

Observation of the Production of Three Massive Gauge Bosons at $\sqrt{s} = 13$ TeVA. M. Sirunyan *et al.*^{*}
(CMS Collaboration)

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The first observation is reported of the combined production of three massive gauge bosons (VVV with $V = W, Z$) in proton-proton collisions at a center-of-mass energy of 13 TeV. The analysis is based on a data sample recorded by the CMS experiment at the CERN LHC corresponding to an integrated luminosity of 137 fb^{-1} . The searches for individual WWW , WWZ , WZZ , and ZZZ production are performed in final states with three, four, five, and six leptons (electrons or muons), or with two same-sign leptons plus one or two jets. The observed (expected) significance of the combined VVV production signal is 5.7 (5.9) standard deviations and the corresponding measured cross section relative to the standard model prediction is $1.02^{+0.26}_{-0.23}$. The significances of the individual WWW and WWZ production are 3.3 and 3.4 standard deviations, respectively. Measured production cross sections for the individual triboson processes are also reported.

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The production of three massive gauge bosons VVV ($V = W, Z$) in high energy proton-proton (pp) collisions is interesting because the standard model (SM) predictions for these processes involve the non-Abelian character of the theory [1]. In particular, the presence of quadruple gauge boson interactions can be probed through VVV production [2,3]. Triple gauge boson interactions and intermediate Higgs bosons (H) also play a role. If physics beyond the SM is present at mass scales not far above 1 TeV, then cross section measurements for triple gauge boson production might deviate from SM predictions [4–7]. Up to now, such measurements have remained elusive because the production cross sections are low and backgrounds are insurmountable, except for rare leptonic final states. Next-to-leading order (NLO) SM calculations predict cross sections of 509, 354, 91.6, and 37.1 fb for WWW , WWZ , WZZ , and ZZZ production at 13 TeV with uncertainties of approximately 10% [8–12]. These calculations include contributions from the associated production of the Higgs boson with a V boson, where H decays to W^+W^- or ZZ [13–16]. In this analysis, these contributions generally are not the dominant ones, even though the cross section for VH production is relatively large, because the event selections described below have lower acceptances for the off-shell vector boson in $H \rightarrow VV^*$.

This Letter reports the first observation of VVV production in pp collisions at 13 TeV, using a data set

corresponding to an integrated luminosity of 137 fb^{-1} . Recently, the first evidence of VVV production in 13 TeV data was reported by the ATLAS Collaboration [17] following earlier searches for WWW production in 8 TeV ATLAS [18] and 13 TeV CMS data [19]. Five final states are considered (where $\ell = e$ or μ): $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \ell^\pm 2\nu q\bar{q}'$, $W^\pm W^\pm W^\mp \rightarrow \ell^\pm \ell^\pm \ell^\mp 3\nu$, $W^\pm W^\mp Z \rightarrow \ell^\pm \ell^\mp 2\nu \ell^\pm \ell^\mp$, $W^\pm ZZ \rightarrow \ell^\pm \nu 2(\ell^\pm \ell^\mp)$, and $ZZZ \rightarrow 3(\ell^\pm \ell^\mp)$. This corresponds to five exclusive channels: two same-sign (SS) leptons with jets, three (3ℓ), four (4ℓ), five (5ℓ), and six (6ℓ) leptons. Searches in the dilepton and trilepton final states target WWW production; four-lepton events are used to search for WWZ production; and five- and six-lepton events are used to search for WZZ and ZZZ production, respectively.

The data were recorded in 2016–2018 with the CMS detector, whose central feature is a superconducting solenoid of 6 m internal diameter providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events are selected using triggers [20] that require two electrons, two muons, or one electron and one muon passing loose isolation requirements and certain transverse momentum (p_T) thresholds. A detailed description of the detector and definitions of the coordinate system are given in Ref. [21].

The CMS event reconstruction is based on the particle-flow (PF) algorithm [22], which combines information from the tracker, calorimeters, and muon systems to identify charged and neutral hadrons, photons, electrons, and muons,

^{*}Full author list given at the end of the article.

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known collectively as PF candidates. Electrons and muons from V decays, known as prompt leptons, are selected for off-line analysis using standard criteria [23,24]. Events containing τ leptons decaying into charged hadrons are rejected by requiring the absence of isolated tracks aside from selected electrons and muons. The PF candidates are clustered into jets using the anti- k_T algorithm with a distance parameter of 0.4 [25–27]. Jets with $p_T > 20$ GeV and $|\eta| < 5$ are selected for the analysis. Defining the distance between a jet and a selected lepton by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ where ϕ is the azimuthal angle, jets are rejected if $\Delta R < 0.4$. Jets containing the decay of a b quark are identified using the loose working point of the deep combined secondary-vertex b tagging algorithm [28]. To increase the efficiency for identifying low- p_T b hadrons not clustered into jets, a soft b tag object [29] is defined using a track-based secondary vertex reconstruction.

The primary pp interaction vertex is the reconstructed vertex with the largest summed p_T^2 calculated using track-based jets and the associated missing transverse momentum ($\vec{p}_T^{\text{miss}}$), the negative $\vec{p}_T$ sum of those jets [30]. Track-based jets are constructed using only tracks associated with the given vertex. In addition to the primary interaction, other pp interactions (pileup) produce extra charged particles and neutral energy. Only tracks associated with the primary vertex are used. The average neutral energy density from pileup is estimated, and subtracted from the reconstructed jet energies and the energy sum used in the calculation of lepton isolation [31].

The previous search for WWW production [19] is based on sequences of requirements called sequential cuts. In this Letter, that approach is extended to cover all five channels. In addition, motivated by the relatively high yields in the SS, 3ℓ , and 4ℓ channels, multivariate techniques based on boosted decision trees (BDTs) [32–36] are applied that outperform the sequential-cut analyses. Both the sequential-cut and BDT-based analyses are presented.

The acceptances, efficiencies, and kinematic properties of the signal and background processes are determined using a combination of data and simulated events. The POWHEG 2.0 [37–40] and the MadGraph5_aMC@NLO (2.2.2 and 2.4.2) generators [41] are used to generate VVV signal events (including VH), diboson (VV), and single- t background events. The MadGraph5_aMC@NLO generator is used in the leading-order (LO) mode with MLM jet matching [42] to generate SM $t\bar{t}$, $t\bar{t} + X$ ($X = W, Z, H$), $W + \text{jets}$, $Z + \text{jets}$, $W\gamma$, and $W^\pm W^\pm$ events. The most precise cross section calculations available are used to normalize the simulated samples, and usually correspond to either NLO or next-to-NLO accuracy [16,41,43–50]. Parton showering, hadronization, and the underlying event are modeled by PYTHIA (8.205 and 8.230) [51] with parameters set by the CUETP8M1 [52] and CP5 tune [53]. The NNPDF 3.0 [54] and 3.1 [55] parton distribution functions (PDFs) are used in the generation of all simulated samples. Pileup is

simulated and the GEANT4 [56] package is used to mimic the response of the CMS detector.

The SS channel targets WWW production [19] and requires exactly two SS leptons with $p_T > 25$ GeV and one or more jets. The dilepton mass $m_{\ell\ell}$ must exceed 20 GeV. This channel is subdivided into nine signal regions according to the flavors of the leptons ($e^\pm e^\pm$, $e^\pm \mu^\pm$, or $\mu^\pm \mu^\pm$) and the jet content. Events with exactly one jet are denoted “1J.” Events with two or more jets are categorized as “ m_{jj} -in” or “ m_{jj} -out” depending on whether the dijet mass for the two jets closest in ΔR is compatible with the W boson mass ($65 < m_{jj} < 95$ GeV). The background processes fall broadly into three categories. The first category contains trilepton processes with one lepton either not selected or not reconstructed (“lost”). Such backgrounds include WZ and $t\bar{t}Z$ production, which typically have only one prompt neutrino in the final state; they are reduced by requiring $m_T^{\text{max}} > 90$ GeV, where m_T^{max} is the largest transverse mass obtained from $\vec{p}_T^{\text{miss}}$ and any lepton in the event. The second category consists of processes with SS lepton pairs, mainly from $W^\pm W^\pm + \text{jets}$ and $t\bar{t}W^\pm$ production. This contribution is suppressed by requiring $m_{JJ} < 500$ GeV and $|\Delta\eta_{JJ}| < 2.5$ for the two highest- p_T jets. The third category includes $W + \text{jets}$ and $t\bar{t} + \text{jets}$ production where a final-state jet or photon is misidentified as a charged lepton, and is labeled nonprompt. These background contributions are suppressed using strict lepton identification and isolation requirements and by requiring $p_T^{\text{miss}} > 45$ GeV. All backgrounds containing top quarks are further reduced by excluding events with b -tagged jets or soft b tags. The background due to charge mismeasurement in Drell-Yan production is relevant only for dielectron events and is reduced to a negligible level by requiring $|m_{\ell\ell} - m_Z| > 10$ GeV.

The 3ℓ channel, which also targets WWW production, is subdivided according to the number of same-flavor opposite-sign (SFOS) lepton pairs: 0SFOS, 1SFOS, and 2SFOS. At least one lepton is required to have $p_T > 25$ GeV, while the others must have $p_T > 20$ GeV, except in 0SFOS where all three leptons are required to have $p_T > 25$ GeV to reduce contamination from nonprompt leptons. Events in 1SFOS and 2SFOS must contain no jets, whereas the presence of one jet is allowed in 0SFOS. The background sources are similar to those in the SS category. Events with b -tagged jets are excluded to suppress the nonprompt-lepton background from processes involving top quarks. The contribution from triple prompt lepton backgrounds is suppressed by requiring $|m_{\ell\ell} - m_Z| > 20$ GeV and $m_{\ell\ell} > 20$ GeV for all SFOS pairs. Additional background reduction is achieved with the following requirements: if exactly one SFOS lepton pair is found then m_T^{3rd} , defined as the transverse mass calculated from $\vec{p}_T^{\text{miss}}$ and the third lepton that is not one of the SFOS pair, must be larger than 90 GeV; and, for events with no SFOS pairs, $m_T^{\text{max}} > 90$ GeV is required. Background contributions from

nonprompt leptons and converted or misidentified photons are reduced by requiring a large p_T of the three-lepton system $|\vec{p}_T^{3\ell}| > 50$ GeV, and a large azimuthal separation $\Delta\phi(\vec{p}_T^{3\ell}, \vec{p}_T^{\text{miss}}) > 2.5$ between $\vec{p}_T^{\text{miss}}$ and $\vec{p}_T^{3\ell}$. Events with a conversion photon emitted in a Z boson decay are suppressed by requiring $|m_{3\ell} - m_Z| > 10$ GeV where $m_{3\ell}$ is the three-lepton invariant mass.

The 4ℓ channel targets WWZ production. The Z boson is identified through its decay to a SFOS lepton pair with $|m_{\ell\ell} - m_Z| < 10$ GeV. These leptons are required to have $p_T > 25(10)$ GeV for the (sub)leading lepton. The (sub)leading lepton of the remaining non- Z leptons must have $p_T > 25(10)$ GeV. The dominant background comes from ZZ production, so the cases of different-flavor ($e\mu$) and same-flavor ($ee/\mu\mu$) non- Z lepton pairs are handled separately. The non- Z same-flavor invariant mass is required to differ from m_Z by at least 10 GeV. Other background contributions consist of $t\bar{t}Z$, tWZ , $t\bar{t}H$, and WZ events. The rejection of events with b -tagged jets reduces contributions from top quarks and a requirement that $m_{\ell\ell} > 12$ GeV for all opposite-sign lepton pairs suppresses backgrounds from low-mass resonances. The 4ℓ channel is subdivided into seven signal regions: for the $e\mu$ category there are four bins in $m_{\ell\ell}$ and m_{T2} [57], and for the $ee/\mu\mu$ category there are three bins based on $p_T^{4\ell}$ and p_T^{miss} .

The 5ℓ and 6ℓ channels target WZZ and ZZZ production, respectively. Event yields are low because of small cross sections and branching fractions. Since background contributions are low, the selection maximizes the signal efficiency. The two leading leptons are required to have $p_T > 25$ GeV and other leptons must have $p_T > 10$ GeV. Events in the 5ℓ channel are required to contain two SFOS lepton pairs with $|m_{\ell\ell} - m_Z| < 15$ GeV. The background in the 5ℓ channel consists almost entirely of ZZ events with a nonprompt lepton, which is usually an electron. The background is reduced by requiring $m_T > 50$ GeV, where m_T is calculated from $\vec{p}_T^{\text{miss}}$ and that electron. Smaller background contributions arise from $t\bar{t}Z$ and $t\bar{t}H$ production, which are reduced by rejecting events with b -tagged jets. Events in the 6ℓ channel are required to have three SFOS pairs and a six-lepton scalar p_T sum larger than 250 GeV. The small 6ℓ background comes from $t\bar{t}H$ and ZZ production.

Background contributions from sources with a particular number of prompt leptons and no nonprompt leptons in signal regions are estimated using simulations with correction factors, typically near unity, derived from several control regions in data enriched in the main sources of background events. Both the predicted numbers of events and relevant kinematic distributions are compared with observations in control regions to derive the correction factors. The precision of the comparison is used to assess systematic uncertainties in these background contributions. Background contributions from sources with one or more nonprompt leptons cannot be reliably evaluated using simulations, so estimates based on control samples in data

are used instead. These estimates rely on the fact that nonprompt leptons tend to be less isolated than prompt ones. For the SS and 3ℓ channels, following Ref. [19], the contribution of events with a nonprompt lepton is evaluated using a sample of events in which one lepton satisfies loose identification criteria but fails the tight criteria. The number of events in this region determines the estimate of the nonprompt background in the signal region using a transfer factor computed with a separate event sample rich in nonprompt leptons. This transfer factor is the ratio of the number of events that pass the tight selection criteria to those that pass the loose criteria. For the 5ℓ channel, a sample of events with three prompt leptons and one nonprompt lepton is dominated by WZ production and used to verify the prediction of background contributions with nonprompt leptons. Nonprompt leptons are a minor background for all other channels.

The signal strength μ , defined as the measured production cross section times branching fraction divided by the expected SM value, is determined through simultaneous fits to all twenty-one signal regions. In one version of the fit, four independent signal strengths (μ_{WWW} , μ_{WWZ} , μ_{WZZ} , and μ_{ZZZ}) are used. In the other version, a common signal strength μ_{comb} is used for all four processes.

The most important sources of systematic uncertainty involve the estimation of background contributions; the uncertainties range from 5% to 25% and come mainly from limited statistical precision in the control regions. The uncertainties in the nonprompt background estimates from control samples in data also contribute significantly at 50%. Uncertainties related to trigger efficiencies, lepton identification and energy resolution, jet energy scale, and b -jet tagging efficiency range from 1% to 9%. A 2.3%–2.5% uncertainty in the integrated luminosity is assessed [58–60]. Uncertainties due to limitations of the theory include missing higher-order corrections (2%–14%), PDF uncertainties (2%–7%), and the strong coupling α_s (1%). Theoretical and experimental uncertainties are correlated across different channels. Statistical uncertainties are much larger than systematic ones. The expected significance of the combined VVV production signal based on the sequential-cut selection is 5.4 standard deviations (s.d.), and the observed significance is 5.0 s.d. The observed (expected) significances for the individual triboson production processes are 2.5 (2.9) s.d. for WWW , 3.5 (3.6) s.d. for WWZ , 1.6 (0.7) s.d. for WZZ , and 0.0 (0.9) s.d. for ZZZ .

The discrimination of signal and background events in the SS, 3ℓ , and 4ℓ channels is enhanced by using BDTs. The training and optimization of the BDTs is carried out for each channel using simulated background and signal events. A minimum value of each BDT output variable substitutes for the categorizations of events and the kinematic requirements applied in the sequential-cut analyses. In the SS and 3ℓ channels, two separate BDTs are trained: the first one to separate the signal from the nonprompt

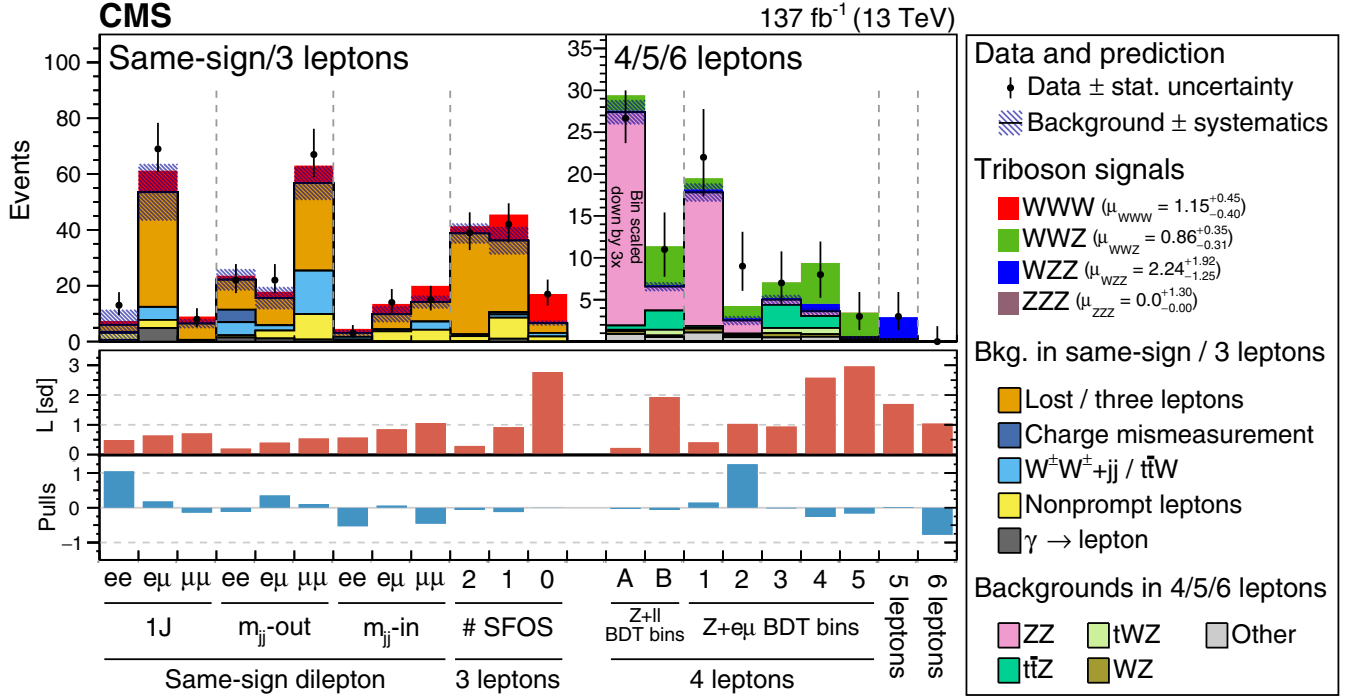


FIG. 1. Comparison of the observed numbers of events to the predicted yields after fitting. For the WWW and WWZ channels, the results from the BDT-based selections are used. The VVV signal is shown stacked on top of the total background. The points represent the data and the error bars show the statistical uncertainties. The expected significance L in the middle panel represents the number of standard deviations (s.d.) with which the null hypothesis (no signal) is rejected; it is calculated for the fit for μ_{comb} . The lower panel shows the pulls for the fit result.

background and the second one to separate the signal from the rest of the background. These two BDTs are applied sequentially. In the 4ℓ channel, a similar strategy is pursued except that the two BDTs are targeted against ZZ and $t\bar{t}Z$ backgrounds specifically. There are two (five) signal regions for events in the $ee/\mu\mu$ ($e\mu$) category. The improvement in sensitivity due to the use of BDTs varies channel by channel and is in the range 5%–15%. No BDTs are used for the 5ℓ and 6ℓ channels.

The yields in the individual signal regions obtained using the BDTs are shown in Fig. 1. The significances L of the expected numbers of events are computed including systematic uncertainties and are evaluated under the asymptotic approximation [61]. Pulls are the differences in the numbers of observed and predicted events normalized to the uncertainties in the numbers of predicted events. Assuming the SM production of VVV events, the expected significance of the fit with a single signal strength μ_{comb} is 5.9 s.d. and the observed significance is 5.7 s.d. The observed (expected) significances for the individual triboson production processes are 3.3 (3.1) s.d. for WWW , 3.4 (4.1) s.d. for WWZ , 1.7 (0.7) s.d. for WZZ , and 0.0 (0.9) s.d. for ZZZ . In the most sensitive signal regions, approximately one third of the VVV events come from VH production. The measured signal strengths, obtained in the asymptotic approximation of the CL_s method [61], correspond to the total cross sections listed in Table I; leptonic

branching fractions for W and Z decays come from Ref. [62]. If VH is considered as a background, then the combined observed (expected) significance for μ_{comb} is 2.9 (3.5) s.d. and the measured cross sections are listed in Table I. For ZZZ production, upper limits are reported at 95% confidence level. Signal strengths obtained using both sequential-cut and BDT-based approaches and with VH production counted as signal are summarized in Fig. 2.

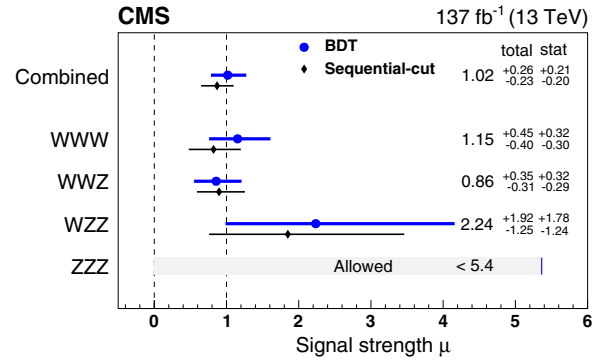


FIG. 2. Best fit values of the signal strengths for the BDT-based analyses (blue solid circles) and the sequential-cut analyses (black solid diamonds). The error bars represent the total uncertainty. For ZZZ production, a 95% confidence level upper limit is shown. The stated numerical values correspond to the BDT-based analysis.

TABLE I. Measured cross sections obtained with the BDT-based analyses. The uncertainties listed are statistical and systematic. For the results listed in the middle (right) column of the table, Higgs boson contributions are counted as signal (background). The VVV cross section is calculated from the fit for μ_{comb} . For ZZZ production, 95% confidence level upper limits are reported.

Process	Cross section (fb)	
	Treating Higgs boson contributions as	
	Signal	Background
VVV	$1010^{+210+150}_{-200-120}$	$370^{+140+80}_{-130-60}$
WWW	$590^{+160+160}_{-150-130}$	$190^{+110+80}_{-100-70}$
WWZ	$300^{+120+50}_{-100-40}$	100^{+80+30}_{-70-30}
WZZ	$200^{+160+70}_{-110-20}$	$110^{+100+30}_{-70-10}$
ZZZ	< 200	< 80

In summary, proton-proton collision data at $\sqrt{s} = 13$ TeV recorded with the CMS experiment and amounting to 137 fb^{-1} were used to observe the production of three massive gauge bosons. The significance of the observation is 5.7 standard deviations (s.d.) with 5.9 s.d. expected. For WWW (WWZ) production, the observed significance is 3.3 (3.4) s.d. compatible with 3.1 (4.1) s.d. expected. Measured cross sections for WWW , WWZ , and WZZ production and an upper limit for ZZZ production are in agreement with the expectations of the standard model. This Letter documents the evidence for WWW and WWZ production and the first observation of the combined production of three massive gauge bosons.

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L. Forthomme,³³ H. Kirschenmann,³³ K. Osterberg,³³ M. Voutilainen,³³ E. Brücken,³⁴ F. Garcia,³⁴ J. Havukainen,³⁴
 V. Karimäki,³⁴ M. S. Kim,³⁴ R. Kinnunen,³⁴ T. Lampén,³⁴ K. Lassila-Perini,³⁴ S. Laurila,³⁴ S. Lehti,³⁴ T. Lindén,³⁴
 H. Siikonen,³⁴ E. Tuominen,³⁴ J. Tuominiemi,³⁴ P. Luukka,³⁵ T. Tuuva,³⁵ M. Besancon,³⁶ F. Couderc,³⁶ M. Dejjardin,³⁶
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 B. Lenzi,³⁶ E. Locci,³⁶ J. Malcles,³⁶ J. Rander,³⁶ A. Rosowsky,³⁶ M. Ö. Sahin,³⁶ A. Savoy-Navarro,^{36,p} M. Titov,³⁶
 G. B. Yu,³⁶ S. Ahuja,³⁷ C. Amendola,³⁷ F. Beaudette,³⁷ M. Bonanomi,³⁷ P. Busson,³⁷ C. Charlot,³⁷ O. Davignon,³⁷ B. Diab,³⁷
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 P. Paganini,³⁷ J. Rembser,³⁷ R. Salerno,³⁷ J. B. Sauvan,³⁷ Y. Sirois,³⁷ A. Zabi,³⁷ A. Zghiche,³⁷ J.-L. Agram,^{38,q} J. Andrea,³⁸
 D. Bloch,³⁸ G. Bourgatte,³⁸ J.-M. Brom,³⁸ E. C. Chabert,³⁸ C. Collard,³⁸ J.-C. Fontaine,^{38,q} D. Gelé,³⁸ U. Goerlach,³⁸
 C. Grimault,³⁸ A.-C. Le Bihan,³⁸ P. Van Hove,³⁸ E. Asilar,³⁹ S. Beauceron,³⁹ C. Bernet,³⁹ G. Boudoul,³⁹ C. Camen,³⁹
 A. Carle,³⁹ N. Chanon,³⁹ D. Contardo,³⁹ P. Depasse,³⁹ H. El Mamouni,³⁹ J. Fay,³⁹ S. Gascon,³⁹ M. Gouzevitch,³⁹ B. Ille,³⁹
 Sa. Jain,³⁹ I. B. Laktineh,³⁹ H. Lattaud,³⁹ A. Lesauvage,³⁹ M. Lethuillier,³⁹ L. Mirabito,³⁹ L. Torterotot,³⁹ G. Touquet,³⁹
 M. Vander Donckt,³⁹ S. Viret,³⁹ T. Toriashvili,^{40,r} Z. Tsamalaidze,^{40,l} L. Feld,⁴¹ K. Klein,⁴¹ M. Lipinski,⁴¹ D. Meuser,⁴¹
 A. Pauls,⁴¹ M. Preuten,⁴¹ M. P. Rauch,⁴¹ J. Schulz,⁴¹ M. Teroerde,⁴¹ D. Eliseev,⁴² M. Erdmann,⁴² P. Fackeldey,⁴²
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 P. Millet,⁴² G. Mocellin,⁴² S. Mondal,⁴² S. Mukherjee,⁴² D. Noll,⁴² A. Novak,⁴² T. Pook,⁴² A. Pozdnyakov,⁴² T. Quast,⁴²
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 S. Zaleski,⁴² C. Dziwok,⁴³ G. Flügge,⁴³ W. Haj Ahmad,^{43,s} O. Hlushchenko,⁴³ T. Kress,⁴³ A. Nowack,⁴³ C. Pistone,⁴³
 O. Pooth,⁴³ D. Roy,⁴³ H. Sert,⁴³ A. Stahl,^{43,t} T. Ziemons,⁴³ H. Aarup Petersen,⁴⁴ M. Aldaya Martin,⁴⁴ P. Asmuss,⁴⁴
 I. Babounikau,⁴⁴ S. Baxter,⁴⁴ O. Behnke,⁴⁴ A. Bermúdez Martínez,⁴⁴ A. A. Bin Anuar,⁴⁴ K. Borrás,^{44,u} V. Botta,⁴⁴
 D. Brunner,⁴⁴ A. Campbell,⁴⁴ A. Cardini,⁴⁴ P. Connor,⁴⁴ S. Consuegra Rodríguez,⁴⁴ V. Danilov,⁴⁴ A. De Wit,⁴⁴
 M. M. Defranchis,⁴⁴ L. Didukh,⁴⁴ D. Domínguez Damiani,⁴⁴ G. Eckerlin,⁴⁴ D. Eckstein,⁴⁴ T. Eichhorn,⁴⁴ A. Elwood,⁴⁴
 L. I. Estevez Banos,⁴⁴ E. Gallo,^{44,v} A. Geiser,⁴⁴ A. Giralddi,⁴⁴ A. Grohsjean,⁴⁴ M. Guthoff,⁴⁴ A. Harb,⁴⁴ A. Jafari,^{44,w}
 N. Z. Jomhari,⁴⁴ H. Jung,⁴⁴ A. Kasem,^{44,u} M. Kasemann,⁴⁴ H. Kaveh,⁴⁴ J. Keaveney,⁴⁴ C. Kleinwort,⁴⁴ J. Knolle,⁴⁴
 D. Krücker,⁴⁴ W. Lange,⁴⁴ T. Lenz,⁴⁴ J. Lidrych,⁴⁴ K. Lipka,⁴⁴ W. Lohmann,^{44,x} R. Mankel,⁴⁴ I.-A. Melzer-Pellmann,⁴⁴
 J. Metwally,⁴⁴ A. B. Meyer,⁴⁴ M. Meyer,⁴⁴ M. Missiroli,⁴⁴ J. Mnich,⁴⁴ A. Mussgiller,⁴⁴ V. Myronenko,⁴⁴ Y. Otariid,⁴⁴
 D. Pérez Adán,⁴⁴ S. K. Pflitsch,⁴⁴ D. Pitzl,⁴⁴ A. Raspereza,⁴⁴ A. Saggio,⁴⁴ A. Saibel,⁴⁴ M. Savitskyi,⁴⁴ V. Scheurer,⁴⁴
 P. Schütze,⁴⁴ C. Schwanenberger,⁴⁴ R. Shevchenko,⁴⁴ A. Singh,⁴⁴ R. E. Sosa Ricardo,⁴⁴ H. Tholen,⁴⁴ N. Tonon,⁴⁴
 O. Turkot,⁴⁴ A. Vagnerini,⁴⁴ M. Van De Klundert,⁴⁴ R. Walsh,⁴⁴ D. Walter,⁴⁴ Y. Wen,⁴⁴ K. Wichmann,⁴⁴ C. Wissing,⁴⁴
 S. Wuchterl,⁴⁴ O. Zenaiev,⁴⁴ R. Zlebcik,⁴⁴ R. Aggleton,⁴⁵ S. Bein,⁴⁵ L. Benato,⁴⁵ A. Benecke,⁴⁵ K. De Leo,⁴⁵ T. Dreyer,⁴⁵
 A. Ebrahimi,⁴⁵ F. Feindt,⁴⁵ A. Fröhlich,⁴⁵ C. Garbers,⁴⁵ E. Garutti,⁴⁵ D. Gonzalez,⁴⁵ P. Gunnellini,⁴⁵ J. Haller,⁴⁵
 A. Hinzmann,⁴⁵ A. Karavdina,⁴⁵ G. Kasieczka,⁴⁵ R. Klanner,⁴⁵ R. Kogler,⁴⁵ S. Kurz,⁴⁵ V. Kutzner,⁴⁵ J. Lange,⁴⁵ T. Lange,⁴⁵
 A. Malara,⁴⁵ J. Multhaupt,⁴⁵ C. E. N. Niemeyer,⁴⁵ A. Nigamova,⁴⁵ K. J. Pena Rodriguez,⁴⁵ O. Rieger,⁴⁵ P. Schleper,⁴⁵
 S. Schumann,⁴⁵ J. Schwandt,⁴⁵ D. Schwarz,⁴⁵ J. Sonneveld,⁴⁵ H. Stadie,⁴⁵ G. Steinbrück,⁴⁵ B. Vormwald,⁴⁵ I. Zoi,⁴⁵
 M. Baselga,⁴⁶ S. Baur,⁴⁶ J. Bechtel,⁴⁶ T. Berger,⁴⁶ E. Butz,⁴⁶ R. Caspart,⁴⁶ T. Chwalek,⁴⁶ W. De Boer,⁴⁶ A. Dierlamm,⁴⁶
 A. Droll,⁴⁶ K. El Morabit,⁴⁶ N. Faltermann,⁴⁶ K. Flöh,⁴⁶ M. Giffels,⁴⁶ A. Gottmann,⁴⁶ F. Hartmann,^{46,t} C. Heidecker,⁴⁶
 U. Husemann,⁴⁶ M. A. Iqbal,⁴⁶ I. Katkov,^{46,y} P. Keicher,⁴⁶ R. Koppenhöfer,⁴⁶ S. Kudella,⁴⁶ S. Maier,⁴⁶ M. Metzler,⁴⁶
 S. Mitra,⁴⁶ M. U. Mozer,⁴⁶ D. Müller,⁴⁶ Th. Müller,⁴⁶ M. Musich,⁴⁶ G. Quast,⁴⁶ K. Rabbertz,⁴⁶ J. Rauser,⁴⁶ D. Savoiu,⁴⁶
 D. Schäfer,⁴⁶ M. Schnepf,⁴⁶ M. Schröder,⁴⁶ D. Seith,⁴⁶ I. Shvetsov,⁴⁶ H. J. Simonis,⁴⁶ R. Ulrich,⁴⁶ M. Wassmer,⁴⁶
 M. Weber,⁴⁶ C. Wöhrmann,⁴⁶ R. Wolf,⁴⁶ S. Wozniowski,⁴⁶ G. Anagnostou,⁴⁷ P. Asenov,⁴⁷ G. Daskalakis,⁴⁷ T. Geralis,⁴⁷
 A. Kyriakis,⁴⁷ D. Loukas,⁴⁷ G. Paspalaki,⁴⁷ A. Stakia,⁴⁷ M. Diamantopoulou,⁴⁸ D. Karasavvas,⁴⁸ G. Karathanasis,⁴⁸
 P. Kontaxakis,⁴⁸ C. K. Koraka,⁴⁸ A. Manousakis-katsikakis,⁴⁸ A. Panagiotou,⁴⁸ I. Papavergou,⁴⁸ N. Saoulidou,⁴⁸
 K. Theofilatos,⁴⁸ K. Vellidis,⁴⁸ E. Vourliotis,⁴⁸ G. Bakas,⁴⁹ K. Kousouris,⁴⁹ I. Papakrivopoulos,⁴⁹ G. Tsiopolitis,⁴⁹
 A. Zacharopoulou,⁴⁹ I. Evangelou,⁵⁰ C. Foudas,⁵⁰ P. Gianneios,⁵⁰ P. Katsoulis,⁵⁰ P. Kokkas,⁵⁰ S. Mallios,⁵⁰ K. Manitaras,⁵⁰
 N. Manthos,⁵⁰ I. Papadopoulos,⁵⁰ J. Strologas,⁵⁰ M. Bartók,^{51,z} R. Chudasama,⁵¹ M. Csanad,⁵¹ M. M. A. Gadallah,^{51,aa}
 S. Lökös,^{51,bb} P. Major,⁵¹ K. Mandal,⁵¹ A. Mehta,⁵¹ G. Pasztor,⁵¹ O. Surányi,⁵¹ G. I. Veres,⁵¹ G. Bencze,⁵² C. Hajdu,⁵²
 D. Horvath,^{52,cc} F. Sikler,⁵² V. Veszpremi,⁵² G. Vesztergombi,^{52,a,bb} S. Czellar,⁵³ J. Karancsi,^{53,z} J. Molnar,⁵³ Z. Szillasi,⁵³
 D. Teyssier,⁵³ P. Raics,⁵⁴ Z. L. Trocsanyi,⁵⁴ B. Ujvari,⁵⁴ T. Csorgo,⁵⁵ F. Nemes,⁵⁵ T. Novak,⁵⁵ S. Choudhury,⁵⁶
 J. R. Komaragiri,⁵⁶ D. Kumar,⁵⁶ L. Panwar,⁵⁶ P. C. Tiwari,⁵⁶ S. Bahinipati,^{57,dd} D. Dash,⁵⁷ C. Kar,⁵⁷ P. Mal,⁵⁷ T. Mishra,⁵⁷

V. K. Muraleedharan Nair Bindhu,⁵⁷ A. Nayak,^{57,ee} D. K. Sahoo,^{57,dd} N. Sur,⁵⁷ S. K. Swain,⁵⁷ S. Bansal,⁵⁸ S. B. Beri,⁵⁸
 V. Bhatnagar,⁵⁸ S. Chauhan,⁵⁸ N. Dhirra,^{58,ff} R. Gupta,⁵⁸ A. Kaur,⁵⁸ A. Kaur,⁵⁸ S. Kaur,⁵⁸ P. Kumari,⁵⁸ M. Lohan,⁵⁸
 M. Meena,⁵⁸ K. Sandeep,⁵⁸ S. Sharma,⁵⁸ J. B. Singh,⁵⁸ A. K. Virdi,⁵⁸ A. Ahmed,⁵⁹ A. Bhardwaj,⁵⁹ B. C. Choudhary,⁵⁹
 R. B. Garg,⁵⁹ M. Gola,⁵⁹ S. Keshri,⁵⁹ A. Kumar,⁵⁹ M. Naimuddin,⁵⁹ P. Priyanka,⁵⁹ K. Ranjan,⁵⁹ A. Shah,⁵⁹ M. Bharti,^{60,gg}
 R. Bhattacharya,⁶⁰ S. Bhattacharya,⁶⁰ D. Bhowmik,⁶⁰ S. Dutta,⁶⁰ S. Ghosh,⁶⁰ B. Gomber,^{60,hh} M. Maity,^{60,ii} S. Nandan,⁶⁰
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 S. C. Behera,⁶¹ P. Kalbhor,⁶¹ A. Muhammad,⁶¹ R. Pradhan,⁶¹ P. R. Pujahari,⁶¹ A. Sharma,⁶¹ A. K. Sikdar,⁶¹ D. Dutta,⁶²
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 S. Dugad,⁶³ R. Kumar Verma,⁶³ U. Sarkar,⁶³ S. Banerjee,⁶⁴ S. Bhattacharya,⁶⁴ S. Chatterjee,⁶⁴ P. Das,⁶⁴ M. Guchait,⁶⁴
 S. Karmakar,⁶⁴ S. Kumar,⁶⁴ G. Majumder,⁶⁴ K. Mazumdar,⁶⁴ S. Mukherjee,⁶⁴ D. Roy,⁶⁴ N. Sahoo,⁶⁴ S. Dube,⁶⁵ B. Kansal,⁶⁵
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 M. Toms,¹¹³ E. Vlasov,¹¹³ A. Zhokin,¹¹³ T. Aushev,¹¹⁴ R. Chistov,^{115,xx} M. Danilov,^{115,xx} A. Oskin,¹¹⁵ P. Parygin,¹¹⁵
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 M. Dubinin,^{117,yy} L. Dudko,¹¹⁷ A. Ershov,¹¹⁷ A. Gribushin,¹¹⁷ V. Klyukhin,¹¹⁷ O. Kodolova,¹¹⁷ I. Lokhtin,¹¹⁷
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 V. Okhotnikov,¹²⁰ L. Sukhikh,¹²⁰ V. Borchsh,¹²¹ V. Ivanchenko,¹²¹ E. Tcherniaev,¹²¹ P. Adzic,^{122,aaa} P. Cirkovic,¹²²
 M. Dordevic,¹²² P. Milenovic,¹²² J. Milosevic,¹²² M. Aguilar-Benitez,¹²³ J. Alcaraz Maestre,¹²³ A. Álvarez Fernández,¹²³
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M. Dobson,¹²⁹ M. Dünser,¹²⁹ N. Dupont,¹²⁹ A. Elliott-Peisert,¹²⁹ N. Emriskova,¹²⁹ F. Fallavollita,^{129,ddd} D. Fasanella,¹²⁹
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 I. R. Tomalin,¹⁴⁴ T. Williams,¹⁴⁴ R. Bainbridge,¹⁴⁵ P. Bloch,¹⁴⁵ S. Bonomally,¹⁴⁵ J. Borg,¹⁴⁵ S. Breeze,¹⁴⁵ O. Buchmuller,¹⁴⁵
 A. Bundock,¹⁴⁵ V. Cepaitis,¹⁴⁵ G. S. Chahal,^{145,bbbb} D. Colling,¹⁴⁵ P. Dauncey,¹⁴⁵ G. Davies,¹⁴⁵ M. Della Negra,¹⁴⁵
 P. Everaerts,¹⁴⁵ G. Fedi,¹⁴⁵ G. Hall,¹⁴⁵ G. Iles,¹⁴⁵ J. Langford,¹⁴⁵ L. Lyons,¹⁴⁵ A.-M. Magnan,¹⁴⁵ S. Malik,¹⁴⁵ A. Martelli,¹⁴⁵
 V. Milosevic,¹⁴⁵ J. Nash,^{145,cccc} V. Palladino,¹⁴⁵ M. Pesaresi,¹⁴⁵ D. M. Raymond,¹⁴⁵ A. Richards,¹⁴⁵ A. Rose,¹⁴⁵ E. Scott,¹⁴⁵
 C. Seez,¹⁴⁵ A. Shtipliyski,¹⁴⁵ M. Stoye,¹⁴⁵ A. Tapper,¹⁴⁵ K. Uchida,¹⁴⁵ T. Virdee,^{145,t} N. Wardle,¹⁴⁵ S. N. Webb,¹⁴⁵
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 C. K. Mackay,¹⁴⁶ I. D. Reid,¹⁴⁶ L. Teodorescu,¹⁴⁶ S. Zahid,¹⁴⁶ A. Brinkerhoff,¹⁴⁷ K. Call,¹⁴⁷ B. Caraway,¹⁴⁷ J. Dittmann,¹⁴⁷
 K. Hatakeyama,¹⁴⁷ A. R. Kanuganti,¹⁴⁷ C. Madrid,¹⁴⁷ B. McMaster,¹⁴⁷ N. Pastika,¹⁴⁷ S. Sawant,¹⁴⁷ C. Smith,¹⁴⁷ R. Bartek,¹⁴⁸
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 K. H. M. Kwok,¹⁵¹ E. Laird,¹⁵¹ G. Landsberg,¹⁵¹ K. T. Lau,¹⁵¹ J. Lee,¹⁵¹ M. Narain,¹⁵¹ S. Sagir,^{151,eeee} R. Syarif,¹⁵¹
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 M. Hohlmann,¹⁶⁵ D. Noonan,¹⁶⁵ M. Rahmani,¹⁶⁵ M. Saunders,¹⁶⁵ F. Yumiceva,¹⁶⁵ M. R. Adams,¹⁶⁶ L. Apanasevich,¹⁶⁶
 H. Becerril Gonzalez,¹⁶⁶ R. Cavanaugh,¹⁶⁶ X. Chen,¹⁶⁶ S. Dittmer,¹⁶⁶ O. Evdokimov,¹⁶⁶ C. E. Gerber,¹⁶⁶ D. A. Hangal,¹⁶⁶
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 V. Khristenko,¹⁶⁷ O. K. Köseyan,¹⁶⁷ J.-P. Merlo,¹⁶⁷ A. Mestvirishvili,^{167,gggg} A. Moeller,¹⁶⁷ J. Nachtman,¹⁶⁷ H. Ogul,^{167,hhhh}
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R. Saradhy,¹⁷⁴ N. Schroeder,¹⁷⁴ N. Strobbe,¹⁷⁴ M. A. Wadud,¹⁷⁴ J. G. Acosta,¹⁷⁵ S. Oliveros,¹⁷⁵ K. Bloom,¹⁷⁶ S. Chauhan,¹⁷⁶
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 G. R. Snow,^{176,a} B. Stieger,¹⁷⁶ W. Tabb,¹⁷⁶ G. Agarwal,¹⁷⁷ C. Harrington,¹⁷⁷ L. Hay,¹⁷⁷ I. Iashvili,¹⁷⁷ A. Kharchilava,¹⁷⁷
 C. McLean,¹⁷⁷ D. Nguyen,¹⁷⁷ A. Parker,¹⁷⁷ J. Pekkanen,¹⁷⁷ S. Rappoccio,¹⁷⁷ B. Roozbahani,¹⁷⁷ G. Alverson,¹⁷⁸
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 V. Nguyen,¹⁷⁸ T. Orimoto,¹⁷⁸ L. Skinnari,¹⁷⁸ A. Tishelman-Charny,¹⁷⁸ T. Wamorkar,¹⁷⁸ B. Wang,¹⁷⁸ A. Wisecarver,¹⁷⁸
 D. Wood,¹⁷⁸ S. Bhattacharya,¹⁷⁹ J. Bueghly,¹⁷⁹ Z. Chen,¹⁷⁹ A. Gilbert,¹⁷⁹ T. Gunter,¹⁷⁹ K. A. Hahn,¹⁷⁹ N. Odell,¹⁷⁹
 M. H. Schmitt,¹⁷⁹ K. Sung,¹⁷⁹ M. Velasco,¹⁷⁹ R. Bucci,¹⁸⁰ N. Dev,¹⁸⁰ R. Goldouzian,¹⁸⁰ M. Hildreth,¹⁸⁰
 K. Hurtado Anampa,¹⁸⁰ C. Jessop,¹⁸⁰ D. J. Karmgard,¹⁸⁰ K. Lannon,¹⁸⁰ W. Li,¹⁸⁰ N. Loukas,¹⁸⁰ N. Marinelli,¹⁸⁰
 I. Mcalister,¹⁸⁰ F. Meng,¹⁸⁰ K. Mohrman,¹⁸⁰ Y. Musienko,^{180,ss} R. Ruchti,¹⁸⁰ P. Siddireddy,¹⁸⁰ S. Taroni,¹⁸⁰ M. Wayne,¹⁸⁰
 A. Wightman,¹⁸⁰ M. Wolf,¹⁸⁰ L. Zygala,¹⁸⁰ J. Alimena,¹⁸¹ B. Bylsma,¹⁸¹ B. Cardwell,¹⁸¹ L. S. Durkin,¹⁸¹ B. Francis,¹⁸¹
 C. Hill,¹⁸¹ W. Ji,¹⁸¹ A. Lefeld,¹⁸¹ B. L. Winer,¹⁸¹ B. R. Yates,¹⁸¹ G. Dezoort,¹⁸² P. Elmer,¹⁸² B. Greenberg,¹⁸² N. Haubrich,¹⁸²
 S. Higginbotham,¹⁸² A. Kalogeropoulos,¹⁸² G. Kopp,¹⁸² S. Kwan,¹⁸² D. Lange,¹⁸² M. T. Lucchini,¹⁸² J. Luo,¹⁸²
 D. Marlow,¹⁸² K. Mei,¹⁸² I. Ojalvo,¹⁸² J. Olsen,¹⁸² C. Palmer,¹⁸² P. Piroué,¹⁸² D. Stickland,¹⁸² C. Tully,¹⁸² S. Malik,¹⁸³
 S. Norberg,¹⁸³ V. E. Barnes,¹⁸⁴ R. Chawla,¹⁸⁴ S. Das,¹⁸⁴ L. Gutay,¹⁸⁴ M. Jones,¹⁸⁴ A. W. Jung,¹⁸⁴ B. Mahakud,¹⁸⁴
 G. Negro,¹⁸⁴ N. Neumeister,¹⁸⁴ C. C. Peng,¹⁸⁴ S. Piperov,¹⁸⁴ H. Qiu,¹⁸⁴ J. F. Schulte,¹⁸⁴ N. Trevisani,¹⁸⁴ F. Wang,¹⁸⁴
 R. Xiao,¹⁸⁴ W. Xie,¹⁸⁴ T. Cheng,¹⁸⁵ J. Dolen,¹⁸⁵ N. Parashar,¹⁸⁵ M. Stojanovic,¹⁸⁵ A. Baty,¹⁸⁶ S. Dildick,¹⁸⁶ K. M. Ecklund,¹⁸⁶
 S. Freed,¹⁸⁶ F. J. M. Geurts,¹⁸⁶ M. Kilpatrick,¹⁸⁶ A. Kumar,¹⁸⁶ W. Li,¹⁸⁶ B. P. Padley,¹⁸⁶ R. Redjimi,¹⁸⁶ J. Roberts,^{186,a}
 J. Rorie,¹⁸⁶ W. Shi,¹⁸⁶ A. G. Stahl Leiton,¹⁸⁶ Z. Tu,¹⁸⁶ A. Zhang,¹⁸⁶ A. Bodek,¹⁸⁷ P. de Barbaro,¹⁸⁷ R. Demina,¹⁸⁷
 J. L. Dulemba,¹⁸⁷ C. Fallon,¹⁸⁷ T. Ferbel,¹⁸⁷ M. Galanti,¹⁸⁷ A. Garcia-Bellido,¹⁸⁷ O. Hindrichs,¹⁸⁷ A. Khukhunaishvili,¹⁸⁷
 E. Ranken,¹⁸⁷ R. Taus,¹⁸⁷ B. Chiarito,¹⁸⁸ J. P. Chou,¹⁸⁸ A. Gandrakota,¹⁸⁸ Y. Gershtein,¹⁸⁸ E. Halkiadakis,¹⁸⁸ A. Hart,¹⁸⁸
 M. Heindl,¹⁸⁸ E. Hughes,¹⁸⁸ S. Kaplan,¹⁸⁸ O. Karacheban,^{188,x} I. Laflotte,¹⁸⁸ A. Lath,¹⁸⁸ R. Montalvo,¹⁸⁸ K. Nash,¹⁸⁸
 M. Osherson,¹⁸⁸ S. Salur,¹⁸⁸ S. Schnetzer,¹⁸⁸ S. Somalwar,¹⁸⁸ R. Stone,¹⁸⁸ S. A. Thayil,¹⁸⁸ S. Thomas,¹⁸⁸ H. Acharya,¹⁸⁹
 A. G. Delannoy,¹⁸⁹ S. Spanier,¹⁸⁹ O. Bouhali,^{190,kkkk} M. Dalchenko,¹⁹⁰ A. Delgado,¹⁹⁰ R. Eusebi,¹⁹⁰ J. Gilmore,¹⁹⁰
 T. Huang,¹⁹⁰ T. Kamon,^{190,llll} H. Kim,¹⁹⁰ S. Luo,¹⁹⁰ S. Malhotra,¹⁹⁰ R. Mueller,¹⁹⁰ D. Overton,¹⁹⁰ L. Perniè,¹⁹⁰
 D. Rathjens,¹⁹⁰ A. Safonov,¹⁹⁰ N. Akchurin,¹⁹¹ J. Damgov,¹⁹¹ V. Hegde,¹⁹¹ S. Kunori,¹⁹¹ K. Lamichhane,¹⁹¹ S. W. Lee,¹⁹¹
 T. Mengke,¹⁹¹ S. Muthumuni,¹⁹¹ T. Peltola,¹⁹¹ S. Undleeb,¹⁹¹ I. Volobouev,¹⁹¹ Z. Wang,¹⁹¹ A. Whitbeck,¹⁹¹ E. Appelt,¹⁹²
 S. Greene,¹⁹² A. Gurrola,¹⁹² R. Janjam,¹⁹² W. Johns,¹⁹² C. Maguire,¹⁹² A. Melo,¹⁹² H. Ni,¹⁹² K. Padeken,¹⁹² F. Romeo,¹⁹²
 P. Sheldon,¹⁹² S. Tuo,¹⁹² J. Velkovska,¹⁹² M. Verweij,¹⁹² L. Ang,¹⁹³ M. W. Arenton,¹⁹³ B. Cox,¹⁹³ G. Cummings,¹⁹³
 J. Hakala,¹⁹³ R. Hirosky,¹⁹³ M. Joyce,¹⁹³ A. Ledovskoy,¹⁹³ C. Neu,¹⁹³ B. Tannenwald,¹⁹³ Y. Wang,¹⁹³ E. Wolfe,¹⁹³ F. Xia,¹⁹³
 P. E. Karchin,¹⁹⁴ N. Poudyal,¹⁹⁴ J. Sturdy,¹⁹⁴ P. Thapa,¹⁹⁴ K. Black,¹⁹⁵ T. Bose,¹⁹⁵ J. Buchanan,¹⁹⁵ C. Caillol,¹⁹⁵ S. Dasu,¹⁹⁵
 I. De Bruyn,¹⁹⁵ L. Dodd,¹⁹⁵ C. Galloni,¹⁹⁵ H. He,¹⁹⁵ M. Herndon,¹⁹⁵ A. Hervé,¹⁹⁵ U. Hussain,¹⁹⁵ A. Lanaro,¹⁹⁵ A. Loeliger,¹⁹⁵
 R. Loveless,¹⁹⁵ J. Madhusudanan Sreekala,¹⁹⁵ A. Mallampalli,¹⁹⁵ D. Pinna,¹⁹⁵ T. Ruggles,¹⁹⁵ A. Savin,¹⁹⁵ V. Shang,¹⁹⁵
 V. Sharma,¹⁹⁵ W. H. Smith,¹⁹⁵ D. Teague,¹⁹⁵ S. Trembath-reichert,¹⁹⁵ and W. Vetens¹⁹⁵

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia

²Institut für Hochenergiephysik, Wien, Austria

³Institute for Nuclear Problems, Minsk, Belarus

⁴Universiteit Antwerpen, Antwerpen, Belgium

⁵Vrije Universiteit Brussel, Brussel, Belgium

⁶Université Libre de Bruxelles, Bruxelles, Belgium

⁷Ghent University, Ghent, Belgium

⁸Université Catholique de Louvain, Louvain-la-Neuve, Belgium

⁹Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

¹⁰Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

^{11a}Universidade Estadual Paulista, São Paulo, Brazil

^{11b}Universidade Federal do ABC, São Paulo, Brazil

¹²Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

¹³University of Sofia, Sofia, Bulgaria

- ¹⁴Beihang University, Beijing, China
- ¹⁵Department of Physics, Tsinghua University, Beijing, China
- ¹⁶Institute of High Energy Physics, Beijing, China
- ¹⁷State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- ¹⁸Sun Yat-Sen University, Guangzhou, China
- ¹⁹Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
- ²⁰Zhejiang University, Hangzhou, China
- ²¹Universidad de Los Andes, Bogota, Colombia
- ²²Universidad de Antioquia, Medellin, Colombia
- ²³University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
- ²⁴University of Split, Faculty of Science, Split, Croatia
- ²⁵Institute Rudjer Boskovic, Zagreb, Croatia
- ²⁶University of Cyprus, Nicosia, Cyprus
- ²⁷Charles University, Prague, Czech Republic
- ²⁸Escuela Politecnica Nacional, Quito, Ecuador
- ²⁹Universidad San Francisco de Quito, Quito, Ecuador
- ³⁰Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
- ³¹Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
- ³²National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- ³³Department of Physics, University of Helsinki, Helsinki, Finland
- ³⁴Helsinki Institute of Physics, Helsinki, Finland
- ³⁵Lappeenranta University of Technology, Lappeenranta, Finland
- ³⁶IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ³⁷Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris, France
- ³⁸Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
- ³⁹Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
- ⁴⁰Georgian Technical University, Tbilisi, Georgia
- ⁴¹RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
- ⁴²RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ⁴³RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
- ⁴⁴Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁵University of Hamburg, Hamburg, Germany
- ⁴⁶Karlsruher Institut fuer Technologie, Karlsruhe, Germany
- ⁴⁷Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
- ⁴⁸National and Kapodistrian University of Athens, Athens, Greece
- ⁴⁹National Technical University of Athens, Athens, Greece
- ⁵⁰University of Ioánnina, Ioánnina, Greece
- ⁵¹MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ⁵²Wigner Research Centre for Physics, Budapest, Hungary
- ⁵³Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ⁵⁴Institute of Physics, University of Debrecen, Debrecen, Hungary
- ⁵⁵Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
- ⁵⁶Indian Institute of Science (IISc), Bangalore, India
- ⁵⁷National Institute of Science Education and Research, HBNI, Bhubaneswar, India
- ⁵⁸Panjab University, Chandigarh, India
- ⁵⁹University of Delhi, Delhi, India
- ⁶⁰Saha Institute of Nuclear Physics, HBNI, Kolkata, India
- ⁶¹Indian Institute of Technology Madras, Madras, India
- ⁶²Bhabha Atomic Research Centre, Mumbai, India
- ⁶³Tata Institute of Fundamental Research-A, Mumbai, India
- ⁶⁴Tata Institute of Fundamental Research-B, Mumbai, India
- ⁶⁵Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶⁶Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁶⁷Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶⁸University College Dublin, Dublin, Ireland
- ^{69a}INFN Sezione di Bari
- ^{69b}Università di Bari
- ^{69c}Politecnico di Bari

- ^{70a}*INFN Sezione di Bologna, Bologna, Italy*
^{70b}*Università di Bologna, Bologna, Italy*
^{71a}*INFN Sezione di Catania, Catania, Italy*
^{71b}*Università di Catania, Catania, Italy*
^{72a}*INFN Sezione di Firenze, Firenze, Italy*
^{72b}*Università di Firenze, Firenze, Italy*
⁷³*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
^{74a}*INFN Sezione di Genova, Genova, Italy*
^{74b}*Università di Genova, Genova, Italy*
^{75a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
^{75b}*Università di Milano-Bicocca, Milano, Italy*
^{76a}*INFN Sezione di Napoli, Napoli, Italy*
^{76b}*Università di Napoli 'Federico II', Napoli, Italy*
^{76c}*Università della Basilicata, Potenza, Italy*
^{76d}*Università G. Marconi, Roma, Italy*
^{77a}*INFN Sezione di Padova, Padova, Italy*
^{77b}*Università di Padova, Padova, Italy*
^{77c}*Università di Trento, Trento, Italy*
^{78a}*INFN Sezione di Pavia*
^{78b}*Università di Pavia*
^{79a}*INFN Sezione di Perugia, Perugia, Italy*
^{79b}*Università di Perugia, Perugia, Italy*
^{80a}*INFN Sezione di Pisa, Pisa, Italy*
^{80b}*Università di Pisa, Pisa, Italy*
^{80c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
^{81a}*INFN Sezione di Roma, Rome, Italy*
^{81b}*Sapienza Università di Roma, Rome, Italy*
^{82a}*INFN Sezione di Torinos, Torino, Italy*
^{82b}*Università di Torino, Torino, Italy*
^{82c}*Università del Piemonte Orientale, Novara, Italy*
^{83a}*INFN Sezione di Trieste, Trieste, Italy*
^{83b}*Università di Trieste, Trieste, Italy*
⁸⁴*Kyungpook National University, Daegu, Korea*
⁸⁵*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
⁸⁶*Hanyang University, Seoul, Korea*
⁸⁷*Korea University, Seoul, Korea*
⁸⁸*Kyung Hee University, Department of Physics, Seoul, Republic of Korea*
⁸⁹*Sejong University, Seoul, Korea*
⁹⁰*Seoul National University, Seoul, Korea*
⁹¹*University of Seoul, Seoul, Korea*
⁹²*Yonsei University, Department of Physics, Seoul, Korea*
⁹³*Sungkyunkwan University, Suwon, Korea*
⁹⁴*Riga Technical University, Riga, Latvia*
⁹⁵*Vilnius University, Vilnius, Lithuania*
⁹⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
⁹⁷*Universidad de Sonora (UNISON), Hermosillo, Mexico*
⁹⁸*Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*
⁹⁹*Universidad Iberoamericana, Mexico City, Mexico*
¹⁰⁰*Benemerita Universidad Autónoma de Puebla, Puebla, Mexico*
¹⁰¹*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
¹⁰²*University of Montenegro, Podgorica, Montenegro*
¹⁰³*University of Auckland, Auckland, New Zealand*
¹⁰⁴*University of Canterbury, Christchurch, New Zealand*
¹⁰⁵*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
¹⁰⁶*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
¹⁰⁷*National Centre for Nuclear Research, Swierk, Poland*
¹⁰⁸*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
¹⁰⁹*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
¹¹⁰*Joint Institute for Nuclear Research, Dubna, Russia*
¹¹¹*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*

- ¹¹²*Institute for Nuclear Research, Moscow, Russia*
- ¹¹³*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia*
- ¹¹⁴*Moscow Institute of Physics and Technology, Moscow, Russia*
- ¹¹⁵*National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia*
- ¹¹⁶*P.N. Lebedev Physical Institute, Moscow, Russia*
- ¹¹⁷*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- ¹¹⁸*Novosibirsk State University (NSU), Novosibirsk, Russia*
- ¹¹⁹*Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia*
- ¹²⁰*National Research Tomsk Polytechnic University, Tomsk, Russia*
- ¹²¹*Tomsk State University, Tomsk, Russia*
- ¹²²*University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia*
- ¹²³*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ¹²⁴*Universidad Autónoma de Madrid, Madrid, Spain*
- ¹²⁵*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- ¹²⁶*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹²⁷*University of Colombo, Colombo, Sri Lanka*
- ¹²⁸*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- ¹²⁹*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ¹³⁰*Paul Scherrer Institut, Villigen, Switzerland*
- ¹³¹*ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹³²*Universität Zürich, Zurich, Switzerland*
- ¹³³*National Central University, Chung-Li, Taiwan*
- ¹³⁴*National Taiwan University (NTU), Taipei, Taiwan*
- ¹³⁵*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
- ¹³⁶*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- ¹³⁷*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹³⁸*Bogazici University, Istanbul, Turkey*
- ¹³⁹*Istanbul Technical University, Istanbul, Turkey*
- ¹⁴⁰*Istanbul University, Istanbul, Turkey*
- ¹⁴¹*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
- ¹⁴²*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- ¹⁴³*University of Bristol, Bristol, United Kingdom*
- ¹⁴⁴*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴⁵*Imperial College, London, United Kingdom*
- ¹⁴⁶*Brunel University, Uxbridge, United Kingdom*
- ¹⁴⁷*Baylor University, Waco, Texas, USA*
- ¹⁴⁸*Catholic University of America, Washington, DC, USA*
- ¹⁴⁹*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹⁵⁰*Boston University, Boston, Massachusetts, USA*
- ¹⁵¹*Brown University, Providence, Rhode Island, USA*
- ¹⁵²*University of California, Davis, Davis, California, USA*
- ¹⁵³*University of California, Los Angeles, California, USA*
- ¹⁵⁴*University of California, Riverside, Riverside, California, USA*
- ¹⁵⁵*University of California, San Diego, La Jolla, California, USA*
- ¹⁵⁶*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
- ¹⁵⁷*California Institute of Technology, Pasadena, California, USA*
- ¹⁵⁸*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹⁵⁹*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁶⁰*Cornell University, Ithaca, New York, USA*
- ¹⁶¹*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁶²*University of Florida, Gainesville, Florida, USA*
- ¹⁶³*Florida International University, Miami, Florida, USA*
- ¹⁶⁴*Florida State University, Tallahassee, Florida, USA*
- ¹⁶⁵*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹⁶⁶*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
- ¹⁶⁷*The University of Iowa, Iowa City, Iowa, USA*
- ¹⁶⁸*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹⁶⁹*The University of Kansas, Lawrence, Kansas, USA*
- ¹⁷⁰*Kansas State University, Manhattan, Kansas, USA*
- ¹⁷¹*Lawrence Livermore National Laboratory, Livermore, California, USA*

- ¹⁷²University of Maryland, College Park, Maryland, USA
¹⁷³Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹⁷⁴University of Minnesota, Minneapolis, Minnesota, USA
¹⁷⁵University of Mississippi, Oxford, Mississippi, USA
¹⁷⁶University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁷⁷State University of New York at Buffalo, Buffalo, New York, USA
¹⁷⁸Northeastern University, Boston, Massachusetts, USA
¹⁷⁹Northwestern University, Evanston, Illinois, USA
¹⁸⁰University of Notre Dame, Notre Dame, Indiana, USA
¹⁸¹The Ohio State University, Columbus, Ohio, USA
¹⁸²Princeton University, Princeton, New Jersey, USA
¹⁸³University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁸⁴Purdue University, West Lafayette, Indiana, USA
¹⁸⁵Purdue University Northwest, Hammond, Indiana, USA
¹⁸⁶Rice University, Houston, Texas, USA
¹⁸⁷University of Rochester, Rochester, New York, USA
¹⁸⁸Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁸⁹University of Tennessee, Knoxville, Tennessee, USA
¹⁹⁰Texas A&M University, College Station, Texas, USA
¹⁹¹Texas Tech University, Lubbock, Texas, USA
¹⁹²Vanderbilt University, Nashville, Tennessee, USA
¹⁹³University of Virginia, Charlottesville, Virginia, USA
¹⁹⁴Wayne State University, Detroit, Michigan, USA
¹⁹⁵University of Wisconsin - Madison, Madison, WI, Wisconsin, USA

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria

^cAlso at Department of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport

^dAlso at Université Libre de Bruxelles, Bruxelles, Belgium

^eAlso at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

^fAlso at Universidade Estadual de Campinas, Campinas, Brazil

^gAlso at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

^hAlso at UFMS

ⁱAlso at Universidade Federal de Pelotas, Pelotas, Brazil

^jAlso at University of Chinese Academy of Sciences

^kAlso at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia

^lAlso at Joint Institute for Nuclear Research, Dubna, Russia

^mAlso at Zewail City of Science and Technology, Zewail, Egypt

ⁿAlso at Ain Shams University, Cairo, Egypt

^oAlso at British University in Egypt, Cairo, Egypt

^pAlso at Purdue University, West Lafayette, Indiana, USA

^qAlso at Université de Haute Alsace, Mulhouse, France

^rAlso at Tbilisi State University, Tbilisi, Georgia

^sAlso at Erzincan Binali Yildirim University, Erzincan, Turkey

^tAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland

^uAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

^vAlso at University of Hamburg, Hamburg, Germany

^wAlso at Department of Physics, Isfahan University of Technology, Isfahan, Iran

^xAlso at Brandenburg University of Technology, Cottbus, Germany

^yAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

^zAlso at Institute of Physics, University of Debrecen, Debrecen, Hungary

^{aa}Also at Physics Department, Faculty of Science, Assiut University

^{bb}Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

^{cc}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

^{dd}Also at IIT Bhubaneswar, Bhubaneswar, India

^{ee}Also at Institute of Physics, Bhubaneswar, India

^{ff}Also at G.H.G. Khalsa College, Punjab, India

^{gg}Also at Shoolini University, Solan, India

^{hh}Also at University of Hyderabad, Hyderabad, India

- ii Also at University of Visva-Bharati, Santiniketan, India
- ji Also at Indian Institute of Technology (IIT), Mumbai, India
- kk Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ll Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- mm Also at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
- nn Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development
- oo Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia
- pp Also at Riga Technical University, Riga, Latvia
- qq Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- rr Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- ss Also at Institute for Nuclear Research, Moscow, Russia
- tt Also at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
- uu Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- vv Also at University of Florida, Gainesville, Florida, USA
- ww Also at Imperial College, London, United Kingdom
- xx Also at P.N. Lebedev Physical Institute, Moscow, Russia
- yy Also at California Institute of Technology, Pasadena, California, USA
- zz Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- aaa Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- bbb Also at Università degli Studi di Siena, Siena, Italy
- ccc Also at Trincomalee Campus, Eastern University, Sri Lanka
- ddd Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- eee Also at National and Kapodistrian University of Athens, Athens, Greece
- fff Also at Universität Zürich, Zurich, Switzerland
- ggg Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- hhh Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- iii Also at Şırnak University
- jjj Also at Department of Physics, Tsinghua University, Beijing, China
- kkk Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- lll Also at Beykent University, Istanbul, Turkey
- mmm Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies)
- nnn Also at Mersin University, Mersin, Turkey
- ooo Also at Piri Reis University, Istanbul, Turkey
- ppp Also at Adiyaman University, Adiyaman, Turkey
- qqq Also at Ozyegin University, Istanbul, Turkey
- rrr Also at Izmir Institute of Technology, Izmir, Turkey
- sss Also at Necmettin Erbakan University, Konya, Turkey
- ttt Also at Bozok Universitetsi Rektörlüğü
- uuu Also at Marmara University, Istanbul, Turkey
- vvv Also at Milli Savunma University
- www Also at Kafkas University, Kars, Turkey
- xxx Also at Istanbul Bilgi University, Istanbul, Turkey
- yyy Also at Hacettepe University, Ankara, Turkey
- zzz Also at Vrije Universiteit Brussel, Brussel, Belgium
- aaaa Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- bbbb Also at IPPP Durham University
- cccc Also at Monash University, Faculty of Science, Clayton, Australia
- dddd Also at Bethel University, St. Paul, Minneapolis, USA
- eeee Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ffff Also at Bingol University, Bingol, Turkey
- gggg Also at Georgian Technical University, Tbilisi, Georgia
- hhhh Also at Sinop University, Sinop, Turkey
- iiii Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- jjjj Also at Nanjing Normal University Department of Physics
- kkkk Also at Texas A&M University at Qatar, Doha, Qatar
- llll Also at Kyungpook National University, Daegu, Korea