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Observation of electroweak W^+W^- pair production in association with two jets in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration *

CERN, Geneva, Switzerland

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ABSTRACT

An observation is reported of the electroweak production of a W^+W^- pair in association with two jets, with both W bosons decaying leptonically. The data sample corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, collected by the CMS detector at the CERN LHC. Events are selected by requiring exactly two opposite-sign leptons (electrons or muons) and two jets with large pseudorapidity separation and high dijet invariant mass. Events are categorized based on the flavor of the final-state leptons. A signal is observed with a significance of 5.6 standard deviations (5.2 expected) with respect to the background-only hypothesis. The measured fiducial cross section is $10.2 \pm 2.0\,\text{fb}$ and this value is consistent with the standard model prediction of $9.1 \pm 0.6\,\text{fb}$.

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1. Introduction

Electroweak (EW) scattering processes of the form $VV' \to VV'$, with V and V′ being W, Z, or γ vector bosons, are crucial tools to investigate the mechanism of EW symmetry breaking [1,2]. The existence of a Higgs boson with a mass of 125 GeV [3–5] prevents the violation of unitarity in such vector boson scattering (VBS) processes by adding new exchange diagrams that cancel divergences in the theoretical calculations involving massive gauge bosons [6]. Therefore, the precise measurement of VBS cross sections in proton-proton (pp) collisions at the CERN LHC can probe the nature of the Higgs sector and search for effects beyond the standard model.

The cross sections of the various VBS processes and their associated backgrounds differ considerably depending on the choice of the pair of bosons and their final state. The EW production of two W bosons with the same electric charge ($W^\pm W^\pm$) in the fully leptonic final state has been extensively studied by the ATLAS and CMS Collaborations [7–12]. In this paper, the full 2016–2018 data set recorded by the CMS experiment is exploited to search for the purely EW production of a pair of opposite-sign (OS) W bosons in association with two jets, a process that has not been observed yet.

This analysis, however, is more challenging than the $W^\pm W^\pm$ channel, mainly due to the large OS background from top pair ($t\bar{t}$) production, which results in a lower experimental sensitivity. From a theoretical perspective, they are both key ingredients to provide a full picture of the EW symmetry breaking mechanism in the SM, but the EW production of W^+W^- bosons is more sensitive to new physics phenomena that might affect the couplings of W bosons to the Higgs boson. In view of a future combination of VBS channels to set constraints on effective-field theory parameters, this process is particularly important for its capability of precisely determining several dimension-6 operators [13].

Fig. 1 (left and middle) shows some typical diagrams at the lowest order in the EW coupling (i.e., α^6 including subsequent W boson decays) that contribute to the signal. In Fig. 1 (right), the production of the W^+W^- final state is instead mediated via gluon exchange, referred to as quantum chromodynamics (QCD)-induced W^+W^- production. These QCD diagrams constitute an irreducible background for the analysis, although they have different kinematic properties that can be used to reduce their contamination in the signal region (SR).

The characteristic signature of VBS events includes two vector bosons and two jets emitted at forward and backward rapidities. The jets in the VBS topology (tagging jets) have large pseudorapidity separation ($|\Delta\eta_{jj}|$), a high dijet invariant mass (m_{jj}), and suppressed hadronic activity between them. The analysis selects final states with two OS leptons (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$). The $e\mu$ channel is less populated by Drell–Yan (DY) events, thus resulting in a lower background contamination and higher sensitivity. The neutrinos in the final state result in large missing transverse momentum (p_T^{miss}).

The main source of reducible background arises from $t\bar{t}$ production. This background is suppressed by vetoing the presence of jets originating from the fragmentation of bottom (b) quarks, and its

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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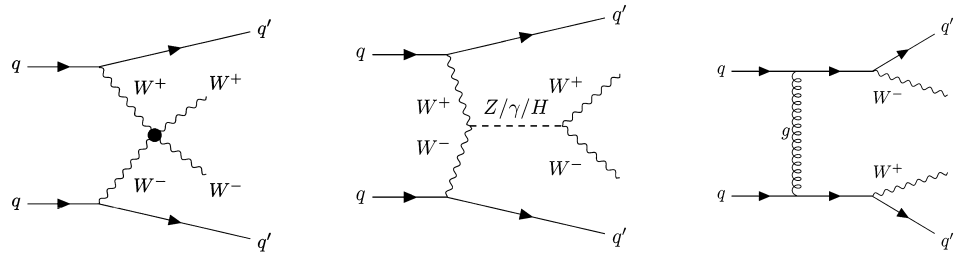

Fig. 1. Examples of Feynman diagrams for the EW (left, center) and QCD-induced (right) production of W^+W^- bosons in association with two quarks.

contamination in the SR is measured from CMS data through dedicated control regions (CRs) enriched in $t\bar{t}$ events. Together with the QCD-induced W^+W^- production, which is reduced by requirements on m_{jj} and $|\Delta\eta_{jj}|$, other relevant sources of background events are DY plus jets and W boson plus jets production, and their yields are all estimated from a CMS data set via dedicated CRs.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections, are installed within the solenoid. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [14].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about $4\,\mu s$ [15]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [16].

During the 2016 and 2017 data taking, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region at $|\eta| > 2.0$ caused a specific trigger inefficiency [15]. For events containing an electron (a jet) with transverse momentum p_T larger than 50 GeV (100 GeV), in the region $2.5 < |\eta| < 3.0$ the efficiency loss is ≈10–20%, depending on p_T, η, and time. Correction factors were computed from data and applied to the acceptance evaluated by simulation.

The particle-flow (PF) algorithm [17] reconstructs and identifies each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [18].

Hadronic jets are clustered from all PF candidates in an event using the infrared and collinear safe anti-k_T algorithm [19,20] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and, on average, is within 5 to 10% of the particle level jet momentum over the whole p_T spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified as originating from pileup vertices are discarded and a correction is applied to remove the remaining spurious neutral contributions [21].

Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and corrections are applied to simulated events [22].

The missing transverse momentum vector $\vec{p}_T^{miss}$ is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [23]. The $\vec{p}_T^{miss}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event. The pileup per particle identification (PUPPI) algorithm [24], which weights the PF candidates according to their probability to originate from the primary interaction vertex, is applied to reduce the pileup dependence of the $\vec{p}_T^{miss}$ observable.

3. Data sets and simulated samples

The 2016–2018 data sets, corresponding to integrated luminosities of 36.3, 41.5, and 59.7 fb^{-1}, respectively, are analyzed. The integrated luminosities for the 2016, 2017, and 2018 data taking years have individual uncertainties of 1.2–2.5% [25–27], whereas the overall uncertainty for the 2016–2018 period is 1.6%. To account for changes in the detector and for the different numbers of pileup interactions, a different simulation is employed in the analysis of each yearly data set.

Our analysis requires events filtered by trigger algorithms that select either a single lepton passing a high p_T threshold, or two leptons with a lower p_T threshold, satisfying both isolation and identification criteria. In the 2016 data set, the p_T threshold of the single electron trigger is 25 GeV for $|\eta| < 2.1$ and 27 GeV for $2.1 < |\eta| < 2.5$, whereas the p_T threshold of the single muon trigger is 24 GeV. Double lepton triggers have lower p_T thresholds, namely 23 GeV (12 GeV) for the leading (trailing) lepton in the double electron trigger, 17 GeV (8 GeV) for the leading (trailing) lepton in the double muon trigger and 23 GeV (8 GeV in the first part of the data set, corresponding to 17.7 fb^{-1}, and 12 GeV in the remainder) for the leading (trailing) lepton in the electron-muon

trigger. In the 2017 data set, single electron and single muon p_T thresholds are raised to 35 and 27 GeV, respectively. In the 2018 data set the corresponding single lepton p_T thresholds are 32 and 24 GeV. Double lepton p_T thresholds in 2017–2018 data sets are the same as those described for the 2016 data set, except for the p_T threshold of the trailing lepton in the electron-muon trigger which is 12 GeV.

All expected physics processes are modeled via Monte Carlo simulation, reweighted to account for known discrepancies between data and simulated events. Corrections to the trigger efficiencies, as well as the efficiencies for electron and muon reconstruction, identification, and isolation as functions of the lepton p_T and η, are extracted from events with leptonic Z boson decays using a "tag-and-probe" technique, as described in Ref. [28]. The b jet tagging efficiency [29] is measured and corrections are derived using data samples enriched in b quark jets. For each data set, simulated events are reweighted according to the pileup profile distribution observed in data.

The signal process is simulated at leading order (LO) with MadGraph5_aMC@NLO (v.2.4.2) [30] interfaced with the event generator PYTHIA 8.240 (8.230) [31] in 2016 (2017 and 2018). We require two quarks and two leptonically decaying W bosons in the final state; contributions from τ decays to lighter leptons are also included in the simulation. Diagrams containing a top quark contribution are not included in the signal matrix element, since EW top quark production is taken into account by the $t\bar{t}$ and single top quark (tW) background samples. W bosons are generated within 15 decay lifetimes from their on-shell mass. Contributions beyond this limit do not significantly increase the overall cross section and therefore are not considered.

The dipole approach [32] is used to model the initial-state radiation, rather than the standard p_T-ordered one used in the PYTHIA parton shower generator, which does not properly describe extra QCD emissions in the vector boson fusion (VBF) and VBS processes [33]. The QCD-induced W^+W^- background is modeled with POWHEG v2 [34], and the production of the second jet is described at LO accuracy in QCD [35]. The interference between the EW and QCD-induced processes was evaluated, and it results in a negligible effect.

Higgs boson production mechanisms are included in the analysis and treated as a background source. All production modes are simulated with POWHEG v2 at next-to-LO (NLO) accuracy in QCD. Gluon-gluon fusion (ggF) events are further reweighted to match next-to-NLO accuracy, according to the NNLOPS scheme [36]. The Higgs boson decay into two W bosons and subsequently into leptons is simulated with the JHUGen generator [37], whereas its decay into two τ leptons is simulated with PYTHIA. Other minor Higgs boson decay channels are neglected.

On-shell VBF Higgs boson production is negligible when simulating two on-shell W bosons, as is done for the signal sample. Accordingly, this contribution is removed from our signal definition, whereas off-shell effects are retained. Furthermore, the SR phase space is tailored to enhance EW W^+W^- production occurring without the exchange of a Higgs boson, which is suppressed by the tight selection on the dilepton invariant mass as discussed in Section 4. A dedicated analysis has been designed to target the on-shell VBF Higgs boson production [38], where, conversely, our signal sample is regarded as a background process.

The following additional background processes are modeled in simulation: nonresonant W boson pair production induced by gluons (included in the QCD-induced W^+W^- background estimation), $t\bar{t}$ and tW production, DY lepton pair production, $W\gamma$ and $Z\gamma$ production, and multiboson production. Most of the event samples are generated at NLO in QCD using either POWHEG v2, MadGraph5_aMC@NLO (v2.4.2), or MCFM (v7.0) [39–41]. Only $W\gamma$ events are generated in the LO mode with MadGraph5_aMC@NLO (v2.4.2). The p_T distribution of the $t\bar{t}$ component of $t\bar{t}$ + tW background is weighted to better match data [42]. A similar procedure is applied to the p_T distribution of the Z boson in DY samples [43]. Other EW-induced diboson channels (WZ, $W\gamma$ and $W^\pm W^\pm$) produced in association with two jets have been evaluated and their contribution to the SR is negligible, hence they have not been included in the background estimation.

The chosen parton distribution functions (PDFs) and underlying event tunes are common to all simulated events for a given data set. The parton showering and hadronization processes are simulated through PYTHIA 8.226 (8.230) in 2016 (2017–2018). The PDF set is NNPDF 3.0 [44,45] (3.1 [46]) and the underlying event tune is CUETP8M1 [47] (CP5 [48]) for the 2016 (2017–2018) samples. All generated events are processed through a simulation of the CMS detector based on GEANT4 [49] and are reconstructed with the same algorithms as used for data.

4. Event selection

The VBS final state is characterized by the presence of two jets from the incoming partons with a large $|\Delta\eta_{jj}|$ and a high m_{jj}, and two OS leptons and two neutrinos from the W boson decays. Candidate events are preselected if they fulfill the following requirements:

- Two OS leptons (electrons or muons), with dilepton mass $m_{\ell\ell} > 50$ GeV and transverse momentum $p_T^{\ell\ell} > 30$ GeV, are selected with the tight selections described in Refs. [50,51]. The thresholds for the highest and second-highest p_T leptons are 25 and 13 GeV, respectively. Events with an additional lepton with $p_T > 10$ GeV are rejected;
- $p_T^{miss} > 20$ GeV;
- At least two jets with $p_T > 30$ GeV, $m_{jj} > 300$ GeV, and $|\Delta\eta_{jj}| > 2.5$.

Requirements on $m_{\ell\ell}$ and $p_T^{\ell\ell}$ variables are added to reduce contributions from on-shell Higgs boson production and DY to $\tau^+\tau^-$ background, respectively, without losing signal efficiency. The kinematic phase space is then divided into a SR and two CRs, which are used to check the agreement between data and simulation and to constrain the normalization of the major backgrounds, i.e., $t\bar{t}$ and DY production. Each region is further categorized according to the charged lepton flavor composition: two electrons (ee), two muons ($\mu\mu$), or one electron and one muon ($e\mu$). The SR is defined by requiring that no b jets, defined with the loose working point of the DeepJet algorithm [29], are present. The transverse mass m_T is defined as $m_T = \sqrt{2 p_T^{\ell\ell} p_T^{miss}[1 - \cos\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{p}_T^{miss})]}$, where ϕ is the azimuthal angle in radians; m_T is required to be above 60 GeV in the $e\mu$ SR. In the SR for ee and $\mu\mu$, the p_T^{miss} threshold is raised to 60 GeV and $m_{\ell\ell}$ is required to be greater than 120 GeV to reject DY Z boson production. In the $e\mu$ category, only a residual DY contribution (from $\tau^+\tau^- \to e\mu$ events) remains.

The SR is further split into two regions to optimize the signal significance. The categorization is based on the centrality of the dilepton system with respect to the tagging jets, quantified by the so-called Zeppenfeld variable [52] $Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|$, where $Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$ with η_ℓ, η_{j_1}, and η_{j_2} being the pseudorapidities of the lepton and two jets, respectively. The categories with $Z_{\ell\ell} < 1$ are enriched with signal and have less background contamination. Post-fit event yields are shown in Table 1.

The $t\bar{t}$ CRs are defined by inverting the b jet veto and thus requiring the presence of at least one b jet with $p_T > 20$ GeV in the final state, resulting in a $\approx 95\%$ pure $t\bar{t}$ sample. In the DY CRs, the b veto requirement is the same as that in the SR. In the DY $e\mu$ category, the m_T requirement is reversed with respect to the SR and a $50 < m_{\ell\ell} < 80$ GeV window is selected. In DY ee and $\mu\mu$

Table 1
Post-fit process yields and uncertainties in each SR (ee and μμ final states combined).

Process	SR eμ $Z_{\ell\ell} < 1$	SR eμ $Z_{\ell\ell} > 1$	SR ee - μμ $Z_{\ell\ell} < 1$	SR ee - μμ $Z_{\ell\ell} > 1$
DATA	2441	2192	1606	1667
Signal + background	2396.8 ± 98.5	2239.6 ± 106.0	1590.4 ± 49.4	1660.5 ± 43.6
Signal	169.1 ± 20.2	69.9 ± 8.4	98.0 ± 6.5	38.3 ± 2.5
Background	2227.7 ± 96.4	2169.7 ± 105.6	1492.4 ± 48.9	1622.1 ± 43.5
$t\bar{t} + tW$	1629.4 ± 71.4	1452.5 ± 69.5	767.8 ± 14.5	642.5 ± 13.2
WW (QCD)	327.0 ± 61.6	409.3 ± 77.3	111.1 ± 16.6	121.5 ± 17.3
Nonprompt	107.0 ± 18.4	109.9 ± 16.4	30.0 ± 4.9	32.0 ± 4.2
DY no PU jets	–	–	259.5 ± 27.3	408.3 ± 17.1
DY + 1 PU jets	–	–	222.7 ± 33.3	337.4 ± 32.9
$DY\tau^+\tau^-$	69.2 ± 4.6	102.0 ± 5.8	–	–
Multiboson	67.7 ± 6.6	75.6 ± 7.3	60.9 ± 3.8	60.1 ± 4.8
Zjj	1.0 ± 0.2	0.4 ± 0.0	40.5 ± 4.2	20.3 ± 1.3
Higgs	26.6 ± 1.5	20.1 ± 1.0	–	–

categories, the dilepton mass is chosen to be close to the Z boson mass peak, $|m_{\ell\ell} - m_Z| < 15$ GeV. Moreover, the DY ee and μμ CRs are divided in two $|\Delta\eta_{jj}|$ bins, as explained in Section 5. The fraction of DY events in the DY CRs are ≈ 64% and ≈ 91% for the eμ and ee/μμ categories, respectively. A summary of all regions included in the analysis is shown in the supplemental material [https://dx.doi.org/10.1016/j.physletb.2022.137495].

5. Background estimation and signal extraction

The normalizations of the major backgrounds are measured by a simultaneous fit of data, including CRs. For the $t\bar{t}$ background the determination mainly comes from the dedicated $t\bar{t}$ CR.

In the ee and μμ categories, DY production is one of the leading background sources, typically arising when a lepton pair is reconstructed with high p_T^{miss} due to instrumental effects. A large fraction of the DY background (≈50%) comes from events where at least one of the two jets originates from a pileup vertex, whereas the remaining DY events are fully associated with the "hard" interaction, in which the two highest p_T jets are radiated by initial-state quarks. These two backgrounds are measured as two independent processes and scaled with different parameters during the fit. Hence, the normalization of the DY background is determined from separate CRs with $|\Delta\eta_{jj}| < 5$ (dominated by events where the jets originate from initial-state QCD radiation) and $|\Delta\eta_{jj}| > 5$ (dominated by events where at least one of the jets comes from a pileup interaction). A third, minor source of DY background is ττ events, and its normalization is determined from the eμ category.

In contrast, there is no CR purely enriched by nonresonant QCD-induced W^+W^- events. The normalization of this background is left to float freely and is determined by the global fit in all regions.

Nonprompt leptons, i.e., either leptons produced in decays of hadrons or jets misidentified as leptons, come mainly from W + jets events. This background is directly estimated from data by applying a transfer function to events entering a W + jets CR, where one of the two leptons fails either the tight identification or isolation criteria applied in the SR, but passes a looser selection [53]. The transfer function is determined in a separate control sample by measuring the rate of objects satisfying loose lepton requirements that also pass the signal lepton criteria. Triggers requiring either one electron and one jet, or a single muon are applied to select this control sample. In both cases, the lepton must be well separated from the highest p_T jet, and the contribution from leptons originating from W boson decays is suppressed by requiring $p_T^{miss} < 20$ GeV. The remaining contamination of prompt leptons from the EW production of a Z boson in association with jets is estimated from simulation and removed.

Other minor backgrounds, such as the Higgs boson and multiboson production, are estimated entirely from simulation.

In the eμ signal category a feed-forward deep neural network (DNN) is used to separate the VBS signal from the $t\bar{t}$ and QCD-induced W^+W^- backgrounds. For optimization purposes, separate DNN models were built for the subregions with low ($Z_{\ell\ell} < 1$) and high ($Z_{\ell\ell} > 1$) values of the Zeppenfeld variable. The two models share the same architecture and are fit using nine discriminating variables, which are chosen from a larger set of observables; these variables are listed in Table 2. The DNN implementation comprises five fully connected hidden layers, the first two (last three) having 128 (64) nodes each, that are trained with the stochastic gradient descent technique of the "Adam" optimizer tool [54] to achieve a good separation of signal and backgrounds. A binary cross-entropy loss function [55,56] is minimized in both models. The m_{jj} and $|\Delta\eta_{jj}|$ post-fit distributions are shown as an example in the supplemental material [URL will be inserted by publisher], and they agree with SM predictions within post-fit uncertainties. These distributions are also shown in the ee and μμ combined top CRs, where the data is in excellent agreement with the simulation. The DNN output is illustrated in the eμ top CR too; less than 5% residual shape dependence is observed. Such disagreement is mostly concentrated in background-dominated regions of the spectrum, and we have checked that it does not affect the signal extraction.

Table 2
Set of variables used as inputs to the DNN for both $Z_{\ell\ell} < 1$ and $Z_{\ell\ell} > 1$ models. The order in the table corresponds to the importance of the discriminating variable for the $Z_{\ell\ell} < 1$ model, as obtained through the SHAP method [57,58].

Variable	Description
m_{jj}	Invariant mass of the two tagging jets pair
$p_T^{j_1}$	p_T of the highest p_T jet
$\lvert\Delta\eta_{jj}\rvert$	Pseudorapidity separation between the two tagging jets
$p_T^{j_2}$	p_T of the second-highest p_T jet
Z_{ℓ_2}	Zeppenfeld variable of the second-highest p_T lepton
$p_T^{\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest p_T lepton
$m_T^{\ell_1}$	Transverse mass of the $(p_T^{\ell_1}, p_T^{miss})$ system

The signal strength modifier of EW W^+W^- production, $\mu_{EW} = \sigma^{obs}/\sigma^{SM}$, is the parameter of interest and is translated to a cross section measurement in two different fiducial volumes; more details are given in Section 7. The signal extraction procedure is based on a binned maximum likelihood fit of the chosen discriminating variable distribution, as specified in the next paragraphs, with signal and background templates, performed simultaneously in all categories. CRs are included as single-bin templates where the number of events is fit to data.

In the eμ SRs, the binned DNN output is chosen as the discriminating variable. The DNN output spans a range between 0 and 1 and can be interpreted as the probability of each event to be identified as signal. Therefore, high DNN values are signal-enriched, whereas background samples mostly populate the low DNN spec-

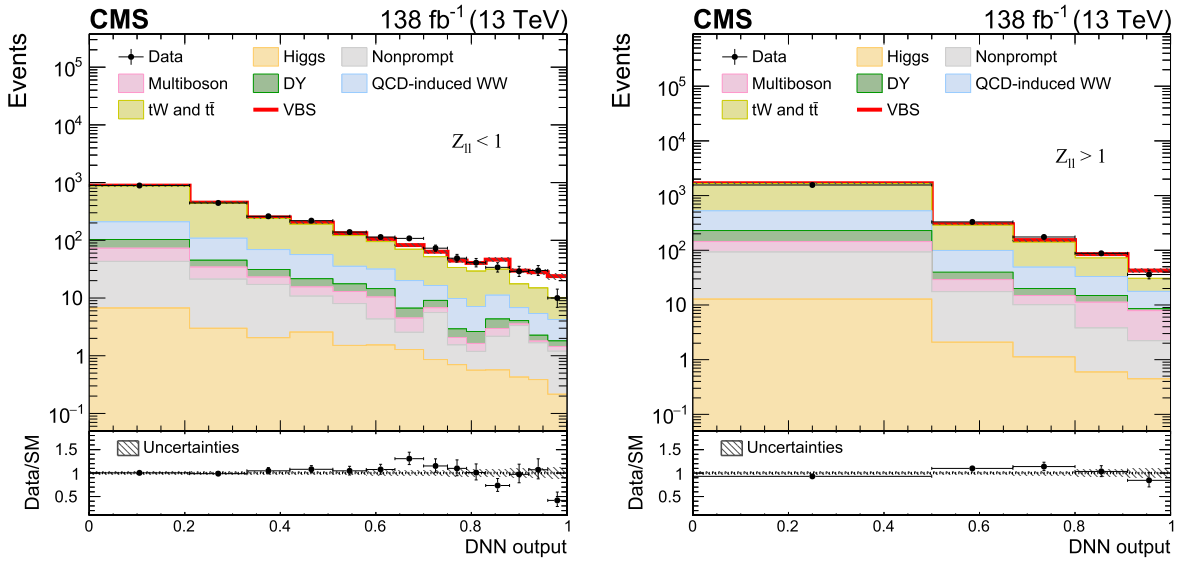

Fig. 2. Post-fit DNN output distribution in different-flavor SRs for $Z_{\ell\ell} < 1$ (left) and $Z_{\ell\ell} > 1$ (right) categories. This variable quantifies how likely each event is signal. The contributions from background and signal (red line) processes are shown as stacked histograms; systematic uncertainties are plotted as dashed gray bands. Data points are displayed with asymmetric Poisson vertical bars to ensure a correct statistical coverage all over the spectrum.

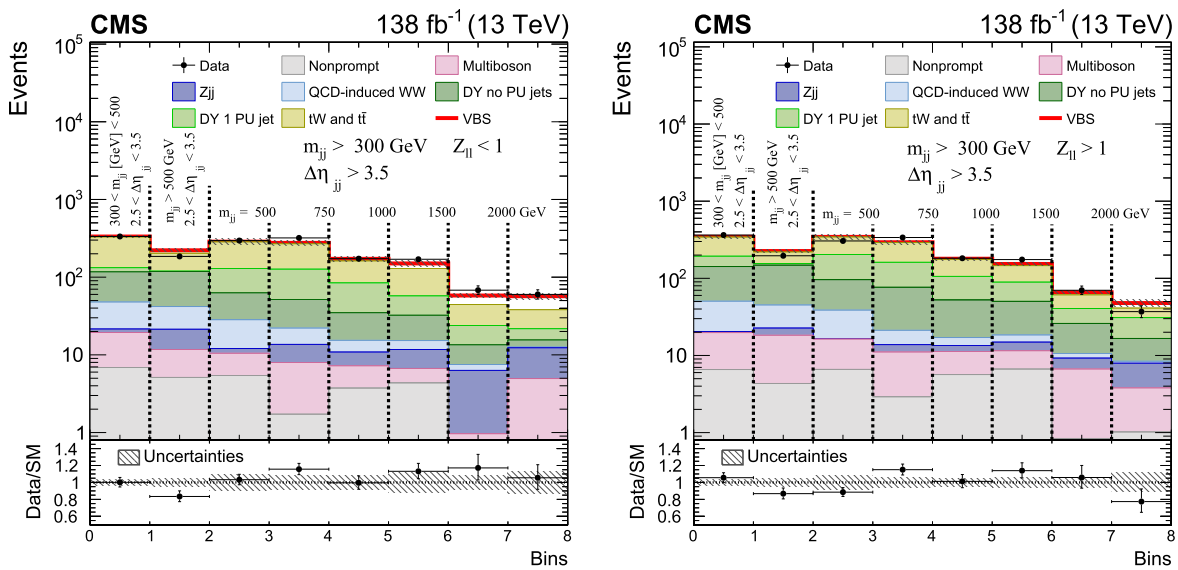

Fig. 3. Post-fit m_{jj} distribution and number of events in same-flavor (ee and $\mu\mu$ combined) SRs for $Z_{\ell\ell} < 1$ (left) and $Z_{\ell\ell} > 1$ (right) categories. The first two bins contain the number of events in the selected region (as reported in the plots themselves). The third bin contains the number of events in the $300 < m_{jj}[\,\text{GeV}] < 500$ and $|\Delta\eta_{jj}| > 3.5$ regions and, for display purposes, is included in the m_{jj} distribution, shown in the last five bins. The contributions from background and signal (red line) processes are shown as stacked histograms; systematic uncertainties are plotted as dashed gray bands. Data points are displayed with asymmetric Poisson vertical bars to ensure a correct statistical coverage all over the spectrum.

trum. In the ee and $\mu\mu$ SRs, different discriminating variables are chosen as a function of m_{jj} and $|\Delta\eta_{jj}|$. For $m_{jj} > 500\,\text{GeV}$ and $|\Delta\eta_{jj}| > 3.5$, where the signal-to-background ratio is the largest, m_{jj} is used. The remaining phase space is divided into three bins for each flavor composition (ee and $\mu\mu$) and $Z_{\ell\ell}$ category ($Z_{\ell\ell} < 1$ and $Z_{\ell\ell} > 1$), the number of events in each region being the discriminating variable. The bins are defined as follows:

- $300 < m_{jj} < 500\,\text{GeV}$ and $2.5 < |\Delta\eta_{jj}| < 3.5$;
- $m_{jj} > 500\,\text{GeV}$ and $2.5 < |\Delta\eta_{jj}| < 3.5$;
- $300 < m_{jj} < 500\,\text{GeV}$ and $|\Delta\eta_{jj}| > 3.5$.

The number of events in each bin of the templates included in the likelihood function is modeled as a Poisson random variable, with a mean value that is the sum of the contributions from all processes. Systematic uncertainties are represented by individual nuisance parameters with log-normal distributions. The uncertainties affect the overall normalizations of signal and background processes, as well as the shapes of the distributions of the observables. The nuisance parameters associated to shape uncertainties are given by a unit Gaussian distribution. Correlations between systematic uncertainties in different categories are included.

Figs. 2 and 3 show the observed post-fit distributions for the full data set in bins of the DNN output for the eμ category, and in bins of m_{jj} and $|\Delta\eta_{jj}|$ for the ee and $\mu\mu$ categories. Similarly, Fig. 4 shows the number of post-fit events in the CRs. The difference between data and MC in the last bin of the DNN output for $Z_{\ell\ell} < 1$ in Fig. 2 was investigated by verifying that input variables

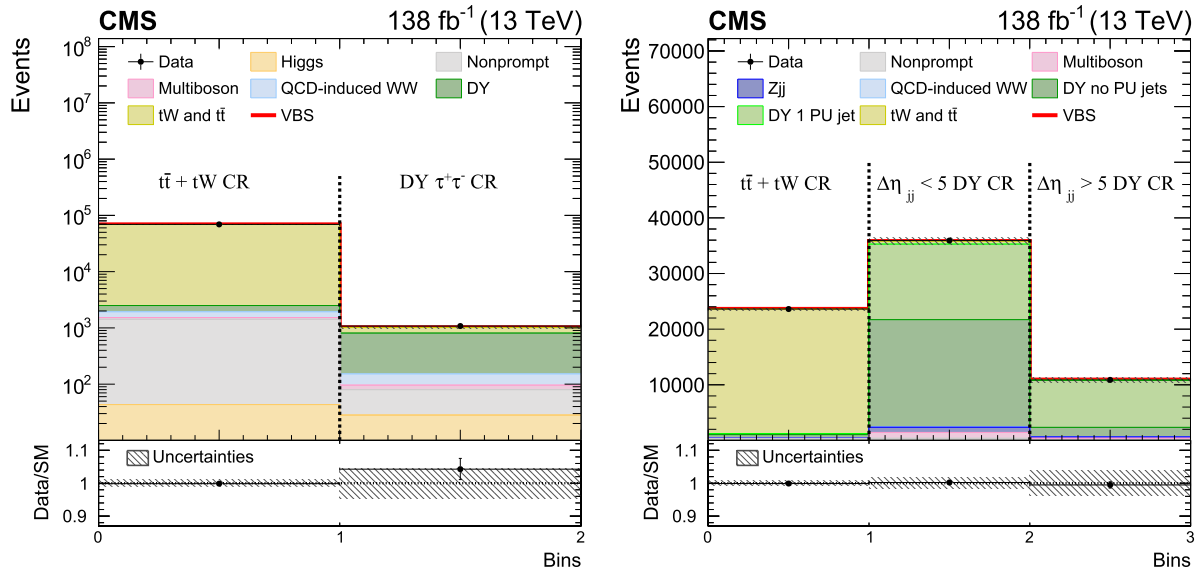

Fig. 4. Post-fit number of events in different-flavor (left) and same-flavor (right, with ee and $\mu\mu$ combined) CRs. In the left plot, the first bin contains the number of events in the $t\bar{t}+tW$ different-flavor CR, and the second bin those in the DY $\tau\tau$ CR. In the right plot, the first bin contains the number of events in the $t\bar{t}+tW$ same-flavor CR, the second bin those in the $|\Delta\eta_{jj}| < 5$ DY CR, and the third bin those in the $|\Delta\eta_{jj}| > 5$ DY CR. The contributions from background and signal processes (red line) are shown as stacked histograms; systematic uncertainties are plotted as dashed gray bands. Data points are displayed with asymmetric Poisson vertical bars to ensure a correct statistical coverage all over the spectrum.

reasonably agreed with data at DNN > 0.88. The discrepancy is not localized in any bins of such distributions and, because of the good modeling of the top background, is therefore considered to be compatible with a statistical under-fluctuation of data.

6. Systematic uncertainties

Uncertainties in the integrated luminosity, lepton reconstruction and identification efficiency [59,51], trigger efficiency and additional trigger timing shift are taken into account. The electron and muon momentum scale uncertainties are computed by varying the momenta of leptons within one standard deviation from their nominal value. Similarly, jet energy scale and resolution uncertainties [22] are evaluated by shifting the p_T of the jets by one standard deviation, and this directly affects the reconstructed jet multiplicity and p_T^{miss} measurement: several independent sources are considered and partially correlated among different data sets. The uncertainties in the residual p_T^{miss} [23] are also included and calculated by varying the momenta of unclustered particles that are not identified with either a jet or a lepton. The b tagging [29] introduces various uncertainty sources. The uncertainties from the b tagging algorithm itself are correlated among all data sets, whereas uncertainties due to the finite size of the control samples are uncorrelated. Finally, the uncertainty in the pileup reweighting procedure is applied to all relevant simulated samples.

Among theoretical uncertainties, effects due to the choice of the renormalization and factorization scales are evaluated, to cover missing higher order terms in the perturbation series of cross section calculations. These are computed by varying the scales up and down independently by a factor of two with respect to their nominal values, ignoring the extreme cases where they are shifted in opposite directions [60,61]; the envelopes of the various distributions are taken as one standard-deviation variation. Only shape effects are included when varying these scales for theoretical uncertainties that affect the signal and main backgrounds, since their normalizations are directly measured in data.

The PDF uncertainties are computed as recommended by the NNPDF prescription [62]. In the signal process, they do not introduce any shape effect in the m_{jj} and DNN output distributions, hence they are not considered. For $t\bar{t}$ and DY backgrounds, since normalization effects have no impact in the fit, PDF uncertainties can only affect the ratio of the expected yields between the SR and the CR. Such uncertainties are included in the CR and estimated to be 1% and 2% for $t\bar{t}$ and DY backgrounds, respectively. The modeling of both the parton shower and the underlying event is included. For the former, the uncertainties are computed using PYTHIA by shifting the renormalization scale of a factor 2 and 0.5 for both initial and final state radiation; these variations are propagated to each sample, but only shape effects are retained for the signal. Underlying event uncertainties are derived from alternative samples obtained by varying the PYTHIA tune parameters as described in Ref. [48]. Two fiducial cross section measurements are provided. Therefore, two sets of theoretical uncertainties are computed as illustrated above in each fiducial volume.

A list of all systematic uncertainties in the cross section measurement is presented in Table 3 and refers to the fiducial volume in which signal candidates are selected, as discussed in Section 7. The systematic component of the overall relative uncertainty in the signal cross section measurement is 13.1%. The statistical uncertainty is evaluated by setting all sources of systematic uncertainty to their best-fit result and its value is 14.9%. The combined relative uncertainty in the cross section measurement is 19.8%.

7. Results

All categories are simultaneously fit to data using a maximum likelihood template fit. Expected results are assessed by using the Asimov data set [63], a pseudoexperiment in which data are set in each bin to the value provided by the prediction. The statistical significance of the signal is quantified by means of a p-value [64], converted to an equivalent Gaussian significance, which corresponds to the probability of observing data with a larger discrepancy with respect to the background-only hypothesis, under the asymptotic approximation [63]. The observed (expected) significance for the signal is 5.6 (5.2) standard deviations.

The EW W^+W^- production cross section is measured in two different fiducial volumes, one more inclusive and one closer to the region defined by kinematic criteria applied in the preselection. In

Table 3
Sources of systematic uncertainty affecting the cross section measurement by more than 1%. The total uncertainty is also reported, as well as the total systematic and statistical contributions.

Uncertainty source	Value
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ scale variation	5.1%
VBS signal scale variation	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Trigger corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
Unclustered p_T^{miss}	2.4%
QCD-induced W^+W^- scale variation	2.1%
Integrated luminosity	2.0%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	<1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%

Table 4
Definition of the fiducial volume similar to the reconstructed SR.

Objects	Requirements
Leptons	$e\mu$, ee, $\mu\mu$ (not from τ decay), opposite charge $p_T^{\text{dressed}\,\ell} = p_T^{\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$ $p_T^{\ell^1} > 25\,\text{GeV}$, $p_T^{\ell^2} > 13\,\text{GeV}$, $p_T^{\ell^3} < 10\,\text{GeV}$ $\lvert\eta\rvert < 2.5$ $p_T^{\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$
Jets	$p_T^{j} > 30\,\text{GeV}$ $\Delta R(j, \ell) > 0.4$ At least 2 jets, no b jets $\lvert\eta\rvert < 4.7$ $m_{jj} > 300\,\text{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$
p_T^{miss}	$p_T^{miss} > 20\,\text{GeV}$

the former one, parton-level requirements define the phase space of interest, in particular the two outgoing partons (qq') are required to have $p_T > 10\,\text{GeV}$ and an invariant mass $m_{qq'} > 100\,\text{GeV}$; τ leptons are included in the simulated signal sample, and their subsequent decay to leptons is included as part of the signal. The measured cross section is $99 \pm 20\,\text{fb}$, compared with the LO prediction of $89 \pm 5\,(\text{scale})\,\text{fb}$, where the theoretical uncertainty is computed by varying the factorization scale of the signal.

The other volume is defined as the preselection region where signal candidates are reconstructed, as outlined in Section 4, but kinematic requirements are transposed to generator-level. If a photon is found within a distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.1$ from a lepton, its four-momentum is added to that of the lepton, making a "dressed" lepton. Additionally, if such a lepton is found within a distance $\Delta R = 0.4$ from a jet axis, the event is discarded. Electrons and muons coming from a τ decay are vetoed. The missing transverse momentum is computed as the modulus of the vector sum of transverse momenta associated with all invisible particles generated in the event, and is required to be greater than 20 GeV. A summary of the requirements of such a fiducial volume is presented in Table 4. The measured fiducial cross section is $10.2 \pm 2.0\,\text{fb}$, while the LO theoretical prediction is $9.1 \pm 0.6\,(\text{scale})\,\text{fb}$.

8. Summary

The EW production of a pair of opposite-sign W bosons in association with two jets has been observed in a data set corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$ collected with the CMS detector at the CERN LHC in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. Tabulated results are provided in the HEPData record for this analysis [65]. Events containing two opposite-sign leptons (electrons or muons), missing transverse momentum, and two jets with large separation in pseudorapidity and high dijet invariant mass were selected. A deep neural network was employed to deal with the irreducible background from the QCD-induced production of W boson pairs, and the dominant background from the production of $t\bar{t}$ quark pairs.

The measured signal corresponds to an observed (expected) significance of 5.6 (5.2) standard deviations with respect to the background-only hypothesis. The EW W^+W^- production cross section has been measured in two fiducial volumes. In the more inclusive one, the cross section is $99 \pm 20\,\text{fb}$ ($89 \pm 5\,\text{fb}$ expected), whereas in that comparable with the experimental phase space the measured cross section is $10.2 \pm 2.0\,\text{fb}$ ($9.1 \pm 0.6\,\text{fb}$ expected). These results are compatible with standard model predictions within one standard deviation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in CMS data preservation, re-use and open access policy.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2022.137495.

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The CMS Collaboration

A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth [2], M. Jeitler [2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck [2], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz [2]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [3], E.A. De Wolf, T. Janssen, T. Kello [4], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Clerbaux, G. De Lentdecker, L. Favart, K. Lee, M. Mahdavikhorrami, I. Makarenko, S. Paredes, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Ghent University, Ghent, Belgium

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

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

G.A. Alves, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [5], E.M. Da Costa, G.G. Da Silveira [6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins [7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo [8], A. Vilela Pereira

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

C.A. Bernardes [6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

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

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

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

University of Sofia, Sofia, Bulgaria

T. Cheng, T. Javaid [9], M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen, Z. Hu, Y. Wang, K. Yi [10,11]

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen [9], H.S. Chen [9], M. Chen, F. Iemmi, A. Kapoor, H. Liao, Z.-A. Liu [12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

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

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

M. Lu, Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao [4], D. Leggat, H. Okawa, Y. Zhang

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

Z. Lin, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

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

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

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov [13], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger [13], M. Finger Jr. [13], A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla [14], E. Salama [15,16]

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

M.A. Mahmoud, Y. Mohammed

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, 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, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [17], P. Simkina, M. Titov, G.B. Yu

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

S. Ahuja, C. Baldenegro Barrera, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, J. Motta, M. Nguyen, C. Ochando, P. Paganini, L. Portales, J. Rembser, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

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

J.-L. Agram [18], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine [18], U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, 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, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, M. Vander Donckt, S. Viret

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

I. Bagaturia [19], I. Lomidze, Z. Tsamalaidze [13]

Georgian Technical University, Tbilisi, Georgia

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

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

A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, A. Pozdnyakov, Y. Rath, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad [20], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, D. Roy, A. Stahl [21], T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman [22], K. Borras [23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo [22], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari [24], N.Z. Jomhari, B. Kaech, A. Kasem [23], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, D. Krücker, W. Lange, K. Lipka, W. Lohmann [25], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham [26], V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger [22], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon [†], M. Van De Klundert, F. Vazzoler, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Albrecht, S. Bein, L. Benato, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, M. Hajheidari, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, C. Matthies, A. Mehta, L. Moureaux, A. Nigamova, K.J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, H. Stadie, G. Steinbrück, A. Tews

University of Hamburg, Hamburg, Germany

J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, W. De Boer [†], A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann [21], C. Heidecker, M. Horzela, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, 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. Wozniewski, S. Wunsch

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Csanád, K. Farkas, M.M.A. Gadallah [27], S. Lökös [28], P. Major, K. Mandal, G. Pásztor, A.J. Rádl, O. Surányi, G.I. Veres

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

M. Bartók [29], G. Bencze, C. Hajdu, D. Horvath [30,31], F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

S. Czellar, D. Fasanella, F. Fienga, J. Karancsi [29], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi [32], B. Ujvari [33]

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo [34], F. Nemes [34], T. Novak

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

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [35], R. Gupta, A. Kaur, H. Kaur, M. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh [36], A.K. Virdi

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber [37], M. Maity [38], P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri [39], D. Kumar [39], A. Muhammad, L. Panwar [39], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari [39]

Indian Institute of Technology Madras, Madras, India

K. Naskar [40]

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, M. Kumar, G.B. Mohanty

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [41], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [42], A. Nayak [42], P. Saha, N. Sur, S.K. Swain, D. Vats [42]

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

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

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

H. Bakhshiansohi [43], A. Gholami [44], E. Khazaie

Isfahan University of Technology, Isfahan, Iran

S. Chenarani [45], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,c,46], 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], W. Elmetenawee [a,b], F. Errico [a,b], L. Fiore [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], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], D. Ramos [a], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], Ü. Sözbilir [a], R. Venditti [a], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, 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], C. Ciocca [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [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,47], 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]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b,48], S. Costa [a,b,48], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,48], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], B. Camaiani [a,b], 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]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], F. Ferro [a], R. Mulargia [a], E. Robutti [a], S. Tosi [a,b]

[a] INFN Sezione di Genova, Genova, Italy
[b] Università di Genova, Genova, Italy

A. Benaglia [a], G. Boldrini [a], F. Brivio [a,b], F. Cetorelli [a,b], 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.T. Lucchini [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], B.S. Pinolini [a], S. Ragazzi [a,b], N. Redaelli [a], T. Tabarelli de Fatis [a,b], D. Valsecchi [a,b,21], D. Zuolo [a,b]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, 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,49], S. Meola [a,d,21], P. Paolucci [a,21], B. Rossi [a], C. Sciacca [a,b]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Università G. Marconi, Roma, 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], G. Grosso [a], L. Layer [a,50], E. Lusiani [a], M. Margoni [a,b], F. Marini [a], A.T. Meneguzzo [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], G. Strong [a], M. Tosi [a,b], H. Yarar [a,b], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, Italy

C. Aimè [a,b], A. Braghieri [a], S. Calzaferri [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]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

P. Asenov [a,51], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,51], A. Piccinelli [a,b], M. Presilla [a,b], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

P. Azzurri [a], G. Bagliesi [a], V. Bertacchi [a,c], L. Bianchini [a], T. Boccali [a], E. Bossini [a,b], D. Bruschini [a], 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], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a], 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]

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

P. Barria [a], 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]

[a] INFN Sezione di Roma, Roma, Italy
[b] Sapienza Università di Roma, Roma, 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], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a],

M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], A. Mecca [a,b], 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], M. Ruspa [a,c], K. Shchelina [a], 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], G. Umoret [a,b], A. Vagnerini [a,b]

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

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

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, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Korea

H. Kim, D.H. Moon

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim

Sejong 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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Maghrbi

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

K. Dreimanis, V. Veckalns

Riga Technical University, Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, S.Y. Hoh [52], Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [53], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, R. Reyes-Almanza, A. Sánchez Hernández

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

C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, J. Mijuskovic [54], N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

V. Avati, L. Grzanka, M. Malawski

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

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

P. Adzic [55], M. Dordevic, P. Milenovic, J. Milosevic

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

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, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, 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, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy [56], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

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

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

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon [†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, C. Caillol, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita [57], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, C. Lourenço, B. Maier, 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, 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. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas [58], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk [59], K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, M. Missiroli [60], L. Noehte [60], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

K. Androsov [59], M. Backhaus, P. Berger, A. Calandri, 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, L. Marchese, 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, J. Steggemann [59], R. Wallny

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

C. Amsler [61], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff [62], C.M. Kuo, W. Lin, A. Roy, T. Sarkar [38], S.S. Yu

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarseckin [63], Z.S. Demiroglu, F. Dolek, I. Dumanoglu [64], E. Eskut, Y. Guler [65], E. Gurpinar Guler [65], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [66], A. Polatoz, A.E. Simsek, B. Tali [67], U.G. Tok, S. Turkcapar, I.S. Zorbakir

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

G. Karapinar, K. Ocalan [68], M. Yalvac [69]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [70], O. Kaya [71], Ö. Özçelik, S. Tekten [72], E.A. Yetkin [73]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [64], Y. Komurcu, S. Sen [74]

Istanbul Technical University, Istanbul, Turkey

S. Cerci [67], I. Hos [75], B. Isildak [76], B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek, D. Sunar Cerci [67], C. Zorbilmez

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [77], K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg [79], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal [80], 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. Nash [81], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee [21], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, TX, USA

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

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio [82], C. West

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez [23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan [83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir [84], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, 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, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Davis, Davis, CA, 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, Los Angeles, CA, USA

Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, CA, USA

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

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

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

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

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

California Institute of Technology, Pasadena, CA, USA

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

Carnegie Mellon University, Pittsburgh, PA, USA

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

University of Colorado Boulder, Boulder, CO, USA

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

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, 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, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, 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, J. Ngadiuba, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena [85], F. Ravera, A. Reinsvold Hall [86], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, D. Guerrero, 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. Wang, Z. Wu, E. Yigitbasi, X. Zuo

University of Florida, Gainesville, FL, 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 State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy [16], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, USA

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

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

M. Alhusseini, K. Dilsiz [87], L. Emediato, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [88], J. Nachtman, H. Ogul [89], Y. Onel, A. Penzo, C. Snyder, E. Tiras [90]

The University of Iowa, Iowa City, IA, USA

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

Johns Hopkins University, Baltimore, MD, USA

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

The University of Kansas, Lawrence, KS, USA

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

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA

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

University of Maryland, College Park, MD, USA

D. Abercrombie, G. Andreassi, R. Bi, 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, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, MA, USA

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

University of Minnesota, Minneapolis, MN, USA

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

University of Nebraska-Lincoln, Lincoln, NE, USA

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

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

G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Hortiangtham, A. Krishna, J. Li, J. Lidrych, 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

Northeastern University, Boston, MA, USA

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

Northwestern University, Evanston, IL, USA

R. Band, R. Bucci, M. Cremonesi, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[13], R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

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

The Ohio State University, Columbus, OH, 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, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, USA

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

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, L. Zhang [91], Y. Zhang

Rice University, Houston, TX, 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, G.P. Van Onsem

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban [25], 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

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

H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali [92], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [93], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

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

Texas Tech University, Lubbock, TX, USA

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

Vanderbilt University, Nashville, TN, USA

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

University of Virginia, Charlottesville, VA, USA

N. Poudyal

Wayne State University, Detroit, MI, USA

S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, 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

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov [94], E. Boos, V. Borshch, D. Budkouski, O. Bychkova, V. Chekhovsky, R. Chistov [94], M. Danilov [94], A. Dermenev,

T. Dimova [94], I. Dremin, M. Dubinin [85], L. Dudko, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev [94], V. Karjavine, A. Karneyeu, V. Kim [94], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova [95], D. Konstantinov, V. Korenkov, A. Kozyrev [94], N. Krasnikov, E. Kuznetsova [96], A. Lanev, A. Litomin, O. Lukina, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev [94], V. Murzin, A. Nikitenko [97], S. Obraztsov, V. Okhotnikov, V. Oreshkin, A. Oskin, I. Ovtin [94], V. Palichik, P. Parygin, A. Pashenkov, V. Perelygin, G. Pivovarov, S. Polikarpov [94], V. Popov, O. Radchenko [94], M. Savina, V. Savrin, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen [94], S. Slabospitskii, I. Smirnov, V. Smirnov, A. Snigirev, D. Sosnov, A. Stepennov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, M. Toms, A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov, S. Volkov, A. Vorobyev, N. Voytishin, B.S. Yuldashev [98], A. Zarubin, I. Zhizhin, A. Zhokin

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

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[5] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[6] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[7] Also at UFMS, Nova Andradina, Brazil.
[8] Also at The University of the State of Amazonas, Manaus, Brazil.
[9] Also at University of Chinese Academy of Sciences, Beijing, China.
[10] Also at Nanjing Normal University Department of Physics, Nanjing, China.
[11] Now at The University of Iowa, Iowa City, Iowa, USA.
[12] Also at University of Chinese Academy of Sciences, Beijing, China.
[13] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[14] Also at Cairo University, Cairo, Egypt.
[15] Also at British University in Egypt, Cairo, Egypt.
[16] Now at Ain Shams University, Cairo, Egypt.
[17] Also at Purdue University, West Lafayette, Indiana, USA.
[18] Also at Université de Haute Alsace, Mulhouse, France.
[19] Also at Ilia 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 University of Hamburg, Hamburg, Germany.
[23] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[24] Also at Isfahan University of Technology, Isfahan, Iran.
[25] Also at Brandenburg University of Technology, Cottbus, Germany.
[26] Also at Forschungszentrum Jülich, Juelich, Germany.
[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] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[32] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[33] Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[34] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[35] Also at Punjab Agricultural University, Ludhiana, India.
[36] Also at UPES – University of Petroleum and Energy Studies, Dehradun, India.
[37] Also at University of Hyderabad, Hyderabad, India.
[38] Also at University of Visva-Bharati, Santiniketan, India.
[39] Also at Indian Institute of Science (IISc), Bangalore, India.
[40] Also at Indian Institute of Technology (IIT), Mumbai, India.
[41] Also at IIT Bhubaneswar, Bhubaneswar, India.
[42] Also at Institute of Physics, Bhubaneswar, India.
[43] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[44] Also at Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan, Iran.
[45] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[46] Also at Helwan University, Cairo, Egypt.
[47] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[48] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[49] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[50] Also at Università di Napoli 'Federico II', Napoli, Italy.
[51] Also at Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy.
[52] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.

[53] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[54] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[55] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[56] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[57] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[58] Also at National and Kapodistrian University of Athens, Athens, Greece.
[59] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[60] Also at Universität Zürich, Zurich, Switzerland.
[61] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[62] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[63] Also at Şırnak University, Sirnak, Turkey.
[64] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[65] Also at Konya Technical University, Konya, Turkey.
[66] Also at Izmir Bakircay University, Izmir, Turkey.
[67] Also at Adiyaman University, Adiyaman, Turkey.
[68] Also at Necmettin Erbakan University, Konya, Turkey.
[69] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[70] Also at Marmara University, Istanbul, Turkey.
[71] Also at Milli Savunma University, Istanbul, Turkey.
[72] Also at Kafkas University, Kars, Turkey.
[73] Also at Istanbul Bilgi University, Istanbul, Turkey.
[74] Also at Hacettepe University, Ankara, Turkey.
[75] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[76] Also at Yildiz Technical University, Istanbul, Turkey.
[77] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at University of Bristol, Bristol, United Kingdom.
[80] Also at IPPP Durham University, Durham, United Kingdom.
[81] Also at Monash University, Faculty of Science, Clayton, Australia.
[82] Also at Università di Torino, Torino, Italy.
[83] Also at Bethel University, St. Paul, Minnesota, USA.
[84] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[85] Also at California Institute of Technology, Pasadena, California, USA.
[86] Also at United States Naval Academy, Annapolis, Maryland, USA.
[87] Also at Bingol University, Bingol, Turkey.
[88] Also at Georgian Technical University, Tbilisi, Georgia.
[89] Also at Sinop University, Sinop, Turkey.
[90] Also at Erciyes University, Kayseri, Turkey.
[91] Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) – Fudan University, Shanghai, China.
[92] Also at Texas A&M University at Qatar, Doha, Qatar.
[93] Also at Kyungpook National University, Daegu, Republic of Korea.
[94] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[95] Also at Yerevan Physics Institute, Yerevan, Armenia.
[96] Also at University of Florida, Gainesville, Florida, USA.
[97] Also at Imperial College, London, United Kingdom.
[98] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.