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Search for Higgs and Z boson decays to J/ψ or Y pairs in the four-muon final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for decays of the Higgs and Z boson to pairs of J/ψ or $Y(nS)$ ($n=1,2,3$) mesons, with their subsequent decay to $\mu^+\mu^-$ pairs, is presented. The analysis uses data from proton-proton collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector at the LHC in 2017 and corresponding to an integrated luminosity of 37.5 fb^{-1} . While an observation of such a decay with this sample would indicate the presence of physics beyond the standard model, no significant excess is observed. Upper limits at 95% confidence level are placed on the branching fractions of these decays. In the J/ψ pair channel, the limits are 1.8×10^{-3} and 2.2×10^{-6} for the Higgs and Z boson, respectively, while in the combined $Y(nS)$ pair channel, the limits are 1.4×10^{-3} and 1.5×10^{-6} , respectively, when the mesons from the Higgs and Z boson decay are assumed to be unpolarized. When fully longitudinal and transverse polarizations are considered the limits reduce by about 22–29% and increase by about 10–13%, respectively.

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1 Introduction

A new boson with a mass of 125 GeV was discovered by the ATLAS and CMS Collaborations at the CERN LHC in 2012 [1–7]. Comprehensive studies in various decay channels and production modes have shown that the properties of the new boson are consistent, so far, with expectations for the standard model (SM) Higgs boson (H) [7–9]. Recently, the Higgs boson couplings to top and bottom quarks have been directly measured [10–13]. Couplings to lighter quarks are still not observed directly. Rare exclusive decays of the Higgs boson to mesons provide experimentally clean final states to study Yukawa couplings to quarks and physics beyond the SM (BSM). Examples of diagrams for decays of the Higgs and Z boson into quarkonium pairs are shown in Fig. 1. The symbol Q refers to charmonium and bottomonium states.

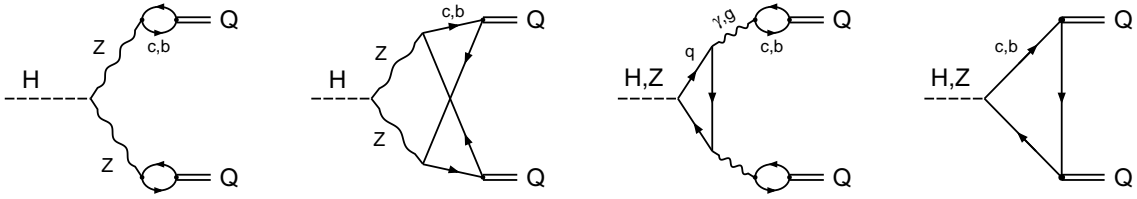


Figure 1: Feynman diagrams for $H \rightarrow QQ$ and $Z \rightarrow QQ$ with $Q = \text{charmonium or bottomonium states}$. In the two leftmost diagrams [14], the virtual particles are Z bosons. The center-right diagram depicts indirect processes in the case where the flavor of the quark q in the loop is top, and direct processes in the case where it is charm or bottom. The other virtual particles are either photons or gluons. In the latter case additional soft-gluon exchange occurs. The rightmost diagram shows direct processes for the Higgs or Z bosons.

The importance of the measurement of such decays has been pointed out by Ref. [15–18]. Using a phenomenological approach for the direct $H\text{-}q\bar{q}$ coupling, Ref. [15] finds that the dominant quarkonium pair decay mode is $H \rightarrow YY$ with an estimated branching fraction (\mathcal{B}) at the level of 10^{-5} . The early calculations of Higgs boson decays into a pair of heavy quarkonia states did not include relativistic corrections caused by the internal motion of quarks [14]. The importance of the latter corrections is underlined by the fact that the predicted $e^+e^- \rightarrow J/\psi\eta_c$ cross section increases by an order of magnitude [19–21] when these effects are included, in agreement with measurements by the Belle and BaBar experiments [22, 23].

With emphasis on amplitudes where the Higgs boson couples indirectly to the final state mesons, such as represented by the two leftmost diagrams in Fig. 1, Ref. [14] arrives at values of about $\mathcal{B}(H \rightarrow J/\psi J/\psi) = 1.5 \times 10^{-10}$ and $\mathcal{B}(H \rightarrow \Upsilon\Upsilon) = 2 \times 10^{-9}$. The mechanism where the Higgs boson couples directly to charm or bottom quarks, which then hadronize to heavy quarkonia, was considered in a recent calculation [24] leading to an increase of an order of magnitude in $\mathcal{B}(H \rightarrow J/\psi\gamma)$. The Higgs boson decay to the J/ψ pair could also occur when the photon in the $J/\psi\gamma$ decay is virtual and transforms into a J/ψ meson. Recently, the decay $H \rightarrow J/\psi\gamma$ has been searched for by the ATLAS and CMS collaborations [25, 26]. This Letter also presents the first search for decays of the Z boson into quarkonium pairs. Feynman diagrams are shown in Fig. 1 (two rightmost plots). The SM prediction for $\mathcal{B}(Z \rightarrow J/\psi J/\psi)$ calculated in the framework of nonrelativistic QCD and leading twist light cone models is of the order of 10^{-12} [27]. Several approximations for the non-perturbative QCD processes are used, including the restriction to color-singlet quarkonium states.

New physics could affect the direct boson couplings or could enter through loops, and alter

the interference pattern between the amplitudes. Any of those possibilities enhance branching fractions with respect to the SM predictions. Many BSM theories predict substantial modifications of the Yukawa couplings of the Higgs boson to quarks, such as models with Higgs-dependent Yukawa couplings [28], the minimal flavor violation framework [29], the Froggatt–Nielsen mechanism [30], and the Randall–Sundrum family of models [31]. An overview of models can be found in Ref. [32]. In the related quarkonium– γ channels, deviations of the H - $q\bar{q}$ couplings from the SM predictions can change the interference between direct and indirect amplitudes, resulting in substantial modifications of the branching fractions, particularly in the Y channel, where the increase is up to several orders of magnitude [24]. The observation of a Higgs or Z boson signal in the quarkonium pair decay modes with the available LHC data sets would indicate the presence of BSM physics.

This Letter presents the first search for the Higgs and Z boson decays into J/ψ or Y meson pairs, where Y stands for the combined contribution of the $Y(nS)$ states with $n = 1, 2, 3$. The subsequent decay of these meson pairs to the 4μ final state offers a very clean experimental signature that is used in this analysis. For the J/ψ meson pairs, feed-down from higher charmonium states are not taken into account. For the $Y(nS)$ meson pairs, decays from higher to lower mass $Y(nS)$ states are included. The results presented in this Letter are based on proton-proton (pp) collision data recorded in 2017 with the CMS detector at a center-of-mass energy of $\sqrt{s} = 13$ TeV, amounting to an integrated luminosity of 37.5 fb^{-1} .

2 The CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [33]. The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in internal diameter, providing an axial 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 the pseudorapidity (η) 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. They are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers.

An entirely new pixel detector has been installed after 2016, featuring an all-silicon device with four layers in the barrel and three disks in the endcaps [34], providing four pixel detector measurements. Reduced material budget in front of the calorimeters was achieved with two-phase CO_2 cooling and light-weight mechanical support, and moving the electronic boards and connections out of the tracking volume.

Events of interest are selected using a two-tiered trigger system [35]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than $4 \mu\text{s}$. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

Dedicated triggers were deployed in 2017 to enhance the selection of events of interest for the present study. They require the presence of at least three muons with p_T greater than 2 GeV. Two of these must be oppositely charged and have to originate from a common vertex with a probability greater than 0.5%, as determined by a Kalman vertex fit [36], thus suppressing

random combinations of two muons. The J/ψ -specific trigger requires a dimuon system's invariant mass to be between 2.95 and 3.25 GeV and its p_T to be greater than 3.5 GeV. The trigger used to select the Y sample requires two of the three muons to have p_T greater than 3.5 GeV, and one muon p_T greater than 5 GeV. The invariant mass for one oppositely charged muon pair must lie in the interval 8.5–11.4 GeV. Both triggers gave an efficiency exceeding 85% to select events satisfying the selection criteria used in the analysis.

3 Signal and background modeling

Simulated samples of the Higgs and Z boson signals are used to estimate the expected signal yields and model the distribution of signal events in the four-muon invariant mass. For the $H \rightarrow J/\psi J/\psi$ and $H \rightarrow YY$ samples the Higgs boson is produced with the POWHEG v2.0 Monte Carlo (MC) event generator [37, 38], which includes the gluon-gluon fusion (ggF) and vector-boson fusion production processes. The parton distribution function (PDF) set used is NNPDF3.1 [39]. The JHUGen 7.1.4 generator [40, 41] is used to decay the Higgs boson into two vector mesons taking into account their helicity. To produce the decay for unpolarized quarkonia, the JHUGen generator is configured to model a uniform muon helicity angle distribution. The generator is interfaced with PYTHIA 8.226 [42] for parton-showering and hadronization according to the CUETP8M1 [43] tune. The total SM Higgs boson production cross section for the calculation of branching fractions is taken from the LHC Higgs cross section working group [32].

The $Z \rightarrow J/\psi J/\psi$ and $Z \rightarrow YY$ samples are produced with the PYTHIA 8.226 generator [42], tune CUETP8M1 [43]. The SM Z boson production cross section includes the next-to-next-to-leading order (NNLO) QCD contributions, and the next-to-leading order (NLO) electroweak corrections from FEWZ 3.1 [44] calculated using the NLO PDF set NNPDF3.0. The Z boson p_T is reweighted to match the NLO calculation [37, 38, 45]. The total cross section is obtained with the $\mathcal{B}(Z \rightarrow \mu^+ \mu^-)$ value from Ref. [46].

In the J/ψ and Y pair channels backgrounds are assumed to originate from prompt nonresonant pair production, which in pp collisions dominantly occurs via ggF [47–50]. Initially, the two mesons are color-octet bound states that then radiate soft gluons to become real mesons. Event samples are generated according to this model [49].

The generated events are processed through a detailed simulation of the CMS detector based on GEANT4 [51]. The high instantaneous luminosity of the LHC results in multiple pp interactions per bunch crossing. Simultaneous pp interactions that overlap with the event of interest, i.e. pileup, are included in simulated samples. The distribution of the number of additional interactions per event in simulation corresponds to that observed in the data, where the average pileup number is found to be 32.

The acceptance of the final states changes with the angular distribution of the muons in the quarkonium decay. The distribution of the decay angle θ , defined as the angle between the positive muon direction of flight in the rest frame of the quarkonium with respect to the quarkonium direction in the boson rest frame, is proportional to $(1 + \lambda_\theta \cos^2 \theta)$. In this Letter, the nominal results are obtained using a signal acceptance calculated for the unpolarized case ($\lambda_\theta = 0$). Two extreme scenarios have also been considered, where the J/ψ and Y mesons are either fully transversely polarized, $\lambda_\theta = +1$, or fully longitudinally polarized, $\lambda_\theta = -1$. No azimuthal anisotropies have been considered. According to Refs. [14, 27] the J/ψ and Y mesons produced in the decays of both bosons are expected to be dominantly longitudinally polarized.

4 Data reconstruction and selection

Muons are reconstructed by combining information from the silicon tracker and the muon system [52]. The matching between tracks reconstructed in each of the subsystems proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track provided by the silicon tracker. In the latter case, tracks that match track segments in only one or two stations of the muon system are also considered in the analysis to collect very low- p_T muons that may not have sufficient energy to penetrate the entire muon system. The muons are selected from the reconstructed muon track candidates that match with at least one segment in any muon station in both x and y . The number of silicon tracker layers with hits used in the muon track candidate has to be greater than 5 and include at least one pixel detector layer. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum (p_T) resolution of 1% in the barrel and 3% in the endcaps for muons with p_T up to 100 GeV. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [52].

The reconstructed vertex with the largest value of summed charged particle p_T^2 is taken to be the primary pp interaction vertex. To suppress muons originating from nonprompt hadron decays, the impact parameter of each muon track, computed with respect to the position of the primary pp interaction vertex, is required to be less than 0.3 (20.0) cm in the transverse plane (longitudinal axis). Events with at least four such muons with $p_T > 3$ GeV and $|\eta| < 2.4$ are accepted. To isolate the leading muon candidate from other hadronic activity in the event, a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ is constructed around its momentum direction, where ϕ is the azimuthal angle in radians. The sum of the p_T of the reconstructed inner-detector tracks originating from the primary pp interaction vertex within the cone has to be less than 50% of the muon's p_T . The transverse momentum of the leading muon is subtracted from the sum and the subleading muon p_T is also subtracted, if this muon falls within the isolation cone of the leading muon.

The J/ψ and Y candidates are built from pairs of oppositely charged muons. Each muon pair must fit to their common vertex with a probability greater than 0.5%. The J/ψ candidate's p_T has to be greater than 3.5 GeV, matching the trigger requirement, and the invariant masses of the higher and lower- p_T J/ψ candidates have to be within 0.1 and 0.15 GeV, respectively, of the nominal mass of the J/ψ . The dimuon mass resolution is about 30 MeV. The mass window of the subleading J/ψ is wider to allow further monitoring of the sideband population. To suppress contributions from nonprompt hadrons, separately produced J/ψ s and muons from other sources, the four-muon Kalman vertex fit probability of J/ψ pairs has to be greater than 5%. Finally, the absolute value of the difference in rapidity between the two J/ψ candidates has to be less than 3. This criterion marginally affects the signal while removing about 20% of the selected events. After the selection, 189 events are found in data in the 40–140 GeV four-muon invariant mass range. Figure 2 (left) shows the four-muon invariant mass distribution.

For the selection of Y pair candidates, the same event selection criteria are applied, except that the Y candidate p_T has to be greater than 5 GeV, and the invariant mass has to fall within the range 8.5–11 GeV. Furthermore, the four-muon Kalman vertex fit probability has to be greater than 1% to suppress random combinations. The nonprompt background is negligible in this channel. After applying the selections, 106 events are found in data in the 20–140 GeV four-muons invariant mass range. Figure 2 (right) shows the four-muon invariant mass distribution.

The differences in efficiencies between data and simulation for the trigger, offline muon reconstruction, identification, and isolation are corrected by reweighting the simulated events with data-to-simulation correction factors, which are obtained with the “tag-and-probe” method [53] using $J/\psi \rightarrow \mu^+\mu^-$ events. The scale correction factors are observed to deviate from unity by

less than 3%. The difference in the four-muon Kalman vertex fit efficiency between data and simulation is evaluated with J/ψ pair event samples and found to be less than 3%. The total signal efficiency, including kinematic acceptance, trigger, reconstruction, identification, and isolation efficiencies, for the $J/\psi J/\psi$ decays with unpolarized J/ψ is approximately 23% for both bosons. For the YY decays the corresponding efficiency is about 27%.

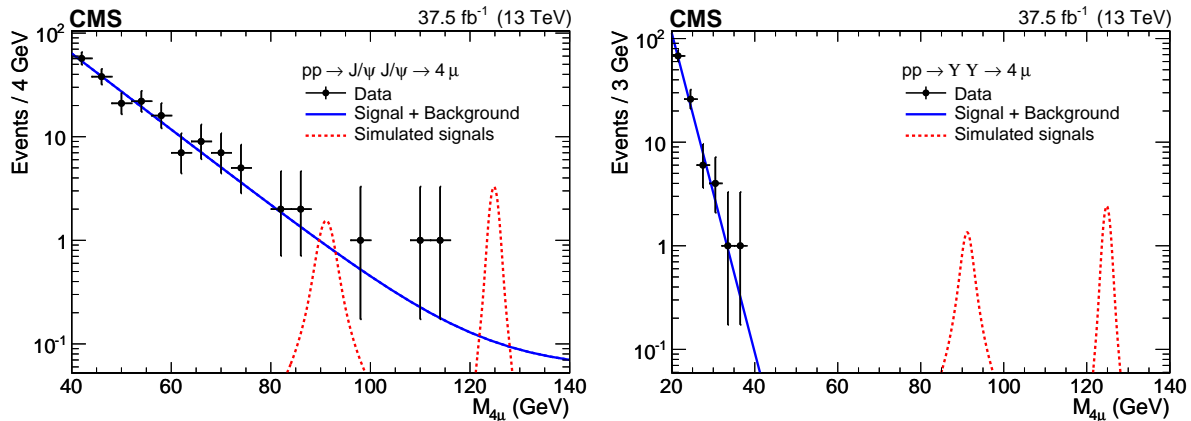


Figure 2: The four-muon invariant mass distributions, for $J/\psi J/\psi$ (left) and YY (right) candidates (error bars for zero entries are omitted). The result of the maximum likelihood fit is superimposed (solid blue line). For illustrative purposes, the plots also show the distributions for simulated Higgs and Z boson signals (dashed red lines), each normalized to two events.

5 Results

Unbinned extended maximum-likelihood fits [54] to the four-muon invariant mass distributions $M_{4\mu}$ are performed. Yields for signals and backgrounds are free parameters in the fit. For the Higgs boson the invariant mass distribution obtained from simulation is described with two Gaussian functions with a common mean. The simulated Z signal is described with a Voigtian function with the world-average value for the resonance width [46]. The mass resolution and mean are taken from the fit to the simulation, and they are fixed in the fit to data.

The four-muon invariant mass distribution up to 140 GeV is described by an exponential plus constant function. The relative contribution and decay constant of the exponential function are varied in the fit to data. The values of both parameters are found to be in close agreement between observation and simulation [49]. The result of the fit is shown as a solid blue line in Fig. 2 (left).

In the Y pair sample, no events are observed above the four-muon invariant mass of 40 GeV. The four-muon invariant mass distribution is modeled analogously to the J/ψ pair channel. The $M_{4\mu}$ distribution below 40 GeV is well described by an exponential function. The decay constant of the exponential function is also varied in the fit. The same function describes an event sample generated with the pair production model [49]. Figure 2 (right) shows the observed $M_{4\mu}$ distribution with the fit superimposed.

Given the absence of a signal for either of the bosons, upper limits on the branching fractions are obtained. They are set by using the modified frequentist approach, CL_s , with the profile likelihood ratio as a test statistic [55–57]. The uncertainties affecting the signal yields include the contributions from the luminosity measurement [58], the corrections applied to the simulated events in order to compensate for differences in trigger, muon reconstruction and identifi-

cation efficiencies, momentum scale and resolution of muon candidates, and four-muon vertex fit. Sources for theoretical uncertainties are the QCD coupling and PDF choice [32, 39, 59], and the renormalization and factorization scale choice [59–62]. The uncertainties in the J/ψ and Y branching fractions to muon pairs are taken from Ref. [46]. The relative impact of the systematic uncertainties on the upper limits is less than 2% in all channels.

The value for $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$ is taken from Ref. [46]. This analysis does not distinguish between the three $Y(nS)$ states. To calculate their contribution to the corresponding H and Z boson branching fraction the coupling strength of the bosons to any $Y(nS)$ pairing is assumed to be the same. All Y states can directly decay into muon pairs with the different branching fractions taken from Ref. [46]. In addition, it is assumed that one of the Y states could be the result of a transition $Y(3S) \rightarrow Y(2S)$, $Y(3S) \rightarrow Y(1S)$, or $Y(2S) \rightarrow Y(1S)$ before decaying into muons [46].

The observed and median expected exclusion limits for the branching fractions at 95% confidence level (CL) for the H and Z boson decays are listed in Table 1.

Table 1: Exclusion limits at 95% CL for the branching fractions of the H and Z boson decays to J/ψ or Y mesons pairs. The second column lists the observed limits. The third column shows the median expected limits with the upper and lower bounds in the expected 68% CL intervals.

Process	Observed	Expected
$\mathcal{B}(H \rightarrow J/\psi J/\psi)$	1.8×10^{-3}	$(1.8^{+0.2}_{-0.1}) \times 10^{-3}$
$\mathcal{B}(H \rightarrow YY)$	1.4×10^{-3}	$(1.4 \pm 0.1) \times 10^{-3}$
$\mathcal{B}(Z \rightarrow J/\psi J/\psi)$	2.2×10^{-6}	$(2.8^{+1.2}_{-0.7}) \times 10^{-6}$
$\mathcal{B}(Z \rightarrow YY)$	1.5×10^{-6}	$(1.5 \pm 0.1) \times 10^{-6}$

The relative changes in the upper limits on the Higgs boson decay branching fractions with respect to the case of unpolarized decay mesons are about -22% for fully longitudinally polarized J/ψ and Y mesons, and $+10\%$ for fully transversely polarized mesons. For the Z boson the relative changes are about -29 (-26)% for fully longitudinally polarized J/ψ (Y) mesons and $+13$ ($+12$)% for fully transversely polarized mesons.

6 Summary

In summary, this Letter presents the first search for decays of the Higgs and Z boson to pairs of J/ψ or $Y(nS)$ ($n=1,2,3$) mesons, with their subsequent decay to $\mu^+\mu^-$ pairs. Data from pp collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 37.5 fb^{-1} are used. No excess has been observed above a small background in the J/ψ pair and with vanishingly small background in the Y pair channels. The observed upper limits at 95% confidence level on the branching fractions for the Higgs boson decays for unpolarized mesons are $\mathcal{B}(H \rightarrow J/\psi J/\psi) < 1.8 \times 10^{-3}$ and $\mathcal{B}(H \rightarrow YY) < 1.4 \times 10^{-3}$. The observed upper limits on the branching fractions for the Z boson decay in the unpolarized scenario are $\mathcal{B}(Z \rightarrow J/\psi J/\psi) < 2.2 \times 10^{-6}$ and $\mathcal{B}(Z \rightarrow YY) < 1.5 \times 10^{-6}$, where all three $Y(nS)$ states are considered. Extreme polarization scenarios give rise to variations in the observed boson decay branching fractions between $-(22-29)\%$ for fully longitudinally polarized J/ψ and Y mesons and $+(10-13)\%$ for fully transversely polarized mesons. This analysis is expected to motivate renewed calculations of the Higgs boson branching fractions for rare standard model decays, as only a few positive signal events would indicate the presence of physics beyond the standard model.

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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, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Er, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, M. Jeitler¹, N. Krammer, I. Krtschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, 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

Universit Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, A. Magitteri, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, 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, L.M. Huertas Guativa, H. Malbouisson, J. Martins⁵, D. Matos Figueiredo, M. Medina Jaime⁶, 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, So Paulo, Brazil

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

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

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

University of Sofia, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁷, X. Gao⁷, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁸, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

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

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

Tsinghua University, Beijing, China

Z. Hu, Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. Gonzalez Hernandez, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar Gonzalez, N. Vanegas Arbelaez

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

D. Giljanović, 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, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

Charles University, Prague, Czech Republic

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

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^{11,12}, S. Elgammal¹²

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, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkil, T. Jrvinen, V. Karimki, R. Kinnunen, T. Lampn, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindn, P. Luukka, T. Menp, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.. Sahin, A. Savoy-Navarro¹³, M. Titov

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

C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, G. Falmagne, R. Granier de Cas-sagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gel, U. Goerlach, M. Jansov, 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

Universit de Lyon, Universit Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nuclaire de Lyon, Villeurbanne, France

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

Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹⁰

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

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

A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Ther, S. Wiedenbeck

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

G. Flgge, W. Haj Ahmad¹⁵, O. Hlushchenko, T. Kress, T. Mller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁶

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermdez Martnez, D. Bertsche, A.A. Bin Anuar, K. Borrás¹⁷, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodriguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domnguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁸, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem¹⁷, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krcker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Prez Adn, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schtze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Frhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, D. Marconi, J. Multhaupt, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrck, F.M. Stober, M. Stver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, A. Gottmann, M.A. Harrendorf, F. Hartmann¹⁶, U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, Th. Mller, M. Musich, A. Nrnberg, G. Quast, K. Rabbertz, M. Schrder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, C. Whrmann, R. Wolf

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National Technical University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ionnina, Ionnina, Greece

I. Evangelou, C. Foudas, P. Giannelis, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strogas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendlet CMS Particle and Nuclear Physics Group, Etsv Lornd University, Budapest, Hungary

M. Bartk²⁰, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surnyi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, F. Sikler, T. Vmi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

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. Bahinipati²³, C. Kar, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁴, D.K. Sahoo²³, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, 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. Bhardwaj²⁵, M. Bharti²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity²⁶, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, T. Sarkar²⁶, M. Sharan, B. Singh²⁵, S. Thakur²⁵

Indian Institute of Technology Madras, Madras, India

P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, 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, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

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

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

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

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Universit 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}, 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}, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a

INFN Sezione di Bologna ^a, Universit 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, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,28}, 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}, N. Tosi^a

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

S. Albergo^{a,b,29}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,29}, C. Tuve^{a,b}

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

G. Barbagli^a, R. Ceccarelli, 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, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, D. Piccolo

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

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

A. Benaglia^a, A. Beschi^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,16}, S. Di Guida^{a,b,16}, M.E. Dinardo^{a,b}, P. Dini^a, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, L. Guzzi^{a,b}, M. Malberti^a, S. Malvezzi^a, D. Menasce^a, F. Monti^{a,b}, L. Moroni^a, G. Ortona^{a,b}, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

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

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,16}, P. Paolucci^{a,16}, B. Rossi^a, C. Sciacca^{a,b}, E. Voevodina^{a,b}

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

P. Azzi^a, N. Bacchetta^a, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S.Y. Hoh, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, M. Presilla^b, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, M. Tosi^{a,b}, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

A. Braghieri^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, Universit di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fan^{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, Universit di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a,

R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, 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}, G. Rolandi³⁰, S. Roy Chowdhury, A. Scribano^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini, A. Venturi^a, P.G. Verdini^a

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

F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, E. Longo^{a,b}, B. Marzocchi^{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,b}

INFN Sezione di Torino ^a, Universit di Torino ^b, Torino, Italy, Universit 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, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, 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. Ruspai^{a,c}, R. Sacchi^{a,b}, R. Salvatico^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

INFN Sezione di Trieste ^a, Universit di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea

B. Kim, D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, 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

B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics

J. Goh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Riga Technical University, Riga, Latvia

V. Veckalns³¹

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, G. Tamulaitis, J. Vaitkus

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

Z.A. Ibrahim, F. Mohamad Idris³², W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³³, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

Universidad Autnoma de San Luis Potos, San Luis Potos, Mexico

A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro

N. Raicevic

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, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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. Grski, M. Kazana, M. Szleper, P. Zalewski

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

K. Bunkowski, A. Byszuk³⁴, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratrio de Instrumentao e Fsica Experimental de Partculas, Lisboa, Portugal

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{35,36}, P. Moisezenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁷, E. Kuznetsova³⁸, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, 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 named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko³⁹, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, 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

O. Bychkova, R. Chistov⁴⁰, M. Danilov⁴⁰, S. Polikarpov⁴⁰, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

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

A. Belyaev, E. Boos, M. Dubinin⁴¹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

A. Barnyakov⁴², V. Blinov⁴², T. Dimova⁴², L. Kardapol'tsev⁴², Y. Skovpen⁴²

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, 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, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences

P. Adzic⁴³, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Alvarez Fernandez, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernandez Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, . Navarro Tobar, A. Prez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sanchez Navas, M.S. Soares, A. Triossi, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocniz

Universidad de Oviedo, Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. Gonzalez Fernandez, E. Palencia Cortezon, V. Rodriguez Bouza, S. Sanchez Cruz

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. Fernandez Manteca, A. Garcia Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Russo⁴⁴, L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka

K. Malagalage

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

W.G.D. Dharmaratna, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dnsner, N. Dupont, A. Elliott-Peisert, F. Fallavollita⁴⁵, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, P. Janot, O. Karacheban¹⁹, J. Kaspar, J. Kieseler, M. Krammer¹, C. Lange, P. Lecoq, C. Loureno, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁶, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabaday, A. Racz, M. Rovere, H. Sakulin, C. Schfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁴⁶, J. Steggemann, V.R. Tavolaro, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, 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, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Doneg, C. Dorfer, T.A. Gmez Espinosa, C. Grab, D. Hits, T. Klijsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitenspiess, D. Ruini, D.A. Sanz Becerra, M. Schenberger, L. Shchutka, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universitt Zrich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

T.H. Doan, C.M. Kuo, W. Lin, A. Roy, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

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

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁴⁹, S. Damarseckin⁵⁰, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, EmineGurpinar Guler⁵¹, Y. Guler, I. Hos⁵², C. Isik, E.E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁴, S. Ozturk⁵⁵, A.E. Simsek, D. Sunar Cerci⁴⁹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁶, G. Karapinar⁵⁷, M. Yalvac

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Glmez, M. Kaya⁵⁸, O. Kaya⁵⁹, B. Kaynak, . zelik, S. Tekten, E.A. Yetkin⁶⁰

Istanbul Technical University, Istanbul, Turkey

A. Cakir, Y. Komurcu, S. Sen⁶¹

Istanbul University, Istanbul, Turkey

S. Ozkorucuklu

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, E. Bhal, S. Bologna, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶², C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, GurpreetSingh CHAHAL⁶³, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash⁶⁴, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁶, N. Wardle, D. Winterbottom, J. Wright, A.G. Zecchinelli, 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, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal

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, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkley, X. Coubez, D. Cutts, Y.t. Duh, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁵, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁶, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, 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, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Wrthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, 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, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius⁶⁷, A. Ryd, S.M. Tan, Z. Tao, J. Thom, 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, 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. Gece, E. Gottschalk, L. Gray, D. Green, S. Grondahl, O. Gutsche, AllisonReinsvold Hall,

J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, 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, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, 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

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA

Y.R. Joshi

Florida State University, Tallahassee, USA

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, 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, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁵¹, W. Clarida, K. Dilsiz⁶⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Kseyan, J.-P. Merlo, A. Mestvirishvili⁶⁹, A. Moeller, J. Nachtman, H. Ogul⁷⁰, Y. Onel, F. Ozok⁷¹, 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, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA

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

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, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg,

J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, 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, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko³⁵, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

Princeton University, Princeton, USA

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Pirou, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, 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

K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷³, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perni, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA

M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, 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

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, F. Fiori, C. Galloni, B. Gomber⁷⁴, M. Herndon, A. Herv, U. Hussain, P. Klabbers, A. Lanaro, A. Loeliger, K. Long, R. Loveless, J. Madhusudanan Sreekala, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, N. Woods

†: Deceased

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

2: Also at IRFU, CEA, Universit 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 UFMS/CPNA Federal University of Mato Grosso do Sul/Campus of Nova Andradina, Nova Andradina, Brazil

6: Also at Universidade Federal de Pelotas, Pelotas, Brazil

7: Also at Universit Libre de Bruxelles, Bruxelles, Belgium

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

- 9: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
- 10: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 11: Also at Suez University, Suez, Egypt
- 12: Now at British University in Egypt, Cairo, Egypt
- 13: Also at Purdue University, West Lafayette, USA
- 14: Also at Universit de Haute Alsace, Mulhouse, France
- 15: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 18: Also at University of Hamburg, Hamburg, Germany
- 19: Also at Brandenburg University of Technology, Cottbus, Germany
- 20: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 22: Also at MTA-ELTE Lendlet CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 24: Also at Institute of Physics, Bhubaneswar, India
- 25: Also at Shoolini University, Solan, India
- 26: Also at University of Visva-Bharati, Santiniketan, India
- 27: Also at Isfahan University of Technology, Isfahan, Iran
- 28: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
- 29: Also at CENTRO SICILIANO DI FISICA NUCLEARE E DI STRUTTURA DELLA MATERIA, Catania, Italy
- 30: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 31: Also at Riga Technical University, Riga, Latvia
- 32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 35: Also at Institute for Nuclear Research, Moscow, Russia
- 36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 38: Also at University of Florida, Gainesville, USA
- 39: Also at Imperial College, London, United Kingdom
- 40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 41: Also at California Institute of Technology, Pasadena, USA
- 42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 44: Also at Università degli Studi di Siena, Siena, Italy
- 45: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 46: Also at National and Kapodistrian University of Athens, Athens, Greece
- 47: Also at Universität Zürich, Zürich, Switzerland
- 48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 49: Also at Adiyaman University, Adiyaman, Turkey
- 50: Also at Sirtak University, SIRTAK, Turkey
- 51: Also at Beykent University, Istanbul, Turkey
- 52: Also at Istanbul Aydın University, Istanbul, Turkey

-
- 53: Also at Mersin University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Gaziosmanpasa University, Tokat, Turkey
56: Also at Ozyegin University, Istanbul, Turkey
57: Also at Izmir Institute of Technology, Izmir, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Institute for Particle Physics Phenomenology Durham University, Durham, United Kingdom
64: Also at Monash University, Faculty of Science, Clayton, Australia
65: Also at Bethel University, St. Paul, USA
66: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
67: Also at Vilnius University, Vilnius, Lithuania
68: Also at Bingol University, Bingol, Turkey
69: Also at Georgian Technical University, Tbilisi, Georgia
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea
74: Also at University of Hyderabad, Hyderabad, India