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Observation of $t\bar{t}H$ production

The CMS Collaboration*

Abstract

The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7, 8,$ and 13 TeV, corresponding to integrated luminosities of up to $5.1, 19.7,$ and 35.9 fb^{-1} , respectively. The data were collected with the CMS detector at the CERN LHC. The results of statistically independent searches for Higgs bosons produced in conjunction with a top quark-antiquark pair and decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom quark jets are combined to maximize sensitivity. An excess of events is observed, with a significance of 5.2 standard deviations, over the expectation from the background-only hypothesis. The corresponding expected significance from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 standard deviations. The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-0.26}$.

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Proton-proton (pp) collisions at the CERN LHC, at the center-of-mass (CM) energies of $\sqrt{s} = 7, 8,$ and 13 TeV, have allowed direct measurements of the properties of the Higgs boson [1–3]. In particular, the 13 TeV data collected so far by the ATLAS [4] and CMS [5] experiments have led to improved constraints on the couplings of the Higgs boson compared to those performed at the lower energies [6], permitting more precise consistency checks with the predictions of the standard model (SM) of particle physics [7–9]. Nonetheless, not all properties of the Higgs boson have been established, in part because of insufficiently large data sets. The lack of statistical precision can be partially overcome by combining the results of searches in different decay channels of the Higgs boson and at different CM energies. Among the properties that are not yet well established is the tree-level coupling of Higgs bosons to top quarks.

In this Letter, we present a combination of searches for the Higgs boson (H) produced in association with a top quark-antiquark pair ($t\bar{t}$), based on data collected with the CMS detector. Results from data collected at $\sqrt{s} = 13$ TeV [10–14] are combined with analogous results from $\sqrt{s} = 7$ and 8 TeV [15]. As a result of this combination, we establish the observation of $t\bar{t}H$ production. This constitutes the first confirmation of the tree-level coupling of the Higgs boson to top quarks.

A top quark decays almost exclusively to a bottom quark and a W boson, with the W boson subsequently decaying either to a quark and an antiquark or to a charged lepton and its associated neutrino. The Higgs boson exhibits a rich spectrum of decay modes that includes the decay to a bottom quark-antiquark pair, a $\tau^+\tau^-$ lepton pair, a photon pair, and combinations of quarks and leptons from the decay of intermediate on- or off-shell W and Z bosons. Thus, $t\bar{t}H$ production gives rise to a wide variety of final-state event topologies, which we consider in our analyses and in the combination of results presented below.

In the SM, the masses of elementary fermions are accounted for by introducing a minimal set of Yukawa interactions, compatible with gauge invariance, between the Higgs and fermion fields. Following the spontaneous breaking of electroweak symmetry [16–21], charged fermions of flavor f couple to H with a strength y_f proportional to the mass m_f of those fermions, namely $y_f = m_f/v$, where $v \approx 246$ GeV is the vacuum expectation value of the Higgs field. Measurements of the Higgs boson decay rates to down-type fermions (τ leptons and bottom quarks) agree with the SM predictions within their uncertainties [22, 23]. However, the top quark Yukawa coupling (y_t) cannot be similarly tested from the measurement of a decay rate since on-shell top quarks are too heavy to be produced in Higgs boson decay. Instead, constraints on y_t can be obtained through the measurement of the $pp \rightarrow t\bar{t}H$ production process. Example tree-level Feynman diagrams for this process are shown in Fig. 1. To date $t\bar{t}H$ production has eluded definite observation, although first evidence has been recently reported by the ATLAS [24] and CMS [10] Collaborations.

The overall agreement observed between the SM predictions and data for the rate of Higgs boson production through gluon-gluon fusion and for the $H \rightarrow \gamma\gamma$ decay mode [6] suggests that the Higgs boson coupling to top quarks is SM-like, since the quantum loops in these processes include top quarks. However, non-SM particles in the loops could introduce terms that compensate for, and thus mask, other deviations from the SM. A measurement of the production rate of the tree-level $t\bar{t}H$ process can provide evidence for, or against, such new-physics contributions.

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

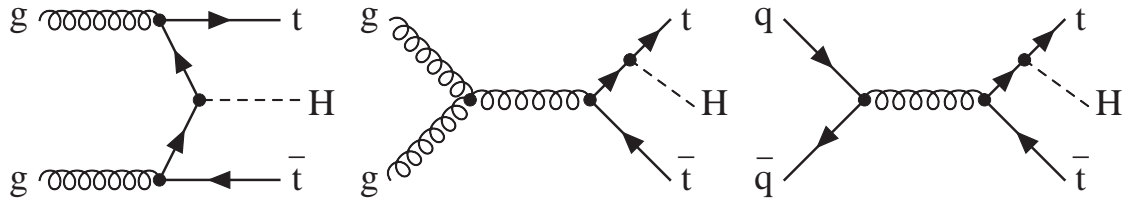


Figure 1: Example tree-level Feynman diagrams for the $pp \rightarrow t\bar{t}H$ production process, with g a gluon, q a quark, t a top quark, and H a Higgs boson. For the present study, we consider Higgs boson decays to a pair of W bosons, Z bosons, photons, τ leptons, or bottom quark jets.

the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector can be found in Ref. [5].

Events of interest are selected using a two-tiered trigger system [25] based on custom hardware processors and a farm of commercial processors running a version of the full reconstruction software optimized for speed. Offline, a particle-flow algorithm [26] is used to reconstruct and identify each particle in an event based on a combination of information from the various CMS subdetectors. Additional identification criteria are employed to improve purities and define the final samples of candidate electrons, muons, hadronically decaying τ leptons (τ_h) [27, 28], and photons. Jets are reconstructed from particle-flow candidates using the anti- k_T clustering algorithm [29] implemented in the FASTJET package [30]. Multivariate algorithms [31, 32] are used to identify (tag) jets arising from the hadronization of bottom quarks (b jets) and discriminate against gluon and light flavor quark jets. The algorithms utilize observables related to the long lifetimes of hadrons containing b quarks and the relatively larger particle multiplicity and mass of b jets compared to light flavor quark jets. The τ_h identification is based on the reconstruction of the hadronic τ decay modes $\tau^- \rightarrow h^- \nu_\tau$, $h^- \pi^0 \nu_\tau$, $h^- \pi^0 \pi^0 \nu_\tau$, and $h^- h^+ h^- \nu_\tau$ (plus the charge conjugate reactions), where h^\pm denotes either a charged pion or kaon. More details about the reconstruction procedures are given in Refs. [10–15].

The 13 TeV data employed for the current study were collected in 2016 and correspond to an integrated luminosity of up to 35.9 fb^{-1} [33]. The 7 and 8 TeV data, collected in 2011 and 2012, correspond to integrated luminosities of up to 5.1 and 19.7 fb^{-1} [34], respectively. The 13 TeV analyses are improved relative to the 7 and 8 TeV studies in that they employ triggers with higher efficiencies, contain improvements in the reconstruction and background-rejection methods, and use more precise theory calculations to describe the signal and the background processes. For the 7, 8 and 13 TeV data, the theoretical calculations of Ref. [35] for Higgs boson production cross sections and branching fractions are used to normalize the expected signal yields.

The event samples are divided into exclusive categories depending on the multiplicity and kinematic properties of reconstructed electrons, muons, τ_h candidates, photons, jets, and tagged b jets in an event. Samples of simulated events based on Monte Carlo event generators, with simulation of the detector response based on the GEANT4 [36] suite of programs, are used to evaluate the detector acceptance and optimize the event selection for each category. In the analysis of data, the background is, in general, evaluated from data control regions. When this is not feasible, either because the background process has a very small cross section or a control region depleted of signal events cannot be identified, the background is evaluated from simulation with a systematic uncertainty assigned to account for the known model dependence. Multivariate algorithms [37–41] based on deep neural networks, boosted decision trees, and matrix element calculations are used to reduce backgrounds.

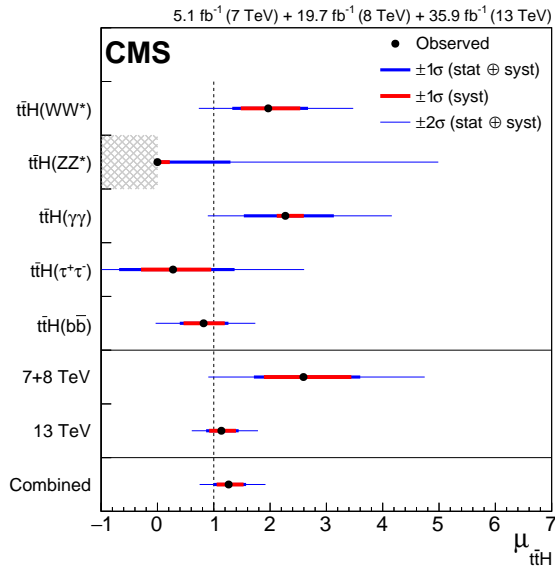


Figure 2: Best fit value of the $t\bar{t}H$ signal strength modifier $\mu_{t\bar{t}H}$, with its 1 and 2 standard deviation confidence intervals (σ), for (upper section) the five individual decay channels considered, (middle section) the combined result for 7+8 TeV alone and for 13 TeV alone, and (lower section) the overall combined result. The Higgs boson mass is taken to be 125.09 GeV. For the $H \rightarrow ZZ^*$ decay mode, $\mu_{t\bar{t}H}$ is constrained to be positive to prevent the corresponding event yield from becoming negative. The SM expectation is shown as a dashed vertical line.

At 13 TeV, we search for $t\bar{t}H$ production in the $H \rightarrow b\bar{b}$ decay mode by selecting events with at least three tagged b jets and with zero leptons [11], one lepton [12], or an opposite-sign lepton pair [12], where “lepton” refers to an electron or muon candidate. A search for $t\bar{t}H$ production in the $H \rightarrow \gamma\gamma$ decay mode is performed in events with two reconstructed photons in combination with reconstructed electrons or muons, jets, and tagged b jets [13]. The signal yield is extracted from a fit to the diphoton invariant mass spectrum. Events with combinations of jets and tagged b jets and with two same-sign leptons, three leptons, or four leptons are used to search for $t\bar{t}H$ production in the $H \rightarrow \tau^+\tau^-$, WW^* , or ZZ^* decay modes [10, 14], where in this case “lepton” refers to an electron, muon, or τ_h candidate (the asterisk denotes an off-shell particle). The searches in the different decay channels are statistically independent from each other. Analogous searches have been performed with the 7 and 8 TeV data [15].

The presence of a $t\bar{t}H$ signal is assessed by performing a simultaneous fit to the data from the different decay modes, and also from the different CM energies as described below. A detailed description of the statistical methods can be found in Ref. [42]. The test statistic q is defined as the negative of twice the logarithm of the profile likelihood ratio [42]. Systematic uncertainties are incorporated through the use of nuisance parameters treated according to the frequentist paradigm. The ratio between the normalization of the $t\bar{t}H$ production process and its SM expectation [35], defined as the signal strength modifier $\mu_{t\bar{t}H}$, is a freely floating parameter in the fit. The SM expectation is evaluated assuming the combined ATLAS and CMS value for the mass of the Higgs boson, which is 125.09 GeV [43]. We consider the five Higgs boson decay modes with the largest expected event yields, namely $H \rightarrow WW^*$, ZZ^* , $\gamma\gamma$, $\tau^+\tau^-$, and $b\bar{b}$. Other Higgs boson decay modes and production processes, including $pp \rightarrow tH + X$ (or $\bar{t}H + X$), with X a light flavor quark or W boson, are treated as backgrounds and normalized using the predicted SM cross sections, subject to the corresponding uncertainties.

The measured values of the five independent signal strength modifiers, corresponding to the

Table 1: Best fit value, with its uncertainty, of the $t\bar{t}H$ signal strength modifier $\mu_{t\bar{t}H}$, for the five individual decay channels considered, the combined result for 7+8 TeV alone and for 13 TeV alone, and the overall combined result. The total uncertainties are decomposed into their statistical (Stat), experimental systematic (Expt), background theory systematic (Thbgd), and signal theory systematic (Thsig) components. The numbers in parentheses are those expected for $\mu_{t\bar{t}H} = 1$.

Parameter	Best fit	Uncertainty			
		Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}^{WW^*}$	$1.97^{+0.71}_{-0.64}$ (+0.57) (-0.54)	+0.42 -0.41 (+0.39) (-0.38)	+0.46 -0.42 (+0.36) (-0.34)	+0.21 -0.21 (+0.17) (-0.17)	+0.25 -0.12 (+0.12) (-0.03)
$\mu_{t\bar{t}H}^{ZZ^*}$	$0.00^{+1.30}_{-0.00}$ (+2.89) (-0.99)	+1.28 -0.00 (+2.82) (-0.99)	+0.20 -0.00 (+0.51) (-0.00)	+0.04 -0.00 (+0.15) (-0.00)	+0.09 -0.00 (+0.27) (-0.00)
$\mu_{t\bar{t}H}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$ (+0.73) (-0.64)	+0.80 -0.72 (+0.71) (-0.64)	+0.15 -0.09 (+0.09) (-0.04)	+0.02 -0.01 (+0.01) (-0.00)	+0.29 -0.13 (+0.13) (-0.05)
$\mu_{t\bar{t}H}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$ (+1.00) (-0.89)	+0.86 -0.77 (+0.83) (-0.76)	+0.64 -0.53 (+0.54) (-0.47)	+0.10 -0.09 (+0.09) (-0.08)	+0.20 -0.19 (+0.14) (-0.01)
$\mu_{t\bar{t}H}^{b\bar{b}}$	$0.82^{+0.44}_{-0.42}$ (+0.44) (-0.42)	+0.23 -0.23 (+0.23) (-0.22)	+0.24 -0.23 (+0.24) (-0.23)	+0.27 -0.27 (+0.26) (-0.27)	+0.11 -0.03 (+0.11) (-0.04)
$\mu_{t\bar{t}H}^{7+8\text{ TeV}}$	$2.59^{+1.01}_{-0.88}$ (+0.87) (-0.79)	+0.54 -0.53 (+0.51) (-0.49)	+0.53 -0.49 (+0.48) (-0.44)	+0.55 -0.49 (+0.50) (-0.44)	+0.37 -0.13 (+0.14) (-0.02)
$\mu_{t\bar{t}H}^{13\text{ TeV}}$	$1.14^{+0.31}_{-0.27}$ (+0.29) (-0.26)	+0.17 -0.16 (+0.16) (-0.16)	+0.17 -0.17 (+0.17) (-0.16)	+0.13 -0.12 (+0.13) (-0.12)	+0.14 -0.06 (+0.11) (-0.05)
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$ (+0.28) (-0.25)	+0.16 -0.16 (+0.15) (-0.15)	+0.17 -0.15 (+0.16) (-0.15)	+0.14 -0.13 (+0.13) (-0.12)	+0.15 -0.07 (+0.11) (-0.05)

five decay channels considered, are shown in the upper section of Fig. 2 along with their 1 and 2 standard deviation confidence intervals obtained in the asymptotic approximation [44]. Numerical values are given in Table 1. The individual measurements are seen to be consistent with each other within the uncertainties.

We also perform a combined fit, using a single signal strength modifier $\mu_{t\bar{t}H}$, that simultaneously scales the $t\bar{t}H$ production cross sections of the five decay channels considered, with all Higgs boson branching fractions fixed to their SM values [35]. Besides the five decay modes considered, the signal normalizations for the Higgs boson decay modes to gluons, charm quarks, and $Z\gamma$, which are subleading and cannot be constrained with existing data, are scaled by $\mu_{t\bar{t}H}$. The results combining the decay modes at 7+8 TeV, and separately at 13 TeV, are shown in the middle section of Fig. 2. The overall result, combining all decay modes and all CM energies, is shown in the lower section, with numerical values given in Table 1. Table 1 includes a breakdown of the total uncertainties into their statistical and systematic components. The overall result is $\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$, which agrees with the SM expectation $\mu_{t\bar{t}H} = 1$ within 1 standard deviation.

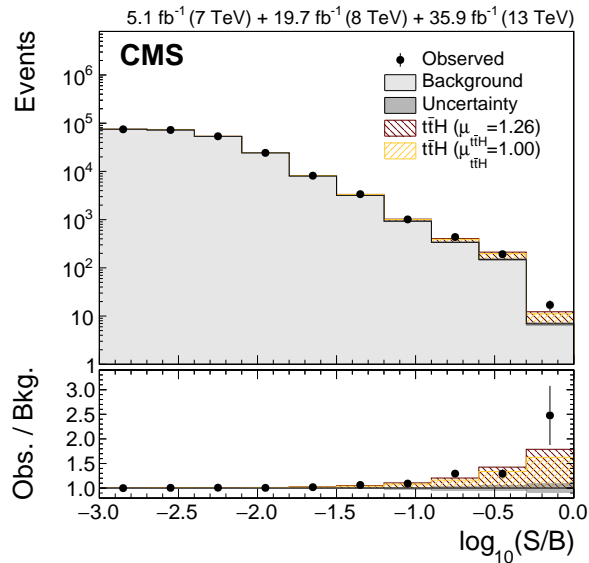


Figure 3: Distribution of events as a function of the decimal logarithm of S/B , where S and B are the expected post-fit signal (with $\mu_{\text{ttH}} = 1$) and background yields, respectively, in each bin of the distributions considered in this combination. The shaded histogram shows the expected background distribution. The two hatched histograms, each stacked on top of the background histogram, show the signal expectation for the SM ($\mu_{\text{ttH}} = 1$) and the observed ($\mu_{\text{ttH}} = 1.26$) signal strengths. The lower panel shows the ratios of the expected signal and observed results relative to the expected background.

The principal sources of experimental systematic uncertainty in the overall result for μ_{ttH} stem from the uncertainty in the lepton and b jet identification efficiencies and in the τ_h and jet energy scales. The background theory systematic uncertainty is dominated by modeling uncertainties in $t\bar{t}$ production in association with a W boson, a Z boson, or a pair of b or c quark jets. The dominant contribution to the signal theory systematic uncertainty arises from the finite accuracy in the SM prediction for the $t\bar{t}H$ cross section because of missing higher order terms and uncertainties in the proton parton density functions [35].

To highlight the excess of data over the expectation from the background-only hypothesis, we classify each event that enters the combined fit by the ratio S/B , where S and B are the expected post-fit signal (with $\mu_{\text{ttH}} = 1$) and background yields, respectively, in each bin of the distributions considered in the combination. The distribution of $\log_{10}(S/B)$ is shown in Fig. 3. The main sensitivity at high values of S/B is given by events selected in the $H \rightarrow \gamma\gamma$ analysis with a diphoton mass around 125 GeV and by events selected in the $H \rightarrow \tau^+\tau^-$, $H \rightarrow WW^*$, and $H \rightarrow b\bar{b}$ analyses with high values of the multivariate discriminating variables used for the signal extraction. A broad excess of events in the rightmost bins of this distribution is observed, consistent with the expectation for $t\bar{t}H$ production with a SM-like cross section.

The value of the test statistic q as a function of μ_{ttH} is shown in Fig. 4, with μ_{ttH} based on the combination of decay modes described above for the combined fit. The results are shown for the combination of all decay modes at 7+8 TeV and at 13 TeV, separately, and for all decay modes at all CM energies. To quantify the significance of the measured $t\bar{t}H$ yield, we compute the probability of the background-only hypothesis (p -value) as the tail integral of the test statistic using the overall combination evaluated at $\mu_{\text{ttH}} = 0$ under the asymptotic approximation [45]. This corresponds to a significance of 5.2 standard deviations for a one-tailed Gaussian distribution. The expected significance for a SM Higgs boson with a mass of 125.09 GeV, eval-

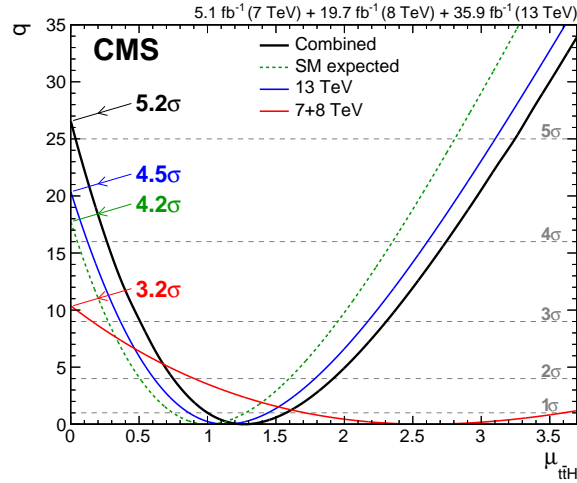


Figure 4: The test statistic q , described in the text, as a function of $\mu_{t\bar{t}H}$ for all decay modes at 7+8 TeV and at 13 TeV, separately, and for all decay modes at all CM energies. The expected SM result for the overall combination is also shown. The horizontal dashed lines indicate the p -values for the background-only hypothesis obtained from the asymptotic distribution of q , expressed in units of the number of standard deviations.

uated through use of an Asimov data set [45], is 4.2 standard deviations.

In summary, we have reported the observation of $t\bar{t}H$ production with a significance of 5.2 standard deviations above the background-only hypothesis, at a Higgs boson mass of 125.09 GeV. The measured production rate is consistent with the standard model prediction within one standard deviation. In addition to comprising the first observation of a new Higgs boson production mechanism, this measurement establishes the tree-level coupling of the Higgs boson to the top quark, and hence to an up-type quark.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerboux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a, D. Romero Abad^b

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

Bulgaria

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

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen⁶, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

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

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

H. Abdalla⁹, A.A. Abdelalim^{10,11}, A. Mohamed¹¹

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

A. Abdulsalam¹², C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

J.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹⁴, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze⁸

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹⁴

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

A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, Y. Rath, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier

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

G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁵

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borrás¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, I. Katkov¹⁴, P. Keicher, S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, M. Waßmer, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannelos, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

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

M. Bartók¹⁹, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati²², C. Kar, P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁴, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur²⁴

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar²⁵

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

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{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}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b},

G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a, G. Zito^a

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

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b,15}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

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

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

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

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

F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, S. Di Guida^{a,d,15}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Zuolo

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, N. Cavallo^{a,c}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, E. Voevodina^{a,b}

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

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, F. Fanzago^a, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

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

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

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

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, F. Fiori^{a,c}, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi, A. Staiano^a

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}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

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

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

J. Goh²⁹, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³⁰, F. Mohamad Idris³¹, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

A. Castaneda Hernandez, J.A. Murillo Quijada

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

M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz³², R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R Reyes-Almanza, M. Ramirez-Garcia, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

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

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

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

K. Bunkowski, A. Byzuk³³, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{34,35}, P. Moiseenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁶, E. Kuznetsova³⁷, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

R. Chistov³⁸, M. Danilov³⁸, P. Parygin, D. Philippov, S. Polikarpov³⁸, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁵, I. Dremin³⁵, M. Kirakosyan³⁵, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³⁹, L. Dudko, V. Klyukhin, O. Kodolova, N. Korneeva, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin, P. Volkov

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴⁰, T. Dimova⁴⁰, L. Kardapoltsev⁴⁰, D. Shtol⁴⁰, Y. Skovpen⁴⁰

State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitiukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁴¹, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez

Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴², D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenov⁴³, F. Moortgat, M. Mulders, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabad, A. Racz, T. Reis, G. Rolandi⁴⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁵, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsiros, V. Veckalns⁴⁶, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁴⁷, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Luster, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁸, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.y. Li, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁴⁹, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵⁰, C. Isik, E.E. Kangal⁵¹, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵², S. Ozturk⁵³, D. Sunar Cerci⁴⁹, B. Tali⁴⁹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁴, G. Karapinar⁵⁵, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁶, O. Kaya⁵⁷, S. Tekten, E.A. Yetkin⁵⁸

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁵⁹

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

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶⁰, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶¹, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶², A. Nikitenko⁷, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶³, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Piperov, S. Sagir⁶⁴, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁵, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁶, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁶⁷, W. Clarida, K. Dilsiz⁶⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁹, Y. Onel, F. Ozok⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁴, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

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

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷², S. Luo, R. Mueller, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

3: Also at Universidade Estadual de Campinas, Campinas, Brazil

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

5: Also at Université Libre de Bruxelles, Bruxelles, Belgium

6: Also at University of Chinese Academy of Sciences, Beijing, China

7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Cairo University, Cairo, Egypt

10: Also at Helwan University, Cairo, Egypt

11: Now at Zewail City of Science and Technology, Zewail, Egypt

12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia

13: Also at Université de Haute Alsace, Mulhouse, France

14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

17: Also at University of Hamburg, Hamburg, Germany

18: Also at Brandenburg University of Technology, Cottbus, Germany

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

20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

- 23: Also at Institute of Physics, Bhubaneswar, India
- 24: Also at Shoolini University, Solan, India
- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at Isfahan University of Technology, Isfahan, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at Kyunghee University, Seoul, Korea
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 34: Also at Institute for Nuclear Research, Moscow, Russia
- 35: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 37: Also at University of Florida, Gainesville, USA
- 38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 39: Also at California Institute of Technology, Pasadena, USA
- 40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 42: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 45: Also at National and Kapodistrian University of Athens, Athens, Greece
- 46: Also at Riga Technical University, Riga, Latvia
- 47: Also at Universität Zürich, Zurich, Switzerland
- 48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 49: Also at Adiyaman University, Adiyaman, Turkey
- 50: Also at Istanbul Aydin University, Istanbul, Turkey
- 51: Also at Mersin University, Mersin, Turkey
- 52: Also at Piri Reis University, Istanbul, Turkey
- 53: Also at Gaziosmanpasa University, Tokat, Turkey
- 54: Also at Ozyegin University, Istanbul, Turkey
- 55: Also at Izmir Institute of Technology, Izmir, Turkey
- 56: Also at Marmara University, Istanbul, Turkey
- 57: Also at Kafkas University, Kars, Turkey
- 58: Also at Istanbul Bilgi University, Istanbul, Turkey
- 59: Also at Hacettepe University, Ankara, Turkey
- 60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 62: Also at Monash University, Faculty of Science, Clayton, Australia
- 63: Also at Bethel University, St. Paul, USA
- 64: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 65: Also at Utah Valley University, Orem, USA
- 66: Also at Purdue University, West Lafayette, USA
- 67: Also at Beykent University, Istanbul, Turkey

68: Also at Bingol University, Bingol, Turkey

69: Also at Sinop University, Sinop, Turkey

70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

71: Also at Texas A&M University at Qatar, Doha, Qatar

72: Also at Kyungpook National University, Daegu, Korea