Search for light pseudoscalar boson pairs produced from decays of the 125 GeV Higgs boson in final states with two muons and two nearby tracks in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is presented for pairs of light pseudoscalar bosons, in the mass range from 4 to 15 GeV, produced from decays of the 125 GeV Higgs boson. The decay modes considered are final states that arise when one of the pseudoscalars decays to a pair of tau leptons, and the other one either into a pair of tau leptons or muons. The search is based on proton-proton collisions collected by the CMS experiment in 2016 at a center-of-mass energy of 13 TeV that correspond to an integrated luminosity of 35.9 fb$^{-1}$. The $2\mu 2\tau$ and $4\tau$ channels are used in combination to constrain the product of the Higgs boson production cross section and the branching fraction into $4\tau$ final state, $\sigma B$, exploiting the linear dependence of the fermionic coupling strength of pseudoscalar bosons on the fermion mass. No significant excess is observed beyond the expectation from the standard model. The observed and expected upper limits at 95% confidence level on $\sigma B$, relative to the standard model Higgs boson production cross section, are set respectively between 0.022 and 0.23 and between 0.027 and 0.19 in the mass range probed by the analysis.

"Published in Physics Letters B as doi:10.1016/j.physletb.2019.135087."

© 2019 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

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

After the discovery of the 125 GeV Higgs boson (H) [1, 2], searches for additional Higgs bosons, based on predictions beyond the standard model (SM), constitute an important part of the scientific program at the CERN Large Hadron Collider (LHC). The present analysis examines theoretical models that contain two Higgs doublets and an additional complex singlet Higgs field (denoted hereafter as 2HD+1S), that does not couple at tree level to fermions or gauge bosons and interacts only with itself and the Higgs doublets [3–10]. In CP conserving models, which are considered in this Letter, the Higgs sector features seven physical states, namely three CP-even, two CP-odd, and two charged bosons, where one of the CP-even states corresponds to the H. This kind of Higgs sector is realized, for example, in next-to-minimal supersymmetric models that solve the so-called $\mu$ problem of the minimal supersymmetric extension of the SM [11]. A large set of the 2HD+1S models is allowed by measurements and constraints set by searches for additional Higgs bosons and supersymmetric particles [12–17].

This Letter addresses specific 2HD+1S models in which the lightest pseudoscalar boson ($a_1$) with mass $2m_{a_1} < 125$ GeV has a large singlet component, and therefore its couplings to SM particles are significantly reduced. For this reason, analyses using direct production modes of $a_1$, such as gluon-gluon fusion (ggF) or b quark associated production, have limited sensitivity. The $a_1$ boson is nonetheless potentially accessible in the H decay to two pseudoscalar bosons. The $a_1$ states can be identified via their decay into a pair of fermions [18–25]. Constraints on the H couplings allow a branching fraction for H decays into non-SM particles as large as 34% [26], which can potentially accommodate the $H \rightarrow a_1 a_1$ decay at a rate sufficiently high for detection at the LHC.

Several searches for $H \rightarrow a_1 a_1$ decays have been performed in the ATLAS and CMS experiments in Run 1 (8 TeV) and Run 2 (13 TeV) of LHC, exploiting various decay modes of the $a_1$ boson, and probing different ranges of its mass [27–40]. These searches found no significant deviation from the expectation of the SM background and upper limits were set on the product of the production cross section and the branching fraction for signal resulting in constraints on parameters of the 2HD+1S models.

This analysis presents a search for light $a_1$ bosons in the decay channels $H \rightarrow a_1 a_1 \rightarrow 4\tau/2\mu2\tau$, using data corresponding to an integrated luminosity of 35.9 fb$^{-1}$, collected with the CMS detector in 2016 at a center-of-mass energy of 13 TeV. The analysis covers the mass range from 4 to 15 GeV and employs a special analysis strategy to select and identify highly Lorentz-boosted muon or tau lepton pairs with overlapping decay products. The study updates a similar one performed by the CMS Collaboration in Run 1 [28], and complements other recent CMS searches for the $H \rightarrow a_1 a_1$ decay performed in Run 2 data in the $2\mu 2\tau$ [30], $2\tau 2b$ [31], $2\mu 2b$ [38] and $4\mu$ [39] final states, covering respective mass ranges of $0.25 < m_{a_1} < 3.40$ GeV for the $4\mu$ final state and $15.0 < m_{a_1} < 62.5$ GeV for the $2\mu2\tau, 2\tau2b$, and $2\mu2b$ final states.

The branching fraction $a_1 \rightarrow \tau \tau$ depends on the details of the model, namely the parameter $\tan \beta$, the ratio of vacuum expectation values of the two Higgs doublets, and on which Higgs doublet couples to either charged leptons, up-type quarks or down-type quarks [41]. In Type-II 2HD+1S models, where one Higgs doublet couples to up-type fermions while the other couples to down-type fermions, the $a_1 \rightarrow \tau \tau$ decay rate gets enhanced at large values of $\tan \beta$. The branching fraction of this decay reaches values above 90% at $\tan \beta > 3$ for $2m_\tau < m_{a_1} < 2m_b$, where $m_\tau$ is the mass of the tau lepton and $m_b$ is the mass of the bottom quark. For higher values of $m_{a_1}$, the branching fraction decreases to 5–6% since the decay into a pair of bottom quarks becomes kinematically possible and overwhelms the decay into a pair of tau leptons. However, in some of the 2HD+1S models the $a_1 \rightarrow \tau \tau$ decay may be dominant even above the
$a_1 \rightarrow b\bar{b}$ decay threshold. This is realized, e.g., for $\tan \beta > 1$ in the Type-III 2HD+1S models, where one Higgs doublet couples to charged leptons, whereas the other doublet couples to quarks \[^{[41]}\].

The signal topology targeted by the present analysis is illustrated in Fig. 1. Each $a_1$ boson is identified by the presence of a muon and only one additional charged particle, the objective of this approach being the decay channels $a_1 \rightarrow \mu\mu$ and $a_1 \rightarrow \tau\mu$. The $\tau\mu$ denotes the muonic tau lepton decay, and $\tau_{\text{one-prong}}$ stands for its leptonic or one-prong hadronic decay. The three-prong modes are not used because of the very high QCD multijet background and lower reconstruction signal efficiency.

Given the large difference in mass between the $a_1$ and the H states, the $a_1$ bosons will be produced highly Lorentz-boosted, and their decay products are highly collimated. This will result in a signature with two muons, each of which is accompanied by a nearby particle of opposite charge. The search focuses primarily on the dominant ggF process, in which the H state is produced with relatively small transverse momentum $p_T$, and the $a_1$ pseudoscalars are emitted nearly back-to-back in the transverse plane, with a large separation in azimuth $\phi$ between the particles originating from one of the $a_1$ decays and those of the other $a_1$. In the ggF process, the H can be also produced with a relatively high Lorentz boost when a hard gluon is radiated from the initial-state gluons or from the heavy-quark loop. In this case, the separation in $\phi$ is reduced, but the separation in pseudorapidity $\eta$ can be large. The analysis therefore searches for a signal in a sample of same-charge (SC) dimuon events with large angular separation between the muons, where each muon is accompanied by one nearby oppositely charged particle originating from the same $a_1$ decay. The requirement of having SC muons in the event largely suppresses background from the top-quark-pair, Drell–Yan, and diboson production. This requirement also facilitates the implementation of a dedicated SC dimuon trigger with relatively low thresholds and acceptable rates as described in Section 4.

![Figure 1: Illustration of the signal topology, in which the H decays into two $a_1$ bosons, where one $a_1$ boson decays into a pair of tau leptons, while the other one decays into a pair of muons or a pair of tau leptons. The analyzed final state consists of one muon and an oppositely charged track in each $a_1$ decay.](image-url)
2 CMS detector

The central feature of the CMS detector 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 $\eta$ 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.

Events of interest are selected using a two-tiered trigger system [42]. The first level, 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, 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 a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [43].

3 Simulated samples

For the simulation of the dominant ggF production process, the Monte Carlo (MC) event generators PYTHIA (v.8.212) [44] and MADGRAPH5_aMC@NLO (v.2.2.2) [45] are used in order to model the $H \to a_1a_1 \to 4\tau$ and $H \to a_1a_1 \to 2\mu2\tau$ signal events, respectively. For both decay modes the $p_T$ distribution of the $H$ emerging from ggF is reweighted with next-to-next-to-leading order (NNLO) $K$ factors obtained by the program HQT (v.2.0) [46, 47] with NNLO NNPDF3.0 parton distribution functions (PDF) [48], hereby taking into account the more precise spectrum calculated to NNLO with resummation to next-to-next-to-leading-logarithms order. Subdominant contributions from other production modes of $H$, namely vector boson fusion process (VBF), vector boson associated production (VH) and top quark pair associated production (t(t)H) are estimated using the PYTHIA (v.8.212) generator.

The backgrounds from diboson production and quantum chromodynamics production of multijet (QCD multijet) are simulated with the PYTHIA (v.8.212) generator. Inclusive Z and W boson production processes are generated with MADGRAPH5_aMC@NLO (v.2.2.2). The single-top and tt production are generated at Next-to-LO (NLO) with the POWHEG (v.2.0) generator [49-53]. The set of PDF used is NLO NNPDF3.0 for NLO samples, and LO NNPDF3.0 for LO samples [48].

Showering and hadronization are carried out by the PYTHIA (v.8.212) generator with the CUETP8M1 underlying event tune [54], while a detailed simulation of the CMS detector is based on the GEANT4 [55] package.

4 Event selection

Events are selected using a SC dimuon trigger with $p_T$ thresholds of 17 (8) GeV for the leading (subleading) muon. To pass the high-level trigger, the tracks of the two muons are additionally required to have points of closest approach to the beam axis within 2 mm of each other along the longitudinal direction.

Events are reconstructed with the particle-flow (PF) algorithm [56] which aims to identify and reconstruct individual particles as photons, charged hadrons, neutral hadrons, electrons, or...
muons (PF objects). The proton-proton (pp) interaction vertices are reconstructed using a Kalman filtering technique \[57\,58\]. Typically more than one such vertex is reconstructed because of multiple pp collisions within the same or neighbouring bunch crossings. The mean number of such interactions per bunch crossing was 23 in 2016.

The reconstructed vertex with the largest value of summed physics-object \( p_T^2 \) is taken to be the primary interaction vertex (PV). The physics objects are the jets, clustered using the jet-finding algorithm \[59\,60\] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the \( p_T \) of those jets. Events must contain at least two SC muons reconstructed with the PF algorithm, which have to fulfil the following requirements.

- The pseudorapidity of the leading (higher \( p_T \)) and the subleading (lower \( p_T \)) muons must be \( |\eta| < 2.4 \).
- The \( p_T \) of the leading (subleading) muon must exceed 18 (10) GeV.
- The transverse (longitudinal) impact parameters of muons with respect to the PV are required to be \( |d_0| < 0.05 \) (\( |d_z| < 0.1 \)) cm.
- The angular separation between the muons is \( \Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 2 \).

If more than one SC muon pair is found in the event to satisfy these requirements, the pair with the largest scalar sum of muon \( p_T \) is chosen.

In the next step, the analysis employs information about tracks associated with the reconstructed charged PF objects, excluding the pair of SC muons. Selected muons and tracks are used to build and isolate candidates for the \( a_1 \rightarrow \tau\mu \tau\mu \) one-prong or \( a_1 \rightarrow \mu\mu \) decays (referred to as \( a_1 \) candidates throughout the Letter). Three types of tracks are considered in the analysis.

- “Isolation” tracks are used to define isolation requirements imposed on \( a_1 \) candidates and have to fulfil the following criteria: \( p_T > 1 \text{ GeV}, |\eta| < 2.4, |d_0| < 1 \text{ cm}, |d_z| < 1 \text{ cm} \).
- “Signal” tracks are selected among “isolation” tracks to build \( a_1 \) candidates. These tracks must have \( p_T > 2.5 \text{ GeV}, |\eta| < 2.4, |d_0| < 0.02 \text{ cm}, |d_z| < 0.04 \text{ cm} \).
- “Soft” tracks are also a subset of “isolation” tracks. They are utilized to define one of the sideband regions, used for the construction of the background model, as described in Section \[5.2\]. “Soft” tracks must satisfy the requirements: \( 1.0 < p_T < 2.5 \text{ GeV}, |\eta| < 2.4, |d_0| < 1 \text{ cm}, |d_z| < 1 \text{ cm} \).

A track is regarded as being nearby a muon if the angular separation \( \Delta R \) between them is smaller than 0.5. Each muon of the SC pair is required to have one nearby “signal” track with a charge opposite to its charge. This muon-track system is accepted as an \( a_1 \) candidate if no additional “isolation” tracks are found in the \( \Delta R \) cone of 0.5 around the muon momentum direction. The event is selected in the final sample if it contains two \( a_1 \) candidates. The set of selection requirements outlined above defines the signal region (SR).

The expected signal acceptance and signal yield for a few representative values of \( m_{a_1} \) are reported in Table \[1\]. The signal yields are computed for a benchmark value of the branching fraction, \( B(H \rightarrow a_1a_1)B^2(a_1 \rightarrow \tau\tau) = 0.2 \) and assuming that the H production cross section is the one predicted in the SM. Contributions from the ggF, VBF, VH and t\( t\)H processes are summed up. The yield of the \( 2\mu2\tau \) signal is estimated under the assumption that the partial
widths of the $a_1 \rightarrow \mu\mu$ and $a_1 \rightarrow \tau\tau$ decays satisfy the relation [23]

$$\frac{\Gamma(a_1 \rightarrow \mu\mu)}{\Gamma(a_1 \rightarrow \tau\tau)} = \frac{m_\mu^2}{m_\tau^2 \left(1 - \frac{2m_\tau}{m_{a_1}}\right)^2}. \quad (1)$$

The ratio of branching fractions of the $a_1a_1 \rightarrow 2\mu2\tau$ and $a_1a_1 \rightarrow 4\tau$ decays is computed through the ratio of the partial widths $\Gamma(a_1 \rightarrow \mu\mu)$ and $\Gamma(a_1 \rightarrow \tau\tau)$ as

$$\frac{B(a_1a_1 \rightarrow 2\mu2\tau)}{B(a_1a_1 \rightarrow 4\tau)} = 2\frac{B(a_1 \rightarrow \mu\mu)}{B(a_1 \rightarrow \tau\tau)} = 2\frac{\Gamma(a_1 \rightarrow \mu\mu)}{\Gamma(a_1 \rightarrow \tau\tau)}. \quad (2)$$

The factor of 2 in Eq. (2) arises from two possible decays, $a_1^{(1)}a_1^{(2)} \rightarrow 2\mu2\tau$ and $a_1^{(1)}a_1^{(2)} \rightarrow 2\tau2\mu$, that produce the final state with two muons and two tau leptons. The ratio in Eq. (2) ranges from about 0.0073 at $m_{a_1} = 15$ GeV to 0.0155 at $m_{a_1} = 4$ GeV.

The contribution from the $H \rightarrow a_1a_1 \rightarrow 4\mu$ decay is estimated taking into account Eq. (1). It ranges between 0.4 and 2% of the total signal yield in the $2\mu2\tau$ and $4\tau$ final states, depending on the probed mass of the $a_1$ boson. This contribution is not considered in the present analysis.

The number of observed events selected in the SR amounts to 2035. A simulation-based study shows that the QCD multijet events dominate the sample of events selected in the SR. Contribution from other background sources constitutes about 1% of events selected in the SR.

Table 1: The signal acceptance and the number of expected signal events after selection in the SR. The number of expected signal events is computed for a benchmark value of branching fraction, $B(H \rightarrow a_1a_1)/B^2(a_1 \rightarrow \tau\tau) = 0.2$ and assuming that the H production cross section is the one predicted in the SM. The quoted uncertainties for predictions from simulation include only statistical ones.

| $m_{a_1}$ [GeV] | Acceptance $\times 10^4$ | Number of events $4\tau$ | Number of events $2\mu2\tau$ |
|-----------------|--------------------------|--------------------------|--------------------------|
| 4               | 3.29 ± 0.16              | 89.3 ± 1.4               | 129.9 ± 6.2              | 54.7 ± 0.9 |
| 7               | 2.50 ± 0.14              | 69.0 ± 1.4               | 98.8 ± 5.5               | 22.5 ± 0.5 |
| 10              | 1.46 ± 0.11              | 47.1 ± 1.2               | 57.8 ± 4.2               | 14.2 ± 0.4 |
| 15              | 0.21 ± 0.04              | 3.5 ± 0.3                | 8.5 ± 1.1                | 1.0 ± 0.1 |

The two-dimensional (2D) distribution of the invariant masses of the muon-track systems, constituting $a_1$ candidates, is used to discriminate between signal and the dominant QCD multijet background in the signal extraction procedure. The 2D distribution is filled with a pair of the muon-track invariant masses $(m_1, m_2)$, ordered by their value, $m_2 > m_1$. The binning of the 2D distribution adopted in the analysis is illustrated in Fig. 2. As $m_2$ is required to exceed $m_1$, only $(i,j)$ bins with $j \geq i$ are filled in the 2D distribution, yielding in total $6(6 + 1)/2 = 21$ independent bins. Bins $(i, 6)$ with $i = 1, 5$ contain all events with $m_2 > 6$ GeV. Bin $(6, 6)$ contains all events with $m_{1,2} > 6$ GeV.

5 Modeling background

A simulation-based study reveals that the sample of SC muon pairs selected as described in Section 4, but without requiring the presence of $a_1$ candidates, is dominated by QCD multijet events, where about 85% of all selected events contain bottom quarks in the final state. The SC muon pairs in these events originate mainly from the following sources:
• muonic decay of a bottom hadron in one bottom quark jet and cascade decay of a bottom hadron into a charm hadron with a subsequent muonic decay of the charm hadron in the other bottom quark jet;
• muonic decay of a bottom hadron in one bottom quark jet and decay of a quarkonium state into a pair of muons in the other jet;
• muonic decay of a bottom hadron in one bottom quark jet and muonic decay of a $B^0$ meson in the other bottom quark jet. The SC muon pair in this case may appear as a result of $B^0$–$\bar{B}^0$ oscillations.

The normalized 2D $(m_1, m_2)$ distribution for the muon-track pairs with $m_2 > m_1$ is represented in the sample of background events by a binned template constructed using the following relation

$$f_{2D}(i, j) = C(i, j)(f_{1D}(i)f_{1D}(j))^{\text{sym}},$$

$$(f_{1D}(i)f_{1D}(j))^{\text{sym}} = f_{1D}(i)f_{1D}(i),$$

$$(f_{1D}(i)f_{1D}(j))^{\text{sym}} = f_{1D}(i)f_{1D}(j) + f_{1D}(j)f_{1D}(i) = 2f_{1D}(i)f_{1D}(j), \quad \text{if } j > i,$$

where

- $f_{2D}(i, j)$ is the content of the bin $(i, j)$ in the normalized 2D $(m_1, m_2)$ distribution;
- $f_{1D}(i)$ is the content of bin $i$ in the normalized one-dimensional (1D) distribution of the muon-track invariant mass;
- $C(i, j)$ is a symmetric matrix, accounting for possible correlation between $m_1$ and $m_2$, the elements of the matrix $C(i, j)$ are referred to as “correlation factors” in the following.

The condition $C(i, j) = 1$ for all bins $(i, j)$ would indicate an absence of correlation between $m_1$ and $m_2$. We sum the contents of the nondiagonal bins $(i, j)$ and $(j, i)$ in the Cartesian product $f_{1D}(i)f_{1D}(j)$ to account for the fact that each event enters the 2D $(m_1, m_2)$ distribution with ordered values of the muon-track invariant masses.
By construction the background model estimates the dominant QCD multijet production as well as small contributions from other processes.

Multiple control regions (CRs) are introduced in order to derive and validate the modeling of $f_{1D}(i)$ and $C(i,j)$. The CRs are defined on the basis of a modified isolation criteria applied to one or both muon-track pairs. The isolation criteria are specified by the multiplicity of “isolation” tracks in the cone of $\Delta R = 0.5$ around the muon momentum direction. The summary of all CRs used to derive and validate the modeling of background shape is given in Table 2.

Table 2: Control regions used to construct and validate the background model. The symbols $N_{\text{sig}}$, $N_{\text{iso}}$, and $N_{\text{soft}}$ denote the number of “signal”, “isolation” (which are a subset of “signal” tracks) and “soft” tracks, respectively, within a cone of $\Delta R = 0.5$ around the muon momentum direction. The last row defines the SR.

| Control region | First $\mu$ | Second $\mu$ | Purpose | Observed events |
|----------------|-------------|--------------|---------|-----------------|
| $N_{23}$       | $N_{\text{iso}} = 1$, $N_{\text{sig}} = 1$ | $N_{\text{iso}} = 2,3$ | Determination of $f_{1D}(i)$ | 62438 |
| $N_{\text{iso,2}} = 1$ | $N_{\text{iso}} > 1$, $N_{\text{sig}} \geq 1$ | $N_{\text{iso}} = 1$, $N_{\text{sig}} = 1$ | Validation of $f_{1D}(i)$ | 472570 |
| $N_{\text{iso,2}} = 2,3$ | $N_{\text{iso}} > 1$, $N_{\text{sig}} \geq 1$ | $N_{\text{iso}} = 2,3$ | Validation of $f_{1D}(i)$ | 17667900 |
| $N_{45}$       | $N_{\text{iso}} = 1$, $N_{\text{sig}} = 1$ | $N_{\text{iso}} = 4,5$ | Assessment of systematics in $f_{1D}(i)$ | 52437 |
| Both muons     | $N_{\text{sig}} = 1$, $N_{\text{soft}} = 1,2$ | | Determination of $C(i,j)$ | 35824 |
| Signal region  | $N_{\text{sig}} = 1$, $N_{\text{iso}} = 1$ | | Signal extraction | 2035 |

5.1 Modeling of $f_{1D}(i)$

The $f_{1D}(i)$ distribution is modeled using the $N_{23}$ CR. Events in this CR pass the SC dimuon selection and contain only one $a_1$ candidate composed of the isolated “signal” track and muon (first muon). The invariant mass of the first muon and associated track enters the $f_{1D}(i)$ distribution. Another muon (second muon) is required to be accompanied by either two or three nearby “isolation” tracks. The simulation shows that more than 95% of events selected in the CR $N_{23}$ are QCD multijet events, while the remaining 5% is coming from $t\bar{t}$, Drell-Yan and other electroweak processes. The modeling of the $f_{1D}(i)$ template is based on the hypothesis that the kinematic distributions for the muon-track system, making up an $a_1$ candidate (the first muon and associated track), are weakly affected by the isolation requirement imposed on the second muon; therefore the $f_{1D}(i)$ distribution of the muon-track system forming an $a_1$ candidate is expected to be similar in the SR and the $N_{23}$ CR.

This hypothesis is verified in control regions labelled $N_{\text{iso,2}} = 1$ and $N_{\text{iso,2}} = 2,3$. Events are selected in these CR if one of the muons (first muon) has more than one “isolation” track ($N_{\text{iso}} > 1$). At least one of these “isolation” tracks should also fulfill the criteria imposed on the “signal” track. As more than one of these tracks can pass the criteria imposed on “signal” tracks, two scenarios have been investigated, namely using either the lowest or the highest $p_T$ “signal” tracks (“softest” and “hardest”) to calculate the muon-track invariant mass. If only one “signal” track is found nearby to the first muon, the track is used both as the “hardest” and the “softest” signal track. For the second muon, two isolation requirements are considered: when the muon is accompanied by only one “signal” track and the muon-track system is isolated as in the SR (CR $N_{\text{iso,2}} = 1$), or when it is accompanied by two or three “isolation” tracks as in the CR $N_{23}$ (CR $N_{\text{iso,2}} = 2,3$). The invariant mass distributions of the first muon and the softest
or hardest accompanying track are then compared for the two different isolation requirements on the second muon, $N_{\text{iso},2} = 1$ and $N_{\text{iso},2} = 2, 3$. The results of this study are illustrated in Fig. 3. In both cases, the invariant mass distributions differ in each bin by less than 6%. This observation indicates that the invariant mass of the muon-track system, making up an $a_1$ candidate, weakly depends on the isolation requirement imposed on the second muon, thus supporting the assumption that the $f_{1D}(i)$ distribution can be determined from the $N_{23}$ CR.

The potential dependence of the muon-track invariant mass distribution on the isolation requirement imposed on the second muon is verified also by comparing shapes in the control regions $N_{23}$ and $N_{45}$. The latter CR is defined by requiring the presence of 4 or 5 “isolation” tracks nearby to the second muon, while the first muon-track pair passes selection criteria for the $a_1$ candidate. The results are illustrated in Fig. 4. A slight difference is observed between distributions in these two CRs. This difference is taken as a shape uncertainty in the normalized template $f_{1D}(j)$ entering Eq. (3).

Figure 5 presents the normalized invariant mass distribution of the muon-track system for data selected in the SR and for the background model derived from the $N_{23}$ CR. The data and background distributions are compared to the signal distributions, obtained from simulation, for four representative mass hypotheses, $m_{a_1} = 4, 7, 10, \text{and } 15 \text{ GeV}$. The invariant mass of the muon-track system is found to have higher discrimination power between the background and the signal at higher $m_{a_1}$. For lower masses, the signal shape becomes more background like, resulting in a reduction of discrimination power.

### 5.2 Modeling of $C(i,j)$

In order to determine the correlation factors $C(i,j)$, an additional CR (labelled Loose-Iso) is used. It consists of events that contain two SC muons passing the identification and kinematic
Each muon is required to have two or three nearby tracks. One of them should belong to the category of “signal” tracks, whereas remaining tracks should belong to the category of “soft” tracks. About 36k data events are selected in this CR. The simulation predicts that the QCD multijet events dominate this CR, comprising more than 99% of selected events. It was also found that the overall background-to-signal ratio is enhanced compared to the SR by a factor of 30 to 40, depending on the mass hypothesis, $m_{a_1}$. The event sample in this region is used to build the normalized distribution $f_{2D}(i,j)$. Finally, the correlation factors $C(i,j)$ are obtained according to Eq. (3) as

$$C(i,j) = \frac{f_{2D}(i,j)}{(f_{1D}(i)f_{1D}(j))^{sym}},$$

(4)

where $f_{1D}(i)$ is the 1D normalized distribution with two entries per event ($m_1$ and $m_2$). The correlation factors $C(i,j)$ derived from data in the Loose-Iso CR are presented in Fig. 6. To obtain estimates of $C(i,j)$ in the signal region, the correlation factors derived in the Loose-Iso CR have to be corrected for the difference in $C(i,j)$ between the signal region and Loose-Iso CR. This difference is assessed by comparing samples of simulated background events. The correlation factors estimated from simulation in the signal region and the Loose-Iso CR are presented in Fig. 7.

The correlation factors in the signal region are then computed as

$$C(i,j)^{SR}_{data} = C(i,j)^{CR}_{data} \frac{C(i,j)^{SR}_{MC}}{C(i,j)^{CR}_{MC}},$$

(5)

where

- $C(i,j)^{CR}_{data}$ are correlation factors derived for the Loose-Iso CR in data (Fig. 6).
Figure 5: Normalized invariant mass distribution of the muon-track system for events passing the signal selection. Observed numbers of events are represented by data points with error bars. The QCD multijet background model is derived from the control region $N_{23}$. Also shown are the normalized distributions from signal simulations for four mass hypotheses, $m_{a_1} = 4, 7, 10,$ and $15$ GeV (dashed histograms), whereas for higher masses the analysis has no sensitivity. Each event in the observed and expected signal distributions contributes two entries, corresponding to the two muon-track systems in each event passing the selection. The signal distributions include $2\mu2\tau$ and $4\tau$ contributions. The lower panel shows the ratio of the observed to expected number of background events in each bin of the distribution. The grey shaded area represents the background model uncertainty.

- $C(i,j)_{\text{SR}}$ are correlation factors derived for the SR in the simulated QCD multijet sample (Fig. 7, left);
- $C(i,j)_{\text{CR}}$ are correlation factors derived for the Loose-Iso CR in the simulated QCD multijet sample (Fig. 7, right).

The difference in correlation factors derived in the SR (Fig. 7, left) and in the Loose-Iso CR (Fig. 7, right) using the QCD multijet sample is taken into account as an uncertainty in $C(i,j)$.

6 Modeling signal

The signal templates are derived from the simulated samples of the $H \to a_1a_1 \to 4\tau$ and $H \to a_1a_1 \to 2\mu2\tau$ decays. The study probes the signal strength modifier, defined as the ratio of the product of the measured signal cross section and the branching fraction into the $4\tau$ final state $B(H \to a_1a_1)B^2(a_1 \to \tau\tau)$ to the inclusive cross section of the H production predicted in the SM. The relative contributions from different production modes of H are defined by the
Figure 6: The \((m_1, m_2)\) correlation factors \(C(i,j)\) with their statistical uncertainties, derived from data in the CR Loose-Iso.

Figure 7: The \((m_1, m_2)\) correlation factors \(C(i,j)\) along with their MC statistical uncertainties, derived from simulated samples in the (left: signal region, right: Loose-Iso CR).

corresponding cross sections predicted in the SM. The contribution of the \(H \to a_1 a_1 \to 2\mu 2\tau\) decay, is computed assuming that the partial widths of \(a_1 \to \tau \tau\) and \(a_1 \to \mu \mu\) decays satisfy Eq. (1).

The invariant mass distribution of the muon-track system in the \(a_1 \to \mu \mu\) decay channel peaks at the nominal value of the \(a_1\) boson mass, while the reconstructed mass of the muon-track
system in the $a_1 \rightarrow \tau\tau$ decay is typically lower, because of the missing neutrinos. This is why
the $H \rightarrow a_1 a_1 \rightarrow 2\mu2\tau$ signal samples have a largely different shape of the $(m_1, m_2)$ distribution
compared to the $H \rightarrow a_1 a_1 \rightarrow 4\tau$ signal samples. Figure 8 compares the $(m_1, m_2)$ distributions
unrolled in a one row between the $H \rightarrow a_1 a_1 \rightarrow 4\tau$ and $H \rightarrow a_1 a_1 \rightarrow 2\mu2\tau$ signal samples
for mass hypotheses $m_{a_1} = 4\text{ GeV}$ and $10\text{ GeV}$. The signal distributions are normalized assuming the
SM $H$ production rate with the branching fraction $B(H \rightarrow a_1 a_1)B^2(a_1 \rightarrow \tau\tau)$ equal to 0.2.

Figure 8: The distribution of the signal templates $f_{2D}(i, j)$ in one row for mass hypothesis $m_{a_1} =
4\text{ GeV}$ (left) and $10\text{ GeV}$ (right). The $H \rightarrow a_1 a_1 \rightarrow 2\mu2\tau$ (blue histogram) and $H \rightarrow a_1 a_1 \rightarrow 4\tau$
(red histogram) contributions are shown. The notation of the bins follows that of Fig. 2.

7 Systematic uncertainties

Table 3 lists the systematic uncertainties considered in the analysis for both signal and back-
ground.

7.1 Uncertainties related to the background

The estimation of the QCD multijet background is based on observed data, therefore it is not
affected by imperfections in the simulation, reconstruction, or detector response.

The shape of the background in the $(m_1, m_2)$ distribution is modeled according to Eq. (3), while
its uncertainty is dominated by uncertainties related to the correlation factors $C(i, j)$ (as
described in Section 5.2). Additionally, it is also affected by the shape uncertainty in the 1D
template $f_{1D}(m)$ (as discussed in Section 5.1). The bin-by-bin uncertainties in mass correlation
factors $C(i, j)$, derived from Eq. (5), are composed of the statistical uncertainties in observed
data and simulated samples, as presented in Figs. 6 and 7 and range from 3 to 60%. These un-
certainties are accounted for in the signal extraction procedure by one nuisance parameter per
bin in the $(m_1, m_2)$ distribution [61]. The systematic uncertainties related to the extrapolation
of $C(i, j)$ from the Loose-Iso CR to the SR are derived from the dedicated MC study outlined
in Section 5.2. The related shape uncertainty is determined by comparing correlation factors
derived in the simulated samples, between the signal region and the Loose-Iso CR.

In the case when $B(H \rightarrow a_1 a_1)B^2(a_1 \rightarrow \tau\tau) = 0.34$, corresponding to an upper limit at 95% 
confidence level (CL) on the branching fraction of the $H$ decay into non-SM particles from
Ref. [26], the impact of possible signal contamination in the Loose-Iso CR is estimated on a bin-
by-bin basis, and it is at most 2.8% in the bin $(6,6)$ which was found to have a negligible effect
on the final results. For all other CRs, the signal contamination was found to be well below 1%.
Table 3: Systematic uncertainties and their effect on the estimates of the QCD multijet background and signal.

| Source                              | Value | Affected sample | Type       | Effect on the total yield |
|-------------------------------------|-------|-----------------|------------|---------------------------|
| Stat. unc. in $C(i,j)$              | 3–60% | bkg.            | bin-by-bin | —                         |
| Extrapolation unc. in $C(i,j)$      | —     | bkg.            | shape      | —                         |
| Unc. in $f_{1D}(i)$                | —     | bkg.            | shape      | —                         |
| Integrated luminosity               | 2.5%  | signal          | norm.      | 2.5%                      |
| Muon id. and trigger efficiency    | 2%    | signal          | norm.      | 4%                        |
| Track id. efficiency               | 4–12% | signal          | shape      | 10–18%                    |
| MC stat. unc. in signal yields      | 8–100%| signal          | bin-by-bin | 5–20%                     |

Theoretical uncertainties in the signal acceptance

- $\mu_R$ and $\mu_F$ variations
  - signal
  - norm.
  - 0.8–2%

- PDF
  - signal
  - norm.
  - 1–2%

Theoretical uncertainties in the signal cross sections

- $\mu_{R,F}$ variations (ggF)
  - signal
  - norm.
  - 5–7%

- $\mu_{R,F}$ variations (other processes)
  - 0.4–9% signal
  - norm.
  - <0.5%

- PDF (ggF)
  - 3.1% signal
  - norm.
  - 3.1%

- PDF (other processes)
  - 2.1–3.6% signal
  - norm.
  - <0.5%

7.2 Uncertainties related to signal

An uncertainty of 2.5% is assigned to the integrated luminosity estimate [62].

The uncertainty in the muon identification and trigger efficiency is estimated to be 2% for each selected muon obtained with the tag-and-probe technique [63]. The track selection and muon-track isolation efficiency is assessed with a study performed on a sample of $Z$ bosons decaying into a pair of tau leptons. In the selected $Z \rightarrow \tau\tau$ events, one tau lepton is identified via its muonic decay, while the other is identified as an isolated track resulting from a one-prong decay. The track is required to pass the nominal selection criteria used in the main analysis. From this study, the uncertainty in the track selection and isolation efficiency is evaluated. The related uncertainty affects the shape of the signal estimate, while changing the overall signal yield by 10–18%. The muon and track momentum scale uncertainties are smaller than 0.3% and have a negligible effect on the analysis.

The bin-by-bin statistical uncertainties in the signal acceptance range from 8 to 100%, while the impact on the overall signal normalization varies between 5 and 20%.

Theoretical uncertainties have an impact on the differential kinematic distributions of the produced $H$, in particular its $p_T$ spectrum, thereby affecting signal acceptance. The uncertainty due to missing higher-order corrections to the ggF process is estimated with the HQT program by varying the renormalization ($\mu_R$) and factorization ($\mu_F$) scales. The $H$ $p_T$-dependent $K$ factors are recomputed according to these variations and applied to the simulated signal samples. The resulting effect on the signal acceptance is estimated to vary between 1.2 and 1.5%, depending on $m_{a_1}$. In a similar way, the uncertainty in the signal acceptance is computed for the VBF, VH and $t\bar{t}H$ production processes. The impact on the acceptance is estimated to vary between 0.8 and 2.0%, depending on the process and probed mass of the $a_1$ boson.

The HQT program is also used to evaluate the effect of the PDF uncertainties. The nominal $K$
factors for the H $p_T$ spectrum are computed with the NNPDF3.0 PDF set \cite{18}. Variations of the NNPDF3.0 PDFs within their uncertainties change the signal acceptance by about 1%, whilst using the CTEQ6L1 PDF set \cite{64} changes the signal acceptance by about 0.7%. The impact of the PDF uncertainties on the acceptance for the VBF, VH and $t\bar{t}H$ production processes is estimated in the same way and a 2% uncertainty is considered to account for these.

Systematic uncertainties in theoretical predictions for the signal cross sections are driven by variations of the $\mu_R$ and $\mu_F$ scales and PDF uncertainties. Uncertainties related to scale variations range from 0.4 to 9%, depending on the production mode. Uncertainties related to PDF vary between 2.1 and 3.6%.

8 Results

The signal is extracted with a binned maximum-likelihood fit applied to the ($m_1, m_2$) distribution. For each probed mass of the $a_1$ boson, the ($m_1, m_2$) distribution is fitted with the sum of two templates, corresponding to expectations for the signal and background, dominated by QCD multijet events.

The normalization of both signal and background are allowed to float freely in the fit. The systematic uncertainties affecting the normalization of the signal templates are incorporated in the fit via nuisance parameters with a log-normal prior probability density function. The shape-altering systematic uncertainties are represented by nuisance parameters whose variations cause continuous morphing of the signal or background template shape, and are assigned a Gaussian prior probability density functions. The bin-by-bin statistical uncertainties are assigned gamma prior probability density functions.

Figure 9 shows the distribution of ($m_1, m_2$), where the notation for the bins follows that of Fig. 2. The shape and the normalization of the background distribution are obtained by applying a fit to the observed data under the background-only hypothesis. Also shown are the expectations for the signal at $m_{a_1} = 4, 7, 10, \text{ and } 15 \text{ GeV}$. The signal normalization is computed assuming that the H is produced in pp collisions with a rate predicted by the standard model, and decays into $a_1 a_1 \rightarrow 4\tau$ final state with a branching fraction of 20%. No significant deviations from the background expectation are observed in the ($m_1, m_2$) distribution.

Results of the analysis are used to set upper limits at 95% CL on the product of the cross section and branching fraction, $\sigma(pp \rightarrow H + X) B(H \rightarrow a_1 a_1) B^2(a_1 \rightarrow \tau\tau)$, relative to the inclusive SM cross section of H production. The modified frequentist CL$_s$ criterion \cite{65, 66}, and the asymptotic formulae are used for the test statistic \cite{67}, implemented in the RooStats package \cite{68}. Figure 10 shows the observed and expected upper limits at 95% CL on the signal cross section times the branching fraction, relative to the total cross section of the H boson production as predicted in the SM. The observed limit is compatible with the expected limit within one standard deviation in the entire range of $m_{a_1}$ considered, and ranges from 0.022 at $m_{a_1} = 9$ GeV to 0.23 at $m_{a_1} = 4$ GeV and reaches 0.16 at $m_{a_1} = 15$ GeV. The expected upper limit ranges from 0.027 at $m_{a_1} = 9$ GeV to 0.16 at $m_{a_1} = 4$ GeV and reaches 0.19 at $m_{a_1} = 15$ GeV. The degradation of the analysis sensitivity towards lower values of $m_{a_1}$ is caused by the increase of the background yield at low invariant masses of the muon-track systems, as illustrated in Figs. 5 and 9. With increasing $m_{a_1}$, the average angular separation between the decay products of the $a_1$ boson is increasing. As a consequence, the efficiency of the signal selection drops down, as we require the muon and the track, originating from the $a_1 \rightarrow \tau\mu$ or $a_1 \rightarrow \mu\mu$ decay, to be within a cone of $\Delta R = 0.5$. This explains the deterioration of the search sensitivity at higher values of $m_{a_1}$. The shaded area in blue indicates the excluded region of $>34\%$ for the branching fraction.
Figure 9: The $(m_1, m_2)$ in one row distribution used to extract the signal. Observed numbers of events are represented by data points with error bars. The background with its uncertainty is shown as the blue histogram with the shaded error band. The shape and the normalization of the background distribution are obtained by applying a fit to the observed data under the background-only hypothesis. Signal expectations for the $4\tau$ and $2\mu 2\tau$ final states are shown as dotted histograms for the mass hypotheses $m_a = 4, 7, 10, 15$ GeV. The relative normalization of the $4\tau$ and $2\mu 2\tau$ final states are given by Eq. (1) as explained in Section 6. The signal normalization is computed assuming that the $H$ boson is produced in pp collisions with a rate predicted by the SM, and decays into $a_1 a_1 \rightarrow 4\tau$ final state with the branching fraction of 20%. The lower plot shows the ratio of the observed data events to the expected background yield in each bin of the $(m_1, m_2)$ distribution.

The new limits improve significantly over the previous 8 TeV limits [28] by 30% (for low masses) and up to 80% (for intermediate masses of 8 GeV), while the new analysis further extends the coverage of $m_{a_1}$ up to 15 GeV.

### 9 Summary

A search is presented for light pseudoscalar $a_1$ bosons, produced from decays of the 125 GeV Higgs boson ($H$) in a data set corresponding to an integrated luminosity of 35.9 fb$^{-1}$ of proton-proton collisions at a center-of-mass energy of 13 TeV. The analysis is based on the H inclusive production and targets the $H \rightarrow a_1 a_1 \rightarrow 4\tau/2\mu 2\tau$ decay channels. Both channels are used in combination to constrain the product of the inclusive signal production cross section and the branching fraction into the $4\tau$ final state, exploiting the linear dependence of the fermionic coupling strength of $a_1$ on the fermion mass. With no evidence for a signal, the observed 95% confidence level upper limit on the product of the inclusive signal cross section and the branching fraction, relative to the SM $H$ production cross section, ranges from 0.022 at $m_{a_1} = 9$ GeV to 0.23 at $m_{a_1} = 4$ GeV and reaches 0.16 at $m_{a_1} = 15$ GeV. The expected upper limit ranges from 0.027 at $m_{a_1} = 9$ GeV to 0.16 at $m_{a_1} = 4$ GeV and reaches 0.19 at $m_{a_1} = 15$ GeV.
Figure 10: The observed and expected upper limits at 95% confidence levels on the product of signal cross section and the branching fraction $\sigma(pp \to H + X) B(H \to a_1 a_1) B^2(a_1 \to \tau\tau)$, relative to the inclusive Higgs boson production cross section $\sigma_{SM}$ predicted in the SM. The green and yellow bands indicate the regions that contain 68% and 95% of the distribution of limits expected under the background-only hypothesis. The shaded area in blue indicates the excluded region of $>34\%$ for the branching fraction of the H decay into non-SM particles at 95% CL from Ref. [26].

Acknowledgments

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 centers 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); MSIP 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); MOSTR (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).
Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124850, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] ATLAS Collaboration, “Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. B 716 (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. B 716 (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[3] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, Nucl. Phys. B 90 (1975) 104, doi:10.1016/0550-3213(75)90636-7.

[4] R. K. Kaul and P. Majumdar, “Cancellation of quadratically divergent mass corrections in globally supersymmetric spontaneously broken gauge theories”, Nucl. Phys. B 199 (1982) 36, doi:10.1016/0550-3213(82)90565-X.

[5] R. Barbieri, S. Ferrara, and C. A. Savoy, “Gauge models with spontaneously broken local supersymmetry”, Phys. Lett. B 119 (1982) 343, doi:10.1016/0370-2693(82)90685-2.

[6] H. P. Nilles, M. Srednicki, and D. Wyler, “Weak interaction breakdown induced by supergravity”, Phys. Lett. B 120 (1983) 346, doi:10.1016/0370-2693(83)90460-4.
[7] J.-M. Frere, D. R. T. Jones, and S. Raby, “Fermion masses and induction of the weak scale by supergravity”, Nucl. Phys. B 222 (1983) 11, doi:10.1016/0550-3213(83)90606-5

[8] J.-P. Derendinger and C. A. Savoy, “Quantum effects and SU(2) \times U(1) breaking in supergravity gauge theories”, Nucl. Phys. B 237 (1984) 307, doi:10.1016/0550-3213(84)90162-7.

[9] U. Ellwanger, C. Hugonie, and A. M. Teixeira, “The next-to-minimal supersymmetric standard model”, Phys. Rept. 496 (2010) 1, doi:10.1016/j.physrep.2010.07.001, arXiv:0910.1785.

[10] M. Maniatis, “The next-to-minimal supersymmetric extension of the standard model reviewed”, Int. J. Mod. Phys. A 25 (2010) 3505, doi:10.1142/S0217751X10049827, arXiv:0906.0777.

[11] J. E. Kim and H. P. Nilles, “The \(\mu\)-problem and the strong CP-problem”, Phys. Lett. B 138 (1984) 150, doi:10.1016/0370-2693(84)91890-2.

[12] G. Belanger et al., “Higgs bosons at 98 and 125 GeV at LEP and the LHC”, JHEP 01 (2013) 069, doi:10.1007/JHEP01(2013)069, arXiv:1210.1976.

[13] G. Belanger et al., “Two Higgs bosons at the Tevatron and the LHC?”, (2012), arXiv:1208.4952.

[14] J. F. Gunion, Y. Jiang, and S. Kraml, “Diagnosing degenerate Higgs bosons at 125 GeV”, Phys. Rev. Lett. 110 (2013) 051801, doi:10.1103/PhysRevLett.110.051801, arXiv:1208.1817.

[15] J. F. Gunion, Y. Jiang, and S. Kraml, “Could two NMSSM Higgs bosons be present near 125 GeV?”, Phys. Rev. D 86 (2012) 071702, doi:10.1103/PhysRevD.86.071702, arXiv:1207.1545.

[16] S. F. King, M. Mühlleitner, and R. Nevzorov, “NMSSM Higgs benchmarks near 125 GeV”, Nucl. Phys. B 860 (2012) 207, doi:10.1016/j.nuclphysb.2012.02.010, arXiv:1201.2671.

[17] S. F. King, M. Mühlleitner, R. Nevzorov, and K. Walz, “Natural NMSSM Higgs bosons”, Nucl. Phys. B 870 (2013) 323, doi:10.1016/j.nuclphysb.2013.01.020, arXiv:1211.5074.

[18] U. Ellwanger, J. F. Gunion, and C. Hugonie, “Difficult scenarios for NMSSM Higgs discovery at the LHC”, JHEP 07 (2005) 041, doi:10.1088/1126-6708/2005/07/041, arXiv:hep-ph/0503203.

[19] U. Ellwanger, J. F. Gunion, C. Hugonie, and S. Moretti, “Towards a no-lose theorem for NMSSM Higgs discovery at the LHC”, in Physics at TeV colliders, Les Houches workshop. 2003, arXiv:hep-ph/0305109.

[20] U. Ellwanger, J. F. Gunion, C. Hugonie, and S. Moretti, “NMSSM Higgs discovery at the LHC”, in Physics at TeV colliders, Les Houches workshop. 2003, arXiv:hep-ph/0401228.

[21] A. Belyaev et al., “The scope of the 4 tau channel in Higgs-strahlung and vector boson fusion for the NMSSM no-Lose Theorem at the LHC”, (2008), arXiv:0805.3505.
[22] A. Belyaev et al., “LHC discovery potential of the lightest NMSSM Higgs boson in the \( h_1 \rightarrow \eta_1 \eta_1 \rightarrow 4\mu \) channel”, Phys. Rev. D 81 (2010) 075021, doi:10.1103/PhysRevD.81.075021, arXiv:1002.1956

[23] M. Lisanti and J. G. Wacker, “Discovering the Higgs boson with low mass muon pairs”, Phys. Rev. D 79 (2010) 115006, doi:10.1103/PhysRevD.79.115006, arXiv:0903.1377

[24] M. M. Almarashi and S. Moretti, “Scope of Higgs production in association with a bottom quark pair in probing the Higgs sector of the NMSSM at the LHC”, (2012). arXiv:1205.1683

[25] M. M. Almarashi and S. Moretti, “LHC signals of a heavy CP-even Higgs boson in the NMSSM via decays into a Z and a light CP-odd Higgs state”, Phys. Rev. D 85 (2012) 017701, doi:10.1103/PhysRevD.85.017701, arXiv:1109.1735

[26] ATLAS and CMS Collaborations, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at \( \sqrt{s} = 7 \) and 8 TeV”, JHEP 08 (2016) 045, doi:10.1007/JHEP08(2016)045, arXiv:1606.02266

[27] CMS Collaboration, “Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at \( \sqrt{s} = 8 \) TeV”, JHEP 10 (2017) 076, doi:10.1007/JHEP10(2017)076, arXiv:1701.02032

[28] CMS Collaboration, “Search for a very light NMSSM Higgs boson produced in decays of the 125 GeV scalar boson and decaying into \( \tau \) leptons in pp collisions at \( \sqrt{s} = 8 \) TeV”, JHEP 01 (2018) 018, doi:10.1007/JHEP01(2018)018, arXiv:1805.04865

[29] CMS Collaboration, “A search for pair production of new light bosons decaying into muons”, Phys. Lett. B 752 (2016) 146, doi:10.1016/j.physletb.2015.10.067, arXiv:1506.00424

[30] CMS Collaboration, “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two \( \tau \) leptons in proton-proton collisions at \( \sqrt{s} = 13 \) TeV”, JHEP 11 (2018) 018, doi:10.1007/JHEP11(2018)018, arXiv:1805.04865

[31] CMS Collaboration, “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two \( \tau \) leptons in proton-proton collisions at \( \sqrt{s} = 13 \) TeV”, Phys. Lett. B 785 (2018) 462, doi:10.1016/j.physletb.2018.08.057, arXiv:1805.10191

[32] ATLAS Collaboration, “Search for the Higgs boson produced in association with a W boson and decaying to four \( b \)-quarks via two spin-zero particles in pp collisions at 13 TeV with the ATLAS detector”, Eur. Phys. J. C 76 (2016) 605, doi:10.1140/epjc/s10052-016-4418-9, arXiv:1606.08391

[33] ATLAS Collaboration, “Search for new light gauge bosons in Higgs boson decays to four-lepton final states in pp collisions at \( \sqrt{s} = 8 \) TeV with the ATLAS detector at the LHC”, Phys. Rev. D 92 (2015) 092001, doi:10.1103/PhysRevD.92.092001, arXiv:1505.07645
[34] ATLAS Collaboration, “Search for new phenomena in events with at least three photons collected in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, Eur. Phys. J. C 76 (2016) 210, doi:10.1140/epjc/s10052-016-4034-8, arXiv:1509.05051

[35] ATLAS Collaboration, “Search for Higgs bosons decaying to $aa$ in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment”, Phys. Rev. D 92 (2015) 052002, doi:10.1103/PhysRevD.92.052002, arXiv:1505.01609

[36] ATLAS Collaboration, “Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Phys. Lett. B 782 (2018) 750, doi:10.1016/j.physletb.2018.06.011, arXiv:1803.11145

[37] ATLAS Collaboration, “Search for Higgs boson decays to beyond-the-standard-model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV”, JHEP 06 (2018) 166, doi:10.1007/JHEP06(2018)166, arXiv:1802.03388

[38] CMS Collaboration, “Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two muons and two b quarks in pp collisions at 13 TeV”, Phys. Lett. B 795 (2019) 398, doi:10.1016/j.physletb.2019.06.021, arXiv:1812.06359

[39] CMS Collaboration, “A search for pair production of new light bosons decaying into muons in pp collisions at 13 TeV”, Phys. Lett. B 796 (2019) 131, doi:10.1016/j.physletb.2019.07.013, arXiv:1812.00380

[40] ATLAS Collaboration, “Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in pp collision at $\sqrt{s} = 13$ TeV with the ATLAS detector”, Phys. Lett. B 790 (2019) 1, doi:10.1016/j.physletb.2018.10.073, arXiv:1807.00539

[41] D. Curtin et al., “Exotic decays of the 125 GeV Higgs boson”, Phys. Rev. D 90 (2014), no. 7, 075004, doi:10.1103/PhysRevD.90.075004, arXiv:1312.4992

[42] CMS Collaboration, “The CMS trigger system”, JINST 12 (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366

[43] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

[44] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, Comput. Phys. Commun. 191 (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012

[45] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, JHEP 07 (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301

[46] G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, “Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC”, Nucl. Phys. B 737 (2006) 73, doi:10.1016/j.nuclphysb.2005.12.022, arXiv:hep-ph/0508068

[47] D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, “Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC”, JHEP 11 (2011) 064, doi:10.1007/JHEP11(2011)064, arXiv:1109.2109
[48] NNPDF Collaboration, “Parton distributions for the LHC Run II”, JHEP 04 (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849

[49] P. Nason, “A New method for combining NLO QCD with shower Monte Carlo algorithms”, JHEP 11 (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146

[50] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, JHEP 11 (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092

[51] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, JHEP 06 (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581

[52] E. Re, “Single-top Wt-channel production matched with parton showers using the POWHEG method”, Eur. Phys. J. C 71 (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450

[53] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO single-top production matched with shower in POWHEG: s- and t-channel contributions”, JHEP 09 (2009) 111, doi:10.1088/1126-6708/2009/09/111, arXiv:0907.4076 [Erratum: doi:10.1007/JHEP02(2010)011].

[54] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, Eur. Phys. J. C 76 (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815

[55] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, Nucl. Instrum. Meth. A 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8

[56] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, JINST 12 (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965

[57] CMS Collaboration, “Track reconstruction in the CMS tracker”, Technical Report CMS-NOTE-2006-041, 2006.

[58] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, JINST 9 (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569

[59] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-\(k_T\) jet clustering algorithm”, JHEP 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189

[60] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet User Manual”, Eur. Phys. J. C 72 (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097

[61] J. S. Conway, “Incorporating nuisance parameters in likelihoods for multisource spectra”, in Proceedings of PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, p. 115. CERN-2011-006, 2011.

[62] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.
[63] CMS Collaboration, “Measurement of the Inclusive $W$ and $Z$ Production Cross Sections in $pp$ Collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.

[64] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.

[65] A. L. Read, “Presentation of search results: the $C_{L_{s}}$ technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[66] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[67] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727 [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[68] L. Moneta et al., “The RooStats Project”, in *13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT2010)*. SISSA, 2010. arXiv:1009.1003.
A The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth, V.M. Ghete, J. Hrubec, M. Jeitler, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz, M. Zarucki

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

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, J. D’Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, A. Grebenyuk, A.K. Kalsi, J. Luetic, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, K. Piotrzkowski, A. Saggion, M. Vidal Marono, P. Vischia, J. Zobec

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

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato, E. Coelho, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydijiev, 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. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang, J. Zhao

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

Universidad de Antioquia, Medellin, Colombia
J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
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, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

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

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
A.A. Abdelalim, Y. Assran, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehatat, 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
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besançon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Siros, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte, J.-C. Fontaine, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, A. Novak, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, A. Sharma, D. Teyszier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkor, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl
Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras, V. Botta, A. Campbell, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, N.Z. Jomhari, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, D. Pérez Adán, S.K. Pflicht, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinze, M. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Schleper, S. Schumann, J. Schwanitz, J. Sonneveld, H. Stadie, G. Steinbrück, E.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, M.A. Harrendorf, F. Hartmann, U. Husemann, I. Katkov, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

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

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Mantiraka, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Trianitis, D. Tsigonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók, M. Csanad, N. Filipovic, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Suráni, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horváth, . 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
S. Bahinipati\textsuperscript{24}, C. Kar, P. Mal, A. Nayak\textsuperscript{25}, S. Roy Chowdhury, D.K. Sahoo\textsuperscript{24}, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumar, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

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
R. Bhardwaj\textsuperscript{26}, M. Bharti\textsuperscript{26}, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep\textsuperscript{26}, D. Bhowmik, S. Dey, S. Dutt\textsuperscript{26}, S. Dutta, S. Ghosh, M. Maity\textsuperscript{27}, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar\textsuperscript{27}, M. Sharan, B. Singh\textsuperscript{26}, S. Thakur\textsuperscript{26}

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, P. Suggisetti

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

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

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\textsuperscript{28}, E. Eskandari Tadavani, S.M. Etesami\textsuperscript{28}, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh\textsuperscript{29}, M. Zeinali

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

INFN Sezione di Bari \textsuperscript{a}, Università di Bari \textsuperscript{b}, Politecnico di Bari \textsuperscript{c}, Bari, Italy
M. Abbrescia\textsuperscript{a,b}, C. Calabria\textsuperscript{a,b}, A. Colaleo\textsuperscript{a}, D. Creanza\textsuperscript{a,c}, L. Cristella\textsuperscript{a,b}, N. De Filippis\textsuperscript{a,c}, M. De Palma\textsuperscript{a,b}, A. Di Florio\textsuperscript{a,b}, F. Errico\textsuperscript{a,b}, L. Fiore\textsuperscript{a}, A. Gelmi\textsuperscript{a,b}, G. Iselli\textsuperscript{a,c}, M. Ince\textsuperscript{a,b}, S. Lezki\textsuperscript{a,b}, G. Maggi\textsuperscript{a,c}, M. Maggi\textsuperscript{a}, G. Minelli\textsuperscript{a,b}, S. My\textsuperscript{a,b}, S. Nuzzo\textsuperscript{a,b}, A. Pompili\textsuperscript{a,b}, G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwilligen\textsuperscript{a}
INFN Sezione di Bologna $^a$, Università di Bologna $^b$, Bologna, Italy
G. Abbiendi$^a$, C. Battilana$^a,b$, D. Bonacorsi$^a,b$, L. Borgonovi$^a,b$, S. Braibant-Giacomelli$^a,b$, R. Campanini$^a,b$, P. Capiluppi$^a,b$, A. Castro$^a,b$, F.R. Cavallo$^a$, S.S. Chhibra$^a,b$, G. Codispoti$^a,b$, M. Cuffiani$^a,b$, G.M. Dallavalle$^a$, F. Fabbri$^a$, A. Fanfani$^a,b$, E. Fontanesi, P. Giacomelli$^a$, C. Grandi$^a$, L. Guiducci$^a,b$, F. Iemmi$^a,b$, S. Lo Meo$^a,30$, S. Marcellini$^a$, G. Masetti$^a$, A. Montanari$^a$, F.L. Navarria$^a,b$, A. Perrotta$^a$, F. Primavera$^a,b$, A.M. Rossi$^a,b$, T. Rovelli$^a,b$, G.P. Siroli$^a,b$, N. Tosi$^a$

INFN Sezione di Catania $^a$, Università di Catania $^b$, Catania, Italy
S. Albergo$^{a,b,31}$, A. Di Mattia$^a$, R. Potenza$^a,b$, A. Tricomi$^{a,b,31}$, C. Tuve$^a,b$

INFN Sezione di Firenze $^a$, Università di Firenze $^b$, Firenze, Italy
G. Barbari$^a$, K. Chatterjee$^{a,b}$, V. Ciulli$^{a,b}$, C. Civinini$^a$, R. D’Alessandro$^{a,b}$, E. Focardi$^{a,b}$, G. Latino, P. Lenzi$^{a,b}$, M. Meschini$^a$, S. Paoletti$^a$, L. Russo$^{a,32}$, G. Sguazzoni$^a$, D. Strom$^a$, L. Viliani$^a$

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova $^a$, Università di Genova $^b$, Genova, Italy
F. Ferro$^a$, R. Mulargia$^{a,b}$, E. Robutti$^a$, S. Tosi$^{a,b}$

INFN Sezione di Milano-Bicocca $^a$, Università di Milano-Bicocca $^b$, Milano, Italy
A. Benaglia$^a$, A. Beschi$^b$, F. Brivio$^{a,b}$, V. Ciriolo$^{a,b,17}$, S. Di Guida$^{a,b,17}$, M.E. Dinardo$^a,b$, S. Fiorendi$^{a,b}$, S. Gennai$^a$, A. Ghizzi$^{a,b}$, P. Govoni$^{a,b}$, M. Malberti$^{a,b}$, S. Malvezzi$^a$, D. Menasce$^a$, F. Monti, L. Moroni$^a$, M. Paganoni$^a$, D. Pedrini$^a$, S. Ragazzi$^a$, T. Tabarelli de Fatis$^{a,b}$, D. Zuolo$^a,b$

INFN Sezione di Napoli $^a$, Università di Napoli ‘Federico II’ $^b$, Napoli, Italy, Università della Basilicata $^c$, Potenza, Italy, Università G. Marconi $^d$, Roma, Italy
S. Buontempo$^a$, N. Cavallo$^{a,c}$, A. De Iorio$^b$, A. Di Crescenzo$^b$, F. Fabozzi$^{a,c}$, F. Fienga$^a$, G. Galati$^a$, A.O.M. Iorio$^{a,b}$, L. Lista$^a$, S. Meola$^{a,d,17}$, P. Paolucci$^{a,17}$, C. Sciacca$^a$, B. Voevodina$^a$

INFN Sezione di Padova $^a$, Università di Padova $^b$, Padova, Italy, Università di Trento $^c$, Trento, Italy
P. Azzi$^a$, N. Bacchetta$^a$, D. Bisello$^{a,b}$, A. Boletti$^{a,b}$, A. Bragagnolo, R. Carlin$^{a,b}$, P. Checchia$^a$, M. Dall’Osso$^{a,b}$, P. De Castro Manzano$^a$, T. Dorigo$^b$, U. Dosselli$^a$, F. Gasparini$^{a,b}$, U. Gasparini$^{a,b}$, A. Gozzelino$^a$, S.Y. Hoh, S. Lacaprara$^a$, P. Lujan, M. Marogna$^a$, A.T. Meneguzzo$^{a,b}$, J. Pazzini$^{a,b}$, M. Presilla$^a$, P. Ronchese$^{a,b}$, R. Rossin$^{a,b}$, F. Simonetto$^{a,b}$, A. Tiko, E. Torassa$^a$, M. Tosi$^a$, M. Zanetti$^{a,b}$, P. Zotto$^{a,b}$, G. Zumerle$^{a,b}$

INFN Sezione di Pavia $^a$, Università di Pavia $^b$, Pavia, Italy
A. Braghieri$^a$, A. Magnani$^a$, P. Montagna$^{a,b}$, S.P. Ratti$^{a,b}$, V. Re$^a$, M. Ressogotti$^{a,b}$, C. Riccardi$^{a,b}$, P. Salvini$^a$, I. Vai$^{a,b}$, P. Vitulo$^{a,b}$

INFN Sezione di Perugia $^a$, Università di Perugia $^b$, Perugia, Italy
M. Biasini$^{a,b}$, G.M. Bilei$^a$, C. Cecchi$^{a,b}$, D. Ciangottini$^{a,b}$, L. Fanò$^{a,b}$, P. Lariccia$^{a,b}$, R. Leonard$^{a,b}$, E. Manoni$^a$, G. Mantovani$^a,b$, V. Marian$^{a,b}$, M. Menichelli$^a$, A. Rossi$^{a,b}$, A. Santocchia$^{a,b}$, D. Spiga$^a$

INFN Sezione di Pisa $^a$, Università di Pisa $^b$, Scuola Normale Superiore di Pisa $^c$, Pisa, Italy
K. Androsov$^a$, P. Azzurri$^a$, G. Bagliesi$^a$, L. Bianchini$^a$, T. Boccali$^a$, L. Borrello, R. Castaldi$^a$, M.A. Ciocci$^{a,b}$, R. Dell’Orso$^a$, G. Fedi$^a$, F. Fiorini$^{a,c}$, L. Giannini$^{a,c}$, A. Giassi$^a$, M.T. Grippo$^a$, F. Ligabue$^{a,c}$, E. Manca$^{a,c}$, G. Mandorli$^{a,c}$, A. Messineo$^{a,b}$, F. Palla$^a$, A. Rizzi$^{a,b}$, G. Rolandi$^{33}$, A. Scribano$^a$, P. Spagnolo$^a$, R. Tenchini$^a$, G. Tonelli$^{a,b}$, A. Venturi$^a$, P.G. Verdini$^a$
INFN Sezione di Roma $^a$, Sapienza Università di Roma $^b$, Rome, Italy
L. Barone$^{a,b}$, F. Cavallari$^a$, M. Cipriani$^{a,b}$, D. Del Re$^{a,b}$, E. Di Marco$^{a,b}$, M. Diemoz$^a$, S. Gelli$^{a,b}$, E. Longo$^{a,b}$, B. Marzocchi$^{a,b}$, P. Meridiani$^a$, G. Organtini$^{a,b}$, F. Pandolfi$^a$, R. Paramatti$^{a,b}$, F. Preiat$o^{a,b}$, C. Quaranta$^{a,b}$, S. Rahatlou$^{a,b}$, C. Rovelli$^a$, F. Santanastasio$^{a,b}$

INFN Sezione di Roma $^a$, Sapienza Università di Roma $^b$, Rome, Italy, Università del Piemonte Orientale $^c$, Novara, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, N. Bartosik$^a$, R. Bellan$^{a,b}$, C. Biino$^a$, A. Cappati$^{a,b}$, N. Cartiglia$^a$, F. Cenna$^{a,b}$, S. Cometti$^a$, M. Costa$^{a,b}$, R. Covarelli$^{a,b}$, N. Demaria$^a$, B. Kiani$^{a,b}$, C. Mariotti$^a$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, E. Monteil$^{a,b}$, M. Monteno$^a$, M.M. Obertino$^{a,b}$, L. Pacher$^{a,b}$, N. Pastrone$^a$, M. Pelliccioni$^a$, G.L. Pinna Angioni$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, R. Salvatico$^{a,b}$, K. Shchelina$^{a,b}$, V. Sola$^a$, A. Solano$^{a,b}$, D. Soldi$^{a,b}$, A. Staiano$^a$

INFN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy
S. Belforte$^a$, V. Candelise$^{a,b}$, M. Casarsa$^a$, F. Cossutti$^a$, A. Da Rold$^{a,b}$, G. Della Ricca$^{a,b}$, F. Vazzoler$^{a,b}$, A. Zanetti$^a$

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

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$^{34}$, T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

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

Riga Technical University, Riga, Latvia
V. Veckalns$^{35}$

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z.A. Ibrahim, M.A.B. Md Ali$^{36}$, F. Mohamad Idris$^{37}$, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli
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 Cruz38, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

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

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

University of Montenegro, Podgorica, Montenegro
N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bartolomeu, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
V. Alexakhin, P. Bunin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, I. Kashunin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev40,41, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Voytishin, B.S. Yuldashev42, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim43, E. Kuznetsova44, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermen, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, A. Shabanov, D. Tlisov, A. Toropin
Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, 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, S. Polikarpov, E. Popova, V. Rusinov

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

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

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

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

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

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
C. Albajar, J.F. deTrocóniz

Universidad Autónoma de Madrid, Madrid, Spain
C. Alvizcarr, J.M. de Tovar

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA)
J. Cuevas, C. Erice, I. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. Gonzalez Fernandez, 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. Fernandez Manteca, A. Garcia Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto,
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, Ö. Özçelik, S. Ozkorucuklu, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, 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
F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash, A. Nikitenko, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

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, O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir, R. Syarif, E. Usai, D. Yu
University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

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

Florida State University, Tallahassee, USA
T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D’Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mergin, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch
University of Minnesota, Minneapolis, USA
A.C. Benvenuti1, R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

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

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

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko40, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

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

Princeton University, Princeton, USA
S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

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

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

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

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus
Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

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

Texas A&M University, College Station, USA
O. Bouhali, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, S. Luo, D. Marley, R. Mueller, D. Overton, L. Pernié, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

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

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
3: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
7: Also at University of Chinese Academy of Sciences, Beijing, China
8: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
9: Also at Joint Institute for Nuclear Research, Dubna, Russia
10: Also at Helwan University, Cairo, Egypt
11: Now at Zewail City of Science and Technology, Zewail, Egypt
12: Also at Suez University, Suez, Egypt
13: Now at British University in Egypt, Cairo, Egypt
14: Also at Fayoum University, El-Fayoum, Egypt
15: Also at Purdue University, West Lafayette, USA
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
61: Also at Ozyegin University, Istanbul, Turkey
62: Also at Izmir Institute of Technology, Izmir, Turkey
63: Also at Marmara University, Istanbul, Turkey
64: Also at Kafkas University, Kars, Turkey
65: Also at Istanbul University, Istanbul, Turkey
66: Also at Istanbul Bilgi University, Istanbul, Turkey
67: Also at Hacettepe University, Ankara, Turkey
68: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
69: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
70: Also at Monash University, Faculty of Science, Clayton, Australia
71: Also at Bethel University, St. Paul, USA
72: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
73: Also at Bingol University, Bingol, Turkey
74: Also at Sinop University, Sinop, Turkey
75: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
76: Also at Texas A&M University at Qatar, Doha, Qatar
77: Also at Kyungpook National University, Daegu, Korea
78: Also at University of Hyderabad, Hyderabad, India