSP is assumed to be a bino- or wino-like neutralino, or a wino-like chargino. In the models used in this analysis the lightest neutralino (\( \tilde{\chi}_1^0 \)) corresponds to the NLSP, which decays to a \( \tilde{G} \) accompanied by a photon (\( \gamma \)), a Z boson, or a Higgs boson (H) depending on its composition. The lightest chargino (\( \tilde{\chi}_1^\pm \)) is assumed to decay to a \( \tilde{G} \) and a W boson. The results are interpreted in a GGM signal scenario with photons in the final state varying the bino and wino mass parameters.

To provide more model-independent results for a broader set of signal topologies, the results are also interpreted in the context of simplified model scenarios (SMS) [22]. In the case of strongly produced SUSY particles, gluino and squark decays result in additional jets in the final state along with the NLSP decay products. For both EW and strong SUSY production, the gaugino branching fractions are varied to probe a range of possible scenarios resulting in final states with photons, Z or W bosons.

All searches used in the combination are performed with pp collision data at \( \sqrt{s} = 13 \text{ TeV} \), corresponding to an integrated luminosity of 35.9 fb\(^{-1}\), collected with the CMS detector in 2016. In the combination, each search corresponds to a category of events. The first category requires the presence of two isolated photons (Diphoton category). This category is based on the search presented in Ref. [18] and targets bino-like neutralino decays. Events with electrons (\( e^\pm \)) or muons (\( \mu^\pm \)) are vetoed in this category. The Photon+Lepton category requires one isolated photon, as well as one isolated \( e^\pm \) or \( \mu^\pm \). This category is based on the search presented in Ref. [19] and targets wino-like chargino decays along with bino-like neutralino decays. The Photon+\( S_T^\gamma \) category requires the presence of at least one isolated photon and large \( p_T^{\text{miss}} \) utilizing the variable \( S_T^\gamma = p_T^{\text{miss}} + \sum_i p_T^{\gamma_i} \), where \( p_T^{\gamma_i} \) is the transverse momentum of photons in the event. This search, presented in Ref. [20], provides sensitivity to both EW and strong production. The Photon+\( H_T^\gamma \) category is based on the search presented in Ref. [21] and focuses on strongly produced gluinos and squarks. This search requires at least one isolated photon and significant hadronic activity by selecting events with large values of \( H_T^\gamma = H_T + p_T^{\gamma} \), where \( H_T \) is the scalar sum of all jet momenta and \( p_T^{\gamma} \) is the transverse momentum of the leading photon in the event.

To ensure exclusive search regions for the combination, any overlapping kinematic regions in the four categories are combined such that a single event is only present in one category. For SUSY scenarios that are based on EW production, all four categories are used. For strong SUSY
production, the Diphoton category is removed.

## 2 Signal scenarios

The SUSY scenarios considered in this Letter are sketched in Fig. 1; they include one GGM scenario (upper left), two EW SMS (upper right and lower left), and one strong production SMS (lower right).

Figure 1: Diagrams of the SUSY processes considered in this Letter: one process within the GGM scenario (upper left), two EW SMS processes, with possible neutralino and chargino decays (upper right and lower left), and a strong SMS process based on gluino pair production (lower right).

For the GGM scenario, the squark and gluino masses are set to be large, rendering them irrelevant to the studied LHC collisions and ensuring that strong production is negligible and EW production of gauginos is dominant. The GGM framework used to derive the GGM scenario is suitable for unifying models of gauge-mediation in a more general way with only a few free parameters \[23-25\]. For the GGM scenario considered in this Letter, the techniques of Ref. \[24\] are used to reduce the 8-dimensional GGM parameter space to two gaugino mass parameters. The GGM scenario is defined by setting the GGM parameters as follows:

\[
M_3 = \mu = 8 \text{ TeV}, \\
m_Q = m_U = 10 \text{ TeV}, \\
m_D = 8 \text{ TeV}.
\]

All parameters are defined at the messenger scale, which is set to \( M_{\text{mess}} = 10^{15} \text{ GeV} \). The parameters \( M_3 \) and \( \mu \) are the gluino and higgsino mass parameters, respectively, and the parameters \( m_Q, m_U, \) and \( m_D \) are the sfermion soft masses. In this GGM scenario, the remaining
bino ($M_1$) and wino ($M_2$) mass parameters are varied and the Higgs boson mass receives large radiative corrections from the heavy stops to yield the observed mass at the EW scale.

In GGM, the lifetime of the NLSP is a function of the NLSP and the gravitino masses. In order to ensure prompt decays of the NLSP in the detector, the gravitino mass is fixed to 10 eV. As was shown in Ref. [25], this implies heavy squarks ($m_{	ilde{q}} \gtrsim 3$ TeV), which is consistent with the model used in this Letter. Because of the heavy squarks and gluinos in the GGM scenario, EW production is dominant, specifically $\tilde{\chi}_1^0 \rightarrow Z \tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow \chi_1^0 (\gamma + \tilde{G})$ production.

One possible diagram for the GGM scenario is shown in Fig. 1 (upper left). The branching fraction of the NLSP decaying into a photon and a gravitino is determined by the composition of the gauge eigenstates of the NLSP, while the chargino always decays to the $W$ boson. As shown in Fig. 2 (left), the branching fraction of the NLSP changes across the parameter space. For large $M_1$ and medium $M_2$, the NLSP is wino-like. This increases the branching fraction for $\tilde{\chi}_1^0 \rightarrow Z \tilde{G}$ decays in the phase space of $M_2 \gtrsim 300$ GeV where the NLSP mass exceeds the $Z$ boson mass. In the remaining phase space, the NLSP is bino-like, which increases the $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ branching fraction. The different compositions of the NLSP can also be extracted from the dependence of the physical NLSP mass on the model parameters $M_1$ and $M_2$, as shown in Fig. 2 (right). With a wino-like NLSP, the physical mass scales with $M_2$, whereas, for the remaining phase space with bino-like NLSPs, the physical mass depends on $M_1$.

![Figure 2: Branching fractions ($B$) for the NLSP decay to a photon and a gravitino for the GGM scenario (left). The phase space is spanned by the bino ($M_1$) and wino ($M_2$) mass parameters showing the change of the NLSP composition. This change also influences the dependence of the physical mass of the neutralino ($m_{\chi_0}$) on the gauge mass parameters (right).](image)

Based on EW production SMSs, two different branching fraction scenarios are constructed. For these scenarios, the chargino and neutralino masses are almost degenerate in mass, such that the $W$ boson from the chargino decay is produced off-shell, resulting in low momentum (soft) particles that are outside the detector acceptance. In the case of the neutralino branching fraction scenario, $\tilde{\chi}_1^0 \chi_1^0$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ are probed as shown in Fig. 2 (upper right). In this scenario, the chargino always decays to the NLSP, whereas the branching fractions for the decay modes $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow Z \tilde{G}$ are varied. In the chargino branching fraction scenario, shown in Fig. 2 (lower left), the chargino can decay to the LSP or NLSP, and the branching fractions for the decay modes $\tilde{\chi}_1^0 \rightarrow W^{\pm} \tilde{G}$ and $\tilde{\chi}_1^0 \rightarrow \chi_1^0 (+\text{soft})$ are varied. In this scenario only $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ is produced. These scenarios probe a range of NLSP compositions with bino- and wino-like neutralinos, and wino-like charginos.
The strong production SMS, shown in Fig. 1 (lower left), is used for the nominal gluino scenario and the gluino branching fraction scenario. In both scenarios, gluino pair production is probed, assuming the gluino decays to a chargino or neutralino. The decay modes for the neutralino and chargino, which are assumed to be mass degenerate, are fixed to $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ and $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$, respectively. In the nominal gluino scenario, the gluino branching fractions to either charginos or neutralinos are both set to 50%, and the gluino and NLSP masses are varied. This probes a range of scenarios where the gluino mass is small. In the gluino branching fraction scenario, the gluino branching fractions are varied along with the NLSP mass, and the gluino mass is set to 1950 GeV, which corresponds to the gluino mass where the largest gain from the combination is expected.

The production cross sections for all points in the GGM scenario are computed at next-to-leading order (NLO) using the PROSPINO2 framework \[26\]. The uncertainties in the cross section calculation are derived with PROSPINO2 following the PDF4LHC recommendations \[27\] and using the parton distribution functions (PDFs) in the LHAPDF data format \[28\]. The simulation incorporates the NNPDF 3.0 \[29\] PDFs and uses PYTHIA8 \[30\] with the CUETP8M1 generator tune to describe parton showering and the hadronization \[31\]. The simplified model signals are generated with MADGRAPH5_aMC@NLO 2.2.2 at leading order \[32\] and scaled to NLO and NLO + next-to-leading logarithmic accuracy \[33–41\]. All generated signal events are processed with a fast simulation of the CMS detector response \[42\]. Scale factors are applied to compensate for any differences with respect to the full simulation, which is based on GEANT4 \[43\].

### 3 The 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 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 ($\eta$) 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.

The analysis only utilizes photons measured in the barrel section of the ECAL. In this section, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1.0$, rising to about 2.5% at $|\eta| = 1.4$ \[44\].

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. \[45\].

### 4 Object reconstruction and identification

Photons, electrons, muons, and jets are reconstructed with the particle-flow (PF) event algorithm \[46\], which identifies particles produced in a collision combining information from all detector subsystems. The energy of photons is directly obtained from the ECAL measurement. Likewise, the energy of electrons is derived from a combination of the momentum measured in the tracker and the energy measured from spatially compatible clusters of energy deposits in the ECAL. The energy of muons is obtained from the curvature of the corresponding track. ECAL and HCAL energy deposits associated to tracks are reconstructed as charged hadrons;
remaining energy deposits are reconstructed as neutral hadrons. Jets are reconstructed from PF candidates using the anti-$k_T$ clustering algorithm \cite{47} with a distance parameter of 0.4.

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as $p_T^{\text{miss}}$. The $\vec{p}_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event \cite{48}.

Photons considered in this Letter are required to be isolated and have an ECAL shower shape consistent with a single photon shower. The photon isolation is determined by computing the transverse energy in a cone centered around the photon momentum vector. The cone has an outer radius of 0.3 in $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ (where $\phi$ is azimuthal angle in radians). The contribution of the photon to this cone is removed. Corrections for the effects of multiple interactions in the same or adjacent bunch crossing (pileup) are applied to all isolation energies, depending on the $\eta$ of the photon. The Diphoton category \cite{18} uses photon identification criteria with an average photon selection efficiency of 80\% to suppress backgrounds from quantum chromodynamics (QCD) multijet events. The other three categories \cite{19,21} use looser identification criteria to preserve a high photon selection efficiency of 90\%. Only photons reconstructed in the barrel region ($|\eta| < 1.44$) are used, because the SUSY signal models considered in this combination produce photons primarily in the central region of the detector.

Reconstructed jets are used to compute the $H_T$ variable as well as the $H_T^\gamma$ variable along with the selected photons. Jets reconstructed within a cone of $\Delta R < 0.4$ around the leading photon are not considered in both variables. Jets with $p_T > 30$ GeV and $|\eta| < 3.0$ are used. In case of the Photon+Lepton only jets with $|\eta| < 2.5$ are taken into account.

Identification of electrons is based on the shower shape of the ECAL cluster, the HCAL-to-ECAL energy ratio, the geometric matching between the cluster and the track, the quality of the track reconstruction, and the isolation variable. The isolation variable is calculated from the transverse momenta of photons, charged hadrons, and neutral hadrons within a cone whose radius is variable depending on the electron $p_T$ \cite{49}, and which is corrected for the effects of pileup \cite{50}.

A set of muon identification criteria, based on the goodness of the global muon track fit and the quality of the muon reconstruction, is applied to select the muon candidates. Muons are also required to be isolated from other objects in the event using a similar isolation variable as in the electron identification.

5 Event selection

Events are divided into the four categories shown in Table 1. Each category is based on one of the four individual searches \cite{18,21}. The minimum photon $p_T$ is mainly determined by the trigger \cite{51} requirements in each of the four searches. The Photon+$S_T^\gamma$ and Photon+$H_T^\gamma$ categories are also referred to as inclusive categories. The signal region for these categories are defined by $S_T^\gamma$ and $H_T^\gamma$ respectively, where the Photon+$H_T^\gamma$ category also has search regions in $p_T^{\text{miss}}$. Selected diphoton events are classified by values of $p_T^{\text{miss}}$, whereas events with a photon and a lepton are classified by values of $p_T^{\gamma}$, $H_T$, and $p_T^{\text{miss}}$.

To enable a statistical combination of the four categories, the overlap between the categories is removed by applying additional vetoes. Since the Diphoton and Photon+Lepton category show the highest sensitivities for the GGM scenario, these categories remain unchanged with respect to the initial searches. Events with leptons or two photons that are selected in the
Table 1: Definitions of the four exclusive categories. The kinematic selections and the search bins are based on the four individual searches, while the additional vetoes shown in the third columns ensure exclusive event categories. The transverse mass of a photon/lepton and $p_T^{\text{miss}}$ is denoted as $m_T(\gamma/\ell,p_T^{\text{miss}})$. The search bins always include the lower bounds. Diphoton and Lepton veto match the kinematic selections of the Diphoton and Photon+Lepton category, respectively.

<table>
<thead>
<tr>
<th>Kinematic selections</th>
<th>Search bins (GeV)</th>
<th>Vetoed events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^\gamma &gt; 180 \text{ GeV}, p_T^{\text{miss}} &gt; 300 \text{ GeV}$</td>
<td>$S_T^\gamma$: [600, 800], [800, 1000], [1000,1300], $H_T^\gamma &gt; 2 \text{ TeV}$ if $p_T^{\text{miss}} &gt; 350 \text{ GeV}$</td>
<td>Diphoton, Lepton</td>
</tr>
<tr>
<td>$S_T^\gamma &gt; 600 \text{ GeV}, m_T(\gamma,p_T^{\text{miss}}) &gt; 300 \text{ GeV}$</td>
<td>$H_T^\gamma$: [700, 2000], $\geq 2000$</td>
<td>Diphoton, Lepton</td>
</tr>
<tr>
<td>$p_T^\gamma &gt; 100 \text{ GeV}, p_T^{\text{miss}} &gt; 350 \text{ GeV}$</td>
<td>$p_T^{\text{miss}}$: [350,450], [450, 600], $\geq 600$</td>
<td>$H_T^\gamma &lt; 2 \text{ TeV}$</td>
</tr>
<tr>
<td>$H_T^\gamma &gt; 700 \text{ GeV},</td>
<td>\Delta\phi(\pm \vec{p}_T^{\text{miss}}, \vec{p}_T^\gamma)</td>
<td>&gt; 0.3$</td>
</tr>
<tr>
<td>$p_T^\gamma &gt; 35 \text{ GeV}, p_T^{\text{miss}} &gt; 120 \text{ GeV}$</td>
<td>$p_T^{\text{miss}}$: [120, 200], [200, 400], $\geq 400$</td>
<td>—</td>
</tr>
<tr>
<td>$p_T^\gamma &gt; 25 \text{ GeV}, m_T(\ell,p_T^{\text{miss}}) &gt; 100 \text{ GeV}$</td>
<td>$H_T^\gamma$: [0,100], [100, 400], $\geq 400$</td>
<td>—</td>
</tr>
<tr>
<td>$p_T^\gamma &gt; 40 \text{ GeV}, p_T^{\text{miss}} &gt; 100 \text{ GeV}$</td>
<td>$p_T^{\text{miss}}$: [100, 115], [115,130], [130,150], [150,185], [185,250], $\geq 250$</td>
<td>—</td>
</tr>
</tbody>
</table>

Other two categories, but also match the requirements of the Diphoton or Photon+Lepton categories, are vetoed in the Photon+$S_T^\gamma$ and Photon+$H_T^\gamma$ categories. To remove the overlap between the two inclusive categories, the two categories are separated as follows. Events with a large hadronic activity ($H_T^\gamma > 2 \text{ TeV}$) are vetoed from the Photon+$S_T^\gamma$ category if they match the $p_T^{\text{miss}}$ requirement of the Photon+$H_T^\gamma$ category. In addition, events with lower hadronic activity ($H_T^\gamma < 2 \text{ TeV}$) are vetoed from the Photon+$H_T^\gamma$ category and assigned to Photon+$S_T^\gamma$. To further increase the sensitivity to strong production the veto strategy is slightly changed for the interpretation of the gluino scenarios. For these scenarios the Diphoton category is not included in the combination and events with two photons are kept in the Photon+$S_T^\gamma$ and Photon+$H_T^\gamma$ categories, which have larger sensitivity to strong production.

The SM background in the Photon+$S_T^\gamma$ and Photon+Lepton categories is dominated by vector boson production with initial-state photon radiation, denoted as “Vector-boson + $\gamma$”. For the Photon+$H_T^\gamma$ category, on the other hand, the $H_T^\gamma$ requirement implies hadronic activity leading to a dominant background from QCD multijet and $\gamma + \text{jet}$ processes, which also holds for the Diphoton category. Additional contributions arise from electrons which are misidentified as photons and jets which are misidentified as leptons. Furthermore, $t\bar{t}$ and diboson processes, summarized as “Rare Backgrounds”, can contribute to all four categories.

6 Results

Fig. 3 and Table 2 show a comparison between the data and the background prediction for the search bins used in the combination. In case of the Photon+Lepton and the Diphoton categories, the comparisons correspond to the published results. The yields of the Photon+$S_T^\gamma$ and Photon+$H_T^\gamma$ categories are based on the modified event selections, which ensure exclusive sig-
nal regions. Overall agreement between the observed number of events and the background prediction is found for the 49 search bins.

Figure 3: Observed yields and the background predictions for all search bins used in the combination. The search bins are defined in Table 2. The hatched red bands in both parts of the plot represent the total uncertainty of the background prediction. The red line in the upper panel shows the signal prediction for one specific signal point of the GGM scenario with $M_1 = 1000$ GeV and $M_2 = 750$ GeV. The lower panel shows the ratio between the observed data and the predicted backgrounds.

The results of the combination are interpreted in terms of the GGM scenario and the simplified models introduced in Section 2. The 95% confidence level (CL) upper limits on the SUSY cross sections are calculated with the CL$_s$ criterion \cite{52, 53} using the LHC-style profile likelihood ratio as a test statistic \cite{54} evaluated in the asymptotic approximation \cite{55}. Log-normal nuisance parameters are used to describe the systematic uncertainties, which follow the treatment used in the initial searches. The majority of the systematic uncertainties in the background predictions are not correlated among the four categories. Only the systematic uncertainties on the cross-section for rare background processes as well as the uncertainties assigned to the electron-to-photon misidentification are treated as fully correlated between all four categories. While the first of these uncertainties is conservatively estimated to 50% in all four categories, the latter uncertainty ranges from 8 to 50% depending on the category and $p_T$. In addition, uncertainties in the prediction of vector boson production in association with photons in the Photon+$S_1$ and Photon+Lepton categories, which can be as large as 20%, are treated as fully correlated, since similar prediction methods are used. Furthermore, all systematic uncertainties affecting the signal acceptance, which are mainly dominated by the fast simulation uncertainty in $p_T^{miss}$, are assumed to be fully correlated among the four categories.

Results for the GGM scenario are presented in the parameters that are scanned ($M_1$ and $M_2$) and in terms of physical mass parameters for the chargino and neutralino. Fig. 4 (left) shows the combined expected exclusion limits at 95% CL for the GGM scenario, where the combination
Table 2: Predicted background yields and observed number of events in data for all search bins used in the combination. In addition the range covered by each individual bin is shown.

<table>
<thead>
<tr>
<th>Bin</th>
<th>Category</th>
<th>Ranges (GeV)</th>
<th>Total bkg.</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Photon+$S_1^\gamma$</td>
<td>$600 \leq S_1^\gamma &lt; 800$</td>
<td>$260 \pm 30$</td>
<td>273</td>
</tr>
<tr>
<td>2</td>
<td>Photon+$S_1^\gamma$</td>
<td>$800 \leq S_1^\gamma &lt; 1000$</td>
<td>$96 \pm 14$</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>Photon+$S_1^\gamma$</td>
<td>$1000 \leq S_1^\gamma &lt; 1300$</td>
<td>$50.0 \pm 7.9$</td>
<td>59</td>
</tr>
<tr>
<td>4</td>
<td>Photon+$S_1^\gamma$</td>
<td>$S_1^\gamma \geq 1300$</td>
<td>$16.8 \pm 3.8$</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>Photon+$H_T^\gamma$</td>
<td>$350 \leq p_T^{\text{miss}} &lt; 450$</td>
<td>$5.7 \pm 2.6$</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Photon+$H_T^\gamma$</td>
<td>$450 \leq p_T^{\text{miss}} &lt; 600$</td>
<td>$2.7 \pm 0.9$</td>
<td>10</td>
</tr>
<tr>
<td>7</td>
<td>Photon+$H_T^\gamma$</td>
<td>$p_T^{\text{miss}} \geq 600$</td>
<td>$2.5 \pm 1.0$</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$p_T^\mu &lt; 200$</td>
<td>$317 \pm 50$</td>
<td>309</td>
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<tr>
<td>9</td>
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<td>501</td>
</tr>
<tr>
<td>10</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
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<td>$100 \pm 27$</td>
<td>86</td>
</tr>
<tr>
<td>11</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$H_T \geq 400$</td>
<td>$26.3 \pm 5.3$</td>
<td>33</td>
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<tr>
<td>12</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$200 \leq p_T^{\text{miss}} &lt; 400$</td>
<td>$61 \pm 14$</td>
<td>65</td>
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<tr>
<td>13</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
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<tr>
<td>14</td>
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<tr>
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<td>17</td>
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<tr>
<td>18</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
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<td>$1.0 \pm 0.2$</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$100 \leq H_T &lt; 400$</td>
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<td>0</td>
</tr>
<tr>
<td>20</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$H_T \geq 400$</td>
<td>$166 \pm 22$</td>
<td>154</td>
</tr>
<tr>
<td>21</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$120 \leq p_T^{\text{miss}} &lt; 200$</td>
<td>$261 \pm 53$</td>
<td>276</td>
</tr>
<tr>
<td>22</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$80 \pm 21$</td>
<td>67</td>
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<tr>
<td>23</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
<td>$H_T \geq 400$</td>
<td>$17.3 \pm 3.2$</td>
<td>32</td>
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<tr>
<td>24</td>
<td>Photon+Lepton ($\mu\gamma$)</td>
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<td>$51 \pm 12$</td>
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<tr>
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<tr>
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<td>$150 \leq p_T^{\text{miss}} &lt; 185$</td>
<td>$17.4 \pm 3.9$</td>
<td>21</td>
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<td>$10.2 \pm 2.6$</td>
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<td>Photon+Lepton ($e\gamma$)</td>
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<td>$5.3 \pm 1.4$</td>
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<td>$114 \pm 13$</td>
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<td>$p_T^{\text{miss}} \geq 250$</td>
<td>$5.3 \pm 1.4$</td>
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Figure 4: The 95% CL exclusion limits for the GGM scenario in terms of the GGM model parameters (left) and the physical neutralino and chargino masses (right). The left panel shows the expected exclusion limits, where the area denoted as “all” is excluded by all four individual categories. The right panel shows both the observed (full lines) and the expected (dotted lines) exclusion limits, where the phase space between the colored lines and the black line is excluded. In the physical mass plane only signal points with a mass difference above 120 GeV are shown to enable a precise projection of the physical masses from the GGM model parameters. 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 spread in the observed limit from variation of the signal cross sections within their theoretical uncertainties.

excludes almost all signal points up to $M_2 = 1300$ GeV across the full range of $M_1$. The figure indicates which category is able to exclude a particular signal point. The grey areas labeled as "combination" show the phase space where only the combination of the categories is expected to exclude the signal points at 95% CL. The area at large $M_1$ values, which is only covered by the Photon+Lepton category, corresponds to signal points with a wino-like NLSP reducing the probability of a second high-energy photon in the event. Fig. 4 (right) shows the observed and expected exclusion limits as a function of the physical masses of the lightest chargino and the lightest neutralino. The exclusion limits of the Diphoton and Photon+Lepton categories are nearly independent of the neutralino mass since these categories have lower $p_T^{\text{miss}}$ requirements. The higher $p_T^{\text{miss}}$ regions used in the Photon+$S^T_1$ and Photon+$H^T_1$ categories mainly contribute closer to the mass diagonal at higher neutralino masses. The combination exceeds the sensitivity of the individual searches by around 100 GeV with respect to the wino mass parameter $M_2$, which translates to an expected gain of up to 100 GeV for the lightest chargino mass limit. For low neutralino masses, the combination is able to improve the observed limit on the chargino mass by up to 30 GeV. For higher neutralino masses, the combination does not improve the current best observed limit mainly because the Diphoton category, which shows an observed excess of about two sigma above the expectation, has the largest sensitivity in this phase space.

Fig. 5 shows the NLSP mass exclusion limits at 95% CL for simplified topologies in EW production scenarios with varying branching fractions of the neutralino (left) and chargino (right) decay. Here, the Photon+$S^T_1$ category provides the highest sensitivity along with the Diphoton category. Smaller contributions arise from the Photon+Lepton category. The sensitivity of the
Figure 5: The combined 95% CL NLSP mass exclusion limits for EW SMS production above 300 GeV. For the neutralino branching fraction scenario (left), the limit is shown as a function of the branching fraction $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$, the other decay channel being $\tilde{\chi}_1^0 \to Z + \tilde{G}$. For the chargino branching fraction scenario (right), the limit is shown as a function of the branching fraction $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 (\gamma \tilde{G}) + \text{soft}$, the other decay channel being $\tilde{\chi}_1^+ \to W + \tilde{G}$. The Photon+$H_T^F$ category shows no exclusion power for the latter scenario. The full lines represent the observed and the dashed lines the expected exclusion limits, where the phase space below the lines is excluded. 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 spread in the observed limit from variation of the signal cross sections within their theoretical uncertainties.

Photon+Lepton category to scenarios with large branching fractions of the decay $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$ especially arises from events where one photon is misidentified as a lepton. For the neutralino branching fraction scenario, which probes the $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production, the combined expected exclusion limits for NLSP masses ranges from 1200 GeV for a branching fraction of 100% for the decay $\tilde{\chi}_1^0 \to \gamma + \tilde{G}$ to 1000 GeV for 50%. For smaller branching fractions, the sensitivity for all categories drops since the probability of a final state with at least one photon decreases. This combined exclusion limit almost coincides with the exclusion limit based on the Photon+$S_T^F$ category. In case of the chargino branching fraction scenario only $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ is produced, leading to a smaller signal cross section. Here, an expected limit on the NLSP mass of up to 1000 GeV can be achieved for high branching fractions for the decay $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 (\gamma \tilde{G}) + \text{soft}$. The largest gain in sensitivity from the combination is found at a branching fraction of 40%, where the sensitivity of Photon+$S_T^F$, Photon+Lepton, and Diphoton categories is of the same order. Observed gaugino mass limits are set up to 1050 and 825 GeV in the neutralino and the chargino branching fraction scenarios, respectively.

The results from simplified topologies in strong production of gluinos are shown in Fig. 6. For these topologies the sensitivity of Diphoton category is reduced and therefore not included in the combination, which allows for a removal of the diphoton veto discussed in Section 5 and mainly increases the sensitivity of the Photon+$H_T^F$ category. In case of the nominal gluino scenario, introduced in Section 2 the combination shows an optimal expected exclusion compared to the different individual categories across a broad region of the mass parameter space. For NLSP masses below 1000 GeV, the sensitivity of the combination is dominated by the Photon+$H_T^F$ category, which mainly targets signal events with large hadronic activity.
However, at NLSP masses above 1700 GeV, the Photon+S category, which benefits from the smaller hadronic activity close to the mass diagonal, provides the highest sensitivity. The Photon+Lepton category selects events where the W boson decays leptonically, leading to a reduced sensitivity compared to the inclusive categories. The largest improvement of the combination is achieved in the phase space where the sensitivity of both inclusive categories is of the same order. Here, the expected limit on the gluino mass is improved by 50 GeV. The right plot of Fig. 6 shows the limits for the same SMS topology with a fixed gluino mass of 1950 GeV but with the gluino branching fraction varied between its decays to $q\bar{q}\chi^{\pm}_1$ and $q\bar{q}\chi^0_1$. Compared to the nominal gluino scenario similar behavior in the two inclusive categories is found.

![Diagram](image)

**Figure 6:** The 95% CL exclusion limits for the nominal gluino scenario (left) assuming equal probabilities of 50% for the gluino decay to $q\bar{q}\chi^{\pm}_1$ and $q\bar{q}\chi^0_1$. For the gluino branching fraction scenario (right) the ratio of the probabilities for both decays are scanned and the gluino mass is fixed to 1950 GeV. The Photon+Lepton category shows no exclusion power for the latter scenario. The full lines represent the observed and the dashed lines the expected exclusion limits, where the phase space below the lines is excluded. 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 spread in the observed limit from variation of the signal cross sections within their theoretical uncertainties.

In most of the simplified topologies, the combination of the different categories outperforms the individual searches with respect to the expected limit. The right plot of Fig. 6 shows a slight degradation of the expected limit at medium branching fractions for the combination compared to the Photon+$H^+_1$ category. This is caused by the removal of the events with moderate $H^+_1$ and lepton events from the Photon+$H^+_1$ category, as explained in Section 5. This strategy is motivated by optimizing the sensitivity to the GGM scenario shown in Fig. 4. In terms of the observed limits, only small improvements compared to the individual searches are found in all interpretations, since in each of the four searches small excesses in data with respect to the background prediction are found, giving rise to differences between observed and expected limits.
7 Summary

A combination of four different searches for general gauge-mediated (GGM) supersymmetry (SUSY) in final states with photons and a large transverse momentum imbalance was performed. Based on the event selection of the individual searches, four event categories were defined. Overlaps between the categories were removed by additional vetoes designed to maximize the sensitivity of the combination. Using data recorded with the CMS detector at the LHC at a center-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 35.9 fb$^{-1}$, the combination improves the expected sensitivity of the searches described in Ref. [18–21].

The results are interpreted in the context of GGM SUSY and in simplified models. The sensitivity of the combination is also interpreted across a range of branching fractions, allowing for generalization to a wide range of SUSY scenarios. The results of the GGM scenario are expressed as limits on the physical mass parameters. Here, chargino masses up to 890 (1080) GeV are excluded by the observed (expected) limit across the tested neutralino mass spectrum, which ranges from 120 to 720 GeV. In electroweak production models, limits for neutralino masses are set up to 1050 (1200) GeV for combined $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\mp \tilde{\chi}_1^\mp$ production, while for pure $\tilde{\chi}_1^\mp \tilde{\chi}_1^\mp$ production these limits are reduced to 825 (1000) GeV. For a strong production scenario based on gluino pair production, the highest excluded gluino mass is at 1975 (2050) GeV. The combination improves on the expected limits on neutralino and chargino masses by up to 100 GeV, while the expected limit on the gluino mass is increased by 50 GeV compared to the individual searches.

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We wish to acknowledge the help of Simon Knapen, David Shih, and Diego Redigolo, who provided us with the signal model used in this analysis.

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References


A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan1, A. Tumasyan

Institut fr Hochenergiephysik, Wien, Austria

Institute for Nuclear Problems, Minsk, Belarus
V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Universit Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Universit Catholique de Louvain, Louvain-la-Neuve, Belgium

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
E.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

Universidade Estadual Paulista a, Universidade Federal do ABC b, So Paulo, Brazil
S. Ahuja, C.A. Bernardes, L. Calligaris4, T.R. Fernandez Perez Tomei6, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, SandraS. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria  
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China  
W. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China  

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China  
A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

Tsinghua University, Beijing, China  
Z. Hu, Y. Wang

Universidad de Los Andes, Bogota, Colombia  
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. Gonzalez Hernandez, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia  
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar Gonzalez, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia  
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia  
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia  
V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus  

Charles University, Prague, Czech Republic  
M. Finger, M. Finger Jr., A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador  
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador  
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt  
S. Abu Zeid, S. Khalili

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia  
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland  
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Universit Paris-Saclay, Gif-sur-Yvette, France

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Universit Paris-Saclay, Palaiseau, France

Universit de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Universit de Lyon, Universit Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nuclaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Velidis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tspirritis

University of Ionnina, Ionnina, Greece

MTA-ELTE Lendlet CMS Particle and Nuclear Physics Group, Etvs Lornd University, Budapest, Hungary

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, F. Sikler, T. Vmi, V. Veszpremi, G. Vesztergombi†
<table>
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<tr>
<td>G. Abbiendi, R. Campanini, M. Bozzo, L. Benussi, S. Bianco, D. Piccolo</td>
<td>INFN Sezione di Genova, INFN Laboratori Nazionali di Frascati, Frascati, Italy</td>
</tr>
<tr>
<td>F.L. Navarria, C. Grandi, G. Barbagli</td>
<td>INFN Sezione di Milano-Bicocca, INFN Sezione di Firenze, Italy</td>
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<td>S.Y. Hoh, P. Lujan, M. Margoni, G. Galati, T. Tabarelli de Fatis, S. Fiorendi</td>
<td>INFN Sezione di Catania, INFN Sezione di Napoli, INFN Sezione di Pavia, Basilicata</td>
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<td>M. Biasini, G.M. Bilei, C. Cecchi, D. Ciangottini, L. Fan, P. Lariccia, R. Leonardi, E. Manoni, G. Mantovani, V. Marianelli, M. Menichelli, A. Rossi, A. Santocchia, D. Spiga</td>
<td>INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy</td>
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<td>K. Androsov, P. Azzurri, G. Bagliesi, V. Bertacchi, L. Bianchini, T. Boccali</td>
<td>INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy</td>
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R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,b}, R. Dell’Orso\textsuperscript{a}, G. Fedi\textsuperscript{a}, L. Giannini\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a}, F. Ligabue\textsuperscript{a,c}, E. Manca\textsuperscript{a,c}, G. Mandorli\textsuperscript{a,c}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzi\textsuperscript{a,b}, G. Rolandi\textsuperscript{31}, S. Roy Chowdhury, A. Scribano\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, N. Turini, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

\textbf{INFN Sezione di Roma} \textsuperscript{a}, \textbf{Sapienza Universit di Roma} \textsuperscript{b}, \textbf{Rome, Italy}

F. Cavallari\textsuperscript{a}, M. Cipriani\textsuperscript{a,b}, D. Del Re\textsuperscript{a,b}, E. Di Marco\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, E. Longo\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b}, P. Meridiani\textsuperscript{a}, G. Organtini\textsuperscript{a,b}, F. Pandolfi\textsuperscript{a}, R. Paramatti\textsuperscript{a,b}, C. Quaranta\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a,b}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}, L. Soffi\textsuperscript{a,b}

\textbf{INFN Sezione di Torino} \textsuperscript{a}, \textbf{Universit di Torino} \textsuperscript{b}, \textbf{Torino, Italy, Universit del Piemonte Orientale} \textsuperscript{c}, \textbf{Novara, Italy}

N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c}, S. Argiro\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, N. Bartosik\textsuperscript{a}, R. Bellan\textsuperscript{a,b}, C. Biino\textsuperscript{a}, A. Cappati\textsuperscript{a,b}, N. Cartiglia\textsuperscript{a}, S. Cometti\textsuperscript{a}, M. Costa\textsuperscript{a,b}, R. Covarelli\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, B. Kiani\textsuperscript{a,b}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, E. Montei\textsuperscript{a,b}, M. Monteno\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Salvatico\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, D. Soldi\textsuperscript{a,b}, A. Staiano\textsuperscript{a}

\textbf{INFN Sezione di Trieste} \textsuperscript{a}, \textbf{Universiti di Trieste} \textsuperscript{b}, \textbf{Trieste, Italy}

S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, A. Da Rold\textsuperscript{a,b}, G. Della Ricca\textsuperscript{a,b}, F. Vazzoler\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

\textbf{Kyungpook National University, Daegu, Korea}


\textbf{Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea}

H. Kim, D.H. Moon, G. Oh

\textbf{Hanyang University, Seoul, Korea}

B. Francois, T.J. Kim, J. Park

\textbf{Korea University, Seoul, Korea}


\textbf{Kyung Hee University, Department of Physics}

J. Goh

\textbf{Sejong University, Seoul, Korea}

H.S. Kim

\textbf{Seoul National University, Seoul, Korea}


\textbf{University of Seoul, Seoul, Korea}


\textbf{Sungkyunkwan University, Suwon, Korea}

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

\textbf{Riga Technical University, Riga, Latvia}

V. Veckalns\textsuperscript{32}
Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropesa Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autonoma de San Luis Potos, San Luis Potos, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Grski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

Laboratorio de Instrumentacao e Fisica Experimental de Particulas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chchtchipounov, V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev
Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko, V. Popov, I. Popdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
O. Bychkova, R. Chistov, M. Danilov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushansky, V. Savrny, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov, V. Blinov, T. Dimova, L. Kardapoltsev, Y. Skovpen

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autonoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocniiz
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

ukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, M. Yalvac

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Glimze, M. Kaya, O. Kaya, B. Kaynak, . zetik, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, Y. Komurcu, S. Seri

Istanbul University, Istanbul, Turkey
S. Ozkorucuklu

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniayl
The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee,

University of Florida, Gainesville, USA

Florida International University, Miami, USA
Y.R. Joshi

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright
University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatriwada, B. Mahakud,

**Purdue University Northwest, Hammond, USA**
T. Cheng, J. Dolen, N. Parashar

**Rice University, Houston, USA**

**University of Rochester, Rochester, USA**
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

**Rutgers, The State University of New Jersey, Piscataway, USA**

**University of Tennessee, Knoxville, USA**
H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

**Texas A&M University, College Station, USA**

**Texas Tech University, Lubbock, USA**

**Vanderbilt University, Nashville, USA**

**University of Virginia, Charlottesville, USA**
M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

**Wayne State University, Detroit, USA**

**University of Wisconsin - Madison, Madison, WI, USA**

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Universit Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at UFMS/CPNA Federal University of Mato Grosso do Sul/Campus of Nova Andradina, Nova Andradina, Brazil
6: Also at Universidade Federal de Pelotas, Pelotas, Brazil
7: Also at Université Libre de Bruxelles, Bruxelles, Belgium
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Ain Shams University, Cairo, Egypt
12: Also at Zewail City of Science and Technology, Zewail, Egypt
13: Also at Purdue University, West Lafayette, USA
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Binali Yıldırım University, Erzincan, Turkey
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at MTA-ELTE Lendulet CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Bari, Italy
29: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
30: Also at CENTRO SICILIANO DI FISICA NUCLEARE E DI STRUTTURA DELLA MATERIA, Catania, Italy
31: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
32: Also at Riga Technical University, Riga, Latvia
33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, USA
40: Also at Imperial College, London, United Kingdom
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, USA
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at Università degli Studi di Siena, Siena, Italy
46: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
47: Also at National and Kapodistrian University of Athens, Athens, Greece
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Sirnak University, SIRNAK, Turkey
52: Also at Beykent University, Istanbul, Turkey
53: Also at Istanbul Aydin University, Istanbul, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Gaziosmanpasa University, Tokat, Turkey
57: Also at Ozyegin University, Istanbul, Turkey
58: Also at Izmir Institute of Technology, Izmir, Turkey
59: Also at Marmara University, Istanbul, Turkey
60: Also at Kafkas University, Kars, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
64: Also at Institute for Particle Physics Phenomenology Durham University, Durham, United Kingdom
65: Also at Monash University, Faculty of Science, Clayton, Australia
66: Also at Bethel University, St. Paul, USA
67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
68: Also at Vilnius University, Vilnius, Lithuania
69: Also at Bingol University, Bingol, Turkey
70: Also at Georgian Technical University, Tbilisi, Georgia
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea
75: Also at University of Hyderabad, Hyderabad, India