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Search for resonant pair production of Higgs bosons in the $\mathrm{b\bar{b}b\bar{b}}$ final state using large-area jets in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search is presented for the resonant production of a pair of standard model-like Higgs bosons using data from proton-proton collisions at a centre-of-mass energy of 13 TeV, collected by the CMS experiment at the CERN LHC in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. The final state consists of two b quark-antiquark pairs. The search is conducted in the region of phase space where at least one of the pairs is highly Lorentz-boosted and is reconstructed as a single large-area jet. The other pair may be either similarly merged or resolved, the latter reconstructed using two b-tagged jets. The data are found to be consistent with standard model processes and are interpreted as 95% confidence level upper limits on the product of the cross sections and the branching fractions of the spin-0 radion and the spin-2 bulk graviton that arise in warped extradimensional models. The limits set are in the range 9.74–0.29 fb and 4.94–0.19 fb for a narrow radion and a graviton, respectively, with masses between 1 and 3 TeV. For a radion and for a bulk graviton with widths 10% of their masses, the limits are in the range 12.5–0.35 fb and 8.23–0.23 fb, respectively, for the same masses. These limits result in the exclusion of a narrow-width graviton with a mass below 1.2 TeV, and of narrow and 10%-width radions with masses below 2.6, and 2.9 TeV, respectively.

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*See Appendix A for the list of collaboration members

1 Introduction

In proton-proton (pp) collisions at the CERN LHC, the standard model (SM) production of a pair of Higgs bosons [1–3] involves gluon fusion and an internal fermion loop dominated by the top quark, t. Its predicted cross section of $33.5^{+2.5}_{-2.8}$ fb at a centre-of-mass energy of 13 TeV [4–6], is too small to be observable with the current data. However, according to many models "beyond the SM" (BSM), other modes of Higgs boson pair production could exist, many involving the production of a massive BSM resonance X that then decays to a Higgs boson pair ($\mathrm{X} \to \mathrm{HH}$). Even for a resonance mass m_{X} too large for X to be directly produced in pp interactions at the LHC, the particle could manifest itself through off-shell effects, leading to anomalous couplings of the Higgs boson to SM particles, including the three-point HHH self-interaction [7]. Thus, BSM effects may modify the differential and integral HH production cross sections, making this process observable with current data.

Models with a warped extra dimension (WED), as proposed by Randall and Sundrum [8, 9], are among the BSM scenarios that predict the existence of resonances with large couplings to the SM Higgs boson, such as a spin-0 radion [10–12] and a spin-2 first Kaluza–Klein (KK) excitation of the graviton [13–15]. The WED models [16] postulate an additional spatial dimension l compactified between two four-dimensional hypersurfaces known as branes, with the region in between, the bulk, warped by an exponential metric κl, where κ is the warp factor. A value of $\kappa l \approx 35$ reproduces the mass hierarchy between the Planck scale M_{Pl} and the electroweak scale [8]. One of the parameters of the model is $\kappa/\overline{M}_{\mathrm{Pl}}$, where $\overline{M}_{\mathrm{Pl}} \equiv M_{\mathrm{Pl}}/\sqrt{8\pi}$. The ultraviolet cutoff scale of the model $\Lambda_{\mathrm{R}} \equiv \sqrt{6}\mathrm{e}^{-\kappa l}\overline{M}_{\mathrm{Pl}}$ [10] is another parameter, and its value is expected to be near the TeV scale.

Searches for HH production have been performed by the ATLAS [17–26] and CMS [27–38] Collaborations using LHC pp collision data at $\sqrt{s} = 8$ and 13 TeV.

A search for a KK bulk graviton or a radion decaying to HH in the $\mathrm{b\overline{b}b\overline{b}}$ final state was performed by CMS [37] using events with four separate b quark jets. A similar search targeting a higher m_{X} range, in which two large-area jets were used to reconstruct the highly Lorentz-boosted Higgs bosons has also been published by the CMS Collaboration [36]. The configuration of a Higgs boson candidate reconstructed as one large-area jet or as two separate narrow jets depends on its momentum [39].

In this paper, we improve upon the CMS search for a high-mass resonance ($1 \leq m_{\mathrm{X}} \leq 3$ TeV) decaying to $\mathrm{HH} \to \mathrm{b\overline{b}b\overline{b}}$ [38] by using data collected at $\sqrt{s} = 13$ TeV in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. We use the scenario of Ref. [40] to describe the KK graviton, where the propagation of SM fields is allowed in the bulk and follows the characteristics of the SM gauge group, with the right-handed top quark localized near the TeV brane. The theoretical values of $\sigma(\mathrm{pp} \to \mathrm{X})\mathcal{B}(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\overline{b}b\overline{b}})$ are calculated for various masses, using $\Lambda_{\mathrm{R}} = 3$ TeV for the radions and $\kappa/\overline{M}_{\mathrm{Pl}} = 0.5$ for the bulk gravitons. For these values of $\kappa/\overline{M}_{\mathrm{Pl}}$ and Λ_{R}, the branching fractions $\mathcal{B}(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\overline{b}b\overline{b}})$ are 10% and 23%, for the bulk graviton and the radion, respectively, for masses of 1 TeV and larger (cf. Figs. 4.5 and 4.10 from Ref. [41]).

Owing to the broad mass range explored, the $\mathrm{H} \to \mathrm{b\overline{b}}$ decay is studied using two analysis topologies. If m_{X} is large, both Higgs bosons are highly Lorentz-boosted and are reconstructed using large-area jets. These "fully-merged" events are then divided into two categories according to their purity. To identify the merged $\mathrm{H} \to \mathrm{b\overline{b}}$ decays, referred to henceforth as "H jets", we use a deep neural network jet classifier ("tagger") algorithm, described in Section 4. For resonances with masses in the intermediate range (0.8–1.5 TeV), the less energetic Higgs boson often does not produce a merged $b\overline{b}$ jet, and thus these events are reconstructed using one large-area jet and a combination of two separate b quark jets ("semi-resolved" category). The inclusion of the semi-resolved events leads to an improvement in the search sensitivity for resonances with m_X around 1 TeV.

The two dominant sources of the SM background are multijet production and top quark pair production in association with jets, referred to here as $t\overline{t}$+jets. Both backgrounds are estimated from data, but the procedure is assisted by simulations. To predict the multijet background, the events that fail the $H \to b\overline{b}$ identification of the leading-p_T jet are also used. To aid in the modelling of the $t\overline{t}$+jets background, two categories enriched in $t\overline{t}$+jets are defined in addition to three signal categories. For all five categories, each composed of two regions with events that pass and fail the $H \to b\overline{b}$ jet identification, the background estimation (described in Section 5) is based on a two-dimensional fit of the reconstructed resonance mass and the mass of the leading-p_T large-area jet. In this joint binned likelihood fit of ten regions the signal strength floats unconstrained, and the nuisance parameters governing the corrections to both multijet and $t\overline{t}$+jets backgrounds are floating within allowed ranges. Thus, the signal extraction and the entire background estimation are done simultaneously.

This paper is organized as follows: a brief description of the CMS detector is given in Section 2 followed by a description of event simulation in Section 3. The event selection criteria are defined in Section 4, and Section 5 describes the modelling of the major background processes. These are followed by Section 6 on the relevant sources of systematic uncertainty and their variations allowed by the fit. Finally, the results are presented in Section 7.

Tabulated results are provided in the HEPData record for this analysis [42].

2 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters, made of steel and quartz fibres, extend the pseudorapidity (η) 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. 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].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of 4 μs [44]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimised for fast processing, and reduces the event rate to around 1 kHz before data storage [45].

A particle flow (PF) algorithm [46] aims to reconstruct and identify each individual particle in an event (PF candidate), with an optimised combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the track momentum at the primary interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The momentum of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [47].

For each event, jets are clustered from these reconstructed particles using the anti-k_{T} algorithm [48, 49] with a distance parameter of 0.4 (AK4 jets) or 0.8 (AK8 jets). Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the whole transverse momentum (p_{T}) spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions [50, 51]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [52]. Additional selection criteria are applied to each jet to remove jets arising from instrumental effects or reconstruction failures [53]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [52].

3 Event simulation

Two scenarios of bulk graviton and radion signal events are considered: "narrow-width" signal shapes with a width of 1 MeV (much smaller than experimental resolution) and a "10%-width" where the width is set to 10% of the resonance mass. All signals are simulated at leading order (LO) in the mass range 1–3 TeV, using the MADGRAPH5_aMC@NLO event generator [54]; version 2.2.2 is used for the 2016 data-taking period, and 2.4.2 for 2017 and 2018. The NNPDF3.0 LO parton distribution function (PDF) set [55], taken from LHAPDF6 library [56–59], with the four-flavour scheme, is used for all signal samples. The parton shower and hadronization are simulated with PYTHIA 8.212 [60].

The dominant background consists of events composed primarily of jets (multijet events) arising from the SM quantum chromodynamics (QCD) interaction, and is modelled entirely from data. The $\mathrm{t\bar{t}}$+jets events comprise most of the remaining background and are generated at next-to-LO using POWHEG 2.0 [61–63] using NNPDF3.0 LO PDF set for 2016 data-taking period, and PDF4LHC15 next-to-next-to-LO PDF set [55, 56, 59, 64–66] to model data from 2017 and 2018. These events are showered by PYTHIA 8, using the CUETP8M2T4 tune [67, 68]. The $\mathrm{t\bar{t}}$+jets background rate is estimated using a next-to-next-to-LO cross section of 832^{+46}_{-52} pb [69], corresponding to the top quark mass of 172.5 GeV. A sample of multijet events from QCD interactions, simulated at LO using MADGRAPH5_aMC@NLO and PYTHIA 8, and NNPDF3.0 (for 2016) or PDF4LHC15 (for 2017 and 2018) is used to develop and validate the background estimation techniques prior to being applied to the data. Other background processes, such as WZ, $\mathrm{t\bar{t}}$Z or Z+jets production, are also considered but their yields are found to be negligible.

All generated samples are processed through a GEANT4-based [70, 71] simulation of the CMS detector. The effect of pileup, averaging 23–32 additional interactions per bunch crossing, for the LHC beam conditions between 2016 and 2018, is included in the simulations, and the samples are reweighted to match the distribution of the number of pp interactions observed in the data, assuming a total inelastic pp collision cross section of 69.2 mb [72].

4 Event selection

Collision events are selected using a logical OR of triggers based on the jet activity in the event. One trigger path requires that the p_T sum of all AK4 jets in the event (H_T) be greater than 800, 900, or 1050 GeV, depending on the data collection year and the LHC beam instantaneous luminosity. A second trigger path collects events with $H_T > 650$ GeV, and with a pair of AK4 jets that has invariant mass above 900 GeV and a pseudorapidity separation $|\Delta\eta| < 1.5$. A third trigger path accepts events if the p_T of the leading AK8 jet is greater than 360 or 400 GeV (depending on the data collection year) and the "trimmed mass" of an AK8 jet is above 30 GeV. The jet trimmed mass is obtained after removing remnants of soft radiation with the jet trimming technique [73], using a subjet size parameter of 0.3 and a subjet-to-AK8 jet p_T fraction of 0.1.

Collected events are split into three categories: one semi-resolved category and two fully-merged categories, further separated by purity. Since the background estimation uses the mass and the $H \rightarrow b\overline{b}$ jet tagger discriminant of the leading-p_T AK8 jet, the events are not preselected based on these variables. The AK8 jets are required to have $|\eta| < 2.4$, and $p_T > 300$ GeV. The fully-merged categories require two such AK8 jets (each representing a Higgs boson candidate), whereas the semi-resolved category requires only one, with the other Higgs boson reconstructed from a pair of b-tagged AK4 jets.

A resonant HH signal of high mass results in a small $|\Delta\eta|$ between the two Higgs bosons, while the multijet background often produces events with larger values of $|\Delta\eta|$. Events in the fully-merged category are therefore required to have $|\Delta\eta| < 1.3$ between the H candidate jets. The subleading AK8 jet is required to have its soft-drop mass, the jet mass that results from applying the soft-drop algorithm [74, 75], between 110–140 GeV, consistent with the Higgs boson mass, $m_H = 125$ GeV [76, 77]. The fully-merged selection is summarized in Table 1.

Table 1: Event selection criteria for the fully-merged topology.

Variable	Selection
Leading two AK8 jets	$p_T > 300$ GeV and $\|\eta\| < 2.4$
$\|\Delta\eta\|$	<1.3
Sub-leading AK8 jet soft-drop mass	$110 < m_{SD} < 140$ GeV
m_{HH}	>750 GeV

A deep neural network based tagger, "DeepAK8" [78], is used to identify the boosted $H \rightarrow b\overline{b}$ candidate jets. We use a "mass-decorrelated" version of this tagger, whose response has been trained to be nearly uniform with respect to the jet mass, enabling the use of this tagger in the background estimation procedure. The DeepAK8 tagger outperforms the "double-b" $H \rightarrow b\overline{b}$ tagger used previously [38], resulting in an increase of the sensitivity by a factor of $\approx$2.5 over the whole search domain.

The AK8 jets with DeepAK8 tagger discriminant above 0.8 are said to pass a "loose" criterion while those with the discriminant above 0.9 pass the "tight" criterion. The efficiency of the tight criterion for H jets from a 1500 GeV narrow radion signal is about 60%, with a misidentification probability of QCD jets of 1%. For jets that pass the loose but not tight criterion, the H jet efficiency is about 20%, with the misidentification probability of 2%. The fully-merged events are split into two signal regions based on the purity of the H candidate jets: events are categorized as either "tight-tight" (TT), where both AK8 jets satisfy the tight threshold, or as "loose-loose" (LL) otherwise. The LL region includes the events where one AK8 jet passes the tight criterion.

We denote the signal regions as "pass" regions. For the purpose of background estimation, for each signal region we also define a control region where the leading-p_T AK8 jet fails the tagging requirement; we denote them as "fail" regions, and define them separately for TT and LL categories. In defining the mutually exclusive TT and LL fail regions, we aim to model the signal regions with events that have the same criteria for the subleading jet, which makes them kinematically similar. The TT fail region (used to predict the background in the TT signal region) is defined by the leading-p_T H jet failing the loose tagger requirement, while the subleading-p_T H jet passes the tight DeepAK8 tagger requirement. Analogously, the LL fail region is defined by the leading H jet failing the loose criterion while the subleading passes it, but fails the tight one. A schematic diagram of these four regions is shown in Fig. 1. The TT selection corresponds to a signal efficiency of 7–11% for a narrow radion signal for masses m_X in the range 1–3 TeV, and slightly higher for the bulk graviton. The LL selection results in signal efficiencies of 3–4% over the same m_X domain.

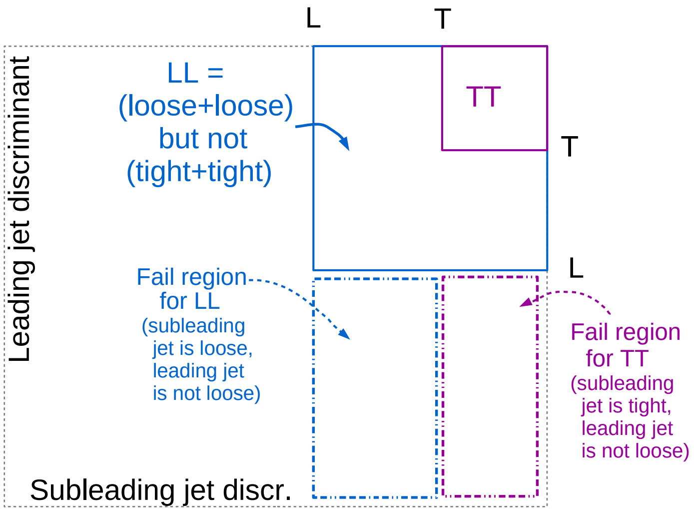

Figure 1: A diagram showing tight-tight (TT, purple) and loose-loose (LL, blue) pass regions (solid) and their corresponding fail regions (dash-dotted).

Two dedicated $t\bar{t}$+jets event control regions (each consisting of corresponding TT and LL events) are also used to correct the modelling of the $t\bar{t}$+jets background component for events with high jet p_T, for which the $t\bar{t}$ simulation does not agree with data. The $t\bar{t}$ control regions use the same selections as the TT and LL categories, except for a window on the soft-drop mass of the subleading-p_T jet, which is shifted from $110 < m_{SD} < 140$ to $140 < m_{SD} < 210$ GeV in order to correspond to the top quark mass.

Events that fail the fully-merged selection for either TT or LL category are considered in the semi-resolved selection. Jets for the semi-resolved category are required to have $|\eta| < 2.4$, and $p_T > 30$ GeV (300 GeV) for AK4 (AK8) jets.

To find a Higgs boson decay into two resolved b quark jets, all AK4 jets in each event are examined by the "DeepJet" algorithm [79, 80], which gives the probability for a jet to have originated from a bottom quark. DeepJet is a neural network trained using information from tracks and secondary vertices associated with the jet.

The DeepJet selection on AK4 jets uses the "medium" working point, which corresponds to a 1% mistag rate for gluon and light-flavoured quark jets. It results in a b tagging efficiency of about 70% for b quark jets in the p_{T} range 80–150 GeV, and decreasing to about 50% for $p_{\mathrm{T}} \approx 1000$ GeV. The b tagging efficiency in the simulation is corrected to match that in the data, using measurements of the b-tagging algorithm performance in a sample of muon-enriched jets and b jets from $\mathrm{t\bar{t}}$+jets events, with the correction factor ranging from 0.95 to 1.1.

Resolved $\mathrm{H} \to \mathrm{b\bar{b}}$ candidates are constructed by considering all pairs of b-tagged AK4 jets. Events are required to have least one pair where both AK4 jets (jets "j_2" and "j_3") are separated by $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.8$ (where ϕ is the azimuthal angle in radians) from the leading-p_{T} AK8 jet (jet "J_1") and are within $\Delta R < 1.5$ of each other. If several such pairs are found, the pair of jets j_2 and j_3 that has the highest sum of the AK4 jet DeepJet discriminant values is selected. The invariant mass of j_2 and j_3, $m_{\mathrm{j_2 j_3}}$, is required to be within 90–140 GeV, forming the resolved $\mathrm{H} \to \mathrm{b\bar{b}}$ candidate. The leading-p_{T} AK8 jet is then identified as the merged H candidate, and the pair of AK4 jets is identified as the resolved H candidate. If no resolved H candidate is found starting from the leading-p_{T} AK8 jet, then this process is repeated with the subleading-p_{T} AK8 jet as a merged H candidate. The event is rejected if a $\mathrm{H} \to \mathrm{b\bar{b}}$ pair is not found even in this case. As in the fully-merged regime, the events are required to have a pseudorapidity difference between the two H candidates $|\Delta\eta| < 1.3$.

In the semi-resolved category, the "pass" region is defined by the leading-p_{T} AK8 jet having a DeepAK8 tagger discriminant above 0.9, and the "fail" region below 0.9. The efficiency of the semi-resolved selection peaks at $\approx$3.5% around 1.2–1.4 TeV, depending on the signal, and rapidly falls at higher m_{X} masses. The requirements for the semi-resolved events are summarized in Table 2.

Table 2: Event selection criteria for the semi-resolved topology.

Variable	Selection
Leading AK8 jet	$p_{\mathrm{T}} > 300$ GeV and $\lvert\eta\rvert < 2.4$
AK4 jets	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 2.4$
$\lvert\Delta\eta\rvert$	< 1.3
DeepJet	Medium working point
Invariant mass of two AK4 jets	$90 < m_{\mathrm{j_2 j_3}} < 140$ GeV
m_{HH}	> 750 GeV

The main variable used in the search for an HH resonance is the "corrected HH mass". For the fully-merged categories it is defined as $m_{\mathrm{HH}} \equiv m_{\mathrm{JJ}} + (m_{\mathrm{H}} - m_{\mathrm{J_1}}) + (m_{\mathrm{H}} - m_{\mathrm{J_2}})$, where m_{JJ} is the dijet invariant mass, $m_{\mathrm{J_1}}$ and $m_{\mathrm{J_2}}$ are the soft-drop masses of the leading and subleading candidate H jets in the event, and $m_{\mathrm{H}} = 125$ GeV is the nominal Higgs boson mass. In the semi-resolved analysis, this quantity is defined by $m_{\mathrm{HH}} \equiv m_{\mathrm{Jjj}} + (m_{\mathrm{H}} - m_{\mathrm{J_1}}) + (m_{\mathrm{H}} - m_{\mathrm{j_2 j_3}})$, where m_{Jjj} is the invariant mass of the three jets comprising a semi-resolved HH candidate. The corrected HH mass is used rather than the invariant mass of the two reconstructed H candidates because effects due to fluctuations in jet reconstruction or to missing p_{T} associated with a neutrino from a b quark decay are correlated between the H jet mass and the invariant mass of the HH system. Adjusting the $\mathrm{H} \to \mathrm{b\bar{b}}$ candidates to the nominal H mass improves our estimate of the HH invariant mass. Using the corrected HH mass leads to an 8–10% improvement in the invariant jet mass resolution [36]. A requirement of $m_{\mathrm{HH}} > 750$ GeV is applied for selecting signal-like events because of trigger turn-on effects.

5 Background model

The background is dominated by multijet production and $t\bar{t}$+jets. The total background model is constructed as a sum of the individual background contributions using a Poisson distribution for each bin of the two-dimensional (m_{J_1}, m_{HH}) distribution. To extract the signal, we compare the number of expected events from both the background-only and signal-plus-background hypotheses with the number of observed events in data using a likelihood ratio fit. The number of extracted signal events can then be related to the production cross section via $N_{\text{signal}} = \sigma_X \mathcal{B}(X \to HH \to b\bar{b}b\bar{b})\varepsilon L$, where σ_X is the production cross section of X (a radion or a bulk graviton), $\mathcal{B}(X \to HH \to b\bar{b}b\bar{b})$ is the product of the branching fractions of $X \to HH$ and the two $H \to b\bar{b}$ decays, ε is the product of the acceptance and the efficiency to reconstruct an HH event, and L is the integrated luminosity of the data set.

The multijet background estimation relies on a "pass-to-fail ratio", a transfer function between the pass and fail regions defined in Section 4 and determined by the discriminant of the leading-p_T H jet. In this analysis, the pass-to-fail ratio is of the order of 10^{-2}. Conceptually, the pass-to-fail ratio is determined in the Higgs boson mass sidebands ($m_{J_1} < 100\,\text{GeV}$ and $m_{J_1} > 140\,\text{GeV}$) and interpolated into the signal region ($100 < m_{J_1} < 140\,\text{GeV}$); however, both steps are done simultaneously with the extraction of the signal yield and profiling over all nuisance parameters, including those that govern the normalizations and shapes of $t\bar{t}$ component. The $t\bar{t}$ nuisance parameters are described in the next section; they are constrained in the two control regions enriched in $t\bar{t}$+jets, which are also a part of the joint likelihood. Therefore, both the signal and all backgrounds are simultaneously determined in a one-step fit to the (m_{J_1}, m_{HH}) planes in the ten pass and fail regions.

The total numbers of expected events failing, n_F, and passing, n_P, the DeepAK8 tagger requirement are given by

$$n_F(i, \vec{\theta}) = n_F^{\text{QCD}}(i) + n_F^{t\bar{t}}(i, \vec{\theta}) + n_F^{X}(i, \vec{\theta}) \tag{1}$$

and

$$n_P(i, \vec{\theta}) = n_P^{\text{QCD}}(i) + n_P^{t\bar{t}}(i, \vec{\theta}) + n_P^{X}(i, \vec{\theta}) \tag{2}$$

where i is a bin in the 2D (m_{J_1}, m_{HH}) plane, and $\vec{\theta}$ is the set of all nuisance parameters that quantify the systematic uncertainties, as described in Section 6. Each bin in the "fail" 2D distribution, $n_F^{\text{QCD}}(i)$, is represented by an individual parameter in the fit that is required to be positive but is otherwise unconstrained.

The predicted multijet yield in the "pass" 2D distribution, $n_P^{\text{QCD}}(i)$, is obtained by

$$n_P^{\text{QCD}}(i) = n_F^{\text{QCD}}(i)\, R_{P/F}(m_{J_1}, m_{HH}) \tag{3}$$

where $R_{P/F}(m_{J_1}, m_{HH})$ is the transfer function.

We define the transfer functions in data and in the QCD multijet simulation as $R_{P/F}^{\text{data}}(m_{J_1}, m_{HH})$ and $R_{P/F}^{\text{sim}}(m_{J_1}, m_{HH})$, respectively. The $R_{P/F}^{\text{data}}(m_{J_1}, m_{HH})$ and $R_{P/F}^{\text{sim}}(m_{J_1}, m_{HH})$ both vary smoothly as a function of m_{J_1} and m_{HH} because HH candidates in multijet processes arise from random combinations of jets. The data-to-simulation ratio of these 2D functions,

$$R_{\text{ratio}}(m_{J_1}, m_{HH}) \equiv \frac{R_{P/F}^{\text{data}}(m_{J_1}, m_{HH})}{R_{P/F}^{\text{sim}}(m_{J_1}, m_{HH})}, \tag{4}$$

is therefore also smooth and can be parameterized with an analytic function of m_{J_1} and m_{HH}.

While $R^{\text{data}}_{\text{P/F}}(m_{\text{J}_1}, m_{\text{HH}})$ could also be described by analytic functions, features of this shape that are hard to model analytically can be factored out by using the QCD simulation, and the fit of the analytic function to data is only responsible for describing the residual differences between data and simulation that can be parameterized with fewer parameters than the shape of $R^{\text{data}}_{\text{P/F}}(m_{\text{J}_1}, m_{\text{HH}})$. Thus the number of events in a given bin of the passing region is obtained from

$$n_{\text{P}}^{\text{QCD}}(i) = n_{\text{F}}^{\text{QCD}}(i)\, R^{\text{sim}}_{\text{P/F}}(m_{\text{J}_1}, m_{\text{HH}})\, R_{\text{ratio}}(m_{\text{J}_1}, m_{\text{HH}}) \tag{5}$$

where $R_{\text{ratio}}(m_{\text{J}_1}, m_{\text{HH}})$ is a surface parameterized by the product of two one-dimensional polynomials in the $(m_{\text{J}_1}, m_{\text{HH}})$ plane with coefficients determined from the fit to data. Second-order polynomials were chosen for $R_{\text{ratio}}(m_{\text{J}_1}, m_{\text{HH}})$ parameterization, along both m_{J_1} and m_{HH} axes, based on a Fisher test [81], where polynomial terms were added until the p-value obtained in the test was larger than 0.05.

To reduce the effect of statistical fluctuations on the calculation of $R^{\text{sim}}_{\text{P/F}}(m_{\text{J}_1}, m_{\text{HH}})$ in the QCD multijet simulation, the pass and fail distributions are smoothed using an adaptive kernel density estimate [82] prior to calculating the ratio.

6 Sources of systematic uncertainty

The following sources of systematic uncertainty affect the expected signal and background event yields. A complete list of systematic uncertainties and ranges for the associated nuisance parameters is given in Table 3. These ranges are used as input to the fit, and the minimization of the likelihood further constrains some of them. None of these lead to a significant change in the signal shape and, after the fit, their impact on the signal yield is significantly smaller than the effect of limited statistics.

Table 3: Summary of the ranges within which the systematic uncertainties in the signal and background yields are varied in the combined fit of all ten regions for a radion resonance at 1500 GeV.

Source	Range (%)
Integrated luminosity	1.6
Pileup	1–2
PDF and scales	0.5
$\mathrm{t\bar{t}}$ cross section	5.0
Trigger efficiency	2.4
Top quark p_{T} re-weighting	0.2–1.5
DeepAK8 $\mathrm{H \to b\bar{b}}$ efficiency	20.0
DeepJet b tagging efficiency	0.5
Jet energy scale and resolution	1–3
Jet mass scale and resolution	1–5
QCD multijet background fit	2–10

The uncertainties in the modelling of the trigger response are particularly important for $m_{\text{HH}} <$ 1100 GeV, where the trigger efficiency drops below 99%. The trigger efficiency in simulation is corrected by a scale factor, which has an uncertainty between 1 and 15%, attributable to the control trigger inefficiency and the sample size used.

The impact of the jet energy scale and resolution uncertainties [53] on the signal yields is estimated to be 1–3%, depending on the signal mass. The jet mass scale and resolution are measured using a sample of boosted $W \to q\overline{q}'$ jets in semileptonic $t\overline{t}$ events. The jet mass scale and resolution have a 2% effect on the signal yields because of a change in the mean of the H jet mass distribution.

Scale factors are used to correct the signal event yields so that their DeepAK8 tagger and DeepJet discriminant efficiencies are the same as for data. The DeepAK8 tagger and the DeepJet discriminant scale factors are taken to be 100% correlated. The associated uncertainty in the scale factor is 2–9% [83], depending on the DeepAK8 tagger working point and jet p_T, and is propagated to the total uncertainty in the signal yield.

The impact of the uncertainties in the renormalization and factorization scale and the parton distribution functions (PDF), the latter derived using the PDF4LHC procedure [59] and the NNPDF3.0 PDF sets, is estimated to be 0.5%. These uncertainties affect the product of the signal acceptance and the selection efficiency. The factorization scale and PDF uncertainties have negligible impact on the signal m_{HH} distributions. Additional systematic uncertainties associated with pileup modelling (1–2%, based on a 4.6% variation on the pp total inelastic cross section [72]) and with the integrated luminosity determination [84–86] (1.6%, combining the measurements of the three years of data taking), are applied to the signal yield.

The systematic uncertainties applied to the signal are also applied to the $t\overline{t}$+jets background, as appropriate. The total uncertainty in the $t\overline{t}$+jets background is 7%.

An additional uncertainty in the "bandwidth" parameter of the kernel density estimate, which acts as a scale for the width of the adaptive kernels is studied by varying this parameter, and its impact is found to be negligible.

The main source of uncertainty in the multijet background estimate is the statistical uncertainty in the fit of R_{ratio}. This uncertainty, amounting to 2–10%, is fully correlated between all m_{HH} bins. Additional statistical uncertainties in the background shape and yield in the signal region result from the finite sizes of the multijet samples in the fail region and are evaluated using the Barlow–Beeston Lite method [87, 88]. These uncertainties are small compared to the uncertainty in the $R_{P/F}$ ratio, and are uncorrelated from bin to bin.

7 Results

Results are obtained using a statistical combination of the semi-resolved and fully-merged event categories. An $X \to HH$ signal is resonant in the 2D space of the different signal event categories, as discussed in Section 5. The likelihood is formed by combining 2D binned likelihoods of ten regions: TT, LL, and semi-resolved signal categories, and TT and LL $t\overline{t}$ control categories, where each category provides both a pass and a fail region. The projections of the slices of the post-fit 2D distributions in the three signal regions (TT, LL, and semi-resolved) are shown in Figs. 2–4. The narrow radion signal corresponding to the resonance mass of 1500 GeV is also shown. The sensitivity is dominated by the TT region over the whole resonance mass domain. At lower resonance masses, the semi-resolved category contributes significantly to the sensitivity of the search. The LL category contributes only at very high resonance masses, where the standard model backgrounds are small.

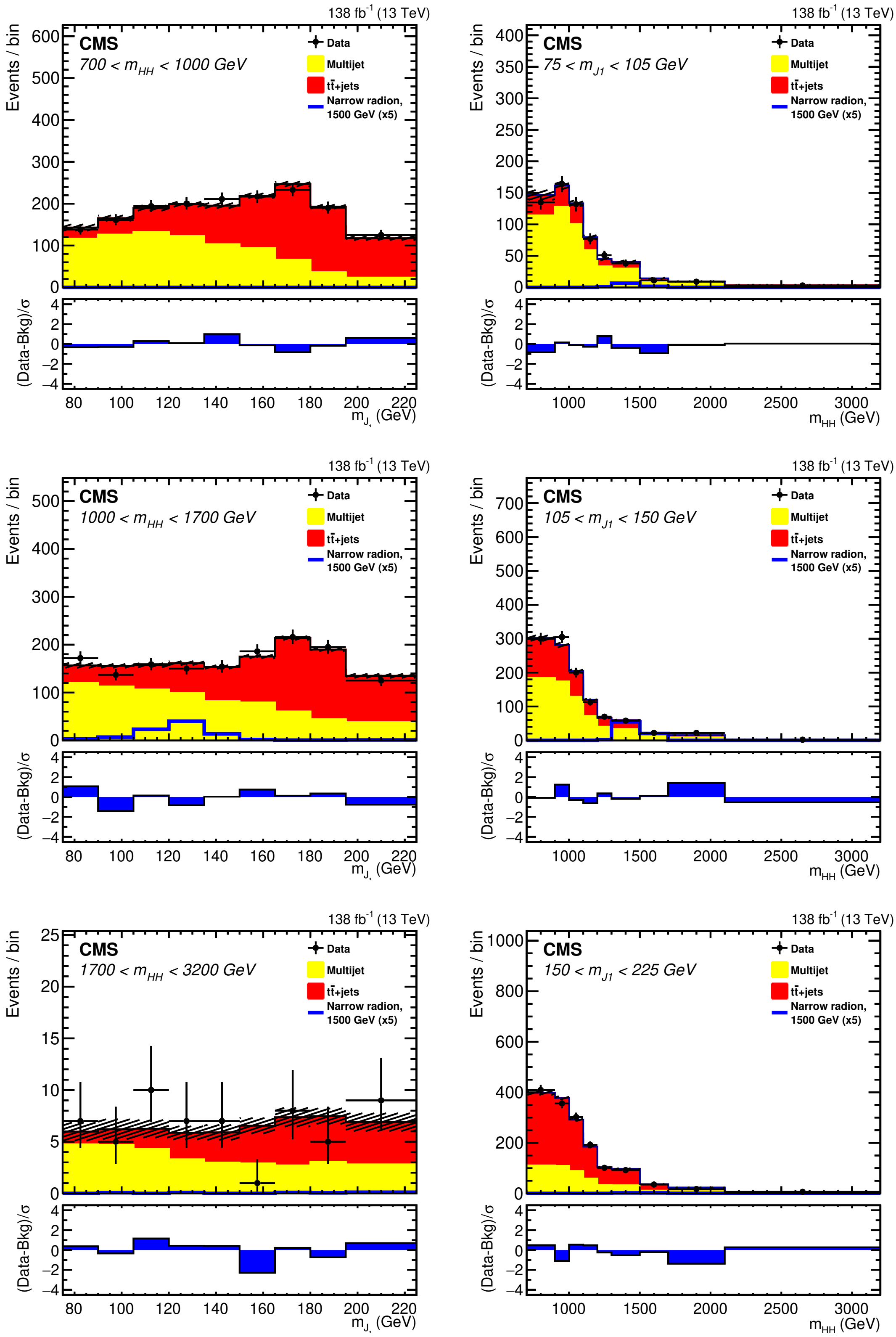

Figure 2: Slices of 2D distributions of observed events and the post-fit templates in the LL signal region, projected onto the plane of leading jet mass m_{J_1} (left) and corrected HH mass m_{HH} (right) axes, together with the signal expected for a radion of mass 1.5 TeV. For this and following figures, the value of σ in the lower panel is $\sigma = \sqrt{\sigma_{bkg}^2 + \sigma_{data}^2}$, where σ_{bkg} is the total uncertainty in the background and σ_{data} is the statistical uncertainty associated with the number of data events in a particular bin.

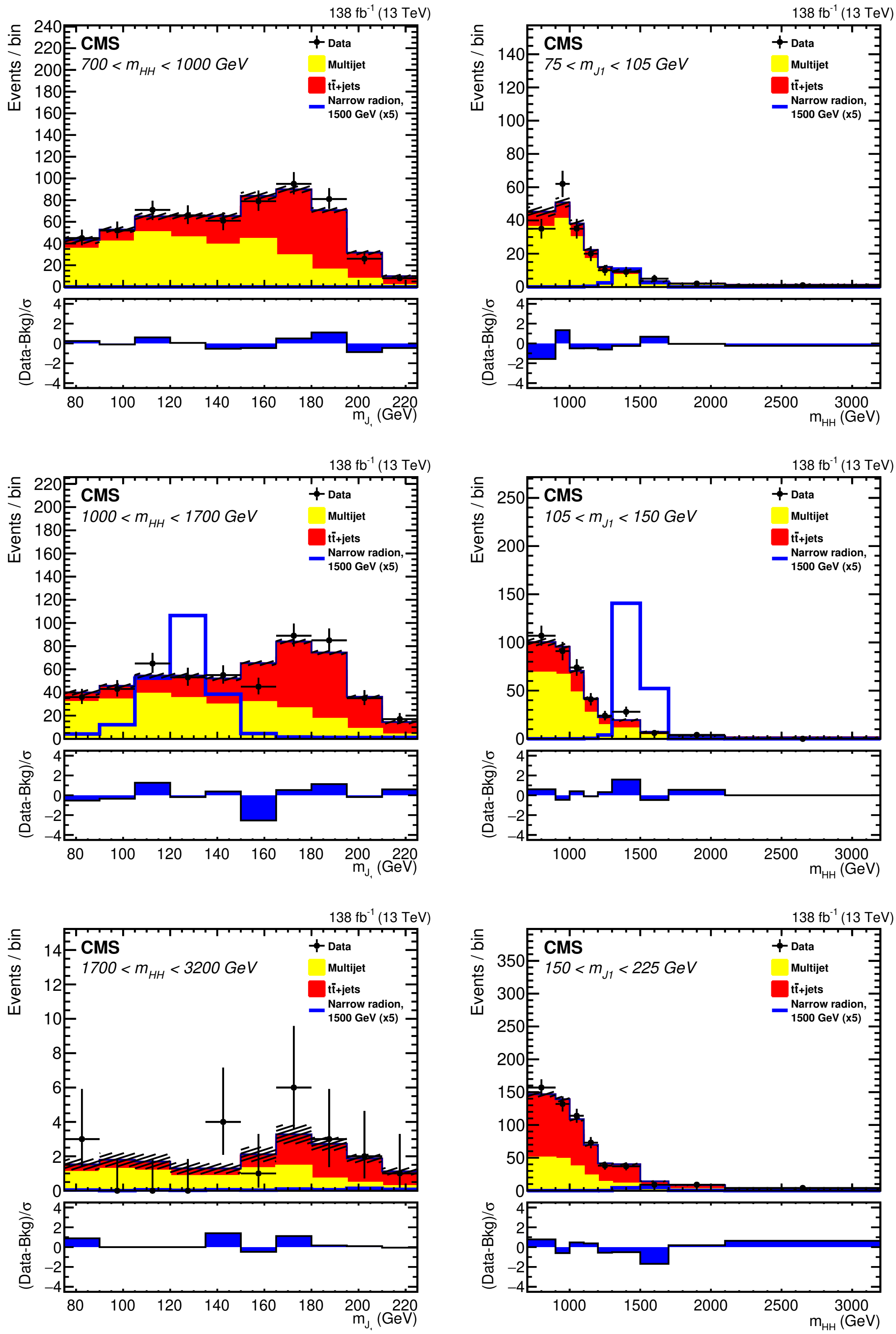

Figure 3: Slices of 2D distributions of observed events and the post-fit templates in the TT signal region, projected onto the m_{J_1} (left) and m_{HH} (right) axes, together with the signal expected for a radion of mass 1.5 TeV.

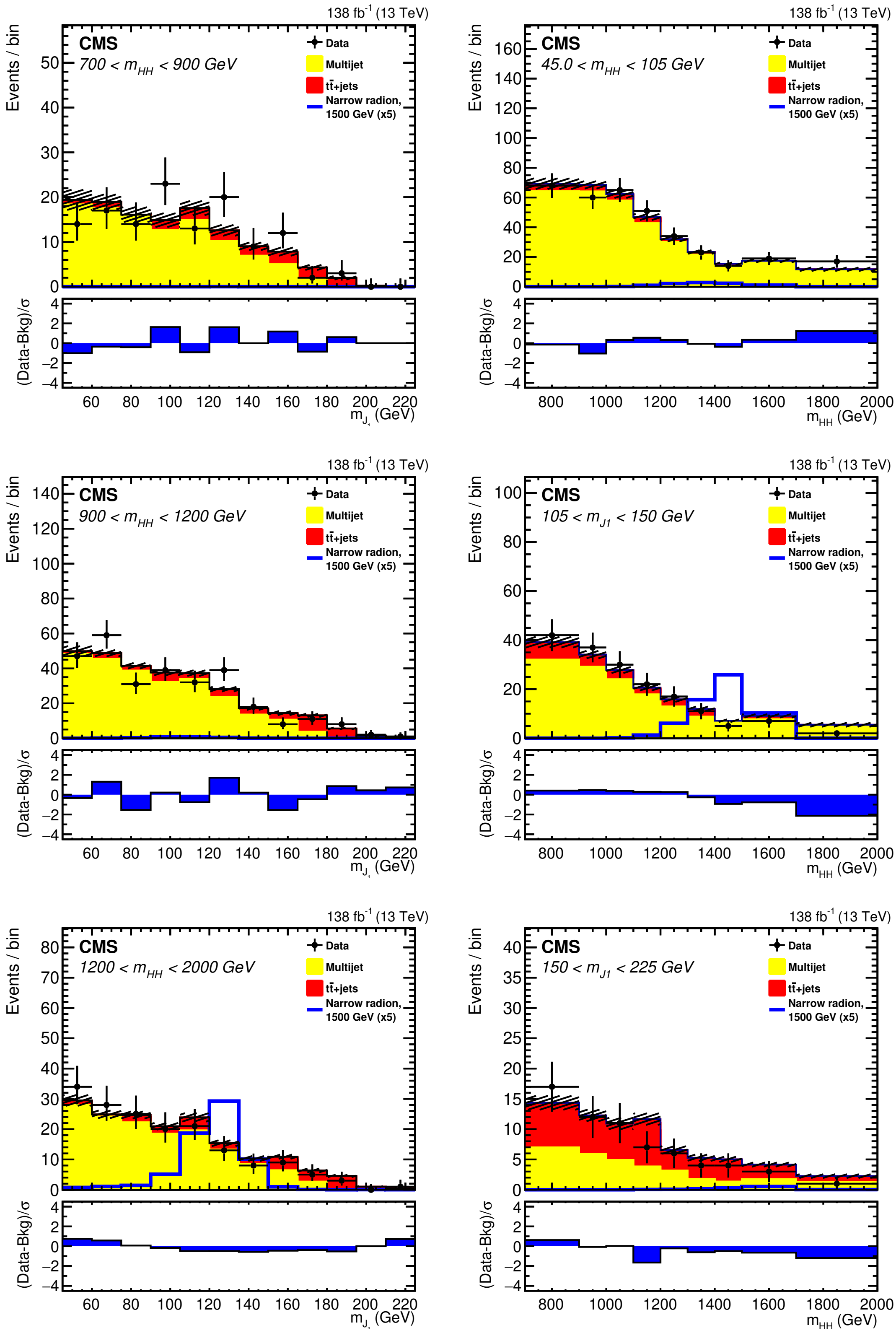

Figure 4: Slices of 2D distributions of observed events and the post-fit templates in the semi-resolved signal region, projected onto the m_{J_1} (left) and m_{HH} together with the signal expected for a radion of mass 1.5 TeV.

The three signal regions are examined for an excess of events above the predicted background, and the data are found to be consistent with the expected background predictions. We proceed to set an upper limit on the number of possible signal events in our data.

Upper limits at 95% confidence level (CL) are set on the product of the production cross section and the branching fractions, $\sigma(\mathrm{pp} \to \mathrm{X})\mathcal{B}(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$. They are obtained using the profile likelihood as a test statistic [89]. The systematic uncertainties are treated as nuisance parameters and are profiled in the minimization of the negative of the logarithm of the profile likelihood ratio, and the distributions of the likelihood ratio are calculated using the asymptotic approximation [90] of the procedure reported in Refs. [91, 92].

As shown in Fig. 5 (left) a narrow radion with mass between 1–2.6 TeV is excluded at 95% CL for the assumed value of the cutoff scale, $\Lambda_R = 3$ TeV. A narrow bulk graviton for the assumed value of the ultraviolet cutoff scale, $k/\overline{M}_{Pl} = 0.5$, is excluded at 95% CL only for masses between 1–1.2 TeV, as shown in Fig. 5 (right). The deviations in the observed limits at graviton and radion masses of 1.3 and 1.5 TeV, respectively, correspond to a small upward fluctuation of data over the background prediction at $m_{HH} \approx 1.4$ TeV, visible in Fig. 3, middle row. The corresponding exclusion limits, assuming a signal with 10% decay width, are shown in Fig. 6.

These limits result in the exclusion of the narrow-width graviton with m_X below 1.2 TeV. Narrow and 10%-width radion with masses below 2.6 TeV, and 2.9 TeV, respectively, are also excluded. This is a substantial improvement over the previous CMS radion exclusion limit of $\approx$1.6 TeV. The analysis presented in this paper complements a previous result from ATLAS that achieved an almost identical sensitivity for $X \to \mathrm{HH} \to 4\mathrm{b}$ for both spin-0 and spin-2 hypotheses [26] between 1.5–3 TeV, while employing a different background estimation strategy and H jet identification. Below 1.5 TeV the ATLAS analysis benefits from the combination with the fully resolved 4b channel.

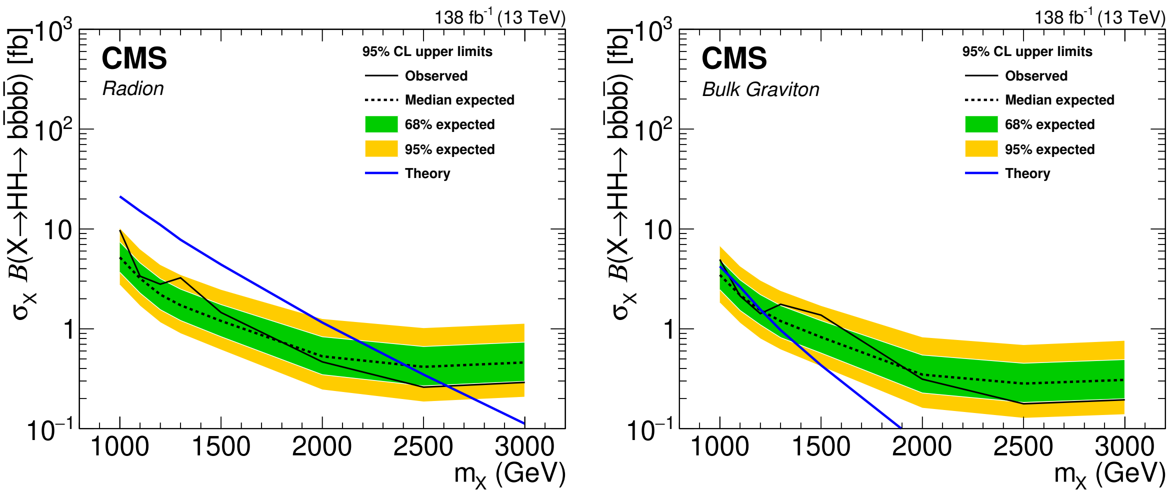

Figure 5: The observed (solid black line) and expected (dashed black line) upper limits at 95% CL on $\sigma(\mathrm{pp} \to \mathrm{X})\mathcal{B}(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$ for a narrow spin-0 radion (left, corresponding to $\Lambda_R = 3$ TeV) and a narrow width spin-2 bulk graviton (right, corresponding to $k/\overline{M}_{Pl} = 0.5$) models. The green (yellow) bands represent one (two) standard deviations from the expected limit. The predicted theoretical cross sections for the narrow radion and bulk graviton are also shown.

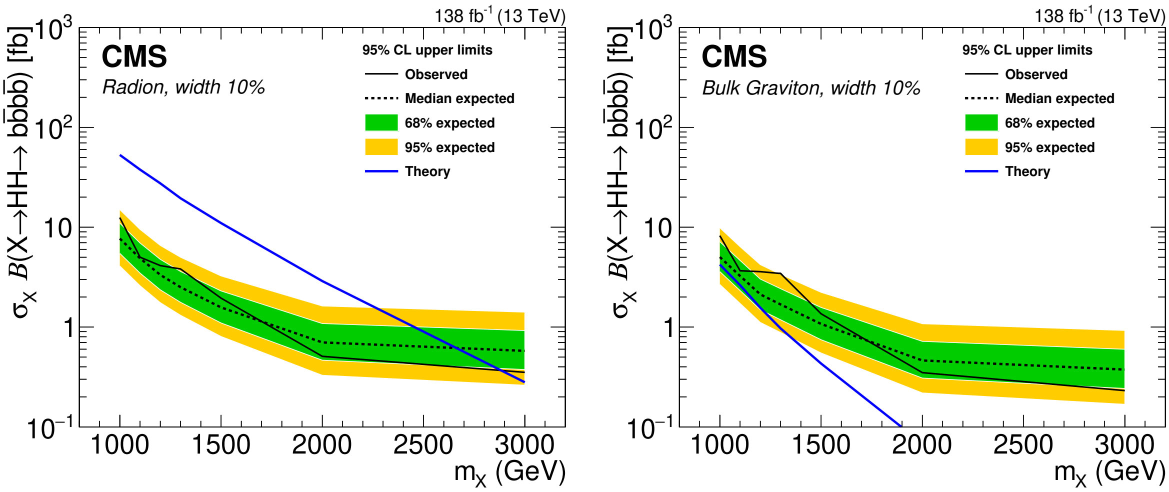

Figure 6: The observed (solid black line) and expected (dashed black line) upper limits at 95% CL on $\sigma(\mathrm{pp} \to \mathrm{X})\mathcal{B}(\mathrm{X} \to \mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}})$ for the 10%-width spin-0 radion (left) and the 10%-width spin-2 bulk graviton (right) models. The green (yellow) bands represent one (two) standard deviations from the expected limit. The predicted theoretical cross sections for the 10%-width radion and bulk graviton are also shown.

8 Summary

A search has been presented for the pair production of standard model Higgs bosons (HH) from the decay of a spin-0 radion or a spin-2 bulk graviton as predicted in warped extradimensional models, using data from proton-proton collisions at a centre-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 138 fb^{-1}.

The search is restricted to the case where each Higgs boson decays to a bottom quark-antiquark pair. It is conducted in the region of phase space where at least one of the Higgs bosons has a large Lorentz boost, so that the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay products are collimated to form a single H jet. The search combines events with one H jet and two b jets with events having two H jets, thus adding sensitivity compared with previous analyses [36, 38].

The results are interpreted in terms of upper limits on the product of the production cross section for the respective resonance particles and the branching fraction to $\mathrm{HH} \to \mathrm{b\bar{b}b\bar{b}}$, at 95% confidence level. The upper limits range from 9.74 to 0.29 fb for a narrow radion and from 4.94 to 0.19 fb for a narrow bulk graviton, each having a mass of 1–3 TeV. Assuming a with of 10% for the radion and the graviton, the limits for the same masses are in the range 12.48–0.35 fb and 8.23–0.23 fb, respectively. As a result, the narrow-width graviton with m_{X} below 1.2 TeV, and narrow and 10%-width radion with masses below 2.6 TeV, and 2.9 TeV, respectively, are excluded.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[1], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz[1]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[2], E.A. De Wolf, T. Janssen, T. Kello[3], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A.K. Kalsi, K. Lee, M. Mahdavikhorrami, I. Makarenko, L. Moureaux, S. Paredes, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, T.T. Tran, P. Vischia, S. Wertz

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

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[4], E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[6], A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[5], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D. S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
T. Cheng, T. Javaid[7], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer, C. Dozen[8], Z. Hu, J. Martins[9], Y. Wang, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen[7], H.S. Chen[7], M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu[12], 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[3], 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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[13], 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[13], M. Finger Jr.[13], 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[14,15], E. Salama[16,17]

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

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. Eerola, 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, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[18], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, J. Motta, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[19], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine[19], U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin,

S. Mondal, S. Mukherjee, D. Noll, A. Novak, A. Pozdnyakov, Y. Rath, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[20], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, D. Roy, A. Stahl[21], T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman, K. Borras[22], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[23], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari[24], N.Z. Jomhari, A. Kasem[22], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, D. Krücker, W. Lange, K. Lipka, W. Lohmann[25], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[26], V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger[23], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon, M. Van De Klundert, F. Vazzoler, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Albrecht, S. Bein, L. Benato, P. Connor, K. De Leo, M. Eich, F. Feindt, 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, K. El Morabit, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[21], 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. Wassmer, 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. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[27], G. Bencze, C. Hajdu, D. Horvath[28,29], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[30], S. Lökös[31], P. Major, K. Mandal, G. Pásztor, A.J. Rádl, O. Surányi, G.I. Veres

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, D. Fasanella, F. Fienga, J. Karancsi[27], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi[32], B. Ujvari

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[33], F. Nemes[33], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[34], 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[35], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[36], M. Maity[37], 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[38], D. Kumar[38], A. Muhammad, L. Panwar[38], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[38]

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[39]

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

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[41], A. Nayak[41], P. Saha, N. Sur, S.K. Swain, D. Vats[41]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[42], E. Khazaie[42], M. Zeinali[43]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[44], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,45], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], M. Gul[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], R. Venditti[a], P. Verwilligen[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], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,46], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[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]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Albergo[a,b,47], S. Costa[a,b,47], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,47], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

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

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,21], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,48], S. Meola[a,d,21], P. Paolucci[a,21], B. Rossi[a], C. Sciacca[a,b]

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], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], S.Y. Hoh[a,b], L. Layer[a,49], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
P. Asenov[a,50], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,50], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], E. Bossini[a,b], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, 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], A. Bellora[a,b], J. Berenguer Antequera[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], A. Vagnerini[a,b]

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], G. Sorrentino[a,b]

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

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

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, M.S. Ryu, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, V. Veckalns[51]

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, Z. Zolkapli

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[52], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, R. Reyes-Almanza, A. Sánchez Hernández

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

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

University of Montenegro, Podgorica, Montenegro

J. Mijuskovic[53], N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

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

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

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[54], M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, N. Trevisani, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[55], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[56], K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Caillol, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[57], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, K. Long, C. Lourenço, B. Maier, L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[58], S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[59], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, M. Missiroli[60], L. Noehte[60], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
K. Androsov[59], M. Backhaus, P. Berger, A. Calandri, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, V. Stampf, J. Steggemann[59], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[61], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[62], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[37], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, P.s. Chen, H. Cheng, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

High Energy Physics Research Unit, Department of Physics, Faculty of Science,

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[63], Z.S. Demiroglu, F. Dolek, I. Dumanoglu[64], E. Eskut, Y. Guler[65], E. Gurpinar Guler[65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[66], A. Polatoz, A.E. Simsek, B. Tali[67], U.G. Tok, S. Turkcapar, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar, K. Ocalan[68], M. Yalvac[69]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], Ö. Özçelik, S. Tekten[72], E.A. Yetkin[73]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[64], Y. Komurcu, S. Sen[74]

Istanbul University, Istanbul, Turkey
S. Cerci[67], I. Hos[75], B. Isildak[76], B. Kaynak, S. Ozkorucuklu, H. Sert, D. Sunar Cerci[67], C. Zorbilmez

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

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[77], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[79], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal[80], D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, D.G. Monk, J. Nash[81], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee[21], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, Texas, USA

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[82], C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[22], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir[84], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, 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, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, L.A.T. Bauerdick, 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. Lammel, 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[85], F. Ravera, A. Reinsvold Hall[86], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

University of Florida, Gainesville, Florida, 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, Florida, 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, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[17], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

University of Illinois Chicago, Chicago, USA, Chicago, USA
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, A.H. Merrit, 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, Iowa, USA
M. Alhusseini, K. Dilsiz[87], L. Emediato, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], J. Nachtman, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

Johns Hopkins University, Baltimore, Maryland, USA
O. Amram, B. Blumenfeld, D. Brehm, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, 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, Kansas, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

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

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, 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, Massachusetts, 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, Minnesota, USA
R.M. Chatterjee, A. Evans, J. Hiltbrand, 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, Nebraska, 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, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Hortiangtham, A. Krishna, J. Li, J. Lidrych, 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, Illinois, 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, Indiana, 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[13], R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

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

Princeton University, Princeton, New Jersey, 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, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, 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[18], J. Thieman, F. Wang, R. Xiao, W. Xie

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

Rice University, Houston, Texas, 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[91], Y. Zhang

University of Rochester, Rochester, New York, 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

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban[25], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[92], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[93], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, Virginia, USA
M.W. Arenton, B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald, S. White

Wayne State University, Detroit, Michigan, USA

N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, USA
S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert, W. Vetens

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[94,95], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[96], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[94], E. Kuznetsova[97], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, A. Toropin, T. Aushev, V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[98], V. Popov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin, O. Bychkova, R. Chistov[94], M. Danilov[94], A. Oskin, P. Parygin, S. Polikarpov[94], V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[85], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, V. Blinov[94], T. Dimova[94], L. Kardapoltsev[94], A. Kozyrev[94], I. Ovtin[94], O. Radchenko[94], Y. Skovpen[94], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Okhotnikov, V. Borshch, V. Ivanchenko, E. Tcherniaev

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
V. Chekhovsky, A. Litomin, V. Makarenko

†: Deceased
[1]Also at TU Wien, Vienna, Austria
[2]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[3]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[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 The University of the State of Amazonas, Manaus, Brazil
[7]Also at University of Chinese Academy of Sciences, Beijing, China
[8]Also at Department of Physics, Tsinghua University, Beijing, China
[9]Also at UFMS, Nova Andradina, Brazil
[10]Also at Nanjing Normal University, Nanjing, China
[11]Now at The University of Iowa, Iowa City, Iowa, 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
[14]Also at Helwan University, Cairo, Egypt
[15]Now at Zewail City of Science and Technology, Zewail, Egypt
[16]Also at British University in Egypt, Cairo, Egypt
[17]Now at Ain Shams University, Cairo, Egypt
[18]Also at Purdue University, West Lafayette, Indiana, USA

[19]Also at Université de Haute Alsace, Mulhouse, France
[20]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[21]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[22]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[23]Also at University of Hamburg, Hamburg, Germany
[24]Also at Isfahan University of Technology, Isfahan, Iran
[25]Also at Brandenburg University of Technology, Cottbus, Germany
[26]Also at Forschungszentrum Jülich, Juelich, Germany
[27]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[28]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[29]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[30]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[31]Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[32]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[33]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[34]Also at Punjab Agricultural University, Ludhiana, India
[35]Also at Shoolini University, Solan, India
[36]Also at University of Hyderabad, Hyderabad, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at Indian Institute of Science (IISc), Bangalore, India
[39]Also at Indian Institute of Technology (IIT), Mumbai, India
[40]Also at IIT Bhubaneswar, Bhubaneswar, India
[41]Also at Institute of Physics, Bhubaneswar, India
[42]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[43]Also at Sharif University of Technology, Tehran, Iran
[44]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[45]Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
[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', Napoli, Italy
[49]Also at Università di Napoli 'Federico II', Napoli, Italy
[50]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[51]Also at Riga Technical University, Riga, Latvia
[52]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[53]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[54]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
[55]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[56]Also at Saegis Campus, Nugegoda, Sri Lanka
[57]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[58]Also at National and Kapodistrian University of Athens, Athens, Greece
[59]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[60]Also at Universität Zürich, Zurich, Switzerland
[61]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[62]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[63]Also at Şırnak University, Sirnak, Turkey

[64]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[65]Also at Konya Technical University, Konya, Turkey
[66]Also at Izmir Bakircay University, Izmir, Turkey
[67]Also at Adiyaman University, Adiyaman, Turkey
[68]Also at Necmettin Erbakan University, Konya, Turkey
[69]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[70]Also at Marmara University, Istanbul, Turkey
[71]Also at Milli Savunma University, Istanbul, Turkey
[72]Also at Kafkas University, Kars, Turkey
[73]Also at Istanbul Bilgi University, Istanbul, Turkey
[74]Also at Hacettepe University, Ankara, Turkey
[75]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76]Also at Ozyegin University, Istanbul, Turkey
[77]Also at Vrije Universiteit Brussel, Brussel, Belgium
[78]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
[80]Also at IPPP Durham University, Durham, United Kingdom
[81]Also at Monash University, Faculty of Science, Clayton, Australia
[82]Also at Università di Torino, Torino, Italy
[83]Also at Bethel University, St. Paul, Minnesota, USA
[84]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85]Also at California Institute of Technology, Pasadena, California, USA
[86]Also at United States Naval Academy, Annapolis, Maryland, USA
[87]Also at Bingol University, Bingol, Turkey
[88]Also at Georgian Technical University, Tbilisi, Georgia
[89]Also at Sinop University, Sinop, Turkey
[90]Also at Erciyes University, Kayseri, Turkey
[91]Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
[92]Also at Texas A&M University at Qatar, Doha, Qatar
[93]Also at Kyungpook National University, Daegu, Korea
[94]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[95]Now at another institute or international laboratory covered by a cooperation agreement with CERN
[96]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[97]Also at University of Florida, Gainesville, Florida, USA
[98]Also at Imperial College, London, United Kingdom