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Search for nonresonant triple Higgs boson production in the final state with six bottom quarks in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for nonresonant triple Higgs boson (HHH) production in the final state with six bottom quarks is performed using proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$ recorded by the CMS experiment. No significant excess of events over the background prediction is seen. Observed (expected) 95% confidence level upper limits on the signal cross section are set at 44 (43) fb, corresponding to 588 (572) times the standard model expectation. The observed (expected) constraint on the trilinear coupling modifier κ_3 is $-7.4 < \kappa_3 < 12.4$ ($-6.4 < \kappa_3 < 11.2$), assuming the quartic coupling modifier $\kappa_4 = 1$. The corresponding constraint on κ_4 is $-177 < \kappa_4 < 185$ ($-180 < \kappa_4 < 190$), assuming $\kappa_3 = 1$. This analysis provides the most stringent constraint to date on nonresonant HHH production and excludes, for the first time, part of the (κ_3, κ_4) space allowed by the perturbative unitarity bound.

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*See Appendix B for the list of collaboration members

Following the discovery of the Higgs boson (H) [1–9], probing the structure of the Higgs potential has become a central goal of the LHC physics program. In the standard model (SM), the potential is determined by the vacuum expectation value $v \approx 246\,\mathrm{GeV}$ and the H mass $m_{\mathrm{H}} = 125\,\mathrm{GeV}$, leading to trilinear ($\lambda_3$) and quartic ($\lambda_4$) self-couplings, both equal to $\lambda_{\mathrm{SM}} = m_{\mathrm{H}}^2/(2v^2)$. Deviations from this prediction could have profound consequences for the early universe and its stability [10–13].

At the LHC, λ_3 and λ_4 can be directly probed via H pair (HH) and triple H (HHH) production. In proton-proton (pp) collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, the dominant production mechanism for both processes is gluon-gluon fusion (ggF), with cross sections of $\sigma_{\mathrm{ggF}}^{\mathrm{HH}} = 31^{+2}_{-7}\,\mathrm{fb}$ [14–23] and $\sigma_{\mathrm{ggF}}^{\mathrm{HHH}} = 0.08 \pm 0.01\,\mathrm{fb}$ [24–27], respectively, calculated at next-to-next-to-leading order (NNLO). Deviations from the SM predictions are parameterized by the H self-coupling modifiers, defined as $\kappa_3 = \lambda_3/\lambda_{\mathrm{SM}}$ and $\kappa_4 = \lambda_4/\lambda_{\mathrm{SM}}$, respectively, following the convention used in the κ framework [28]. Both the HH and HHH processes are under active investigation at the LHC, with searches in multiple final states [29–43]. Although HH production is primarily sensitive to κ_3, it also depends on κ_4 through electroweak corrections. This dependence is subleading for LHC energies [44, 45], and no dedicated extraction of κ_4 from HH measurements is currently available. The ATLAS and CMS experiments have set 95% confidence level (CL) upper limits on the HH signal-strength modifier, defined as $\mu_{\mathrm{HH}} = \sigma_{\mathrm{HH}}/\sigma_{\mathrm{HH}}^{\mathrm{SM}}$, of $\mu_{\mathrm{HH}} < 2.9$ and < 3.5, respectively, assuming SM production [38, 39, 46]. The κ_3 coupling modifier is constrained by ATLAS and CMS to be $-1.2 < \kappa_3 < 7.2$ [38] and $-1.4 < \kappa_3 < 7.0$ [39, 46] at 95% CL, respectively. The HHH production provides direct sensitivity to both κ_3 and κ_4, but suffers from a small cross section due to destructive interference among contributing diagrams. The ATLAS Collaboration reported an observed (expected) limit on the signal strength, relative to the SM, of $\mu_{\mathrm{HHH}} = 760$ (750) in the HHH $\to$ 6b final state using $139\,\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 13\,\mathrm{TeV}$ [43], with coupling modifier constraints $-11 < \kappa_3 < 17$ for $\kappa_4 = 1$ and $-230 < \kappa_4 < 240$ for $\kappa_3 = 1$. Perturbative unitarity of the HH $\to$ HH scattering imposes bounds on κ_3 and κ_4, thereby delineating the region where interpretations remain theoretically consistent [47]. Extended Higgs sectors motivated by the electroweak phase transition can produce large deviations of the HHH cross section with respect to the SM prediction, with modest modifications to the HH cross section, while spontaneous flavor violation provides additional well-motivated scenarios with distinctive H phenomenology [48–50]. The HHH production has also been studied as a probe of the H self-couplings at future 100 TeV pp colliders [51, 52].

This Letter presents a search for nonresonant HHH $\to$ 6b production, using pp collision data collected by the CMS experiment between 2016 and 2018 at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$ [53–55]. The CMS apparatus [56, 57] is a multipurpose, nearly hermetic detector, designed to trigger on [58–60] and identify electrons, muons, photons, charged and neutral hadrons [61–63]. The ggF HHH signal is modeled with the leading-order (LO) MadGraph5_aMC@NLO event generator [64] and normalized to the NNLO cross section; the irreducible ggF HH background is simulated at next-to-LO (NLO) with the POWHEG program [23, 65–74] and normalized to NNLO. Parton showering and hadronization are modeled with PYTHIA 8.205 [75] using the CP5 tune [76] and NNPDF3.1 NNLO parton distribution functions (PDFs) [77]. Events are reconstructed with the particle-flow algorithm [78]. The effects of additional pp interactions in the same or neighboring bunch crossings (pileup) are mitigated using charged-hadron subtraction for small-radius jets [79] and the PUPPI algorithm for large-radius jets [80, 81]. Jets are clustered with the anti-k_{T} algorithm [82] using distance parameters 0.4 (small-radius) and 0.8 (large-radius), as implemented in FastJet [83], and b jets are identified with the ParticleNet tagger [84, 85], with performance calibrated as in Ref. [86].

Large-radius H candidates from $H \to b\bar{b}$ decays are tagged with the PARTICLENET $b\bar{b}$ discriminator, calibrated as in Ref. [87]. Events are selected with multijet triggers [58–60], giving an acceptance of ∼80–90% for signal events in the analysis phase space. The offline selection requires at least four small-radius jets with $p_T > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$–2.5, depending on the data-taking period, and large-radius jets with $p_T > 300\,\mathrm{GeV}$ and $|\eta| < 2.5$. Further details of the signal and background simulated samples, detector subsystems, trigger requirements, and object definitions are provided in the End Matter. Tabulated results are provided in the HEPData record for this analysis [88].

Owing to the large branching fraction of $H \to b\bar{b}$ (∼60%), this final state offers a rich topology in which each H is reconstructed either from two small-radius jets (resolved) or a single large-radius jet (merged). To maximize sensitivity, novel H tagging techniques are employed as well as an attention-based deep neural network with a transformer architecture that enables inclusive identification of signal events across all combinations of resolved and merged H candidates. An inclusive strategy is employed that targets four distinct reconstruction topologies of the H candidates: *resolved*, where all three H are reconstructed from pairs of small-radius jets; *partially resolved* and *partially merged*, where, respectively, one or two H are reconstructed from a single large-radius jet and the remainder from small-radius jets; and *merged*, where all three H are reconstructed from large-radius jets.

A symmetry-preserving attention network (SPANET) [89–91] is trained on simulated samples to separate the signal from the main backgrounds: quantum chromodynamics (QCD) multijet, top quark-antiquark ($t\bar{t}$), and $HH \to 4b$ production. The same network is also used to categorize the signal among distinct topologies by assigning or combining jets to form H candidates. The SPANET algorithm addresses the jet assignment problem by explicitly preserving the permutation symmetry of identical final-state particles, and has recently been shown to be potentially effective for both HH and HHH event reconstruction [92, 93]. It yields per-jet assignment probabilities and topology scores that are used to define signal-enriched categories. The features input to SPANET include the transverse momentum p_T, pseudorapidity η, $\cos\phi$, $\sin\phi$, where ϕ is the azimuthal angle, and mass of up to ten small-radius and three large-radius jets, ordered by decreasing b- and $b\bar{b}$-tagging scores. The corresponding discretized PARTICLENET b and $b\bar{b}$ tagging scores are also included. Small- and large-radius jets are both retained as network inputs, including spatially overlapping jets. For training-target definition and object calibration, overlaps are resolved by prioritizing large-radius jets, which avoids double counting and reduces combinatorics. Additional inputs comprise jet pairwise angular separations, dijet masses, and event-level variables, such as the scalar jet p_T sum H_T and missing transverse momentum p_T^{miss}. The data-taking period is also included as a discrete input feature to account for differences in conditions, including trigger configurations, detector performance, and pileup.

The classification proceeds in two stages to enhance the sensitivity to the $HHH \to 6b$ signal. The first stage, referred to as the inclusive classifier, is trained on events passing the trigger selection and containing at least four small-radius jets to classify them into four categories: $HHH \to 6b$, $HH \to 4b$, QCD multijet, and $t\bar{t}$. Its normalized outputs, $\mathrm{Prob}_j^{\mathrm{incl}}$, can be interpreted as the probabilities for an event to originate from process j. Events in which $\mathrm{Prob}_{\mathrm{HHH}}^{\mathrm{incl}}$ is maximal are selected, retaining ∼80% of $HHH \to 6b$ events while accepting ∼2% of QCD multijet, 3% of $t\bar{t}$, and 20% of $HH \to 4b$ events.

The selected events are then passed to a second classifier, trained on this signal-enriched subset using the same architecture, hyperparameters, and target classes as the first stage to further refine the identification of the target topology. In this selected sample, the background is dominated by QCD multijet production ($\sim$95%), with $\mathrm{t\bar{t}}$ contributing the remaining $\sim$5%. The outputs are interpreted as class probabilities $\mathrm{Prob_{HHH}}$, $\mathrm{Prob_{HH}}$, $\mathrm{Prob_{QCD}}$, and $\mathrm{Prob_{t\bar{t}}}$ (normalized to sum to unity). In this stage, an additional reduction is achieved, retaining $\sim$90% of the $\mathrm{HHH} \to 6\mathrm{b}$ signal, while reducing the QCD multijet, $\mathrm{t\bar{t}}$, and $\mathrm{HH} \to 4\mathrm{b}$ backgrounds by additional factors of 4, 2, and 1.3, respectively. This two-stage approach is effectively a boosting ensemble method [94]: the first network performs a coarse event selection, and the second focuses on the signal-enriched sample, adapting to the remaining difficult-to-classify events and thereby improving the overall discrimination power. No further gain is observed from additional classifier stages.

Based on simulations, only 27% of signal events have three H (3H) that can be reconstructed within the detector acceptance, 52% have two reconstructible H (2H), and 21% have one (1H) or zero (0H) reconstructible H. Considering the classifications according to reconstructible H, a third deep neural network, trained with optimized hyperparameters using the same input features, assigns each event to one of ten categories, defined by the number of merged H (mh) and resolved H (h): 0mh0h, 0mh1h, 1mh0h, 2mh0h, 1mh1h, 0mh2h, 3mh0h, 2mh1h, 1mh2h, and 0mh3h. For events with maximal $\mathrm{Prob_{HHH}}$, the signal regions (SRs) are formed by the seven 3H and 2H categories, while the three 1H and 0H categories define control regions (CRs) used to assess the agreement between data and the background model.

Signal extraction is performed via a binned maximum likelihood fit to the $\mathrm{ProbMultiH} \equiv \mathrm{Prob_{HH}} + \mathrm{Prob_{HHH}}$ distribution. In each category, only the region with $\mathrm{ProbMultiH} > 0.8$ is considered and divided into ten bins. This requirement preserves 56% of the highest purity $\mathrm{HHH} \to 6\mathrm{b}$ events, summed over all SR categories. The most sensitive bin is defined such that the relative statistical uncertainty originating from the background model is $\sim$20%. The remaining nine bins are evenly spaced in ProbMultiH.

At high values of $\mathrm{Prob_{HHH}}$, the kinematic properties of the QCD multijet and $\mathrm{t\bar{t}}$ backgrounds mimic those of the HHH and HH signals. Many QCD multijet events exhibit signal-like kinematics, but fail the selection because of their jet flavor composition. To model the background in the SRs, data events failing the inclusive $\mathrm{HHH} \to 6\mathrm{b}$ and $\mathrm{HH} \to 4\mathrm{b}$ classifications are used. Their discretized b and $\mathrm{b\bar{b}}$ tagging scores are replaced with the corresponding set of scores sampled from events in the SR, so that event-level patterns, such as correlations among high b tagging scores across the jets, are preserved. In each category, the normalization of this background model is fixed to the corresponding data yield. The SPANET inference is applied to these embedded events, yielding an inclusive description of all backgrounds. The method is validated in categories enriched with $\mathrm{HH} \to 4\mathrm{b}$ events, where $\mathrm{HHH} \to 6\mathrm{b}$ contamination is negligible, and in sidebands of the multijet mass with respect to the 3H expectation. It is found to reproduce the data within uncertainties. A separate $\mathrm{t\bar{t}}$ CR is included, defined by events with high predicted $\mathrm{t\bar{t}}$ score $\mathrm{Prob^{incl}_{t\bar{t}}}$ and a purity of $\sim$99%. Agreement between data and $\mathrm{t\bar{t}}$ simulation validates the analysis strategy and the jet-tagging calibrations.

While the ggF HH contribution is nonnegligible in the SR, particularly for constraints on H self-couplings, other H and HH production modes are negligible even under variations of the trilinear coupling modifier κ_3. These include HH production via vector boson fusion (VBF), and H and HH production in association with top quarks ($\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}HH}$) or electroweak vector bosons (VH, VHH). Their yields depend only weakly on κ_3 and κ_4 [95–97], and they are therefore omitted from the signal extraction.

Three primary sources of systematic uncertainties are considered: theoretical uncertainties, uncertainties related to corrections affecting the HHH and HH signal templates, and uncertainties in the background estimate using control samples in data. Theoretical uncertainties in the

HHH and HH signals are evaluated through renormalization and factorization scales ($\sim$20%), PDF ($\sim$3%), and branching fraction ($\sim$1%) variations. These affect the overall normalization and induce small shape variations through bin migration driven by changes in jet kinematics.

Jet-related uncertainties, including the energy scale, energy resolution, and mass resolution, affect jet and dijet kinematics and hence the SPANET prediction. For each variation, the event classification and categorization score is recalculated, and new signal templates are constructed to assess both shape and normalization uncertainties. Changes in event selection efficiency due to these variations lead to normalization shifts. Corrections related to flavor tagging result in a $\sim$15% reduction of the HHH signal yield in the highest ProbMultiH bins. Associated uncertainties are propagated to the signal templates following the prescription of Ref. [86]. For small-radius jets, uncertainties are decomposed into sources corresponding to data-to-simulation scale factors (SFs) for b tagging derived from the Z+jets, W+jets, and $\mathrm{t\bar{t}}$ processes, as well as modeling effects from parton showering, b fragmentation, pileup, integrated luminosity, and jet-related uncertainties. For large-radius jets, a single $\mathrm{b\bar{b}}$ tagging uncertainty is applied, corresponding to that in the data-to-simulation SF measured in $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ events. All sources are treated as uncorrelated and implemented as event weight variations. The dominant uncertainty arises from the statistical precision of the b-tagging calibration on small-radius jets, leading to a $\sim$5% uncertainty in the yield. For large-radius jets, the $\mathrm{b\bar{b}}$ tagging uncertainty in the yield is $\sim$22%.

The uncertainty in the QCD multijet background estimate based on control samples in data accounts for potential mismodeling beyond statistical fluctuations. As an extreme variation, the shape of the background model in the 1H category is assigned as an alternative background model in the HHH SR and treated as uncorrelated across categories. This decorrelated shape variation allows the fit to adjust for mismodeling in the lower-score bins of the falling ProbMultiH distribution.

The precision of the analysis is primarily limited by data statistical uncertainties, which account for $\sim$52% of the nominal expected limit. The dominant systematic uncertainty arises from the QCD multijet background model, including its shape uncertainty and the per-bin statistical variance. Theory uncertainties in the signal and experimental uncertainties from jet reconstruction and flavor identification are subdominant.

The contribution from the HH process in the SR is suppressed by requiring events to have a maximum probability in $\mathrm{Prob_{HHH}}$. In the SR, the expected HH yield is about one order of magnitude larger than the HHH yield for the SM hypothesis; this hierarchy is even stronger for anomalous couplings, because the HH cross section increases more rapidly than the HHH cross section [45]. In the statistical model, the central value of the HH contribution is fixed to its SM expectation, $\mu_{\mathrm{HH}} = 1$, while its uncertainty is profiled. The SM top quark Yukawa coupling is assumed.

No evidence for an HHH signal is observed, and two interpretations are presented: an upper limit (UL) on the SM-like HHH production rate and constraints in the (κ_3, κ_4) parameter space. The post-fit distributions in the 3H SR are shown in Fig. 1.

The ULs at 95% CL on the HHH signal strength are derived based on the asymptotic formulae for the profile likelihood ratio test statistic $-2\Delta\ln(L)$ [98, 99] and the CL_s [100, 101] criterion. The results have been obtained using the CMS statistical analysis tool COMBINE [102], which is based on the ROOFIT [103] and ROOSTATS [104] frameworks. Figure 2 (left) shows the resulting limits across resolved, partially resolved and partially merged, and merged event topologies. The resolved categories provide the highest sensitivity. Partially resolved, partially merged,

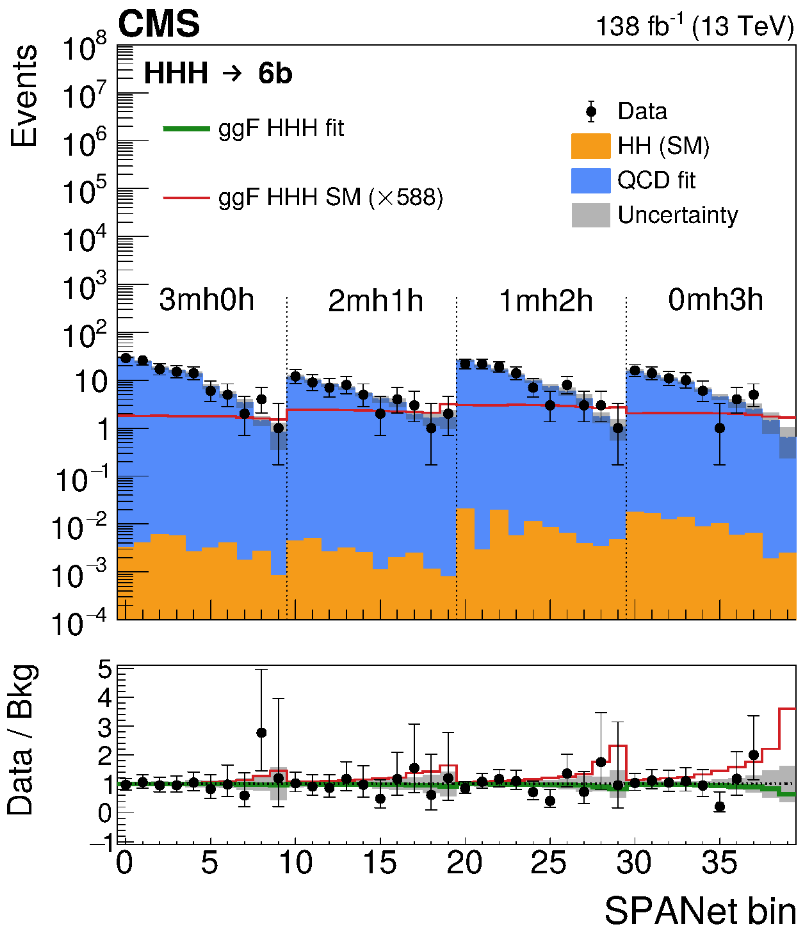

Figure 1: Post-fit yields in the SR categories with three reconstructed H. Bins correspond to ten intervals per category of the SPANET score ProbMultiH in the high-score range 0.8–1.0, ordered by increasing purity.

and merged topologies enhance the overall sensitivity by up to 20% relative to the resolved categories alone. While the 3H region alone yields the strongest constraint among individual groups, the combination of all categories improves the sensitivity by $\sim$10%. The observed (expected) UL on the HHH production signal strength is 588 (572) times the SM prediction at 95% CL, corresponding to an UL on the cross section of 44 (43) fb.

To constrain the H self-coupling modifiers, two types of profile likelihood scans are performed: one-dimensional (1D) scans, in which one coupling modifier is varied while the other is fixed to its SM value, and 2D scans, in which both couplings are varied simultaneously. The 1D scans provide the most stringent constraints on κ_3 and κ_4.

The observed (expected) constraints are $-7.4 < \kappa_3 < 12.4$ ($-6.4 < \kappa_3 < 11.2$) assuming $\kappa_4 = 1$, and $-177 < \kappa_4 < 185$ ($-180 < \kappa_4 < 190$) assuming $\kappa_3 = 1$, at 95% CL. Including the HH process in the fit improves the expected κ_3 constraint by $\sim$9%. Two-parameter likelihood scans in the (κ_3, κ_4) plane yield the 68 and 95% CL contours shown in Fig. 2 (right). The scans fix the top quark Yukawa coupling to its SM value and account only for overall normalization effects in both the HHH and HH processes. For HHH and HH production, both κ_3 and κ_4 are varied following the parametrization in Refs. [44, 105]. Notably, the simultaneous (κ_3, κ_4) fit yields expected and observed constraints that exclude regions of parameter space permitted

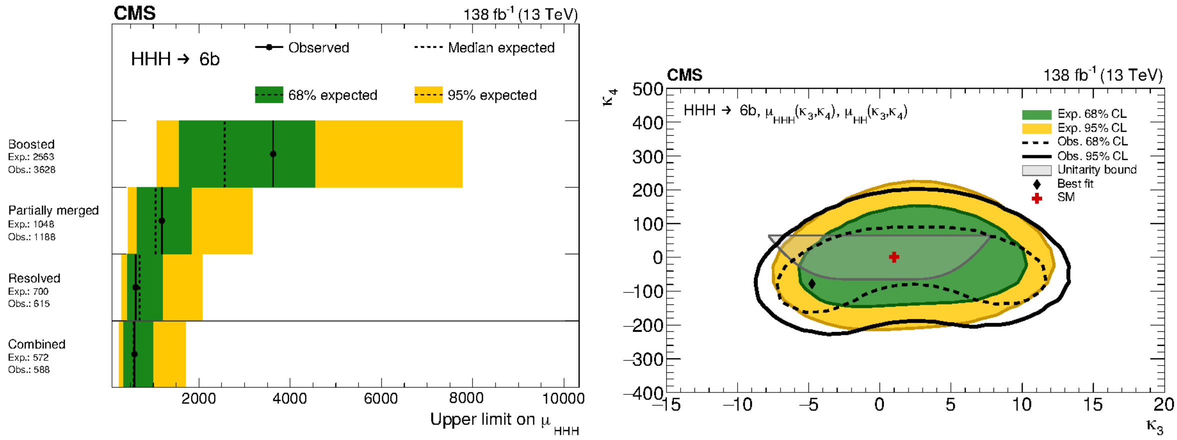

Figure 2: Expected and observed ULs on the HHH signal strength shown separately for merged, partially merged, and resolved event topologies, along with the combined result (left). The 68 and 95% CL contours in the (κ_3, κ_4) plane from the combined profile likelihood scan (right). The gray region denotes parameter space allowed by perturbative unitarity in HH $\to$ HH scattering [47].

by the perturbative unitarity bound [47]. Complementary projected sensitivities for the high-luminosity (HL)-LHC scenario ($\sqrt{s} = 14\,\text{TeV}$, $3\,\text{ab}^{-1}$) are presented in the End Matter. The coupling-strength results focus on cross-section-only scaling for both HHH and HH, assuming the SM signal topology for every coupling value. In the HH process, changes in couplings result in substantial alterations in signal kinematics; increasing κ_3 leads to a softer signal [106, 107], resulting in a loss of efficiency. A similar effect occurs in the HHH process, also for large κ_4 variations. Using the event reweighting method as in Refs. [41, 46], the inclusion of kinematic effects on both HHH and HH processes is estimated to worsen the κ_3 constraint by 12–15% on the expected boundary for $\kappa_4 = 1$. For $\kappa_3 = 1$, including κ_4-dependent kinematic effects in HHH degrades the expected κ_4 boundary by $\sim$2–4%. The state-of-the-art predictions for HH considering electroweak κ_4 effects were studied in recent references, including an event-generation implementation, which is summarized in Ref. [27]. The results are presented by considering the effect of κ_4 on the HH cross section in the SM-like event topology, as computed in Ref. [44]. A dedicated treatment of κ_4-dependent shape effects in HH is beyond the scope of this analysis.

In summary, this Letter presents a search for nonresonant triple Higgs boson (HHH) production in the final state with six bottom quarks using $138\,\text{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 13\,\text{TeV}$ collected by the CMS experiment between 2016 and 2018. No significant deviation from the background prediction is observed. At 95% confidence level, the observed (expected) upper limit on the HHH production cross section is 44 (43) fb, corresponding to 588 (572) times the standard model prediction. In the framework of Higgs boson self-coupling modifiers (κ), the search constrains the trilinear coupling modifier κ_3 to $-7.4 < \kappa_3 < 12.4$ for the quartic coupling modifier $\kappa_4 = 1$ and constrains κ_4 to $-177 < \kappa_4 < 185$ for $\kappa_3 = 1$. The two-dimensional (κ_3, κ_4) scan constrains, for the first time in a direct search for nonresonant HHH production, the perturbative unitarity boundary and excludes part of the allowed parameter space. These results are the most stringent constraints to date on nonresonant HHH production and on κ_4.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

A End Matter

A.1 The CMS detector

The CMS apparatus [56, 57] is a multipurpose, nearly hermetic detector, designed to trigger on [58–60] and identify electrons, muons, photons, charged and neutral hadrons [61–63]. A global "particle-flow" algorithm [78] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker, and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors interleaved with the layers of the 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 4 μs [58]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [59, 60].

A.2 Datasets and object reconstruction

Signal samples for ggF HHH production, with representative Feynman diagrams shown in Fig. 3, are generated at LO with MADGRAPH5_aMC@NLO 2.6.5 [64], using the model file of

Ref. [25]. Nine samples with different (κ_3, κ_4) values are produced using the implementation of Ref. [25], and intermediate points are obtained by event reweighting following Refs. [41, 46]. The samples are normalized to the inclusive cross section at NNLO in perturbative QCD, including finite top quark mass effects [26]. A single SM K-factor [26] is applied to all beyond-SM points, derived for the SM case to match the NNLO prediction. The ggF HH process is simulated at NLO using POWHEG 2.0 [23, 65–74], with additional κ_3 points constructed by reweighting and normalized to the corresponding NNLO cross sections [14–21]. Associated $\mathrm{t\bar{t}}$HH and VHH production processes are generated at LO with MADGRAPH5_aMC@NLO and included to study contamination effects, using the model files of Refs. [95, 108].

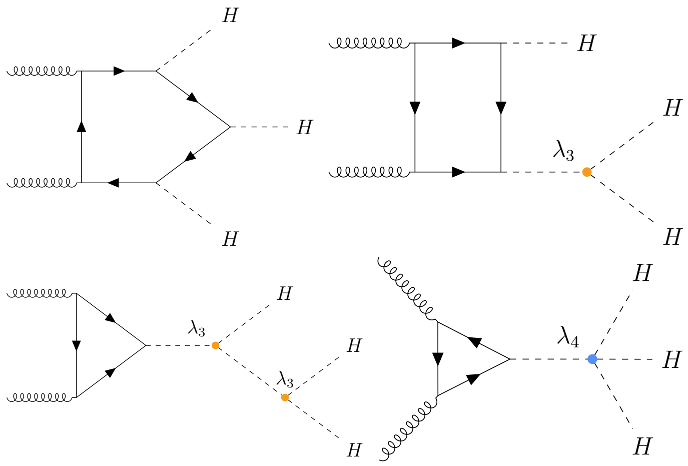

Figure 3: Representative leading-order Feynman diagrams for nonresonant HHH production via gluon fusion. The last three diagrams provide direct sensitivity to the trilinear (λ_3) and quartic (λ_4) H self-couplings.

The dominant background, accounting for ∼95% of events, is QCD multijet production. It is modeled with a method fully based on control samples in data, while simulated samples produced with MADGRAPH5_aMC@NLO 2.6.5 [64] at LO with up to four partons in the matrix element and binned in H_{T} are used exclusively for analysis optimization. The next-to-largest background is $\mathrm{t\bar{t}}$ production, generated at NLO with POWHEG 2.0 [65–67, 109, 110] and normalized to the NNLO cross section using TOP++ [111, 112]. Samples of W and Z bosons produced in association with jets, diboson processes, and single H production are simulated with MADGRAPH5_aMC@NLO or POWHEG and contribute negligibly after the final selection.

Parton showering, hadronization, and the underlying event are modeled with PYTHIA 8.205 [75] using the CP5 tune [76] and NNPDF 3.1 NNLO PDFs [77]. The CMS detector response is simulated with GEANT4 [113], and pileup interactions are overlaid and reweighted to match the distribution observed in data.

The HHH → 6b process is characterized by six b quarks reconstructed as jets, balanced transverse momentum, and the absence of isolated charged leptons. Standard jet energy corrections are applied as functions of η and p_{T} [114]. The vector $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is computed from the p_{T} sum of all reconstructed particles with PUPPI weights [115] and corrected for the scale of the reconstructed jets in the event. Electrons and muons are reconstructed and identified according to Refs. [61, 62, 116, 117], and events containing isolated leptons within the tracker and muon detector acceptance are vetoed.

Events of interest are selected using a two-tiered trigger system [58–60]. In 2016, triggers required at least six jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $H_{\mathrm{T}} > 450\,\mathrm{GeV}$ with one b-tagged jet, or six jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $H_{\mathrm{T}} > 400\,\mathrm{GeV}$, and two b-tagged jets. In 2017 (2018), triggers required at least four jets with $p_T > 40$, 45, 60, and 75 GeV, and $H_T > 300$ (330) GeV with at least three b-tagged jets. To avoid biases, events are required to have $H_T > 450$ GeV, yielding an acceptance of ∼80% for HHH → 6b signal events. A high-purity hadronic $t\bar{t}$ CR is used to derive a residual H_T-dependent nonclosure uncertainty of 5–10%.

In the offline selection, events are required to contain at least four small-radius jets with $|\eta| < 2.4$ (2.5) and $p_T > 25$ GeV for 2016 (2017–2018). Small-radius jets must satisfy a tight particle-flow jet identification working point, and for $p_T < 50$ GeV a medium pileup discriminant requirement. Large-radius jets are selected with $p_T > 300$ GeV and $|\eta| < 2.5$.

The identification of jets originating from b quarks and of $b\bar{b}$ pairs is crucial for the analysis. The PARTICLENET algorithm [84, 85] is employed for both small- and large-radius jets. For small-radius jets, a 2D distribution is constructed from p_{B+C}, the probability for a jet to originate from a heavy-flavor quark (b or c), and p_{BvsC}, the probability for a jet to originate from a bottom rather than a charm quark. This distribution is discretized into ten categories, following the definitions and calibrations in Ref. [86], and all categories are used in the analysis. For reference, the highest efficiency bin corresponds to a b-tagging efficiency of ∼44% for b jets with $p_T > 60$ GeV, and misidentification probabilities of 0.01 and 0.10% for light-flavor quark or gluon jets and charm jets, respectively. The PARTICLENET algorithm is also used for the identification of $H \to b\bar{b}$ in large-radius jets, with the discriminator output discretized into three categories corresponding to two tagging-efficiency working points, with efficiencies of 40 and 20%, respectively, and calibrated using the $Z \to b\bar{b}$ process, as described in Ref. [87].

A.3 Projection for the High-Luminosity LHC program

Projections are derived under the S3 scenario [118, 119], which assumes improved b-tagging performance based on PARTICLENET optimization studies. The projected limits include the effects of κ_4 in the HH modeling, as done for the main result. Figures 4 and 5 show the current and HL-LHC sensitivities for the HHH → 6b analysis.

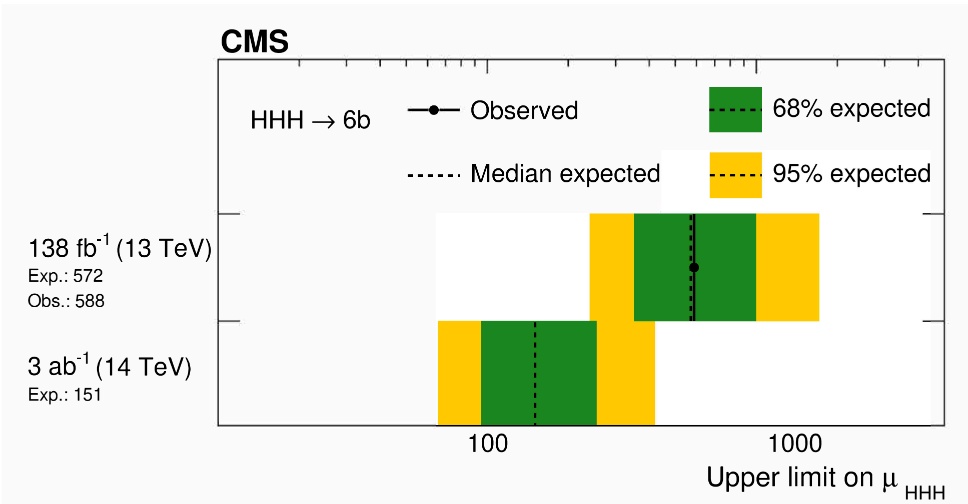

Figure 4: Observed and expected 95% CL upper limits on the HHH signal strength μ_{HHH}. Results are shown for the analyzed dataset of 138 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV, along with projections for 14 TeV and an integrated luminosity of 3 ab^{-1}.

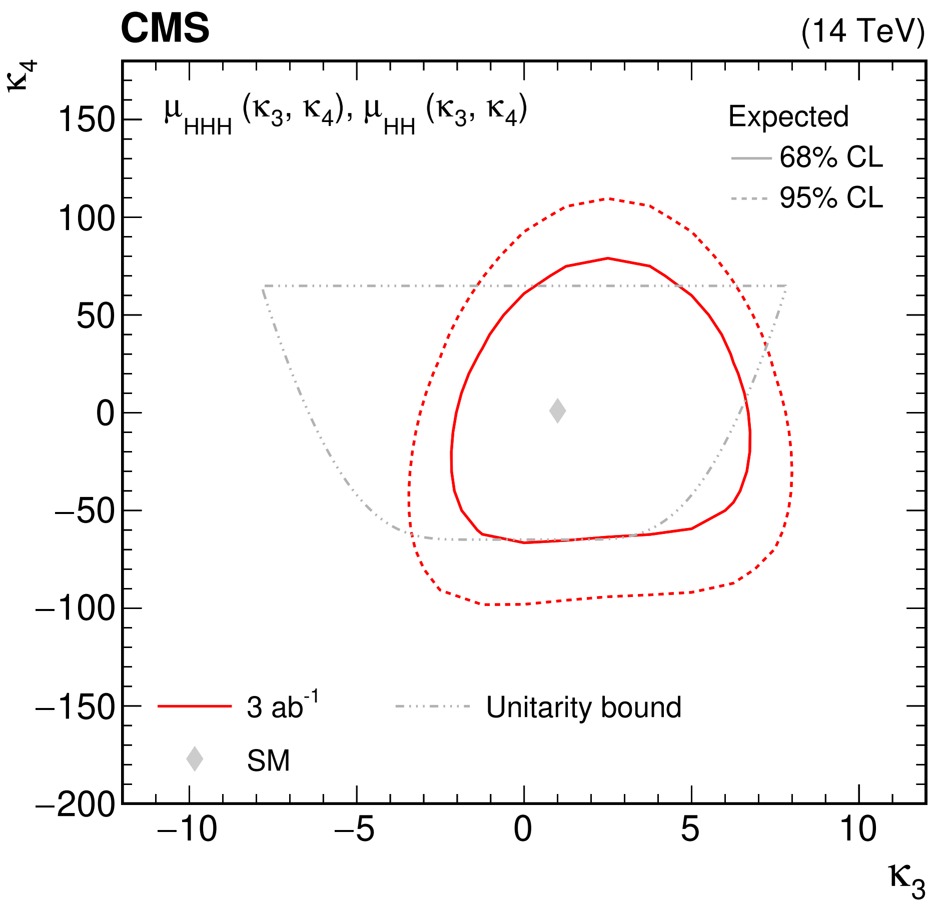

Figure 5: Expected 68 and 95% CL constraints in the (κ_3, κ_4) plane for the HHH $\rightarrow$ 6b analysis in the HL-LHC scenario ($\sqrt{s} = 14\,\text{TeV}$, $3\,\text{ab}^{-1}$). The unitarity boundary is overlaid, and the best-fit point from the projection is indicated.

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B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Gevorgyan, A. Hayrapetyan, V. Makarenko, A. Tumasyan[1]

Marietta Blau Institute for Particle Physics, Vienna, Austria
W. Adam, L. Benato, T. Bergauer, M. Dragicevic, S. Gundacker, A.K. Guven, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, J. Schieck[2], R. Schöfbeck[2], M. Shooshtari, M. Sonawane, N. Van Den Bossche, W. Waltenberger, C.E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, D. Ocampo Henao, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
D. Ahmadi, J. Bierkens, N. Breugelmans, S. Dansana, A. De Moor, M. Delcourt, S.A.G. Duponcheel, C. Gupta, F. Heyen, Y. Hong, K. Kang, P. Kashko, S. Lowette, I. Makarenko, S. Nandakumar, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, T. Wybouw

Université Libre de Bruxelles, Bruxelles, Belgium
A. Beshr, B. Bilin, F. Caviglia Roman, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, E. Ducarme, H. Evard, L. Favart, I. Kalaitzidou, A. Khalilzadeh, A. Malara, A. Potrebko, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, C. Yuan, F. Zhang

Ghent University, Ghent, Belgium
A. Cauwels, M. De Coen, D. Dobur, C. Giordano, G. Gokbulut, K. Kaspar, D. Kavtaradze, D. Marckx, A. Mehta, K. Skovpen, A.M. Tomaru, J. van der Linden, J. Vandenbroeck

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Aarup Petersen, A. Benecke, A. Bethani, G. Bruno, A. Cappati, J. De Favereau De Jeneret, C. Delaere, F. Gameiro Casalinho, A. Giammanco, A.O. Guzel, M. Hussain, Z. Lawrence, V. Lemaitre, J. Lidrych, P. Malek, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G. Alves, M. Barroso Ferreira Filho, E. Coelho, M.V. Gonçalves Sales, C. Hensel, D. Matos Figueiredo, T. Menezes De Oliveira, C. Mora Herrera, P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[4], A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], G. Correia Silva, M. Costa Reis, E.M. Da Costa, D. Da Silva Dalto, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. Jesus, T. Laux Kuhn[6], K. Maslova Gioseffi Defante, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[7], D. Torres Machado

Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil
C.A. Bernardes, L. Calligaris, J. Carvalho Leite, F. Damas, E. De Moraes Gregores, B. Lopes Da Costa, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, S. Padula, M. Pereira Coelho, V. Scheurer, T. Tomei

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,

Bulgaria
A. Aleksandrov, G. Antchev, P. Danev, R. Hadjiiska, P. Iaydjiev, M. Shopova, G. Sultanov

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

Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
S. Keshri, D.N. Laroze Navarrete, M. Meena, S. Thakur

Universidad Técnica Federico Santa María, Valparaiso, Chile
W. Brooks

Beihang University, Beijing, China
T. Cheng, L. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
J. Gu, Z. Hu, Z. Liang, J. Liu, X. Wang, Y. Wang, H. Yang, S. Zhang, Y. Zhao

Institute of High Energy Physics, Beijing, China
N. Bi[8], G.M. Chen[8], H.S. Chen[8], M. Chen[8], Y. Chen, B. Hou[8], Q. Hou, F. Iemmi, C.H. Jiang, P.z. Lai, H. Liao, G. Liu, Z. Liu[9], S. Song[8], J. Tao, C. Wang[8], J. Wang, A. Zada[8], H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, X. Geng, B. Guo, Q. Guo, Z. He, C. Jiang, A. Levin, C. Li, L. Li, Q. Li, X. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, C. Quaranta, X. Sun, D. Wang, J. Wang, T. Yang, M. Zhang, M. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China, Guangzhou, China
X. Hua, S. Yang

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

University of Science and Technology of China, Hefei, China
N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[10,11], L. Chen, Z. Cui[11], B. Li[12], H. Wang, K. Yi[13], J. Zhang, F. Zhu

Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China
C. Li

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Y. Li, Z. Wang, Y. Zhou[14]

Zhejiang University - Department of Physics, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[15]

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

Universidad de Antioquia, Medellin, Colombia

C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

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

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, S. Konstantinou, C. Leonidou, L. Paizanos, F. Ptochos, P.A. Razis, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Acurio

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla[16], Y. Assran[17,18], B. El-mahdy[16]

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Jaffel, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, N. Seeba, L. Tani

Department of Physics, University of Helsinki, Helsinki, Finland
E. Brücken, A. Milieva, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
F.I. Garcia Fuentes, T. Hilden, P. Inkaew, K.T.S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, N.T. Toikka, J. Tuominiemi, E. Veikkola

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
N. Bin Norjoharuddeen, H. Kirschenmann, P.R. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, F. Guilloux, G. Hamel de Monchenault, M. Kumar, V. Lohezic, Y. Maidannyk, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M.Ö. Sahin, P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
R. Amella Ranz, F. Beaudette, K. Biriukov, G. Boldrini, P. Busson, F. Cetorelli, C. Charlot, M. Chiusi, T.D. Cuisset, O. Davignon, A. De Wit, T. Debnath,

I.T. Ehle, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, L.m. Rabour, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, Y. Song, L. Urda Gómez, B. Voirin, A. Zabi, A. Zghiche

Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
J.L. Agram[19], J. Andrea, D. Bloch, E.C. Chabert, C. Collard, G. Coulon, C. Eschenlauer, S. Falke, U. Goerlach, A.C. Le Bihan, G. Saha, A. Savoy-Navarro[20], P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio, G. Mauceri, B. Orzari

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, J. Daniel, P. Depasse, H. El Mamouni, J. Fay, E. Fillaudeau, S. Gascon, M. Gouzevitch, C. Greenberg, B. Ille, E. Jourd'Huy, M. Lethuillier, K. Long, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, C. Verollet

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[21]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
K.F. Adamowicz, V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, E. Ehlert, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, M.Z. Farkas, B. Fischer, T. Hebbeker, K. Hoepfner, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, J.G. Schulz, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, U. Willemsen, S. Zaleski, F.P. Zinn

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M.R. Beckers, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
A. Abel, A. Akhil, M. Aldaya Martin, J. Alimena, Y. An, I. Andreev, J. Bach, S. Baxter, H. Becerril Gonzalez, O. Behnke, F. Blekman[22], K. Borras[23], L. Braga Da Rosa, A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[22], A. Geiser, M. Guthoff, A. Hinzmann, U. Husemann, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, F. Labe, W. Lange, D. Leyva Pernia, J.h. Li, K.y. Lin, K. Lipka[24], W. Lohmann[25], J. Malvaso, R. Mankel, I.A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[26,23], S. Schnake[23], C. Schwanenberger[22], D. Schwarz, P. Schütze, D. Selivanova, K. Sharko, M. Shchedrolosiev, A. Sritharan, D. Stafford, M. Torkian, S. Vashishtha, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[23], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, L. Ebeling,

K. El Morabit, Y. Fischer, M. Frahm, P.P. Gadow, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, M. Jalalvandi, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, J. Lange, A. Lobanov, J. Matthiesen, L. Moureaux, K. Nikolopoulos, K.J. Pena Rodriguez, N. Prouvost, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, T. von Schwartz, R. Ward, B. Wiederspan, M. Wolf, C. Yede

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany
J. Ahäuser, A. Brusamolino, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[27], F. Hummer, J. Kieseler, M. Klute, H.A. Krause, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J.M. Lawhorn, S. Maier, N. Meenamthuruthil Radhakrishnan, T. Mehner, M. Molch, A.A. Monsch, M. Mormile, T. Müller, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, T. Selezneva, N. Shadskiy, L. Sowa, L. Stockmeier, M. Toms, B. Topko, N. Trevisani, C. Verstege, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, J.H. Voss, C. Winter, R. Wolf, W.D. Zeuner, X. Zuo

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

National and Kapodistrian University of Athens, Athens, Greece
P. Iosifidou, P. Katris, M. Kotsarini, G. Melachroinos, Z. Painesis, N. Plastiras, N. Saoulidou, K. Theofilatos, E. Tzovara, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, K. Paschos, L.P. Rouseliotaki, E. Siamarkou, A. Taxeidi, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

Department of Physics, School of Sciences Democritus, University of Thrace, Kavala, Greece
E. Tziaferi

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[28,29], Á. Kadlecsik, C. Lee, K. Márton, A.J. Rádl[30], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
G. Balint, M. Csanad, K. Farkas, A. Fehérkuti[31], M.M.A. Gadallah[32], M. León Coello, G. Pasztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T.F. Csorgo[31], F. Nemes[31], T. Novak, I. Szanyi[33]

Indian Institute of Science (IISC), Bangalore, India
J.R. Komaragiri

Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
S. Bahinipati, R. Raturi

Panjab University, Chandigarh, India
S. Bansal, V. Bhatnagar, B. Chauhan, S. Chauhan, N. Dhingra[34], A. Kaur, H. Kaur, S. Kumar, T. Sheokand, A. Singla, K. Verma

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, S. Phor, C. Prakash, K. Ranjan, M.K. Saini

Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India
M. Kumari, P. Palni, S. Rana, A. Rathore, A. Sarkar

University of Hyderabad, Hyderabad, India
S. Acharya[35], B. Gomber, S.K. Satapathy

Indian Institute of Technology Kanpur, Kanpur, India
S. Mukherjee

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, P.R. Pujahari, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Indian Institute of Science Education and Research Mohali, Mohali, India
A. Chauhan, S. Nayak, H. Rajpoot, B.K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, T. Mishra, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Barman[36], R.M. Chatterjee, J. Chhikara, M. Guchait, S. Jain, A. Jaiswal, S. Kumar, M. Maity[36], G. Majumder, K. Mazumdar, R. Pramanik, R. Saxena, P. Sharma, A. Thachayath

National Institute of Science Education and Research, Jatni, Khorda, Odisha 752050, India Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India, Odisha, India
R. Kumar Agrawal, D. Maity[37], P. Mal, K. Naskar[37], A. Nayak[37], K. Pal, P. Sadangi, S. Shuchi, S.K. Swain, S. Varghese[37], D. Vats[37]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, P. Hazarika, A. Laha, R. Sharma, S. Sharma, K.Y. Vaish

Indian Institute of Technology Hyderabad, Telangana, India
C. Agrawal, B. Babu, S. Ghosh

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[38], A. Jafari[39], V. Sedighzadeh Dalavi, M. Zeinali[40]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[41], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, M. Nourbakhsh, S. Tizchang[42]

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

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,43], N. Ferrara[a,c], L. Fiore[a], L. Generoso[a,b], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], S. My[a,b], F. Nenna[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], F.M. Procacci[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,b], A. Stamerra[a,b], Ü. Sözbilir[a,44], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], S. Balducci[a,b], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F.R. Cavallo[a], M. Cruciani[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], R. Farinelli[a], D. Fasanella[a], L. Ferragina[a,b], P. Giacomelli[a], C. Grandi[a], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], F. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], A. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,45], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,45]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], G. Barbagli[a], G. Bardelli[a], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Colafranceschi[46], S. Meola[47], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca, Milano[b], Milano-Bicocca, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Università della Basilicata (Potenza)[c], Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], F. Confortini[a,b], C. Di Fraia[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,48], P. Paolucci[a,27], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Universita degli Studi di Cagliari[c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,49], D. Bisello[a,b], L. Borella[a], P. Bortignon[a,c], G. Bortolato[a,b],

A.C.M. Bulla[a,c], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,50], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], P. Grutta[a], N. Lai[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Missiroli[a], J. Pazzini[a,b], F. Primavera[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Toffano[a], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], 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
S. A. AbuZeid[a,51], C. Aimè[a], A. Braghieri[a], M. Brunoldi[a,b], P. Montagna[a,b], M. Pelliccioni[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[a], W.D. Buitrago Ceballos[a,b], C. Carrivale[a,b], D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,52], F. Napolitano[a], 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], Università di Siena[d], Pisa, Italy
C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Dhani[a,d], S. Donato[a,b], A. Feliziani[a,d], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], M. Del Vecchio[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], L. Martikainen[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], T. Pauletto[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Università del Piemonte Orientale (Novara)[c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a,c], F. Bashir[a,b], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], L. Bulaja[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], E. Ferrando[a,b], M. Ferrero[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Luongo[a,b], C. Mariotti[a,53], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], F. Rotondo[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], C. Tarricone[a,b], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b,54], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b], C. Giraldin[a,b]

Joint Institute for Nuclear Research, Dubna, Russia, JINR
S. Afanasiev, V. Alexakhin, Y. Andreev, D. Budkouski, R. Chistov, M. Danilov, T. Dimova, I. Gorbunov, A. Kamenev, V. Karjavine, O. Kodolova[55], V. Korenkov, I. Korsakov, A. Kozyrev, A. Lanev, A. Malakhov, V. Matveev, A. Nikitenko[56,55],

V. Palichik, V. Perelygin, O. Radchenko, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen, K. Slizhevskiy, V. Smirnov, O. Teryaev, A. Toropin, N. Voytishin, A. Zarubin, I. Zhizhin

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, J. Kim, T. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - Gangneung-Wonju National University, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, H. Lee, S. Lee, D.H. Moon, J. Seo

Department of Physics, Chung-Ang University, Seoul, Korea
K. Lee, Y. Lee

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[57], T.J. Kim, Y. Ryou, J. Song, T. Yang

Korea University, Seoul, Korea
S. Ha, B.S. Hong, J. Kim, K. Lee, K. Lee, S. Lee, J. Padmanaban, B.A.N. Putra, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, J. Shin, S. Yang

Sejong University, Seoul, Korea
L. Kalipoliti, Y. Kang, H. Kim, Y. Kim, B. Ko, S. Lee

Seoul National University, Seoul, Korea
J. Choi, J. Choi, W. Jun, H. Kim, J. Kim, J. Kim, T. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, J. Shin, U. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Heo, W. Jang, D. Kim, S. Kim, Y. Roh, I. J. Watson

Yonsei University, Department of Physics, Seoul, Korea
S. Calzaferri, G. Cho, Y. Eo, K. Hwang, H. Jang, B. Kim, D. Kim, S. Kim, J.S.H. Lee, G. Mocellin, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Lee, I. Yu

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

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O.M. Eberlins, A. Gaile, J.K. Heikkilä, M. Klevs, C. Munoz Diaz, D. Osite, G. Pikurs, R. Plese, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, S. Nargelas, S. Nayak, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[58], Z. Zolkapli

University of Sonora (UNISON), Hermosillo, Mexico
J.P. Barajas Ibarria, J.F. Benitez, A. Castaneda Hernandez, A. Cota Rodriguez, L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic, N. Raicevic

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, W.A. Khan, I. Sohail

AGH University of Krakow, Krakow, Poland
V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
H. Awedikian, M. Bluj, M. Ghimiray, 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, W. Matyszkiewicz, A. Muhammad, S. Slawinski

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi[53,59], G. Da Molin, M. Gallinaro, R. Guitton, J. Hollar, H. Legoinha, N. Leonardo[60], G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, L. Markovic, P. Milenovic, V. Milosevic, J. Mitic

Vinca Institute of Nuclear Science, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

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

M. Alcalde Martinez, J. Alcaraz Maestre, J.A. Brochero Cifuentes, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Escalante Del Valle, C. Fernandez Bedoya, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, M. Gonzalez Hernandez, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, O. Manzanilla, C. Martin Perez, E. Martin Viscasillas, D. Moran, C.M. Morcillo Perez, Á. Navarro Tobar, J. Puerta Pelayo, A.M. Pérez-Calero Yzquierdo, I. Redondo, D.D. Redondo Ferrero, J. Vazquez Escobar

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
E. Aller Gutierrez, B. Alvarez Gonzalez, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, S. Sanchez Cruz, A. Soto Rodríguez, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I.J. Cabrillo, A. Calderon, M. Caserta, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, C. Quintana San Emeterio, V. Rodriguez, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[61]

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G. Dharmaratna[62], N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, I. Bestintzanos, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, K. Cormier, D. D'Enterria, A. Dabrowski, P. Das, A. David Tinoco Mendes, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, L. Favilla, P.J. Fernández Manteca, E. Fialova, B.A. Fontana Santos Alves, E. Fontanesi, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, R. Hofsaess, B. Huber, T. James, P. Janot, L. Jeppe, O. Kaluzinska, O. Karacheban[25], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, J. León Holgado, C. Lourenco, A.m. Lyon, M. Magherini, L. Malgeri, E. Manca, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M.C. Muehlnikel, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, F. Pereira Carneiro, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Scarfi, S.F. Schaefer, M. Selvaggi, P. Silva, P. Sphicas[63], A.G. Stahl Leiton, A. Steen, S. Summers, G. Terragni, D. Treille, P. Tropea, E. Vernazza, M. Vojinovic, J. Wanczyk[64], S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

Synthetic Institute for people with CERN contract, Geneva, Switzerland
L. Dudko, V. Kim[65], V. Murzin, V. Oreshkin, D. Sosnov

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
L. Caminada[66], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, A. Nigamova, L. Noehte[66], L. Redard-Jacot[66], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, A. Belvedere, T. Bevilacqua[66], G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'Archiacchiac[64], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Glessgen, C. Grab, T.G. Harte, N. Härringer, B. Kaynak, M. Koppel, W. Lustermann, M. Malucchi, R.A. Manzoni, L. Marchese, F. Nessi-Tedaldi, F. Pauss, A.A. Petre, J. Prendi, B. Ristic, S. Rohletter, P.M. Sander, R. Seidita, A. Tarabini, C.Z. Tee, D. Valsecchi, P.H. Wagner, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[67], F. Bilandzija, P. Bärtschi, M.F. Canelli, G. Celotto, Z. Ghafoor, T.A. Goldschmidt, V. Guglielmi, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, J. Motta, P. Robmann, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

Çukurova University, Adana, Türkiye
D. Agyel, F. Dolek, I. Dumanoglu[68], Y. Guler[69], E. Gurpinar Guler[69], A. Kayis Topaksu, G. Onengut, K. Ozdemir[70], B. Tali[71], U.G. Tok, E. Uslan

Hacettepe University, Ankara, Türkiye
S. Sen

Bogazici University, Istanbul, Türkiye
B. Akgun, I.O. Atakisi[72], E. Gülmez, M. Kaya[73], O. Kaya[74], M.A. Sarkisla[75], S. Tekten[76]

Istanbul Technical University, Istanbul, Türkiye
D. Boncukcu, A. Cakir, K. Cankocak[68,77], M. Gumustekin, A.D. Gungordu

Istanbul University, Istanbul, Türkiye
B. Hacisahinoglu, I. Hos[78], S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Türkiye
S. Cerci, C. Dozen[79], E. Iren[80], B. Isildak, E. Simsek, D. Sunar Cerci, T. Yetkin[79]

National Central University, Chung-Li, Taiwan
D. Bhowmik, Y.h. Chou, C.M. Kuo, P.K. Rout, S. Taj, P.C. Tiwari[81]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, Z.g. Chen, A. De Iorio, G.W.S. Hou, H.w. Hsia, T.h. Hsu, S. Karmakar, F. Khuzaimah, G. Kole, Y.y. Li, R.S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

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

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
K. Klimenko, O. Kurov, L. Levchuk, S. Lukyanenko, A. Pristavka, D. Soroka

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F.J.J. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.l. Holmberg, A. Karakoulaki, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[38], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A. Ball, K.W. Bell, A. Belyaev[82], C. Brew, R.M. Brown, D.J. Cockerill, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, T. Schuh, C. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, S. Awan, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, A. Cox, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, L. Lyons, A.M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, J. Nash[83], M. Pesaresi, P.B. Pradeep, E.V. Protopapa, B.C. Radburn-Smith, A. Richards, A. Rose, T.B. Runting, L. Russell, K. Savva, R. Schmitz, C. Seez, R. Shukla, A. Tapper, T. Travis, K. Uchida, G.P. Uttley, T. Virdee[27], N. Wardle, D. Winterbottom, J. Xiao

Brunel University, Uxbridge, United Kingdom
J. Cole, L. Juckett, A. Khan, P. Kyberd, I. Reid

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, R. Kaur, A. Khukhunaishvili, K. Matchev, E. Pearson, P. Rumerio[84], E. Usai

University of California, Davis, Davis, California, USA
S. Abbott, S. Baradia, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P.T. Cox, F. Eble, R. Erbacher, C. Fairchild, O. Kukral, S. Ostrom, I. Salazar Segovia, J.H. Steenis, J.S. Tafoya Vargas, W. Wei, S. Yoo

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, R. Marroquin Solares, M. Masciovecchio, F. Mokhtar, S. Morovic, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

University of California, Los Angeles, California, USA
K. Adamidis, H. Ancelin, M. Bachtis, D. Campos, R. Cousins, S. Crossley, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, A. Nunez Del Prado, D. Saltzberg, V. Valuev

California Institute of Technology, Pasadena, California, USA
A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, Z. Hao, R. Kansal, L. Mori, H.B. Newman, G. Reales Gutiérrez, T. Sievert, P. Simmerling, E. Sledge, M. Spiropulu, C. Sun, J.R. Vlimant, R.A. Wynne, S. Xie, R.Y. Zhu

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[85], K. Downham, C. Grieco, J.S. Guo, M.M. Hussain, D. Imani, J. Incandela, A. Krishna, M.W.K. Lai, P. Masterson, J.J.H. Ockenfuss, J. Richman, S.N. Santpur, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, J. Fraticelli, A. Hart, M. Herrmann, S. Kwan, J. Pearkes, N. Schonbeck, K. Stenson, K. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

The Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, B. Sahu, A.E. Simsek, B. Singhal, S.S. Yu

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, C. Basile, D. Bourilkov, P. Chang, V. Cherepanov, M. Dittrich, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Das, S. Demarest, L. Hasa, M. Hohlmann, M. Lavinsky, E. Yanes

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, D. Alam, A. Askew, S. Bower, R. Goff, R. Hashmi, A. Hassani, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P.R. Prova, R. Yohay

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H. Cheung, F. Chlebana, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, J. Hirschauer, V. Innocente, B. Jayatilaka, S. Jindariani, M. Johnson, R.S. Kim, S. Lammel, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[86], C.E. Perez Lara, V. Perovic, F. Ravera, A. Reinsvold Hall[87], L. Ristori, M. Safdari, E. Sexton-Kennedy, E. Smith, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Wang, I. Zoi

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, N. Barnett, A. Baty, C. Bennett, N. Brandman-hughes, R. Cavanaugh, S.J. Das, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, Z. Huang, J.h. Lee, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, V. Pant, T. Phan, D. Pilipovic, R. Pradhan,

E. Prifti, T. Roy, D. Shekar, N. Singh, F. Strug, A. Thielen, M. Tonjes, N. Varelas, M.A. Wadud, A. Wang, J. Yoo

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, S. King, D. Li, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco, J. Wang, D. Wilbern

Purdue University Northwest, Hammond, Indiana, USA
N. Parashar, A. Pathak, E. Shumka

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, S. Castells, A. Das, A. Datta, A. Ehnis, R. Goldouzian, M. Hildreth, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, D. Lutton, J. Mariano, N. Marinelli, P. Mastrapasqua, A. Masud, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[88], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

Purdue University, West Lafayette, Indiana, USA
S. Chandra, A. Gu, L. Gutay, L. He, M. Huwiler, M. Jones, A.W. Jung, I.G. Karslioglu, D. Kondratyev, J. Li, M. Liu, M. Macedo, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, N.R. Saha, J.F. Schulte, R. Sharma, F. Wang, A.L. Wesolek, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[89], O.K. Köseyan, A. Mestvirishvili[59], O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, R. Bhattacharya, M. Chukwuka, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, E. Reynolds, C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, J.A. Velazquez Corral, G. Wilson

Kansas State University, Manhattan, Kansas, USA
A. Ahmad, B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G.G. Reddy, D. Roy, G. Sorrentino

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A. Gritsan, Z. Huang, L. Kang, P. Maksimovic, N. Pinto, M. Roguljic, S. Sekhar, M.V. Srivastav, M. Swartz

University of Maryland, College Park, Maryland, USA
Z. Alton, D. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, J. Lee, P. Major, A. Mignerey, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[91], A. Shevelev, M. Wrotny, L. Zhang

Boston University, Boston, Massachusetts, USA
S. Cholak, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, J. Fulcher, J. Garcia De Castro, F. Golf, S. Jeon, G. Linney, J. O'Cain, I. Reed, J. Rohlf, D. Sperka, I. Suarez, A. Tsatsos, E. Wurtz, A.G. Zecchinelli

Northeastern University, Boston, Massachusetts, USA
A. Aarif, G. Alverson, E. Barberis, S. Bein, J. Bonilla, B. Bylsma, M. Campana, R. Clark, J. Dervan, Y. Haddad, Y. Han, I. Israr, M. Lu, N. Manganelli,

R. Mccarthy, D.M. Morse, T. Orimoto, L. Skinnari, C.S. Thoreson, E. Tsai, D. Wood

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I.A. Cali, Y.c. Chen, P.c. Chou, M. D'Alfonso, K. Devereaux, J. Eysermans, C. Freer, G. Gomez Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, A. Holtermann, G.M. Innocenti, K. Ivanov, G. Kopp, D. Kovalskyi, J. Lang, L. Lavezzo, Y.J. Lee, P. Lugato, C. Mcginn, E. Moreno, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, T.a. Sheng, G. Stephans, D. Walter, J. Wang, Z. Wang, B. Wyslouch, T. Yang, K. Yoon

Wayne State University, Detroit, Michigan, USA
P.E. Karchin

University of Minnesota, Minneapolis, Minnesota, USA
A. Alpana, B. Crossman, W.J. Jackson, C. Kapsiak, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, S.V. Dixit, G. Haza, J. Hossain, C. Joo, I. Kravchenko, K.H.M. Kwok, Y. Mehra, J. Morris, A. Rohilla, J.E. Siado, A. Vagnerini, A. Wightman

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, C. Houghton, D. Jaroslawski, A. Kaur, A. Kobert, A. Lath, J. Martins, P. Meltzer, M. Perez Prada, K. Ramdin, B. Rand, J. Reichert, P. Saha, S. Salur, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, K. Kennedy, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully, S. Yoon

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, C. McLean, D. Nguyen, O. Poncet, S. Rappoccio, H. Rejeb Sfar, W. Terrill, D. Yu

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, G. De Castro, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, P. Kotamnives, K. Krzyzanska, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, A. Ryd, J. Thom, H.A. Weber, B. Weiss, P. Wittich, Y. Wu, R. Zou, L. Zygala

University of Rochester, Rochester, New York, USA
O. Bessidskaia Bylund, A. Bodek, R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, Y.w. Kao, N. Parmar, P. Parygin[91], H. Seo, R. Taus, Y.h. Yu

The Ohio State University, Columbus, Ohio, USA
M. Carrigan, R. De Los Santos, L.S. Durkin, C. Hill, M. Joyce, L. Nestor, D.A. Wenzl, B.L. Winer, B. Yates

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, A. Khanal, C. Liu, M. Marchegiani, P. Meiring, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, Y. Zhou

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, R. Sharma

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, S. Gottlieb, L. Gouskos, M. Hadley, L. Hay, U. Heintz, K.W. Ho, R. Jain, T. Kwon, L. Lambrecht, G. Landsberg, K.T. Lau, M. LeBlanc, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[92], X. Shen, M. Stamenkovic, S. Sunnarborg, J. Tang, N. Venkatasubramanian

University of Tennessee, Knoxville, Tennessee, USA
A. Abdelhamid, D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier, C. Thompson, A. Vendrasco

Vanderbilt University, Nashville, Tennessee, USA
U. Acharya, E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, I. Shvetsov, S. Tuo, J. Velkovska, J. Zhang

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Basnet, A. Bolshov, O. Bouhali[93], A. Cagnotta, S. Cooperstein, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, R. Mueller, G. Pizzati, A. Safonov

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, K.M. Ecklund, F.J. Geurts, I. Krommydas, N. Lewis, W. Li, J. Lin, X. Liu, C. Loizides, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, C. Vico Villalba, M. Wulansatiti, E. Yigitbasi, Y. Zhang

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, W. Jin, S.W. Lee, C. Madrid, S. Magedov, A. Mankel, T. Peltola, I. Volobouev

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, R. Menon Raghunandanan, C. Neu, C. Ramón Álvarez, Z. Wu

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, R. Cruz, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, S. Lomte, R. Loveless, J. Marquez, A. Mohammadi, S. Mondal, T. Nelson, G. Parida, D. Pinna,

A. Savin, V. Sharma, R. Simeon, W.H. Smith, D. Teague, M. Thakore, A. Thete, A. Warden

[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at Technische Universität Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
[5]Also at Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[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 University of Chinese Academy of Sciences, Beijing, China
[10]Also at School of Physics, Zhengzhou University, Zhengzhou, China
[11]Now at Henan Normal University, Xinxiang, China
[12]Also at University of Shanghai for Science and Technology, Shanghai, China
[13]Also at The University of Iowa, Iowa City, Iowa, USA
[14]Also at Nanjing Normal University, Nanjing, China
[15]Also at Center for High Energy Physics, Peking University, Beijing, China, Beijing, China
[16]Also at Cairo University, Cairo, Egypt
[17]Also at Suez University, Suez, Egypt
[18]Now at British University in Egypt, Cairo, Egypt
[19]Also at Université de Haute Alsace, Mulhouse, France
[20]Also at Purdue University, West Lafayette, Indiana, USA
[21]Also at Joint Institute for Nuclear Research, Dubna, Russia, JINR
[22]Also at University of Hamburg, Hamburg, Germany
[23]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[24]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[25]Also at Brandenburg University of Technology, Cottbus, Germany
[26]Also at Institute for Advanced Simulation - Jülich Supercomputing Centre, Juelich, Germany
[27]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[28]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[29]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[30]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[31]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[32]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[33]Also at The University of Kansas, Lawrence, Kansas, USA
[34]Also at Punjab Agricultural University, Ludhiana, India
[35]Also at University of Hyderabad, Hyderabad, India
[36]Also at University of Visva-Bharati, Santiniketan, India
[37]Also at Institute of Physics, Bhubaneswar, India
[38]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[39]Also at Isfahan University of Technology, Isfahan, Iran
[40]Also at Sharif University of Technology, Tehran, Iran
[41]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[42]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[43]Also at Helwan University, Cairo, Egypt
[44]Also at Kocaeli University, Kocaeli, Türkiye
[45]Also at Centro Siciliano di Fisica Nucleare e di Struttura della Materia, Catania, Italy

[46]Also at James Madison University, Harrisonburg, Virginia, USA
[47]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[48]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[49]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[50]Also at Lulea University of Technology, Lulea, Sweden
[51]Also at Ain Shams University, Cairo, Egypt
[52]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[53]Also at Boston University, Boston, Massachusetts, USA
[54]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[55]Now at Yerevan Physics Institute, Yerevan, Armenia
[56]Also at Imperial College, London, United Kingdom
[57]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[58]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[59]Also at Georgian Technical University, Tbilisi, Georgia
[60]Also at Departamento de Física Instituto Superior Técnico Universidade de Lisboa, Lisbon, Portugal
[61]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[62]Also at Saegis Campus, Nugegoda, Sri Lanka
[63]Also at National and Kapodistrian University of Athens, Athens, Greece
[64]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[65]Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
[66]Also at Universität Zürich, Zurich, Switzerland
[67]Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
[68]Also at Near East University, Research Center of Experimental Health Science, Mersin, Türkiye
[69]Also at Konya Technical University, Konya, Türkiye
[70]Also at Izmir Bakircay University Faculty of Engineering and Architecture, Izmir, Türkiye
[71]Also at Adiyaman University, Adiyaman, Türkiye
[72]Also at Istanbul Sabahattin Zaim University, Istanbul, Türkiye
[73]Also at Marmara University, Istanbul, Türkiye
[74]Also at Milli Savunma University, Naval Academy, Istanbul, Türkiye
[75]Also at The Science and Technological research Council of Türkiye, Informatics and Information Security Research Center, Gebze/Kocaeli, Türkiye
[76]Also at Kafkas University, Kars, Türkiye
[77]Now at Istanbul Okan University, Istanbul, Türkiye
[78]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Türkiye
[79]Also at Istinye University Vadi Campus, Ayazağa District Azerbaijan Street (Vadistanbul 4A) Sarıyer, İstanbul, Türkiye
[80]Also at Mimar Sinan University, Istanbul, Istanbul, Türkiye
[81]Also at Indian Institute of Science (IISC), Bangalore, India
[82]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[83]Also at Monash University, Faculty of Science, Clayton, Australia
[84]Also at Università di Torino, Torino, Italy
[85]Also at California Lutheran University, Thousand Oaks, California, USA
[86]Also at California Institute of Technology, Pasadena, California, USA
[87]Also at United States Naval Academy - Physics Department, Annapolis, Maryland, USA
[88]Also at Institute for Nuclear Research, Moscow, Russia

[89]Also at Bingol University, Bingol, Türkiye
[90]Also at Sinop University, Sinop, Türkiye
[91]Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
[92]Also at Karamanoğlu Mehmetbey University, Karaman, Türkiye
[93]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar