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Search for resonances decaying to three W bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for resonances decaying into a W boson and a radion, where the radion decays into two W bosons, is presented. The data analyzed correspond to an integrated luminosity of 138 fb^{-1} recorded in proton-proton collisions with the CMS detector at $\sqrt{s} = 13$ TeV. One isolated charged lepton is required, together with missing transverse momentum and one or two massive large-radius jets, containing the decay products of either two or one W bosons, respectively. No excess over the background estimation is observed. The results are combined with those from a complementary channel with an all-hadronic final state, described in an accompanying paper. Limits are set on parameters of an extended warped extra-dimensional model. These searches are the first of their kind at the LHC.

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The existence of heavy resonances accessible at the CERN LHC is suggested by various theoretical models that try to address limitations of the standard model (SM). Searching for these resonances in decays to boson pairs (dibosons) has received much attention in recent years [1–6]. In the context of such searches, merged jet reconstruction and classification techniques that aim to identify the origin of a large-radius jet from a Lorentz-boosted hadronically decaying particle have been developed and exploited extensively [7]. Nonetheless, a direct search for a resonance decaying to three vector bosons, a triboson resonance, has never been performed at the TeV scale. In the sub-TeV range, a search for a heavy neutral Higgs boson in the ZWW channel has recently been published [8]. The TeV-scale diboson resonance searches [3–6] are potentially sensitive to a triboson signal. However, as only two of the three bosons are reconstructed, they have not been interpreted in this way. A search at the TeV-scale is motivated by various theoretical scenarios including extended warped extra-dimensional models presented in Refs. [9–17] indicating a discovery potential within LHC reach. These models provide extensions of the SM that simultaneously address the problems of the Planck–electroweak hierarchy and the origins of flavor structure.

In this Letter and in an accompanying paper [18], we present the first searches for massive resonances decaying to three W bosons in cascade through $W_{\text{KK}} \rightarrow WR$ and $R \rightarrow WW$. The W_{KK} is a Kaluza–Klein (KK) [19–22] excited massive gauge boson and R is a scalar radion [23]. The W_{KK} and R bosons are postulated in the Randall–Sundrum extra-dimension scenario [19, 20]. The size of the extra dimension is stabilized by introducing a potential with a modulus field [20], resulting in a bulk scalar boson, the radion.

We concentrate on the final-state topology comprising one isolated, charged lepton (ℓ), either electron (e) or muon (μ), missing transverse momentum ($p_{\text{T}}^{\text{miss}}$), and one or two massive large-radius jets. A similar topology without an isolated ℓ in the final state is considered in Ref. [18]. These two searches use common techniques for jet identification and calibration, which are detailed in Ref. [18], while the combination of the two results is presented in this Letter. The topology studied in this Letter originates from a W boson decaying to an isolated ℓ and its neutrino ν , and two other W bosons decaying into quarks forming hadrons, which are either reconstructed as two individual merged W boson jets, as shown in Fig. 1 (left), or—depending on the relative masses of the W_{KK} and R resonances—as a single jet containing the decay products of both W bosons, as shown in Fig. 1 (right). We also consider the case where one of the two merged W bosons originating from the radion decays leptonically, yielding a nonisolated ℓ inside the jet in addition to the isolated one from the separated W boson decay. The main backgrounds in this analysis are from W + jets and top quark-antiquark pair ($t\bar{t}$) production. They are estimated using control regions (CRs) with kinematic properties similar to the corresponding signal regions (SRs). While the analysis is interpreted in terms of one specific model, the search is generic as it is sensitive to many resonant diboson and triboson signals. For example, resonances decaying into WW and WZ can also be detected through this search, although with a lower efficiency than in the dedicated analyses [3, 4]. Tabulated results are provided in the HEPData record for this analysis [24].

The analysis is based on proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment at the LHC during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} [25–27].

The CMS apparatus [28] is a multipurpose, nearly hermetic detector, designed to trigger on [29, 30] and identify electrons, muons, photons, and (charged and neutral) hadrons [31–34]. A global reconstruction “particle-flow” (PF) algorithm [35] combines the information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron

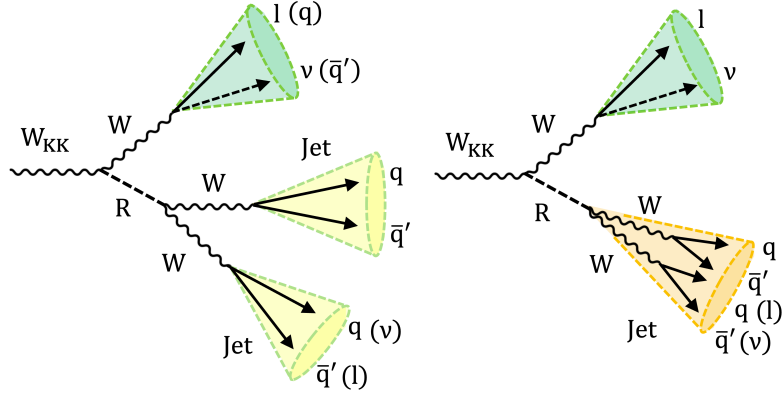


Figure 1: Schematic representation of the decay of a KK excitation W_{KK} to the final states considered in this analysis. Left: three individually reconstructed W bosons with resolved R ; right: one individually reconstructed W boson and two merged W bosons reconstructed as a single large-radius jet.

calorimeters, operating inside a 3.8 T superconducting solenoid, with data from gas-ionization muon detectors interleaved with the solenoid return yoke, to build τ leptons, jets, $p_{\text{T}}^{\text{miss}}$, and other physics objects [36–38].

Signal events are simulated at leading order (LO) using MADGRAPH5_aMC@NLO v2.4.2 [39] with the recommended parameters according to Refs. [11–13, 15], i.e., the KK gravity coupling $g_{\text{grav}} = 6$, the KK gauge couplings $g_{W_{\text{KK}}} = 3$ and $g_{Z_{\text{KK}}} = 6.708$, and the confinement parameter $\epsilon = 0.5$. In the two-dimensional parameter space, W_{KK} masses $m_{W_{\text{KK}}}$ from 1.5 to 5.0 TeV and R masses m_R from 6 to 90% of $m_{W_{\text{KK}}}$ are covered. The decay branching fraction of $W_{\text{KK}} \rightarrow WR \rightarrow WWW$ for these parameters typically exceeds 50% [13]. For the background simulation, $t\bar{t}$ production is modeled at next-to-LO (NLO) with POWHEG v2 [40]. Quantum chromodynamics multijet production and W + jets production are simulated at LO with MADGRAPH5_aMC@NLO. The other backgrounds are generated at NLO with MADGRAPH5_aMC@NLO (WW , s -channel single t) and POWHEG (WZ , ZZ , t -channel single t , Wt).

The generated events are interfaced with PYTHIA 8.230 [41] to simulate the fragmentation, parton shower, and hadronization of partons in the initial and final states, along with the underlying event. The same simulation settings as for Ref. [18], where further details can be found, have been used. The interactions of all final-state particles with the CMS detector are simulated using GEANT4 [42]. Simulated events include the contribution of particles from additional pp interactions within the same or nearby bunch crossings (pileup) and are corrected to reproduce the distribution of the number of pileup interactions observed in data.

The events are collected with single-electron or single-muon triggers [29, 30] and then undergo global event reconstruction based on the PF algorithm [35]. The PF candidates are corrected for the effect of pileup [43], and are clustered into jets with the anti- k_{T} algorithm [44] as implemented in the FASTJET package [45]. Two distance parameters are used: 0.4 for AK4 jets and 0.8 for large-radius AK8 jets. The AK4 jets are required to be well separated from any selected AK8 jet with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.8$, where η is the pseudorapidity and ϕ the azimuthal angle. The quantity $p_{\text{T}}^{\text{miss}}$ is defined as the magnitude of the vector transverse momentum (p_{T}) sum of all reconstructed PF candidates in an event.

The AK4 jets arising from b quark hadronization and decay (b jets) are identified using the deep neural network (DNN) algorithm DEEPCSV, which takes as input tracks that are displaced from the primary vertex, secondary vertices, and jet kinematic variables [46]. A working point

on the output of the DEEPCSV algorithm is chosen such that the efficiency of identifying a b jet is about 65–75%, while the probability of misidentifying a light-flavor (q) or gluon (g) jet as a b jet is about 1%. To identify massive AK8 jets, a “modified mass-drop” correction algorithm [47, 48], known as the “soft-drop” algorithm [49] (with parameters $\beta = 0$ and $z_{\text{cut}} = 0.1$), is applied to remove soft and wide-angle radiation from the jet, and the resulting “groomed jet mass” (m_j) is used.

Events with exactly one isolated e (μ) with $p_T > 55$ GeV and $|\eta_{e(\mu)}| < 2.5$ (2.4) and no second isolated e (μ) with $p_T > 35$ (20) GeV are selected. Furthermore, we require $p_T^{\text{miss}} > 80$ (40) GeV for the e (μ) channel. The p_T of the reconstructed leptonically decaying W boson candidate must exceed 200 GeV. The neutrino is reconstructed as in Ref. [50] using p_T^{miss} and requiring the effective mass of the $\ell\nu$ system to be consistent with the W boson mass. Jets overlapping with the selected isolated lepton within $\Delta R_{j\ell} < 1.0$ are removed. Selected events need to have one or two AK8 jets with $p_T^j > 200$ GeV and $|\eta^j| < 2.4$. For events with only one jet, m_j is required to be greater than 60 GeV, while for events with two jets the jet with maximum m_j is required to have $60 < m_j^{\text{max}} < 100$ GeV and the other jet mass is referred to as m_j^{min} . Events with identified b jets or more than two AK4 jets are vetoed. The scalar p_T sum of the reconstructed leptonically decaying W boson and the selected AK8 jets is required to be greater than 1 TeV. The invariant mass of the reconstructed $\ell\nu$ +jet(s) system, $m_{j\ell\nu}$ or $m_{jj\ell\nu}$ for one or two selected AK8 jets, respectively, must exceed 1.1 TeV.

Several different radion decay topologies are considered. A collimated radion decay into two merged hadronic W boson jets ($R \rightarrow WW \rightarrow 4q$) yields a single jet containing the decay products of either all four quarks (designated as R^{4q}) or only three of them (R^{3q}). A merged radion decay with one of the W bosons decaying leptonically ($R \rightarrow WW \rightarrow \ell\nu qq$) yields a jet containing the decay products of two quarks from the $W \rightarrow q\bar{q}'$ decay as well as an overlapping nonisolated charged lepton. This topology is designated as $R^{\ell qq}$. In rare cases where the decay $R \rightarrow WW \rightarrow \ell\nu qq$ results in a lepton that still fulfills the isolation criteria even though it is overlapping with a jet, we remove the overlapping jet and consider the only remaining jet to correspond to the W boson from the W_{KK} resonance decay. Possibilities other than these contribute less than 5% of the signal yield and therefore are not considered.

To increase discrimination of signal from background, the substructure of the selected AK8 jets is analyzed using the DNN-based DEEPAK8 jet classification algorithm [51]. This algorithm has been trained using simulated events to identify hadronic decays of W and Higgs bosons (H, in the 4q mode), as well as top quarks, based on the reconstructed particles and secondary vertices associated with the corresponding jet. In the default training of the algorithm, the masses of the signal jets are used, and therefore signals with masses different to the ones mentioned above cannot be identified. Thus, we make use of the algorithm’s mass-decorrelated version to identify jets exhibiting substructure compatible with a merged radion decay (R^{4q} , R^{3q} , $R^{\ell qq}$), but with arbitrary mass. For the identification of merged radion jet candidates, we combine the algorithm’s outputs to simultaneously discriminate $W \rightarrow q\bar{q}'$ jets and signal jets similar to $H \rightarrow WW \rightarrow 4q$ from jets originating from the hadronization of a q or g. We call the resulting discriminants for merged radion decays “deep-WH”, and for W bosons “deep-W”. Similarly, a discriminant named “deep-t” is formed to distinguish top quarks from q/g jets. The DEEPAK8 discriminant values peak towards unity for the selected type of jets and towards zero for the rejected q/g background jets. A detailed description of these variables together with their performance for different jet types can be found in Ref. [18].

Using the jet mass and the deep-WH and deep-W discriminants, selected events are split into six SRs based on the signal topology. Jets with $m_j > 100$ GeV ($60 < m_j < 100$ GeV) are con-

sidered as radion (W boson) candidates and thus required to pass a deep-WH (deep-W) selection, while for lower-mass jets with $m_j < 60$ GeV no such condition is applied. For events with one selected jet, targeting the merged radion jet topology, three regions (SR1–3) are defined using different m_j windows of 60–100, 100–200, and >200 GeV, respectively. For SR1 (SR2–3), we additionally demand deep-W > 0.7 (deep-WH > 0.7). Events with two jets, considered as candidates for the resolved radion topology, are categorized into SR4–6 as follows. The SR4 (SR5) categories have both jets with $60 < m_j < 100$ GeV and require exactly two (one) jets with deep-W > 0.5 . Events with $60 < m_j^{\max} < 100$ GeV and deep-W > 0.7 for the higher-mass jet and $m_j^{\min} < 60$ GeV for the lower-mass jet are placed in SR6. Requiring deep-W (deep-WH) > 0.7 results in a background rejection of approximately 74 (67)%, while maintaining a signal selection efficiency of about 65 (70)%.

The deep-W and deep-WH variables are both calibrated in the same data regions enriched in SM W + jets and top quark events. To serve as proxies, the SM events are split into various W , q/g , and top quark categories mimicking the signal decay structure. Both signal and proxy jets are categorized by geometrically matching parton-level information to the reconstructed jets. Jets from single W boson decays in SM events are used as proxy jets for resolved signal and merged $R^{\ell q q}$ events. As there is no direct correspondence to any SM event topology for R^{4q} and R^{3q} events, fully merged top quark jets ($t \rightarrow bqq$) serve as proxies in this case. By performing a simultaneous fit of the proxy templates to the data in regions with different relative compositions, we derive corresponding scale factors (SFs) and associated uncertainties. These SFs are applied per matched jet category to correct selection efficiencies in simulation for the deep-W and deep-WH spectra. This calibration procedure is validated in various jet samples. The detailed procedure is presented in Ref. [18].

The main backgrounds, W + jets and $t\bar{t}$ production, are estimated using CRs. The $t\bar{t}$ CRs are defined by inverting the b jet veto, removing the deep-W (deep-WH) discriminant selection criteria defined for the SRs, and allowing for up to four additional AK4 jets to increase the number of selected events. Similarly, for the W + jets CRs, the deep-W (deep-WH) selection criteria are inverted, and $t\bar{t}$ events are vetoed by requiring deep- $t < 0.4$. All other backgrounds are estimated using simulation and are subtracted from the data for this procedure. A linear fit is performed to the ratio of the data to the background of interest (W + jets or $t\bar{t}$), using the $m_{j\ell\nu}$ or $m_{jj\ell\nu}$ distributions, depending on the region, to extract a correction function for the background shape and normalization in the corresponding SR.

The final signal and background yields are determined simultaneously by performing a maximum likelihood fit to the $m_{j\ell\nu}$ and $m_{jj\ell\nu}$ distributions in data for SR1–3 and SR4–6, respectively. Systematic uncertainties affecting signal and background yields are treated as nuisance parameters and profiled in the statistical interpretation using log-normal and Gaussian constraints for rate and shape uncertainties, respectively.

Uncertainties in the background normalization and shape are derived from the data in the CRs. In particular, the statistical uncertainty in the CR fits to the $m_{j\ell\nu}$ and $m_{jj\ell\nu}$ distributions is propagated to the SRs through constraints on modeling parameters common to the SR and CR. Both rate and shape uncertainties are evaluated separately for the W + jets and top quark backgrounds, and are treated as uncorrelated across the SRs.

Several uncertainties are taken into account for the DEEPAK8 discriminants and are evaluated as functions of m_j and p_T^j . Residual differences between data and simulation observed in the validation regions result in a 10% uncertainty for all jet types. Additional uncertainties are derived by considering an alternative parton shower simulation and evaluating the effect on the

SFs for signal and background jets. Since the objects used in the calibration procedure have a similar decay structure to the signal, but can exhibit features such as different color flow and quark flavor that affect the DEEPAK8 performance, additional uncertainties are considered for the signal. These uncertainties are evaluated based on the shape differences between signal and SM proxy jets in the deep-W and deep-WH spectra. They amount to 10–40% for $R^{\ell qq}$, R^{3q} and R^{4q} events, and to 100% for signal events not matching these categories. To further account for the different p_T^j regimes of signal and proxy jets used in the derivation of the SFs, signal events are simulated with the HERWIG 2.7 parton shower program [52]. The resulting differences in the SR yields of up to 25% are assigned as rate uncertainties. A detailed description of the uncertainty evaluation procedure can be found in Ref. [18]. Uncertainties due to pileup, integrated luminosity, trigger, lepton reconstruction, parton distribution functions (PDFs), renormalization and factorization scales, and jet energy scale and resolution, largely affecting signal only, are in total found to be less than 3% in the rate. They have negligible effect on the shape of the $\ell\nu$ +jets mass distributions.

The results of this search are statistically combined with those from the search in the fully hadronic final state [18]. The SF uncertainties are treated as correlated among the two channels. Uncertainties in pileup modeling, PDFs, renormalization and factorization scales, as well as the jet energy scale and resolution are also treated as correlated. All other uncertainties are treated as uncorrelated.

The background-only post-fit distribution of the reconstructed $\ell\nu$ +jets system $m_{jj\ell\nu}$ for the most sensitive region for the resolved signal, SR4, is shown in Fig. 2. The results for the six SRs of this search are presented in the form of pull distributions $[(\text{Data} - \text{Prediction}) / \sigma_{\text{stat}}]$ of the background-only fit in Fig. 3. Selected signals have been added on top of the background. The data are consistent with the background expectation.

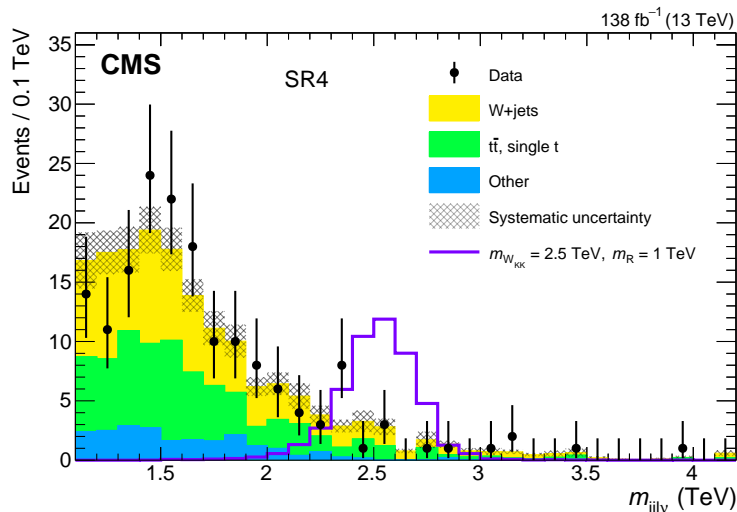


Figure 2: Background-only post-fit distribution of the reconstructed $\ell\nu$ +jets system $m_{jj\ell\nu}$ in data and simulation for SR4. The shape of a triboson signal with $m_{W_{KK}} = 2.5$ TeV and $m_R = 1$ TeV is also shown as a violet solid line, normalized to the theoretical production cross section.

The asymptotic approximation [53] of the CL_s technique [54, 55] is used to set limits. The lower mass limits at 95% confidence level (CL) of the $\ell\nu$ +jets analysis are shown in Fig. 4. An excess of events in data around $m_{jj\ell\nu} = 3.5$ TeV in SR6 results in a weaker than expected observed limit for the resolved signal. For the combination with the fully hadronic analysis [18], lower mass limits are also shown as well as upper limits on the product of the signal cross section

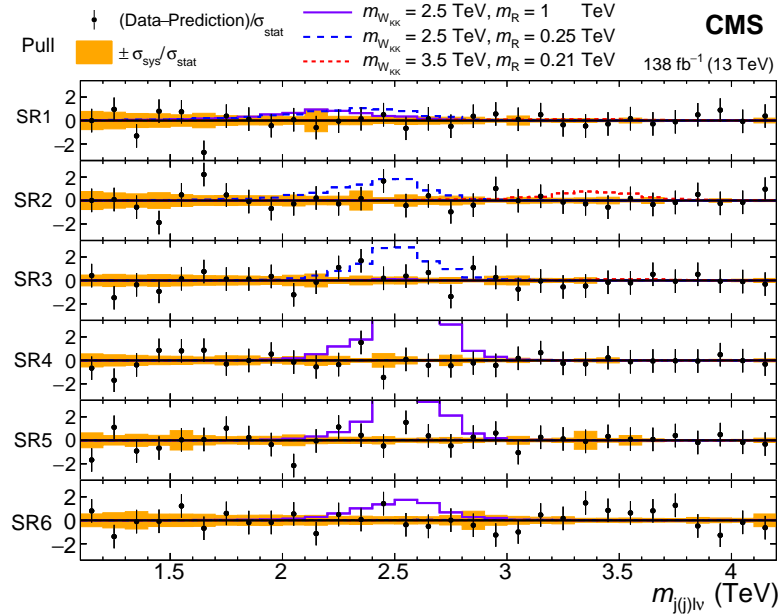


Figure 3: Pull distributions showing $(\text{Data}-\text{Prediction})/\sigma_{\text{stat}}$ of the background-only fit to the reconstructed $\ell\nu$ +jets system $m_{j\ell\nu}$ or $m_{jj\ell\nu}$ for all SRs, where σ_{stat} is the statistical uncertainty. Post-fit systematic uncertainties are indicated by the shaded bands. Examples of signal scenarios normalized to their theoretical production cross section are shown using solid, dashed, and dotted lines.

and the branching fraction to three W bosons for a resonance with decay width significantly smaller than the detector resolution. For radion masses between 0.2 and 1.2 TeV, triboson resonances are excluded up to $m_{W_{\text{KK}}} = 3.3$ and 3.7 TeV by the $\ell\nu$ +jets analysis and the combination, respectively.

In summary, a search has been presented for resonances decaying in cascade through $W_{\text{KK}} \rightarrow WR$ and $R \rightarrow WW$ to three W bosons, where W_{KK} is a massive Kaluza–Klein excitation of a gauge boson and R is a scalar radion. The analysis is performed using proton-proton collision data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} . The final states considered contain one isolated charged lepton, missing transverse momentum, and one or two massive large-radius jets. Radion decay configurations with two W bosons merged in a single jet and those with two separated W boson jets are simultaneously probed by combining jet substructure algorithms. These novel radion identification and calibration techniques are also applicable to Lorentz-boosted Higgs boson decays. Results agree with the predictions of the standard model and are combined with those of the analysis in the fully hadronic final state [18]. Limits are set on an extended warped extra-dimensional model. These are the first searches for the production of TeV-scale triboson resonances at the LHC.

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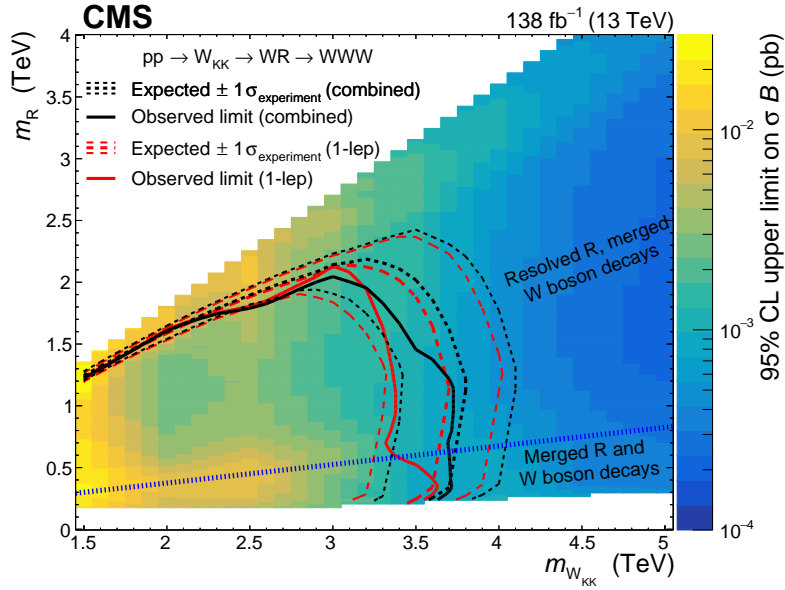


Figure 4: Observed upper limits at 95% CL on the product of the signal cross section and the branching fraction ($\sigma\mathcal{B}$) to three W bosons as functions of the W_{KK} and R resonance masses. Expected (dashed lines) and observed (solid lines) lower mass limits are shown as well for the particular parameters of the explored model. The blue straight dashed line indicates the border between merged and resolved radion cases. The limits obtained from this analysis are shown in red, and the results of the combination with Ref. [18] are shown in black.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth¹, M. Jeitler¹ , N. Krammer, L. Lechner , D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck¹ , R. Schöfbeck , M. Spanring , S. Templ , W. Waltenberger , C.-E. Wulz¹ 

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko 













Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish², E.A. De Wolf, T. Janssen , T. Kello³, A. Lelek , H. Rejeb Sfar, P. Van Mechelen , S. Van Putte, N. Van Remortel 




Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman , E.S. Bols , J. D'Hondt , J. De Clercq , M. Delcourt, H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, P. Van Mulders













Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin , B. Clerbaux , G. De Lentdecker, L. Favart , A. Grebenyuk, A.K. Kalsi , K. Lee, M. Mahdavihorrani, I. Makarenko , L. Moureaux , L. Pétéré, A. Popov , N. Postiau, E. Starling , L. Thomas , M. Vanden Bemden, C. Vander Velde , P. Vanlaer , D. Vannerom , L. Wezenbeek

Ghent University, Ghent, Belgium

T. Cornelis , D. Dobur, J. Knolle , L. Lambrecht, G. Mestdach, M. Niedziela , C. Roskas, A. Samalan, K. Skovpen , M. Tytgat , W. Verbeke, B. Vermassen, M. Vit















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

A. Bethani , G. Bruno, F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel, Sa. Jain , V. Lemaître, K. Mondal , J. Prisciandaro, A. Taliercio, M. Teklishyn , T.T. Tran, P. Vischia , S. Wertz 

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , C. Hensel, A. Moraes 

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. Chinellato⁴, E.M. Da Costa , G.G. Da Silveira⁵ , D. De Jesus Damiao , S. Fonseca De Souza , D. Matos Figueiredo, C. Mora Herrera , K. Mota Amarilo, L. Mundim , H. Nogima, P. Rebello Teles , A. Santoro, S.M. Silva Do Amaral , A. Sznajder , M. Thiel, F. Torres Da Silva De Araujo , A. Vilela Pereira 

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

C.A. Bernardes⁵ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D.S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 

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


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

G. Sultanov





University of Sofia, Sofia, Bulgaria

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












Beihang University, Beijing, China

T. Cheng , Q. Guo, T. Javaid⁶, M. Mittal, H. Wang, L. Yuan





Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer, C. Dozen⁷ , Z. Hu , J. Martins⁸ , Y. Wang, K. Yi^{9,10}


Institute of High Energy Physics, Beijing, China

E. Chapon , G.M. Chen⁶ , H.S. Chen⁶ , M. Chen , F. Iemmi, A. Kapoor , D. Leggat, H. Liao, Z.-A. Liu⁶ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker, J. Wang , H. Zhang , S. Zhang⁶, J. Zhao 


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

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin , Q. Li , X. Lyu, Y. Mao, S.J. Qian, D. Wang , Q. Wang , J. Xiao

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You 





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

X. Gao³, H. Okawa 



Zhejiang University, Hangzhou, China, Zhejiang, China

Z. Lin , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , A. Cabrera , C. Florez , J. Fraga, A. Sarkar , M.A. Segura Delgado


Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez , C.A. Salazar González 

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac 


Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic , D. Ferencek , D. Majumder , M. Roguljic, A. Starodumov¹¹ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou, E. Erodoutou, A. Ioannou, G. Kole , M. Kolosova, S. Konstantinou, J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis, H. Rykaczewski, H. Saka 


Charles University, Prague, Czech Republic

M. Finger¹², M. Finger Jr.¹² , A. Kveton


Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala



Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 




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

A.A. Abdelalim^{13,14} , Y. Assran^{15,16}






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

A. Lotfy , M.A. Mahmoud 

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal , L. Tani, 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

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














Lappeenranta University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow, T. Tuuva

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

C. Amendola , M. Besancon, F. Couderc , M. Dejardin, D. Denegri, J.L. Faure, F. Ferri , S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault , P. Jarry, B. Lenzi , E. Locci, J. Malcles, J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷, M. Titov , G.B. Yu 













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

S. Ahuja , F. Beaudette , M. Bonanomi , A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne , S. Ghosh, R. Granier de Cassagnac , A. Hakimi, I. Kucher , M. Nguyen , C. Ochando , P. Paganini , J. Rembser, R. Salerno , J.B. Sauvan , Y. Sirois , A. Zabi, A. Zghiche 

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

J.-L. Agram¹⁸ , J. Andrea, D. Apparau, D. Bloch , G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard , D. Darej, J.-C. Fontaine¹⁸, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira , P. Van Hove 



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

E. Asilar , S. Beauceron , C. Bernet , G. Boudoul, C. Camen, A. Carle, N. Chanon , D. Contardo, P. Depasse , H. El Mamouni, J. Fay, S. Gascon , M. Gouzevitch , B. Ille, I.B. Laktineh, H. Lattaud , A. Lesauvage , M. Lethuillier , L. Mirabito, S. Perries, K. Shchablo, V. Sordini , L. Torterotot , G. Touquet, M. Vander Donckt, S. Viret






Georgian Technical University, Tbilisi, Georgia

I. Lomidze, T. Toriashvili¹⁹, Z. Tsamalaidze¹²

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

L. Feld , K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, N. Röwert, J. Schulz, M. Teroerde 

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


































A. Dodonova, D. Eliseev, M. Erdmann , P. Fackeldey , B. Fischer, S. Ghosh , T. Hebbeker , K. Hoepfner, F. Ivone, H. Keller, L. Mastrolorenzo, M. Merschmeyer 

A. Meyer , G. Mocellin, S. Mondal, S. Mukherjee , D. Noll , A. Novak, T. Pook , A. Pozdnyakov , Y. Rath, H. Reithler, J. Roemer, A. Schmidt , S.C. Schuler, A. Sharma , L. Vigilante, S. Wiedenbeck, S. Zaleski





















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

C. Dziwok, G. Flügge, W. Haj Ahmad²⁰ , O. Hlushchenko, T. Kress, A. Nowack , C. Pistone, O. Pooth, D. Roy , H. Sert , A. Stahl²¹ , T. Ziemons 














Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau , S. Baxter, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar , K. Borrás²², V. Botta, D. Brunner, A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva, V. Danilov, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos , O. Filatov , E. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean , M. Guthoff, A. Jafari²⁴ , N.Z. Jomhari , H. Jung , A. Kasem²² , M. Kasemann , H. Kaveh , C. Kleinwort , D. Krücker , W. Lange, J. Lidrych , K. Lipka, W. Lohmann²⁵, R. Mankel, I.-A. Melzer-Pellmann , J. Metwally, A.B. Meyer , M. Meyer , J. Mnich , A. Mussgiller, Y. Otari, D. Pérez Adán , D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham, V. Scheurer, C. Schwanenberger²³ , A. Singh, R.E. Sosa Ricardo , D. Stafford, N. Tonon , O. Turkot , M. Van De Klundert , R. Walsh , D. Walter, Y. Wen , K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl 

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Albrecht , S. Bein , L. Benato , A. Benecke, P. Connor , K. De Leo , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, J. Haller , A. Hinzmann , G. Kasieczka, R. Klanner , R. Kogler , T. Kramer, V. Kutzner, J. Lange , T. Lange , A. Lobanov , A. Malara , A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder , J. Schwandt , D. Schwarz, J. Sonneveld , H. Stadie, G. Steinbrück, A. Tews, B. Vormwald , I. Zoi 





Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel , T. Berger, E. Butz , R. Caspart , T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann , M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann²¹ , C. Heidecker, U. Husemann , I. Katkov²⁶, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra , Th. Müller, M. Neukum, A. Nürnberg, G. Quast , K. Rabbertz , J. Rauser, D. Savoie , M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich , J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber , S. Wieland, R. Wolf , S. Wozniowski, S. Wunsch


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

G. Anagnostou, G. Daskalakis, T. Geralis , A. Kyriakis, D. Loukas, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis , C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece

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






University of Ioánnina, Ioánnina, Greece

I. Evangelou , C. Foudas, P. Giannelis, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos , J. Strogas 


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

M. Csanad , K. Farkas, M.M.A. Gadallah²⁷ , S. Lökös²⁸ , P. Major, K. Mandal , A. Mehta , G. Pasztor , A.J. Rádl, O. Surányi, G.I. Veres 


Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁹ , G. Bencze, C. Hajdu , D. Horvath³⁰ , F. Sikler , V. Veszpremi , G. Vesztergombi[†]


Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁹ , J. Molnar, Z. Szillasi, D. Teyssier




Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³¹ , B. Ujvari






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

T. Csorgo³² , F. Nemes³², T. Novak











Indian Institute of Science (IISc), Bangalore, India

J.R. Komaragiri , D. Kumar, L. Panwar , P.C. Tiwari 








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

S. Bahinipati³³ , C. Kar , P. Mal, T. Mishra , V.K. Muraleedharan Nair Bindhu³⁴, A. Nayak³⁴ , P. Saha, N. Sur , S.K. Swain, D. Vats³⁴






Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , R. Gupta, A. Kaur, M. Kaur , S. Kaur, P. Kumari , M. Meena, K. Sandeep , J.B. Singh , A.K. Viridi 




University of Delhi, Delhi, India

A. Ahmed, A. Bhardwaj , B.C. Choudhary , M. Gola, S. Keshri , A. Kumar , M. Naimuddin , P. Priyanka , K. Ranjan, A. Shah 




Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³⁶, R. Bhattacharya, S. Bhattacharya , D. Bhowmik, S. Dutta, S. Dutta, B. Gomber³⁷ , M. Maity³⁸, P. Palit , P.K. Rout , G. Saha, B. Sahu , S. Sarkar, M. Sharan, B. Singh³⁶, S. Thakur³⁶


Indian Institute of Technology Madras, Madras, India

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



Bhabha Atomic Research Centre, Mumbai, India

D. Dutta , V. Jha, V. Kumar , D.K. Mishra, K. Naskar³⁹, P.K. Netrakanti, L.M. Pant, P. Shukla 






Tata Institute of Fundamental Research-A, Mumbai, India











































































































T. Aziz, S. Dugad, M. Kumar, U. Sarkar 

Tata Institute of Fundamental Research-B, Mumbai, India

























S. Banerjee , R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee 

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








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

Isfahan University of Technology, Isfahan, IranH. Bakhshiansohi⁴⁰ , M. Zeinali⁴¹**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani⁴², S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi **University College Dublin, Dublin, Ireland**M. Grunewald **INFN Sezione di Bari ^a, Bari, Italy, Università di Bari ^b, Bari, Italy, Politecnico di Bari ^c, Bari, Italy**M. Abbrescia^{a,b} , R. Aly^{a,b,43} , C. Aruta^{a,b}, A. Colaleo^a , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b}, A. Di Pilato^{a,b} , W. Elmetenawee^{a,b} , L. Fiore^a , A. Gelmi^{a,b} , M. Gul^a , G. Iaselli^{a,c} , M. Ince^{a,b} , S. Lezki^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b}, V. Mastrapasqua^{a,b} , J.A. Merlin^a, S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b}, A. Pompili^{a,b} , G. Pugliese^{a,c} , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , R. Venditti^a , P. Verwilligen^a **INFN Sezione di Bologna ^a, Bologna, Italy, Università di Bologna ^b, Bologna, Italy**G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a, L. Brigliadori^a, R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b}, S. Lo Meo^{a,44}, L. Lunerti^{a,b}, S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} **INFN Sezione di Catania ^a, Catania, Italy, Università di Catania ^b, Catania, Italy**S. Albergo^{a,b,45} , S. Costa^{a,b,45} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,45} , C. Tuve^{a,b} **INFN Sezione di Firenze ^a, Firenze, Italy, Università di Firenze ^b, Firenze, Italy**G. Barbagli^a , A. Cassese^a , R. Ceccarelli^{a,b}, V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^{a,b}, M. Meschini^a , S. Paoletti^a , R. Seidita^{a,b}, G. Sguazzoni^a , L. Viliani^a **INFN Laboratori Nazionali di Frascati, Frascati, Italy**L. Benussi , S. Bianco , D. Piccolo **INFN Sezione di Genova ^a, Genova, Italy, Università 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, Milano, Italy, Università di Milano-Bicocca ^b, Milano, Italy**A. Benaglia^a , F. Brivio^{a,b}, F. Ceteorelli^{a,b}, V. Ciriolo^{a,b,21}, F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M. Malberti^a, S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Valsecchi^{a,b,21}, D. Zuolo^{a,b} **INFN Sezione di Napoli ^a, Napoli, Italy, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy**S. Buontempo^a , F. Carnevali^{a,b}, N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b} , S. Meola^{a,d,21} , P. Paolucci^{a,21} , B. Rossi^a , C. Sciacca^{a,b} **INFN Sezione di Padova ^a, Padova, Italy, Università di Padova ^b, Padova, Italy, Università**












di Trento ^c, Trento, Italy

P. Azzi^a , N. Bacchetta^a , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Dosselli^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , S.Y. Hoh^{a,b} , L. Layer^{a,46}, M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , M. Presilla^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b}, F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. YARAR^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b} 




























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

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













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

P. Asenov^{a,47} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , P. Lariccia^{a,b}, M. Magherini^b, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a , F. Moscatelli^{a,47} , A. Piccinelli^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 



































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

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , L. Bianchini^a , T. Boccali^a , E. Bossini^{a,b} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , M.R. Di Domenico^{a,d} , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , E. Manca^{a,c} , G. Mandorli^{a,c} , A. Messineo^{a,b} , F. Palla^a , S. Parolia^{a,b}, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b} , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , A. Venturi^a , P.G. Verdini^a 








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

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









INFN Sezione di Torino ^a, Torino, Italy, 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} , J. Berenguer Antequera^{a,b} , C. Biino^a , N. Cartiglia^a , S. Cometti^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , B. Kiani^{a,b} , F. Legger^a , C. Mariotti^a , S. Maselli^a , E. Migliore^{a,b} , E. Monteil^{a,b} , M. Monteno^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c} , K. Shchelina^{a,b} , F. Siviero^{a,b} , V. Sola^a , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , M. Tornago^{a,b}, D. Trocino^{a,b} , A. Vagnerini

INFN Sezione di Trieste ^a, Trieste, Italy, Università 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} , G. Sorrentino^{a,b}, F. Vazzoler^{a,b} 




Kyungpook National University, Daegu, Korea

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




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

H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

S. Cho, S. Choi , Y. Go, B. Hong , K. Lee, K.S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo





Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea

J. Goh , A. Gurtu

Sejong University, Seoul, Korea

H.S. Kim , Y. Kim

Seoul National University, Seoul, Korea

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


University of Seoul, Seoul, Korea

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

Yonsei University, Department of Physics, Seoul, Korea

S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea

M. Choi, Y. Jeong, H. Lee, Y. Lee, I. Yu 

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

T. Beyrouthy, Y. Maghrbi


Riga Technical University, Riga, Latvia

T. Torims, V. Veckalns⁴⁸ 

Vilnius University, Vilnius, Lithuania

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

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

N. Bin Norjoharuddeen , W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , 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, E. De La Cruz-Burelo , I. Heredia-De La Cruz⁴⁹ , R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera , M. Ramírez García , F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico




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

University of Montenegro, Podgorica, Montenegro








J. Mijuskovic⁵⁰, N. Raicevic

University of Auckland, Auckland, New Zealand


D. Krofcheck 


University of Canterbury, Christchurch, New ZealandS. Bheesette, 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, 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, PolandH. Bialkowska, M. Bluj , B. Boimska , M. Górski, M. Kazana, M. Szeleper , P. Zalewski**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski, K. Doroba, A. Kalinowski , M. Konecki , J. Krolikowski , M. Walczak **Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**M. Araujo, P. Bargassa , D. Bastos, A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad, M. Pisano, J. Seixas , O. Toldaiev , J. Varela **Joint Institute for Nuclear Research, Dubna, Russia**S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov , V. Karjavine, V. Korenkov , A. Lanev, A. Malakhov, V. Matveev^{51,52}, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev⁵³, A. Zarubin, I. Zhizhin**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**G. Gavrilo , V. Golovtsov, Y. Ivanov, V. Kim⁵⁴ , E. Kuznetsova⁵⁵, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov , V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev**Institute for Nuclear Research, Moscow, Russia**Yu. Andreev , A. Dermenev, S. Gninenko , N. Golubev, A. Karneyeu , D. Kirpichnikov , M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov , D. Tlisov[†], A. Toropin**Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia**V. Epshteyn, V. Gavrilo , N. Lychkovskaya, A. Nikitenko⁵⁶, V. Popov, A. Spiridonov, A. Steppenov, 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, RussiaR. Chistov⁵⁷ , M. Danilov⁵⁷ , A. Oskin, P. Parygin, S. Polikarpov⁵⁷ **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 , V. Bunichev, M. Dubinin⁵⁸ , L. Dudko , A. Ershov, A. Gribushin, V. Klyukhin , O. Kodolova , I. Lokhtin , S. Obraztsov, S. Petrushanko, V. Savrin**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov⁵⁹, T. Dimova⁵⁹, L. Kardapoltsev⁵⁹, A. Kozyrev⁵⁹, I. Ovtin⁵⁹, Y. Skovpen⁵⁹ 


**Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’,
Protvino, Russia**

I. Azhgirey , I. Bayshev, D. Elumakhov, 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, V. Okhotnikov




















Tomsk State University, Tomsk, Russia

V. Borshch, V. Ivanchenko , E. Tcherniaev 


**University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences,
Belgrade, Serbia**

P. Adzic⁶⁰ , M. Dordevic , P. Milenovic , J. Milosevic 









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

M. Aguilar-Benitez, J. Alcaraz Maestre , A. Álvarez Fernández, I. Bachiller, M. Barrio Luna,
Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada, N. Colino ,
B. De La Cruz, A. Delgado Peris , J.P. Fernández Ramos , J. Flix , M.C. Fouz ,
O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. León Holgado ,
D. Moran, Á. Navarro Tobar , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo ,
I. Redondo , L. Romero, S. Sánchez Navas, L. Urda Gómez , C. Willmott















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, R. Reyes-Almanza 

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de As-
turias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez , J. Cuevas , C. Erice , J. Fernandez Menendez , S. Folgueras ,
I. Gonzalez Caballero , J.R. González Fernández, E. Palencia Cortezon , C. Ramón Álvarez,
J. Ripoll Sau, V. Rodríguez Bouza , A. Trapote, N. Trevisani 

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

J.A. Brochero Cifuentes , I.J. Cabrillo, A. Calderon , J. Duarte Campderros , M. Fernan-
dez , C. Fernandez Madrazo , P.J. Fernández Manteca , A. García Alonso, G. Gomez,
C. Martinez Rivero, P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas ,
J. Piedra Gomez , C. Prieels, T. Rodrigo , A. Ruiz-Jimeno , L. Scodellaro , I. Vila,
J.M. Vizan Garcia 






















University of Colombo, Colombo, Sri Lanka














M.K. Jayananda, B. Kailasapathy⁶¹, D.U.J. Sonnadara, D.D.C. Wickramarathna

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland








T.K. Aarrestad , D. Abbaneo, J. Alimena , E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†],
D. Barney , J. Bendavid, M. Bianco , A. Bocci , T. Camporesi, M. Capeans Garrido ,
G. Cerminara, S.S. Chhibra , M. Cipriani , L. Cristella , D. d’Enterria , A. Dabrowski ,
N. Daci , A. David , A. De Roeck , M.M. Defranichis , M. Deile , M. Dobson,
M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁶², D. Fasanella ,
S. Fiorendi , A. Florent , G. Franzoni , W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege,

L. Gouskos , M. Haranko , J. Hegeman , Y. Iiyama , V. Innocente , T. James, P. Janot , J. Kaspar , J. Kieseler , M. Komm , N. Kratochwil, C. Lange , S. Laurila, P. Lecoq , K. Long , C. Lourenço , L. Malgeri , S. Mallios, M. Mannelli, A.C. Marini , F. Meijers, S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , L. Pape, E. Perez, M. Peruzzi , A. Petrilli, G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo, M. Pitt , H. Qu , T. Quast, D. Rabady , A. Racz, G. Reales Gutiérrez, M. Rieger , M. Rovere, H. Sakulin, J. Salfeld-Nebgen , S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi , A. Sharma, P. Silva , W. Snoeys , P. Sphicas⁶³ , S. Summers , V.R. Tavolaro , D. Treille, A. Tsirou, G.P. Van Onsem , M. Verzetti , J. Wanczyk⁶⁴, K.A. Wozniak, W.D. Zeuner








Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶⁵ , A. Ebrahimi , W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli , T. Rohe



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

K. Androsov⁶⁴ , M. Backhaus , P. Berger, A. Calandri , N. Chernyavskaya , A. De Cosa, G. Dissertori , M. Dittmar, M. Donegà, C. Dorfer , F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa , C. Grab , D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni , C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela , F. Pauss, V. Perovic, S. Pigazzini , M.G. Ratti , M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic , D. Ruini, D.A. Sanz Becerra , M. Schönenberger , V. Stampf, J. Steggemann⁶⁴ , R. Wallny , D.H. Zhu






Universität Zürich, Zurich, Switzerland

C. AMSLER⁶⁶ , P. Bäertschi, C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier, A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler, A. Jofrehei , B. Kilminster , S. Leontsinis , A. Macchiolo , P. Meiring, V.M. Mikuni , U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz , K. Schweiger , Y. Takahashi



National Central University, Chung-Li, Taiwan

C. Adloff⁶⁷, C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁸ , S.S. Yu








National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao, K.F. Chen , P.H. Chen , W.-S. Hou , Y.y. Li, R.-S. Lu, E. Paganis , A. Psallidas, A. Steen, H.y. Wu, E. Yazgan , P.r. Yu



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

B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 





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

F. Boran , S. Damarseckin⁶⁸, Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁹ , E. Eskut, Y. Guler , E. Gurpinar Guler⁷⁰ , I. Hos⁷¹, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu , G. Onengut, K. Ozdemir⁷², A. Polatoz, A.E. Simsek , B. Tali⁷³, U.G. Tok , S. Turkcapar, I.S. Zorbakir , C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁷⁴, G. Karapinar⁷⁵, K. Ocalan⁷⁶ , M. Yalvac⁷⁷ 


Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi , E. Gülmez , M. Kaya⁷⁸ , O. Kaya⁷⁹, Ö. Özçelik, S. Tekten⁸⁰, E.A. Yetkin⁸¹ 

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁹ , Y. Komurcu, S. Sen⁸² 

Istanbul University, Istanbul, Turkey

S. Cerci⁷³, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁷³ 












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

D. Anthony, E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , J. Goldstein , G.P. Heath, H.F. Heath , M.-L. Holmberg⁸³, L. Kreczko , B. Krikler , S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸⁴ , K. Walkingshaw Pass, R. White





Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁸⁵ , C. Brew , R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt, T. Reis , T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams 









Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , S. Breeze, O. Buchmuller, V. Cepaitis , G.S. Chahal⁸⁶ , D. Colling, P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli , D.G. Monk, J. Nash⁸⁷ , M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott , C. Seez, A. Shtipliyski, A. Tapper , K. Uchida, T. Virdee²¹ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid , L. Teodorescu, S. Zahid 

Baylor University, Waco, Texas, USA

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

Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez














The University of Alabama, Tuscaloosa, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸⁸ , C. West 











Boston University, Boston, Massachusetts, USA

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

Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²², D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁹ , G. Landsberg , K.T. Lau , M. Lukasik, J. Luo , M. Narain, S. Sagir⁹⁰ , E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang

University of California, Davis, Davis, California, USA

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




















University of California, Los Angeles, California, USA

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










University of California, Riverside, Riverside, California, USA

K. Burt, Y. Chen, R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganeli, M. Olmedo Negrete, W. Si , S. Wimpenny, Y. Zhang














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

J.G. Branson, P. Chang , S. Cittolin, S. Cooperstein , N. Deelen , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , D. Gilbert , J. Guiang, R. Kansal , V. Krutelyov , R. Lee, J. Letts , M. Masciovecchio , S. May , M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel, A. Vartak , F. Würthwein , Y. Xiang , A. Yagil 







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

N. Amin, C. Campagnari , M. Citron , A. Dorsett, V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , B. Marsh, H. Mei, M. Oshiro, M. Quinnan , J. Richman, U. Sarica , J. Sheplock, D. Stuart, S. Wang 

California Institute of Technology, Pasadena, California, USA

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














Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews, P. Bryant , T. Ferguson , A. Harilal, C. Liu, T. Mudholkar , M. Paulini , A. Sanchez












































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani, E. MacDonald, R. Patel, A. Perloff , C. Savard, K. Stenson , K.A. Ulmer , S.R. Wagner 














Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , Y. Cheng , D.J. Cranshaw , S. Hogan, J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd, W. Sun , J. Thom , P. Wittich , R. Zou 








Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari, A. Apresyan , A. Apyan , S. Banerjee, 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, M. Cremonesi, K.F. Di Petrillo , V.D. Elvira , Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl , 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 , V. O'Dell, V. Papadimitriou, K. Pedro , C. Pena⁵⁸ , O. Prokofyev, F. Ravera , A. Reinsvold Hall , L. Ristori , B. Schneider , E. Sexton-Kennedy , N. Smith , A. Soha , W.J. Spalding , L. Spiegel, S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk, N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber 







University of Florida, Gainesville, Florida, USA

D. Acosta , P. Avery, D. Bourilkov , L. Cadamuro , V. Cherepanov, F. Errico , R.D. Field, D. Guerrero, B.M. Joshi , M. Kim, E. Koenig, J. Konigsberg , A. Korytov, K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi , J. Sturdy , J. Wang , E. Yigitbasi , X. Zuo















Florida State University, Tallahassee, Florida, USA

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








Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla, T. Elkafrawy⁹¹ , M. Hohlmann , R. Kumar Verma , D. Noonan , M. Rahmani, F. Yumiceva 









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

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

















The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , K. Dilsiz⁹² , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁹³, J. Nachtman, H. Ogul⁹⁴ , Y. Onel , A. Penzo, C. Snyder, E. Tiras⁹⁵ 




Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu, J. Anguiano, C. Baldenegro Barrera , P. Baringer , A. Bean , A. Bylinkin , Z. Flowers, T. Isidori, S. Khalil , J. King, G. Krintiras , A. Kropivnitskaya , M. Lazarovits, C. Lindsey, J. Marquez, N. Minafra , M. Murray , M. Nickel, C. Rogan , C. Royon, R. Salvatico , S. Sanders, E. Schmitz, C. Smith , J.D. Tapia Takaki , Q. Wang , Z. Warner, J. Williams , G. Wilson 

Kansas State University, Manhattan, Kansas, USA

S. Duric, A. Ivanov , K. Kaadze , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam

















Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo, D. Wright







University of Maryland, College Park, Maryland, USA

E. Adams, A. Baden, O. Baron, A. Belloni , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel , A. Skuja , L. Wang, K. Wong 






Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza , I.A. Cali, Y. Chen , M. D'Alfonso , J. Eysermans, C. Freer , G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute , D. Kovalskyi , J. Krupa, Y.-J. Lee , B. Maier, C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland, Z. Shi , G.S.F. Stephans , K. Tatar , J. Wang, Z. Wang , B. Wyslouch 

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, A. Evans , P. Hansen, J. Hiltbrand, Sh. Jain , M. Krohn, Y. Kubota, J. Mans , M. Revering, R. Rusack , R. Saradhy, N. Schroeder , N. Strobbe , M.A. Wadud










University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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






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

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












Northeastern University, Boston, Massachusetts, USA

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






Northwestern University, Evanston, Illinois, USA

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
















University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, A. Das , N. Dev , R. Goldouzian , M. Hildreth, K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence, N. Loukas , D. Lutton, N. Marinelli, I. Mcalister, T. McCauley , F. Meng, K. Mohrman, Y. Musienko⁵¹, R. Ruchti, P. Siddireddy, A. Townsend, M. Wayne, A. Wightman, M. Wolf , M. Zarucki , L. Zygala

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, B. Cardwell, L.S. Durkin , B. Francis , C. Hill , M. Nunez Ornelas , K. Wei, B.L. Winer, B.R. Yates 













Princeton University, Princeton, New Jersey, USA

F.M. Addesa , B. Bonham , P. Das , G. Dezoort, P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich, S. Higginbotham, A. Kalogeropoulos , G. Kopp, S. Kwan , D. Lange, M.T. Lucchini , D. Marlow , K. Mei , I. Ojalvo, J. Olsen , C. Palmer , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg











Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , S. Karmarkar, M. Liu, G. Negro, N. Neumeister , G. Paspalaki, C.C. Peng, S. Piperov , A. Purohit, J.F. Schulte , M. Stojanovic¹⁷, J. Thieman , F. Wang , R. Xiao , W. Xie 







Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar

Rice University, Houston, Texas, USA








A. Baty , M. Decaro, S. Dildick , K.M. Ecklund , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li, B.P. Padley , R. Redjimi, W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang, Y. Zhang 

University of Rochester, Rochester, New York, USA

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

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


B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart,

M. Heindl , O. Karacheban²⁵ , I. Laflotte, A. Lath , R. Montalvo, K. Nash, M. Osherson, S. Salur , S. Schnetzer, S. Somalwar , R. Stone, S.A. Thayil , S. Thomas, H. Wang 




University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Spanier 







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

O. Bouhali⁹⁶ , M. Dalchenko , A. Delgado , R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹⁷, H. Kim , S. Luo , S. Malhotra, R. Mueller, D. Overton, D. Rathjens , A. Safonov 












Texas Tech University, Lubbock, Texas, USA

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


Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns, A. Melo, H. Ni, K. Padeken , F. Romeo , P. Sheldon , S. Tuo, J. Velkovska 













University of Virginia, Charlottesville, Virginia, USA

M.W. Arenton , B. Cox , G. Cummings , J. Hakala , R. Hirosky , M. Joyce , A. Ledovskoy , A. Li, C. Neu , B. Tannenwald , S. White , E. Wolfe 

Wayne State University, Detroit, Michigan, USA

N. Poudyal 

University of Wisconsin - Madison, Madison, WI, Wisconsin, USA

K. Black , T. Bose , J. Buchanan , C. Caillol, S. Dasu , I. De Bruyn , P. Everaerts , F. Fienga , C. Galloni, H. He, M. Herndon , A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala , A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma , W.H. Smith , D. Teague, S. Trembath-Reichert, W. Vetens 

†: Deceased

1: Also at TU Wien, Wien, Austria

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

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

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

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

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

7: Also at Department of Physics, Tsinghua University, Beijing, China

8: Also at UFMS, Nova Andradina, Brazil

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

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

11: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

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

13: Also at Helwan University, Cairo, Egypt

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

15: Also at Suez University, Suez, Egypt

16: Now at British University in Egypt, Cairo, Egypt

17: Also at Purdue University, West Lafayette, Indiana, USA

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

19: Also at Tbilisi State University, Tbilisi, Georgia

-
- 20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
 - 21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
 - 22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
 - 23: Also at University of Hamburg, Hamburg, Germany
 - 24: Also at Isfahan University of Technology, Isfahan, Iran
 - 25: Also at Brandenburg University of Technology, Cottbus, Germany
 - 26: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
 - 27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
 - 28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
 - 29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
 - 30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
 - 31: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
 - 32: Also at Wigner Research Centre for Physics, Budapest, Hungary
 - 33: Also at IIT Bhubaneswar, Bhubaneswar, India
 - 34: Also at Institute of Physics, Bhubaneswar, India
 - 35: Also at G.H.G. Khalsa College, Punjab, India
 - 36: Also at Shoolini University, Solan, India
 - 37: Also at University of Hyderabad, Hyderabad, India
 - 38: Also at University of Visva-Bharati, Santiniketan, India
 - 39: Also at Indian Institute of Technology (IIT), Mumbai, India
 - 40: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
 - 41: Also at Sharif University of Technology, Tehran, Iran
 - 42: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
 - 43: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
 - 44: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
 - 45: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
 - 46: Also at Università di Napoli 'Federico II', Napoli, Italy
 - 47: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
 - 48: Also at Riga Technical University, Riga, Latvia
 - 49: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
 - 50: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
 - 51: Also at Institute for Nuclear Research, Moscow, Russia
 - 52: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
 - 53: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
 - 54: Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
 - 55: Also at University of Florida, Gainesville, Florida, USA
 - 56: Also at Imperial College, London, United Kingdom
 - 57: Also at P.N. Lebedev Physical Institute, Moscow, Russia
 - 58: Also at California Institute of Technology, Pasadena, California, USA
 - 59: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
 - 60: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
 - 61: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
 - 62: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy

- 63: Also at National and Kapodistrian University of Athens, Athens, Greece
- 64: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 65: Also at Universität Zürich, Zurich, Switzerland
- 66: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- 67: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 68: Also at Şırnak University, Şırnak, Turkey
- 69: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 70: Also at Konya Technical University, Konya, Turkey
- 71: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- 72: Also at Piri Reis University, Istanbul, Turkey
- 73: Also at Adiyaman University, Adiyaman, Turkey
- 74: Also at Ozyegin University, Istanbul, Turkey
- 75: Also at Izmir Institute of Technology, Izmir, Turkey
- 76: Also at Necmettin Erbakan University, Konya, Turkey
- 77: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 78: Also at Marmara University, Istanbul, Turkey
- 79: Also at Milli Savunma University, Istanbul, Turkey
- 80: Also at Kafkas University, Kars, Turkey
- 81: Also at Istanbul Bilgi University, Istanbul, Turkey
- 82: Also at Hacettepe University, Ankara, Turkey
- 83: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 84: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 85: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 86: Also at IPPP Durham University, Durham, United Kingdom
- 87: Also at Monash University, Faculty of Science, Clayton, Australia
- 88: Also at Università di Torino, Torino, Italy
- 89: Also at Bethel University, St. Paul, Minneapolis, USA
- 90: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 91: Also at Ain Shams University, Cairo, Egypt
- 92: Also at Bingol University, Bingol, Turkey
- 93: Also at Georgian Technical University, Tbilisi, Georgia
- 94: Also at Sinop University, Sinop, Turkey
- 95: Also at Erciyes University, Kayseri, Turkey
- 96: Also at Texas A&M University at Qatar, Doha, Qatar
- 97: Also at Kyungpook National University, Daegu, Korea