A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV

The CMS Collaboration

Abstract

A search for new light bosons decaying into muon pairs is presented using a data sample corresponding to an integrated luminosity of 35.9 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy $\sqrt{s} = 13$ TeV, collected with the CMS detector at the CERN LHC. The search is model independent, only requiring the pair production of a new light boson and its subsequent decay to a pair of muons. No significant deviation from the predicted background is observed. A model independent limit is set on the product of the production cross section times branching fraction to dimuons squared times acceptance as a function of new light boson mass. This limit varies between 0.16 and 0.45 fb over a range of new light boson masses from 0.25 to 8.5 GeV. It is then interpreted in the context of the next-to-minimal supersymmetric standard model and a dark supersymmetry model that allows for nonnegligible light boson lifetimes. In both cases, there is significant improvement over previously published limits.
1 Introduction

The standard model (SM) is known to give an incomplete description of particle physics and a number of extensions of the SM predict the existence of new light bosons \[1–3\]. In this Letter, we present a model independent search for the pair production of a light boson that decays into a pair of muons. A simple example of pair production in proton-proton (pp) collisions is \( pp \rightarrow h \rightarrow 2a + X \rightarrow 4\mu + X \), where \( h \) is a Higgs boson (either SM or non-SM), \( a \) is the new light neutral boson, and \( X \) are spectator particles that are predicted in some models \[4\]. While production via the \( h \) boson is possible, it is not required in the search presented here: the only requirement is that a pair of identical light bosons are created at a common vertex and each light boson subsequently decays to a pair of muons. These muon pairs are referred to as “dimuons”; the dimuon and new light boson production vertices are allowed to be displaced. The generic nature of this signature means that any limit set on the product of the cross section, branching fraction to dimuons squared, and acceptance is model independent; it can thus be reinterpreted in the context of specific models.

To help ensure model independence, two different classes of benchmark models are used to design the analysis and interpret the results: the next-to-minimal supersymmetric standard model (NMSSM) \[1, 5–12\] and supersymmetry (SUSY) models with hidden sectors (dark SUSY) \[3, 13, 14\]. In the NMSSM benchmark models, two of the three charge parity (CP) even neutral Higgs bosons \( h_1 \) or \( h_2 \) can decay to one of the two CP odd neutral Higgs bosons via \( h_1,2 \rightarrow 2a_1 \). The light boson \( a_1 \) subsequently decays to a pair of oppositely charged muons. In the dark SUSY benchmark models, the breaking of a new \( U(1)_D \) symmetry (where the subscript “D” means “Dark”) gives rise to a massive dark photon \( \gamma_D \). This dark photon can couple to SM particles via a small kinetic mixing parameter \( \epsilon \) with SM photons. The lifetime, and thus the displacement, of the dark photon is dependent upon \( \epsilon \) and the mass of the dark photon \( m_{\gamma_D} \).

The signal topologies investigated feature an SM-like Higgs boson \( h \) that decays via \( h \rightarrow 2n_1 \), where \( n_1 \) is the lightest nondark neutralino. Both of the \( n_1 \) then decay via \( n_1 \rightarrow n_D + \gamma_D \), where \( n_D \) is a dark neutralino that is undetected. The dark photon \( \gamma_D \) decays to a pair of oppositely charged muons.

This analysis contributes to an existing body of experimental work in the search for new light bosons. Previous searches at the LHC for \( h \rightarrow 2a \) include \( 4\mu \) \[15–18\], \( 4\tau \) \[19\], \( 4\ell \) \[20, 21\], \( 4\ell/4\tau \) \[22\], \( 4b \) \[23\], \( 4\gamma \) \[25\], \( 2b \) \[26\], \( 2\mu \) \[27\], and \( 6q \) \[28\] final states. A more thorough description of the NMSSM and dark SUSY models, their empirical and theoretical motivations, and constraints for their search set by previous experiments is included in Refs. \[15\] and \[18\].

The search presented in this Letter includes several improvements compared to the previous results published by the CMS Collaboration on light boson pair production decaying to muons given in Ref. \[15\]. The data used for this analysis correspond to an integrated luminosity of 35.9 fb\(^{-1}\) of pp collisions at 13 TeV, compared to 20.7 fb\(^{-1}\) at 8 TeV. There is a new trigger with increased sensitivity to signatures with displaced vertices. Improvements were made to the CMS detector; these improvements are discussed in detail in Ref. \[29\]. The analysis criteria were improved to enhance the sensitivity of the search for a new light boson \( a_1 \) with a mass between 0.25 and 3.55 GeV in the context of NMSSM benchmark models and a dark photon \( \gamma_D \) with a mass ranging from 0.25 to 8.5 GeV and lifetime up to \( c\tau_{\gamma_D} = 100 \text{ mm} \) in the context of benchmark dark SUSY models. These changes lead to greater detection sensitivity and coverage of the model parameter space.
2 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, and a brass and scintillator hadron calorimeter, 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.

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single muon trigger efficiency exceeds 90% over the full $\eta$ range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with $p_T$ up to 100 GeV, of 1% in the barrel and 3% in the endcaps. The $p_T$ resolution in the barrel is better than 7% for muons with $p_T$ up to 1 TeV [29].

Events of interest are selected using a two-tiered trigger system [30]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 $\mu$s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate below 1 kHz before data storage.

A more detailed description of the CMS detector, together with definitions of the coordinate system used and the relevant kinematic variables, can be found in Ref. [31].

3 Data selection

The data were collected with a trigger that uses muon reconstruction algorithms optimized for vertices displaced from the primary vertex by as much as 9.8 cm in the plane transverse to the beam line. The HLT is seeded by requiring the presence of two muons selected by the L1 trigger in an event, the leading muon with $p_T > 12$ GeV, the subleading muon with $p_T > 5$ GeV, and both satisfying $|\eta| < 2.4$. Events that later pass the HLT are required to have at least three reconstructed muons: one with $p_T > 15$ GeV and $|\eta| < 2.4$, the other two with $p_T > 5$ GeV and $|\eta| < 2.4$. Events selected with this trigger are then reconstructed with the particle-flow (PF) algorithm, which reconstructs the final-state particles using a global fit that combines the information from each subdetector [32].

The offline event selection in this analysis requires events to have a primary vertex reconstructed using a Kalman filtering (KF) technique [33]. In addition, each event contains at least four muons reconstructed with the PF algorithm and identified as PF muons or as muons identified using information that originates from the tracking system and is corroborated via calorimeter and muon systems. Each muon is required to have $p_T > 8$ GeV and $|\eta| < 2.4$. At least one muon must be a “high-$p_T$” muon, i.e., it must be found in the barrel region ($|\eta| < 0.9$) and must have $p_T > 17$ GeV in order to ensure that the trigger reconstruction has no dependence on $\eta$.

Dimuons are constructed from pairs of oppositely charged muons that share a common vertex, reconstructed using a KF technique, and must have an invariant mass $m_{(\mu\mu)}$ less than 9 GeV. These muons pairs must not have any muons in common with one another. Exactly
two dimuons must be present in each event. A dimuon that contains a high-\(p_T\) muon is called a “high-\(p_T\) dimuon”. When only one high-\(p_T\) muon is present in the event, the high-\(p_T\) dimuon is denoted as \((\mu\mu)_1\), while the other is denoted as \((\mu\mu)_2\). When both dimuons have at least one high-\(p_T\) muon, the dimuons are labeled randomly to prevent a bias in kinematic distributions. Single muons not included in dimuons are called “orphan” muons. No requirement is applied on the number of orphan muons. Each dimuon must have at least one hit reconstructed within the pixel system. The dimuons are required to originate from the same primary vertex, \(|z_{(\mu\mu)}_1 - z_{(\mu\mu)}_2| < 0.1\) cm, where \(z_{(\mu\mu)}\) is the \(z\) position of the secondary vertex associated with the dimuon propagated back to the beamline along the dimuon direction vector. Furthermore, each dimuon must be sufficiently isolated. The dimuon isolation \(I_{(\mu\mu)}\) is calculated as the \(p_T\) sum of charged-particle tracks with \(p_T > 0.5\) GeV in the vicinity of the dimuon within \(\Delta R < 0.4\) and \(|z_{\text{track}} - z_{(\mu\mu)}| < 0.1\) cm. Here, \(\Delta R\) is defined in terms of the track separation in \(\eta\) and azimuthal angle (\(\phi\), in radians) as \(\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}\), while \(z_{\text{track}}\) is defined as the \(z\) coordinate of the point of closest approach to the primary vertex along the beam axis. Tracks included in the dimuon reconstruction are excluded from the isolation calculation. The total isolation sum must be less than 2 GeV. Since the dimuons are expected to originate from the same type of light bosons, the dimuon masses should be consistent with each other to within 5% of the detector resolution. This requirement carves out a signal region (SR) in the two-dimensional plane of the dimuon invariant masses \(m_{(\mu\mu)_1}\) and \(m_{(\mu\mu)_2}\).

### 4 Signal modeling

The pp collisions at \(\sqrt{s} = 13\) TeV are simulated for samples in each of the two benchmark models, NMSSM and dark SUSY. The parton distribution functions (PDFs) are modeled using NNPDF2.3LO [34]. The underlying event activity at the LHC and jet fragmentation is modeled with the Monte Carlo (MC) event generator \textsc{pythia} [35] using the “CUETP8M1” tune [36]. Specifically, \textsc{pythia} 8.212 is used for NMSSM and \textsc{pythia} 8.205 for the dark SUSY models. In each model, only Higgs boson production via gluon-gluon (gg) fusion is considered. A single mass point is also generated through vector boson fusion (VBF) and associated vector boson production (VH) to determine their contribution to the \(h_2 \to 2a_1\) rate; this is included in a simplified reference scenario discussed later.

In the case of the NMSSM, a simulated Higgs boson, either \(h_1\) or \(h_2\) (generically denoted by \(h_{1,2}\)), is forced to decay to a pair of light bosons \(a_1\). Each \(a_1\) subsequently decays to a pair of oppositely charged muons. Since the \(h_{1,2}\) in \(h_{1,2} \to 2a_1\) might not be the observed SM Higgs boson [37–39], mass values of \(m_{h_{1,2}}\) between 90 and 150 GeV are simulated. This range is motivated by constraints set by the relic density measurements from WMAP [40] and Planck [41], as well as searches at LEP [42–47]. The light boson mass is simulated to vary between 0.25 and 3.55 GeV, or approximately \(2m_{\mu}\) and \(2m_{\tau}\), as motivated in Ref. [48].

In the case of dark SUSY, production of SM Higgs bosons is simulated with the MC matrix-element generator \textsc{madgraph} 4.5.2 [49] at leading order. The non-SM decay of the Higgs bosons is modeled using the BRIDGE 2.24 program [50]. Higgs bosons are forced to decay to a pair of SUSY neutralinos \(n_1\) via \(h \to 2n_1\). Each SUSY neutralino in turn decays to a dark photon and a dark neutralino via \(n_1 \to n_0 + \gamma_D\). The dark neutralino mass \(m_{n_0}\) is set to 1 GeV; they are considered stable and thus escape detection. We set the dark photons to decay to a pair of oppositely charged muons 100% of the time, \(\gamma_D \to \mu^- \mu^+\). The Higgs boson and \(n_1\) masses are fixed to 125 and 10 GeV, respectively. Dark photon masses \(m_{\gamma_D}\) are simulated between 0.25 and 8.5 GeV. Since dark photons interact weakly with SM particles, their decay width is negligible compared to the resolution in the dimuon mass spectrum. Muon displacement is
modeled with an exponential distribution with $cT_{\gamma D}$ between 0 and 100 mm. All MC generated events are run through the full CMS simulation based on GEANT4 [51] and reconstructed with the same algorithms that are used for data.

One of the key features of this analysis is the model independence of the results. This is confirmed by verifying that the ratio of the full reconstruction efficiency $\epsilon_{\text{full}}$ over the generator level acceptance $\alpha_{\text{gen}}$ is independent of the signal model. The signal acceptance is defined as the fraction of MC-generated events that pass the generator level selection criteria. The criteria are as follows: at least four muons in each event with $p_T > 8$ GeV and $|\eta| < 2.4$, at least one muon with $p_T > 17$ GeV and $|\eta| < 0.9$, and both light bosons must have a transverse decay length $L_{xy} < 9.8$ cm and longitudinal decay length $|L_z| < 46.5$ cm. The upper limits on $L_{xy}$ and $|L_z|$ correspond to the dimensions of the outer layer of the CMS pixel system. The parameter $\epsilon_{\text{full}}$ is defined as the fraction of MC-generated events that pass the trigger and full offline selection described above. The insensitivity to the model used is displayed in Table 1.

Table 1: The full reconstruction efficiency over signal acceptance $\epsilon_{\text{full}}/\alpha_{\text{gen}}$ in % for several representative signal NMSSM (upper) and dark SUSY benchmark models (lower). All uncertainties are statistical.

<table>
<thead>
<tr>
<th>$m_{h_1}$ [GeV]</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{A_1}$ [GeV]</td>
<td>2</td>
<td>0.5</td>
<td>3</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}$ [%]</td>
<td>8.85 ± 0.06</td>
<td>13.23 ± 0.08</td>
<td>11.96 ± 0.07</td>
<td>14.68 ± 0.08</td>
<td>18.48 ± 0.09</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>13.93 ± 0.08</td>
<td>20.47 ± 0.09</td>
<td>19.24 ± 0.09</td>
<td>23.59 ± 0.10</td>
<td>29.93 ± 0.10</td>
</tr>
<tr>
<td>$\epsilon_{\text{full}}/\alpha_{\text{gen}}$ [%]</td>
<td>63.52 ± 0.29</td>
<td>64.62 ± 0.24</td>
<td>62.19 ± 0.25</td>
<td>62.23 ± 0.22</td>
<td>61.73 ± 0.20</td>
</tr>
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Scale factors are determined to correct for the differences between observed data and simulated samples. Corrections for the identification and isolation of muons and isolation of dimuons are measured using $Z \rightarrow \mu^-\mu^+$ and $J/\psi \rightarrow \mu^-\mu^+$ samples using a “tag-and-probe” technique [52]; the samples used are events from simulated data and from observed data control regions enriched in events from the aforementioned SM processes. All muons in these samples are required to have $p_T > 8$ GeV, the “tag” muon is required to be a loose muon as described in Ref. [29], while the “probe” muon criteria vary according to the variable under study. Corrections for the trigger efficiency are calculated using $WZ \rightarrow 3\mu$ and $t\bar{t}Z \rightarrow 3\mu$ events that are also extracted from simulated data samples and enriched observed data samples; these samples are selected using a missing transverse momentum requirement such that they do not contain events in common with the data sample used in this analysis. A scale factor per event of $\epsilon_{\text{data}}/\epsilon_{\text{sim}} = 0.93 ± 0.06$ (stat) is obtained.

5 Background estimation

The selection criteria described in Section 3 are effective at reducing and eliminating most SM backgrounds with similar topology to our signal. As a result, this analysis is expected to have a very small background contribution in the SR. Three SM backgrounds are found to be non-negligible and are presented here: bottom quark pair production ($b\bar{b}$), prompt double $J/\psi$ me-
son decays, and electroweak production of four muons. Contributions from Y mesons are also considered; they are found to be negligible below the 8.5 GeV upper bound on $m_\omega$. The total background contribution in the SR is estimated to be $9.90 \pm 1.24$ (stat) $\pm 1.84$ (syst) events; the contributions from each process are described below.

### 5.1 The $b\bar{b}$ background

The largest background, $b\bar{b}$ production, is dominated by events in which both $b$ quarks decay to $\mu^+\mu^- + X$ or decay through low-mass meson resonances such as $\omega, \rho, \phi, J/\psi$, and $\psi(2S)$. The $J/\psi$ meson decay contribution considered in this background is nonprompt; the prompt $J/\psi$ meson decay contribution is discussed in Section 5.2. A minor contribution comes from events with charged particle tracks misidentified as muons. A two-dimensional template $S(m_{\mu\mu_1}, m_{\mu\mu_2})$ is constructed in the plane of the two dimuon invariant masses and used to estimate the contribution to the SM background from $b\bar{b}$ decays. The template is constructed as follows.

First, a $b\bar{b}$-enriched control sample is selected from events with similar kinematic properties as the signal events, but not included in the SR. Events are required to pass the signal trigger and have exactly three muons. One of these muons must have $p_T > 17$ GeV within $|\eta| < 0.9$, while the other two have $p_T > 8$ GeV within $|\eta| < 2.4$. In addition, the control sample selection requires a good primary vertex, exactly one dimuon, and one orphan muon. The longitudinal distance between the projections of the dimuon trajectory starting from its vertex and the orphan muon track back to the beam axis, $\Delta z((\mu\mu), \mu_{\text{orphan}})$ must have an absolute value of less than 0.1 cm. The dimuon is required to have at least one hit in the pixel system as explained in Section 3. Finally, the dimuon isolation value cannot be higher than 2 GeV.

Next, two one-dimensional templates, $S_1(m_{\mu\mu})$ and $S_{II}(m_{\mu\mu})$, are obtained from the $b\bar{b}$-enriched events. In the case of $S_1(m_{\mu\mu})$, at least one high-$p_T$ muon is contained in the dimuon. In the case of $S_{II}(m_{\mu\mu})$, the high-$p_T$ muon is the orphan muon and the dimuon may or may not contain another high-$p_T$ muon. This procedure ensures that kinematic differences between signal events that have exactly two high-$p_T$ dimuons or just one high-$p_T$ dimuon are taken into account. Each distribution is fitted with a shape comprised of a Gaussian distribution for each light meson resonance, a double-sided Crystal Ball function for the $J/\psi$ meson signal peak, and a set of sixth-degree Bernstein polynomials for the bulk background shape. The template $S(m_{\mu\mu_1}, m_{\mu\mu_2})$ is obtained as $S_1(m_{\mu\mu_1}) \otimes S_{II}(m_{\mu\mu_2})$, where $\otimes$ represents the Cartesian product.

Finally, the two-dimensional template is normalized in the dimuon-dimuon mass space from 0.25 to 8.5 GeV. The template is represented as a function of $m_{\mu\mu_1}$ and $m_{\mu\mu_2}$ in Fig. [5](#) (left) by a gray scale. The SR defined in Section 3 is outlined by dashed lines. The region of the mass space outside the SR represents the control region for the $b\bar{b}$ background. The ratio between the integral of the template in the SR $A_{SR}$ and the control region $A_{CR}$ is calculated to be $R = A_{SR}/A_{CR} = 0.141/0.859$. The same figure also shows the 56 events found in the data that pass all selection criteria except for the $m_{\mu\mu_1} \simeq m_{\mu\mu_2}$ requirement and thus fall outside the SR. The number of $b\bar{b}$ events in the SR is then estimated to be $(56 \pm \sqrt{56}) R = 9.21 \pm 1.23$ (stat).

This method of estimating the $b\bar{b}$ contribution to background events is further validated by repeating the procedure for different dimuon isolation values (5, 10, 50 GeV) and without any isolation. The $b\bar{b}$ event yield is stable in the SR within 20%, which is assigned as a systematic uncertainty.
5.2 Prompt double $J/\psi$ meson background

Two mechanisms contribute to prompt double $J/\psi$ meson production: single parton scattering (SPS) and double parton scattering (DPS); these processes have been measured by CMS and ATLAS [54, 55]. They can mimic the signal process when each $J/\psi$ meson decays to a pair of muons. The prompt double $J/\psi$ meson decay background is estimated with a method that uses both experimental and simulated data. In a control sample of experimental data, the prompt and nonprompt double $J/\psi$ meson decay contributions are separated using the matrix method (also called the “ABCD” method [56]). The prompt contribution is then extrapolated into the SR. Double $J/\psi$ meson events are selected with a trigger dedicated to bottom quark physics. Each event is required to have at least four muons with $p_T > 3.5$ GeV within $|\eta| < 2.4$. No high-$p_T$ muon is required. Events must have exactly two dimuons, with labels $(\mu\mu)_1$ or $(\mu\mu)_2$ assigned randomly. The dimuon isolation follows the same definition as in Section 5. The kinematic properties of SPS and DPS events are studied using MC simulation. These events are generated using PYTHIA 8.212 and HERWIG 2.7.1 [57]. The variable with the best SPS–DPS separation power is found to be the absolute difference in rapidity between the two dimuons, $|\Delta y|$. To remove nonresonant muon pairs from the sample, the dimuon masses are required to be within 2.8 and 3.3 GeV. The ABCD method is then employed using the dimuon isolation values as uncorrelated variables in the plane $(I_{(\mu\mu)_1}, I_{(\mu\mu)_2})$. The maximum isolation on $(\mu\mu)_1$ and $(\mu\mu)_2$ is set to 12 GeV. Here, region “A” is the region bounded by $I_{(\mu\mu)_1,2} < 2$ GeV. Conversely, “B”, “C”, and “D” are nonisolated sideband regions used to extrapolate the nonprompt contribution into region “A”. The nonprompt $|\Delta y|$ distribution is determined from the sideband regions; this distribution is scaled to match the nonprompt contribution in region “A”. This is then subtracted from the $|\Delta y|$ distribution, leaving the prompt $|\Delta y|$ distribution in region “A”. To separate the prompt SPS from prompt DPS in data, a template distribution $f_{SPS}|\Delta y_{SPS}| + (1 - f_{SPS})|\Delta y_{DPS}|$ is fitted to the corresponding $|\Delta y|$ distribution in data, where $f_{SPS}$ and $1 - f_{SPS}$ are the fractions of prompt SPS and DPS events, respectively. Finally, this result is used to determine the number of events that are expected in the SR of our experimental data sample. The contribution of the prompt double $J/\psi$ meson decay events in data passing the signal selections in Section 5 is calculated to be $N_{data}(SR) = 0.33 \pm 0.08 \text{ (stat)} \pm 0.05 \text{ (syst)}$.

5.3 Electroweak background

Electroweak production of four muons, pp → 4$\mu$, is estimated using MC events generated with CALCHEP 3.6.25 [58]. The processes studied include $q\bar{q} \rightarrow ZZ^* \rightarrow 2\mu^+2\mu^-$ and $q\bar{q} \rightarrow Z \rightarrow \mu^+\mu^-$, where one of the muons radiates a second Z boson that decays to a $\mu^+\mu^-$ pair. Other electroweak processes, such as $pp \rightarrow h(125) \rightarrow ZZ^* \rightarrow 2\mu^+2\mu^-$, are determined to be negligible a priori and thus are not included. Based on the simulation, the electroweak background is found to be 0.36 ± 0.09 (stat). Unlike the prompt double $J/\psi$ meson decay background, the electroweak background is not concentrated at any particular mass value; its contribution to any mass bin is negligible compared to the $b\bar{b}$ background. Consequently, these background events are neglected in any limit setting computation.

6 Systematic uncertainties

Both instrumental and theoretical sources of uncertainty are considered in this section. The leading source of instrumental uncertainty is the triple-muon trigger scale factor (6%). It is dominated by the statistical uncertainty in events in the control region used to measure the scale factor. Other sources of instrumental uncertainty include the uncertainty in the measurement of the integrated luminosity recorded by the CMS detector (2.5%) [59], the muon iden-
Figure 1: Left: Distribution of the invariant masses $m_{(\mu\mu)}$ vs. $m_{(\mu\mu)}$ of the isolated dimuon systems; triangles represent data events passing all the selection criteria and falling in the SR $m_{(\mu\mu)} \approx m_{(\mu\mu)}$ (outlined by dashed lines); white bullets represent data events that pass all selection criteria but fall outside the SR. Right: The 95% CL upper limit set on $\sigma(pp \to 2a + X)B^2(a \to 2\mu)\alpha_{\text{gen}}$ over the range $0.25 < m_a < 8.5$ GeV.

The theoretical uncertainties are dominated by the uncertainty in the PDFs, knowledge of the strong coupling constant $\alpha_S$, and the renormalization ($\mu_R$) and factorization ($\mu_F$) scales. The PDF and $\alpha_S$ uncertainties are estimated using a technique that follows the PDF4LHC recommendations [60, 61]. The uncertainty in the scale factors is determined by simultaneously varying $\mu_R$ and $\mu_F$ up and down by a factor of two using MCFM 8.0 [62]. The effect of PDF choice and PDF parameter variation upon the central values is also studied. When all previously described theoretical uncertainties are added in quadrature, the sum is 8%. The uncertainty in the branching fraction is taken to be 2% [39].

7 Results

After applying all selection criteria to the data sample, 13 events are found in the SR. Their distribution in $m_{(\mu\mu)}$ and $m_{(\mu\mu)}$ is shown in Fig. 1 (left). This result is consistent with the sum of all background estimates described in Section 5, which results to be $9.90 \pm 1.24$ (stat) $\pm 1.84$ (syst) events. A model independent 95% confidence level (CL) upper limit is set on the product of the production cross section times branching fraction to dimuons squared times acceptance. Limits are set using the CL$_{s}$ method [63, 64], a technique in which the problem of excluding models to which one is not sensitive is mitigated by effectively penalizing the p-value of a tested parameter by an amount that increases with decreasing sensitivity. The test statistic used is based on the logarithm of the likelihood ratio [65], where the unbinned likelihood has been obtained by parameterizing the background and signal distributions. The systematic uncertainties and their correlations have been accounted for by profiling the likelihood with respect to the nui-
For the NMSSM scenario, the 95% CL upper limit is derived for \( \sigma(pp \to h_1 \to 2a_1) B^2(a_1 \to 2\mu) \) as a function of \( m_{h_1} \) for two choices of \( m_{a_1} \) as shown in Fig. 2 (left) and as a function of \( m_{a_1} \) for three choices of \( m_{h_1} \) as shown in Fig. 2 (right). Since the choice of \( m_{h_1} \) does not restrict \( m_{h_2} \), we choose to set \( \epsilon_{\text{full}}(m_{h_2}) = \epsilon_{\text{full}}(m_{h_1}) \) to simplify the expression. This choice is conservative because \( \epsilon_{\text{full}}(m_{h_2}) > \epsilon_{\text{full}}(m_{h_1}) \) if \( m_{h_2} > m_{h_1} \), for any \( m_{h_1} \). In this simplified scenario, \( B(a_1 \to 2\mu) \) is a function of \( m_{h_1} \) as calculated in Ref. [48]. To facilitate comparison between the upper limits derived from this analysis and upper limits following from setting parameters in theoretical models, we include reference curves (solid line) in both Fig. 2 left and right. For both reference curves, the ratio of the vacuum expectation values of the Higgs doublets \( \tan \beta \) is set to 20. We also set \( \sigma(pp \to h_i) = \sigma_{\text{SM}}(m_{h_i}) \) [66] and \( B(m_{h_i} \to 2a_1) = 0.3\% \) so that the resulting reference curves are similar to the upper limits that are determined from the yield of dimuon pair events observed in the data. In Fig. 2 (left), the representative value of \( B(a_1 \to 2\mu) \) is equal to 7.7% for \( m_{a_1} \approx 2 \text{ GeV} \). In the region where \( m_{h_1} < 125 \text{ GeV} \), \( m_{h_1} \) is the independent variable and it is assumed that \( m_{h_1} \) is the mass of the observed 125 GeV Higgs boson. In the region where \( m_{h_1} > 125 \text{ GeV} \), \( m_{h_2} \) is the independent variable and it is assumed that \( m_{h_1} \) is the observed Higgs boson mass. Compared to the upper limits shown in Refs. [15], Fig. 2 (left) represents an improvement of a factor of \( \approx 1.5 \) for \( m_{a_1} = 3.55 \text{ GeV} \) (dotted curve) and a factor of \( \approx 3 \) for \( m_{a_1} = 0.25 \text{ GeV} \) (dashed curve). In Fig. 2 (right), we present 95% CL upper limits as functions of \( m_{a_1} \) in the NMSSM scenario on \( \sigma(pp \to h_i \to 2a_1) B^2(a_1 \to 2\mu) \) with \( m_{h_1} = 90 \text{ GeV} \) (dashed curve), \( m_{h_1} = 125 \text{ GeV} \) (dash-dotted curve), and \( m_{h_1} = 150 \text{ GeV} \) (dotted curve). It is assumed that all contributions come from either \( h_1 \) or \( h_2 \); there is no case
in which both $h_1$ and $h_2$ decay to the $a_1$. The sharp inflections in the reference curve are due to the fact that $B(a_1 \rightarrow 2\mu)$ is affected by the $a_1 \rightarrow s\bar{s}$ and $a_1 \rightarrow gg$ channels. As $m_{h_1}$ crosses the internal quark loop thresholds, $B(a_1 \rightarrow gg)$ changes rapidly, giving rise to structures in $B(a_1 \rightarrow 2\mu)$ at these values of $m_{h_1}$.

![Figure 3: The 90% CL upper limits (black solid curves) from this search as interpreted in the dark SUSY scenario, where the process is $pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D \rightarrow 4\mu + X$, with $m_{n_1} = 10$ GeV, and $m_{\gamma_D} = 1$ GeV. The limits are presented in the plane of the parameters ($\varepsilon$ and $m_{\gamma_D}$). Constraints from other experiments [22, 67–82] showing their 90% CL exclusion contours are also presented. The colored contours for the CMS and ATLAS limits represent different values of $B(h \rightarrow 2\gamma_D + X)$ that range from 0.1 to 40%.](image-url)

For the dark SUSY scenario, a 90% CL upper limit is set on the product of the Higgs boson production cross section and the branching fractions of the Higgs boson (cascade) decay to a pair of dark photons. The limit set by this experimental search is presented in Fig. 3 as areas excluded in a two-dimensional plane of $\varepsilon$ and $m_{\gamma_D}$. Also included in Fig. 3 are limits from other experimental searches [22, 67, 82]. For both this search, and the ATLAS searches, limits are shown for values of $B(h \rightarrow 2\gamma_D + X)$ in the range 0.1–40%. The kinetic mixing parameter $\varepsilon$, the mass of the dark photon $m_{\gamma_D}$, and the lifetime of the dark photon $\tau_{\gamma_D}$ are related via an analytic function $f(m_{\gamma_D})$ that is solely dependent on the dark photon mass [83], namely, $\tau_{\gamma_D}(\varepsilon, m_{\gamma_D}) = \varepsilon^{-2} f(m_{\gamma_D})$. The lifetime of the dark photon is allowed to vary from 0 to 100 mm and $m_{\gamma_D}$ can range from 0.25 to 8.5 GeV. Because of the extensions in the ranges of these parameters, this search constrains a large and previously unexplored area in the $\varepsilon$ and $m_{\gamma_D}$ parameter space. The limits on $\varepsilon$ presented in this Letter improve on those in Ref. [15] by a factor of approximately 2.5.
8 Summary

A search for pairs of new light bosons that subsequently decay to pairs of oppositely charged muons is presented. This search is developed in the context of a Higgs boson decay, \( h \rightarrow 2a + X \rightarrow 4\mu + X \) and is performed on a data sample collected by the Compact Muon Solenoid experiment in 2016 that corresponds to an integrated luminosity of 35.9 fb\(^{-1}\) proton-proton collisions at 13 TeV. This data set is larger and collected at a higher center-of-mass energy than the previous CMS search [15]. Additionally, both the mass range of the light boson \( a \) and the maximum possible displacement of its decay vertex are extended compared to the previous version of this analysis. Thirteen events are observed in the signal region (SR), with 9.90 ± 1.24 (stat) ± 1.84 (syst) events expected from the standard model (SM) backgrounds. The distribution of events in the SR is consistent with SM expectations. A model independent 95% confidence level upper limit on the product of the production cross section times branching fraction to dimuons squared times acceptance is set over the mass range 0.25 < \( m_a < 8.5 \) GeV and is found to vary between 0.16 and 0.45 fb. This model independent limit is then interpreted in the context of dark supersymmetry (dark SUSY) with nonnegligible light boson lifetimes of up to \( c\tau_D = 100 \) mm and in the context of the next-to-minimal supersymmetric standard model (NMSSM). For the dark SUSY interpretation, the upper bound of \( m_{\gamma D} \) was increased from 2 to 8.5 GeV and the excluded \( \epsilon \) was improved by a factor of approximately 2.5. In the NMSSM, the 95% CL upper limit was improved by a factor of \( \approx 1.5 \) (3) for \( m_a = 3.55 \) (0.25) GeV over previously published limits.

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References


A The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria

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

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 Fisicas, Rio de Janeiro, Brazil

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

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

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,
Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang5, X. Gao5, L. Yuan

Institute of High Energy Physics, Beijing, China

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

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, 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, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov7, T. Susa

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Finger8, M. Finger Jr.8

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
H. Abdalla9, A.A. Abdelalim10,11, A. Mohamed11

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, H. Kirschenmann, J. Pekkanen, M. Voutilainen
Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

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

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

Université 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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire 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
A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

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

University of Ioánnina, Ioánnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, Á. Hunyadi, F. Sikler, T. Vámi, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi
Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

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

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

Panjab University, Chandigarh, India

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

Indian Institute of Technology Madras, Madras, India
P.K. Behera, A. Muhammad

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

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

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

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
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{29}, P. Spagnolo\textsuperscript{a}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini\textsuperscript{a}

INFN Sezione di Roma \textsuperscript{a}, Sapienza Universit`a di Roma \textsuperscript{b}, Rome, Italy
L. Barone\textsuperscript{a,b}, 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}, S. Gelli\textsuperscript{a,b}, 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}, F. Preiato\textsuperscript{a,b}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}

INFN Sezione di Torino \textsuperscript{a}, Universit`a di Torino \textsuperscript{b}, Torino, Italy, Universit`a del Piemonte Orientale \textsuperscript{c}, 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}, F. Cenna\textsuperscript{a,b}, 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. Monteil\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. Sacchi\textsuperscript{a,b}, R. Salvatico\textsuperscript{a,b}, K. Shchelina\textsuperscript{a,b}, V. Solà\textsuperscript{a}, A. Solano\textsuperscript{a,b}, D. Soldi\textsuperscript{a,b}, A. Staiano\textsuperscript{a}

INFN Sezione di Trieste \textsuperscript{a}, Universit`a di Trieste \textsuperscript{b}, 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}

Kyungpook National University, Daegu, Korea

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, J. Goh\textsuperscript{30}, T.J. Kim

Korea University, Seoul, Korea

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea

University of Seoul, Seoul, Korea

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, 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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz,  

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

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, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sokov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lyakhovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, 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
M. Chadeeva,39 P. Parygin, D. Philippov, S. Polikarpov,39 E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin,36 M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow,
Russia
A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin,40 L. Dudko, A. Gribushin,
V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin,
A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov,41 V. Blinov,41 T. Dimova,41 L. Kardapoltsev,41 Y. Skovpen,41

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’,
Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bityukov, V. Kachanov, D. Konstantinov, P. Mandrik,
V. Petrov, R. Ryutin, S. Slabospitski, A. Sobol, S. Troshin, N. Tsyrlin, A. Uzunian, A. Volkov

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade,
Serbia
P. Adzic,42 P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT),
Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes,
M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya,
J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez,
M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero,
S. Sánchez Navas, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero,
J.R. González Fernández, E. Palencia Cortezon, V. Rodriguez Bouza, S. Sanchez Cruz,
J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez,
P.J. Fernández Manteca, A. García Alonso, J. García-Ferrero, G. Gomez, A. Lopez Virto,
J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matarras, J. Piedra Gomez,
Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka
N. Wickramage
CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

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

Universität Zürich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan
T.H. Doan, B. Hsu, K. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

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

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Ozkorumculu, S. Tekten, E.A. Yetkin
Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, A. Cakir, K. Cancakocak, Y. Komurcu, S. Sen

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, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez

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

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

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, D.M. Morse, T. Orimoto, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

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

Princeton University, Princeton, USA

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

Purdue University, West Lafayette, USA

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

Rice University, Houston, USA

University of Rochester, Rochester, USA

Rutgers, The State University of New Jersey, Piscataway, USA
University of Tennessee, Knoxville, USA
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, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, 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 IFIR, 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 Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Cairo University, Cairo, Egypt
10: Also at Helwan University, Cairo, Egypt
11: Now at Zewail City of Science and Technology, Zewail, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, 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: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
30: Also at Kyunghee University, Seoul, Korea
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
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 P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Monash University, Faculty of Science, Clayton, Australia
64: Also at Bethel University, St. Paul, USA
65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
66: Also at Utah Valley University, Orem, USA
67: Also at Purdue University, West Lafayette, USA
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea