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Search for the Z boson decay to $\tau\tau\mu\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

The first search for the Z boson decay to $\tau\tau\mu\mu$ at the CERN LHC is presented, based on data collected by the CMS experiment at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 138 fb^{-1} . The data are compatible with the predicted background. For the first time, an upper limit at the 95% confidence level of 6.9 times the standard model expectation is placed on the ratio of the $Z \rightarrow \tau\tau\mu\mu$ to $Z \rightarrow 4\mu$ branching fractions. Limits are also placed on the six flavor-conserving four-lepton effective-field-theory operators involving two muons and two tau leptons, for the first time testing all such operators.

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The large data set collected by the CMS experiment [1] at the CERN LHC facilitates searches for rare processes within the standard model (SM) of particle physics. The CMS experiment was the first to observe the rare decays $Z \rightarrow J/\psi \ell \ell$ [2] and $Z \rightarrow \ell \ell \ell' \ell'$ [3] in proton-proton (pp) collisions, where ℓ denotes a charged lepton and ℓ' a charged lepton of a possibly different flavor. At leading order (LO), the latter process occurs via a $Z \rightarrow \ell \ell \rightarrow \ell \ell \ell' \ell'$ transition. These transitions are of particular interest because they can receive contributions from hypothetical new particles, such as a Z' boson, that can modify the branching fractions predicted by the SM. Theories predicting such new particles have been reported [4–13] and exclusive couplings to muons and tau leptons are predicted in many models, making $Z \rightarrow \tau \tau \mu \mu$ decays, shown in Fig. 1, important to explore.

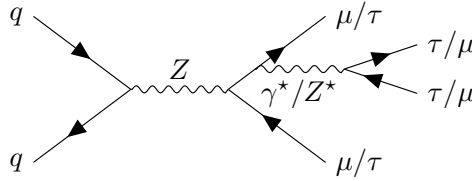


Figure 1: Leading-order Feynman diagram of the decay $Z \rightarrow \tau \tau \mu \mu$.

To derive constraints on possible beyond-the-SM (BSM) effects, the framework of the SM effective field theory [14, 15] (SMEFT) is used in this Letter. Here, the SM Lagrangian density \mathcal{L}_{SM} is extended by an infinite series of operators of even canonical dimension six and above, $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_6 + \dots$, where $\mathcal{L}_6 = 1/\Lambda^2 \sum_i C_i \mathcal{O}_i^6$. In this expression, Λ is the characteristic energy scale of possible BSM interactions, taken to be $\Lambda = 1 \text{ TeV}$, \mathcal{O}_i^6 are the dimension-six SMEFT operators, and C_i are the corresponding dimensionless Wilson coefficients (WCs). We exclusively consider four-lepton operators and include only the lowest-order contributions from the dimension-six operators to the four-lepton decays of the Z boson. We neglect odd-dimensional operators in this Letter because they would induce lepton- and baryon-number violating processes. Stringent constraints on four-muon operators have been derived from the branching fraction of the $Z \rightarrow 4\mu$ decay [16]. Throughout this Letter, the notation $Z \rightarrow 4\mu$ refers to the prompt decay of the Z boson to four muons that do not originate from decays of tau leptons or hadrons. However, four-lepton operators of dimension six involving two tau leptons and two muons are currently poorly constrained because of a lack of measurements of processes to which they could contribute at LO. Only one of these operators is constrained by measurements of the tau lepton decay to muons and neutrinos via charged-current interactions, whereas all others have never been probed [16, 17].

In this Letter, we report the first LHC search for the Z boson decay to two tau leptons and two muons relative to the Z boson decay to four muons. This search benefits from a partial cancellation of experimental systematic uncertainties that affect both decay modes. The two tau leptons are reconstructed via their decays to muons and neutrinos, hence the $Z \rightarrow \tau \tau \mu \mu$ decay is studied in the final state with four muons with a total electric charge of zero. In this analysis, we use pp collision data recorded by the CMS experiment in the years 2016–2018 at a center-of-mass energy of 13 TeV that correspond to an integrated luminosity of 138 fb^{-1} [18–20]. Measurements of four-fermion events possibly produced by the Z boson decay studied here have previously been reported at LEP [21–24]. Tabulated results are provided in the HEPData record for this analysis [25].

The CMS apparatus [1] is a multipurpose, nearly hermetic detector, designed to trigger on [26, 27] and identify [28–31] electrons, muons, photons, and hadrons. A global particle-flow algorithm [32] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracking detector and by the crystal electromagnetic and

brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to identify τ leptons and jets and to measure the missing transverse momentum [33–35].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about $4 \mu\text{s}$ [26]. 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 [27]. In this analysis, a single-muon trigger is used to record events with at least one isolated muon candidate having transverse momentum $p_T > 27$ (24) GeV in the 2017 (2016 and 2018) data-taking period(s).

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The efficiency to reconstruct and identify muons is greater than 96% over the full η range. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the endcaps [30]. The primary vertex of an event is taken to be the vertex corresponding to the most energetic scattering, evaluated using tracking information alone, as described in Ref. [36].

In this analysis, all reconstructed muons are required to pass a set of loose identification criteria, although the highest- p_T muon must satisfy a tighter condition. Both the loose and the tight criteria, are defined in Ref. [30]. All muons are required to be isolated from other activity in the event, quantified by the scalar p_T sum of hadrons and photons with an angular distance from the muon $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$, where ϕ is the azimuthal angle. This sum does not include contributions from charged particles identified as originating from pileup vertices and is corrected for the remaining average hadronic activity in an event due to pileup. The ratio of this corrected sum to the muon p_T is required to be smaller than 0.15 for the muon with the highest p_T and at most 0.25 for all other muons.

Processes leading to a final state with four prompt charged leptons via quark-initiated single or double electroweak gauge boson production are simulated at next-to-LO (NLO) in quantum chromodynamics, including all lepton flavors, using the POWHEG v2 [37–41] Monte Carlo event generator. The invariant mass of any two generated same-flavor leptons with opposite electric charges is required to exceed 4 GeV. Events containing the lepton flavor combinations targeted in this analysis, $\tau\tau\mu\mu$ and 4μ , are isolated from this sample using generator-level information.

Events of triple vector boson (VVV) production and top quark-antiquark ($t\bar{t}$) production in association with a Z boson are generated at NLO with MADGRAPH5_aMC@NLO v2.6.5 [42]. Higgs boson (H) production and its subsequent decay to four charged leptons is simulated at NLO with POWHEG v2 [43, 44] and JHUGEN v.7.0.11 [45–47]. Small background contributions due to combinations of prompt and nonprompt charged leptons come from $t\bar{t}$ and quark-initiated double vector boson (VV) production. The former process, as well as WW and ZZ production with decays to two charged leptons and two neutrinos, are simulated at NLO with POWHEG v2 [40, 41, 48]. All other VV processes producing two or three charged leptons are generated at NLO using MADGRAPH5_aMC@NLO v2.6.5. Gluon-induced VV production is negligible compared with the corresponding quark-initiated process and not included in the simulated samples.

All events are generated using the NNPDF3.1 next-to-NLO parton distribution functions [49].

The parton shower and subsequent hadronization are simulated with PYTHIA 8.205 [50] and the underlying event is modeled using the CP5 tune [51]. Additional inelastic pp interactions in the same or adjacent bunch crossings (pileup) are simulated for all processes, and events are reweighted to match the measured number of pileup interactions in the data. The full CMS detector is simulated using GEANT4 [52].

The generator-level phase space is defined by a set of criteria imposed on events at the generator level. The presence of exactly four muons that form two pairs with opposite electric charges consistent with the decays $Z \rightarrow 4\mu$ and $Z \rightarrow \tau\tau\mu\mu$, the latter followed by two $\tau \rightarrow \mu\nu\nu$ decays, is required. The invariant mass of the four muons, $m_{4\mu}$, must satisfy $40 < m_{4\mu} < 100$ GeV. The pair of oppositely charged muons with the highest invariant mass is required to have $12 < m_{\mu\mu}^{\max} < 75$ GeV, whereas for all other such pairs $m_{\mu\mu} > 4$ GeV is imposed.

The same requirements are applied to both data and simulated events at the reconstructed level as well. Additionally, the p_T -leading muon must have $p_T > 29$ (26) GeV in the 2017 (2016 and 2018) data-taking period(s), reflecting the single-muon trigger threshold. Minimum transverse momenta of 3.5 GeV are required for the two muons with the second- and third-highest p_T in the event. The fourth muon must satisfy $p_T > 3.5$ GeV for $|\eta| < 1.2$ and $p_T > 2.5$ GeV for $1.2 < |\eta| < 2.4$ to ensure it reaches the outer muon detectors, considering the CMS magnetic field and the energy loss of the muon traversing the detector. Finally, each muon is required to have an angular distance of $\Delta R > 0.02$ from any other muons, and the four selected muons must form a valid vertex.

The background due to nonprompt muons, most copiously produced in quantum chromodynamics multijet events via decays of bottom or charm quarks, is estimated using control samples in the data. Three additional, signal-depleted event categories are defined by inverting the requirement on the isolation of at least one of the three p_T -subleading muon candidates, on their total electric charge, or both. The inverted variables are independent, and the shape of the four-muon invariant mass distribution is consistent between any of these control regions and the search region. The shape and normalization of the background due to nonprompt muons in the latter is obtained by scaling the $m_{4\mu}$ distribution of data in the control region with inverted isolation criterion, from which the residual contribution of prompt muons is subtracted using simulated events. The scale factor is derived from the same extrapolation in the regions with inverted charge requirement. A correction accounting for differences between the regions with and without inverting the total electric charge criterion is derived by repeating the extrapolation between two subsets of events with inverted muon isolation.

A 47% uncertainty in the extrapolation factor used in the estimation of the background from nonprompt muons is due to the statistical uncertainty in the data in the signal-depleted regions; it is the dominant uncertainty in this search. Additional large sources of uncertainty are the number of events in the measurements and the simulation as well as the estimate of the nonprompt muon background in the search region. Minor experimental uncertainties in the efficiencies of different criteria imposed on the muons affect the shape and normalization of all simulated processes. The minor effect ($< 10\%$) of theoretical uncertainties in the renormalization and factorization scales, parton distribution functions, and strong coupling $\alpha_S(m_Z)$ on the $m_{4\mu}$ distribution are also included. For the former, the change in acceptance is estimated from independent variations of each scale by a factor of 0.5 or 2, whereas the uncertainty due to the latter two is estimated following the description in Ref. [53]. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [18–20] that affect only the rate of simulated processes, and the overall luminosity uncertainty for the 2016–2018 period is 1.6%. The uncertainties in the SM cross section of the individual simulated

backgrounds amount to 5–25% depending on the process. The effect of all systematic uncertainties is also propagated to the background with nonprompt muons estimated from data via the subtraction of simulated events with prompt muons.

The yield of $Z \rightarrow \tau\tau\mu\mu$ events is extracted from a binned maximum likelihood template fit of the expected signal and background to the data in the $m_{4\mu}$ distribution, which is performed with the CMS statistical analysis tool COMBINE [54]. Because of the neutrinos arising from the tau lepton decays, $Z \rightarrow \tau\tau\mu\mu$ events are expected to form a broad distribution in $m_{4\mu}$ in the region below the Z boson mass. Each systematic uncertainty is taken into account as a nuisance parameter in this fit. Uncertainties not affecting the shape of the distribution are modeled with log-normal probability distributions, whereas those affecting both the shape and normalization are instead modeled with Gaussian distributions.

The number of $Z \rightarrow 4\mu$ events is scaled by an unconstrained parameter in the fit. A second unconstrained parameter, r , is used to scale the ratio of the number of $Z \rightarrow \tau\tau\mu\mu$ and $Z \rightarrow 4\mu$ events. Both parameters are defined with respect to the SM expectation, which corresponds to parameter values of 1. In the generator-level phase space defined by the requirements on the dimuon and four-muon invariant mass discussed above, the ratio $\mathcal{R}_{\tau\tau\mu\mu}$ of the $Z \rightarrow \tau\tau\mu\mu$ to $Z \rightarrow 4\mu$ branching fractions is given by

$$\mathcal{R}_{\tau\tau\mu\mu} = \frac{N(Z \rightarrow \tau\tau\mu\mu)}{N(Z \rightarrow 4\mu)} \frac{(A\epsilon)_{Z \rightarrow 4\mu}}{(A\epsilon)_{Z \rightarrow \tau\tau\mu\mu}} \frac{1}{\mathcal{B}^2(\tau \rightarrow \mu\nu\nu)} \frac{f_\tau}{f_\mu}. \quad (1)$$

Here, $N(Z \rightarrow \tau\tau\mu\mu)$ and $N(Z \rightarrow 4\mu)$ are the event yields of the respective processes, where only $\tau \rightarrow \mu\nu\nu$ decays are considered for the former. The acceptance and efficiency of selecting events from the generator-level region are denoted by A and ϵ , respectively. Their products are $(A\epsilon)_{Z \rightarrow 4\mu} = (6.40 \pm 0.01)\%$ and $(A\epsilon)_{Z \rightarrow \tau\tau\mu\mu} = (1.32 \pm 0.02)\%$ for the respective Z boson decay modes and are determined from simulation. The parameters f_τ and f_μ are the fractions of selected events in the simulated signal and reference sample, respectively, that are due to the decay of a single Z boson produced in the s channel. The remaining events are due to VV production leading to the same final state. The parameters, which are computed by MADGRAPH5_aMC@NLO, are $f_\tau = (83.9 \pm 0.1)\%$ and $f_\mu = (85.5 \pm 0.2)\%$, where the uncertainties are statistical. The known branching fraction of the tau lepton decay to a muon and the corresponding neutrinos is $\mathcal{B}(\tau \rightarrow \mu\nu\nu) = (17.39 \pm 0.04)\%$ [55]. The SM expectation in the generator-level phase space, derived using generator-level information of events simulated with POWHEG v2 at NLO, is $\mathcal{R}_{\tau\tau\mu\mu}^{\text{SM}} = 0.90 \pm 0.02$, where the uncertainty includes statistical uncertainties in the number of generated events of each process and the uncertainties in the other factors of Eq. (1), as stated above.

In the combined fit of signal and background to the data, the best fit ratio of branching fractions is extracted from the fitted value of r ,

$$\mathcal{R}_{\tau\tau\mu\mu} = r\mathcal{R}_{\tau\tau\mu\mu}^{\text{SM}} = -12.5_{-8.2}^{+6.8}. \quad (2)$$

This agrees with the SM expectation within two standard deviations and has a negative value due to the deficit of data in the region $60 < m_{4\mu} < 75 \text{ GeV}$.

A second maximum likelihood fit of the background-only expectation to the data is performed. The $m_{4\mu}$ distribution after this fit is shown in Fig. 2. The observed data agree with the background prediction within the uncertainties. The postfit number of $Z \rightarrow 4\mu$ events is consistent between the signal-and-background and background-only fits with values of 1.10 ± 0.07 and 1.09 ± 0.07 times the SM expectation, respectively.

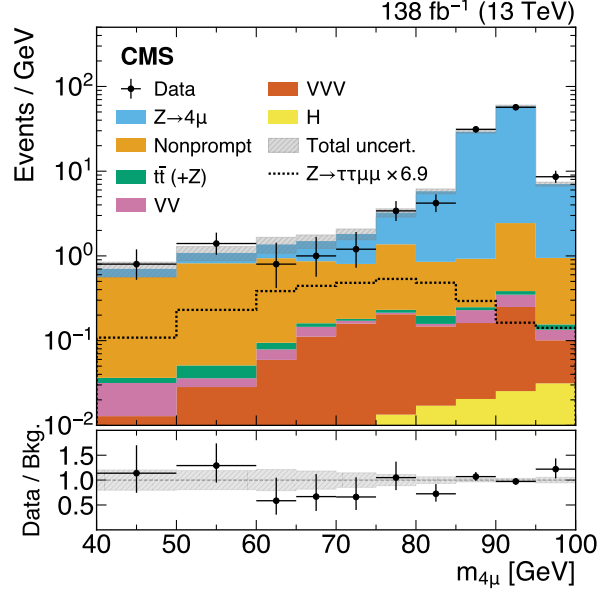


Figure 2: Distribution of $m_{4\mu}$ after the maximum likelihood fit of the background-only model (stacked histograms) to the data (black points). The nuisance parameters are set to their post-fit values and the signal (black dotted line) is overlaid, scaled to the upper limit on its cross section of 6.9 times the SM expectation. The gray shaded areas in both panels correspond to the total uncertainty in the background prediction. The black vertical bars indicate the statistical uncertainty in the data.

In addition, upper limits at the 95% confidence level (CL) are placed on $\mathcal{R}_{\tau\tau\mu\mu}$ for the first time, derived using the CL_s technique [56, 57] and the COMBINE tool [54]. The observed and median expected upper limits on $\mathcal{R}_{\tau\tau\mu\mu}$ are 6.2 and 10.0, respectively, reflecting the deficit of data discussed above. The intervals [7.3, 13.9] ([5.5, 18.8]) include 68 (95%) of the distribution of expected limits under the background-only hypothesis. The observed and median expected limits correspond to 6.9 and 11.1 times the SM expectation of $\mathcal{R}_{\tau\tau\mu\mu}^{\text{SM}} = 0.90$, respectively.

The 95% CL upper limits are used in the SMEFT framework to derive constraints on potential BSM contributions to $\mathcal{R}_{\tau\tau\mu\mu}$ as suggested in Ref. [16]. In this Letter, the notation C_{AB}^{ijkl} is used for the WC corresponding to the four-lepton operator $(\bar{\ell}_A^i \gamma_\mu \ell_A^j)(\bar{\ell}_B^k \gamma^\mu \ell_B^l)$ contributing to the process $\ell^l \rightarrow \ell^k \ell^j \ell^i$, where the superscripts denote the lepton generation and A and B indicate the chirality. Constraints on the WCs are derived in terms of C/Λ^2 with $\Lambda = 1$ TeV.

In this analysis, all six SMEFT operators in the so-called Warsaw basis [58] that have a canonical dimension of six and involve two muons and two tau leptons are considered. These operators affect only the $Z \rightarrow \tau\tau\mu\mu$ but not the $Z \rightarrow 4\mu$ decay. The effect of each operator on Eq. (1), relative to the SM prediction, is computed using MADGRAPH5_aMC@NLO v2.7.2 with the SMEFTSIM 3.0 package [59, 60]. The multiplicative BSM correction to each factor in Eq. (1) is expressed in terms linear or quadratic in the corresponding WC, where the linear terms are due to interference of the BSM process with the SM and the quadratic terms correspond to pure BSM contributions. The total correction to $\mathcal{R}_{\tau\tau\mu\mu}^{\text{SM}}$ is given by the product of the individual corrections to each factor. In what follows, distinctions between linear and quadratic terms refer to the order of the individual correction factors, their product therefore also depends on higher orders of the WCs in both cases.

When we consider one nonzero WC at a time, the intervals allowed at the 95% CL for C/Λ^2

are given in Table 1. When we consider two nonzero WCs and linear and quadratic terms, the regions allowed and excluded at the 95% CL are shown in Fig. 3 for four representative combinations of WCs that exhibit characteristic features discussed below. These are the first constraints on all flavor-conserving four-lepton WCs involving two muons and two tau leptons with the exception of \mathcal{C}_{LL}^{2332} [16, 17], which was limited more stringently by Ref. [17].

The effect of any WC on the event yield is dominant compared to BSM contributions to the signal acceptance and f_τ . It was verified that BSM shape distortions of the $m_{4\mu}$ distribution after applying the event selection are negligible compared to changes in the overall event yield. The expected value of $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$ in Eq. (1) is only affected by two WCs, \mathcal{C}_{LL}^{2332} and \mathcal{C}_{LR}^{2332} . For these WCs, however, it has the dominant impact on the determination of the allowed and excluded regions and leads to a larger allowed parameter space when considering quadratic terms as shown in Fig. 3 (left). The limit on a combination of WCs including neither \mathcal{C}_{LL}^{2332} nor \mathcal{C}_{LR}^{2332} (light blue) is approximately 5 times more stringent than the limits on combinations that include one or both of these WCs. For combinations that include only \mathcal{C}_{LR}^{2332} (red), which enhances $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$, the limit is most stringent for $\mathcal{C}_{LR}^{2332} = 0$ and relaxes for nonzero values as shown in Fig. 3 (right). Including only \mathcal{C}_{LL}^{2332} (orange), which causes negative interference with the SM prediction of $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$, leads to an excluded region at small positive values of \mathcal{C}_{LR}^{2332} . Considering both \mathcal{C}_{LR}^{2332} and \mathcal{C}_{LL}^{2332} , their combined effect results in a second excluded region shown in Fig. 3 (right, dark blue). In this analysis, external constraints on $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$ are neglected, but produce stronger constraints on \mathcal{C}_{LL}^{2332} [17] and \mathcal{C}_{LR}^{2332} than those presented here due to the small uncertainty in the measured value of $\mathcal{B}(\tau \rightarrow \mu\nu\nu)$ [55].

Table 1: Intervals allowed at the 95% CL for \mathcal{C}/Λ^2 for all 6 dimension-six Wilson coefficients conserving lepton flavor and involving two muons and two tau leptons. The second column shows the allowed intervals considering only terms linear in \mathcal{C} , in which case the lower and upper bounds originate from unphysical negative event yields and the limit on $\mathcal{R}_{\tau\tau\mu\mu}$, respectively. For the third column, quadratic terms are considered as well and all bounds are determined by the limit on $\mathcal{R}_{\tau\tau\mu\mu}$.

\mathcal{C}	95% CL allowed region for \mathcal{C}/Λ^2 [$10^3/\text{TeV}^2$]	
	Only linear terms	Linear and quadratic terms
\mathcal{C}_{LL}^{2233}	[-2.7, 15.2]	[-3.8, 3.1]
\mathcal{C}_{LL}^{2332}	[-2.74, 0.01]	[-21.62, 0.01] \cup [0.05, 20.82]
\mathcal{C}_{LR}^{2233}	[-3.0, 18.5]	[-4.3, 3.5]
\mathcal{C}_{LR}^{3322}	[-3.0, 17.2]	[-4.2, 3.4]
\mathcal{C}_{LR}^{2332}	—	[-17.4, 17.4]
\mathcal{C}_{RR}^{2233}	[-3.6, 20.0]	[-4.4, 3.6]

When we consider only linear terms, each factor in Eq. (1) may take on unphysical values at sufficiently large absolute values of the WCs, such as a negative event yield or $f_\tau \notin [0, 1]$. The allowed regions given in Table 1 are obtained excluding these and other unphysical scenarios. Considering only linear terms, all lower (upper) limits originate from negative event yields (the limit on $\mathcal{R}_{\tau\tau\mu\mu}$). No linear terms exist for \mathcal{C}_{LR}^{2332} because the corresponding operator cannot interfere with the SM process. When considering both linear and quadratic terms, no unphysical regimes are reached within the limits derived from the upper limit on $\mathcal{R}_{\tau\tau\mu\mu}$.

In summary, the first search for the Z boson decay to $\tau\tau\mu\mu$ at the LHC has been presented. The sample of proton-proton collision data analyzed was collected at $\sqrt{s} = 13$ TeV by the CMS experiment and corresponds to an integrated luminosity of 138 fb^{-1} . No excess over the standard model background prediction was observed. For the first time, an upper limit at 95%

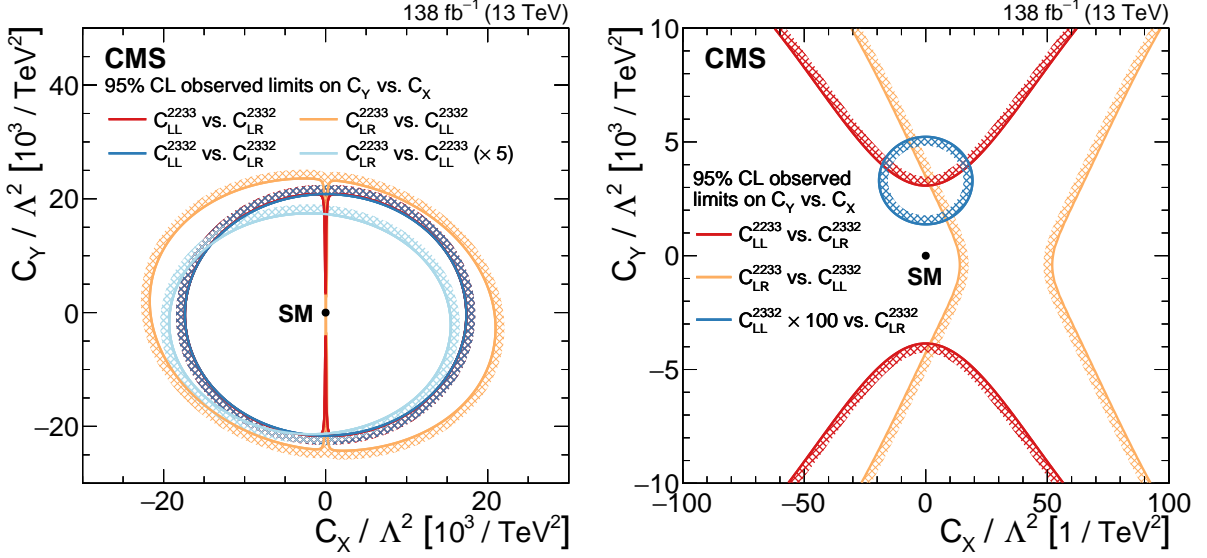


Figure 3: Observed limits at the 95% CL on different combinations of two Wilson coefficients (colors) showing the full ranges (left) and an enlarged view of the region around values of 0 (right). In the left (right) figure, the limit on C_{LR}^{2233} vs. C_{LL}^{2233} (only C_{LL}^{2332}) is scaled by a factor of 5 (100) for visibility. The SM expectation is indicated by a black dot. The hatches indicate the excluded side of each limit.

confidence level of 6.2 was placed on the ratio of the $Z \rightarrow \tau\tau\mu\mu$ to $Z \rightarrow 4\mu$ branching fractions in the phase space considered, equivalent to 6.9 times the standard model expectation of 0.90. Also for the first time, constraints were placed on all flavor-conserving four-lepton Wilson coefficients involving two muons and two tau leptons.

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













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A The CMS Collaboration




Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 













Institut für Hochenergiephysik, Vienna, Austria

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

















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , P. Van Mechelen 













Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat⁴ , G.P. Van Onsem , S. Van Putte , D. Vannerom 















Université Libre de Bruxelles, Bruxelles, Belgium

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








Ghent University, Ghent, Belgium

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



















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 










Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁶, E.M. Da Costa , G.G. Da Silveira⁷ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, M. Macedo , J. Martins⁸ , C. Mora Herrera , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

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

C.A. Bernardes⁷ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maitto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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

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




University of Sofia, Sofia, Bulgaria

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



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

S. Keshri , S. Thakur 













Beihang University, Beijing, China

T. Cheng , T. Javaid , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

Z. Hu , Z. Liang, J. Liu, K. Yi^{9,10} 

Institute of High Energy Physics, Beijing, China

G.M. Chen¹¹ , H.S. Chen¹¹ , M. Chen¹¹ , F. Iemmi , C.H. Jiang, A. Kapoor¹² , H. Liao , Z.-A. Liu¹³ , M.A. Shahzad¹¹, R. Sharma¹⁴ , J.N. Song¹³, J. Tao , C. Wang¹¹, J. Wang , Z. Wang¹¹, H. Zhang , J. Zhao 


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

A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou 

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

S. Yang 

Sun Yat-Sen University, Guangzhou, China

Z. You 

University of Science and Technology of China, Hefei, China

K. Jaffel , N. Lu 

Nanjing Normal University, Nanjing, China

G. Bauer¹⁵, B. Li, J. Zhang 

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

X. Gao¹⁶ 





Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega



Universidad de Antioquia, Medellin, Colombia

F. Ramirez , M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

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

D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 







University of Split, Faculty of Science, Split, Croatia

M. Kovac , A. Petkovic, T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovic, S. Mishra , A. Starodumov¹⁷ , T. Susa 

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

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

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 









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

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

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

M.A. Mahmoud , Y. Mohammed 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

H. Kirschenmann , K. Osterberg , M. Voutilainen 


















Helsinki Institute of Physics, Helsinki, Finland

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



























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow 

















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro²⁰ , P. Simkina , M. Titov , M. Tornago 

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

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


















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

J.-L. Agram²¹ , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 




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

A. Di Florio 

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

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen²² , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , E. Jourd’huy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 






























Georgian Technical University, Tbilisi, Georgia

I. Bagaturia²³ , I. Lomidze , Z. Tsamalaide¹⁷ 









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

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




































































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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo²⁴ , S. Wiedenbeck , S. Zaleski







































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

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 


Deutsches Elektronen-Synchrotron, Hamburg, Germany






































H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman²⁵ , K. Borrás²⁶ , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²⁵ , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁷ , W. Lohmann²⁸ , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otariid, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham^{29,26} , S. Schnake²⁶ , P. Schütze , C. Schwanenberger²⁵ , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁶ , C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Fal-

termann , M. Giffels , A. Gottmann , F. Hartmann³⁰ , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link , A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum , M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa , L. Stockmeier , K. Tauqeer , M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig , R. Wolf , X. Zuo 







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

G. Anagnostou , G. Daskalakis , A. Kyriakis , A. Papadopoulos³⁰ , A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis , G. Melachroinos , Z. Painesis , A. Panagiotou , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 







National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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




HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu , D. Horvath^{31,32} , K. Márton , A.J. Rádl³³ , F. Sikler , V. Veszpremi 





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

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

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

P. Raics , B. Ujvari , G. Zilizi 

















Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

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

T. Csorgo³⁴ , T. Novak 

Panjab University, Chandigarh, India

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



















University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁷ , S. Bhattacharya , S. Das Gupta , S. Dutta , S. Dutta , S. Sarkar 








Indian Institute of Technology Madras, Madras, India

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri³⁸ , D. Kumar³⁸ , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh , P. Verma , S. Verma , A. Vijay 












Tata Institute of Fundamental Research-A, Mumbai, India

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










Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 




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

S. Bahinipati³⁹ , C. Kar , D. Maity⁴⁰ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁰ , K. Naskar⁴⁰ , A. Nayak⁴⁰ , S. Nayak, K. Pal, P. Sadangi, S.K. Swain , S. Varghese⁴⁰ , D. Vats⁴⁰ 








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

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

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴² , A. Jafari⁴³ , M. Zeinali⁴⁴ 





























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

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
































University College Dublin, Dublin, Ireland

M. Felcini , M. Grunewald 






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

M. Abbrescia^{a,b} , A. Colaleo^{a,b} , D. Creanza^{a,c} , B. D'Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , M. Louka^{a,b}, G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^a , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^{a,b} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,c} , Ü. Sözbilir^a , A. Stamerra^{a,b} , D. Troiano^{a,b} , R. Venditti^{a,b} , P. Verwilligen^a , A. Zaza^{a,b} 


















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

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , I. Brivio^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^a , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,48} , M. Lorusso^{a,b} , L. Lunerti^a , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , G. Paggi^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , S. Rossi Tisbeni^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,49} , A. Di Mattia^a , A. Lapertosa^a , R. Potenza^{a,b}, A. Tricomi^{a,b,49} , C. Tuve^{a,b} 

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

P. Assiouras^a , G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^a , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , T. Kello^a, G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^a , M. Meschini^a , S. Paoletti^a , A. Papanastassiou^{a,b}, G. Sguazzoni^a , L. Viliani^a 









INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵⁰ , D. Piccolo 






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

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









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

A. Benaglia^a , G. Boldrini^{a,b} , F. Brivio^a , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^a , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , S. Palluotto^{a,b} , D. Pedrini^a , A. Perego^{a,b} , B.S. Pinolini^a, G. Pizzati^{a,b}, S. Ragazzi^{a,b} , T. Tabarelli de Fatis^{a,b}









INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,51} , P. Paolucci^{a,30} , B. Rossi^a , C. Sciacca^{a,b}









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

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,52} , M. Biasotto^{a,53} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , A.C.M. Bulla^a , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , F. Gasparini^{a,b} , E. Lusiani^a, M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}









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

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









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

S. Ajmal^{a,b} , M.E. Ascioti^{a,b}, G.M. Bilei^a , C. Carrivale^{a,b}, D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,54} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b}

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






































C.A. Alexe^{a,c} , P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , D. Matos Figueiredo^a, A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , F. Vaselli^{a,c} , A. Venturi^a , P.G. Verdini^a

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







C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , M. Campana^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , F. Errico^{a,b} , E. Longo^{a,b} , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a

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

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a 

R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , C. Borca^{a,b} , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , L. Finco^a , M. Grippo^{a,b} , B. Kiani^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , L. Markovic^{a,b} , S. Maselli^a , A. Mecca^{a,b} , L. Menzio^{a,b} , P. Meridiani^a , E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , D. Trocino^a , G. Umoret^{a,b} , E. Vlasov^{a,b} , R. White^{a,b} 

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

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a , G. Della Ricca^{a,b} 


Kyungpook National University, Daegu, Korea

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

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim 









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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 











Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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



Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee , Y. Lee , I. Yu 

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy , Y. Gharbia 

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , G. Pikurs , A. Potrebko , M. Seidel , D. Sidiropoulos Kontos 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 







Vilnius University, Vilnius, Lithuania

M. Ambrozias , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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

I. Yusuff⁵⁵ , Z. Zolkapli



Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁶ , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera, A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja , N. Raicevic 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

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

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







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

V. Avati, L. Grzanka , M. Malawski 

National Centre for Nuclear Research, Swierk, Poland

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

















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

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



Warsaw University of Technology, Warsaw, Poland

K. Pozniak , W. Zabolotny 

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

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , P. Milenovic 

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

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

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT),















Madrid, Spain

J. Alcaraz Maestre , Cristina F. Bedoya , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , E. Martin Viscasillas , D. Moran , C.M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 




















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

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

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

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasiosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizan Garcia 












































































University of Colombo, Colombo, Sri Lanka

B. Kailasapathy⁵⁷ , D.D.C. Wickramarathna 









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

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























CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , C. Botta , E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , L. Gouskos , J. Hegeman , J.K. Heikkilä , B. Huber, V. Innocente , T. James , P. Janot , O. Kaluzinska , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , A.C. Marini , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabadý , B. Ribeiro Lopes , M. Rovere , H. Sakulin , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁵⁹ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk⁶⁰ , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner







Paul Scherrer Institut, Villigen, Switzerland

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




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

T.K. Aarrestad , K. Androsov⁶⁰ , M. Backhaus , G. Bonomelli, A. Calandri , C. Cazaniga , K. Datta , P. De Bryas Dexmiers D'archiac⁶⁰ , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer , T.G. Harte, D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani⁶⁰ , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , R. Seidita , J. Steggemann⁶⁰ , A. Tarabini , D. Valsecchi , R. Wallny







Universität Zürich, Zurich, Switzerland

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


National Central University, Chung-Li, Taiwan

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








National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, H.y. Wu, E. Yazgan


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

C. Asawatangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

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

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac⁶⁸ 

Bogazici University, Istanbul, Turkey

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





Istanbul Technical University, Istanbul, Turkey

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

Istanbul University, Istanbul, Turkey

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

Yildiz Technical University, Istanbul, Turkey

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


















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

A. Boyaryntsev , B. Grynyov 

























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

L. Levchuk 














































University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou⁷⁷ , K. Walkingshaw Pass






Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball , K.W. Bell , A. Belyaev⁷⁸ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 

Imperial College, London, United Kingdom

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







Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

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





















Catholic University of America, Washington, DC, USA

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





















The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio⁸¹ , E. Usai , R. Yi 





















Boston University, Boston, Massachusetts, USA

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

Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²⁶ , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸² , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , S. Sagir⁸³ , F. Simpson , M. Stamenkovic , N. Venkatasubramanian , X. Yan , W. Zhang 

University of California, Davis, Davis, California, USA

S. Abbott , J. Bonilla , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , Y. Yao , S. Yoo , F. Zhang 

























University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si , S. Wimpenny[†] 

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

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 

















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Sheplock , D. Stuart , T.Á. Vámi , S. Wang , D. Zhang















California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 































































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 







Cornell University, Ithaca, New York, USA






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

Fermi National Accelerator Laboratory, Batavia, Illinois, USA








M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁴ , F. Ravera , A. Reinsvold Hall⁸⁵ , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 

University of Florida, Gainesville, Florida, USA






C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig 

M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang






Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Habibullah , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang






Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy⁸⁶ , M. Hohlmann , M. Rahmani, E. Yanes







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

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








The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , D. Blend, K. Dilsiz⁸⁷ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁸ , O. Neogi, H. Ogul⁸⁹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹⁰







Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz







The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , N. Minafra , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹¹ , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , G. Wilson







Kansas State University, Manhattan, Kansas, USA

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino

University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, L. Wang


Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. Mcginn, A. Novak , C. Paus , D. Rankin , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans , Z. Wang , B. Wyslouch , T. J. Yang













University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , M. Revering , R. Rusack , R. Saradhy , N. Strobbe











University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 
















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado ,
W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 








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

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos ,
A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams ,
P. Young 



























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Dervan, Y. Haddad , Y. Han , A. Krishna , J. Li ,
M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto ,
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





Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt ,
A. Taliercio , M. Velasco


















University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,
K.W. Ho , K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence ,
N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady ,
C. Moore , Y. Musienko¹⁷ , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

The Ohio State University, Columbus, Ohio, USA

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



















Princeton University, Princeton, New Jersey, USA

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




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 







Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones ,
A.W. Jung , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,
S. Piperov , V. Scheurer, J.F. Schulte , M. Stojanovic , J. Thieman , A. K. Viridi ,
F. Wang , W. Xie 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 


Rice University, Houston, Texas, USA

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






















University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar, P. Parygin⁹² , E. Popova⁹² , R. Taus 




The Rockefeller University, New York, New York, USA

K. Goulianos 















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , O. Karacheban²⁸ , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

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












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

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







Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























University of Virginia, Charlottesville, Virginia, USA

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

Wayne State University, Detroit, Michigan, USA


























S. Bhattacharya , P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA

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

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Alexakhin , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , V. Blinov⁹⁵, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , M. Chadeeva⁹⁵ , V. Chekhovsky, R. Chistov⁹⁵ , A. Dermenev , T. Dimova⁹⁵ , D. Druzhkin⁹⁶ , M. Dubinin⁸⁴ , L. Dudko , G. Gavrilo , V. Gavrilo , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , Y. Ivanov , V. Kachanov , V. Karjavine , A. Karneyeu , V. Kim⁹⁵ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁷ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁵ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁸ , O. Lukina , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁵ , V. Murzin , A. Nikitenko^{99,97} , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , M. Perfilov, S. Polikarpov⁹⁵ 

V. Popov , O. Radchenko⁹⁵ , M. Savina , V. Savrin , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁵ , S. Slabospitskii , V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , A. Vorobyev[†], G. Vorotnikov , N. Voytishin , B.S. Yuldashev¹⁰⁰, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Ghent University, Ghent, Belgium

⁵Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁶Also at Universidade Estadual de Campinas, Campinas, Brazil

⁷Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁸Also at UFMS, Nova Andradina, Brazil

⁹Also at Nanjing Normal University, Nanjing, China

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

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

¹²Also at China Center of Advanced Science and Technology, Beijing, China

¹³Also at University of Chinese Academy of Sciences, Beijing, China

¹⁴Also at China Spallation Neutron Source, Guangdong, China

¹⁵Now at Henan Normal University, Xinxiang, China

¹⁶Also at Université Libre de Bruxelles, Bruxelles, Belgium

¹⁷Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁸Also at Suez University, Suez, Egypt

¹⁹Now at British University in Egypt, Cairo, Egypt

²⁰Also at Purdue University, West Lafayette, Indiana, USA

²¹Also at Université de Haute Alsace, Mulhouse, France

²²Also at Istinye University, Istanbul, Turkey

²³Also at Ilia State University, Tbilisi, Georgia

²⁴Also at The University of the State of Amazonas, Manaus, Brazil

²⁵Also at University of Hamburg, Hamburg, Germany

²⁶Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁷Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

²⁸Also at Brandenburg University of Technology, Cottbus, Germany

²⁹Also at Forschungszentrum Jülich, Juelich, Germany

³⁰Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

³¹Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

³²Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

³³Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

³⁴Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

³⁵Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

³⁶Also at Punjab Agricultural University, Ludhiana, India

³⁷Also at University of Visva-Bharati, Santiniketan, India

³⁸Also at Indian Institute of Science (IISc), Bangalore, India

³⁹Also at IIT Bhubaneswar, Bhubaneswar, India

⁴⁰Also at Institute of Physics, Bhubaneswar, India

- ⁴¹Also at University of Hyderabad, Hyderabad, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁷Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵¹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵²Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵³Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁷Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁸Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁵⁹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶⁰Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶¹Also at Universität Zürich, Zurich, Switzerland
- ⁶²Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶³Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁴Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁵Also at Konya Technical University, Konya, Turkey
- ⁶⁶Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁷Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁸Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁶⁹Also at Marmara University, Istanbul, Turkey
- ⁷⁰Also at Milli Savunma University, Istanbul, Turkey
- ⁷¹Also at Kafkas University, Kars, Turkey
- ⁷²Now at Istanbul Okan University, Istanbul, Turkey
- ⁷³Also at Hacettepe University, Ankara, Turkey
- ⁷⁴Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ⁷⁵Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁶Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁷Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁷⁸Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁹Also at IPPP Durham University, Durham, United Kingdom
- ⁸⁰Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸¹Also at Università di Torino, Torino, Italy
- ⁸²Also at Bethel University, St. Paul, Minnesota, USA
- ⁸³Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁴Also at California Institute of Technology, Pasadena, California, USA

⁸⁵Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁶Also at Ain Shams University, Cairo, Egypt

⁸⁷Also at Bingol University, Bingol, Turkey

⁸⁸Also at Georgian Technical University, Tbilisi, Georgia

⁸⁹Also at Sinop University, Sinop, Turkey

⁹⁰Also at Erciyes University, Kayseri, Turkey

⁹¹Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

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

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

⁹⁴Also at Kyungpook National University, Daegu, Korea

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

⁹⁶Also at Universiteit Antwerpen, Antwerpen, Belgium

⁹⁷Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at Northeastern University, Boston, Massachusetts, USA

⁹⁹Also at Imperial College, London, United Kingdom

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