CERN-EP-2022-233
2023/07/31

CMS-HIG-21-012

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

The CMS Collaboration*

Abstract

A search for the standard model (SM) Higgs boson (H) produced with transverse momentum (p_T) greater than 450 GeV and decaying to a charm quark-antiquark ($c\bar{c}$) pair is presented. The search is performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC, corresponding to an integrated luminosity of 138 fb^{-1} . Boosted $H \rightarrow c\bar{c}$ decay products are reconstructed as a single large-radius jet and identified using a deep neural network charm tagging technique. The method is validated by measuring the $Z \rightarrow c\bar{c}$ decay process, which is observed in association with jets at high p_T for the first time with a signal strength of $1.00^{+0.17}_{-0.14} (\text{syst}) \pm 0.08 (\text{theo}) \pm 0.06 (\text{stat})$, defined as the ratio of the observed process rate to the SM expectation. The observed (expected) upper limit on $\sigma(H) \mathcal{B}(H \rightarrow c\bar{c})$ is set at 47 (39) times the SM prediction at 95% confidence level.

Published in Physical Review Letters as doi:10.1103/PhysRevLett.131.041801.

The standard model (SM) Higgs boson (H) has been observed at the LHC [1–3] in all its expected primary production modes and most of its dominant decay channels. With the observations of direct couplings to τ leptons [4, 5], top quarks [6, 7], and bottom quarks [8, 9] confirming that the SM Yukawa sector gives rise to the masses of third-generation fermions, attention naturally turns to probing the second generation, specifically muons and charm quarks.

The search for H decays to muon pairs is the most experimentally accessible channel, and has been explored by the ATLAS [10, 11] and CMS [12] Collaborations. The latter recently found evidence of the H coupling to muons [13].

In contrast, the search for H decays to charm quark-antiquark pairs ($H \rightarrow c\bar{c}$) is considerably more challenging, because of the difficulty of identifying such decays and due to the enormous multijet background. However, recent advances in jet substructure and flavor tagging techniques [14] have greatly improved the experimental sensitivity to this decay mode. Prior searches by ATLAS [15, 16] and CMS [17, 18] have focused on H production in association with a vector boson (VH, where V stands for a W or Z boson), which benefits from strong background rejection thanks to leptonic decays of the vector bosons. The gluon-gluon fusion (ggF) and vector boson fusion (VBF) production modes have larger cross sections, but have yet to be explored.

This letter reports on the first search for the $H \rightarrow c\bar{c}$ decay at the LHC, where the H is produced with transverse momentum (p_T) greater than 450 GeV, enriched in events from the ggF production. The search employs the same general strategy as earlier CMS searches for boosted H in the $b\bar{b}$ decay channel [19, 20], but uses new mass decorrelated discriminators to define a charm-enriched signal region. This search strategy provides an additional constraint on the decay process to the existing ATLAS and CMS measurements, in terms of production mode and H p_T .

The search is performed using a dataset of proton-proton collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector at the LHC, and corresponding to an integrated luminosity of 138 fb^{-1} . Candidate events are selected by requiring a high- p_T , large-radius jet with substructure observables compatible with those expected from an $H \rightarrow c\bar{c}$ decay. Deep neural network (DNN) discriminators are employed to separate the H signal events from the dominant background, specifically quantum chromodynamics (QCD)-induced multijet events. The discriminators are designed to be independent of jet mass, which allows for both an estimation of the QCD background from control samples in data and for the validation of the analysis procedure through a search for $Z \rightarrow c\bar{c}$ decays. A model of the jet mass distributions for the $H \rightarrow c\bar{c}$ and $Z \rightarrow c\bar{c}$ signals, QCD multijet events, and other background processes is fit simultaneously in several disjoint signal and control regions to extract the signal production cross sections.

The CMS apparatus [21] is a multipurpose, nearly hermetic detector, designed to trigger on [22, 23] and identify electrons, muons, photons, and (charged and neutral) hadrons [24–26]. A global “particle-flow” (PF) algorithm [27] 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 τ leptons, jets, and missing transverse momentum (p_T^{miss}) [28–30].

Simulated samples of signal and background events are produced at the matrix element level using various Monte Carlo (MC) event generators. The QCD multijet, Z+jets, and W+jets processes are modeled at QCD leading order (LO) accuracy using the MADGRAPH5_aMC@NLO v2.4.2

generator [31]. The vector boson samples contain decays to all flavors of quarks, and include up to 3 (4) extra partons at the matrix element level for V+jets events. Jets from the matrix element calculations and the parton shower description are matched using the MLM prescription [32]. The $t\bar{t}$ and single top quark processes are modeled at next-to-LO (NLO) using POWHEG 2.0 [33–38]. The diboson processes are modeled at LO accuracy with PYTHIA 8.226 [39]. For 2016 data-taking conditions, QCD samples are modeled with MADGRAPH5_aMC@NLO v2.2.2, and diboson samples are modeled with PYTHIA 8.205.

The differential cross sections for the Z+jets and W+jets (V+jets) samples are corrected with boson p_T -dependent functions for higher-order QCD and electroweak (EW) effects. The QCD NLO corrections are derived using MADGRAPH5_aMC@NLO, simulating W and Z production with up to two additional partons and the FxFx matching to the parton shower [40]. The EW NLO corrections are taken from theoretical calculations of Refs. [41–44]. Additionally, the total cross sections for the diboson samples are corrected to next-to-NLO (NNLO) accuracy with the MCFM 7.0 program [45].

The ggF H production process is simulated using the HJ-MINLO [35, 46–48] event generator with mass $m_H = 125$ GeV and including finite top quark mass effects, following the recommendation in Ref. [48]. The POWHEG [49] generator is used to model the H production through the VBF, VH, and $t\bar{t}H$ processes [47, 50, 51].

For parton showering and hadronization, the POWHEG and MADGRAPH5_aMC@NLO samples are interfaced with PYTHIA 8.205 (8.230) for 2016 (2017–2018) running conditions. The corresponding PYTHIA parameters for the underlying event description are set to the CUETP8M1 [52] (CP5 [53]) tune. For 2016 samples the parton distribution function (PDF) set NNPDF3.0 [54] is used, with either LO or NLO accuracy, corresponding to that used in the matrix element calculations, while for 2017–2018 samples NNPDF3.1 [55] at NNLO accuracy is used for all processes. The detector response is modeled with GEANT4 [56].

Reconstructed particles are clustered into jets using the anti- k_T algorithm [57, 58]. Small-radius jets are clustered with a distance parameter of 0.4 (AK4 jets). Large-radius jets arising from the decays of boosted heavy particles are reconstructed with a distance parameter of 0.8 (AK8 jets). The effect of particles from additional proton-proton interactions within the same or nearby bunch crossings (pileup) is mitigated through the charged hadron subtraction [27] and pileup-per-particle identification [59] algorithms for AK4 and AK8 jets, respectively. Additional corrections are applied to the jet energy as functions of jet pseudorapidity (η) and p_T to account for the detector response.

The H candidate is reconstructed as a single AK8 jet with $p_T > 450$ GeV. A mix of triggers using jet p_T or a scalar sum of the jet p_T in the event is employed for online selection. At $p_T = 450$ GeV, the online selection is 90% efficient with respect to the offline selection, reaching full efficiency by 500 GeV. The soft-drop (SD) algorithm [60] with parameters $\beta = 0$ and $z = 0.1$ is applied to the jet mass (m_{SD}) to remove soft and wide-angle radiation, which reduces the mass of jets originating from QCD background events while preserving the mass of jets originating from heavy boson decays. The range of interest is set to $40 < m_{SD} < 201$ GeV. To match the tracker acceptance region, jets are required to have $|\eta| < 2.5$. In case of several jets in the event passing the criteria, the jet with the highest charm versus light tagging score, defined below, is taken to be the H candidate.

After the above selections, the dominant background is the QCD multijet production, which accounts for more than 95% of the expected yield and is estimated from data. The V+jets processes are significant resonant backgrounds at approximately 4%, and are estimated from

simulation. The $t\bar{t}$ process constitutes a subdominant nonresonant background across the m_{SD} spectrum, the shape of which is taken from simulation, while the total yield is estimated from data. Other EW processes, including diboson, triboson, and $t\bar{t}V$ processes, are estimated from simulation and found to be negligible.

Events containing leptons are vetoed to reduce SM EW backgrounds. The selection criteria for electrons, muons, and hadronic τ leptons are $p_T > 10, 10,$ and 20 GeV and $|\eta| < 2.5, 2.4,$ and 2.3 , along with “veto”, “loose”, and “very loose” identification requirements [24, 28, 61], respectively. In addition, muons are required to have a relative isolation (scalar p_T sum of the PF candidates within a cone with a distance parameter of 0.4, divided by the lepton p_T) of less than 0.25. Events with $p_T^{\text{miss}} > 140\text{ GeV}$, as well as events with AK4 b-tagged jets with $p_T > 30\text{ GeV}$ opposite in azimuth to the H candidate jet ($\Delta\phi(\text{AK4}, \text{AK8}) > \pi/2$), are removed to reduce the top quark background. The AK4 b jet identification is performed using the DEEPCSV DNN algorithm [62] with a working point corresponding to a 1% misidentification probability for light (u, d, s quark, or gluon) jets.

The dimensionless mass scale variable $\rho = 2\ln(m_{SD}/p_T)$ [63, 64] is used to parametrize the QCD background model (described below) as its distribution is approximately invariant versus jet p_T , unlike jet m_{SD} . A selection of $-6.0 < \rho < -2.1$ is imposed to avoid instabilities and edge effects from the SD algorithm and jet clustering [65]. The lower ρ threshold implies an upper jet p_T threshold, which is made explicit by requiring $p_T < 1200\text{ GeV}$. In simulation, less than 1% of signal events are found above this upper bound.

The N_2^1 variable [66], a ratio of energy correlation functions [67], is a powerful way to identify two-pronged signatures. However, using it for selection distorts the background jet mass distribution as a function of p_T . To mitigate this effect, the designing decorrelated taggers (DDT) technique [64], effectively a sliding selection, is applied. The selection is on $N_2^{1,\text{DDT}} \equiv N_2^1 - q_{0.26}(p_T, \rho) < 0$, where $q_{0.26}(p_T, \rho)$ is the N_2^1 value corresponding to the 26% efficiency for the QCD background, as a function of jet p_T and ρ . The target percentile is chosen to optimize the $H \rightarrow c\bar{c}$ expected significance.

Finally, jet flavor is determined by the DEEPDOUBLEX DNN algorithm [68]. The model comprises convolutional and recurrent units processing low-level features of secondary vertices and PF candidates, the outputs of which are joined with expert variables [62] in a fully connected layer. The application of feature importance ranking techniques, such as integrated gradients [69] and deep Taylor decomposition [70], indicates the key features to be the angular distances of the PF candidates from both the jet and 2-subjetiness [71] axes. The kinematic properties of the PF candidates defined relative to the parent jet have subleading importance. The model is trained to distinguish between two-pronged H-like signatures of bottom and charm flavors, as well as the QCD background, yielding two per-jet classifiers: charm versus light, referred to as DEEPDOUBLECVL (DDCVL), and charm versus bottom, referred to as DEEPDOUBLECVB (DDCVB). The performance of the two classifiers is shown, prior to any analysis-specific selection, in Fig. 1. The optimal working point, maximizing the $H \rightarrow c\bar{c}$ expected significance after all previous selections are applied, is found with respect to both classifiers at a QCD efficiency of 0.5% and a $H \rightarrow c\bar{c}$ efficiency of 20.6%. The corresponding efficiency for $H \rightarrow b\bar{b}$ events is 4.8%. As the classifiers are mass independent, the quoted efficiencies also apply to $Z \rightarrow c\bar{c}$ and $Z \rightarrow b\bar{b}$.

The relative contributions of H production modes to the overall signal yield are 55%, 25%, and 20% for ggF, VBF, and VH, respectively, and are similar for both $c\bar{c}$ and $b\bar{b}$ decay modes. The $t\bar{t}H$ contribution is suppressed due to the top veto and found to be negligible. Events passing all of the selection requirements described above constitute the signal or “passing” region (SR),

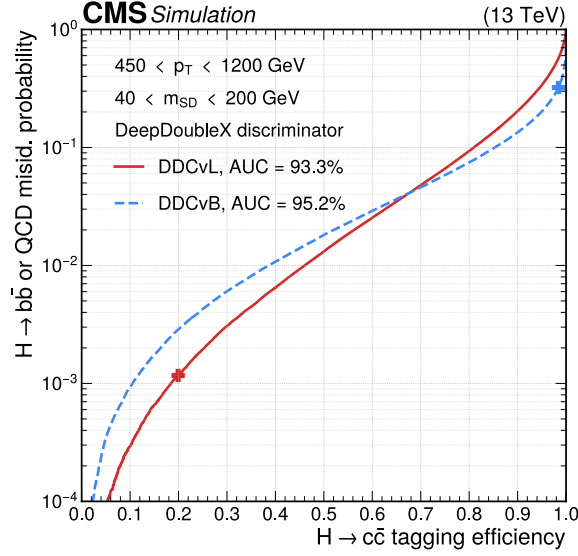


Figure 1: The DDCvL and DDCvB performance for $H \rightarrow c\bar{c}$ identification versus QCD and $H \rightarrow b\bar{b}$ processes, respectively. No selection apart from the displayed m_{SD} and p_{T} requirements is applied. The working points used in this search are marked with a cross. The AUC is the area-under-curve metric.

whereas events failing the DDCvL requirement while passing the rest, including the DDCvB requirement, constitute the control or “failing” region (CR). Both the SR and CR are subdivided into 23 evenly spaced bins of jet m_{SD} in the range 40–201 GeV and 6 p_{T} bins from 450 (or 475) to 1200 GeV. Additionally, all regions are subdivided according to the three data-taking years (2016–2018).

The QCD background is not accurately predicted in simulation. Since the flavor discrimination is nearly independent of the jet p_{T} and mass, the ratio of the passing and failing region distributions, $R_{\text{p/f}}$, is expected to be approximately flat with respect to the jet p_{T} and m_{SD} . This can be exploited to obtain an SR prediction of the QCD background from the CR via an appropriate efficiency scaling. A residual difference in shapes can be accounted for by parametrizing the $R_{\text{p/f}}$ shape in the two dimensions. In order to take into account a potential mass dependence of the flavor selection efficiency, a correction factor, $R_{\text{p/f}}^{\text{QCD}}(p_{\text{T}}, \rho)$, is fit to the simulated QCD background shapes. Then, a second correction factor of the same functional form, $R^{\text{data}}(p_{\text{T}}, \rho)$, accounts for mismodellings in simulation. Both are parametrized in terms of Bernstein polynomials [72] in p_{T} and ρ :

$$R(p_{\text{T}}, \rho) = \sum_{k=0}^{n_{\rho}} \sum_{\ell=0}^{n_{p_{\text{T}}}} a_{k,\ell} b_{\ell, n_{p_{\text{T}}}}(p_{\text{T}}) b_{k, n_{\rho}}(\rho), \quad (1)$$

where $n_{p_{\text{T}}}$ is the degree of the polynomial in p_{T} , n_{ρ} is the degree of the polynomial in ρ , $a_{k,\ell}$ is a Bernstein coefficient, and $b_{\ell, n}$ is a Bernstein basis polynomial of degree n . The coefficients $a_{k,\ell}$ of $R_{\text{p/f}}^{\text{QCD}}(p_{\text{T}}, \rho)$ are determined in a fit to simulated QCD background events; $a_{k,\ell}$ of $R^{\text{data}}(p_{\text{T}}, \rho)$ are unconstrained and are determined during the maximum likelihood fit to data. The total effective $R_{\text{p/f}}$ is then expressed as:

$$R_{\text{p/f}}(p_{\text{T}}, \rho) = R_{\text{p/f}}^{\text{QCD}}(p_{\text{T}}, \rho) R^{\text{data}}(p_{\text{T}}, \rho). \quad (2)$$

The $R_{\text{p/f}}$ are expected to vary between data-taking years because of changes in detector conditions, and are thus fit independently for each year. The minimal degree of the polynomials

necessary to fit the QCD simulation and the data is determined by a Fisher F-test [73] and found to be $(n_{p_T}, n_\rho) = (0, 2), (1, 2),$ and $(0, 2)$ for $R_{p/f}^{\text{QCD}}(p_T, \rho)$ and $(1, 0), (0, 0),$ and $(1, 0)$ for $R^{\text{data}}(p_T, \rho)$ for the years 2016, 2017, and 2018, respectively. Bias tests were performed with respect to the choice of parametrization, and no significant bias was found.

The V+jets processes are modeled using simulation. The differential $t\bar{t}$ contribution is taken from simulation; however, the normalizations in the SR and CR are corrected via two scale factors measured in a dedicated $t\bar{t}$ -enriched control region, parametrizing the overall normalization and the efficiency of the DDCvL selection between the SR and CR. This control region is adapted from the SR selection by lowering the H candidate p_T threshold, requiring exactly one muon, and inverting the selection requirements on p_T^{miss} and b-tagged AK4 jets. The scale factor measurement is performed *in situ* during the signal extraction, separately for each data-taking period, and the values are given in Table 1. The $H \rightarrow b\bar{b}$ contribution is taken from the simulation and is fixed to the SM expectation. While its expected SR yield is greater by approximately a factor of 5 than that of the $H \rightarrow c\bar{c}$ signal, its impact is negligible with respect to the overall background uncertainty.

The dominant systematic uncertainties for this search are related to the flavor tagging efficiency and jet mass shape. Corrections of the jet mass, jet mass resolution, and $N_2^{1,\text{DDT}}$ and DDCvB efficiencies are derived from data using W boson jets from semileptonic $t\bar{t}$ events. These corrections are measured independently of jet flavor, and as such are correlated among all considered resonant (H, Z, W) production and decay processes. The DDCvL misidentification efficiency of the W process is measured here as well. The corrections and their associated uncertainties are given in Table 1.

Table 1: Summary of the applied data-to-simulation scale factors for the jet mass, jet mass resolution, $N_2^{1,\text{DDT}}$ selection, $t\bar{t}$ normalization, and DEEPDOUBLEX selections for different data-taking periods. The jet mass correction is additive, in units of GeV.

Data period	Jet mass correction [GeV]	Jet mass resolution	$N_2^{1,\text{DDT}}$, CvB selection	$t\bar{t}$ normalization	CvL selection $t\bar{t}$	CvL selection (W+jets)	CvL selection (signal)
2016	-1.17 ± 0.22	1.021 ± 0.017	0.89 ± 0.02	0.84 ± 0.05	0.93 ± 0.15	0.62 ± 0.09	1.15 ± 0.25
2017	-1.19 ± 0.23	1.019 ± 0.016	0.90 ± 0.02	0.86 ± 0.09	0.93 ± 0.15	0.64 ± 0.09	0.85 ± 0.16
2018	-0.12 ± 0.21	1.090 ± 0.031	0.92 ± 0.02	0.86 ± 0.08	1.00 ± 0.14	0.72 ± 0.08	0.74 ± 0.20

The efficiency of the DDCvL selection for the signal processes is estimated using data and simulation samples enriched in $c\bar{c}$ pairs from gluon splitting [62]. Signal-like events are selected by requiring each of the two SD subjects of an AK8 jet to contain a muon, targeting semileptonic decays of b/c hadrons. The efficiency is extracted from a template fit to the combined mass of all matched secondary vertices; the measured correction factors are given in Table 1. The relative uncertainty of the misidentification efficiency of $b\bar{b}$ decays is assigned to be 30%. Varying this value from 10 to 50% has a negligible effect on reported results.

Other systematic uncertainties are assigned to cover potential mismodeling of the H signal, in particular for the ggF and VBF production modes [48], and higher-order corrections to the W and Z processes [44]. Finally, systematic uncertainties for experimental effects, including jet energy scale and resolution [74], trigger and veto efficiencies [75, 76], variations in the measured pileup [77], finite simulated sample size [78], and an integrated luminosity measurement [79–81], are also included, but are found to have a comparatively small effect.

The parameter of interest in this analysis is the signal strength μ_H or μ_Z , defined as the ratio of the observed to the SM expected H or Z boson production cross section times the $H \rightarrow c\bar{c}$ or $Z \rightarrow c\bar{c}$ branching fraction, respectively. These parameters are extracted from a binned

$(m_{\text{SD}}, p_{\text{T}})$ maximum likelihood fit to the observed data, where the expected value is the sum of the signal contribution (scaled by the signal strength parameter) and the background contributions, each modified by nuisance parameters to account for the previously discussed systematic effects. The magnitude of each systematic uncertainty is encoded in the likelihood model as an additional constraint, treated according to the frequentist paradigm [82]. The fit is performed simultaneously across all subdivisions of the SR and CR described previously, as well as the per-year $t\bar{t}$ background enriched CRs.

To validate the analysis strategy, and to confirm the presence of $Z \rightarrow c\bar{c}$ decays, the Z signal strength μ_Z is measured via a profile likelihood fit, treating μ_H as a nuisance parameter, and is found to be $1.00^{+0.17}_{-0.14} (\text{syst}) \pm 0.08 (\text{theo}) \pm 0.06 (\text{stat})$. This corresponds to an excess, both observed and expected, over the $\mu_Z = 0$ hypothesis with a significance of well over 5 standard deviations. The precision of the μ_Z measurement is primarily limited by the systematic uncertainty in the DDCvL signal tagging efficiency. The subleading uncertainty comes from the modeling of the Z +jets production cross section.

For the extraction of μ_H , since the Z cross section has been measured in leptonic decay channels and found to agree with theoretical predictions within 5% in this p_{T} regime [83] and since the $Z \rightarrow c\bar{c}$ branching ratio is known to 2% precision [84], we fix $\mu_Z \equiv 1$, constraining the expected Z contribution to be within the applicable uncertainties of its SM value. This serves to further constrain *in situ* the DDCvL signal tagging efficiency uncertainty. The measured efficiencies are compatible with the values quoted in Table 1 and have approximately 30% lower uncertainty.

An observed (expected) upper limit is placed on the signal strength μ_H using the profile likelihood ratio test statistic [82], CL_s criterion [85, 86], and asymptotic formulae [87], and found to be 47 (39) at 95% confidence level. For the best fit value of $\mu_H = 9.4^{+20.3}_{-19.9}$, the total m_{SD} distributions in the passing and failing regions are shown in Fig. 2, and a breakdown of the sources of uncertainty affecting the measurement is shown in Table 2. Tabulated results are provided in the HEPData record for this analysis [88].

Table 2: Sources of uncertainty in the measurement of the signal strength $\mu_H = 9.4^{+20.3}_{-19.9}$, and their observed impact ($\Delta\mu_H$) in the fit to the full data set. The impact of each uncertainty is evaluated by computing the uncertainty excluding that source and subtracting it in quadrature from the total uncertainty. The total uncertainty does not match the sum in quadrature of each source because of correlations among the components.

Uncertainty source	$\Delta\mu_H$	
Statistical	+16.7	-16.6
Signal extraction	+14.2	-14.1
QCD pass-fail ratio (data correction)	+7.4	-7.4
$t\bar{t}$ normalization and misidentification	+0.9	-0.7
Systematic	+10.5	-10.4
QCD pass-fail ratio (simulation)	+9.7	-9.8
Flavor (mis-)tagging efficiency	+1.7	-2.2
Simulated sample size	+4.2	-3.6
Other experimental uncertainties	+2.1	-1.4
Theoretical	+3.9	-1.6
V+jets modeling	+2.3	-1.2
H modeling	+3.2	-1.0
Total	+20.3	-19.9

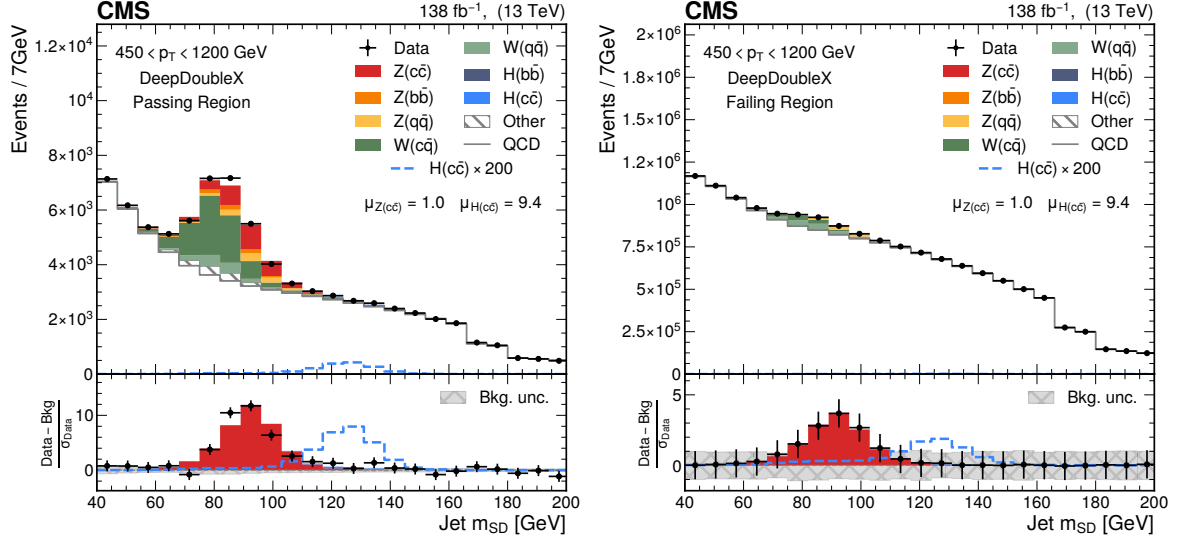


Figure 2: The observed and fitted m_{SD} distributions for the passing (left) and failing (right) regions, combining all p_T categories and the three data-taking years. The fit is performed under the signal-plus-background hypothesis with a single inclusive $H \rightarrow c\bar{c}$ signal strength parameter. The $t\bar{t}$ background yields and the QCD background yields and shapes are estimated from data. The $t\bar{t}$ process constitutes the majority of contributions labeled “other”. The dashed line represents the $H \rightarrow c\bar{c}$ expectation, multiplied by a factor of 200. The steplike features at 166 and 180 GeV are due to the ρ acceptance upper bound, which excludes bins with high m_{SD} and low p_T from the analysis. The lower panel shows the residual difference between the data and the overall background (excluding $Z \rightarrow c\bar{c}$), divided by the statistical uncertainty in the data. The near perfect model agreement with data in the failing region (right) is by construction.

In conclusion, a search for standard model (SM) Z and Higgs bosons produced with transverse momenta greater than 450 GeV and decaying to charm quark-antiquark ($c\bar{c}$) pairs has been performed in a data sample corresponding to an integrated luminosity of 138 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. New algorithms based on deep neural networks have been developed to identify jets originating from charm quark pairs. The $Z \rightarrow c\bar{c}$ process is observed in association with jets at a hadron collider for the first time, with a signal strength of $1.00^{+0.19}_{-0.17}$ relative to the SM prediction. This observation establishes $Z \rightarrow c\bar{c}$ as an important reference for future $X \rightarrow c\bar{c}$ searches. An observed (expected) upper limit on the product of the Higgs boson production cross section and branching fraction to $c\bar{c}$ of 47 (39) times the SM expectation is set at 95% confidence level.

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: 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); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); 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); LAS (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).

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, “Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector”, *Phys. Lett. B* **779** (2018) 283, doi:10.1016/j.physletb.2018.02.004, arXiv:1708.00373.
- [5] ATLAS Collaboration, “Measurements of Higgs boson production cross-sections in the $H \rightarrow \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **08** (2022) 175, doi:10.1007/JHEP08(2022)175, arXiv:2201.08269.
- [6] CMS Collaboration, “Observation of $t\bar{t}H$ Production”, *Phys. Rev. Lett.* **120** (2018) 231801, doi:10.1103/PhysRevLett.120.231801, arXiv:1804.02610.
- [7] ATLAS Collaboration, “Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector”, *Phys. Lett. B* **784** (2018) 173, doi:10.1016/j.physletb.2018.07.035, arXiv:1806.00425.
- [8] ATLAS Collaboration, “Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector”, *Phys. Lett. B* **786** (2018) 59, doi:10.1016/j.physletb.2018.09.013, arXiv:1808.08238.
- [9] 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.
- [10] CMS Collaboration, “Search for the Higgs Boson Decaying to Two Muons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **122** (2019) 021801, doi:10.1103/PhysRevLett.122.021801, arXiv:1807.06325.

- [11] ATLAS Collaboration, “A search for the dimuon decay of the standard model Higgs boson with the ATLAS detector”, *Phys. Lett. B* **812** (2021) 135980, doi:10.1016/j.physletb.2020.135980, arXiv:2007.07830.
- [12] ATLAS Collaboration, “Search for the Dimuon Decay of the Higgs boson in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector”, *Phys. Rev. Lett.* **119** (2017) 051802, doi:10.1103/PhysRevLett.119.051802, arXiv:1705.04582.
- [13] 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.
- [14] CMS Collaboration, “Performance of deep tagging algorithms for boosted double quark jet topology in proton-proton collisions at 13 TeV with the Phase-0 CMS detector”, CMS Detector Performance Note CMS-DP-2018-046, 2018.
- [15] ATLAS Collaboration, “Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment”, *Phys. Rev. Lett.* **120** (2018) 211802, doi:10.1103/PhysRevLett.120.211802, arXiv:1802.04329.
- [16] ATLAS Collaboration, “Direct constraint on the Higgs-charm coupling from a search for Higgs boson decays into charm quarks with the ATLAS detector”, *Eur. Phys. J. C* **82** (2022) 717, doi:10.1140/epjc/s10052-022-10588-3, arXiv:2201.11428.
- [17] CMS Collaboration, “A search for the standard model Higgs boson decaying to charm quarks”, *JHEP* **03** (2020) 131, doi:10.1007/JHEP03(2020)131, arXiv:1912.01662.
- [18] CMS Collaboration, “Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV”, 2022. arXiv:2205.05550. *Phys. Rev. Lett.* (to be published).
- [19] CMS Collaboration, “Inclusive Search for a Highly Boosted Higgs Boson Decaying to a Bottom Quark-Antiquark Pair”, *Phys. Rev. Lett.* **120** (2018) 071802, doi:10.1103/PhysRevLett.120.071802, arXiv:1709.05543.
- [20] 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.
- [21] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [22] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [23] 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.
- [24] 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.

-
- [25] 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.
- [26] 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.
- [27] 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.
- [28] 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.
- [29] 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.
- [30] 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.
- [31] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [32] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [33] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [34] S. Frixione, P. Nason, and G. Ridolfi, “A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction”, *JHEP* **09** (2007) 126, doi:10.1088/1126-6708/2007/09/126, arXiv:0707.3088.
- [35] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: The POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [36] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [37] E. Re, “Single-top Wt-channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [38] R. Frederix, E. Re, and P. Torrielli, “Single-top t -channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO”, *JHEP* **09** (2012) 130, doi:10.1007/JHEP09(2012)130, arXiv:1207.5391.

- [39] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [40] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [41] S. Kallweit et al., “NLO electroweak automation and precise predictions for W+multijet production at the LHC”, *JHEP* **04** (2015) 012, doi:10.1007/JHEP04(2015)012, arXiv:1412.5157.
- [42] S. Kallweit et al., “NLO QCD+EW automation and precise predictions for V+multijet production”, in *50th Rencontres de Moriond, QCD and high energy interactions*, p. 121. 2015. arXiv:1505.05704.
- [43] S. Kallweit et al., “NLO QCD+EW predictions for V+jets including off-shell vector-boson decays and multijet merging”, *JHEP* **04** (2016) 021, doi:10.1007/JHEP04(2016)021, arXiv:1511.08692.
- [44] J. M. Lindert et al., “Precise predictions for V+jets dark matter backgrounds”, *Eur. Phys. J. C* **77** (2017) 829, doi:10.1140/epjc/s10052-017-5389-1, arXiv:1705.04664.
- [45] J. M. Campbell and R. K. Ellis, “MCFM for the Tevatron and the LHC”, *Nucl. Phys. Proc. Suppl.* **205-206** (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
- [46] K. Hamilton, P. Nason, C. Oleari, and G. Zanderighi, “Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching”, *JHEP* **05** (2013) 082, doi:10.1007/JHEP05(2013)082, arXiv:1212.4504.
- [47] G. Luisoni, P. Nason, C. Oleari, and F. Tramontano, “HW[±]/HZ+0 and 1 jet at NLO with the POWHEG box interfaced to GoSam and their merging within MiNLO”, *JHEP* **10** (2013) 083, doi:10.1007/JHEP10(2013)083, arXiv:1306.2542.
- [48] K. Becker et al., “Precise predictions for boosted Higgs production”, 2020. arXiv:2005.07762.
- [49] E. Bagnaschi, G. Degrandi, P. Slavich, and A. Vicini, “Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM”, *JHEP* **02** (2012) 088, doi:10.1007/JHEP02(2012)088, arXiv:1111.2854.
- [50] P. Nason and C. Oleari, “NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG”, *JHEP* **02** (2010) 037, doi:10.1007/JHEP02(2010)037, arXiv:0911.5299.
- [51] H. B. Hartanto, B. Jäger, L. Reina, and D. Wackeroth, “Higgs boson production in association with top quarks in the POWHEG BOX”, *Phys. Rev. D* **91** (2015) 094003, doi:10.1103/PhysRevD.91.094003, arXiv:1501.04498.
- [52] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [53] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

-
- [54] NNPDF Collaboration, “Parton distributions for the LHC run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [55] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [56] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Methods Phys. Res. Sect. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [57] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [58] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [59] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.
- [60] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, “Soft drop”, *JHEP* **05** (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.
- [61] CMS Collaboration, “Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P02027, doi:10.1088/1748-0221/15/02/P02027, arXiv:1912.03516.
- [62] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [63] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, “Towards an understanding of jet substructure”, *JHEP* **09** (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.
- [64] J. Dolen et al., “Thinking outside the ROCs: Designing decorrelated taggers (DDT) for jet substructure”, *JHEP* **05** (2016) 156, doi:10.1007/JHEP05(2016)156, arXiv:1603.00027.
- [65] ATLAS Collaboration, “Measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV”, *Phys. Rev. D* **101** (2020) 052007, doi:10.1103/PhysRevD.101.052007, arXiv:1912.09837.
- [66] I. Moutl, L. Necib, and J. Thaler, “New angles on energy correlation functions”, *JHEP* **12** (2016) 153, doi:10.1007/JHEP12(2016)153, arXiv:1609.07483.
- [67] A. J. Larkoski, G. P. Salam, and J. Thaler, “Energy correlation functions for jet substructure”, *JHEP* **06** (2013) 108, doi:10.1007/JHEP06(2013)108, arXiv:1305.0007.
- [68] CMS Collaboration, “Performance of the mass-decorrelated DeepDoubleX classifier for double-b and double-c large-radius jets with the CMS detector”, CMS Detector Performance Note CMS-DP-2022-041, 2022.
- [69] M. Sundararajan, A. Taly, and Q. Yan, “Axiomatic attribution for deep networks”, in *Proceedings of the 34th International Conference on Machine Learning*, p. 3319. PMLR, 2017. arXiv:1703.01365.

- [70] G. Montavon et al., “Explaining nonlinear classification decisions with deep Taylor decomposition”, *Pattern Recognit.* **65** (2017) 211, doi:10.1016/j.patcog.2016.11.008, arXiv:1512.02479.
- [71] J. Thaler and K. Van Tilburg, “Identifying boosted objects with N-subjettiness”, *JHEP* **03** (2011) 015, doi:10.1007/JHEP03(2011)015, arXiv:1011.2268.
- [72] S. Bernstein, “Démonstration du théorème de Weierstrass fondée sur le calcul des probabilités”, *Comm. Kharkov Math. Soc.* **13** (1912) 01.
- [73] R. A. Fisher, “On the interpretation of χ^2 from contingency tables, and the calculation of P”, *J. R. Stat. Soc.* **85** (1922) 87, doi:10.2307/2340521.
- [74] CMS Collaboration, “Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016–2018”, CMS Detector Performance Note CMS-DP-2020-019, 2020.
- [75] CMS Collaboration, “Performance of heavy flavour identification algorithms in proton-proton collisions at 13 TeV at the CMS experiment”, CMS Detector Performance Note CMS-DP-2017-012, 2017.
- [76] CMS Collaboration, “Performance of b-tagging algorithms in proton-proton collisions at 13 TeV with Phase 1 CMS detector”, CMS Detector Performance Note CMS-DP-2018-033, 2018.
- [77] CMS Collaboration, “Performance of the pile up jet identification in CMS for Run 2”, CMS Detector Performance Note CMS-DP-2020-020, 2020.
- [78] R. J. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comput. Phys. Commun.* **77** (1993) 219, doi:10.1016/0010-4655(93)90005-W.
- [79] 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.
- [80] 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.
- [81] 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.
- [82] The ATLAS Collaboration, The CMS Collaboration, The 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.
- [83] CMS Collaboration, “Measurement of the Z boson differential production cross section using its invisible decay mode ($Z \rightarrow \nu\bar{\nu}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **05** (2021) 205, doi:10.1007/JHEP05(2021)205, arXiv:2012.09254.
- [84] Particle Data Group, “Review of particle physics”, *Prog. Theor. Exp. Phys.* 083C01, doi:10.1093/ptep/ptac097.
- [85] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Methods Phys. Res. Sect. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

- [86] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [87] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [88] “HEPData record for this analysis”, 2022. doi:10.17182/hepdata.139717.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic , T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch , 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. Kello⁴ , H. Rejeb Sfar , P. Van Mechelen 

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrami , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau , L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 

Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach , C. Rendón , A. Samalan , K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen , L. Wezenbeek 

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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre , K. Mondal , A. Taliencio , T.T. Tran , P. Vischia , S. Wertz 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵ , E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁷ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , A. Vilela Pereira 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

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

A. Aleksandrov , G. Antchev , R. Hadjiiska , P. Iaydjiev , M. Misheva , M. Rodozov , M. Shopova , G. Sultanov 

University of Sofia, Sofia, Bulgaria

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S.Thakur 

Beihang University, Beijing, China

T. Cheng , T. Javaid⁸ , M. Mittal , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer⁹, Z. Hu , S. Lezki , K. Yi^{9,10}

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu¹¹ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 

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

A. Agapitos , Y. An , Y. Ban , A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu , Z. You 

University of Science and Technology of China, Hefei, China

N. Lu 

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

X. Gao⁴ , D. Leggat, H. Okawa , Y. Zhang 

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 

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

D. Giljanovic , N. Godinovic , D. Lelas , I. Puljak 

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac , T. Sculac 

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov¹² , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

Charles University, Prague, Czech Republic

M. Finger , M. Finger Jr. , A. Kveton 

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran^{13,14}, S. Elgammal¹⁴

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

M. Abdullah Al-Mashad , M.A. Mahmoud 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , 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

P. Eerola , H. Kirschenmann , K. Osterberg , M. Voutilainen 

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow , T. Tuuva[†]

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

C. Amendola , M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁵ , P. Simkina , M. Titov 

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche

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

J.-L. Agram¹⁶ , J. Andrea , D. Apparu , D. Bloch , G. Bourgatte , J.-M. Brom , E.C. Chabert , C. Collard , D. Darej, U. Goerlach , C. Grimault, A.-C. Le Bihan , P. Van Hove 

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

S. Beauceron , B. Blancon , G. Boudoul , A. Carle, N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen¹⁷ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹² , I. Lomidze , Z. Tsamalaidze¹² 

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert , M. Teroerde 

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo , M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny , A. Pozdnyakov , Y. Rath , W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler , A. Sharma , A. Stein , F. Torres Da Silva De Araujo¹⁸ , L. Vigilante , S. Wiedenbeck , S. Zaleski 

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

C. Dziwok , G. Flügge , W. Haj Ahmad¹⁹ , O. Hlushchenko , 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 , P. Asmuss , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Bermúdez Martínez , S. Bhat-tacharya , A.A. Bin Anuar , F. Blekman²⁰ , K. Borras²¹ , D. Brunner , A. Campbell , A. Cardini , C. Cheng , F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin , D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁰ , A. Geiser , A. Giraldi , G. Greau , A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²² , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange , D. Leyva Pernia , K. Lipka²³ , W. Lohmann²⁴ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally , A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid , D. Pérez Adán , E. Ranken , A. Raspereza , B. Ribeiro Lopes , J. Rübenach , A. Saggio , M. Savitskyi , M. Scham^{25,21} , V. Scheurer , S. Schnake²¹ , P. Schütze , C. Schwanenberger²⁰ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford , N. Tonon[†] , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann , L. Wiens²¹ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich , K. El Morabit , F. Feindt , A. Fröhlich , C. Garbers , E. Garutti , M. Hajheidari , J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , P. Keicher , R. Klanner , W. Korcar , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz , A. Nigamova , Y. Nissan , A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , M. Rieger , O. 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 , J.O. Gosewisch , A. Gottmann , F. Hartmann²⁶ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , M. Link , A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum , M. Oh , G. Quast , K. Rabbertz , J. Rauser , I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniowski , S. Wunsch , X. Zuo 

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou , P. Assiouras , G. Daskalakis , A. Kyriakis , A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 

National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, K. Kousouris , I. Papakrivopoulos , G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

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

M. Csanád , K. Farkas , M.M.A. Gadallah²⁷ , S. Lökös²⁸ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl²⁹ , O. Surányi , G.I. Veres 

Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³⁰ , G. Bencze, C. Hajdu , D. Horvath^{31,32} , F. Sikler , V. Veszpremi 

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi³⁰ , J. Molnar, Z. Szillasi, D. Teyssier 

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³³ , G. Zilizi 

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

T. Csorgo²⁹ , F. Nemes²⁹ , T. Novak 

Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁴ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁵ , A. Singla , A. K. Viridi 

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁶ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁷ , M. Maity³⁶, P. Palit , G. Saha , B. Sahu , S. Sarkar

Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , S. Chatterjee , P. Kalbhor , J.R. Komaragiri³⁸ , D. Kumar³⁸ , A. Muhammad , L. Panwar³⁸ , R. Pradhan , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 

Bhabha Atomic Research Centre, Mumbai, India

K. Naskar³⁹ 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , M. Guchait , S. Karmakar , S. Kumar , G. Majumder , K. Mazumdar , S. Mukherjee , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati⁴⁰ , A.K. Das , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴¹ , A. Nayak⁴¹ , P. Saha , S.K. Swain , D. Vats⁴¹ 

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

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴² , E. Khazaie , M. Zeinali⁴³ 

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

S. Chenarani⁴⁴ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 

University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,c,45} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} , L. Cristella^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , W. Elmetenawee^{a,b} , F. Errico^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^a , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a 

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

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borghonovi^a , L. Brigliadori^a , R. Campanini^{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} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,46} , L. Lunerti^{a,b} , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,47} , A. Di Mattia^a , R. Potenza^{a,b} , A. Tricomi^{a,b,47} , C. Tuve^{a,b} 

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

G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^{a,b} , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , G. Sguazzoni^a , L. Viliani^a 

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁴⁸ , D. Piccolo 

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

M. Bozzo^{a,b} , P. 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 , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} 

M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a, S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Zuolo^{a,b} 

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy

S. Buontempo^a , F. Carnevali^{a,b}, N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,49} , P. Paolucci^{a,26} , B. Rossi^a , C. Sciacca^{a,b} 

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

P. Azzi^a , N. Bacchetta^{a,50} , M. Bellato^a , M. Benettoni^a , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Gasparini^{a,b} , G. Grosso^a, L. Layer^{a,51}, E. Lusiani^a , M. Margoni^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b} 

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

S. Abu Zeid^{a,52} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^a , P. Vitulo^{a,b} 

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

P. Asenov^{a,53} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,53} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , S. Parolia^a , G. Ramirez-Sanchez^{a,c} , 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} , A. Venturi^a , P.G. Verдини^a 

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b} 

INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , M. Grippio^{a,b} , B. Kiani^{a,b} , F. Legger^a , C. Mariotti^a , S. Maselli^a , A. Mecca^{a,b} , 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} , K. Shchelina^a , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , M. Tornago^{a,b} , D. Trocino^a , G. Umoret^{a,b} , A. Vagnerini^{a,b} , E. Vlasov^{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 , G. Della Ricca^{a,b} ,
G. Sorrentino^{a,b} 

Kyungpook National University, Daegu, Korea

S. Dogra , C. Huh , B. Kim , D.H. Kim , G.N. Kim , J. Kim, J. Lee , S.W. Lee ,
C.S. Moon , Y.D. Oh , S.I. Pak , M.S. Ryu , S. Sekmen , Y.C. Yang 

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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin,
I.C. Park , Y. Roh, D. Song, Watson, I.J. , S. Yang 

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. Maghrbi 

Riga Technical University, Riga, Latvia

K. Dreimanis , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns 

Vilnius University, Vilnius, Lithuania

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

N. Bin Norjoharuddeen , S.Y. Hoh⁵⁴ , I. Yusuff⁵⁴ , 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. Sehwat , L. Valencia Palomo 

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵⁵ , R. Lopez-Fernandez 

C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁶, N. Raicevic 

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, M. Gul , H.R. Hoorani , W.A. Khan 

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeleper , P. Zalewski 

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski 

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo , P. Bargassa , D. Bastos , A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

P. Adzic⁵⁷ , M. Dordevic , P. Milenovic , J. Milosevic 

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

M. Aguilar-Benitez, J. Alcaraz Maestre , M. Barrio Luna, Cristina F. Bedoya , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba 

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasasa García , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , J. Piedra Gomez , C. Prieels, L. Scodellaro , I. Vila , J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁸ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

W.G.D. Dharmaratna , K. Liyanage , N. Perera , N. Wickramage 

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , E. Auffray , G. Auzinger , J. Baechler, P. Baillon[†], D. Barney , J. Bendauid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita⁵⁹, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabaday , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁶⁰ , A.G. Stahl Leiton , S. Summers , K. Tatar , D. Treille , P. Tropea , A. Tsiros, J. Wanczyk⁶¹ , K.A. Wozniak , W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶² , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶² , L. Noehte⁶² , T. Rohe 

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

T.K. Aarrestad , K. Androsov⁶¹ , M. Backhaus , A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁶¹ , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra , R. Seidita , J. Steggemann⁶¹ , D. Valsecchi²⁶ , R. Wallny 

Universität Zürich, Zurich, Switzerland

C. Amsler⁶³ , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁴, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁸ , S.S. Yu 

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao , K.F. Chen , P.s. Chen, H. Cheng , W.-S. Hou , R. Khurana, G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas, A. Steen , H.y. Wu, E. Yazgan 

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

C. Asawatangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁵ , E. Eskut , Y. Guler⁶⁶ , E. Gurpinar Guler⁶⁶ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁷ , A. Polatoz , A.E. Simsek , B. Tali⁶⁸ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁶⁹, K. Ocalan⁷⁰ , M. Yalvac⁷¹ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷² , O. Kaya⁷³ , S. Tekten⁷⁴ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁵ , Y. Komurcu , S. Sen⁷⁵ 

Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁶⁸ , B. Hacisahinoglu , I. Hos⁷⁶ , B. Isildak⁷⁷ , B. Kaynak , S. Ozkorucuklu , C. Simsek , D. Sunar Cerci⁶⁸ 

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

B. Grynyov 

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

L. Levchuk 

University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁸ , K. Walkingshaw Pass, R. White 

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸⁰ , Sh. Jain , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin, T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , V. Cepaitis , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , D.G. Monk , J. Nash⁸² , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁶ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

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

Catholic University of America, Washington, DC, USA

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

The University of Alabama, Tuscaloosa, Alabama, USA

R. Chudasama , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸³ , C. West 

Boston University, Boston, Massachusetts, USA

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

Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²¹, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁵ , F. Simpson , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 

University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , D. Saltzberg , B. Stone , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganelli , W. Si , S. Wimpenny 

University of California, San Diego, La Jolla, California, USA

J.G. Branson, S. Cittolin, S. Cooperstein , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , 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

N. Amin, C. Campagnari , M. Citron , G. Collura , A. Dorsett , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , P. Siddireddy, D. Stuart , S. Wang 

California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, I. Dutta , A. Latorre, J.M. Lawhorn , J. Mao , H.B. Newman , T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , V. Dutta , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

University of Colorado Boulder, Boulder, Colorado, USA

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

Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , 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 , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , 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 , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , P. Chang , V. Cherepanov , R.D. Field , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , E. Kuznetsova , K.H. Lo , K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 

Florida State University, Tallahassee, Florida, USA

T. Adams , A. Askew , N. Bower , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez , H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang 

Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy⁵² , M. Hohlmann , R. Kumar Verma , M. Rahmani , F. Yumiceva 

University of Illinois at Chicago (UIC), Chicago, Illinois, USA

M.R. Adams , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , K. Dilsiz⁸⁸ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo , A. Mestvirishvili⁸⁹ , J. Nachtman , O. Neogi , H. Ogul⁹⁰ , Y. Onel , A. Penzo , C. Snyder , E. Tiras⁹¹ 

Johns Hopkins University, Baltimore, Maryland, USA

O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , S. Kyriacou , P. Maksimovic , J. Roskes , S. Sekhar , M. Swartz , T.Á. Vámi 

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey , J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 

Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim 

Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 

Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 

University of Maryland, College Park, Maryland, USA

E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , D. Mahon , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin, I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 

State University of New York at Buffalo, Buffalo, New York, USA

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 

Northeastern University, Boston, Massachusetts, USA

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

Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹² , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 

Princeton University, Princeton, New Jersey, USA

F.M. Addesa , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , S. Higginbotham , G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg

Purdue University, West Lafayette, Indiana, USA

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

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 

Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , S. Dildick , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter , S. Yang , E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova , R. Taus , G.P. Van Onsem 

The Rockefeller University, New York, New York, USA

K. Goulianos 

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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslawski , O. Karacheban²⁴ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 

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

O. Bouhali⁹² , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹³ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , V. Hegde , K. Lamichhane , S.W. Lee , T. Mengke, S. Muthumuni , T. Peltola , I. Volobouev , A. Whitbeck 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USA

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 , 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. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁹⁴, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , V. Chekhovsky, R. Chistov⁹⁴ , M. Danilov⁹⁴ , A. Dermenev , T. Dimova⁹⁴ , I. Dremin , M. Dubinin⁸⁶ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁴ , V. Karjavine , A. Karneyeu , V. Kim⁹⁴ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁵ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁴ , N. Krasnikov , A. Lanev , P. Levchenko , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁴ , V. Murzin , A. Nikitenko⁹⁶ , S. Obraztsov , I. Ovtin⁹⁴ , V. Palichik , V. Perelygin , M. Perfilov, S. Petrushanko , S. Polikarpov⁹⁴ , V. Popov, O. Radchenko⁹⁴ , M. Savina , V. Savrin , D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁴ , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , A. Vorobyev[†], N. Voytishin , B.S. Yuldashev⁹⁷, 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 Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at UFMS, Nova Andradina, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at Nanjing Normal University Department of Physics, Nanjing, China

¹⁰Now at The University of Iowa, Iowa City, Iowa, USA

¹¹Also at University of Chinese Academy of Sciences, Beijing, China

¹²Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹³Also at Suez University, Suez, Egypt

¹⁴Now at British University in Egypt, Cairo, Egypt

¹⁵Also at Purdue University, West Lafayette, Indiana, USA

¹⁶Also at Université de Haute Alsace, Mulhouse, France

¹⁷Also at Department of Physics, Tsinghua University, Beijing, China

¹⁸Also at The University of the State of Amazonas, Manaus, Brazil

¹⁹Also at Erzincan Binali Yildirim University, Erzincan, Turkey

²⁰Also at University of Hamburg, Hamburg, Germany

²¹Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

-
- ²²Also at Isfahan University of Technology, Isfahan, Iran
- ²³Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁴Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁵Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁶Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²⁷Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ²⁸Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ²⁹Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³⁰Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³¹Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³²Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- ³³Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁴Also at Punjab Agricultural University, Ludhiana, India
- ³⁵Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁶Also at University of Visva-Bharati, Santiniketan, India
- ³⁷Also at University of Hyderabad, Hyderabad, India
- ³⁸Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁹Also at Indian Institute of Technology (IIT), Mumbai, India
- ⁴⁰Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴¹Also at Institute of Physics, Bhubaneswar, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Sharif University of Technology, Tehran, Iran
- ⁴⁴Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁵Also at Helwan University, Cairo, Egypt
- ⁴⁶Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁷Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁸Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁴⁹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵⁰Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵¹Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵²Also at Ain Shams University, Cairo, Egypt
- ⁵³Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁴Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁵Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁶Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁷Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁶⁰Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶¹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶²Also at Universität Zürich, Zurich, Switzerland
- ⁶³Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁴Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁵Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey

- ⁶⁶Also at Konya Technical University, Konya, Turkey
- ⁶⁷Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁸Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁹Also at Istanbul Gedik University, Istanbul, Turkey
- ⁷⁰Also at Necmettin Erbakan University, Konya, Turkey
- ⁷¹Also at Bozok Universititesi Rektörlüğü, Yozgat, Turkey
- ⁷²Also at Marmara University, Istanbul, Turkey
- ⁷³Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁴Also at Kafkas University, Kars, Turkey
- ⁷⁵Also at Hacettepe University, Ankara, Turkey
- ⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸⁰Also at University of Bristol, Bristol, United Kingdom
- ⁸¹Also at IPPP Durham University, Durham, United Kingdom
- ⁸²Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸³Also at Università di Torino, Torino, Italy
- ⁸⁴Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁶Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁸Also at Bingöl University, Bingöl, Turkey
- ⁸⁹Also at Georgian Technical University, Tbilisi, Georgia
- ⁹⁰Also at Sinop University, Sinop, Turkey
- ⁹¹Also at Erciyes University, Kayseri, Turkey
- ⁹²Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹³Also at Kyungpook National University, Daegu, Korea
- ⁹⁴Also at another institute or international laboratory covered by a cooperation agreement with CERN
- ⁹⁵Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁶Also at Imperial College, London, United Kingdom
- ⁹⁷Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan