Search for light Higgs bosons from supersymmetric cascade decays in pp collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration

CERN, 1211 Geneva 23, Switzerland

Received: 28 April 2022 / Accepted: 1 July 2022 / Published online: 6 July 2023
© CERN for the benefit of the CMS collaboration 2023

Abstract A search is reported for pairs of light Higgs bosons ($H_1$) produced in supersymmetric cascade decays in final states with small missing transverse momentum. A data set of LHC pp collisions collected with the CMS detector at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 138 fb$^{-1}$ is used. The search targets events where both $H_1$ bosons decay into $b\bar{b}$ pairs that are reconstructed as large-radius jets using substructure techniques. No evidence is found for an excess of events beyond the background expectations of the standard model (SM). Results from the search are interpreted in the next-to-minimal supersymmetric extension of the SM, where a “singlino” of small mass leads to squark and gluino cascade decays that can predominantly end in a highly Lorentz-boosted singlet-like $H_1$ and a singlino-like neutralino of small transverse momentum. Upper limits are set on the product of the squark or gluino pair production cross section and the square of the $b\bar{b}$ branching fraction of the $H_1$ in a benchmark model containing almost mass-degenerate gluinos and light-flavour squarks. Under the assumption of an SM-like $H_1 \rightarrow b\bar{b}$ branching fraction, $H_1$ bosons with masses in the range 40–120 GeV arising from the decays of squarks or gluinos with a mass of 1200–2500 GeV are excluded at 95% confidence level.

1 Introduction

This paper presents a search for pairs of light Higgs bosons ($H_1$) produced in supersymmetric (SUSY) [1–8] cascade decays in final states with small missing transverse momentum ($p_T^{\text{miss}}$). Such events can arise from the pair production of squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) in the next-to-minimal supersymmetric extension of the standard model (SM) [9] when the lightest SUSY particle (LSP) is a singlino-like neutralino ($\tilde{\chi}_S^0$) of small mass [10]. The $\tilde{\chi}_S^0$ mass eigenstate is dominated by the singlino component and has only small couplings to other SUSY particles, suppressing direct squark or gluino decays to the $\tilde{\chi}_S^0$. Squarks and gluinos decay via the next-to-LSP $\tilde{\chi}_2^0$ into a $\tilde{\chi}_S^0$ and a Higgs, Z, or W boson [10,11]. The case of a singlet-like $CP$-even $H_1$, shown in Fig. 1, is the focus of this search. When the $\tilde{\chi}_S^0$ has a far smaller mass than the $H_1$ and the phase space for the decay $\tilde{\chi}_2^0 \rightarrow H_1 + \tilde{\chi}_S^0$ is small, the $H_1$ carries much larger momentum than the $\tilde{\chi}_S^0$. In such $p_T^{\text{miss}}$-suppressed scenarios, the key signature for the pair production of squarks and gluinos is a pair of Lorentz-boosted $H_1$ bosons.

This search targets events with two highly boosted $H_1$ bosons that decay into $b\bar{b}$ pairs that are reconstructed as large-radius jets using substructure techniques. This is the first search at the LHC to focus on this type of event, where particles invisible to the detector have only small transverse momentum ($p_T$) and therefore the events are not selected by searches requiring significant $p_T^{\text{miss}}$ [10,12]. Previous searches by the ATLAS and CMS experiments with similar final states have considered events with two boosted SM Higgs bosons and large values of $p_T^{\text{miss}}$ [13,14], or two SM Higgs bosons in resolved final states where each of the four $b$ quarks is reconstructed as a separate jet, with either small [15] or large [14–17] values of $p_T^{\text{miss}}$. This search uses data from

---

* e-mail: cms-publication-committee-chair@cern.ch

---

Fig. 1 Diagram of squark pair production and subsequent cascade decay in the benchmark signal model. The particle $\tilde{\chi}_2^0$ is the next-to-LSP, $\tilde{\chi}_S^0$ is the singlino-like LSP, and $H_1$ is the $CP$-even singlet-like Higgs boson
pp collisions collected by the CMS detector at $\sqrt{s} = 13$ TeV during 2016–2018, corresponding to an integrated luminosity of 138 fb$^{-1}$ [18–20].

2 Benchmark signal model

A benchmark signal model is established following the work of Ellwanger and Teixeira [10,11]. The eight first- and second-generation squarks are assumed mass-degenerate at the mass $m_{\text{SUSY}}$, and the gluino mass is set at 1% larger. The small gluino-squark mass gap means that the kinematics of the final-state particles are very similar in the $q\bar{q}$, $qg$, and $gg$ production modes, as little momentum is transferred to the quark in the $g \rightarrow q + q$ decay. All SUSY particles other than gluinos and those shown in Fig. 1 are assumed decoupled.

This search targets squarks and gluinos with $m_{\text{SUSY}} > 1200$ GeV. Less massive squarks and gluinos can be probed by $p_T^{\text{miss}}$-based searches, owing to their larger pair-production cross sections [12]. Smaller $m_{\text{SUSY}}$ values can also lead to smaller $p_T$ of the H1 than is necessary for the $b\bar{b}$ pair to be merged in a single jet. The cross sections ($\sigma$) for the signal probed in this search, calculated at next-to-leading order (NLO) accuracy in the strong coupling constant ($\alpha_{\text{S}}$) including approximate next-to-NLO (NNLO) corrections and next-to-next-to-leading logarithmic (NNLL) soft gluon corrections [21–29], are shown in Table 1.

The values considered of the H1 mass ($m_{\text{H1}}$) and the corresponding $H_1 \rightarrow b\bar{b}$ branching fractions ($B$) are shown in Table 2. Only events where both H1 bosons decay into b\bar{b} pairs are used as signal. The B values are chosen to be those of an SM-like Higgs boson ($H_{\text{SM}}$) of the corresponding mass [10], as calculated using HDECAY 6.61 [30,31]. The $B$ values decrease for larger H1 masses as the virtual WW$^*$ and ZZ$^*$ decay channels, both of which have sizeable leptonic branching fractions, become more accessible. The region $m_{\text{H1}} < m_Z$ is therefore where the $p_T^{\text{miss}}$-suppressed all-jet signature is of greatest experimental importance. Nevertheless, to preserve generality, this search attempts to probe as much of the region $m_{\text{H1}} < 125$ GeV as possible.

In addition to $m_{\text{H1}}$ and $m_{\text{SUSY}}$, there are two other unknown masses in the benchmark model: those of the $\tilde{\chi}_0^0$ and the $\tilde{\chi}_2^0$. The corresponding degrees of freedom are parameterised by $R_m \equiv m_{\text{H1}}/m_{\tilde{\chi}_2^0}$ and $\Delta m \equiv m_{\tilde{\chi}_2^0} - m_{\text{H1}} - m_{\tilde{\chi}_0^0}$. The $p_T^{\text{miss}}$-suppressed signature arises for values of $R_m$ close to 0, corresponding to $\tilde{\chi}_2^0$ decay. In this case, the phase space for the $\tilde{\chi}_2^0$ decay is small and the $\tilde{\chi}_S^0$ has much smaller mass than the H1, so the $\tilde{\chi}_S^0$ always carries much less momentum than the H1. The $p_T^{\text{miss}}$-suppressed signature probed in this search is representative of a significant part of the model parameter space since the momenta of reconstructed objects do not exhibit a strong dependence on $R_m$ and $\Delta m$ in the region $R_m \approx 0.9$. Models with smaller $R_m$ can be probed by $p_T^{\text{miss}}$-based searches [10,12]. For the benchmark model, the values $R_m = 0.99$ and $\Delta m = 0.1$ GeV are assumed.

Branching fractions of unity are assumed for the decays $\tilde{q} \rightarrow q + \tilde{\chi}_2^0$ and $\tilde{\chi}_2^0 \rightarrow H_1 + \tilde{\chi}_S^0$. In the $R_m$ and $\Delta m$ region of the benchmark model, this is true except where $m_{\tilde{\chi}_2^0} > m_Z + m_{\tilde{\chi}_0^0}$. In that case, the $\tilde{\chi}_2^0 \rightarrow Z + \tilde{\chi}_S^0$ decay is permitted if the $\tilde{\chi}_2^0$ has a higgsino component [11]. However, the $\tilde{\chi}_2^0$ is expected to be mainly bino-like for relevant values of its mass [10]. For configurations where the H1 mass is close to that of the HSM, the decay $\tilde{\chi}_2^0 \rightarrow H_{\text{SM}} + \tilde{\chi}_S^0$ is also possible. The signatures for such H1 and HSM bosons are indistinguishable in this search. The assumption that the branching fraction for $\tilde{\chi}_2^0 \rightarrow H_1 + \tilde{\chi}_S^0$ decay is 100% can therefore be relaxed to the assumption that the branching fractions to H1 and HSM sum to unity.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. 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, reside within the solenoid volume. Forward calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. 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 fixed latency of about 4 $\mu$s [32]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimised

Table 1 Inclusive pair-production cross sections calculated at approximately NNLO and NNLL in $\alpha_S$ [21–29] for squark mass $m_{\text{SUSY}}$ and gluino mass 1% larger. The quoted uncertainty is obtained from variations in the choice of scales, parton distribution functions, and $\alpha_S$

| $m_{\text{SUSY}}$ (GeV) | $\sigma(pp \rightarrow \tilde{q}\tilde{\bar{q}}, \tilde{g}\tilde{g}, \tilde{g}\tilde{\bar{g}})$ [fb] | Uncertainty (%) |
|---------------------------|----------------------------------|-----------------|
| 1200                      | 580                              | 8               |
| 1600                      | 69                               | 9               |
| 2000                      | 10                               | 11              |
| 2200                      | 4.1                              | 13              |
| 2400                      | 1.6                              | 14              |
| 2600                      | 0.67                             | 16              |
| 2800                      | 0.27                             | 18              |
for fast processing, and reduces the event rate to around 1 kHz before data storage [33]. A more detailed description of the CMS detector, together with a definition of the coordinate system and the kinematic variables, can be found in Ref. [34].

4 Event simulation

The primary background in this search originates from multijet production. Simulated multijet events are used to validate the multijet background estimation based on data (described in Sect. 6), but are not used for any of the final predictions. The remaining significant background is from events with vector bosons that decay into quark–antiquark pairs. Simulated events are used to determine the contributions from tt, Z+jets, and W+jets production. The expected yields from all other SM sources of background are found to be negligible.

The multijet, Z+jets, and W+jets processes are simulated at leading order (LO) in perturbative quantum chromodynamics (QCD) using MadGraph5_aMC@NLO 2.4.2 [35] with up to four additional partons at the matrix element (ME) level. Simulated signal events for each pair of mH1, and mSUSY values of the benchmark model are generated at LO at the ME level with up to one additional parton using MadGraph5_aMC@NLO 2.3.3. The MLM [36] prescription is used to match partons from the LO ME calculations to those from the parton showers. Simulated tt events are produced at NLO in QCD at the ME level with the POWHEG v2.0 [37–40] generator. The NNPDF2.3, NNPDF3.0, and NNPDF3.1 [41–44] parton distribution functions (PDFs) are used for the signal, 2016 background, and 2017–2018 background simulations, respectively. The parton shower and hadronisation are performed via PYTHIA 8.2 [45]. The CUETP8M1 [46,47] tune is used for the signal and 2016 background simulations, while the CP5 tune [48] is used for the 2017 and 2018 background simulations. The cross section used to normalise the tt simulation is calculated at NNLO+NNLL in QCD [49], and those for Z+jets and W+jets are calculated at NNLO in QCD [50–52]. Additional pp interactions within the same or nearby bunch crossings (pileup) are simulated for all events according to the distribution of the number of interactions observed in each bunch crossing [53]. The interactions of particles with the CMS detector are simulated using GEANT4 [54].

5 Object reconstruction and event selection

The data are collected using triggers based on the scalar sum of jet pT (HT), with a requirement of HT > 900 GeV (2016) and HT > 1050 GeV (2017 and 2018). Events are reconstructed offline using a particle-flow (PF) algorithm [55] that reconstructs and identifies each individual particle (PF candidate) in an event using an optimised combination of information from the components of the CMS detector.

Jets are reconstructed by clustering the PF candidates using the anti-kt clustering algorithm [56], as implemented in the FASTJET package [57]. A distance parameter of 0.4 or 0.8 is used for standard- and large-radius jets, referred to as AK4 and AK8 jets, respectively. The jet momentum is defined as the vectorial sum of all particle momenta in the jet. To mitigate the effect of pileup, constituent charged PF candidates identified to be originating from vertices other than the primary pp interaction vertex are not used in the clustering algorithm. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4 of Ref. [58]. For AK4 jets, an offset correction is applied to correct for remaining pileup contributions. For AK8 jets, the pileup-per-particle identification algorithm [59,60] is used to rescale the momenta of constituent neutral particles according to the probability they originated from the primary vertex. This probability is based on a local shape variable that distinguishes between collinear and soft diffuse distributions of the surrounding charged particles that are compatible with the primary vertex. For all jets, jet energy corrections are derived from simulation to bring the measured average response of jets to that of particle-level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multi-jet events are used to account for any residual differences in jet energy scale and resolution between data and simulation [61,62]. Additional criteria are imposed to reject jets from spurious sources, such as electronics noise and detector malfunctions [63,64].

The identification of AK8 jets originating from two collimated b quarks (double-b tagging) is integral to the reconstruction of the H1. A discriminant is calculated for each jet using a double-b tagging algorithm that combines tracking and vertexing information in a multivariate approach with no strong dependence on jet mass or pT [65].

The event preselection requires two AK8 jets with pT > 170 GeV and |η| < 2.4 (so that they are within the acceptance of the tracker). If there are more than two candidate

| mH1 [GeV] | 30 | 35 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 125 |
|-----------|----|----|----|----|----|----|----|----|-----|-----|-----|-----|
| B(H1 → bb) | 0.86 | 0.86 | 0.86 | 0.86 | 0.85 | 0.84 | 0.83 | 0.81 | 0.79 | 0.75 | 0.65 | 0.58 |
AK8 jets, the two with the largest double-b tag discriminants are selected as most likely to have originated from $H_1 \rightarrow b\bar{b}$ decays. For the offline analysis, $H_T$ is defined as the scalar $p_T$ sum of all AK4 jets with $p_T > 40$ GeV and $|\eta| < 3.0$, including AK4 jets with PF candidates clustered into AK8 jets. The $H_T$ distributions for various simulated signal and background processes are shown in Fig. 2, after implementing all preselection requirements. Since the final state contains only jets, the average signal event $H_T$ depends significantly on $m_{\text{SUSY}}$, and signal events with $m_{\text{SUSY}} > 1200$ GeV tend to have $H_T > 1500$ GeV.

Additional requirements based on the expected kinematic properties of signal events are applied after the preselection. They define the kinematic event selection:

1. Both selected AK8 jets must have $p_T > 300$ GeV and $|\eta| < 2.4$, characteristic of the jets originating from $H_1 \rightarrow b\bar{b}$ decay in signal events.
2. There must be at least one AK4 jet with $p_T > 300$ GeV and $|\eta| < 3.0$, characteristic of the quarks from squark decays in signal events. Such jets must be separated by $\Delta R \equiv \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 1.4$ from both selected AK8 jets, to avoid being constructed from the same PF candidates.
3. The event $H_T$ must exceed 1500 GeV.

Although the offline $H_T$ resolution is better than that of the trigger-level variable, the offline $H_T$ threshold is comfortably above the trigger-level $H_T$ requirements. The trigger efficiency for this analysis is measured using events collected with a single muon trigger with a muon $p_T$ threshold between 24 and 27 GeV. The efficiency for each data-taking year is nearly 100%. For the 2018 data, the $|\eta|$ selection for the AK4 jets is reduced from 3.0 to 2.4 to avoid a region of the endcap electromagnetic calorimeters affected by large losses in crystal transparency, and therefore increased energy-equivalent electronics noise [66]. This change has a negligible effect on signal acceptance for all considered masses.

The fraction of signal events that satisfy the kinematic selection is essentially independent of $m_{H_1}$. It increases from about 60 to 80% as $m_{\text{SUSY}}$ increases from 1200 to 2000 GeV, after which it remains approximately constant.

5.1 Double-b tag based event selection

The two AK8 jets that are classified as the $H_1 \rightarrow b\bar{b}$ candidates in each event are randomly assigned the labels “A” and “B”. Their double-b tag discriminants define a two-dimensional (2D) parameter space, shown with simulated signal and multijet event distributions in Fig. 3. The signal events are expected to contain two $H_1 \rightarrow b\bar{b}$ decays and therefore accumulate in the region where both double-b tag discriminants are large. The signal-enhanced tag region (TR) is defined as the region where the sum of the two double-b tag discriminants exceeds 1.3, illustrated by the shaded triangle in Fig. 3. Two additional regions are defined in Fig. 3 for use in the multijet background estimation and validation: the control region (CR), a multijet-dominated region with negligible signal; and the validation region (VR), a more signal-like region where one of the two jets has a large double-b tag discriminant. The VR is defined sufficiently far from the TR for the signal contamination to be negligible.

About 50% of the signal events that satisfy the kinematic selection populate the TR, with variation at the level of ±10% across the $m_{H_1}$ and $m_{\text{SUSY}}$ parameter space considered. Since the multijet background is dominated by light-flavour quark and gluon initiated jets, only about 3% of these events populate the TR. For the $t\bar{t}$, $Z+jets$, and $W+jets$ backgrounds, the corresponding figures are 13, 6, and 3%, respectively.

5.2 Soft-drop mass based signal and sideband regions

In signal events, both selected AK8 jets are likely to originate from $H_1 \rightarrow b\bar{b}$ decays and therefore have a jet mass close to $m_{H_1}$. The multijet background has no resonant mass peak, while the other backgrounds are only expected to exhibit peaks near the known top quark and vector bosons masses, which means that an accurate reconstruction of the jet mass is important in distinguishing signal from background. The AK8 jet masses are evaluated using the “soft-drop” algorithm [67] (with a soft-drop threshold of $z_{\text{cut}} = 0.1$ and angular exponent of $\beta = 0$), in which wide-angle soft radiation is removed recursively from a jet. In signal events this algorithm achieves a relative jet mass resolution from 10% for $m_{H_1} = 125$ GeV to 20% for $m_{H_1} = 30$ GeV.
The soft-drop masses of the two AK8 jets define a 2D parameter space, shown in Fig. 4, in which 10 signal regions (S_i) and 10 sideband regions (U_j) are defined. The S_i contain events in which the two H_1-candidate jets have approximately the same soft-drop mass. The width of each S_i corresponds to about four times the experimental soft-drop mass resolution for the relevant simulated value of m_{H_1}.

The event distributions for a set of signal models with different m_{H_1} values are shown in Fig. 5, with the signal and sideband mass regions overlaid. The peaks in the signal distributions where one or both AK8 jets have a soft-drop mass close to zero result from a selected jet originating from a single parton or one of the H_1 → b̄b decays lying outside the acceptance of the jet reconstruction algorithm. The latter can happen when the angular separation of the b quarks exceeds the AK8 jet distance parameter, or when the ratio of the b quark p_T values is larger than 9 (such that the softer b quark would not satisfy the c_{cut} threshold in the soft-drop algorithm). For signal models with 40 < m_{H_1} < 125 GeV, ≈50% of the events that satisfy the kinematic and TR selection fall within any of the S_i. However, for m_{H_1} < 35 GeV the bulk of the distribution is lower in mass than S_1, leading to a rapid decrease in signal acceptance.

The distributions of background events are also shown in Fig. 5. The majority of multijet events contain at least one AK8 jet evaluated to have a small soft-drop mass, reflecting the characteristic one-prong structure of quark and gluon jets. After applying the kinematic and TR selection criteria, approximately 5% of multijet events fall within any of the S_i, with greater probability at small masses. For the vector boson and t̄t backgrounds the corresponding figures are 7 and 19%, respectively, concentrated in the S_i corresponding to masses between the W boson and top quark masses.

For each S_i there are two corresponding sideband regions, U_j, used for the multijet background estimation described in Sect. 6. The sideband regions U_1 have a triangular form to avoid the region of very small soft-drop masses, where the density from multijet events increases sharply.

5.3 Categorisation in H_T and expected yields

The selected events are classified according to three H_T categories: 1500–2500, 2500–3500, and above 3500 GeV. Each H_T category is divided into the 10 mass signal regions S_i defined in Fig. 4, resulting in a total of 30 search regions for each data-taking year. As can be seen in Fig. 6 for TR data summed over the three data-taking years, the search region yields can be visualised through a 30-bin histogram where bins 1–10 represent the S_i, in ascending order, for the first H_T category. The subsequent two sets of 10 bins represent the results for the second and third H_T categories. The primary background is from multijet events, estimated from data using the method described in Sect. 6. The expected contribution from t̄t events is also significant, particularly in the larger soft-drop mass regions populated by jets from hadronic top quark or W boson decays. The t̄t simulation is validated in a dedicated t̄t-enriched control region in data. In Fig. 4 this is the triangular region of the parameter space with both jet masses below 200 GeV and above the upper boundary of mass region 10. The yields from Z+jets and W+jets production are small in comparison. All expected SM backgrounds tend to exhibit small values of H_T compared to signal.
Fig. 5 The normalised distribution of events in the 2D soft-drop mass plane overlaid by the map of mass regions. The upper left, upper right, and middle left panels correspond to signal events for \( m_{\text{SUSY}} = 2000 \text{ GeV} \) and \( m_{H_1} \) values of 40, 70, and 125 GeV, respectively. The panels at middle right, lower left, and lower right correspond to simulated multijet, \( t\bar{t} \), and vector boson backgrounds, respectively. All events satisfy the TR requirement and the kinematic selection.

The distributions in signal events for \( m_{H_1} = 70 \text{ GeV} \) and \( m_{\text{SUSY}} = 1200, 2000 \) and 2800 GeV are also shown in Fig. 6. Although the production cross section decreases quickly with increasing \( m_{\text{SUSY}} \), the fraction of events in the larger \( H_T \) categories increases. Within each \( H_T \) category, the distribution of events in the 10 \( S_y \) bins is described by a peak with a width of about three bins, centred near the model value of \( m_{H_1} \).
6 Multijet background estimation from data

The mass sideband regions $U_i$ form a basis for using data to estimate the multijet background. The density of the multijet background is approximately uniform within each of the 10 mass regions (spanning $S_i$ and $U_i$ for each region $i$ illustrated in Fig. 4). Apart from $U_1$, each $U_i$ is constructed to have the same area as $S_i$ such that the corresponding multijet yields, respectively denoted $\hat{U}_i$ and $\hat{S}_i$, are approximately equal. The observed ratios of $S_i$ to $U_i$ yields, $F_i$, are measured in CR data. The $F_i$ factors are found to be close to unity except for the $F_1$ values which are approximately 1.5.

The multijet background in the TR is estimated independently for each signal region $S_i$:

$$\hat{S}_i^{\text{TR}} = F_i \hat{U}_i^{\text{TR}},$$

where $\hat{U}_i^{\text{TR}}$ is the observed TR yield in sideband region $U_i$ after subtracting the contributions from the other simulated backgrounds. In rare cases where the prediction $\hat{S}_i^{\text{TR}}$ is negative, it is set equal to zero.

Since the $F_i$ factors are measured and applied in different regions of double-$b$ tag discriminant space, any correlation between the soft-drop mass and the double-$b$ tag discriminant of AK8 jets can bias the prediction of Eq. (1). Using a sample of data satisfying an alternative kinematic event selection with the requirement for one or more AK4 jets inverted, the variation of $F_i$ between the TR and the CR is found to be less than 10%.

The overall accuracy of the multijet estimation is assessed through closure tests. First the method is applied to simulated multijet events in the TR where, within statistical uncertainties, the predicted yields are consistent with the simulated yields for each data-taking year. Second the method is applied in the multijet-dominated VR data (defined in Fig. 3) by making the appropriate modification to Eq. (1): $\hat{S}_i^{\text{VR}} = F_i \hat{U}_i^{\text{VR}}$. The resulting predicted and observed VR yields are consistent within uncertainties, as shown in Fig. 7. Based on the results of the closure tests, a systematic uncertainty of 15 (30%) is assigned in the lower two $H_T$ categories (upper $H_T$ category).

7 Systematic uncertainties

The simulated events for signal and the $t\bar{t}$, $Z$+jets, and $W$+jets backgrounds are affected by various systematic uncertainties. The efficiency for tagging (mistagging) a jet originating from two b quarks (a light-flavour quark or gluon) is corrected to match that observed in data [65]. The uncertainty in this correction corresponds to $\approx 10\%$ in the simulated signal and background yields. The uncertainties related to the jet energy corrections are applied to the jet properties in bins of $p_T$ and $\eta$. These uncertainties affect the event $H_T$, leading to an $\approx 4\%$ migration of events between adjacent $H_T$ categories.

The uncertainty in the soft-drop mass scale in simulation relative to data leads to a migration of events between adjacent $S_i$ and $U_i$ regions of up to 10%. The uncertainty in the simulated soft-drop mass resolution affects the widths of the simulated mass peaks. This effect is larger for signal models.
with small $m_{H_1}$ and can reduce the $S_i$ selection efficiency by up to 20%.

The systematic uncertainties are assumed to be fully correlated among the data-taking years except for the 2016 double-$b$ tagging uncertainties, which are assumed uncorrelated because the CMS pixel detector was upgraded prior to 2017 data-taking. Changing these correlation assumptions is found to have only a small effect on the final results. Systematic uncertainties related to integrated luminosity, pileup, PDFs, renormalisation and factorisation scales, modulation of initial-state radiation, and background cross sections were also evaluated, along with the statistical uncertainties in the simulation, and were found to make negligible contributions to the total uncertainty.

Systematic uncertainties in multijet yields arise from the systematic uncertainties in the $F_i$ factors. As described in Sect. 6, an uncertainty of 15% is applied to the $F_i$ in the lower two $H_T$ categories and 30% in the upper $H_T$ category, uncorrelated among different $F_i$. Except in the lowest $H_T$ category, the total uncertainty in the multijet yield is dominated by the statistical uncertainty in $\hat{U}_{i,TR}$.

8 Results

Binned maximum likelihood fits to the data in all 30 search regions $S_i$ for each data-taking year are carried out under background-only and signal+background hypotheses. The corresponding sideband regions $U_i$ are fitted simultaneously, thereby constraining the multijet contributions to the search region yields through Eq. (1). The likelihood functions are defined through the product of $90 \times 2$ Poisson distributions [68], one for each search region and one for each sideband region, with additional constraint terms for the “nuisance” parameters that account for the systematic uncertainties summarised in Sect. 7. Figure 8 compares the result of the background-only fit to the yields in the search regions for the combination of 2016, 2017, and 2018 data. There is no evidence for deviations of the data from the fitted background. The values and uncertainties of most nuisance parameters are unchanged in the fit, but the ones corresponding to the $F_i$ are constrained through Eq. (1) when the yields $\hat{S}_{i,TR}$ and $\hat{U}_{i,TR}$ are sufficiently large.

Signal+background fits are used to set 95% confidence level (CL) upper limits on the product $\sigma B^2$ for the mass points in the benchmark signal model. The limits are set using the modified frequentist CL$_s$ criterion [69,70], with the profile likelihood ratio as test statistic [68]. The observed and expected 95% CL upper limits on $\sigma B^2$ are shown in Fig. 9, as functions of $m_{H_1}$ for constant $m_{SUSY}$. The upper limits are weaker for models with $m_{H_1} < 35$ GeV, for which the signal-event distribution in the 2D soft-drop mass plane peaks outside the signal regions. The limits have no significant dependence on $m_{SUSY}$ for models with $m_{SUSY} > 2000$ GeV, whose signal events mostly populate the upper $H_T$ category (as shown in Fig. 6).

The $\sigma B^2$ upper limits are used in conjunction with the theoretical $\sigma$ and $B$ values from Sect. 2 to exclude ranges of masses in $m_{H_1}$ and $m_{SUSY}$ in the benchmark model. The observed 95% CL upper limits on $r$, the ratio of measured and theoretical values of $\sigma B^2$, are shown in Fig. 10, with the corresponding exclusion contours at $r = 1$. Masses $1200 < m_{SUSY} < 2500$ GeV are excluded within the range $40 < m_{H_1} < 120$ GeV. Expected exclusion contours for the background-only scenario agree within one standard deviation with the observed contours. In the region $110 < m_{H_1} < 125$ GeV, $B$ starts to decrease more quickly (as shown in Table 2), leading to a corresponding reduction in sensitivity. Most of the sensitivity at large $m_{SUSY}$ comes from the $H_T > 3500$ GeV region, where the statistical uncertainties in the observed yields are dominant over systematic uncertainties. This search does not explore the region outside of that shown in Fig. 10.

To aid reinterpretation of the search by reducing the model-dependence, limits evaluated using only the upper $H_T$ category are presented in Appendix A. Tabulated results are provided in the HEPData record for this analysis [71].

9 Summary

This paper presents a search for pairs of light Higgs bosons ($H_1$) produced in supersymmetric cascade decays. The targeted final states have small amounts of missing transverse momentum and two $H_1 \to b\bar{b}$ decays that are reconstructed.
as large-radius jets using substructure techniques. The search is based on data from pp collisions collected by the CMS experiment at $\sqrt{s} = 13$ TeV during 2016–2018, corresponding to an integrated luminosity of 138 $fb^{-1}$.

With no evidence found for an excess of events beyond the background expectations of the standard model (SM), the results are interpreted in the next-to-minimal supersymmetric extension of the SM (NMSSM), where a “singlino” of small mass leads to squark and gluino cascade decays that can predominantly end in a highly Lorentz-boosted singlet-like $H_1$ and a singlino-like neutralino of small transverse momentum.

Upper limits are set on the product of the production cross section and the square of the $b\bar{b}$ branching fraction of the $H_1$ for an NMSSM benchmark model with almost mass-degenerate gluinos and light-flavour squarks and branching fractions of unity for the cascade decays ending with the $H_1$. Under the assumption of an SM-like $H_1 \rightarrow b\bar{b}$ branching fraction, $H_1$ bosons with masses in the range 40–120 GeV arising from the decays of squarks or gluinos with a mass of 1200 to 2500 GeV are excluded at 95% confidence level.

Data Availability Statements This manuscript has no associated data or the data will not be deposited. [Authors’ comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=6032&filename=CMSDataPolicyV1.2.pdf&version=2 CMSdatapreservation,re-useandopenaccesspolicy.]
A Simplified analysis for reinterpretation

To aid reinterpretation of the search, a simplified analysis is performed using only the 10 search regions in the upper $H_T$ category. The value $A_{\text{kin}}$ is defined as the product of acceptance and efficiency for a signal event to satisfy the kinematic selection (defined in Sect.5) and the $H_T > 3500$ GeV requirement. The value of $A_{\text{kin}}$ is common among all 10 search regions in the simplified analysis, and is quoted for the benchmark signal model in Table 3. Upper limits on the product $\sigma B^2 A_{\text{kin}}$ as a function of $m_{H_1}$ are set in Fig. 11, from which $\sigma B^2$ limits for different signal models can be derived through division by the appropriate value of $A_{\text{kin}}$. Since the upper $H_T$ category provides most of the sensitivity for $m_{\text{SUSY}} > 2000$ GeV in the nominal analysis, the $\sigma B^2$ upper limits in this region are not much weaker in the simplified analysis. This is not the case in the region $m_{\text{SUSY}} < 2000$ GeV, where the lower $H_T$ categories become important.

The double-b tag and mass region selections are not considered in $A_{\text{kin}}$. This is done for simplicity, and because the fraction of events satisfying these selections is not found to be strongly model-dependent (except for the dependence on $m_{H_1}$, which is accounted for explicitly in Fig. 11). For the benchmark model, this fraction is found to be independent of $m_{\text{SUSY}}$ within 10% in the region $1600 < m_{\text{SUSY}} < 2800$ GeV and $35 < m_{H_1} < 125$ GeV. This approximate independence does not hold for models with $m_{\text{SUSY}} < 1600$ GeV, where the $H_1$ $p_T$ distribution has substantial contributions below the $p_T$ necessary for the $H_1 \rightarrow b\bar{b}$ decay products to be merged in a single AK8 jet. Only models with typical $b\bar{b}$ angular separation $\Delta R < 0.8$ should be considered for reinterpretation.

| $m_{\text{SUSY}}$ [GeV] | 1600 | 2000 | 2200 | 2400 | 2600 | 2800 |
|-------------------------|------|------|------|------|------|------|
| $A_{\text{kin}}$        | 0.17 | 0.46 | 0.58 | 0.66 | 0.71 | 0.74 |

References

1. P. Ramond, Dual theory for free fermions. Phys. Rev. D 3, 2415 (1971). https://doi.org/10.1103/PhysRevD.3.2415
2. Y.A. Golfand, E.P. Likhtman, Extension of the algebra of Poincaré group generators and violation of P invariance. JETP Lett. 13, 323 (1971). http://jetpletters.ru/ps/1584/article_24309.pdf
3. A. Neveu, J.H. Schwarz, Factorizable dual model of pions. Nucl. Phys. B 31, 86 (1971). https://doi.org/10.1016/0550-3213(71)90448-2
4. D.V. Volkov, V.P. Akulov, Possible universal neutrino interaction. JETP Lett. 16, 438 (1972). http://www.jetpletters.ru/ps/1766/article_26864.pdf
5. J. Wess, B. Zumino, A Lagrangian model invariant under supergauge transformations. Phys. Lett. B 49, 52 (1974). https://doi.org/10.1016/0370-2693(74)90578-4
6. J. Wess, B. Zumino, Supergauge transformations in four dimensions. Nucl. Phys. B 70, 39 (1974). https://doi.org/10.1016/0550-3213(74)90355-1
7. P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino. Nucl. Phys. B 90, 104 (1975). https://doi.org/10.1016/0550-3213(75)90636-7
Institute of High Energy Physics, Beijing, China
E. Chapon, G. M. Chen, H. S. Chen, M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu, V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, Q. Li, X. Lyu, Y. Mao, S. J. Qian, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Shanghai, China
X. Gao, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, J. D. Ruiz Alvarez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski, H. Saka

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

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, S. Elgammal

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R. K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Erola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M. S. Kim, R. Kinnunen, T. Lampén

Springer
A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, M. Hajheidari, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, A. Mehta, A. Nigamova, K. J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, N. Faltermann, G. Giffels, J. O. Gosewisch, A. Gottmann, F. Hartmann, C. Heidecker, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H. J. Simonis, R. Ulrich, J. Van Der Linden, R. F. Von Cube, M. Wässmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, C. K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Koussouris, I. Paparkivopoulos, G. Tsiropolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Giannios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M. M. A. Gadallah, S. Lókös, S. Major, K. Mandal, G. Pásztor, A. J. Rádl, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók, G. Bencze, C. Hajdu, D. Horvath, F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, D. Fasanella, F. Fienga, J. Karancsi, J. Molnar, Z. Szillasi, D. Teyssier

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

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo, F. Nemes, T. Novak

Panjab University, Chandigarh, India
S. Bansal, S. B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhangra, R. Gupta, A. Kaur, H. Kaur, M. Kaur, P. Kumari, M. Meena, K. Sandeep, J. B. Singh, A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B. C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber, M. Maity, P. Palit, P. K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan

Indian Institute of Technology Madras, Madras, India
P. K. Behera, S. C. Behera, P. Kalbhor, J. R. Komaragiri, D. Kumar, A. Muhammad, L. Panwar, R. Pradhan, P. R. Pujahari, A. Sharma, A. K. Sikdar, P. C. Tiwari

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar
Cornell University, Ithaca, NY, USA
J. Alexander, S. Bright-Thonney, X. Chen, Y. Cheng, D. J. Cranshaw, S. Hogan, J. Monroy, J. R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, IL, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, L. A. T. Bauerick, D. Berry, J. Berryhill, P. C. Bhat, K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, K. F. Di Petrillo, J. Dickinson, V. D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R. M. Harris, R. Heller, T. C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K. H. M. Kwok, S. Lamml, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, V. Papadimitriou, K. Pedro, C. Pena, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, H. A. Weber

University of Florida, Gainesville, FL, USA
P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R. D. Field, D. Guerrero, B. M. Joshi, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K. H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, FL, USA
T. Adams, A. Askew, R. Habibullah, V. Hagopian, K. F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, FL, USA
M. M. Baarmand, S. Butalla, T. Elkafrawy, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, IL, USA
M. R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C. E. Gerber, D. J. Hofman, A. H. Merritt, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M. B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Ye

The University of Iowa, Iowa City, IA, USA
A. Alhusseini, K. Dilsiz, L. Emediato, R. P. Gandrajula, O. K. Köseyan, J.-P. Merlo, A. Mestvirishvili, J. Nachtman, H. Ogul, Y. Onel, A. Penzo, C. Snyder, E. Tiras

Johns Hopkins University, Baltimore, MD, USA
O. Amram, B. Blumenfeld, L. Cocoridilos, J. Davis, A. V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T. A. Vámi

The University of Kansas, Lawrence, KS, USA
A. Abreu, I. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, Q. Wang, Z. Warner, J. Williams, G. Wilson

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

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

University of Maryland, College Park, MD, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S. C. Enó, N. J. Hadley, S. Jabeen, R. G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A. C. Mignerey, S. Nabili, C. Palmer, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, MA, USA
D. Abercrombie, G. Andreassi, R. Bi, W. Busza, I. A. Cali, Y. Chen, M. D’Alfonso, J. Eysermans, C. Freer,
G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G. S. F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, MN, USA
R. M. Chatterjee, A. Evans, J. Hilbrand, Sh. Jain, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M. A. Wadud

University of Nebraska-Lincoln, Lincoln, NE, USA
K. Bloom, M. Bryson, S. Chauhan, D. R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, I. Reed, J. E. Siado, G. R. Snow, W. Tabb, A. Wightman, F. Yan, A. G. Zecchinelli

State University of New York at Buffalo, Buffalo, NY, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, MA, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Hortiangtham, A. Krishna, J. Li, J. Lidych, G. Madigan, B. Marzocchi, D. M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, IL, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K. A. Hahn, Y. Liu, N. Odell, M. H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, IN, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko, R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

The Ohio State University, Columbus, OH, USA
B. Bylsma, L. S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B. L. Winer, B. R. Yates

Princeton University, Princeton, NJ, USA
F. M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

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

Purdue University, West Lafayette, IN, USA
A. S. Bakshi, V. E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A. W. Jung, D. Kondratyev, A. M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J. F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, IN, USA
J. Dolen, N. Parashar

Rice University, Houston, TX, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K. M. Ecklund, S. Freed, P. Gardner, F. J. M. Geurts, A. Kumar, W. Li, B. P. Padley, R. Redjimi, J. Rotter, W. Shi, A. G. Stahl Leiton, S. Yang, L. Zhang, Y. Zhang

University of Rochester, Rochester, NY, USA
A. Bodek, P. de Barbaro, R. Demina, J. L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G. P. Van Onsem
7: Also at The University of the State of Amazonas, Manaus, Brazil
8: Also at University of Chinese Academy of Sciences, Beijing, China
9: Also at UFMS, Nova Andradina, Brazil
10: Also at Nanjing Normal University Department of Physics, Nanjing, China
11: Now at The University of Iowa, Iowa City, IA, USA
12: Also at University of Chinese Academy of Sciences, Beijing, China
13: Also at an institute or an international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
14: Also at Helwan University, Cairo, Egypt
15: Now at Zewail City of Science and Technology, Zewail, Egypt
16: Now at British University in Egypt, Cairo, Egypt
17: Also at Purdue University, West Lafayette, IN, USA
18: Also at Université de Haute Alsace, Mulhouse, France
19: Also at Ilia State University, Tbilisi, Georgia
20: Also at Erzincan Binali Yıldırım University, Erzincan, Turkey
21: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
22: Also at University of Hamburg, Hamburg, Germany
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Brandenburg University of Technology, Cottbus, Germany
25: Also at Forschungszentrum Jülich, Jülich, Germany
26: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyöngyös, Hungary
29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
31: Now at Universitatea Babes-Bolyai-Facultatea de Fizica, Cluj-Napoca, Romania
32: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
33: Also at Wigner Research Centre for Physics, Budapest, Hungary
34: Also at Punjab Agricultural University, Ludhiana, India
35: Also at UPES-University of Petroleum and Energy Studies, Dehradun, India
36: Also at Shoolini University, Solan, India
37: Also at University of Hyderabad, Hyderabad, India
38: Also at University of Visva-Bharati, Santiniketan, India
39: Also at Indian Institute of Science (IISc), Bangalore, India
40: Also at Indian Institute of Technology (IIT), Mumbai, India
41: Also at IIT Bhubaneswar, Bhubaneswar, India
42: Also at Institute of Physics, Bhubaneswar, India
43: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
44: Also at Sharif University of Technology, Tehran, Iran
45: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
46: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
47: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
48: Also at Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Naples, Italy
49: Also at Università di Napoli ‘Federico II’, Naples, Italy
50: Also at Consiglio Nazionale delle Ricerche-Istituto Officina dei Materiali, Perugia, Italy
51: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
52: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
53: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
54: Also at Trincomalee Campus, Eastern University, Nilaveli, Sri Lanka
55: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
56: Also at National and Kapodistrian University of Athens, Athens, Greece
57: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
58: Also at Universität Zürich, Zurich, Switzerland
59: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria

Springer
60: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
61: Also at Şırnak University, Şırnak, Turkey
62: Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
63: Also at Konya Technical University, Konya, Turkey
64: Also at Izmir Bakircay University, İzmir, Turkey
65: Also at Adiyaman University, Adiyaman, Turkey
66: Also at Necmettin Erbakan University, Konya, Turkey
67: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
68: Also at Marmara University, Istanbul, Turkey
69: Also at Milli Savunma University, Istanbul, Turkey
70: Also at Kafkas University, Kars, Turkey
71: Also at Istanbul Bilgi University, Istanbul, Turkey
72: Also at Hacettepe University, Ankara, Turkey
73: Also at Istanbul University-Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
74: Also at Ozyegin University, Istanbul, Turkey
75: Also at Vrije Universiteit Brussel, Brussels, Belgium
76: Also at Rutherford Appleton Laboratory, Didcot, UK
77: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
78: Also at IPPP Durham University, Durham, UK
79: Faculty of Science, Also at Monash University, Clayton, Australia
80: Also at Università di Torino, Turin, Italy
81: Also at Bethel University, St. Paul, MN, USA
82: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
83: Also at California Institute of Technology, Pasadena, CA, USA
84: Also at United States Naval Academy, Annapolis, MD, USA
85: Also at Ain Shams University, Cairo, Egypt
86: Also at Bingol University, Bingol, Turkey
87: Also at Georgian Technical University, Tbilisi, Georgia
88: Also at Sinop University, Sinop, Turkey
89: Also at Erciyes University, Kayseri, Turkey
90: Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Fudan University, Shanghai, China
91: Also at Texas A&M University at Qatar, Doha, Qatar
92: Also at Kyungpook National University, Daegu, Korea
93: Also at another institute or international laboratory covered by a cooperation agreement with CERN, Geneva, Switzerland
94: Now at Istanbul University, Istanbul, Turkey
95: Also at Yerevan Physics Institute, Yerevan, Armenia
96: Also at University of Florida, Gainesville, FL, USA
97: Also at Imperial College, London, UK
98: Now at University of Rochester, Rochester, NY, USA
99: Now at Baylor University, Waco, TX, USA
100: Now at INFN Sezione di Torino, Università di Torino, Turin, Italy, Università del Piemonte Orientale, Novara, Italy
101: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan