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

The CMS Collaboration*

CERN, Switzerland

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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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$_{T}$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 interpretation of the combination focuses only on bino and wino, which 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 ($\tilde{\chi}^0_1$) corresponds to the NLSP, which decays to a $G$ accompanied by a photon ($\gamma$) or a Z boson depending on its composition. The lightest chargino ($\tilde{\chi}^\pm_1$) is assumed to decay to a W boson along with a $\tilde{\chi}^0_1$ or a $G$. The results are interpreted in a GGM signal scenario with photons in the final state varying the bino and wino mass parameters.

To provide 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 $\sqrt{s} = 13$ 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 (Di-photon 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-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 $S_T^\gamma = p_T^\text{miss} + \sum p_T^\gamma$, where $p_T^\gamma$ 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 Diphotonic 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).

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, namely $\tilde{\chi}_1^\pm$, $\tilde{\tau}_1^\pm$, and $\tilde{\chi}_2^\pm$ production, 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 $M_{\text{mess}} = 10^{15}$ 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 ($m_Q \gtrsim 3$ TeV), which is consistent with the model used in this Letter.

One possible diagram for the GGM scenario is shown in Fig. 1 (upper left). The chargino always decays to the W boson along with the lightest neutralino, and the $\tilde{\chi}_2^0$ could decay to a Z boson or an H boson along with the lightest neutralino. 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. As shown in Fig. 2 (upper), 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 $\tilde{\chi}_2^0 \rightarrow Z\tilde{G}$ 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 $\tilde{\chi}_2^0 \rightarrow \gamma\tilde{G}$ 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 (lower). 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 $M_1$.

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,
The CMS Collaboration / Physics Letters B 801 (2020) 135183

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 ($|\eta| < 1.44$). 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 [47] with a distance parameter of 0.4.

The missing transverse momentum vector $p_T^{\text{miss}}$ 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 $p_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event [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 of all PF charged hadrons, neutral hadrons,
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 $m_T(y/e, p_T^{\text{miss}})$. The search bins always include the lower bounds. The Diphoton and Lepton veto to match the kinematic selections of the Diphoton and Photon+Lepton category, respectively. The Diphoton veto is only used in the interpretation of the EW produced scenarios, but dropped for the strong produced scenarios, where the Diphoton category is not part of the combination.

<table>
<thead>
<tr>
<th>Kinematic selections</th>
<th>Search bins (GeV)</th>
<th>Vetoes events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^\gamma$ &gt; 40 GeV</td>
<td>Diphoton category</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ &gt; 100 GeV</td>
<td>$p_T^{\text{miss}}$: [100, 115], [115,130], [130,150], [150,185], [185,250], ≥250</td>
<td></td>
</tr>
<tr>
<td>$m_T(y, p_T^{\text{miss}})$ &gt; 105 GeV</td>
<td>Lepton veto for $p_T^\gamma$ &gt; 25 GeV</td>
<td></td>
</tr>
<tr>
<td>$p_T^\gamma$ &gt; 35 GeV</td>
<td>Photon+Lepton category</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ &gt; 120 GeV</td>
<td>$p_T^{\text{miss}}$: [120, 200], [200, 400], ≥400</td>
<td></td>
</tr>
<tr>
<td>$m_T(y, p_T^{\text{miss}})$ &gt; 25 GeV</td>
<td>$p_T^\gamma$: [35,200], ≥200</td>
<td></td>
</tr>
<tr>
<td>$p_T^\gamma$ &gt; 180 GeV</td>
<td>Photon+S$_T^\gamma$ category</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ &gt; 300 GeV</td>
<td>$S_T^\gamma$: [600, 800], [800, 1000], [1000,1300], ≥1300</td>
<td></td>
</tr>
<tr>
<td>$m_T(y, p_T^{\text{miss}})$ &gt; 600 GeV</td>
<td>$H_T^\gamma$: [120,200], ≥120 GeV</td>
<td></td>
</tr>
<tr>
<td>$p_T^\gamma$ &gt; 100 GeV</td>
<td>Photon+H$_T^\gamma$ category</td>
<td></td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ &gt; 350 GeV</td>
<td>$p_T^{\text{miss}}$: [350,450], [450,600], ≥600</td>
<td></td>
</tr>
<tr>
<td>$H_T^\gamma$ &gt; 700 GeV</td>
<td>$H_T^\gamma$: [700, 2000], ≥2000</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi(\pm p_T^{\text{miss}}, p_T^\gamma)</td>
<td>$ &gt; 0.3</td>
</tr>
</tbody>
</table>

and other photons 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 [18] uses photon identification criteria to preserve an average photon selection efficiency of 80% while suppressing backgrounds from quantum chromodynamics (QCD) multijet events. The other three categories [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. The Diphoton category makes use of no jet variables.

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 $p_T$ [49], and which is corrected for the effects of pileup [50]. Hits in the pixel detector are used to distinguish electrons from converted photons.

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 [18–21]. The minimum photon $p_T$ is mainly determined by the trigger 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 regions 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 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 ($H_T > 2$ 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 ($H_T < 2$ 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 + $\gamma$", which is in each case estimated from simulation scaled in a particular control re-
Fig. 3. Predicted pre-fit background yields, where the values are not constrained by the likelihood fit, and observed number of events in data 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.

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 yields correspond to the results of the published searches. The yields of the Photon+$S^\gamma_T$ and Photon+$H^+_T$ categories are based on the modified event selections, which ensure exclusive signal regions. Overall agreement between the observed number of events and the background prediction is found for the 49 search bins.

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 CLs method [51,52] using the LHC-style profile likelihood ratio as a test statistic [53] evaluated in the asymptotic approximation [54]. Log-normal nuisance parameters are used to describe the systematic uncertainties, which follow the treatment used in the initial searches. 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 estimated to be 50% in all four categories, the latter uncertainty ranges from 8 to 50% depending on the category and $p_T^\gamma$. The uncertainties in the prediction of vector boson production in association with photons in the Photon+$S^\gamma_T$ and Photon+Lepton categories, which can be as large as 20%, are treated as fully correlated, since similar prediction methods are used. In addition, the following sources of uncertainty on the simulation affect the background estimations and signal acceptance: photon identification and isolation efficiency, simulation of pileup, modeling of initial state radiation, determination of the integrated luminosity and jet energy scale. These uncertainties are also treated as fully correlated across search bins. Furthermore, all systematic uncertainties in the signal acceptance, which are mainly dominated by the fast simulation uncertainty (up to 36%) 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 (upper left) shows the combined expected exclusion limits at 95% CL for the GGM scenario, where the combination excludes almost all signal points up to $M_{\tilde{t}} = 1300$ 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 (upper right) shows both the observed and expected exclusion for the combination in the GGM model parameters. Fig. 4 (lower) 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 $p_T^{miss}$ requirements. The higher $p_T^{miss}$ regions used in the Photon+$S^\gamma_T$ and Photon+$H^+_T$ 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 chargino 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 large sensitivity in this phase space along with the Photon+Lepton category. Fig. 4 also shows that at higher neutralino masses the expected exclusion limits from the Diphoton
Table 2
Predicted pre-fit background yields, where the values are not constrained by the likelihood fit, the observed number of events in data, and the post-fit background yields after the constraint from the likelihood fit 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>
<th>Post-fit Total bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diphoton $p_T^Y \geq 40$</td>
<td>$110 \leq p_T^{\text{miss}} &lt; 115$</td>
<td>$114 \pm 13$</td>
<td>105</td>
<td>$110 \pm 9$</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$115 \leq p_T^{\text{miss}} &lt; 130$</td>
<td>$42.9 \pm 7.2$</td>
<td>39</td>
<td>$41.6 \pm 5.5$</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>$130 \leq p_T^{\text{miss}} &lt; 150$</td>
<td>$27.3 \pm 5.4$</td>
<td>21</td>
<td>$25.9 \pm 3.6$</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>$150 \leq p_T^{\text{miss}} &lt; 185$</td>
<td>$17.4 \pm 3.9$</td>
<td>21</td>
<td>$18.0 \pm 3.0$</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>$185 \leq p_T^{\text{miss}} &lt; 250$</td>
<td>$10.2 \pm 2.6$</td>
<td>11</td>
<td>$10.8 \pm 2.0$</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>$p_T^{\text{miss}} \geq 250$</td>
<td>$5.3 \pm 1.4$</td>
<td>12</td>
<td>$5.9 \pm 1.4$</td>
</tr>
<tr>
<td>7</td>
<td>Photon+Lepton ($\mu\gamma$) $35 \leq p_T^Y &lt; 200$</td>
<td>$H_T &lt; 100$</td>
<td>$317 \pm 50$</td>
<td>309</td>
<td>$318 \pm 19$</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$470 \pm 98$</td>
<td>501</td>
<td>$490 \pm 32$</td>
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<td>9</td>
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<td>$H_T \geq 400$</td>
<td>$100 \pm 27$</td>
<td>86</td>
<td>$99 \pm 7$</td>
</tr>
<tr>
<td>10</td>
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<td>$200 \leq p_T^{\text{miss}} &lt; 400$</td>
<td>$H_T &lt; 100$</td>
<td>$26.3 \pm 5.3$</td>
<td>$33$</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$61 \pm 14$</td>
<td>65</td>
<td>$63 \pm 5$</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$45 \pm 14$</td>
<td>45</td>
<td>$46 \pm 5$</td>
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<tr>
<td>13</td>
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<td>$p_T^{\text{miss}} \geq 400$</td>
<td>$H_T &lt; 100$</td>
<td>$1.2 \pm 0.4$</td>
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<tr>
<td>14</td>
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<td>$100 \leq H_T &lt; 400$</td>
<td>$2.4 \pm 1.1$</td>
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<td>$2.1 \pm 0.7$</td>
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<tr>
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<td></td>
<td>$H_T \geq 400$</td>
<td>$5.3 \pm 2.0$</td>
<td>5</td>
<td>$5.4 \pm 1.1$</td>
</tr>
<tr>
<td>16</td>
<td>Photon+Lepton ($e\gamma$) $p_T^Y \geq 200$</td>
<td>$H_T &lt; 100$</td>
<td>$6.3 \pm 2.4$</td>
<td>12</td>
<td>$9.1 \pm 1.6$</td>
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<tr>
<td>17</td>
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<td>$100 \leq H_T &lt; 400$</td>
<td>$21.1 \pm 7.2$</td>
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<td>$23.2 \pm 2.5$</td>
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<td>18</td>
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<td>$H_T \geq 400$</td>
<td>$15.3 \pm 4.8$</td>
<td>20</td>
<td>$17.2 \pm 2.0$</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>$200 \leq p_T^{\text{miss}} &lt; 400$</td>
<td>$H_T &lt; 100$</td>
<td>$4.8 \pm 1.8$</td>
<td>4</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$6.3 \pm 3.2$</td>
<td>13</td>
<td>$9.0 \pm 1.1$</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$5.4 \pm 2.0$</td>
<td>7</td>
<td>$6.3 \pm 0.9$</td>
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<tr>
<td>22</td>
<td></td>
<td>$p_T^{\text{miss}} \geq 400$</td>
<td>$H_T &lt; 100$</td>
<td>$0.7 \pm 0.4$</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$0.6 \pm 0.2$</td>
<td>1</td>
<td>$0.8 \pm 0.1$</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$0.5 \pm 0.2$</td>
<td>0</td>
<td>$0.6 \pm 0.1$</td>
</tr>
<tr>
<td>25</td>
<td>Photon+Lepton ($\mu\gamma$) $35 \leq p_T^Y &lt; 200$</td>
<td>$H_T &lt; 100$</td>
<td>$166 \pm 22$</td>
<td>154</td>
<td>$167 \pm 12$</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$261 \pm 53$</td>
<td>276</td>
<td>$271 \pm 18$</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$80 \pm 21$</td>
<td>57</td>
<td>$80 \pm 7$</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td>$200 \leq p_T^{\text{miss}} &lt; 400$</td>
<td>$H_T &lt; 100$</td>
<td>$17.3 \pm 3.2$</td>
<td>32</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$51 \pm 12$</td>
<td>46</td>
<td>$51 \pm 4$</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$28.8 \pm 9.0$</td>
<td>32</td>
<td>$29.6 \pm 3.0$</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>$p_T^{\text{miss}} \geq 400$</td>
<td>$H_T &lt; 100$</td>
<td>$1.3 \pm 0.5$</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>$100 \leq H_T &lt; 400$</td>
<td>$1.2 \pm 0.5$</td>
<td>1</td>
<td>$1.2 \pm 0.4$</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>$H_T \geq 400$</td>
<td>$2.8 \pm 0.8$</td>
<td>4</td>
<td>$3.3 \pm 0.6$</td>
</tr>
<tr>
<td>34</td>
<td>Photon+$S_T^Y$ $p_T^Y \geq 180$</td>
<td>$H_T \geq 2000$</td>
<td>$600 \leq S_T^Y &lt; 800$</td>
<td>$260 \pm 30$</td>
<td>273</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>$800 \leq S_T^Y &lt; 1000$</td>
<td>$96 \pm 14$</td>
<td>98</td>
<td>$100 \pm 9$</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>$1000 \leq S_T^Y &lt; 1300$</td>
<td>$50.0 \pm 7.9$</td>
<td>59</td>
<td>$53.8 \pm 6.4$</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td>$S_T^Y \geq 1300$</td>
<td>$16.8 \pm 3.8$</td>
<td>20</td>
<td>$18 \pm 3.5$</td>
</tr>
<tr>
<td>38</td>
<td>Photon+$H_T^\gamma$ $p_T^Y \geq 100$</td>
<td>$H_T \geq 2000$</td>
<td>$350 \leq p_T^{\text{miss}} &lt; 450$</td>
<td>$5.7 \pm 2.6$</td>
<td>4</td>
</tr>
<tr>
<td>39</td>
<td></td>
<td>$450 \leq p_T^{\text{miss}} &lt; 600$</td>
<td>$2.7 \pm 0.9$</td>
<td>10</td>
<td>$4.1 \pm 1.2$</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>$p_T^{\text{miss}} \geq 600$</td>
<td>$2.5 \pm 1.0$</td>
<td>4</td>
<td>$3.1 \pm 1.5$</td>
</tr>
</tbody>
</table>

and Photon+Lepton categories cross as the branching fraction from photons decreases and the branching fraction to Z bosons increases as shown in Fig. 2.

Fig. 5 shows the NLSL mass exclusion limits at 95% CL for simplified topologies in EW production scenarios with varying branching fractions of the neutralino (upper) and chargino (lower) decay. Here, the Photon+$S_T^Y$ category provides the highest sensitivity along with the Diphoton category. Smaller contributions arise from the Photon+Lepton category. The sensitivity of the Photon+Lepton category to scenarios with large branching fractions of the decay $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{g}$ especially arises from events where one photon is misidentified as a lepton. For the neutralino branching fraction scenario, which probes the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production, the combined expected exclusion limits for NLSL masses ranges from 1200 GeV for a branching fraction of 100% for the decay $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{g}$ 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+$S_T^Y$ category. In case of the chargino branching fraction scenario only $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ is produced, leading to a smaller signal cross section. Here, an expected limit on the NLSL mass of up to 1000 GeV can be achieved for high branching fractions for the decay $\tilde{\chi}_1^\pm \rightarrow \gamma \tilde{g}$ or $\tilde{g}$ soft. The largest gain in sensitivity from the combination is found at a branching fraction of 40%, where the sensitivity of Photon+$S_T^Y$, Photon+Lepton, and Diphoton categories is of the same order. The
Photon+$H_T^\gamma$ category shows no exclusion power for this scenario. 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+$H_T^\gamma$ category. Table 3 shows the data and the background prediction yields without the diphoton veto. 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+$H_T^\gamma$ category, which mainly targets signal events with large hadronic activity. However, at NLSP masses above 1700 GeV, the Photon+$S_T^\gamma$ 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 lower 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 $q\bar{q}Z_1^\pm$ and $q\bar{q}Z_1^-$. Compared to the nominal gluino scenario similar behavior in the two inclusive categories is found.

In most of the simplified topologies, the combination of the different categories outperforms the individual searches with respect to the expected limit. The lower plot of Fig. 6 shows a slight degration of the expected limit at medium branching fractions for the combination compared to the Photon+$H_T^\gamma$ category. This is caused by the removal of the events with moderate $H_T^\gamma$ and lepton events from the Photon+$H_T^\gamma$ category, as explained in Section 5. This strategy is motivated by optimizing the sensitivity to the GGM scenario shown in Fig. 4. Small excesses in data with respect to the background prediction are found in each of the four categories, which give rise to differences in the observed and expected limits. As a result, only small improvements are made in the observed limits compared to the individual searches in all interpretations.

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 $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\tilde{\chi}_1^0\tilde{\chi}_1^0$ production, while for pure $\tilde{\chi}_1^+\tilde{\chi}_1^-$ 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.

Acknowledgements

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.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and
personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoST (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References


The CMS Collaboration

A.M. Sirunyan†, A. Tumasyan
Yerevan Physics Institute, Yerevan, Armenia

Institut für Hochenergiephysik, Wien, Austria

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

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

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

a Universidade Estadual Paulista, São Paulo, Brazil 
b Universidade Federal do ABC, São Paulo, Brazil 

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang\textsuperscript{7}, X. Gao\textsuperscript{7}, L. Yuan

Beihang University, Beijing, China


Institute of High Energy Physics, 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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Z. Hu, Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov\textsuperscript{9}, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia


University of Cyprus, Nicosia, Cyprus

M. Finger\textsuperscript{10}, M. Finger Jr.\textsuperscript{10}, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Abu Zeid\textsuperscript{11}, S. Khalil\textsuperscript{12}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

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

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland


Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland


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


Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, France


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

S. Gadrat

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France


Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze

Tbilisi State University, Tbilisi, Georgia


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


RWTH Aachen University, III. Physikalisches Institut A, 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

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsimpolis

National Technical University of Athens, Athens, Greece


University of Ioánnina, Ioánnina, Greece


MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellár, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, D. Teysssier, Z.L. Trocsanyi, B. Ujvari
Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak
Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari
Indian Institute of Science (IISc), Bangalore, India

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma
University of Delhi, Delhi, India

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar
Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla
Bhabha Atomic Research Centre, Mumbai, India

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant
Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma
Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani, E. Eskandari Tadavani, S.M. Etessami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi
Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald
University College Dublin, Dublin, Ireland


S. Albergo, S. Costa, A. Di Mattia, R. Potenza, A. Tricomi, C. Tuve

L. Benussi, S. Bianco, D. Piccolo

M. Bozzo, F. Ferro, R. Mulargia, E. Robutti, S. Tosi


A. Braghieri, P. Montagna, S.P. Ratti, V. Re, M. Ressegotti, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

a INFN Sezione di Bari, Bari, Italy
b Università di Bari, Bari, Italy
c Politecnico di Bari, Bari, Italy

a INFN Sezione di Bologna, Bologna, Italy
b Università di Bologna, Bologna, Italy

a INFN Sezione di Catania, Catania, Italy
b Università di Catania, Catania, Italy

a INFN Sezione di Firenze, Firenze, Italy
b Università di Firenze, Firenze, Italy

INFN Laboratori Nazionali di Frascati, Frascati, Italy

a INFN Sezione di Genova, Genova, Italy
b Università di Genova, Genova, Italy

a INFN Sezione di Milano-Bicocca, Milano, Italy
b Università di Milano-Bicocca, Milano, Italy

a INFN Sezione di Napoli, Napoli, Italy
b Università di Napoli 'Federico II', Napoli, Italy

a Università della Basilicata, Potenza, Italy
b Università G. Marconi, Roma, Italy

a INFN Sezione di Padova, Padova, Italy
b Università di Padova, Padova, Italy

a INFN Sezione di Pavia, Pavia, Italy
b Università di Pavia, Pavia, Italy

A. Braghieri, P. Montagna, S.P. Ratti, V. Re, M. Ressegotti, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

a INFN Sezione di Padova, Padova, Italy
b Università di Padova, Padova, Italy

a INFN Sezione di Pavia, Pavia, Italy
b Università di Pavia, Pavia, Italy
M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fanò\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Perugia, Perugia, Italy
\textsuperscript{b} Università di Perugia, Perugia, Italy

K. Androsov\textsuperscript{a}, P. Azzurri\textsuperscript{a}, G. Bagliesi\textsuperscript{a}, V. Bertacchi\textsuperscript{a,c}, L. Bianchini\textsuperscript{a}, T. Boccali\textsuperscript{a}, 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{30}, S. Roy Chowdhury, A. Sribano\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a}, N. Turini, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

\textsuperscript{a} INFN Sezione di Pisa, Pisa, Italy
\textsuperscript{b} Università di Pisa, Pisa, Italy
\textsuperscript{c} Scuola Normale Superiore di Pisa, Pisa, 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. Sofi\textsuperscript{a,b}

\textsuperscript{a} INFN Sezione di Roma, Roma, Italy
\textsuperscript{b} Sapienza Università di Roma, Roma, 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. Monteila\textsuperscript{b}, M. Monteno\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pellicioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, R. Salvatico\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, D. Soldi\textsuperscript{a,b}, A. Staiano\textsuperscript{a}

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

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


Kyungpook National University, Daegu, Republic of Korea

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

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

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

Hanyang University, Seoul, Republic of Korea


Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

Seoul National University, Seoul, Republic of Korea


University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns 31
Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

Vilnius University, Vilnias, Lithuania


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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz 33, R. Lopez-Fernandez, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropesa Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

University of Belgrade, Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia


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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain


Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain


Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

K. Malagalage

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka


CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland


ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

Universitat Zürich, Zurich, Switzerland

T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

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

B. Isildak, G. Karapinar, M. Yalvac

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, B. Kaynak, Ö. Özçelik, S. Tekten, E.A. Yetkin

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

Istanbul Technical University, Istanbul, Turkey

S. Ozkorumu

Istanbul University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine


University of Bristol, Bristol, United Kingdom


Rutherford Appleton Laboratory, Didcot, United Kingdom


Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez, R. Uniyal

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA


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

The University of Kansas, Lawrence, USA


Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA


University of Maryland, College Park, USA


Massachusetts Institute of Technology, Cambridge, USA


University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, 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

University of Nebraska-Lincoln, Lincoln, USA


State University of New York at Buffalo, Buffalo, USA


Northeastern University, Boston, USA


Northwestern University, Evanston, USA


University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA


Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA


Rice University, Houston, 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

University of Rochester, Rochester, USA


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

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA


Texas A&M University, College Station, USA


Texas Tech University, Lubbock, USA


Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, USA


Wayne State University, Detroit, USA

University of Wisconsin – Madison, Madison, WI, USA

* Corresponding author.
E-mail address: George.Alverson@cern.ch (G. Alverson).

1 Also at Vienna University of Technology, Vienna, Austria.
2 Also at IRFU, CEA, Université 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, 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 Erzincan 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, Debrecen, Hungary.
21 Also at Institute of Nuclear ResearchATOMKI, Debrecen, Hungary.
22 Also at IT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.
23 Also at Institute of Physics, Bhubaneswar, India.
24 Also at Shoolini University, Solan, India.
25 Also at University of Visva-Bharati, Santiniketan, India.
26 Also at Isfahan University of Technology, Isfahan, Iran.
27 Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy.
28 Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
29 Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
30 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
31 Also at Riga Technical University, Riga, Latvia, Riga, Latvia.
32 Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
33 Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
34 Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
35 Also at Institute for Nuclear Research, Moscow, Russia.
36 Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
37 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
38 Also at University of Florida, Gainesville, USA.
39 Also at Imperial College, London, United Kingdom.
40 Also at P.N. Lebedev Physical Institute, Moscow, Russia.
41 Also at California Institute of Technology, Pasadena, USA.
42 Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
43 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
44 Also at Università degli Studi di Siena, Siena, Italy.
45 Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy, Pavia, Italy.
46 Also at National and Kapodistrian University of Athens, Athens, Greece.
47 Also at Universität Zürich, Zurich, Switzerland.
48 Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria.
49 Also at Şırnak University, Şırnak, Turkey.
50 Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey.
51 Also at İstanbul Aydın University, İstanbul, Turkey.
52 Also at Mersin University, Mersin, Turkey.
53 Also at Piri Reis University, İstanbul, Turkey.
54 Also at Gaziosmanpasa University, Tokat, Turkey.
55 Also at Adıyaman University, Adıyaman, Turkey.
56 Also at Ozyegin University, Istanbul, Turkey.
57 Also at Izmir Institute of Technology, Izmir, Turkey.
58 Also at Marmara University, Istanbul, Turkey.
Also at Kafkas University, Kars, Turkey.

Also at Istanbul Bilgi University, Istanbul, Turkey.

Also at Hacettepe University, Ankara, Turkey.

Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

Also at IPPP Durham University, Durham, United Kingdom.

Also at Monash University, Faculty of Science, Clayton, Australia.

Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.

Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.

Also at Vilnius University, Vilnius, Lithuania.

Also at Bingol University, Bingol, Turkey.

Also at Georgian Technical University, Tbilisi, Georgia.

Also at Sinop University, Sinop, Turkey.

Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

Also at Texas A&M University at Qatar, Doha, Qatar.

Also at Kyungpook National University, Daegu, Korea, Daegu, Republic of Korea.

Also at University of Hyderabad, Hyderabad, India.