Search for a cH signal in the associated production of at least one charm quark with a Higgs boson in the diphoton decay channel in pp collisions at $$\sqrt{s}=13$$ TeV

Published for SISSA by Springer

Received: *March 11, 2025*
Accepted: *September 19, 2025*
Published: *November 12, 2025*

Search for a cH signal in the associated production of at least one charm quark with a Higgs boson in the diphoton decay channel in pp collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: This paper presents the first search for a cH signal sensitive to the coupling of the charm quark (c) to the Higgs boson (H) in the associated production of at least one charm quark with a Higgs boson decaying to two photons. The results are based on a data set of proton-proton collisions at a center-of-mass energy of 13 TeV collected with the CMS experiment at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. Assuming the standard model (SM) rates for all other Higgs boson production processes, the observed (expected) upper limit at 95% confidence level on the cH signal strength is 243 (355) times the SM prediction. Under the same assumption, the observed (expected) allowed interval on the Higgs boson to charm quark coupling modifier, κ_c, is $|\kappa_c| < 38.1$ ($|\kappa_c| < 72.5$) at 95% confidence level.

Keywords: Charm Physics, Hadron-Hadron Scattering, Higgs Physics

ArXiv ePrint: 2503.08797

https://doi.org/10.1007/JHEP11(2025)060

Contents

1 Introduction

The Higgs boson (H) was discovered [1–3] by the ATLAS and CMS experiments in 2012, completing the fundamental particle spectrum of the standard model (SM) and setting a milestone for particle physics. Since then, many measurements of the Higgs boson's properties including its spin, mass, and several of its couplings [4–12] have been performed. They refine our understanding of the Brout-Englert-Higgs mechanism [13–16] responsible in the SM for the masses of fundamental particles. Any deviation from the SM predictions for the properties of the Higgs boson would provide an indication of possible new physics beyond the SM.

The couplings of the Higgs boson to all third-generation fermions (b quark, t quark, and tau lepton) have been observed [17–29]. The couplings to second-generation fermions are still under investigation. In the searches for the Higgs boson decay to muons with the CMS and ATLAS experiments [30, 31], the observed significance at the Higgs boson mass of the incompatibility with the background-only hypothesis was 3 and 2 standard deviations, respectively. An important next step will be the observation of the Higgs boson coupling to second-generation quarks. Currently, the most sensitive process used to probe Higgs boson couplings to the charm quark, c, is the $\mathrm{H} \to \mathrm{c\bar{c}}$ decay. The upper limits on the $\mathrm{H} \to \mathrm{c\bar{c}}$ signal strength based on the full Run 2 data sets of the ATLAS and CMS experiments, are, respectively, 11.5 and 14 times the SM prediction [32, 33]. The corresponding observed 95% CL interval for the Yukawa coupling modifier of the Higgs boson to charm quarks, κ_c, is $|\kappa_\mathrm{c}| < 4.2$ and $1.1 < |\kappa_\mathrm{c}| < 5.5$, respectively. Improving the experimental sensitivity to this coupling is one of the major goals of the CMS Higgs boson physics program. Further, but weaker, constraints could be obtained from searches for a Higgs boson decay to a quarkonium state and a photon [34, 35].

JHEP11(2025)060

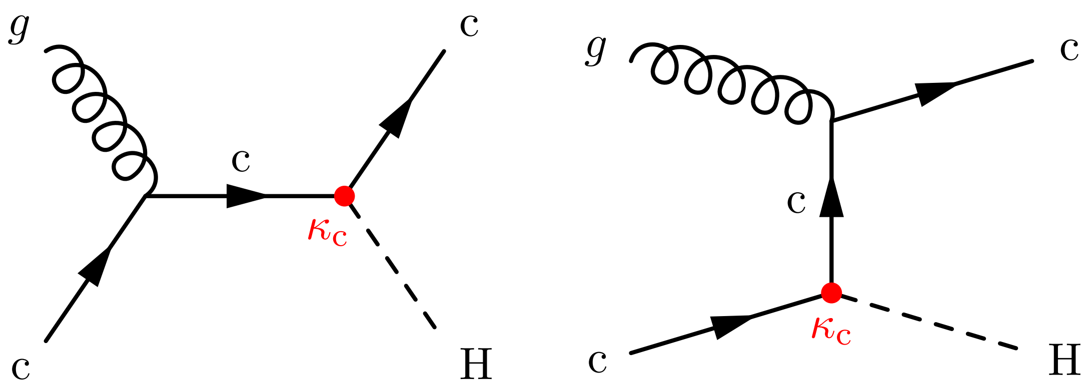

Figure 1. Leading order Feynman diagrams that contribute to the pp $\to$ cH process. Red dots correspond to vertices where the charm Yukawa coupling modifier κ_c enters.

An additional possibility is to search for a cH signal containing a ccH vertex in the associated production of a Higgs boson and at least one charm quark [36, 37]. Leading order (LO) Feynman diagrams contributing to the pp (proton-proton) $\to$ cH process are shown in figure 1. These κ_c-dependent contributions will be indicated with cH in the following, and correspond to the target signal processes of this analysis. The ATLAS collaboration has recently reported on a search for the inclusive production of a Higgs boson and at least one charm quark (the inclusive H+c process dominated by gluon-gluon fusion) [38]. The ATLAS analysis did not measure the cH component that is sensitive to the Yukawa coupling of the Higgs boson to charm quarks. Hence no constraint on $|\kappa_c|$ was reported.

This paper presents the first search for a $|\kappa_c|$ sensitive cH signal with a Higgs boson that decays to two photons. The results are based on the CERN LHC Run 2 data set of pp collisions at a center-of-mass energy of 13 TeV, collected with the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} [39–41]. The main background processes are the continuous quantum chromodynamics (QCD) diphoton production and γ+jets processes, where the jet is mis-identified as a photon, and a resonant background from other Higgs boson production mechanisms. The former does not produce a peak in the diphoton mass spectrum and is estimated from data, while the latter is signal-like and estimated using simulation, assuming the SM hypothesis. In the SM scenario, i.e., for $\kappa_c = 1$, cH production has a very low cross section compared to the main background processes. However, in certain scenarios beyond the SM, κ_c could be significantly different from one and therefore result in a higher cH production cross section [42–47].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there 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. ECAL consists of 75 848 lead tungstate crystals, which provide coverage

JHEP11(2025)060

in pseudorapidity $|\eta| < 1.48$ in a barrel region and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). Preshower detectors consisting of two planes of silicon sensors interleaved with a total of 3 radiation length of lead are located in front of each EE detector. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. Muons are reconstructed in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in refs. [48, 49].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [50]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [51, 52].

3 Simulated samples

Signal and background processes are simulated with several Monte Carlo (MC) programs. The generator POWHEGBOX [53–55] at next-to-leading order (NLO) in QCD is used to simulate Higgs boson production through gluon-gluon fusion (ggH) [56], while the generator MADGRAPH5_aMC@NLO [57–59] (version 2.4.2) at NLO in QCD is used to generate Higgs boson production processes through vector boson fusion (VBF), associated production with a vector boson (VH, V = W/Z), associated production with a pair of top quarks ($\mathrm{t\bar{t}H}$), associated production with a bottom quark (bH), and associated production with a charm quark (cH). The process where a Higgs boson is produced in association with a single top quark (tH) is not included since its contribution is negligible. The cross sections and branching fractions for the processes are taken from the LHC Higgs Cross Section Working Group report [60].

For the cH signal and the bH background processes, a new dedicated simulation is designed specifically for this analysis. This simulation considers the most important production modes, which are proportional to the square of the charm and bottom Yukawa couplings for the cH and bH processes, respectively. The contributions coming from the interference between cH/bH and ggH terms and the H+c and H+b parts that are not sensitive to the Yukawa couplings of the c and b quarks were found to be negligible for the sensitivity reached by this analysis. In these associated production processes there are two ways of performing the fixed order amplitude calculation, i.e. depending on whether the c and b quarks are considered to be massive or not in the computation. By convention, b quarks are considered massive in the 4-flavor scheme (4FS) and massless in the 5-flavor scheme (5FS). This applies in the same way to the c quarks in the 3- and 4-flavor schemes, respectively. These approaches are supposed to address issues that arise in different kinematic regimes, which one may classify by considering if the mass of the quark plays the role of a hard scale in the process under investigation. Considering the quarks as massless objects at the level of short-distance interactions has the advantage of resulting in much simpler calculations than their massive counterparts, but leads to divergences at low energies so that such events are not simulated down to $p_{\mathrm{T}} = 0$ at matrix element level. When matched to parton showers (PS) though, this information can be recovered thanks to the backward evolution of the initial-state c and b quarks. This will generate heavy-flavor hadrons in the final state, thus recovering realistic c- and b-tagging requirements, regardless of their transverse momenta [61].

After studying the dependence of the cross section and the kinematics with respect to the FS, as well as the treatment of the renormalization (μ_R), factorization (μ_F) and PS scales in the simulation, by comparing samples with different starting values for these parameters and exploring both a fixed and dynamic scale choices [59], the nominal cH and bH samples used in the analysis were generated treating the charm and bottom quarks as massless (4FS for cH and 5FS for bH). A dynamic treatment of the renormalization and factorization scale parameters was adopted, each with a starting value of $H_\mathrm{T}/4$, where $H_\mathrm{T} = \sum_i \sqrt{m_i^2 + p_{Ti}^2}$ and i runs over the outgoing parton of the fixed order calculation. This massless-quark approach enables the use of the FxFx merging procedure [58] within the NLO simulation, thus improving the description of the kinematic observables by reducing the dependence on the PS for additional emissions. The cross sections are found to be $\sigma_\mathrm{cH} = 90\,\mathrm{fb}$ and $\sigma_\mathrm{bH} = 660\,\mathrm{fb}$, where the calculation is obtained from a dedicated study following the method presented in ref. [61]. An uncertainty covering the residual discrepancies in the yield prediction between massive and massless FSs after the scale optimization, mostly due to cross section differences and the distribution of the c-quark jet η, was extracted by comparing the expected event counts obtained using a massive and a massless FS of each process (cH, bH). The typical size of this uncertainty is 25–30%.

The signal and resonant background samples are processed with PYTHIA version 8.240 [62] for modeling of parton showering, hadronization and underlying events with the CUETP8M1 [63] (CP5 [64]) tune for the simulation of 2016 (2017–2018) data. Parton distribution functions (PDFs) are taken from the NNPDF 3.0 [65] (3.1 [66]) set, when simulating 2016 (2017–2018) data. In contrast, the diphoton background ($\gamma\gamma$+jets) is generated with SHERPA version 2.2.4 [67], which produces tree-level processes with up to three additional jets, as well as loop-induced processes. The single-photon (γ+jet) background is modeled with PYTHIA 8.212 at LO. The continuous background MC samples are used only for the optimization of the analysis, while the background model for signal extraction is entirely derived from the data. For all the processes, GEANT4 [68] is used to simulate the detector response. The simulated events include additional pp interactions within the same or nearby bunch crossings (pileup), as observed in the data.

4 Object selection

The primary collision vertex is identified using a multivariate technique based on a boosted decision tree (BDT) [69]. Charged hadrons originating from other vertices are removed from the analysis.

A global “particle-flow” algorithm [70] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the ECAL and HCAL, with data from the gas-ionization muon detectors. Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory to the ECAL. Electrons are identified as a primary charged-particle track and potentially many ECAL energy clusters corresponding to this track extrapolation to the ECAL and to possible

JHEP11(2025)060

bremsstrahlung photons emitted along the way through the tracker material. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Charged hadrons are identified as charged-particle tracks neither identified as electrons, nor as muons, also using HCAL information. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged-hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged-hadron energy deposit.

The photon energy is measured with the ECAL. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected 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.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti-k_T algorithm [71, 72] with a distance parameter of 0.4. Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Pileup interactions can contribute with additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for the remaining contributions [73]. Jet energy corrections derived from simulation are used to bring the measured jet energy to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [74]. The jet energy resolution is 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [74]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [73].

The photons used in the analysis are required to satisfy an identification (photon ID) criterion based on a BDT classifier trained to separate photons from jets [75]. Inputs to the photon ID BDT, such as shower shape and isolation variables in the simulation, are corrected with a chained quantile regression method [76] to match the data better than a few percent across the whole spectrum of the output BDT.

Jets originating from charm quarks are identified by a DeepJet algorithm based on deep neural networks [77–79]. For each jet, the algorithm outputs a CvsL score to separate charm from light-quark or gluon (u, d, s, g) jets. The chosen working point has a typical efficiency for charm jets of $\sim$30% and a typical rejection for light-quark or gluon jets of $\sim$95%. The DeepJet algorithm also provides a CvsB score to discriminate charm and bottom quark jets. However, given that the dominant backgrounds are the continuous background and the ggH process (most events of which do not contain bottom quark jets), the CvsB score provides only minor improvement in analysis sensitivity and hence is not used.

JHEP11(2025)060

5 Event selection

Events are selected at the HLT using a diphoton trigger level [52] that includes a calorimeter-based photon identification requirement, with photon transverse momentum (p_{T}^{γ}) thresholds of 30 and 18 GeV for the leading and subleading photons, respectively, in 2016 data. For the 2017–2018 data-taking periods, the subleading p_{T}^{γ} threshold is increased to 22 GeV.

To target the $\mathrm{H} \rightarrow \gamma\gamma$ decay, events are required to have two identified photon candidates that are within the ECAL and tracker fiducial region ($|\eta| < 2.5$), excluding the ECAL barrel-endcap transition region ($1.44 < |\eta| < 1.57$). The diphoton candidates are required to pass the following criteria: $100 < m_{\gamma\gamma} < 180$ GeV, $p_{\mathrm{T}}^{\gamma 1}/m_{\gamma\gamma} > 1/3$, and $p_{\mathrm{T}}^{\gamma 2}/m_{\gamma\gamma} > 1/4$, where $m_{\gamma\gamma}$ denotes the diphoton mass and $p_{\mathrm{T}}^{\gamma 1}$ ($p_{\mathrm{T}}^{\gamma 2}$) denotes the transverse momentum of the leading photon (subleading photon). The diphoton mass resolution, as measured in $\mathrm{H} \rightarrow \gamma\gamma$ decays, is typically in the 1–2% range, depending on the measurement of the photon energies in the ECAL and the event topology [11]. These criteria were optimized in the context of the inclusive $\mathrm{H} \rightarrow \gamma\gamma$ analysis [11] and are suitable for the cH analysis as well.

Furthermore, to target the associated charm quark in the signal process, events are required to have at least one jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. The jet with the largest p_{T} must be c tagged by requiring a CvsL score > 0.25. The CvsL score distributions for the leading jet in simulated cH signal and resonant background events, as well as sideband data events, are shown in figure 2. Sideband data events are selected in the diphoton signal mass intervals $100 < m_{\gamma\gamma} < 120$ GeV and $130 < m_{\gamma\gamma} < 180$ GeV.

6 Event categorization

Two BDT classifiers are constructed using the XGBoost package [80]. The first, BDT1, is trained using events from simulated samples of the cH signal and the ggH background, which accounts for more than 60% of the resonant background. The second, BDT2, is trained using events from simulated samples of the cH signal and the continuous background. The BDTs are constructed to have an output between 0 and 1.

For the training of both BDTs, the input features are $p_{\mathrm{T}}/m_{\gamma\gamma}$, η, and photon ID [69] score of the two leading photons, the p_{T} and η of the leading jet, the difference in ϕ (azimuthal angle) between the leading jet and each of the two photons, and the jet multiplicity. As no simulation is available to reliably model events with high jet multiplicity, the jet multiplicity feature is a categorical variable with only three possible values: 1, 2, and more than 2. The BDT input features are chosen based on their capacity to separate signal from background. The BDT trainings avoid using c tagging information, so that the event yield ratio between ggH+c jet and ggH+(u, d, s, g) jet is not strongly correlated with the BDT outputs and hence the heavy flavor (HF) modeling uncertainty can be applied on the overall normalization of ggH. The use of tagging information in training classifiers can be further explored in future analyses. Distributions of the outputs of the two BDTs for simulated cH signal and resonant background, as well as sideband data (as defined above, representing the continuous background) events passing the selection described in section 5, are shown in figure 3. The plots are indicative of the shapes of the distributions, showing that BDT1 separates cH from ggH production and BDT2 separates cH production from the continuous background. The

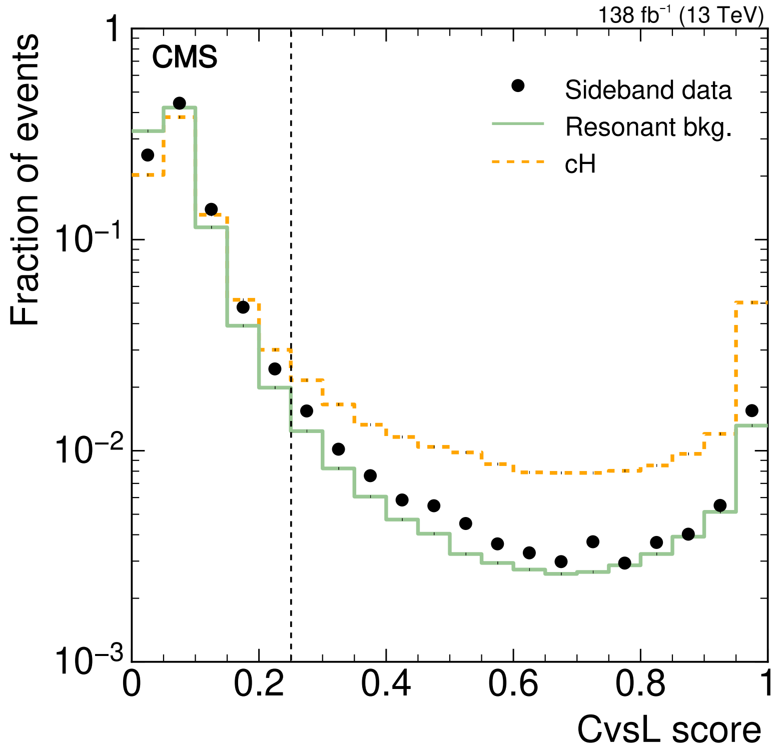

Figure 2. Distributions of the CvsL score for the leading jet in simulated cH signal and resonant background events and sideband data events. Error bars representing the statistical uncertainties in the data are too small to be displayed. Events with CvsL score values below the dashed vertical line are not included in the signal region.

plots should not be interpreted as a comparison of their magnitudes. The BDT1 plot shows the classifier is separating cH and resonant background, and the BDT1 plots

A two-dimensional classification is created to separate the cH signal from the main backgrounds. First, events are split into three classes according to the output of BDT1. The class boundaries are optimized to enhance the separation between the cH and ggH processes. The optimization is performed using an approximate formula based on event yields. Secondly, in each class, events are split into three categories according to the output of BDT2. The category boundaries are optimized to maximize the expected sensitivity of the analysis to the cH process. For simplicity, the same boundaries are adopted for the three classes, whose sensitivity is close to the case where boundaries in the three classes are optimized independently. The nine event categories are created for each of the three data-taking years, resulting in 27 categories in total. Two-dimensional distributions of BDT1 output and BDT2 output for cH, ggH, and sideband data in 2017 event categories are shown in figure 4. The boundaries of the nine event categories Tag0–8 are also shown.

7 Signal and background modeling

The diphoton mass distributions of the cH signal and the other Higgs boson processes are modeled using sums of multiple Gaussian functions, which are parametrized from simulation.

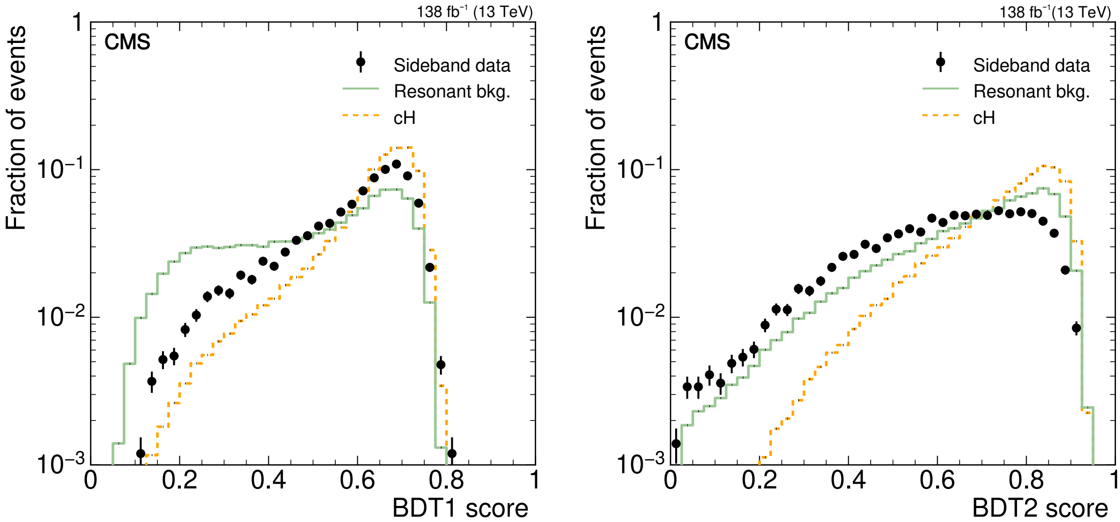

Figure 3. Distributions of BDT1 (left) and BDT2 outputs (right) for simulated cH signal and resonant background events, as well as sideband data (representing the continuous background) events. The BDT1 score discriminates the cH signal from the resonant background. The BDT2 score discriminates the cH signal from the continuous background. The plots are indicative of the shapes of the distributions and should not be interpreted as a comparison of their magnitudes. The error bars correspond to the statistical uncertainties.

The Higgs boson mass is fixed to 125.38 GeV, which is the best CMS measurement combining the diphoton and four-lepton channels [11]. An F-test [81] is performed to determine the optimal number of Gaussian functions for the signal model. In a given event category, a separate function is constructed for each Higgs boson process and the final signal model is obtained by summing the individual functions for all Higgs boson processes [69]. Figure 5 shows signal models for the analysis category with the tightest requirement in both BDT1 and BDT2 scores (left) and for the sum of all analysis categories (right).

The continuous background mass distributions are modeled using data with the discrete profiling method [82], which treats the choice of the analytic function as a discrete nuisance parameter in the likelihood fit. Several families of functions are considered, including exponential functions, Bernstein polynomials, Laurent series, and power law functions. For each family, an F-test [81] using the data sidebands ($100 < m_{\gamma\gamma} < 120$ GeV and $130 < m_{\gamma\gamma} < 180$ GeV) is performed to determine the maximum number of degrees of freedom, while the minimum number of degrees of freedom is determined based on goodness-of-fit criterion in the data sidebands. A signal injection test is also performed, which shows no significant bias of our background modeling.

8 Systematic uncertainties

The uncertainties in the continuous background estimation are accounted for by using the discrete profiling method. Shape uncertainties in the mass distributions of the cH signal and the other resonant background processes related to the photon energy scale and resolution and

JHEP11(2025)060

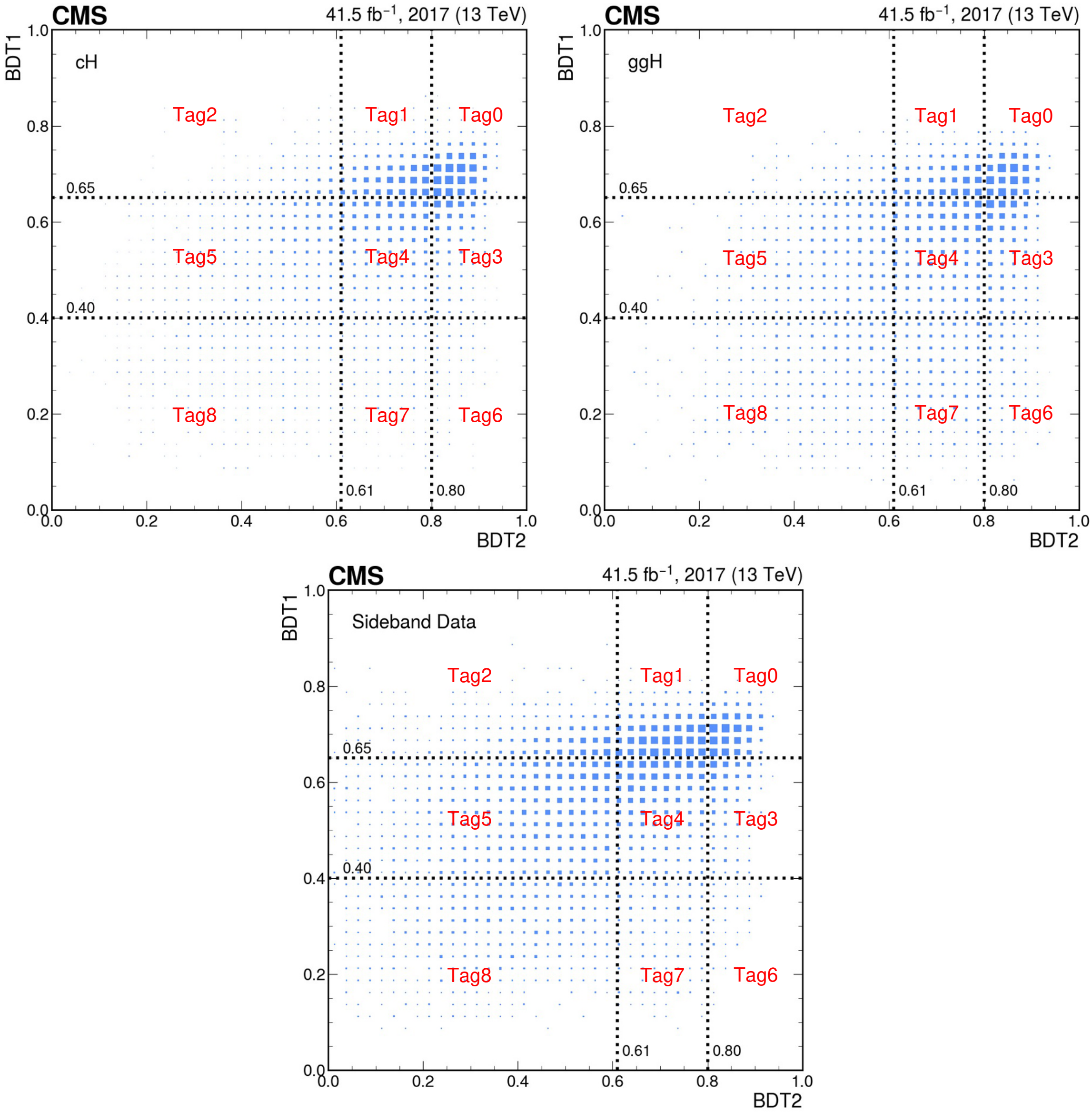

Figure 4. Two-dimensional distributions of BDT1 output (y axis) and BDT2 output (x axis) for cH (upper left), ggH (upper right), and sideband data (lower) in 2017 event categories. The BDT1 score discriminates the cH signal from the resonant background while the BDT2 score discriminates the cH signal from the continuous background. Event category boundaries on BDT scores are illustrated as dashed lines.

the assumed Higgs boson mass are considered as well. They are incorporated in the fit model as nuisance parameters that affect the mean and width of the respective Gaussian functions.

The dominant theoretical uncertainties in the yields of the Higgs boson processes across the event categories are due to the choice of the flavor scheme for cH and bH production and the HF modeling for ggH production. The typical size of the flavor scheme uncertainty is 25–30%. For the HF modeling, we assume the theoretical uncertainty found in ggH+b$\overline{\text{b}}$ [83] and therefore apply a 50% uncertainty in the inclusive ggH yield, larger than the current uncertainty in the inclusive ggH production. Future theoretical and experimental studies

JHEP11(2025)060

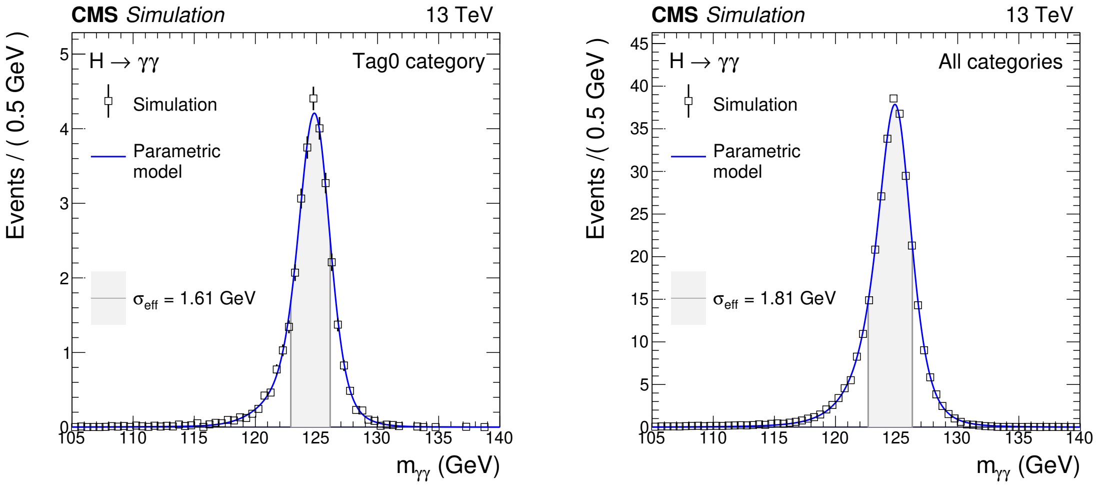

Figure 5. The shape of the parametric signal model for the analysis category with the tightest requirement in both BDT1 and BDT2 scores (left) and for the sum of all analysis categories (right). The open squares represent simulated events and the blue line represents the corresponding model. Also shown is the σ_{eff} value (half the width of the narrowest interval containing 68.3% of the diphoton mass distribution) in the grey shaded area.

may reduce the size of this modeling uncertainty. The uncertainties in the renormalization and factorization scales, the α_S value, PDFs, underlying event and parton shower modeling, and the $\mathrm{H} \to \gamma\gamma$ branching fraction are also considered. Their typical sizes are in the range of 1–20%. The theoretical uncertainties are correlated between the years. The main experimental uncertainties are related to c quark and photon identification as well as the jet and photon energy scales and resolutions. Their typical sizes are in the 2–10% range. Other experimental uncertainties, including those in the trigger efficiency, the diphoton preselection, and the pileup jet identification are less than 2%. Most of the experimental uncertainties are not correlated between the years. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [39–41], while the overall uncertainty for the 2016–2018 period is 1.6%.

9 Results

The following results have been obtained using the CMS statistical analysis tool Combine [84]. To extract the signal strength μ_{cH} of the cH process, defined as the ratio of the measured yield to the one predicted by the SM, we perform a simultaneous maximum likelihood fit to the $m_{\gamma\gamma}$ distributions in the 27 event categories. In the likelihood fit, the yields of all resonant Higgs boson production modes assume their SM predictions and are allowed to vary within their uncertainties, while the normalization and shape parameters of the continuous background in each category are unconstrained. All systematic uncertainties are included as nuisance parameters in the profile likelihood ratio [85, 86].

The invariant mass distribution of the selected events in all categories is shown in figure 6. For each category, the events are scaled by $\mathrm{S}/(\mathrm{S}+\mathrm{B})$, where S (B) is the number of expected signal (background) events in the smallest mass window containing 68.3% of the expected signal events. Curves for the signal + background fit, separately showing the resonant and

JHEP11(2025)060

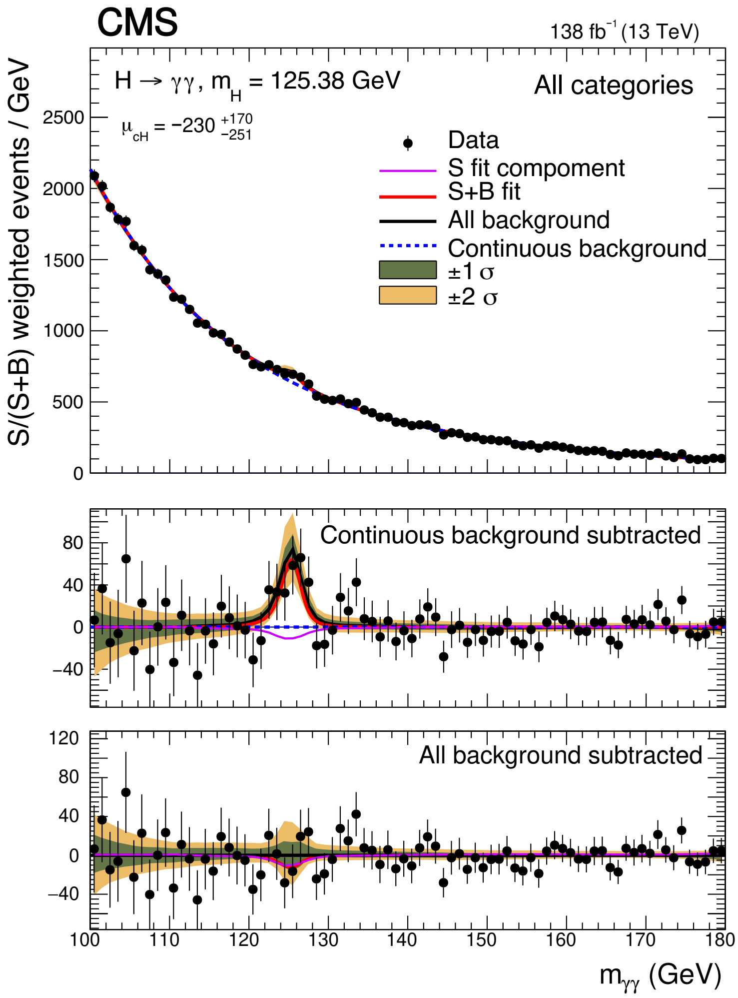

Figure 6. Invariant mass distribution of the selected events in all categories. For each category, the events are scaled by $\mathrm{S}/(\mathrm{S}+\mathrm{B})$, where S (B) is the number of expected signal (background) events in the smallest mass window containing 68.3% of the expected signal events. Curves for the signal + background fit (red), separately showing the resonant (black) and continuous (blue) backgrounds, as well as bands representing the 68.3% and 95.5% CL intervals in the background estimation, are overlaid. The middle (lower) panel shows the $m_{\gamma\gamma}$ distribution after subtracting only the continuous background (subtracting all background components) and overlaying the curve for the fitted signal (purple).

continuous backgrounds, as well as bands representing the 68.3% and 95.5% CL intervals in the background estimation, are overlaid. The resonant background visible in the figure is dominated by ggH production, where the leading jet consists of 25% c jet, 19% b jet and 57% (u, d, s, g) jet after the CvsL $>$ 0.25 selection. Table 1 shows the number of expected signal, resonant background and continuous background events in the mass window [122.88, 127.88] GeV around the assumed Higgs boson mass of 125.38 GeV [11] for all categories. The size of the mass window is about twice the diphoton invariant mass resolution.

The observed data are compatible with the background-only hypothesis. The observed μ_{cH} is evaluated to be -230^{+170}_{-251}. Using asymptotic distributions for the test statistic based on the profile likelihood ratio [85, 86], an observed (expected) upper limit at 95% CL on μ_{cH} is set at 243 (355) times the SM prediction.

JHEP11(2025)060

Category	Signal	Resonant background						Continuous	S/B
	cH	ggH	$t\bar{t}H$	VBF	VH	bH	Total	bkg. ($\times 10^3$)	($\times 10^{-5}$)
Tag0	0.013	84%	< 0.1%	5.3%	3.4%	7.5%	2.4	0.50	2.6
Tag1	0.016	79%	0.33%	7.3%	6.3%	7.3%	3.3	1.5	1.0
Tag2	0.0072	72%	4.0%	8.3%	9.1%	6.4%	1.8	7.4	0.10
Tag3	0.0034	72%	< 0.1%	16%	5.9%	5.6%	1.3	0.17	2.0
Tag4	0.0087	68%	1.2%	16%	9.9%	4.9%	3.5	0.96	0.90
Tag5	0.0094	54%	15%	15%	14%	3.6%	5.1	9.9	0.10
Tag6	0.00029	42%	1.9%	43%	12%	1.5%	0.52	0.019	1.5
Tag7	0.00095	43%	14%	25%	17%	1.3%	1.8	0.16	0.59
Tag8	0.0017	36%	32%	15%	17%	1.1%	3.3	1.9	0.087
All	0.060	61%	9.4%	14%	11%	4.5%	23	23	0.27

Table 1. Number of expected signal cH ($H \to \gamma\gamma$), resonant background and continuous background events, as well as the resulting signal-over-background ratio (S/B) in the diphoton mass window [122.88, 127.88] GeV for all categories. For each category, the event yields for the three years are summed. The fraction of different production processes contributing to the resonant background (ggH, $t\bar{t}H$, VBF, VH, and bH) is also reported.

Furthermore, a specific fit is performed to set constraints on κ_c. Taking the "flat direction" approach introduced in ref. [37], the modifier of the other Higgs coupling strengths, κ_H, depends on κ_c and the branching fraction of the $H \to c\bar{c}$ decay predicted by the SM, $\mathcal{B}^{SM}_{c\bar{c}}$, so that the signal strengths of non-cH Higgs boson processes in the diphoton decay channel are always unity:

$$\kappa_H^2 = \frac{(1 - \mathcal{B}^{SM}_{c\bar{c}})}{2} + \frac{\sqrt{(1 - \mathcal{B}^{SM}_{c\bar{c}})^2 + 4\mathcal{B}^{SM}_{c\bar{c}}\kappa_c^2}}{2}. \tag{9.1}$$

The signal strength of the cH process μ_{cH} can, however, be modified by κ_c through the production cross section as well as partial and total decay widths:

$$\mu_{cH} = \frac{\kappa_c^2\kappa_H^2}{(1 - \mathcal{B}^{SM}_{c\bar{c}})\kappa_H^2 + \mathcal{B}^{SM}_{c\bar{c}}\kappa_c^2}. \tag{9.2}$$

At 95% CL, the observed (expected) constraint is $|\kappa_c| < 38.1\,(72.5)$. The confidence intervals presented in this analysis are based on an asymptotic approximation. As demonstrated in ref. [87], the coverage achieved using this asymptotic method aligns reasonably well with the intended coverage across all tested parameters, including scenarios similar to this analysis.

The sensitivity of this analysis is limited by the statistical uncertainty in the data, and the systematic uncertainties in the choice of flavor scheme, factorization and renormalization scales for cH production, and the HF modeling of ggH production. Table 2 shows the impacts of several uncertainty groups divided by the total uncertainty in the signal strength measurement.

As a cross-check of the resonant background normalization, we perform another maximum likelihood fit floating the inclusive signal strength of Higgs boson production (including cH,

Uncertainty group	Fraction of total impact
Statistical	66%
Theoretical in the cH signal	38%
Theoretical in the resonant background	59%
Experimental in the yields	27%
Experimental in the mass shapes	$<1\%$
Integrated luminosity	$<1\%$

Table 2. Impacts of several uncertainty groups divided by the total uncertainty in the signal strength measurement. The systematic uncertainties are described in section 8.

ggH, and the other Higgs boson production modes) in all analysis categories. The observed (expected) inclusive signal strength is evaluated to be $0.8^{+0.8}_{-0.4}$ $(1.0^{+0.7}_{-0.4})$, also compatible with the SM prediction.

Tabulated results are provided in the HEPData record for this analysis [88].

10 Summary

We have presented the first search for a cH signal sensitive to the coupling of the charm quark (c) to the Higgs boson (H) in the associated production of at least one charm quark with a Higgs boson in proton-proton collisions at a center-of-mass energy of 13 TeV. Assuming the signal strengths of non-cH Higgs production processes in the diphoton decay channel to be as predicted by the standard model (SM), the observed and expected upper limits at 95% confidence level on the cH signal strength are 243 and 355 times the SM predictions, respectively. This search also provides sensitivity to the Yukawa coupling between the Higgs boson and the charm quark. Under the same assumption, the observed (expected) allowed interval on the Higgs boson to charm quark coupling modifier κ_c is $|\kappa_c| < 38.1$ ($|\kappa_c| < 72.5$) at 95% confidence level. The analysis is presently limited by statistical and theoretical uncertainties. Improvements can be achieved by incorporating complementary Higgs boson decay channels and, as larger data sets become available, implementing more refined selection criteria and categorization strategies, such as discriminating charm and bottom quark jets and constructing classifiers distinguishing between more Higgs boson production modes.

Acknowledgments

We thank M. Zaro and D. Pagani for their help in the calculation and generation of the signal process.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction

JHEP11(2025)060

and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, TKP2021-NKTA-64, and 2021-4.1.2-NEMZ_KI-2024-00036 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MICIU/AEI/10.13039/501100011033, ERDF/EU, "European Union NextGenerationEU/PRTR", and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

JHEP11(2025)060

Data Availability Statement. 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.

Code Availability Statement. The CMS core software is publicly available on GitHub.

References

[1] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [arXiv:1207.7214] [INSPIRE].

[2] CMS collaboration, *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [arXiv:1207.7235] [INSPIRE].

[3] CMS collaboration, *Observation of a New Boson with Mass Near 125 GeV in pp Collisions at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **06** (2013) 081 [arXiv:1303.4571] [INSPIRE].

[4] ATLAS collaboration, *Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment*, *Eur. Phys. J. C* **76** (2016) 6 [arXiv:1507.04548] [INSPIRE].

[5] CMS collaboration, *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV*, *Eur. Phys. J. C* **75** (2015) 212 [arXiv:1412.8662] [INSPIRE].

[6] CMS collaboration, *Study of the Mass and Spin-Parity of the Higgs Boson Candidate Via Its Decays to Z Boson Pairs*, *Phys. Rev. Lett.* **110** (2013) 081803 [arXiv:1212.6639] [INSPIRE].

[7] ATLAS collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, *Phys. Lett. B* **726** (2013) 120 [arXiv:1307.1432] [INSPIRE].

[8] ATLAS and CMS collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **08** (2016) 045 [arXiv:1606.02266] [INSPIRE].

[9] CMS collaboration, *Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **11** (2017) 047 [arXiv:1706.09936] [INSPIRE].

[10] ATLAS collaboration, *Combined measurement of differential and total cross sections in the $H \to \gamma\gamma$ and the $H \to ZZ^* \to 4\ell$ decay channels at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett. B* **786** (2018) 114 [arXiv:1805.10197] [INSPIRE].

[11] CMS collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, *Phys. Lett. B* **805** (2020) 135425 [arXiv:2002.06398] [INSPIRE].

[12] CMS collaboration, *Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. D* **111** (2025) 092014 [arXiv:2409.13663] [INSPIRE].

[13] P.W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, *Phys. Rev. Lett.* **13** (1964) 508 [INSPIRE].

[14] P.W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. **12** (1964) 132 [INSPIRE].

[15] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett. **13** (1964) 321 [INSPIRE].

[16] P.W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. **145** (1966) 1156 [INSPIRE].

[17] ATLAS collaboration, *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. D **90** (2014) 112015 [arXiv:1408.7084] [INSPIRE].

[18] CMS collaboration, *Observation of the Diphoton Decay of the Higgs Boson and Measurement of Its Properties*, Eur. Phys. J. C **74** (2014) 3076 [arXiv:1407.0558] [INSPIRE].

[19] ATLAS collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. D **91** (2015) 012006 [arXiv:1408.5191] [INSPIRE].

[20] CMS collaboration, *Measurement of the Properties of a Higgs Boson in the Four-Lepton Final State*, Phys. Rev. D **89** (2014) 092007 [arXiv:1312.5353] [INSPIRE].

[21] ATLAS collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, Phys. Rev. D **92** (2015) 012006 [arXiv:1412.2641] [INSPIRE].

[22] ATLAS collaboration, *Study of $(W/Z)H$ production and Higgs boson couplings using $H \to WW^*$ decays with the ATLAS detector*, JHEP **08** (2015) 137 [arXiv:1506.06641] [INSPIRE].

[23] CMS collaboration, *Measurement of Higgs Boson Production and Properties in the WW Decay Channel with Leptonic Final States*, JHEP **01** (2014) 096 [arXiv:1312.1129] [INSPIRE].

[24] ATLAS collaboration, *Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*, JHEP **04** (2015) 117 [arXiv:1501.04943] [INSPIRE].

[25] CMS collaboration, *Evidence for the 125 GeV Higgs Boson Decaying to a Pair of τ Leptons*, JHEP **05** (2014) 104 [arXiv:1401.5041] [INSPIRE].

[26] CMS collaboration, *Search for Higgs boson pair production in events with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Lett. B **778** (2018) 101 [arXiv:1707.02909] [INSPIRE].

[27] CMS collaboration, *Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13$ TeV*, Phys. Lett. B **791** (2019) 96 [arXiv:1806.05246] [INSPIRE].

[28] ATLAS collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, Nature **607** (2022) 52 [*Erratum ibid.* **612** (2022) E24] [arXiv:2207.00092] [INSPIRE].

[29] CMS collaboration, *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, Nature **607** (2022) 60 [arXiv:2207.00043] [INSPIRE].

[30] CMS collaboration, *Evidence for Higgs boson decay to a pair of muons*, JHEP **01** (2021) 148 [arXiv:2009.04363] [INSPIRE].

[31] ATLAS collaboration, *A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector*, Phys. Lett. B **812** (2021) 135980 [arXiv:2007.07830] [INSPIRE].

[32] ATLAS collaboration, *Measurements of WH and ZH production with Higgs boson decays into bottom quarks and direct constraints on the charm Yukawa coupling in 13 TeV pp collisions with the ATLAS detector*, JHEP **04** (2025) 075 [arXiv:2410.19611] [INSPIRE].

[33] CMS collaboration, *Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev. Lett.* **131** (2023) 061801 [arXiv:2205.05550] [INSPIRE].

[34] ATLAS collaboration, *Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon using* $139\,fb^{-1}$ *of ATLAS* $\sqrt{s} = 13$ *TeV proton-proton collision data*, *Eur. Phys. J. C* **83** (2023) 781 [arXiv:2208.03122] [INSPIRE].

[35] CMS collaboration, *Search for rare decays of Z and Higgs bosons to* J/ψ *and a photon in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *Eur. Phys. J. C* **79** (2019) 94 [arXiv:1810.10056] [INSPIRE].

[36] I. Brivio, F. Goertz and G. Isidori, *Probing the Charm Quark Yukawa Coupling in Higgs+Charm Production*, *Phys. Rev. Lett.* **115** (2015) 211801 [arXiv:1507.02916] [INSPIRE].

[37] N.M. Coyle, C.E.M. Wagner and V. Wei, *Bounding the charm Yukawa coupling*, *Phys. Rev. D* **100** (2019) 073013 [arXiv:1905.09360] [INSPIRE].

[38] ATLAS collaboration, *Search for the associated production of charm quarks and a Higgs boson decaying into a photon pair with the ATLAS detector*, *JHEP* **02** (2025) 045 [arXiv:2407.15550] [INSPIRE].

[39] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at* $\sqrt{s} = 13$ *TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [arXiv:2104.01927] [INSPIRE].

[40] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at* $\sqrt{s} = 13$ *TeV*, CMS-PAS-LUM-17-004 CERN, Geneva (2018).

[41] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at* $\sqrt{s} = 13$ *TeV*, CMS-PAS-LUM-18-002 CERN, Geneva (2019).

[42] C. Delaunay, T. Golling, G. Perez and Y. Soreq, *Enhanced Higgs boson coupling to charm pairs*, *Phys. Rev. D* **89** (2014) 033014 [arXiv:1310.7029] [INSPIRE].

[43] G. Perez, Y. Soreq, E. Stamou and K. Tobioka, *Constraining the charm Yukawa and Higgs-quark coupling universality*, *Phys. Rev. D* **92** (2015) 033016 [arXiv:1503.00290] [INSPIRE].

[44] D. Ghosh, R.S. Gupta and G. Perez, *Is the Higgs Mechanism of Fermion Mass Generation a Fact? A Yukawa-less First-Two-Generation Model*, *Phys. Lett. B* **755** (2016) 504 [arXiv:1508.01501] [INSPIRE].

[45] F.J. Botella, G.C. Branco, M.N. Rebelo and J.I. Silva-Marcos, *What if the masses of the first two quark families are not generated by the standard model Higgs boson?*, *Phys. Rev. D* **94** (2016) 115031 [arXiv:1602.08011] [INSPIRE].

[46] R. Harnik, J. Kopp and J. Zupan, *Flavor Violating Higgs Decays*, *JHEP* **03** (2013) 026 [arXiv:1209.1397] [INSPIRE].

[47] W. Altmannshofer et al., *Collider Signatures of Flavorful Higgs Bosons*, *Phys. Rev. D* **94** (2016) 115032 [arXiv:1610.02398] [INSPIRE].

[48] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

[49] CMS collaboration, *Development of the CMS detector for the CERN LHC Run 3*, 2024 *JINST* **19** P05064 [arXiv:2309.05466] [INSPIRE].

[50] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, 2020 *JINST* **15** P10017 [arXiv:2006.10165] [INSPIRE].

JHEP11(2025)060

[51] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [arXiv:1609.02366] [INSPIRE].

[52] CMS collaboration, *Performance of the CMS high-level trigger during LHC Run 2*, 2024 *JINST* **19** P11021 [arXiv:2410.17038] [INSPIRE].

[53] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [hep-ph/0409146] [INSPIRE].

[54] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [arXiv:0709.2092] [INSPIRE].

[55] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [arXiv:1002.2581] [INSPIRE].

[56] E. Bagnaschi, G. Degrassi, P. Slavich and A. Vicini, *Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM*, *JHEP* **02** (2012) 088 [arXiv:1111.2854] [INSPIRE].

[57] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J. C* **53** (2008) 473 [arXiv:0706.2569] [INSPIRE].

[58] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [arXiv:1209.6215] [INSPIRE].

[59] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[60] LHC Higgs Cross Section Working Group, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, in *CERN Yellow Reports: Monographs* **2**, CERN (2017), pp. 1–869 [CERN-2017-002-M] [DOI:10.23731/CYRM-2017-002] [arXiv:1610.07922] [INSPIRE].

[61] M. Wiesemann et al., *Higgs production in association with bottom quarks*, *JHEP* **02** (2015) 132 [arXiv:1409.5301] [INSPIRE].

[62] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[63] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [arXiv:1512.00815] [INSPIRE].

[64] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [arXiv:1903.12179] [INSPIRE].

[65] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [arXiv:1410.8849] [INSPIRE].

[66] NNPDF collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663 [arXiv:1706.00428] [INSPIRE].

[67] E. Bothmann et al., *Event Generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [arXiv:1905.09127] [INSPIRE].

[68] GEANT4 collaboration, *GEANT4 — A Simulation Toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].

JHEP11(2025)060

[69] CMS collaboration, *Measurements of Higgs boson properties in the diphoton decay channel in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *JHEP* **11** (2018) 185 [arXiv:1804.02716] [INSPIRE].

[70] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [arXiv:1706.04965] [INSPIRE].

[71] M. Cacciari, G.P. Salam and G. Soyez, *The anti-*k_t *jet clustering algorithm*, *JHEP* **04** (2008) 063 [arXiv:0802.1189] [INSPIRE].

[72] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [arXiv:1111.6097] [INSPIRE].

[73] CMS collaboration, *Pileup mitigation at CMS in* 13 *TeV data*, 2020 *JINST* **15** P09018 [arXiv:2003.00503] [INSPIRE].

[74] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at* 8 *TeV*, 2017 *JINST* **12** P02014 [arXiv:1607.03663] [INSPIRE].

[75] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, 2021 *JINST* **16** P05014 [arXiv:2012.06888] [INSPIRE].

[76] E. Spyromitros-Xioufis, W. Groves, G. Tsoumakas and I. Vlahavas, *Multi-target regression via input space expansion: treating targets as inputs*, *Mach. Learn.* **104** (2016) 55 [arXiv:1211.6581].

[77] E. Bols et al., *Jet Flavour Classification Using DeepJet*, 2020 *JINST* **15** P12012 [arXiv:2008.10519] [INSPIRE].

[78] CMS collaboration, *Performance of the DeepJet b tagging algorithm using* 41.9/*fb of data from proton-proton collisions at* 13 *TeV with Phase 1 CMS detector*, CMS-DP-2018-058 (2018).

[79] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at* 13 *TeV*, 2018 *JINST* **13** P05011 [arXiv:1712.07158] [INSPIRE].

[80] T. Chen and C. Guestrin, *XGBoost: A Scalable Tree Boosting System*, in the proceedings of the *The 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, San Francisco, CA, U.S.A., 13–17 August 2016, pp. 785–794 [arXiv:1603.02754] [DOI:10.1145/2939672.2939785] [INSPIRE].

[81] R.A. Fisher, *On the interpretation of* χ^2 *from contingency tables, and the calculation of* p, *J. Roy. Stat. Soc.* **85** (1922) 87.

[82] P.D. Dauncey, M. Kenzie, N. Wardle and G.J. Davies, *Handling uncertainties in background shapes: the discrete profiling method*, 2015 *JINST* **10** P04015 [arXiv:1408.6865] [INSPIRE].

[83] S. Manzoni et al., *Taming a leading theoretical uncertainty in HH measurements via accurate simulations for* $b\bar{b}H$ *production*, *JHEP* **09** (2023) 179 [arXiv:2307.09992] [INSPIRE].

[84] CMS collaboration, *The CMS Statistical Analysis and Combination Tool: Combine*, *Comput. Softw. Big Sci.* **8** (2024) 19 [arXiv:2404.06614] [INSPIRE].

[85] ATLAS and CMS collaborations and LHC Higgs Combination Group, *Procedure for the LHC Higgs boson search combination in Summer 2011*, CMS-NOTE-2011-005 CERN, Geneva (2011) [ATL-PHYS-PUB-2011-11] [INSPIRE].

[86] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

[87] CMS collaboration, *Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multi-jet measurements*, arXiv:2504.02958 [INSPIRE].

[88] HEPData record for this analysis, DOI:10.17182/hepdata.157578, (2025).

JHEP11(2025)060

The CMS collaboration

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

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck[2], R. Schöfbeck[2], D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, Y. Hong, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, A. Khalilzadeh, F.A. Khan, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, G. Gokbulut, J. Knolle, L. Lambrecht, D. Marckx, K. Skovpen, N. Van Den Bossche, J. van der Linden, J. Vandenbroeck, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bein, A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera[4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[5], A. Vilela Pereira[4]

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[6], E.M. Da Costa, G.G. Da Silveira[7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, T. Laux Kuhn[7], M. Macedo, J. Martins, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula, V. Scheurer

JHEP11(2025)060

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

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, S. Thakur

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

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, Z. Liang, J. Liu

Institute of High Energy Physics, Beijing, China
G.M. Chen[8], H.S. Chen[8], M. Chen[8], F. Iemmi, C.H. Jiang, A. Kapoor[9], H. Liao, Z.-A. Liu[10], R. Sharma[11], J.N. Song[10], J. Tao, C. Wang[8], J. Wang, Z. Wang[8], H. Zhang, J. Zhao

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

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China
S. Yang

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

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

Nanjing Normal University, Nanjing, China
G. Bauer[12], B. Li[13], H. Wang, K. Yi[14], J. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Y. Li

JHEP11(2025)060

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

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

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, 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
D. Giljanovic, N. Godinovic, D. Lelas, 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, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov[15], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla[16], R. Aly[17], Y. Assran[18,19]

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

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

Department of Physics, University of Helsinki, Helsinki, Finland
K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Myllymäki, M.m. Rantanen, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[20], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, T.D. Cuisset, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[21], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[22], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, N. Kumar,

JHEP11(2025)060

M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, A. Cardini, F. Colombina, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[26], W. Lohmann[27], F. Lorkowski, 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, J. Rübenach, L. Rygaard, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, D. Hundhausen, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, B. Wiederspan, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, E. Butz, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[29], A. Stakia

JHEP11(2025)060

National and Kapodistrian University of Athens, Athens, Greece
G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis

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

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, 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. Csorgo[33], F. Nemes[33], T. Novak

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[36], 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.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[37], D. Kumar[37], T. Mishra, B. Parida[38], P.R. Pujahari, N.R. Saha, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

JHEP11(2025)060

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

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Bhowmik[39], R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, B.M. Joshi, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[40], C. Kar, D. Maity[41], P. Mal, K. Naskar[41], A. Nayak[41], S. Nayak, K. Pal, R. Raturi, P. Sadangi, S.K. Swain, S. Varghese[41], D. Vats[41]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Acharya[42], A. Alpana, S. Dube, B. Gomber[42], P. Hazarika, B. Kansal, A. Laha, B. Sahu[42], S. Sharma, K.Y. Vaish

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[43], A. Jafari[44], M. Zeinali[45]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[46], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang[47]

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], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,17], N. Ferrara[a,b], L. Fiore[a], G. Iaselli[a,c], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], 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], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], A. Castro[†,a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. 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,49], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,49]

JHEP11(2025)060

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy

P. Assiouras[a], G. Barbagli[a], G. Bardelli[a,b], M. Bartolini[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[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. Bianco, S. Meola[50], 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[b], Milano, Italy

A. Benaglia[a], F. Brivio[a], F. Cetorelli[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], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], B.S. Pinolini[a], G. Pizzati[a,b], S. Ragazzi[a,b], T. Tabarelli de Fatis[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], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,51], P. Paolucci[a,29], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy

R. Ardino[a], P. Azzi[a], N. Bacchetta[a,52], D. Bisello[a,b], P. Bortignon[a], G. Bortolato[a,b], A.C.M. Bulla[a], R. Carlin[a,b], T. Dorigo[a,53], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Michelotto[a], M. Migliorini[a,b], F. Montecassiano[a], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy

A. Braghieri[a], S. Calzaferri[a], D. Fiorina[a], P. Montagna[a,b], M. Pelliccioni[a], 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], C. Carrivale[a,b], D. Ciangottini[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,54], 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

C. Aimè[a], C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b],

JHEP11(2025)060

M. Cipriani[a,b], V. D'Amante[a,d], R. Dell'Orso[a], S. Donato[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], D. Matos Figueiredo[a], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b,41], M. Musich[a,b], S. Nandan[a], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], 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. Barria[a], C. Basile[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], F. Errico[a,b], R. Gargiulo[a,b], E. Longo[a,b], L. Martikainen[a,b], J. Mijuskovic[a,b], 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], V. Vladimirov[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], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], F. Luongo[a,b], C. Mariotti[a], L. Markovic[a,b], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[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], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, J. Hong, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea

M.S. Kim

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

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, J. Choi[55], D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh, S. Yang

JHEP11(2025)060

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

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, K. Hwang, B. Kim, K. Lee, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, 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, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

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

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[56], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, 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, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[57], R. Lopez-Fernandez, J. Mejia Guisao, A. Sánchez Hernández

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

JHEP11(2025)060

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, N. Raicevic

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

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, 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, A. Muhammad

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, D. Bastos, C. Beirão Da Cruz E. Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C.M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, J. Sastre, J. Vazquez Escobar

JHEP11(2025)060

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, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, E. Palencia Cortezon, J. Prado Pico, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

S. Blanco Fernández, I.J. Cabrillo, A. Calderon, 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, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

B. Kailasapathy[58], D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna[59], K. Liyanage, N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, C. Amendola, E. Auffray, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, E. Brondolin, C.E. Brown, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], G. Karathanasis, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, M. Magherini, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, D. Rabady, B. Ribeiro Lopes, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[61], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T. Bevilacqua[62], L. Caminada[62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[62], L. Noehte[62], T. Rohe, A. Samalan

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

T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'Archiac[61], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà,

F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[63], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[64], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[37]

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, K.F. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, 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, V. Wachirapusitanand

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[65], E. Eskut, Y. Guler[66], E. Gurpinar Guler[66], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[67], A. Polatoz, B. Tali[68], U.G. Tok, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[69]

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

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[65,73], S. Sen[74]

Istanbul University, Istanbul, Turkey
O. Aydilek[75], B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak[77], D. Sunar Cerci, T. Yetkin

JHEP11(2025)060

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, V.J. Smith, K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, L. Russell, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom

J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

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

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, A.E. Simsek, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[81], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA

A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[83], X. Shen, M. Stamenkovic, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, B. Barton, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo, F. Zhang

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

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

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, M.M. Hussain, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA
S. Bhattacharya, A. Bornheim, O. Cerri, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, N. Manganelli, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

JHEP11(2025)060

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, D.J. Cranshaw, J. Dickinson, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, 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, 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, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, 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[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

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

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Butalla, S. Das, T. Elkafrawy[86], M. Hohlmann, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D.S. Lemos, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, P. Roy, T. Roy, S. Rudrabhatla, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[87], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[88], O. Neogi, H. Ogul[89], Y. Onel, A. Penzo, C. Snyder, E. Tiras[90]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[91], C. Rogan, C. Royon, S. Sanders, C. Smith, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[92], A. Shevelev, L. Wang, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, J. Bendavid, S. Bright-Thonney, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T.J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, P. Levchenko, J. Li, M. Lu, R. Mccarthy, D.M. Morse, T. Orimoto, A. Parker, L. Skinnari, E. Tsai, D. Wood

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

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas,

JHEP11(2025)060

L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[15], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA

A. Basnet, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, D.A. Wenzl, B.L. Winer, B.R. Yates

Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui, K. Coldham, P. Das, G. Dezoort, P. Elmer, P. Fackeldey, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully, L.H. Vage

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, J.F. Schulte, A.K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA

D. Acosta, A. Agrawal, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[92], R. Taus

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora

University of Tennessee, Knoxville, Tennessee, USA

D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA

D. Aebi, M. Ahmad, T. Akhter, K. Androsov[61], O. Bouhali[93], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, R. Mueller, D. Overton, A. Safonov

JHEP11(2025)060

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

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez

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

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[95], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†]

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, Yu. Andreev, D. Budkouski, A. Ershov, I. Golutvin[†], I. Gorbunov, V. Karjavine, V. Klyukhin, O. Kodolova[96,92], V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[95], A. Nikitenko[97,96], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[†,98], A. Zarubin, I. Zhizhin, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, K. Ivanov, V. Gavrilov, N. Lychkovskaya, V. Popov, A. Zhokin, R. Chistov[95], M. Danilov[95], S. Polikarpov[95], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[84], L. Dudko, M. Perfilov, S. Petrushanko, V. Savrin, G. Vorotnikov, V. Blinov[95], T. Dimova[95], A. Kozyrev[95], O. Radchenko[95], Y. Skovpen[95], V. Kachanov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin

[†] *Deceased*
[1] *Also at Yerevan State University, Yerevan, Armenia*
[2] *Also at TU Wien, Vienna, Austria*
[3] *Also at Ghent University, Ghent, Belgium*

JHEP11(2025)060

[4] *Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[5] *Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil*
[6] *Also at Universidade Estadual de Campinas, Campinas, Brazil*
[7] *Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil*
[8] *Also at University of Chinese Academy of Sciences, Beijing, China*
[9] *Also at China Center of Advanced Science and Technology, Beijing, China*
[10] *Also at University of Chinese Academy of Sciences, Beijing, China*
[11] *Also at China Spallation Neutron Source, Guangdong, China*
[12] *Now at Henan Normal University, Xinxiang, China*
[13] *Also at University of Shanghai for Science and Technology, Shanghai, China*
[14] *Now at The University of Iowa, Iowa City, Iowa, USA*
[15] *Also at an institute formerly covered by a cooperation agreement with CERN*
[16] *Also at Cairo University, Cairo, Egypt*
[17] *Also at Helwan University, Cairo, Egypt*
[18] *Also at Suez University, Suez, Egypt*
[19] *Now at British University in Egypt, Cairo, Egypt*
[20] *Also at Purdue University, West Lafayette, Indiana, USA*
[21] *Also at Université de Haute Alsace, Mulhouse, France*
[22] *Also at Istinye University, Istanbul, Turkey*
[23] *Also at The University of the State of Amazonas, Manaus, Brazil*
[24] *Also at University of Hamburg, Hamburg, Germany*
[25] *Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[26] *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*
[27] *Also at Brandenburg University of Technology, Cottbus, Germany*
[28] *Also at Forschungszentrum Jülich, Juelich, Germany*
[29] *Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[30] *Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary*
[31] *Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania*
[32] *Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
[33] *Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*
[34] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*
[35] *Also at Punjab Agricultural University, Ludhiana, India*
[36] *Also at University of Visva-Bharati, Santiniketan, India*
[37] *Also at Indian Institute of Science (IISc), Bangalore, India*
[38] *Also at Amity University Uttar Pradesh, Noida, India*
[39] *Also at UPES - University of Petroleum and Energy Studies, Dehradun, India*
[40] *Also at IIT Bhubaneswar, Bhubaneswar, India*
[41] *Also at Institute of Physics, Bhubaneswar, India*
[42] *Also at University of Hyderabad, Hyderabad, India*
[43] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*
[44] *Also at Isfahan University of Technology, Isfahan, Iran*
[45] *Also at Sharif University of Technology, Tehran, Iran*
[46] *Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran*
[47] *Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran*
[48] *Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy*
[49] *Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy*
[50] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*
[51] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[52] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[53] *Also at Lulea University of Technology, Lulea, Sweden*
[54] *Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*
[55] *Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*

JHEP11(2025)060

[56] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[57] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[58] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[59] *Also at Saegis Campus, Nugegoda, Sri Lanka*
[60] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[61] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[62] *Also at Universität Zürich, Zurich, Switzerland*
[63] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[64] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[65] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[66] *Also at Konya Technical University, Konya, Turkey*
[67] *Also at Izmir Bakircay University, Izmir, Turkey*
[68] *Also at Adiyaman University, Adiyaman, 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] *Now at Istanbul Okan University, Istanbul, Turkey*
[74] *Also at Hacettepe University, Ankara, Turkey*
[75] *Also at Erzincan Binali Yildirim University, Erzincan, Turkey*
[76] *Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[77] *Also at Yildiz Technical University, Istanbul, Turkey*
[78] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[79] *Also at IPPP Durham University, Durham, United Kingdom*
[80] *Also at Monash University, Faculty of Science, Clayton, Australia*
[81] *Also at Università di Torino, Torino, Italy*
[82] *Also at Bethel University, St. Paul, Minnesota, USA*
[83] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[84] *Also at California Institute of Technology, Pasadena, California, USA*
[85] *Also at United States Naval Academy, Annapolis, Maryland, USA*
[86] *Also at Ain Shams University, Cairo, Egypt*
[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 Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
[92] *Now at another institute formerly covered by a cooperation agreement with CERN*
[93] *Also at Texas A&M University at Qatar, Doha, Qatar*
[94] *Also at Kyungpook National University, Daegu, Korea*
[95] *Also at another institute formerly covered by a cooperation agreement with CERN*
[96] *Also at Yerevan Physics Institute, Yerevan, Armenia*
[97] *Also at Imperial College, London, United Kingdom*
[98] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

JHEP11(2025)060