



Constraints on the Higgs boson self-coupling from the combination of single and double Higgs boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

The Higgs boson (H) trilinear self-coupling, λ_3 , is constrained via its measured properties and limits on the HH pair production using the proton-proton collision data collected by the CMS experiment at $\sqrt{s} = 13$ TeV. The combination of event categories enriched in single-H and HH events is used to measure κ_λ , defined as the value of λ_3 normalized to its standard model prediction, while simultaneously constraining the Higgs boson couplings to fermions and vector bosons. Values of κ_λ outside the interval $-1.2 < \kappa_\lambda < 7.5$ are excluded at 2σ confidence level, which is compatible with the expected range of $-2.0 < \kappa_\lambda < 7.7$ under the assumption that all other Higgs boson couplings are equal to their standard model predicted values. Relaxing the assumption on the Higgs couplings to fermions and vector bosons the observed (expected) κ_λ interval is constrained to be within $-1.4 < \kappa_\lambda < 7.8$ ($-2.3 < \kappa_\lambda < 7.8$) at 2σ confidence level.

Submitted to Physics Letters B

1 Introduction

Significant progress has been made in the study of the properties of the Higgs boson (H) since its discovery [1–5]. The characterization of the Higgs boson is one of the primary goals of the CERN LHC physics program. This includes the measurement of its couplings to the vector bosons and fermions to test the compatibility with the standard model (SM) predictions. The Higgs boson plays a special role in several theories beyond the standard model (BSM), which could lead to deviations of the Higgs boson couplings from the SM predictions. A crucial property of the Higgs boson predicted by the SM which is still only weakly constrained by the LHC data is its self-coupling. At low energy the potential V of the Higgs boson field H in the SM Lagrangian can be expressed as:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 \quad (1)$$

where m_H is the mass of the Higgs boson and $v \simeq 246$ GeV is the vacuum expectation value of the Higgs field. The second and third term of Eq. (1) correspond to the trilinear and a quartic self-interactions of the Higgs boson. The parameters λ_3 and λ_4 control the strength of the trilinear and quartic self-interactions of the Higgs boson, respectively. In the SM the strength of the quartic interaction λ_4 is also fully determined by λ_3 because one is proportional to the other. The form of the Higgs potential, hence the self-coupling constant, is tightly connected to the cosmological evolution of the Universe [6]. The trilinear self-coupling predicted by the SM [7] is:

$$\lambda_3^{\text{SM}} = \frac{m_H^2}{2v^2} \simeq 0.13, \quad (2)$$

The modifier of the Higgs boson trilinear self-coupling with respect to the SM prediction is defined as $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$. The κ_λ value can be determined from the measurement of the Higgs boson pair production (HH) cross section. In the SM, the main production mechanism for HH in proton-proton collisions at $\sqrt{s} = 13$ TeV is gluon fusion (ggF HH) with a cross section of $31.0_{-7.2}^{+2.1}$ fb [8–15]. The second-largest HH production mechanism is via vector boson fusion (VBF HH) with a cross section of 1.726 ± 0.036 fb [16–20]. The Feynman diagrams corresponding to the ggF HH and VBF HH productions at the leading order (LO) are shown in Figs 1 and 2, respectively. The diagrams show that both mechanisms depend at the LO on κ_λ . A deviation of κ_λ from unity could significantly modify the cross sections and change the HH kinematics. The most stringent observed (expected) upper limit on the HH inclusive cross section previously set by the CMS Collaboration is 3.4 (2.5) times the SM prediction, and the observed constraint on κ_λ is $[-1.24, 6.49]$ at 95% confidence level (CL) assuming all the other Higgs boson couplings fixed to their SM value [4].

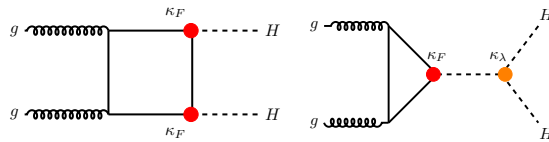


Figure 1: Feynman diagrams for the LO HH production via gluon fusion.

Another property of the Higgs boson predicted by the SM which can be probed through HH searches is the coupling between two Higgs bosons and two massive vector bosons. The strength of the HHVV coupling affects the cross section of the VBF HH mechanism, and it is tightly related to the strength of the coupling between one Higgs boson and a pair of massive vector bosons. In particular, the conservation of the asymptotic unitarity of the VBF HH process imposes the strength of the HHVV coupling to be equal to the square of the strength

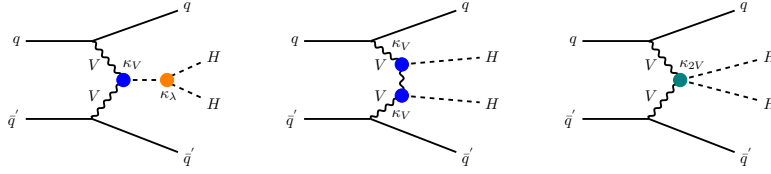


Figure 2: Feynman diagrams for the LO HH production via vector boson fusion.

of the HVV coupling [21]. A deviation from this relationship would require the presence of BSM physics, e.g. a BSM particle, to maintain the asymptotic unitarity of the process or could significantly increase the rate of the VBF HH production. Allowing for such a deviation and assuming all the other Higgs boson couplings equal to their SM-predicted values, the HHVV coupling values smaller than or equal to zero are excluded at a CL corresponding to more than 5 standard deviations [4].

Other Higgs boson couplings also affect the HH production cross sections. In particular at LO, the HH cross section in the ggF production mode depends on the Higgs boson coupling to the top quark and the VBF HH cross section depends on the couplings of the Higgs boson to the vector bosons. Further dependencies on Higgs boson couplings arise when considering different HH decay channels. The searches for HH production generally provide weaker constraints on the Higgs boson couplings to fermions and vector bosons compared to single-H measurements because of the much smaller cross sections.

An alternative way to determine κ_λ is from the cross sections of the main single-H production mechanisms utilizing next-to-LO (NLO) electroweak corrections that depend on κ_λ because of the appearance of loops and vertices with three Higgs bosons [22]. These corrections affect the single-H production cross sections and partial decay widths, as well as the Higgs boson propagator, as visible in the example Feynman diagrams of Fig. 3.

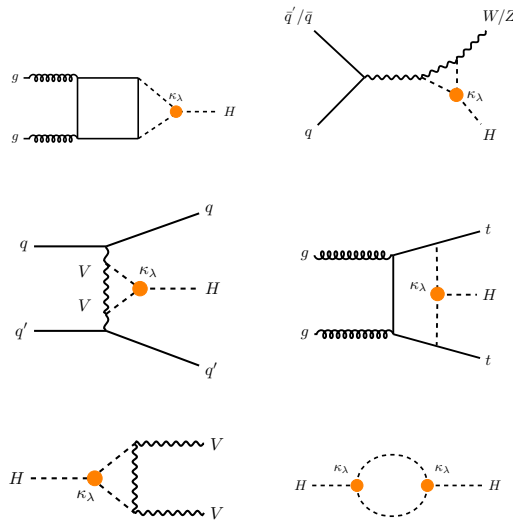


Figure 3: Feynman diagrams corresponding to κ_λ -dependent NLO corrections to the main single-H production mechanisms (in the two top rows), to the $H \rightarrow VV$ decay width (bottom left) and to the Higgs boson propagator (bottom right).

The parametrizations of the Higgs boson production cross section and branching fraction variations as functions of κ_λ are provided in Refs [22, 23]. The largest corrections affect the Higgs boson production in association with a Z or a W boson (ZH and WH, respectively, or generally VH), a top quark-antiquark pair ($t\bar{t}H$), or a single top quark (tH). In particular, the variation

of the $t\bar{t}H$ cross section is up to about $\pm 10\%$ for κ_λ between -2 and 6 . The variations of the Higgs boson production cross sections via gluon fusion (ggF H) and via vector boson fusion (VBF H) are milder but still relevant, i.e. up to about $-3\%/+2\%$. Additional information can be extracted from the single-H differential cross sections. Some kinematic variables that are experimentally accessible, such as the Higgs boson transverse momentum (p_T^H), are particularly sensitive to κ_λ . The single-H production mechanisms that receive the largest κ_λ -dependent corrections to the p_T^H spectrum are $t\bar{t}H$ and VH.

A framework to study the single-H production cross sections with a well-defined phase space granularity is provided by the simplified template cross sections (STXS) [24, 25]. The phase space divisions, known as *stages*, provide varying levels of granularity, with the most detailed being *stage 1.2*. Depending on the production mode, the measurements are performed in intervals of numbers of jets and p_T^H , or for the VH processes in intervals of the transverse momentum of the vector boson. The variations of the single-H cross sections as functions of κ_λ with the granularity defined by the STXS of *stage 1.2* are provided in Ref. [26].

The constraints on the Higgs boson couplings from the measurement of the single-H cross sections are complementary to those from the HH searches. In particular, the single-H measurements provide stringent constraints on the Higgs boson couplings to fermions and vector bosons and a mild constraint on κ_λ , while the HH searches provide tighter constraints on κ_λ . Therefore, the inclusion of single-H measurements improves the sensitivity with respect to HH searches, where other Higgs boson couplings are assumed equal to their SM values, and it also enables more generic interpretations where constraints on κ_λ and other Higgs boson couplings are obtained from data simultaneously.

The combination of measurements and searches for the single-H and HH processes performed by the ATLAS Collaboration [27] excludes values of κ_λ outside the range $-0.4 < \kappa_\lambda < 6.3$ or $-1.4 < \kappa_\lambda < 6.1$ at 95% CL assuming the other Higgs boson couplings at their SM values or by treating them as unconstrained parameters, respectively.

This letter presents a statistical combination of single-H measurements and HH searches to constrain the Higgs boson trilinear self-coupling under minimal assumptions on the Higgs boson couplings to fermions and to vector bosons. Constraints on κ_λ are also set assuming all the other Higgs boson couplings fixed to their SM values. The analyses considered are based on data from proton-proton (pp) collisions produced by the LHC at $\sqrt{s} = 13$ TeV and collected by the CMS experiment, corresponding to integrated luminosities of up to 138 fb^{-1} [28–30]. The tabulated results are provided as HepData records [31].

The CMS apparatus [32, 33] is a multipurpose, nearly hermetic detector, designed to trigger on [34, 35] and identify electrons, muons, photons, and (charged and neutral) hadrons [36–38]. A global “particle-flow” algorithm [39] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build tau leptons, jets, and missing transverse momentum [40–42].

2 Analysis channels

The single-H analyses considered are summarized in Table 1, which includes information on the production modes targeted by dedicated event categories and the maximum available

phase space granularity of the cross section measurements, while the HH searches included in the combination are listed in Table 2. A more detailed description can be found in the references listed in Tables 1 and 2. Most of the analyses considered are based on the pp collision data collected between 2016 and 2018 with the CMS detector, corresponding to an integrated luminosity of 138 fb^{-1} , while two analyses use a subset of this data set. The $H \rightarrow \text{leptons}$ ($t\bar{t}H$) and $HH \rightarrow \text{leptons}$ analyses target final states with electrons, muons or hadronically decaying τ leptons from the $H \rightarrow WW$ and $H \rightarrow \tau\tau$ decay channels.

Table 1: Analyses targeting single-H production modes and decay channels included in the combination and the corresponding data set sizes, in terms of integrated luminosity. The production modes targeted with dedicated analysis categories and the maximum phase space granularity of each cross section measurement are also reported.

Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity	References
$H \rightarrow 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2	[43]
$H \rightarrow \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2	[44, 45]
$H \rightarrow WW$	138	ggF, VBF, VH	STXS 1.2	[46]
$H \rightarrow \text{leptons}$ ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive	[47]
$H \rightarrow b\bar{b}$ (ggF)	138	ggF	Inclusive	[48]
$H \rightarrow b\bar{b}$ (VH)	77	VH	Inclusive	[49, 50]
$H \rightarrow b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive	[51]
$H \rightarrow \tau\tau$	138	ggF, VBF, VH	STXS 1.2	[52]
$H \rightarrow \mu\mu$	138	ggF, VBF	Inclusive	[53]

Table 2: The HH searches included in the combination and the corresponding data set sizes, in terms of integrated luminosity. The HH production modes targeted with dedicated event categories are also reported.

Analysis	Int. luminosity (fb^{-1})	Targeted HH production modes	References
$HH \rightarrow \gamma\gamma b\bar{b}$	138	ggF and VBF	[45]
$HH \rightarrow \tau\tau b\bar{b}$	138	ggF and VBF	[54]
$HH \rightarrow b\bar{b}b\bar{b}$	138	ggF, VBF, and VHH	[55–57]
$HH \rightarrow \text{leptons}$	138	ggF	[58]
$HH \rightarrow WWb\bar{b}$	138	ggF and VBF	[59]

3 Changes to the analyses in the combination

One of the main challenges of this combination is estimating the overlaps between the signal regions considered in different analyses and optimizing a strategy for the removal of the nonnegligible overlaps. This is crucial to avoid significant double-counting, ensuring accurate constraints on the Higgs boson trilinear self-coupling and its couplings to fermions and vector bosons. The event selections of the single-H analyses considered in this combination are orthogonal to each other by construction. The study of the overlap between the different HH analysis signal regions was performed for the HH combination presented in Ref. [4] and the only relevant overlap was found between the searches for $HH \rightarrow b\bar{b}b\bar{b}$ in the resolved-jet and merged-jet final states. An additional veto on events with large-radius jets with $p_T > 300 \text{ GeV}$ is applied in the resolved-jet analysis to remove the overlap with minimal impact on the final results. The overlaps between the selections of the $HH \rightarrow b\bar{b}b\bar{b}$ (VHH) analysis, which targets

a previously unexplored HH production mode, and the other HH analyses have been investigated for this combination. Categories of the $HH \rightarrow b\bar{b}b\bar{b}$ (VHH) analysis targeting fully hadronic final states show significant overlap with signal regions of the $HH \rightarrow b\bar{b}b\bar{b}$ (ggF) analysis. Since the ggH analysis sets stronger constraints on κ_λ , the hadronic categories of the VHH analysis are removed.

Overlaps between single-H and HH analyses are identified by comparing the event selection criteria of the analysis subcategories. Two analysis regions are considered to be overlapping if both categories in single-H and HH analyses select more than 1% of the same events in simulated single-H or HH event samples. The overlap of HH events in single-H analyses is negligible because of the low yield of the HH signal in the single-H analysis categories, while significant overlaps are identified for single-H events. In case two analysis regions are considered overlapping, one of the two is dropped. The removal of the overlap is optimized to provide the highest sensitivity to κ_λ , without significantly compromising the sensitivity to the Higgs boson couplings to fermions and vector bosons. The $HH \rightarrow b\bar{b}ZZ(4l)$ analysis [60] has not been included in this combination because of its comparatively low sensitivity and high expected overlap with the $H \rightarrow 4l$ analysis.

Significant overlaps are generally found between the categories targeting $t\bar{t}H$ events and the ones targeting HH events. In the $H \rightarrow \gamma\gamma$ final state, the $t\bar{t}H$ STXS 1.2 categories defined in Ref. [44] are replaced by the inclusive $t\bar{t}H$ categories defined in Ref. [45] for the combined measurement of the $H \rightarrow \gamma\gamma$ ($t\bar{t}H$) and $HH \rightarrow \gamma\gamma b\bar{b}$ cross sections, which are by construction orthogonal to each other. In the $H \rightarrow$ leptons ($t\bar{t}H$) analysis, categories with subleading sensitivity to the $t\bar{t}H$ signal are removed because they target final states with the same lepton multiplicity as the signal regions defined in the $HH \rightarrow$ leptons or $HH \rightarrow \tau\tau b\bar{b}$ analyses. In the $H \rightarrow b\bar{b}$ ($t\bar{t}H$) analysis, the signal regions targeting fully-hadronic decays of the top quark-antiquark pair are removed to prevent overlaps with the $HH \rightarrow b\bar{b}b\bar{b}$ analysis categories.

Overlaps are also found between $HH \rightarrow \gamma\gamma b\bar{b}$ analysis categories and some $H \rightarrow \gamma\gamma$ analysis categories enriched in ggF H, VBF H, or VH events. The overlapping $H \rightarrow \gamma\gamma$ analysis categories target ggF H or VBF H events with large p_T^H , or VH events with hadronic decays of the vector boson. Those categories are removed. The $H \rightarrow WW$ analysis categories targeting VH events in final states with either two same-sign leptons or three leptons are expected to have a nonnegligible overlap with the $HH \rightarrow$ leptons analysis categories targeting the same lepton multiplicities. The three-lepton categories of the $H \rightarrow WW$ analysis and the same-sign dilepton category of the $HH \rightarrow$ leptons analysis are dropped. The impact on the coupling constraints of interest is negligible because those categories play a subdominant role in their respective analyses. Overlaps are also found between most of the $H \rightarrow \tau\tau$ analysis categories and the $HH \rightarrow \tau\tau b\bar{b}$ ones which target HH events with a $H \rightarrow b\bar{b}$ candidate reconstructed as a pair of jets with exactly one of them identified as a b jet. The overlapping $HH \rightarrow \tau\tau b\bar{b}$ categories are removed to preserve the sensitivity to the H coupling to the tau lepton with minimal impact on the constraints on κ_λ . Furthermore, the $HH \rightarrow \tau\tau b\bar{b}$ analysis categories enriched in single-H events are removed, along with a few remaining $H \rightarrow \tau\tau$ categories targeting ggF H and VBF H events with large p_T^H or with two additional jets in the final state.

Finally, overlaps in control regions, which are used to constrain background processes, are studied by comparing selected data events. In cases of significant overlap, one of the overlapping control regions is removed. The removal strategy is optimized to preserve the constraints from data on the background processes and on the related systematic uncertainties. Control regions of the $H \rightarrow b\bar{b}$ (VH) and $HH \rightarrow WWb\bar{b}$ analyses enriched in $t\bar{t}$ events are removed because of overlaps with control regions of the $HH \rightarrow b\bar{b}b\bar{b}$ (VHH) and $H \rightarrow WW$ analyses,

respectively, which target similar phase space. The control regions of the $HH \rightarrow$ leptons analysis enriched in ZW and ZZ events are also removed because of expected overlaps with the signal regions of the $H \rightarrow WW$ analysis enriched in VH events.

4 Statistical procedure

The statistical interpretation of the data is based on the methodology common to the ATLAS and CMS Collaborations [61, 62] and the results have been obtained using the CMS statistical analysis tool COMBINE [63]. A profile likelihood ratio q is used as a test statistic to estimate the parameters of interest (POIs) $\vec{\alpha}$ of the model and their associated confidence intervals, taking into account the systematic uncertainties (Section 5) as independent nuisance parameters $\vec{\theta}$:

$$q(\vec{\alpha}) = -2 \log \left(\frac{L(\vec{\alpha}, \hat{\vec{\theta}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})} \right), \quad (3)$$

where L is the likelihood function, which is built as the product of the individual Poisson probability functions, accounting for the observed data and expected number of events across all the analysis channels, and additional terms representing constraints on the nuisance parameters from external measurements. The POIs and nuisance parameter values maximizing the likelihood function are given by $(\hat{\vec{\alpha}}, \hat{\vec{\theta}})$, while $\hat{\vec{\theta}}(\vec{\alpha})$ is the set of nuisance parameter values that maximize the likelihood function for a given set of POI values. Each source of systematic uncertainty corresponds to a nuisance parameter in the likelihood function, possibly correlated among all the input channels affected by that uncertainty.

The $\hat{\vec{\alpha}}$ are taken as the best-fit values of the considered POIs. The intervals at 68.3% and 95.4% CL correspond to one (1σ) and two (2σ) standard deviations, respectively. For one-dimensional measurements, the 1σ and 2σ intervals are identified as the regions of POI values for which $q < 1$ and $q < 4$, respectively, while for two-dimensional measurements they correspond to the regions where $q < 2.30$ and $q < 6.18$, respectively.

In addition to κ_λ , this combination takes into consideration the modifiers of the H couplings to fermions or vector bosons. The modifiers of the H couplings to a pair of fermions or vector bosons, which are referred to as κ_f and κ_V , respectively, have been introduced in the κ -framework [64] to parametrize possible deviations of the Higgs boson production cross sections and decay branching fractions from the SM predictions. The κ_f and κ_V parameters are defined in such a way that the deviations from the SM prediction for a single-H production mechanism i and its cross section σ_i , or a H decay channel j and the corresponding partial decay width Γ_j , is parametrized as:

$$\frac{\sigma_i}{\sigma_i^{\text{SM}}} = \kappa_i^2 \text{ or } \frac{\Gamma_j}{\Gamma_j^{\text{SM}}} = \kappa_j^2. \quad (4)$$

The loop-induced H production via gluon fusion and H decay to a pair of photons or gluons are parametrized as a function of the H couplings to the fermions or vector bosons entering in the loop. This combination alternatively considers the κ_f parameter, which coherently modifies the H couplings to all fermions, or the κ_t , κ_b , κ_μ , and κ_τ parameters which independently modify the couplings to the corresponding fermions. In this second case, the H couplings to the remaining fermions are assumed to be fixed to their SM predictions because no analyses sensitive to such parameters are included in the combination. The $H \rightarrow c\bar{c}$ searches [65, 66] are not included because major overlaps are expected with the considered $H \rightarrow b\bar{b}$ analyses.

Searches sensitive to the Higgs couplings to the strange quark and first generation fermions [67, 68] are not considered, since their contribution in constraining the corresponding Higgs boson couplings would be negligible in a combined fit.

The modifier of the SM couplings between two Higgs bosons and two massive vector bosons κ_{2V} is used to describe possible deviations from the SM expectation for the HH production from VBF mechanism. One or at most two coupling modifiers among κ_λ , κ_t , κ_{2V} , and κ_V are chosen as the POIs in this combination. The remaining coupling modifiers are assumed to be either equal to the SM prediction or treated as unconstrained nuisance parameters.

The modeling of the dependence of the single-H cross sections and branching fractions on κ_λ are provided in Refs [22, 23, 26]. Those parametrizations are valid under the assumption of small deviations of κ_V and κ_f from unity. The reason is that the parametrizations are based on an incomplete perturbative order expansion, which is at LO in κ_V and κ_f and at NLO in electroweak theory in κ_λ . This is a good approximation for deviations of κ_V and κ_f within a few percent from unity because in this range the missing higher-order terms would have a negligible effect on the cross sections and branching fractions compared to the experimental and theoretical uncertainties.

5 Systematic uncertainties

The systematic uncertainties, which affect the modeling of a signal or a background process, are described as uncertainties in the shape of the distributions or normalization uncertainties in the yield of the affected processes. The systematic uncertainties may originate either from the theoretical predictions or from the measurement. The most important uncertainties are described in the next paragraphs. The HH production searches are limited by the statistical power of the data. In the combination of HH channels, the overall impact of the systematic uncertainties on the constraints on κ_λ is about 8%. The most impactful systematic uncertainties are in the theory predictions of the ggF HH cross section, and in the estimations from data of important background components in the $b\bar{b}b\bar{b}$ and $\tau\tau b\bar{b}$ channels. In the single-H channels, the systematic uncertainties tend to be more important. The overall impact of the systematic uncertainties on the constraints on κ_λ from the combination of single-H channels is about 30%. The leading uncertainties are in the theory predictions of the ggF H and $t\bar{t}H$ production cross sections [24]. Several modifications to the input channels are performed to use a consistent uncertainty model similar to the uncertainty model in the single-H combination presented in Ref. [4]. The impact of all these modifications on the results is found to be negligible.

The uncertainties in the theory predictions of the single-H and HH cross sections are among the dominant sources of systematic uncertainty on κ_λ . The uncertainties in the HH and single-H cross sections originate from the renormalization and factorization scales, the parton distribution functions (PDF), as well as the branching fraction predictions. An additional important source of uncertainty in the ggF HH cross section is related to the renormalization scheme and scale dependence of the virtual top quark mass [15]. Such theory uncertainties are fully correlated among all affected channels and likewise for the uncertainties in the theoretical prediction of the cross section of a background process. In the single-H channels the uncertainty scheme for the ggF H cross section is defined according to Ref. [24]. This consists of a set of nuisance parameters that cover for the uncertainty in the total ggF H cross section, as well as the cross sections in the exclusive phase space regions targeted by the STXS framework. The HH analyses with a nonnegligible contamination from ggF H production do not perform any explicit classification of the ggF H events in STXS bins. Therefore, in the HH channels only the uncertainty in the total ggF H cross section is taken into account and correlated with the single-H

channels.

The most impactful experimental uncertainties that are correlated among multiple channels are the uncertainties in the integrated luminosity, in the reconstruction and identification of photons, electrons, muons, hadronically decaying tau leptons, in the b jet identification, and in the jet energy scale and resolution. These uncertainties are generally correlated among all the affected channels following the same procedure as for the combinations presented in Ref. [4]. Additional experimental uncertainties related to measurement procedures specific to each channel, which are detailed in the dedicated publications (listed in Tables 1 and 2), are uncorrelated among the channels.

The contribution of HH events in the signal regions targeting single-H events is also studied. This can be nonnegligible for the $t\bar{t}H$ -enriched categories because the $t\bar{t}H$ cross section is about 16 times larger than the HH cross section, and because the HH events with one Higgs boson decaying to a $b\bar{b}$ quark pair have a final state similar to the $t\bar{t}H$ events. The categories targeting $t\bar{t}H$ events in the $H \rightarrow \gamma\gamma$ and multilepton final states are the most sensitive to this process among the $t\bar{t}H$ categories considered for this combination. The HH contamination in the $t\bar{t}H$ -enriched categories is either modeled, as in the $H \rightarrow \gamma\gamma$ ($t\bar{t}H$) categories, or its impact on the results is studied and found to be small. In particular, a possible HH contamination in the $H \rightarrow \text{leptons}$ ($t\bar{t}H$) analysis categories is estimated to be at most 5% with respect to the total $t\bar{t}H$ signal yield in the categories. This possible contamination is expected to cause a shift of the allowed 2σ κ_λ interval for the combination of single-H channels and for the combination of single-H and HH channels of at most 2% and 1% with respect to the width of the interval towards higher values of κ_λ , respectively.

6 Results

The profile likelihood scan of the κ_λ parameter is shown in Fig. 4, comparing the separate combinations of the single-H or HH channels to the full combination of the two, assuming in all cases the other H couplings equal to their SM predictions. The observed best-fit κ_λ from the combination of the HH channels is found very close to unity, and the observed 2σ allowed interval is found to be $-1.7 < \kappa_\lambda < 7.0$, in agreement with the expected interval of $-2.3 < \kappa_\lambda < 8.0$, assuming the other Higgs boson couplings fixed to the SM prediction. The observed best-fit κ_λ from the combination of the single-H channels is larger than one, although compatible with the SM within the 2σ uncertainty. The observed and expected 2σ allowed intervals are $-1.8 < \kappa_\lambda < 12.0$ and $-4.5 < \kappa_\lambda < 11.7$, respectively. The profile likelihood obtained considering both the single-H and HH channels is qualitatively flat around the minimum. The shift in the κ_λ interval from the single-H combination is mostly driven by the $H \rightarrow \gamma\gamma$ ($t\bar{t}H$) channel. The observed (expected) 2σ allowed interval from single-H and HH combination is $-1.2 < \kappa_\lambda < 7.5$ ($-2.0 < \kappa_\lambda < 7.7$). The observed allowed interval on κ_λ can be compared to the corresponding one from the HH combination of Ref. [4]. The lower bounds are compatible, while the upper bound from this combination is weaker because of the single-H channels shifting the interval towards higher values of κ_λ .

The two-dimensional likelihood scan of the κ_λ and κ_t parameters is shown in Fig. 5. A large degeneracy of the ggF HH cross section with respect to κ_λ and κ_t limits the κ_λ sensitivity of the HH channels. In that case, the constraints on κ_t arise mostly from the contamination of single-H events in the HH enriched categories, and from the κ_t dependence of the H branching fractions, especially in the $H \rightarrow \gamma\gamma$ channel. Instead, the single-H combination provides a stringent constraint on κ_t , which is utilized in the combination of the single-H and HH channels.

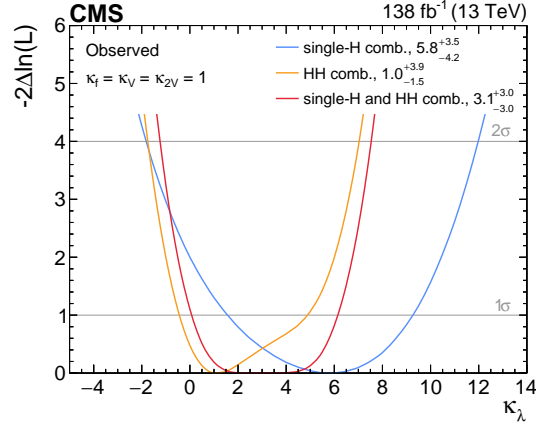


Figure 4: Observed profile likelihood scans of κ_λ comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels. The legend includes the best-fit values and the 1σ uncertainties.

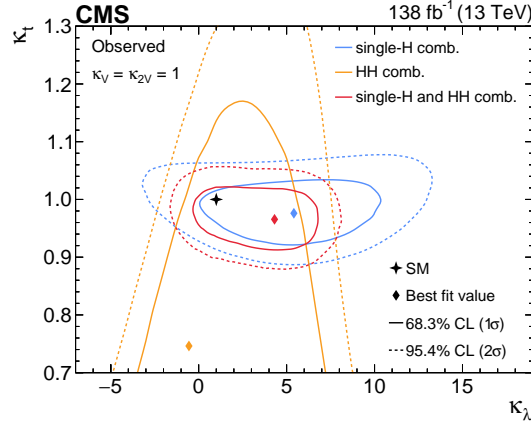


Figure 5: Observed two-dimensional likelihood scans of $(\kappa_\lambda, \kappa_t)$ comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels.

The complementarity of the single-H and HH channels is also employed in the simultaneous measurement of the κ_V and κ_{2V} parameters. The two-dimensional likelihood scan of the κ_V and κ_{2V} parameters is shown in Fig. 6. The constraint on κ_{2V} is driven by the HH categories enriched in VBF HH events. However, the VBF HH cross section has a large degeneracy with respect to the κ_V and κ_{2V} parameters. The single-H channels have no sensitivity on the κ_{2V} parameter but provide a stringent constraint on κ_V . This allows the exclusion of $\kappa_{2V} = 0$ for any value of κ_V with a significance larger than five standard deviations.

Constraints on κ_λ are also set under less restrictive assumptions on the Higgs boson couplings to the fermions and vector bosons. In particular, the κ_λ likelihood scan treating κ_V , κ_{2V} , κ_t , κ_b , κ_τ , and κ_μ as unconstrained nuisance parameters is shown in Fig. 7. The degeneracy that would be present if only HH categories were considered is fully resolved in the combination of the single-H and HH channels. The resulting expected constraint on κ_λ is comparable to the one expected from the HH combination assuming the other Higgs boson couplings equal to their SM value. The constraints on κ_λ under the aforementioned assumptions, along with some alternative assumptions, are summarized in Table 3. The results are found to be consistent with the combination of single-H and HH measurements and searches from the ATLAS

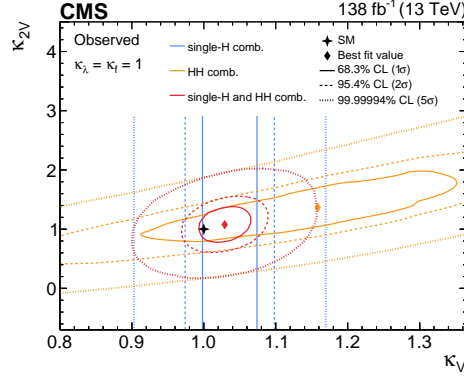


Figure 6: Observed two-dimensional likelihood scans of (κ_V, κ_{2V}) comparing the full combination of single-H and HH (red) to the combinations of only single-H (blue) or only HH (yellow) channels. The single-H combination has no sensitivity on the κ_{2V} parameter.

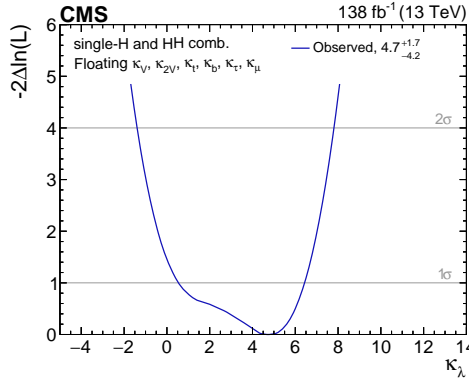


Figure 7: Observed likelihood scans of κ_λ assuming $\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau,$ and κ_μ as unconstrained nuisance parameters. The legend includes the best-fit value and the 1σ uncertainty.

Collaboration [27].

Table 3: Expected and observed constraints on κ_λ at 2σ and best fit values from the combination of the single-H and HH channels under different assumptions on the Higgs boson couplings to fermions and vector bosons. The floating coupling parameters are either treated as POIs or as unconstrained nuisance parameters in the fit. The parameters that are not listed as floating are always assumed fixed to the SM prediction.

Hypothesis	Best fit κ_λ value $\pm 1\sigma$		2σ interval	
	Expected	Observed	Expected	Observed
Other couplings fixed to the SM prediction	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_f$)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating ($\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

7 Summary

A combination of Higgs boson (H) measurements and searches for Higgs boson pair production (HH) to constrain the Higgs boson trilinear self-coupling has been presented. Proton-proton collision data at $\sqrt{s} = 13$ TeV, collected by the CMS experiment between 2016 and

2018, were analyzed. This is the first combination of single-H and HH channels from the CMS Collaboration. The complementarity of the constraints on the Higgs boson couplings of the single-H and HH channels is employed in the combination. The single-H channels lessen the assumptions on the measurements on the modifier of the Higgs boson trilinear self-coupling κ_λ , allowing for simultaneous constraint of the Higgs boson couplings to fermions and vector bosons. The observed (expected) interval at 2σ confidence level on κ_λ under the assumption that the other Higgs boson couplings are fixed to the standard model prediction, is found to be $-1.2 < \kappa_\lambda < 7.5$ ($-2.0 < \kappa_\lambda < 7.7$). Relaxing the assumption on the Higgs couplings to fermions and vector bosons the corresponding observed (expected) interval on κ_λ is $-1.4 < \kappa_\lambda < 7.8$ ($-2.3 < \kappa_\lambda < 7.8$).

Acknowledgments

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

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. 22r1-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. 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), 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, and TKP2021-NKTA-64 (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; MCIN/AEI/10.13039/501100011033, ERDF “a way of making Europe”, and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 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 B37G660013 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [3] 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, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.
- [4] CMS Collaboration, “A portrait of the Higgs boson by the CMS experiment ten years after the discovery”, *Nature* **607** (2022) 60, doi:10.1038/s41586-022-04892-x, arXiv:2207.00043.
- [5] ATLAS Collaboration, “A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery”, *Nature* **607** (2022) 52, doi:10.1038/s41586-022-04893-w, arXiv:2207.00092.
- [6] Particle Data Group Collaboration, “Review of Particle Physics”, *PTEP* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.
- [7] S. Weinberg, “A model of leptons”, *Phys. Rev. Lett.* **19** (1967) 1264, doi:10.1103/PhysRevLett.19.1264.
- [8] S. Dawson, S. Dittmaier, and M. Spira, “Neutral Higgs-boson pair production at hadron colliders: QCD corrections”, *Phys. Rev. D* **58** (1998) 115012, doi:10.1103/PhysRevD.58.115012, arXiv:hep-ph/9805244v1.
- [9] S. Borowka et al., “Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence”, *Phys. Rev. Lett.* **117** (2016) 012001, doi:10.1103/PhysRevLett.117.012001, arXiv:1604.06447.

- [10] J. Baglio et al., “Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme”, *Eur. Phys. J. C* **79** (2019) 459, doi:10.1140/epjc/s10052-019-6973-3, arXiv:1811.05692.
- [11] D. de Florian and J. Mazzitelli, “Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD”, *Phys. Rev. Lett.* **111** (2013) 201801, doi:10.1103/PhysRevLett.111.201801, arXiv:1309.6594v2.
- [12] D. Y. Shao, C. S. Li, H. T. Li, and J. Wang, “Threshold resummation effects in Higgs boson pair production at the LHC”, *JHEP* **07** (2013) 169, doi:10.1007/JHEP07(2013)169, arXiv:1301.1245.
- [13] D. de Florian and J. Mazzitelli, “Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC”, *JHEP* **53** (2015) 1029, doi:10.1007/JHEP09(2015)053, arXiv:1505.07122.
- [14] M. Grazzini et al., “Higgs boson pair production at NNLO with top quark mass effects”, *JHEP* **05** (2018) 059, doi:10.1007/JHEP05(2018)059, arXiv:1803.02463.
- [15] J. Baglio et al., “ $gg \rightarrow HH$: Combined uncertainties”, *Phys. Rev. D* **103** (2021) 056002, doi:10.1103/PhysRevD.103.056002, arXiv:2008.11626v3.
- [16] J. Baglio et al., “The measurement of the Higgs self-coupling at the LHC: theoretical status”, *JHEP* **04** (2013) 151, doi:10.1007/JHEP04(2013)151, arXiv:1212.5581.
- [17] R. Frederix et al., “Higgs pair production at the LHC with NLO and parton-shower effects”, *Phys. Lett. B* **732** (2014) 142, doi:10.1016/j.physletb.2014.03.026, arXiv:1401.7340.
- [18] L.-S. Ling et al., “NNLO QCD corrections to Higgs pair production via vector boson fusion at hadron colliders”, *Phys. Rev. D* **89** (2014) 073001, doi:10.1103/PhysRevD.89.073001, arXiv:1401.7754.
- [19] F. A. Dreyer and A. Karlberg, “Fully differential vector-boson fusion Higgs pair production at next-to-next-to-leading order”, *Phys. Rev. D* **99** (2019) 074028, doi:10.1103/PhysRevD.99.074028, arXiv:1811.07918.
- [20] F. A. Dreyer and A. Karlberg, “Vector-boson fusion Higgs pair production at N³LO”, *Phys. Rev. D* **98** (2018) 114016, doi:10.1103/PhysRevD.98.114016, arXiv:1811.07906.
- [21] F. Bishara, R. Contino, and J. Rojo, “Higgs pair production in vector-boson fusion at the LHC and beyond”, *Eur. Phys. J. C* **77** (2017) 481, doi:10.1140/epjc/s10052-017-5037-9, arXiv:1611.03860.
- [22] G. Degrandi, P. P. Giardino, F. Maltoni, and D. Pagani, “Probing the Higgs self coupling via single Higgs production at the LHC”, *JHEP* **12** (2016) 080, doi:10.1007/JHEP12(2016)080, arXiv:1607.04251.
- [23] F. Maltoni, D. Pagani, A. Shivaji, and X. Zhao, “Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC”, *Eur. Phys. J. C* **77** (2017) 887, doi:10.1140/epjc/s10052-017-5410-8, arXiv:1709.08649.

-
- [24] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector”, CERN Report CERN-2017-002-M, 2016. doi:10.23731/CYRM-2017-002, arXiv:1610.07922.
- [25] LHC Higgs Cross Section Working Group, “Simplified template cross sections - Stage 1.1”, CERN Report LHCHSWG-2019-003, DESY-19-070, 2019. arXiv:1906.02754.
- [26] LHC Higgs Working Group, “Modelling of the single-Higgs simplified template cross-sections (STXS 1.2) for the determination of the Higgs boson trilinear self-coupling”, CERN Report LHCHWG-2022-002, 2022.
- [27] ATLAS Collaboration, “Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s}=13$ TeV”, *Phys. Lett. B* **843** (2023) 137745, doi:10.1016/j.physletb.2023.137745, arXiv:2211.01216.
- [28] 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, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [29] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [30] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [31] HEPData record for this analysis, 2024. doi:10.17182/hepdata.152689.
- [32] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [33] CMS Collaboration, “Development of the CMS detector for the CERN LHC Run 3”, *JINST* **19** (2024) P05064, doi:10.1088/1748-0221/19/05/P05064, arXiv:2309.05466.
- [34] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [35] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [36] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [37] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [38] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

- [39] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [40] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [41] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [42] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [43] CMS Collaboration, “Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **81** (2021) 488, doi:10.1140/epjc/s10052-021-09200-x, arXiv:2103.04956.
- [44] CMS Collaboration, “Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2021) 027, doi:10.1007/JHEP07(2021)027, arXiv:2103.06956.
- [45] CMS Collaboration, “Search for nonresonant Higgs boson pair production in final states with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2021) 257, doi:10.1007/JHEP03(2021)257, arXiv:2011.12373.
- [46] CMS Collaboration, “Measurements of the Higgs boson production cross section and couplings in the W boson pair decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **83** (2023) 667, doi:10.1140/epjc/s10052-023-11632-6, arXiv:2206.09466.
- [47] CMS Collaboration, “Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **81** (2021) 378, doi:10.1140/epjc/s10052-021-09014-x, arXiv:2011.03652.
- [48] CMS Collaboration, “Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **12** (2020) 085, doi:10.1007/JHEP12(2020)085, arXiv:2006.13251.
- [49] CMS Collaboration, “Observation of Higgs boson decay to bottom quarks”, *Phys. Rev. Lett.* **121** (2018) 121801, doi:10.1103/PhysRevLett.121.121801, arXiv:1808.08242.
- [50] CMS Collaboration, “Evidence for the Higgs boson decay to a bottom quark-antiquark pair”, *Phys. Lett. B* **780** (2018) 501, doi:10.1016/j.physletb.2018.02.050, arXiv:1709.07497.
- [51] CMS Collaboration, “Search for $t\bar{t}H$ production in the $H \rightarrow b\bar{b}$ decay channel with leptonic $t\bar{t}$ decays in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2019) 026, doi:10.1007/JHEP03(2019)026, arXiv:1804.03682.

-
- [52] CMS Collaboration, “Measurements of Higgs boson production in the decay channel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C* **83** (2023) 562, doi:10.1140/epjc/s10052-023-11452-8, arXiv:2204.12957.
- [53] CMS Collaboration, “Evidence for Higgs boson decay to a pair of muons”, *JHEP* **01** (2021) 148, doi:10.1007/JHEP01(2021)148, arXiv:2009.04363.
- [54] CMS Collaboration, “Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **842** (2023) 137531, doi:10.1016/j.physletb.2022.137531, arXiv:2206.09401.
- [55] CMS Collaboration, “Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **129** (2022) 081802, doi:10.1103/PhysRevLett.129.081802, arXiv:2202.09617.
- [56] CMS Collaboration, “Search for nonresonant pair production of highly energetic Higgs bosons decaying to bottom quarks”, *Phys. Rev. Lett.* **131** (2023) 041803, doi:10.1103/PhysRevLett.131.041803, arXiv:2205.06667.
- [57] CMS Collaboration, “Search for Higgs boson pair production with one associated vector boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”, 2024. arXiv:2404.08462. Submitted to *JHEP*.
- [58] CMS Collaboration, “Search for Higgs boson pairs decaying to $WWWW$, $WW\tau\tau$, and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2023) 095, doi:10.1007/JHEP07(2023)095, arXiv:2206.10268.
- [59] CMS Collaboration, “Search for Higgs boson pair production in the $bbWW$ decay mode in proton-proton collisions at $\sqrt{s} = 13$ TeV”, 3, 2024. arXiv:2403.09430. Submitted to *JHEP*.
- [60] CMS Collaboration, “Search for nonresonant Higgs boson pair production in the four leptons plus twob jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **06** (2023) 130, doi:10.1007/JHEP06(2023)130, arXiv:2206.10657.
- [61] ATLAS and CMS Collaborations, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV”, *JHEP* **08** (2016) 045, doi:10.1007/JHEP08(2016)045, arXiv:1606.02266.
- [62] ATLAS and CMS Collaborations, and LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.
- [63] CMS Collaboration, “The CMS statistical analysis and combination tool: COMBINE”, 2024. arXiv:2404.06614. Submitted to *Comput. Softw. Big Sci.*
- [64] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 3. Higgs properties”, CERN Report CERN-2013-004, 2013. doi:10.5170/CERN-2013-004, arXiv:1307.1347.

- [65] CMS Collaboration, “Search for Higgs boson and observation of Z boson through their decay into a charm quark-antiquark pair in boosted topologies in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **131** (2023), no. 4, 041801, doi:10.1103/PhysRevLett.131.041801, arXiv:2211.14181.
- [66] 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, doi:10.1103/PhysRevLett.131.061801, arXiv:2205.05550.
- [67] CMS Collaboration, “Search for rare decays of the Higgs boson into a photon and a ρ , ϕ or K^{*0} meson”, CMS Physics Analysis Summary CMS-PAS-HIG-23-005, 2024.
- [68] CMS Collaboration, “Search for the Higgs boson decay to a pair of electrons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **846** (2023) 137783, doi:10.1016/j.physletb.2023.137783, arXiv:2208.00265.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 













Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck² , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 

















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , 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, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat⁴ , G.P. Van Onsem , S. Van Putte , D. Vannerom 















Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 










Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 


















Université Catholique de Louvain, Louvain-la-Neuve, Belgium

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. Wertz 










Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira⁵ 

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. Chinellato⁶, E.M. Da Costa , G.G. Da Silveira⁷ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, M. Macedo , J. Martins⁸ , C. Mora Herrera , 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. Bernardes⁷ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maietto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. 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 , 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, K. Yi^{9,10} 


Institute of High Energy Physics, Beijing, China

G.M. Chen¹¹ , H.S. Chen¹¹ , M. Chen¹¹ , J. Guo¹¹, F. Iemmi , A. Kapoor¹² , H. Liao , Z.-A. Liu¹³ , R. Sharma¹⁴ , J.N. Song¹³, J. Tao , C. Wang¹¹, J. Wang , Z. Wang¹¹, H. Zhang , J. Zhao 

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

A. Agapitos , Y. Ban , 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, L. 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. Bauer¹⁵, B. Li, J. Zhang 

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

X. Gao¹⁶ 

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

F. Ramirez , 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. Jakovic, S. Mishra , A. Starodumov¹⁷ , 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 

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

Y. Assran^{18,19}, B. El-mahdy, S. Elgammal¹⁹

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M.A. Mahmoud , Y. Mohammed 
















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

K. Ehataht , M. Kadastik, T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

Department of Physics, University of Helsinki, Helsinki, Finland

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 




























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

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-Navarro²⁰ , 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 , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 






Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France













J.-L. Agram²¹ , J. Andrea , D. Apparú , 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. Dozen²² , 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

I. Bagaturia²³ , I. Lomidze , Z. Tsamalaidze¹⁷ 









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 , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo²⁴ , 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 , S. Bhattacharya , F. Blekman²⁵ , K. Borrás²⁶ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁵ , 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. Lipka²⁷ , W. Lohmann²⁸ , 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 , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham^{29,26} , S. Schnake²⁶ , P. Schütze , C. Schwanenberger²⁵ , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁶ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , 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. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany






S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann³⁰ , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link,

A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mornile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , 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. Papadopoulos³⁰, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , 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. Tsiopolitis , A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, 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^{31,32} , K. Márton, A.J. Rádl³³ , F. Sikler , V. Veszpremi 

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanád , K. Farkas , A. Fehérkuti³⁴ , M.M.A. Gadallah³⁵ , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

B. Ujvari , G. Zilizi 















Institute of Nuclear Research ATOMKI, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

F. Nemes³⁴ , T. Novak 

Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁶ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 
















University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M.K. Saini, S. Saumya 


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁷ , 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. Komaragiri³⁸ , D. Kumar³⁸ , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay












Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, G.B. Mohanty , B. Parida , M. Shelake, P. Suryadevara











Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, 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. Bahinipati³⁹ , C. Kar , D. Maity⁴⁰ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁰ , K. Naskar⁴⁰ , A. Nayak⁴⁰ , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese⁴⁰ , D. Vats⁴⁰ 

Indian Institute of Science Education and Research (IISER), Pune, India

S. Acharya⁴¹ , A. Alpana , S. Dube , B. Gomber⁴¹ , P. Hazarika , B. Kansal , A. Laha , B. Sahu⁴¹ , S. Sharma , K.Y. Vaish 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴² , A. Jafari⁴³ , M. Zeinali⁴⁴ 































Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Bashiri, S. Chenarani⁴⁵ , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie⁴⁶ , M. Mohammadi Najafabadi , S. Tizchang⁴⁷ 






























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,48} , 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. Diotallevi^{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,49} , 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,50} , A. Di Mattia^a , A. Lapertosa^a , R. Potenza^{a,b}, A. Tricomi^{a,b,50} , C. Tuve^{a,b} 


INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

P. Assiouras^a , G. Barbagli^a , G. Bardelli^{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. Meola⁵¹ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, ItalyP. Chatagnon^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 , 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,52} , P. Paolucci^{a,30} , 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,53} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , A.C.M. Bulla^a , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Gasparini^{a,b} , F. Gonella^a , A. Gozzelino^a , E. Lusiani^a , M. Margoni^{a,b} , M. Migliorini^{a,b} , 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} , G. Zumerle^{a,b} **INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy**C. Aimè^a , A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} **INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy**S. Ajmal^{a,b} , M.E. Ascioti^{a,b}, G.M. Bilei^a , C. Carrivale^{a,b}, D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{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.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} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , A.C. Marini^a , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , 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**C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , M. Campana^{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} , E. Longo^{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 **INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy**N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , 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. Pelliccioni^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

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 , C. Huh , B. Kim , 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 - GWNNU, 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 , 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 








Sejong University, Seoul, Korea

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 , S. Ko , H. Kwon , 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, 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 , 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

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , 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. Yusuff⁵⁵ , 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 Cruz⁵⁶ , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera, A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 


Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista , 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, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , 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

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, T. Niknejad , 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

M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic















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

J. Alcaraz Maestre , Cristina F. Bedoya , 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 , E. Martin Viscasillas , D. Moran , C.M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 




















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , P. Leguina , E. Palencia Cortezon , J. Prado Pico, C. Ramón Álvarez , 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. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , 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. Kailasapathy⁵⁷ , D.D.C. Wickramarathna 













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

W.G.D. Dharmaratna⁵⁸ , K. Liyanage , N. Perera 




CERN, European Organization for Nuclear Research, Geneva, Switzerland


































D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Boronovi , C. Botta , E. Brondolin , 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 , J. Hegeman , J.K. Heikkilä , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban²⁸ , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , 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 , H. Qu , D. Rabady , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁵⁹ , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk⁶⁰ , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland




















T. Bevilacqua⁶¹ , L. Caminada⁶¹ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶¹ , L. Noehte⁶¹ , T. Rohe 

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




T.K. Aarrestad , K. Androsov⁶⁰ , M. Backhaus , G. Bonomelli, A. Calandri , C. Caz-

zaniga , K. Datta , P. De Bryas Dexmiers D'archiac⁶⁰ , 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 , C. Martin Perez , A. Mascellani⁶⁰ , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶⁰ , A. Tarabini , D. Valsecchi , R. Wallny 












Universität Zürich, Zurich, Switzerland

C. Amsler⁶² , P. Bäertschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 




National Central University, Chung-Li, Taiwan

C. Adloff⁶³, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁸ , S.S. Yu 



















National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen , P.s. 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, H.y. Wu, E. Yazgan 


High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangkuldee , N. Srimanobhas , V. Wachirapusanand 

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu⁶⁴ , E. Eskut , Y. Guler⁶⁵ , E. Gurpinar Guler⁶⁵ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁶ , A. Polatoz , B. Tali⁶⁷ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 






Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac⁶⁸ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁶⁹ , O. Kaya⁷⁰ , S. Tekten⁷¹ 





Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{64,72} , G.G. Dincer⁶⁴ , Y. Komurcu , S. Sen⁷³ 

Istanbul University, Istanbul, Turkey

O. Aydilek⁷⁴ , B. Hacisahinoglu , I. Hos⁷⁵ , B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 


Yildiz Technical University, Istanbul, Turkey

S. Cerci⁶⁷ , B. Isildak⁷⁶ , D. Sunar Cerci , T. Yetkin 

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 , M. Glowacki, J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁷ , K. Walkingshaw Pass




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁸ , 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 , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal⁷⁹ , D. Colling , J.S. Dancu, I. Das , P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Mallios, M. Mieskolainen , J. Nash⁸⁰ , M. Pesaresi , P.B. Pradeep, B.C. Radburn-Smith , A. Richards, A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee³⁰ , M. Vojinovic , N. Wardle , D. Winterbottom 






Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , E. Collins , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 



















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , C. Huerta Escamilla, A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 



















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. Rumerio⁸¹ , 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. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan⁸² , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , T. Russell, S. Sagir⁸³ , F. Simpson , M. Stamenkovic , N. Venkatasubramanian, X. Yan 

University of California, Davis, Davis, California, USA

S. Abbott , 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 , Y. Yao , S. Yoo , F. Zhang 

University of California, Los Angeles, California, USA

























M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko 

M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 

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 , M. Quinnan , B.V. Sathia Narayanan , 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 , 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 , S. Wang , D. Zhang















California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, A. Latorre, 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, 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 , G. Karathanasis , N. Manganelli , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 

Cornell University, Ithaca, New York, USA








J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , 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 , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁴ , F. Ravera , A. Reinsvold Hall⁸⁵ , 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, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mit-

selmakher , 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. Habibullah , V. Hagopian , 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, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy⁸⁶ , M. Hohlmann , M. Rahmani, E. Yanes












University of Illinois Chicago, Chicago, USA, Chicago, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , 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. Dilsiz⁸⁷ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁸ , O. Neogi, H. Ogul⁸⁹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹⁰ 









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 , M. Pitt , S. Popescu⁹¹ , C. Rogan , C. Royon , R. Salvatico , 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, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, L. Wang 













Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , 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. Kovalskiy , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. MCGinn, A. Novak , C. Paus , 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 , B.M. Joshi , 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 , 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 , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , D. Wood 









Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , 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.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore , Y. Musienko¹⁷ , 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 , B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 


















Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , A. Shevelev , D. Stickland , C. Tully 




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 













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 , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi , F. Wang , W. Xie 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, Texas, USA
















D. Acosta , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , 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. Parygin⁹² , E. Popova⁹² , 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. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

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 , O. Bouhali⁹³ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁴ , H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 







Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , 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 , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Neu 

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 , S. Dasu , I. De Bruyn , 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 institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Alexakhin , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , V. Blinov⁹⁵, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , V. Chekhovsky, R. Chistov⁹⁵ , M. Danilov⁹⁵ , A. Dermenev , T. Dimova⁹⁵ , D. Druzhkin⁹⁶ , M. Dubinin⁸⁴ , L. Dudko , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin[†] , I. Gorbunov , Y. Ivanov , V. Kachanov , V. Karjavine , A. Karneyeu , V. Kim⁹⁵ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁷ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁵ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁸ , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁵ , V. Murzin , A. Nikitenko^{99,97} , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , M. Perfilov, S. Petrushanko , S. Polikarpov⁹⁵ , V. Popov , O. Radchenko⁹⁵ , M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁵ , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , P. Volkov , A. Vorobyev[†], G. Vorotnikov , N. Voytishin , B.S. Yuldashev¹⁰⁰, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

-
- ³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
- ⁴Also at Ghent University, Ghent, Belgium
- ⁵Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- ⁶Also at Universidade Estadual de Campinas, Campinas, Brazil
- ⁷Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- ⁸Also at UFMS, Nova Andradina, Brazil
- ⁹Also at Nanjing Normal University, Nanjing, China
- ¹⁰Now at The University of Iowa, Iowa City, Iowa, USA
- ¹¹Also at University of Chinese Academy of Sciences, Beijing, China
- ¹²Also at China Center of Advanced Science and Technology, Beijing, China
- ¹³Also at University of Chinese Academy of Sciences, Beijing, China
- ¹⁴Also at China Spallation Neutron Source, Guangdong, China
- ¹⁵Now at Henan Normal University, Xinxiang, China
- ¹⁶Also at Université Libre de Bruxelles, Bruxelles, Belgium
- ¹⁷Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- ¹⁸Also at Suez University, Suez, Egypt
- ¹⁹Now at British University in Egypt, Cairo, Egypt
- ²⁰Also at Purdue University, West Lafayette, Indiana, USA
- ²¹Also at Université de Haute Alsace, Mulhouse, France
- ²²Also at Istinye University, Istanbul, Turkey
- ²³Also at Ilia State University, Tbilisi, Georgia
- ²⁴Also at The University of the State of Amazonas, Manaus, Brazil
- ²⁵Also at University of Hamburg, Hamburg, Germany
- ²⁶Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁷Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁸Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁹Also at Forschungszentrum Jülich, Juelich, Germany
- ³⁰Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³¹Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³²Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³³Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ³⁴Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³⁵Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁶Also at Punjab Agricultural University, Ludhiana, India
- ³⁷Also at University of Visva-Bharati, Santiniketan, India
- ³⁸Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁹Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴⁰Also at Institute of Physics, Bhubaneswar, India
- ⁴¹Also at University of Hyderabad, Hyderabad, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁷Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran

- ⁴⁸Also at Helwan University, Cairo, Egypt
- ⁴⁹Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁵⁰Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵¹Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵²Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵³Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁷Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁸Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁵⁹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶⁰Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶¹Also at Universität Zürich, Zurich, Switzerland
- ⁶²Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶³Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁴Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁵Also at Konya Technical University, Konya, Turkey
- ⁶⁶Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁷Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁸Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁶⁹Also at Marmara University, Istanbul, Turkey
- ⁷⁰Also at Milli Savunma University, Istanbul, Turkey
- ⁷¹Also at Kafkas University, Kars, Turkey
- ⁷²Now at Istanbul Okan University, Istanbul, Turkey
- ⁷³Also at Hacettepe University, Ankara, Turkey
- ⁷⁴Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ⁷⁵Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁶Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁷Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁸Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁹Also at IPPP Durham University, Durham, United Kingdom
- ⁸⁰Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸¹Also at Università di Torino, Torino, Italy
- ⁸²Also at Bethel University, St. Paul, Minnesota, USA
- ⁸³Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁴Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁵Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁶Also at Ain Shams University, Cairo, Egypt
- ⁸⁷Also at Bingol University, Bingol, Turkey
- ⁸⁸Also at Georgian Technical University, Tbilisi, Georgia
- ⁸⁹Also at Sinop University, Sinop, Turkey
- ⁹⁰Also at Erciyes University, Kayseri, Turkey
- ⁹¹Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH),

Bucharest, Romania

⁹²Now at an institute or an international laboratory covered by a cooperation agreement with CERN

⁹³Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁴Also at Kyungpook National University, Daegu, Korea

⁹⁵Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁹⁶Also at Universiteit Antwerpen, Antwerpen, Belgium

⁹⁷Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at Northeastern University, Boston, Massachusetts, USA

⁹⁹Also at Imperial College, London, United Kingdom

¹⁰⁰Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan